HAWT POWER ENHANCEMENT USING ITS CHARACTERISTICS

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Abstract— **It is imperative that wind turbine is a modern concept in our country for using free natural resources. Many earlier studies have been conducted on aerodynamic performance and geometric characteristics of large capacity Horizontal Axis Wind Turbine (HAWT) rotors between 3 MW to around 10 MW. The present study have been performed varying the key performance characteristic parameters like rated wind speed, blade tip speed, coefficient of performance, tip speed ratio and using winglet at the tip.**

The basic objective of the study is efficient performance wind turbine with a highest possible annual usable energy pattern factor and least possible dimension, getting the maximum wind energy (kWh) and producing the maximum power in MW. The impact of these performance parameters on the HAWT rotor geometry has been investigated. The variation patterns of aerodynamic and geometric parameters are obtained, analyzed and discussed. The same then compared with each other and with the existing large capacity HAWT machines of reputed manufacturers. This study analysis and its results can be a basis for evaluating aerodynamic performance of large capacity HAWT wind turbine. The current study provides a detail configuration of wind turbine blade design that indicates dominance of modern HAWT which is for use of horizontal axis rotors.

***Keywords*-Aerodynamic performance, HAWT, performance characteristic parameters and maximum power.**

I. INTRODUCTION

Wind power generation is free and renewable that reduces greenhouse gas (GHG) emissions while used in place of electricity generated using fossil fuels. Wind turbines mostly produce electricity by harnessing the natural & free power from the wind to drive a generator. Wind-derived electrical power comes from two main sources industrial wind farms i.e. onshore & offshore. New era HAWT generally uses a tip speed ratio of nine to ten for two bladed rotors and six to nine for three blades [1]. This has been investigated to produce efficient conversion of the winds kinetic energy into electrical power [1, 6]. The available power in a stream of wind of the same cross-sectional area as the wind turbine can easily be shown to be the theoretical maximum power efficiency of any design of wind turbine is 0.59 i.e. no more than 59% of the energy carried by the wind can be extracted by a wind turbine.

$$P_{avail} = \frac{1}{2} \rho A v^3 C_p \quad \text{....[1]}$$

Similarly, with varying speed and considering larger diameter, the available maximum power from the subject HAWT can be calculated.

A. Tip Speed Ratio

To find the Tip Speed, the following factors are important:

i. Measure the rotor radius (length of one blade)
ii. Speed = distance divided by time. The distance travelled is the circumference (2Π r).
iii. Speed: V = the blades travel one circumference (2Πr) in a rotation time of T (seconds).

TSR refers to the ratio between the wind speed and the speed of the tips of the wind turbine blades.

$$TSR\ (\lambda) = \text{Tip Speed of Blade} \div \text{Wind Speed} \quad \text{... [2]}$$

Wind turbines must be designed with optimal tip speed ratios to get the maximum amount of power from the wind. Before calculating the tip speed ratio, it is necessary to know how long it takes the rotor to make one full revolution.

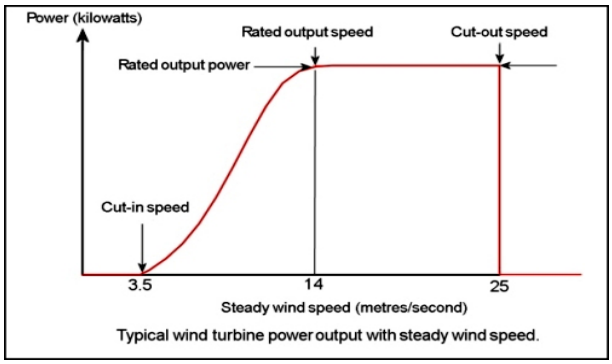

Fig -1: Power Output Variation with Steady Wind Speed

The ideal plan form of a HAWT rotor blade is defined using the BEM method by calculating the chord length according to Betz limit, local air velocities and aerofoil lift. Several theories exist for calculating the optimum chord length which range in complexity [1, 4, 10, 12], with the simplest theory based on the Betz optimisation [Equation (3)] [1]. For blades with tip speed ratios of six to nine utilising aerofoil sections with negligible drag and tip losses, Betz's momentum theory gives a good approximation [1]. In instances of low tip speeds, high drag aerofoil sections and

blade sections around the hub, this method could be considered inaccurate. In such cases, wake and drag losses should be accounted for [4,12]. The Betz method gives the basic shape of the modern wind turbine blade (Figure 2). However, in practice more advanced methods of optimization are often used [12–14].

$$C_{opt} = \frac{2\pi r}{n}\frac{8}{9C_L}\frac{U_{wd}}{\lambda V_r} \quad \text{where } V_r = \sqrt{V_w^2 + U^2} \qquad \ldots[3]$$

r = radius (m)
n = Blade quantity
C_L = Lift coefficient
λ = Local tip speed ratio
V_r = Local resultant air velocity (m/s)
U = wind speed (m/s)
U_{wd} = Design windspeed (m/s)
C_{opt} = Optimum chord length

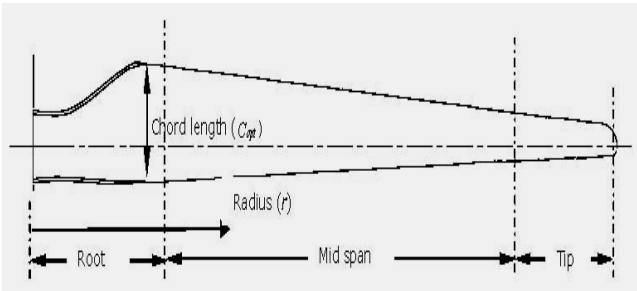

Figure 2. Typical plan and region classification of wind turbine blade

Assuming that a reasonable lift coefficient is maintained, utilising a blade optimisation method produces blade plans principally dependant on design tip speed ratio and number of blades.

Low tip speed ratios produce a rotor with a high ratio of solidity, which is the ratio of blade area to the area of the swept rotor. It is useful to reduce the area of solidity as it leads to a decrease in material usage and therefore production costs. However, problems are associated with high tip speeds.

For optimum chord dimensioning (Equation 3) the quantity of blades is considered negligible in terms of efficiency. The imposing size and location of wind turbines signify that the visual impact must be considered. Three bladed designs are said to appear smoother in rotation therefore more aesthetically pleasing. Faster one and two bladed designs have an apparent jerky motion [1]. Three bladed rotors are also thought to appear more orderly when in the stationary position [17].

A selection of different turbine sizes by different manufacturers and their weight configurations are shown in table I.

TABLE I
A selection of turbine size and weight configurations.[46]

Turbine Name	Pitch or Stall	Rotor Dia (m)	No. of Blades	Nacelle and Rotor Weight (kg)	Weight per Swept Area (kg/m²)
Mitsubishi MWT-1000 (1 MW)	P	57	3	unspecified	
Nordex N90 (2.3 MW)	P	90	3	84,500	13.3
Nordex N80 (2.5 MW)	P	80	3	80,500	16
Repower 5M (5 MW)	P	126	3	Unspecified	
Siemens SWT-3.6-107 (3.6 MW)	P	107	3	220,000	24.5
Siemens SWT-2.3-93 (2.3 MW)	P	93	3	142,000	20.9
Gamesa G90-2MW (2 MW)	P	90	3	106,000	16.7
Gamesa G58-850 (850 kW)	P	58	3	35,000	13.3
Enercon E82 (2 MW)	P	82	3	Unspecified	
GE wind 3.6sl (3.6 MW)	P	111	3	Unspecified	
Vestas V164 (7.0 MW)	P	164	3	Unspecified	
Vestas V90 (2 MW)	P	90	3	106,000	16.7
Vestas V82 (1.65 MW)	P	82	3	95,000	18

The wind turbine rotor, blade and tower specifications of typical modern HAWT wind turbine has been depicted for 2 MW machine in table II, III and IV.

TABLE III
Modern 2MW wind turbine rotor specification [46]

Rotor	
Diameter	90 m
Swept Area	6362 m²
Rotational Speed	9–19 rpm
Direction of Rotation	Clockwise from front
Weight (including hub)	36 T
Top Head Weight	106 T

The wind turbine using 44 metre blade length specification has been shown in table III here below.

TABLE IIIII
Modern 2MW wind turbine blade specification [46]

Blades	
Quantity	3
Length	44 m
Aerofoils	Delft University and FFA-W3
Material	Pre impregnated epoxy glass fibre + carbon fibre
Mass	5800 kg

TABLE IV
Modern 2MW wind turbine tower specification [46]

Tower		
Tubular modular design	*Height*	*Weight*
3 Section	67 m	153 T
4 Section	78 m	203 T
5 Section	100 m	255 T

II. Aerodynamics of HAWT ROTOR

Aerodynamic performance is fundamental for efficient rotor design [19]. Aerodynamic lift is the force responsible for the power yield generated by the turbine and it is therefore essential to maximize this force using appropriate design. A resistant drag force which opposes the motion of the blade is also generated by friction which must be minimised. It is then apparent that an aerofoil section with a high lift to drag ratio [Equation (4)], typically greater than 30 [20], be chosen for rotor blade design [19]:

Lift to Drag Ratio= Coefficient of lift/ Coefficient of Drag

$$LDR = C_L / CD \quad .....[4]$$

The co-efficient for the lift and drag of aerofoils is difficult to predict mathematically, although freely available software, such as XFOIL [21] model results accurately with the exception of post stall, excessive angles of attack and aerofoil thickness conditions [22,23]. Traditionally aerofoils are tested experimentally with tables correlating lift and drag at given angles of attack and Reynolds numbers [24]. Historically wind turbine aerofoil designs have been borrowed from aircraft technologies with similar Reynolds numbers and section thicknesses suitable for conditions at the blade tip. However, special considerations should be made for the design of wind turbine specific aerofoil profiles due to the differences in operating conditions and mechanical loads.

III. Profile of HAWT blade airfoil

National Advisory Committee for Aeronautics (NACA) four and five digit designs have been used for early modern wind turbines [1]. The classification shows the geometric profile of a NACA aerofoil where the 1st digit refers to maximum chamber to chord ratio, 2nd digit is the camber position in tenths of the chord and the 3rd & 4th digits are the maximum thickness to chord ratio in percent [24]. The emergence of wind turbine specific aerofoils such as the Delft University [23], LS, SERI-NREL and FFA [6] and RISO [26] now provide alternatives specifically tailored to the needs of the wind turbine industry.

The angle of attack is the angle of the oncoming flow relative to the chord line, and all figures for *CL* and *CD* are quoted relative to this angle. The use of a single aerofoil for the entire blade length would result in inefficient design [19]. Each section of the blade has a differing relative air velocity and structural requirement and therefore should have its aerofoil section tailored accordingly. At the root, the blade sections have large minimum thickness which is essential for the intensive loads carried resulting in thick profiles. Approaching the tip blades blend into thinner sections with reduced load, higher linear velocity and increasingly critical aerodynamic performance. The differing aerofoil requirements relative to the blade region are apparent when considering airflow velocities and structural loads (Table V).

TABLE V
The aerofoil requirements for blade regions [26].

Parameter	Blade Position (Figure 2)		
	Root	Mid Span	Tip
Thickness to chord ratio (%) ($(\frac{d}{c})$ Figure 2)	>27	27–21	21–15
Structural load bearing requirement	High	Med	Low
Geometrical compatibility	Med	Med	Med
Maximum lift insensitive to leading edge roughness			High
Design lift close to maximum lift off-design		Low	Med
Maximum CL and post stall behaviour		Low	High
Low Aerofoil Noise			High

An aerodynamic phenomenon known as stall should be considered carefully in turbine blade design. Stall typically occurs at large angles of attack depending on the aerofoil design. The boundary layer separates at the tip rather than further down the aerofoil causing a wake to flow over the upper surface drastically reducing lift and increasing drag forces [6]. This condition is considered dangerous in aviation and is generally avoided. However, for wind turbines, it can be utilised to limit the maximum power output to prevent generator overload and excessive forces in the blades during extreme wind speeds and could also occur unintentionally during gusts. It is therefore preferable that the onset of the stall condition is not instantaneous for wind turbine aerofoils as this would create excessive dynamic forces and vibrations [1].

The sensitivity of blades to soiling, off design conditions including stall and thick cross sections for structural purposes are the main driving forces for the development of wind turbine specific aerofoil profiles [1,26]. The use of modern materials with superior mechanical properties may allow for thinner structural sections with increased lift to drag ratios at root sections. Thinner sections also offer a chance to increase efficiency through reducing drag. Higher lift coefficients of thinner aerofoil sections will in turn lead to reduced chord lengths reducing material usage [Equation (3)].

IV. Better & Efficient Blade

The current research trend in blade design is the so called "Smart Blades", which alter their shape depending on the wind conditions. Within this category of blade design are numerous approaches which are wind speed, coefficient of performance, variable chord length, winglet at the tip of rotor and tip speed ratio etc.

An efficient rotor blade consists of several aerofoil profiles blended at an angle of twist terminating at a circular flange (Figure 3) [4,34]. It may also include tip geometries for reducing losses. To facilitate production, several simplifications maybe made:

- Reducing the angle of twist.
- Linearization of the chord width.
- Reducing the number of differing aerofoil profiles.

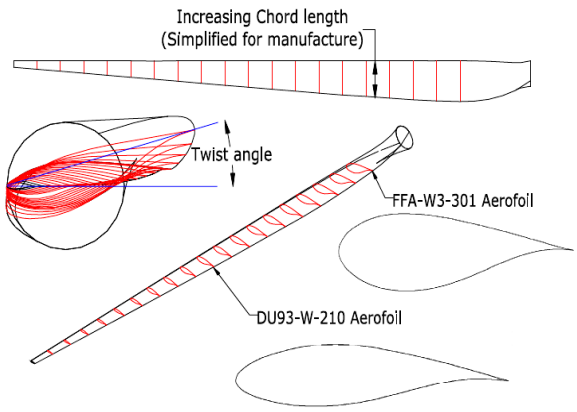

Figure 3. A typical modern HAWT blade with multiple aerofoil profiles

The present blade can be divided into three main areas classified by aerodynamic and structural function (Fig 4):

- The blade root. The transition between the circular mount and the first aerofoil profile this section carries the highest loads. Its low relative wind velocity is due to the relatively small rotor radius. The low wind velocity leads to reduced aerodynamic lift leading to large chord lengths. Therefore the blade profile becomes excessively large at the rotor hub. The problem of low lift is compounded by the need to use excessively thick aerofoil sections to improve structural integrity at this load intensive region. Therefore the root region of the blade will typically consist of thick aerofoil profiles with low aerodynamic efficiency.
- The mid span. Aerodynamically significant the lift to drag ratio will be maximised. Therefore utilising the thinnest possible aerofoil section that structural considerations will allow.
- The tip. Aerodynamically critical the lift to drag ratio will be maximised. Therefore using slender aerofoils and specially designed tip geometries to reduce noise and losses. Such tip geometries are as yet unproven in the field [1], in any case they are still used by some manufacturers.

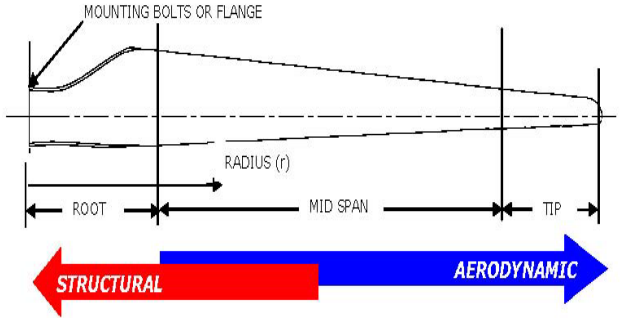

Figure 4. The three blade regions.[46]

V. Maximum Power Using Winglet

A parameter study is carried out where four of the key parameters describing a winglet are varied and the various effects are analyzed based on resulting mechanical power and thrust. Results show that adding a winglet to an existing wind turbine rotor increases produced power of around 1.0 % to 2.8 %. The additional increase in thrust is around 1.2 % to 3.6 %. [47]

The main purpose of adding a winglet to a wind turbine rotor is to decrease the total drag from the blades and thereby increase the aerodynamic efficiency of the turbine. Reduction of total drag is obtained if the additional drag from the winglet is less than the reduction of the induced drag on the remaining blade. [52]

The art is then to design a winglet, which optimizes drag reduction, maximizes power production and minimizes thrust increase. The resulting pressure difference on an operating wind turbine blade causes inward spanwise flow on the suction side and outward span wise flow on the pressure side near the tip. At the trailing edge, vorticity is generated, which is the origin of induced drag.

A winglet is a load carrying device that reduces the span wise flow, diffuses and moves the tip vortex away from the rotor plane reducing the downwash and thereby the induced drag on the blade.

Mac Gaunaa & Jeppe Johansen et al. (2007) in his work contains theoretical considerations and computational results on the nature of using winglets on wind turbines. Mac Gaunaa & Jeppe Johansen, in their thesis used TSR of 8 and shorter downwind winglets >2%, the result was increase of Cp of 0.512. [48]

Rinaldo Gonzalez Galdamez et al. (2011) has developed a project based on the design and analysis of winglets for wind turbine rotor blades. He used the rotor diameter for the wind turbine is 30 meters, and the winglet configuration selected will add approximately one meter to this dimension, depending on the configuration used. This dimension could be

altered by changes in one or more characteristics of the winglet.[50]

Saravanan P., Parammasivam K and Selvi Rajan et al, indicated experimental investigation on small horizontal axis wind turbine rotor using winglets. It is observed that presence of winglet at the tip of the wind turbine blade will improve the power coefficient for low wind speed regions. It is recommended that the smaller curvature radius with sufficient winglet height added to the wind turbine rotor captures more wind energy in low wind speed region as against wind turbine rotors without winglets. [49]

Jeppe Johansen and Niels N. Sørensen et al 2007, investigation [55], results has shown that adding a winglet to the existing blade can change the downwash distribution leading to increased produced power, but a load analysis is necessary to verify whether the increased thrust can be accepted. In general the following can be stated:

- Mechanical power and thrust increases as curvature radius decreases
- Sweeping the winglet 30° backwards does not increase mechanical power.
- Mechanical power and thrust increases as winglet height increases
- Only small dependence on winglet tip twist is seen.
- The effect of toe angle has not been investigated here but might have a positive effect on the produced power.

Finally, it should be mentioned that tip noise can possibly be affected by a winglet.

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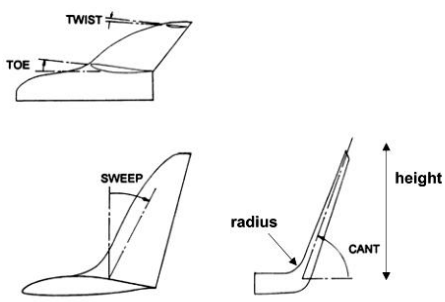

Fig5: Parameter of winglet geometry [53]

The winglet height, curvature radius, sweep and twist have been reviewed and studied. The winglet either upstream or downstream will have an effect on the impact of bending. Based on above, only winglets bended towards the suctions side (downward inside) have been analyzed in the present study. Local airfoil shape and taper is not accounted for. Several winglets have been designed and analyzed based on increase in produced power and thrust compared to the original rotor without winglets. Based on the results of the initial winglet design each of the parameters has been varied for obtaining the most efficient winglet configuration.

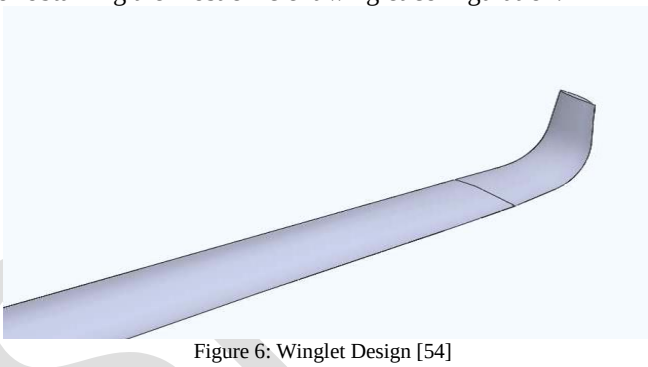

Figure 6: Winglet Design [54]

Based on the available data given for Vestas V80 turbine with an 80 meter rotor as an example, the amount of wind energy available in a 20 mph (8.9 m/s) wind for this turbine with 5027 m2 of swept area is:

½×1.2 kg/m3 ×π× (40 m)2 ×(8.9 m/s)3 0.4
= 2.3 × 106 kg·m2/s3 = 2.3 MW …..[5]

Other existing Vesta model, Vestas V112 turbine with 112 meter rotor and 54.65 meter blade length as an example, the amount of wind energy available at Cp of 0.4 in a 12 m/s wind for this turbine with 9852 m2 of swept area is:

½×1.2 kg/m3 × π × (54.65 m) 2 ×(12 m/s)3 x 0.4
= 3.8×106 kgm2/s3 = say3.0 MW …. [6]

Similarly, E126 having 7.58 MW capacity at the wind velocity of around 14 m/s. Adopting minor modification in these models by using downwind winglets >2%, and increased Cp of 0.512. may be reduced considering velocity variation and losses and fixing it at 0.5. Recent manufacturers have also considered Cp as 0.5 in their models of large capacity of more than 3 MW. Hence, using this, 50% of power coefficient (0.5) has been considered.

VI. Result & Discussions

Recent manufacturers have also considered Cp as 0.5 in their models of large capacity of more than 3 MW. Hence, using this, 50% of power coefficient has been considered over existing model HAWT wind turbine in proposed model. Various combinations of parameters vary and maximum power has been investigated and results are obtained for

different wind turbine blade radius. However, results are discussed for 60 meter radius HAWT here.

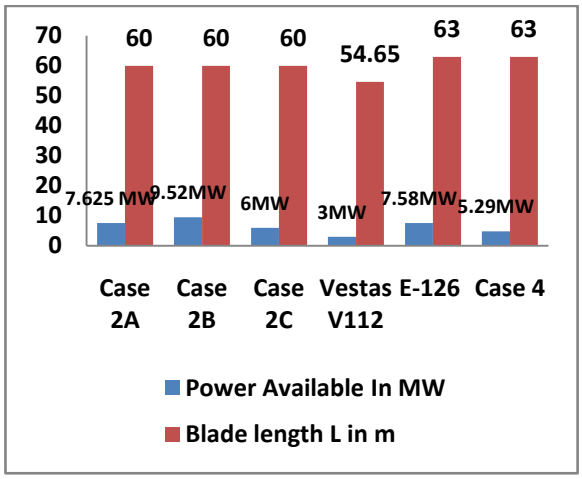

Fig 7: Graphical presentation of Maximum Power Available at different characteristics [51]

From the figure 7, it is observed that at 60 meter blade length, the available power ranging from 6.01 MW to 9.54 MW at different speeds. Case2B (9.54MW) can be compared with existing E-126 (7.58MW) and Case2C (6.01MW) can be compared with existing Vesta V112 (3.0MW). In this way Case2B and Case2C are better design. The results depict various characteristics of HAWT wind turbine with the existing manufacturer's models running in the market. There are certain advantages over this design.

VII. Advantages & Disadvantages

Electricity generated by the wind does not emit CO2 or leave any waste. Wind is also an infinite resource that cannot be exhausted. Wind turbine electricity generated can cut reliance on traditional fossil fuel resources.

Wind turbines rely on simple mechanical processes. Once the wind turbine is running there are few running costs.

Large-scale wind farms can be built at sea or land to exploit the country surrounding abundant wind flow.

Some of the disadvantages of wind power are wind turbine costs are high. Large-scale wind farms also require a significant start-up investment from industry. The amount of electricity generated is dependent on the speed and direction of the wind. The wind speed itself depends on a number of factors, such as location, height of the turbine and nearby obstructions.

Many people dislike the appearance and sound of wind turbines in the landscape, although noise pollution is less significant for micro-wind turbines. Anti-wind-farm groups argue that wind farms damage habitats and harm birds and marine ecology. Wind is an unpredictable energy source and requires the back up of more traditional and polluting methods of energy generation.

VIII. Conclusion

During the evolution of this design many alternatives have been explored and have eventually seeking greater cost efficiency which has exploited the ability to scale the design, with the latest models reaching above 100 meter in diameter. This study investigate the maximum power obtained for nearly 60 meter radius wind turbine blade using various characteristics and results show that the power available is comparatively higher than the present existing models available. A comprehensive look at rotor blade design shows that an efficient blade shape is defined by aerodynamic calculations based on chosen parameters and the performance of the selected airfoils. Currently manufacturers are seeking greater cost effectiveness through increased turbine size rather than minor increases through improved blade efficiency. This is likely to change as larger models become problematic through construction, transport and assembly issues. Therefore, it is likely that the general shape will remain fixed and will increase in size until a plateau is reached. Minor changes to blade shape may then occur as manufacturers incorporate new airfoils, tip designs and winglet.

The results depict various characteristics of HAWT wind turbine comparing with the existing manufacturer's models running in the market.

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References

[1]. Hau, E. *Wind Turbines, Fundamentals, Technologies, Application, Economics*, 2nd ed.; Springer: Berlin, Germany, 2006.

[2]. Dominy, R.; Lunt, P.; Bickerdyke, A.; Dominy, J. Self-starting capability of a darrieus turbine. *Proc. Inst. Mech. Eng. Part A J. Power Energy* 2007, *221*, 111–120.

[3]. Holdsworth, B. *Green Light for Unique NOVA Offshore Wind Turbine*, 2009. Available online: http://www.reinforcedplastics.com (accessed on 8 May 2012).

[4]. Gasch, R.; Twele, J. *Wind Power Plants*; Solarpraxis: Berlin, Germany, 2002.

[5]. Gorban, A.N.; Gorlov, A.M.; Silantyev, V.M. Limits of the turbine efficiency for free fluid flow. *J. Energy Resour. Technol. Trans. ASME* **2001**, *123*, 311–317.

[6]. Burton, T. *Wind Energy Handbook*; John Wiley & Sons Ltd.: Chichester, UK, 2011.

[7]. Hull, D.G. *Fundamentals of Airplane Flight Mechanics*; Springer: Berlin, Germany, 2007.

[8]. Anderson, D.; Eberhardt, S. *Understanding Flight*; McGraw-Hill: New York, NY, USA, 2001.

[9]. Yurdusev, M.A.; Ata, R.; Cetin, N.S. Assessment of optimum tip speed ratio in wind turbines using artificial neural networks. *Energy* **2006**, *31*, 2153–2161.

[10]. Duquette, M.M.; Visser, K.D. Numerical implications of solidity and blade number on rotor performance of horizontal-axis wind turbines. *J. Sol. Energy Eng.-Trans. ASME* **2003**, *125*, 425–432.
[11]. Oerlemans, S.; Sijtsma, P.; Lopez, B.M. Location and quantification of noise sources on a wind turbine. *J. Sound Vib.* **2006**, *299*, 869–883.
[12]. Chattot, J.J. Optimization of wind turbines using helicoidal vortex model. *J. Sol. Energy Eng. Trans. ASME* **2003**, *125*, 418–424.
[13]. Fuglsang, P.; Madsen, H.A. Optimization method for wind turbine rotors. *J. Wind Eng. Ind. Aerodyn.* **1999**, *80*, 191–206.
[14]. Jureczko, M.; Pawlak, M.; Mezyk, A. Optimisation of wind turbine blades. *J. Mater. Proc. Technol.* **2005**, *167*, 463–471.
[15]. Habali, S.M.; Saleh, I.A. Local design, testing and manufacturing of small mixed airfoil wind turbine blades of glass fiber reinforced plastics Part I: Design of the blade and root. *Energy Convers. Manag.* **2000**, *41*, 249–280.
[16]. Thresher, R.W.; Dodge, D.M. Trends in the evolution of wind turbine generator configurations and systems. *Wind Energy* **1998**, *1*, 70–86.
[17]. Gipe, P. The Wind Industrys Experience with Aesthetic Criticism. *Leonardo* **1993**. *26*, 243–248.
[18]. Chamberlain, D.E. The effect of avoidance rates on bird mortality predictions made by wind turbine collision risk models. *Ibis* **2006**, *148*, 198–202.
[19]. Maalawi, K.Y.; Badr, M.A. A practical approach for selecting optimum wind rotors. *Renew. Energy* **2003**, *28*, 803–822.
[20]. Griffiths, R.T. The effect of aerofoil charachteristics on windmill performance. *Aeronaut. J.* **1977**, *81*, 322–326.
[21]. Drela, M. *XFoil*; Massachusetts Institute of Technology: Cambridge, MA, USA, 2000.
[22]. Drela, M. *Xfoil User Primer*; Massachusetts Institute of Technology: Cambridge, MA, USA, 2001.
[23]. Timmer, W.A.; van Rooij, R.P.J.O.M. Summary of the Delft University wind turbine dedicated airfoils. *J. Sol. Energy Eng. Trans. ASME* **2003**, *125*, 488–496.
[24]. Abbott, I.H.; Doenhoff, A.V. *Theory of Wind Sections*; McGraw-Hill: London, UK, 1949.
[25]. Rooij, R.P.J.O.M.; Timmer, W. Roughness sensitivity considerations for thick rotor blade airfoils. *J. Solar Energy Eng. Trans. ASME* **2003**, *125*, 468–478.
[26]. Fuglsang, P.; Bak, C. Development of the Riso wind turbine airfoils. *Wind Energy* **2004**, *7*, 145–162.
[27]. Polinder, H. Comparison of direct-drive and geared generator concepts for wind turbines. *IEEE Trans. Energy Convers.* **2006**, *21*, 725–733.
[28]. Gupta, S.; Leishman, J.G. Dynamic stall modelling of the S809 aerofoil and comparison with experiments. *Wind Energy* **2006**, *9*, 521–547.
[29]. Stol, K.A.; Zhao, W.X.; Wright, A.D. Individual blade pitch control for the controls advanced research turbine (CART). *J. Sol. Energy Eng. Trans. ASME* **2006**, *128*, 498–505.
[30]. Bossanyi, E.A. Individual blade pitch control for load reduction. *Wind Energy* **2003**, *6*, 119–128. *Energies* **2012**, *5* **3449**
[31]. Barlas T.K.; van Kuik, G.A.M. Review of state of the art in smart rotor control research for wind turbines. *Prog. Aerosp. Sci.* **2010**, *46*, 1–27.
[32]. Barlas, T.; Lackner, M. The Application of Smart Structures for Large Wind Turbine Rotor Blades. In *Proceedings of the Iea Topical Expert Meeting*; Delft University of Technology: Delft, The Netherlands, 2006.
[33]. Thor, S. The Application of Smart Structures for Large Wind Turbine Rotor Blades. In *Proceedings of the IEA Topical Expert Meeting*; Sandia National Labs: Alberquerque, NM, USA, 2008.
[34]. Kong, C.; Bang, J.; Sugiyama, Y. Structural investigation of composite wind turbine blade considering various load cases and fatigue life. *Energy* **2005**, *30*, 2101–2114.
[35]. Quarton, D.C. *The Evolution of Wind Turbine Design Analysis—A Twenty Year Progress Review*; Garrad Hassan and Partners Ltd.: Bristol, UK, 1998; pp. 5–24.
[36]. Ahlstrom, A. Emergency stop simulation using a finite element model developed for large blade deflections. *Wind Energy* **2006**, *9*, 193–210.
[37]. Kishinami, K. Theoretical and experimental study on the aerodynamic characteristics of a horizontal axis wind turbine. *Energy* **2005**, *30*, 2089–2100.
[38]. Brondsted, P.; Lilholt, H.; Lystrup, A. Composite materials for wind power turbine blades. *Ann. Rev. Mater. Res.* **2005**, *35*, 505–538.
[39]. Jensen, F.M. Structural testing and numerical simulation of a 34 m composite wind turbine blade. *Compos. Struct.* **2006**, *76*, 52–61.
[40]. Veritas, D.N. *Design and Manufacture of Wind Turbine Blades, Offshore and Onshore Turbines*; Standard DNV-DS-J102; Det Norske Veritas: Copenhagen, Denmark, 2010.
[41]. Case, J.; Chilver, A.H. *Strength Of Materials*; Edward Arnold Ltd.: London, UK, 1959.
[42]. Griffin, D.A.; Zuteck, M.D. Scaling of composite wind turbine blades for rotors of 80 to 120 meter diameter. *J. Sol. Energy Eng. Trans. ASME* **2001**, *123*, 310–318.
[43]. Shokrieh, M.M.; Rafiee, R. Simulation of fatigue failure in a full composite wind turbine blade. *Compos. Struct.* **2006**, *74*, 332–342.
[44]. *Wind Turbines. Part 1: Design Requirements*; BS EN 61400-1:2005; BSi British Standards: London, UK, January 2006.
[45]. Kensche, C.W. Fatigue of composites for *wind turbines*. Int. J. Fatigue 2006, 28, 1363–1374.
[46]. Peter J., *Richard J., Wind Turbine Blade Design. Energies 2012, 5, 3425-3449; doi:10.3390/en5093425.*
[47]. Jeppe Johansen† and Niels N. Sørensen, paper published in Intl Conference entitle, Numerical Analysis of Winglets on Wind Turbine Blades using CFD, available at http://proceedings.ewea.org/ewec2007/allfiles2/344_Ewec2007fullpaper.pdf
[48]. Mac Gaunaa & Jeppe Johansen, "Determination of Maximum Aerodynamic Efficiency of Wind Turbine Rotors with Winglets "Journal of Physics, Conference Series 75 (2007) 012006.
[49]. Saravanan P., Parammasivam K. M.2 and Selvi Rajan S., "Experimental Investigation on Small Horizontal Axis Wind Turbine Rotor Using Winglets" Journal of Applied Science and Engineering, Vol. 16, No. 2, pp. 159_164 (2013).
[50]. R Gonzales, Thesis, Winglet Design and Analysis for Wind Turbine Rotor Blades 100% Report, EML 4905 Senior Design Project, November 30, 2011.
[51]. Installing a wind turbine, available at http://www.which.co.uk/energy/creating-an-energy-saving-home/guides/installing-a-wind-turbine/why-use-wind-power/
[52] Kohli N.K., "Evaluation of Aerodynamic Performance of Large Capacity HAWT", AARJMD, VOLUME 1 ISSUE 16 (DECEMBER 2013) ISSN : 2319 – 2801.
[53] Jeppe Johansen & Niels N, "Aerodynamic investigation of Winglets on Wind Turbine Blades using CFD" published by Risø National Laboratory Information Service Department , Feb, 2006.
[54] R. Gonzales, A B.S. THESIS, Winglet Design and Analysis for Wind Turbine Rotor Blades 100% Report, EML 4905 Senior Design Project, November 30, 2011.
[55] Jeppe Johansen and Niels N. Sørensen, "Numerical Analysis of winglets on wind turbine blade using CFD", 2007, proceedings of conference ewea 2007,http://proceedings.ewea.org/ewec2007/allfiles2/344_Ewec2007fullpaper.pdf