Reliability & Condition Monitoring of Wind Turbines

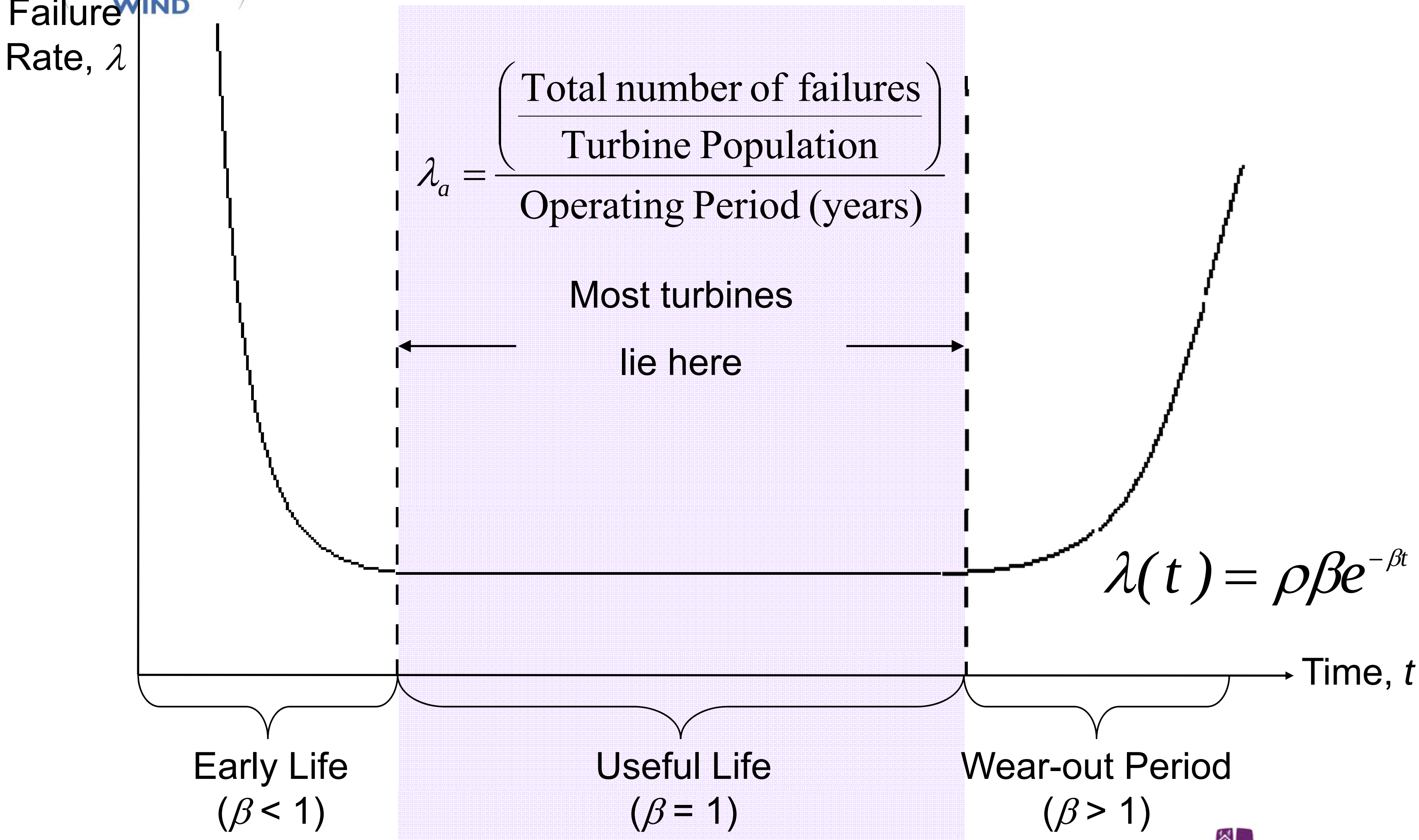
Work to date
March 2006-Jan 2008
of the
Supergen Wind Consortium
March 2006-March 2010
Themes W & X

Presentation Summary

- To identify current wind turbine reliability and condition monitoring issues
- To describe the work being done by Supergen Wind to address these issues
- To identify how issues can be resolved
- Introduction to Reliability and application to Wind Turbines
- Identification of primary Failure Modes
- Experience from real Wind Turbine Blade Structural Monitoring
- Experience from real Wind Turbine Condition Monitoring
- Experience from Test Rig Condition Monitoring & Diagnosis
- Conclusions

Introduction to Reliability

The Bathtub Curve

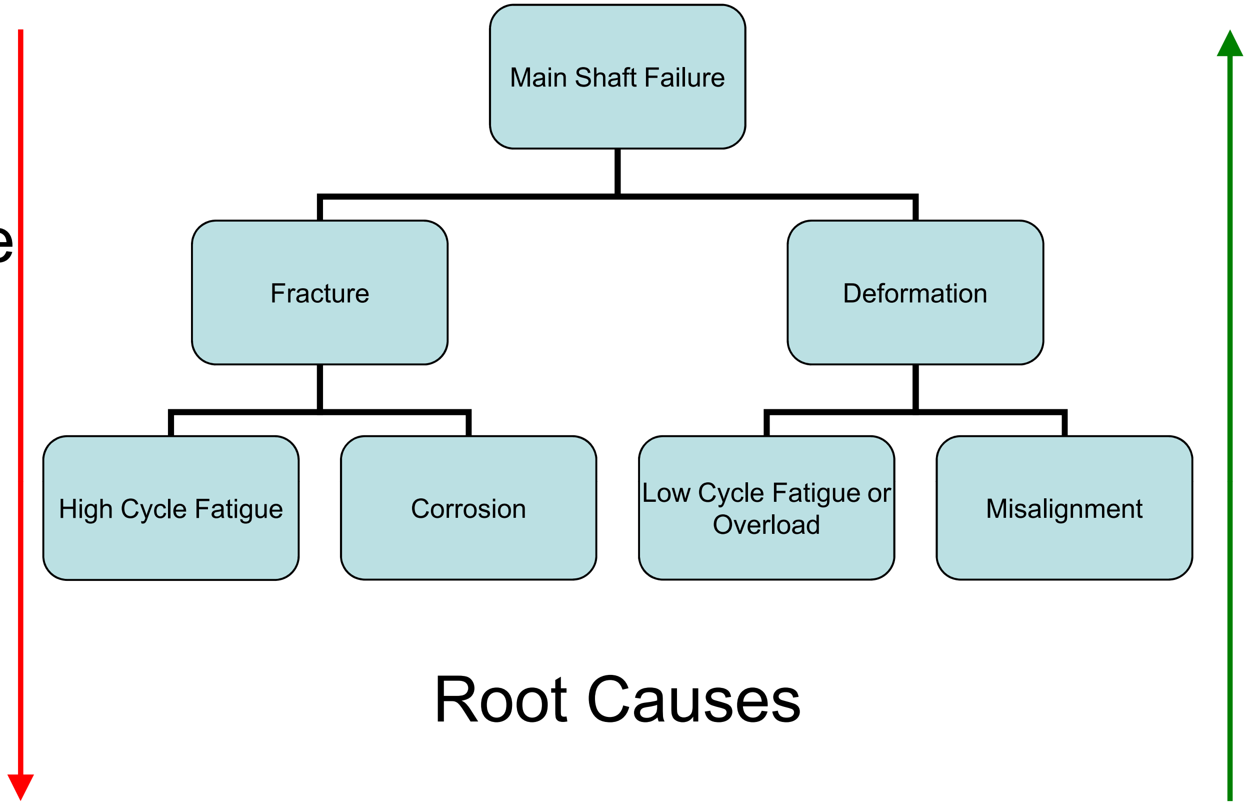


Root Causes & Failure Modes

Failure Mode

Why?

Root Cause Analysis



How?

Condition Monitoring

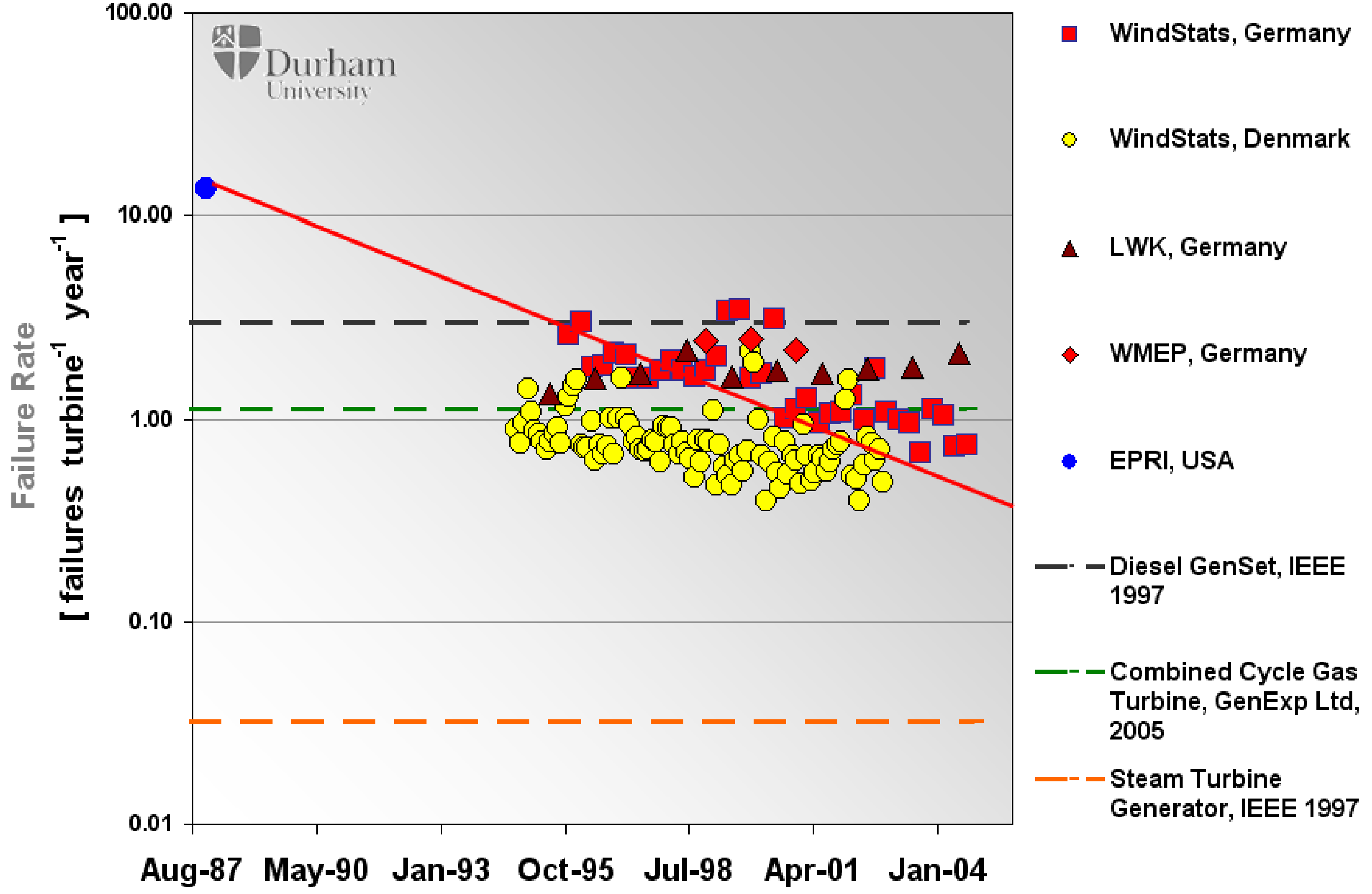
& Diagnosis

Wind Turbine Reliability

Failure Rates

- Failure data taken from 2 Surveys:
  - Windstats in Germany and Denmark
  - LWK in Schleswig Holstein, Germany
- Data averaged over about 10 years
- Data taken from 3 populations of between 300 and 4000 turbines
- Failure rates collected for 10-14 subassemblies in each turbine
- Distribution of failures shows the subassemblies with the most significant failure modes
- LWK data also allows comparative analysis between wind turbine concepts of the downtime

Trend in Turbine Failure Rates with time



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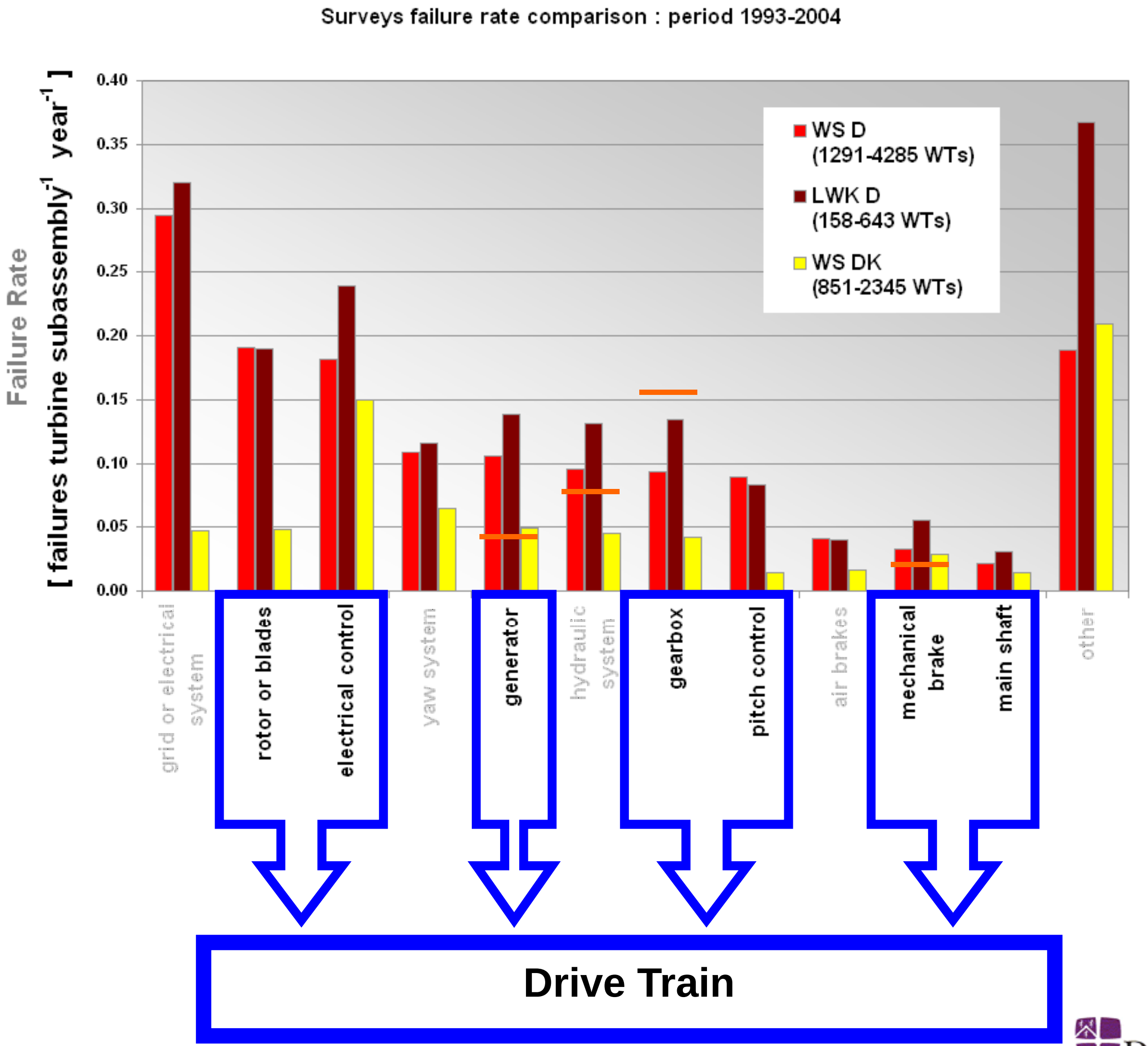
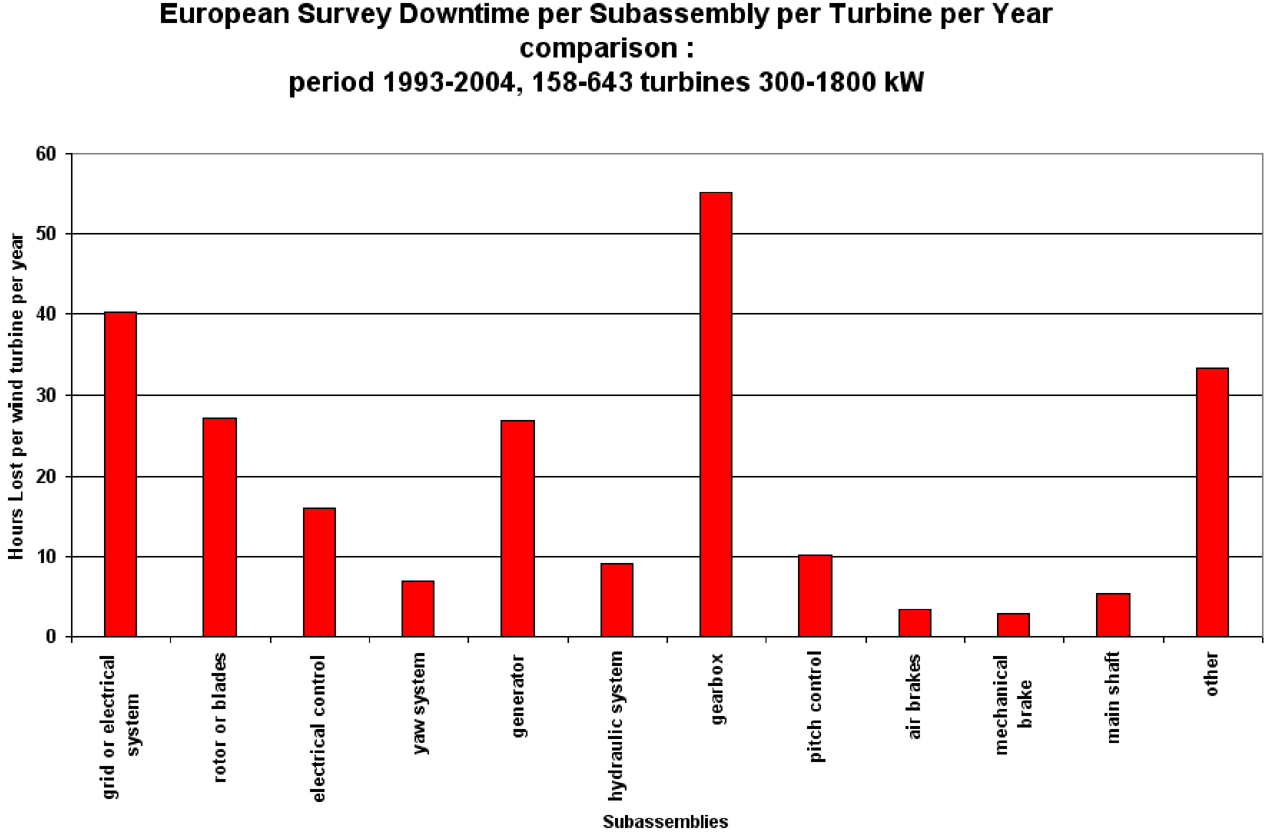
Reliability & Subassemblies

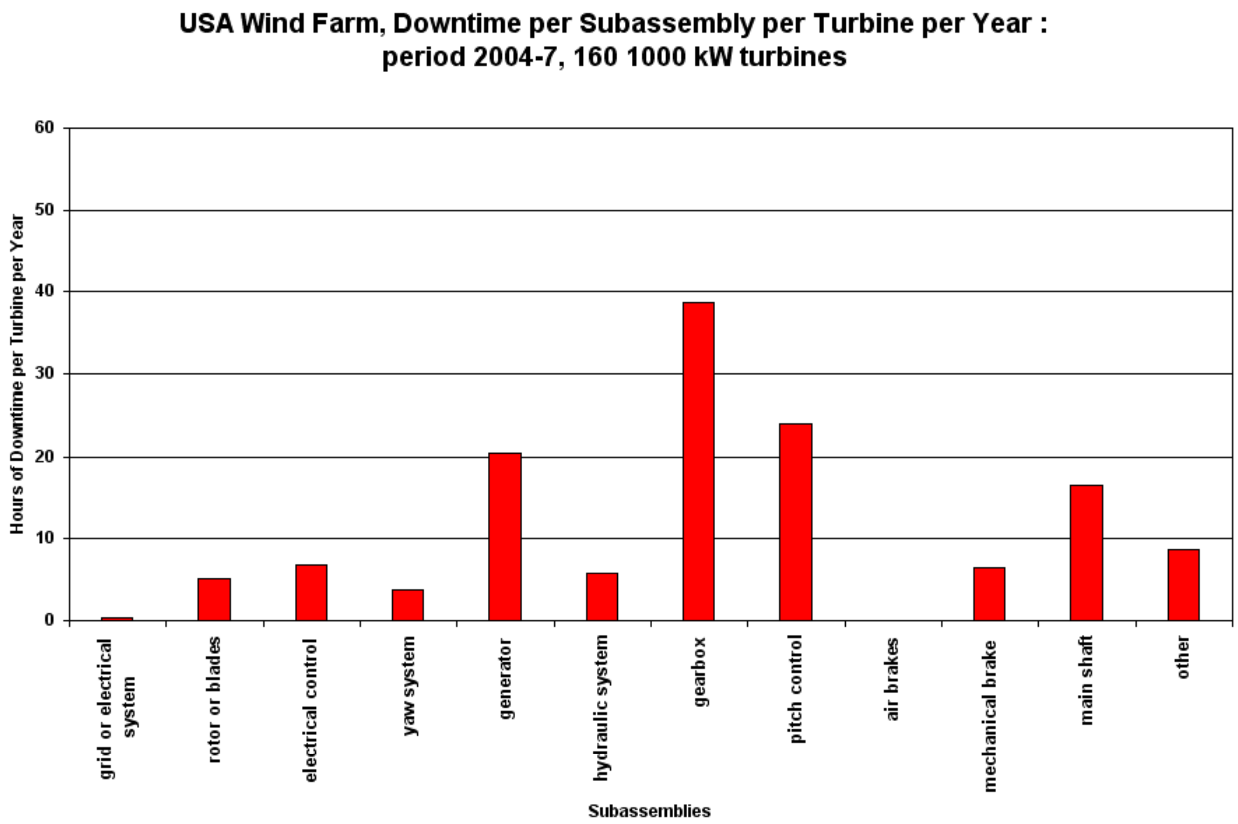
Industrial Reliability figures



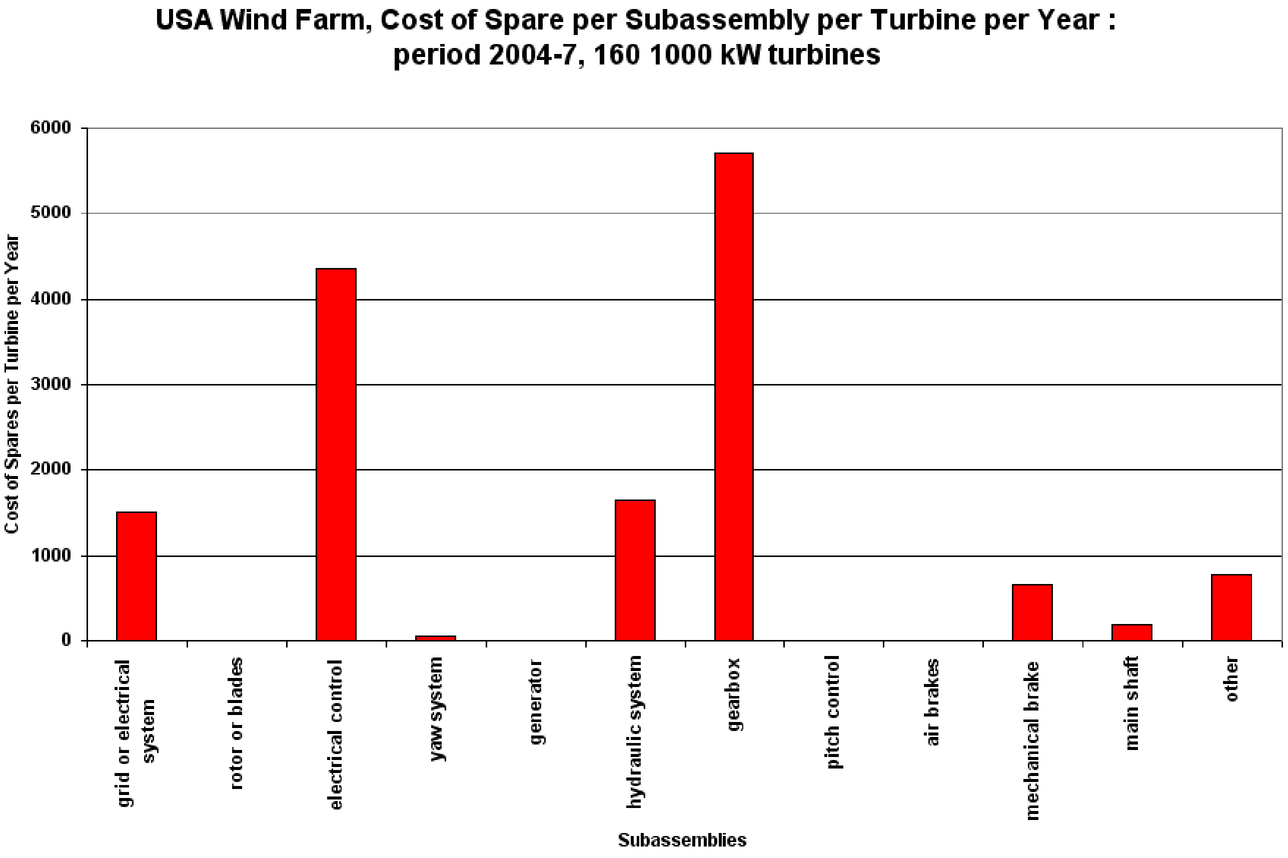
Reliability & Downtime EU



Reliability & Downtime US



Reliability & Cost US



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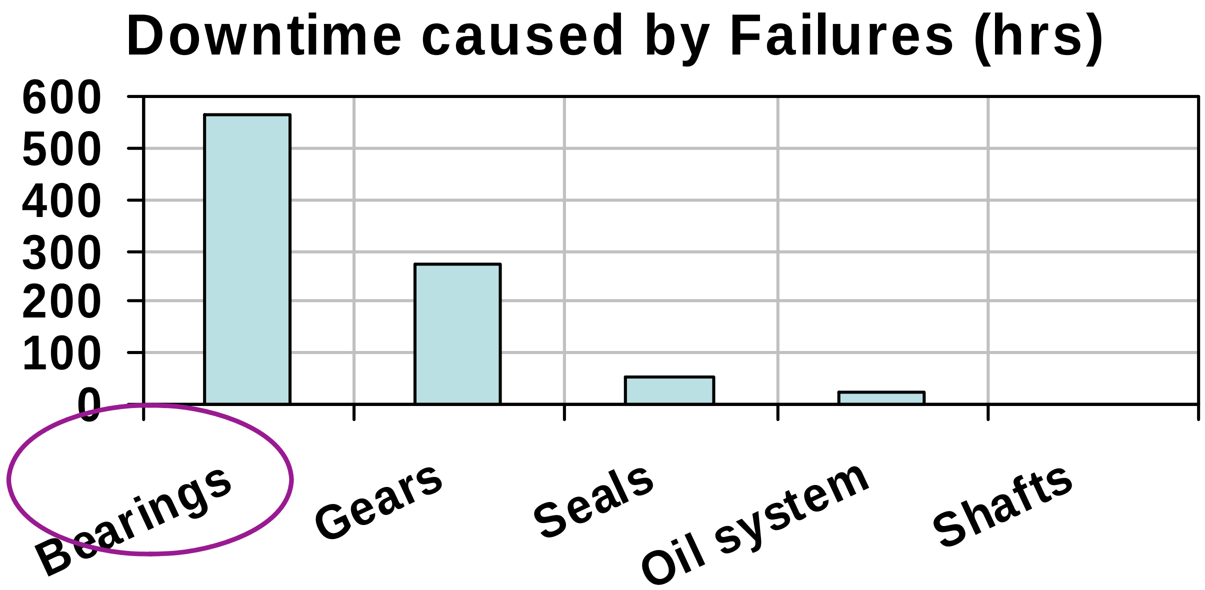
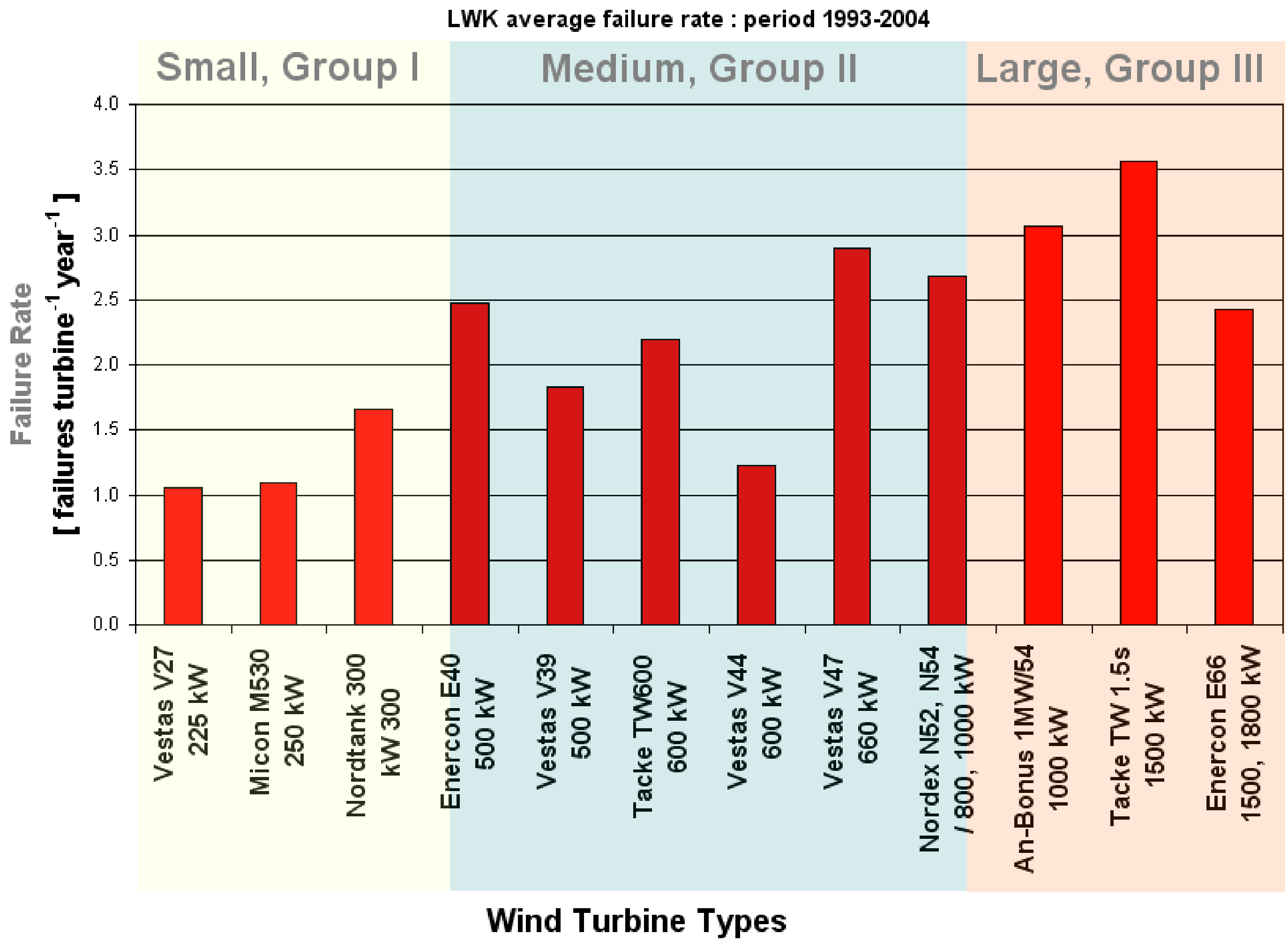
Downtime due to Gearbox Failure



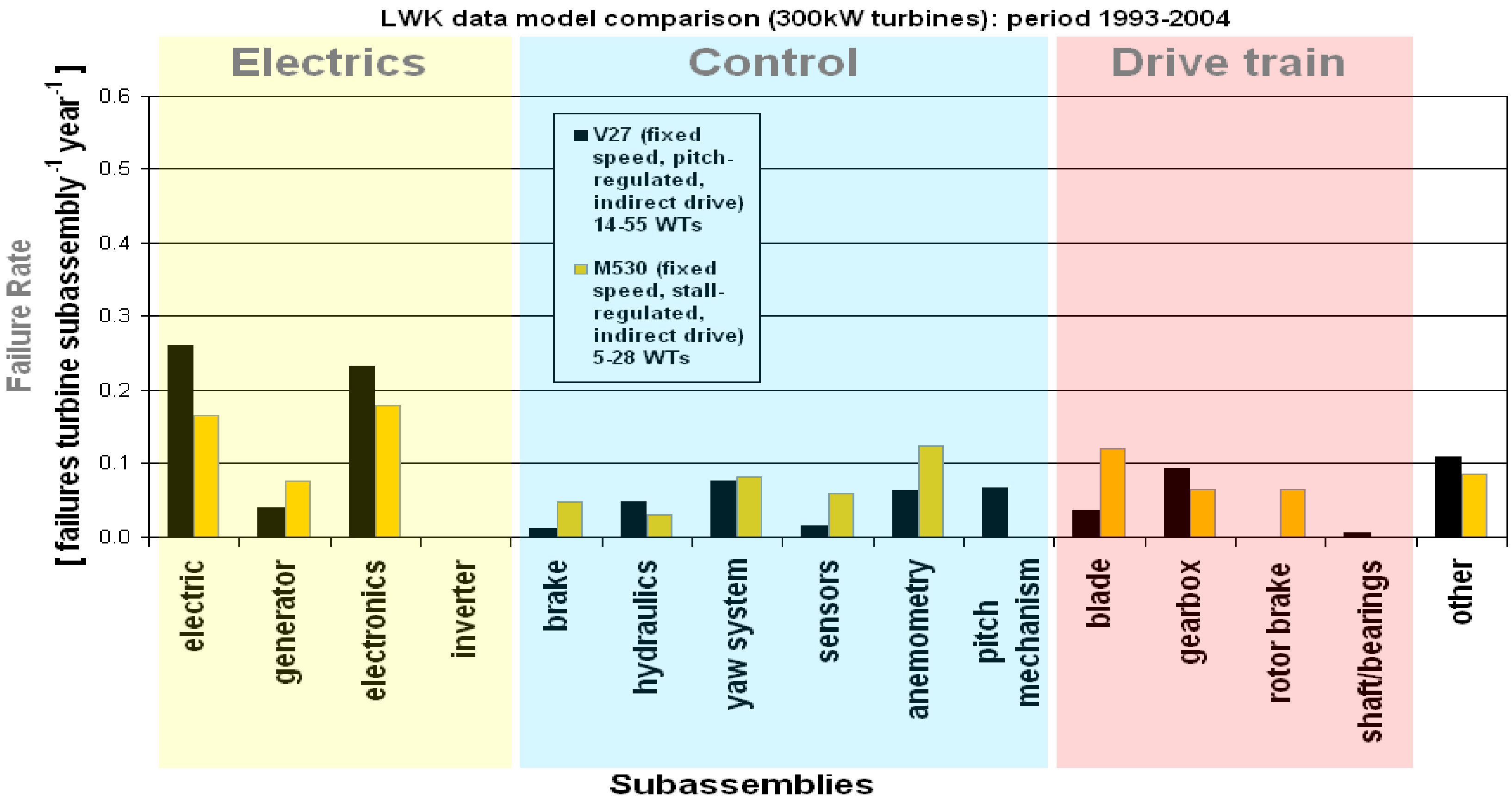
The main causes of gearbox gear & bearing failure:

- Misalignment of components
  - System deformations;
  - Dynamic loads
  - Poor bearing selection
  - Lubrication issues

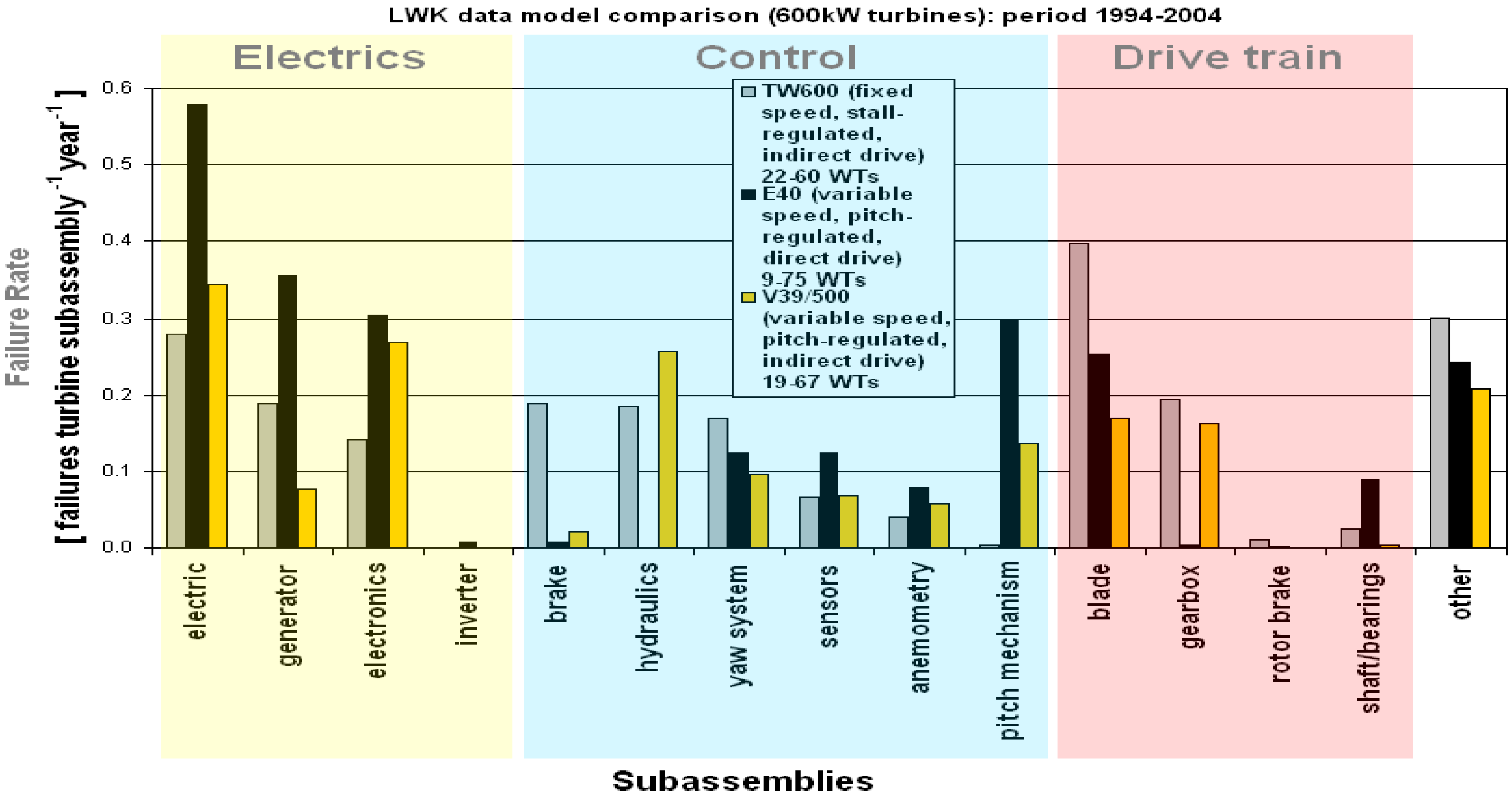
Reliability & Size



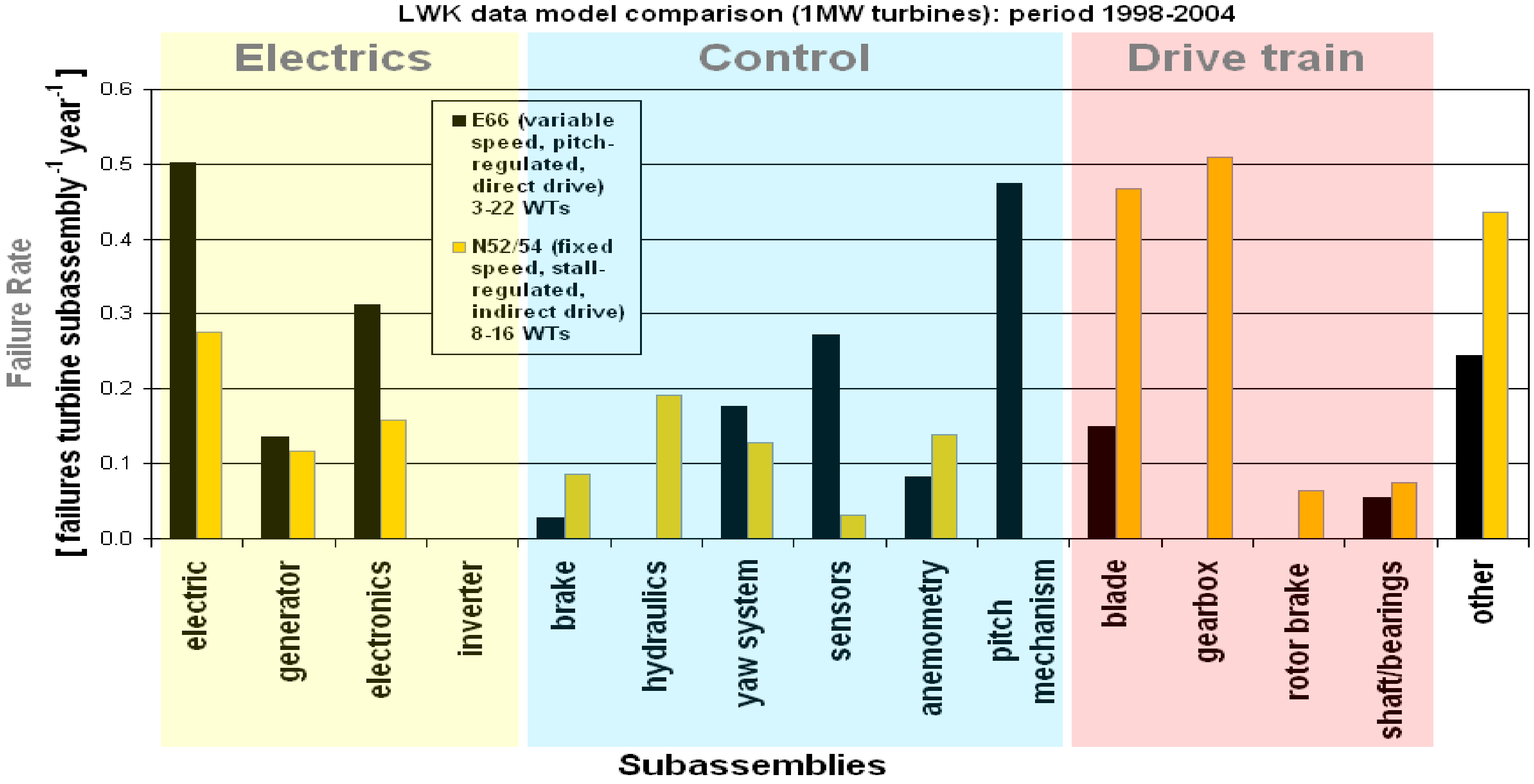
Reliability & Concept



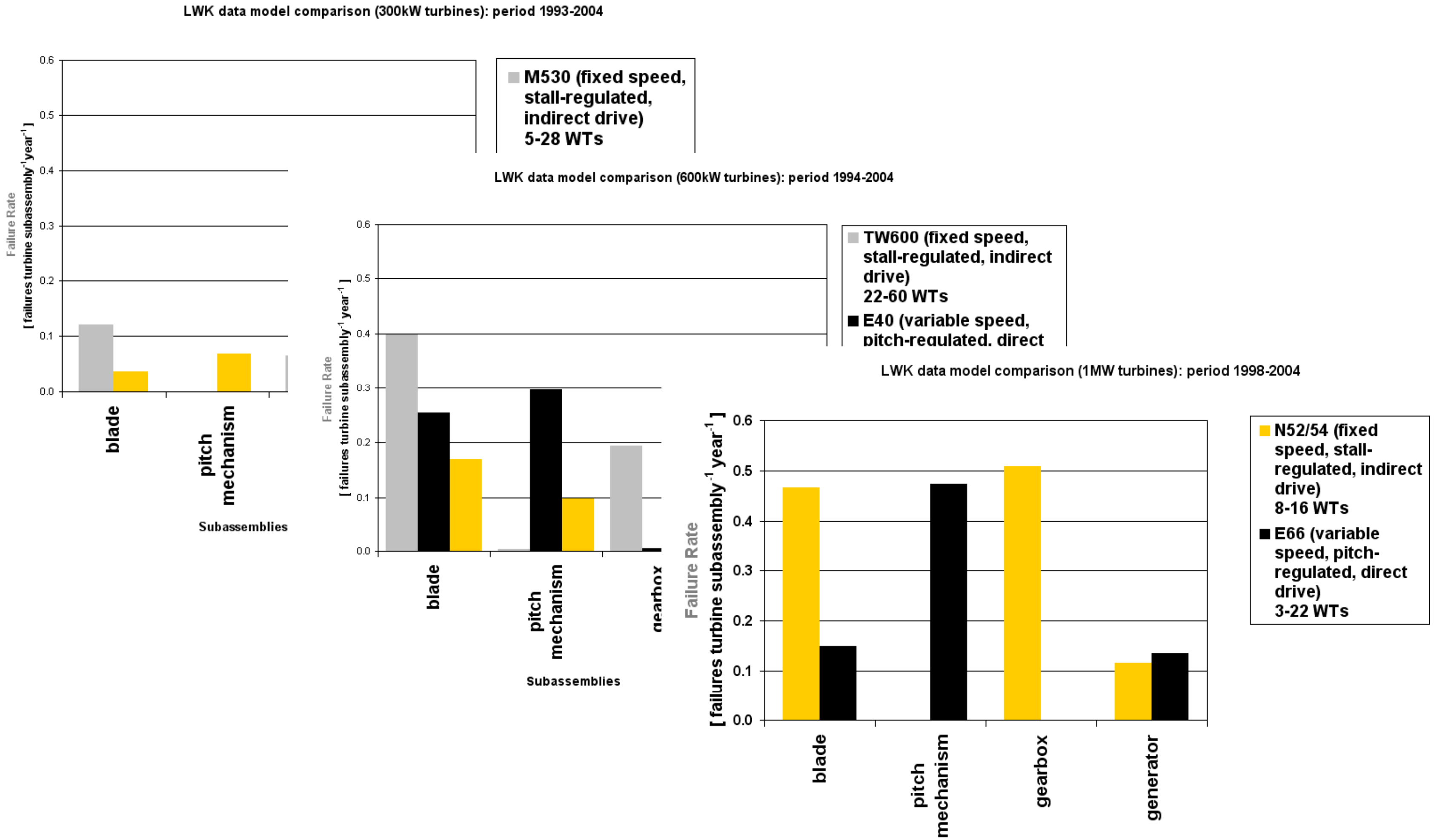
Reliability & Concept



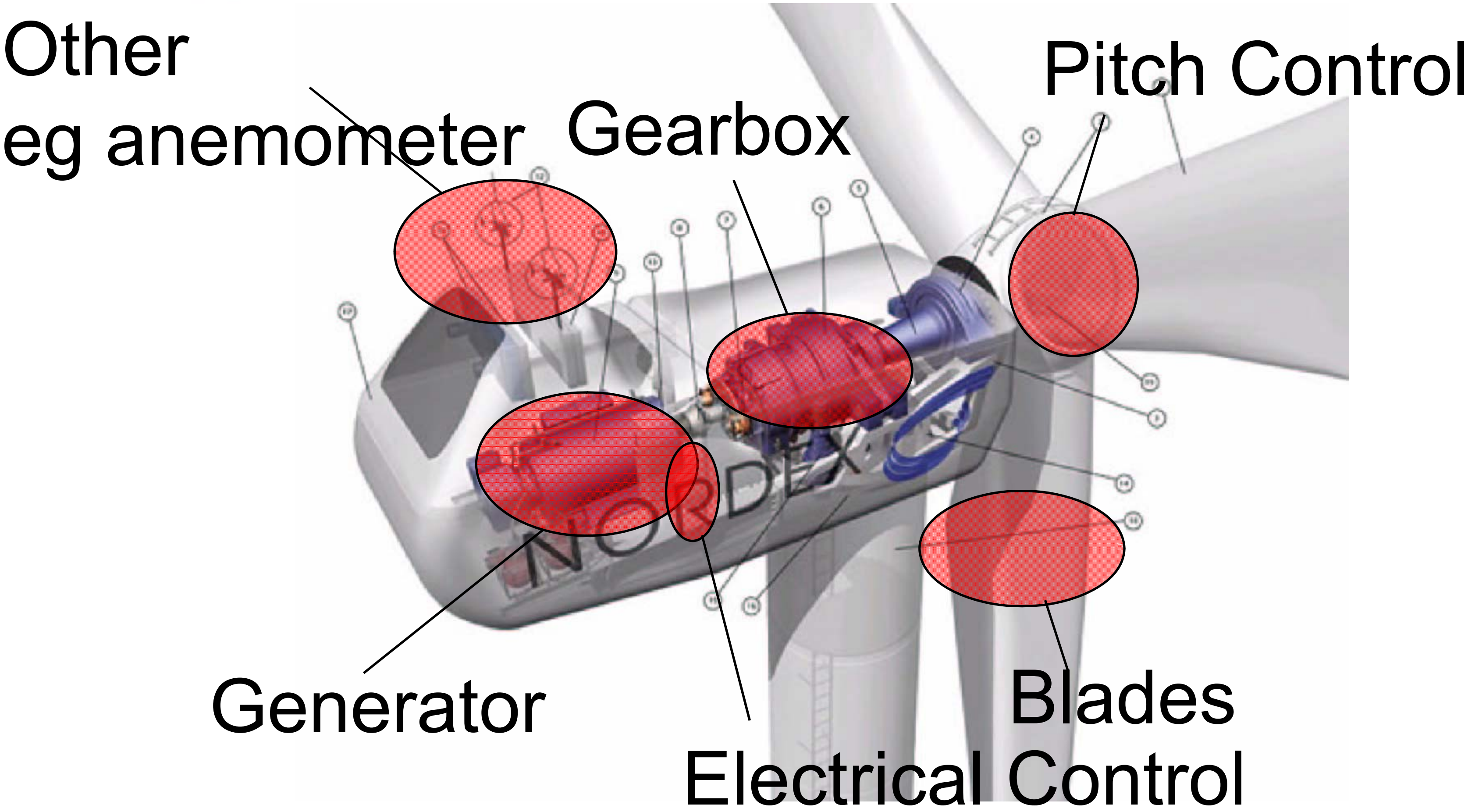
Reliability & Concept



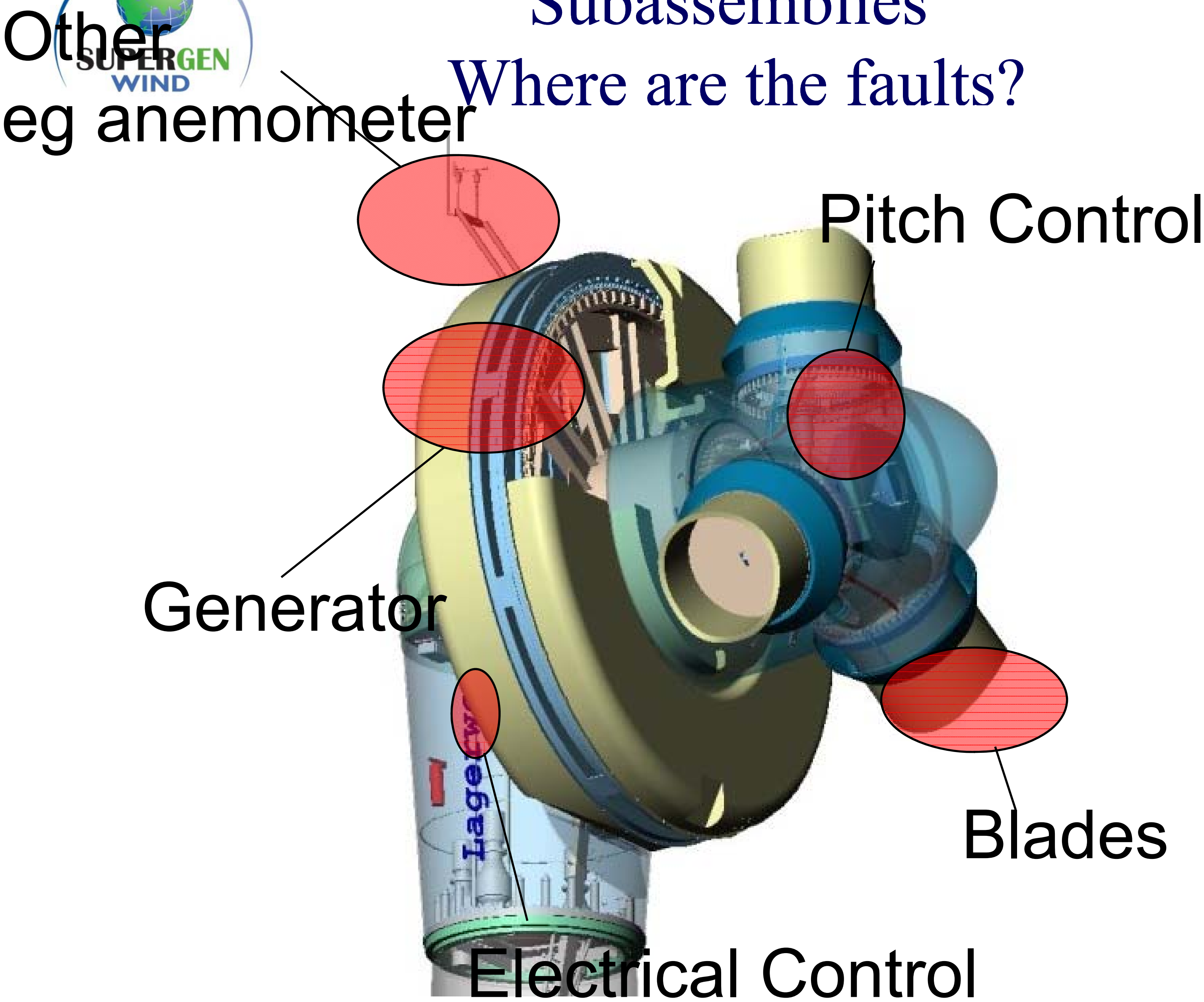
Reliability & Concept



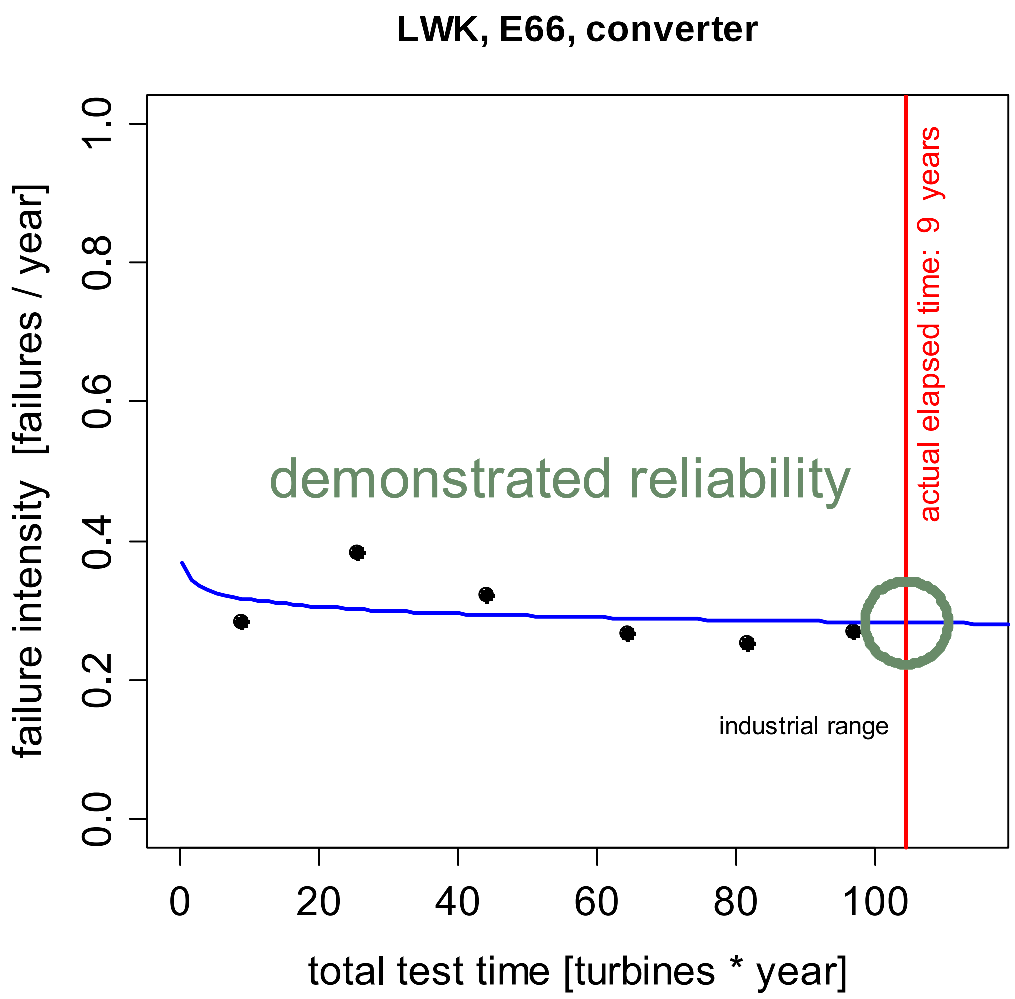
Key Geared Wind Turbine Subassemblies
Where are the faults?



Key Direct Drive Wind Turbine Subassemblies
Where are the faults?



Reliability & Time



Reliability & Time, Generators

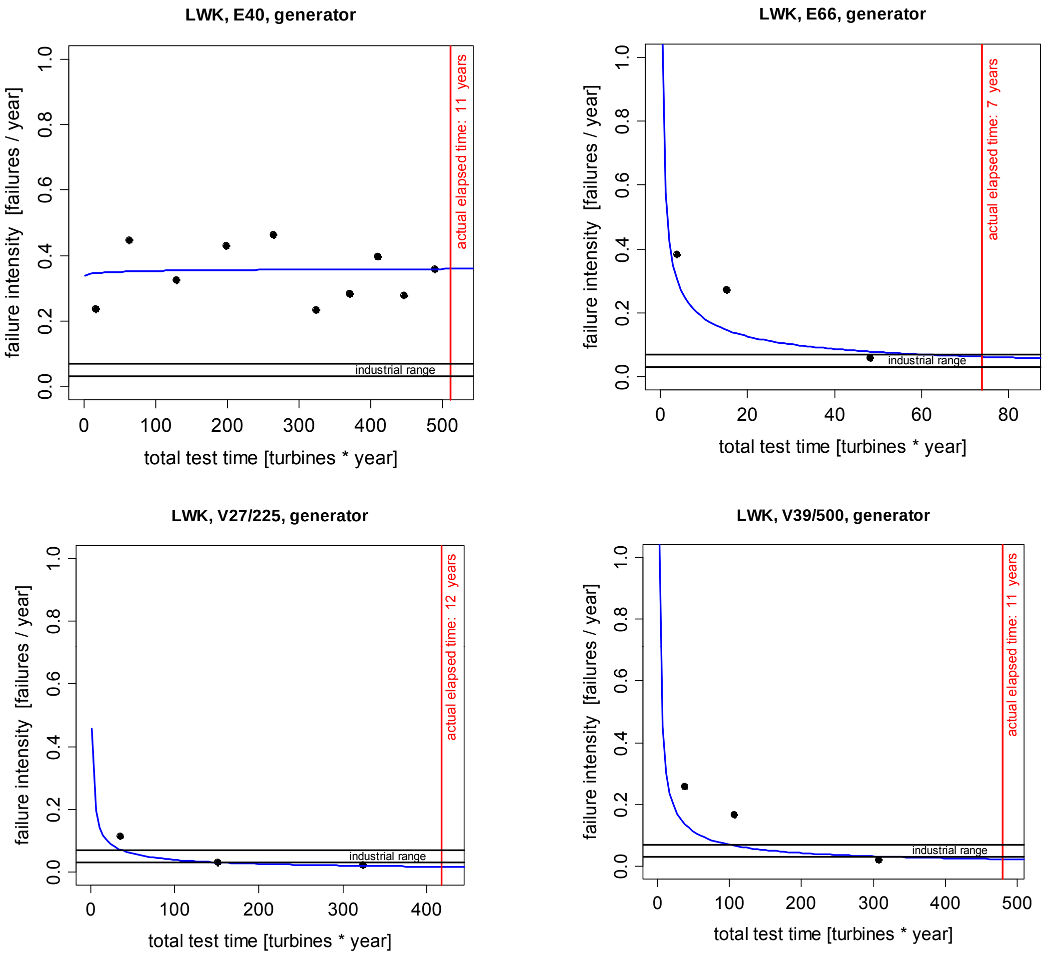


Figure 4.4: Variation between the failure rates of generator subassemblies, in the LWK population of German WTs, using the PLP model.
The upper two are low speed direct drive generators while the lower two are high speed indirect drive generators.

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Reliability & Time, Gearboxes

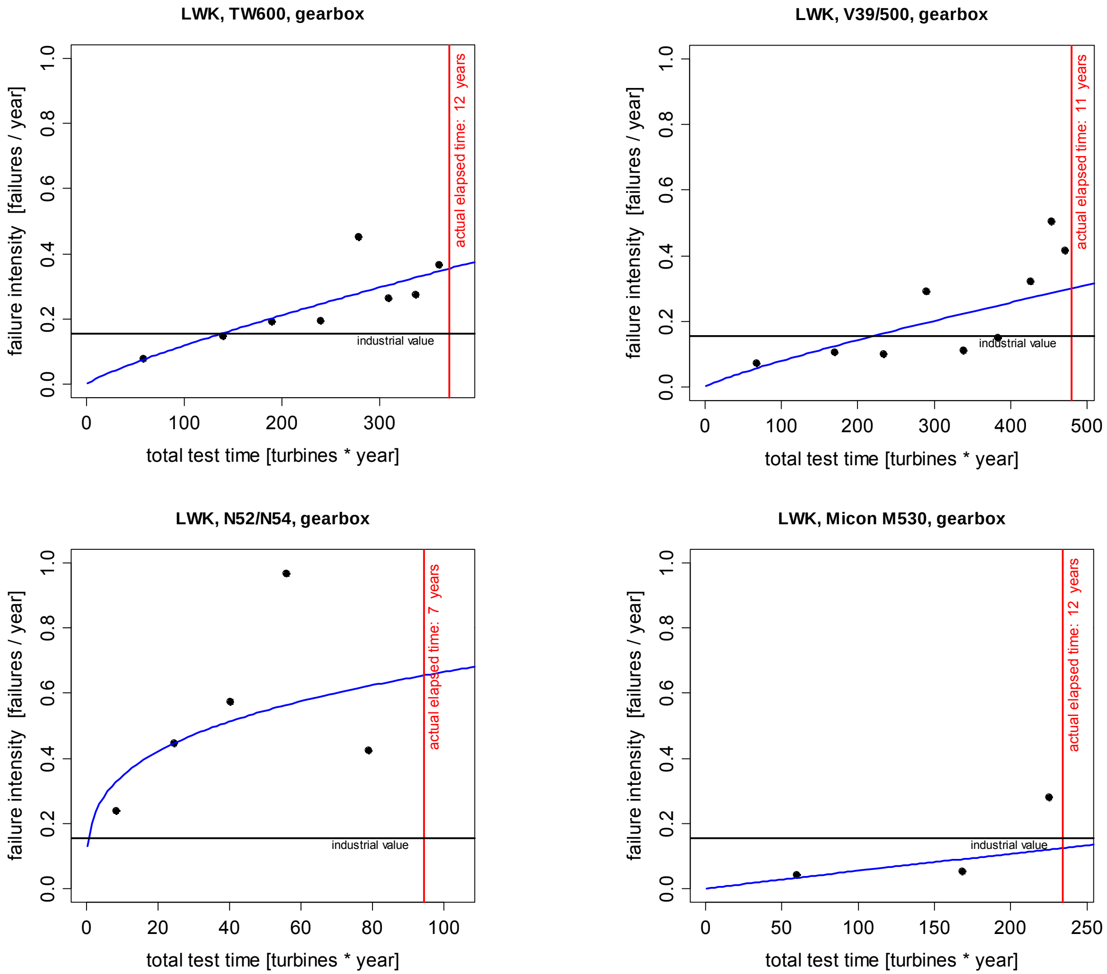

Figure 4.5: Variation between the failure rates of gearbox subassemblies, using the PLP model, in the LWK population of German WTs.

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Reliability & Time, Electronics

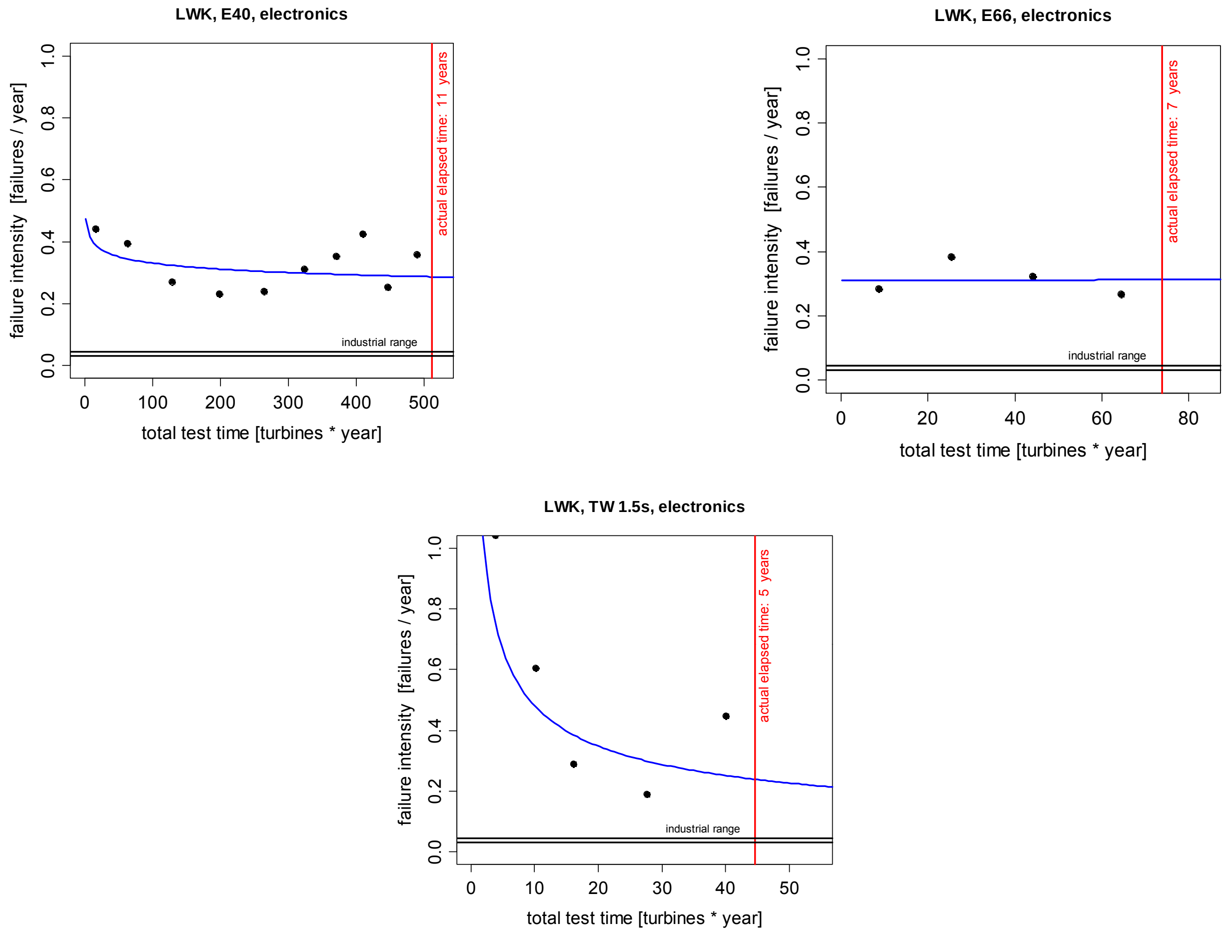

Figure 4.6: Variation between the failure rates of electronics subassemblies, or converter, using the PLP model, in the LWK population of German WTs.

The upper two are low speed direct drive generators with fully rated converters while the lower two are high speed indirect drive generators with partially rated converters.

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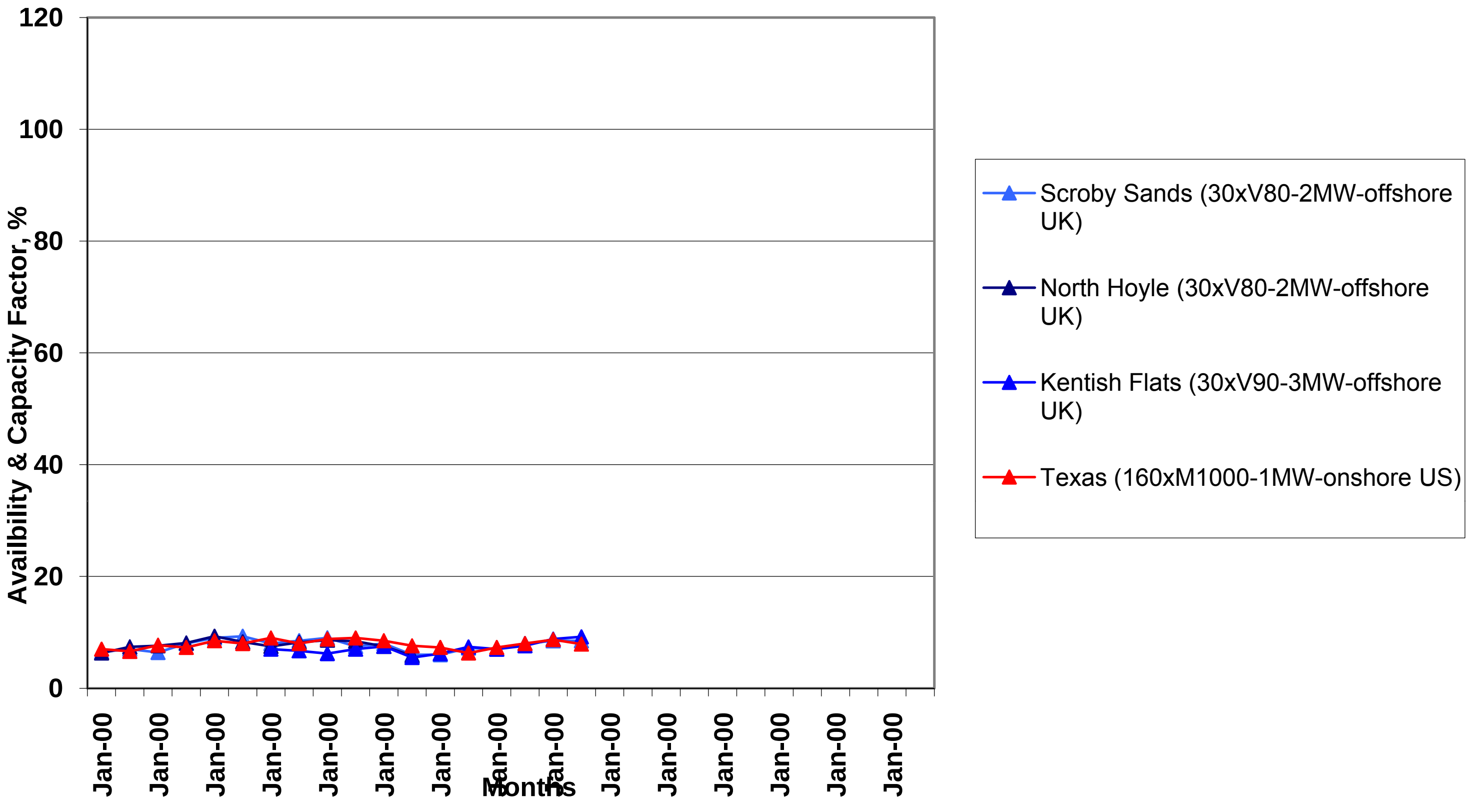
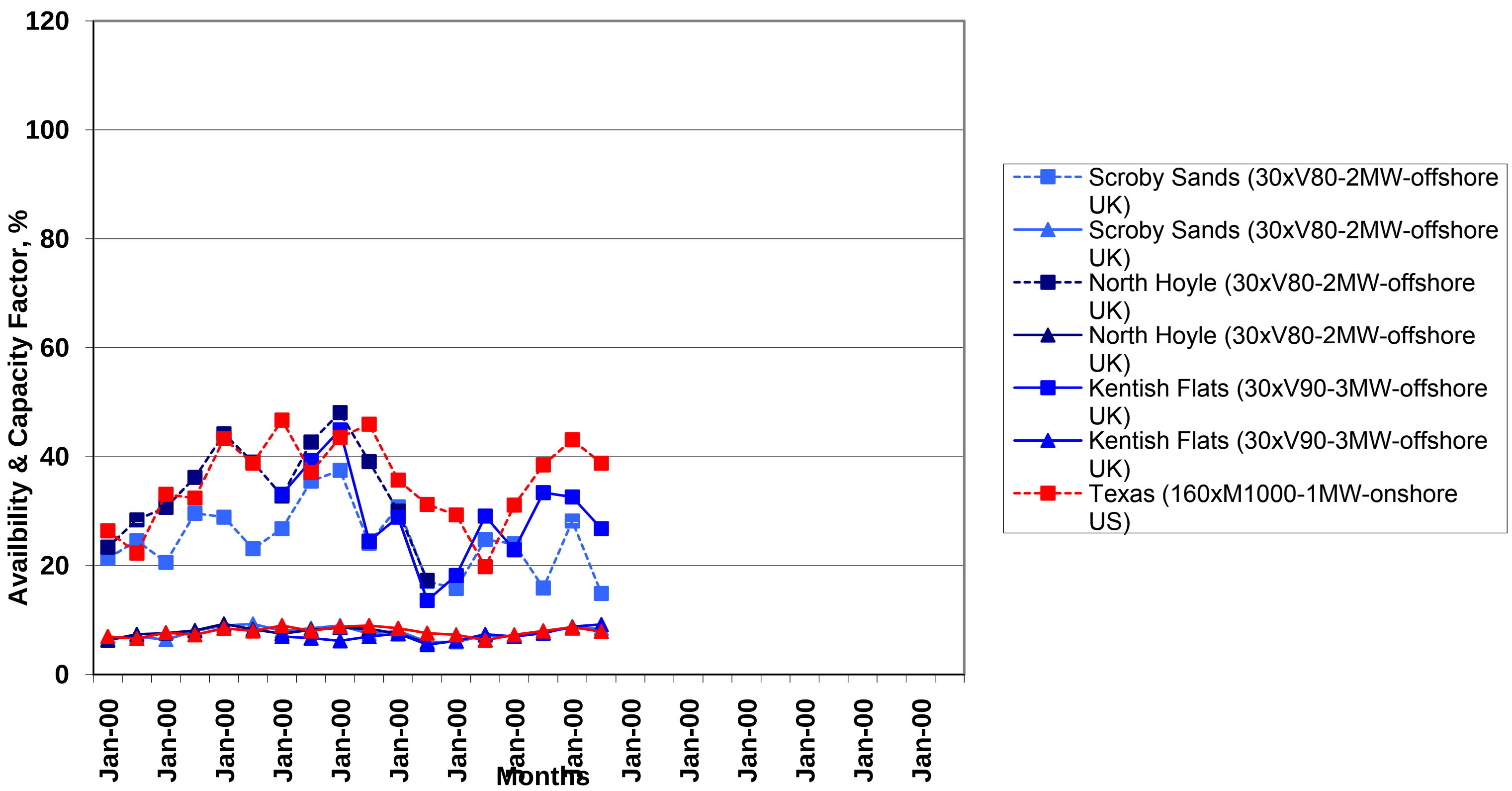
Onshore vs Offshore , USA, UK

Availability, Capacity Factor & Wind Speed Onshore & Offshore

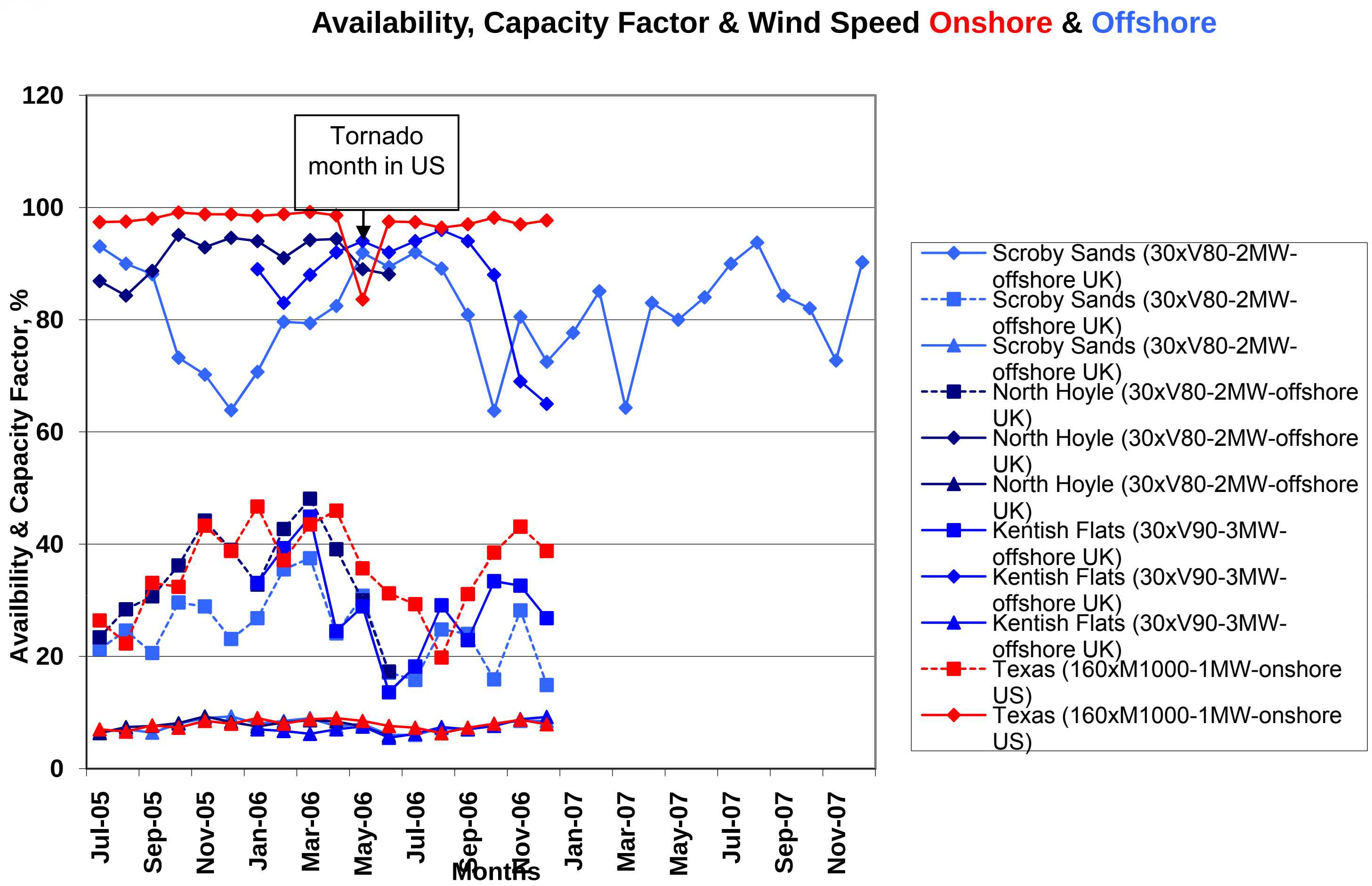


Onshore vs Offshore , USA, UK

Availability, Capacity Factor & Wind Speed Onshore & Offshore



Onshore vs Offshore , USA, UK



Reliability Conclusions

- Onshore λ is > 1 failure/year/turbine
- Offshore λ should be < 0.5 failure/year/turbine
- "Other" and "Grid & Electrical System" show highest failure rates
- Otherwise loss of reliability is concentrated mainly in the Drive Train particularly the electrical parts
- Therefore concentrate on Drive Train and electrical parts

Reliability Solutions

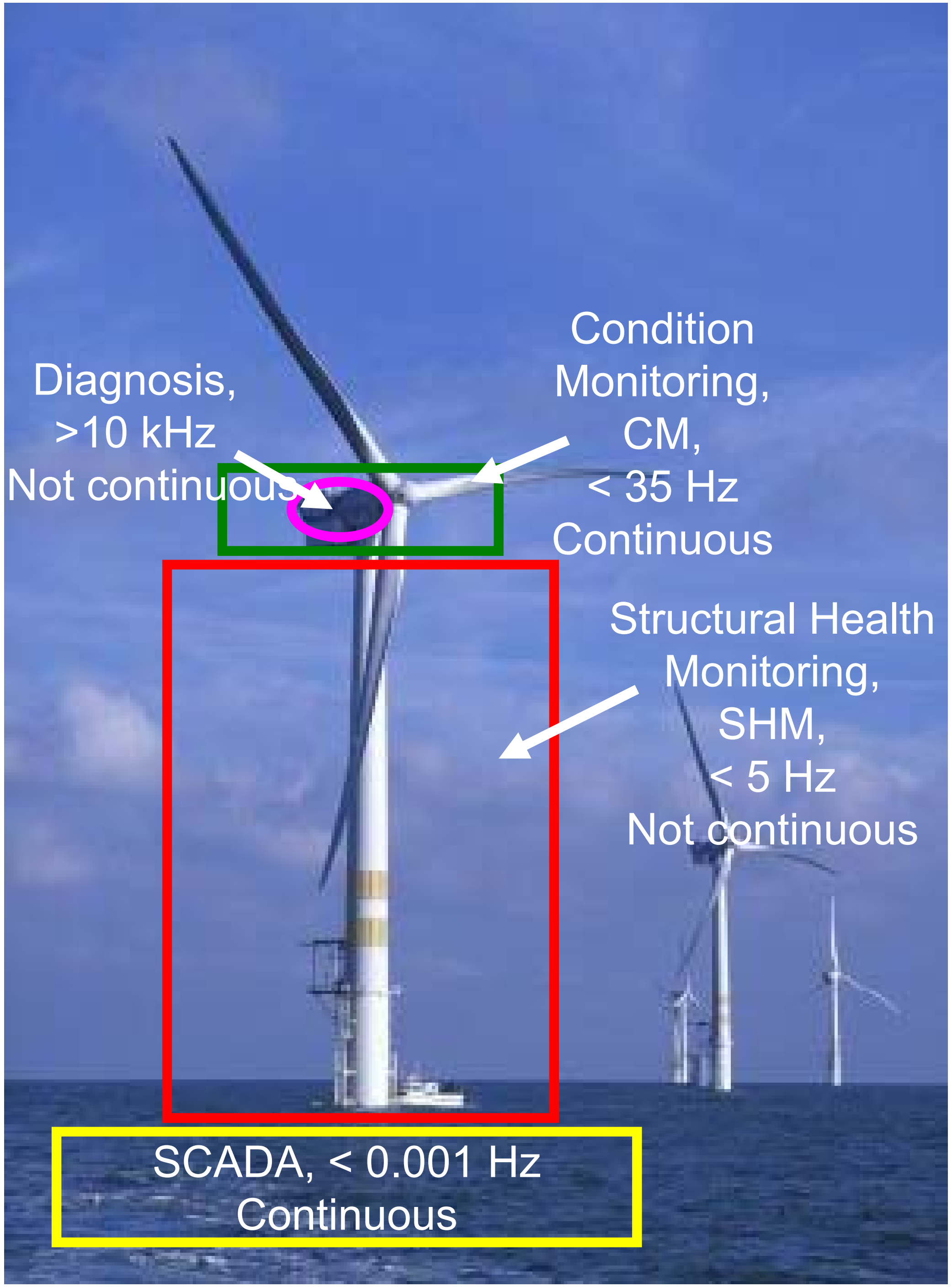
- Turbine Manufacturers
  - Turbine concepts do make a difference
  - Identify less reliable components during turbine design
  - Concentrate on Drive Train and electrical parts
  - Tool to use – Failure Modes & Effects Analysis
- Turbine Operators
  - Improve Operation & Maintenance strategies to concentrate maintenance and replacement on weak subassemblies
  - Improve condition monitoring of turbines through SCADA

Condition Monitoring

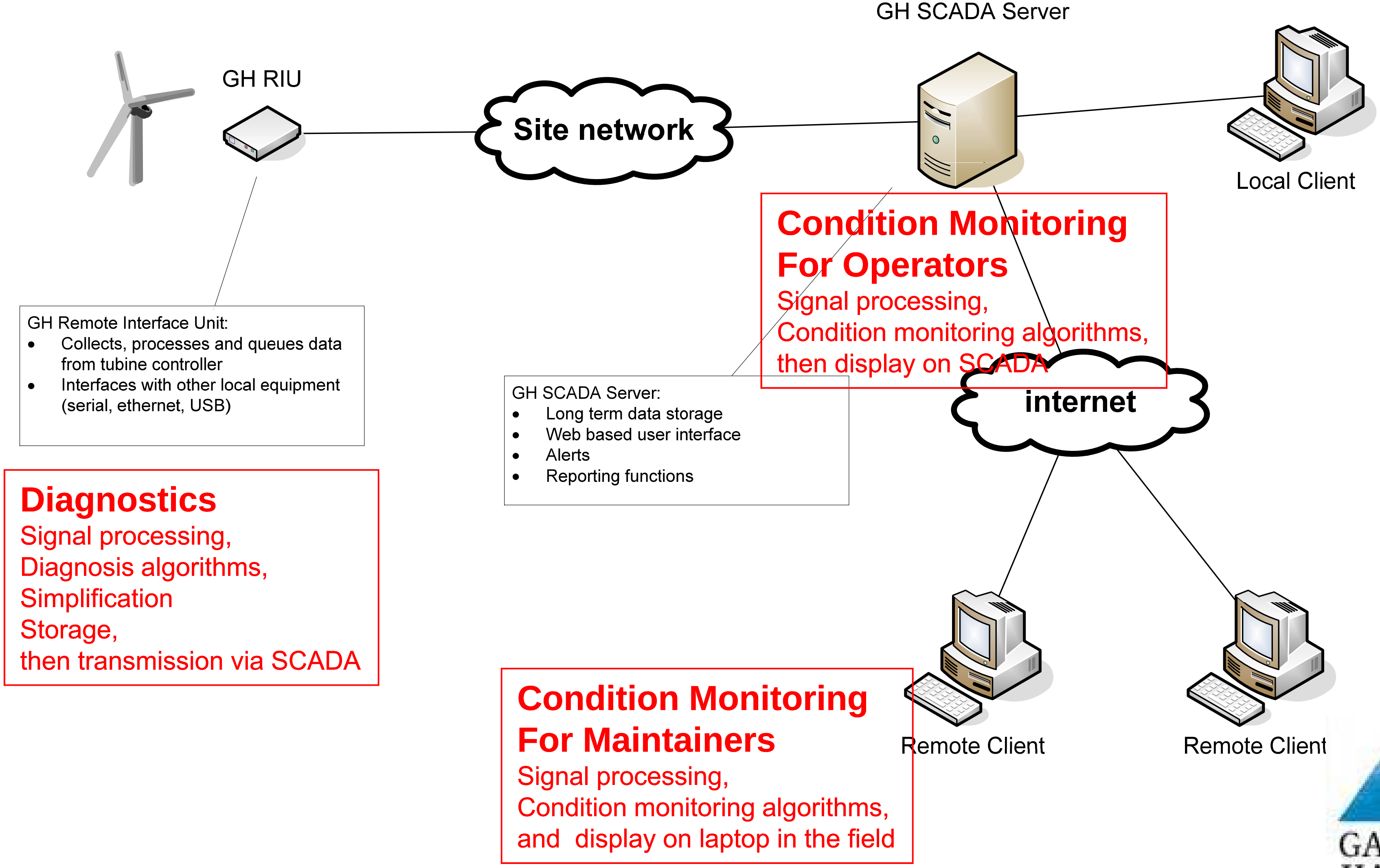
Condition Monitoring Issues

- Signal numbers monitored per wind turbine > 30
- There are >2000 large turbines currently installed in UK
- Remote monitoring of these turbines is excellent
- Monitoring done by SCADA designed to measure turbine energy production and downtime at 5-10 min intervals
- Therefore 60000 data items are currently generated monitoring UK wind turbines every 10 mins
- Most SCADA signals are associated with condition rather than production and downtime
- Operators are currently overwhelmed by the quantity of data being produced

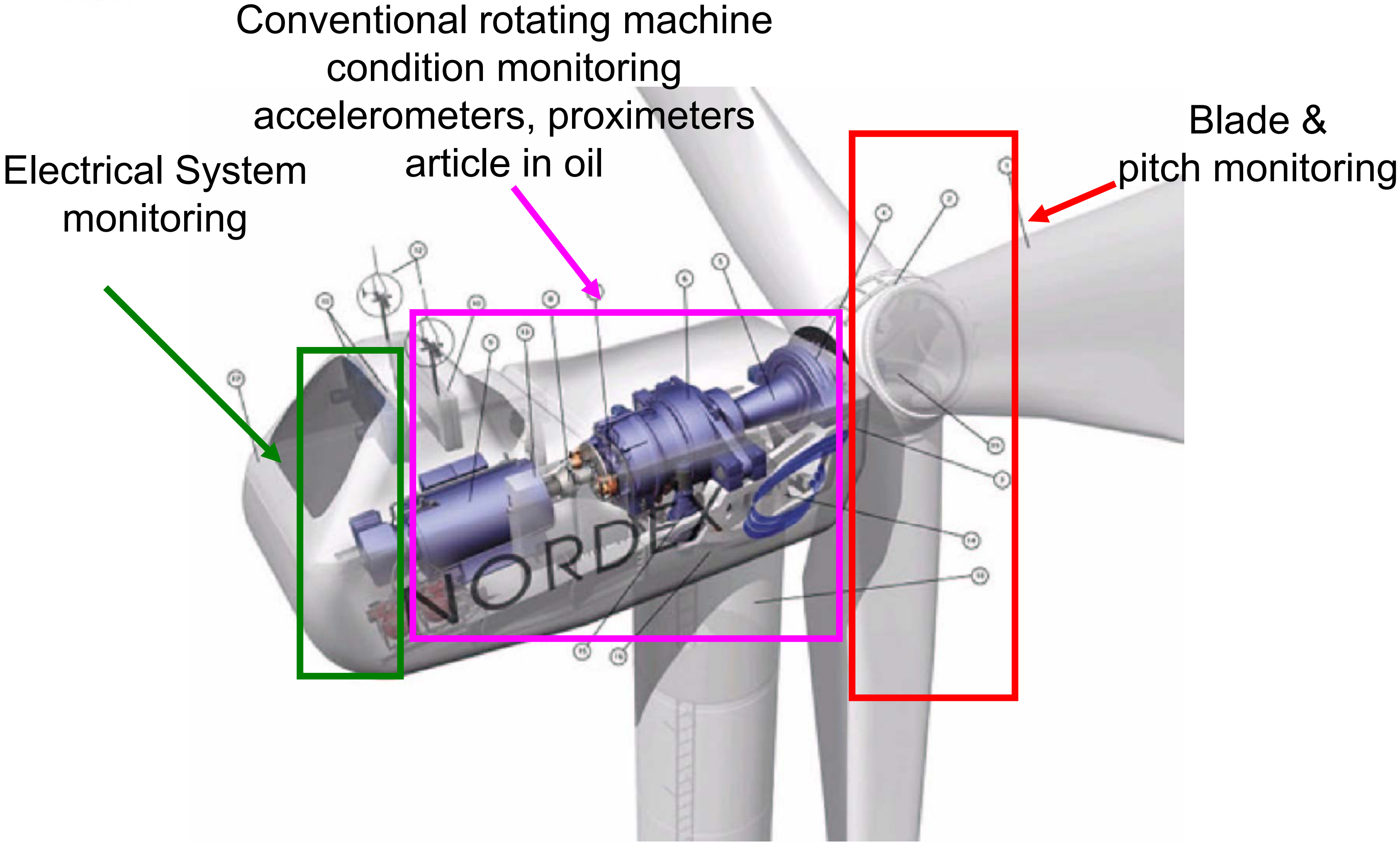
SCADA & Condition Monitoring in Context



SCADA & Condition Monitoring in Context



Condition Monitoring in Context

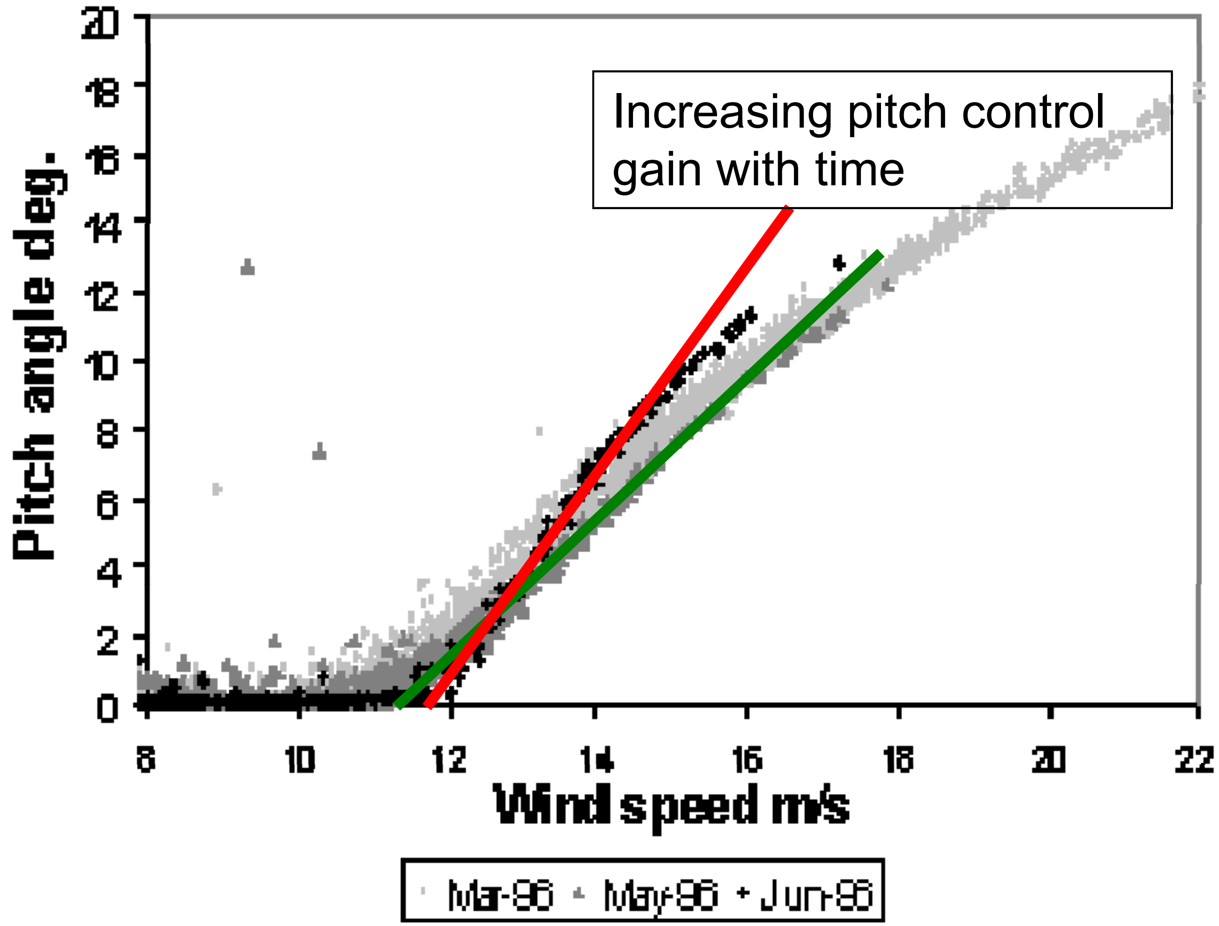


Condition Monitoring Issues

- Issues for condition monitoring
  - SCADA- slow data rate, 1/10 min ≈ 0.001 Hz
  - Power signal- medium data rate, 30-32 Hz
  - Vibration and Current signals- high data rate, >10 kHz
  - When monitoring real Turbines you can only develop techniques after machines experience real faults
  - If you monitor Test Rigs you can apply faults and develop techniques
- Following work shows:
  - Very slow rate data from real Wind Turbine blades
  - Slow & medium rate data from real Wind Turbines from CONMOW Project and others
    - Nordex Turbines, Sites X & Y
    - GE Turbines, Site Z
    - Vestas V27 Turbines, Site W
  - Fast rate data from two Test Rigs

Slow Data Rate from SCADA from 10^{-min} from real Wind Turbines

Pitch Angle:
Trends in Time
T1 Site Y



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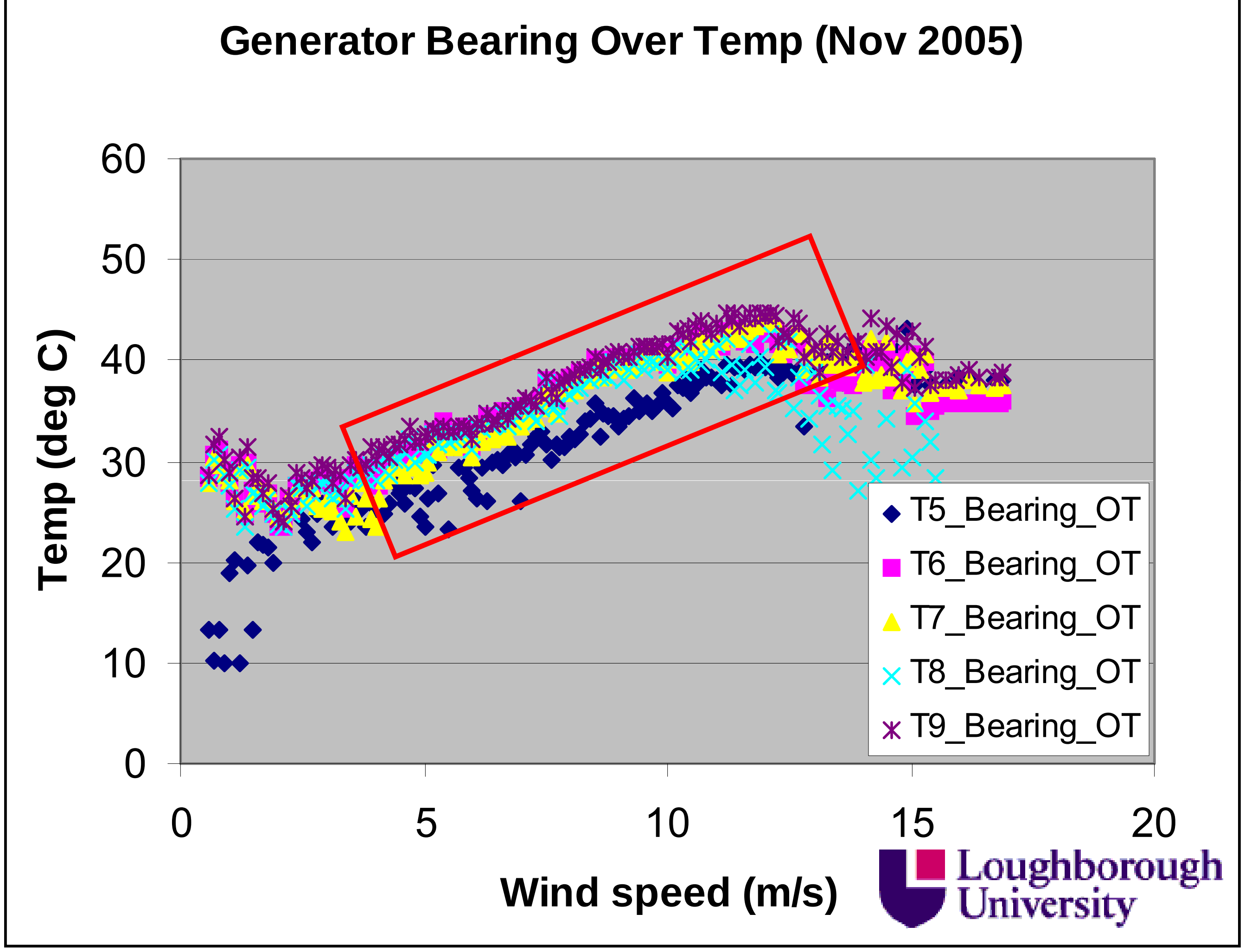
Generator Bearing Temp Rise: One Month T5, 6, 7, 8 & 9 Site X



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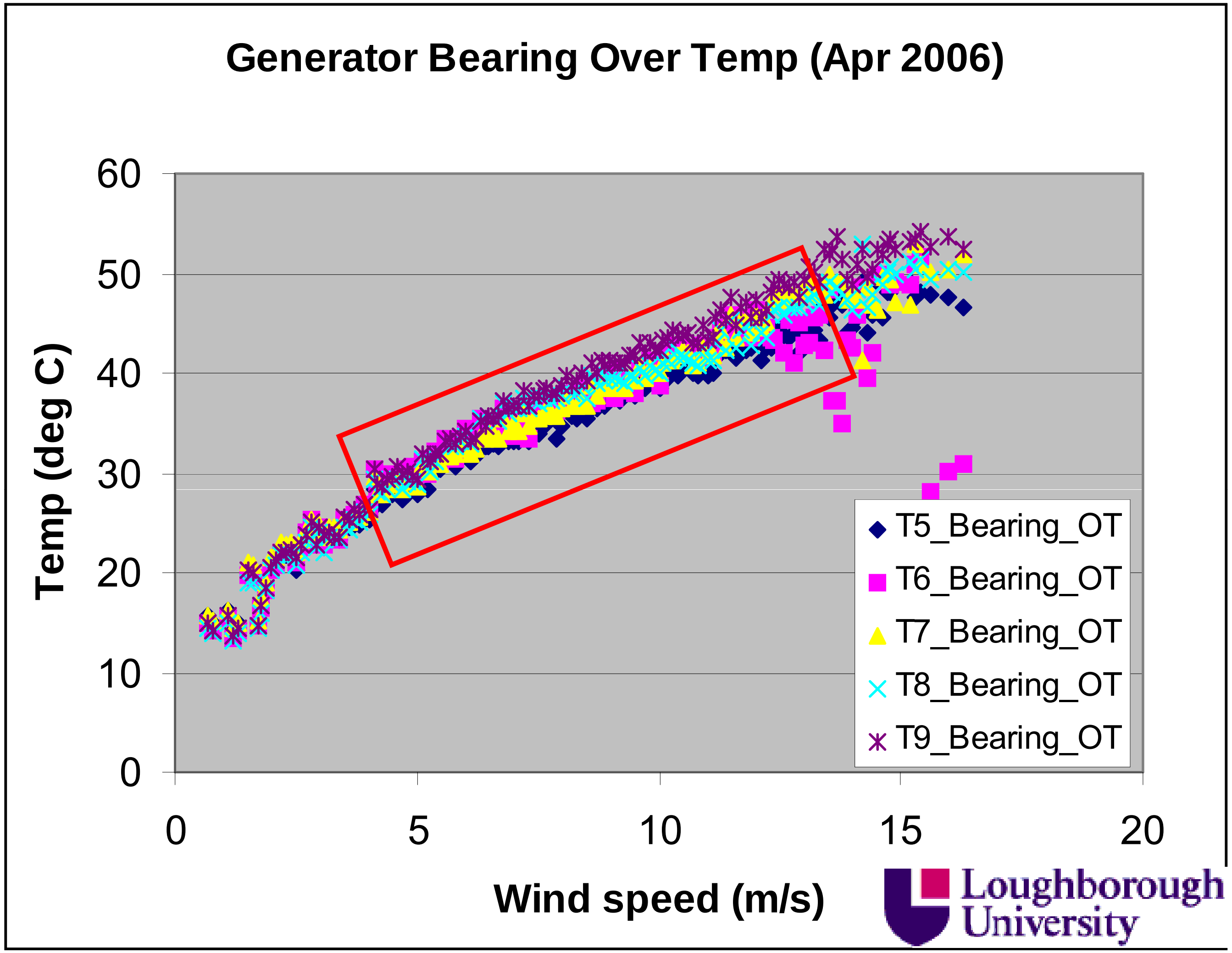
Generator Bearing Temp Rise: Later Month T5, 6, 7, 8 & 9 Site X



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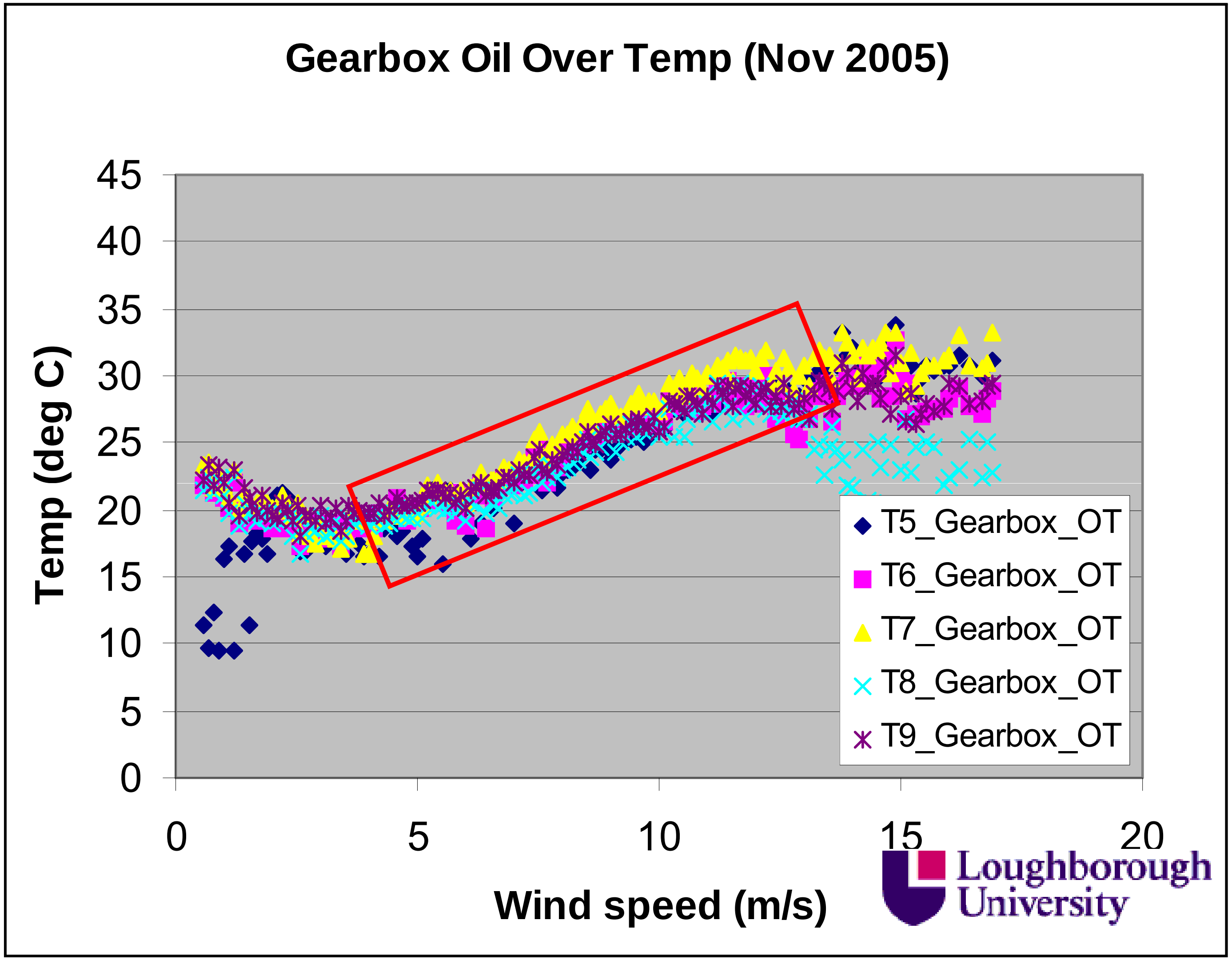
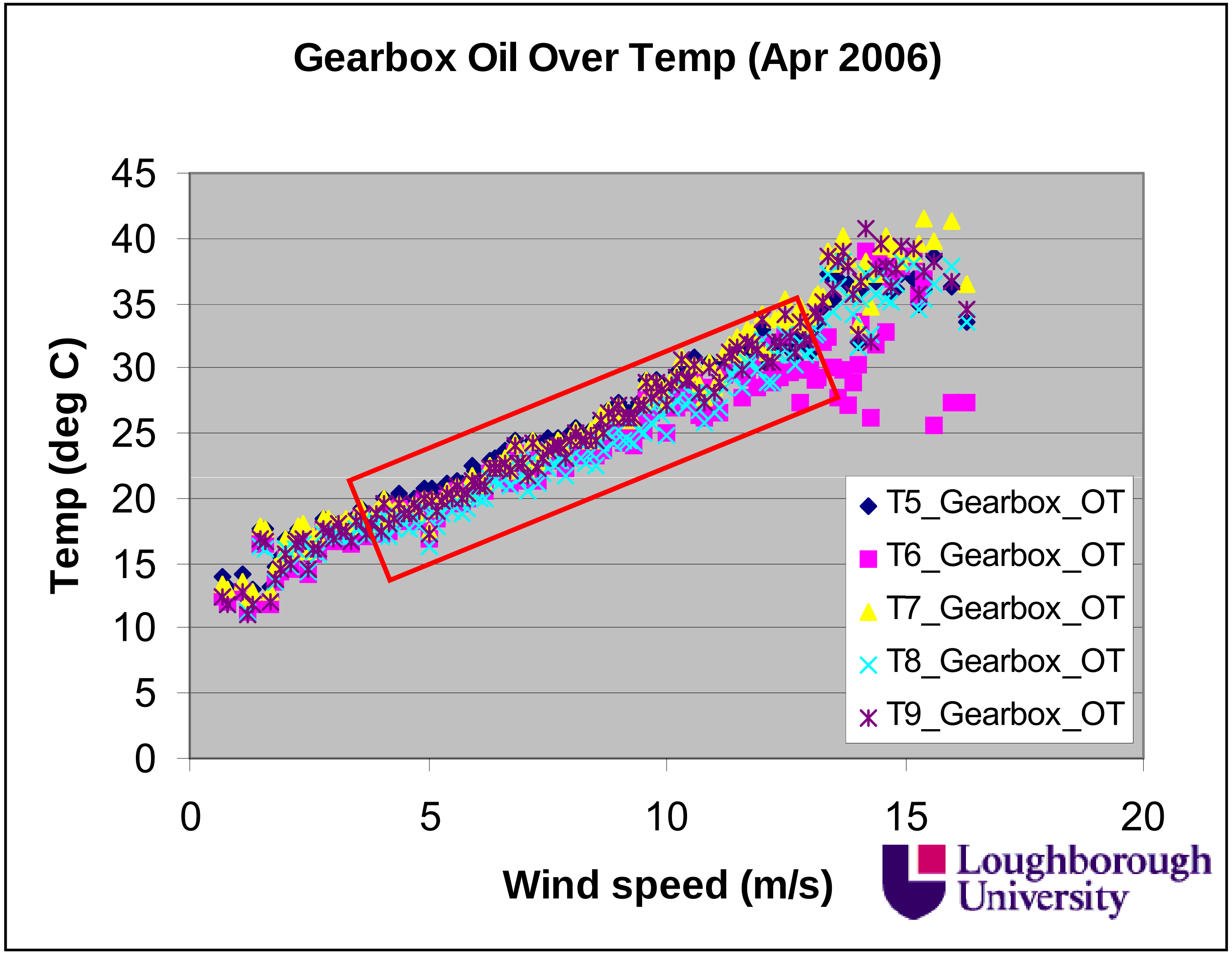
Gearbox Oil Temp Rise: One Month T5, 6, 7, 8 & 9 Site X



Gearbox Oil Temp Rise: Later Month T5, 6, 7, 8 & 9 Site X

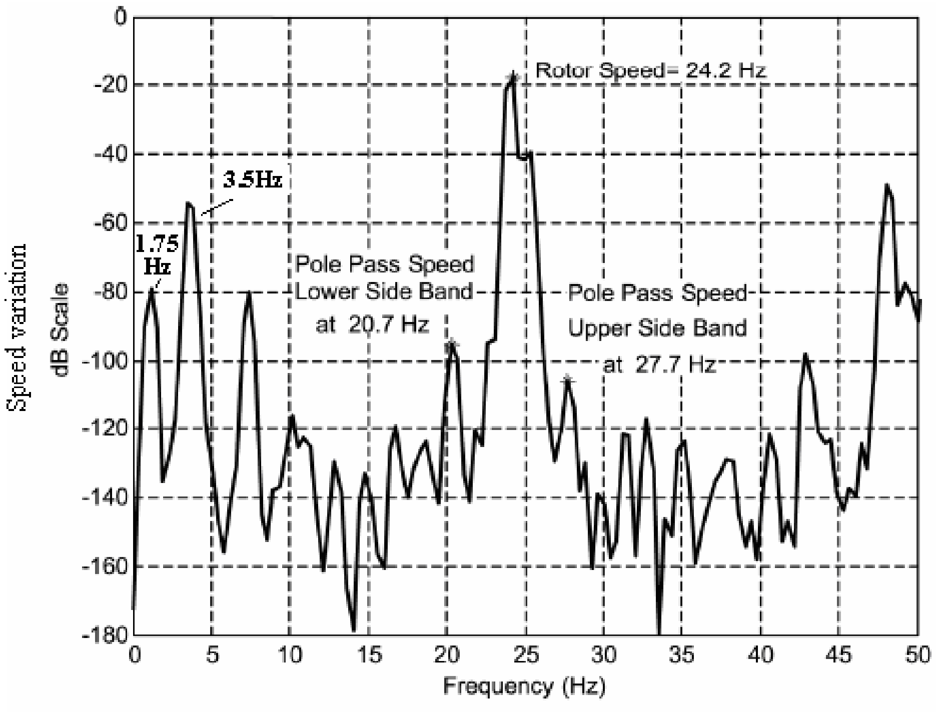


Medium Data Rate 30-35 Hz from real Wind Turbines

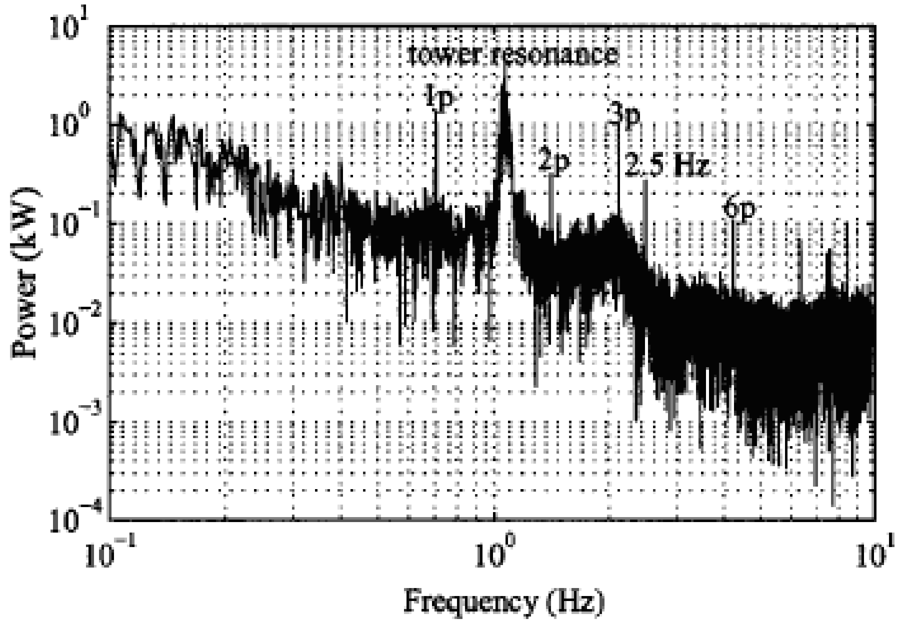
Power:
Signal Analysis

- Fourier transform or Wavelet analysis
- Trend fault frequency components
- CONMOW project has twice detected generator misalignment or bearing problems
- 1st resulted in a bearing failure
- 2nd showed some indication in temperature and vibration analysis

Power:
Evidence of frequency content in speed and power spectra in the literature



Induction motor speed variation
signal of instantaneous angular speed (Ben Sasi et al, 2004)



Wind turbine power (Thiringer, T et al.)

GE turbine at Site Z
Measured: Daily 2s comp in power spectrum
Fault: Generator misaligned, bearing change

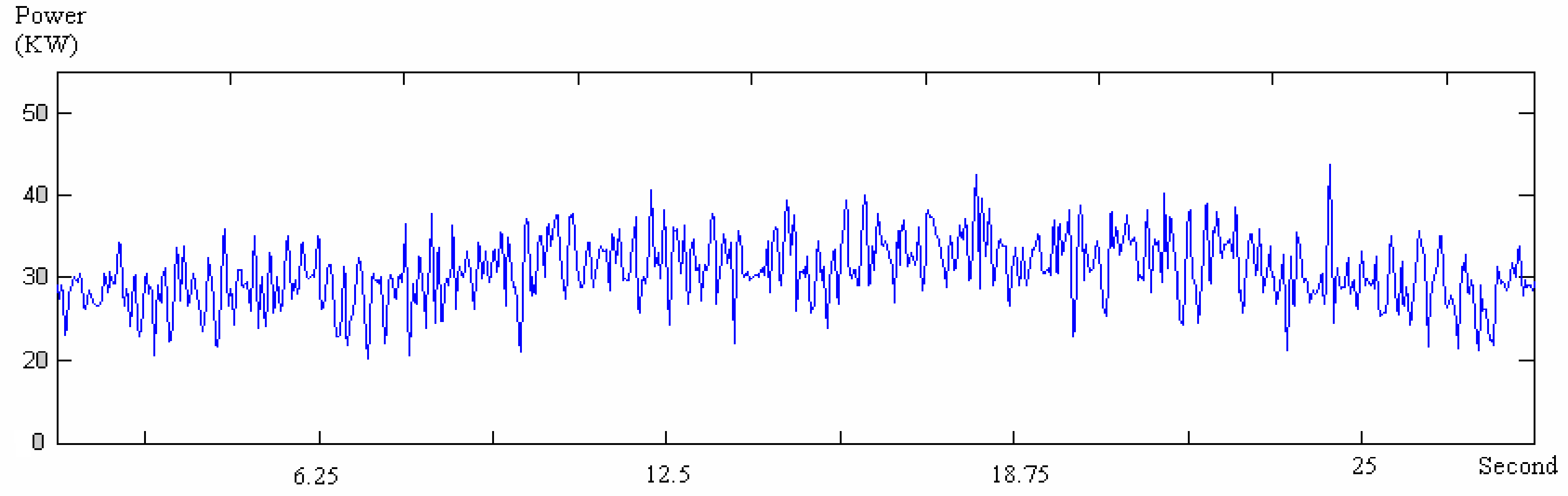


Figure 1. Power data from Nordex Turbine

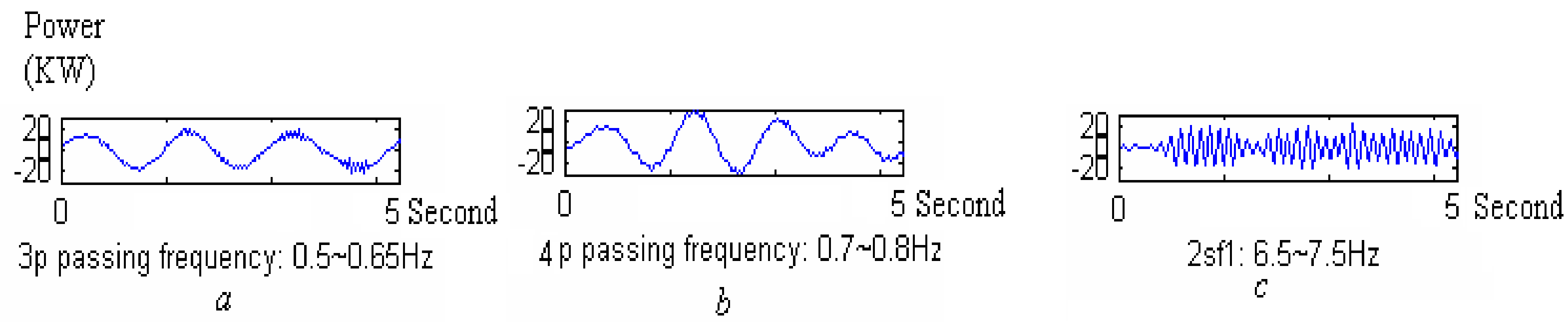
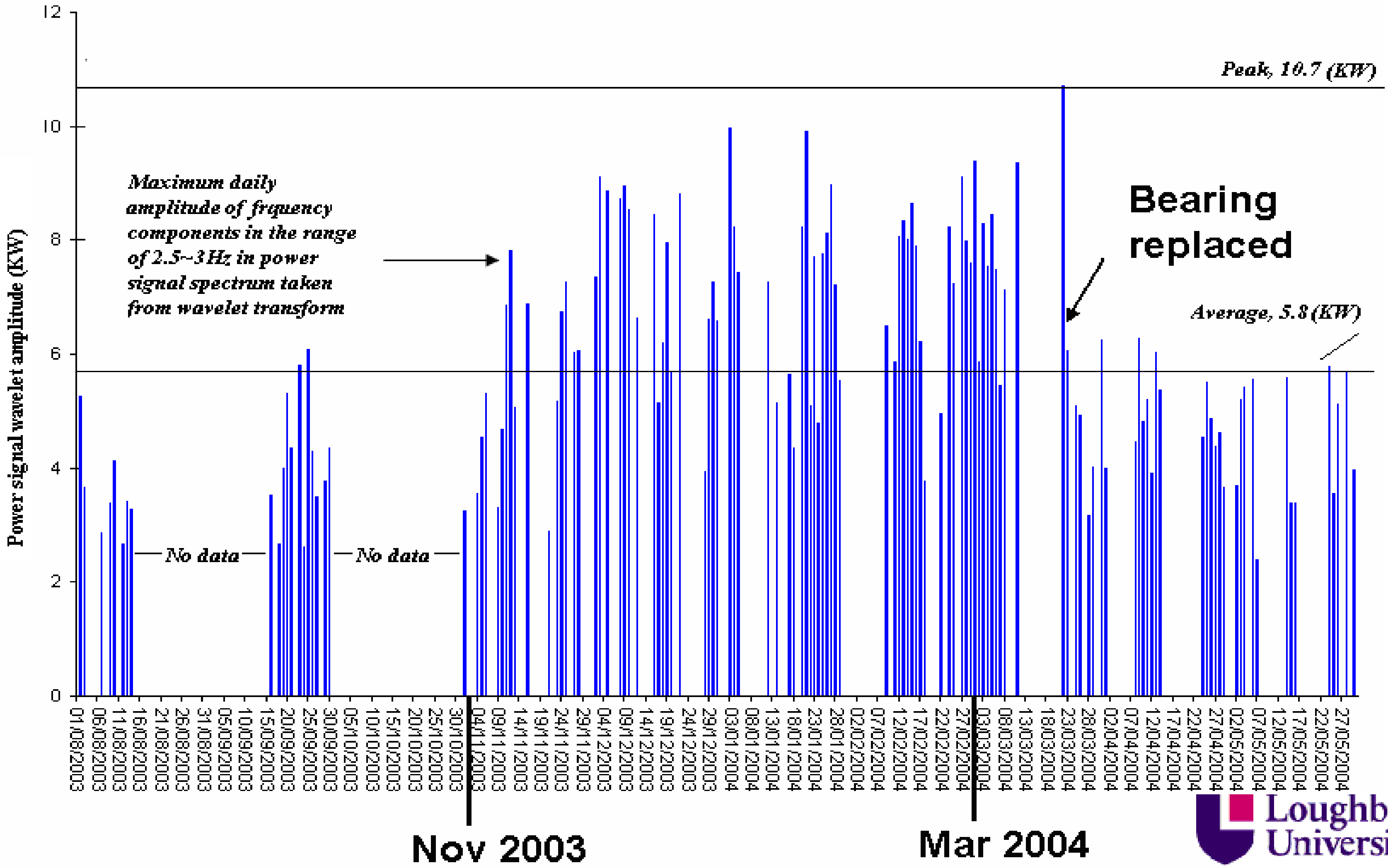


Figure 2. Vibration signals due to failure modes extracted from power data using Morlet wavelet transform

GE turbine at Site Z
Measured: Daily 2s comp in power spectrum
Fault: Generator misaligned, bearing change



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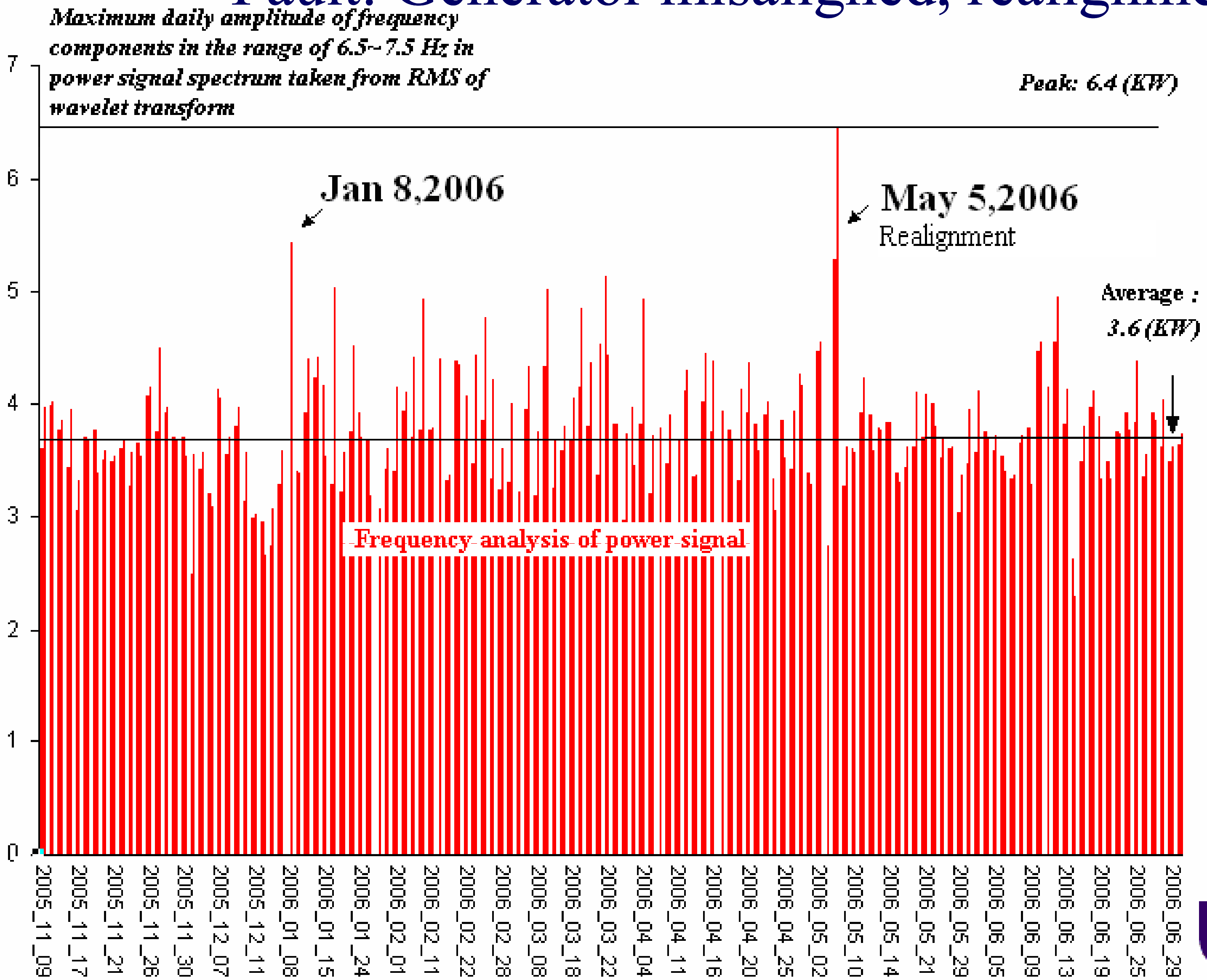
Nordex T8 at Site X
Measured: Nacelle vibration & daily 2s component
Fault: Generator misaligned, realignment



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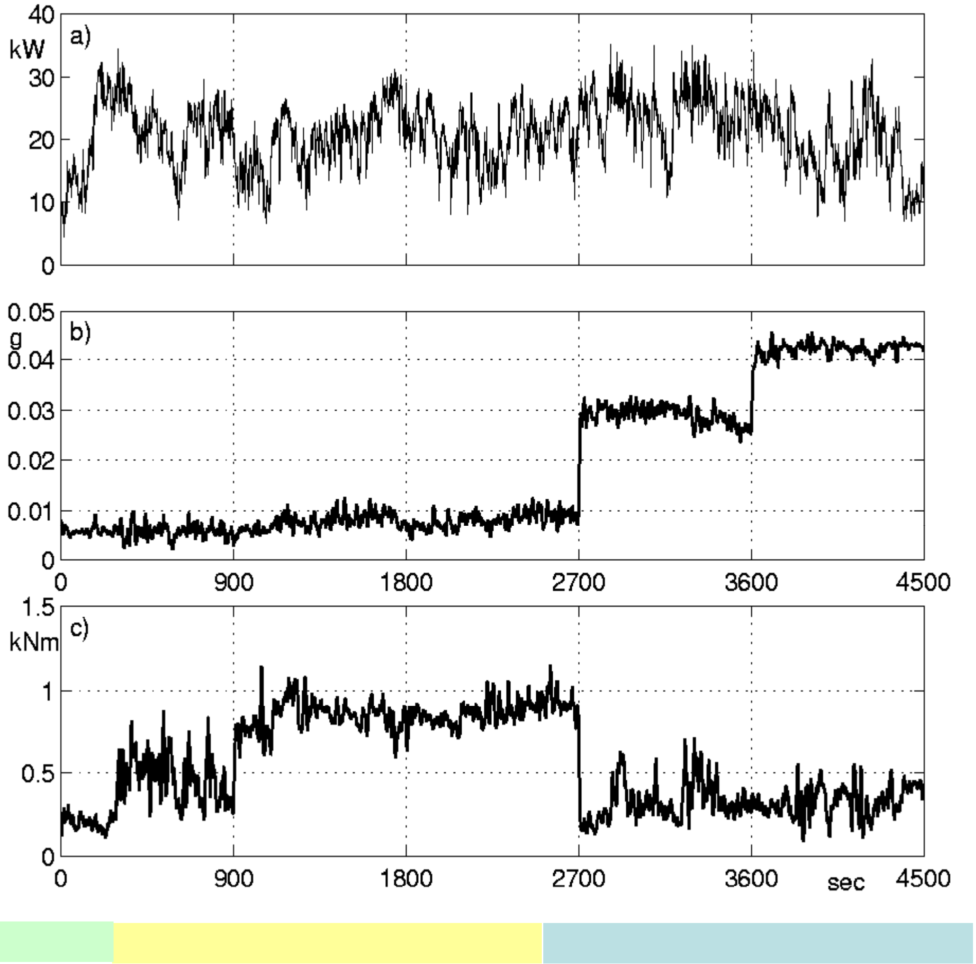
Fast Data Rate >10kHz from Test Rigs Diagnosis

Condition Monitoring Test Rigs

- Measurements have been made on 2 Test Rigs
  - Generator Test Rig at Manchester
  - Drive Train Test Rig at Durham
- Purpose is to identify causal links between real root causes, failure modes and measurable signals
- Thereby to develop:
  - Signal processing to enable these faults to be detected under all conditions including wind driving
  - Diagnose the causes of faults
  - Dynamic Models to simulate the effects of real faults in a turbine
  - Compare the responses of Test Rigs and Models with the signals from real Wind Turbines faults, and vice versa
  - Thereby gain Operator confidence in proposed condition monitoring methods
  - Develop a successful condition monitoring system architecture for wind turbines

Real Wind Turbine Results AEROMAN 14.8/33

Five sections of 900 s with normal operation, mass imbalance and aerodynamic asymmetry

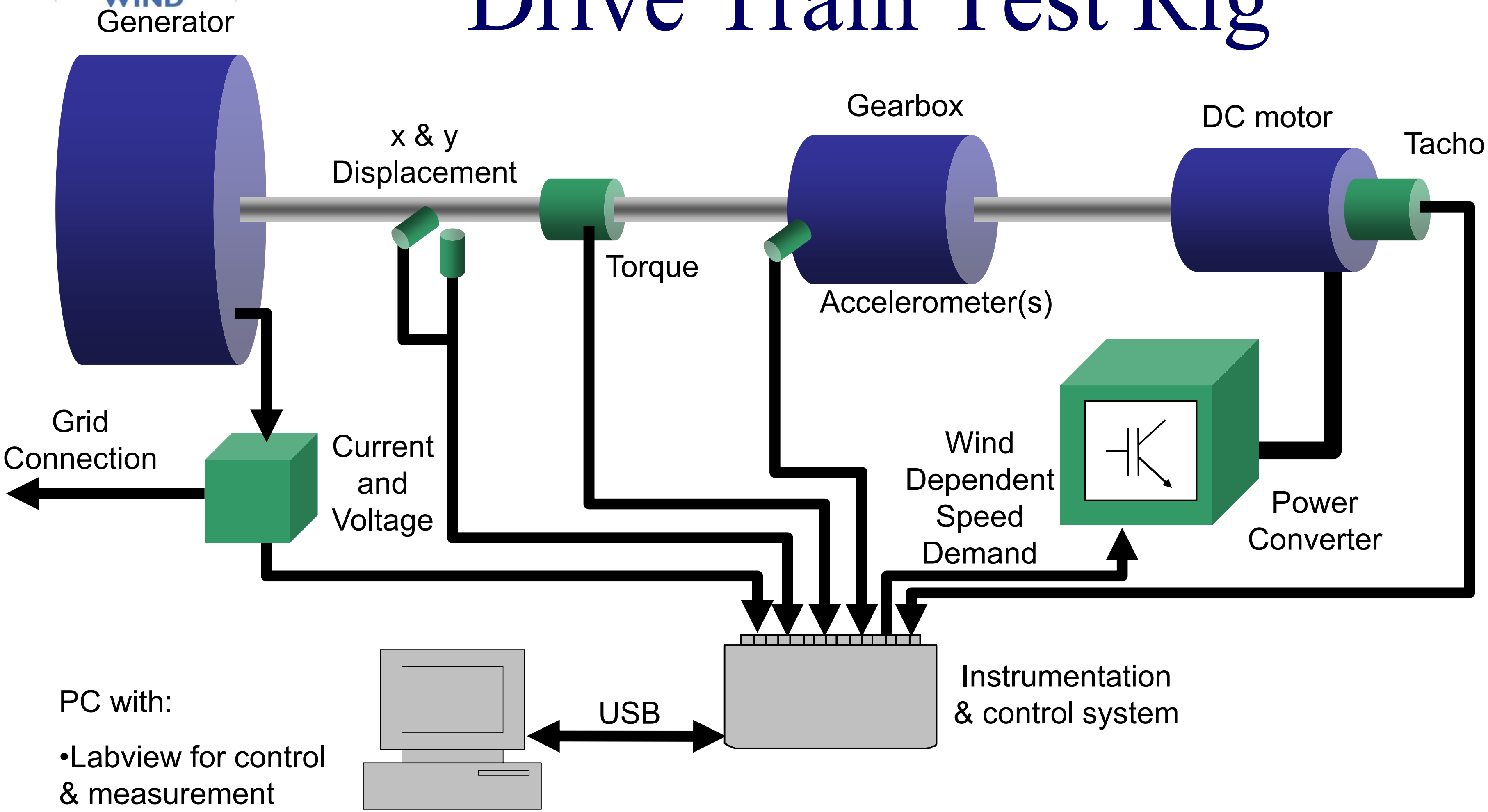


El. Power output

Transverse tower bending at 1p frequency

Tower torsion (1p)

Wind Turbine Drive Train Test Rig



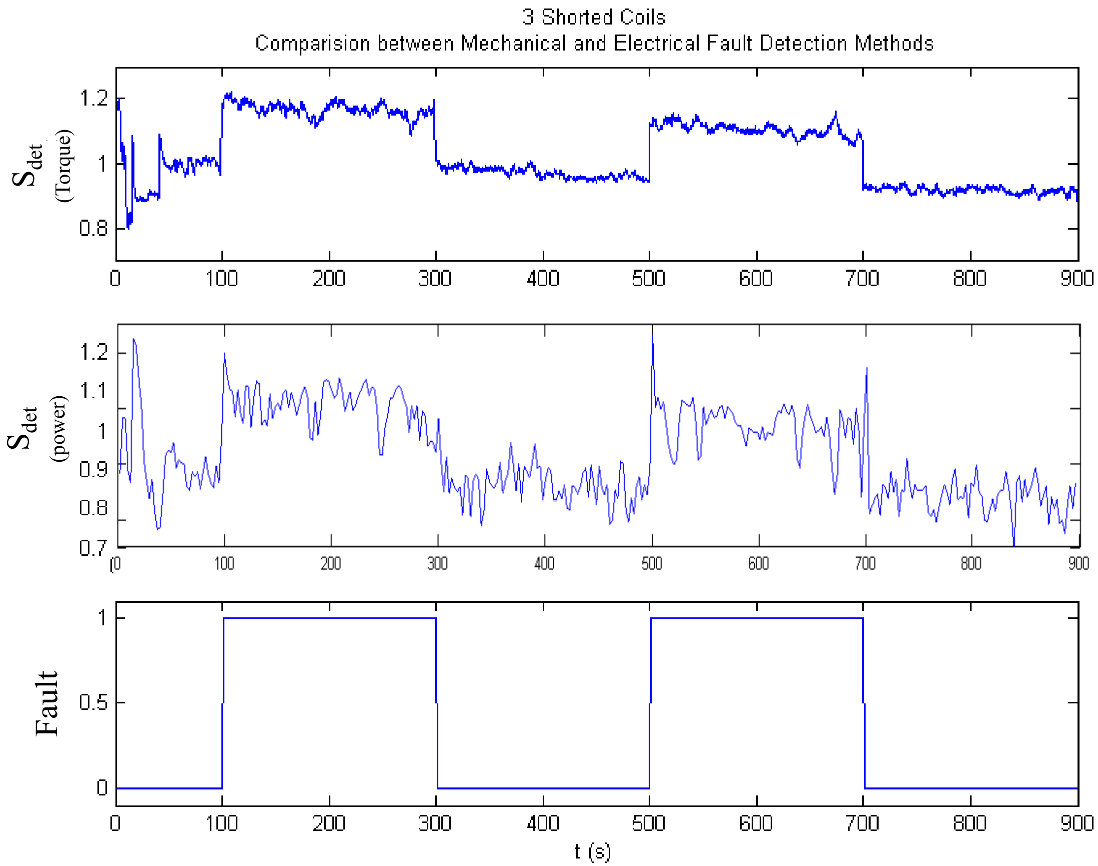
PC with:

•Labview for control & measurement

• Wind Turbine Model

•Signal Processing software

Drive Train Test Rig
Measured: Torque & Power
Fault: Stator Shorted Coil



Power signal
With narrowband filtering

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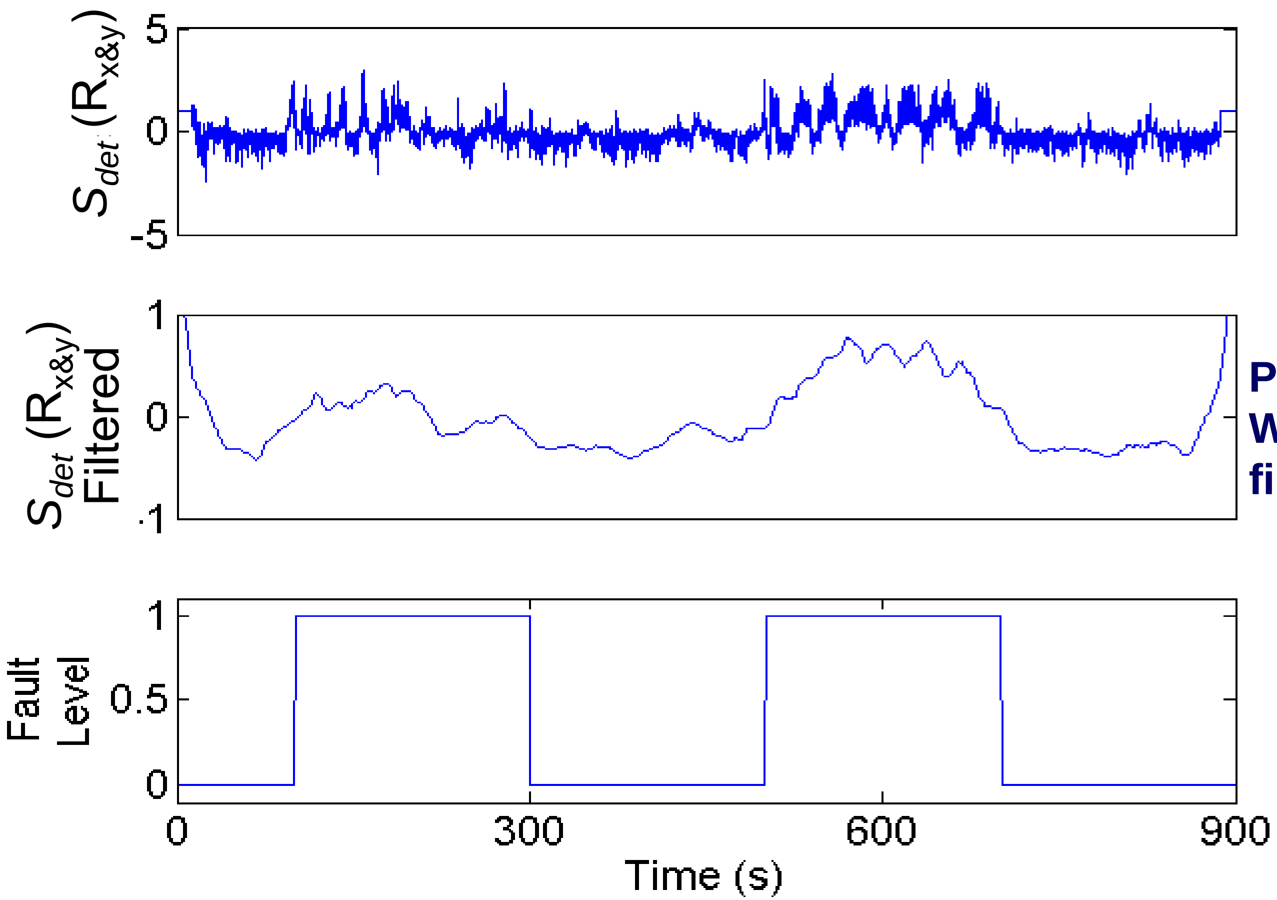
Drive Train Test Rig
Measured: Shaft Displacement
Fault: Stator Shorted Coil



Proximeter signal With narrowband filtering

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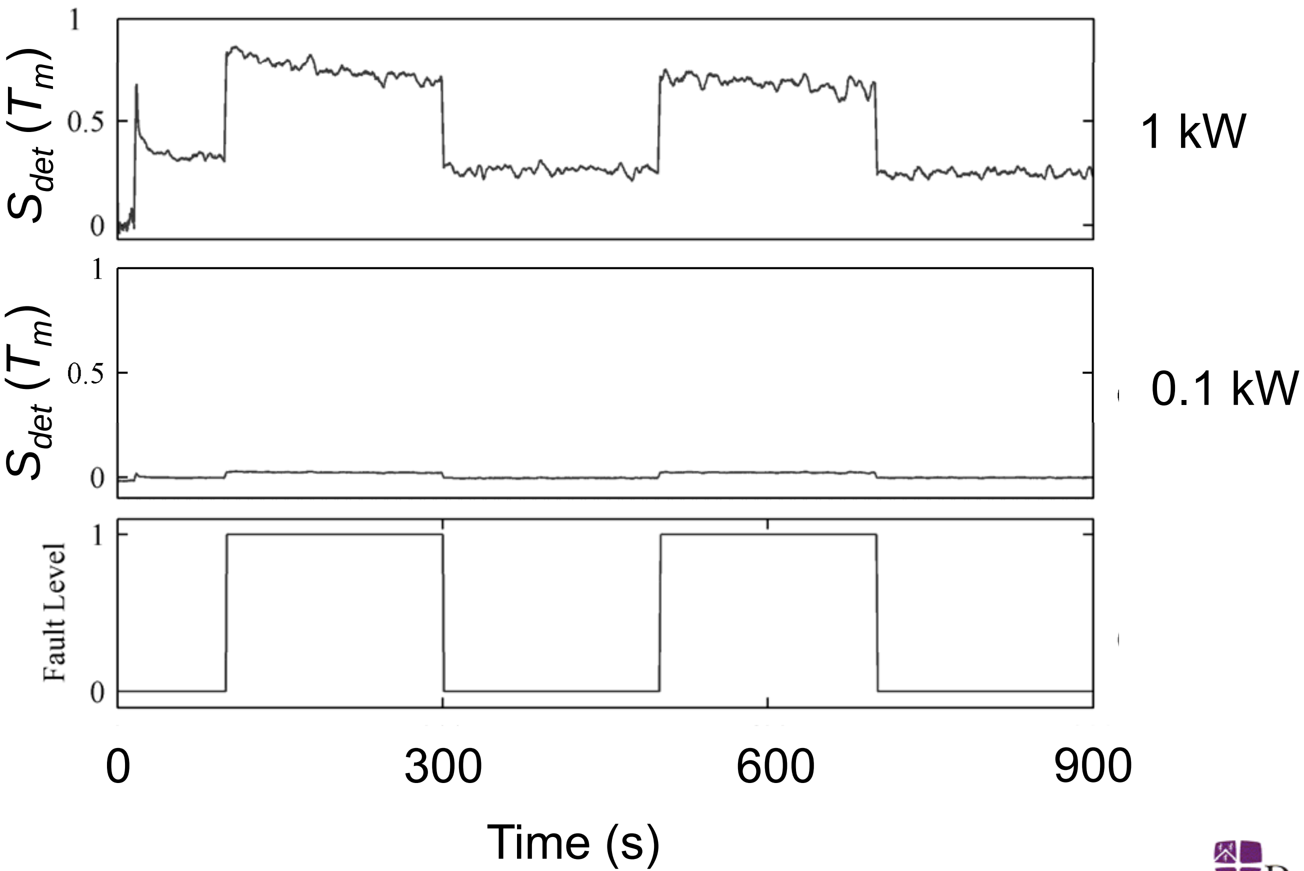
Drive Train Test Rig
Measured: Torque at Varying Load
Fault: Stator Shorted Coil



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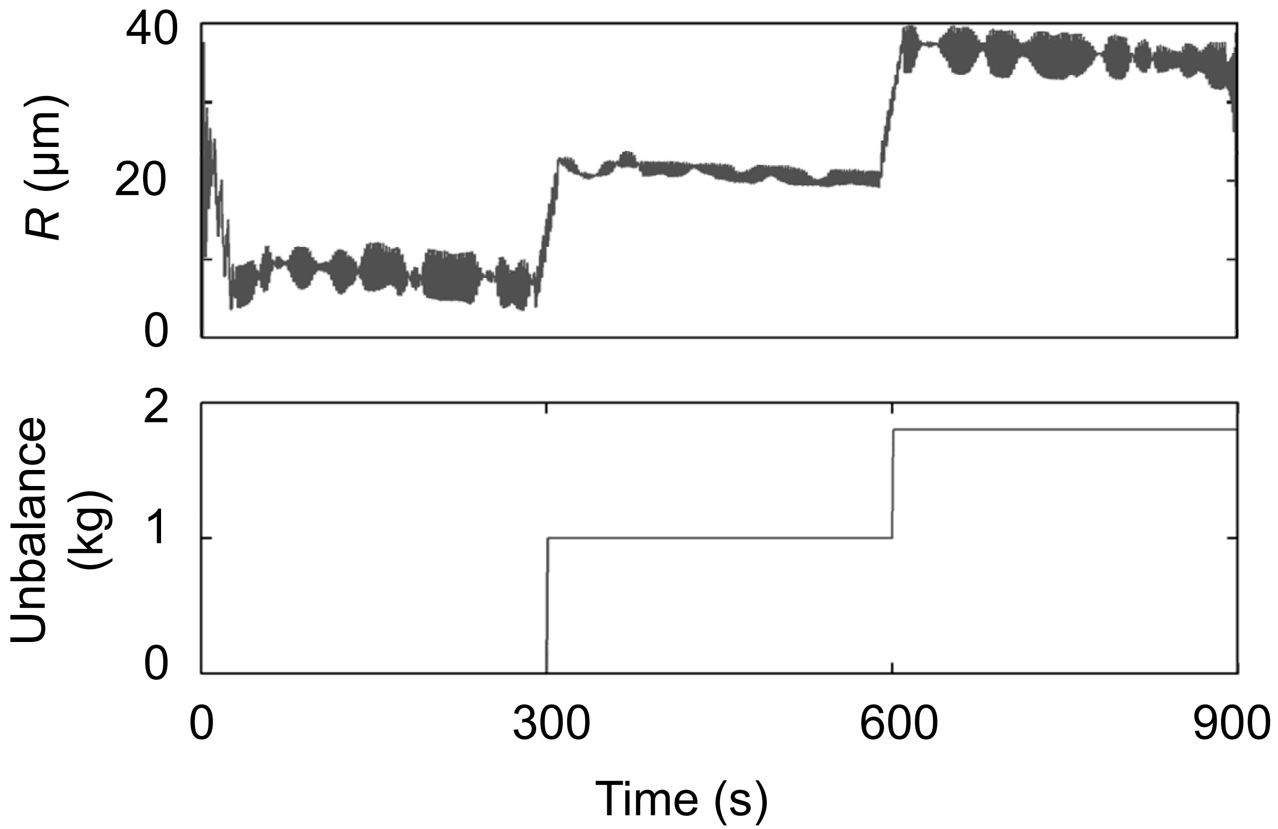
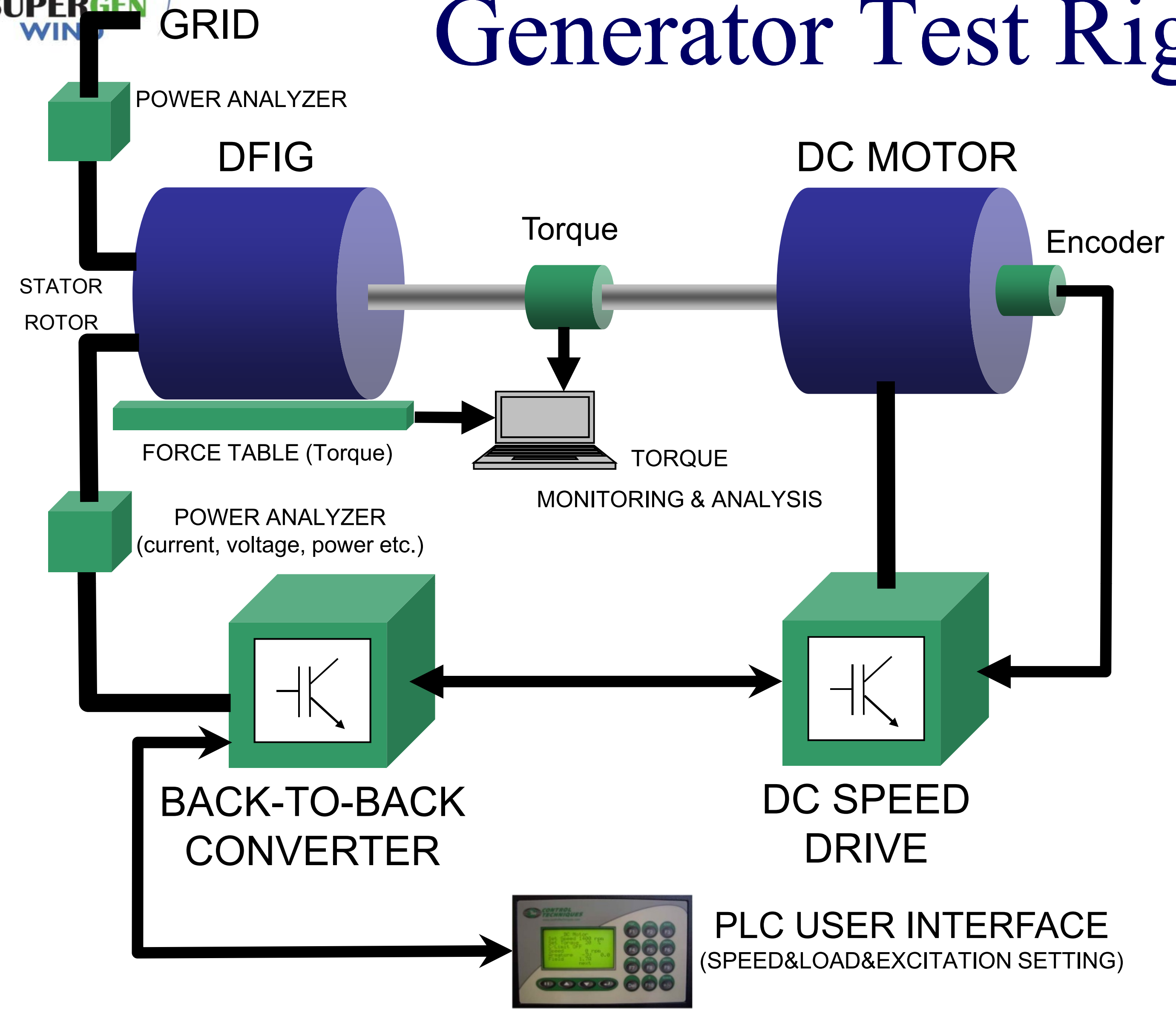
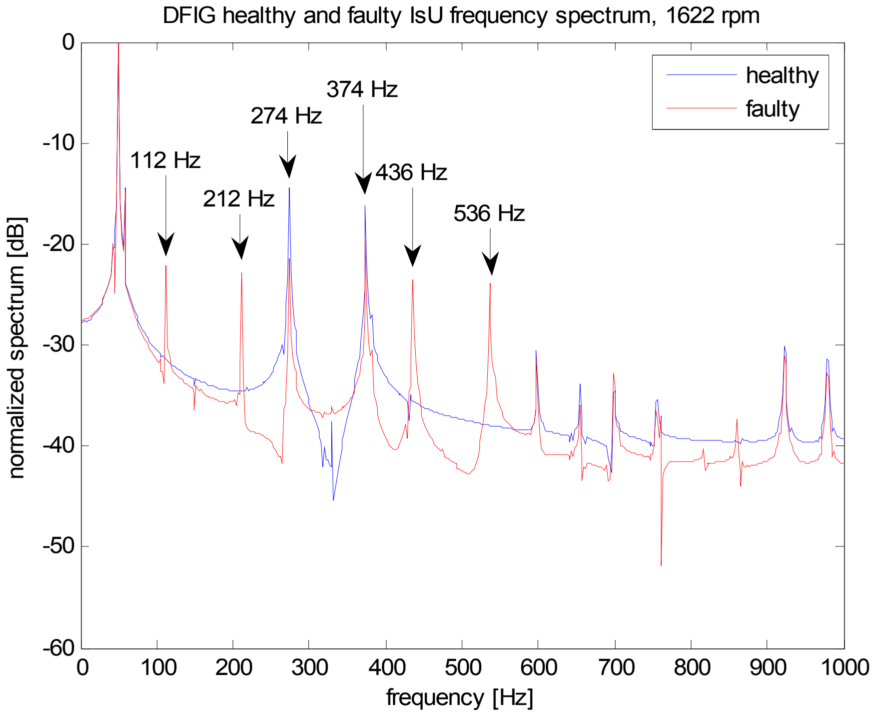
Drive Train Test Rig
Measured: Shaft Displacement
Fault: Rotor Mass Unbalance



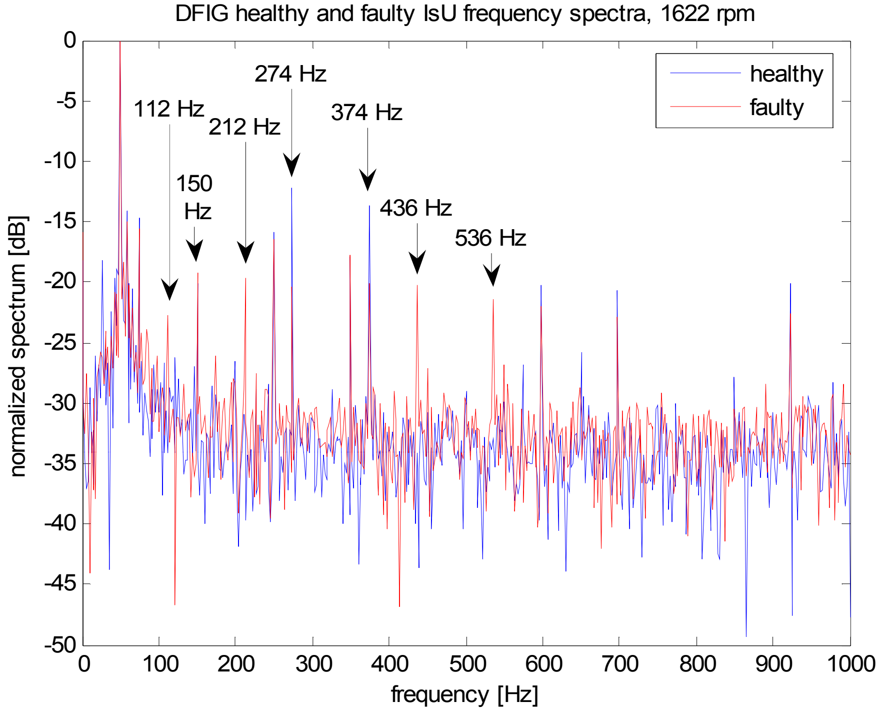
Wind Turbine Generator Test Rig



Generator Test Rig
Measured: Supply Current
Fault: Stator Open Circuit Coil

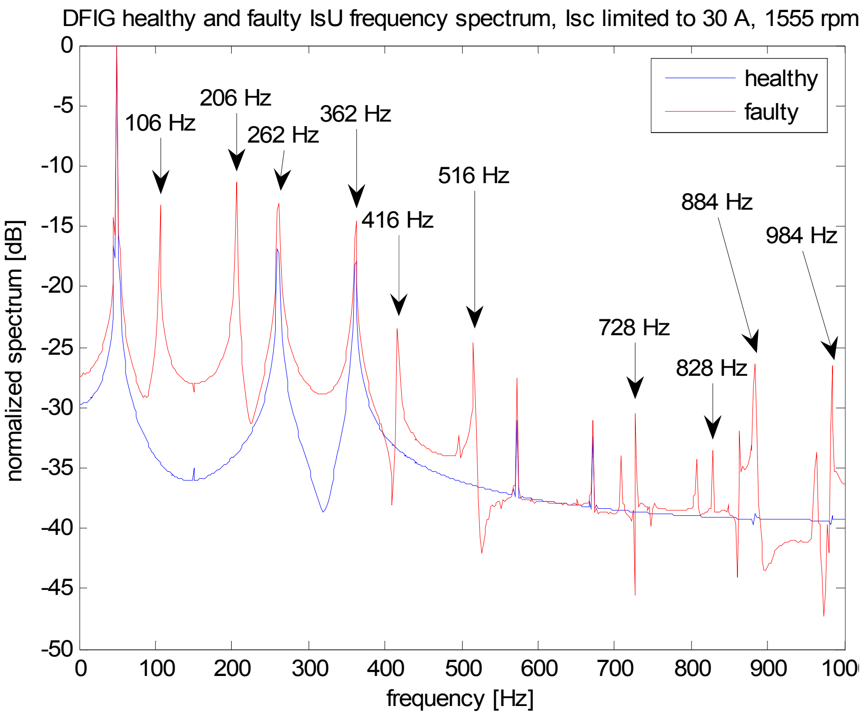


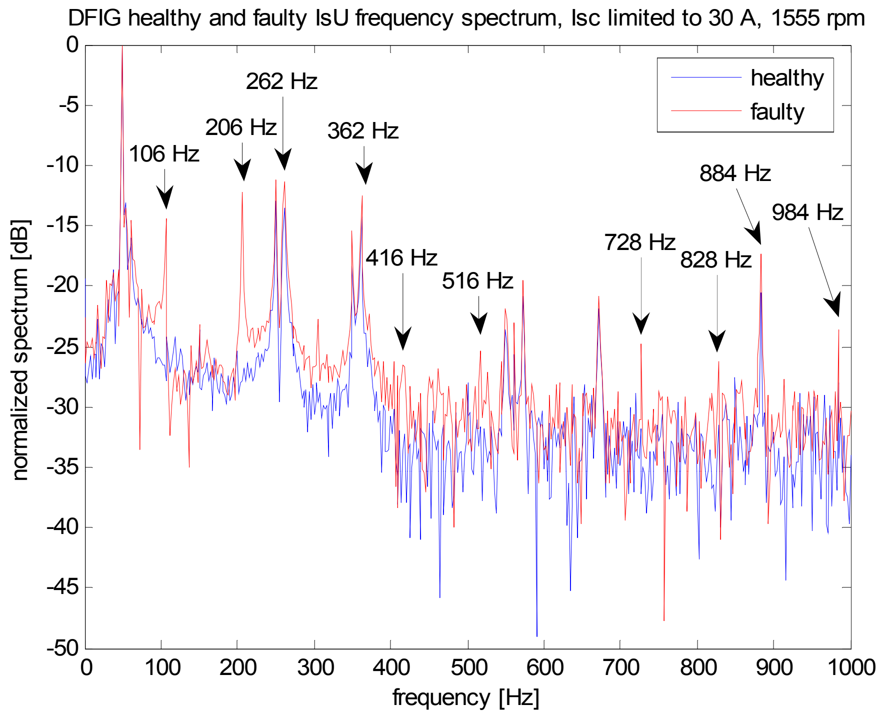
Stator phase U current FFT spectrum: open circuit in phase U (model results)



Stator phase U current FFT spectrum: open circuit in phase U (experimental results)

Generator Test Rig
Measured: Supply Current
Fault: Stator Shorted Coil





Stator phase U current FFT spectrum:
Short circuit in phase U (model results)

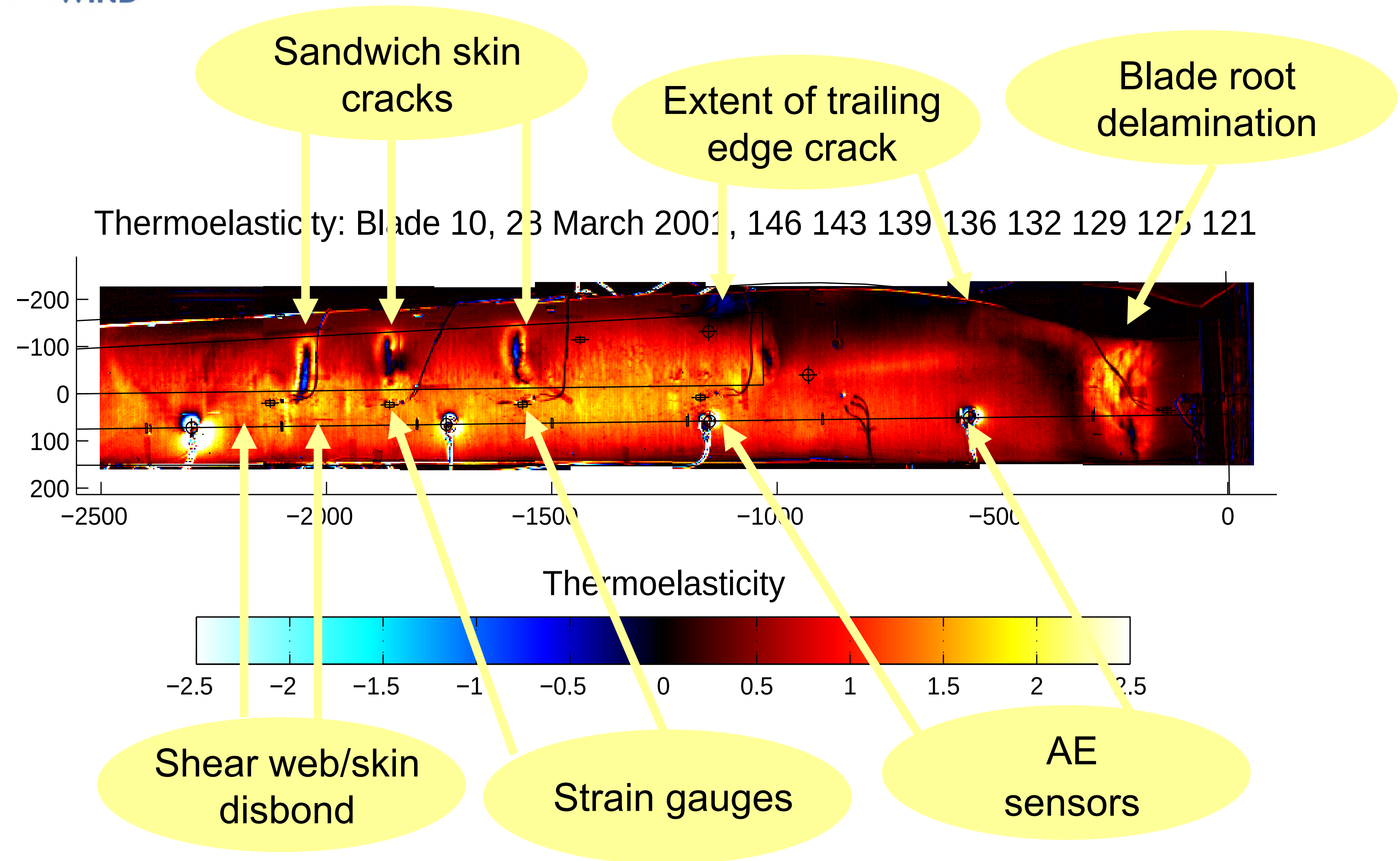
Stator phase U current FFT spectrum:
short circuit in phase U (experimental results)

Very Slow Data Rate Structural Health Monitoring from Real Turbine Blades

Can we condition monitor operational blades?

- Transfer Non Destructive Testing (NDT) methods from laboratory blade (certification) tests:
  - Strain gauges (including optical fibres)
  - Thermoelastic Stress Analysis (useful at low loads, design validation)
  - Infra Red Thermography (useful at elevated loads, identify damaged areas)
  - Acoustic Emission Testing (proof test, damage location, possible extension to CM)
- Develop new approaches:
  - Vibration monitoring (blades, nacelle, tower)
  - Power signal analysis and feature extraction

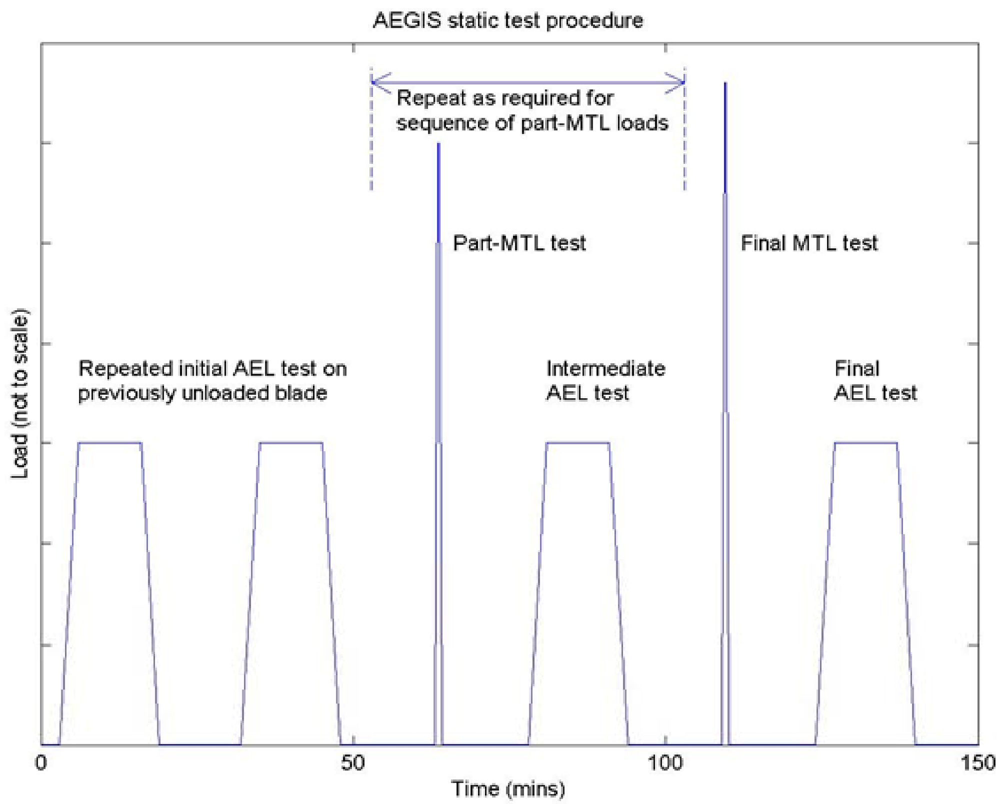
Thermoelastic Stress Analysis – 98% of blade life



Acoustic Emission Testing
AEGIS static blade test procedure

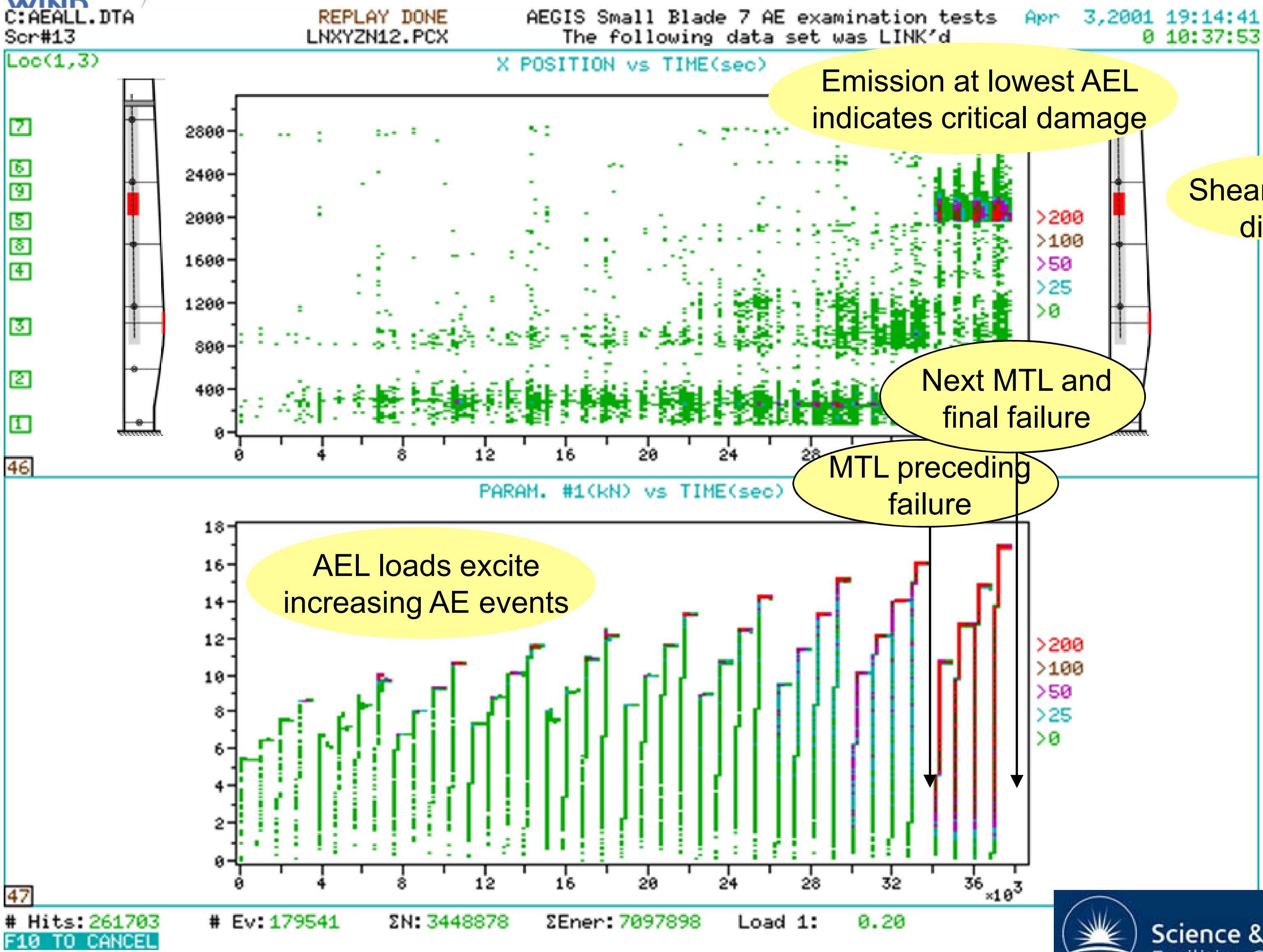
Two part test:

- Mandatory certification loading to Maximum Test Load (MTL) Typically a 10s "spike" load representative of a 50 years' maximum gust
- Acoustic Emission Examination Loading (AEL) Trapezium-shaped load envelope including a load-hold period of several minutes, performed before and after any certification loading

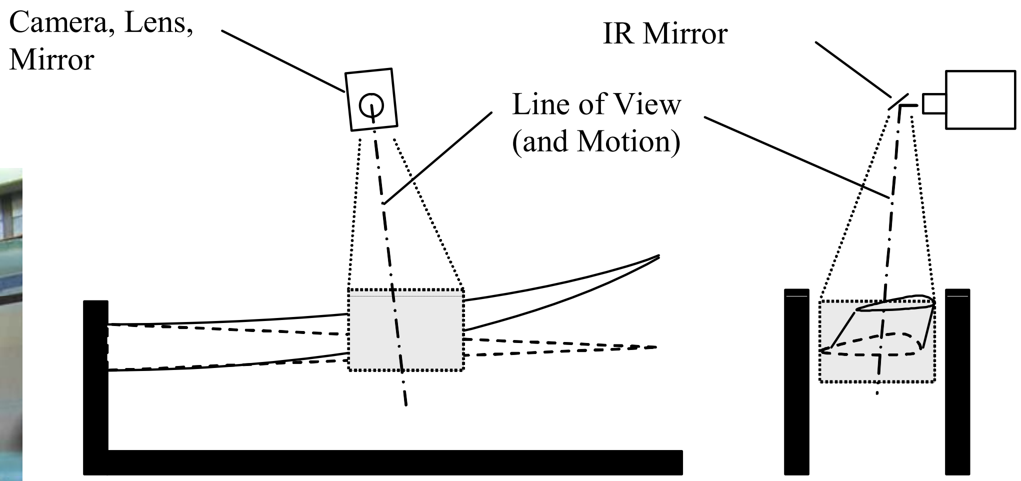


Evaluate procedure using a series of increasing MTLs

Acoustic Emission Testing
AEL procedure evaluation (MTLs omitted)



Acoustic Emission Testing
AEGIS Test arrangement



Condition Monitoring Solutions

- To target condition monitoring to known unreliability
- Utilise signals with known relationships to that unreliability
- Develop simple algorithms to give warning of faults
- Develop a diagnosis strategy with an integrated approach to condition monitoring
- Condition monitoring & diagnosis need to be part of the SCADA architecture embed detection algorithms in SCADA
- SCADA architecture needs to limit data rate to the minimum necessary for communication and still preserve signal quality
- There must be a data rate hierarchy for wind turbines
- Use Test Rigs as a means to develop fault detection algorithms
- Relate Test Rig work to real Wind Turbine SCADA measurements on known faults

Conclusions

- Identify common faults & root causes to focus on areas of turbine for monitoring
- Identify the best sensors to use and which signals to monitor
- Decide what data rate required (very slow, slow, medium or fast) and whether monitoring is continuous or not
- Reduce the number of signals to the lowest possible, the data rate to the slowest possible and have as much as possible not continuous
- Identify signal processing methods and fingerprint common faults
- Continue Test Rig monitoring work but compare with models
- Continue Wind Turbine monitoring work but cross compare signals and present on a common axis
- Compare Wind Turbine & Test Rig & Model results

Thank you

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