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Aerodynamic Performance Analysis of A Flat plate Hawt

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Abstract:- ***Composite material design has almost become routine due to the palpable advantages like considerable weight saving and opportunity to adapt the structure to the given set of design requirements. Pollution free electricity generation, low operation and maintenance costs, quick installation, commissioning capability, free renewable energy are the added advantages of wind electric generators. This paper also addresses the design parameters of composite wind turbine blades. The key factors for proper utilization of wind power and designing wind energy conversion systems are the performance characteristics of available wind energy conversion system and the availability of wind resources. The performance characteristics depend on the aerodynamic, mechanical and electrical subsystems whereas the wind resources depend on the weather conditions of the region. The goal in designing a wind turbine is to attain highest possible output under specified atmospheric conditions and profit from better structural model using suitable composite material and optimization techniques in manufacturing. Determining optimal shape of the blade and optimal composite material is complex one, as the mathematical description of aerodynamic load is complex and it should satisfy both the constraints and objectives of the problem. This paper incorporates the performance and design aspects, siting requirements, classification of wind electric conversion systems, choice of rotors and generators, environmental aspects and optimization concepts of wind turbine rotors.***

Index Terms:- ***Aerodynamic, Composite material, Wind-Electric Conversion Systems, Optimization***

I. INTRODUCTION

1. *PERFORMANCE AND DESIGN ASPECTS OF HORIZONTAL AXIS WIND TURBINE*

Designing wind turbines to achieve satisfactory levels of performance and durability should have deep knowledge in the factors affecting wind power, aerodynamic forces acting in the turbine. Energy conservation, pollution prevention, resource efficiency, systems integration and life cycle costing are very important terms for sustainable construction. Designing wind turbine principles includes: (i) minimizing non-renewable resource consumption, (ii) enhancing the natural environment and (iii) eliminating or minimizing the use of toxins, thus combining energy efficiency with the impact of materials on occupants [1]. Therefore, possible use of wind energy must be evaluated in terms of its impact on the environment.

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1.1. *POWER AVAILABLE IN THE WIND*

The three factors that determine the output from a wind energy converter are wind speed, cross-section of wind swept by rotor, and overall conversion efficiency of the rotor, transmission system and generator. Energy available in wind is equal to the kinetic energy of wind. If ρ is the density of the air in kg/m^3, A is the swept area in m^2, and V_m is the mean velocity of wind in m/s, then total wind power available, P_a,

$$P_a = \frac{m_w . V_m{}^2}{2} Watts = \frac{\rho . A . V_m{}^3}{2} Watts$$

The above equation shows that the wind power varies as the cube of the wind velocity. However density varies with pressure, temperature and relative humidity. Unfortunately, the total wind energy cannot be recovered in a wind turbine because the output wind velocity cannot be reduced to zero, otherwise there would be no flow through the turbine [2]. Let V_i be the inlet wind velocity and V_o be the outlet wind velocity, $m_w = \rho\ A\ V_{ave}$ be the mass flow rate with average velocity $(V_i + V_o)/2$ and the power recovered from the wind (P_{out}) is equal to the rate of change in the kinetic energy.

$$P_{out} = m_w (V_i^2 - V_o^2) / 2$$
$$= \rho\ A\ V_{ave} (V_i^2 - V_o^2) / 2$$
$$= (\rho\ A) (V_i + V_o) /2 (V_i^2 - V_o^2) / 2$$
$$= (\rho\ A / 4) (V_i^3 + V_i^2 V_o - V_i V_o^2 - V_o^3) / V_i^3$$

Take $x = V_o / V_i$

$$P_{out} = (1 + x - x^2 - x^3) P_a /2 \quad \text{------}\rightarrow (1)$$

Differentiating (1) with respect to x and equating to zero, we get the optimum value of x for maximum power output.

$$d(P_{out}) /dx = 0$$
$$\Rightarrow \quad 1 - 2x - 3x^2 = 0$$

Solving the quadratic equation, the value of x = 1/3.

Substituting the value of x in (1), we get

$$P_{out\ max.} = 0.593\ P_a$$

Thus the maximum that can be drawn from the wind system is 59.3 % of the total wind power available, which is called Betz limit in aerodynamics.

The power coefficient C_p is defined as [3]

$$C_p = \frac{P_s}{\frac{1}{2} . \rho . \pi . R^2 . U_o{}^3}$$

where, P_s is the shaft power output in Watts, U_o is the upstream undisturbed wind speed in m/s. The power performance of a wind turbine can be expressed using fixed angular velocity. This parameter is defined as

$$C_M = \frac{C_p}{\lambda}$$

Wind turbines have various C_p values depending on the wind velocity. Therefore, their efficiency is best represented by a C_p–k curve. The tip speed ratio, λ, is given by

$$\lambda = \frac{\omega R}{V}$$

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where λ is tip speed ratio, R is maximum rotor radius (m), ω is rotor speed (rad/s) and V is wind velocity (m/s).
The available wind energy, E_a in the time period T is given by [4]

$$E_a = \int_T P_a dt = \frac{1}{2}\rho A \int_T V_m^{\ 3} dt$$

$$= \frac{1}{2}\rho A V_m^{\ 3} = E_{as} A$$

where V_m^3 and E_{as} are the cubic mean wind speed and the available energy flux in the period T.

1.2. ELECTRICAL POWER OUTPUT

The power in the wind is converted into mechanical power with power coefficient C_p, with generator efficiency η_g, and mechanical power transmission efficiency η_m, then the electrical power output P_e is given as

$$P_e = C_p.\eta_g.\eta_m.P_a \text{ Watts}$$

Optimum values of C_p, η_g and η_m are 0.45, 0.9 and 0.95 respectively which give an overall efficiency of 38 %. Actual values will probably range between 25 and 30 % [2] which may vary with wind speed, type of turbine and the nature of load. As the wind increases from a low value, the turbine overcomes all mechanical and electrical losses and start delivering electrical power to the load at cut – in – speed V_C. Rated output power will reach at rated wind speed V_R, above which constant power output is maintained. At the furling speed V_F, the machine is shut down to protect it from high winds.

The efficiency of a wind turbine is usually characterized by its power coefficient as given below. Maximum values of C_p can be 0.5926 according to Betz criteria [5].

$$C_{pe} = \frac{I.V}{\eta_{mech}.\eta_{alternator}.\frac{1}{2}.\rho.R^2.V^{\ 3}}$$

1.3. BLADE DESIGN

1.3.1. AERODYNAMIC DESIGN

Blade design consists of aerodynamic and structural design. The challenge is designing rotor blades for different applications with optimised weight and aerodynamic performance. The major applications of rotor blades are: (i).Stall control with constant speed, (ii). Stall control with variable speed, (iii). Pitch control with constant speed, (iv). Pitch control with variable speed. The usage of advanced design tools, production technology and material choice are the dominating parameters. As the power curve is based on the C_p – λ characteristics of a certain rotor blade, the main parameters for obtaining an optimum power curve is the rotor diameter, rotational speed and pitch angle [7]. The design of the windmill blade depends on the following parameters: diameter of windmill D, aerofoil characteristics (C_L, C_D versus angle of incidence) and the number of blades Z [8].

1.3.2. PRODUCTION TECHNOLOGY

With composite material, production technology influences significantly the design. In the field of rotor blade production, the traditional hand lay-up procedure using polyester and/or epoxy resin as matrix material together with glass fibres will be substituted in the near future by more advanced technologies. The application of preimpregnated material usually suffer from too high material costs, as it is more economic to use the raw materials itself in the production, thus using resin and fibres. An on-line impregnation technology during the production is to be used for an adequate production of unidirectional stiffeners. The usage of raw materials, such as filaments of glass fibre, is generally said cheaper than using fabrics with different lay-up combinations. Therefore, a compromise has to be found between the usage of the different raw materials and its consequences in design, especially in the flexibility of the structure.

1.3.3. MATERIAL PROPERTIES

Basically, there exist four material groups used for rotor blades: Epoxy resin/glass fibre, Polyester resin/glass fibre, Epoxy resin/wood, Epoxy resin/carbon-glass fibres. Further improvements in the material choice, such as using carbon fibres in a hybrid system together with glass fibres has been used for rotor blades larger than 25 m, as a sufficient bending stiffness is required [7]. Combined with an optimised structural design and thick profiles, it is also possible to use only glass fibres for rotor blade with a length of 30 m. The weight/strength ratio is the driving parameter for the determination of the optimum material and lay-up combination. Sandwich structures with foams are necessary for the structural stability. On the other hand, material damping is one of the mayor issues concerning the dynamic behavior of the complete system rotor blades-wind turbines, especially for epoxy/glass fibre and polyester resin/glass fibre systems. The material wood, combined with epoxy resin, seems theoretically to have excellent performance. Most of the wind turbine blades are made of fiberglass reinforced with polyester or epoxy resin. Small turbine blades are made of steel or aluminium, but the drawback is huge weight. Lighter and more effective blades decrease material requirements for other wind turbine component making overall costs to be lower. Materials with lower density such as fiber aramid (Technora) have higher natural frequencies and bigger deflection [9]. Blades made of fiberglass can be reconstructed with carbon based composites to reduce mass and increase its stiffness.

Suggestions for increasing performance and safety of windmill systems listed by Onder Ozgener [5] are as follows.

- Blades can be made of epoxy–carbon fiber or glass fiber reinforced plastics.
- To produce a smooth surface a steel mold can be used.
- A long and narrow airfoil can be selected having larger aspect ratio than the classical (short and wide wing) blade.
- Steel blades should not be used due to their weight and corrodibility.
- Lighting protection can be provided for GRP epoxy–carbon fiber blades.
- There is no requirement that the same profile should be used throughout the blade length.

1.3.4. WEIGHT

The blade mass is one of the most important parameters for dynamic loads of blade and wind turbine. The aim is to achieve an optimum between a low weight blade, related to low-cost production and a high performance. The blade weight can be reduced by thick profiles, thus increasing the moment of inertia of the blade cross section. This allows, taking into account the material elastic properties, a high bending stiffness.

1.3.5. NOISE

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The major sources of noise emission of rotor blades [7] are (i). Turbulence in flow noise, (ii). Trailing edge, (iii). Tip. The aerodynamic lay-out, which aims an optimum aerodynamic performance, is influenced by the obligation to design low-noise profiles and to adapt the structural lay-out, especially the profile thickness Furthermore, dirt on the blade surface contributes to noise emission.

1.3.6. LIGHTNING PROTECTION

The most typical damage due to lightning is at the tip region, where the increasing temperature leads to the build-up of air pressure. Therefore, a metal alloy receptor is integrated in the tip region, and a metal stripe inside the blades transports the energy to the blade root connection. From there, the energy is transported to earth through the turbine structure. With this lightning receptor, it is only necessary to repair the area around the tip.

1.4. WIND STATISTICS

Wind is a highly variable power source, and there are several methods of characterizing this variability. The most common method is the power duration curve which is a good concept but is not easily used to select V_C and V_R for a given wind site, which is an important design requirement. Another method is to use a statistical representation, particularly a Weibull function [2]. Local values of wind velocity should be 3 m/s or higher, and the wind should be steady, to produce electricity effectively [5].

1.5. WIND ELECTRIC CONVERSION SYSTEMS

Wind electric conversion systems can be broadly classified as follows:

1.10.1. BASED ON THE SIZE OF USEFUL ELECTRICAL POWER OUTPUT

(i) Small size (up to 2 kW)

These may be used for applications requiring relatively low power.

(ii) Medium size (2–100 kW)

These turbines may be used to supply less than 100 kW rated capacity to several residences or local use.

(iii) Large size (100 kW and up)

They are used to generate power for distribution in central power grids.

1.10.2. ACCORDING TO THE ROTATIONAL SPEED OF THE AEROTURBINE

(I). CONSTANT SPEED CONSTANT FREQUENCY (CSCF)

In the CSCF scheme, the rotor is held constant by continuously adjusting the blade pitch and generator characteristics. For synchronous generators, the requirement of constant speed is very rigid and only minor fluctuations of about 1% for short durations could be allowed [2]. As the wind fluctuates, a control mechanism becomes necessary to vary the pitch of the rotor so that the power derived from the wind system is held fairly constant. Such a control is necessary since wind power varies with the cube of the wind velocity. During gusty periods, the machine is subjected to rapid changes in the input power. The control mechanism must be sensitive enough to damp out these transients so that the machine output does not become unstable. Such a mechanism is expensive and adds complexity to the system. Induction generators with small negative slip can also be considered as constant speed. An induction generator can operate on a bus bar at a slip of 1–5% above the synchronous speed. Induction generators are simpler than synchronous generators. They are easier to operate, control and maintain, have no synchronization problem and are economical. The CSCF schemes that mostly employ synchronous generators [2] tend to be more expensive because of the precise blade pitch control mechanisms required on the wind turbine to maintain constant speed, as the synchronous generators run at constant speed, and hence, require costly speed controls. However, synchronous generators can supply reactive power to the system. If the electric power derived from wind is significant compared with the capacity of the grid system, synchronous machines stability becomes a serious problem.

(II). VARIABLE SPEED CONSTANT FREQUENCY (VSCF)

The variable speed operation of a wind electric system yields higher output for both low and high wind speeds. This results in higher annual energy yields per rated installed capacity. Both horizontal and vertical axis wind turbines (VAWT) exhibit this gain under variable speed operation. The VSVF scheme mostly employs an induction generator. In this scheme, the need for a costly blade control mechanism is avoided. An induction generator requires reactive power, but induction generators are low in initial cost, leading to an overall reduction of 5–10% in total system capital cost, and are maintenance free and most reliable. Generation schemes involving variable speed rotors are more complicated than constant speed systems. Variable frequency power must be converted to constant frequency power, and this can be done by using thyristors.

(III). VARIABLE SPEED VARIABLE FREQUENCY (VSVF)

Generally, resistive heating loads are less frequency sensitive. Synchronous generators can be affected at variable speed, corresponding to the changing drive speed. For this purpose, self-excited induction generators (SEIG) can be conveniently used. This scheme is gaining importance for stand alone wind power applications.

1.10.3. ACCORDING TO THE ORIENTATION OF TURBINES:

There are two classes of wind turbines, horizontal axis and vertical axis machines:

(I).HORIZONTAL AXIS WIND TURBINES

In horizontal axis wind turbines (HAWT), the axis of rotation is parallel to the direction of the wind. There may be many designs of horizontal axis wind mills. Depending upon the number of blades, these may be classified as single bladed, double bladed, three bladed, multi bladed and bicycle bladed. Depending upon the orientation of the blades with respect to wind direction these may be classified as up wind and down wind type. As the wind changes direction, all horizontal axis wind machines have some means for keeping the rotor into the wind. On smaller wind machines, such as the farm windmill, the tail vane keeps the rotor pointed into the wind, regardless of changes in wind direction. Both tail vanes and fan tails use forces in the wind itself to orient the rotor upwind of the tower.

(II).VERTICAL AXIS WIND TURBINES

In VAWT, the axis of rotation is perpendicular to the direction of the wind. These machines are also called cross wind axis machines. The main designs of vertical axis machines are the Savonious rotor and Darrieus rotor. The principal advantages of VAWT over conventional HAWT are that VAWT are omni-directional, i.e. they accept the wind from any direction.

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This simplifies their design and eliminates the problem imposed by gyroscopic forces on the rotor of conventional machines as the turbines yaw into the wind. The vertical axis rotation also permits mounting the generator and gear at the ground level. On the negative side, the VAWT requires guy wires attached to the top for support, which may limit its application, particularly for offshore sites.

1.6. CHOICE OF GENERATORS

There are mainly the following three classes of generators

(I). D.C. GENERATORS

DC generators are relatively unusual in wind/micro-hydro turbine applications because they are expensive and require regular maintenance. Nowadays it is more common to employ an a.c. generator to generate a.c., which is then converted to d.c. with simple solid state rectifiers.

(II). SYNCHRONOUS GENERATOR

The major advantage of synchronous generator is that its reactive power characteristic can be controlled, and therefore such machines can be used to supply reactive power to other items of power systems that require reactive power. It is normal for a stand alone wind-Diesel system to have a synchronous generator, usually connected to the Diesel engine. Synchronous generators, when fitted to a wind turbine, must be controlled carefully to prevent the rotor speed accelerating through synchronous speed especially during turbulent winds. Moreover, it requires a flexible coupling in the drive train, or to mount the gearbox assembly on springs or dampers to absorb turbulence. Synchronous generators are costlier than induction generators, particularly in smaller size ranges. Synchronous generators are more prone to failures.

(III). INDUCTION GENERATORS

An induction generator offers many advantages over a conventional synchronous generator as a source of isolated power supply. Reduced unit cost, ruggedness, brushless (in squirrel cage construction), reduced size, absence of separate DC source and ease of maintenance, self-protection against severe overloads and short circuits are the main advantages. Further, induction generators are loosely coupled devices, i.e. they are heavily damped and, therefore, have the ability to absorb slight changes in rotor speed, and drive train transients to some extent, can, therefore, be absorbed, whereas synchronous generators are closely coupled devices and when used in wind turbines, are subjected to turbulence and require additional damping devices, such as flexible couplings in the drive train or mounting the gearbox assembly on springs and dampers. Reactive power consumption and poor voltage regulation under varying speed are the major drawbacks of the induction generators, but the development of static power converters has facilitated control of the output of voltage of the induction generator, within limits.

1.7. THREE BASIC DESIGN PHILOSOPHIES

Designs for wind turbines have been driven by three basic design philosophies for handling wind loads

(i) withstanding the loads,
(ii) shedding or avoiding of loads
(iii) managing loads mechanically and/or electrically.

Based on the first design philosophy important characteristics of such designs are optimization for reliability, high solidity but non-optimum blade pitch, low tip speed ratio (TSR) and three or more blades [2]. Turbines based on the second design philosophy (Hutter design) have design criteria like optimization for performance, low solidity, optimum blade pitch, high TSR, etc. Designs based on the third philosophy (Smith Putnam), designed to manage the load mechanically and/or electrically, have design considerations like optimization for control, two or three blades, moderate TSR, mechanical and electrical innovations (flapping or hinged blades, variable speed/low speed generators). The second and third designs, based on shedding or avoiding of loads and managing loads mechanically and/or electrically, have been relatively later developments and are now becoming predominant. The third design utilizes direct mechanical or electrical intervention to mitigate turbine loads. This design is associated with utility projects or projects developed specifically to satisfy high utility power quality requirements.

1.8. WIND TURBINE DESIGN

A wind turbine is composed of a number of subsystems: rotor, power train, control and safety system, nacelle structure, tower, foundations etc. Modern wind turbine manufacturers must weigh many factors before selecting a final configuration for development. The intended wind environment is the most important consideration. Turbines designed for high wind or for use at highly fluctuating wind sites will generally have rotors of smaller diameter and more robust than turbines for lower wind sites. The design criteria specified by the International Electrotechnical Commission (IEC) base the design loads on the mean wind speed and the turbulence level. Minimizing cost is the next most important design criterion. In fact, cost is probably the key force that drives the designers towards increased innovation and diversity. Electricity generated by wind is still more expensive than power from conventional power plants, unless the environmental benefits of wind power are taken into account. If the cost of wind energy could be cut by an additional 30 – 50%, then it would be globally competitive. The goal to achieve this 30–50% reduction has inspired designers to look for cost reduction by increasing size, tailoring turbines for specific sites, exploring new structural dynamic concepts, developing custom generators and power electronics, as well as implementing modern control system strategies.

1.9. CHOICE BETWEEN TWO AND THREE BLADE ROTORS

Blades are one of the most critical components of a wind turbine rotor. Initially, blades were made from wood. Wooden blades were replaced by galvanized steel blades. Later, steel blades were also replaced by aluminium, which is lighter and stronger. In recent years, fiber glass as rotor blades is becoming very popular. Light weight, highly flexible turbines are usually two bladed and have a teeter hinge, coning hinges or .ex beams to allow blade motion to relieve the flap load, whereas structurally stiff and robust turbines are usually the three blade, upwind yaw driven type. The structural dynamic difference between two and three blades is the rotor moment of inertia. The three bladed rotor mass movements has polar symmetry, whereas the two bladed rotor mass movements do not have the same, so the structural dynamic equations for the two bladed turbine system are significantly more complex. The three bladed system governing equations have constant coefficients making them easier to solve and most importantly making the cause-and-effect relationship easier to understand.

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Often visual aesthetics, lower noise and polar symmetry are reasons for using three blade designs. However, the greater weight and higher cost of the three blades provide a compelling reason for designers to explore the possibilities of two blade rotors more thoroughly.

1.10.WEIGHT AND SIZE CONSIDERATIONS

Towers are as integral to the performance of the wind system as the wind turbine itself. The tower must be strong enough to withstand the thrust on the wind turbine and the thrust on the tower. The tower must also support the weight of the wind turbine. Tall towers are preferred as they minimize the turbulence induced. Tall towers allow more flexibility in siting. The most important factor is the ability of a tower to withstand the forces acting on it in high winds. Towers are rated by the thrust load they can endure without buckling. The thrust on the tower at high speeds depends on the rotor diameter of the wind turbine and its mode of operation under such conditions. As the turbine weight increases, the initial cost also increases. However initial turbine cost alone does not determine the cost per kilowatt hour of electrical output. The cost of operation and maintenance (O&M) and the cost of major overhauls and repairs must be included. To be cost effective, a turbine must have high availability and low O&M costs. This leads to different design perspectives. Designers of heavier weight and robust turbines argue that such designs have high availability and low maintenance and reducing weight excessively will increase O&M costs. Lightweight turbines, while reducing initial cost and weight must have low O&M costs. This technical challenge requires a thorough understanding of the dynamic behavior of the lightweight turbines and how to control the structure responses. The variation in tower top weight is 20–30 kg/m^2 for an increase in rotor diameter from 30 to 60 m. The weight of the tower increases with the number of blades. Pitch controlled turbines are somewhat lighter than stall regulated turbines with increase in the size, the cost increases, but with the increase in tower height, the energy capture is more, which negates such high cost.

1.11.ENVIRONMENTAL ASPECTS

1.11.1. AUDIBLE NOISE

The wind turbine is generally quiet. It poses no objectionable noise disturbance in the surrounding area. The wind turbine manufacturers generally supply the noise level data in dB versus the distance from the tower. A typical 600 kW wind turbine may produce 55 dB noises at 50 m distance from the turbine and 40 dB at a 250 m distance. This noise is, however, a steady state noise. The wind turbine makes loud noise while yawing under changing wind direction. Local noise ordinances must be satisfied before installing wind turbines.

1.11.2. ELECTROMAGNETIC INTERFERENCE

Any stationary or moving structure in the proximity of a radio or TV station interferes with the signals. The wind turbine towers can cause objectionable electromagnetic interference on the performance of the nearby transmitters or receivers. In other aspects, the visual impact of the wind farm can be of concern to someone. The breeding and feeding patterns of birds may be disturbed. They may even be injured and even killed if they collide with the blades.

2. OPTIMIZATION FOR WIND TURBINE ROTORS

This optimization of aeroturbine focuses on the development of multi-disciplinary optimization algorithm for designing of horizontal axis wind turbines with multiple constraints. The aim of the optimization process is to optimum potential reduction in cost, the optimum specific power and the optimum airfoil characteristics. Design variables were rotor chord, twist, relative thickness and structural shell thickness along the blades with the tip pitch angle [10].

2.1. OPTIMUM COST OF ENERGY

To compensate the reduction in annual energy production, the swept area can be increased to gain energy yield, without increasing generator size and design fixed loads and hence total cost. It would be possible to constrain the energy yield to a minimum acceptable value.

2.2. OPTIMUM ROTOR GEOMETRY

The optimization of rotor geometry returns smooth shapes. On reducing the chord, the blade weight, extreme loads and fatigue loads are reduced from the reduction in projected blade area [10]. The twist in the root region is of minor importance to the power.

2.3. OPTIMUM AIRFOIL CHARACTERISTICS

To investigate the optimum airfoil characteristics, the lift and drag characteristics should be considered as design variables. The high at the root is often studied because of increased production at low wind speeds before rated power. A reduction in chord reduces both blade weight and extreme loads, but should be counterbalanced by an increase in the $C_{L. max}$ to maintain power.

2.4. COST OF ENERGY VERSUS SPECIFIC POWER

Optimizations were done with different constraints on the maximum generator power to investigate the variation of cost of energy with the specific power. Optimum aerodynamic efficiency at some design wind speed is closely related to the rotor shape, however the efficiency depends on the number of rotor.

2.5. BLADE PROPERTIES

The aerodynamic profiles of wind turbine blades have crucial influence on aerodynamic efficiency of wind turbine. When blades of length more than 45 m are used, the dynamic behavior of the blade should be taken into account, and the position and shape of the spars have to be analyzed. The location of main spar together with the location of the stiffness ribs will have the biggest influence on the bending modes of the blade [8].

2.6. AERODYNAMIC LOADS

Blade Element Momentum (BEM) method is used for the analysis of aerodynamic loads. It is an iterative method, which assumes the value of axial retardation coefficient ‘a’ to be zero at the beginning. The aerodynamic loads are expressed in the following formulas: (c is the chord of aerodynamic profile)

Lift, $$L = \frac{1}{2}.\rho.V_{rel}{}^{2}.c.C_L$$

Drag, $$D = \frac{1}{2}.\rho.V_{rel}{}^{2}.c.C_D$$

2.7. BLADE MATERIAL

The blade is made of composite materials with more than one bonded material with different structural properties to achieve the combination of desirable properties, with the main advantage of high ratio of stiffness to weight. One of the materials, reinforcing phase is embedded with the other material, matrix phase.

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The special care must be taken in defining the properties and orientations of the various layers since each layer may have different orthotropic material properties. Carbon fiber composites allow to less blade mass.

2.8. OPTIMIZATION ALGORITHM

The important features optimization algorithms are (i) rate of convergence, (ii) time consumption for each iteration, (iii) robustness.

The advantages of the optimization algorithm are [10]:

- An inverse design process.
- A large number of design variables are varied simultaneously.
- An unlimited number of constraints are automatically taken into account.

The disadvantages are:

- The iterative procedure that can involve long calculation time.
- High calculation accuracy is required for a reliable sensitivity analysis.

2.9. POSSIBLE DESIGN VARIABLES

Sl. No.	Design variable type	Design variable	Dependence
1.	Rotor shape	Rotor diameter	Scalar
		Chord Twist Relative thickness	Blade radius
		Shell thickness	
2.	Airfoil characteristics	Lift characteristics Drag characteristics	Angle of incidence, relative thickness
3.	Regulation	Rotational speed Tip pitch angle	Scalar/wind speed

Table : 1 Design variables

3. COMPOSITE ROTOR BLADES:

The primary objective of composite rotor blades is to minimize the blade weight, subject to frequency and auto rotational inertia constraints. A composite is a structural material which consists of combining two or more constituents. The constituents are combined at microscopic level and are not soluble in each other. One constituent is called the reinforcing phase and the one which is embedded is called the matrix. The reinforcing phase material may be in forms of fibers, particles and flakes. The matrix phase materials are generally continuous. Strength of the composite materials depend on (i).Orientation of the fiber (ii).Type and amount of the fiber present. Fiber orientation in each layer as well as stacking sequence of the plies plays a major role in strength and modulus of the composite laminates. Fibers oriented in one direction will have high strength and stiffness in the direction of orientation.

3.1. DESIGN FUNCTION REQUIREMENTS

The design functions to be considered are as follows [12]

3.1.1. STIFFNESS AND STRENGTH

A combination of high strength and stiffness is desirable because of the vibration from the natural frequencies in the air frame and the periodic loads experienced by the blade.

3.1.2. WEIGHT

The most important fact of using composite material is considerable weight saving which is determined by the mass moment of inertia.

3.1.3. SAFETY

Predictable and confidence in the material arises only with the realistic safety margins, to maintain safety in the blades.

3.1.4. IMPACT RESISTANCE

The blades should have the ability to resist not only the impact of foreign bodies but also certain level of mishandling during servicing.

3.1.5. EROSION

The erosion materials, particles in the air such as dust, sand are very abrasive in nature. CORROSION

Corrosion increases the safety margins and decreases the maintenance. So the entire part of the blade should be made of corrosive resistant materials.

3.1.6. COST

The main design optimization of composite material is to satisfy the cost requirement, i.e., at low cost. The cost includes low initial cost, low operating cost and low maintenance cost.

3.1.7. ENDURANCE

Improving the survival will lead to high reliability and less maintenance. The life of the blades has important implications on operating cost and must be maximized to ensure economic viability.

3.1.8. DE-ICING

A facility for locally heating the leading edge of the blade is required for de-icing purpose.

3.1.9. LIGHTNING STRIKE PROTECTION

If lightning strikes occur, an electrically conductive path is required along the blade length to discharge the high voltage.

GENERAL MOMENTUM THEORY FOR HORIZONTAL AXIS WIND TURBINE

The assumptions made in this theory are (i) the turbine must be a horizontal axis configuration such that an average stream tube can be identified, (ii) The portion of kinetic energy in the swirl component of velocity in the wake is neglected and (iii) the effect of the radial pressure gradient is excluded. The upstream wind velocity V is decelerated to $V(1-a)$ at the turbine disk and to V(1-2a) in the wake of the turbine. Momentum analysis predicts the axial thrust on the turbine of radius R to be

$$T = 2\pi R^2 \rho V^2 a(1-a) \text{ (in N)} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where T is the axial thrust on the wind turbine (N), R is the turbine radius (m), ρ is the air density at sea-level at standard atmospheric conditions (kg/m^3), V is the wind speed (m/s), a is the axial induction factor.

Thrust coefficient C_T,

$$C_T = \frac{T}{0.5\rho\pi R^2 V^2} = 4a(1-a) \quad \ldots\ldots(2)$$

Mechanical power produced by the turbine is given as P,

$$P = 2\pi R^2 \rho V^3 a(1-a)^2 \text{ (in W)}\ldots\ldots\ldots\ldots(3)$$

Wind power in the upstream wind covering an area equal to rotor disk P_W (in W),

$$P_W = 0.5\rho V^3 \pi R^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

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Power coefficient, $Cp = \frac{P}{Pw} = 4a(1-a)^2$ ….(5)

Maximum value of power coefficient is at $a = 1/3$, substituting the value of ‘ a ' in equation (5), $C_{p\max} = 0.593$

Torque coefficient, C_Q,

$$C_Q = \frac{Q}{0.5\rho\pi R^2 V^2}$$

where Q is the turbine torque.

Also, $C_Q = \frac{C_P}{(U/V)}$ ………………….(6)

BLADE-ELEMENT THEORY FOR HORIZONTAL AXIS WIND TURBINE

Blade-element theory helps to analyze the relationship between the individual airfoil properties and axial induction factor, power produced and the axial thrust of the turbine. The elemental torque which acts on all blade elements in an annular ring is

$$dQ = 0.5Bcr\rho W^2 (C_L \sin\phi - C_D \cos\phi)dr \quad ….(7)$$

where B is the number of blades, c is the chord (m), r is the radius of blade element (m), W is the velocity of the wind relative to the airfoil (m/s), C_L is the lift coefficient and C_D is the drag coefficient, ϕ is the flow angle.

The sectional lift and drag coefficients are obtained from empirical airfoil data and are unique functions of the local flow angle of attack and the local Reynolds number of the flow. If dL and dD are the lift and drag forces on the blade element respectively, then lift and drag coefficients are defined as

$$dL = C_L (0.5\rho W^2)c.dr \quad …………….(8)$$

$$dD = C_D (0.5\rho W^2)c.dr \quad …………….(9)$$

Power = torque x turbine angular velocity, which can be obtained by integrating equation (7) and multiplying the same with angular velocity of turbine.

$$P = 0.5\rho B\Omega \int_0^R cW^2 (C_L \sin\phi - C_D \cos\phi)dr \quad .(10)$$

Similarly, total thrust force on the turbine is given by

$$T = 0.5\rho B \int_0^R cW^2 (C_L \cos\phi + C_D \sin\phi)dr \quad ….(11)$$

From figure,

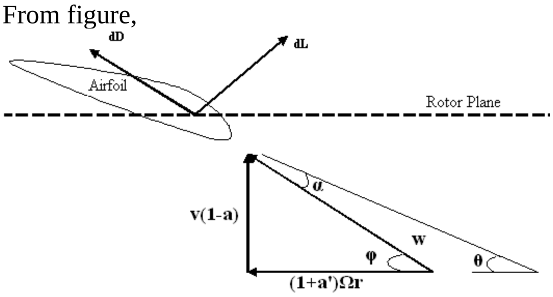

Fig: 1 : forces acting on the blade

$$\sin\phi = V(1-a)/W \quad ………………….(12)$$

$$\cos\phi = (1+a')r/W \quad ………………….(13)$$

where a' is the tangential induction factor $= \omega/2\Omega$

$$W = \left[V^2(1-a)^2 + (1+a')^2\Omega^2 r^2\right]^{0.5} \quad ……….(14)$$

$$\sin\alpha = \sin(\phi-\theta) \quad ………………….(15)$$

Relation between angle of attack α and lift coefficient.

For flat plate airfoil, $C_L = 2\pi\sin\alpha$ …………….(16)

For symmetric airfoil, $C_L = 2\pi\alpha$ …………….(17)

For circular arc airfoil, $C_L = 2\pi[\alpha + (2f/c)]$ ….(18)

where f is the maximum thickness of circular arc airfoil (m)

ASSUMPTION IN THIS WORK

Maximum thickness of a circular-arc airfoil is assumed to be 6% of the chord, hence the lift coefficient equation will be

$$C_L = 2\pi[\alpha + (0.12)] \quad ….(19)$$

Flat – plate and symmetric airfoil Horizontal Axis Wind Turbine

Power produced by the wind turbine can be obtained by substituting equations (12) to (16) in equation (10). i.e.,

$$P = \pi\rho B\Omega \left\{ \int_0^R V^2.c.(1-a)^2.c.\cos\theta.r.dr - \int_0^R V.(1-a).(1+a').c.\Omega.\sin\theta.r^2.dr - \int_0^R V.(1-a).(1+a').c.\Omega(C_D/C_L)..\cos\theta.r^2.dr + \int_0^R (1+a')^2.c.\Omega^2(C_D/C_l).\sin\theta.r^{3.dr} \right\} \quad …………….(20)$$

Simplifying assumptions made for integrating equation (20) are

i) Uniform distribution of upstream wind speed along the blade

ii) Constant chord along the blade (parallel plan form blade)

iii) Constant blade angle during steady state operation

iv) Constant drag-to-lift coefficient ratio

v) Uniform distribution of axial and tangential induction factors along the blade.

These assumptions agree with the result of V.H. Morcos for low and high tip-speed ratios for axial and tangential induction factors respectively.

Introducing the definitions of solidity and power coefficient and integrating the above equation (20) for obtaining power coefficient,

$$C_P = \pi\sigma(1-a)(U/V) \{[1-a-(2/3)(1+a')(C_D/C_L)(U/V)]\cos\theta - \left[\frac{(2/3)(1+a')(U/V) - 0.5(C_D/C_L)(1+a')^2(U/V)^2}{(1-a)}\right]\sin\theta\}$$

………………….(21)

Equate equations (21) and (5) to get the axial induction factor,

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$$a=\left[\frac{\pi\sigma(U/V)(1-a)}{4}\right]\Bigg\{\left[1-a-(2/3)(1+a^{'})(C_D/C_L)(U/V)\right]\cos\theta-\left[(2/3)(1+a^{'})(U/V)-\frac{0.5(C_D/C_L)(1+a^{'})^2(U/V)^2}{(1-a)}\right]\sin\theta\Bigg\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(22)$$

Similarly, to get the total thrust force on the turbine, substitute the equations (12) to (16) in equation (11)

$$T=\pi\rho B\Bigg[\int V(1-a)(1+a^{'})c\Omega\cos\theta r dr-\int_0^R(1+a^{'})^2c\Omega^2\sin\theta r^2dr+\int_0^R V^2(1-a)^2c(C_D/C_L)\cos\theta dr-\int_0^R V(1-a)(1+a^{'})c\Omega(C_D/C_L)\sin\theta r dr\Bigg] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(23)$$

Integrating equation (23) and introducing the definition of solidity,

$$T=\rho\pi^2\sigma(1-a)R^2V^2\Bigg\{\left[0.5(1+a^{'})(U/V)+(C_D/C_L)(1-a)\right]\cos\theta-\left[\frac{(1+a^{'})^2(U/V)^2(1-a)}{3}+0.5(C_D/C_L)(1+a^{'})(U/V)\right]\sin\theta\Bigg\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(24)$$

Equate equations (24) and (1) to get the tangential induction factor.

$$a^{'}=\left[\frac{2}{(U/V)}\cos\theta\right]\left(\frac{2a}{\pi\sigma}\right)-0.5(U/V)\cos\theta-(1-a)(C_D/C_L)\cos\theta+\left[\frac{2}{(U/V)}\cos\theta\right]\left[\frac{(1+a^{'})^2(U/V)^2(1-a)}{3}+0.5(1+a^{'})(C_D/C_L)(U/V)\right]\sin\theta \quad \ldots\ldots\ldots\ldots\ldots(25)$$

THEORETICAL ANALYSIS

The theoretical analysis was performed to investigate the effect and dependence of the various parameters in the wind turbine rotor geometry. The analysis includes the recommended values at specified operating conditions to maximize the power extracted by the wind turbine rotor. In this study, the variation in the parameters is as follows; blade angle (θ) was varied between 0 and 10º; (C_D/C_L) was varied between 0 and 0.10; rotor solidity, (σ) was varied between 0.10 and 0.30; tip speed ratio (U/V) was varied between 2 and 14. To solve the equations **(23)** and **(26),** since they are coupled equations, the solution of those equations was obtained with the help of Newton-Rapheson two variable method using MATLAB. The values of a, a′, (C_D/C_L), (U/V), σ and θ were substituted in the equations of C_P, C_T, C_Q using C – program. The optimized values obtained were drawn using SPSS. The recommended values i.e., the optimized or efficient value were tabulated by finding coefficient of variation (C.V.) where

$$C.V.=\frac{S\tan dard \quad Deviation}{Mean}x100$$

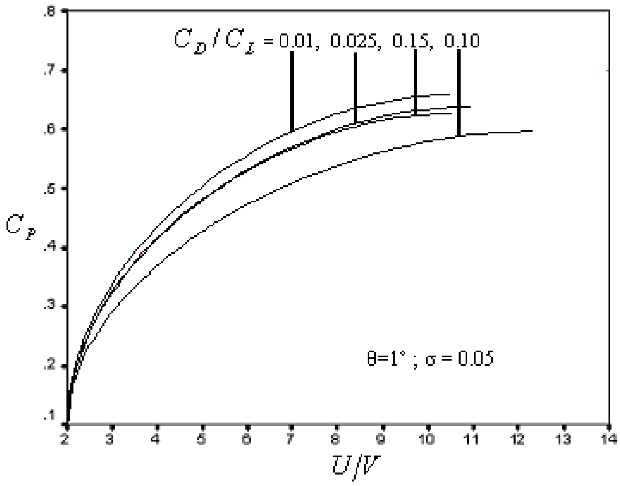

Fig.2: Effect of power coefficient C_P with tip speed ratio (U/V) for different (C_D/C_L) ratio with blade angle θ = 1° and rotor solidity (σ) as 0.05

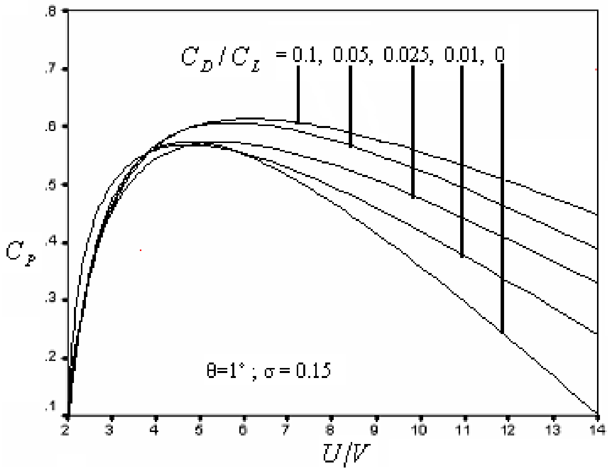

Fig.3: Effect of power coefficient C_P with tip speed ratio (U/V) for different (C_D/C_L) ratio with blade angle θ = 1° and rotor solidity (σ) as 0.15

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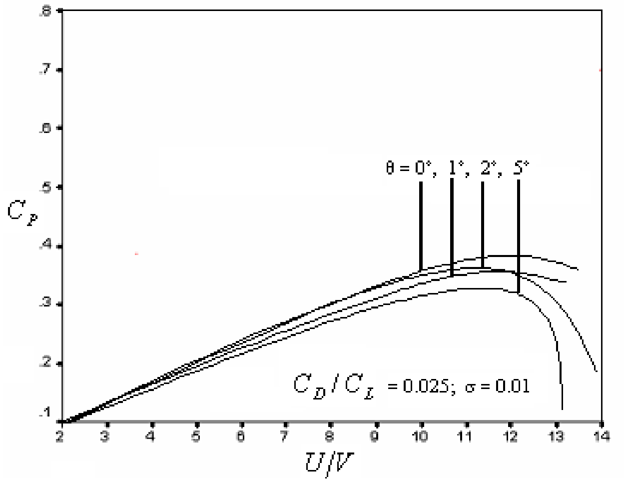

Fig.4: Effect of power coefficient C_P with tip speed ratio (U/V) for different blade angle θ with (C_D/C_L) ratio of 0.025 and rotor solidity (σ) as 0.01

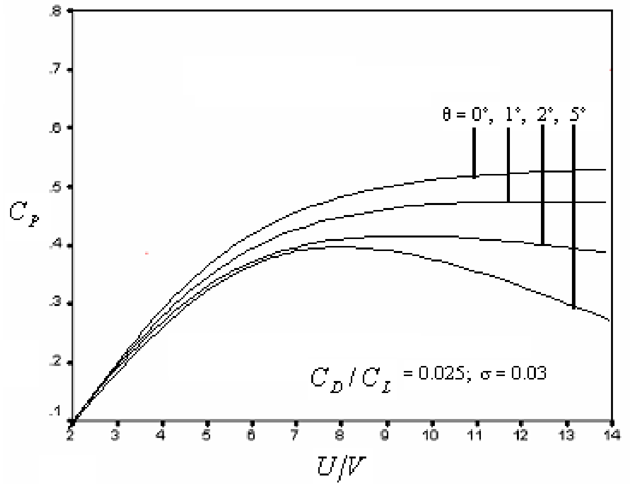

Fig.5: Effect of power coefficient C_P with tip speed ratio (U/V) for different blade angle θ with (C_D/C_L) ratio of 0.025 and rotor solidity (σ) as 0.03

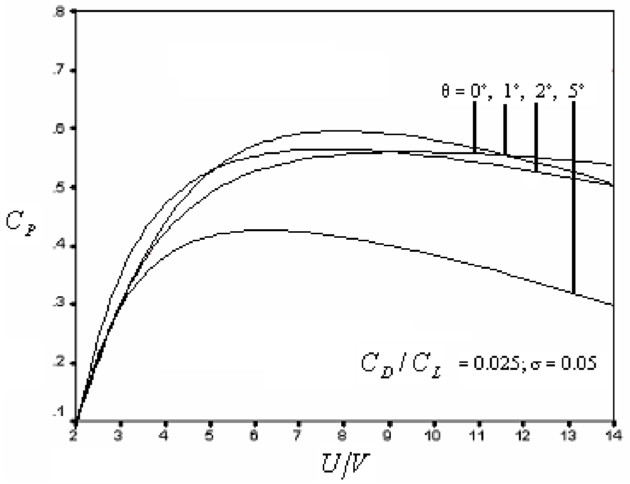

Fig.6: Effect of power coefficient C_P with tip speed ratio (U/V) for different blade angle θ with (C_D/C_L) ratio of 0.025 and rotor solidity (σ) as 0.05

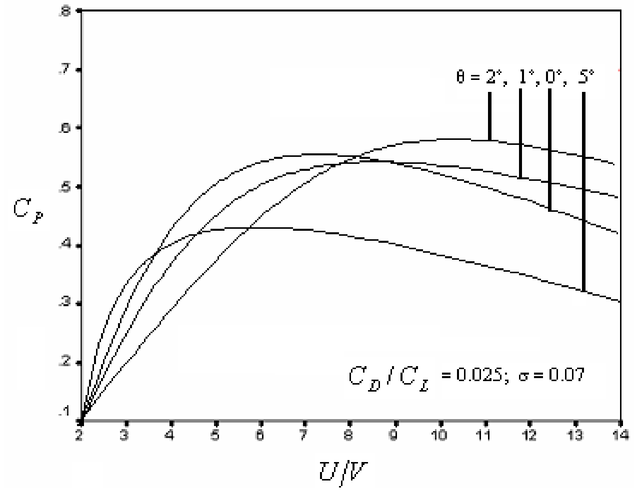

Fig.7: Effect of power coefficient C_P with tip speed ratio (U/V) for different blade angle θ with (C_D/C_L) ratio of 0.025 and rotor solidity (σ) as 0.07

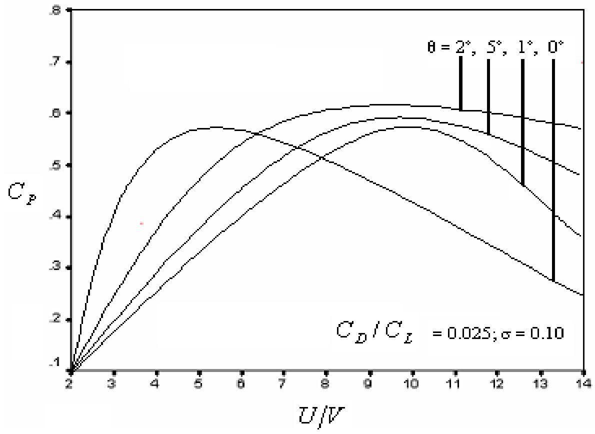

Fig.8: Effect of power coefficient C_P with tip speed ratio (U/V) for different blade angle θ with (C_D/C_L) ratio of 0.025 and rotor solidity (σ) as 0.10

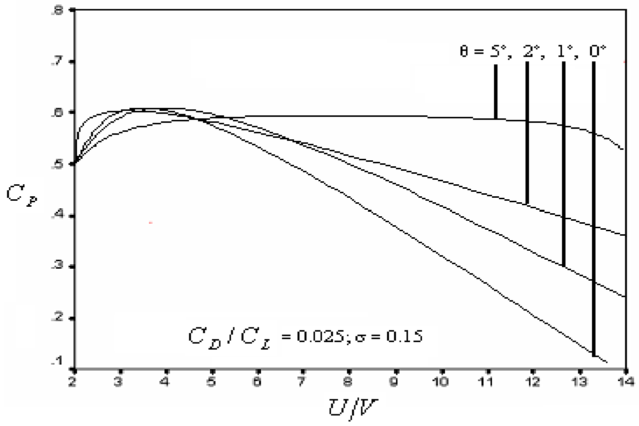

Fig.9: Effect of power coefficient C_P with tip speed ratio (U/V) for different blade angle θ with (C_D/C_L) ratio of 0.025 and rotor solidity (σ) as 0.15

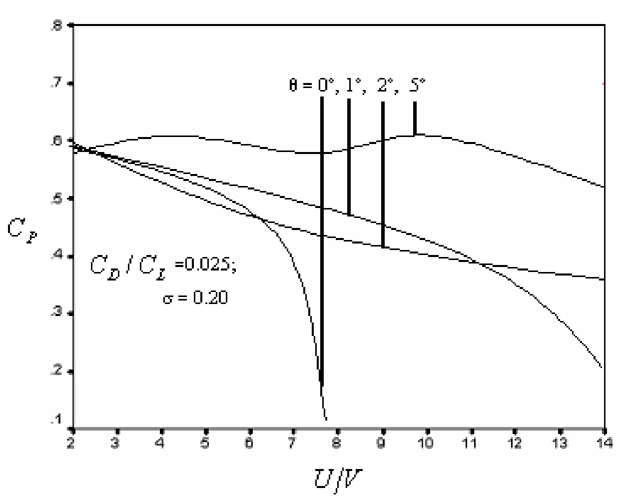

Fig.10: Effect of power coefficient C_p with tip speed ratio (U/V) for different blade angle θ with (C_D/C_L) ratio of 0.025 and rotor solidity (σ) as 0.20

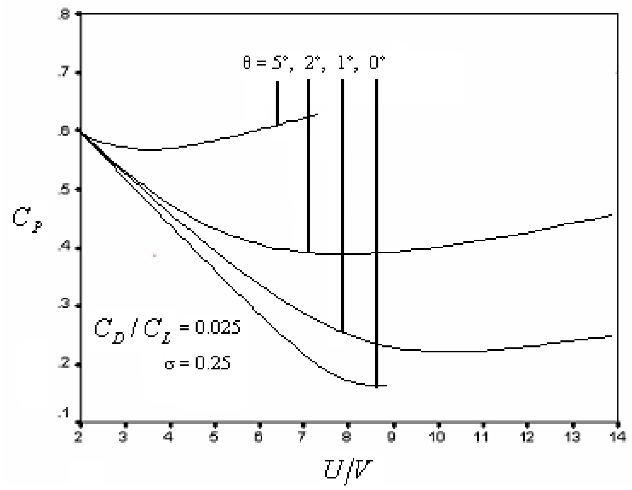

Fig.11: Effect of power coefficient C_p with tip speed ratio (U/V) for different blade angle θ with (C_D/C_L) ratio of 0.025 and rotor solidity (σ) as 0.25

4. CONCLUSION

The design of wind energy conversion systems is a very complex task and requires interdisciplinary skills, like civil, mechanical, electrical and electronics, geography, aerospace, environmental etc. An attempt has been made to discuss the important design aspects of WECs. In this paper, design aspects, siting requirements for WECs, classification of wind electric generation schemes, choice of generators and rotors, three basic design philosophies, choice between two and three blade rotors, weight and size considerations and environmentally related aspects with WECs, optimization concepts of aero turbine design have been critically discussed. The figures 2 to 11 show the effects of parameters on the blade section which explains the range of parameters with which the HAWT works effectively. The prospering future in wind turbine technology is a challenge for rotor blade design in order to enable an economic, reliable, safe and maintenance less production of wind energy. This paper also addresses the first significant step by defining the design parameters of developing an integrated dynamic, aerodynamic, and structural of wind turbine blades made of composite materials.

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5. NOMENCLATURE

SYMBOLS

A swept area in m^2
P_a total wind power available in Watts
P_e electrical power output in Watts
m_w mass flow rate of the wind in kg/s
V_m mean velocity of wind in m/s
V_i inlet wind velocity in m/s
V_o outlet wind velocity in m/s
V_{ave} average velocity in m/s
V_C cut-in-speed in m/s
V_R rated wind speed in m/s
V_F furling speed in m/s
P_{out} power recovered from the wind in Watts
$P_{out.max}$ maximum power that can be drawn from the wind in Watts
E_a available wind energy
V_m mean wind speed
E_{as} available energy flux
T time period
P_e electrical power output in Watts
C_p power coefficient
I current in amps
V voltage in volts
R maximum rotor radius in m
P_s Shaft power output in Watts
U_o upstream undisturbed wind speed in m/s
C_L aerodynamic lift coefficient
C_D aerodynamic drag coefficient
C_M power performance of a wind turbine
c chord of aerodynamic profile
L lift force
D drag force
F_M moment force
I inclination angle
i incidence angle

GREEK SYMBOLS

α pitch angle
λ tip speed ratio
ω angular rotor speed in rad/s
μ Hellmann coefficient
η_g generator efficiency
η_m mechanical efficiency
η_a alternator efficiency
ρ density of air in kg/m^3

ABBREVIATIONS

GRP Glass fiber Reinforced Plastics
NACA National Advisory Committee of Aeronautics
HAWT Horizontal Axis Wind Turbine
VAWT Vertical Axis Wind Turbine
CSCF Constant Speed Constant Frequency

VSCF Variable Speed Constant Frequency
VSVF Variable Speed Variable Frequency
TSR Tip Speed Ratio
O&M Operation & Maintenance cost
WECS Wind Electric Conversion System
IEC International Electrotechnical Commission
SEIG Self- Excited Induction Generators

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