B-NOW Visit to NREL/NWTC
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Model-Based and Data-Driven Strategies for Wind Turbine Prognostics and Health Management

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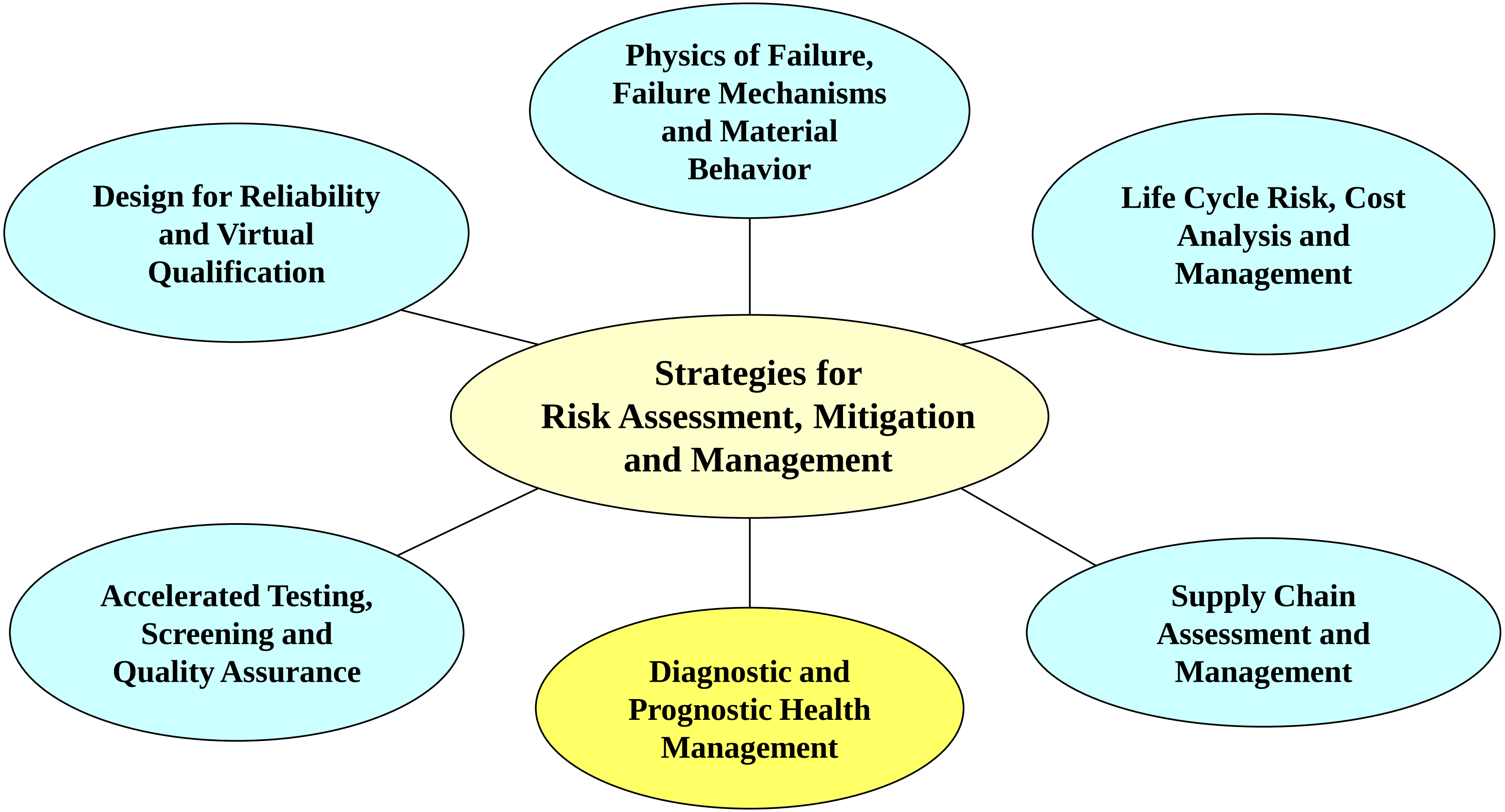
CALCE Research Focus



Physics of Failure, Failure Mechanisms and Material Behavior

Design for Reliability and Virtual Qualification

Life Cycle Risk, Cost Analysis and Management

Strategies for Risk Assessment, Mitigation and Management

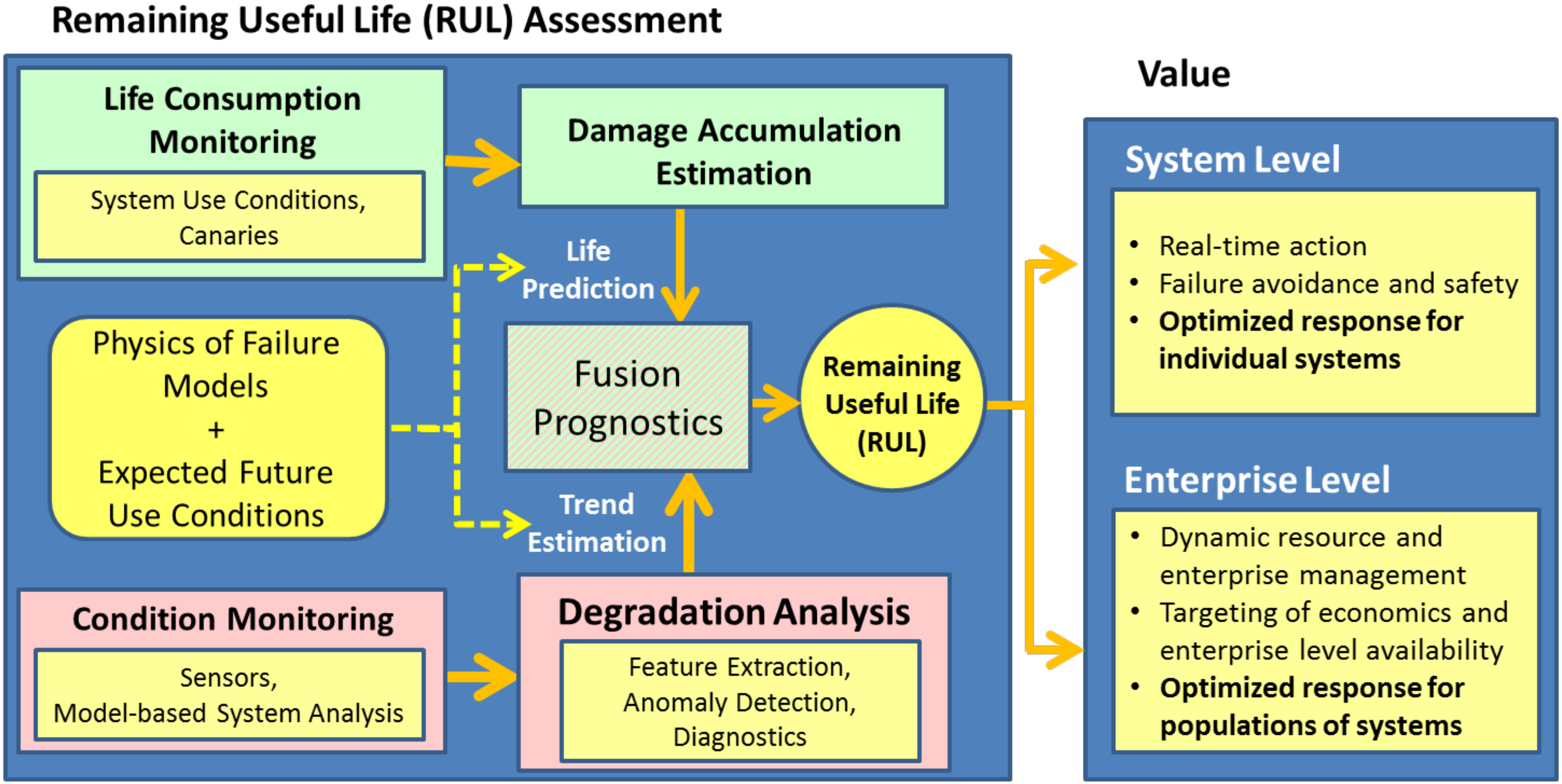
Accelerated Testing, Screening and Quality Assurance

Diagnostic and Prognostic Health Management

Supply Chain Assessment and Management

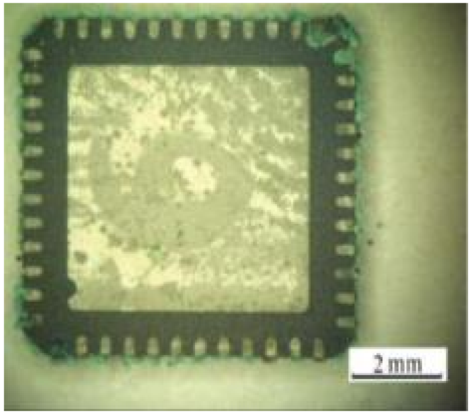
PHM Approach

- ***Data-driven condition monitoring*** and ***physics-of-failure based damage assessments*** are used to evaluate the health of a system, to predict its remaining useful life, and to implement risk-mitigating actions such as *preventative maintenance*.

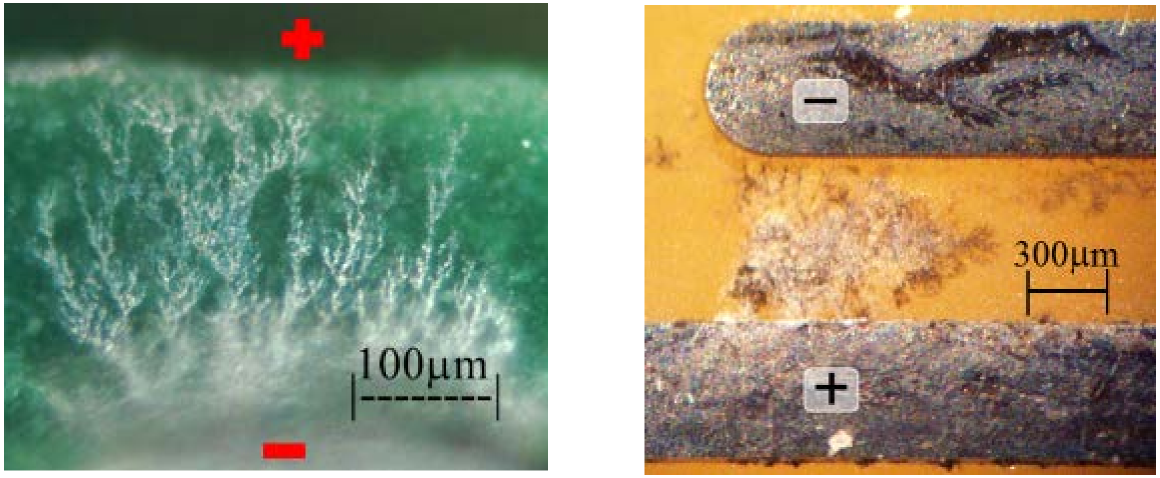


Canaries for PHM of Offshore Electronics: MOWER Project

- Offshore wind turbines operate in harsh environmental conditions that include humidity, salt contamination, and temperature variations that can lead to electrical failures due to *corrosion* and *electrochemical migration* of metals.
- Electrical system failures account for a large percentage of wind turbine failures.
- Advanced warning of these failures can be provided by “**canaries**,” which are ***structures designed to degrade faster than the functional product into which they are incorporated***.



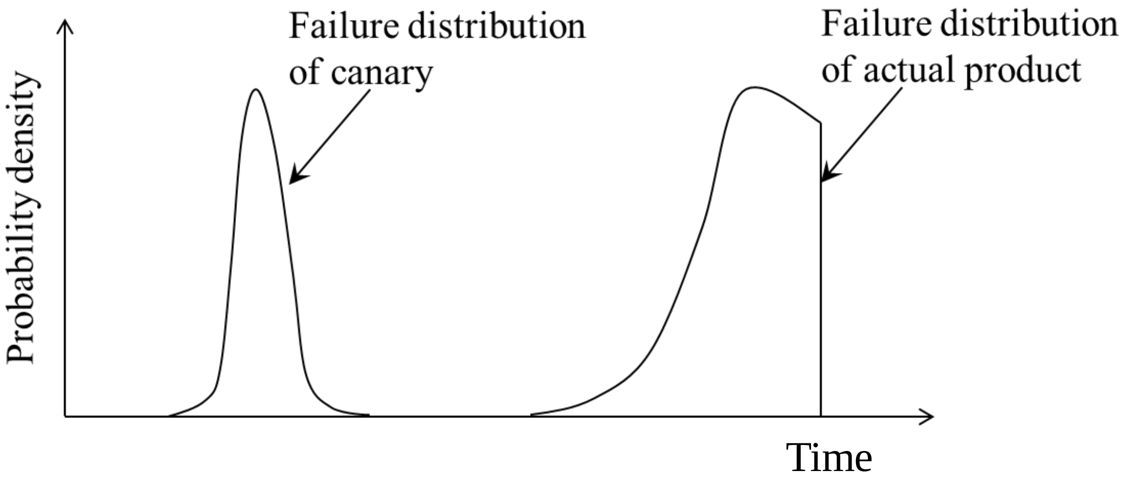
Corrosion on an IC package

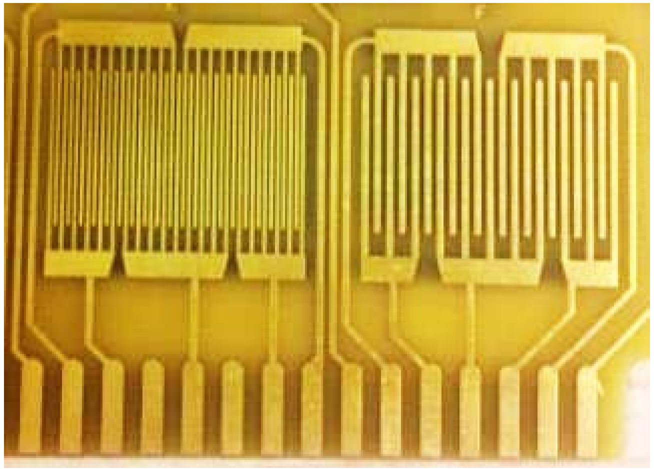


Electrical failures due to moisture and metal migration

Canary Design Approach

- Canary design by *geometric error-seeding*: acceleration of ECM failure relative to the functional circuit can be obtained by changing the spacing of the conductors in the comb structure under different salt contamination levels.
- Canary design by *load error-seeding*: Accelerating the failure mechanism by increasing the voltage applied across the adjacent conductors.

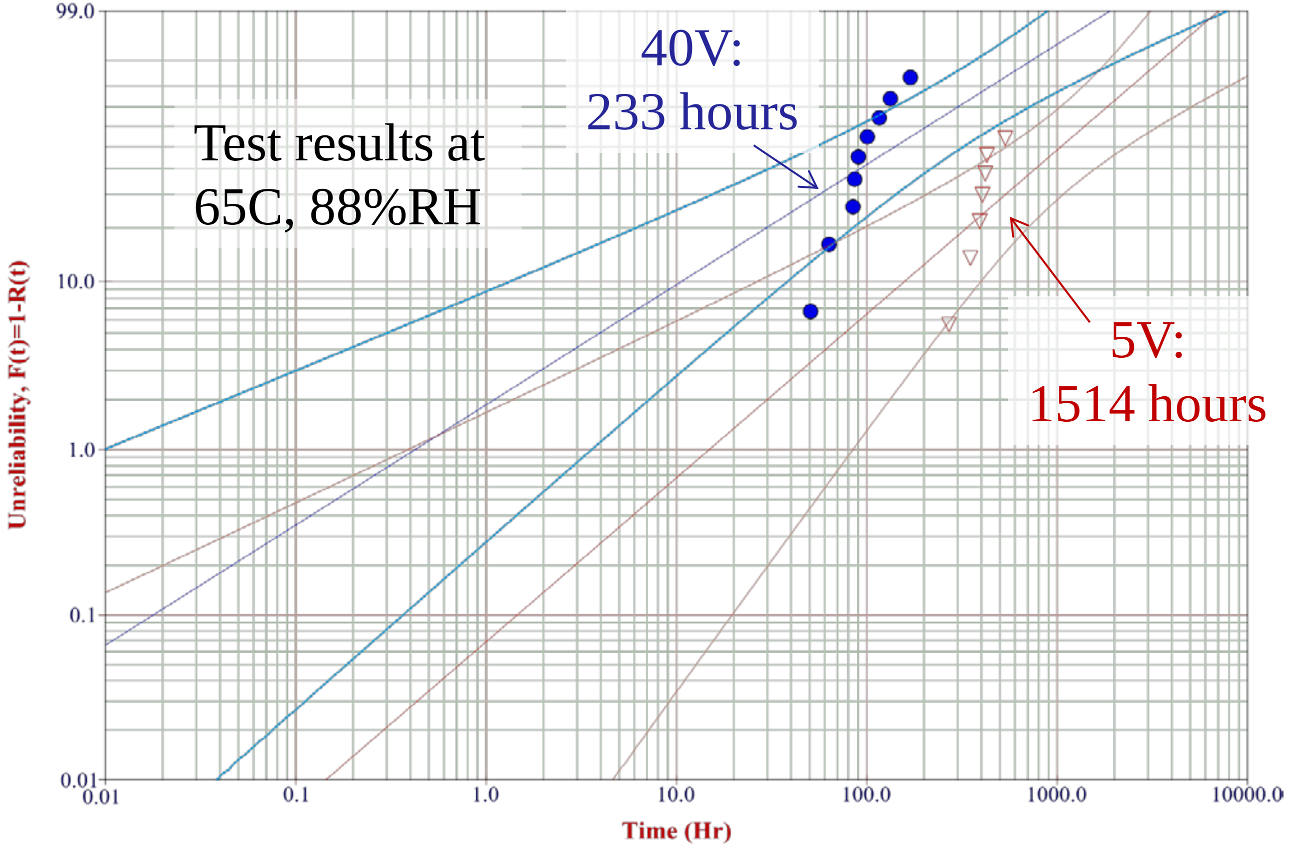




Examples of canary test structures

Canaries: Testing and Simulation

- The lifetime at 40V is about 15% of the lifetime at 5V due to electrochemical migration – this provides a basis for canary design using load error-seeding.


Test results at 65C, 88%RH

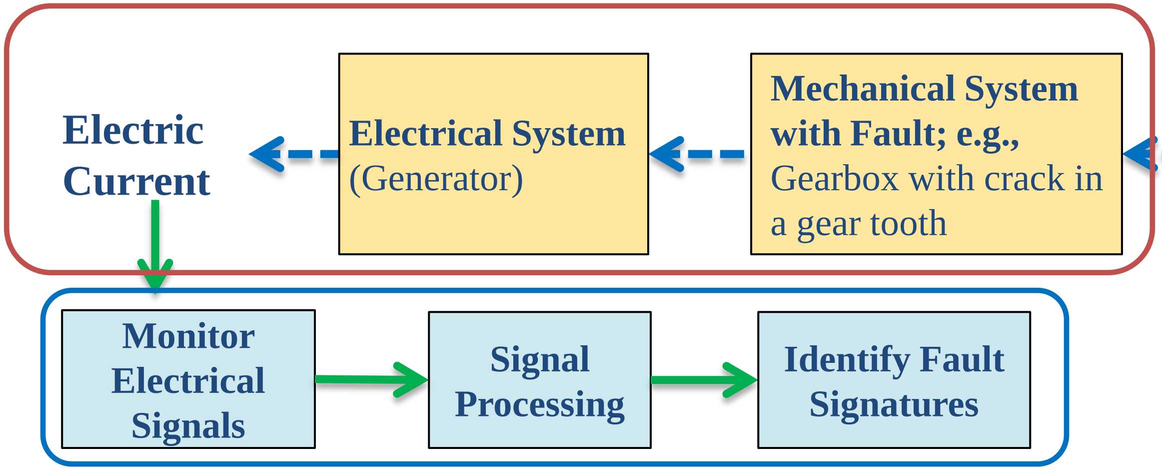
40V: 233 hours

5V: 1514 hours

- Simulations have been performed for design of canaries applicable to indeterminate or varying operating conditions.

Model-Based Signal Analysis: Condition Monitoring of Gearbox using Electrical Signals

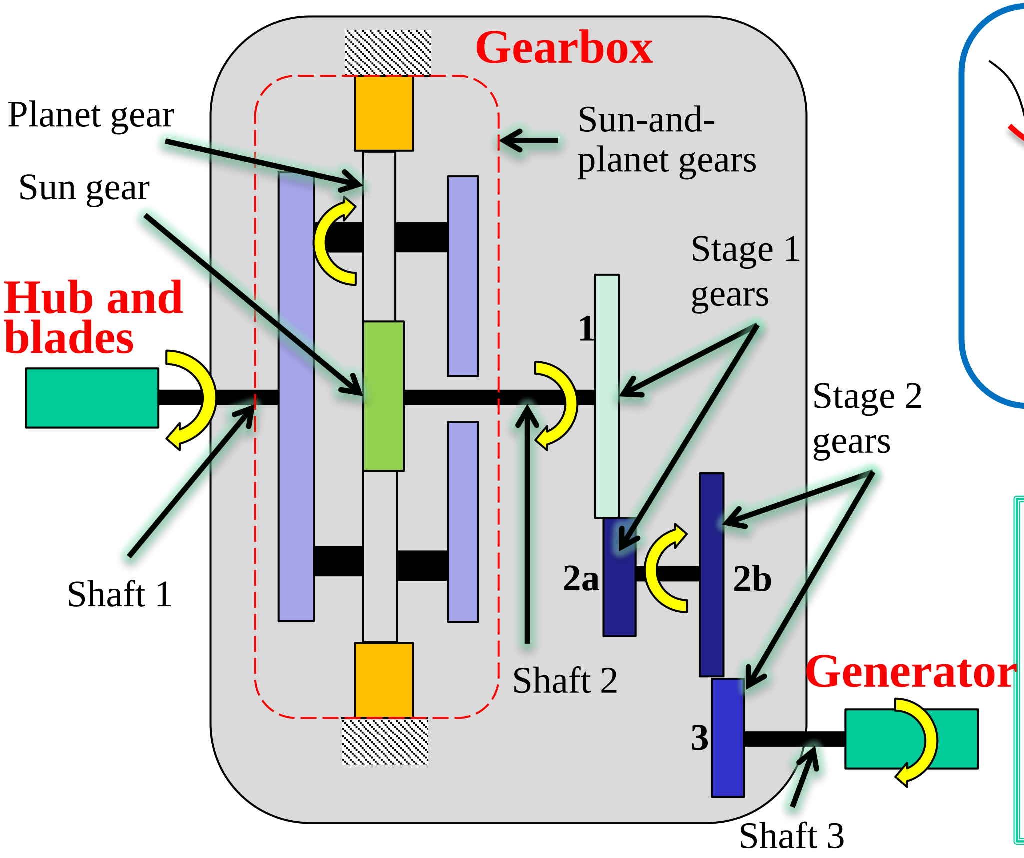
- Gearbox failures are responsible for long down-time and high repair costs.
- Fault detection of mechanical structures by monitoring the electrical signal would be a low-cost and non-intrusive method of health monitoring, complementing existing techniques.
- Objective: ***Detection of mechanical faults by analyzing the electrical output from the turbine.***

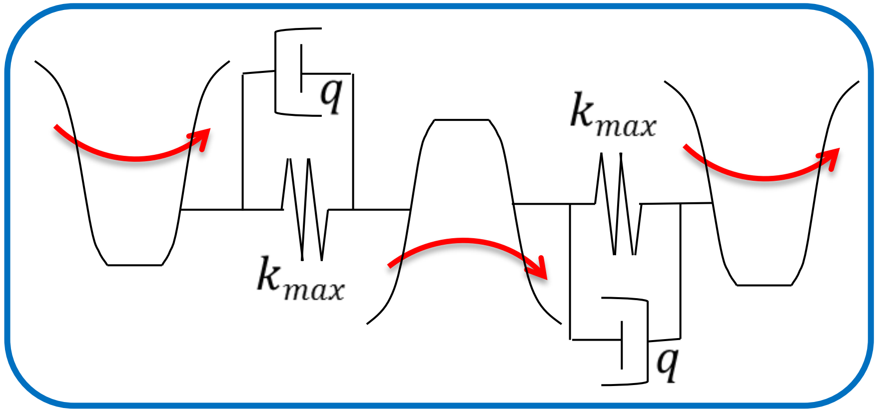


Energy Flow in Wind Turbine	⇠
Signal Analysis	→

Dynamic System Modeling Approach

Input torque from the wind → Lumped parameter modeling of all mechanical components → Dynamic modeling of the doubly-fed induction generator (DFIG)





Double Tooth Contact

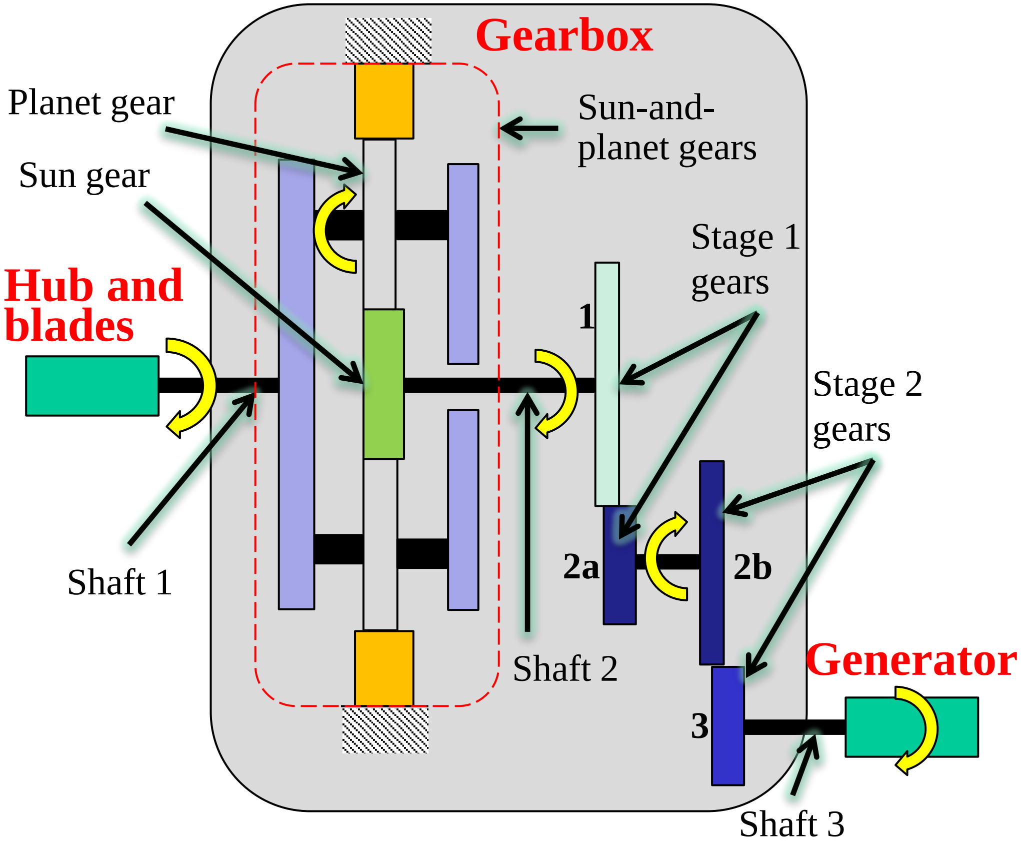
Dynamic modeling of the electrical and mechanical components using a lumped parameter approach is carried out for **fault simulation and diagnostics**

Dynamic System Modeling Approach

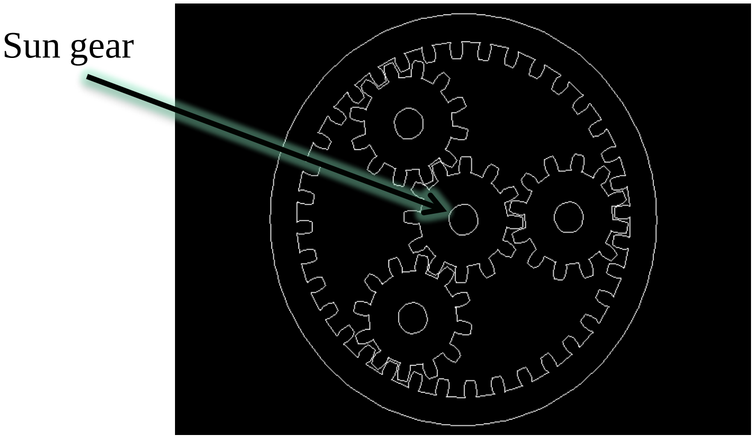
Input torque from the wind

Lumped parameter modeling of all mechanical components

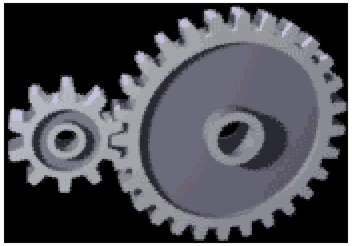
Dynamic modeling of the doubly-fed induction generator (DFIG)



Schematic of sun-and-planet gears with sun gear in the center and three planet gears[1]



Schematic of meshing of stage 1 and stage 2 gears[2]



Dynamic System Modeling Procedure

1. Estimation of input torque captured by the blades

   Aerodynamic torque generated due to wind acting on the rotor blades

2. Wind turbine gearbox modeling

   Dynamic equations derived by carrying out a force balance on the lumped components, using parameters obtained from the literature

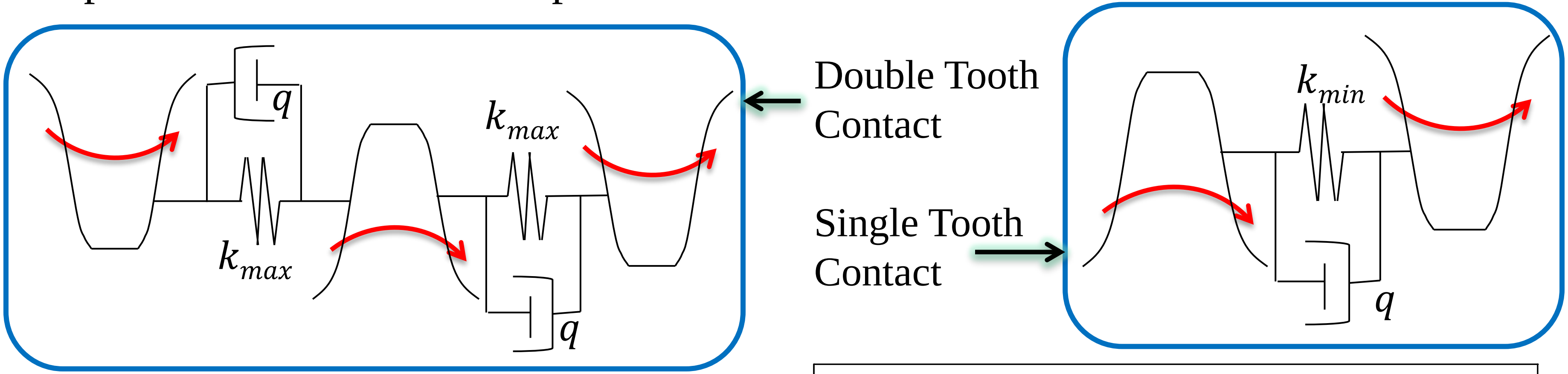
3. DFIG modeling: Equivalent circuit

4. Gear fault modeling and sensitivity analysis

   Occurrence of cracks in gear 1/2a and 2b/3 were simulated and analyzed.

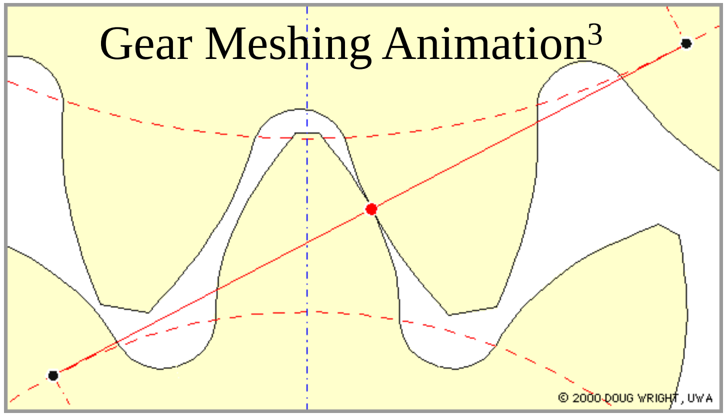
Gear Mesh Modeling

- Mechanical coupling between gear stages is modeled using a spring (k) and dashpot (q) to represent the gear tooth interactions.
- During the meshing of gears, the load is transmitted alternately through two points of contact and one point of contact.



Double Tooth Contact

Single Tooth Contact


Gear Meshing Animation[3]

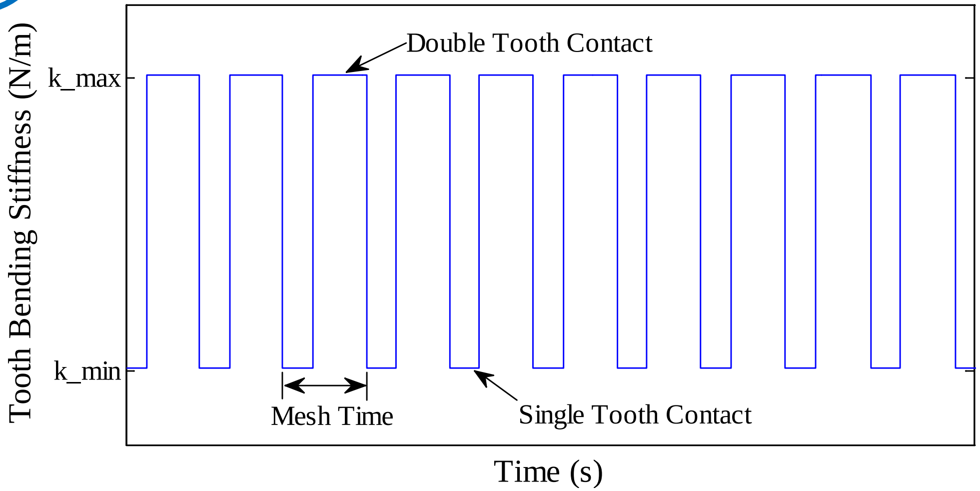


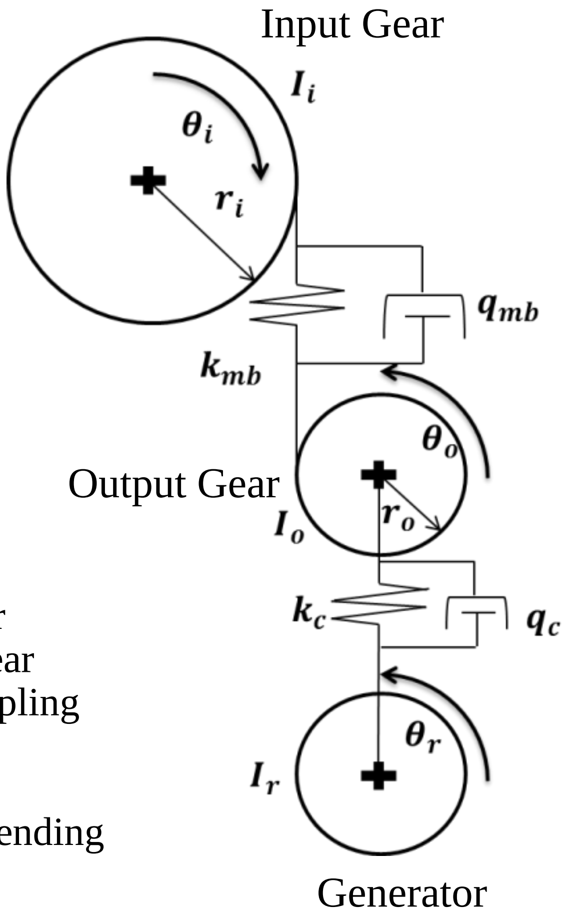
Illustration of Lumped Component Modeling

- A force balance is used to derive the system of governing equations for the gearbox.
- A representative illustration of this method is shown here for a simplified gearbox.

$$I_i\ddot{\theta}_i + r_i k_{mb}(r_i\theta_i - r_o\theta_o) + r_i q_{mb}\left(r_i\dot{\theta}_i - r_o\dot{\theta}_o\right) = T_{in}$$

$$\begin{aligned} I_o\ddot{\theta}_o + r_o k_{mb}(r_o\theta_o - r_i\theta_i) + r_o q_{mb}\left(r_o\dot{\theta}_o - r_i\dot{\theta}_i\right) \\ + k_c(\theta_o - \theta_r) + q_c\left(\dot{\theta}_o - \dot{\theta}_r\right) = 0 \end{aligned}$$

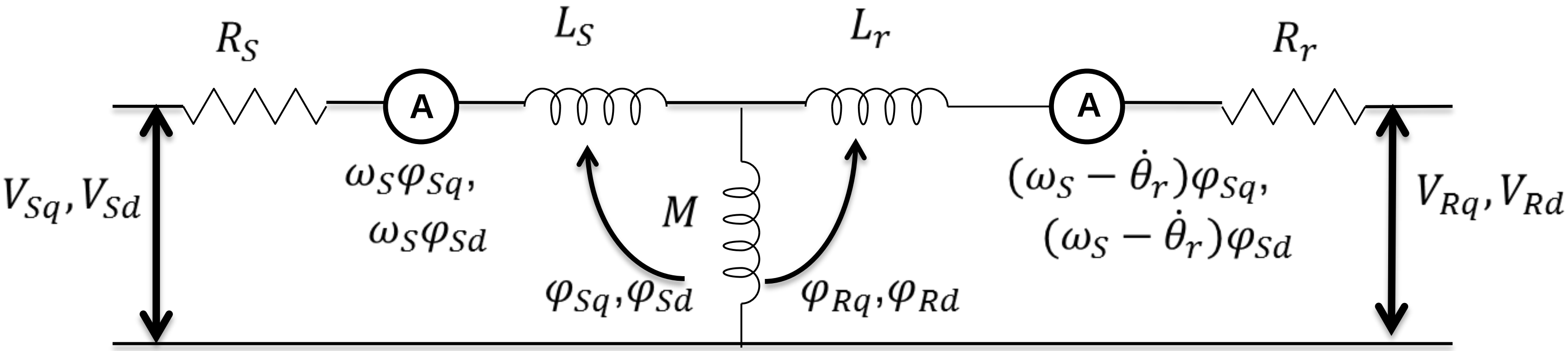
$$I_r\ddot{\theta}_r + k_c(\theta_r - \theta_o) + q_c\left(\dot{\theta}_r - \dot{\theta}_o\right) = -T_{el}$$



Nomenclature:
I – inertia
T – torque
k – stiffness
q – damping
θ – angle of rotation
r – radius

Subscripts:
i – input gear
o – output gear
c – shaft coupling
r – rotor of generator
mb – tooth bending
in – input
el - electrical

DFIG Modeling: Equivalent Circuit



- Using Ohm's law and Faraday's law, the dynamic equations of the flux linkages in the generator are calculated.

$$V_{Sq} = R_S i_{Sq} + \frac{d\varphi_{Sq}}{dt} + \omega_e \varphi_{Sd}$$

$$V_{Rq} = R_R i_{Rq} + \frac{d\varphi_{Rq}}{dt} + \boxed{(\omega_e - \omega_r)}\varphi_{Rd}$$

Coupling between electrical and mechanical model

Electrical torque generated is given by:

$$T_{el} = \frac{3}{2}\left(\frac{p}{2}\right)(\varphi_{Sd} i_{Sq} - \varphi_{Sq} i_{Sd})$$

Nomenclature:

φ – flux

V – voltage

R – resistance

M – mutual inductance

L – self inductance

$\omega, \dot{\theta}$ - angular velocity

p – number of pole pairs

Subscripts:

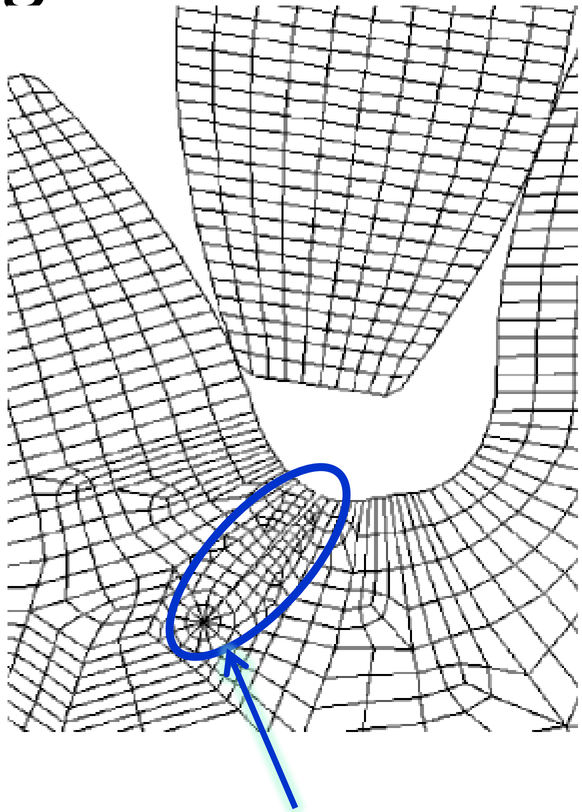
S – stator of generator

r – rotor of generator

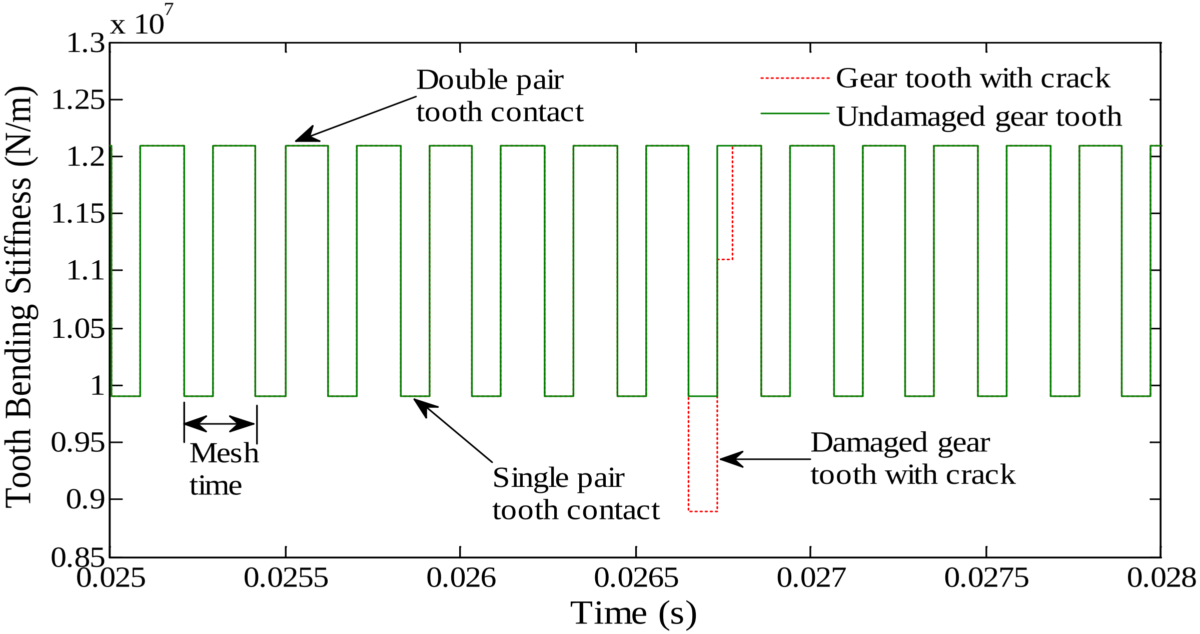
Gear Fault Modeling

- Presence of a crack in a gear tooth is modeled as a reduced tooth bending stiffness during contact.

Crack in a gear tooth[4]

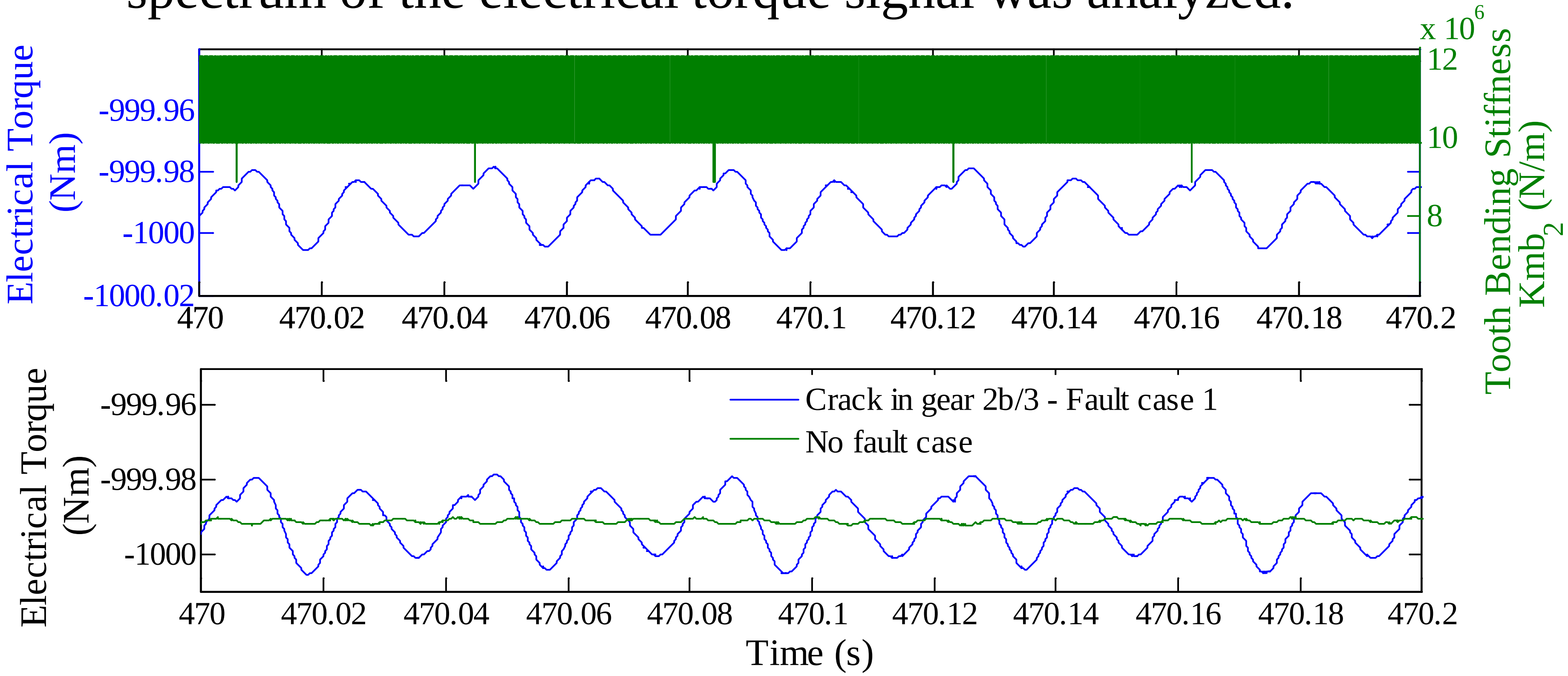


Finite element model of crack in a gear tooth to calculate tooth bending stiffness[5] (20% reduction in stiffness)



Simulation Result: Effect of Crack in Gear 2b/3 on Electrical Torque Signal

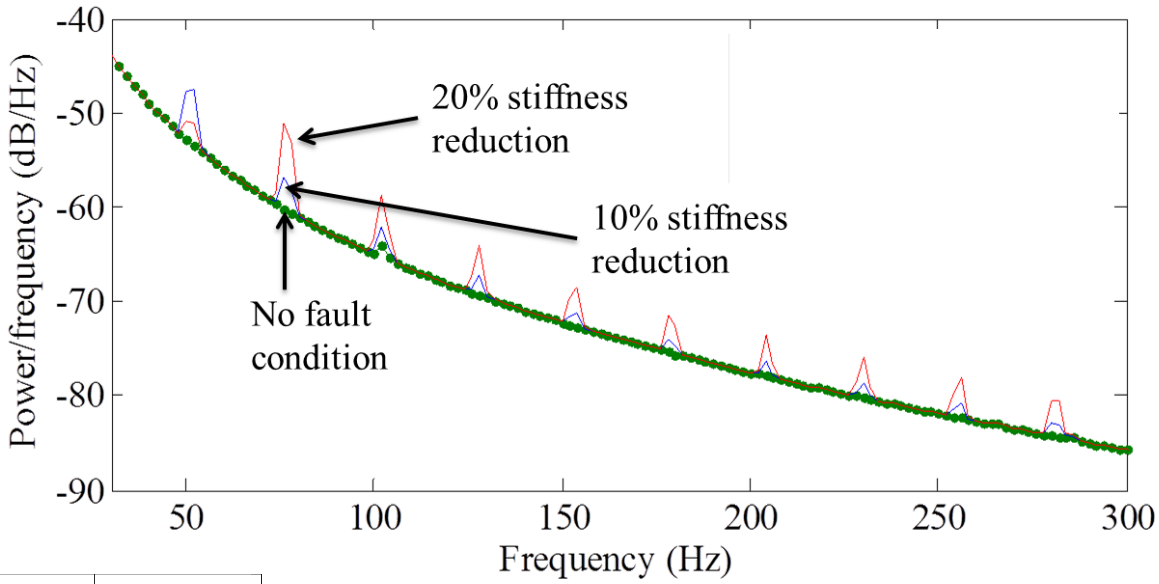
- Variations can be observed in the electrical torque time domain signal due to presence of a crack in gear 2b/3.
- Different levels of fault were simulated and the frequency spectrum of the electrical torque signal was analyzed.

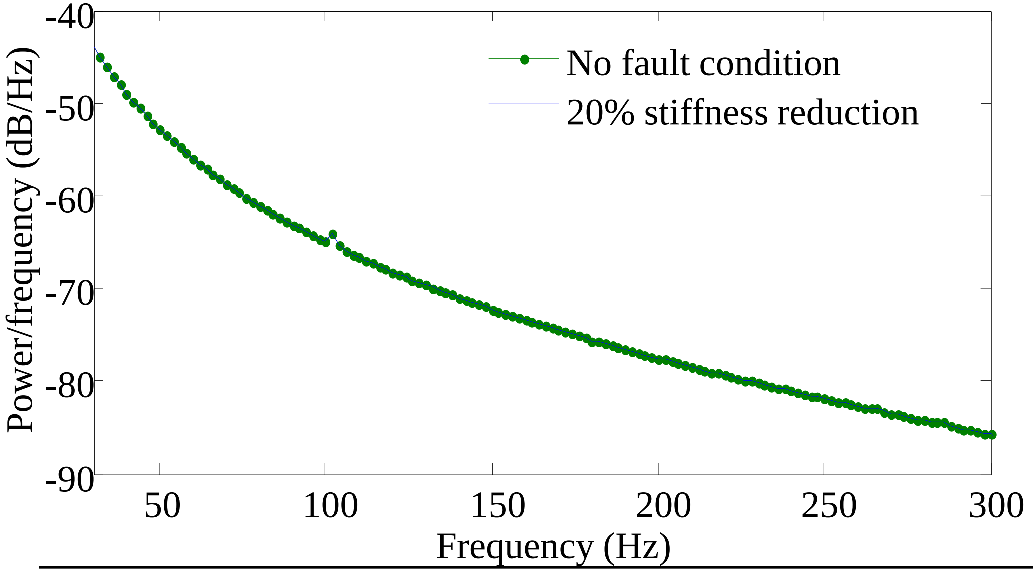


Simulation Result: Effect of Fault Severity

- Peaks are observed only when there is a fault in a gear tooth.

Fault level in gear 2b/3:
Case-1: k_{min} = 0.9E7 N/m
Case-2: k_{min} = 0.8E7 N/m
No fault: k_{min} = 1E7 N/m





- Fault in gear 1/2a is difficult to observe in the electrical torque frequency spectrum.

Fault level in gear 1/2a:
Case-3: k_{min} = 1.6E9 N/m
No fault: k_{min} = 1.8E9 N/m

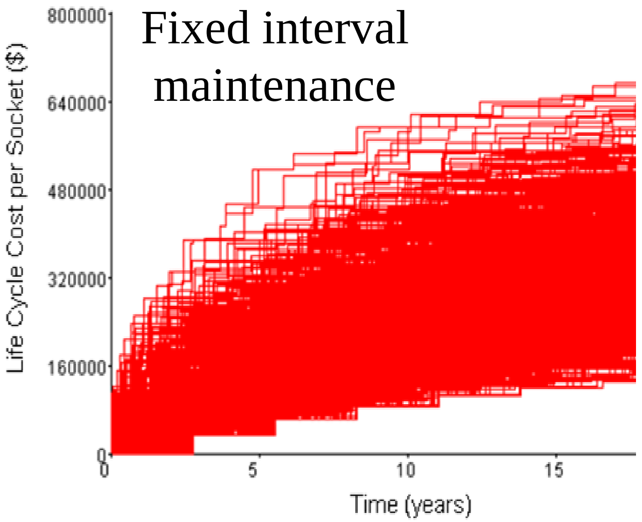
Deriving Value from PHM at the System and Enterprise Levels

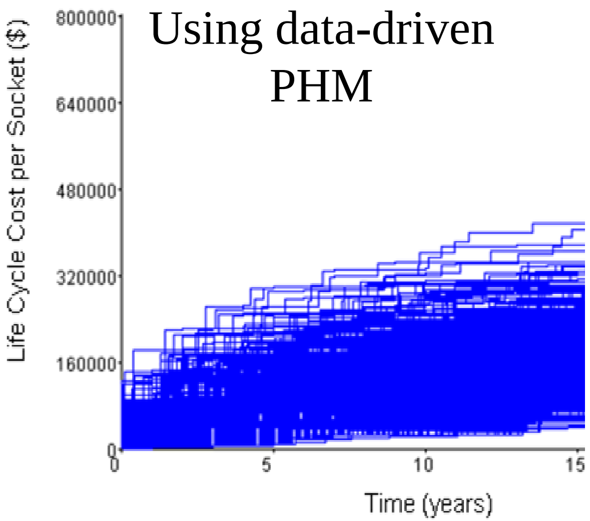
- System-level PHM value means taking action based on prognostics to manage one specific instance of a system, e.g., one vehicle or one turbine. The actions tend to be “real-time” and consist of:
  - Modify how you sustain the system (e.g., arrange for a maintenance action)
  - Modify the mission (e.g., reduce speed, take a different route)
  - Modify the system (e.g., adaptive re-configuration)

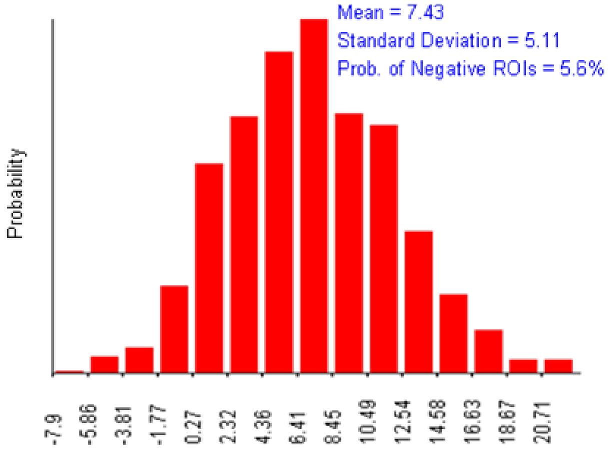
- Enterprise-level PHM value means taking action based on prognostics to manage an enterprise, e.g., a fleet or a farm of turbines. The actions are longer-term strategic planning things (usually not real-time):
  - Optimizing the logistics
  - Management via availability and other types of outcome-based contracts

Understanding the Cost of PHM

Return on Investment for One Turbine


Fixed interval maintenance


Using data-driven PHM

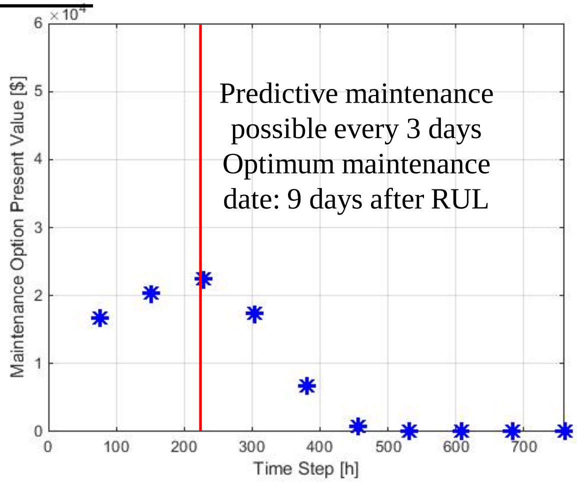

Mean = 7.43
Standard Deviation = 5.11
Prob. of Negative ROIs = 5.6%

Return on Investment

Maintenance Optimization Under a PPA for a Farm

Real Options Analysis ("maintenance options"):

- Allow determination of optimum wait time after an RUL indication for individual turbines
- Extended to wind farms managed using power purchase agreements where the state of repair of other turbines is incorporated into the maintenance decision process


Predictive maintenance possible every 3 days
Optimum maintenance date: 9 days after RUL

Understanding the O&M Cost of Wind Turbines and Wind Farms

- The optimum for an individual system instance is not necessarily the optimum for the system instance within a population, if the population is managed via an "outcome-based" contract (like many PPAs)

Point of contact for cost modeling:

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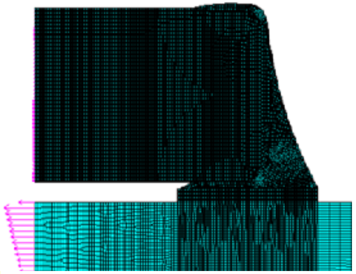
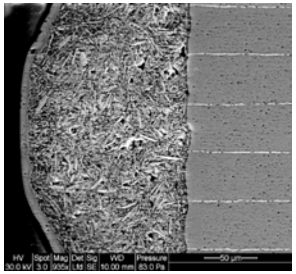
Capacitor Reliability and Risk Mitigation

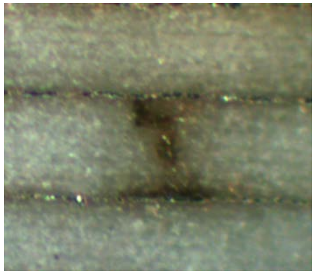
MLCC modeling



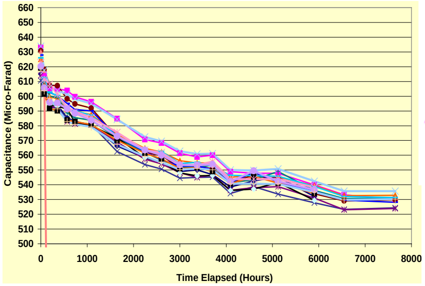
Flex MLCC



MLCC leakage

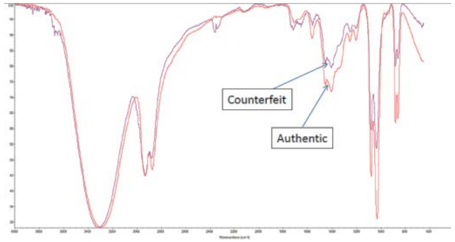


Al Electrolytic



- Reliability assessment
- Statistical lifetime distributions
- Critical-to-reliability parameters
- Lot acceptance
- Technology adoption
- Part selection and screening
- Quality assurance
- Supply chain management
- Counterfeit detection
- Stress modeling
- Failure risk estimation
- Lifetime modeling
- Failure analysis techniques
- Dielectric conduction mechanisms

EDLC (Supercap)



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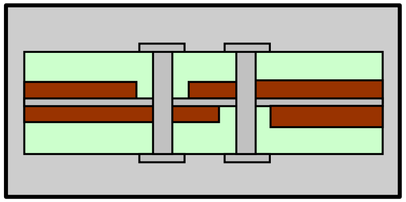

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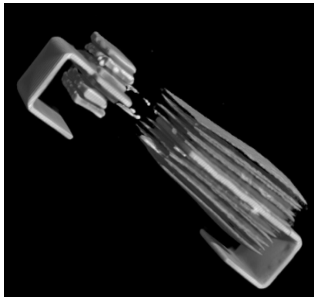
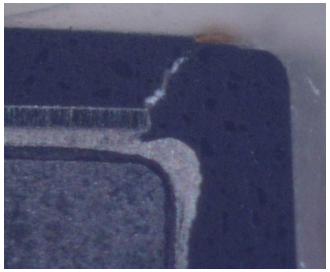


Polymer Al

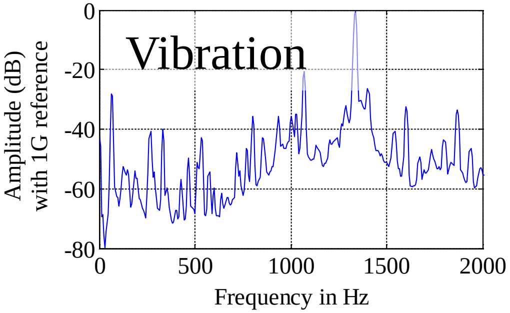
Film

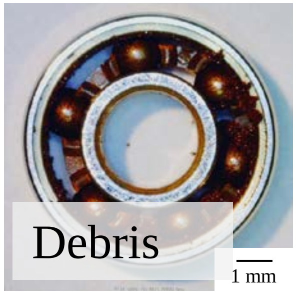
MnO_2-Tantalum

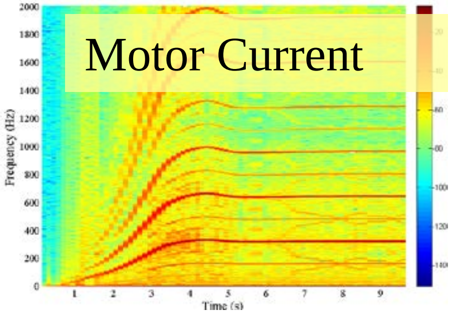


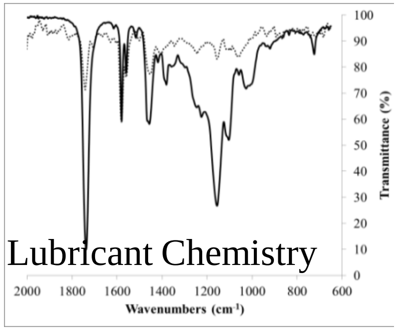
Polymer Tantalum

Bearing Reliability and Condition Monitoring





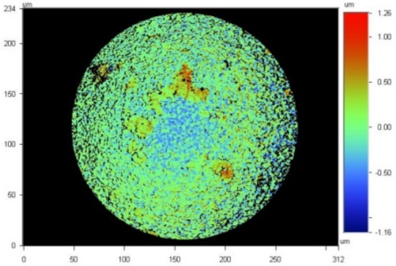


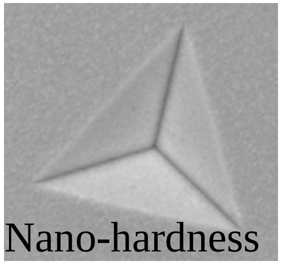


A wide range of characteristics are monitored and analyzed for fault detection, diagnosis of defects, and prognostics:

vibration; acoustic emission; acoustic sound; wear debris; nano-hardness; surface topography; lubricant chemistry; motor current; rotational speed.

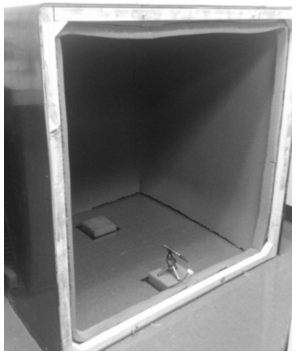
Surface Topography



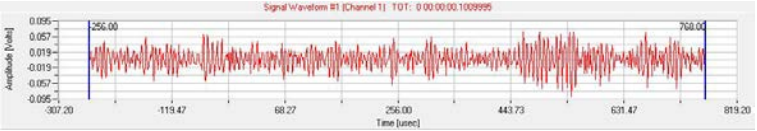


Acoustic Sound Level

(semi-anechoic chamber)

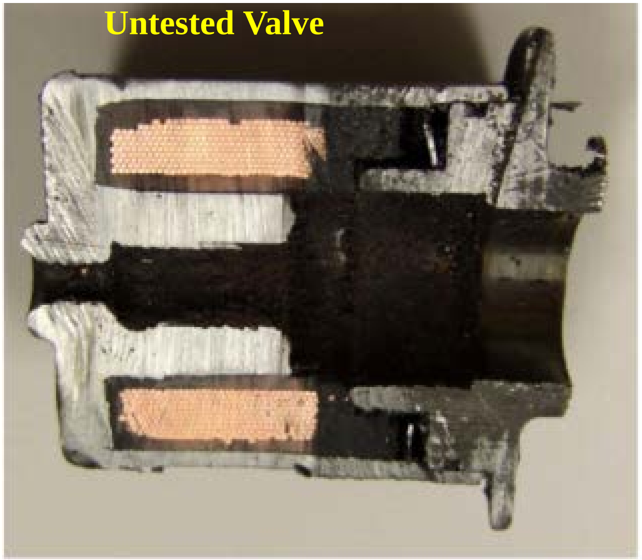


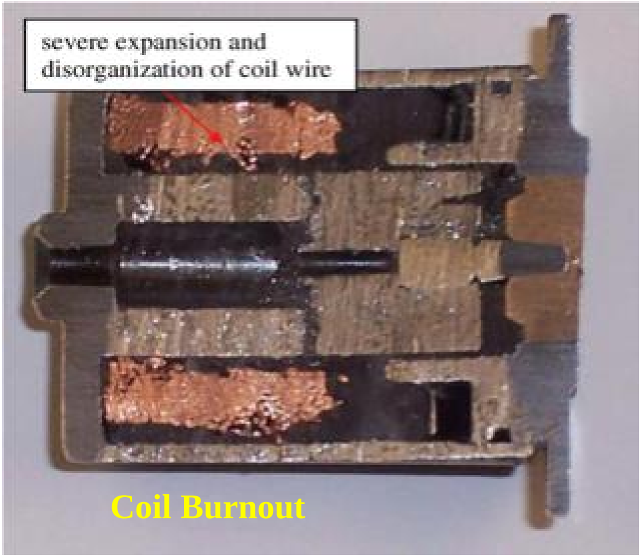
Acoustic Emission



Fault Detection and Prognostics of Coils

- Failure Modes
  - Wire-to-wire or wire-to-ground short
  - Coil open
- Failure Mechanisms
  - Dielectric breakdown (from thermal loading, electrical transients, defects)
  - Corrosion can cause wire necking and loss of material, or terminal damage
- Prognostics and Health Monitoring
  - Identify signatures that correlate with electrical coil aging and degradation
  - Determine and predict how the electrical characteristics of the coil change during the aging process





Opportunities for Collaborative Research

- Key components (e.g., control electronics, power electronics, drivetrain):
  - Reliability assessment
  - Failure model development
  - Health monitoring approaches
  - PHM algorithm development
- Model-based health monitoring
  - Sharing of data and models
  - Application to new designs
- O&M cost modeling analysis
  - ROI, optimization of decision-making, data sharing, etc.

➢ **CALCE can serve as a team member on proposals for reliability, PHM, and ROI analysis.**