Data Center Load Fluctuations and Impact on Generation

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ENERGY DELIVERY AND CUSTOMER SOLUTIONS

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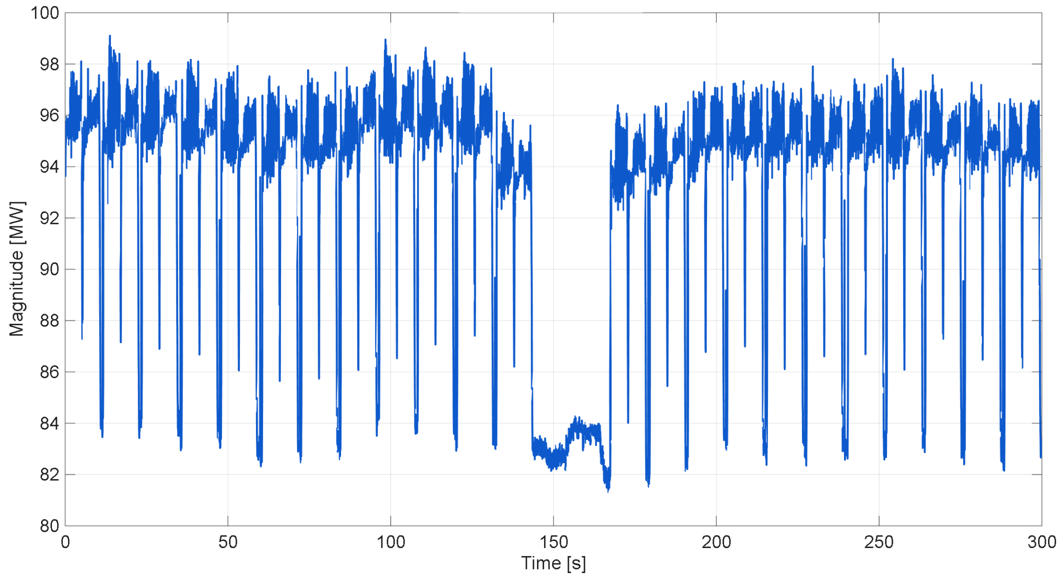
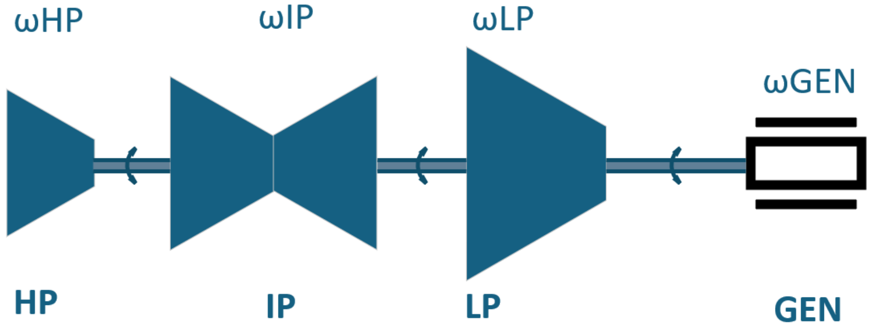
Agenda

- **Industry Challenge**
  - Defining acceptable limits on data center load changes remains a persistent industry challenge.
- **Problem Overview**
  - Overview of the technical issue and challenges.
- **Need for Cross-Sector Alignment**
  - Effective solutions require coordination across generator owners, data center operators, and planners to balance equipment limitations, load requirements, and planning practicality.
- **Generator Limitations**
  - Summary of synchronous generator torsional and operational constraints relevant to load variability.
- **Illustrative Test Case**
  - Presentation of a representative test case highlighting the challenge.
- **Proposed Path Forward**
  - Provide approach of planning solution to manage load-induced risks.

Load Interactions

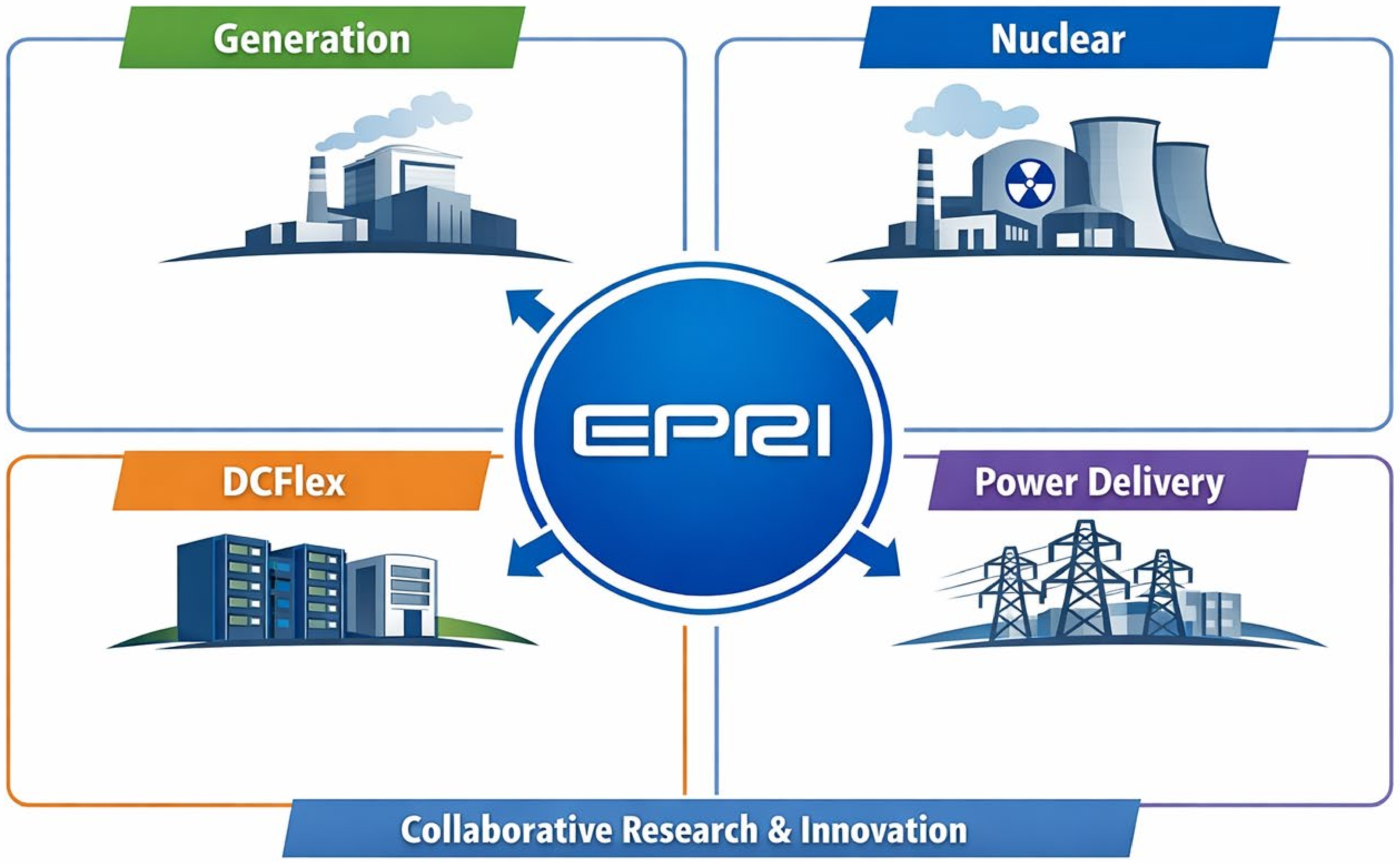


Data Center Load



Steam turbine torsional model

- Synchronous generators have torsional modes of oscillations in the 5-55 Hz range (oscillations between different turbine sections and the generator) referred to as Sub-Synchronous Torsional interactions (SSTI)
- Data center pulsating loads can excite these torsional modes
- Over an extended period, this can cause fatigue and even damage the turbine shaft


Generation
Nuclear
EPRI
DCFlex
Power Delivery
Collaborative Research & Innovation

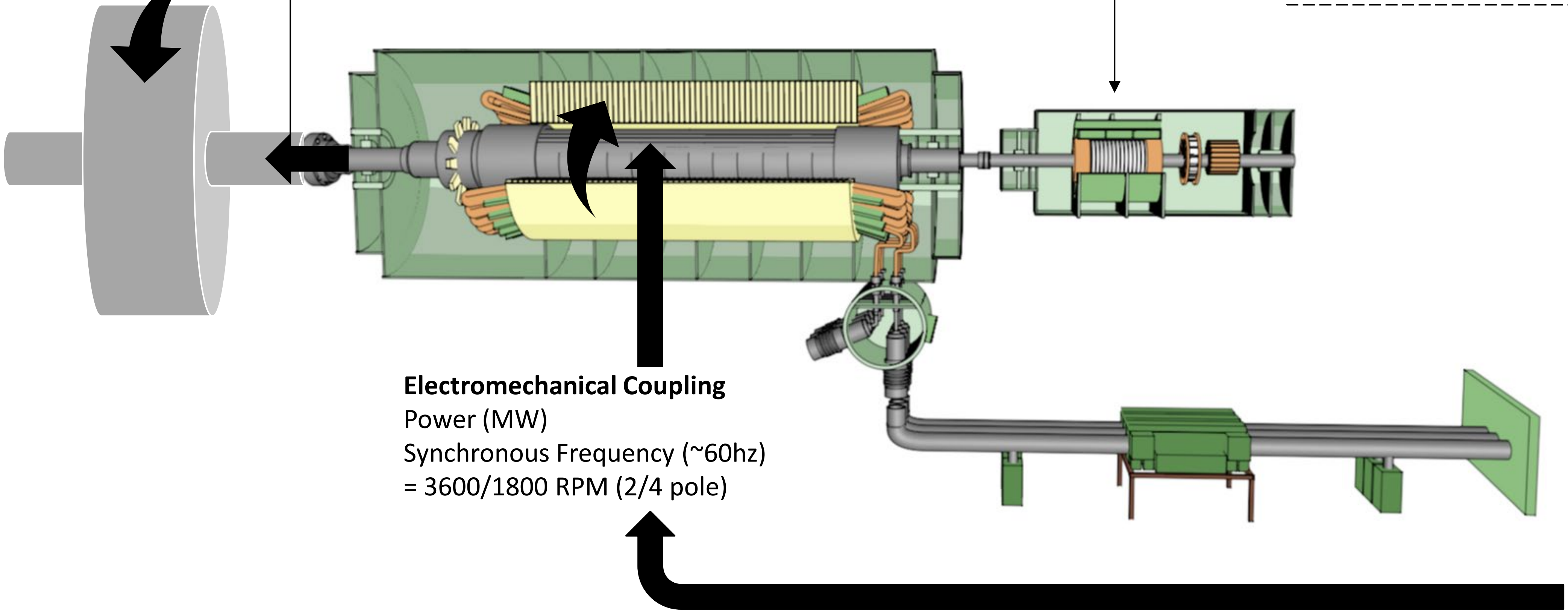
Simplifying Shaft Torsional Loads

Load Response/ Balance

Frequency Response
Voltage Regulation

Shaft Power
ST Power =m(h1-h2)
Mass Inertia/Stiffness
/Momentum

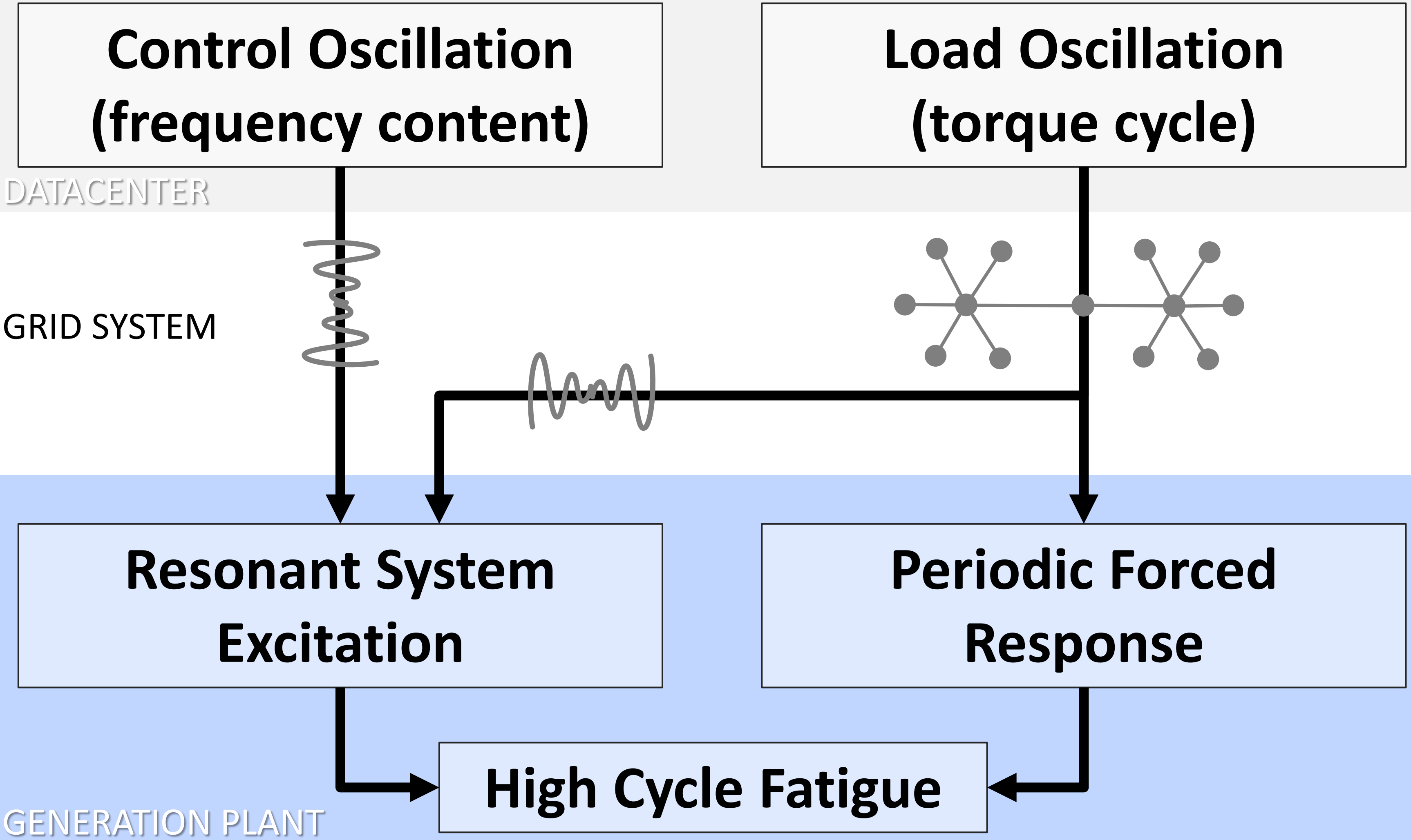
Shaft Torque $T = P / (2\pi \times RPM / 60)$
Power (MW)
Speed = 3600/1800 RPM



Electromechanical Coupling
Power (MW)
Synchronous Frequency (~60hz)
= 3600/1800 RPM (2/4 pole)

Load
Power (MW)
Grid Frequency (~60hz)

Effects Related on Synchronous Generation Resources

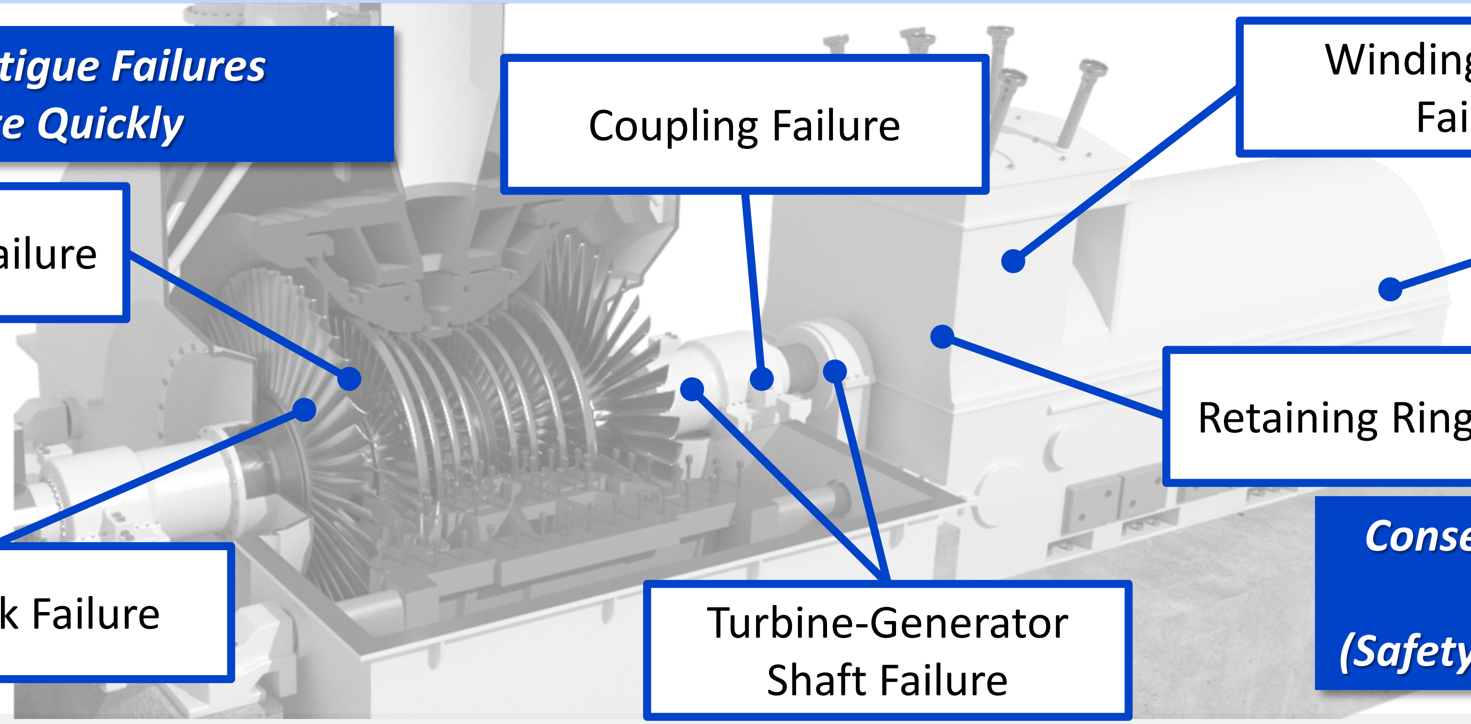


Effects Related on Synchronous Generation Resources

Resonant System Excitation → **High Cycle Fatigue**

Periodic Forced Response → **High Cycle Fatigue**

High Cycle Fatigue Failures Propagate Quickly



Consequences of Shaft Failures are Major Losses (Safety – Financial – Lost Generation)

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Understanding the Design Risk

Loads

It's the *force* behind design

Alternating stresses on components

- Forces generated on components and features.
- Features and fits generate stress intensities
- Transient behaviors (inertia, thermal, load)

&

Vibratory characteristics of components in the system

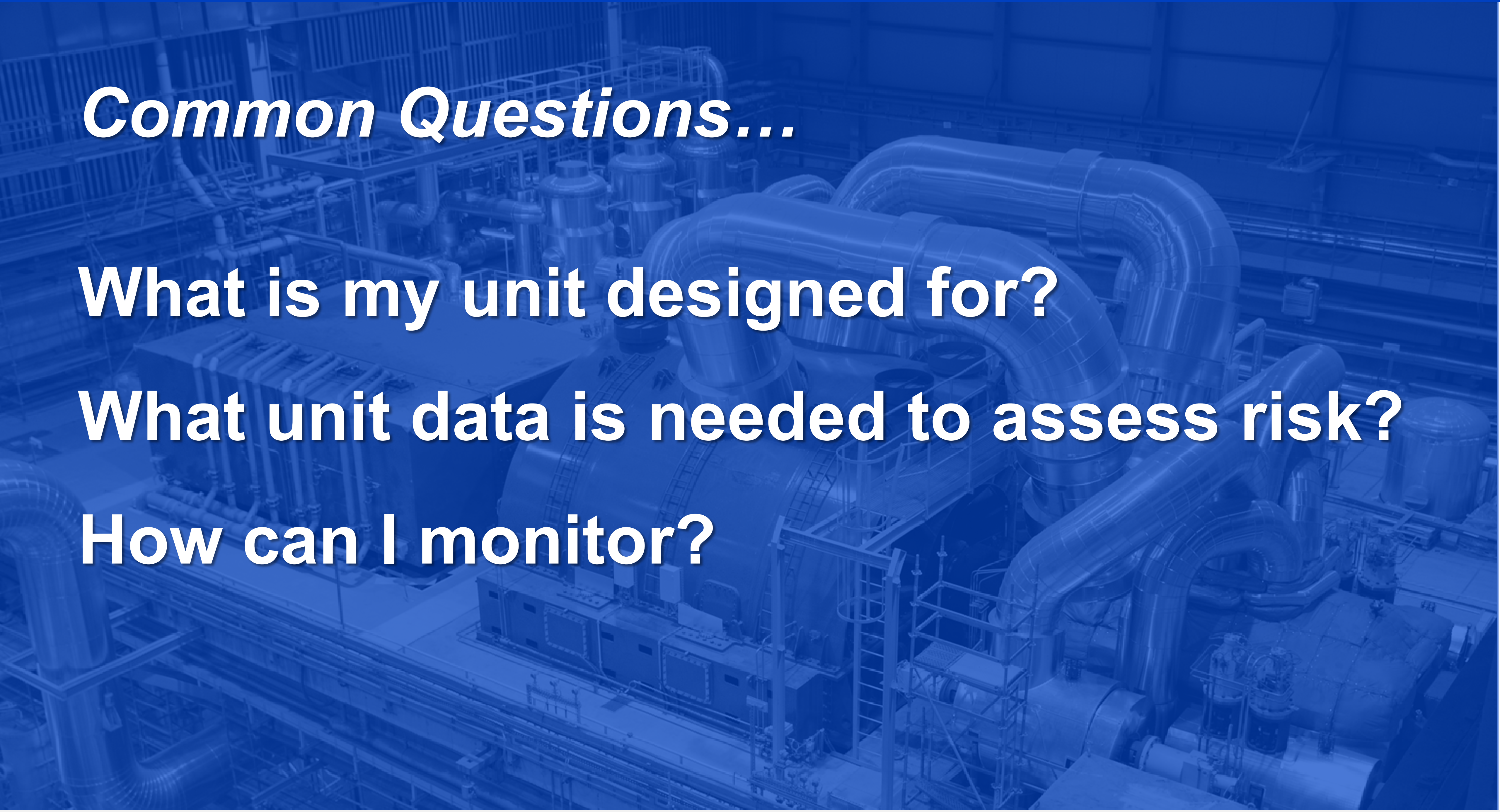
- Natural frequencies
- Excitation forces
- Stress Amplification

It's more than just the shaft, assembled components will all have vibratory failure risk

Modes

Excitement that can lead to major failures

Stress → Strain and Material Endurance (HCF)



Common Questions…

What is my unit designed for?

What unit data is needed to assess risk?

How can I monitor?

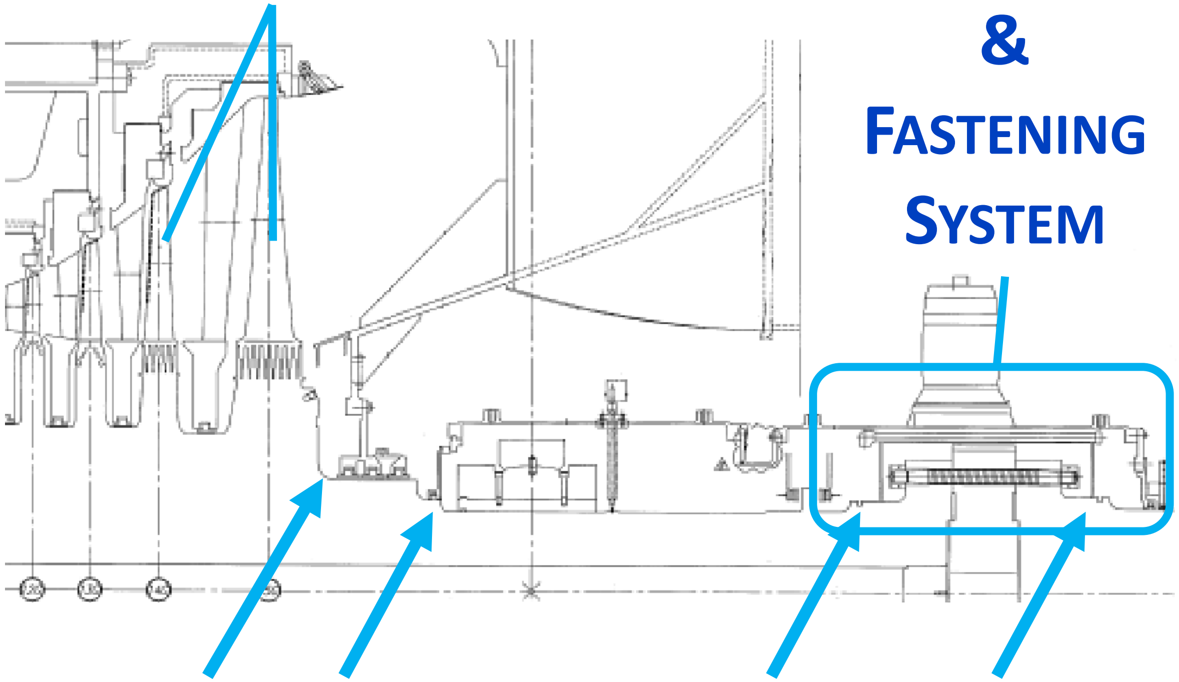
The Basics for Rotating Equipment

Mechanical Loads

- Rated Conditions
- Rated Duty
- Overload Assumptions

Resonant Conditions

- Passing Frequencies
- Grid Frequencies
- RPM Driver



Mechanical Design Principles for Turbo-Generator Systems

Plant Operation

Continuous Operation

- Line Resonance

Operation Events

- Turbine-Generator Load Rejection
- Out-of-Phase Synchronization
- Generator Line Phase Faults
- Loss of Synchronization

Plant Operating Conditions Considered in Standard Rotating Machinery Design Cases

High Cycle Fatigue

- Shaft and coupled vibratory modes do not intersect with 1x/2x line frequency
- Adequate separation exists to account for calculation error and periodic system frequency deviations
- Key Factor: Resonant Stress, Fatigue Endurance

Overload & Low Cycle Fatigue

- Load capacity to endure singular events
- Event cycle accumulation considered infrequent
- Key Factor: Permissible strain

Not Considered in Standard Mechanical Design

Grid Disturbances

Intermittent Events w/ Varying Duration

- Faults or Short Circuits
- Transmission Line Switching
- System Oscillations
- Demand Center Loads
- Power Electronics
- Unbalanced Phase Currents

No Design Cases for Associated Torsional Loads, Reliance on Generator Protection Schemes

Managing Grid Operations Behaviors

- Demonstrated transmission codes
- Applied generator protection

Historically Considered Effective

Managing Generation & Load Center Behaviors

- Interconnection impact studies (proactive)
- System screening and corrective actions
  - Generation/load center control and operation tuning
  - Power filter

! *Increased System Penetration of Inverter-Based Resources & New Intermittent Large Loads Create a Difficult Problem to Address in Design*

Understanding the Design Risk

High Cycle Fatigue

Resonant System Excitation

Periodic Forced Response

	1			2		
Failure Mechanism	**T-G Shaft Modes**	**ST Coupled Modes**	**GEN Coupled Modes**	**T-G Shaft Load**	**ST Coupled Loads**	**GEN Coupled Loads**
	High Stress Magnification – Fast Accumulated Cycles			Proportional Stress – Accumulated Cycles		
Potential Impacts	**HIGH**	**HIGH-MED**	**HIGH-MED**	**HIGH**	**MED**	**MED**
	Natural frequencies often available, avoid excitation	Natural frequencies often not available, avoid excitation		Fatigue endurance not available, establish threshold	Fatigue endurance not available, establish threshold/increase inspection intervals	

EPRI

Ongoing EPRI Activities to Manage Risk

1

Resonant conditions of shaft torsional and coupled system modes represent risks that are difficult to generalize due to amplification factors

2

Estimating Shaft Endurance Thresholds

- For *non-resonant shaft stress*, analysis confirms torque is proportional with power oscillations
- By evaluating minimum design standards (elevated stress assumptions) for LCF design, a reference mean operating stress can be developed (e.g. Gerber, Goodman, Soderberg, Endurance Characterization Methods)
- By assessing the HCF strain-cycle curves for each alloy, an endurance threshold can be established to define forced oscillation limits on shafts

Easier Said than Done - Existing Fleet Challenges

Age/Vintage of Machine

- Data may not be available/accessible at OEM
- Historical calculation margins unknown
- Turbine configuration variability
- Turbine design variability
- Accumulated damage
- Service induced variations of current condition

New Equipment Supply

- Retrofits of modules need to account for full train behavior
- New unit supply …(it's a seller's market)
  - Detailed analyses may not be part of offer since specification enhancement not available
  - No known design standards for emerging risks

Torsional Measurements Help with Identifying Resonant Conditions, but lack insights Endurance Limits without Sufficient Modeling

Knowing the Areas of Stress Amplifications and Cycles

Where will damage occur?

What other system monitoring could verify damage accumulation?

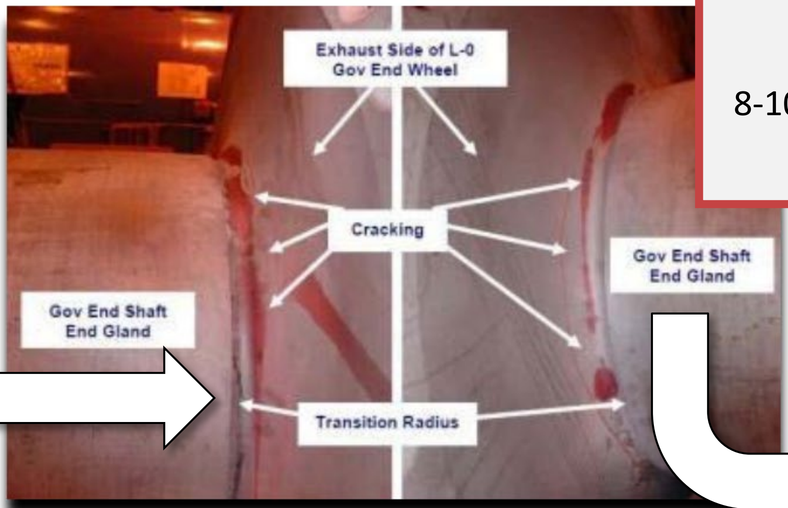
How can I inspect without conducting full outages?

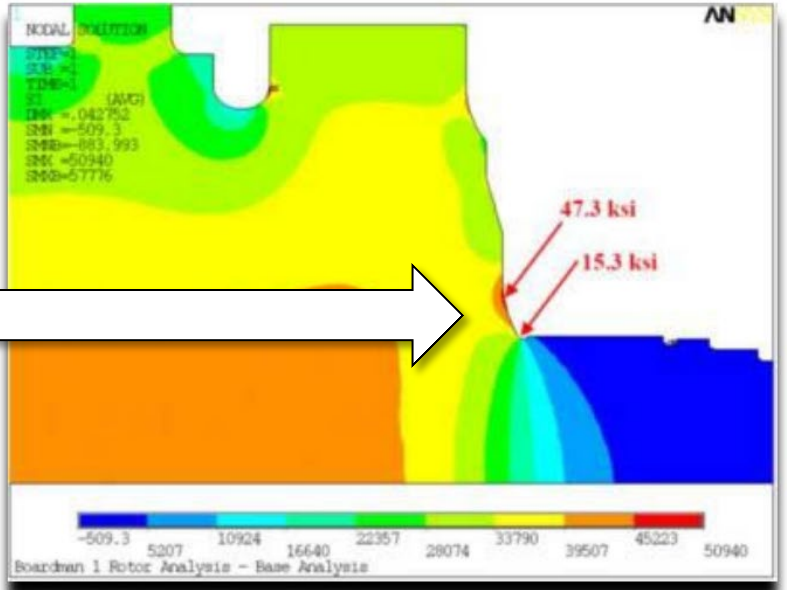
Targeted Inspections (Shaft Example)

- WH BB271 Retrofitted DFLP Rotor (v.2000)
- 617MW, 2400psi / 1000F / 1000F
- 360 Degree intermittent crack on transition radius and wall of LP
  - 6 crack initiations around periphery
  - Conical cracks propagating axial-tangential to the rotor center
  - Detected by lateral vibration amplitude and phase angle movement

Root Cause & Contributing Factors:

1. Initiation at gland transition radius pits near non-metallic inclusions
2. Propagation dominated by stress from torsional oscillation load
   I. Stress concentration from centrifugal loading
   II. Stress magnification from bending due to alignment
3. Propagation transformed to LCF from inertial load





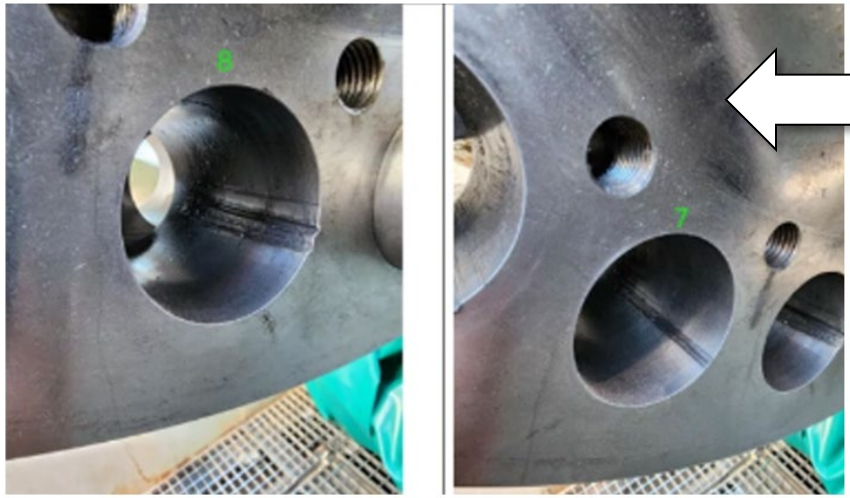
IMPACT

8-10 month repair ($270M in lost generation)
Major loss event avoided

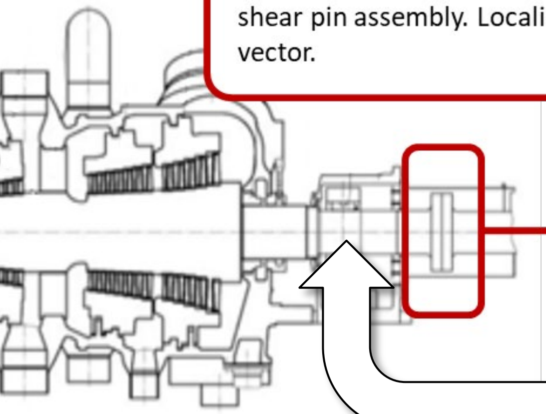
- Remaining fracture surface at terminal crack propagation

- Fell out during shaft severing operations

Targeted Inspections (Coupling Example)



Coupling Hole - Apparent impression displacing material on fitted shear pin assembly. Localized damage in line with load transmission vector.



Friction Coupling Displacement

- Tight or damaged bolts/nuts/sleeves…increased galling or stuck
- Clocking of position…face galling

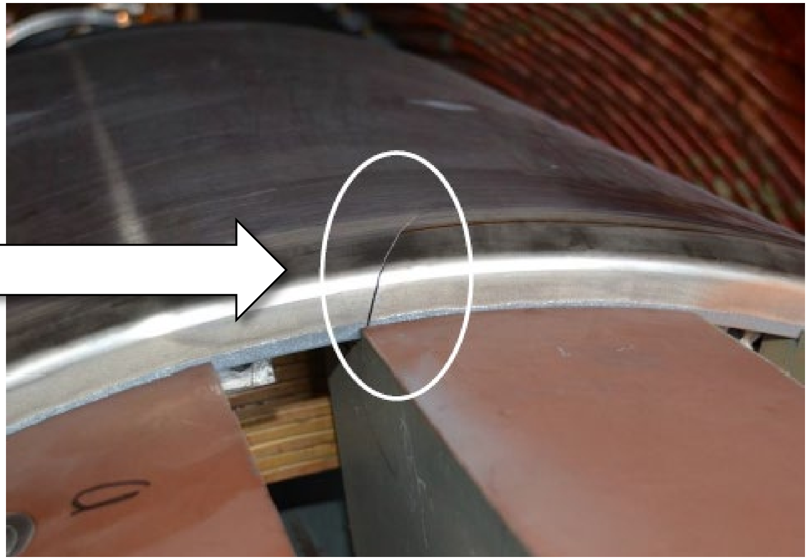
Shaft Cracking or Displacement

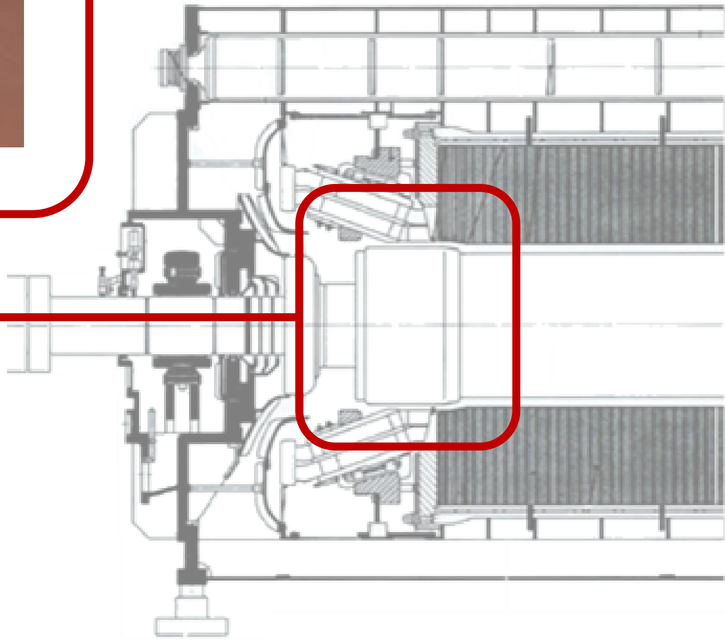
- Hole/transition stress concentrations
- Coupling unbalance (lateral)

Targeted Inspections (Retaining Ring Example)

Retaining Ring

- Cracking at fit hub
- Fretting or galling





Inspection Scope Considerations

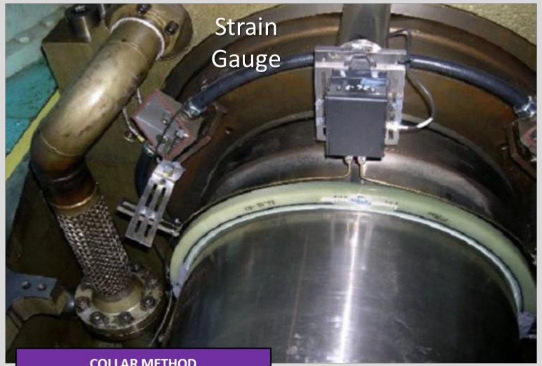
- VT: Borescope
- ECT/PAUT: Retaining Ring Robotic Inspection

Torsional Monitoring Systems

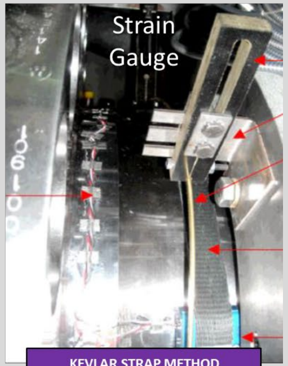
Sensors integrated with models to enhance risk insights

EPRI TDMS

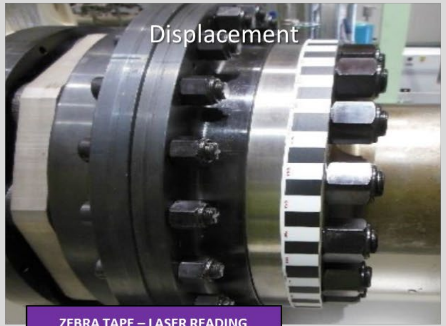
Shaft-mounted Sensor Package
- *Increased measurement parameters*
- *Eliminates machine induce noise*



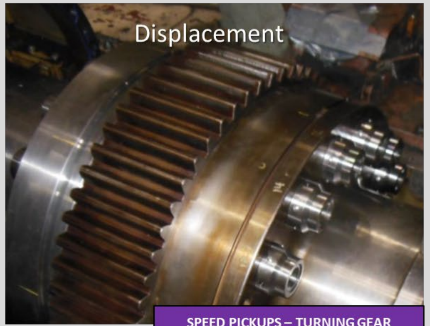
COLLAR METHOD



KEVLAR STRAP METHOD



ZEBRA TAPE – LASER READING



SPEED PICKUPS – TURNING GEAR

SPEED PICKUPS - SPEEDWHEEL

Data Visualization

- Vibration trending
- Event alarms

Actions limited unless thresholds are identified

Requires basic model

Data Analytics

- Strain Amplitude
- Strain Cycles

Actions limited unless thresholds are identified

May require more detailed model

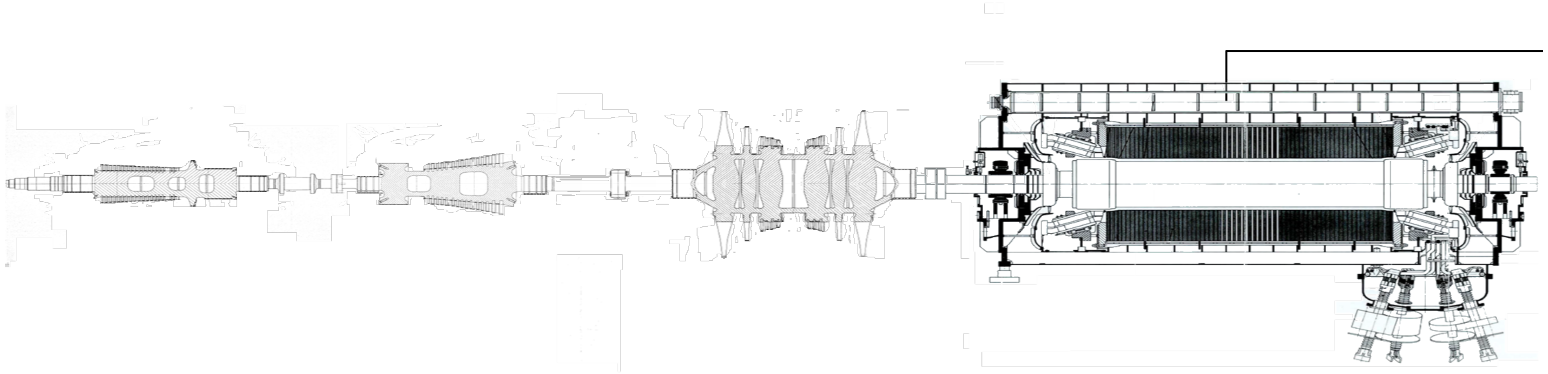
Damage Prediction

- Damage Accumulation
- Damage Detection

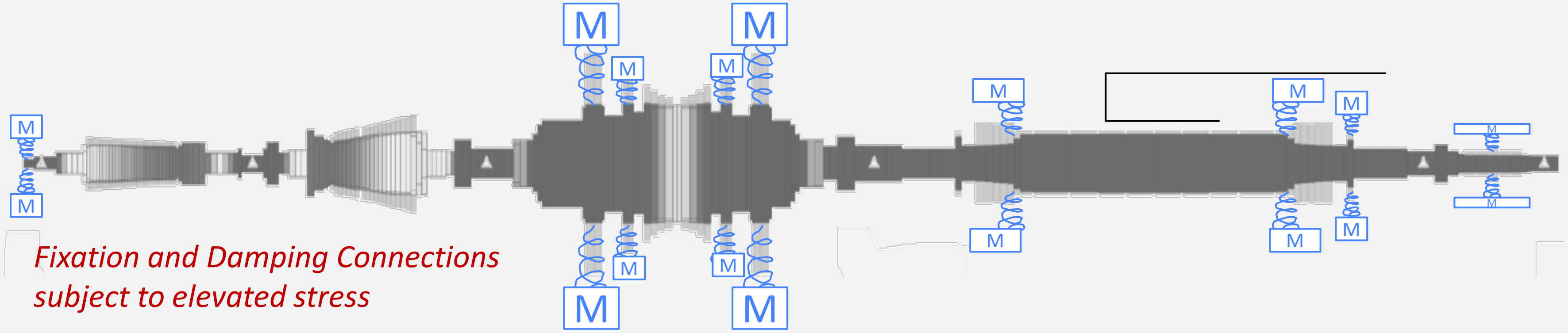
Model accuracy and level of automation

Generator Torsional Model

Turbine-Generator
Cross Section



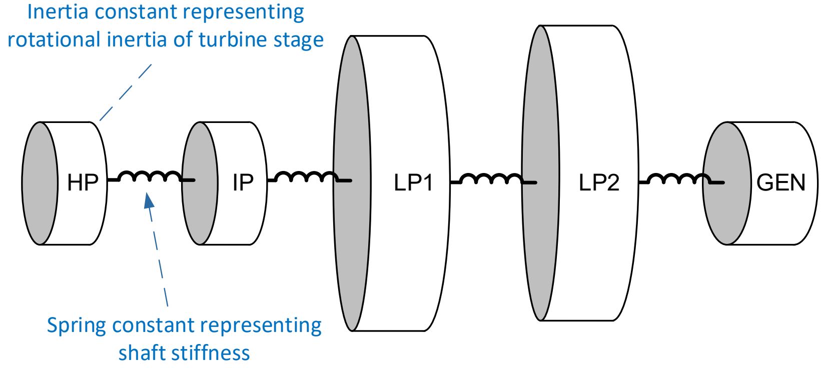
Lumped-Mass
Model
(w/ coupled mass)



Fixation and Damping Connections subject to elevated stress

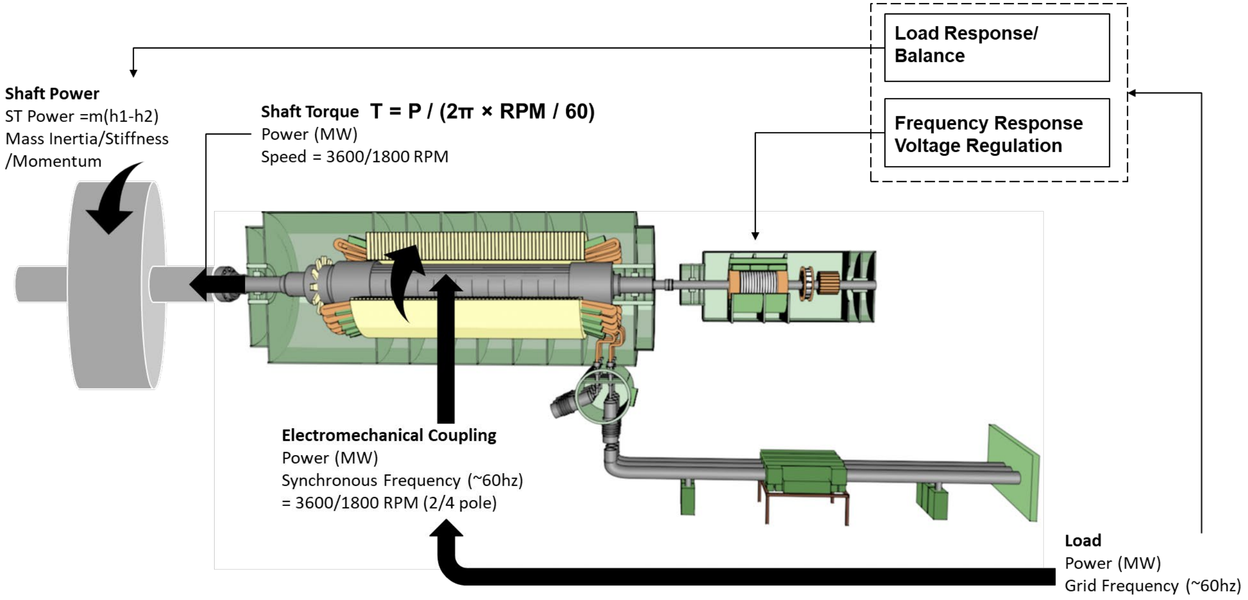
Simplified
EMT Model

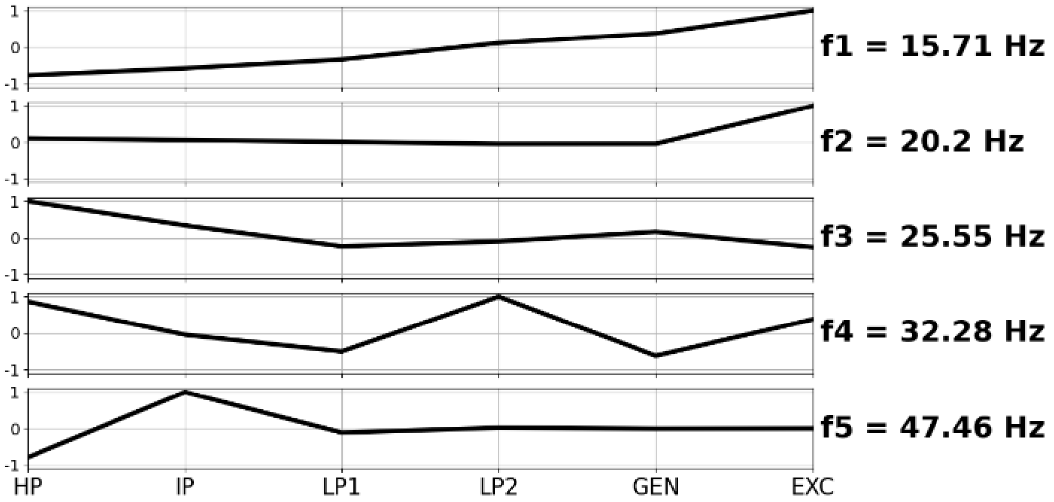
Reduced order model:
for behavior, not reliability



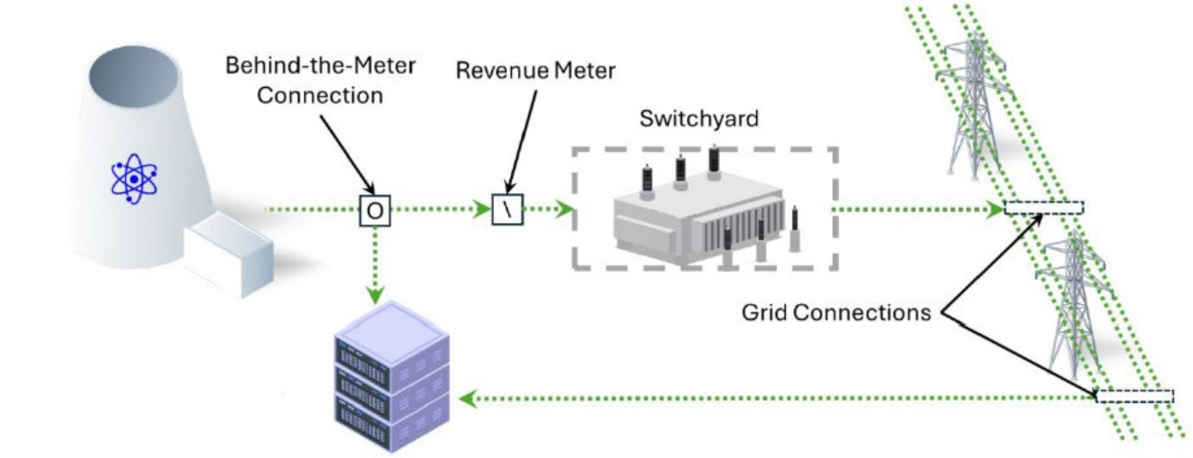
Data Center Load Fluctuations and Impact on Generation

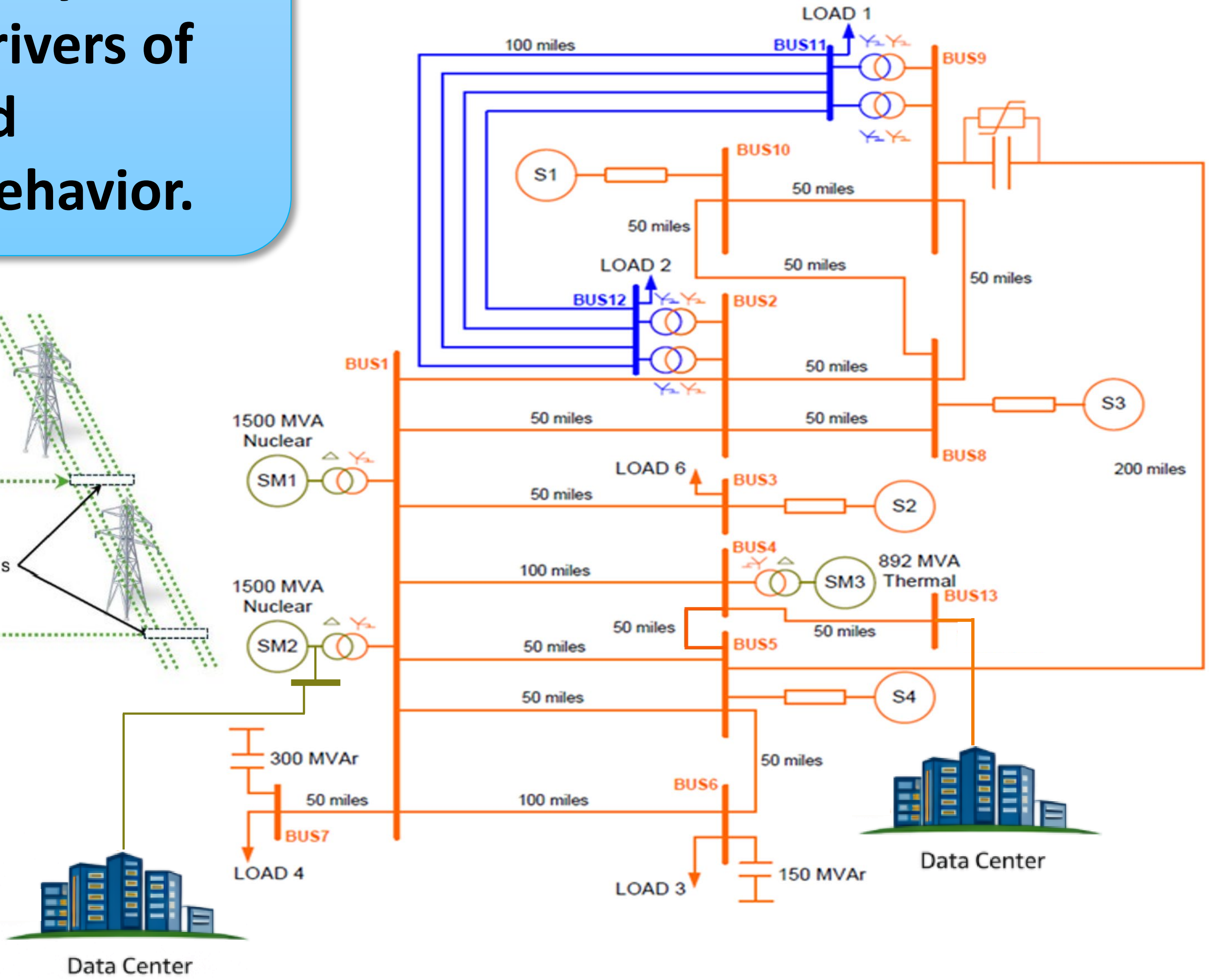
- When properly parameterized, multi-mass models have been shown to closely match field test measurements of torsional frequencies and modes.
  - Accuracy is high for frequency identification, but more uncertain for damping estimation, which is often not well documented by OEMs.
- Torsional mode amplification difficult to define.
  - Difficult to arrive at hard thresholds at torsional mode because of variation in shaft response at torsional frequencies and uncertainty in modeling.



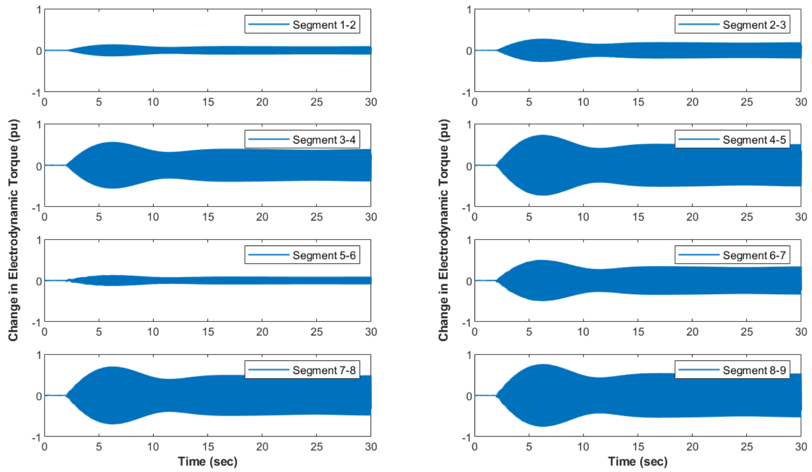


Data center location and system configuration are key drivers of performance and generator-interaction behavior.

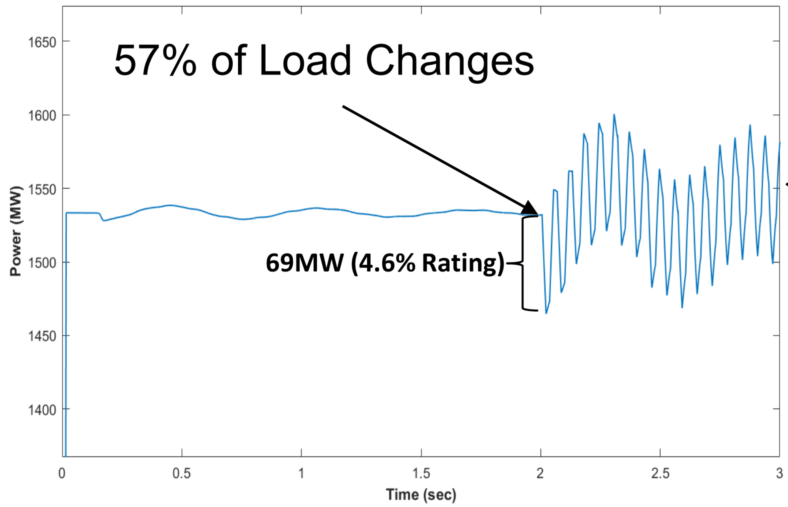


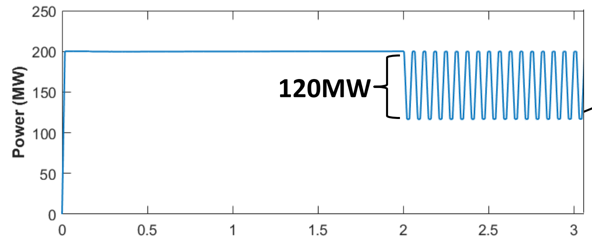


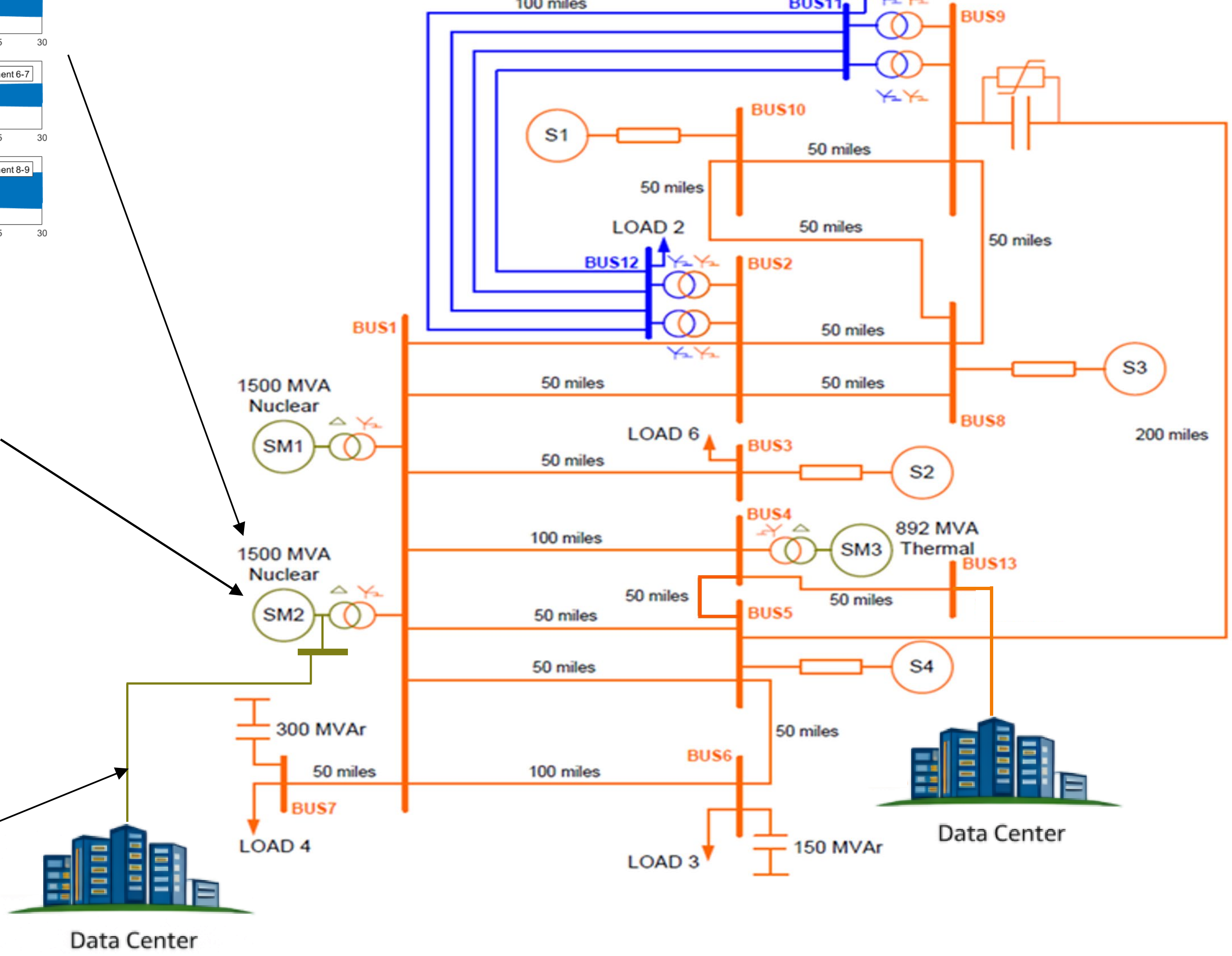
Nuclear Unit (4 Pole, 1500 MVA)



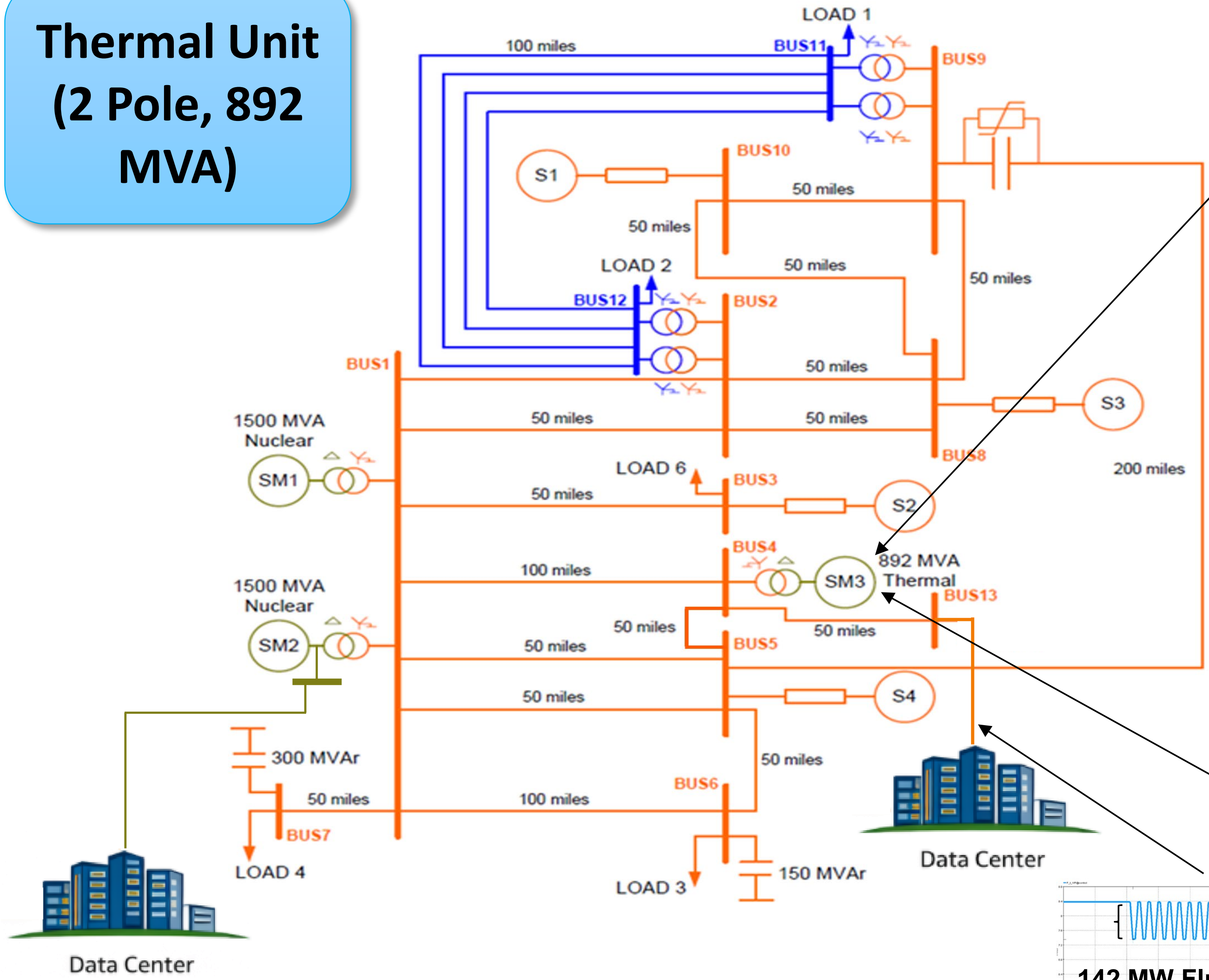
54% of Rated Torque
(12x Oscillatory Load)

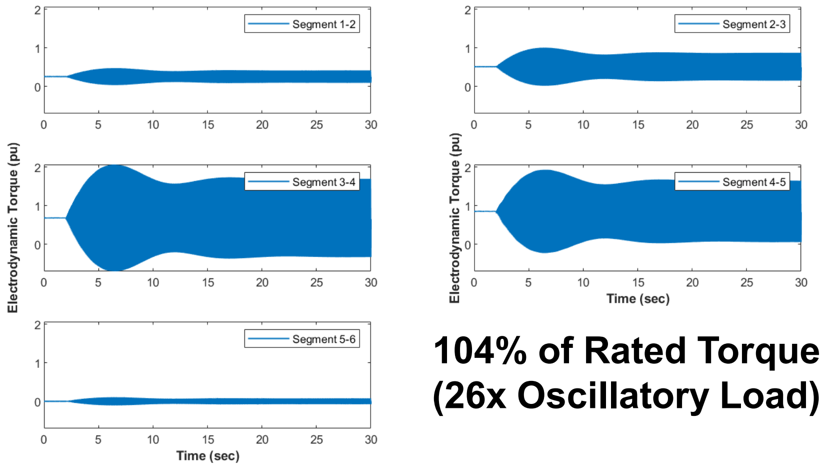




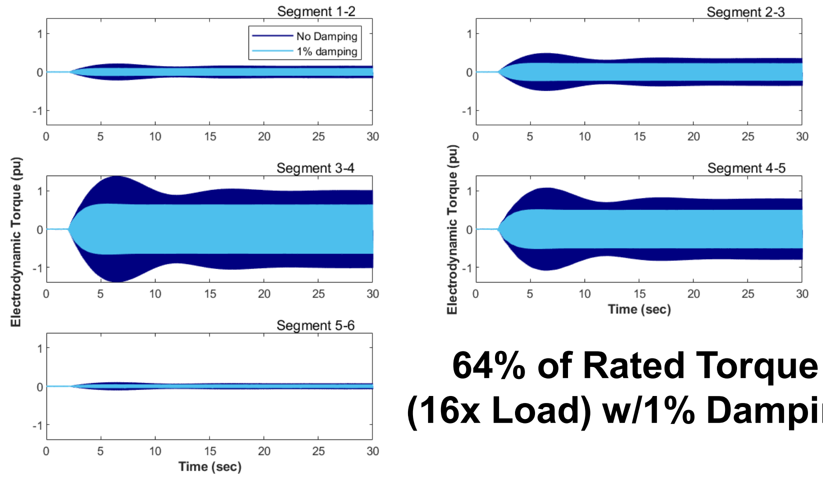


Thermal Unit (2 Pole, 892 MVA)

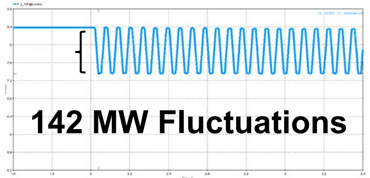




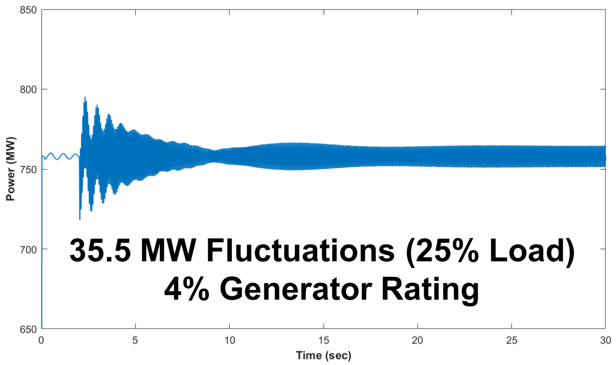
104% of Rated Torque
(26x Oscillatory Load)



64% of Rated Torque
(16x Load) w/1% Damping



142 MW Fluctuations



35.5 MW Fluctuations (25% Load)
4% Generator Rating

Example Case Analysis

Generator	Mode Excited	Max Torque/Load (% Gen Rating)
Thermal Unit (2 Pole, 892 MVA)	Torsional – 15.71Hz	**~26**
Thermal Unit (2 Pole, 892 MVA)	Non-Torsional – 6 Hz	~1
Nuclear Unit (4 Pole, 1500 MVA)	Torsional – 15.83Hz	**~12**
Nuclear Unit (4 Pole, 1500 MVA)	Non-Torsional – 6 Hz	~1

For Torsional Mode:

For Example, on Thermal Unit a 4% load at the generator results in a max torque of 104% (Rated Torque) on the shaft. (4%*26)

For Example, on Nuclear Unit a 4% load at the generator results in a max torque of 48% (Rated Torque) on the shaft. (4%*12)

For Non-Torsional Mode

For Example, on both units a 4% load results in a max torque of 4% (Rated Torque) on the shaft. (4%*1)

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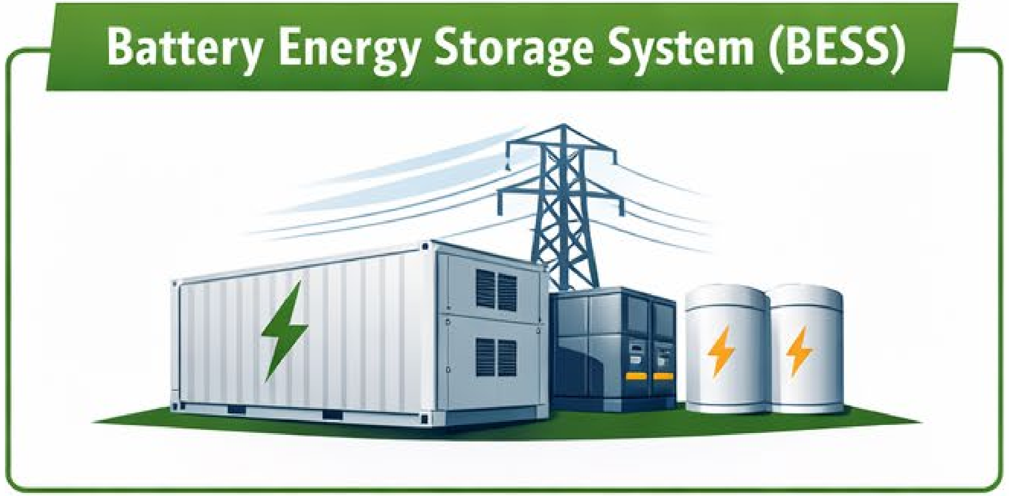
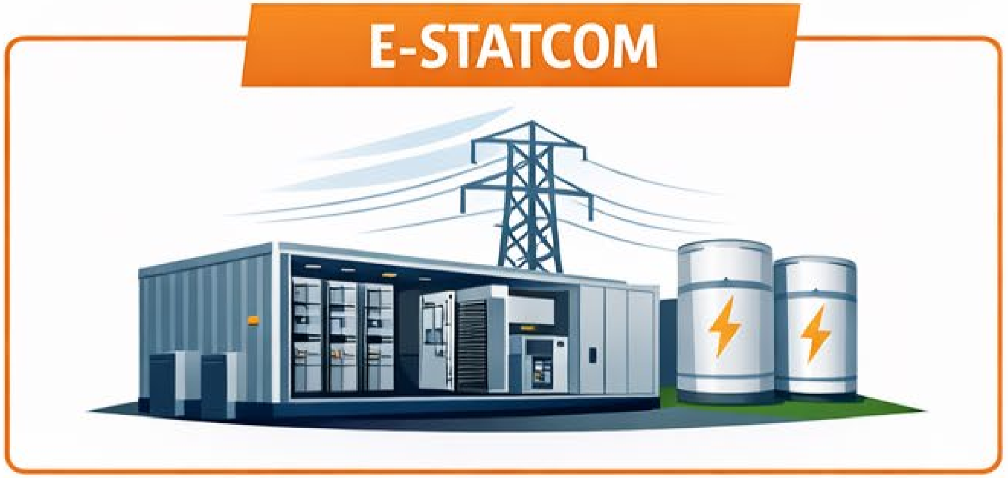
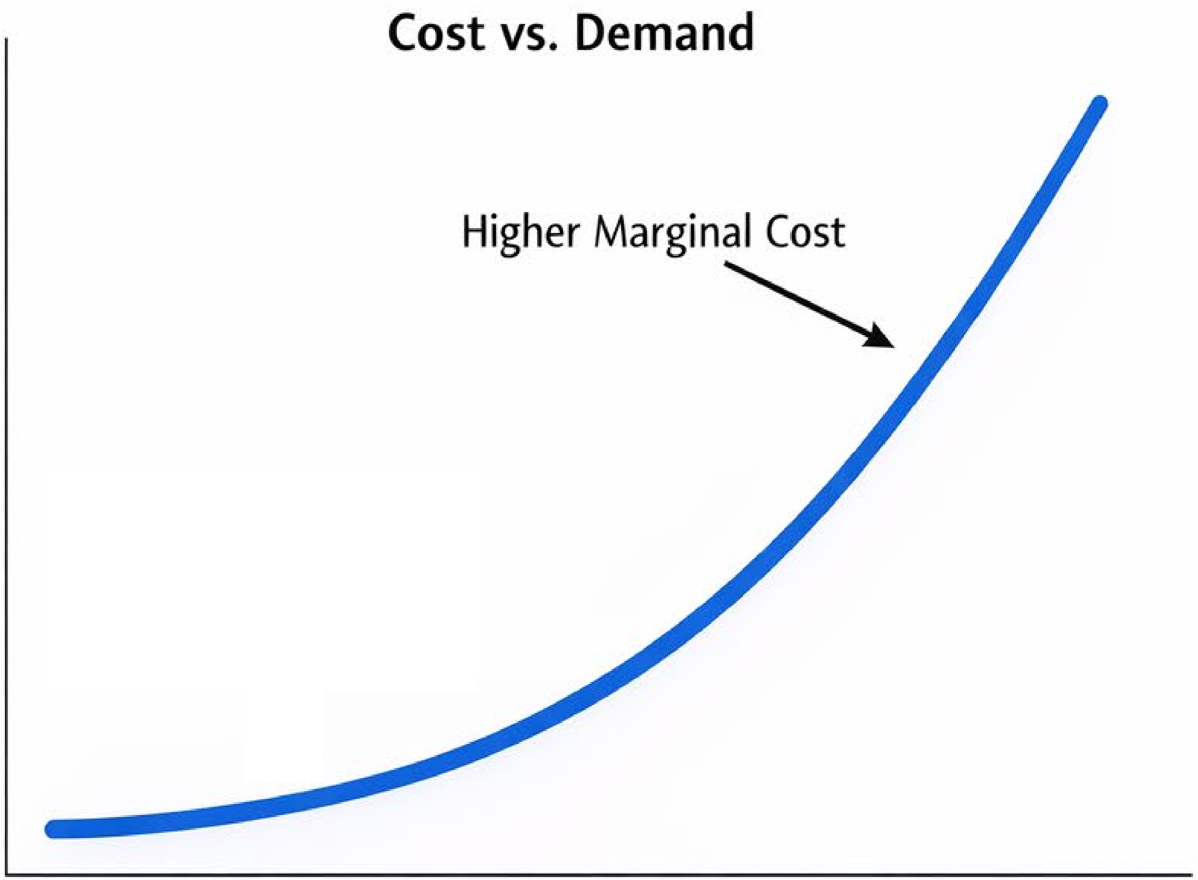
Mitigation Equipment







General Approach

- Can determine load sharing in positive-sequence models (e.g. PSSE). Methodology provides a practical alternative.
- Detailed-EMT models are neither required and may not be reliable for defining allowable load fluctuations
- Limiting load fluctuations only at torsional modal frequencies may be overly restrictive
- Load-level protection for torsional modes effectively safeguards synchronous generators
- This approach prevents torsional damage and avoids unnecessary generator trips

EPRI is collaborating with utility members to evaluate data center integrations using established and emerging assessment methodology.

Closing gaps in system understanding…

- ✓ **Complexity in design of synchronous machines**
- ✓ **Interdependencies that impact reliability, safety and affordability**
- ✓ **Collaboration between ED&CS, Nuclear & Generation**

There is More to Consider…

How will large load variations impact plant control/protection?

Nuclear/Boiler/CCST chasing/hunting?

Switchyard equipment reliability risks?

Together…Shaping the Future of Energy™