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Multi-Objective Design Optimization of Wind Turbine Blade using Genetic Algorithm

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***Abstract*—Among all renewable energy resources wind energy is the more widely using form. The highly fluctuating behaviour of wind rises the need for an optimized blade design for various wind energy capturing devices for ensuring maximum usable power output. In this work, based on the real experimental data of an already established wind turbine (Nordtank 150kW) a new optimized design is generated and compared with results of existing literatures. The objective function of this optimization was to maximize the Annual Energy Production (AEP) and to minimize the Blade Mass. The genetic algorithm optimization method employed here allowed a means of tackling the multi-objective problem such that the aerodynamic characteristics of the blade can be optimized for a particular wind speed range with structural constraints. This problem of optimization is done by using an open source horizontal axis wind turbine optimization code developed by National Renewable Energy Laboratories (NREL). The aerodynamic optimization was done with Blade Element Momentum theory and structural optimization was done based on the Euler-Bernoulli beam theory. In optimization the actual single airfoil type used is replaced with a span wise arrangement of 3 different airfoils. The resulted blade design from optimization offered substantial improvements in aerodynamics of blade and hence by consistent performance within the range of design points than the reference design.**

Keywords*— *Airfoil, Genetic Algorithm, Annual Energy Production, Blade Mass, QBLADE, Optimization, NREL etc.

I. INTRODUCTION

In recent years, the global awareness towards the usage of renewable energy resources was found increasing. Among the various forms of renewable energy resources wind energy is the most widely used energy form. But in case of wind energy the efficiency in power generation is still lower than other forms. This is mainly because of the highly fluctuating nature of wind. So in this work the need for an optimized wind turbine blade in order to ensure the maximum power output over a wide range of wind speed is analysed.

In this work the aerodynamic shape and blade mass of Nordtank 150 kW wind turbine are modified and optimized based on multi objective genetic algorithm and blade element theory. Optimization studies are performed to maximize the power production and to minimize the blade mass. Here the design variables considered are pre-twist of blade, chord length, percentage thickness and shell thickness of the blade. Here the optimization study is having limits and penalties of wind speed range, rotor rpm range, maximum power value, maximum strain value and cavitation considerations.

Here based on the Blade element momentum theory the total blade span is divided into a number of segments and optimization study is carried out in each of these elements considering the structural variables like micro strain values, moment values and mass per unit span etc.

II. LITERATURE SURVEY

“Implementation of design improvements within the wind turbine industry is hampered by the lack of practical prediction tools having the appropriate level of complexity” [3]. Wind turbine design is graduated from the airfoil design industry with much of the same theory being applied. However, the flow conditions are different so the assumptions made in flight aerodynamics are not applicable to wind turbine flow fields. In case of wind turbines flow field is three-dimensional, incompressible, unsteady, turbulent, and separated to a large extent; therefore numerical analysis is complex and costly. Most prediction tools in industry are based on suitably evolved blade element methods, with semi-empirical correlations to account for the three-dimensional effects, boundary-layer separation, and unsteady flow conditions. The benefit of these methods is that they are cost efficient, relative to the analysis time of full computational fluid dynamics (CFD). Unfortunately, their prediction of wind turbine performance has been found to be much lower than that encountered in the field [12]. Nevertheless, the blade element methods are widely applied in the wind turbine industry.

Prediction of wind turbine performance within the context of fluctuating wind conditions complicates the application of steady-state theory. In the Blade Element Momentum (BEM) Theory, the wind turbine blade is discretised into separate blade segments and analysed from a two-dimensional (2D) perspective. The angles of incidence and the consequent forces experienced by the wind turbine profile vary as a result of the rotation of the blade and the fluctuating wind. Not only do the forces experienced by the structure become dynamic, but also prediction methods such as BEM are compromised due to their assumptions of steady-state flow. The problem of oscillating airfoils is of particular importance for wind turbine design since airfoils spend a large amount of their time in the stall region [3].

The effect of turbine rotation on the boundary layer of the airfoil profile also affects the prediction of the aerodynamic forces, since rotation affects the transition to turbulence. Du and Selig [5] pointed out the difficulty of using the BEM methods since they do not model the effect of rotation on the boundary layer of the wind turbine blade. There is an estimated 15 to 20% under-prediction of the performance. The fact that the angle of incidence is continuously varying during the rotation cycle means that the circulation around each blade element is also varying. The conservation of angular momentum requires therefore that vorticity is shed into the wake of the turbine, also continuously. There is a bound vortex around each blade element and there is a free vortex system being convected downstream with the wake.

Sorensen and Hansen (1998) investigated calculation of rotor performance using a one-bladed and a three-bladed model. Their research compared the blade forces at 5 m/s and 10 m/s. At the low speed, the induced velocities for both models were a large fraction of the undisturbed velocity. At the higher speed, the induced velocities were a smaller fraction. Naturally the three-bladed rotor experienced much greater induced velocities than the single-bladed. The under- prediction of power production was greatest at the higher wind speed and specifically for the single-bladed mod

This review summarized that in case of wind turbine blades rotational effects on the boundary layer, induced velocity and wind rotor yaw are but a few of the operational conditions to consider when designing a wind turbine blade. Generating an accurate analytical model is problematic when considering these operational conditions. However, simplified models for wind turbine blades have been verified as a dependable design strategy due to their common occurrence in literature. The advancement of computational tools will allow greater consideration of the unsteady aerodynamics associated with wind turbines in the future.

III. METHODOLOGY

The various steps involved in this optimization study includes selection of reference turbine data, design of reference turbine blade, multi-objective genetic algorithm optimization, design of optimized blade and comparison study of both aerodynamic and structural variables of reference blade with optimized blade.

A. Selection and design of refernce turbine blade.

Nordtank 150 kW wind turbine is selected as the reference turbine for this optimization. Nordtank series wind turbines are invented by Nordtank Energy Group, Denmark in the year of 1988 and this Nordtank 150 kW wind turbine is first installed in 1989. As a part of technology advancement the initial design was modified a number of times and at last it is completely retrofitted in 2006. The intention behind the selection of this Nordtank 150 kW wind turbine is to reduce the computational complexity which may arise while doing analysis on large wind turbines having power output in megawatts.

The technical data of Nordtank 150 kW is given below,

1.Tower – Hub height -32.5 m, Material – Galvanized tubular steel, single section with access doors at top and bottom, Safety – Inside tower ladder, climbing cable, no slip and lockable doors.

2. Component Weights - Tower - 10,500 kg, Nacelle - 3,900 kg, Blades - 3 x 790 kg.

3. Rotor - 3 Bladed, upwind, fixed pitch, stall regulated., Diameter - 24.6 m, Swept Area - 475m^2, Material - Glass fiber reinforced polymer, Wing profile type - NACA 63 Airfoil family.

4. Drive Train - Gearbox - Flender, Tyskland or Jahnel / kestermann / Tyskland. (Gear ratio1:40), Power - 165 kW, Oil volume - 60 liters, Speed - 38 to 1520 rpm

5. Generator - Made - ABB Motors , Finland or EMOD Germany, Type - Asynchronous, 4 Pole, Rating - 165 kW, 1520 rpm, 400 V, 50 Hz, Certification - ISO 9002

6. Operational Data - Cut-in wind speed - 4 m/s, Rated windspeed - 12 m/s, Cut-out wind speed - 25 m/s.

7. Blades - Fibreglass reinforced polyester, Rotor speed-Nominal 38.1 rpm, Tip speed - Nominal 49 m/s.

8. Controller and Yaw System - Type - KK Controller, Microprocessor system with data logger, Cut-in system - Soft by Thyristors w/PLC, Yaw - Slide bearing 2 yaw gears / Active Yaw brakes, Drive - Yaw gears and dual electric drives, Control - Active yaw / wind vane , speed.

The power curve for the original Nordtank 150 kW wind turbine is given below (Fig.3.1),

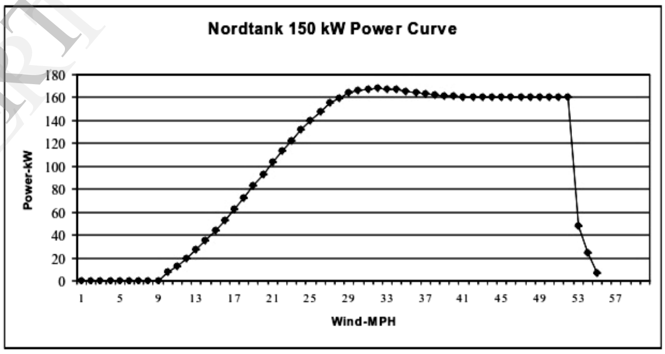

Fig.3.1. The original power curve of Nordtank 150 kW.

Based on the data sheet the Nordtank 150 kW wind turbines original blade parameters are defined and basic design is done in Qblade blade design software. The blade design is shown below (Fig.3.2),

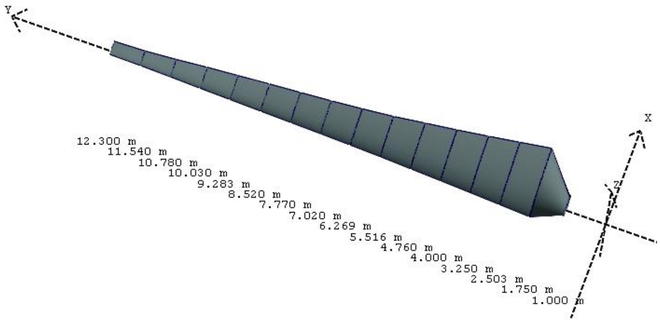

Fig.3.2. Nordtank original blade designed in Qblade.

After the design in Qblade the coordinate file for the total blade is generated and that single coordinate file is again subdivided into coordinate files of different airfoils at different span-wise stations. Then those coordinate files of airfoils at various stations are imported into Solidworks using the curve through xyz points option for design and the airfoils at various stations can be aligned as shown below (Fg.3.3),

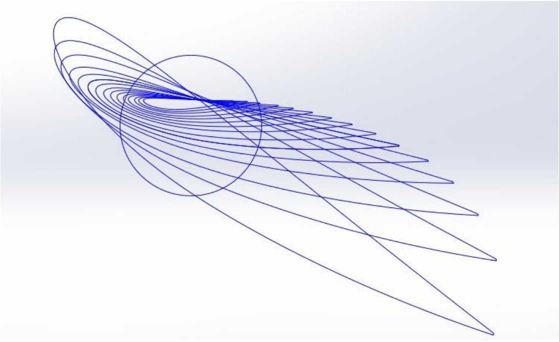

Fig.3.3. Airfoils at various stations imported as curves in Solidworks.

Using the lofting feature the airfoil curves at various stations are lofted to create the complete blade span as shown below (Fig.3.4)

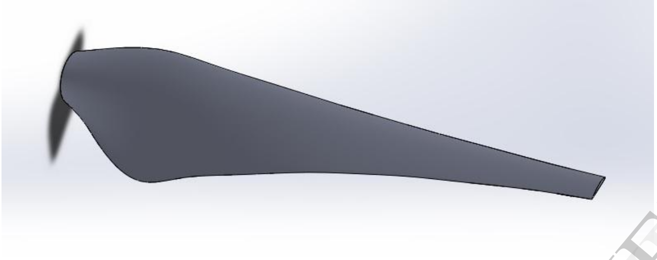

Fig.3.4. 3D Design of original blade in Solidworks.

B. *Multi Objective Design Optmisation Using Genetic Algorithm.*

The multi-objective design optimization of wind turbine blade with Annual energy production and Blade mass as the objective functions is carried out using the Horizontal Axis Rotor Performance Optimization (HARP Opt.) code developed by NREL. The HARP Opt. code works with MATLAB Genetic Algorithm Optimization Toolbox and Statistics Toolbox. It also uses the blade element momentum (BEM) theory model to design horizontal axis turbine rotors.

The optimization objectives are to maximize the turbine's annual energy production (AEP) and minimize the blade mass. Annual energy production is calculated using the Weibull flow distribution. Maximum power is bounded, and maximum power point tracking (MPPT) is a combined objective with AEP. AEP is calculated using the following equation.

$$AEP = \sum_{i=1}^{N-1} \frac{1}{2}(\mathrm{P}(\mathrm{V}_{i+1}) + \mathrm{P}(\mathrm{V}_i)) \times f(V_i < V_0 < V_{i+1}) \times 8760$$

(3.1)

Where the $P(V_{i+1})$ and $P(V_i)$ representing the power at cut-out and cut-in velocities and f $(V_i<V_0<V_{i+1})$ corresponds to the wind flow probability density using Weibull distribution and 8760 represents the total number of hours in an year.

$$f(V_i < V_0 < V_{i+1}) = \exp(-(\frac{V_i}{C})^k) - \exp(-(\frac{V_{i+1}}{C})^k)$$

(3.2)

Where c is the scale parameter, k is the shape parameter and V is the wind speed.

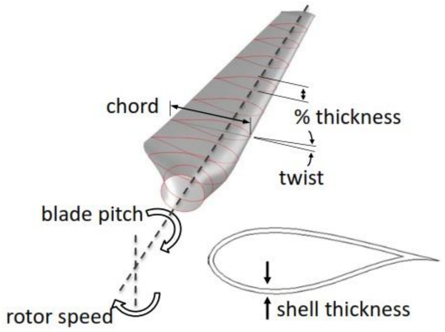

Fig.3.5. Variables and Constraints for GA Optimization.

Maximizing energy production and minimizing blade mass are somewhat conflicting objectives, However here in this work the blade mass is reduced based on some structural constraints like micro-strain and moment. To meet this objective, HARP Opt calculates the optimal blade shape in terms of these variables. (Pre-twist, Chord length, Percentage thickness and Shell thickness.).

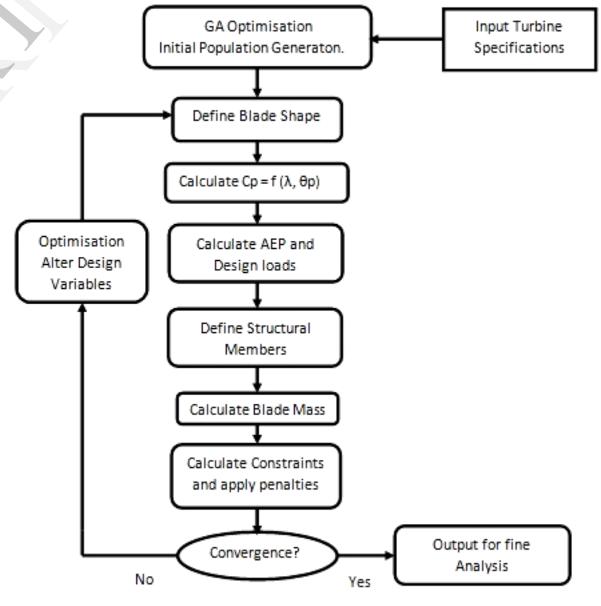

Fig.3.6. HARP Optimization Multi-objective design algorithm.

(Danny Sale (2012)).

The HARP Optimization code proceeds with the following algorithm in which the multi objective optimization code begins to proceed with the input turbine specifications and calculated both the aerodynamic and structural design parameters in order to satisfy the objectives and constraints.

The structural objective, ie, minimizing the blade mass is achieved using the Euler- Bernoulli Beam Theory. In Euler - Bernoulli theory we are assuming the wind turbine blade as a thin - shell Cantilever beam which is having isotropic material properties. In order to analyse structural stability the design load is resolved from maximum root moment over full range of operating conditions along with applied safety factor. This structural optimization only considering the maximum allowable bending strain.

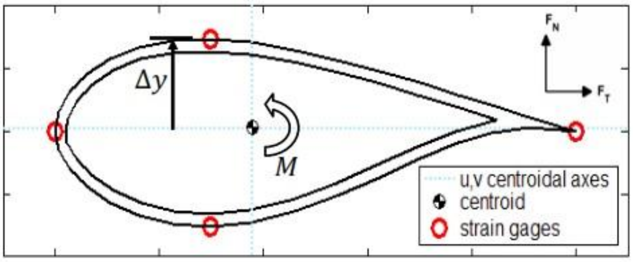

Fig.3.7. Wind turbine blade cross section showing centroidal axes, centroid and locations of strain gauges. (Danny Sale (2012)).

During structural optimization, the blade is modelled as a simple beam with bulk isotropic material properties. The blade cross section is modelled as a thin shell and strain is calculated at four strain gauges as shown in figure 6.4. Strain is calculated using equation 6.7 , where the span wise bending moments result from the maximum root bending moment experienced over the range of flow speeds.

$$\text{Bending Strain } \varepsilon_r = (\text{Safety Factor}) \frac{M_r C_r}{E I_r}$$

(3.1)

In equation 3.1, M is the bending moment, C is the distance from the neutral axis, E is the modulus of elasticity, I is the moment of inertia, and the subscript r denotes the local radial position value. Along with the technical data of original blade described above, in order to start the optimization the following limiting data also required.

Minimum flow speed = 2 m/s, Maximum flow speed = 26 m/s, Minimum allowable rotor speed = 4 rpm, Maximum allowable rotor speed = 32.5 rpm, Initial Weibull distribution long-term mean flow speed = 6.03 m/s, Weibull shape factor = 1.91, Weibull scale factor = 6.8, Shell thickness increment (mm) = 0.2, Minimum shell thickness (mm) = 1, Safety factor multiplied to bending moments = 1.2, Maximum allowable strain (micro-strain) = 3000, Density of bulk material (kgm^3) = 1800, E (Modulus of elasticity of bulk material (GPa) = 27.6.

Along with these aerodynamic and structural constraints the genetic algorithm configuration values also defined before optimization to get accurate control over the total optimization process. That values are, Populaton size (Number of individuals per generation) = 200, Maximum number of generations for GA iterations = 150, Fraction of individuals created by crossover = 0.25, Number of elite individuals per generation =1, Error tolerance for the GA fitness value) = 1.0x10^{-6}.

IV. RESULTS AND DISCUSSIONS

The GA Optimization for maximizing the Annual Energy Production (AEP) using harp optimization algorithm has been converged with 127 iterations as the number of stall generations exceeds the limiting value of 50 which have been defined already in the code.

A. GA Optimization Results: Best Individuals

The best individual from the 200 individuals defined as the population size for each generation, for variables like pre-twist, chord length, % thickness and dimensional thickness are obtained and are represented as span wise distribution, i.e, blade radius in the abscissa.

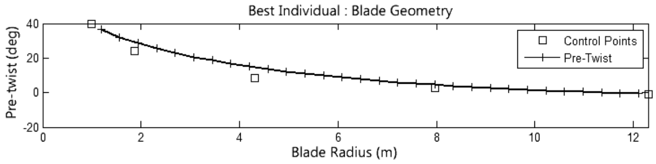

Fig.4.1. GA optimization result: Best individual for Pre-twist.

Here the optimized pre-twist is generated based on the Bezier curve optimally drawn through 5 control points. So the fifth order Bezier curve is used for fit over these control points. Here it can see from this best individual figure , the pre-twist is having a higher variation in the region nearer to the root and the twist is almost linearly varying into the tip of the blade.

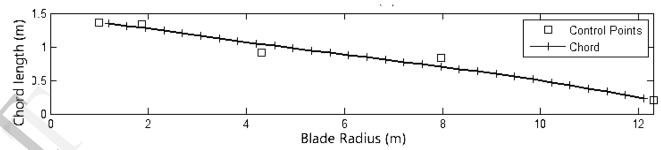

Fig.4.2. GA optimization result: Best individual for Chord length (m) distribution.

Then the chord length is optimized in a fashion which reduces the total blade mass which is our second objective. Optimized chord length distribution is also having a linearly reducing pattern from the root to the tip (Fig.4.2).

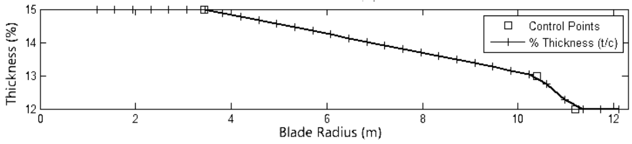

Fig.4.3. GA optimization result: Best individual for % thickness span-wise distribution.

The percentage thickness is always considering as a ratio, that means the thickness per unit chord length ie, (100*t/c). The percentage thickness (100*t/c) distribution defines the spanwise placement of airfoils, that means the radial distribution of various airfoils. Here the best thickness percentage is about 15% from the root to about 2.3 m of blade radius and then it is reducing linearly to about 13% at a radial position of 10.4 m, then it is decreasing to 12% and lesser values when it approaches the blade tip.

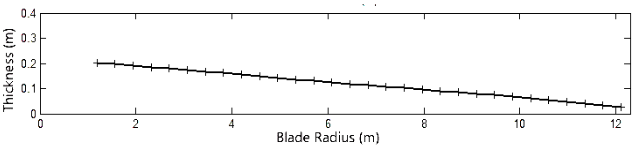

Fig.4.4. GA optimization result: Best individual for dimensional thickness.

The next best individual distribution graph (Fig.4.4.) is of dimensional thickness distribution, Dimensional thicnesss is calculated by combining the chord length and percentage thickness, ie, t=c*(t/c). As this method of optimsation is multi objective the dimensional thickness is having greater importance in reducing the blade mass. But, the maximum strain value constrain defined prevents the blade mass reduction in order to keep the blade within the microstrain value of 3000.

B. Comparison of Original Blade Parameters with the Optimized Blade Parameters

In this comparison study section, the comparison of original blade parameters with the optimized blade parameters are performed and the results are represented as span wise distribution graphs. Span wise distribution comparison graphs gives an idea about how the different parameters like blade pre-twist, chord length, %thickness and dimensional thickness are changing for actual blade and optimized blade from root region to the tip region of the wind turbine blade. That means aerodynamic and structural parameters of original blade are compared with the best individual values obtained from optimization.

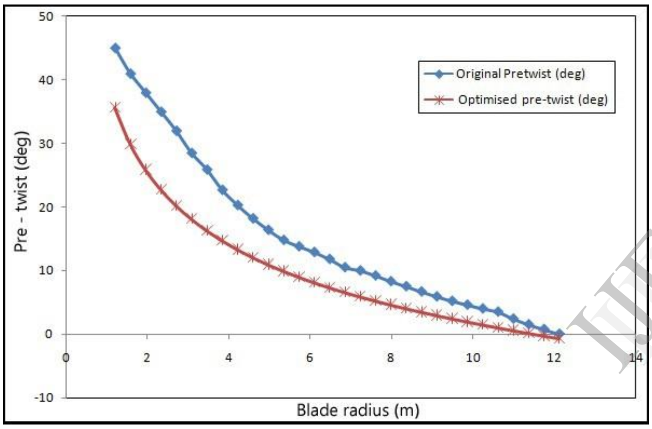

Fig.4.5. Comparison of Blade pre-twist (deg) of original and optimized blade.

Figure 4.5 represents the pre-twist comparison, from this graph it is clear that the pre-twist distribution values reduced almost linearly in optimization from the original pre-twist values. During optimization it is given an upper bound of 40 degree and a lower bound of -10 degree. So the twist values are reduced and aligned in a uniform fashion in the radial direction. This twist reduction contributes to stall regulation and thus by improvements in aerodynamic performance is obtained.

The comparison of chord length of original blade and optimized blade is represented in figure 4.6. Here it is clear that the chord length is reducing than the original chord length up to 5 m of blade radius. But the reduction is in a converging fashion from root to 5 m of blade radius. optimization can't reduce the chord length to a large extend since the structural constraints are there in consideration.

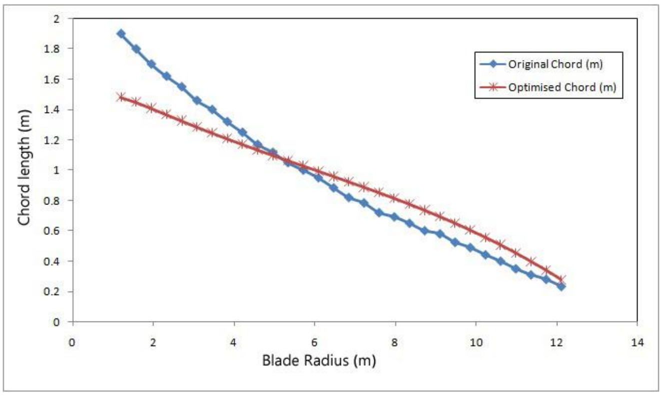

Fig.4.6. Comparison of Blade chord length (m) of original and optimized blade.

The micro strain values having an important role among the structural constraints. So the chord length in the root region is reduced and also in order to keep the structural stability the chord length is increasing linearly up to the blade tip region. Here after 5 m of blade radius the optimized chord length values are found increasing in consideration of the structural stability.

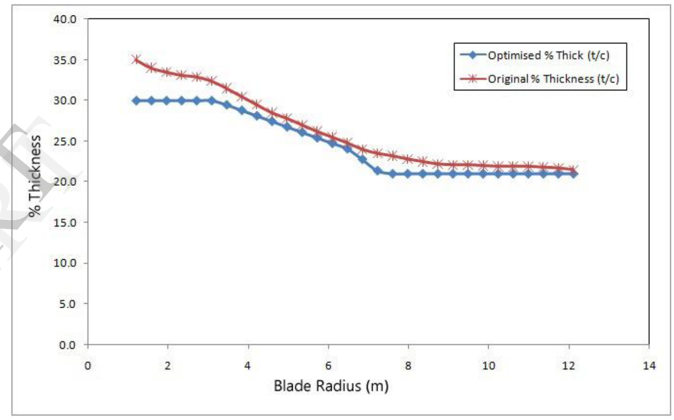

Fig.4.7. Comparison of Blade % thickness of original and optimized blade.

Figure 4.5 explains the distribution of % thickness in the radial direction of the blade. As the graph shows, by optimization a reduction in the percentage thickness throughout the blade span is happening. But, the reduction is not in a linear pattern. Because as before in the case of chord length here also the algorithm has to consider the structural rigidity. So the % thickness reduction is having a specific pattern as, the % thickness distribution is linear up to 3 m blade radius since it is the nearest region to the root where the moments are having the higher values. After that the % thickness distribution is decreasing almost linearly up to about 7 m of blade radius. Since the moments are having very low magnitude nearer to the tip, the optimized % thickness is having a linear pattern up to the tip.

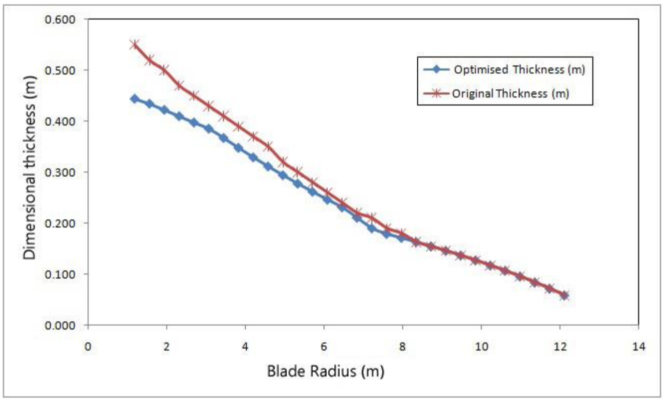

Fig.4.8. Comparison of Blade dimensional thickness (m) of original and optimized blade.

In case of comparison graph of dimensional thickness (t=c*(t/c)) (Figure 4.8) it is clear that it is having a linear pattern from root to the tip. There is a high dimensional thickness reduction nearer to the root in order to reduce the blade mass. After 8 m of blade radius the dimensional thickness of optimized blade is same as that of the original blade. Also a linear reduction pattern is observed up to about 9 m of blade radius.

Mass per unit span (kg/m) distribution graph (Figure 4.9) shows that the mass in kg per unit span is having larger values near the root and reduces almost linearly up to the blade tip.

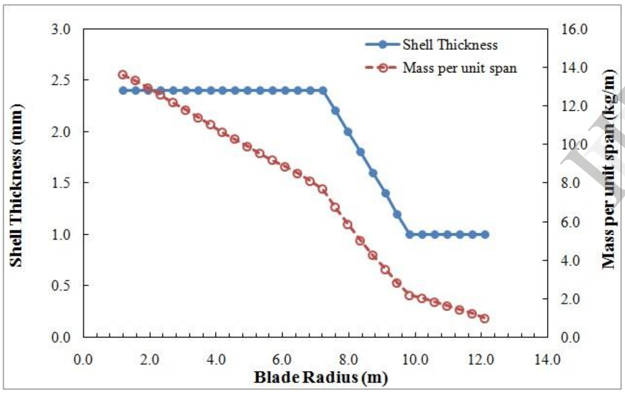

Fig 4.9. Mass per unit span (kg/m) and Shell thickness (mm) distribution.

This uniformity in mass reduction in radial direction is actually to withstand moments acting as in the same pattern. ie, having higher values in the root region and reducing almost linearly into the tip region.

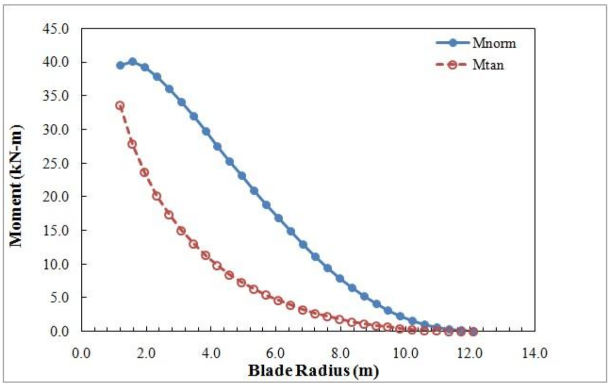

Fig.4.10. Moments M normal and M tangential vs Blade Radius (m))

The moments distribution graph (Figure 4.10) shows the variation of moment values in kN-m for both normal and tangential moments in radial direction. From this moment distribution graphs it is clear that, both the normal and tangential moments are having higher values near the root region of the blade and it is found deceasing in the radial direction. Especially in case of tangential moment, it is having very small values beyond half of the blade length and it found decreased to zero in the blade tip.

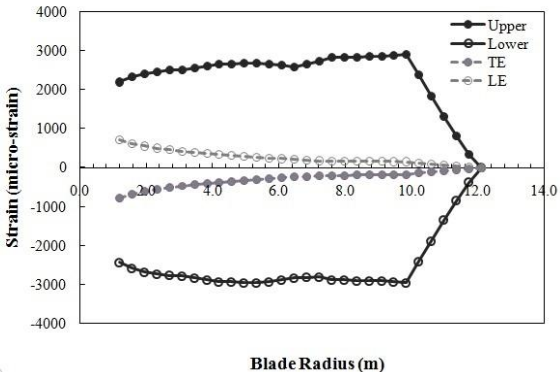

Fig 4.11. Figure 6.11: Upper bound, Lower bound, Trailing edge and Leading edge micro strains vs Blade Radius (m).

The micro strain distribution graph (Figure 4.11) shows the upper and lower bounds of micro strain values which has defined during the optimization stage. In this optimization study based on the material properties of fibre glass reinforced polyester blade the micro strain is limited to 3000 in upper and lower faces of the blade. The span wise variation of trailing edge (TE) and leading edge (LE) micro strain values are also represented in this figure. It is clear that both micro strain values are having the maximum value nearer to the root because of the higher moment values at that region and then reducing almost linearly to the blade tip.

C. *Optimized Blade Design Stage*

The optimized blade design parameters which are used to design the optimized blade in Qblade are represented in table 6.1. From this table it is clear that the NACA 63 airfoil family is purposefully changed into NACA 4415, 4413 and 4412 airfoils and also the chord length and pre-twist values are modified based on the optimization results.

Table 4.1. Optimized Blade Design Parameters.

Sl No.	Position (m)	Chord (m)	Pre-twist (m)	Airfoil
1	1	0.5	45.03	Circular
2	1.75	1.48	35.67	NACA 4415
3	2.503	1.325	25.90	NACA 4415
4	3.250	1.276	18.14	NACA 4415
5	4.000	1.207	14.74	NACA 4413
6	4.760	1.134	12.09	NACA 4413
7	5.516	1.081	9.97	NACA 4413

8	6.269	0.974	7.52	NACA 4413
9	7.020	0.896	5.92	NACA 4412
10	7.770	0.852	5.27	NACA 4412
11	8.520	0.736	4.07	NACA 4412
12	9.283	0.694	2.98	NACA 4412
13	10.030	0.605	1.51	NACA 4412
14	10.780	0.454	1.05	NACA 4412
15	11.540	0.341	-0.24	NACA 4412
16	12.300	0.278	-0.65	NACA 4412

Based on these blade design parameters obtained from the genetic algorithm optimization the optimized blade is first modelled in Qblade blade design software. After making an accurate design based on the optimized blade parameters the coordinate file of the total blade geometry is generated as before. The coordinate file which is having the details of airfoils at various radial stations is further imported in to the Solidworks 3D design software by using the importing curves through xyz points option. The airfoils profiles at various radial stations which are generated from coordinate files are shown in figure 4.12.

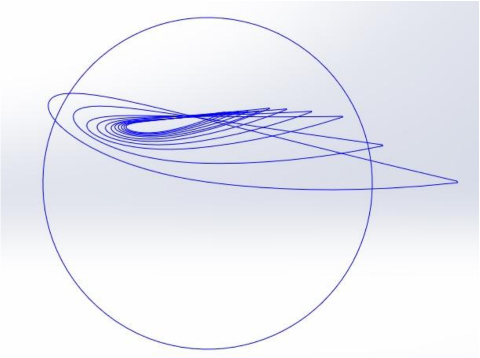

Fig 4.12 Airfoils generated after GA Optimizaton.

These airfoils are joined together by using the lofting feature in Solidworks as explained before and final optimized blade3D design is generated as shown in figure 4.13.

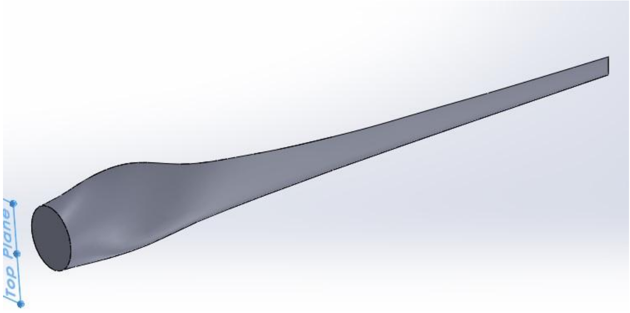

Fig 4.13. Optimized blade after design in Solidworks.

A. Cp Curve and Power Curve Comparison

Here the performance optimization has done in terms of the coefficient of performance (Cp) value . The coefficient of performance can also be defined as the ability of a wind turbine to develop power. The Cp curve for the original blade is generated based on the available technical data sheets of Nordtank 150 kW and Cp values for the optimized blade can be obtained from the GA optimization results. The coefficient of performance (Cp) value is found increased during optimization. These variations are represented in figure 4.14.

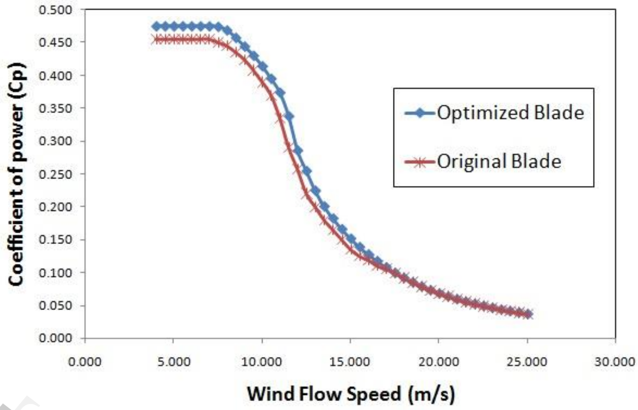

Fig.4.14. Cp Curve Showing Increase In Cp Value Due by Optimization.

It is clear that for larger wind speeds ie, more than 17 m/s the Cp value doesn't have much increase from the original Cp values. This is because, in case of larger wind speeds the high seed flow over the rotor reduces the chances of rotation.

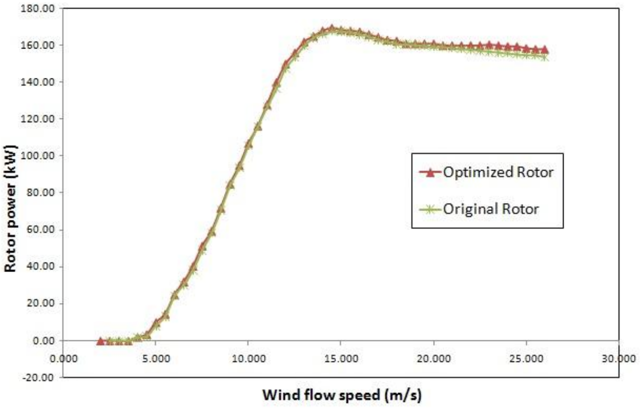

Fig.4.13 Power curve showing increase in power due to optimization

Accordingly the output power values in both these three cases are also compared and the results are represented in figure 4.13. It shows that the optimization of wind turbine blade geometry for aerodynamic and structural objectives optimized the power output and an increase of about 2% is obtained.

V. CONCLUSION

The design process of a wind turbine is very time consuming, methods and techniques are being refined in order to produce fastest and more reliable designs. The implementation of Qblade and harp optimizaton packages reduces largely the load of the design process and also it optimized the power output within the given constraints. The multi-objective design optimization using harp genetic algorithm is performed in order to obtain an optimized design. An optimized design is obtained with the objectives of maximizing the Annual Energy Production and minimizing the Blade Mass. The improvements in variables such as pre-twist, chord length, % thickness and dimensional thickness are also compared with those of original blade. A power increment of about 2% has been achieved by optimization with a reduction of about 15% in material requirement. This material reduction is also checked within the strain limits. Thus the objectives of improving the AEP via aerodynamic optimization and minimizing the blade mass via structural optimization have been completed successfully within the allowable strain values.

VI. FUTURE WORK POSSIBILITIES

The structural optimization method used can be modified using more structural theory models like classical laminaton theory, linear (eigenvalue) buckling theory and also some in depth finite- element model analysis. The structural modelling can be improved by using realistic models of composite blades where material properties and topology will be conidererd with greater importance. Composite layup analysis can be extended for optimization for minimising blade mass subjected to constraints like maximum allowable laminae stresses, blade tip deflection, panel buckling stresses and separation of blade natural frequencies. The genetic algorithm optimization method can be replaced with pattern search optimization algorithm in future studies since that is much faster and deterministic than genetic algorithm. Improvement in the design optimization code can be made possible by adding more design variables and constraint considerations in order to get the real time results.

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