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Strategies for Refining IEC 61400-2: Wind Turbine Generator Systems – Part 2: Safety of Small Wind Turbines

Preprint

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STRATEGIES FOR REFINING IEC 61400-2: WIND TURBINE GENERATOR SYSTEMS – PART 2: SAFETY OF SMALL WIND TURBINES

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ABSTRACT: This paper provides a status of the changes currently being made by IEC Maintenance Team 02 (MT02) to the existing IEC 61400-2 "Safety of small wind turbines." In relation to the work done by IEC MT02, work has been done by NREL and Windward Engineering under the DOE/NREL Small Wind Turbine (SWT) Project. Aeroelastic models were built and measurements taken on a Whisper H40 turbine and an AOC 15/50. Results from this study were used to verify the simple design equations. This verification will be used to evaluate how changes made in the design load estimation section of the standard work out for a broad range of turbine configurations. The work presented here builds on work performed by Van Hulle (1996) [1]
Keywords: Small Wind Turbine, Certification, International, Models (Mathematical)

1 CONSIDERATION FOR REWRITING THE STANDARD

The wind marketplace needs to ensure that small turbines will not dampen the market by safety failures; such failures could influence the general public's view of the safety of turbines as a whole. This is a challenging task because small turbine designs are often not closely scrutinized and are typically installed on a stand-alone basis with high visibility. It is imperative that an international standard be adopted to ensure safe small turbines and to preserve the growing wind market worldwide.

A paper presented at EWEC in 1996 [1] made several recommendations on how to improve the current version of the 61400-2 standard [2]. The paper was based on work done within the Joule program "Verification of Design Loads for Small Wind Turbines" [3].
Specific recommendations from that project were:
1) Improve the equations especially for blade flapwise moment (fatigue) and the methods to calculate blade root centrifugal loads (fatigue) and rotor thrust loads.
2) Expand the guidelines to include more turbine types than defined in the existing standard by building off of the Danish methods.
3) Provide clearer guidelines on support structure.
4) Provide guidance on how to perform tests and how to measure power and rotational speed characteristics.
5) Provide guidance on how to extrapolate to determine the maximum rotational speed and the maximum yaw speed. These recommendations, combined with the recognition that there are pockets of interest in small turbines throughout the world and favorable timing in the U.S., Australia, and Japan for funding a rewrite activity, all led to a proposal to TC88 for rewriting the existing standard.

There is a growing market for home-based renewables in the U.S., high-volume manufacturing of micro turbines in China, interest and development of new small turbines in Australia, interest in setting up small turbine manufacturing in Japan, and in Denmark, a 1994 standard titled "Last-, og sikkerhedsforskrifter for husstandsmoller" [5]. All these areas of activity indicated the need for the development of an international small turbine safety standard.

The effort for rewriting the existing 61400-2 standard started at the request of IEC TC88, which recommended that the standard:

1) Be reevaluated in terms of size limits, including the possibility of setting different size classifications.
2) Strive for clarity and simplicity in application.
3) Clearly describe the design load cases and conditions. (The standard would attempt to achieve consistency with IEC 61400-1 in this regard, though some differences are to be expected due to the difference in size and application of small turbines.)
4) Clearly define requirements.
5) Acknowledge the different types of generator loading and influence of the application upon design loads and fault conditions.
6) Propose a method for demonstrating design verification based upon full-scale atmospheric testing.

In addition, TC-88 asked the MT02 to consider creation of a third turbine size class, i.e., to split the small turbine category into two categories with different standards applicable to each as appropriate.

Consequently, invitations were sent out in June 1999 to world experts on small turbines in order to convene a maintenance team to reevaluate the current 61400-2 small turbine safety standard.

2 RESULTING CHANGES TO THE STANDARD

The following list gives a summary of the main changes suggested to date for the revision of IEC61400-2.

- Where possible, aligned sections with sections in IEC 61400-1.
- Extended the scope of the standard to turbines up to 200m^2 swept rotor area.
- Made design data testing mandatory as recommended by Van Hulle et al. [1, 3]
- Opened up the simplified load calculations by introducing the concept factor as developed by the Danes [5].
- Inserted the requirements for structural dynamics calculations with specific recommendations for small turbines.
- Gave a more detailed description of test methods specifically for small turbines.
- Split the one large safety factor into load factor, material factor, and construction factor. The construction factor is dependent on the strength verification work done on the components.
- Introduced the duration test (as proposed by the IEC 61400-22 working group) as a means to check the reliability and functionality of the SWT
- Due to the large range of turbine sizes covered in this standard, size-dependent requirements were made for the control and protection system. Above 100m^2, an emergency stop will be required. Below 100m^2, the requirement is that the turbine comes to an idling state or standstill. For all turbine sizes, there is a requirement to bring the turbine to a stop to perform maintenance and a description of what to do in case of an emergency.
- Developed a micro turbine class for turbines < 2m^2.
- Identified additional loads cases not included in the original 61400-2 standard for simple loads equations.
- Introduced the System Safety and Function Test proposed by the 61400-22 working group to verify turbine functionality and safety, demonstrate control and protection system functions, and verify the dynamic behavior of the turbine.

3 COMPARISON OF SIMPLE EQUATIONS, AEROELASTIC MODELING, AND TEST RESULTS

The objective of this work is to improve and quantify the accuracy of simple design equations by comparison to aeroelastic model and measurement results.
Data from several sources is used:

- Results of a study performed under the Field Verification Project (FVP) performed by Windward Engineering [4],
- Results from an IEA round robin on the AOC 15/50[6] and,
- the results of the Joule project [3].

Results from these programs form the basis on which decisions can be made for changes.

3.1 Whisper H40

Under DOE's FVP for Small Wind Turbines, a Whisper H40 was installed at a test site in Spanish Fork, Utah. The project has two objectives:
1) Determine and demonstrate the reliability and energy production of a furling turbine at a highly turbulent site.
2) Take measurements and conduct computer modeling of a furling turbine to improve industry understanding of the mechanics and nature of furling.

3.1.1 Turbine Description

The Whisper H40 is a three-bladed, upwind, furling turbine with a rated power of 900 W (see Figure 1). This free-yaw turbine is manufactured by Southwest Windpower. The version used in the this project is the 24V model in combination with a Trace inverter.

Figure 1: Whisper H40 in Spanish Fork, Utah.

3.1.2 Ultimate Loads

An ADAMS model was used to determine the turbine loading when subjected to IEC extreme wind events. Many of the highest loads generated from the IEC extreme wind events came from the ECD (extreme coherent gust with direction change). As the gust hits the turbine, rotor thrust increases and the turbine begins to furl, increasing the angle between the rotor axis and wind (yaw error). At the same time, the wind direction rotates in the same direction as furling, which reduces the yaw error. The result is that the turbine is exposed to high winds while it is facing into the wind. This consistently generates very high loads for passively furling wind turbines because it reduces the effectiveness of the furling (power regulation) action.
From these results we predicted the maximum rotor speed (loaded and unloaded), the maximum yaw rate, and the highest loads. The maximum rotor speed and the maximum yaw rate predicted by ADAMS were then used as input parameters for the simple design equations. This provides the opportunity to test the accuracy of the simple equations.

Table I shows that the simple design equations under-predicted the ADAMS model results by approximately 60% for both the blade root flap bending moment and for the rotor shaft bending moment. However, the simple equations accurately predict the blade root tension force using the RPM from the ADAMS simulation. This example is consistent with other results, which indicate the simple equations accurately represent the large inertial loads (due to yaw rate, gravity, and centrifugal force) while underestimating the more complex aerodynamic loads.

Table I: Ratio of aeroelastic model/simple design equation loads

	Whisper H40 Windward Engineering	AOC 15/50 NREL
Load case A Normal operation		
Blade root edge bending	-	0.86
Blade root flap bending	-	**1.44**
Thrust force	-	-
Shaft torsion	-	-
Shaft bending	-	-
Loadcase B : Yawing		
Blade root flap bending	**1.67**	0.99
Shaft bending	**1.68**	**1.02**
Load case C: Loss of load (max rotational speed)		
Centrifugal force	1.00	-
Shaft bending	-	-

When comparing the simple design equations to the ADAMS model, we have assumed that the ADAMS model will accurately predict the turbine behavior and loading. Some model validations have been completed against measured test data to determine the accuracy of this assumption. Although we have not yet measured anything as extreme as an IEC gust during our testing, we did measure a gust which had a 9 m/s rise over a relatively short 5-second period (Figure 2).

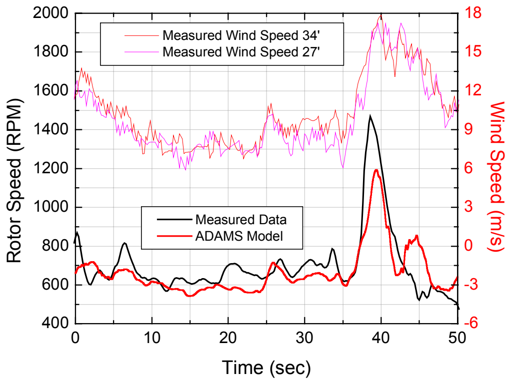

Figure 2: Comparison of Whisper H40 RPM measurements and ADAMS™ model prediction.

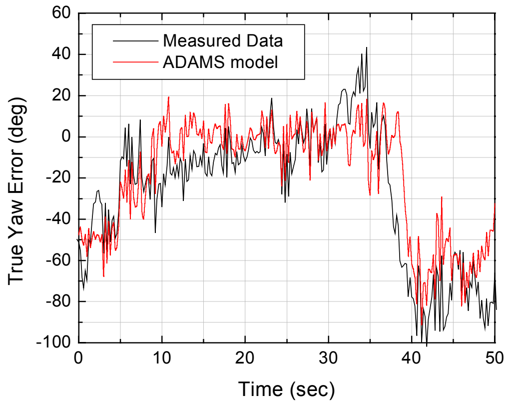

Figure 3: True yaw error for Whisper H40 measurements and ADAMS™ model prediction during a high-rotor-speed event.

This gust did result in a significant increase in rotor speed with a maximum measured rotor speed of 1467 rpm. This measured data has been used for validation of the ADAMS model. Figure 2 shows that the ADAMS model predicted the nature of the rotor speed response to the gust but underpredicted the maximum speed. Figure 3 shows that the yaw error for the same event was predicted with similar accuracy. These types of results suggest that the ADAMS model can predict the complex behavior of a passively furling wind turbine during an extreme wind event.

3.2 AOC 15/50

Load measurements have been performed on the AOC 15/50 located at NREL's National Wind Technology Center as part of the IEA round robin test program. Under the IEA round robin program, a YawDyn model has been built to facilitate the comparison of loads between the individual institutes, these results were presented at Windpower 2001 [6].

3.2.1 Turbine Description

The AOC 15/50 is a three-bladed, free-yaw, stall-controlled turbine with a rated power of 50 kW (See Figure 4.). Its 15-meter diameter rotor operates downwind of the tower at constant speed.

Figure 4: AOC 15/50 in Boulder, Colorado, at NWTC

3.2.2 Loads

Comparison of measured AOC data with aeroelastic model predictions from YawDyn are shown in Figure 5 for load case A, blade root flap bending moment. These fatigue loads seem to agree reasonably well. However, both give higher values then the simple design equations.

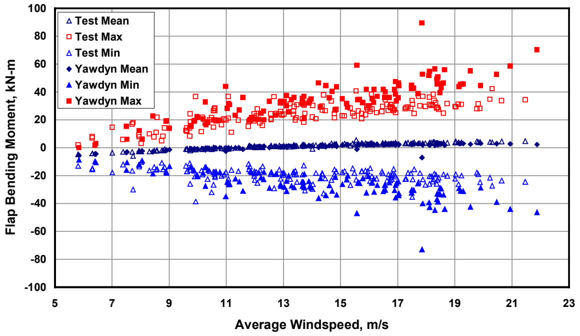

Figure 5: Flap bending moment for AOC 15/50 from measurements and YawDyn model output.

The measured shaft loads for load case A and B (see Table II) agree reasonably well with the simple design equations. However, for cases C and D, there are very large differences between the measured values and the aeroelastic and simple calculations. For a turbine with a brake on the high-speed shaft, drivetrain dynamics can play a major role in the peak shaft loads seen during transient events. The simple YawDyn model and the simple design equations do not have any drivetrain dynamics modeled.

Table II: Ratio of measurements/simple design equations

	LMW1003 CRES	Inventus 6 DEWI	Proven 2200 NEL	AOC 15/50 NREL
Load case A Normal operation (equivalent ranges)				
Blade root edge bending	-	**1.3**	**1.06**	0.96
Blade root flap bending	**3.31**	**1.01**	-	**1.20**
Thrust force				0.19
Shaft torsion	-	0.8	**1.12**	0.25
Shaft bending	-	-	-	**1.56**
Loadcase B : Yawing				
Blade root flap bending	**1.2**	0.55	-	0.99
Shaft bending	-	-	-	0.85
Load case C: Loss of load (max rotational speed)				
Centrifugal force	-	-	-	-
Shaft bending	-	-	-	**12.47**
Loadcase E: Shut down				
Shaft torsion	-	-	-	**2.78**
Blade root edge bending	-	0.7	-	**1.95**

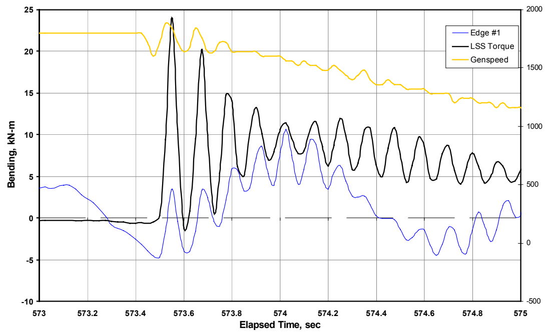

Figure 6: Shaft load during shutdown for AOC 15/50 NREL measurement

Figure 6 shows the shows a time series of blade edge bending, shaft torque bending, and generator speed during a normal shutdown. The peak loads are all due to vibration of the drivetrain. However, if these dynamics were ignored, then the loads would match the simple design calculations quite well. Extensions to the round robin work will include building a FAST_AD model that will simulate the shaft degrees of freedom particularly for these types of events.

3.3 Results from Joule project

The work performed by Van Hulle et al. [1,3], was based on comparing measured loads with simple loads. Three very diverse turbines were used in this project: the LMW1003, the Proven WT2200, and the Inventus 6. These turbines were tested by CRES, NEL, and DEWI respectively. Results from this project are summarized in Table II.

3.4 Results of load comparison

In Table II, the ratio of either measured load over simple loads or modeled loads over simple loads is given. If this number is larger then 1.0 (bold numbers), then the simple design equations underpredict the loads in comparison to either the measurements or aeroelastic model.

The main conclusions which can be drawn from Table I and Table II are:

- The flapwise loads are underpredicted by the simple design equations.
- The edgewise loads are close to both measured and aeroelastic loads.
- The measured loads in the shutdown case are overshadowed by dynamic effects in the drivetrain, which are not included in the simple design equations.
- More data is needed to draw solid conclusions on the simple design equations and the applicability of aeroelastic models for small turbines.

4 FUTURE WORK

The work for refining the 61400-2 small turbine safety standard is ongoing and we plan to work on refining our current aeroelastic models for the AOC 15/50 and the Whisper H40 in comparison to measurements. We will look at the Bergey XL.10 and its measurements to aid in further determining the factors of safety. Load measurements will be taken on the Whisper H40 to make additional comparisons possible. Comparison to the Danish simple design equations will be part of future work.

We encourage participation from any other small turbine manufacturers and research institutes to assist in the validation effort that is to be completed by the spring of 2002.

Our plan is to complete the Committee Draft by spring of 2002.

5 REFERENCES

[1] F. Van Hulle, Validation of Design Criteria for Small Wind Turbines EWEC ‘96
[2] IEC 61400-2: Wind Turbine Generator Systems-Part 2: Safety of small wind turbines, ed.1, 1996-04
[3] F.J.L. Van Hulle et al., Verification of Design Loads for Small Wind Turbines, ECN-C--96-033,
[4] D. A. Davis, A. C. Hansen, Performance, Reliability and Adams Model Predictions of a Small Furling Wind Turbine (Southwest Windpower Whisper H40)
[5] Last-, og sikkerhedsforskrifter for husstandmøller, december 1994, Bilag1, rev. april 1999
[6] R. Santos, Comparison of Results from the IEA Round Robin Mechanical Loads Testing

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