Improving Component Reliability Through Performance and Condition Monitoring Data Analysis


Photo by Dennis Schroeder, NREL 21883

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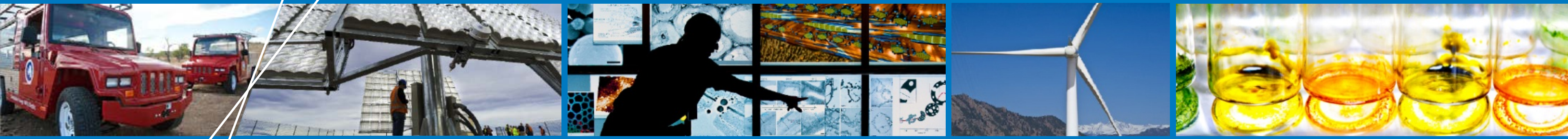
Outline

- Introduction
  - Reliability
  - Reliability-Critical Turbine Subsystems/Components
  - Typical Failure Modes
- Data Analysis
  - Performance Monitoring
  - Condition Monitoring
- Case Studies
  - Main Bearings
  - Gearboxes
  - Generators
- Concluding Remarks
  - Summary
  - Future Opportunities

DOE 1.5 MW Turbine/PIX17245



Introduction

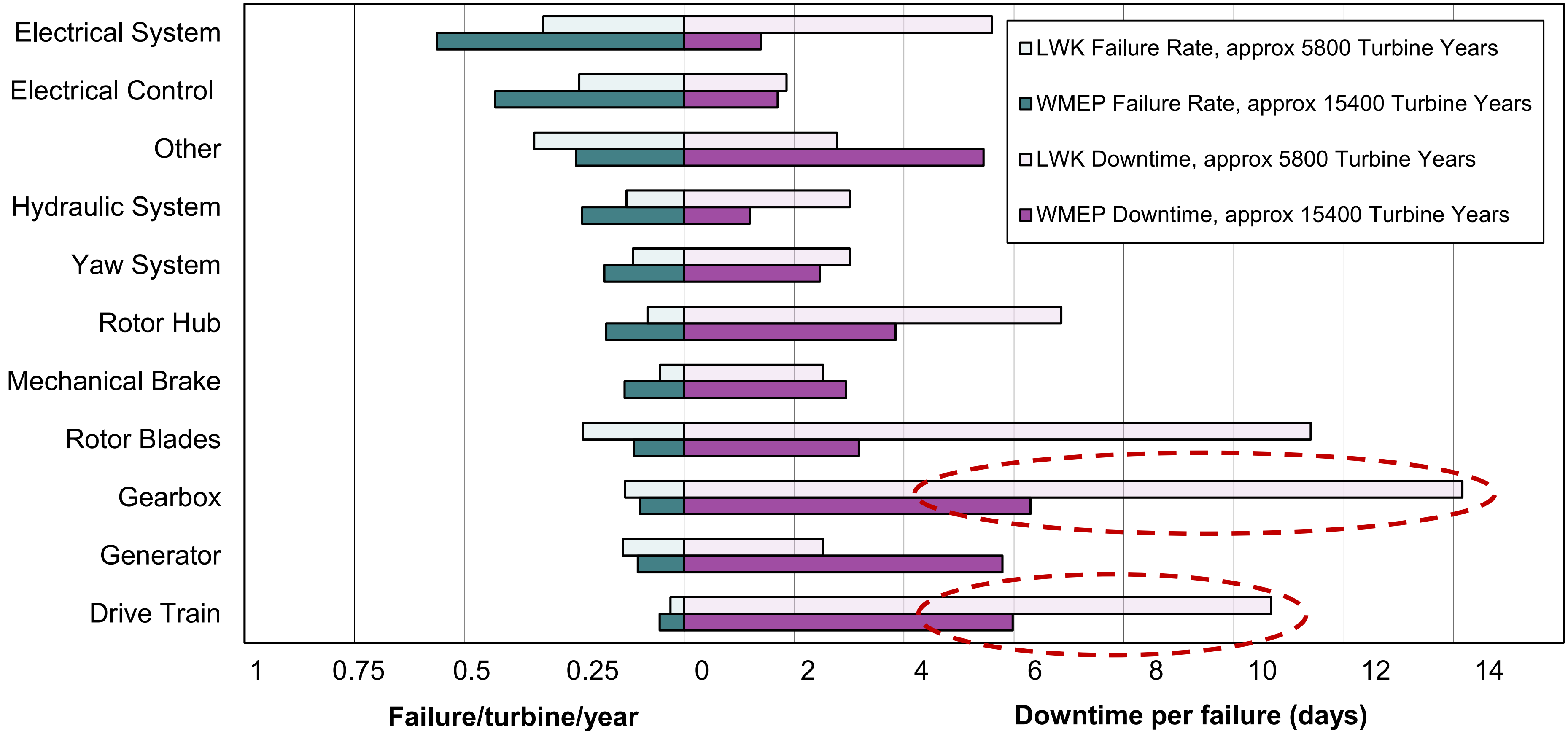
Reliability [1]

- One Definition of Reliability:
  - The probability that an asset or component will perform its intended function without failure for a specified period of time under specified conditions.

- Metrics: choose one to track reliability improvements
  - Mean time to repair or replace (MTTR) or mean time between maintenance (MTBM)
  - Mean time between failure (MTBF): primarily repairable
  - Mean time to failure (MTTF): primarily nonrepairable
  - Total downtime
  - Mean downtime

Reliability of Turbine Subassemblies: Old Statistics [2,3]

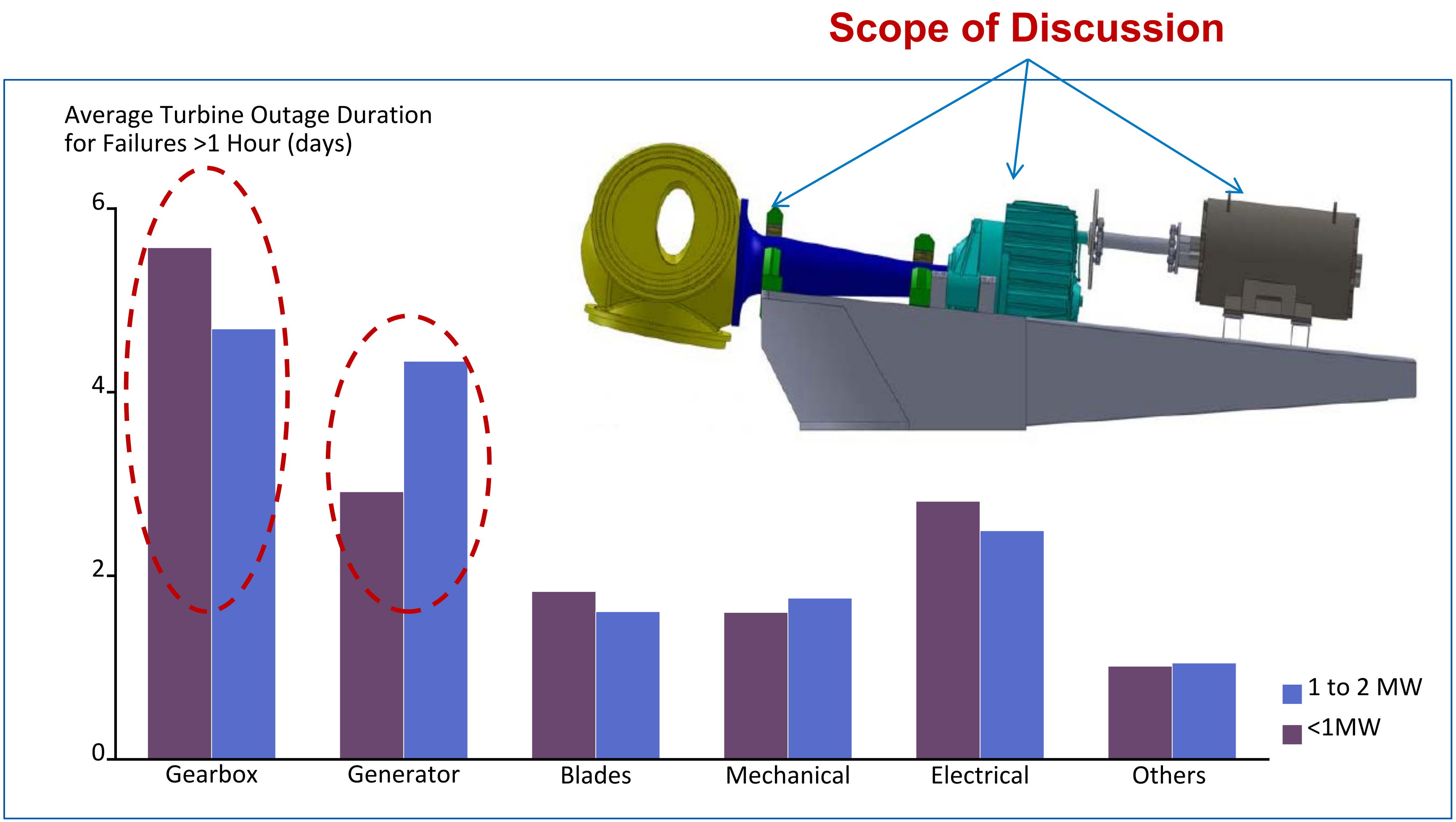
Failure/turbine/year and downtime from two large surveys of land-based European wind turbines over 13 years



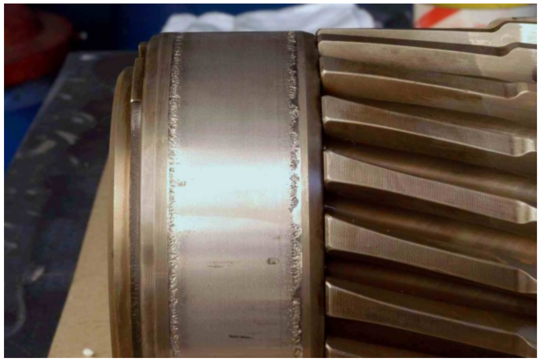
- The Wissenschaftliches Mess-und Evaluierungsprogramm (WMEP) database was accomplished from 1989 to 2006 and contains failure statistics from 1,500 wind turbines.
- Failure statistics published by Landwirtschaftskammer Schleswig-Holstein (LWK) from 1993 to 2006 contain failure data from more than 650 wind turbines.

Outage Duration for Different Components: New Statistics [4]

- Mechanical: Yaw Systems, Mechanical Brakes, Hydraulic Systems, Rotor Hubs, Drivetrain
- Electrical: Sensors, Electrics , Control Systems



Typical Failure Modes: Gearbox Bearings

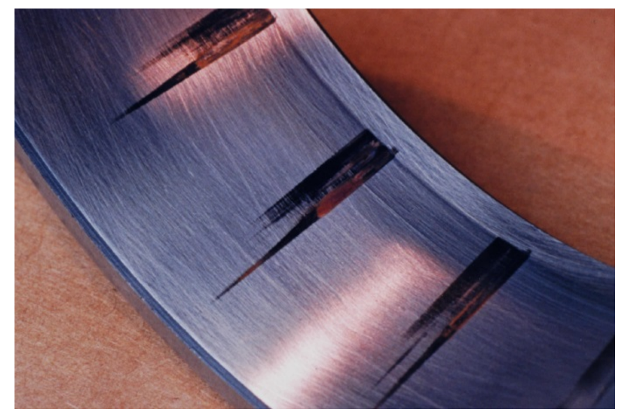


Micropitting

Scuffing

Axial Cracks

Spalling

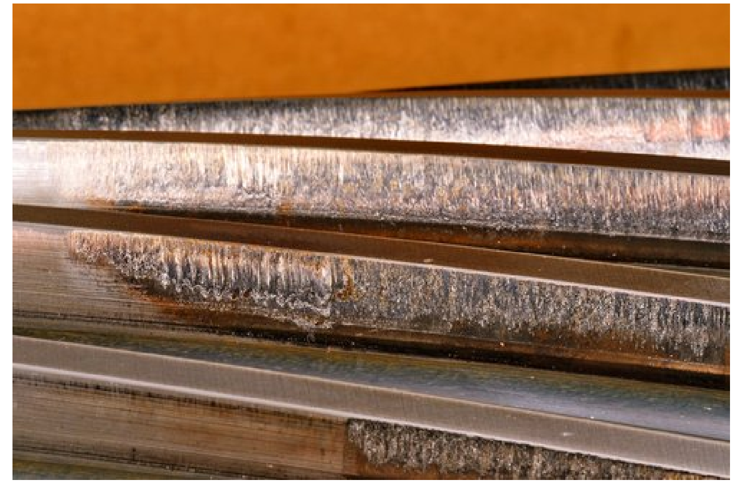


Fretting Corrosion

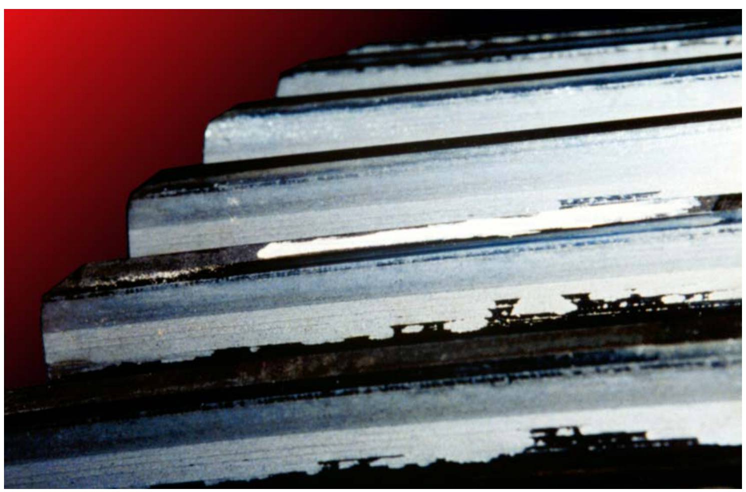
Photo Credit: Robert Errichello, GEARTECH; Andy Milburn, Milburn Engineering; Gary Doll, University of Akron; and Ryan Evans, Timken

Typical Failure Modes: Gearbox Gears

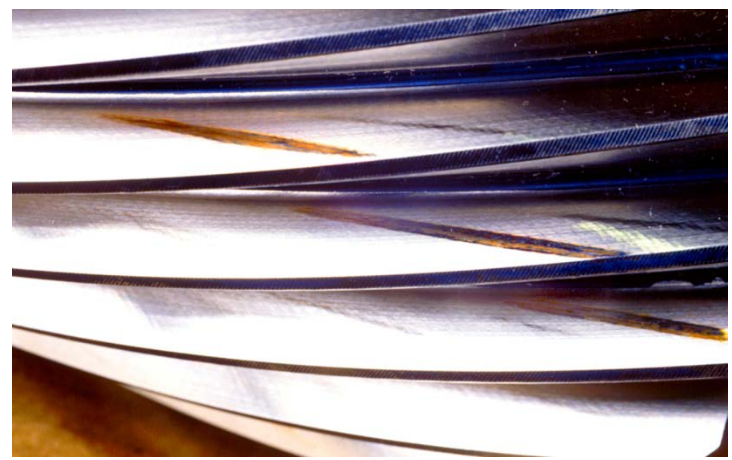
Bending Fatigue
(intermediate-stage pinion)



Scuffing
(high-speed-stage pinion)



Micropitting



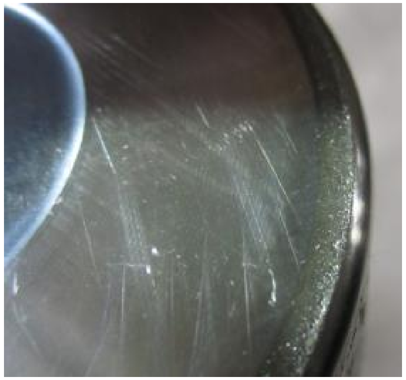
Fretting Corrosion

Photo Credit: Rainer Eckert, Northwest Laboratory and Bob Errichello, GEARTECH

Typical Failure Modes: Main Bearings

Micropitting

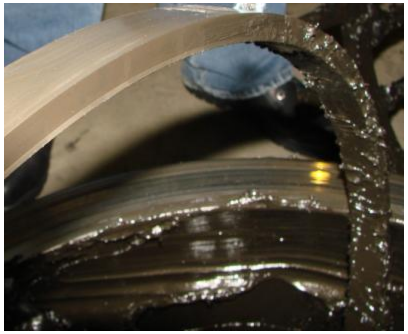
Debris Damage



Roller End Thrust

Edge Loading

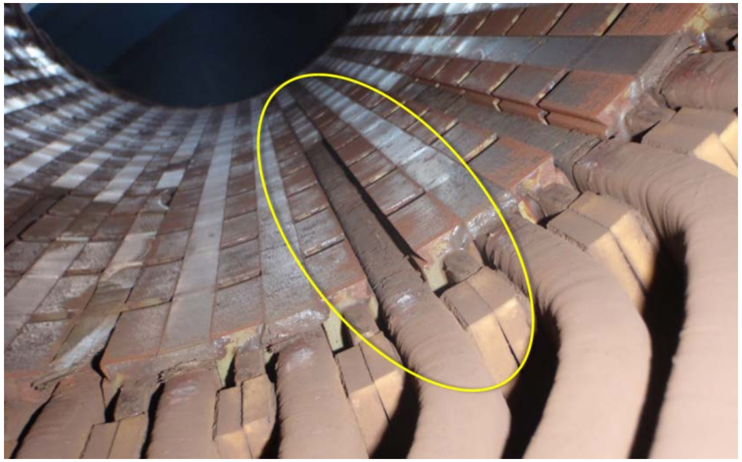
Cage Failure



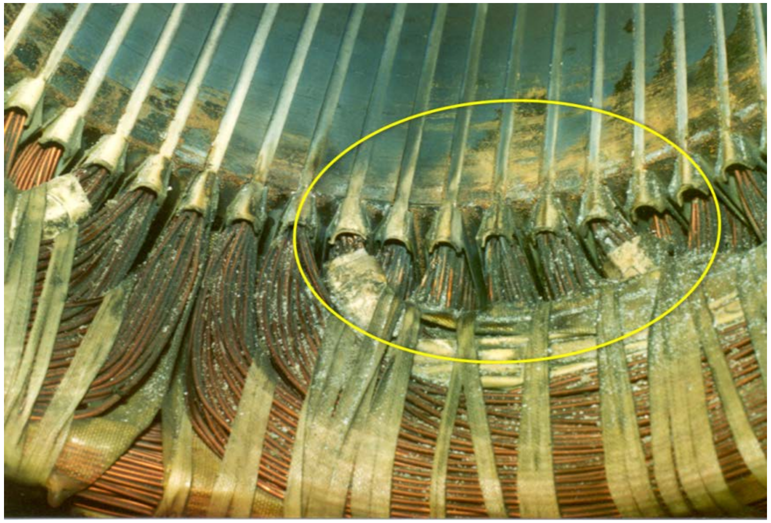
Center Guide Ring Wear

Photo Credit: Richard Brooks, Timken

Typical Failure Modes: Generators



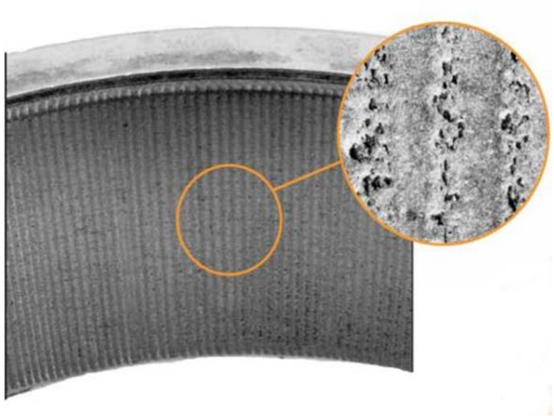
Magnetic Wedge Loss



Contamination

(a) (b)

Electric Arc Damage

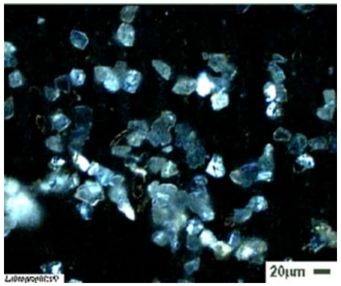


Fluting

Photo Credit: Kevin Alewine, Shermco Industries; Gary Doll, University of Akron; and Ryan Evans, Timken

Typical Failure Modes: Lubrication [5]

- Temperature
  - Overloading
  - Over greasing
  - Wrong viscosity
  - Improper cooling
- Moisture
  - Hot operation, then shutdown
  - Improper seals
  - Additive depletion
  - Improper vent/breather device
  - Leaking cooling system

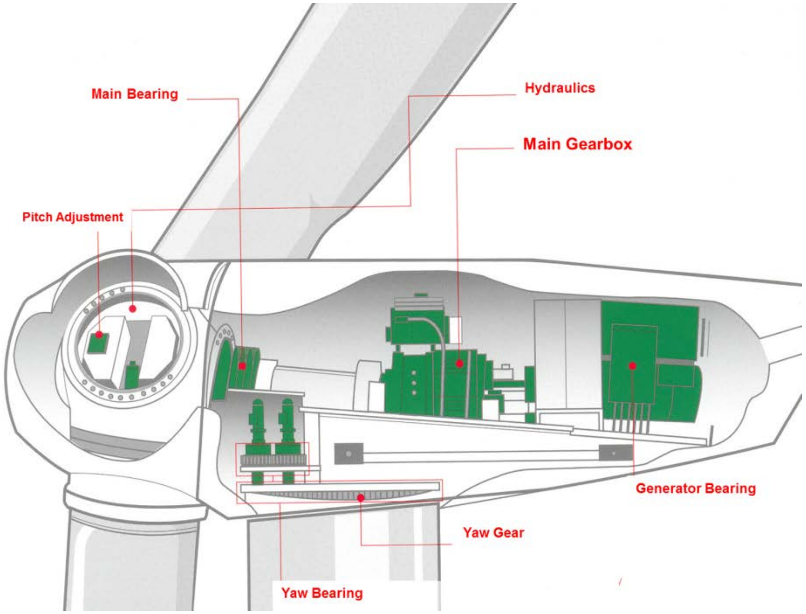


- Foreign Materials
  - Wear particles
  - Improper filtration
  - Poor lube storage methods
  - Poor lube equipment storage
- Viscosity
  - Temperature
  - Oxidation
  - Moisture/chemicals
  - No/lack of additives

Photo Credit: Bill Herguth, SGS Herguth and Art Miller, EDF

Summary

- Major turbine components have diverse and complex failure modes.
- Wind turbine reliability improvement is not a simple task:
  - The number of subsystems/components a turbine has
  - The modes of each subsystem/component may fail
  - The challenges with identifying root causes for each failure mode
- Terminology challenge:
  - Definitions of failure modes
  - Definition of "failure" for different subsystems/component.



Tehachapi Pass Wind Farm, CA/NREL 18453

Illustration Credit: Jon Leather, Castrol

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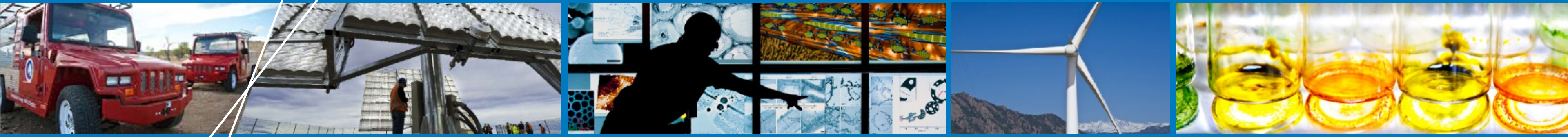
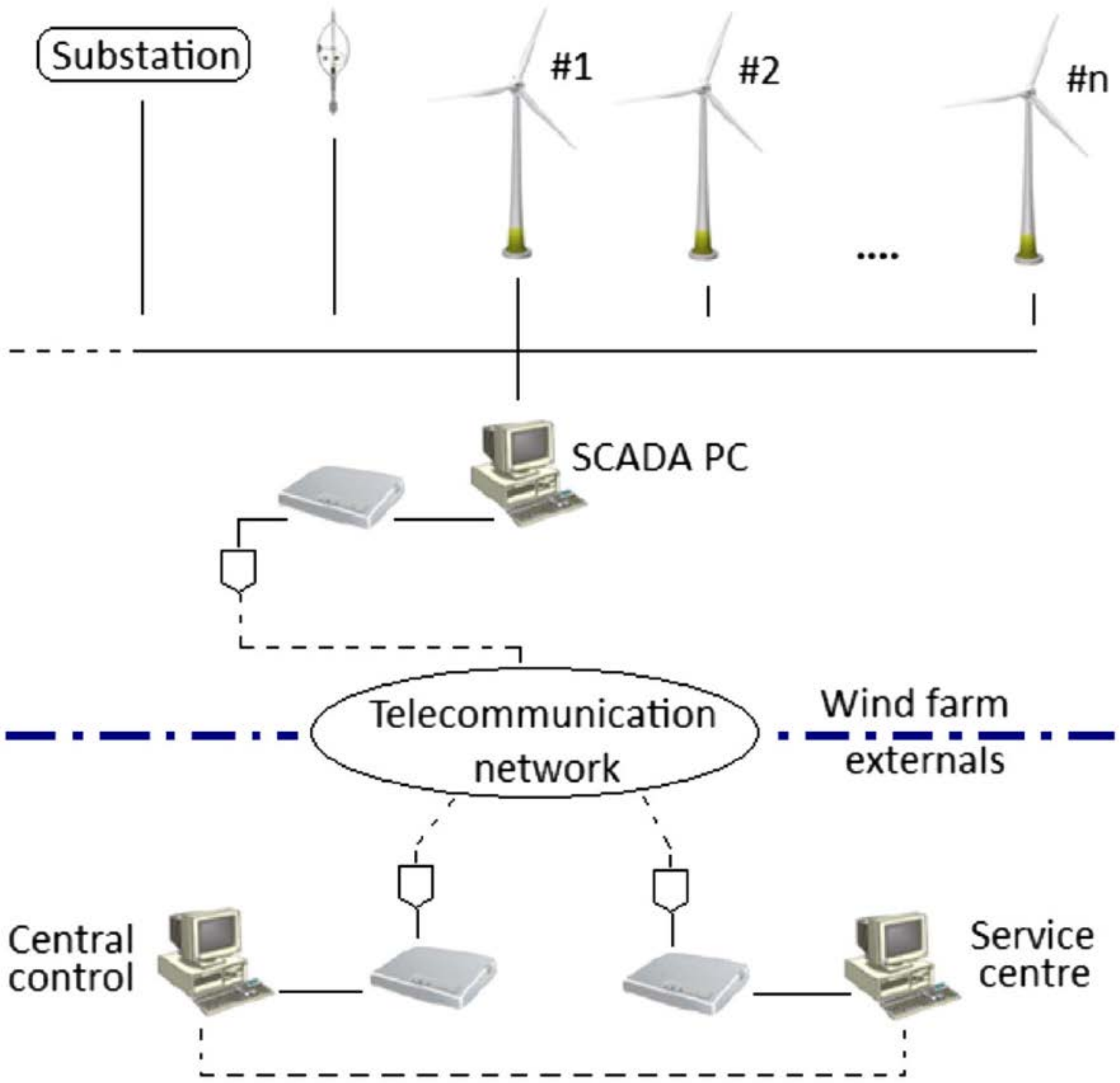


Data Analysis

Performance Monitoring Based on SCADA [6]



Performance Monitoring

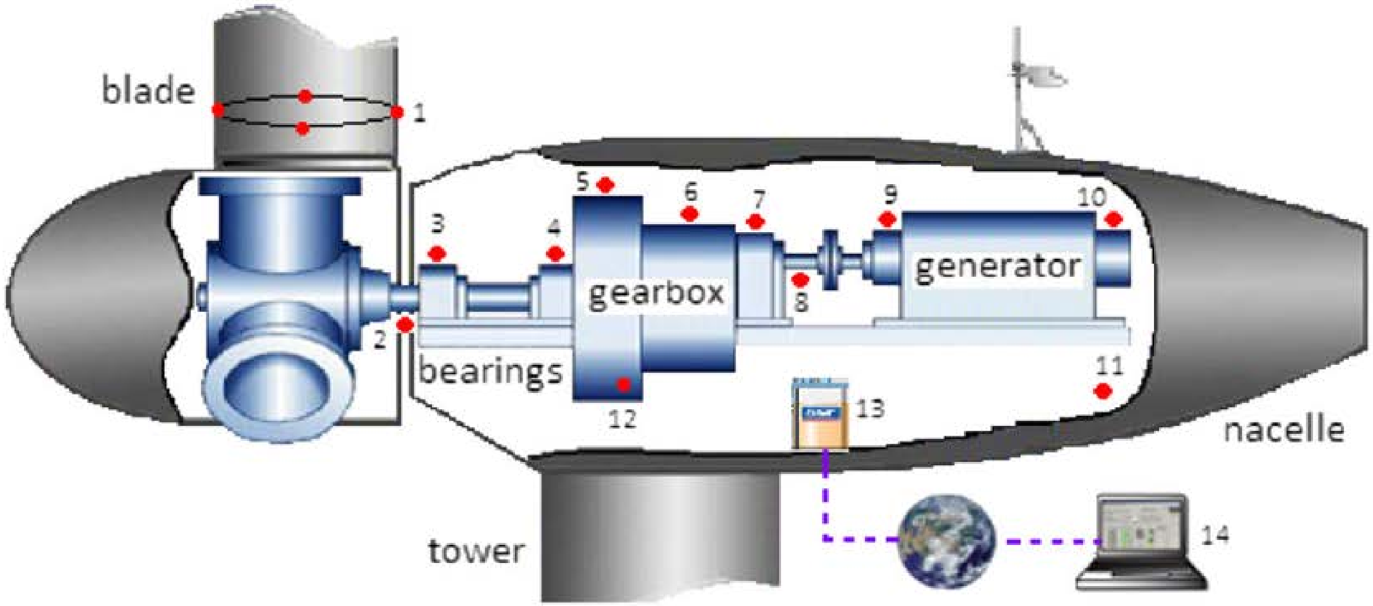
- Classification of Measured Parameters [7]:
  - Wind parameters: e.g. speed, deviation
  - Performance parameters: e.g. power output, rotor speed, blade pitch angle
  - Vibration parameters: e.g. tower acceleration, drivetrain acceleration
  - Temperature parameters: e.g. bearing and gearbox temperature
- Grouping of Control System Status Report [8]:
  - Status codes: e.g. error, warning
  - Operating states: e.g. brake, start, yaw, pitch
- Analysis:
  - Correlate different groups of parameters (e.g. power and wind), develop models for normal operational states, and use these models to identify abnormal scenarios
  - Conduct statistical analysis of events (e.g. status codes) experienced by turbines at a wind plant
  - Investigate measured parameters under the same operating state

Performance Monitoring [6,9]

- Benefits:
  - Readily available and no need of investment in dedicated condition monitoring (CM) instrumentation
  - Beneficial for identifying outliers by looking at key performance parameters or status codes
  - Can call attention to turbines identified as outliers that may need further inspection.

- Drawbacks:
  - May not be straightforward in pinpointing exact damaged subsystems/components (e.g. bearings or gears inside gearboxes)
  - Many false alarms due to varying loads experienced by turbines
  - Does not meet full turbine CM needs, such as fault diagnosis

Condition Monitoring Based on Dedicated Instrumentation [6,10]



1 --- fibre optic transducers; 2, 8 --- speed transducers; 3, 4, 5, 6, 7, 9, 10, 11 --- accelerometers; 12 --- oil debris counter; 13 --- online CMS; 14 --- PC at control center.

- Illustrated:
  - Blade Root Loads
  - Vibration
  - Oil
- Additional:
  - Acoustic Emission
  - Electrical
  - Shock Pulse Method
  - Thermography

Condition Monitoring with Drivetrain as a Focus

- Raw Signal Examples:
  - Strains, accelerations, acoustic emissions
  - Oil debris counts, oil condition measurements
  - Currents, voltages

- Feature (Condition Indicator) Examples:
  - Preprocessing: filtering
  - Time-domain: peak, root mean square
  - Frequency-domain: gear meshing frequencies and sidebands, bearing fault frequencies

- Typical Diagnosis:
  - Trending or rate of changes of features or condition indicators
  - Appearance of frequency components corresponding to certain faults or abnormal modulation of signal spectra
  - Violating thresholds set for certain features

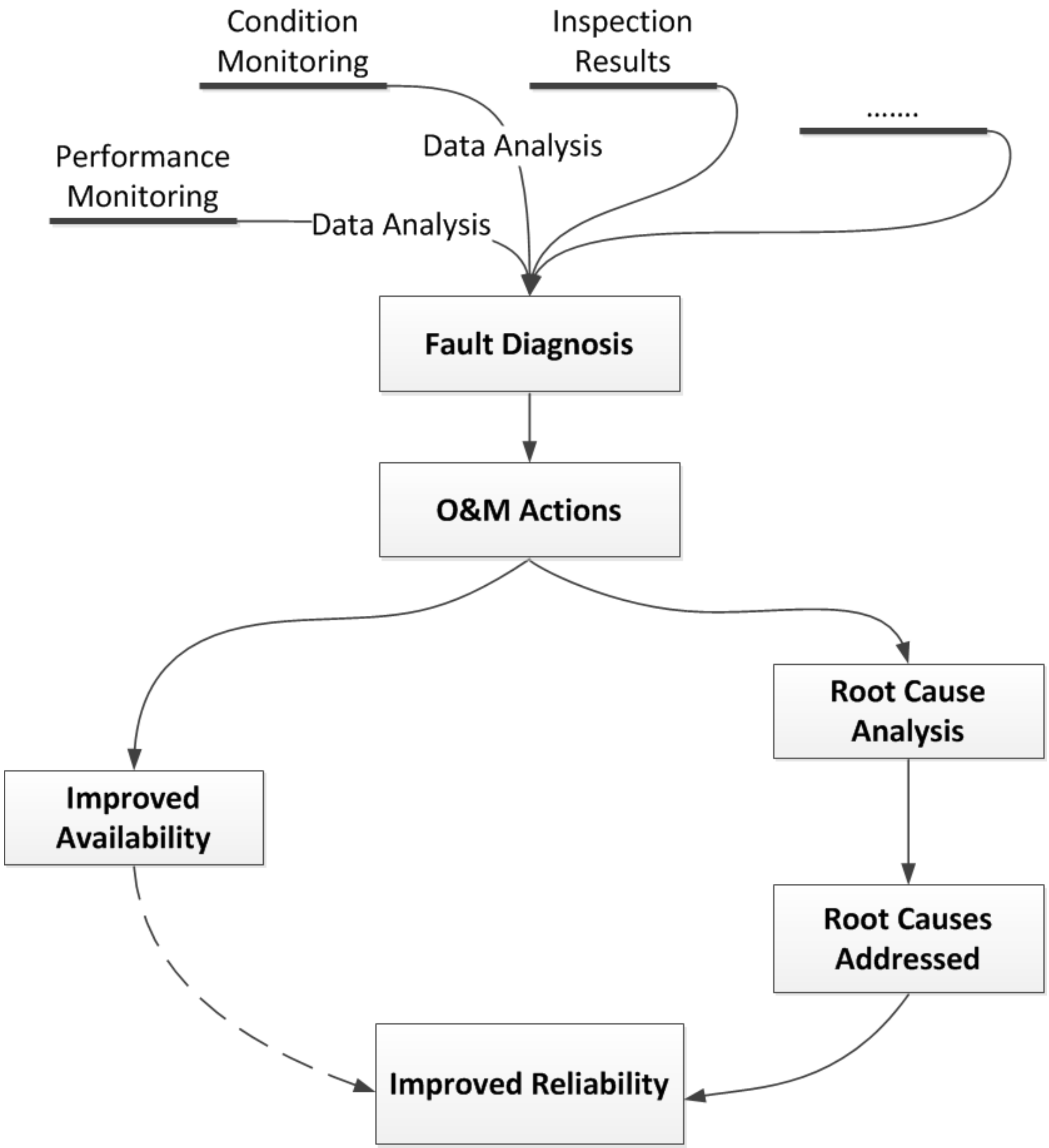
- Typical Prognosis:
  - Data-driven models: regressions, neural networks
  - Empirical or physics-based models: crack propagation by Paris Law

Condition Monitoring

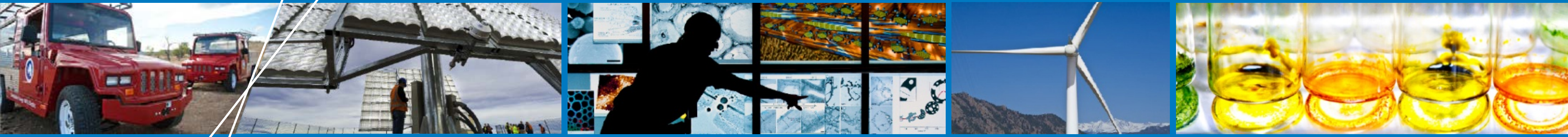
- Benefits:
  - Capture of high frequency dynamics normally not achievable with a typical SCADA system
  - Identification of more failure modes occurred to turbine subsystems or components
  - Capability in pinpointing exact damaged locations/components
  - Enable condition or reliability-based maintenance

- Drawbacks:
  - Additional investment required for instrumentation and monitoring service
  - Dedicated resources on data analysis and interpreting results

Improved Component Reliability

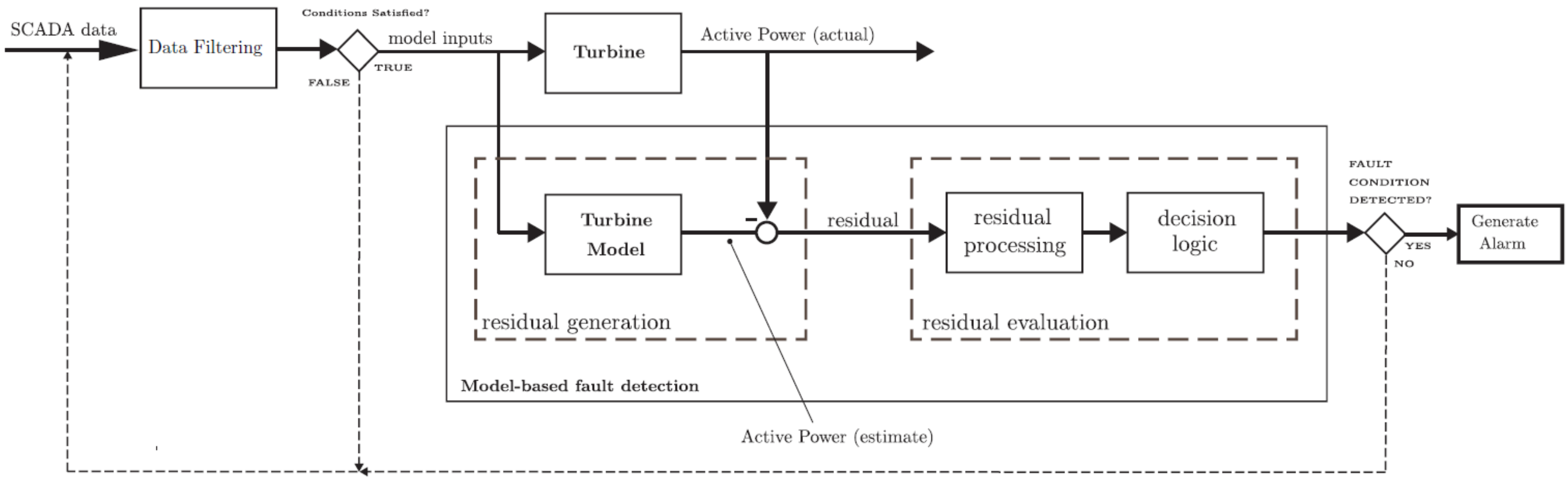


- Performance and condition monitoring data analyses are two tools to achieve fault diagnosis
- Immediate impacts on O&M actions leading to improved turbine availability, an indirect measure of reliability
- Root cause analysis, if conducted to identify faults, and addressing the root causes can lead to direct improvement in component reliability

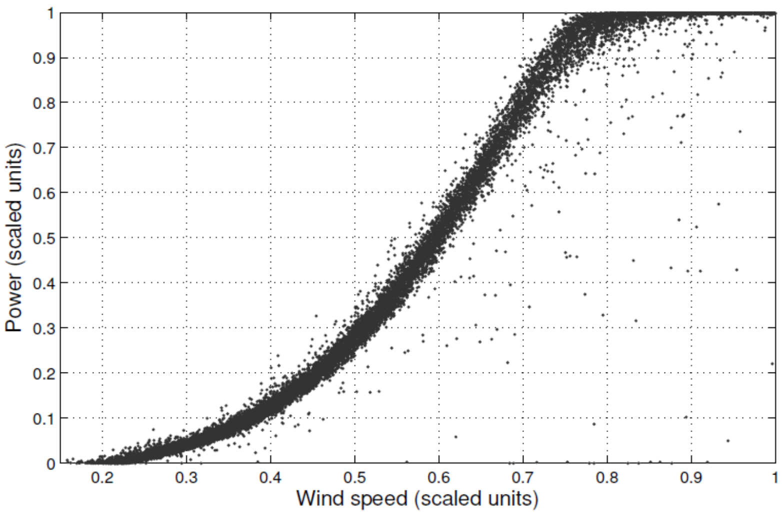


Case Studies

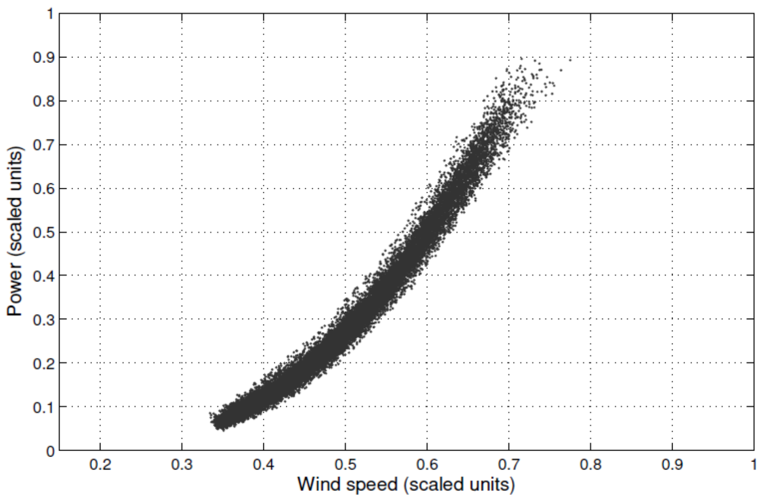
Main Bearings: Performance Monitoring [11]



Performance monitoring diagram

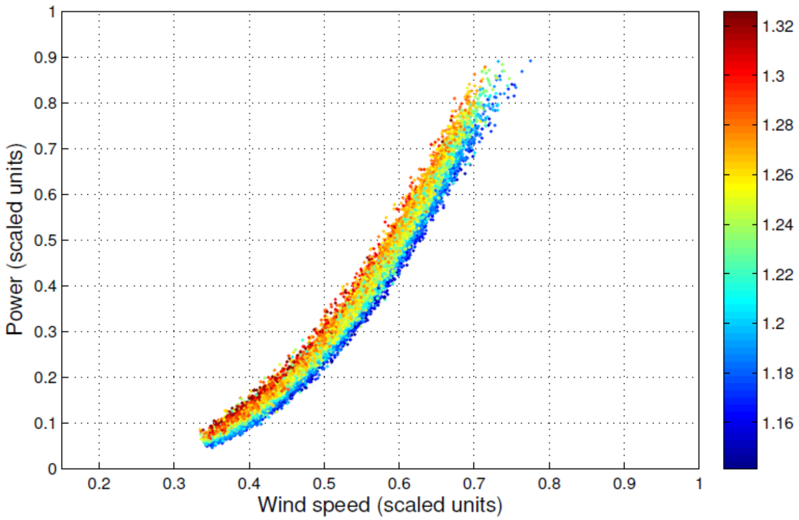


All data: power vs. wind speed

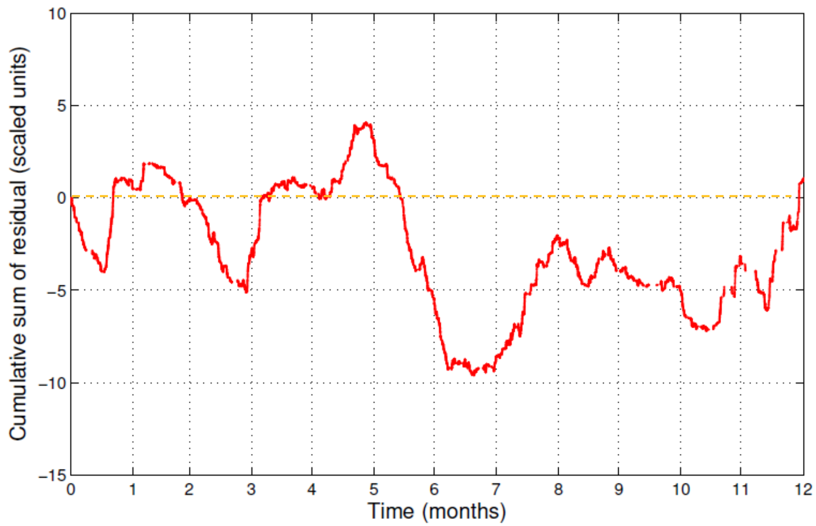


Filtered data: power vs. wind speed

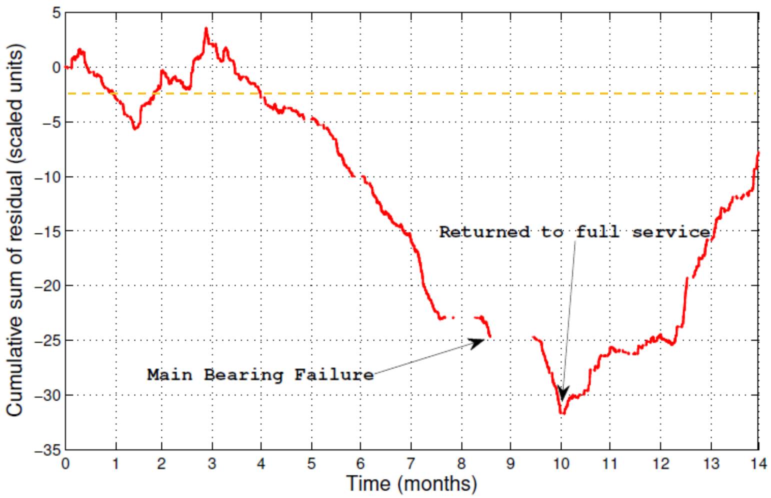
Main Bearings: Performance Monitoring [11]



Power vs. wind speed color coded by air density



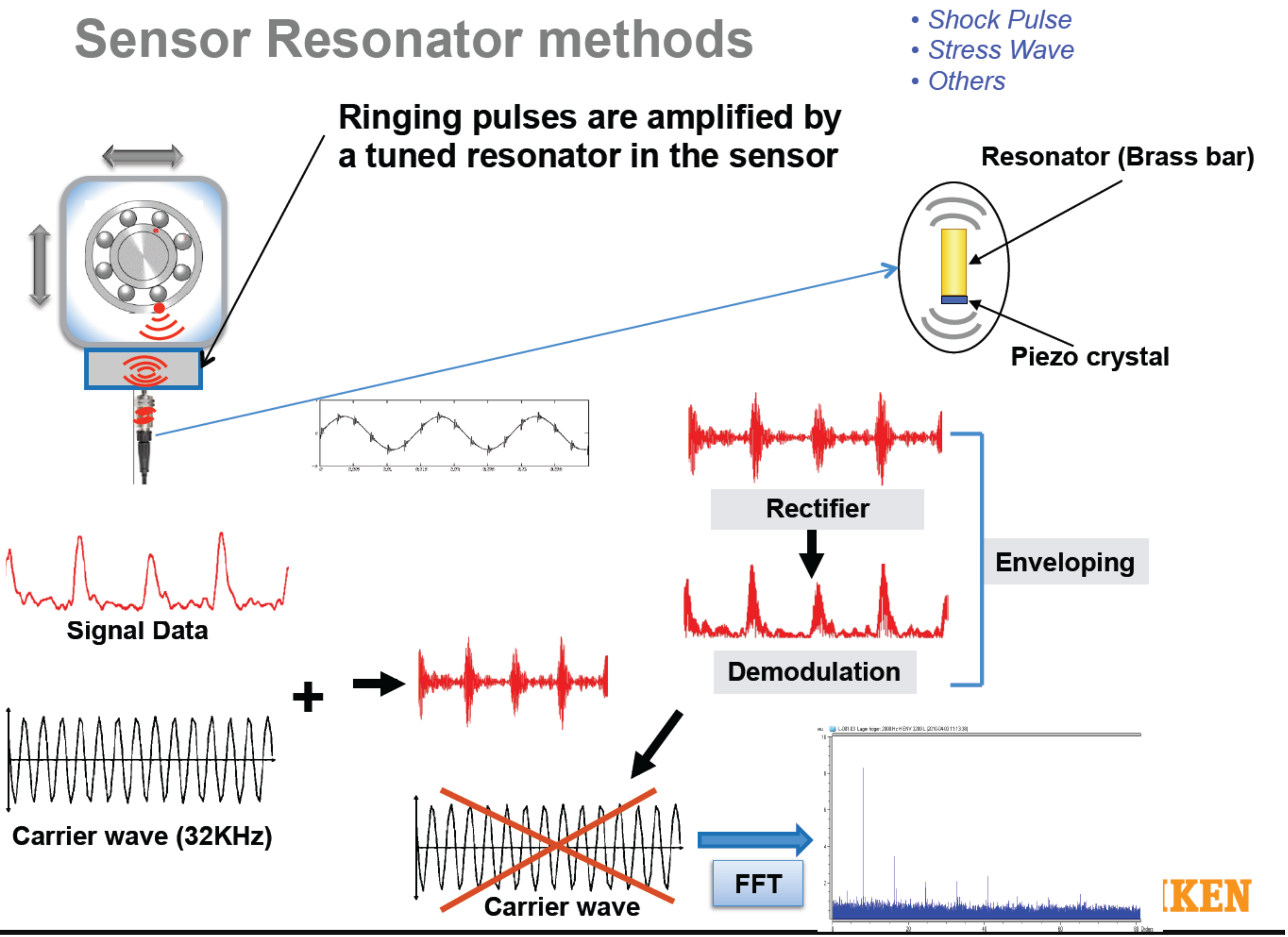
Cumulative sum of residual for a turbine that was fault-free through 12-month test period



Cumulative sum of residual for a turbine with a main bearing failure and replacement

- Modeling turbine power using both wind speed and air density reduced root mean squared error by 16%
- Fault free: cumulative sum of residual oscillates about a value of zero
- Temperature trending: typically reliable for failure identification but may be too late to save the bearing.

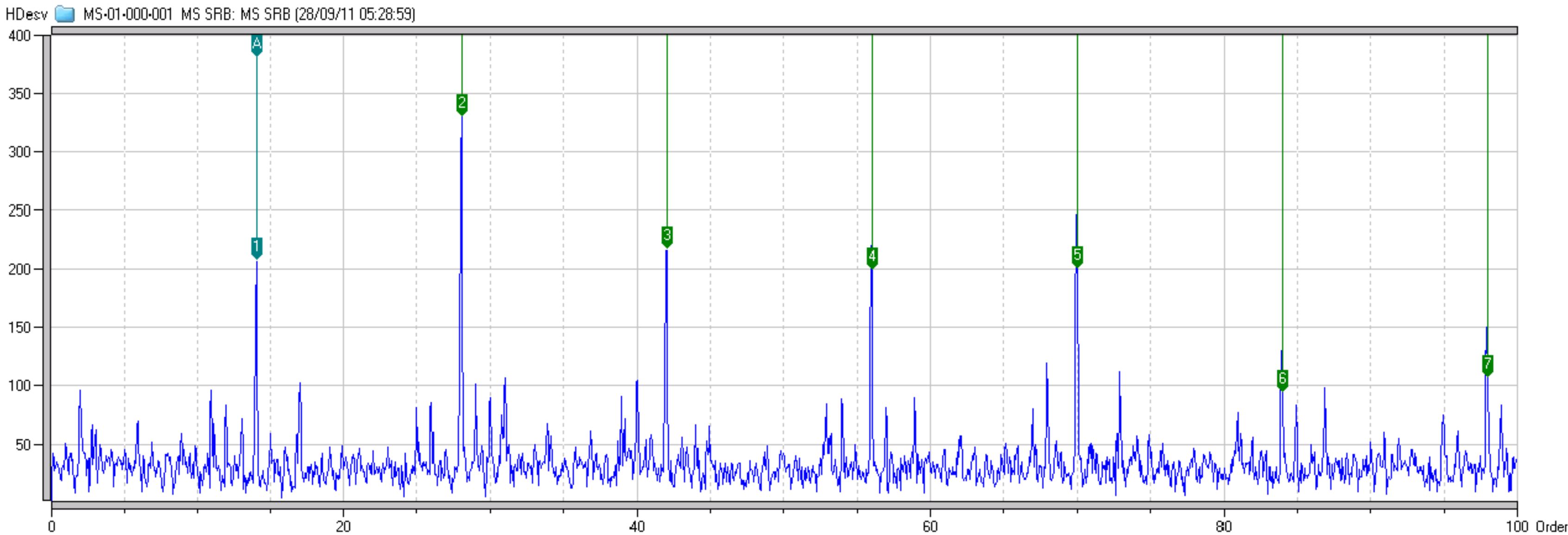
Main Bearings: Condition Monitoring [12]



Main Bearings: Condition Monitoring [12]

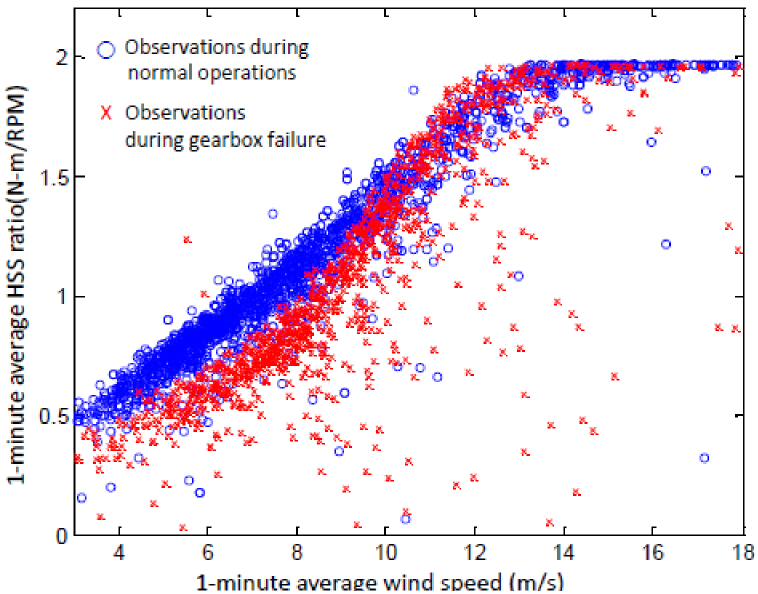
MAIN SHAFT 240/600 BEARING MICROPITTING & SPALLING

- Vibration analysis based on accelerometers is feasible but may present challenges.

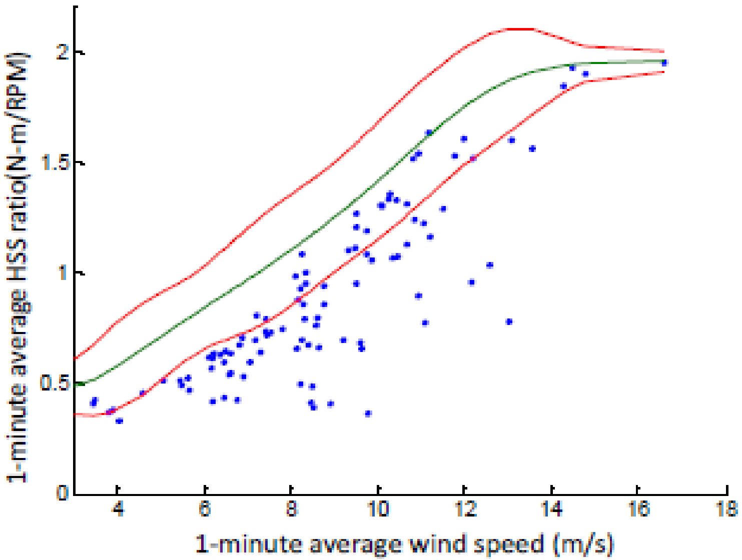


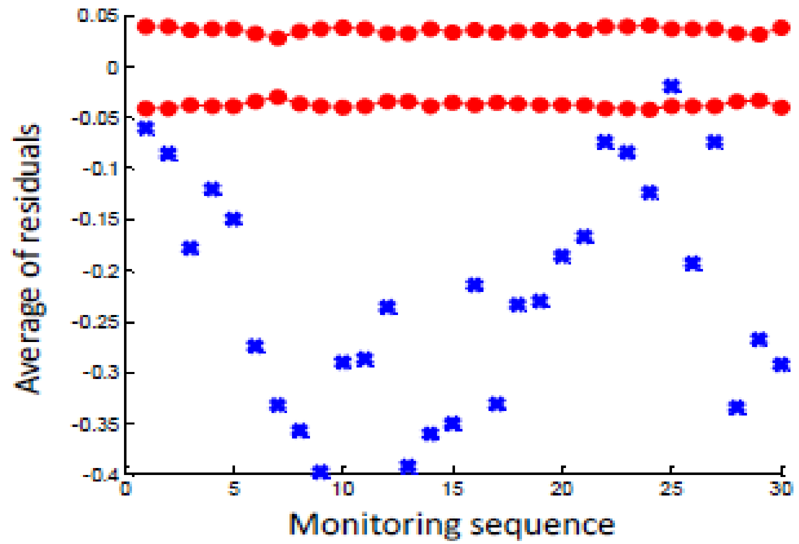
Spectrum: Inner Race Damage Frequencies Prominent

Gearboxes: Performance Monitoring [13]



- High-speed shaft (HSS) ratio: HSS torque to HSS rpm
- Model developed based on normal operation
- Thresholds established based on a certain allowable false alarm rate
- Two angles: response and residual
- Abnormal: outside of the established thresholds





Gearboxes: Condition Monitoring [14]

1. Completed dynamometer run-in test
2. Sent for field test: experienced two oil losses (root cause)
3. Stopped field test
4. Retested in the dynamometer under controlled conditions

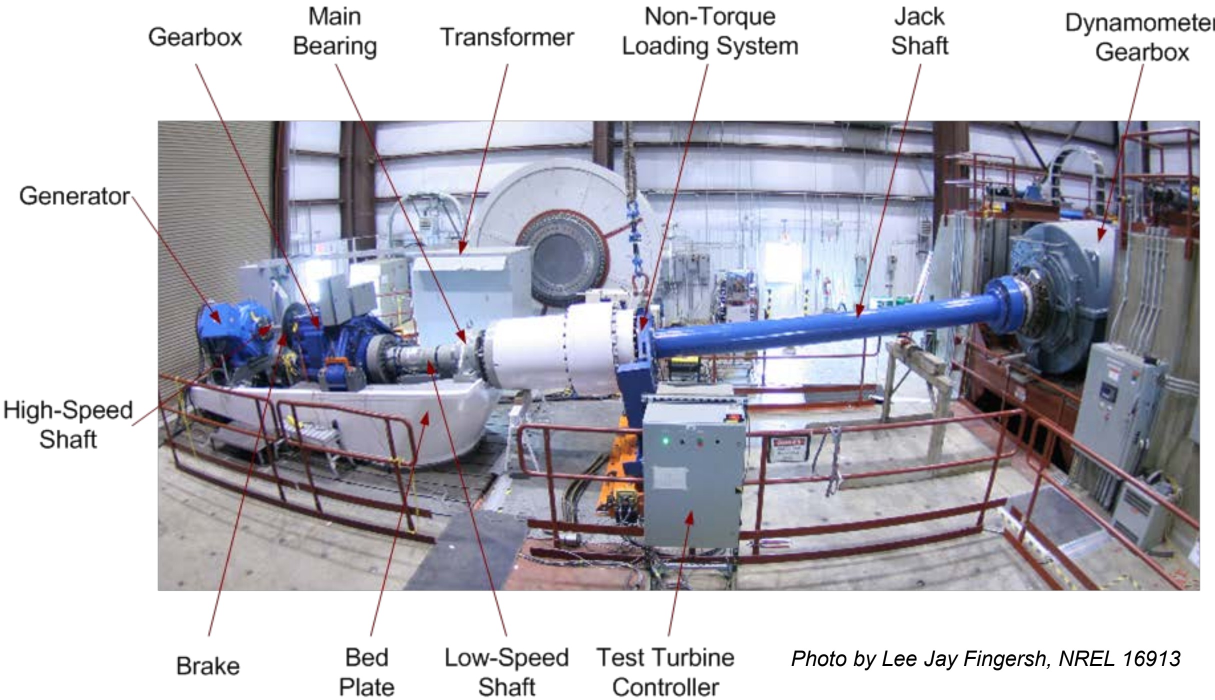
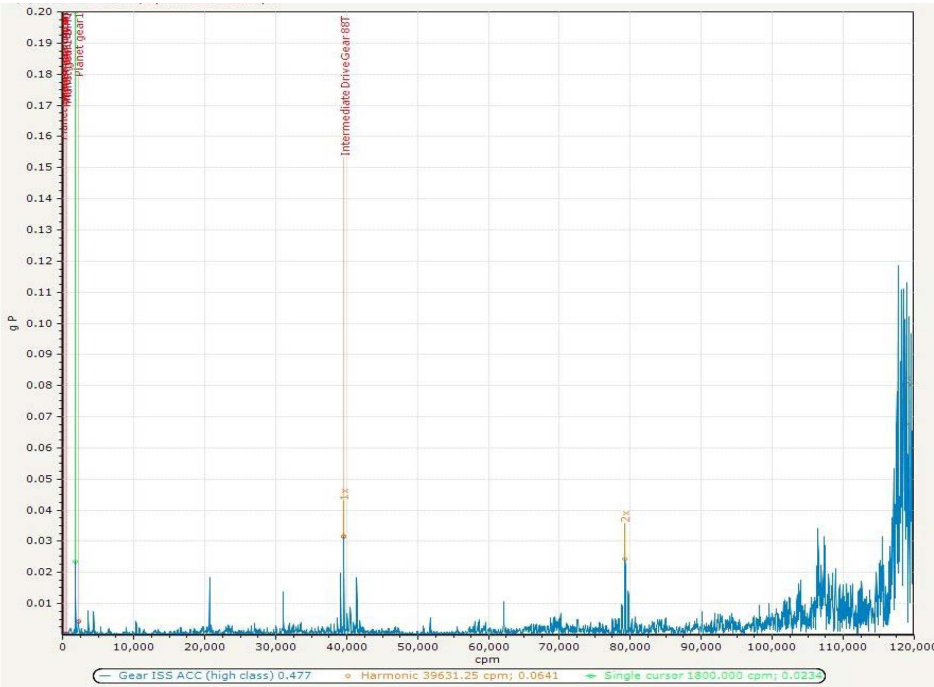


Photo by Lee Jay Fingersh, NREL 16913

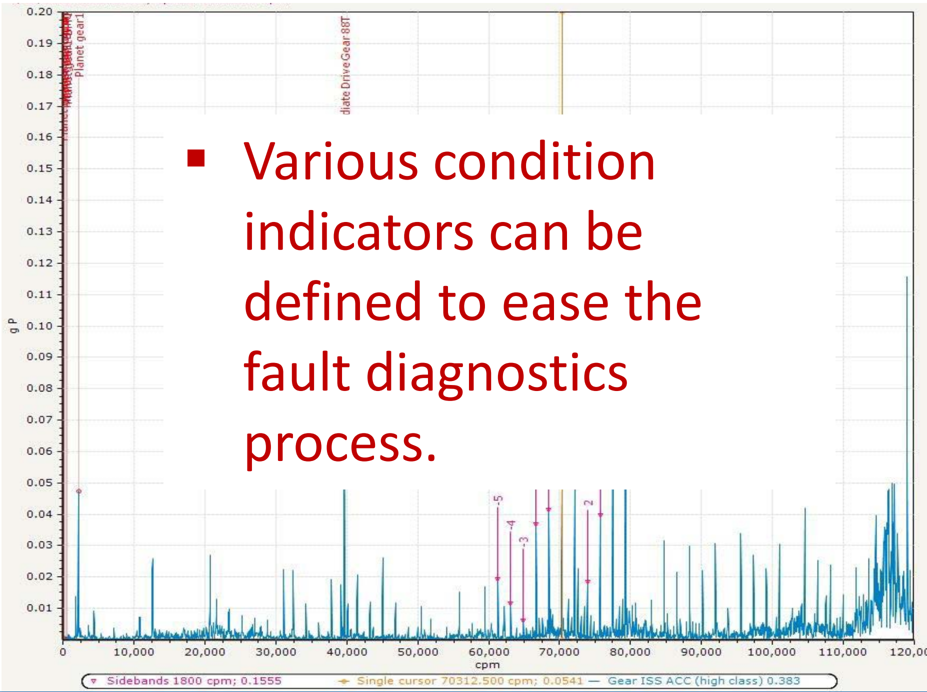
High-Speed Stage Gear Damage

Photo by Robert Errichello, NREL 19599

Gearboxes: Vibration Analysis [15]



- Intermediate-speed shaft sensor
- Dynamometer test of the same reference gearbox (left) indicated healthy gearbox behavior
- Dynamometer retest of the damaged gearbox (right) indicated abnormal behavior
  - More side band frequencies
  - Elevated gear meshing frequency amplitudes



- Various condition indicators can be defined to ease the fault diagnostics process.

Gearboxes: Vibration Analysis [16]

Interpretation

Analysis of the latest time waveform reveals very high levels with impacts associated to running speed. Detailed spectral analysis reveals the presence of Ball Pass Frequency of the Inner Race (BPFI). A severity 2 is issued due to the high and progressing vibration levels.

- Inspected by EDPR 11/11/2014 – HS GS Bearing Axial Cracks
- NOTE: Previously inspected June 2014 with no findings
- HS bearings replaced 12/16/2014

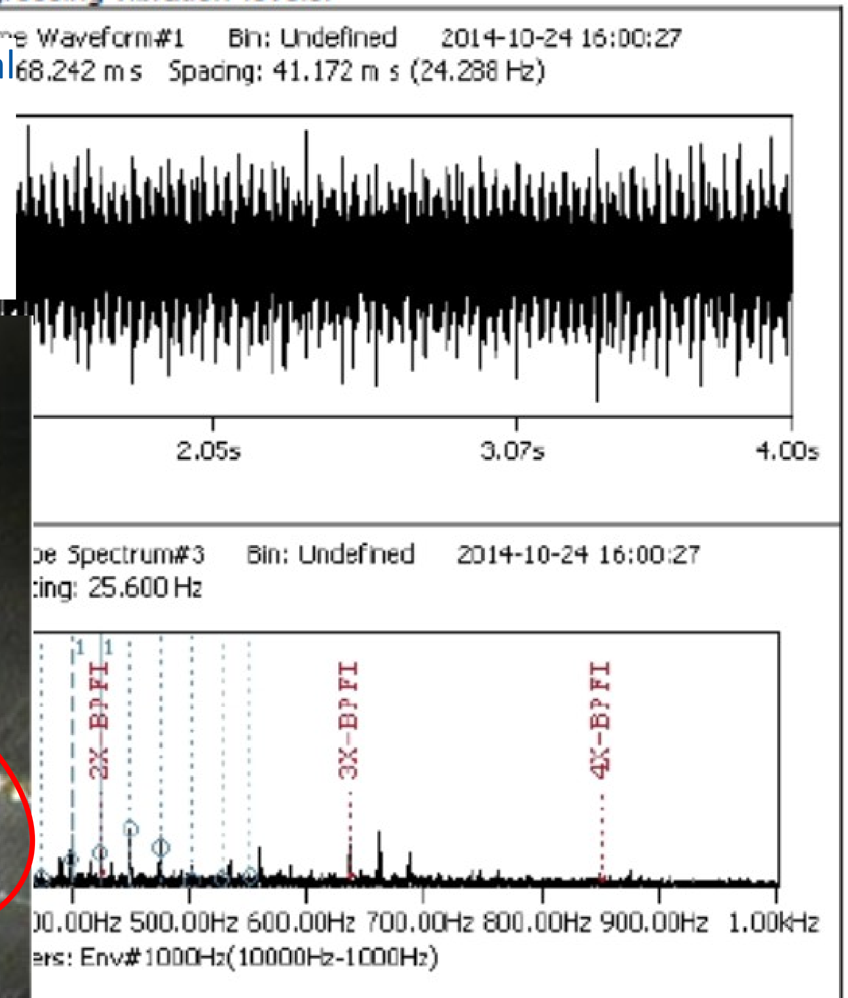
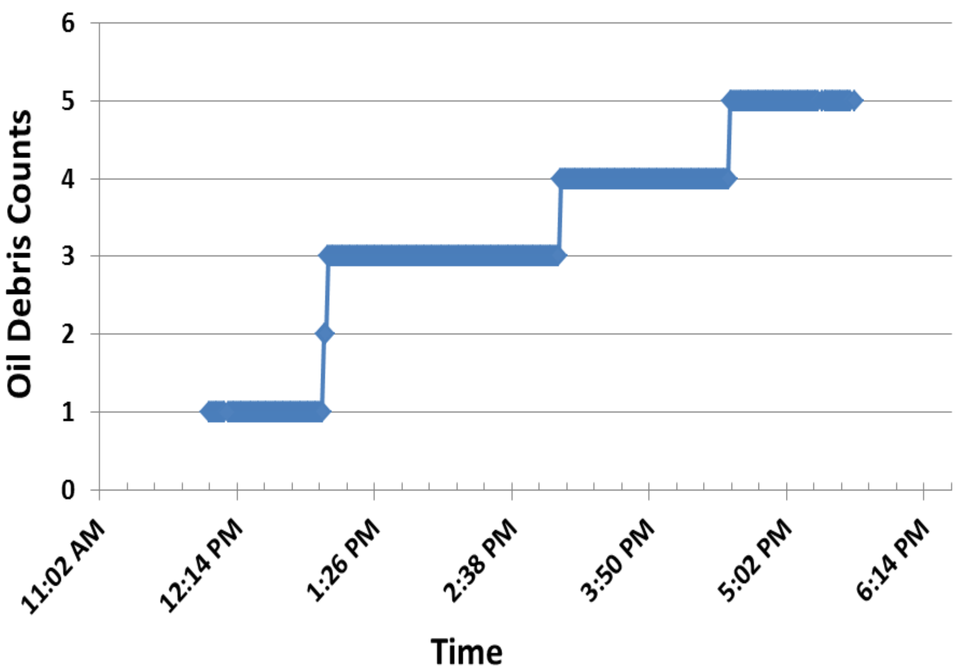
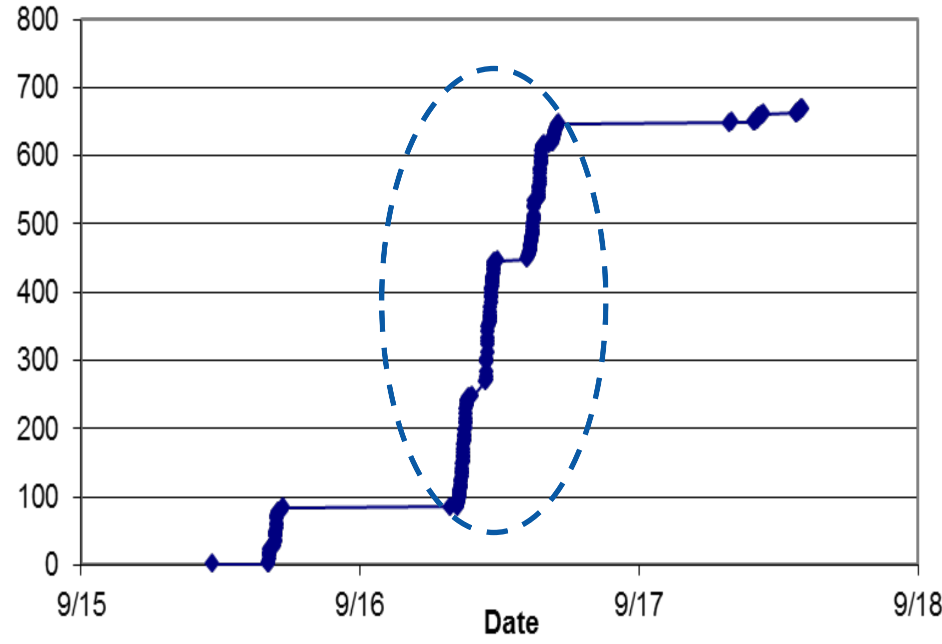


Photo Credit: Adam Johs, EDPR

Gearboxes: Oil Debris Monitoring [17]



Oil debris during the test of a healthy test gearbox



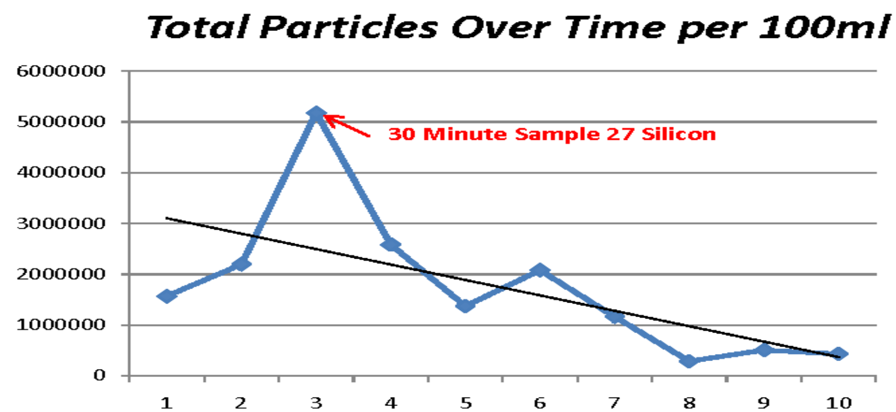
Oil debris during the test of a damaged test gearbox

- Damaged gearbox shed debris much faster:
  - Left (healthy gearbox): about 1 particle per hour
  - Right (damaged gearbox): 70 particles per hour

- Caution:
  - Rely more on the averaged particle generation rates than those calculated in real time

Gearboxes: Oil Sample Analysis [18]

- Results: dynamometer test of the reference gearbox
  - Particle counts: important to identify particle types



ISO 4406 Code

21/17/12
22/18/12
23/22/20
22/21/16
21/18/13
22/18/12
21/17/12
19/15/11
20/17/10
19/17/13

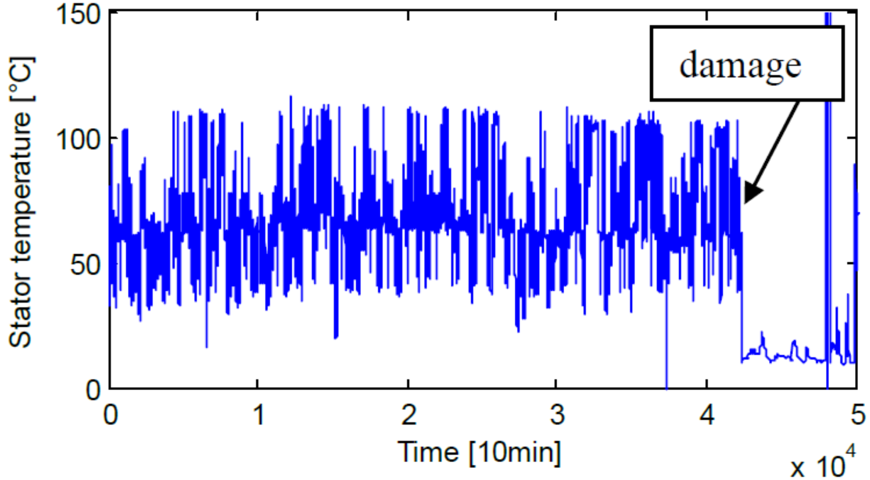
  - Element identification

Metals		Reference Limits	Analysis Results					
Iron ppm		2	<1	1	1	1	1	1
Aluminum ppm		4	<1	<1	<1	<1	<1	<1
Chromium ppm		4	<1	<1	<1	<1	<1	<1
Copper ppm		2	<1	1	1	1	1	1
Lead ppm		1	<1	1	1	1	1	1
Tin ppm		4	<1	<1	<1	<1	<1	<1
Nickel ppm		4	<1	<1	<1	<1	<1	<1
Silver ppm		4.5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Silicon ppm		20	<1	3	4	3	3	5
Sodium ppm			<2	<2	<2	<2	<2	<2
Boron ppm			<1	2	2	1	1	1
Zinc ppm			1	21	24	24	24	29
Phosphorus ppm			4	31	38	31	31	54
Calcium ppm			11	24	27	23	24	24
Magnesium ppm			<1	<1	<1	1	<1	<1
Barium ppm			3	8	9	6	7	7
Molybdenum ppm			<1	11	12	11	11	12
Potassium ppm			<3	<3	<3	<3	<3	<3

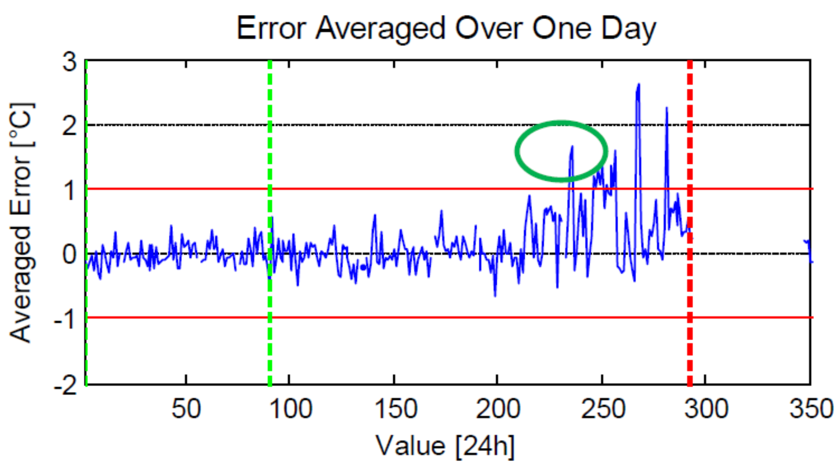
Reference Limits

Analysis Results

Generators: Performance Monitoring [19]



Time series of the stator temperature on a generator



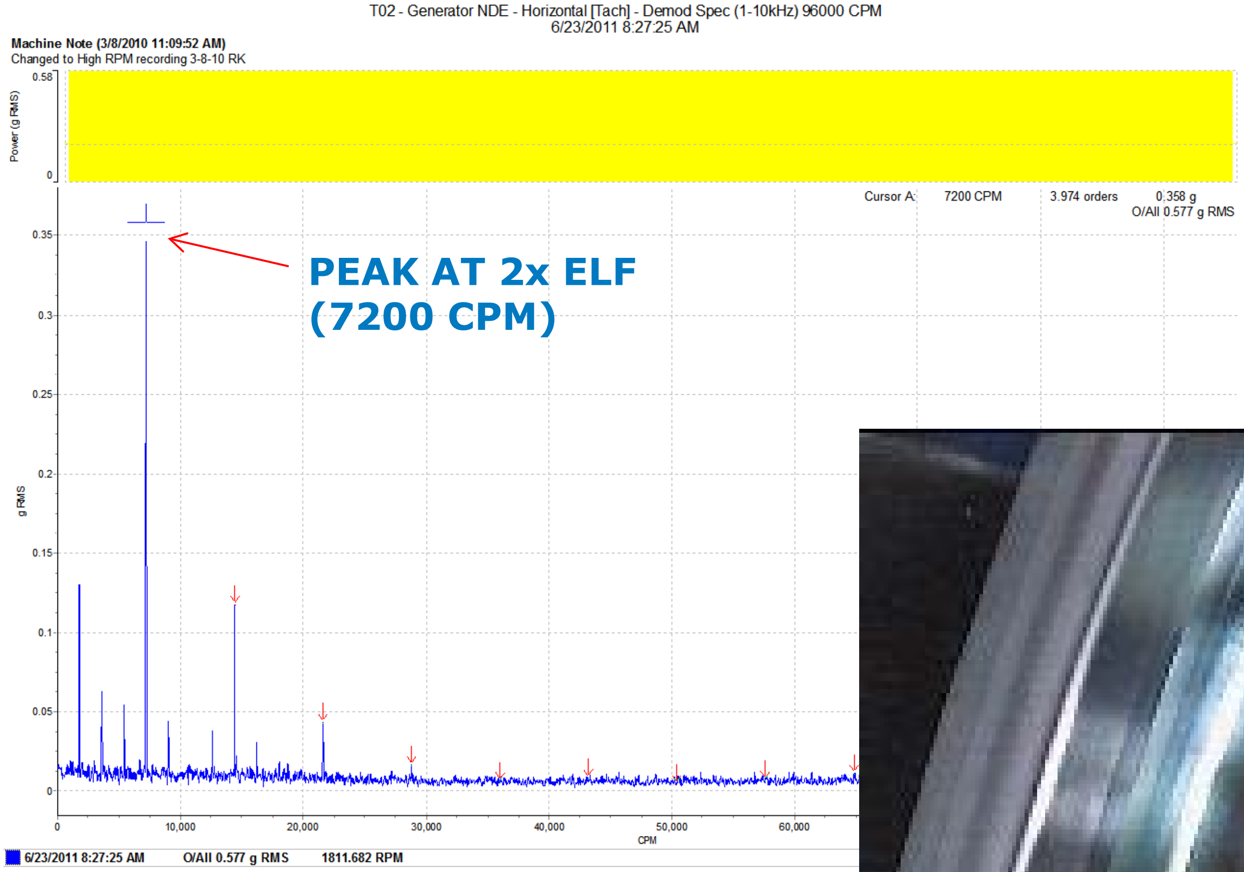
Averaged prediction error for the autoregressive neural network model

- Autoregressive Neural Network Model:
  - Inputs: stator temperature; power output; nacelle temperature; and ambient temperature
  - Output: stator temperature
  - Error: modeled temperature vs. measurements

- Damage: generator replacement

- Model Performance:
  - Accuracy: ±1°C
  - First alarm violation: 59 days ahead
  - Second alarm violation: 48 days ahead

Generators: Condition Monitoring [20]



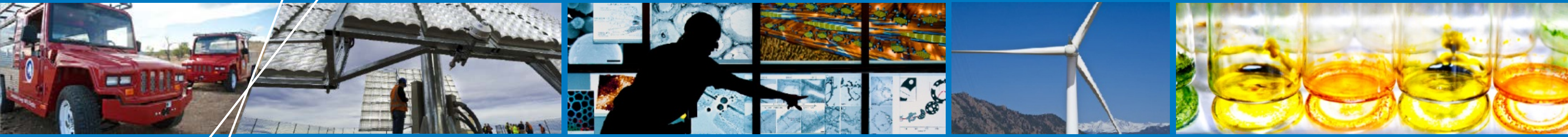
- Electric signature analysis based on numerical simulations or small-scale test rigs not much on utility-scale turbines.

Summary: Performance Monitoring

- Most data analysis techniques can identify abnormal behaviors
- Nonlinear modeling approaches may be more accurate for wind turbine applications. Neural networks-based models are hard to generalize
- Wind speed, power output, and various temperatures are the main parameters investigated. Combining wind speed with air density can improve modeling accuracy
- Temperature is typically a reliable indicator of component failure but may not provide enough lead time to save the monitored component.

Summary: Condition Monitoring

- Most condition monitoring data analysis techniques can help pinpoint specific subsystems/components with faults
- Vibration analysis appears to be the most widely investigated and reported technique. It can monitor the health of most drivetrain, and even turbine, subsystems/components
- Oil debris counting results are easier to interpret and provide unique information on gearboxes (typically the only oil-lubricated subsystem in a wind turbine)
- Shock pulse method may be more effective for the low-speed stage in wind turbine.



Concluding Remarks

Summary

- **Improving turbine component reliability is not a simple task:**
  - Complexity of turbines operating in harsh environments
  - Diverse subsystem/component failure modes with inconsistent definitions
  - Identification of and addressing root causes is time consuming or challenging
  - Performance and condition monitoring data analysis can help
- **Performance monitoring data analysis:**
  - Readily available measured parameters and status codes
  - Initial screening to identify abnormal turbine behaviors
  - Not enough to meet full turbine condition monitoring needs
- **Condition monitoring data analysis:**
  - Covers more failure modes than typical performance monitoring data analysis
  - Pinpoints damaged locations/components and enables condition based maintenance
  - Requires additional investment for instrumentation and resources for data analysis or results interpretation

Future Opportunities

- Field application feasibility study of various data analysis techniques; if not yet feasible but deemed beneficial, investigate enabling approaches
- Data analysis or modeling work that enables remaining useful life estimation of turbine subsystems/components
- Fusion with additional data streams to improve operation & maintenance practices, reduce loads and extend life of turbine subsystems/components
- Conduct root cause analysis, when feasible and economical, address root causes in the field, and provide feedback to subsystem/component suppliers for reliability improvement of future products.

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Thanks for Your Attention!

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