

Wind Turbine Drivetrain Condition Monitoring — An Overview



Photo by Dennis Schroeder, NREL 19018

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**ASME Turbo Expo 2013
June 5, 2013**

San Antonio, TX

NREL/PR-5000-58774

Agenda

- Introduction
- Drivetrain Condition Monitoring (CM)
- Case Studies and Discussions
- Concluding Remarks



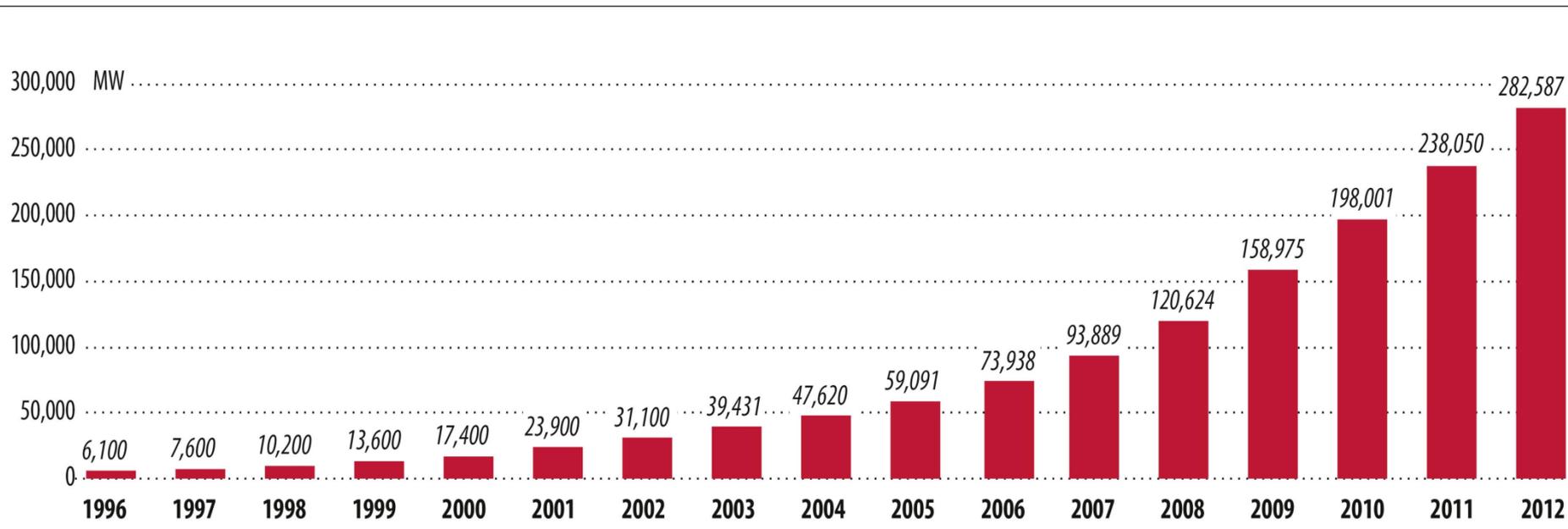
U.S. Department of Energy 1.5-MW wind turbine, Photo by Lee Jay Fingersh, NREL 17245

Introduction

- Global Wind Energy
- Wind Turbine Gearbox Reliability Challenge
- Gearbox Reliability Collaborative
- Benefits of Condition Monitoring
- Operation and Maintenance of Wind Plants

Global Wind Energy [1]

Global Cumulative Installed Wind Capacity 1996-2012

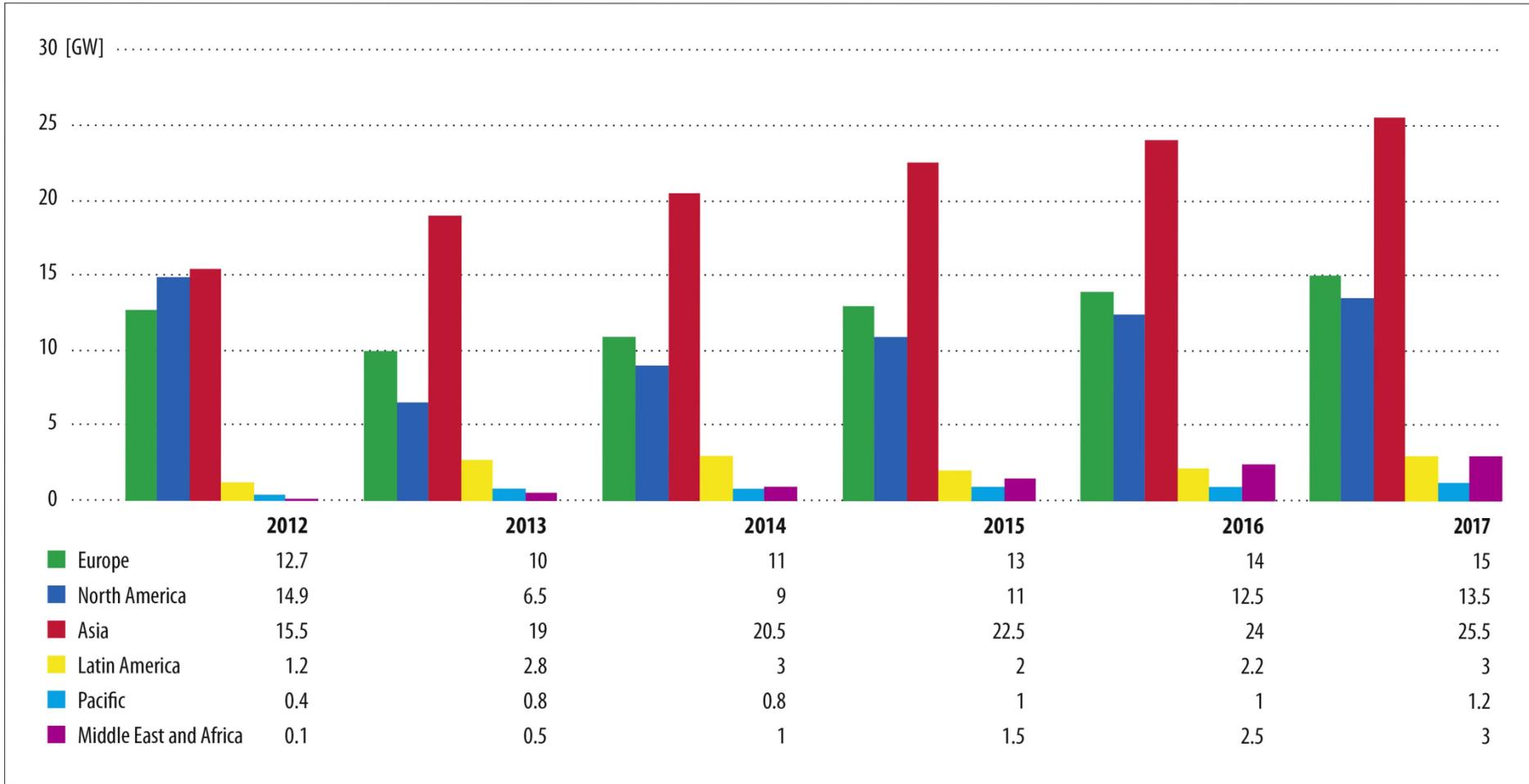


Source: GWEC



Global Wind Energy (Continued) [1]

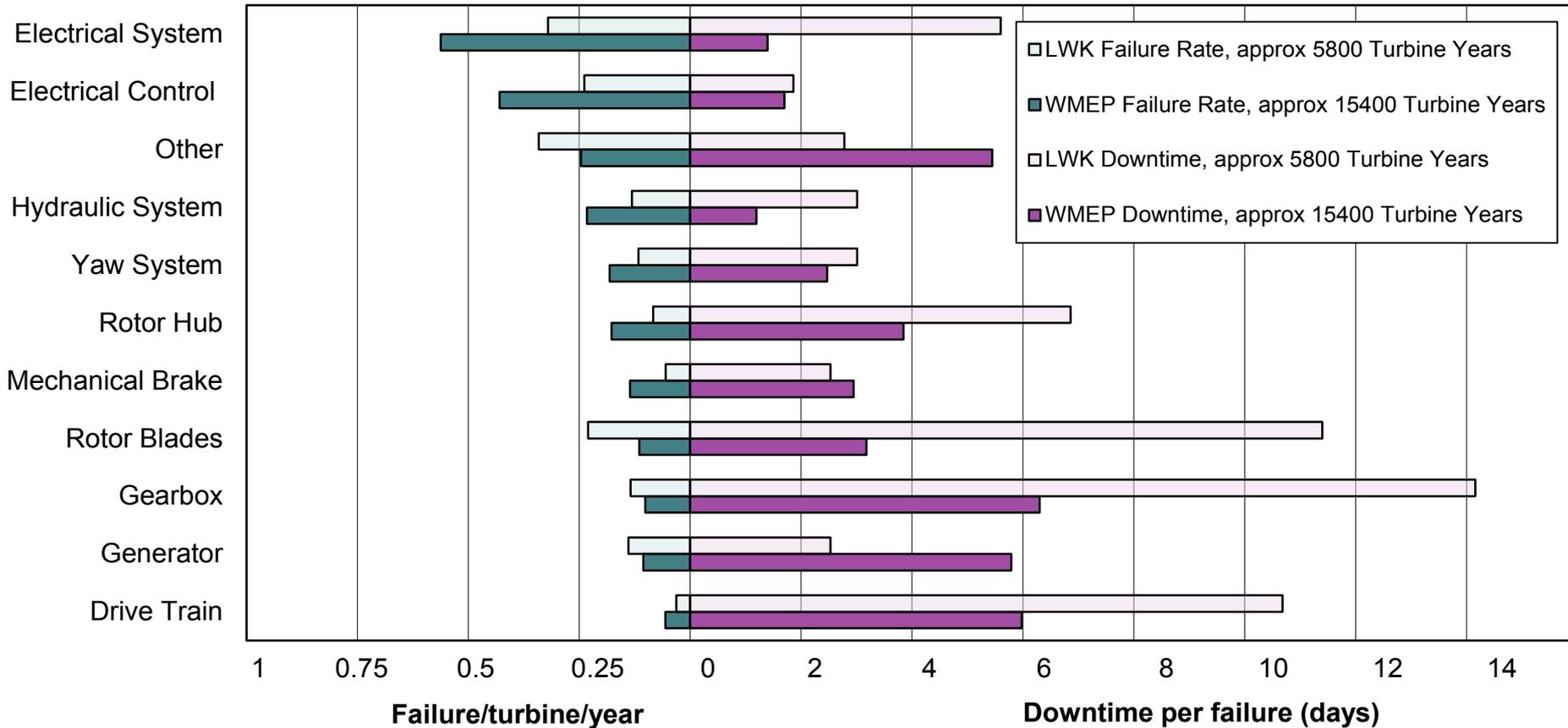
Annual Market Forecast by Region 2012-2017



Source: GWEC

Reliability and Downtime of Turbine Subassemblies [2,3]

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



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

Failure Modes of Wind Turbine Gearboxes

- Gearboxes do not always achieve their 20-year design lifetime

Gearbox Component	Failure Modes
Gear case	Fracture
Suspension	Wear, looseness
Torque arm	Wear, looseness
Lubrication system	Loss of lubricant, contaminated lubricant, aged lubricant, lubricant system failure, lubricant pump failure, blocked lubrication filters, blocked jets
Epicyclic part - planet carrier	Lubrication
Epicyclic part - planet bearing	Bearing failure, lubrication
Epicyclic part - planet gear	Tooth failure, lubrication
Epicyclic part - internal gear	Tooth failure, lubrication, fracture
Epicyclic part - sun gear	Tooth failure, lubrication
Epicyclic part - shaft	Cracking, journal damage
Parallel shaft part - gear	Tooth failure, lubrication
Parallel shaft part - bearing	Bearing failure, lubrication
Parallel shaft part - pinion	Tooth failure, lubrication
Parallel shaft part - shaft	Cracking, journal damage
High-speed shaft	Cracking, permanent bend

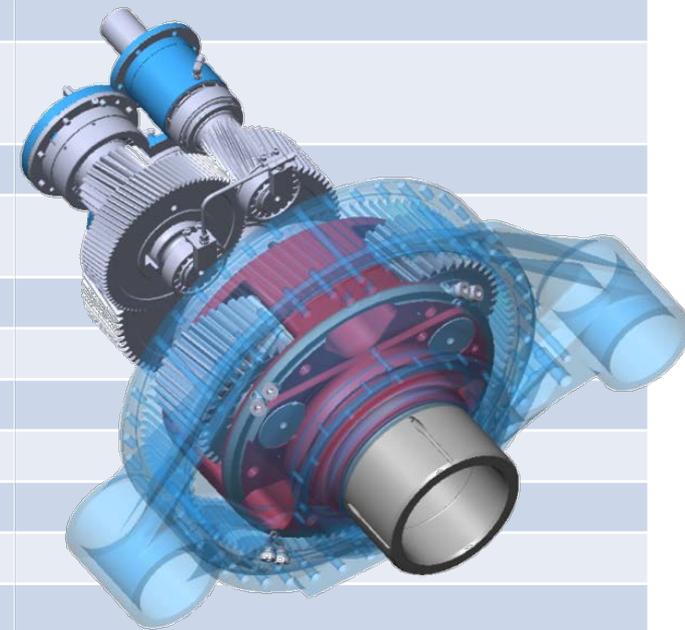
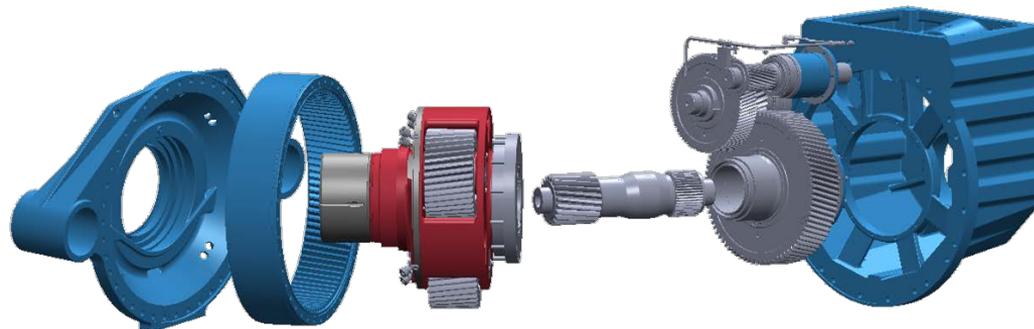
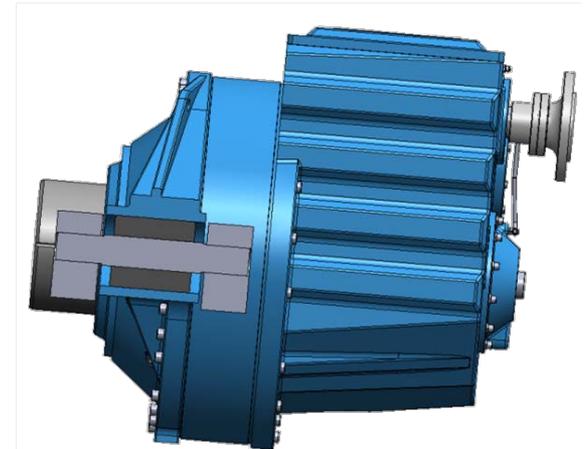


Illustration by NREL

Impact of Gearbox Failures

- Premature failure of gearboxes increases the cost of energy and may include:
 - Turbine downtime
 - Unplanned maintenance
 - Gearbox replacement and rebuild
 - Increased warranty reserves
- The problem:
 - Is widespread
 - Affects most original equipment manufacturers
 - Is not caused by manufacturing practices



Need an industry-wide solution, but ...

Gearbox Reliability Collaborative (GRC)

- Facilitate dialog among all parties
 - Designers and consultants
 - Suppliers and rebuilders
 - Operation and maintenance organizations
- Understand gearbox response to specific loading
 - Pure torque, bending, and thrust (dynamometer)
 - Turbulence (field)
- **Understand** the physics of premature wind turbine gearbox failure
- Identify gaps in the design process
- **Suggest** improvements in design practices and analytical tools

Gearbox Reliability Collaborative (Continued)

- Technical approach
 - Modeling and analysis
 - Field test
 - Dynamometer test
 - Failure database
 - Condition monitoring (CM)
- Goal
 - To improve gearbox reliability and increase turbine availability, which will reduce the cost of energy

Field Test

- Test plan
- Test turbine
- Test setup and execution

Test Turbine at NREL/Photo by Dennis Schroeder, NREL 19022



Dynamometer Test

- Test plan
- Test article
- Test setup and execution



NREL dynamometer/Photo by Lee Jay Fingersh, NREL 16913



Analysis

- Load cases
- System loads
- Internal loads

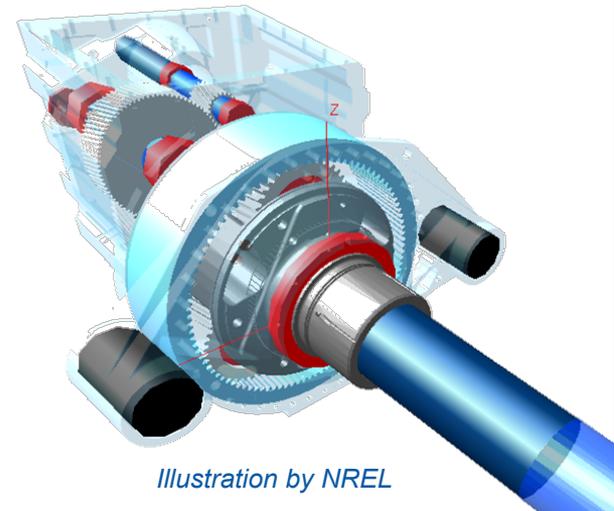


Illustration by NREL

Benefits of Condition Monitoring

- Early deterioration detection to avoid catastrophic failure
- Accurate damage evaluation to enable cost-effective maintenance practices (proactive instead of reactive)
- Increase turbine availability and reduce operation and maintenance costs
- Root cause analysis to recommend improvements in component design or equipment operation and control strategies



Test turbine at Ponnequin/Photo by Jeroen van Dam, NREL 19257

Operation and Maintenance of Wind Plants

- Operation and maintenance (O&M) research needs:
 - A globally installed capacity of ~280 gigawatts (GW); majority of which are out of warranty
 - A 1% performance improvement: ~\$88.2 billion additional revenue [assumed: 30% capacity factor, \$120/megawatt-hour (MWh) electricity rate]
 - Extremely high replacement costs for most subsystems

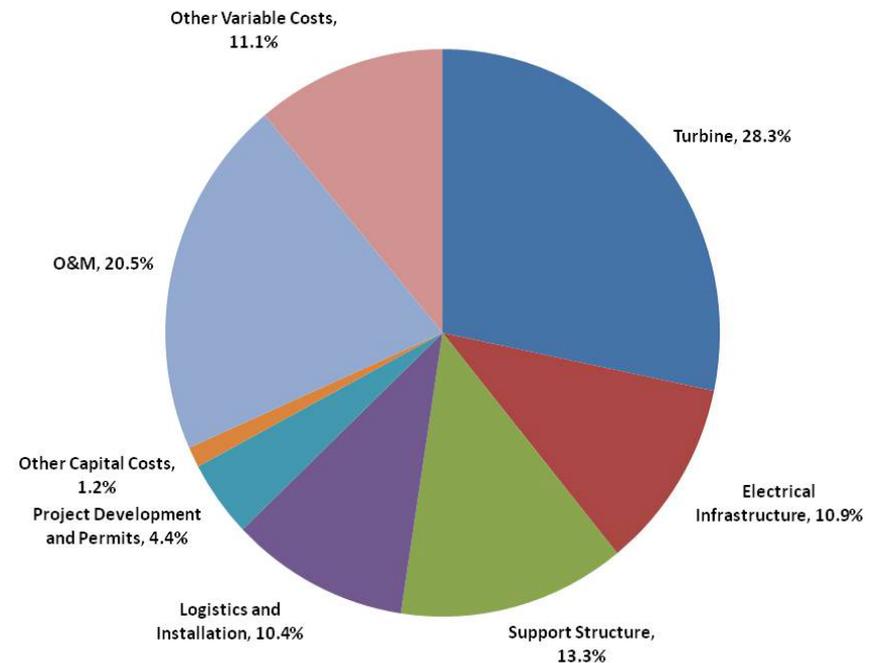


Land-based wind plant / Photo by David Hicks, NREL 18453

- Example replacement costs for a 5-megawatt (MW) wind turbine [4]:
 - For a rotor: \$1.9–\$2.3 million
 - For a blade: \$391,000–\$547,000
 - For a blade bearing: \$62,500–\$78,200
 - For a gearbox: \$628,000
 - For a generator: \$314,000
 - For electronic modules: \$16,000

O&M of Wind Plants (Continued)

- O&M cost reduction opportunity:
 - Is ~21% for offshore plants
 - Is ~11% for land-based plants
 - Could be further reduced if O&M practices are improved, by:
 - Considering performance monitoring for operation
 - Introducing condition-based maintenance
 - And so on...
- CM is an enabling technique with significant opportunity in offshore plants because of accessibility challenges



Estimated life cycle cost breakdown for a baseline offshore wind project [5]

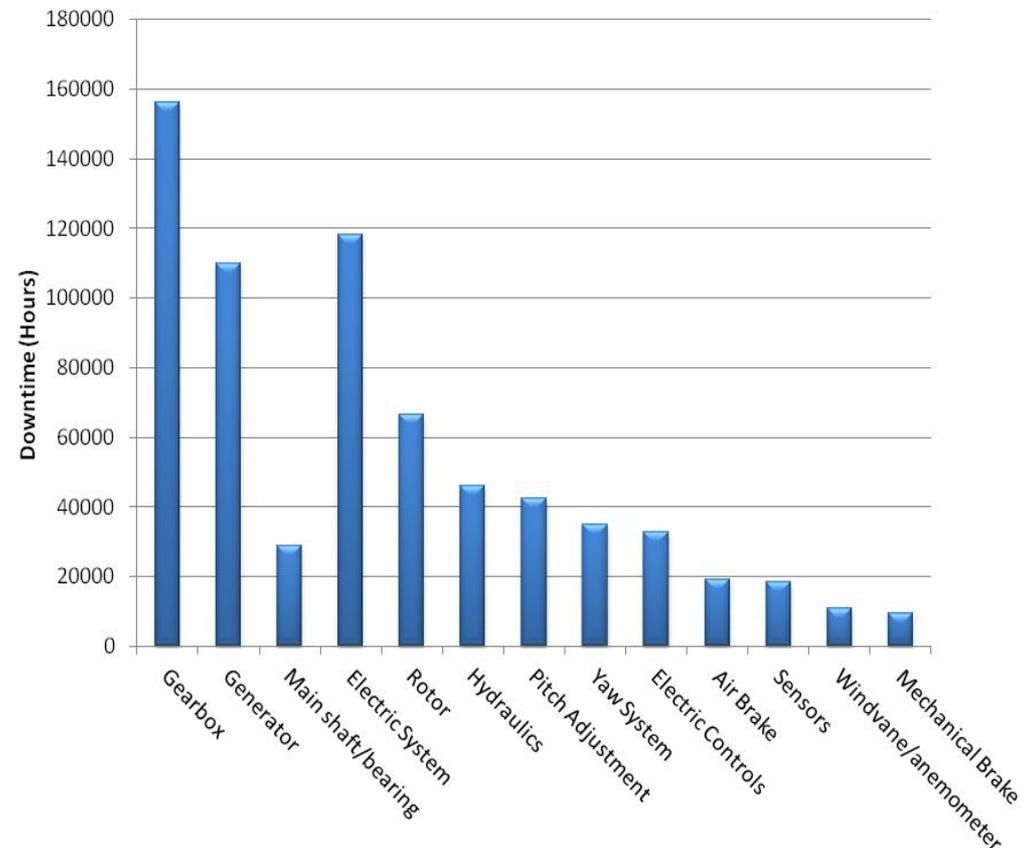
Drivetrain Condition Monitoring

- Downtime caused by turbine subsystems
- Typical drivetrain CM practices



Downtime Caused by Subsystems

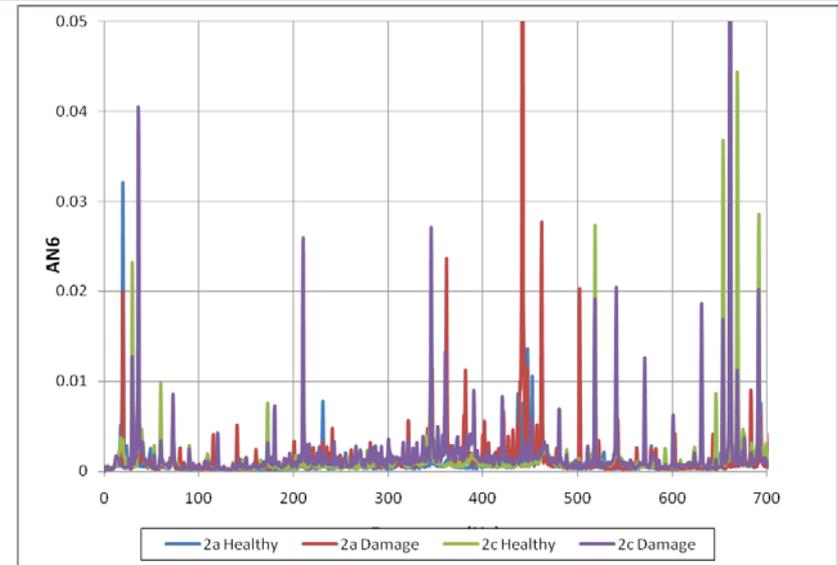
- Data source: Wind Stats Newsletter, Vol. 16, Issue 1 to Vol. 22 Issue 4, covering 2003 to 2009 [6]
- Based on the data reported to Wind Stats for the first quarter of 2010, the data represents about 27,000 turbines, ranging from 500 kW to 5 MW
- Top three:
 1. Gearbox
 2. Generator
 3. Electric Systems
- Consider crane cost:
 - Main bearing also needs attention
 - Electric systems often do not need an expensive crane rental



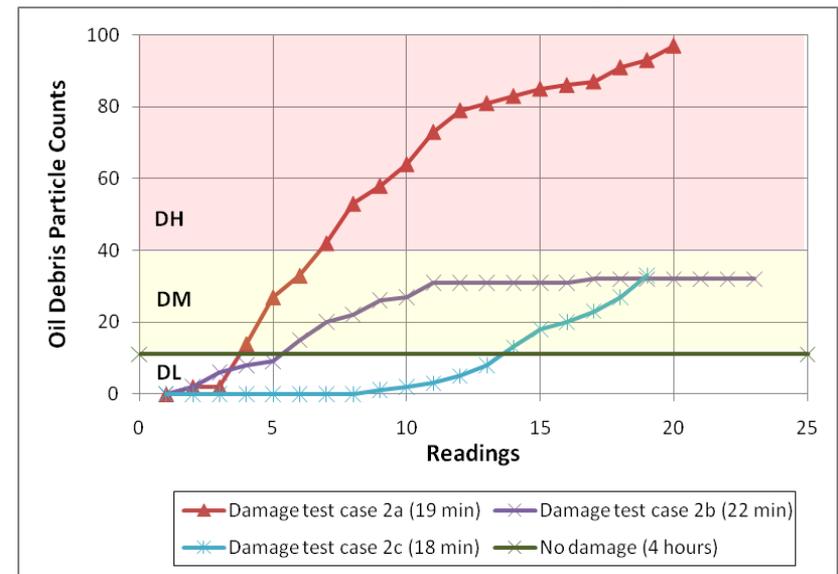
Downtime caused by turbine subsystems [7]

Typical Drivetrain CM Practices

- Techniques
 - Supervisory control and data acquisition (SCADA) data
 - Acoustic emission (e.g., stress wave) analysis
 - Vibration analysis
 - Oil or grease analysis
 - Filter element
 - Electric signature
- Real-time continuous or offline periodic
- One or a combination of several



Sample vibration spectra [8]



Sample oil debris counts [8]

Case Studies and Discussions

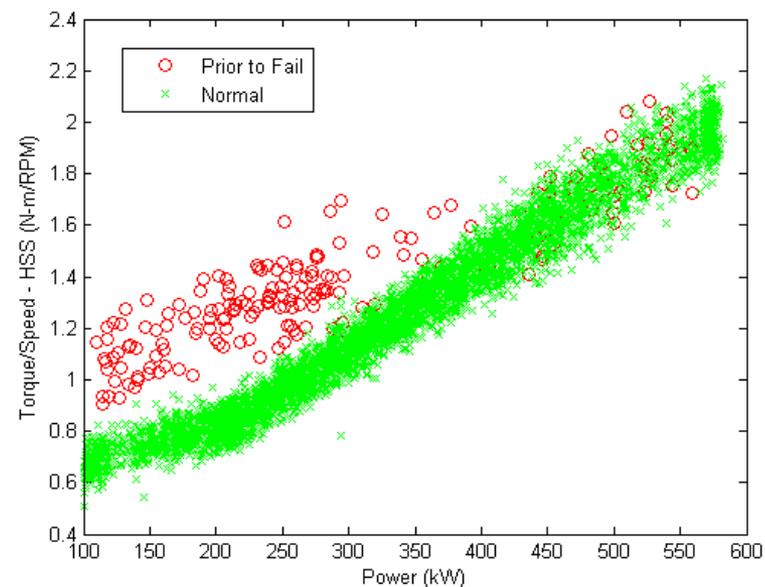
- A 600-kilowatt (kW) test turbine
 - SCADA data
- A 750-kW test gearbox
 - Stress wave analysis
 - Vibration analysis
 - Oil debris monitoring
 - Oil condition monitoring
 - Oil sample analysis
- A 1.5-MW test turbine
 - Filter element analysis
- A 30-kW test rig
 - Electric signature analysis



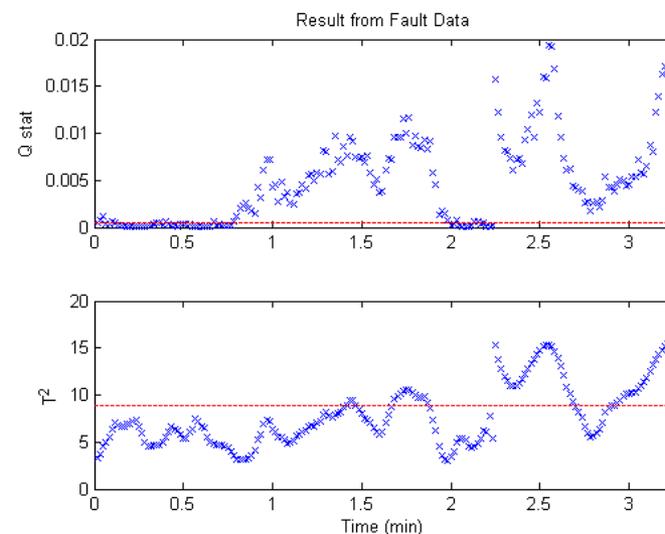
Wind turbines at the National Wind Technology Center,
Photo by Dennis Schroeder, NREL 21928

SCADA Data

- A 600-kW test turbine experienced gearbox damage and replacement
- SCADA data:
 - Readily available and no need of investment on dedicated CM systems
 - Beneficial for identifying outliers by looking at key performance parameters, e.g., power
 - Temperature channels may be used for CM of main bearings, generator bearings, and gearbox high-speed stage bearings, and so on
 - Not straightforward in pinpointing exact damaged subsystems/components



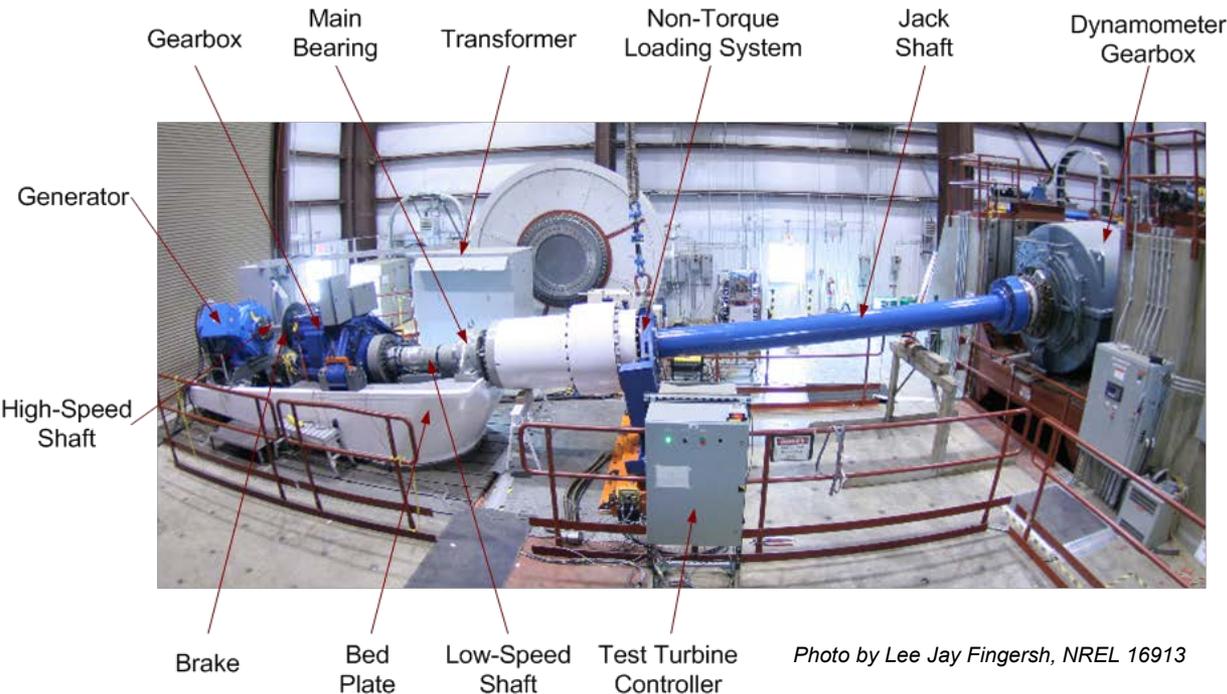
Torque to high-speed shaft speed ratio vs. power [9]



Q-Stat and T^2 values for baseline and fault cases [9]

A 750-kW Test Gearbox

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

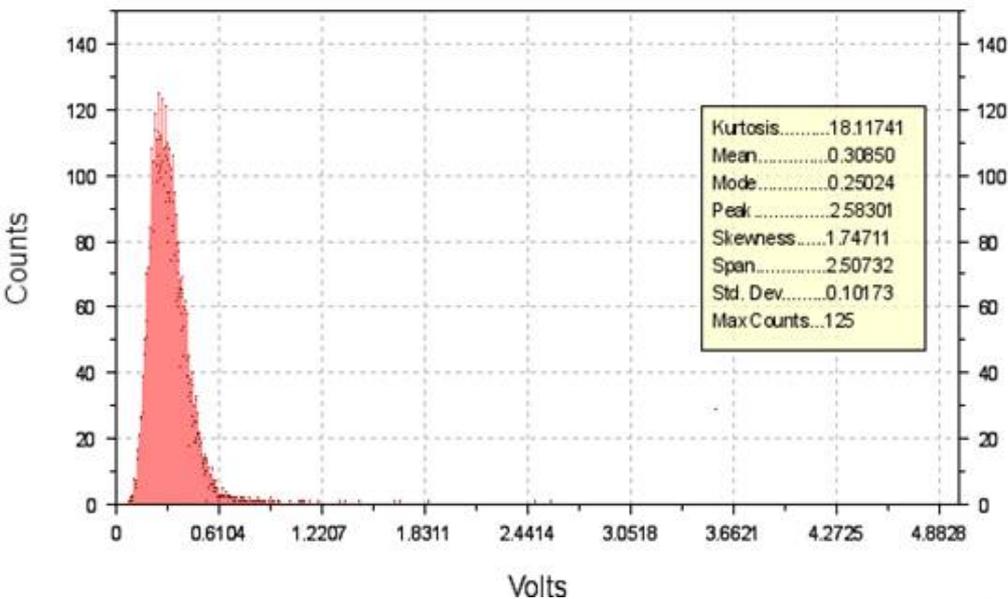


High-speed stage gear damage

Photo by Robert Errichello, NREL 19599

Stress Wave Analysis [10]

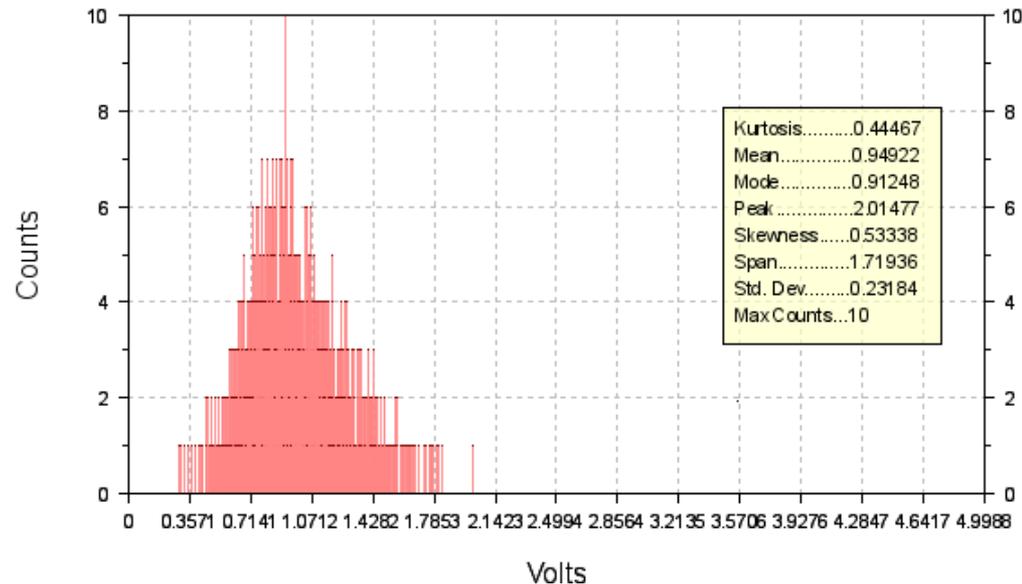
Date Recorded: 11/11/09 19:35:55



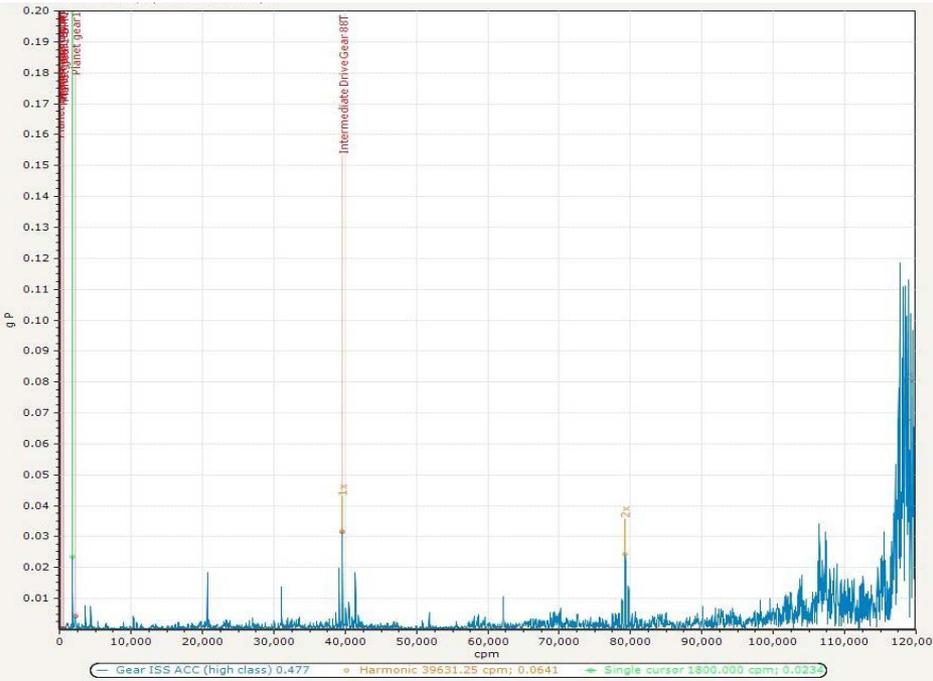
- Parallel stages sensor
- Stress wave amplitude histogram [11]
- Dynamometer test of a reference gearbox of the same design (left) indicates healthy gearbox behavior

- Dynamometer retest of the damaged gearbox (right) indicated abnormal gearbox behavior: distorted distribution and relatively higher amplitudes

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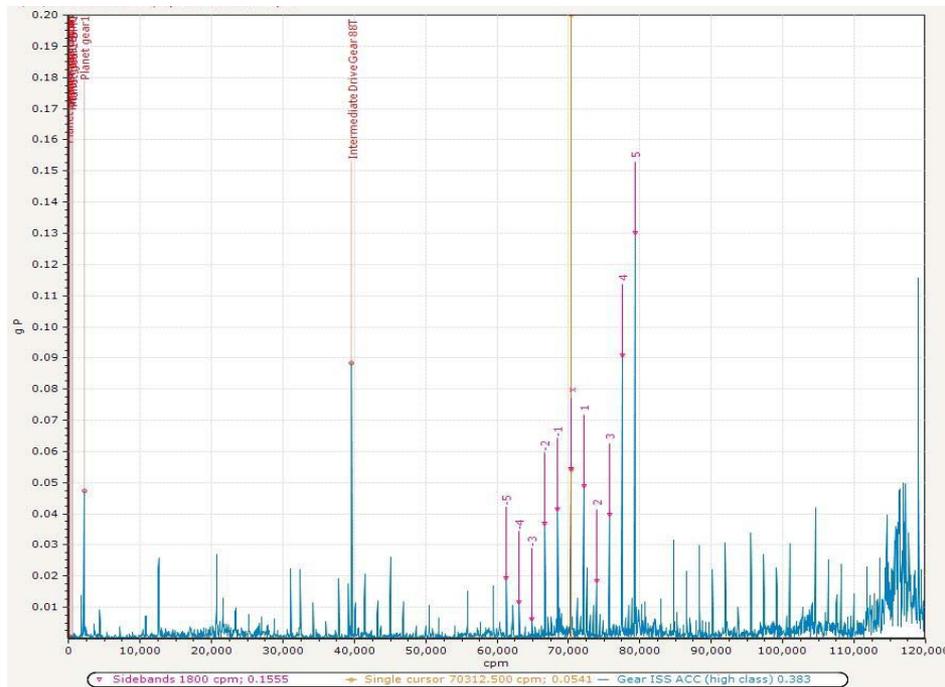


Vibration Analysis [10]



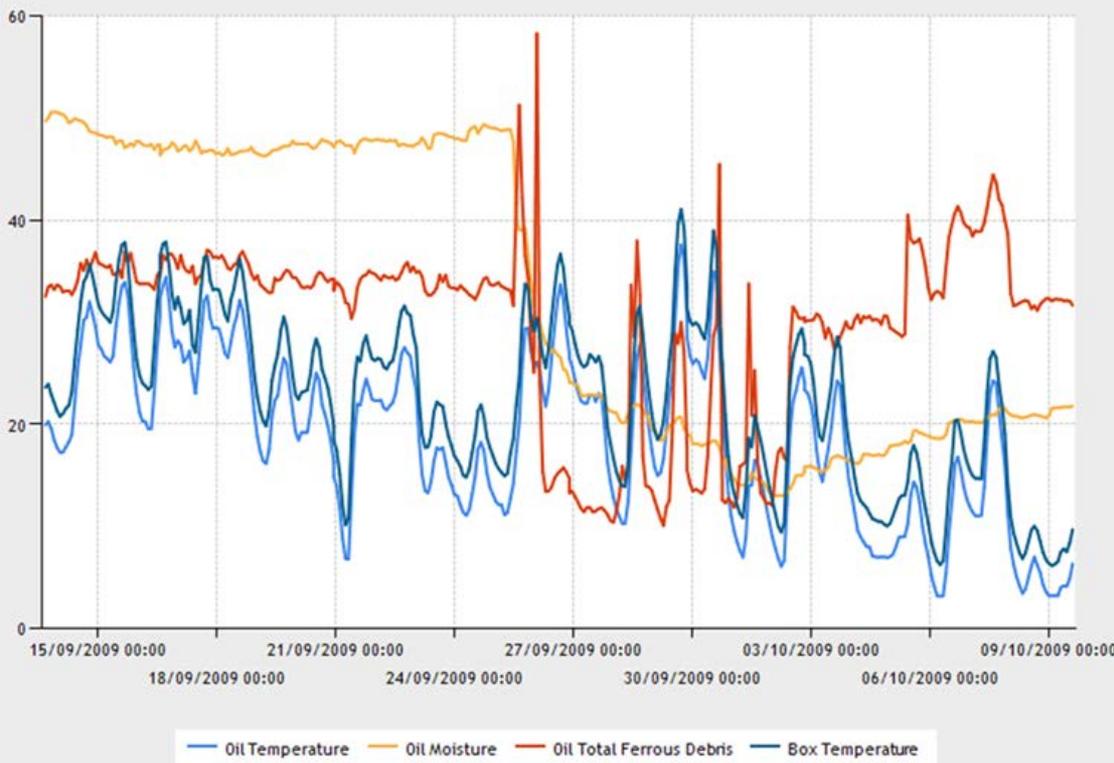
- Intermediate speed shaft sensor
- Dynamometer test of the same reference gearbox (left) indicated healthy gearbox behavior

- Dynamometer retest of the damaged gearbox (right) indicated abnormal behavior
 - More side band frequencies
 - Elevated gear meshing frequency amplitudes

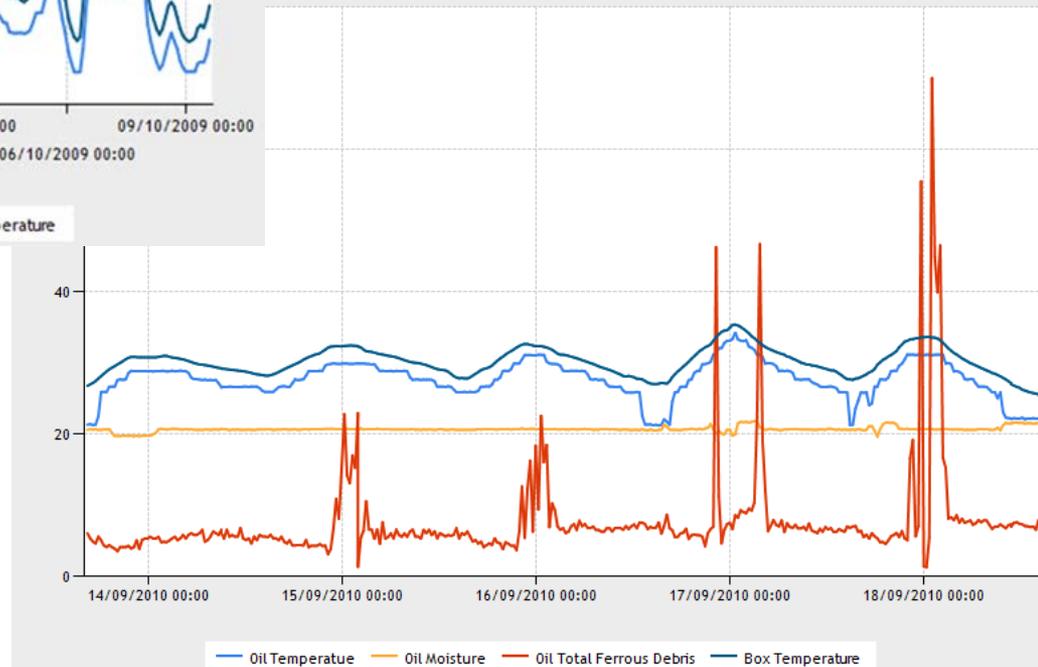


Oil Condition Monitoring (Continued)

- Field test of the test gearbox (left):
 - Wild dynamics
 - Possible damage



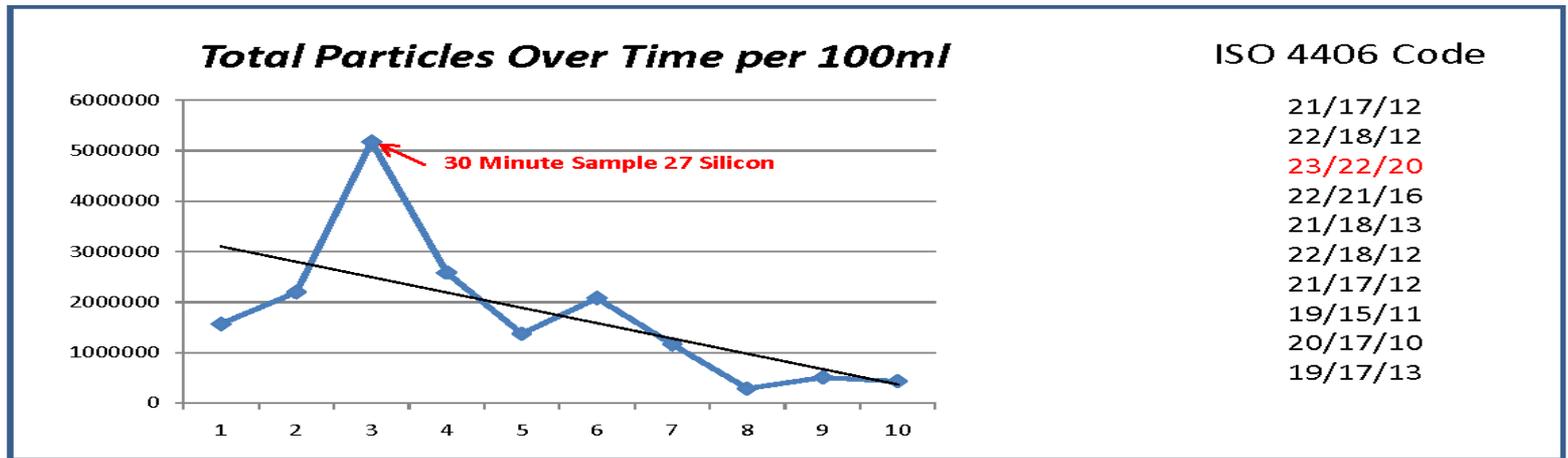
Dyno 2 Total Ferrous Debris
Mon 13 September 2010 - Sat 18 September 2010



- Dynamometer retest (right):
 - Well-controlled test conditions
 - Possible damage

Oil Sample Analysis [12]

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



Element identification

Metals	Reference Limits	Analysis Results
Iron ppm	2	<1
Aluminum ppm	4	<1
Chromium ppm	4	<1
Copper ppm	2	1
Lead ppm	1	1
Tin ppm	4	<1
Nickel ppm	4	<1
Silver ppm	4.5	<1
Silicon ppm	20	<0.1
Sodium ppm	<2	<2
Boron ppm	<1	2
Zinc ppm	1	21
Phosphorus ppm	4	31
Calcium ppm	11	24
Magnesium ppm	<1	<1
Barium ppm	3	8
Molybdenum ppm	<1	11
Potassium ppm	<3	<3

A 1.5-MW Test Turbine [13]

- U.S. Department of Energy (DOE) 1.5-MW GE Turbine
 - Model: GE 1.5 SLE
 - Tower height: 80 m
 - Rotor diameter: 77 m
 - Located at the National Wind Technology Center at the National Renewable Energy Laboratory in Colorado
 - DOE-owned
 - Used for research and education



Filter Element Analysis [13]

- Direct reading Ferrography results normal
- Important spectrometer results (ppm): Fe = 22, Cu = 36, Zn = 1621 (Additive masks alloy)
 - Hard to conclude the debris includes brass and steel
- Filter element analysis
 - Indicated high level of brass and steel
 - Uncovered what might not be detectable by a conventional oil sample analysis

Classification Rules

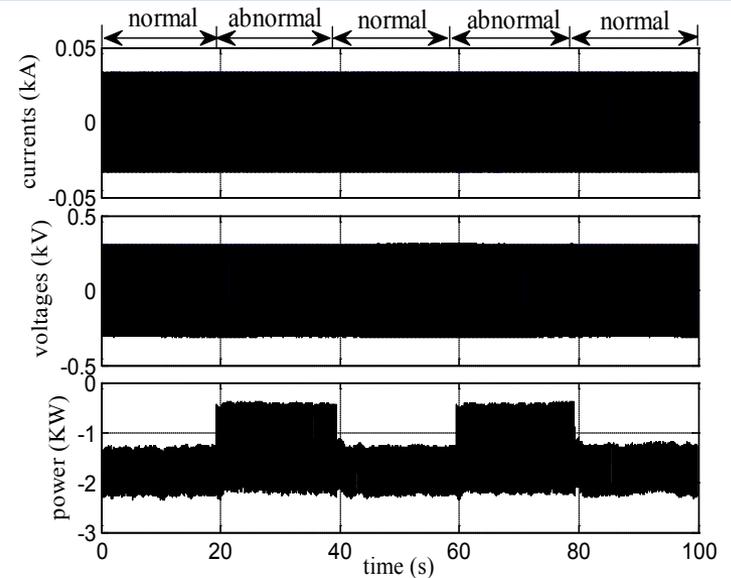
Classification	Rule
Barium	Ba >40%
Brass	Cu + Zn >40% and Cu >10%
Zinc	Zn >40%
Iron Oxide	Fe >30% and O >15%
Steel	Fe >30%
Additives	S + P + Zn >50%
Silicates	Si >5%
Miscellaneous	All remaining particles

Main Loop Filter Element Analysis

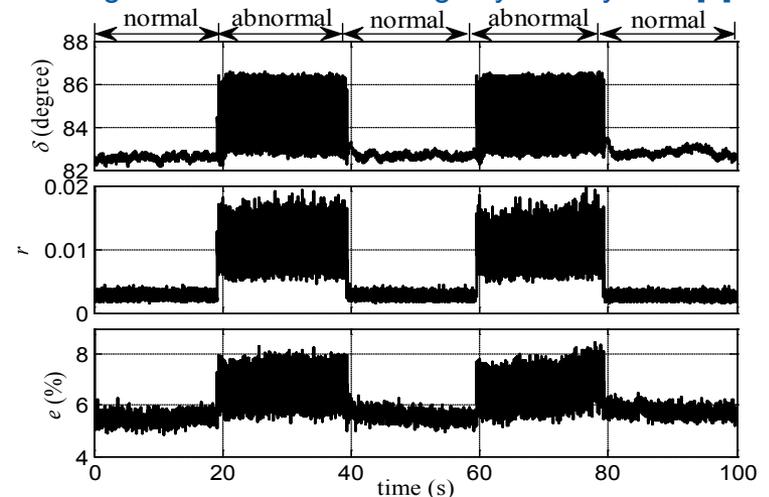
Element	Brass	Zinc	FeO	Steel	Total
Cr	0.0	0.1	0.0	2.2	0.2
Mn	0.1	0.1	0.3	0.1	0.1
Fe	0.8	2.9	59.9	81.8	8.9
Co	0.1	0.5	0.3	0.6	0.2
Ni	0.3	0.5	0.7	0.9	0.4
Cu	46.6	4.5	1.5	1.7	39.6
Zn	38.5	57.5	3.6	5.4	35.1

Electric Signature Analysis

- Did not reveal many fault signatures in the 750-kW damaged gearbox test
- In literature, electric signature analysis has mainly been explored based on generator test rigs or small-scale wind turbines for generators CM [14]
 - Power signals appeared more effective than either currents or voltages [15]
 - Capable of detecting both mechanical and electrical faults seen in generators [15]
 - Not considered to be a suitable alternative to vibration monitoring in geared wind turbines [16]
- May have potential for direct-drive wind turbine drivetrain CM, as generators will replace gearboxes to become the critical component



Electric signals collected from a 30-kW generator test rig with simulated winding asymmetry fault [4]



Faults indicated by three different CM criteria [4]

Discussions

- SCADA data are beneficial for identifying abnormal turbines by tracking key performance parameters, but are limited when carrying out a full condition monitoring of wind turbine subsystems/components.
- Temperature channels may be used for the CM of main bearings, generator bearings, or gearbox high-speed stage bearings, and so on.
- Stress wave analysis (amplitude histogram) appears effective for detecting gearbox abnormal health conditions, but the sensors may be prone to environmental noises.
- Spectrum analysis of the vibration signal (or stress waves) can, to a certain extent, pinpoint the location of damaged gearbox components, but may have challenges with low-speed components, such as gearbox planet stage bearings or main bearings.

Discussions (Continued)

- Oil debris monitoring, specifically particle counts, is effective for monitoring gearbox component damage, but not effective for pinpointing damage locations
- Damaged gearbox releases particles at increased rates
- Oil condition monitoring, specifically moisture, total ferrous debris, and oil quality:
 - Oil total ferrous debris appears indicative for gearbox component damage
 - More data is required to understand oil moisture and quality
- When obtaining particle counts through oil sample analysis, attention should be given to identifying particle types
- Periodic oil sample analysis may help pinpoint failed component and root cause analysis

Discussions (Continued)

- Filter element analysis may reveal what is typically missed in conventional oil sample analysis
- Electric current analysis appears effective for generator mechanical and electric fault detections:
 - Only verified on laboratory test rigs or small-scale wind turbines thus far
 - Some validations on utility-scale wind turbines are needed before the technique can have a bigger impact
 - Direct-drive wind turbines may present a good opportunity for electric signature analysis
- Given the diverse and complex failure modes seen in wind turbine drivetrains, an integration approach is recommended, starting with an initial digest of SCADA data and then fusing several dedicated techniques by considering their advantages and disadvantages.

Concluding Remarks

- Challenges
- Future research and development areas



Offshore wind turbine/Photo by Eric Nelson, NREL 21965

Challenges [17]

- Justification of cost benefits for CM: each wind turbine has a relatively lower revenue stream than traditional power generation and site variations
- Limited machine accessibility: makes retrofitting of CM systems or taking oil/grease samples difficult
- Cost-effective and universal measurement strategy: sensor readings are affected by mounting locations and various drivetrain and gearbox configurations
- Diagnostics: variable-speed and load conditions and very low rotor speeds challenge traditional diagnostic techniques developed for other applications

Challenges (Continued) [17]

- Data interpretation for both SCADA and dedicated CM systems: requires expert assistance for data analysis and maintenance recommendations
- Oil sample analysis: sample variations, different lubricant may require different sets of tests or procedures
- Additional complexity for offshore: foundation, undersea transmission lines, saltwater and wave influences on turbine, and weather forecast
- The limitations of existing industry standards in the application to wind industry

Future Research and Development Areas [17]

- Research on improved use of SCADA data
- Determine cost-effective monitoring strategy
- Improve accuracy and reliability of diagnostic decisions, including level of severity evaluation
- Automate data interpretation to deliver actionable maintenance recommendations
- Develop reliable and accurate prognostic techniques
- Research fleet-wide condition monitoring and asset management
- Improve turbine operation, control strategy, and component design through root cause analysis

Challenging yet rewarding

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Thanks for Your Attention!

Special thanks go to DOE and the condition monitoring research partners!



HC Sorensen, Middelgrunden Wind Turbine Cooperative, Photo by HC Sorensen, NREL 17855

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