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Datacenter Load Impact on Torsional Vibrations of Turbine-Generators

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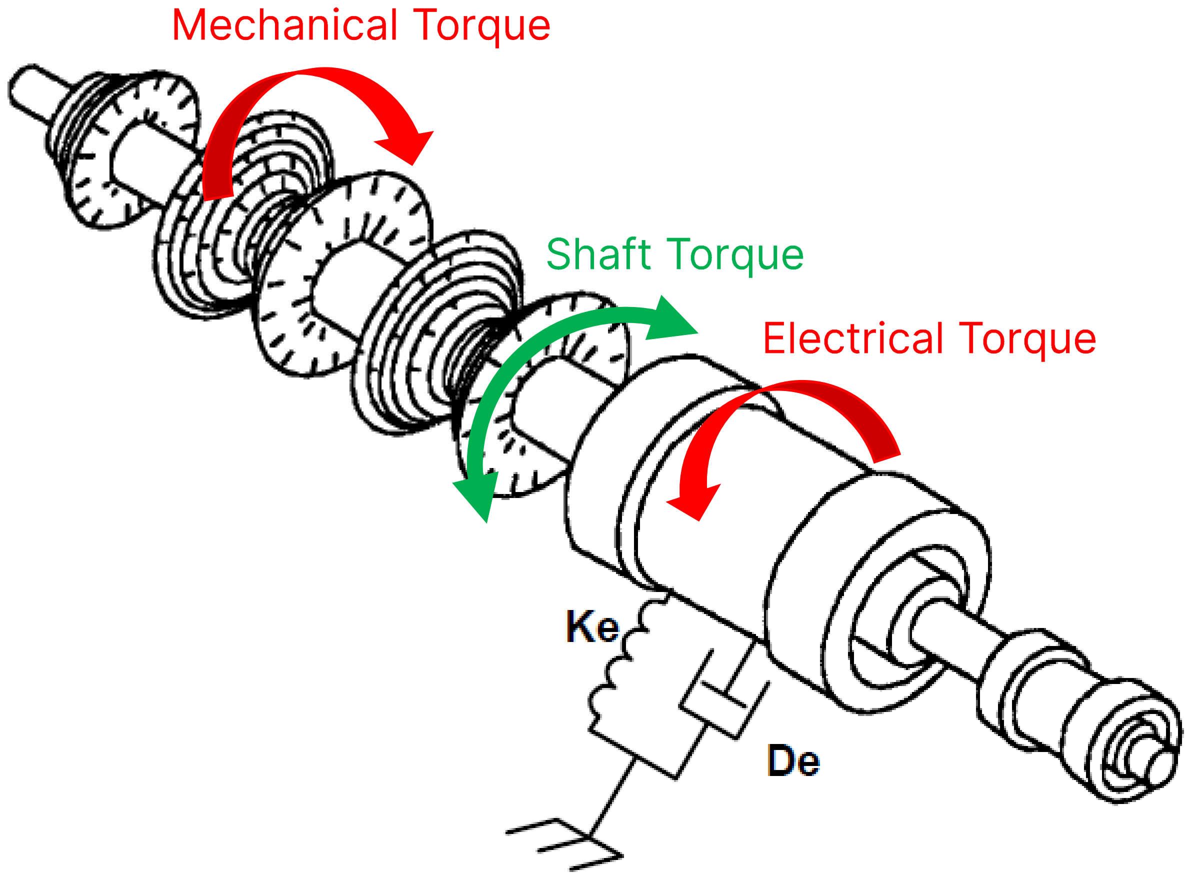
Agenda

- Background on torsional vibrations
- Torsional Risk Considerations with Datacenters
- Example Simulation Results
- Final Thoughts

BACKGROUND INFO ON TORSIONAL VIBRATIONS

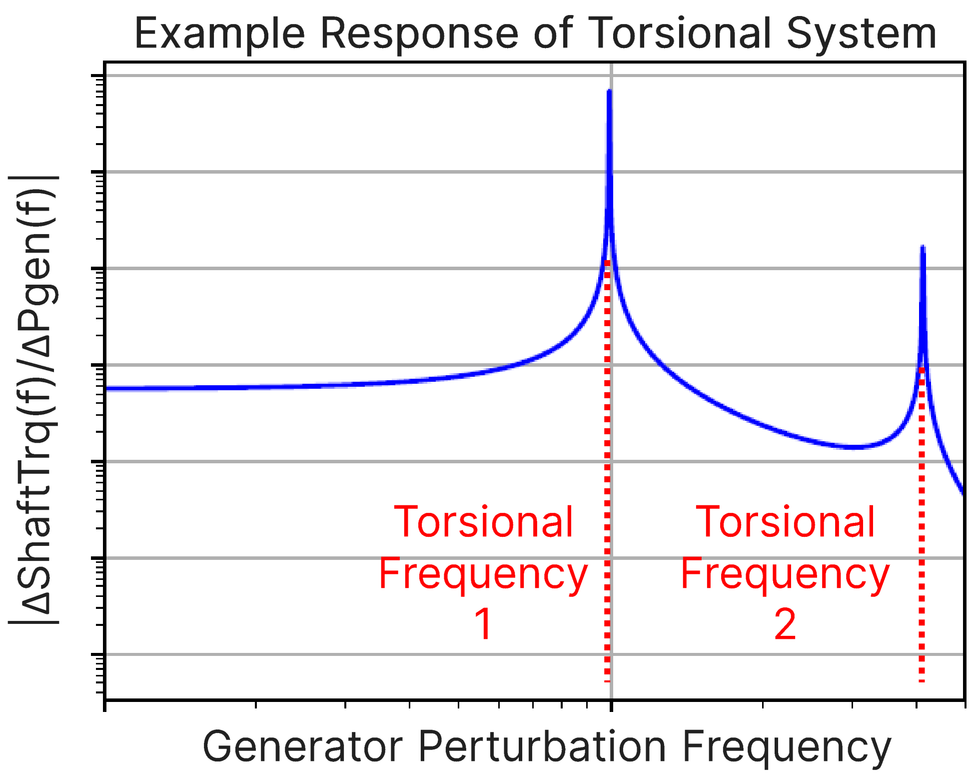
Background – Torsional Dynamics

- Turbine-generator torsional vibrations
  - Manifests as twisting motion between inertias along shaft
  - Tends to vibrate at one or more natural torsional resonant frequencies (sub- and super-synchronous)
  - Very light inherent mechanical damping
  - Electrical network influences vibrations thru generator air gap
    - Equivalent to electrical damping (De) and synchronizing torque (Ke)
    - Changes/oscillations in electrical torque due to electrical load changes



Background – Torsional Response to Electrical Stimulus

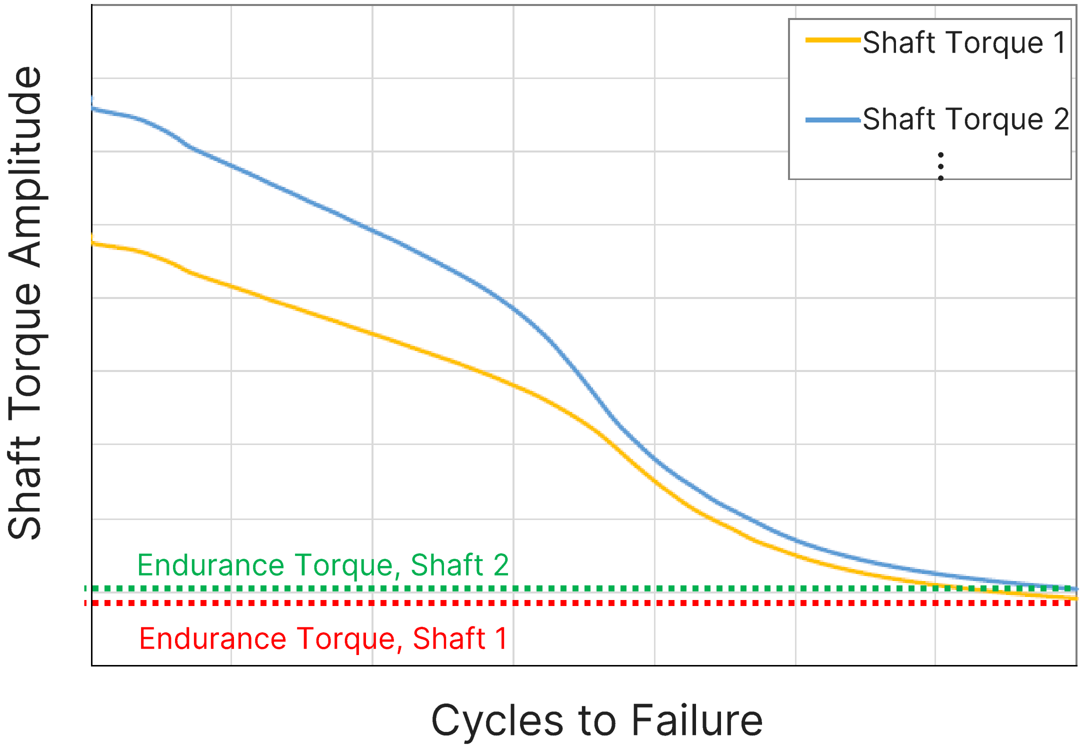
- Torsional response to electrical perturbations
  - Turbine-generators highly sensitive to perturbations in generator power/torque around torsional frequencies
  - Small amount of power/energy content present can cause potentially unacceptable levels of shaft torque
  - Some risks with perturbations with non-torsional frequencies, but more power/energy content required to cause excessive torque
  - Shaft sections experience different torque levels depending on frequency of oscillation



Background – Shaft Fatigue

- Torsional Fatigue
  - Torsional vibrations manifest as shear stress along shaft elements
  - Turbine-generators designed to withstand certain level of torque continuously
  - Fatigue characteristics primarily determined by shaft dimensions and material characteristics
  - Endurance torque defines amplitude of torque oscillations a certain shaft can withstand before accumulating fatigue
  - Temporary exceedance of endurance torque likely not a big risk if occurrence is rare
  - Electrical system must be designed to avoid instabilities or oscillations that cause continuous or frequent exceedance of endurance torque

Example fatigue characteristics of two shaft sections on a turbine-generator

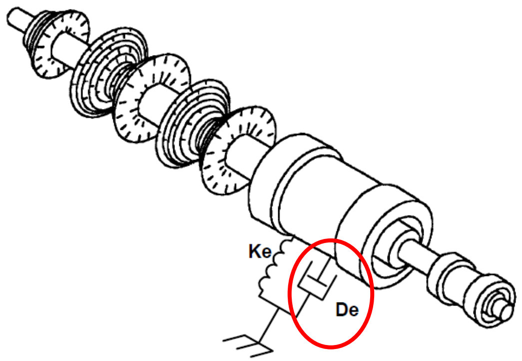


TORSIONAL RISK CONSIDERATIONS WITH DATACENTERS

Torsional Risks Introduced by Datacenters

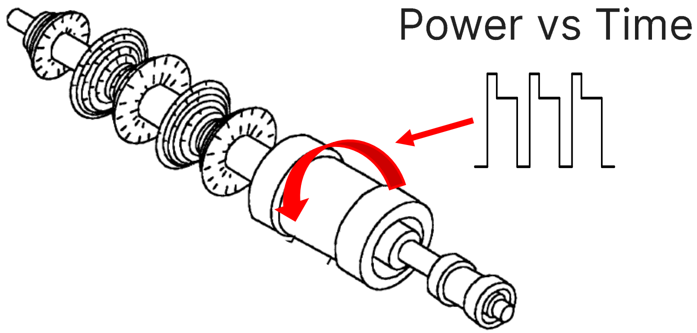
SSTI – Subsynchronous Torsional Interaction

- Phenomena in which datacenter causes torsional vibrations to grow unstably or reduce inherent damping so more time for decay
- Stability related phenomena are independent of pulsating characteristic of datacenter loads



FPO – Forced Power Oscillation

- Characteristic pulsating loads of datacenter propagates through turbine-generator drivetrain
- Primarily related to forcing function on power pulsations from datacenter



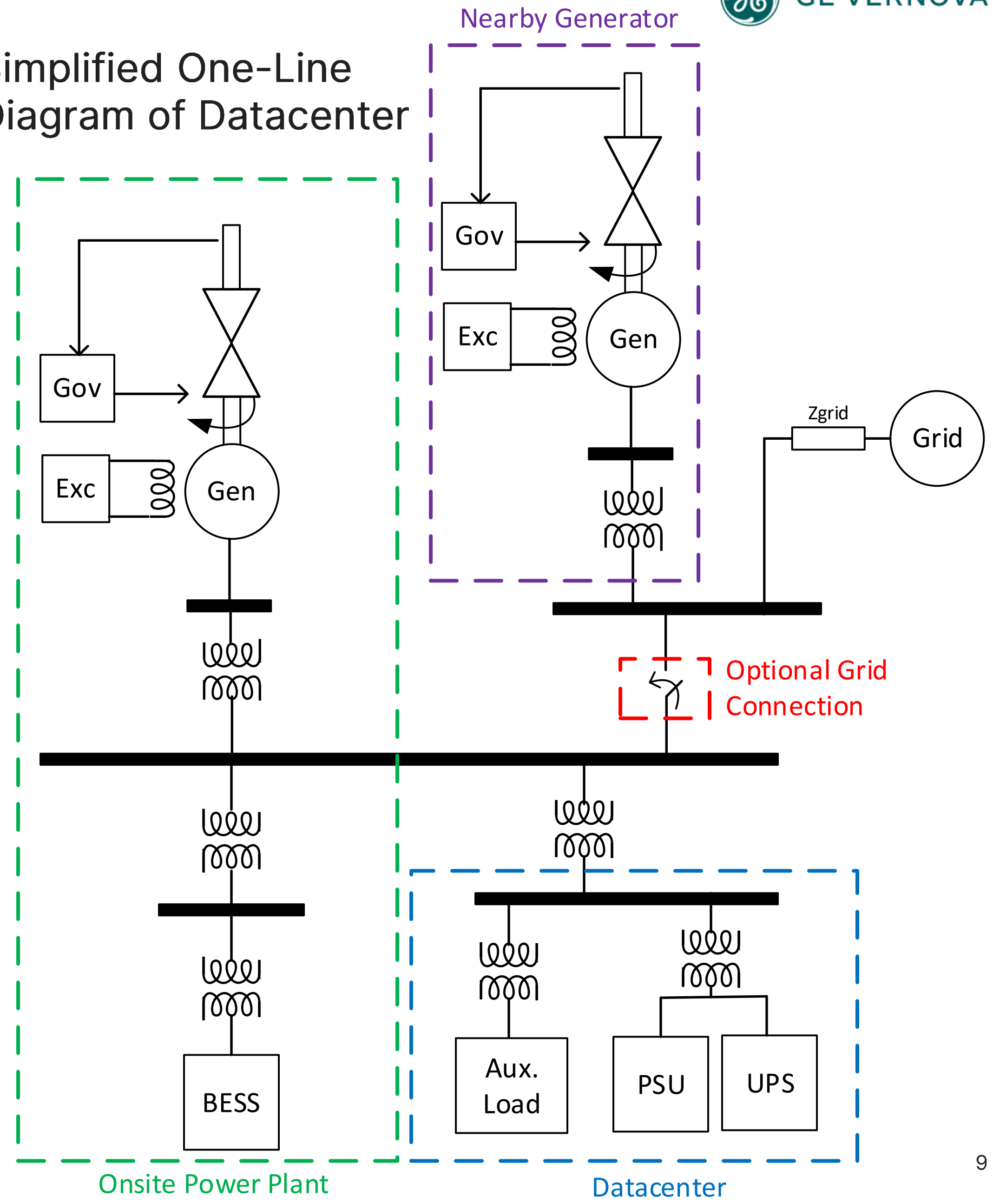
Fatigue can result from either SSTI or FPO, though physical mechanisms causing them are different

Evaluation of Risks for Datacenters

<u>Many aspects affect SSTI/FPO Risks</u>

- # of generating units online
- Type of generating units online
- Rating of BESS online
- Variations in BESS controls
- Dispatch of generating units
- Datacenter load profiles (e.g. power pulsation frequency/duty cycle)
- Variations in Datacenter load controls
- Variations in types/proportion of datacenter loads
- Variation in torsional frequency of units
- Topology of electrical network
- Presence/absence of grid connection

Simplified One-Line Diagram of Datacenter



Application Requirements to Limit Torsional Risks

Protection

- Prevents damage to shaft components for unplanned conditions or failure of mitigation

Monitoring

- Permits early detection of undesirable content in spectrum of datacenter power
- Supports root cause analysis in case of undesirable trips

Mitigation

- Permits continuous operation of the plant without trips or equipment damage

Mitigation of SSTI/FPO

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- Likely required for off-grid datacenter applications
  – High coupling to data center load
- Sometimes needed for grid-connected applications
  – Generally expected to have lower risk than off-grid applications due to diverse generation mix providing damping/shielding of datacenter effects
  – More generating plants to consider, outside scope of data center project
  – Need to consider possible contingencies that cause islanding from grid

Mitigation Options

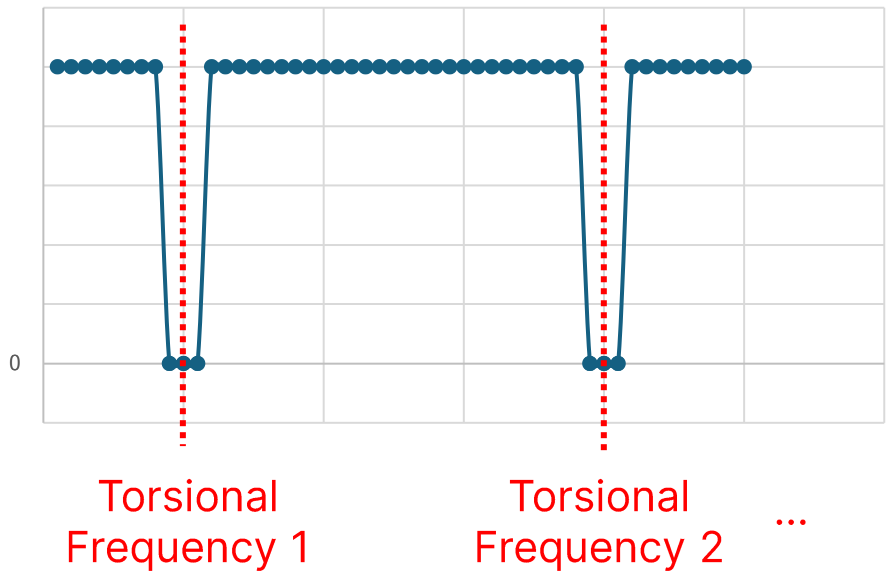
- Mitigation via Datacenter Design
  - Design pulsation pattern to avoid stimulation of torsional modes (FPO)
  - Design power supply units to minimize negative damping effect on torsionals (SSTI)
- Mitigation via Compensation System (e.g. BESS, E-STATCOM)
  - BESS or other power electronics device can be designed to reduce torsional risks
    - Compensation device selection based on energy requirements for other functions (e.g. managing frequency in off grid application)
    - Torsional issues are not deciding factor on device selection
  - Equipment rating and control design are significant factors in effectiveness
  - Requires custom control design/tuning

Both compensation system and datacenter design aspects are required for mitigation

Compensation System Requirements

- Torsional-Requirements
  - Positive electrical damping for all anticipated operating conditions
  - Limit active power spectral content in generator
    - Likely limit of ~0 around torsional frequencies due to large amplification
- Non-torsional requirements
  - Off-grid applications
    - Arrest system frequency deviations caused by fast/large changes in datacenter loads
  - On-grid applications
    - Mitigate excessive power fluctuations to grid
    - Compensate datacenter load loss in case of grid fault (load switches to UPS)

Example Power Limits vs Frequency



Protection

- Torsional protection not standard generator protection
  - Typically only deployed in specific units with specific risk (e.g. units near series capacitors or HVDC)
- Protects equipment in case of failure of mitigation or otherwise unanticipated events
  - Most effective methods involve sensing turbine-generator shaft vibrations directly

Monitoring

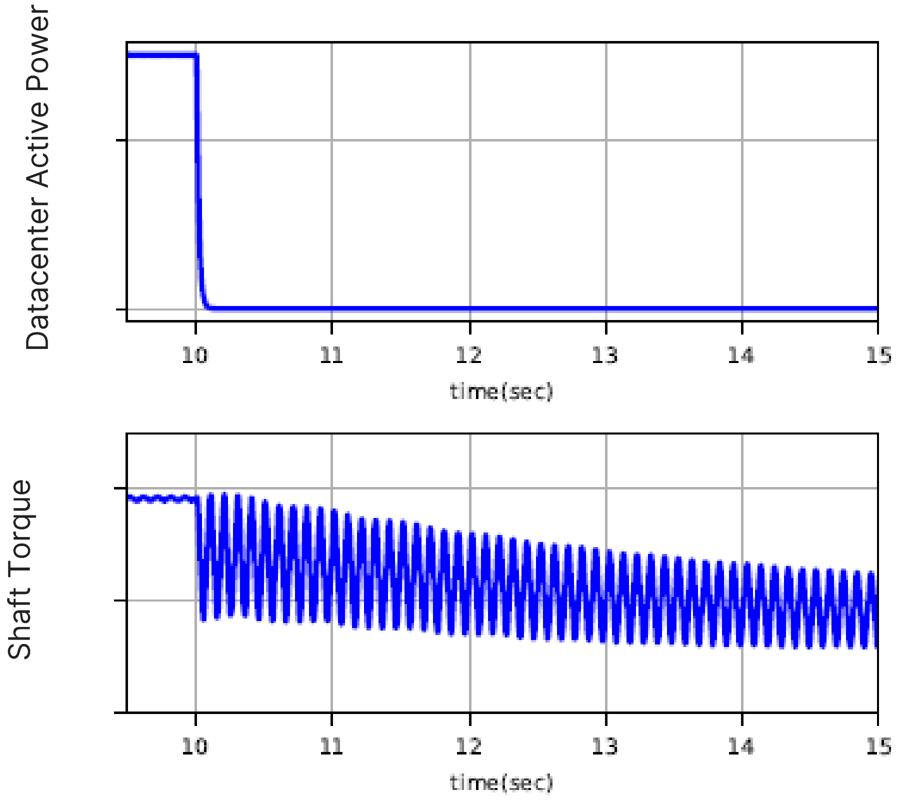
- Senses active power of both data center and of nearby generators
- Provides continuous recording of power
- Processes data to show spectrum of power –vs- time
- Provides alarm to control room if operation close to pulsation constraint

EXAMPLE SIMULATION RESULTS

Negative Damping Effect of Datacenter Load

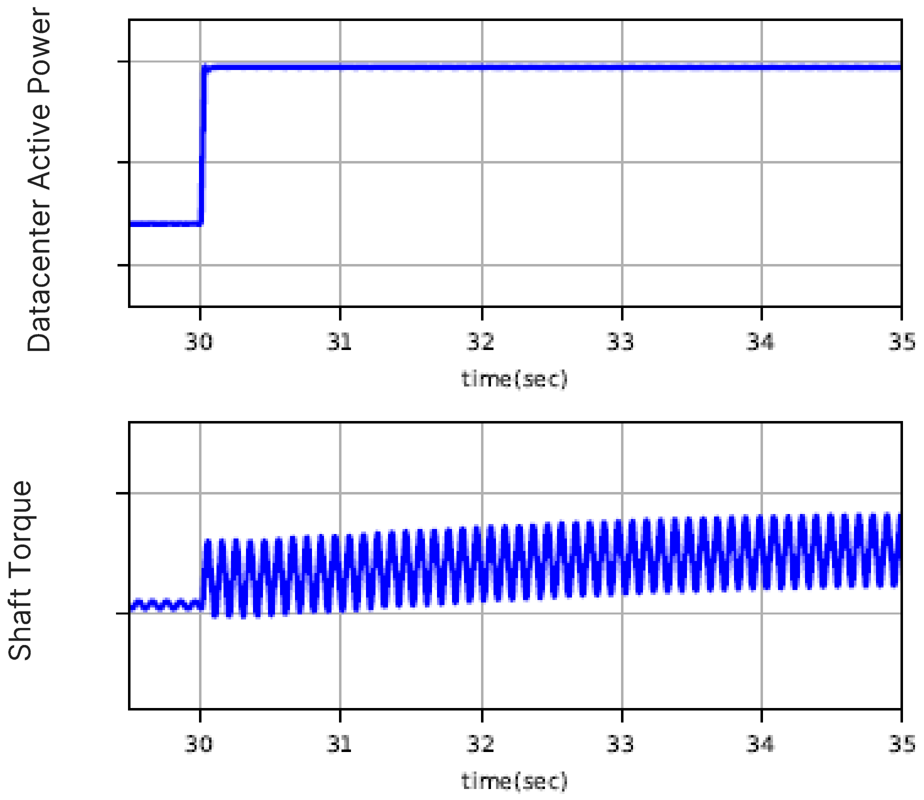
Trip load from 25%

Shows inherent damping



Step load from 75% to 100%

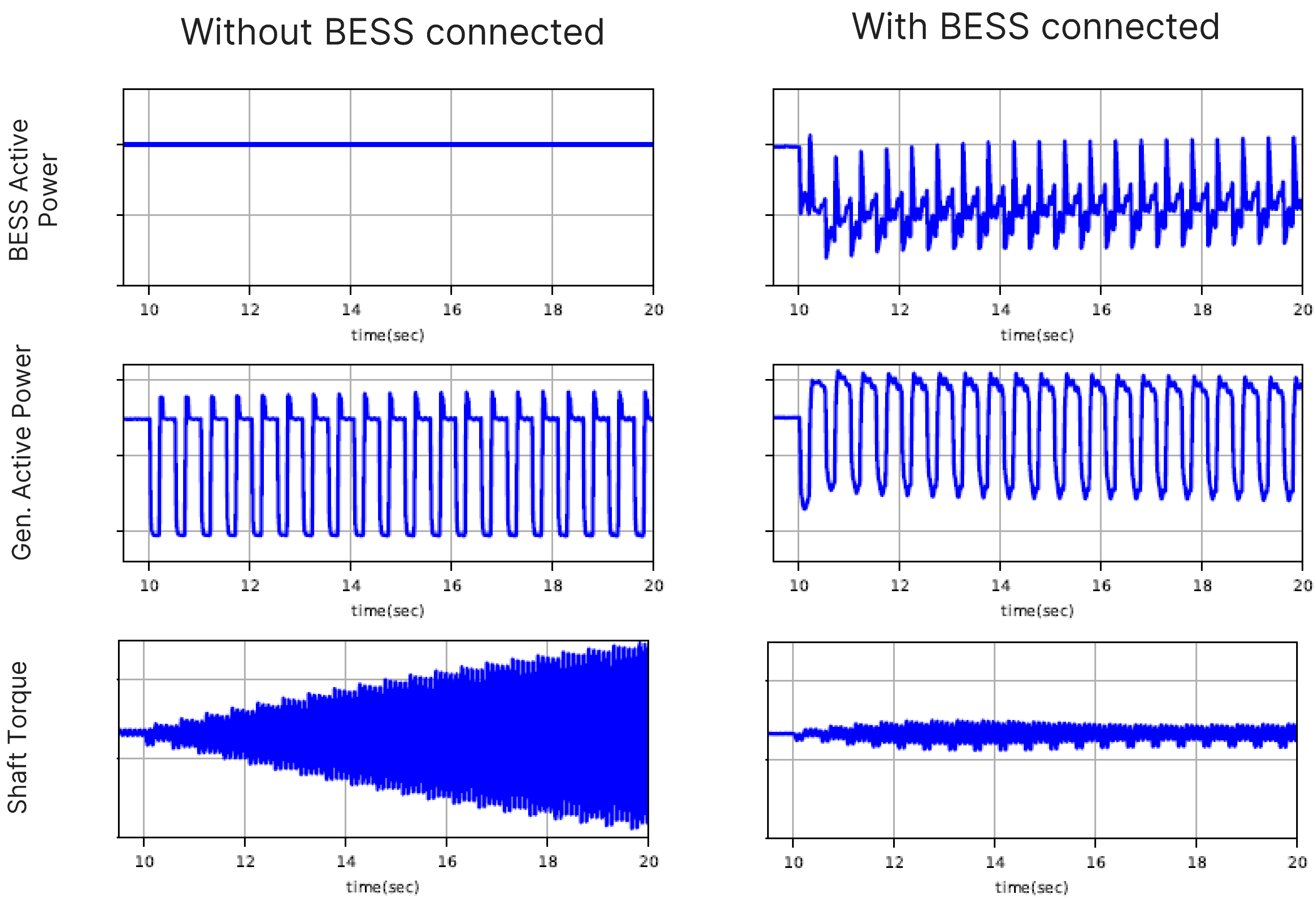
Shows virtually no damping



Datacenter reduces damping of torsional vibrations, even without forced oscillations

Benefits of BESS

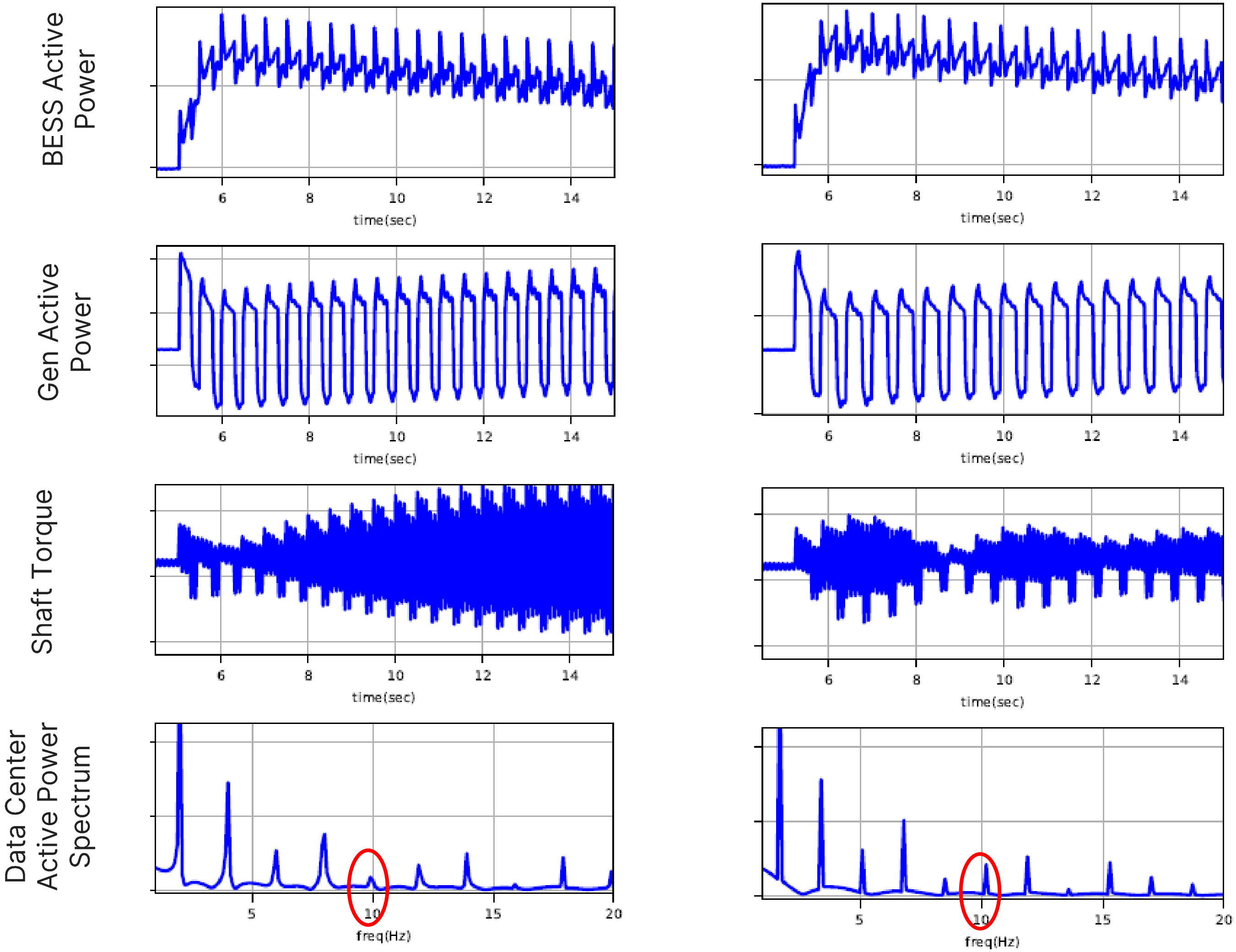
- Example off-grid datacenter with/without BESS
- BESS control designed to have beneficial impact on torsionals
- BESS provides significant benefit
  - Adds positive electrical damping
  - “Picks up” some of the pulsating power from the load, reducing impacts on the turbine-generator
- While BESS reduces cyclic fatigue, some risk remains



FPO Impact on Torsional Vibrations

- Example result with a turbine-generator with torsional frequency at ~10Hz
- Frequency content of power pulsations dictates how shaft torque is impacted
  - Worst-case is pulsations at the torsional mode frequency (~10Hz)
- Avoiding frequency content around the torsional frequency is effective risk mitigation for FPO

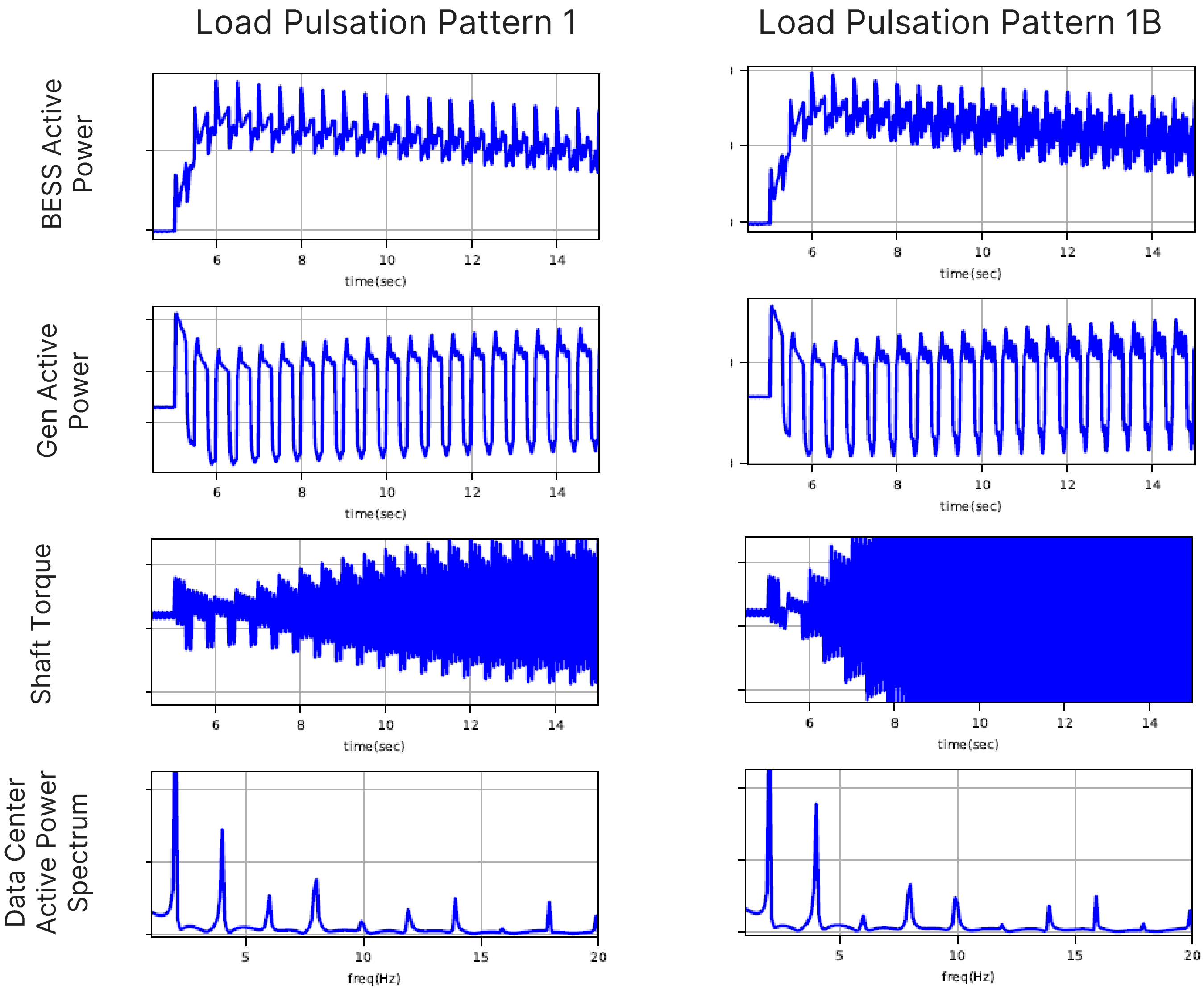
Load Pulsation Pattern 1 | Load Pulsation Pattern 1A



Power content at 10Hz | Power content slightly > 10Hz

FPO Impact on Torsional Vibrations

- In addition to the frequency of the power pulsations, the duty cycle also has a big impact
- Small differences in pulsation duty cycle have very large impact on torsional stress



Load Duty cycle ~62%

Load Duty Cycle ~67%

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