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INVESTIGATION OF THE IEC SAFETY STANDARD FOR SMALL WIND TURBINE DESIGN THROUGH MODELING AND TESTING*

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ABSTRACT

Since 1999, the International Electrotechnical Commission (IEC) Maintenance Team 2 (MT2) has been working on a revision of the IEC 61400–2 standard on the safety, quality, integrity, and design requirements of small wind turbines (SWTs). During this effort, a study was conducted to evaluate the quality of the structural design criteria specified by the original –2 standard. Test measurements and aeroelastic predictions of loads were gathered for a collection of SWTs and evaluated against the simplified load models and load cases specified in the standard. The collection of turbines included variations in rotor size, blade number, rotor location (upwind / downwind), hub type (rigid / teetered), yaw mechanism (free / active), and others. In general, the comparison of load measurements and model predictions exemplified the inaccuracy of the design load levels in the original –2 standard and suggested methods of improvement. Revisions being made to the standard include enhanced load models, new load cases, and improved safety factors. This work should culminate in a revised IEC 61400–2 standard that has a higher degree of applicability and dependability than the original.

INTRODUCTION

A key element of assuring potential installers of wind energy systems that their investments are sensible is certification. Wind turbine manufacturers acquire certification through accredited agencies to demonstrate that their wind turbines comply with internationally recognized standards for safety, quality, and integrity. For detailed information on the wind turbine certification process in the United States, see [1].

Certification for small wind turbines (SWTs) is obtained through compliance with the International Electrotechnical Commission (IEC) standard numbered 61400–2, last released in 1996 [2]. In the 1996 release of the –2 standard, an SWT is defined as any wind turbine with a swept area smaller than 40 m^2 (rotor diameters smaller than 7.14 m across); however, this size restriction is in the process of being relaxed. The IEC 61400–2 standard specifies minimum requirements of an SWT for structural integrity, safety, and other design features in order to ensure safe operation throughout the turbine's intended life. The standard pertains to all subsystems of SWTs including internal electrical systems, mechanical systems, control and protection systems, support structures, foundations, and load interconnection equipment.

A considerable portion of the –2 standard relates to the identification of design load levels for both ultimate strength and fatigue-based load quantities for the blade root, drive shaft, and tower-top. These design load levels are defined through application of simplified load models and load cases (i.e., nonaeroelastic models). Inputs into the simplified load models include general turbine geometrical properties (rotor diameter, overhang distance, etc…), lumped inertial properties (blade mass and inertia, etc…), design characteristics (power, rotational speed, wind speed), and basic configuration information (passive or active yaw control; pitch, stall, or furling regulated; etc…). This simplified method of obtaining design criteria is unique to the certification of SWTs.

An attempt to validate the simplified load method was made by Frans Van Hulle through a project funded by the European Commission [3]. In his conference paper documenting this effort [4], several problems with the –

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2 standard were highlighted. To summarize, these problems include:

(1) The entire standard, in general, is too narrowly focused and often only vaguely descriptive. For instance, the –2 standard prohibits the use of aeroelastic models prematurely, the size limit of 40 m^2 is hastily restrictive, and the applicability of the simplified methods is unclear.

(2) The method of obtaining design criteria through the application of simplified load models is not well verified.

(3) The safety factors defining design load levels are lumped into uninformative numbers, which are confusing and misleading to the users of the standard.

To address these issues and others, the IEC Maintenance Team 2 (MT2) has been working on a revision of the –2 standard since 1999. In this effort, a study was undertaken to collect test measurements and to develop aeroelastic predictions of SWT loads and to evaluate them against the simplified load models and load cases specified in the standard. The resulting data were normalized and placed into a test matrix. The purpose of this study was fourfold:

(1) To identify which extreme loads (both ultimate and fatigue) are not covered by the simplified method.

(2) To assess the range of turbine configurations for which the simplified load method applies.

(3) To check whether aeroelastic modeling tools can be used to model small, furling turbines.

(4) To quantify the relative magnitude of load safety factors among the various methods.

MT2 expects to complete a "committee draft" of the revision of the IEC 61400–2 standard by the end of the 2002 calendar year.

This paper documents the development and evaluation of the aforementioned test matrix and the revisions to the standard that resulted from the investigation. Some of the challenges involved with modeling SWTs are also discussed.

DEVELOPMENT OF THE TEST MATRIX

For the greatest effectiveness, data from several sources pertaining to a diverse collection of SWTs were used to complete the comparison of test measurements, aeroelastic models, and simple models. A complete summary of configuration data for the array of turbines is provided in Table 1.

The first three SWTs listed in this table, LMW 1003, Inventus 6, and Proven WT2200 were the turbines used in the original project funded by the European Commission [3]. They were field-tested by the Center for Renewable Energy Sources (CRES), the German Wind Energy Institute (DEWI), and the National Engineering Laboratory (NEL) respectively. Test data from the two Micon 65 turbines were obtained from a large wind farm operating in San Gorgonio Pass in California. The two turbines were identical except for their

Figure 1: Proven WT2200

Table 1: General Turbine Configuration Data

	Unit	LMW 1003	Inventus 6	Proven WT2200	Micon 65 SERI Blades	Micon 65 AeroStar Blades	UAE Phase IV	UAE Phase V	UAE Phase VI Seq. H	UAE Phase VI Seq. E	Whisper H40	AOC 15/50	Generic 1800
Rated Power	kW	1.0	4.8	2.2	65.0	65.0	12.0	11.4	8.9	8.9	0.9	50.0	1.8
Rated Wind Speed	m/s	12.0	11.9	11.9	14.0	14.0	13.0	13.0	13.0	13.0	11.9	11.3	11.9
Rated Rotor Speed	rpm	700.0	128.0	320.0	47.4	47.4	72.2	72.2	72.2	72.2	730.0	65.0	360.0
Rotor Diameter	m	3.1	6.0	3.4	17.1	16.0	10.0	10.0	10.1	10.1	2.1	15.0	4.0
Swept Area	m^2	7.7	28.3	9.1	229.7	201.1	79.3	79.3	79.5	79.5	3.6	176.7	12.6
Number of Blades	-	3	4	3	3	3	3	2	2	2	3	3	3
Orientation	-	Upwind	Upwind	Downwind	Upwind	Upwind	Downwind	Downwind	Upwind	Downwind	Upwind	Downwind	Upwind
Hub Type	-	Rigid	Rigid	Flap Hing.	Rigid	Rigid	Rigid	Teetered	Rigid	Rigid	Rigid	Rigid	Rigid
Overspeed Mechanism	-	Horizontal Furling	High Spd. Shft. Brake	Passive Pitch	High Spd. Shft. Brake	High Spd. Shft. Brake	High Spd. Shft. Brake	High Spd. Shft. Brake	High Spd. Shft. Brake	High Spd. Shft. Brake	Horizontal Furling	Tip Plate & Dyn. Brk.	Low Spd. Shft. Brake
Yaw Mechanism	-	Passive / Free	Passive / Free	Passive / Free	Active	Active	Passive / Free	Passive / Free	Locked	Locked	Passive / Free	Passive / Free	Passive / Free
Test Measurements From	-	Field	Field	Field	Field	Field	Field	Field	Wind Tunnel	Wind Tunnel	Field	Field	N/A
Models Ran	-	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Simple & ADAMS®	Simple & YawDyn	Simple & ADAMS®

rotors: one was based on the NREL (originally SERI) thin-airfoil family and the other was based on the original AeroStar design. The four Unsteady Aerodynamics Experiment (UAE) turbines were tested by NREL—the first two listed reflect tests taken in the field at the NWTC and the second two reflect tests made in the NASA-Ames wind tunnel. All four turbine configurations are based on modifications to a Grumman Wind Stream 33. The Whisper H40 was tested in Spanish Fork, Utah by Windward Engineering as part of the U.S. Department of Energy's (DOE's) Field Verification Project (FVP). The AOC 15/50 was tested in the field at the NWTC as part of the International Energy Agency (IEA) round robin test program. The Generic 1800 turbine was a "fictitious turbine" only tested in the modeling environment. Finally, three additional "fictitious" turbines, named Turbine1, Turbine2, and Turbine3, were also only tested in the modeling environment. Their configuration information is proprietary, which is why they are not listed in Table 1.

For all turbines, configuration data and general mechanical properties were collected in order to obtain design levels through implementation of the simple load models and load cases. For the turbines modeled aeroelastically, more detailed mechanical information was collected. Datasets of all available test measurements on the operating turbines were gathered. An effort was made to neglect all datasets in which measurement equipment failures existed that could have compromised the quality of the datasets. Due to the difficulty and expense involved in measuring axial and shear forces in the field, most load cases involving these types of loads were disregarded in this study.

When comparing test measurements of ultimate loads to model predictions, simple maximum absolute values of the measured loads were used. Little attempt was made to correlate test conditions to load case scenarios. For fatigue load cases, damage equivalent load ranges were computed from all the available test measurements and were compared to the model predictions of the associated load ranges. Damage equivalent loads were calculated using appropriate Wöhler curve exponents and assumed equivalent load frequencies of 1 Hz or 1P. All models were run using the –2 standard's specification of air density (1.225 kg/m^3). No attempt was made to extrapolate the load predictions to variations in air density at the test sites.

Once all test measurements were gathered and model predictions made, the test measured- and aeroelasticly-predicted loads were normalized by dividing them by the loads obtained using the simplified modeling method. The results are given in Table 2 and Table 3 below. Note that the load ratios given in these tables reflect the changes made to the –2 standard by MT2. These revisions and the reasons behind them, along with references to and insights gleaned from Table 2 and Table 3, are documented next.

Table 2: Load Ratios of Test Measurements to Simplified Load Method Predictions

Load Cases		Load Components		LMW 1003	Inventus 6	Proven WT2200	Micon 65 SERI Blades	Micon 65 AeroStar Blades	UAE Phase IV	UAE Phase V	UAE Phase VI Seq. H	UAE Phase VI Seq. E	Whisper H40	AOC 15/50
A	Normal operation	ΔF_{zB}	Force range at root along blade											
		ΔM_{xB}	Edge moment range at root		**1.32**	1.00			0.93	0.72	0.79	0.81		0.96
		ΔM_{yB}	Flap moment range at root	**3.09**	0.83		**1.18**	**1.20**	**1.82**	0.73	0.60	0.83		**1.20**
		$\Delta F_{x\text{-shaft}}$	Thrust force range along shaft			**4.95**								0.19
		$\Delta M_{x\text{-shaft}}$	Shaft torque range						0.74	0.58	0.35	0.49		0.24
		$\Delta M_{y\text{-shaft}}$	Shaft bending moment range		0.71	0.63			**2.31**	**1.90**	**1.89**	**1.87**		**1.56**
B	Yawing	M_{yB}	Max. flap moment at root	0.09	0.12		**4.03**	**3.44**	0.41	0.30	**3.62**	**3.12**	0.46	**1.02**
		$M_{y\text{-shaft}}$	Max. shaft bending moment				**1.18**	**1.21**	0.47	0.22	**2.05**	**1.55**		0.94
C	Yaw error	M_{yB}	Max. flap moment at root	0.05	0.17		**1.54**	**1.70**	**1.59**	**1.22**	**1.12**	0.96	0.16	**1.17**
D	Maximum thrust	$F_{x\text{-shaft}}$	Max. thrust force along shaft										0.87	0.63
			Max. tower-top force											
E	Maximum rot. speed	F_{zB}	Max. force at root along blade											
		$M_{y\text{-shaft}}$	Max. shaft bending moment				**2.75**	**2.49**	**5.81**	**3.03**	**3.64**	**2.75**		**38.89**
F	Short at load connection	M_{xB}	Max. edge moment at root				0.67	0.85						0.98
		$M_{x\text{-shaft}}$	Max. shaft torque				0.26	0.30						0.37
G	Shut-down	M_{xB}	Max. edge moment at root		0.86		0.54	0.62	0.84	0.44	0.45	0.46		**2.18**
		$M_{x\text{-shaft}}$	Max. shaft torque			**2.69**	0.24	0.29	0.38	0.26	0.25	0.30		**1.42**
H	Survival wind	M_{yB}	Max. flap moment at root				0.58	0.58	0.49	0.38	0.35	0.30	0.20	0.56
		$F_{x\text{-shaft}}$	Max. thrust force along shaft										0.17	0.35
			Max. tower-top force											
I	Maximum exposure	M_{yB}	Max. flap moment at root											
		$F_{x\text{-shaft}}$	Max. thrust force along shaft											
			Max. tower-top force											

Table 3: Load Ratios of Aeroelastic Predictions to Simplified Load Method Predictions

Load Cases		Load Components		Whisper H40	AOC 15/50	Generic 1800	Turbine1	Turbine2	Turbine3
A	Normal operation	ΔF_{zB}	Force range at root along blade	**1.04**		0.67			
		ΔM_{xB}	Edge moment range at root		0.86				
		ΔM_{yB}	Flap moment range at root	0.98	**1.44**	0.56			
		$\Delta F_{x\text{-shaft}}$	Thrust force range along shaft						
		$\Delta M_{x\text{-shaft}}$	Shaft torque range	0.25		0.20			
		$\Delta M_{y\text{-shaft}}$	Shaft bending moment range	0.58		0.31			
B	Yawing	M_{yB}	Max. flap moment at root	**1.21**	0.86	0.15	0.69	**1.47**	0.43
		$M_{y\text{-shaft}}$	Max. shaft bending moment	**1.72**	0.89	0.31	0.58	**1.17**	0.29
C	Yaw error	M_{yB}	Max. flap moment at root	0.42	0.98	0.05	0.33	0.57	0.85
D	Maximum thrust	$F_{x\text{-shaft}}$	Max. thrust force along shaft	0.78		0.79	0.52	0.86	0.39
			Max. tower-top force						
E	Maximum rot. speed	F_{zB}	Max. force at root along blade	1.00		1.00		0.78	
		$M_{y\text{-shaft}}$	Max. shaft bending moment	**1.20**		0.86	**4.22**	**1.53**	**7.57**
F	Short at load connection	M_{xB}	Max. edge moment at root	**10.00**		**2.58**	**2.39**	**7.24**	
		$M_{x\text{-shaft}}$	Max. shaft torque				0.26	0.63	0.65
G	Shut-down	M_{xB}	Max. edge moment at root	**12.34**		**3.16**	**2.70**	**6.21**	
		$M_{x\text{-shaft}}$	Max. shaft torque				0.52	**1.26**	**1.30**
H	Survival wind	M_{yB}	Max. flap moment at root	0.52		0.05	0.47	0.69	0.37
		$F_{x\text{-shaft}}$	Max. thrust force along shaft	0.15		0.50	0.16	0.40	0.18
			Max. tower-top force						
I	Maximum exposure	M_{yB}	Max. flap moment at root						
		$F_{x\text{-shaft}}$	Max. thrust force along shaft						
			Max. tower-top force						

REVISIONS TO THE –2 STANDARD

Strategies for refining the IEC 61400–2 standard are well documented in [5]. One significant change implemented in the new standard by MT2, apart from those dictated by loads comparisons, is the extension of the scope to include turbines up to a swept area of 200 m^2 (rotor diameters up to 15.96 m). This revision follows the recommendations made by Frans Van Hulle [4] and many other persons in the SWT community. This increase in scope underscores the need to assess the quality of the simplified load method for obtaining design criteria.

Another change to the –2 standard, which addresses the narrowness concerns, is that in the revised standard, certifying agents will have the option of determining design loads by one of three methods: simplified load modeling, aeroelastic modeling, or mechanical loads measurement and extrapolation. This is a significant departure from the original standard, whereby design loads determined by any method other than the simplified method had to follow the techniques governed by IEC 61400–1. The IEC 61400–1 is a standard used to govern the safety of any wind turbine and is much more exhaustive than the –2 standard [6].

Although loads measurement is a distinct method of determining design loads, the simplified and aeroelastic modeling methods will also require at least some field measurements per the revised –2 standard. The required measurements are for design power, design rotor speed, and maximum rotor speed. In addition, the manufacturer must specify the design wind class. In the revised –2 standard, these data measurements are required inputs into the simple models. The term "design" is comparable to the term "rated", which was used throughout the original –2 standard. Because the term "rated" is used and abused in many different ways, however, for marketing reasons, it was decided to depart from this designation to avoid confusion. Also, in the old, released standard, the manufacturer could estimate these data. However, manufacturer specifications of these data can lead to under- or overestimation of loads by as much as 80%. In Figure 2 are plotted simple loads calculated from manufacturer estimates of design power, design rotor speed, and wind speed class divided by simple loads calculated from field measurements for the LMW 1003 turbine (see Table 4 for a listing and description of the simple load cases and components). This figure clearly demonstrates how estimations of these data drastically influence the load predictions obtained through application of the simple equations. For aeroelastic models, design power and rotor speed are the minimum data necessary for proper model tuning.

Figure 2: Simple Loads from Estimates Divided By Simple Loads from Measurements, LMW 1003

In the released –2 standard, the overall safety factors for design loads are dependent on the load case and component materials. As mentioned previously, these factors are currently lumped into uninformative numbers, which are confusing and misleading to the users of the standard. For clarification, MT2 decided that the overall safety factors in the revised standard should be separated into distinct load, material, and component / construction factors. The load factors are dependent on the method in which the design loads are determined as follows: 3.0 for simplified load modeling, 1.5 for aeroelastic modeling, and 3.0 for mechanical loads measurement and extrapolation.

The load factor of 1.5 for aeroelastic modeling was decided upon by MT2 since small wind turbine dynamic responses (such as furling) are, in many instances, more difficult to model than the responses of larger turbines, which have an aeroelastic load factor of 1.35 (see IEC 61400–1 [6]).

Table 3 shows that aeroelastic models occasionally predict larger loads than those obtained using the simple models. To cover all of these instances in which the load ratios in this table are greater than 1.0, MT2 decided that the load factor for the simplified modeling method should be twice that of aeroelastic modeling. This is how the simplified load method factor of 3.0 was established. At first glance, it may appear that the load factor for the simple equations being double that of the aeroelastic models is not consistent with shaft bending in load case E of Table 3, in which two of the ratios of aeroelastic to simple predictions are larger than 2.0. However, for all of the turbines modeled except the Whisper H40, design of the shaft in bending is driven by load case B. This is because load case B predicts larger ultimate shaft bending moments than load case E, which is evident from the fact that all the load ratios from case B are smaller than those from case E, except for the Whisper H40 (again, see Table 3). Thus, the large load ratios seen in load case E are *not* critical. The Whisper H40 is not a critical exception to this because neither of the load ratios for ultimate shaft bending are larger than 2.0. The only load component where the load ratios between the simplified modeling method and the aeroelasticly-predicted loads might not be sufficient is the ultimate root edge moment in load cases F and G. Table 3 shows that all of the load ratios for this component are larger than 2.0. In the coming months, MT2 will be investigating justification for adding a new load case or changing an existing load case in the simplified load method to accommodate the discrepancy for this load component.

The load factor of 3.0 for the simplified method of obtaining design loads is in harmony with the safety factors given in the released –2 standard and is consistent with the load ratios given in Table 2. As in the previous paragraph, at first glance it may appear that the large load ratios for shaft bending in load case E and blade root flap bending in load case B are not consistent with the load factor of 3.0, because many of these load ratios are larger than 3.0. However, following similar reasoning to that of the previous paragraph, it can be concluded that design of the shaft in bending and design of the blade root in flap bending are driven by load cases B and C respectively. Consequently, the large load ratios found in load cases E and B are also *not* critical. Other instances in Table 2 in which the load ratios of test measurements to simple model predictions are larger than 3.0 were not deemed as design drivers and were consequently considered uncritical as well.

For the mechanical loads measurement and extrapolation method of determining design loads, the load factor of 3.0 was proposed by MT2. This conservative value reflects the lack of experience with basing design loads completely on loads measurements for SWTs. The uncertainties for load measurements lay in the extrapolation of the data, where there is almost no SWT experience to draw upon. Furthermore, for small turbines, high rotor speed, lack of space for reliable strain measurement, free yaw, possible furl and flutter, and possible influence of measurement equipment on the performance of the turbine could affect the results.

The revisions associated with each of the three new design load determination methods are documented independently in the following subsections.

Simplified Load Modeling

In the current –2 standard, it is unclear which small wind turbine configurations can make use of the simplified load method because of the vagueness of the document. To address this issue, MT2 developed a clarified list based on the loads comparison work as follows:

- ✓ Horizontal axis
- ✓ 2- or more bladed rotor
- ✓ Rigid hub
- ✓ Cantilever blades

Furthermore, the SWT may be variable or constant speed, have an upwind or downwind rotor, and may have furling (either vertical or horizontal).

The core restrictions in this list are the rigid hub and cantilever blades criteria. These restrictions were adopted because only two of the 15 turbines in the test matrix had such features (one turbine for each restriction) and MT2 considered this sample too small to warrant confidence in the findings for turbines with such features.

A listing of MT2's proposed design load cases for the simplified modeling method is given in Table 4. There are several differences between these load cases and those specified in the released –2 standard. These differences pertain to the details of some and the existence of others. The entirely new load cases include yaw error (C), maximum thrust (D), survival wind (H), and one to be determined by the manufacturer for transport, assembly, maintenance, and repair (J). These load cases were added after surveying load cases listed in other standards (e.g., the IEC 61400–1 [6]).

Table 4: Simple Design Load Cases

Design Situation	Load Cases		Wind Inflow	Type of Analysis	Load Components		Remarks
Power production	A	Normal operation	Cyclic varying around V_{design}	Fatigue ↓	ΔF_{zB}	Force range at root along blade	
					ΔM_{xB}	Edge moment range at root	
					ΔM_{yB}	Flap moment range at root	
					$\Delta F_{x\text{-}shaft}$	Thrust force range along shaft	
					$\Delta M_{x\text{-}shaft}$	Shaft torque range	
					$\Delta M_{y\text{-}shaft}$	Shaft bending moment range	
	B	Yawing	$V_{hub} = V_{design}$	Ultimate strength ↓	M_{yB}	Max. flap moment at root	
					$M_{y\text{-}shaft}$	Max. shaft bending moment	
	C	Yaw error	$V_{hub} = V_{design}$		M_{yB}	Max. flap moment at root	
	D	Maximum thrust	$V_{hub} = 2.5\ V_{ave}$		$F_{x\text{-}shaft}$	Max. thrust force along shaft	n at V_{ave} - rotor spinning but could be furling or fluttering
						Max. tower-top force	
Power production with fault	E	Maximum rot. speed			F_{zB}	Max. force at root along blade	Maximum rotational speed, n_{max}
					$M_{y\text{-}shaft}$	Max. shaft bending moment	
	F	Short at load connection	$V_{hub} = V_{design}$		M_{xB}	Max. edge moment at root	Maximum short-circuit generator torque
					$M_{x\text{-}shaft}$	Max. shaft torque	
Shut-down	G	Shut-down	$V_{hub} = V_{design}$		M_{xB}	Max. edge moment at root	
					$M_{x\text{-}shaft}$	Max. shaft torque	
Parked (idling or standstill)	H	Survival wind	$V_{hub} = V_{e50}$		M_{yB}	Max. flap moment at root	
					$F_{x\text{-}shaft}$	Max. thrust force along shaft	
						Max. tower-top force	
Parked and fault conditions	I	Maximum exposure	$V_{hub} = V_{e1}$		M_{yB}	Max. flap moment at root	Turbine is parked in most unfavourable way at V_{e1}
					$F_{x\text{-}shaft}$	Max. thrust force along shaft	
						Max. tower-top force	
Transport, assembly, maint., and repair	J	To be stated by the manufacturer					

Load case D for maximum thrust is a straightforward new load case for predicting ultimate shaft thrust loads, $F_{x\text{-}shaft}$, via the following formula:

$$F_{x-shaft} = C_T \frac{1}{2} \rho \left(2.5 V_{ave} \right)^2 A \qquad (1)$$

where ρ is the air density, A is the rotor-swept area, V_{ave} is the average wind speed for the specified wind class, and C_T is the thrust coefficient specified as 0.5. This value of 0.5 is based on comparisons of Eq. (1) with aeroelastic simulations of maximum thrust events—the more intuitive C_T value of 1.0 for maximum thrust is believed to be excessively and unnecessarily safe.

The new load case H associated with a survival wind and no fault is applied differently for turbines that park and those that furl or keep spinning under extreme winds. The extreme wind is taken to be the 50-year extreme, V_{e50}. For turbines that park under extreme winds, the simple prediction of ultimate flap bending moment, M_{yB}, is based on the assumption that the blades of planform area $A_{proj,B}$ and radius R are parked normal to the incoming flow stream as follows:

$$M_{yB} = \left(C_d \frac{1}{2} \rho V_{e50}^2 A_{proj,B} \right) \left(\frac{1}{2} R \right) \qquad (2)$$

where the drag coefficient, C_d, is taken to be 1.5. For turbines that furl or keep spinning under extreme winds, M_{yB} is assumed to occur when the lift coefficient linearly increases from zero at the root to its maximum possible of $C_{l,max}$ at the tip as follows:

$$M_{yB} = \left[C_{l,max} \frac{1}{2} \rho V_{e50}^2 \left(\frac{1}{2} A_{proj,B} \right) \right] \left(\frac{2}{3} R \right) \qquad (3)$$

In the absence of any proven more precise values, $C_{l,max}$ shall be assumed to equal 2.0.

The ultimate shaft thrust load, $F_{x\text{-}shaft}$, for rotors with B blades that park during the 50-year extreme wind follows directly from Eq. (2):

$$F_{x-shaft} = C_d \frac{1}{2} \rho V_{e50}^2 \left(A_{proj,B} B \right) \qquad (4)$$

For turbines that furl or keep spinning under extreme winds, the maximum thrust coefficient is assumed to follow from helicopter rotor theory [7]. This results in an ultimate shaft thrust load of:

$$F_{x-shaft} = \left(0.34 \lambda_{e50}^2 \right) \frac{1}{2} \rho V_{e50}^2 \left(A_{proj,B} B \right) \qquad (5)$$

where λ_{e50} is the 50-year extreme tip speed ratio estimated to equal the product of the runaway rotor speed and R and divided by V_{e50}.

Load case C for yaw error is added to the revised –2 standard because load case B predicts nonconservative ultimate blade root flap moments, M_{yB}, for active yaw machines. This can be seen by comparing load ratios of M_{yB} for the Micon 65 and UAE Phase VI turbines (actively controlled and fixed yaw machines respectively) to those of the other turbines for load case B in Table 2. The simple prediction of M_{yB} for load case C is based on the assumption that the entire blade experiences maximum lift, $C_{l,max}$, when operating at rated conditions (design rotor speed, $\omega_{n,design}$, and design wind speed, V_{design}) and a fixed yaw error of 30˚ as follows:

$$M_{yB} = \int_0^R \left\{ C_{l,max} \frac{1}{2} \rho \left[r\omega_{n,design} + V_{design} \sin\left(30^\circ\right) \right]^2 \left(\frac{A_{proj,B}}{R} \right) \right\} rdr \quad (6)$$

In this expression, the term in square brackets is the approximate maximum tangential velocity of the wind relative to the blade neglecting induction effects. Upon integrating and simplifying with the help of the design tip speed ratio, λ_{design}, Eq. (6) reduces to:

$$M_{yB} = C_{l,max} \frac{1}{8} \rho R^3 \omega_{n,design}^2 \left[1 + \frac{4}{3\lambda_{design}} + \left(\frac{1}{\lambda_{design}} \right)^2 \right] A_{proj,B} \quad (7)$$

Unlike in the released –2 standard, in the revised standard, users will not be able to use measured values of the maximum yaw rate as input into the yawing load case B for passive yaw machines. This is because the maximum yaw rate is found to be a critical design driver for many SWTs and measured values may be inaccurate. One problem with recording a maximum yaw rate via test measurements is that there is a low probability the highest value will be observed during the measurement period. It is thought that the maximum yaw rate is highly influenced by external conditions. Thus, testing would have to take place under the most severe conditions, which puts high requirements on the test site and duration of the test period. In addition, very little data on direct yaw rate measurements are available. Datasets of measured yaw position are available, and yaw rate data have been extracted from them. However, the values extracted are highly dependent on the differentiation process and the sample rate. For example, a reprocessing of 40 Hz yaw position data recorded during field tests on the AOC 15/50 lead to maximum yaw rate values ranging from 17°/s (1 Hz sample rate) to 56°/s (40 Hz sample rate) and 56°/s (2 point differentiation) to 44°/s (40 point differentiation).

Figure 3: AOC 15/50

The revision of the –2 standard specifies the maximum yaw rate for passive yaw machines, $\omega_{yaw,max}$, to scale with the rotor-swept area, A, as follows:

$$\omega_{yaw,max} = \begin{cases} \left[3 - 2\left(\frac{A - 2m^2}{200m^2 - 2m^2} \right) \right] rad/s & A > 2m^2 \\ 3 rad/s & A \le 2m^2 \end{cases} \quad (8)$$

This equation estimates linearly decreasing $\omega_{yaw,max}$ with increasing A (or quadratically decreasing $\omega_{yaw,max}$ with increasing diameter), which is consistent with the fact that smaller rotors tend to yaw faster than larger ones. Equation (8) is plotted along with measurements in Figure 4. The original –2 standard specified a maximum yaw rate of 1 rad/s for turbines with no available yaw rate data. The imprecision of this value is easily seen.

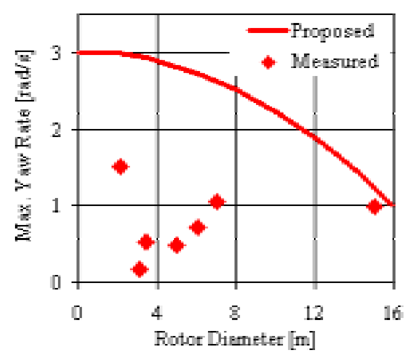

Figure 4: Measured and Proposed Maximum Yaw Rate

In the original –2 standard for the shut-down load case G, the ultimate shaft torque, $M_{x\text{-}shaft}$, is assumed equal to the sum of the maximum low-speed shaft braking torque, M_{brake}, and the design torque, Q_{design}:

$$M_{x-shaft} = M_{brake} + Q_{design} \quad (9)$$

and the ultimate blade root edge bending moment, M_{xB}, is predicted as follows:

$$M_{xB} = \frac{M_{x-shaft}}{B} + (m_B g) R_{cog} \qquad (10)$$

where B is the number of blades, each of mass m_B and with center of gravity R_{cog}, and g is the gravitational acceleration constant. However, field tests have shown a dynamic amplification of loads in the drivetrain for turbines consisting of a high-speed shaft brake and gearbox. For example, measurements of drivetrain dynamics for a shut-down maneuver of the AOC 15/50 are depicted graphically in Figure 5.

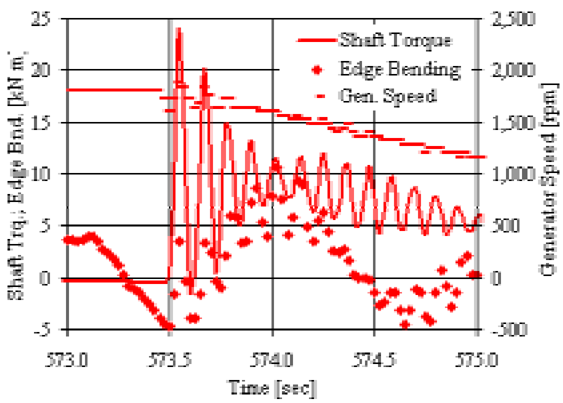

Figure 5: Measured Shut-Down Dynamics

To account for the dynamic amplification of loads in the drivetrain during a shut-down maneuver for turbines with these features, the revised –2 standard requires that Eq. (9) be scaled up. In the absence of any proven more precise values, Eq. (9) shall be multiplied with a factor of 2.0.

Aeroelastic Modeling

The design load cases for aeroelastic modeling from the –1 standard [6] were used as the starting point for evaluation of aeroelastic model load cases in the –2 standard. A listing of MT2's proposed design load cases for the aeroelastic modeling method is given in Table 5.

In general, the rated wind speed referred to in the –1 standard has been replaced by the design wind speed, V_{design}, because rated wind speed is difficult to define for many SWTs as discussed earlier. Also, because small turbines do not always have a cut-out wind speed, V_{out}, the cut-out wind speed in those load cases that specify such a wind speed can be exchanged with a maximum wind speed. Depending on the load case, this is identified to be either 2.5 or 3.0 times the average wind speed for the specified wind class, V_{ave} (see Table 5). In the normal shut-down load case 3.2, the maximum wind speed must be specified by the manufacturer as the highest wind speed at which a shut-down maneuver can be safely performed. For turbines without any automatic shut-down control and thus without a cut-out wind speed accordingly (e.g., many passively controlled machines), the fatigue load case 3.1 can be neglected and thus no replacement for V_{out} need be defined.

For several load cases, where the –1 standard uses specific wind speeds, the –2 standard uses wind speed ranges. From MT2's experience, this will not have a major impact on the workload but it does eliminate the possibility of overlooking a critical wind speed.

For the power production load cases, the one-year extreme operating gust (EOG_1) with loss of electrical connection load case was moved to the power production plus occurrence of fault design situation. The extreme wind shear (EWS) load case was removed because it was found that the wind model does not yield realistic wind conditions for turbines in the lower range of rotor diameters covered by the –2 standard. Furthermore, experience has shown that extreme wind shear is not a design limiting case for SWTs.

Table 5: Aeroelastic Design Load Cases

Design Situation	Load Cases	Wind Condition	Type of Analysis	Other Conditions
1) Power production	1.1	NTM $V_{in} < V_{hub} < V_{out}$ or $V_{in} < V_{hub} < 3.0\ V_{ave}$	Fatigue, Ultimate	
	1.2	ECD $V_{hub} < V_{design}$	Ultimate strength ↓	
	1.3	EOG$_{50}$ $V_{in} < V_{hub} < V_{out}$ or $V_{in} < V_{hub} < 3.0\ V_{ave}$		
	1.4	EDC$_{50}$ $V_{in} < V_{hub} < V_{out}$ or $V_{in} < V_{hub} < 3.0\ V_{ave}$		
	1.5	ECG $V_{hub} = V_{design}$		
2) Power production plus occurance of fault	2.1	NWP $V_{hub} = V_{design}$ or V_{out} or $2.5\ V_{ave}$	Ultimate strength	Control system fault
	2.2	NTM $V_{in} < V_{hub} < V_{out}$ or $V_{in} < V_{hub} < V_{e1}$	Fatigue, Ultimate	Control or protection system fault
	2.3	EOG$_1$ $V_{in} < V_{hub} < V_{out}$ or $V_{in} < V_{hub} < 2.5\ V_{ave}$	Ultimate strength	Loss of electrical connection
3) Normal shut-down	3.1	NTM $V_{in} < V_{hub} < V_{out}$	Fatigue	
	3.2	EOG$_1$ $V_{hub} = V_{out}$ or V_{max} (shutdown)	Ultimate strength	
4) Emergency or manual shut-down	4.1	NTM $V_{hub} = V_{design}$ or V_{out}	Ultimate strength	
5) Parked (standing still or idling)	5.1	EWM $V_{hub} = V_{e50}$	Ultimate strength	Possible loss of electrical power network
	5.2	NTM $V_{hub} < 0.7\ V_{ref}$	Fatigue	
6) Parked and fault conditions	6.1	EWM $V_{hub} = V_{e1}$	Ultimate strength	
7) Transport, assembly, maint., and repair	7.1	To be stated by the manufacturer	Ultimate strength	

Under the power production plus occurrence of fault design situation, the IEC 61400–1 has two load cases using the normal wind profile (NWP) model. In the –2 revision, these have been combined into a single load case.

The start-up load cases have been removed. In general small turbines do not have real start-up sequences proscribed by a sophisticated controller. Furthermore, the loads comparison work showed that start-up load cases did not result in any design-driving loads.

For the normal and emergency shut-down load cases with the NWP, the IEC 61400–2 revision requires the use of the NTM. The normal shut-down load case is combined with EOG_1 for the maximum wind speed the SWT will see during a shut-down / overspeed control event.

Mechanical Loads Measurement and Extrapolation

The Whisper H40, currently being tested in Spanish Fork, Utah, has been instrumented with three load channels: blade flap bending moment and two perpendicular tower bending gages. Also being monitored are rotor speed, yaw rate, yaw postion, furl position, output power, wind speed and direction, as well as ambient temperature and pressure. The combination of measured test data and aeroelastic modeling makes the Whisper H40 turbine unique in the test matrix.

Figure 6: Whisper H40

It is not only the test data and modeling that make the Whisper H40 unique but also the fact that the turbine has been monitored and data has been collected during extreme wind events. Some of these extreme wind events were found to be comparable to the IEC 50-year extreme gusts (see [6] for details). Also captured were some high winds greater than 30 m/s [8].

Although the extreme loads captured during the extreme wind events may ultimately (and most likely) not be the maximum loads expected during the life of the wind turbine, they do demonstrate that the maximum loads will be at least as large, and they do give insight into an approximate magnitude of where the actual maximum loads will fall. This is valuable information for evaluation of the simple equations and the aeroelastic modeling. Also, these extreme loads have been used to evaluate some extrapolation routines, which are being proposed for incorporation into a revised IEC 61400–1 standard. This method [9] will use loads predicted from aeroelastic simulations of normal operation in turbulent winds, extrapolated out to determine the maximum loads expected during the turbine's lifetime.

These extrapolation routines can also be used to extrapolate test data at normal conditions out to the maximum expected loads. This method is being considered by MT2 for inclusion in the revised –2 standard through reference to the IEC 61400–13 standard [10]. The –13 standard is concerned with measurements of mechanical loads on general wind turbines.

An analysis of loads extrapolation using measured loads has been accomplished for the Whisper H40 wind turbine, the results of which are posted in Table 6. The extrapolated values were based on 115 hours of normal operation data. From this table it is seen that extrapolated values are between 33% and 54% higher than the values actually measured during extreme events for all channels except the blade root flap bending moment. These values appear reasonable and are appropriately larger than the measured values. On the other hand, the blade flap bending moment shows the extrapolated value to be less than the actual measured value. This is problematic because the extrapolation method is underestimating this load channel. However, the addition of more (and higher) winds will most likely improve the predicted extrapolations.

Table 6: Maximum Channel Values During Extreme Events and Normal Op. with Extrapolation

Data Channel	Unit	Measured During Extreme Events	Measured During Normal Op. + Extrapolation	Measured + Extrapolation / Measured Extreme
Flap moment at root	Nm	31	24	77.4%
Tower moment at guy attach.	Nm	687	1,056	153.7%
Yaw rate	°/sec	89	119	133.7%
Rotor speed	rpm	1,367	1,855	135.7%

SWT MODELING CHALLENGES

It is constructive to discuss the complexities involved in modeling SWTs. As mentioned earlier, the –2 standard now covers a wide variety of wind turbine sizes and control strategies. As a result, the computer modeling can vary widely as well. For example, some of the larger wind turbines that fall under the –2 standard might be constant speed, stall regulated turbines with a shaft brake. The modeling for this type of turbine is relatively straightforward with a few different modeling codes available for the analysis. These codes would vary from relatively simple codes like YawDyn [11] to more complex codes like FAST [12] or ADAMS® [11]. Many of these codes have been validated against test data collected on these "simpler" turbine configurations. However, many of the smaller turbines, which fall under the –2 standard, will be variable speed, furling turbines. These turbines present unique difficulties for computer modeling.

The first difficulty arises due to the variable speed. Yaw and furling behavior is very sensitive to rotor speed, making the prediction accuracy dependent on knowledge of airfoil and generator characteristics. This is often a challenge for small rotors. Also, dynamic furling behavior requires the most complex modeling codes, such as ADAMS® [11]. Although ADAMS® (with AeroDyn) is capable of simulating a small variable speed-furling wind turbine, the current codes are not set up to handle the tail aerodynamics (although they can be modified).

The challenges reside not only in the codes but also in the nature of a variable speed-furling wind turbine. Research has shown that in addition to the rotor thrust force there is a rotor aerodynamic restoring moment that affects furling behavior. The thrust force and the restoring moment often resist each other with the larger of these contributors determining the furling behavior. The difficulty arises from the fact that these rotor forces are *driven by* the furling behavior (through rotor speed and yaw error) and at the same time they are *driving* the furling behavior. Finally, the entire furl / rotor interaction is further complicated by the influence of the electrical load on the small wind turbine generating system, which is often varying due to the state of charge of the battery bank.

Although interactions such as the above-mentioned can make accurate simulations more difficult, a limited number of model validations (ADAMS® to test data) have been undertaken, showing good results [8, 13]. On the other hand there are still some SWTs that have not been modeled and validated. One such example is the micro-turbine, which often uses flutter as a means of power regulation.

CONCLUSIONS

To address the issues and recommendations advocated by van Hulle [4] and others, MT2 has been working on the revision of the IEC 61400–2 standard on the safety, quality, and integrity of SWTs. Many of the revisions to the standard are guided by the comparison of loads measurements and model predictions. One crucial change to the –2 standard, apart from the loads comparison activities, is the extension of scope to include turbines up to a rotor-swept area of 200 m^2; however, this revision exemplified the need to perform the load comparisons.

Key revisions to the simplified modeling method include a new specification of the maximum yaw rate, changes to the drivetrain dynamics equations, and the addition of new load cases for yaw error, survival wind with no fault, and maximum thrust.

A comprehensive inspection of the test matrix led to the establishment of a set of load factors, which, when combined with a set of material factors and component / construction factors, are used to designate the design load levels of SWTs. The resulting load factors are dependent on whether the turbine design is based on the application of simplified load models, aeroelastic predictions of loads, or test measurements and loads extrapolation techniques.

Other key issues with the draft –2 standard include an expansion of the electrical requirements with discussion of electrical load sensitivities and a detailed testing section that addresses duration testing. This section also gives recommendations for load measurements, component tests and power performance—however, the details of those tests are handled in other IEC documentation.

In all cases, the design of SWTs must now be based on measured values of rotor power and rotor speed and a specified wind class. This is a significant departure from the original standard. The work should culminate in a revised IEC 61400–2 standard that has a higher degree of applicability and dependability than the original.

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13. ABSTRACT *(Maximum 200 words)*

Since 1999, the International Electrotechnical Commission (IEC) Maintenance Team 2 (MT2) has been working on a revision of the IEC 61400–2 standard on the safety, quality, integrity, and design requirements of small wind turbines (SWTs). During this effort, a study was conducted to evaluate the quality of the structural design criteria specified by the original –2 standard. Test measurements and aeroelastic predictions of loads were gathered for a collection of SWTs and evaluated against the simplified load models and load cases specified in the standard. The collection of turbines included variations in rotor size, blade number, rotor location (upwind/downwind), hub type (rigid/teetered), yaw mechanism (free/active), and others. In general, the comparison of load measurements and model predictions exemplified the inaccuracy of the design load levels in the original –2 standard and suggested methods of improvement. Revisions being made to the standard include enhanced load models, new load cases, and improved safety factors. This work should culminate in a revised IEC 61400–2 standard that has a higher degree of applicability and dependability than the original.

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