Rolling Element Bearing Dynamics in Wind Turbines

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Wind Turbine Drivetrain Reliability Challenges

- **Predominant drivetrain failure modes are:**
  - Not accounted for in design standards
  - Not attributable to material deficiencies or quality control
  - Complex and independent of the component supplier

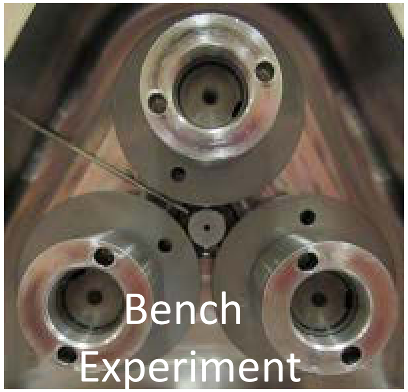

Photo from Argonne National Laboratory

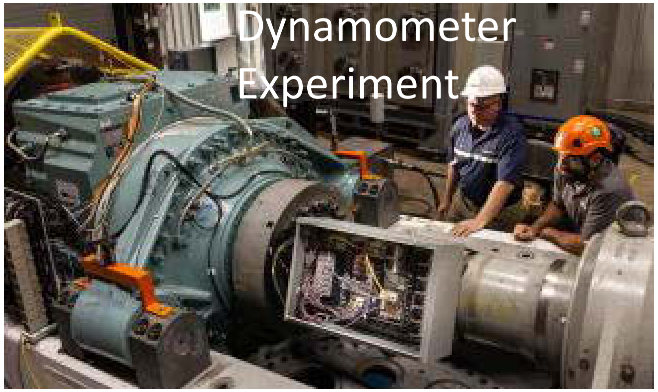

Photo by Mark McDade, National Renewable Energy Laboratory (NREL) 40432

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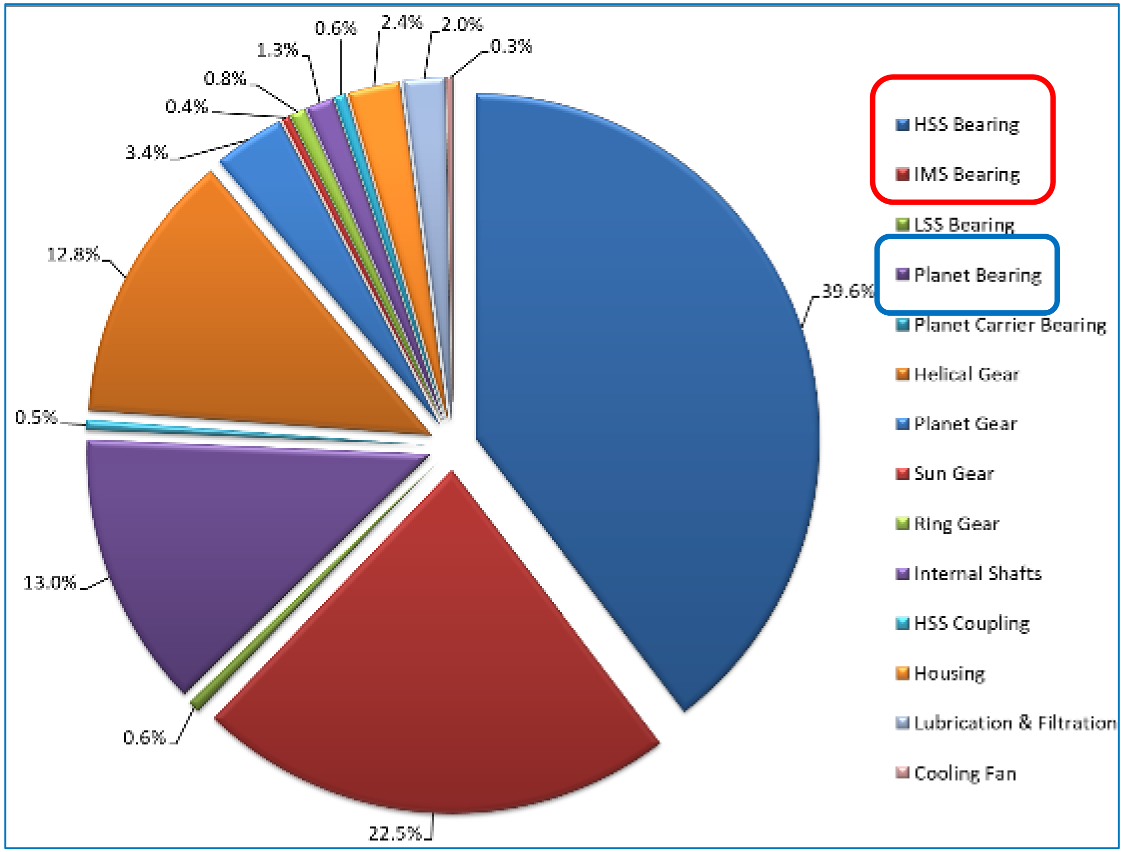
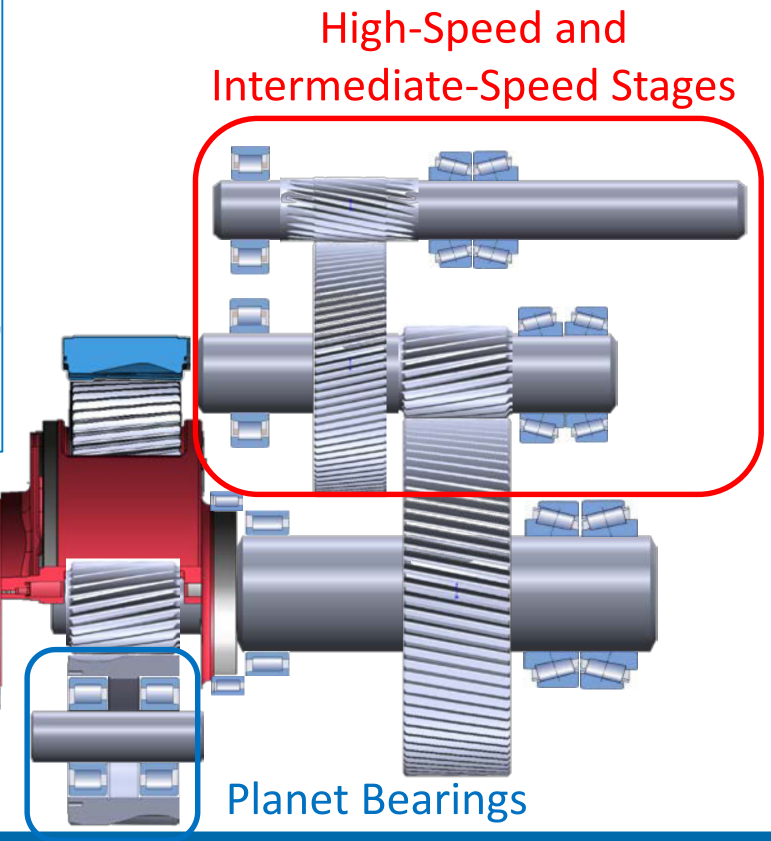
- **Conduct testing and analysis to enable:**
  - Improvement of inherent reliability
  - Increase of availability with less effort and drama
  - Reduction in wind plant operation and maintenance costs.

Most Frequent Failures



Source: S. Sheng, GRC Failure Database, 2018
Note: HSS = high-speed shaft; IMS = intermediate-speed shaft; LSS = low-speed shaft

- **High & intermediate speed stage bearings contribute 62% of total drivetrain failures.**
- **A planet bearing failure is more costly.**



Uptower Experiment Objectives

What turbine operations and grid conditions result in critical contact conditions for high-speed shaft and main bearings?

Gearbox Bearing Axial Cracking

Errichello, R., S. Sheng, J. Keller, and A. Greco. 2012. *Wind Turbine Tribology Seminar–A Recap.* U.S. Department of Energy Wind and Water Power Program. Photo from Jurgen Gegner, SKF.

Main Bearing Failure

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

Load impacts on component reliability addressed properly?

Gearbox Instrumentation[1]

- **Winergy PEAB 4410.4 gearbox and SKF cylindrical roller bearings**
  - Instrumentation focused on high-speed shaft, bearings, and lubricant
    - Shaft speed
    - Cage speed
    - Roller speed

    Sliding

    - Shaft torque and bending
    - Stray current
    - Bearing temperatures
    - Air temperature and humidity
    - Lubricant temperatures and moisture content
    - LogiLube and Poseidon lubricant monitoring and routine oil samples
    - SKF IMx-8 system.

Photo by Mark McDade, NREL 49050

Modeling of Bearing Loads & Stresses

- **Lumped-parameter dynamics model**
  - Transmission error
  - Bearing clearance
  - Nontorque loads
  - Gravity

Nonlinear, Time-Dependent Equations of Motion

$$\underbrace{\mathbf{M}\ddot{\mathbf{q}}+\mathbf{D}\dot{\mathbf{q}}}_{\text{Dynamic terms}}+\left[\mathbf{K}(\mathbf{q},t)+\mathbf{B}\right]\mathbf{q}=\mathbf{f}(\mathbf{q},t)$$

Gear mesh stiffness
PCL nonlinearity

Bearing stiffness

Applied torque &
surface mods.

Turbine Load Model

Drivetrain Load Stress Model

Roller Sliding Model

Component Degradation Model

- **Simulate normal operation and transient events efficiently**
- **Failure modes, such as planet bearing fatigue, can be included**
- **Validation on loads will be performed during DRC 1.5 uptower testing.**

Planet-Bearing-Stage Model

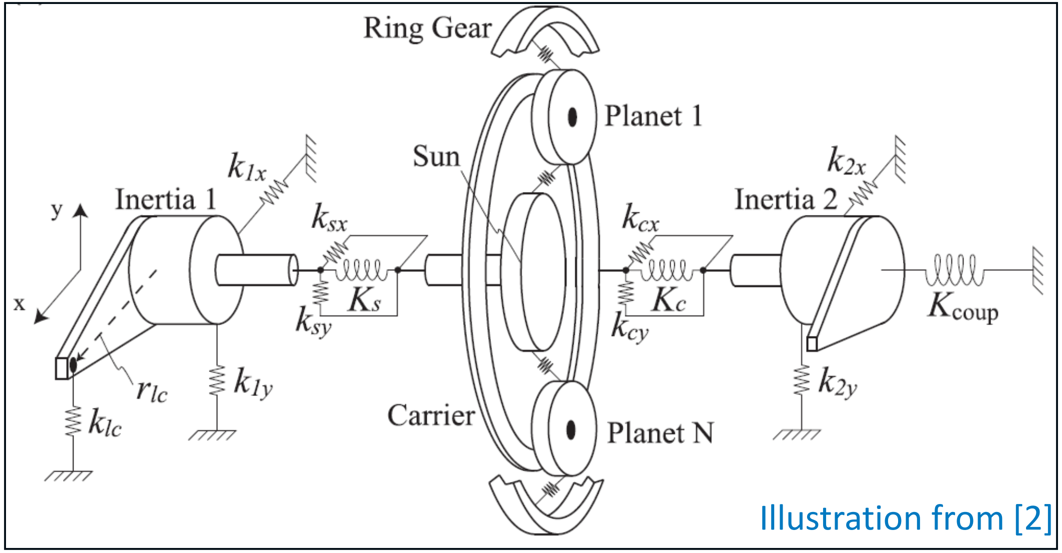
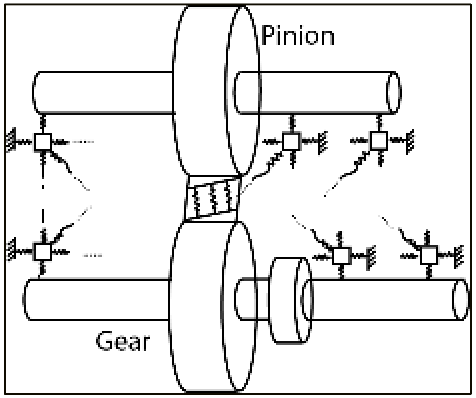


Illustration from [2]

High-Speed-Shaft Model



Different modules used to reduce computation time

Model Development: Roller Dynamics

- **Roller dynamics model (analytical) based on:**
  - Harris roller dynamics model [3,4]
- **Lubricant hydrodynamics model based on:**
  - Bercea cage friction model [5]
  - Dowson and Higginson lubricant model [6]

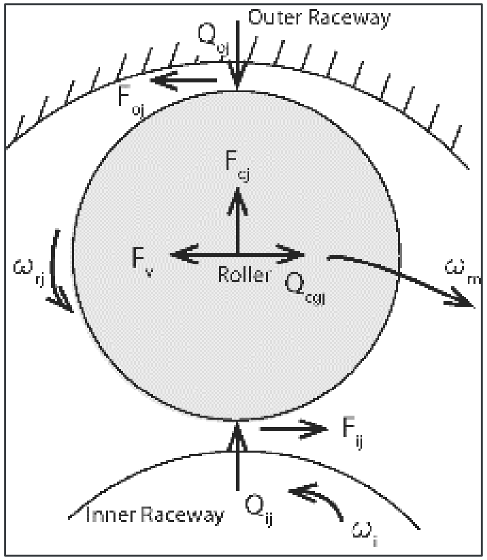
Turbine Load Model

Drivetrain Load Stress Model

Roller Sliding Model

Component Degradation Model

Forces and speeds of a roller



Force balance of a single roller

$$Q_{ij} - Q_{oj} + F_{cj} = 0 \quad (1)$$

$$F_{ij} - F_{oj} + F_v - Q_{cgj} = 0 \quad (2)$$

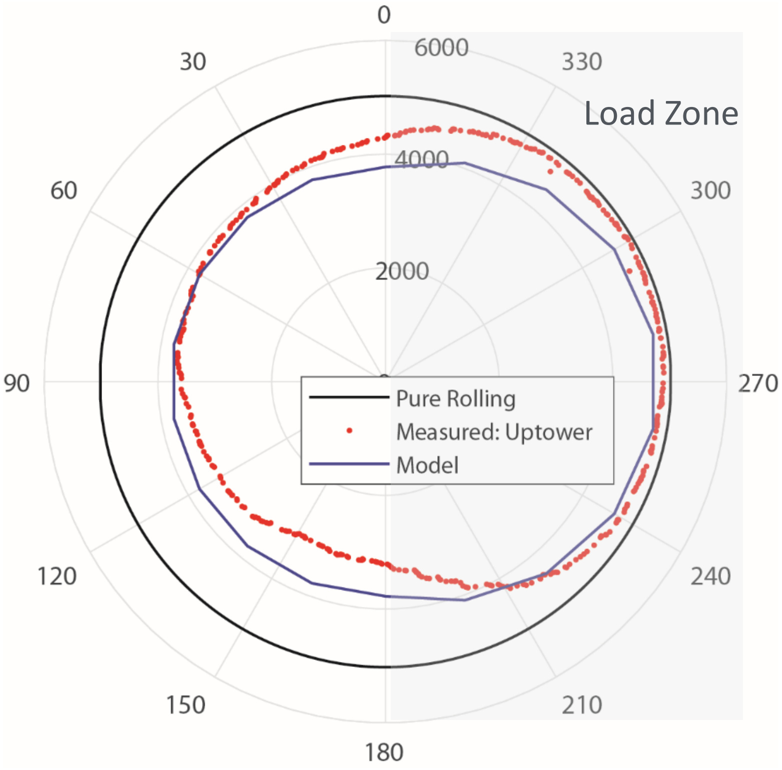
$$M_{ij} - M_{oj} + \frac{1}{2}\mu_{cg} D Q_{cgj} = F\omega_m \frac{d\omega_{rj}}{d\psi} \quad (3)$$

$$\sum_{j=1}^{z} Q_{ij}\, cos\psi_j - F_r = 0 \quad (4)$$

$$d_m \sum_{j=1}^{z} Q_{cgj} - D_{cr} F_{cl} = 0 \quad (5)$$

Model Validation: Roller Speed Zone

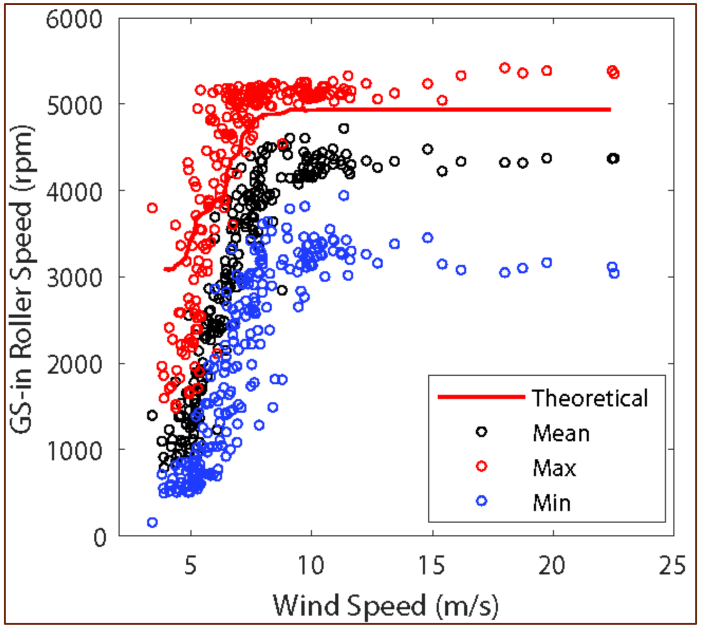
- **Good agreement between model & experiments**
- **Outside the load zone, the roller speed is less than its theoretical value for pure rolling conditions.**



Rated power

Roller Speed Statistics

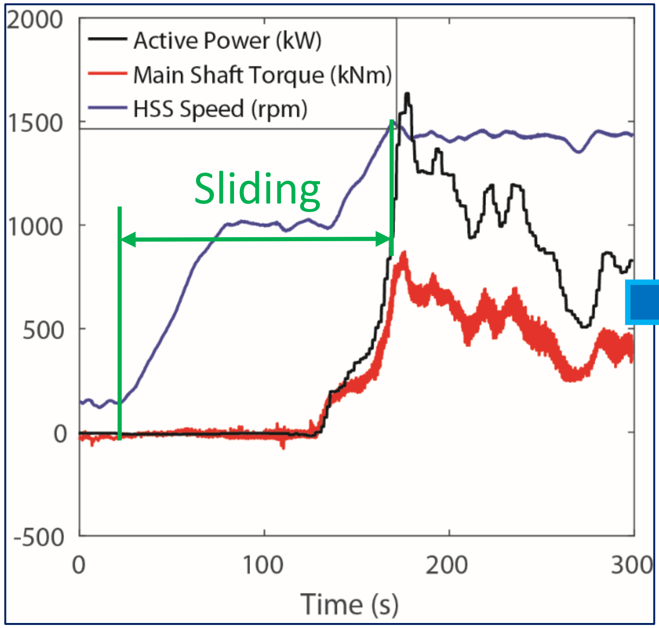
- **Good correlation between model and experimental results**
- **Roller speed less than theoretical at low wind speed**
  - Indicates significant roller sliding



Note: GS-in = inboard generator side; rpm = revolutions per minute; m/s = meters per second

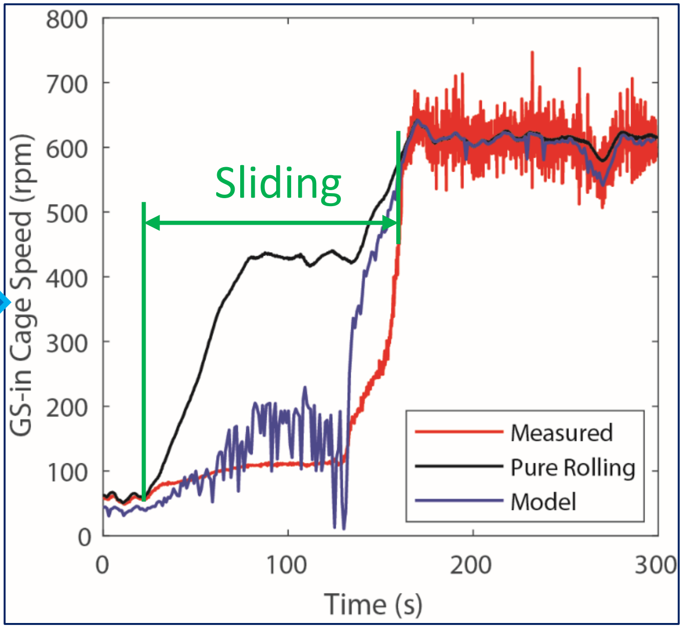
Roller Sliding During Startup

- **Significant sliding present between 110 & 220 seconds**
  - Related to controller settings
- **Sliding occurred because of high speed with no load**
  - Roller/raceway wear could occur.



Operating Condition

Note: kW = kilowatt; kNm = kilonewton-meter



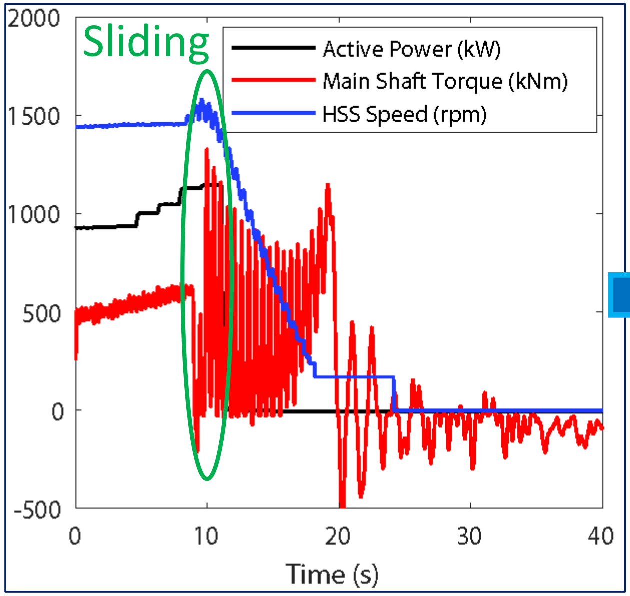
Cage Speed

Note: GS-in = generator side inboard

Roller Sliding During Emergency Stop

- **No significant sliding occurred**
    - Limited roller sliding present only when braking started
- **Strong impact loading initiated by the braking**
- **Maximum torque exceeded 169% of rated.**

Operating Condition



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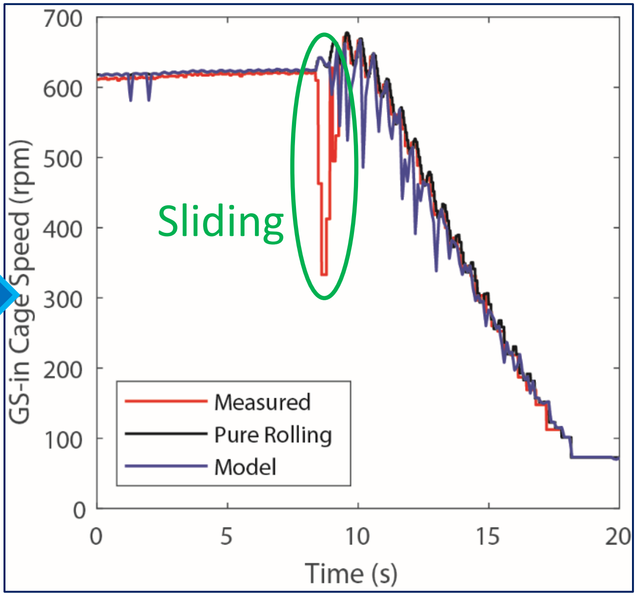
Cage Speed



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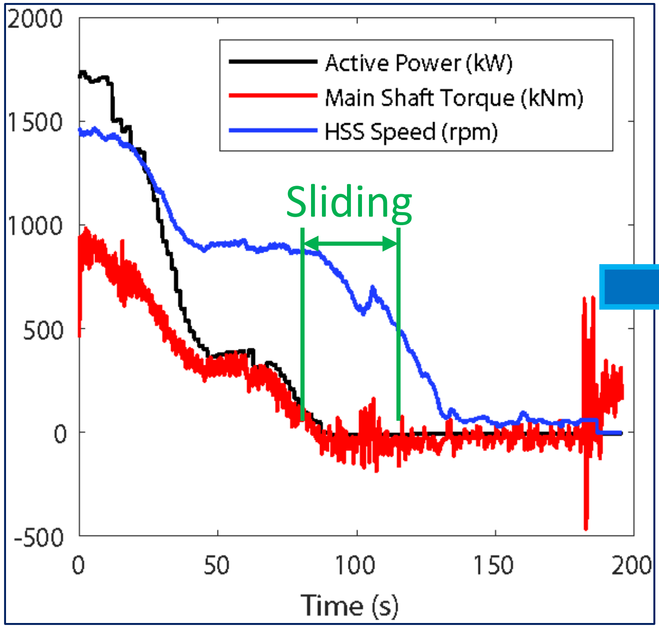
Roller Sliding During Normal Stop

- Sliding occurs when generator disconnected at 75 seconds
- High sliding risks under high-speed & low to zero load.

Operating Condition



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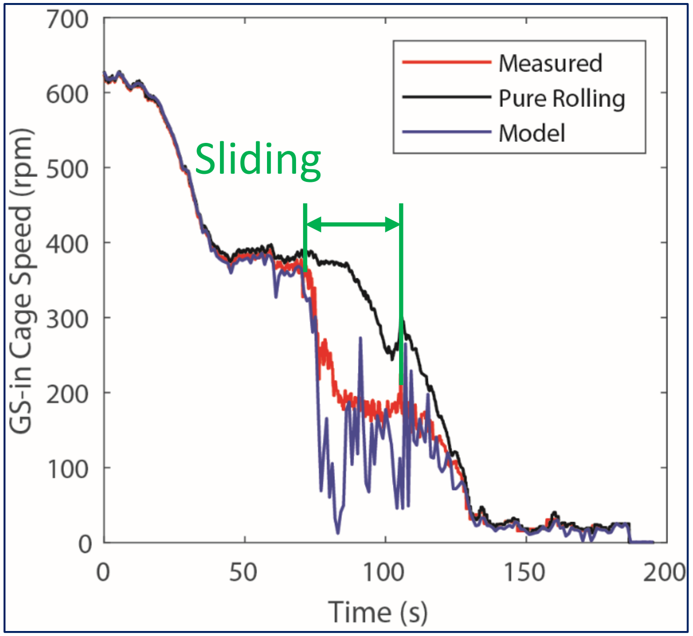
Cage Speed



Note: GS-in = generator side inboard

Conclusions

- **Unique experimental results on bearing roller and cage speed presented**
- **Analytic model for calculating bearing speed described**
  - Model validated through uptower experiments
- **Bearing speed affected by drivetrain load and speed**
- **Bearing sliding widely present during regular turbine operations**
- **Significant sliding occurs during transient events**
  - Can lead to bearing failures or shortened life
  - Risks of sliding-induced failures to be quantified in the future.

Acknowledgments

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Photo by Dennis Schroeder, NREL 49418

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[1] J. Keller and S. Lambert. *Gearbox Instrumentation for the Investigation of Bearing Axial Cracking* (Technical Report). NREL/TP-5000-70639. National Renewable Energy Laboratory, Golden, CO (US). https://www.nrel.gov/docs/fy18osti/70639.pdf, 2018

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