What we know about Onshore & Offshore Wind Turbine Reliability with particular reference to Future Offshore Wind Farm Operational Performance

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Past President, European Academy of Wind Energy

“The darkest regions of hell are reserved for those who remain neutral at times of moral crisis”

Dante Alighieri
Keynotes

• Aim to reduce risk, raise turbine Reliability and Availability, Reduce offshore wind Cost of Energy;
• Wind Turbine Reliability from onshore experience;
• What we know about WT reliability;
• Wind Turbine Availability, what is happening Offshore?
Wind Turbine Power Curves

Alstom 1.67 MW, Variable-speed, Variable-pitch

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Wind Turbine Operation - 18 days

WT rating = 1.67 MW
Variable-speed, Variable-pitch
Average output = 490 kW
Capacity factor = 500/1670 = 29%
Actual Wind Power Production
UK & Spain

http://www.bmreports.com/bsp/bsp_home.htm
https://demanda.ree.es/eolicaEng.html
Trend in Turbine Failure Rates with Time

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WT Reliability and Size, EU

LWK average failure rate: period 1993–2004

Small, group I
Medium, group II
Large, group III

failures/turbine/year

Vestas V27 225 kW
Micon M530 250 kW
Nordtank 300 300 kW
Enercon E40 500 kW
Vestas V39 500 kW
Talke TW600 600 kW
Vestas V44 600 kW
Vestas V47 600 kW
Nordex N52 N54 800, 1000 kW
An-Bonus 1MW/54 1000 kW
Talke TW1.5s 1500 kW
Enercon E66 1500, 1800 kW
Reliability, Downtime and Subassemblies, EU

Failure Rate and Downtime from 3 Large Surveys of European Onshore Wind Turbines over 13 years

- Electrical System
- Electrical Control
- Other
- Hydraulic System
- Yaw System
- Rotor Hub
- Mechanical Brake
- Rotor Blades
- Gearbox
- Generator
- Drive Train

Annual failure frequency

Downtime per failure (days)

WMEP Failure Rate, approx 15400 Turbine Years, 1993-2006
LWK Failure Rate, approx 5800 Turbine Years, 1993-2006
Swedish Survey Failure Rate, 3122 Turbine Years, 1997-2005
LWK Downtime, approx 5800 Turbine Years, 1983-2006
WMEP Downtime, approx 15400 Turbine Years, 1993-2006
Swedish Survey Downtime, 3122 Turbine Years, 1997-2005
Typical WT Generator Failure Intensities

Figure 4.4 Variation between failure intensities of generator sub-assembly, in LWK population, using PLP model. Upper graphs: Low-speed direct drive, Fig 4.4(a); High-speed geared drive generators, Fig 4.4(b) [Source: Reference 6 of Chapter 2]
More detail on WT Generator Failures

Figure 4.5 Location of failures in WT generators and other electrical machines

[Source: [7]]
Figure 4.6 Variation in failure intensities of gearbox sub-assembly, in LWK population, using PLP model [Source: Reference 6 of Chapter 2]
WT Reliability-Downtime per Assembly

Stop Rate and Downtime from Egmond aan Zee Wind Farm, the Netherlands, over 3 Years

Control System
Yaw System
Scheduled Service
Pitch System
Gearbox
Ambient
Generator
Converter
Electrical
Blade System
Structure
Grid
Brake System

Annual Stop Frequency

Downtime per Stop (days)

Egmond aan Zee Failure Rate, 108 Turbine Years
Egmond aan Zee Downtime, 108 Turbine Years

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Figure 4.7  Variation in failure intensities of converter sub-assembly, in LWK population, using PLP model [Source: Reference 6 of Chapter 2]
Reliability & Subassemblies, EU, Reliawind

Data Source:
Reliawind Deliverable D.1.3 – Reliability Profiles Figures subject to update.

Lighter larger background blocks show sub-systems;
Darker smaller foreground blocks show assemblies;
The line shows the Pareto cumulative contribution.
Downtime & Subassemblies, EU, Reliawind

Data Source:
Reliawind Deliverable D.1.3 – Reliability Profiles

Lighter large background blocks show sub-systems;
Darker smaller foreground blocks show assemblies;
The line shows the Pareto cumulative contribution.
### Summary of least reliable sub-assemblies & their failure modes

<table>
<thead>
<tr>
<th>Sub-system / Assembly</th>
<th>Failure Mode 1</th>
<th>Failure Mode 2</th>
<th>Failure Mode 3</th>
<th>Failure Mode 4</th>
<th>Failure Mode 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pitch System</strong></td>
<td><strong>Battery Failure</strong></td>
<td><strong>Pitch Motor Failure</strong></td>
<td><strong>Pitch Motor Converter Failure</strong></td>
<td><strong>Pitch Bearing Failure</strong></td>
<td><strong>Temperature or Humidity Sensor Failure</strong></td>
</tr>
<tr>
<td><strong>Hydraulic</strong></td>
<td><strong>Internal leakage of proportional valve</strong></td>
<td><strong>Internal leakage of solenoid valve</strong></td>
<td><strong>Hydraulic cylinder leakage</strong></td>
<td><strong>Position sensor degraded or no signal</strong></td>
<td><strong>Pressure control valve sensor degraded signal</strong></td>
</tr>
<tr>
<td><strong>Frequency Converter</strong></td>
<td><strong>Generator-side or Grid-side Inverter Failure</strong></td>
<td><strong>Loss of Generator Speed Signal</strong></td>
<td><strong>Crowbar Failure</strong></td>
<td><strong>Converter Cooling Failure</strong></td>
<td><strong>Control Board Failure</strong></td>
</tr>
<tr>
<td><strong>Yaw System</strong></td>
<td><strong>Yaw gearbox &amp; pinion lubrication out of specification</strong></td>
<td><strong>Degraded wind direction signal</strong></td>
<td><strong>Degraded guiding element function</strong></td>
<td><strong>Degraded hydraulic cylinder function</strong></td>
<td><strong>Brake operation valve does not operate</strong></td>
</tr>
<tr>
<td><strong>Control System</strong></td>
<td><strong>Temperature sensor modules malfunction</strong></td>
<td><strong>PLC analogue input malfunction</strong></td>
<td><strong>PLC analogue output malfunction</strong></td>
<td><strong>PLC digital input malfunction</strong></td>
<td><strong>PLC In Line Controller malfunction</strong></td>
</tr>
<tr>
<td><strong>Generator Assembly</strong></td>
<td><strong>Worn slip ring brushes</strong></td>
<td><strong>Stator winding temperature sensor failure</strong></td>
<td><strong>Encoder failure</strong></td>
<td><strong>Bearing failure</strong></td>
<td><strong>External fan failure</strong></td>
</tr>
<tr>
<td><strong>Gearbox Assembly</strong></td>
<td><strong>Planetary Gear Failure</strong></td>
<td><strong>High Speed Shaft Bearing Failure</strong></td>
<td><strong>Intermediate Shaft Bearing Failure</strong></td>
<td><strong>Planetary Bearing Failure</strong></td>
<td><strong>Lubrication System Malfunction</strong></td>
</tr>
</tbody>
</table>
Studies on Different WTs

• WT Make A
  – 153x1.5-2MW WT with 3-blades, electric pitch-regulation, geared-drive, DFIG generator and partially-rated converter
  – 6 Wind Farms
  – Over 2 years

• WT Make B
  – 366x2.5MW WT with 3-blades, electric pitch-regulation, geared-drive, synchronous generator and fully-rated converter
  – 1 year
SCADA Alarm System
Performance Evaluation -KPIs

• Reference: Alarm systems, a guide to design, management and procurement No. 191 Engineering Equipment and Materials Users Association 1999 ISBN 0 8593 1076 0

• KPIs: Key Performance Indices *
  – KPI 1, Average Alarm Rate: Long term average of the number of alarm triggers occurring within a 10 min SCADA interval.
  – KPI 2, Maximum Alarm Rate: Maximum number of alarm triggers occurring within a 10 min SCADA interval.

• Additional Definitions *
  – Alarm Shower: A single fault causing a large number of alarm triggers, in this work an Alarm Shower consists of > 10 alarm triggers
# Alarm KPIs from 7 Wind Farms

<table>
<thead>
<tr>
<th>Alarm KPIs</th>
<th>Geared Drive, Variable Speed, 1.67 MW WTs</th>
<th>Geared Drive, Fixed Speed, 1.0 MW WTs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wind Farm1</td>
<td>Wind Farm2</td>
</tr>
<tr>
<td>Total WT Numbers</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>KPI1: Average Alarm Per Wind Farm</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Rate Per 10 mins Per Wind Turbine</td>
<td>0.34</td>
<td>0.50</td>
</tr>
<tr>
<td>KPI2: Maximum Alarm Per Wind Farm</td>
<td>391</td>
<td>1143</td>
</tr>
<tr>
<td>Rate per 10 mins Per Wind Turbine</td>
<td>30.1</td>
<td>76.2</td>
</tr>
</tbody>
</table>
WT Make A – Alarm System Performance

- **Reactive** - peak alarm rate during upset is unmanageable and alarm system will continue to present an unhelpful distraction to the operator for long period.
- **Stable** - Alarms have been well defined for normal operation, but the system is less useful during plant upset.

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WT Pitch Mechanism Taxonomy

Figure 10. Typical WT electrical pitch system for one blade.
WT Pitch Alarm, Relationships over 2 years, Qiu et al

b: Probability-based Analysis Venn Diagram

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Figure 8. WT with double fed induction generator and converter connected to the grid.
WT Converter Alarms, Statistical Relationships over 2 years, Qiu et al

- 322 - Inverter
- 332 - Inverter
- 337 - Grid-side Inverter Over-current
- 338/343 - Rotor-side Inverter Over-current/Over-temperature
- 345 - DC Overvoltage
- 349 - Grid Voltage Dip
- 263 - Main Switch
- 369 - Pitch
- 372-374 - Blade1-3 Emergency
WT Converter Alarm
Showers, 2 years, Qiu et al
Fig. 8: Geographical distribution of failure root causes in power electronics systems, from [15]
WT Unreliability & Importance of Pre-Testing

Root Causes → Condition Monitoring Signals → SCADA Signal Analysis → Failure Modes And Effects Analysis, FMEA → Failure Location

Wind condition
Weather
Faulty design
Faulty materials
Poor maintenance

How?
Pre-Testing during Prototype Development
Or In-Service SCADA & CMS Analysis & Diagnosis

Why?
Root Cause Analysis

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Onshore Availability and Wind Speed

Brazos, Texas, USA, 160 MW, 160 x Mitsubishi MWT1000, 1 MW

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Offshore Availability and Wind Speed

Barrow, UK, 90 MW, 30 x Vestas V90, 3 MW

Scroby Sands, UK, 60 MW, 30 x Vestas V80, 2 MW

Kentish Flats, UK, 90 MW, 30 x Vestas V90, 3 MW

Egmond aan Zee, Netherlands, 108 MW, 36 x Vestas V90, 3 MW

North Hoyle, UK, 60 MW, 30 x Vestas V80, 2 MW
Onshore Availability and Wind Speed, World

40% energy produced at wind speeds >11m/s
North European Offshore Wind Farm Performance

Three North European Offshore Wind Farms
Scroby Sands North Hoyle Egmond aan Zee

Wind Speed, m/s; Capacity Factor, %; Availability, %

Availability
Capacity Factor
Wind Speed

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Relationship between Failures & Weather

Pizza Hut

Durham University

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[Graph showing the relationship between failures and weather with data points and a trend line highlighting the correlation between the two variables.]
Relationship between Failures & Weather

![Bar chart showing the relationship between failures and weather from January to December. The chart indicates high correlation in some months.]
Power Curves & Turbulence from SCADA

Power curves

**Red** – SCADA real power curve

**Blue** – Manufacturer’s theoretical power curve
Wind Turbulence from Fast Data

Is this difference driving failures?

Probability density function of spatial transversal wind velocity increments over a distance of 10 m, for $\tau=4$ s compared to a Gaussian distribution.
Wind Turbulence from Slow Data

WT SCADA

Probability density function of wind velocity from 10 min SCADA

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Wind Turbulence from Slow Data
WT SCADA

Region of most interest for reliability of large WT drive trains

ωsv (ω) (m/s²)

0 2 4 6

0.001 0.01 0.1 1.0 10 100 1000 cycles / h

4 days semiannual 5 min.
Turbulence in context

But turbulence of this dimension could affect drive train

Turbulence of this dimension will not affect drive train
SCADA Load Changes, 18 different WTs

- Most based on 2.2 years data
- Use bin size of 100 N
- High variety between 0-6000N
- WTs are from 5 different sites

Radial load change on left HSS gearbox bearing every 10 mins (N)

Courtesy: Dr Hui Long  NTNU, EU FR7 MARE WINT Project  September 2013
Healthy WTs with relatively low load change
WTs from same site have similar load change
distributions

Radial load change on left HSS gearbox bearing every 10 mins (N)

Courtesy: Dr Hui Long
NTNU, EU FR7 MARE WINT Project
September 2013
Two WT's on this site had serious failures

Radial load change on left HSS gearbox bearing every 10 mins (N)

Difference between sites, Site 4

Courtesy: Dr Hui Long, NTNU, EU FR7 MARE WINT Project
September 2013
PDF of HSS Bearing Radial Load Increments from SCADA

- Compared with Gaussian distribution the evident different tail corresponds to large load increments;
- Suggesting large load increments observed more frequently than expected;
- Two WTs have different bearing load increment occurrence frequencies.

Courtesy: Dr Hui Long
Conclusions

- For onshore WTs 75% faults cause 5% downtime, 25% faults cause 95% downtime.
- Pitch and Main Converters suffer from many faults but with low downtimes.
- Pitch and Main Converters represent a significant part of the 75%.
- This behaviour could be problematic offshore.
- WT reliability is affecting offshore performance.
- Sub-assemblies with high failure rates are consistent.
- Turbulence seems to be causing failures.
- Analysis of SCADA wind speeds, torques & shaft speeds is showing ample evidence of turbulent effects.
- Link between turbulence and failures is difficult to prove.
- The mathematical tools to be used are not yet clear.
References


