U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Wind Turbine Drivetrain Reliability

Project ID #T15

Jonathan Keller

NREL

FY17-FY18 Wind Office Project Organization

"Enabling Wind Energy Options Nationwide"

Technology Development

- Atmosphere to Electrons
- Offshore Wind
- Distributed Wind
- Testing Infrastructure
- Standards Support and International Engagement
- Advanced Components, Reliability, and Manufacturing

Market Acceleration & Deployment

- Stakeholder Engagement, Workforce Development, and Human Use Considerations
- Environmental Research
- Grid Integration
- Regulatory and Siting

Analysis and Modeling (cross-cutting)

Project Overview

T15: Wind Turbine Drivetrain Reliability

Project Summary

- Conduct drivetrain validation testing and analysis to characterize failure modes and predict remaining useful life, thereby improving drivetrain reliability, availability, and reducing wind plant operations and maintenance (O&M) costs. The predominant failure modes are not accounted for in design standards, not attributable to quality control, and not specific to individual component suppliers.

Project Objective & Impact

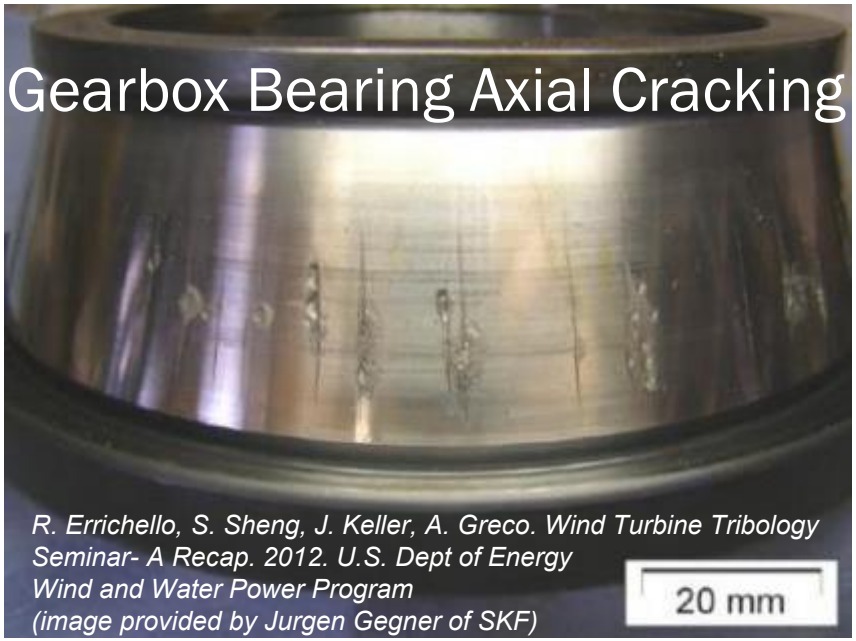
- Wind plant O&M is a $2B to $3B annual market in the United States, consumes up to one-half of revenue, and will increase as wind plants age. Owners and operators report a large portion of these costs are related to drivetrain reliability.
- Increasing reliability is the primary means to reduce O&M costs for the existing land-based fleet and is even more critical for offshore wind plants.

Project Attributes

Project Principal Investigator(s)
Jonathan Keller – NREL Shawn Sheng – NREL Aaron Greco – ANL
DOE Lead
Bradley Ring
Project Partners/Subs
Shawn Doner – Flender Corporation David Vaes – SKF GmbH Dayananda Raju – SKF USA Doug Lucas – The Timken Company Kuba Rydel – Afton Chemical
Project Duration
2 years

Technical Merit and Relevance

- **O&M costs are an important part of cost of energy!**
  - U.S. market is $2B–$3B; may be $4B in 2025
  - Up to 50% of the power purchase agreement price
  - Predominant failures are not accounted for in design standards, or preventable using current technologies



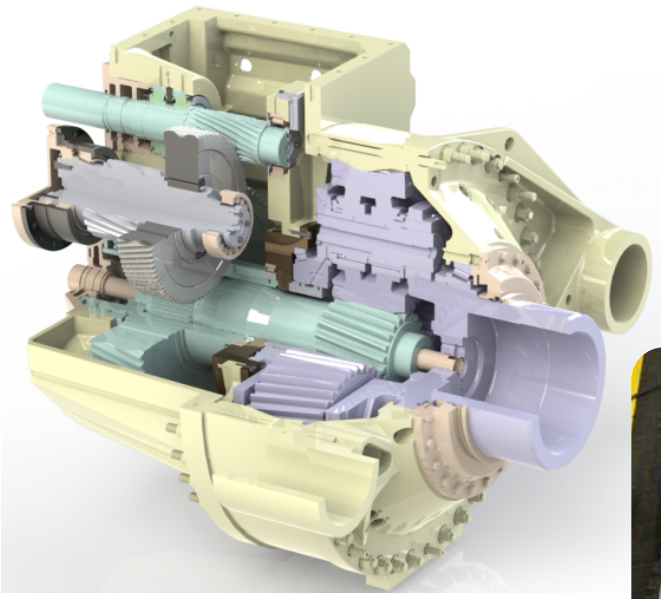
R. Errichello, S. Sheng, J. Keller, A. Greco. Wind Turbine Tribology Seminar- A Recap. 2012. U.S. Dept of Energy Wind and Water Power Program (image provided by Jurgen Gegner of SKF)

Main Bearing Wear

D. Brake. WTG SRB Main Bearing Failures. Presented at the 2013 UVIG Wind Turbine/Plant Operations & Maintenance Users Group Meeting.

Approach and Accomplishments

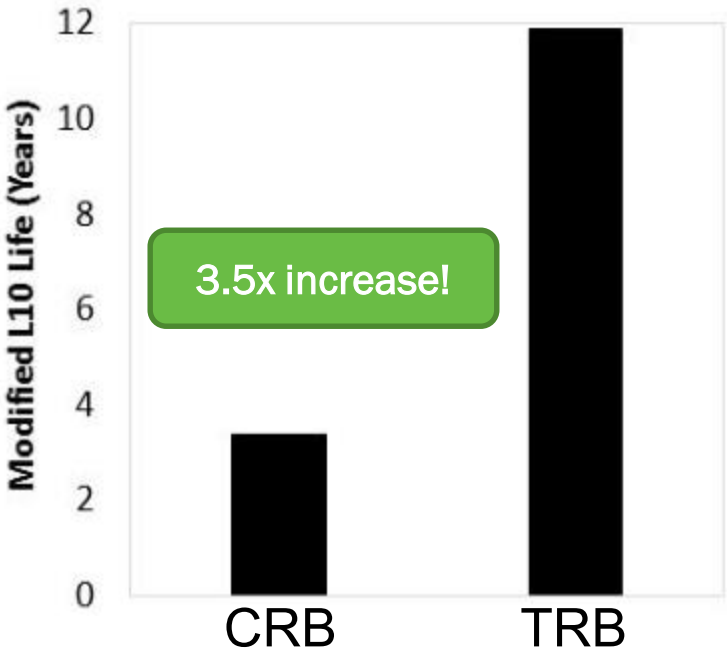
- **Planetary Bearing Load Sharing**
  - Load-sharing improvement demonstrated, 3x L10 increase



750-kW Gearbox

Photo by Jonathan Keller, NREL 36523

Photo by Jonathan Keller, NREL 36524



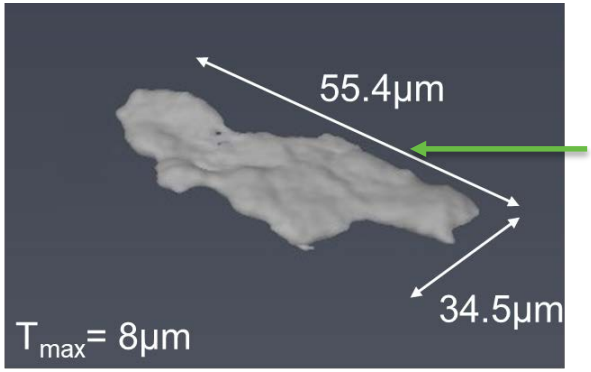
  - Project concluded mid-FY17 with summaries at U.S. and European drivetrain conferences, and Wind Energy Science article. All models and dynamometer test data public.

Approach and Accomplishments

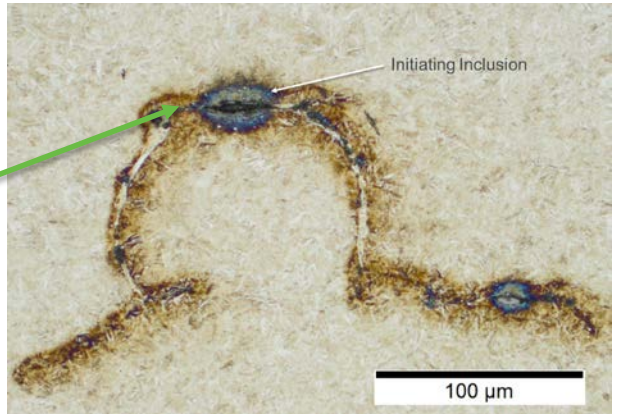
- **Gearbox Bearing Axial Cracking – Failure Analysis**
  - Advanced material characterization of white etching cracks

X-ray tomography of WEC

Argonne's Advanced Photon Source



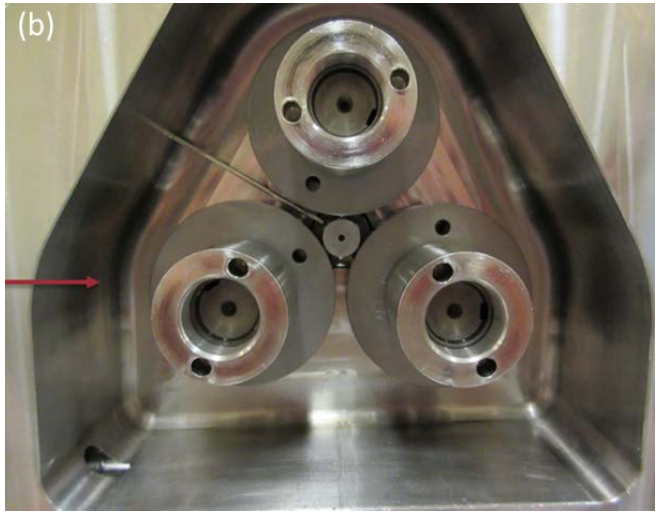
Specific inclusion type identified as WEC initiators



Approach and Accomplishments

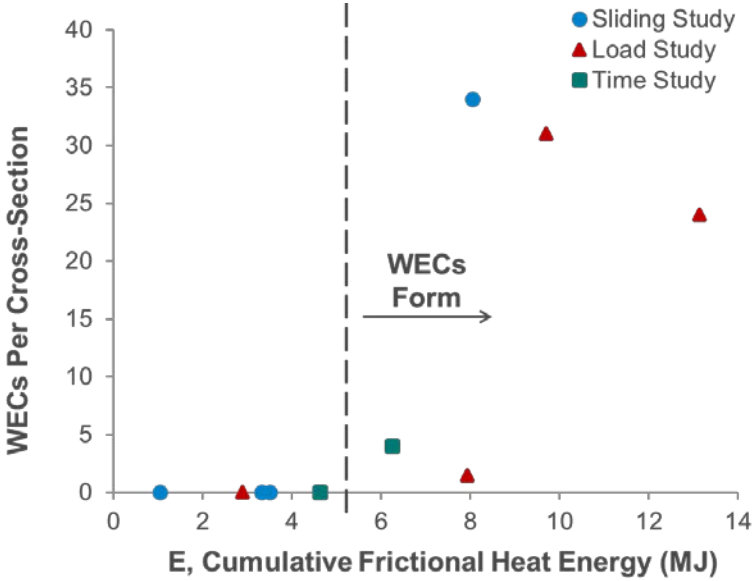
- **Gearbox Bearing Axial Cracking – Benchtop Testing**
  - Accelerated benchtop test method developed to replicate WECs
  - Discovered frictional energy criteria for WEC failures

Benchtop test rig



Frictional energy criteria

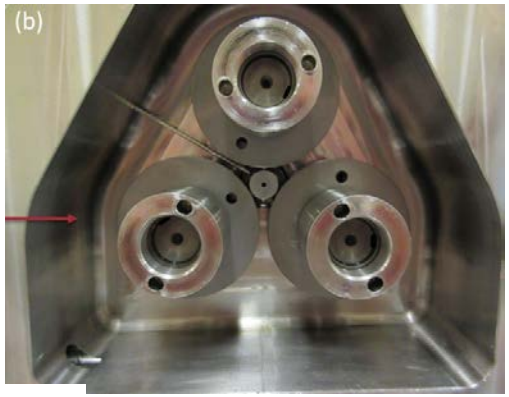
$$E \propto Sliding\ Velocity \cdot Friction\ Coef \cdot Load \cdot Duration$$

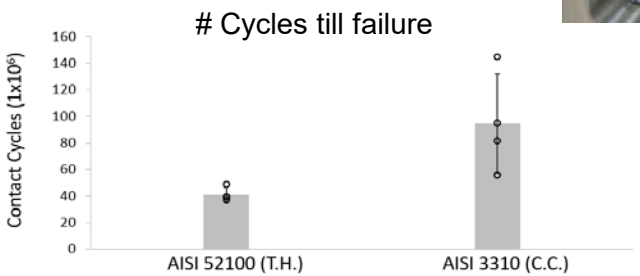


Approach and Accomplishments

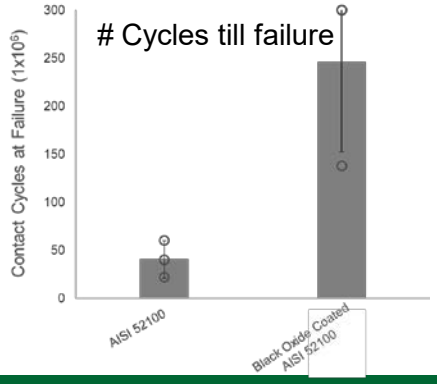
- **Gearbox Bearing Axial Cracking – Initial testing on mitigation technologies**
  - Benchtop testing of material-based mitigation technologies
  - Both technologies prolonged time to WEC failure

Case Carburization





Black Oxide Treatment



Approach and Accomplishments

- Gearbox Bearing Axial Cracking – Uptower Testing

Photos by Jonathan Keller, NREL 40979 and 40981

Standard bearings

- Black oxide coating
- One magnetized roller -> roller speed
- Pin in cage -> cage speed
- Encoder on shaft -> shaft speed
- Measurements yield sliding speed

Strain gages yield roller load

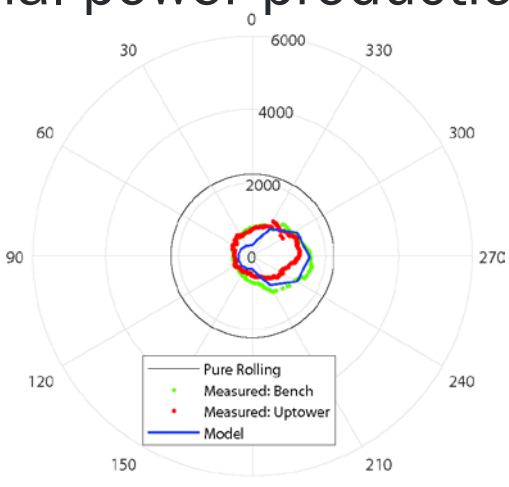
Photo by Jonathan Keller, NREL 49037

Photo by Shawn Doner, NREL 49745

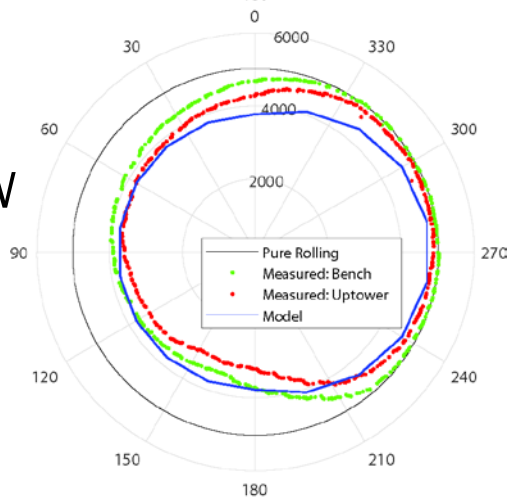
Approach and Accomplishments

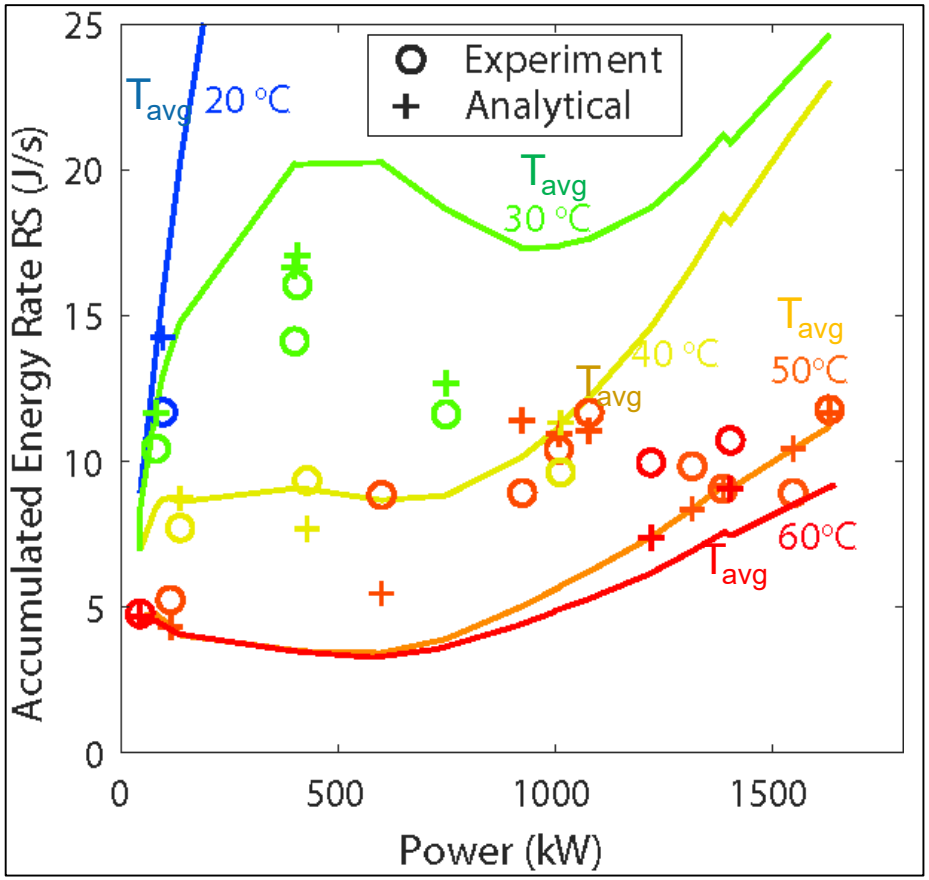
- **Gearbox Bearing Axial Cracking – Uptower Testing**
  - Normal power production

250 kW
Low Load
Continuous
Sliding



Rated 1,500 kW
High Load
Low Sliding

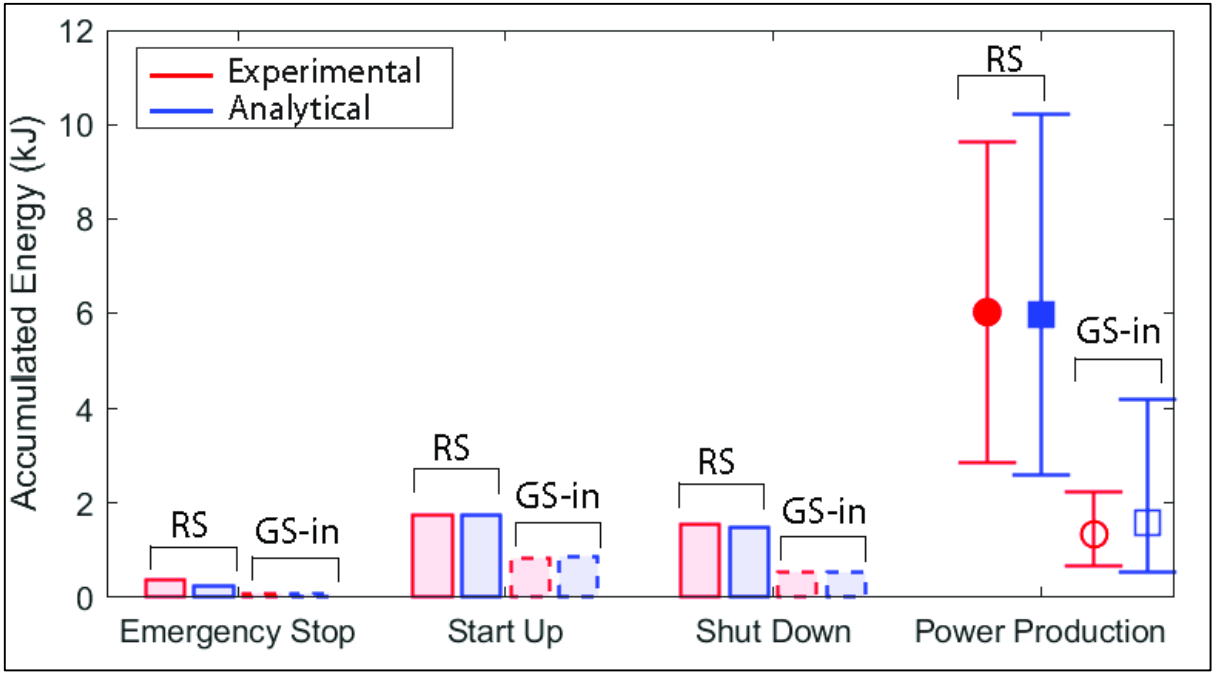




Cold operations at low power generate more frictional energy than warm operations at high power

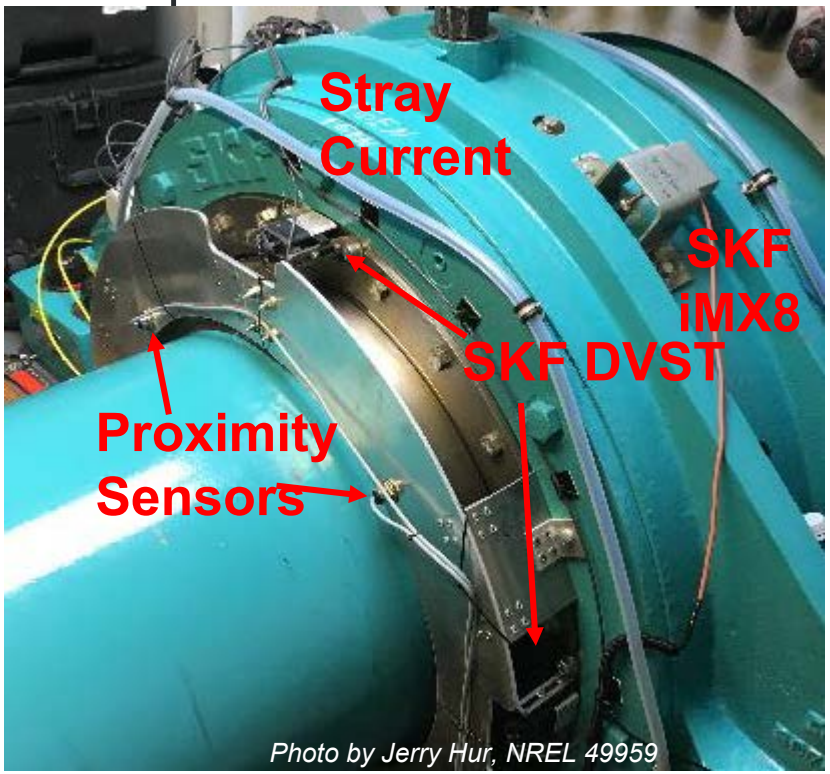
Approach and Accomplishments

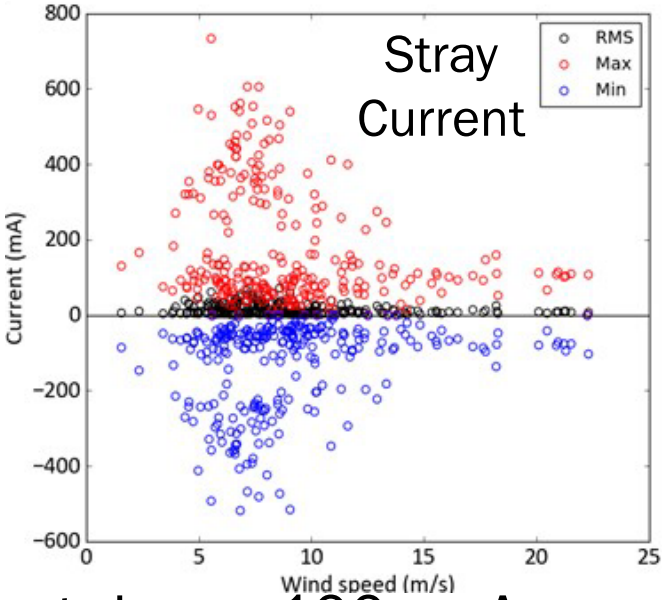
- **Gearbox Bearing Axial Cracking – Uptower Testing**
  - Compare total sliding energy between turbine operations
  - Transients vs 10-minute projections of normal power
  - Normal power contributes more energy
  - More energy for rotor-side (RS) than generator-inboard (GS-in)



Approach and Accomplishments

- **Main-Bearing Progressive Wear**
  - Instrumentation for axial motion and on both bearing rows for roller load, stray current, acoustic emission, temperature and vibration





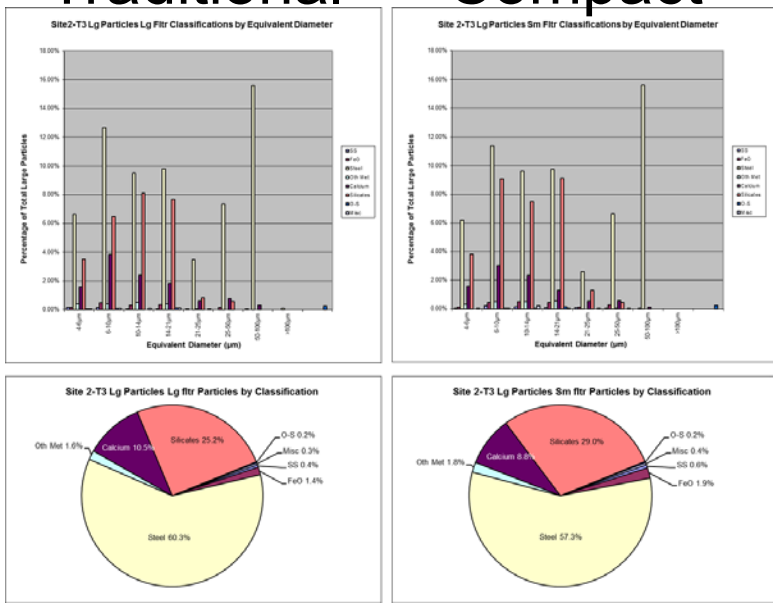
What does ~100s mA current do to main-bearing contact conditions?

  - Nonprotected uptower test data public.

Approach and Accomplishments

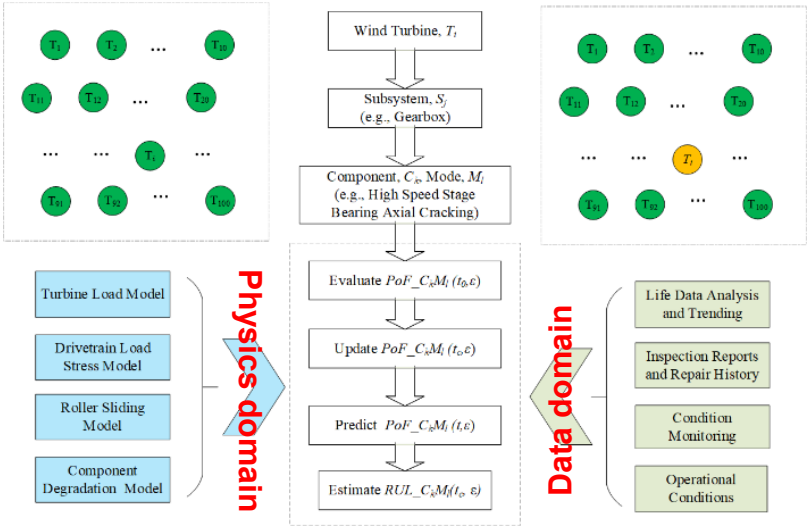
- **Compact Filter Testing and Analysis**
  - In-kind support by six industry partners
  - Completed field trials on 9 turbines at two wind plants
  - Sample processing and analysis procedure fine-tuned
  - Top element identification (top three being Steel, silicates, and calcium) consistent between large and compact filters at reduced cost
  - AWEA O&M recommended practice developed

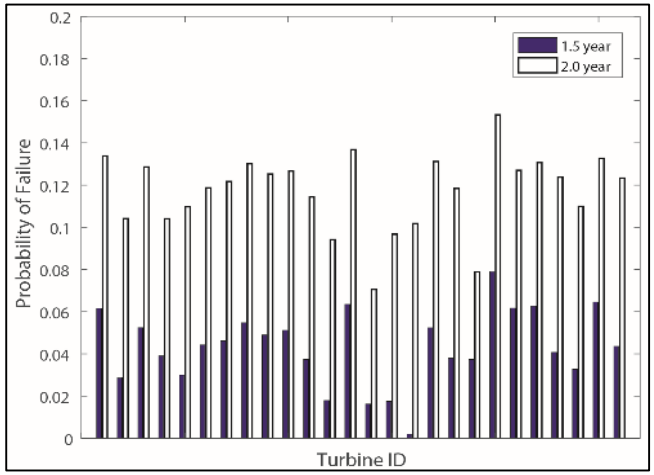
Traditional | Compact



Approach and Accomplishments

- **Reliability Assessment and Prediction**
  - Prognostics and health management framework with emphasis on remaining useful life prediction (top right figure)
    - Features a physics (left bottom) and data (right bottom) domain hybrid approach
  - Reliability prediction methodology developed for bearing axial cracking
    - Frictional energy used as risk criterion for axial cracking and probability of failure (PoF) as a reliability metric

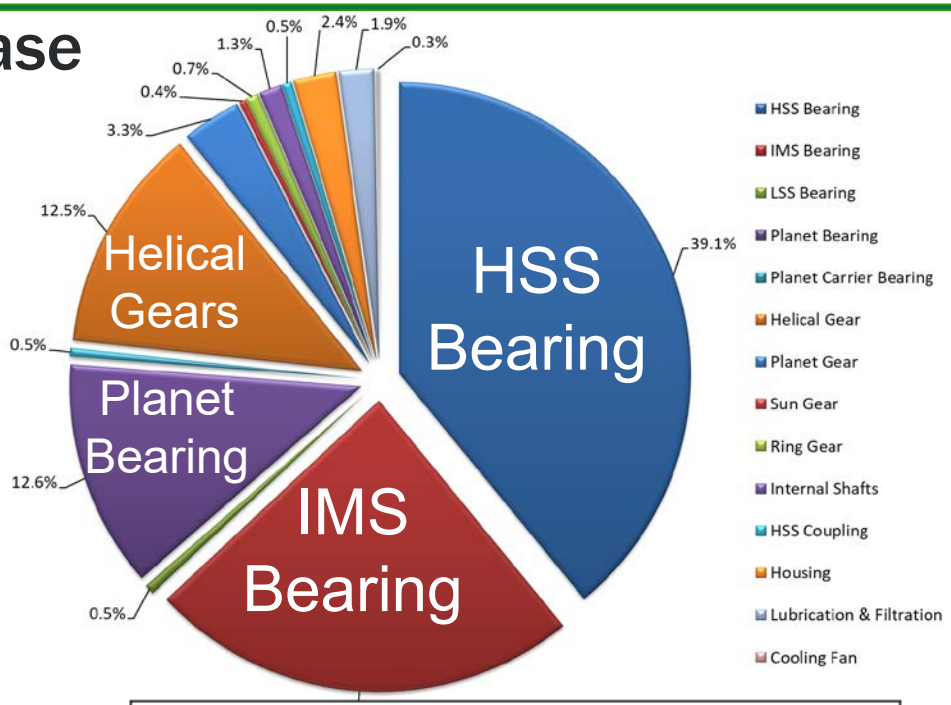


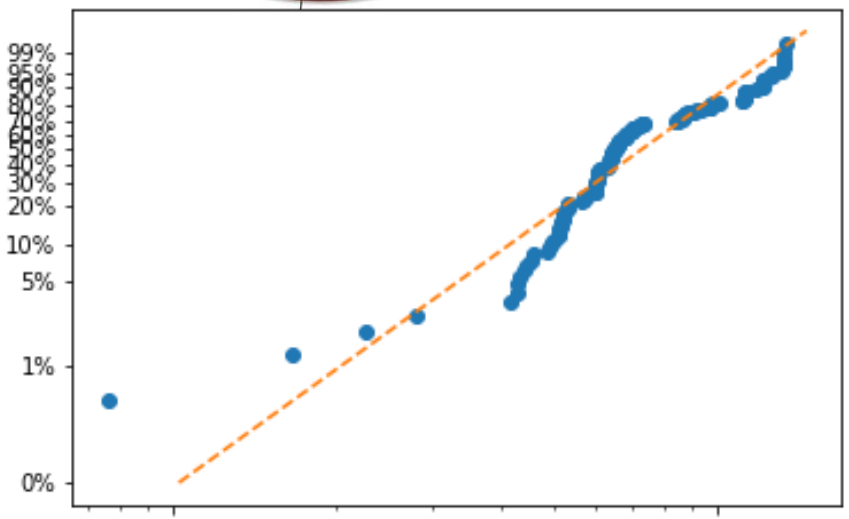


PoF comparison between 1.5 and 2 years for gearbox high speed stage bearings failed by axial cracking

Approach and Accomplishments

- **Gearbox Reliability Database**
  - Released latest damage distribution pie chart
    - About 1,100 confirmed records
    - Bearings, 76.7% Gears, 16.9% Others, 6.4%.
  - Developed codes for Weibull analysis
  - Conducted a survey and circulated results among database partners





Communication, Coordination, and Commercialization

- **Collaborative Meetings and Tribology Seminars**
  - Attended by 100+ industry and academia
- **Cooperative Research and Development Agreements**
  - Planetary load-sharing: Romax and Timken
  - Axial cracking: Flender, SKF GmbH, Schaeffler, and Afton
  - Main bearing: SKF USA
  - O&M and Failure Statistics: Numerous contributors
- **Publications and Data Release**
  - 9 journal articles, 2 book chapters, numerous others
  - Planetary bearing data (doi: 10.7799/1254154 and 1337868)
  - Uptower data (https://nrel.box.com/s/fx1wu3pkvgbeu5ikv7ghn61pjg1oao20)
  - Gearbox failure statistics (https://grd.nrel.gov/)

Upcoming Project Activities

- **Focus shifts from developing understanding of uncharacterized failures to identifying and validating**
  - mitigation methods, ranging from lubricants, materials, coatings, and reengineered components to changes in turbine controller;
  - and remaining useful life prediction techniques with hybrid physics- and model-based RUL prediction methods for multiple failure modes informed by “big data” analytics.
- **Begin main-bearing validation and endurance testing and new tasks in extended life lubricants, gear-tooth micropitting, and large-diameter pitch bearings**