Optimization of Hurricane Resistance Wind Turbine Blades

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Abstract*– Blade design optimization for the Naguabo Punta Lima Wind Farm will be detailed and presented in the wake of the damage caused by Hurricane Maria. An alternative approach for the design of the blades was performed using the data and information collected by the turbines' sensors during the hurricane, as well as the design specifications of the damaged wind turbines. With these factors, the main objective was a blade design that can withstand wind speeds of around 64.6 m/s, which were the maximum speeds recorded by the wind turbines. Details for the aerodynamic design such as the blade efficiency, airfoil selections, angles of attack, operational conditions, power generation, power coefficient and loads are included. Three blades were modeled using same energy production capabilities and high wind resistance, providing a starting point for the design and use of extreme wind resistant blades.

Keywords—Hurricane, wind speeds, blade, design

I. Introduction

Wind has been a resource that has been harnessed by mankind for ages to accomplish different tasks with better efficiency. Since the start of the 20th century, windmills has been be used as an alternate source of energy paving the way for the modern wind turbine. There are two main designs that classifies said machinery, the Horizontal Axis Wind Turbine (HAWT) and the Vertical Axis Wind Turbine (VAWT). The HAWT model is a turbine with the shaft, rotor, and other main components mounted horizontally, parallel to the ground. By contrast, the VAWT model has the shaft and components mounted vertically, perpendicular to the ground [3]. Both designs offer different advantages and disadvantages when directly compared with each other. For the purpose of this research, the HAWT model was chosen since it's the same model installed at the Punta Lima Wind Farm in Naguabo. This site is composed of 13 Vestas V100/1.8MW which have been in production since October 2012. The Punta Lima Wind Farm has a capacity of 25 Megawatts of clean energy with the potential of generating the energy demand of 9,000 homes in several towns in the eastern region of Puerto Rico making this the second most productive source of renewable energy in the island. The first and largest production of renewable energy is the Santa Isabel Wind Farm, currently generating 101 Megawatts of energy to fulfill the needs of around 30,000 houses. The Punta Lima wind farm was severely impacted by the hurricane Maria, since winds gusts off up to 350 km/h were recorded. All the turbines had structural damage, thus 100% of the wind field was completely affected taking the turbines out of commission. The most common type of damage was structural failure of the blades which can be appreciated on Fig. 1.

Figure 1: Damaged turbines at Punta Lima Wind Farm After the Passing of Hurricane María

The impact of hurracaine Maria is one of the few instances where there was a direct impact of of a category 5 huricaine on a utility scale wind farm. The objective of this study is to do a preliminary analysis of blades that could withstand extreme wind conditions while having the same dimensions and similar power generating capabilities as the blades of the original wind turbines installed on site.

For further simplification on the blade design, the same parameters and specifications given by the manufacturer as for cut-in wind speed, rated wind speed, cut-out wind speed, rated power, pitch degrees, blade length and max chord, hub diameter and hub height were used. Some of the parameters were followed for the design and optimization of the blades. The efficiency of the wind turbine, airfoil designs (thickness, lift to drag coefficient, angles of attack) and materials were prioritized for the design and objectives completion. The governing equations and values for some parameters needed were calculated such as the tip speed ratio (1) which is the relationship that exists between the rotor blade velocity and the relative wind velocity:

Eq. [1] $$\lambda = \frac{\Omega r}{V_W}$$

λ = Tip speed ratio
Ω = Rotational velocity (rpm)
r = Radius (m)
Vw= Wind speed (m/s)

The tip speed ratio was used in the design process and impacts the efficiency drastically. Other relevant values were determined using QBlade an open source blade design software which includes all the necessary tools and tests required for an optimal blade aerodynamic design and parameters. The airfoils used in the different designs were sourced form Airfoil Tools which is a website with a catalog of 1,636 different airfoils [1,2,3]. Studies for several types of airfoils, thicknesses and lift to drag ratio were crucial when selecting the correct foils for the blade sections development from the root, mid span and tip. Once the blade was partially completed according to the number of sections and the placement of a specific airfoil in each section, the blade was optimized using the Betz limit. The Betz optimization theory indicates the coefficient of which a turbine cannot capture more than 16/27 (0.593) of the kinetic energy in the wind. Once the designs were completely developed and tested for efficiency and power generation, the design coordinates were transferred to Microsoft Excel so the designs could be exported to SolidWorks. SolidWorks allowed for a more customizable setting for the blades to be viewed and analyzed. The loads testing was performed using Autodesk Fusion 360, an open source Computer Aided Design program. It allowed an easier materials test and load applications by displaying status, bars and possible solutions to whether the design withstands the applied loads (wind pressures) and the capability of the materials used.

II. PROCESS

An analysis of the retrieved data of the hurricane from the wind turbines in Naguabo Punta Lima Wind Farm was done to understand the magnitude of the damage caused, speed winds and relevant information used in the new blade designs.
By looking up the company manufacturer and wind turbine model used, we could determine more parameters to be used for the functionality of the new blades on the whole turbine. Some familiarization with the QBlade program was needed to understand its inner workings as well as the types of graphs, tests and details of the air foils, and as of this, air foil analysis and comprehension were crucial for optimum aerodynamics. Three blade designs were created using the original wind turbine specifications as it follows in **Table 1**.

Table 1: Vestas V100/1.8MW Wind Turbine Specifications

Parameter	Value
Capacity (MW)	1.8 MW
Rotor Diameter (m)	100 m
Blade Length (m)	49 m
Max Chord (m)	3.9 m
Cut-in wind speed (m/s)	4.0 m/s
Cut-out wind speed	20.0 m/s
Rated wind speed	12 m/s
Dynamic Rotational Speed Range	9.3 rpm to 16.6 rpm
Upwind, Hub diameter	3.3 m
Swept area	7850 m^2
Tip speed ratio start	1
Tip speed ratio end	7
Wind speed (blade efficiency test)	21 m/s
Pitch range	(-5º to 90º).

The design characteristics of the first blade model created are summarized in Table 2.

Table 2: Blade 1 Air foil Sections

Sections	Description
1-4	Circular Foil (100% thickness),
5	5 DU99W405LM airfoil (40% thickness, max CL/Cd at 1º)
6-7	DUW350LM airfoil (34.99% thickness, max CL/Cd at 5º)
8	DU97W300LM airfoil (30% thickness, max CL/Cd at 7º)
9-10	DU91W2250LM airfoil (25% thickness, max CL/Cd at 6º)
11-12	DU93W210LM airfoil (21% thickness, max CL/Cd at 6º)
13-19	13-19 NACA64618 airfoil (18% thickness, max CL/Cd at 5º)

The blade design geometry with all its sections can be seen in **Figure 2**.

Figure 2: Blade Design 1

Based on the maximum chord of the original blades used on the Vestas V100 model, the chord was set to be 3.9m at the root. The twist per sections were automatically calculated by QBlade optimizing the blade using the Betz limit theory. **Figure 3** shows the efficiency graph of the blade.

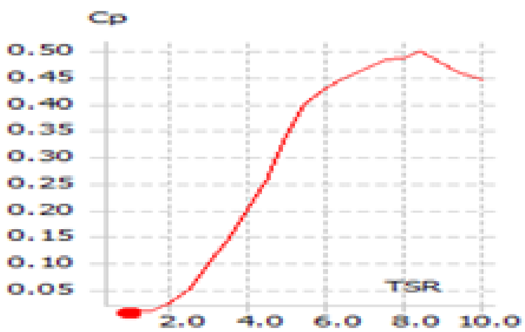

Figure 3. Power Coefficient Graph of Blade Design 1. (TSR 7)

The graph shown on **Figure 3** demonstrates that the design performs well and has a considerable power coefficient. However, since the airfoils employed on the design have a high thickness percentage, the blade are heavier compared to the original blades used on the Vestas models. Therefore, the cut-in speed is increased from 4 m/s to 5 m/s.

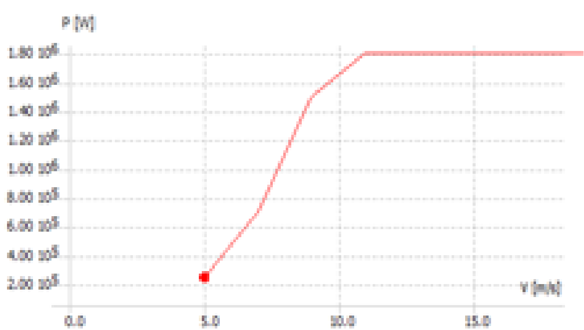

Figure 4. Power Generation Graph of Blade Design 1

The second blade design was created following the same procedure as the previous one. However, different air foil combinations were used on this model. In this iteration, 21 sections were created to perform with the best results for this type of design. The sections are described in **Table 3** and the geometry can be seen in **Figure 5**.

Table 3: Blade 2 Air foil Sections

Sections	Description
1-2	Circular Foils (100% thickness at 1.2 drag coefficient)
3-21	GOE 434 airfoil (22.70% thickness, max CL/Cd at 2.5°)

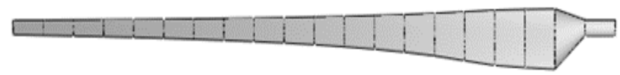

Figure 5: Blade Design 2

Twist angles were calculated using the optimization option from the software according to the angle of attack that produced the maximum lift to drag coefficient (Cl/Cd) and the Betz limit theory. Chord length max was established based on the original specifications from the wind turbine.

Figure 6 demonstrate the efficiency of the blade at a tip speed ratio of 7. **Figure 7** represents the generation capacity of the blade which fulfills the generation parameters of the original blades used on the Vestas turbine.

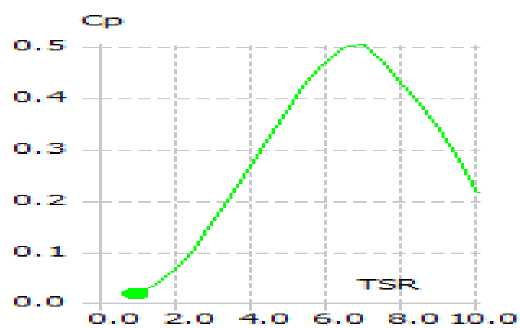

Figure 6. Power Coefficient Graph of Blade Design 2. (TSR 7)

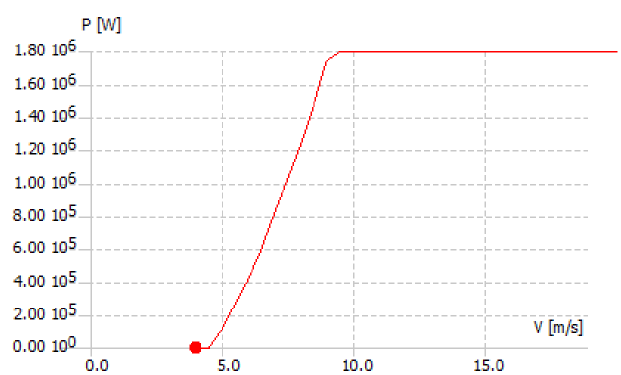

Figure 7: Power Generation Graph of Blade Design 2

On the third blade model, the same design procedure of the previous two blades was also followed as well as the same requirements and parameters. However, this blade design is divided into 16 sections for which the descriptions are shown in **Table 4** and the geometry can be seen in **Figure 8**.

Table 4: Blade 3 Air foil Sections

Sections	Description
1-2	Circular Foils (100% thickness at 1.2 drag coefficient)
3-16	NREL'S S815 airfoil (26.19% thickness, max CL/Cd at 8º)

Figure 8: Blade Design 3

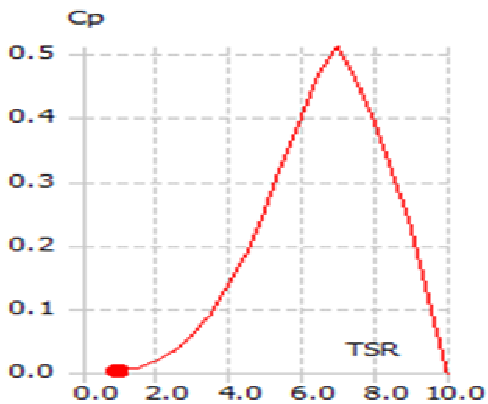

Figure 9: Power Coefficient Graph of Blade Design 3. (TSR 7)

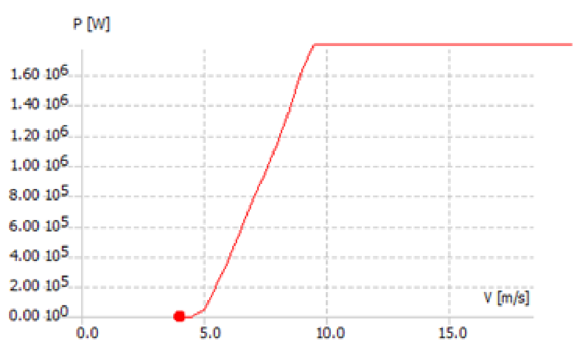

Figure 10: Power generation of design 3

Twist angles were calculated using the optimization options from the software according to the angle of attack that produced the maximum lift to drag coefficient (Cl/Cd) and the Betz limit theory. The maximum chord length was established to be 3.9 m which is the same maximum chord length as the original blades from the Vestas wind turbine. **Figure 9** demonstrates the power coefficient of the blade at a tip speed ratio of 7 while **Figure 10** demonstrates the power generation capacity of the blade.

Once the designs were completed and analyzed using the QBlade software, the data files of the blades and airfoils were transferred to Microsoft Excel, where the design coordinates are edited and reconstructed using the airfoils data. This was done and saved in a text delimited and comma delimited format to be used with SOLIDWORKS. In order to transfer the design, different planes must be generated depending on the number of sections. The distance that separates each plane needs to be the same along the whole blade according to the overall length of the design. One by one, the coordinates of each air foil along with the twist angle are exported to SOLIDWORKS according the corresponding section. This process makes it possible to connect each section and generate the design on the CAD software. In order to study the designs and perform static analysis the models were transferred to Autodesk Fusion 360. Due to the evident structural limitations of materials and compounds in plastic and glass a specific and complex material was chosen for strength, stresses and safety factor tests. The material selected was Carbon Fiber Reinforced Polymer (CFRP) which is a compound used in the design of aero-dynamical and structural components such as helicopter blades, chassis and car parts for better resistance and performance, the material properties are shown in **Table 5**.

Table 5: CFRP Material Properties

Parameter	Values
Density	1.43 e-06 kg/mm3
Young Modulus	133000 MPa
Poisson Ration	0.39
Yield Strength	300 MPa
Ultimate Tensile Strength	577 MPa
Thermal Conductivity	0.105 W/ (mm º C)
Thermal Expansion Coefficient	9.93 e-06/º C
Specific Heat	1130 J/(kgº C)

Using the maximum air speed recorded on the sheet data collected from the wind turbine sensors during the hurricane, the air pressure amount was then converted into a punctual force by multiplying the pressure exerted by the wind along the area of the blade (an average width was calculated based on the chord of each section due to irregular geometry of the blade0) to have the punctual force given in kN.

Three wind pressures were selected to be the basis for the analysis of the blades. The force applying test included the maximum registered wind speeds at the site were of 64.6 m/s (236 km/hr), the maximum sustained wind speeds measured and wind gust speeds of 78.23 m/s (283 km/hr) and 89.40 m/s (321 km/hr), Maria. Stress calculations and safety factor comparisons were done to solidify the results and validation [6].

Eq. [2] $$\sigma = \frac{F}{A}$$

σ = Stress (MPa)
F = Force (lbf)
A = Blade area (ft^2)

III. Results

Each blade was designed to have a power generation curve like the existing blades and power coefficient of 0.5. To analyse the blades' behaviour under a hurricane scenario a stress analysis was performed to determine the resistance to extreme wind conditions as seen in **Figure 11**. The stress analysis was done in the Autodesk Fusion 360 software where the circular foil located at the root of the blade simulating the attachment of the blade to the hub was chosen as a fixed point and the wind pressure as a total punctual force was applied in the middle. For validation purposes on the designs, the stresses were calculated by estimating the force per unit area exerted in each blade and compared the theoretical value of the blades with the experimental ones. This data validation will estimate the difference between a theoretical design with the actual design as the team strived to achieve a design with as little difference as possible for optimum efficiency and application.

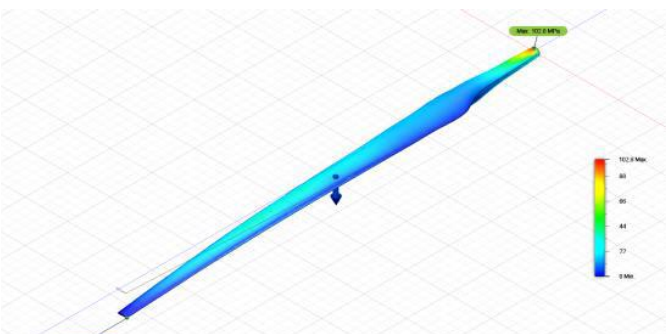

Figure 11: Stress Analysis for Design 1 at 89.4 m/s

Each turbine blade was subjected to each pressure individually using the same material for all models. After the analysis process ended, the stress calculations performed by the program were compared to the manual calculations performed by the team to see the similarities in the numbers and error percentage. The stress results are displayed in **Table 6** with experimental results and **Table 7** and demonstrate that the calculated values for the devised models are well below the yield and ultimate tensile strength.

The error percentage was minimal in the first two blade designs when compared to the third one, as a difference or change in a length or chord could have altered the structural design and therefore, the experimental stress calculation. Each pressure exerted in every blade is different depending on the area.

Table 6: Experimental Stress (Autodesk Fusion 360)

	Windspeeds		
	64.6 m/s	78.2 m/s	89.4 m/s
Design	Experimental Stress (MPa)		
1	53.67	78.66	102.85
2	65.11	88.15	115.16
3	65.36	95.86	125.27

Table 7: Theoretical Stress Calculation (Using Eq. (2))

	Windspeeds		
	64.6 m/s	78.2 m/s	89.4 m/s
Design	Theoretical Stress (MPa)		
1	56.34	82.55	107.86
2	56.31	82.59	107.87
3	56.31	82.59	107.86

The safety factors were estimated comparing the strength of the blades and the given the force that the wind conditions exert. The calculated safety factor calculated on Autodesk Fusion 360 for each wind speed is presented in **Figure 12**.

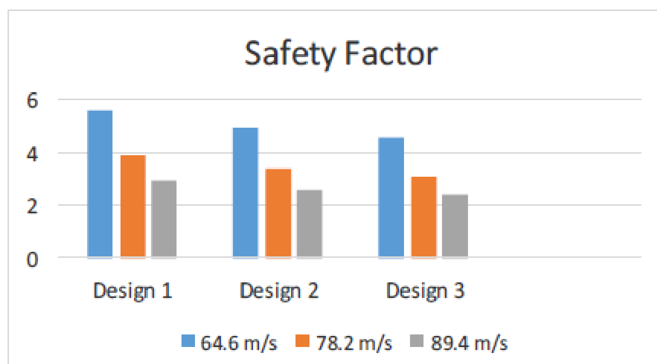

Figure 12: Safety Factor of the Blades at Different Wind Speeds

Based on the resulting safety factors, the three designs were shown to resist the recorded wind speeds of 64.6 m/s without suffering major damage or breaking off entirely which fulfils the most important objective of the research. Further on, the blades were pushed to a limit of 78.2 m/s and 89.4 m/s for maximum load resistance testing to verify the highest wind speeds these blades could take. As the results came in, the Blade Design 1 was shown to be the most successful one, as it had the highest safety factor in all three of the load studies. This was due to it being designed with the air foil with the highest thickness percentages of all the three designs. Blade Design 2 managed to withstand all the loads applied with a good safety factor despite the low thickness percentage off the air foil used when compared to Blade Design 1. Finally, Blade Design 3 Was shown to be a great design, resisting the first load of 64.6 m/s. However, the model has a lowest safety factor of the last two load studies when compared to the previous two designs. The low thickness percentage of the air foil used on the design resulted in a poor durability when the tests were performed. Since the research was focused only on blade design resistance and durability, noise decibels were not taken in consideration.

IV. Conclusion

The process design of the blades fulfilled all the parameters of the original blade located in Naguabo Punta Lima Wind Farm. Studies of power coefficient, power generation and lift to drag coefficients were realized individually for each blade design, to find the most optimum design and aerodynamics. As part of the research done, further studies are being performed on different material types, resistances and weight, to help produce a more reliable blade design that can withstand the hurricane Maria like winds with the possibility of even higher speeds. Some design parameters were relatively new, as there has been not register any other wind turbines that had been struck by winds of more than the ones registered by the Vestas V100/1.8Mw models in Naguabo during the passing of the hurricane. Load studies on the wind blades were done, as the team strived to perform more research and design optimization to overcome these abnormal weather conditions. As the blades do not have a geometrical design, the area of the blades was calculated by choosing an average overall chord taking into account the chord of each section, thickness and full blade length to design a rectangular equivalent of the blade in which a total static load will be applied in the figure for resistance measurements. The three designs were shown to resist the recorded wind speeds of 64.6 m/s to fulfil the most important objective of the research. Further on, the blades were pushed to a limit of 78.2 m/s and 89.4 m/s for maximum load resistance to verify the highest wind speeds these blades could resist. It was demonstrated that a low thickness percentage resulted in lower performance when the load simulations were performed. As mentioned before, noise decibels were not taken in consideration, as the team focused only on achieving blade designs with considerable resistance and durability under high wind speed conditions. Safety factor numbers in the program delivers a realistic percentage of resistance and safety in any desired parameters established. Each blade was studied for each load separately to obtain the factors and design effectiveness. Other improvements for the wind turbines in infrastructure should be also a priority in a better design development, as not only the blades were affected, but also the hub, tower and other components.

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