Innovation in Wind Energy Systems: Design, Certification and Commercial Implementation*

*Or – Where do good ideas get stuck before becoming commercial products?

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Chief Engineer: NREL’s National Wind Technology Center

14 March 2012
(“Pi Day”: 3.14)

Happy “Wind Day”!
Pathway from Research to Commercialization

Reducing the innovation risk

Laboratory Research

Design and Evaluation of Concepts

Development of Commercial products

High Risk Ideas

Time

Industry Contribution

Commercial Success
Where do good ideas get stuck before becoming commercial products?

Problem Areas:

• Failure to demonstrate System (LCOE) Value in a Certified design
• Failure to overcome real or perceived Risk
• Failure to address critical System Impacts
• IP issues

Discussion:

• Certification Requirements
• Risk is related to the Reliability of the system
• Case Studies
• Not addressed in this presentation
Wind Power Basics

Wind Power output is proportional to wind speed cubed.

\[ WindPower = \frac{1}{2} \rho AC_P V^3 \]

\[ C_{P \text{ max}} \approx 0.3 \quad \text{(Drag)} \]

\[ C_{P \text{ max}} \approx 0.59 \quad \text{(Lift)} \]

The Betz Limit
Turbine Power: What is available and what is useable?

Regions of the Power Curve

Region I – not enough power to overcome friction

Region II – Operate at maximum efficiency at all times

Region III – Fixed power operation

“Rated Power” governs the size and cost of the entire turbine infrastructure
Performance Enhancement Options

Power Curve

Windspeed (m/s)
0 5 10 15 20 25 30

Power (kW)
0 500 1000 1500 2000 2500 3000 3500 4000

Turbine power
Betz Power

Rayleigh Probability
Weibull Probability

Wind, Energy
0 5 10 15 20 25 30 35 40

Weibull Betz Turbine Energy Weibull Cp

Larger Rotor

Rotor costs increase with diameter cubed,
Rotors power grows with the diameter squared

Taller Tower

Tower costs increase with height to the fourth power (constrained base diameter)

Greater Output

The cost benefits are constrained by the squared-cubed law

We can only win this battle if we build rotors that are smarter and components that are lighter to beat the squared-cubed law.

Imperfect Conversion Losses
Lost Energy from Rating

Weibull Betz Turbine Energy Weibull Cp

Weibull Betz Turbine Energy Weibull Cp

Weibull Betz Turbine Energy Weibull Cp

Weibull Betz Turbine Energy Weibull Cp
Risk and Reliability – Failure Mode and Effect Avoidance

Quotation: Timothy Davis, Quality Director of Jaguar and Land Rover

“There are competing definitions of reliability that are often fudged or confused.”

• The probability that a unit will perform ... under specified usage...
• The probability that a unit will perform ... under encountered usage...

\[
Pr[ T > t \mid N_s ]
\]

versus

\[
Pr[ T > t \mid N_i ]Pr[ N_i ]
\]

Three Factors that lead to challenges with reliability:

1. High Production Rate (variation in parts)
2. Variable Demand Space (Site-specific conditions)
3. Product Complexity (Interaction between components)
One Tool: Industry Consensus Standards

• Value
  o Objective design criteria based on shared industry experience
  o Standard products – volume manufacturing
  o Consistent specifications – multiple vendors
  o Feedback from field performance to design requirements

The Tay Bridge Collapse, December 28, 1879

Much of the improvement in quality of wind turbine systems, from the high frequency of failures in the 1980’s until today, has been driven by the industry development and use of high quality International Standards for design evaluation and testing.

Structural design was based solely on experience. No codes had been written for Sir Thomas Bouch (the designer) to follow. http://filebox.vt.edu/users/aschaeff/tay/tay.html
Things break for different reasons

<table>
<thead>
<tr>
<th>Environment (Loads)</th>
<th>Strength (Resistance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loads inadequately specified</td>
<td>Strength not as great as assumed</td>
</tr>
<tr>
<td>Environment outside the specification</td>
<td>As-built strength not up to specification</td>
</tr>
<tr>
<td>You know the design is inadequate for the environment but you assess the frequency of occurrence to low enough to absorb the loss. (Strategy - Purchase Insurance)</td>
<td></td>
</tr>
</tbody>
</table>

- Design Errors
- Manufacturing and Operating Errors
For some events:
Protect Lives and Buy Insurance!
Greensburg, Kansas, USA – May 4, 2007

Question for standards: Should offshore turbines be designed to withstand all hurricane categories?
**Turbine Specifications – Design Standards**

- **Characteristic Loads**
  - Suite of “Design Load Cases” (DLCs)
  - Uses aeroelastic model to apply atmospheric conditions to the dynamic structure

- **Characteristic Strength**
  - Material properties
  - Damage rules
  - Statistical variation

Design Criteria

\[ \alpha L < \varphi R \]
IEC Standards have a suite of Design Load Cases (DLCs)

Table 2 – Design load cases

<table>
<thead>
<tr>
<th>Design situation</th>
<th>DLC</th>
<th>Wind condition</th>
<th>Other conditions</th>
<th>Type of analysis</th>
<th>Partial safety factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Power production</td>
<td>1.1</td>
<td>NTM</td>
<td>$V_{in} &lt; V_{hub} &lt; V_{out}$</td>
<td>For extrapolation of extreme events</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>NTM</td>
<td>$V_{in} &lt; V_{hub} &lt; V_{out}$</td>
<td></td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>ETM</td>
<td>$V_{in} &lt; V_{hub} &lt; V_{out}$</td>
<td></td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>ECD</td>
<td>$V_{hub} = V_{in} + 2 \text{ m/s}$, $V_{in}$</td>
<td></td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>EWS</td>
<td>$V_{in} &lt; V_{hub} &lt; V_{out}$</td>
<td></td>
<td>U</td>
</tr>
<tr>
<td>2) Power production plus occurrence of fault</td>
<td>2.1</td>
<td>NTM</td>
<td>$V_{in} &lt; V_{hub} &lt; V_{out}$</td>
<td>Control system fault or loss of electrical network</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>2.2</td>
<td>NTM</td>
<td>$V_{in} &lt; V_{hub} &lt; V_{out}$</td>
<td>Protection system or precluding internal electrical fault</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>EOG</td>
<td>$V_{hub} = V_{in} + 2 \text{ m/s}$ and $V_{in}$</td>
<td>External or internal electrical fault including loss of electrical network</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>2.4</td>
<td>NTM</td>
<td>$V_{in} &lt; V_{hub} &lt; V_{out}$</td>
<td>Control, protection or electrical system fault including loss of electrical network</td>
<td>F</td>
</tr>
<tr>
<td>3) Start up</td>
<td>3.1</td>
<td>NWP</td>
<td>$V_{in} &lt; V_{hub} &lt; V_{out}$</td>
<td></td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
<td>EOG</td>
<td>$V_{hub} = V_{in} + 2 \text{ m/s}$ and $V_{in}$</td>
<td></td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>EDC</td>
<td>$V_{hub} = V_{in} + 2 \text{ m/s}$ and $V_{in}$</td>
<td></td>
<td>U</td>
</tr>
<tr>
<td>4) Normal shut down</td>
<td>4.1</td>
<td>NWP</td>
<td>$V_{in} &lt; V_{hub} &lt; V_{out}$</td>
<td></td>
<td>F</td>
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<td></td>
<td>4.2</td>
<td>EOG</td>
<td>$V_{hub} = V_{in} + 2 \text{ m/s}$ and $V_{in}$</td>
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<td>5) Emergency shut down</td>
<td>5.1</td>
<td>NTM</td>
<td>$V_{hub} = V_{in} + 2 \text{ m/s}$ and $V_{in}$</td>
<td></td>
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<td>6) Parked (standing still or idling)</td>
<td>6.1</td>
<td>EWM</td>
<td>50-year recurrence period</td>
<td></td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>6.2</td>
<td>EWM</td>
<td>50-year recurrence period</td>
<td>Loss of electrical network connection</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>6.3</td>
<td>EWM</td>
<td>1-year recurrence period</td>
<td>Extreme yaw misalignment</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>6.4</td>
<td>NTM</td>
<td>$V_{hub} &lt; 0.7 \ V_{ref}$</td>
<td></td>
<td>F</td>
</tr>
<tr>
<td>7) Parked and fault conditions</td>
<td>7.1</td>
<td>EWM</td>
<td>1-year recurrence period</td>
<td></td>
<td>U</td>
</tr>
<tr>
<td>8) Transport, assembly, maintenance and repair</td>
<td>8.1</td>
<td>NTM</td>
<td>$V_{hub}$ to be stated by the manufacturer</td>
<td></td>
<td>U</td>
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</table>
The Standard requires load extrapolation for extreme loads and load spectra for fatigue

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#### 7.6.2 Ultimate strength analysis

The limit state function can be separated into load and resistance functions $S$ and $R$ so that the condition becomes

$$
\gamma_n \cdot S(F_d) \leq R(f_d)
$$

(30)

The resistance $R$ generally corresponds with the maximum allowable design values of material resistance, hence $R(f_d) = f_d$, whilst the function $S$ for ultimate strength analysis is usually defined as the highest value of the structural response, hence $S(F_d) = F_d$. The equation then becomes

$$
\gamma_f F_k \leq \frac{1}{\gamma_m \gamma_n} f_k
$$

(31)
The Normal Turbulence Model must be extrapolated to estimate the extreme event in 50 years of operation.

The atmospheric conditions are defined by the following:

\[ P_R(V_{hub}) = 1 - \exp\left[ -\pi \left( \frac{V_{hub}}{2V_{ave}} \right)^2 \right] \]

Wind Speed Probability of Occurrence

Turbulence Intensity

\[ \frac{f S_k(f)}{\sigma_k^2} = \frac{4f L_k / V_{hub}}{(1 + 6f L_k / V_{hub})^{5/3}} \]

Turbulence Frequency Content

Coherence

\[ \text{Coh}(r, f) = \exp\left[ -12 \left( \left( \frac{f \cdot r}{V_{hub}} \right)^2 + \left( 0.12 \frac{r}{L_c} \right)^2 \right)^{0.5} \right] \]

Parameters are defined for each wind speed class.

NREL’s TurbSim turns these descriptors into wind inputs – FAST turns them into turbine loads.
Load Extrapolation: Extreme Design Loads

- Load extrapolation uses many short operational simulations to estimate a long term extreme.

Sometimes the largest loads come from moderate wind speeds.
Long-term fatigue load analysis

Fatigue loading is summed over all wind speeds and therefore is dependent on the response of the turbine under all conditions.

\[ EFL = \left( \frac{1}{N} \sum_{i=1}^{N} \frac{S_i^m}{N} \right)^{1/m} \]

Fatigue Damage Estimate
Summary of Certification Issues

- The design standards used across the entire industry will drive the reliability across all suppliers.
- Any single innovation that does not promise improvement across all design load cases will not have value.
- Modeling and simulation tools and component testing capabilities must be able to demonstrate ability to meet the standard.
Case Studies
Fiberglass Composite Tower Shafts for Small Wind Turbines

- **Innovation:** fiberglass towers are lightweight and very strong.
  - Shipping and handling are facilitated.
  - Can be erected with a winch – no crane.
  - Any color – highly corrosion resistant

- **Fiberglass light and utility poles are used extensively, but ...**
  - IBC\(^1\) is the accepted civil-structural standard. It invokes other standards, none of which addresses the use of composite structures for wind turbine towers.
  - There are no prescribed and accepted methods of analysis or safety factors so P.E. might invoke inappropriate or overly conservative standard.
  - Recently drafted TIA\(^2\) small wind turbine standard was not coordinated with wind energy experts and it adds little clarity.

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AnemErgonics, LLC: 15 March 2012

1. IBC: International Building Code
2. TIA: Telecommunications Industries Association

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Compliments of Paul Migliore, AnemErgonics
• **Innovation:** use castings instead of weldments for interface with the wind turbine and foundation.
  – Effective use of materials
  – Better material properties in some cases
  – Eliminates high stress concentrations and mitigates risk of failure at welds.
  – Larger fillet radii are possible.

• **But there are acceptance problems**
  – Most standards anticipate the use of welded steel components, so methods of analysis and allowable stresses are prescribed for anticipated weld details, not castings.
  – Because “cook book” methods do not apply, castings invite greater scrutiny.
  – Innovation is likely to be held to a higher standard than traditional solutions.
Traditional Drive Train

The traditional drive train approach lays the components out along a Bed Plate with simple assembly and disassembly as well as easy access. The result is a heavy bed plate and long and heavy high strength steel shafts.
Integrated Drive Train

Benefits:
• Load path through gearbox housing
• Significant reduction in material and weight

Examined in detail by:
• WindPACT Studies (FY 2000)
• Vestas
• GE
• Multibrid
• Others

Not implemented due to:
• Anyone? Class... Class...
Integrated Drive Train Problems

• O&M becomes difficult?
  o Failure in one component requires crane for disassembly
• Limits multiple suppliers in supply chain?
• Increased perceived risk of case failure – uncertain load path?

Will this issue repeat with Direct Drive for offshore?
A design innovation must be checked against all requirements – static and fatigue

**Controls Example:**
- Clear advantage of Independent Blade Pitch Control (Published in 2003 by Bossanyi)
- No OEMs have implemented it

**Why so long?**
- Risk of additional pitch mechanism damage and thus increased maintenance due to higher pitch usage.
- Systems might not take advantage if the structure is sized by other design load cases other than operating loads.
The next steps in Smart Blade Control

Sandia National Laboratories Smart Blades – Courtesy John Berg, 2012

Can reliability be demonstrated? Can a system benefit be proven?

NREL LIDAR testing with feed-forward control on the Controls Advanced Research Turbines (CARTs)
• Rotor study results:
  o Blades are 10% of total system cost
  o Blades generate all the energy
  o Blades can be designed to reduce the loads passed through to the rest of the structure

• **Grow the rotor diameter with adaptive blades:**
  o Maintain size (cost) of the balance of plant
  o Energy capture increases
  o Blade cost increases marginally or – with advanced design – not at all.
  o System return on investment increases 10-20%
Example of Fundamental Research findings

Aero-Elastic Tailoring: Passive load reduction

New Materials – Carbon Fiber

- 0° Carbon
- -45° Fiberglass
- +45° Fiberglass

Geometry-based
Example of full-scale commercialization project

- Knight & Carver
  - 27.1m swept blade
  - Replacement blades – Zond 750
  - 5-10% increased energy capture with longer blades
  - Maintained dynamic load envelop

How many commercial turbines are using swept blades? Why?
Example of sub-scale Blade Innovation at Sandia

Carbon is used to make longer, stronger, adaptive, and lighter blades.

Partnerships with TPI Composites and Knight & Carver
Blade Innovation: Lessons Learned

• **System-level analysis defines the technology opportunities**
  
  o Ideas can not be just thrown over the fence from industry to the research labs without system context

• **Sustained collaboration is required from bench-level research through to comprehensive prototype evaluation**
  
  o Innovations can not be simply thrown over the fence at industry without sustained involvement

• **Small and start-up companies can be avenues to introduce innovation into an industry.**

• **The target of a collaborative development program is to reduce the **Innovation Risk** that keeps improvements from entering the market place.**

• **How many twist-coupled blades in the marketplace? Why?**
The Siemens 2.3 MW turbine at NWTC

First implementation of significant flat back airfoils by industry - 2008.

Why so slow?
- Perceived risk of increased noise and reduced performance from Flat-Back
- New carbon fabric has a minimum threshold in manufacturing volume
What is the Wind Program doing about these issues?

• **Systems Impacts:**
  - Development of a Systems Engineering Tool to address subsystem interactions and system level value
  - Roadmapping that analyzes system interactions

• **Real and Perceived Risk:**
  - National Wind/Water Innovation Reliability Laboratory: NWIRL (on the drawing board)
  - On-ramp for component and subcomponent supply chain innovation

• **Certification Requirements:**
  - Engage in the development of International Standards
  - Comprehensive Modeling and Simulation tools (FAST, etc.) to address all IEC standards-driven requirements
The Design Standard: IEC MT1 - Issues

• IEC 61400-1 Maintenance Team (MT1) is actively meeting to resolve open issues

• Subcommittees are being formed
  o Assessment of site conditions (Thomas Hahm)
  o Tropical wind conditions (Typhoon and Hurricane) (proposal from Japan)
  o Cold climate conditions (proposal from Finland)
  o Medium size wind turbines (Julian Martin)
  o Wake effects (Graeme McCann)
  o Load cases/load calculation requirements (Enrique Gomez de Las Heras)
  o Safety factors (John Dalsgaard Sørensen)

• Next Meeting Hosted by NWTC, June 6-8, 2012
Thank you.

Questions?