Development of an Open Source Tool for the Preliminary Structural Design of a Small Wind Turbine Based on National and International Standards

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Abstract *— Wind energy have proven to be a viable option in the production of electricity. The benefits from wind energy sources include reductions in greenhouse gas emissions, water conservation and the diversification of the electricity production portfolio, among others. All wind turbines sold in the United States must be certified by a recognized institution following the AWEA Small Wind Turbine Performance and Safety Standard [1]. The certification process involves the mechanical analysis to ensure the structural integrity of the wind turbine. The approach follows the AWEA Small Wind Turbine Performance and Safety Standard and incorporates the "Simple Method" as described in IEC 61400-2 [4]. The purpose of this project is to develop an open source tool to perform preliminary structural analyses in the design of small wind turbines. The tool takes into consideration the key characteristics of the wind turbine's tower, blades and shaft to perform fatigue, strength and vibrations analyses. The results from the tool were successfully verified against published results.*

Key Terms **—** *Design, Tool, Software, Small Wind Turbines.*

INTRODUCTION

The proliferation of Small Wind Turbines (SWTs) in the United States have generated a controversy over the safety of the available models in the market. Many states are emitting installation permits only for Small Wind Turbines approved by recognized entities such as the Underwriters Laboratories (UL) or the American Wind Energy Association (AWEA). The requirements for the AWEA certifications are based on the AWEA Small Wind Turbine Performance and Safety Standard, which in turn is based on the International Electrotechnical Commission's standard IEC 61400-2 (AWEA, 2009) [1]. These documents describes different methods for designing and testing small wind turbines. The criterion in these documents is extensive and complex and its application requires multiple calculations.

The AWEA Small Wind Turbine Performance and Safety Standard was created by the small wind turbine industry, scientists, state officials, and consumers to provide consumers with realistic and comparable performance ratings and an assurance the small wind turbine products certified by the standard have been engineered to meet carefully considered standards for safety and operation (AWEA, 2009). The structural analysis of the national standard is based on the international standard. To this date, there are no free open source tools widely available with the specific purpose of designing small wind turbines according to the national or international standards.

The tool created in this project is geared towards the engineer and the graduate student as an aid in understanding and performing the design of Small Wind Turbines based on the national and international standards. It is designed to cover all the basic structural integrity analyses required by the standards for the rotor, blades and tower of the turbine, making use of the "Simplified Load Model" provided by International Electrotechnical Commission. [4]

PROGRAMING PLATFORM

The purpose of this project is to create a tool to aid in the preliminary design of small wind turbines. It was decided to create the tool using Microsoft

Excel because it is simple to program as a spreadsheet and, if required, scripts could be created without the need of compiling. This enables more users to keep improving the tool in the future, eliminates the need to install extra software to use it, and provides a proven and accessible platform for future development.

DESIGN METHODOLOGY

This tool will verify that the blade root, main shaft, the yaw axis and mounting pole does not exceed the limit states as per ISO 2394 (General Principles on Reliability for Structures, International Standard) **Error! Reference source not found.**, as required by the IEC standard. For this purpose, the Simplified Load Equations described in chapter 7.4 of IEC 61400-2 will be used (IEC, 2006)**.**

EXTERNAL CONDITIONS

Small Wind Turbines are subjected to multiple external conditions such as wind, earthquakes, handling and installation, etc. The IEC standard for Small Wind Turbines deals with a very limited set of external conditions. This tool takes into consideration only wind conditions, which are divided into the following categories:

- General
    - Frequent wind conditions
    - Extreme (1 year or 50 years recurrence period)
    - ±8° mean flow inclination
- Normal wind conditions
    - Wind speed distribution
    - Normal wind profile model (NWP)
    - Normal turbulence model (NTM)
- Extreme wind conditions
    - Extreme wind speed model (EWM)
    - Extreme operating gust (EOG)
    - Extreme direction change (EDC)
    - Extreme coherent gust (ECG)
    - Extreme coherent gust with direction change (ECD)

DESIGN LOADS

The following design loads will be taken into account by this tool:

- Vibration, inertial and gravitational loads, resulting from inertia, gyroscopic, vibration, rotation and gravity.
- Aerodynamic loads caused by airflow and its interaction with stationary and moving parts. Airflow is dependent on the rotational speed of the rotor, wind speed across the rotor plane, turbulence, air density and aerodynamic shapes of the turbine components.

SIMPLIFIED LOAD METHOD

Table 1 shows a summary list of all the load cases considered in this tool. It categorizes the load cases as either "F" for fatigue loads to be used in the assessment of fatigue strength or "U" for the analysis of ultimate loads such as exceeding the maximum material strength, tip deflection and stability.

Table 1
Design Load Cases for the Simplified Load Calculation Method (IEC, 2006)

Design situation	Load cases		Wind inflow	Type of analysis	Remarks
Power production	A	Normal operation		F	
	B	Yawing	$V_{hub} = V_{design}$	U	
	C	Yaw error	$V_{hub} = V_{design}$	U	
	D	Maximum thrust	$V_{hub} = 2,5V_{ave}$	U	Rotor spinning but could be furling or fluttering
Power production plus occurrence of fault	E	Maximum rotational speed		U	
	F	Short at load connection	$V_{hub} = V_{design}$	U	Maximum short-circuit generator torque
Shutdown	G	Shutdown (braking)	$V_{hub} = V_{design}$	U	
Parked (idling or standstill)	H	Parked wind loading	$V_{hub} = V_{e50}$	U	
Parked and fault conditions	I	Parked wind loading, maximum exposure	$V_{hub} = V_{ref}$	U	Turbine is loaded with most unfavourable exposure
Transport, assembly, maintenance and repair	J	To be stated by manufacturer		U	

LOAD CASES

As part of the design process, a wind turbine must be analyzed for the various loads it will experience during its design life. The purpose is to verify that the turbine will be able to withstand these loads with a sufficient safety margin.

For design purposes, the life of a Small Wind Turbine can be represented by a set of design situations covering the most significant conditions the turbine may experience. For certain turbine configurations, these conditions can be derived from simple, conservative equations. The Small Wind Turbine shall meet the following requirements in order to be able to use these equations, and hence this tool:

- Horizontal Axis
- 2 or more bladed propeller-type rotor
- Cantilever blades
- Rigid hub (not teetering or hinged hub)
- Rotor swept area less than $200m^2$

The turbine configuration of the rotor may be upwind or downwind and it can be either a fixed speed or variable speed rotor with fixed, active or inactive pitch mechanism. It may also have or not have a furling mechanism. Design load cases to be analyzed during the design process of a wind turbine are constructed by a combination of relevant design situations and external conditions.

Figure 1 shows the different coordinate systems of the Small Wind Turbine as defined by the IEC standard. The coordinate systems are defined as follow:

- Tower: X is positive in the downwind direction, Z is pointing up, and Y completes the right hand coordinate system.
- Shaft: X is such that positive moment about the X axis acts in the rotational direction of the rotor. Y and Z are not used (only the combined moment is used). The shaft axis system rotates with the nacelle.
- Blade: X is such that a positive moment about the X axis acts in the rotational direction. Y is such that a positive moment acts to bend the blade tip downwind. Z is positive towards the blade tip.

It is worth to note that the blade coordinate system follows the right-hand convention for a rotor that spins clockwise and the left-hand convention for a rotor that spins counterclockwise when viewed from an upwind location. Also, the blade axis rotates with the rotor.

The following load cases are the minimum the IEC standard requires for the certification of a Small Wind Turbine as requested by the IEC standard. These load cases are calculated by the tool using the formulas provided by the IEC 61400-2 standard found in Appendix I: Formulas.

Load Case A: Normal Operation

Under normal operation the Small Wind Turbine is subjected to fatigue loads. This load case assumes a constant range fatigue for the blade and shaft.

On the blade, the loading is considered to occur at the point with the lowest ultimate strength. The range of stress is the combination of the centrifugal loading and bending moments.

On the shaft, the loading is considered to occur at the first bearing (nearest to the rotor). The range of stress is calculated by combining the thrust loading, the torsion moment and the bending moment.

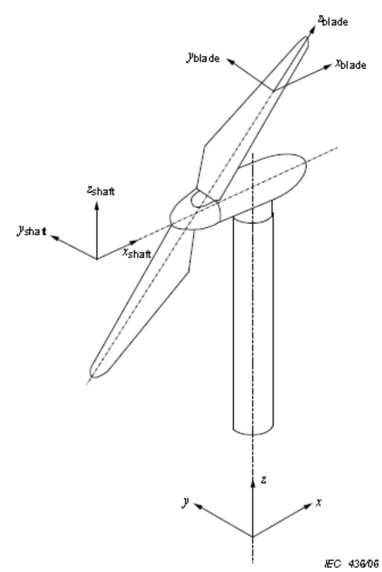


Figure 1
Definition of the System of Axes for the Small Wind Turbine (IEC, 2006)

Load Case B: Yawing

For this load case, the limiting loads are gyroscopic forces and moments. These loads are calculated assuming the maximum yaw speed occurring at the same time the rotor is spinning at the design rotational speed. The IEC standard provides a simple formula for calculating the maximum yaw speed based on the radius of the rotor radius, and for all turbines with a swept rotor area of less than $2m^2$ the maximum yaw rate shall be limited to 3 rad/s. This tool will only deal with passive yaw systems in order to keep it simple and since most of the Small Wind Turbines use this design.

The maximum yaw rate is used to calculate the loads due to the bending moment on the blade and the shaft bending moment. For the shaft, the loads depend on the number of blades. There are different formulas for two bladed and 3 bladed (or more) Small Wind Turbines. The tool has the capability to differentiate the two.

Load Case C: Yaw Error

Since all turbines operate under a certain yaw error, the IEC standard takes it into account by implementing a very conservative analysis, assuming a 30° error. Formulas are provided to calculate the flapwise bending moment caused by this error, based on the blade's projected area, its lift coefficient, radius, rotational speed and the design tip speed ratio at design speed. The standard specifies that if not data is available, the maximum lift coefficient shall be 2.0

Load Case D: Maximum Thrust

Maximum thrust loads on the rotor, acting parallel to the rotor shaft, are calculated using a formula provided by the standard, based on the air density, average wind speed, rotor radius and a thrust coefficient, which is simply defined as 0.5.

Load Case E: Maximum Rotational Speed

In this case, loads on the blade and the shaft are taken into consideration. The centrifugal load in the blade root and the shaft bending moment due to the centrifugal load and rotor unbalance are calculated from equations provided by the standard.

This case needs the maximum rotational speed of the rotor. This is property is a characteristic of the Small Wind Turbine and shall be determined by means of testing under the conditions specified by the IEC standard.

Load Case F: Short at Load Connection

This case assumes a direct electrical short at the output of the Small Wind Turbine or internal short I the generator. In either case, a high moment is created about the rotor shaft due to the short circuit torque of the alternator. For simplicity, this moment is assumed to be twice the Design Shaft Torque, as specified in the standard. This moment is transferred to the blades and is used to calculate bending stresses by dividing the moment by the number of blades.

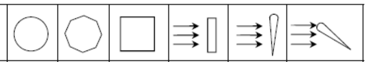
Load Case G: Shutdown (braking)

For this case, a brake load which shall be determined by the designer is assumed to be applied while the generator is delivering design torque. The total shaft moment is then the sum of the brake moment and the design torque. Similar to Load Case F, the bending moment on the blades is determining by dividing the moment by the number of blades and adding the torque caused by the blade's inertia. These loads need to be increased if the Small Wind Turbine has a gearbox. The increase is calculated by the tool.

Load Case H: Parked Wind Loading

These load case assumes the Small Wind Turbine is parked (not producing energy). Although the turbine may not rotating, the wind is still acting on its exposed surfaces. Loads are calculated assuming the 50 year extreme wind speed (V_{e50}) as defined in the IEC standard. The out of plane blade root bending moment is dominated by drag and is calculated based on this wind speed, air density, the blade's planform area, the rotor radius and the drag coefficient. The drag coefficient is taken as 1.5 as defined by the standard.

Loads on the different components of the Small Wind Turbine, caused by air drag, are calculated individually based on its projected area normal to the wind direction, air speed and the coefficient of drag of the components.



Characteristic length < 0,1 m	1,3	1,3	1,5	1,5	1,5	2,0
Characteristic length > 0,1 m	0,7	1,2	1,5	1,5	1,5	2,0

Figure 2
Drag Coefficients for Different Shapes (IEC, 2006)

TOOL USAGE

The tool is divided into 5 modules made into different tabs in Excel:

- **Materials**: Input of different material properties for the blade, shaft and tower. This tab allows for the specification of the material characterization level. This controls the factors of safety applied to the materials properties as specified in the IEC standard.
- **Turbine**: Turbine characteristics, dimensions, specs, etc. This tab also determines, based on the user inputs, the applicability of the Simplified Loads Methods to the particular Small Wind Turbine.
- **Wind**: Provides a space for specifying the air density and Rated Wind Speed of the turbine. Most of the parameters in this tab are calculated automatically per the IEC standard requirement.
- **Loads**: This tab calculates all the loads required by the IEC standard for all the required load cases.
- **Results**: Provides a summary of all the individual stresses in all applicable directions for the blades, shaft and the tower. It automatically calculates the applicable material and load safety factors as required by the IEC standard, based on the user inputs. Shows the equivalent stresses on each part for each load case, as well as its safety factor against the materials mechanical limits. A vibration assessment is also shown, where the natural frequency of the blades and the tower is compared against the rotor rotational frequency and blade passing frequency. Determines the fatigue life of the component based on the equivalent stress and the fatigue limit at 10^3 cycles, which is considered to be conservative.

Data input is in the Materials, Turbine, Wind and Loads tabs is straight forward. All inputs are well labeled and color coded.

- Green boxes are constants.
- Yellow boxes require user input.
- Grey boxes are automatically calculated, no user modification is required.

The results tab has a different color coding:

- Red boxes means a particular safety factor is less than 1.00 or than a frequency is within 5% of the rotational frequency of the rotor or the blade passing frequency.
- Green boxes means a particular safety factor is equal to 1.00 or more, and that a frequency is above or below 5% of the rotational frequency of the rotor or the blade passing frequency.

In order to make future modifications to the tool, all important parameters and all results are assigned its own range name (parameter name). This parameter name can be accessed from any sheet within the document, thus simplifies the creation of new calculations and makes formulas more readable. All parameters show its units (where applicable), and there are drawings in each tab to help understand the loads and stress results.

MATERIALS

The materials tab provides a space to specify different material properties required for the calculations of stresses, fatigue life and natural frequencies. There are individual materials for the blade, shaft and tower. The "Material Characterization" parameter is used to specify the level of confidence and probability for the materials. This parameter controls the material safety factor the tool is going to use for scaling material strengths.

SAFETY FACTORS

The IEC standard requires using safety factors to scale both material properties and calculated loads. All safety factors are automatically calculated and applied for their respective cases.

Material Safety Factors

For a fully characterized material the IEC standard requires a fatigue strength safety factor of 1.25 and an ultimate strength safety factor of 1.1. For a minimally characterized material, the values are 10.0 and 3.0 respectively. These safety factors are used to scale down ultimate strength properties for using in strength and fatigue calculations.

Loads Safety Factors

Partial safety factors for loads are based solely on the type of load calculation used for the analysis. Since this tool uses the Simplified Loads Method, the IEC requires using a safety factor of 1.0 for fatigue loads and 3.0 for ultimate loads. These safety factors are used to scale up loads for using in strength and fatigue calculations.

STRESS CALCULATION

Stresses are calculated on the three most important components of a Small Wind Turbine. The blade, the shaft and the tower. After superimposing the loads, directional stresses are calculated and used to calculate principal stresses. These principal stresses are then used to calculate equivalent stress (von Mises) as required by the IEC standard.

FATIGUE CALCULATIONS

The IEC standard specifies that all fatigue loads are to be assumed as fully reversible peak-to-peak loads. This allows for the estimation of the fatigue life by simply interpolating it using the S-N curve parameters. These parameters are obtained from the ultimate strength and fatigue limit of the material. For convenience, the user has the option to either enter the endurance limit for each material or have the tool estimate it automatically as 50% of the ultimate strength of the material, which is conservative for metal alloys. For stresses below the fatigue limit of the material, a life of 1E99 is reported (infinite life).

DYNAMIC BEHAVIOR

The IEC standard requires the designer to pay attention to the excitation of the natural frequencies of the turbine system. No other indication is made on this subject. This tool calculates the natural frequency of the turbine/tower system as a cantilever beam with a point mass at the free end. Also, the blades natural frequency is obtained using a cantilevered beam idealization. Both frequencies are compared against the rotor 1E and 3E frequencies in order to assess the possibility of mode excitation due to blade passing. Results within 5% of either 1E or 3E are flagged.

RESULTS VERIFICATION

In order to verify the loads and results calculated by the tool, the values where compared to published results found in the report *"ECN-C—96-033, Verification of design loads for small wind turbines"* (Hulle, et al., 1996) [7], hereafter known as the Inventus report. This report compares different calculations and measurement methods done to the Inventus 6 Small Wind Turbine, show in Figure 3 [8]. The calculations in this report are based on an old version of the IEC standard. There were significant changes to the current IEC standard, such as the formulas used to calculate loads, safety factors, etc. These changes make the previous calculations not accurate to today's standards but are a good comparison source.

Materials, turbine properties, and wind speeds found in the report where used as input in the tool and the load case values and results were compared to the values returned by the tool.

All the values calculated by the tool match the values found in the report. Some small discrepancies where found between the report results and the ones obtained with the tool. These are the result of updated formulas in the new standard. For example, the torsion moment range on the shaft (load case A) was updated to include the effect of rotor eccentricity. Also, the new standard added extra terms to multiple formulas that made the values differ. However, the results are very similar and within the expected values. Some results were not able to be validated since the load cases were not contemplated by the old standard, thus not included in Inventus report.

Table 2 in the Appendix shows a comparison of the Inventus report's calculations and the ones done by this tool. It can be seen that the values calculated by this tool are very similar in most of the cases. The differences between the two are mainly caused by updates to the standard that makes the loads more conservative. Another difference between the Inventus report and the new standard is the addition of material and load safety factors. These factors are very conservative and hence, increase the loads and decrease the material capability.

Figure 3
Inventus 6 Small Wind Turbine, Inventus GmbH

FUTURE WORK

This tool is by no mean a complete Small Wind Turbine design solution and requires further work to add more capabilities to it. The following are some possible additions to be considered:

- Blade geometry
- Fluids analysis
- Turbine performance
- Modal analysis: Mode shape plotting
- Seismic analysis
- Buckling analysis

Also, it would be beneficial to identify Small Wind Turbine analyses performed using the Simple Loads method of the newest IEC standard in order to have a more thorough validation of the tool.

APPENDIX I: FORMULAS

The following is a summary of the formulas used in the tool, as found in the IEC 61400-2 standard.

Load Case A: Normal Operation

Load Step A is the design load for normal operation, treated as a fatigue load. Loads are assumed to be fully reversible peak-to-peak values with negligible mean value. The fatigue load on the blade occurs on the junction with the lowest ultimate strength. The fatigue load on the rotor shaft is considered at the first bearing nearest to the rotor.

Blade Loads:

$$\Delta F_{zB} = 2 m_B R_{cog} \omega_{n,design}^2 \quad (1)$$

$$\Delta M_{zB} = \frac{Q_{design}}{B} + 2 m_B g R_{cog} \quad (2)$$

$$\Delta M_{yB} = \frac{\lambda_{design} Q_{design}}{B} \quad (3)$$

Shaft Loads

$$\Delta F_{x-shaft} = \frac{3}{2} \frac{\lambda_{design} Q_{design}}{R} \quad (4)$$

$$\Delta M_{x-shaft} = Q_{design} + 2 m_r g e_r \quad (5)$$

$$\Delta M_{shaft} = 2 m_r g L_{rb} + \frac{R}{6} \Delta F_{x-shaft} \quad (6)$$

$$e_r = 0.005R \quad (7)$$

Load Case B: Yawing

The ultimate loads on this case are gyroscopic forces and moments under a maximum yaw speed:

$$\omega_{yaw,max} = 3 - 0.01(\pi R^2 - 2) \quad (8)$$

If the turbine has a swept rotor area of less than 2 m^2, the maximum yaw rate is fixed at 3 rad/s.

$$M_{yB} = m_B \omega_{yaw}^2 L_{rt} R_{cog} + 2 \omega_{yaw} I_B \omega_n + \frac{R}{9} \Delta F_{x-shaft} \quad (9)$$

For two bladed rotors:

$$M_{shaft} = 4\omega_{yaw}\omega_n I_B + m_r g L_{rb} + \frac{R}{6}\Delta F_{x-shaft} \quad (10)$$

For three or more bladed rotors:

$$M_{shaft} = B\omega_{yaw}\omega_n I_B + m_r g L_{rb} + \frac{R}{6}\Delta F_{x-shaft} \quad (11)$$

Load Case C: Yaw error

A yaw error of 30° is assumed.

$$M_{yB} = \frac{1}{8}\rho A_{proj,B} C_{L,max} R^3 \omega_{n,design}^2 \left[1 + \frac{4}{3\lambda_{design}} + \left(\frac{1}{\lambda_{design}}\right)^2\right] \quad (12)$$

If no data is available, a $C_{l,max}$ of 2 is used.

Load Case D: Maximum Thrust

$$F_{x-shaft} = 3.125 C_T \rho V_{ave}^2 \pi R^2 \quad (13)$$

C_T is the thrust coefficient, equal to 0.5.

Load Case E: Maximum Rotational Speed

$$F_{zB} = m_B \omega_{n,max}^2 R_{cog} \quad (14)$$

$$M_{shaft} = m_r g L_{rb} + m_r e_r \omega_{n,max}^2 L_{rb} \quad (15)$$

Load Case F: Short at Load Connection

$$M_{x-shaft} = G\, Q_{design} \quad (16)$$

G is assumed to be 2.0 in the absence of a more accurate value.

$$M_{xB} = \frac{M_{x-shaft}}{B} \quad (17)$$

Load Case G: Shutdown (Braking)

$$M_{x-shaft} = M_{brake} + Q_{design} \quad (18)$$

Where M_{brake} is the braking moment, which is multiplied by the gearbox ratio if the brake is on the high speed shaft.

$$M_{xB} = \frac{M_{x-shaft}}{B} + m_B g R_{cog} \quad (19)$$

Load Case H: Parked Wind Loading

$$M_{yB} = 0.25\, C_d\, \rho\, V_{e50}^2\, A_{proj,B}\, R \quad (20)$$

Where C_d is the drag coefficient and shall be taken as 1.5, and $A_{proj,B}$ is the planform area of the blade.

$$F_{x-shaft} = 0.5\, B\, C_d\, \rho\, V_{e50}^2\, A_{proj,B} \quad (21)$$

$$\lambda_{e50} = \frac{\eta_{max}\pi R}{30 V_{e50}^2} \quad (22)$$

The load on each component is given by:

$$F = 0.5\, C_f \rho V_{e50}^2 A_{proj} \quad (23)$$

Where C_f is the force coefficient, which is a characteristic of the shape of the component, and A_{proj} is the component area projected to a plane perpendicular to the wind direction.

Limit State Analysis

The IEC requires that all ultimate stresses are compared to the adjusted material strength using the following formula.

$$\sigma_d \le \frac{f_k}{y_m y_f} \quad (24)$$

Where f_k is the material strength, y_m is the partial material safety factor and y_f is the partial load safety factor.

This tool follows this same principle by scaling up the loads by the partial load safety factor and the material ultimate strength by the partial material safety factor. A Margin of safety is then calculated and displayed to the user. A margin of safety below 1 is marked red for easy identification of a non-conformant design.

Fatigue Analysis

The IEC standard requires fatigue life to be calculated using an appropriate fatigue damage calculation. This tool uses the Miner's rule method in which the limit state is reached when the accumulated damage exceeds 1 using the following formula:

$$\text{Damage} = \sum_i \frac{n_i}{N(\gamma_f \gamma_m s_i)} \leq 1.0 \quad (25)$$

Where n_i is the number of fatigue cycles, s_i is the stress level associated with the counted cycles, and N is the number of cycles to failure as a function of stress.

Since this tool uses the Simplified Loads Method, the fatigue life is calculated by performing a logarithmic interpolation in the S-N curve, using the equivalent stress value (after applying the required safety factor) to obtain the number of cycles to failure. This number is then compared against the required design life of the turbine to determine the fatigue safety factor.

Vibration Analysis

Blade natural frequency:

$$f_n = \frac{\alpha_n^2}{2\pi}\sqrt{\frac{EI}{mL^4}} \quad (26)$$

$$\alpha_n = 1.875, 4.694, 7.855 \quad (27)$$

Tower Natural Frequency [6]

$$f_n = \frac{1}{2\pi}\sqrt{\frac{3EI}{(0.23\,m_{tower} + m_{turbine})L^3}} \quad (28)$$

APPENDIX II: TOOL SCREENSHOTS

	Blade Root	Shaft	Tower Base
Material Name	Precision Steel (DIN 2391) St 35	C 45	Steel tube R St 37-2
Material Characterization	Full Characterization	Full Characterization	Full Characterization
Density (kg/m^3)	7820	7820	7820
Young Modulus (GPa)	210	210	210
Tensile Yield Strength (MPa)	235	305	235
Ultimate Tensile Strength (MPa)	330	630	340
Poisson's Ratio	0.29	0.29	0.29
Endurance Limit (User Input)		400	280
Endurance Limit (Calculated with 0.5xUS)	165	315	170
Endurance Limit to Use	Calculated	User input	User input

Figure 4
Material Input Tab

	Dimension	Variable	Value	Units
General Properties	Small Wind Turbine Class	swtclass	I	DropDown
	Is this an horizontal axis turbine?	horizontal	Yes	Boolean
	Propeller type rotor?	rotortype	Yes	Boolean
	Are the blades cantilever?	cantilever	Yes	Boolean
	Number of blades	b	4	#
	Is the hub rigid?	rigidhub	Yes	Boolean
	Pasive yaw system	yawsystem	Yes	Boolean
	Output voltage	voltage	12	V
	Voltage Type	voltagetype	AC	---
	Brake location	brakelocation	Low Speed Shaft	Text
	Does the rotor spin when parked?	spinwhenparked	No	Text
	Does it have a gearbox	gearbox	No	Boolean
	Gearbox ratio	gearboxratio	1.438	---
	Design life of the turbine	Td	1.000	Years
Cate-gory Re-sults	Wind Turbine Size Category	wtsize	Small	Text
	Support System needed?	ssneeded	Yes	Text
	Can the "Simplified Load Model" be Used?	canuseslm	Yes	Boolean

Figure 5
Turbine Tab - General Properties Section

Wind (Air) Specs	Variable	Value	Units
Air Density	rho	1.225	kg/m^3
Characteristic of a the turbulence intensity at 15 m/s	Ififteen	0.18	---
Slope parameter for turbulence std dev model	a	2	---
Reference wind speed average over 10 min	vref	50	m/s
Average wind speed	vave	10	m/s
Design wind speed	vdesign	14	m/s
50 year extreme wind speed	Vext50	70.00	m/s
1 year extreme wind speed	Vext1	52.50	m/s
Rated Wind Speed	Vr	10.5	m/s

Figure 6

Wind Tab - Air Specs

		Dimension	Variable	Value	Units
Rotor Properties	Blade Properties	Rotor Diameter (Blade Tip Diameter)	rd	6	m
		Rotor Radius (Blade Tip Radius)	rr	3	m
		Rotor's sweep Area	area	28.27433388	m^2
		Radial Distance between blade's CG and rotor center	rcog	0.986	m
		Blade root type	brt	Circular	Text
		Blade root diameter	bt	0.030	m
		Not used!	brw	0.050	m
		Blade's root crosssectional area	Across	0.000706858	m^2
		Blade's planform area	Aplanform	0.690	m^2
		Blades Moment of Inertia	Ib	26.000	kg-m^2
		Blade's polar moment of inerta around thickness (x)	Ibt	3.98E-08	m^4
		Blade's polar moment of inerta around chord (y)	Ibc	3.98E-08	m^4
		Blade's tortion constant	Jtb	1.00E-05	m^4
		Blade's maximum lif coefficient	Clmax	2.000	---
		Blade mass (mB)	mb	12.000	kg
	Shaft	Shaft Diameter	ds	0.010	m
		Shaft Area	as	7.85E-05	m^2
		Shaft Torsion Constant	Jts	9.82E-10	m^4
		Distance between rotor center and first bearing	lrb	0.150	m
		Distance between rotor center and yaw axis	lrt	0.700	m
		Moment at the rotor shaft due to short circuit	Gsc	2.000	---
		Hub mass	mh	27.000	kg
		Turbine mass	turbinemass	75.000	kg
Others		Drag coefficient of the hood	cdhood	1.300	---
		Hood section area projected on a plane perpendicular to the wind direction	aprojhood	0.140	m^2
		Drag coefficient of the rotor	cdrotor	1.500	---
		Rotor section area projected on a plane perpendicular to the wind direction	aprojrotor	2.760	m^2
		Drag coefficient of the tower	cdtower	0.700	---
		Tower section area projected on a plane perpendicular to the wind direction	aprojtower	2.188	m^2
		Drag coefficient of the vane	cdvane	1.500	---
		Vane section area projected on a plane perpendicular to the wind direction	aprojvane	0.192	m^2
		Rotor ecentricity	erotor	0.003	m
Tower		Tower height	htower	13.000	m
		Distance between tower top and guyed wire	hguy	2.820	m
		Tower tickness	towert	0.004	m
		Tower outer diameter (base)	dod	0.168	m
		Tower inner diameter (base)	did	0.160	m
		Tower cross sectional area	atower	2.06E-03	m^2
		Tower moment of inertia	itower	6.97E-06	m^4
		Tower mass	mtower	209.9	kg
		Tower foundation	towerfoundation	Concrete	Text
		Tower damping ratio	towerdr	0.016	
Specs		Rotor speed in rpm	n	300.00	rpm
		Rotor speed in rad/s	wn	31.42	rad/s
		Ultimate rotor speed in rpm	nmax	179.00	rpm
		Ultimate rotor speed in rad/2	wnmax	18.74	rad/s
		Design power production (at design wind speed)	pdesign	5000.00	Watts
		Design rotor speed in rmp (at design wind speed)	ndesign	128.00	rpm
		Design rotor speed in rad/s (at design wind speed)	wndesign	13.40	rad/s
		Drive train efficiency (at design wind speed)	efficiency	0.80	---
		Design shaft torque (at design wind speed)	qdesign	466.274	N-m
		Design tip speed ratio (at design wind speed)	lambdadesign	3.830	---
		Tip speed ratio at Vext50	lambdaext50	0.803	---
		Maximum yaw rate	wyawmax	1.00	rad/s
		Braking Moment	mbrake	1816.000	N-m

Figure 7

Turbine Tab - Rotor and Tower Properties, Turbine Specs.

Load Case A: Normal Operation (Fatigue)			
Blade Loads			
Rotor mass	mr	39.000	kg
Centrifugal load range	fzb_range	4251.727	N
Blade root bending moment range around x	mxb_range	348.712	N-m
Blade root bending moment range around y	myb_range	446.429	N-m
Shaft Loads			
Thrust loading range	deltafxshaft	892.857	N
er	er	0.003	m
Torsion moment range (M-xshaft)	deltamxshaft	468.570	N-m
Bending moment range	deltamshaft	667.154	N-m

Load Case B: Yawing			
Maximum yaw rate	wyawmax_yawing	1.000	rad/s
Blade root bending moment range around y	myb_yawing	1002.916	N-m
Shaft bending moment range around y	msb_yawing	3771.073	N-m

Load Case C: Yaw error			
Flapwise bending moment on the blade	myb_flapwise	9.713	N-m

Load Case D: Maximum thrust			
Thrust coefficient	Ct	0.500	---
Maximum thrust load	fxshaftmax	5411.884	N

Load Case E: Maximum rotational speed			
Centrifugal load in the blade root	Fzb	4157.397	N
Shaft bending moment due to centrifugal load	Mshaft_centrifugal	63.555	N-m

Load Case F: Short at load connection			
ween rated torque and short circuit torque for the generator	GG	2.000	---
Moment at the rotor shaft due to short circuit	Mxshaft_sc	932.548	N-m
Blade bending moment around x due to a short circuit	mxb_sc	233.137	N-m

Load Case G: Shutdown (Braking)			
Maximum shaft torque	mxshaft	2282.274	N-m
Blade Load	mxb	686.640	N

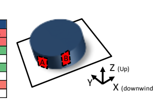
Load Case H: Parked Wind Loading			
Blade out of plane root bending moment	myb	4.773	N-m
Thrust load	fxshaft	12.729	N
Hub force	Fhub	546.228	N
Rotor force	Frotor	12425.175	N
Tower force	Ftower	4596.504	N
Vane force	Fvane	1210.104	N
Total Force	Ftotal	18778.011	N

Figure 8

Loads Tab - Load Cases Required by the IEC 61400-2

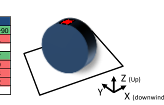
Blades

Load Case	Name	Type	Load SF	Material SF	Tension/Thrust (MPa)	Bending X (MPa)	Bending Y (MPa)	Sza	Szb	S1 (MPa)	Required Fatige Cycles	Cycles to Failure	MS
A	Normal Operation	Fatigue	1.00	1.25	6.0150	131.5539	131.5539	137.6	137.6	137.6	2.69E+08	6.62E+02	2.46E-06
B	Yawing	Ultimate load	3.00	1.10			416.1919	416.2	0.0	416.2	N/A	N/A	0.72
C	Yaw Error	Ultimate load	3.00	1.10			4.0309	4.0	0.0	4.0	N/A	N/A	74.43
D	Maximum Thrust	Ultimate load	3.00	1.10				0.0	0.0	0.0	N/A	N/A	
E	Maximum Rotational Speed	Ultimate load	3.00	1.10	6.4697			6.5	6.5	6.5	N/A	N/A	46.37
F	Short at Load Connection	Ultimate load	3.00	1.10				0.0	0.0	0.0	N/A	N/A	
G	Shutdown (Braking)	Ultimate load	3.00	1.10		284.9433		0.0	284.9	284.9	N/A	N/A	1.05
H	Parked Wind Loading	Ultimate load	3.00	1.10				0.0	0.0	0.0	N/A	N/A	



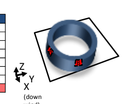
Shaft

Load Case	Name	Type	Load SF	Material SF	Tension/Thrust (MPa)	Bending (MPa)	Torsional Shear (MPa)	Sx (MPa)	Sy (MPa)	Txy (MPa)	S1 (MPa)	S2 (MPa)	VM (MPa)	Required Fatige Cycles	Cycles to Failure	MS
A	Normal Operation	Fatigue	1.00	1.25	11.3682	3397.7852	2386.4063	3409.1534		2386.4063	4637.2	-1228.1	5357.9	2.69E+08	1.00E+99	3.71E+90
B	Yawing	Ultimate load	3.00	1.10		57617.7578		#########		0.0000	57617.8	0.0	57617.8	N/A	N/A	0.01
C	Yaw Error	Ultimate load	3.00	1.10				0.0000		0.0000	0.0	0.0	0.0	N/A	N/A	
D	Maximum Thrust	Ultimate load	3.00	1.10	206.7188			206.7188		0.0000	206.7	0.0	206.7	N/A	N/A	2.77
E	Maximum Rotational Speed	Ultimate load	3.00	1.10		971.0492		971.0492		0.0000	971.0	0.0	971.0	N/A	N/A	0.59
F	Short at Load Connection	Ultimate load	3.00	1.10		14248.2914		#########		0.0000	14248.3	0.0	14248.3	N/A	N/A	0.04
G	Shutdown (Braking)	Ultimate load	3.00	1.10		34870.5819		#########		0.0000	34870.6	0.0	34870.6	N/A	N/A	0.02
H	Parked Wind Loading	Ultimate load	3.00	1.10				0.0000		0.0000	0.0	0.0	0.0	N/A	N/A	



Tower

Load Case	Name	Type	Load SF	Material SF	Bending (MPa)	VM (MPa)	MS
A	Normal Operation	Fatigue	1.00	1.25		0.0	N/A
B	Yawing	Ultimate load	3.00	1.10		0.0	N/A
C	Yaw Error	Ultimate load	3.00	1.10		0.0	N/A
D	Maximum Thrust	Ultimate load	3.00	1.10		0.0	N/A
E	Maximum Rotational Speed	Ultimate load	3.00	1.10		0.0	N/A
F	Short at Load Connection	Ultimate load	3.00	1.10		0.0	N/A
G	Shutdown (Braking)	Ultimate load	3.00	1.10		0.0	N/A
H	Parked Wind Loading	Ultimate load	3.00	1.10	1917.7	1917.7	0.16



Vibrations

	Variable	Frequency
Tower's first natural frequency	tnf1	0.6
Blade's first natural frequency	bnf1	43.3
Rotor speed frequency	rotorspeedfreq	5.0
Blade passing frequency	bladepassingfreq	15.0
Tower 1E % difference	Tower1Ed	29%
Tower 3E % difference	Tower3Ed	96%
Blade 1E % difference	Blade1Ed	255%
Blade 3E % difference	Blade3Ed	189%

Figure 9

Results Tab

APPENDIX III: TOOL VALIDATION

Table 2

Results Comparison between Inventus SWT Results and the Tool's Results

Load Case	Kind of load	Inventus	Tool Results	% Difference	Reason for difference
A	Tip Speed Ratio	3.83	3.83	0%	
	Qr	466 N-m	466 N-m	0%	
	Centrifugal load range	4252 N-m	4252 N-m	0%	
	Blade root bending moment range around x	344 N-m	349 N-m	1%	1
	Blade root bending moment range around y	375N-m	446 N-m	19%	1
	Thrust loading range	893 N	893 N	0%	
	Torsion moment range (M-xshaft)	448 N-m	468 N-m	4%	2
	Bending moment range	596 N-m	667.154	12%	2
B	Blade root bending moment range around y	705 N-m	1003 N-m	42%	3
	Shaft bending moment range around y	1879 N-m	3771 N-m	101%	3
C	Flapwise bending moment on the blade	---	20 N-m	---	4
D	Thrust coefficient	---	0.5 N	---	4
	Maximum thrust load	---	5411.884	---	4
E	Centrifugal load in the blade root	4157 N-m	4157 N-m	0%	
	Shaft bending moment due to centrifugal load	122 N-m	64 N-m	-48%	5
F	Moment at the rotor shaft due to short circuit	---	933 N-m	---	4
	Blade bending moment around x due to a short circuit	---	233 N-m	---	4
G	Maximum shaft torque	2264 N-m	2282 N-m	1%	3
	Blade Load	682 N	687 N	1%	3
H	Blade out of plane root bending moment	Not provided	10 N	---	3
	Thrust load	Not provided	27 N	---	3
	Hub force	268 N	546 N	104%	3
	Rotor force	3106 N	12425 N	300%	3
	Tower force	1147 N	4596 N	301%	3
	Vane force	1227 N	1210 N	-1%	3

1: The new standard requires a more aggressive design wind speed

2: This formula was updated to account for eccentricity

3: This formula was updated.

4: This loadcase was not calculated in the paper

5: The calculation in the paper is wrong. For some reason they multiplied it by 2…

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