



Effects of AI Training Power Fluctuations on Hydro-Generator Systems

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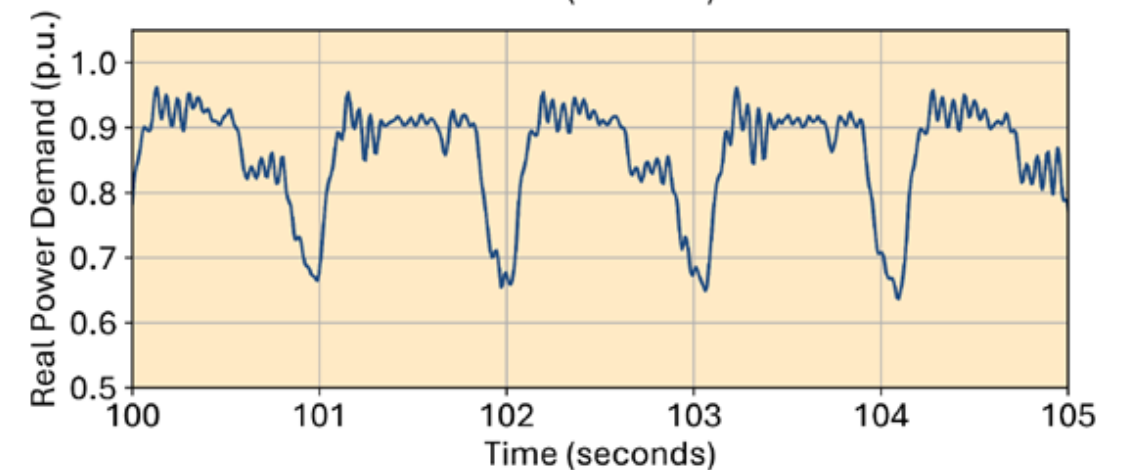
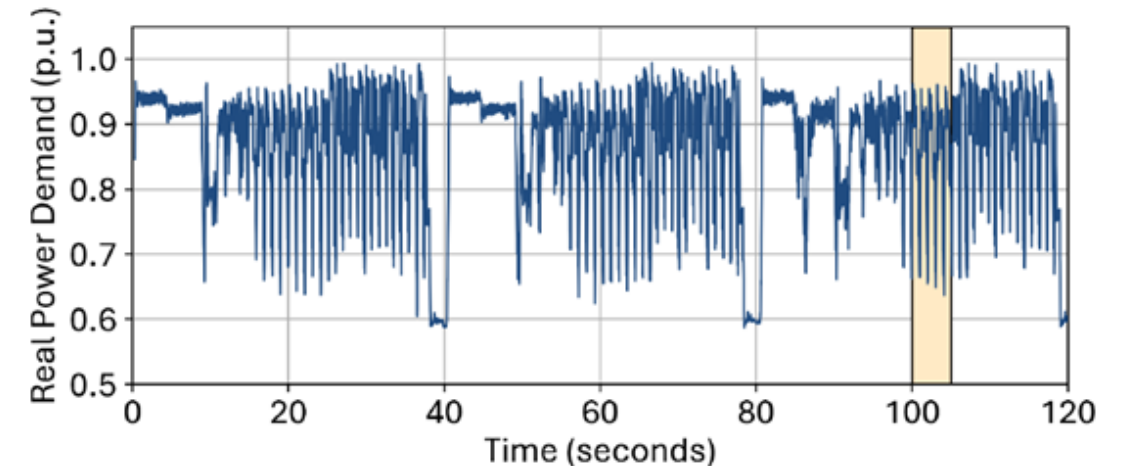


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Motivation

- Grid operators are seeing an unprecedented growth in hyper-scale AI data center loads
 - This has introduced new operational challenges
- **AI training workloads have periodic demand profile that may induce forced oscillations in power system**
 - Demand alternates between a high-power compute phase and a low-power data transfer and synchronization phase
- Induced oscillations can span a broad frequency range
 - Lower frequencies: <1 Hz
 - Sub-synchronous frequencies: 5-59 Hz
- Forced oscillations (FOs) can pose reliability risks
 - May adversely interact with systems' natural oscillation modes



AI Training-Induced Oscillations and Impacts

- AI training oscillations can span wide range and may have different impacts on the grid

Higher-frequency FOs in Sub-synchronous Range (5—59 Hz)

- May align with torsional modes of nearby synchronous generators
- Can amplify mechanical oscillations and torque pulsations in the generator shaft inducing stress and fatigue

- Mostly localized around the data center – may impact co-located or nearby generators

Lower-frequency FOs in Electromechanical Range (0.1—2 Hz)

- Can cause resonance with systems' poorly-damped inter-area modes
- Can amplify power oscillation in important tie-lines and corridors potentially leading to tripping and/or other protection actions

- Wide-area propagation and impact observed across interconnection

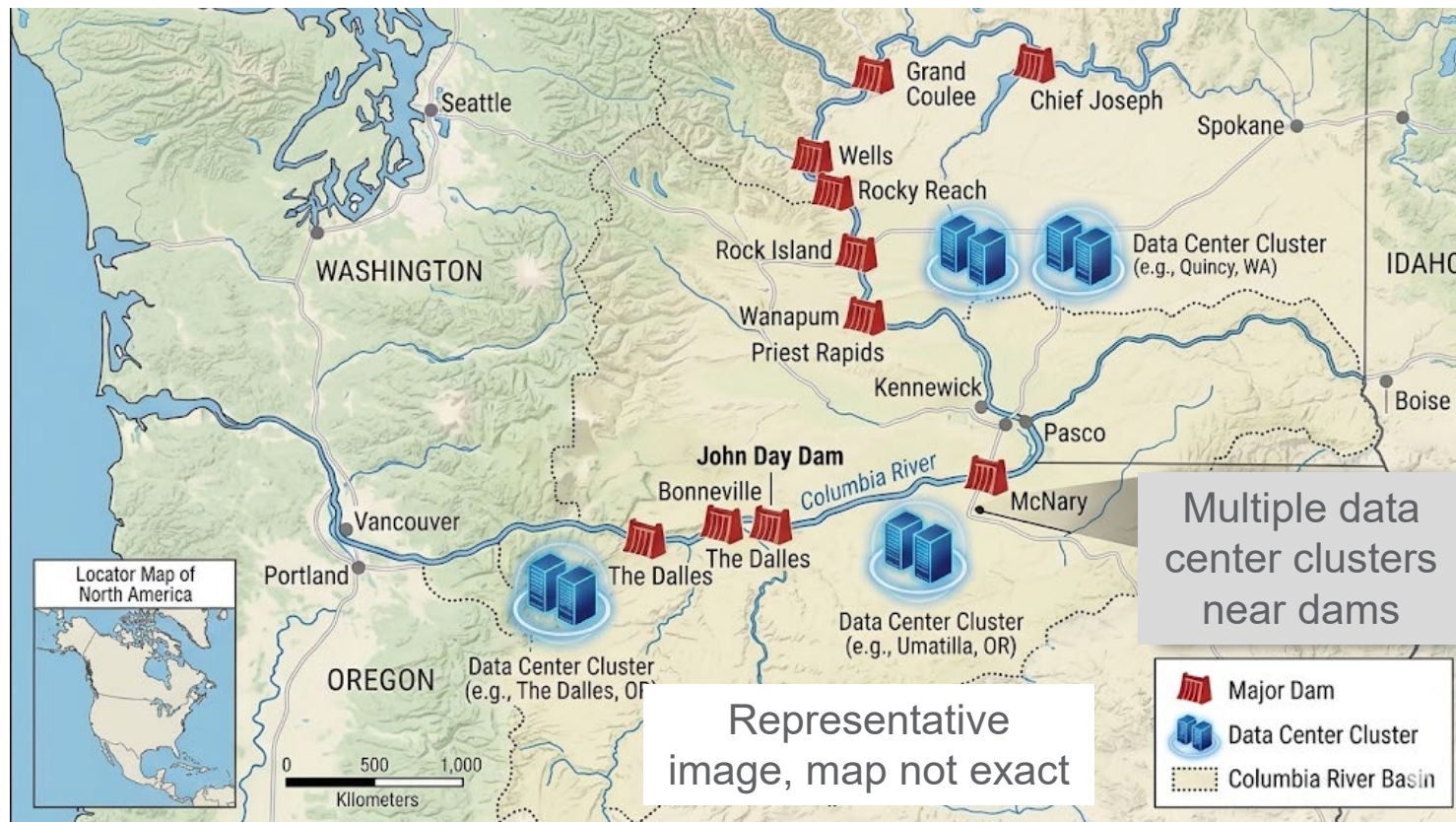
Ultra low-frequency FOs (< 0.1 Hz)

- May adversely interact with governor modes, particularly in hydro-generators
- Hydro-governors may provide negative damping to ultra low-frequency oscillations

- Wide-area propagation and impact

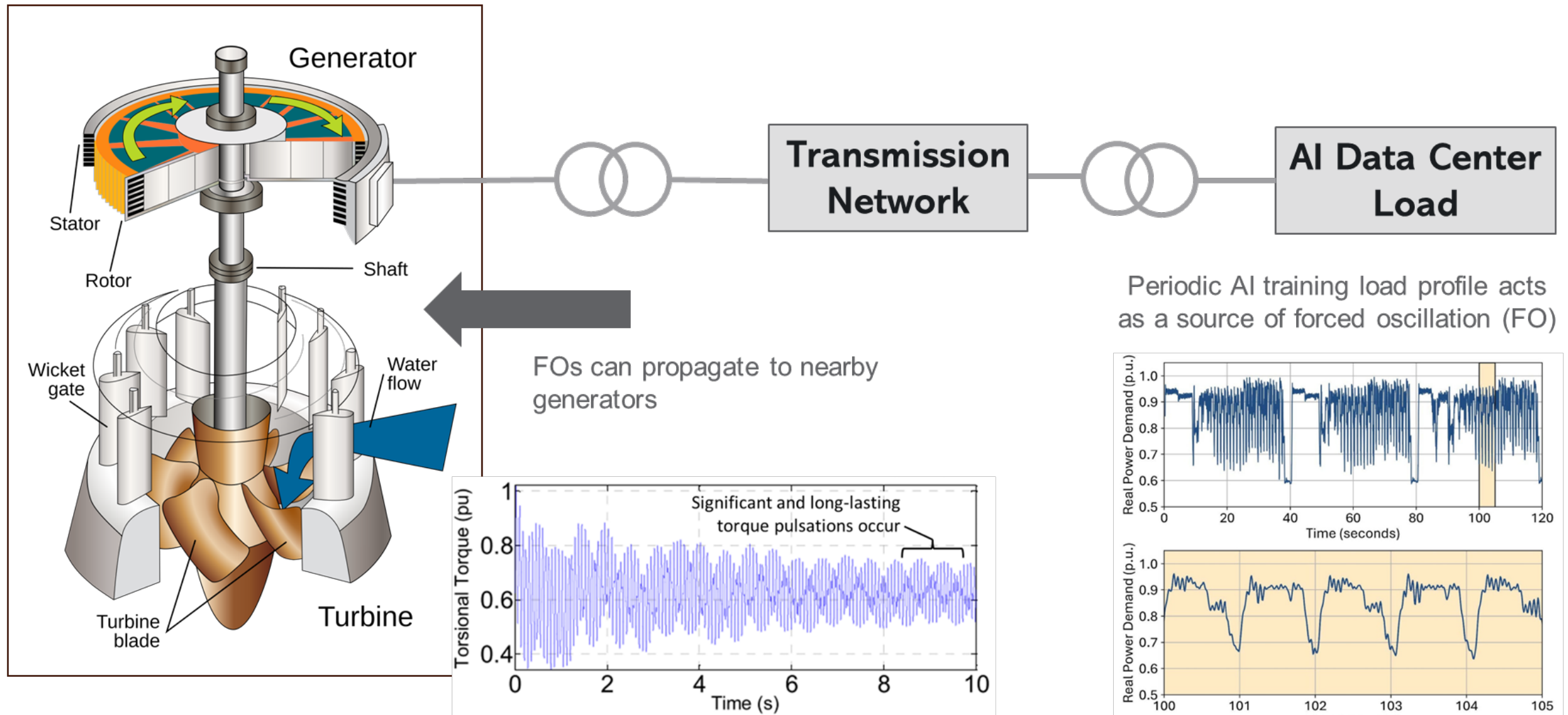
Impacts on Hydro-generator Units

- Why focus on hydro? -- Multiple data centers located (or are coming up) around hydroelectric dams
 - Examples: in the Columbia River Basin in Oregon-Washington region



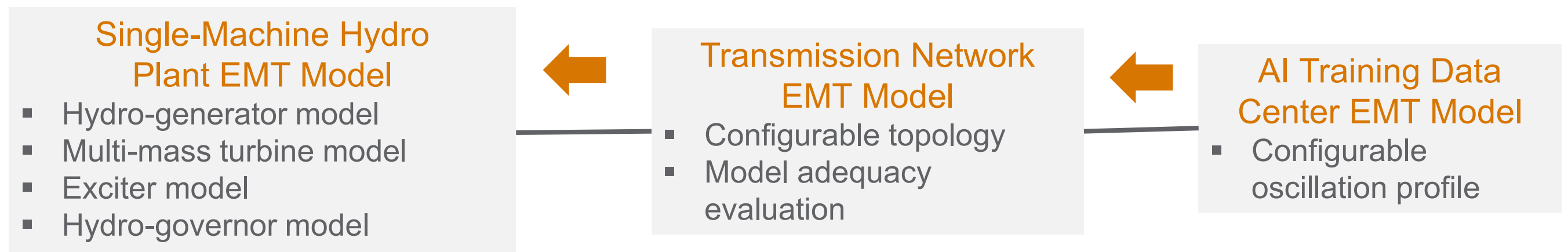
- Can oscillations from data center clusters impact existing hydro facilities in vicinity?
- Traditionally, torsional interaction has not been of concern in hydro-generators
 - That might change with emerging designs
 - Reevaluate and assess the risks

High-Frequency Oscillatory Interactions between AI Data Center Load and Nearby Generator



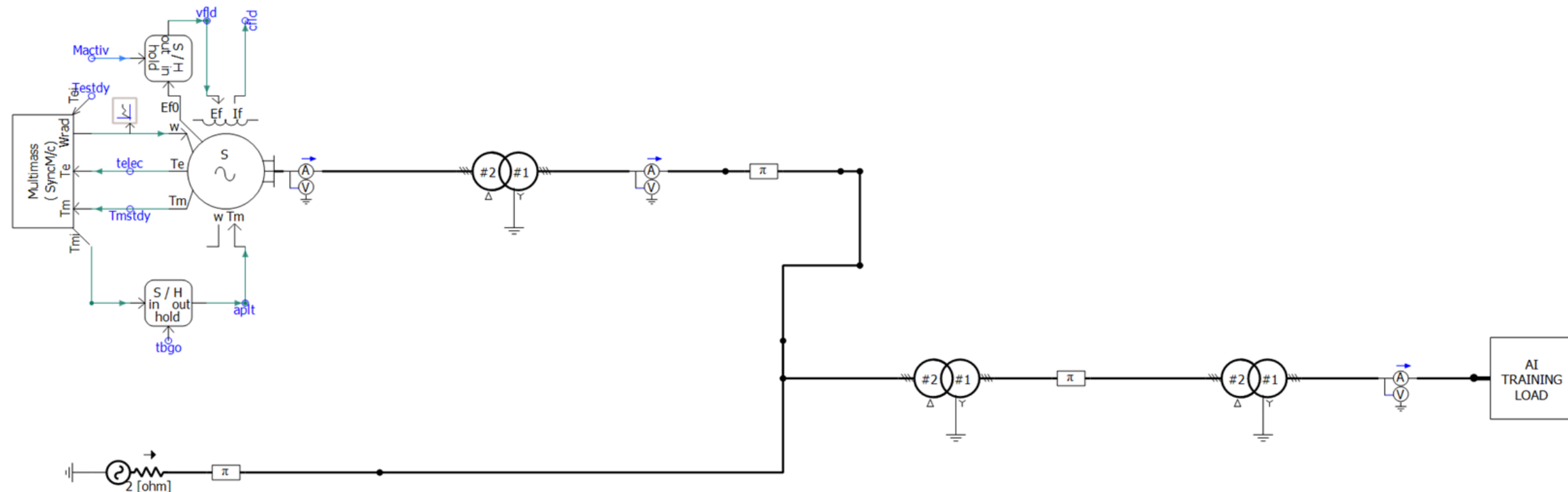
Risk Assessment Objectives

- Risk analysis to assess the impacts of forced oscillations on electrical and mechanical components of hydro resources
 - To quantify the impact of sub-synchronous forced oscillations on shaft/shaft components
 - ✓ Torque amplification and/or resonance, shaft fatigue
 - To study governor interactions for low and ultra-low frequency forced oscillations
- Simulation-based sensitivity study to quantify the impacts of –
 - AI training profile on oscillation amplification
 - Hydro-generator parameters on torsional and governor modes
 - Electrical distance between data center cluster and hydro plant



Test System for Torsional Risk Analysis

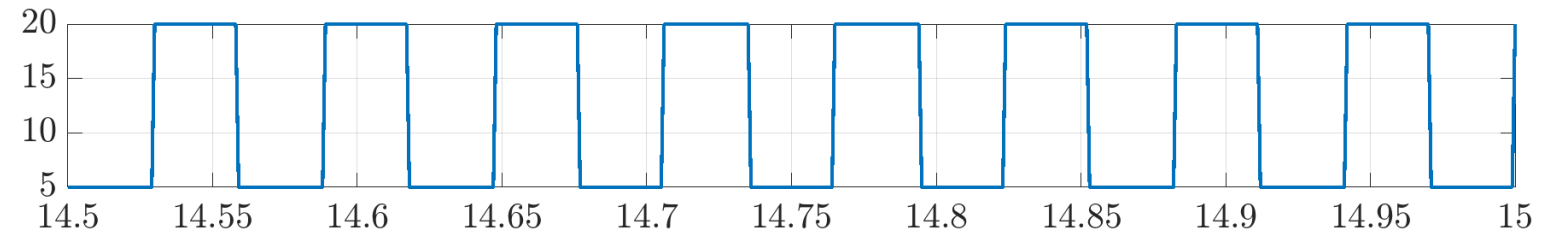
- We have developed an electromagnetic transient (EMT) model of a test system for AI-load induced FO risk evaluation, consisting of:
 - **PSCAD library model of a hydrogenator incorporating a multi-mass model of turbine**
 - Configurable model parameters derived from real-world and literature data
 - **PNNL-developed EMT model of AI training load**
 - Configurable to inject FO at desired frequencies as periodic pulse train
 - Configurable to playback AI load profiles from real-world



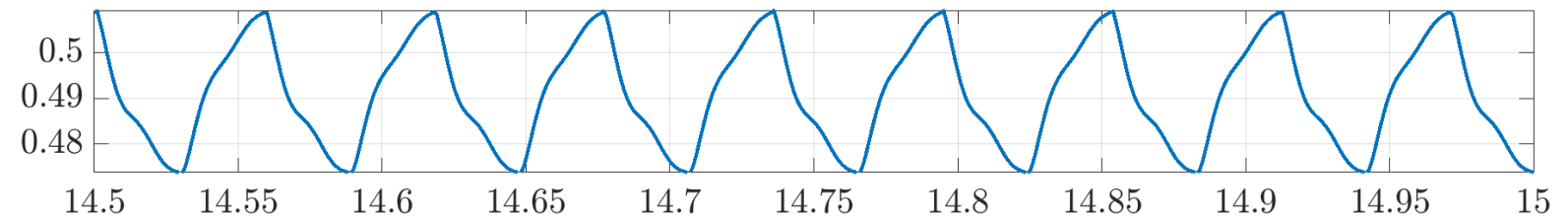
Torsional Oscillations in Generator Shaft

- Model-based simulations

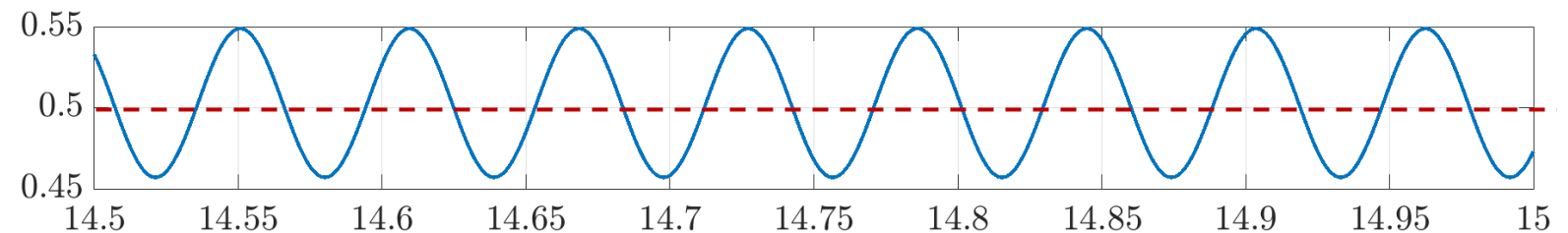
Periodic AI load profile (MW)
17 Hz FO source



Generator output power
oscillations (p.u)



Shaft torque torsional
oscillations (p.u)

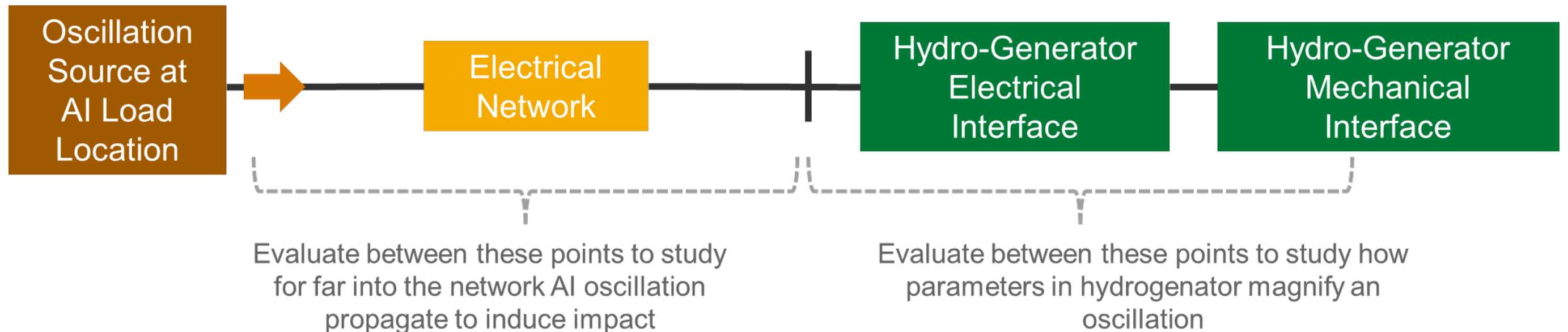


Steady-
state
mean
torque

- Torsional oscillations/vibrations manifest as angular shear stress on shaft elements
- Turbines not designed to withstand continuous torsional oscillations above an endurance limit – violations lead to fatigue, reduces shaft life

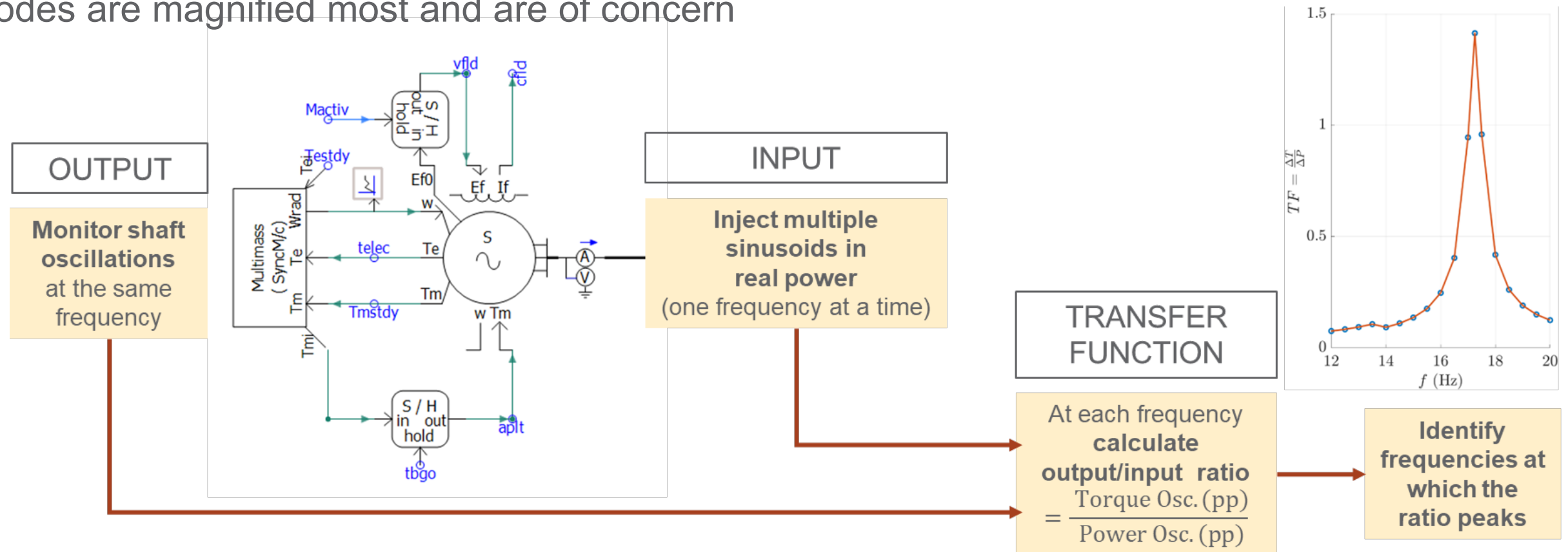
Risk Assessment Methodology

- Inject sinusoids with different frequencies from data center locations and evaluate
 - Attenuation between the source and the POI of the hydro generator
 - ✓ quantifies the impact of distance and network topology
 - Amplification ratio between electrical power and shaft torque
 - ✓ quantifies how the generator and turbine parameters amplify electrical oscillations observed at POI into mechanical shaft oscillations
 - Amplification ratio between electrical power and mechanical power
 - ✓ quantifies how governor parameters amplify oscillations seen in the feedback quantities into oscillations in mechanical power



Risk Assessment for Torsional Interaction

- Power fluctuations from AI training that are at frequencies of torsional modes are magnified most and are of concern



Transfer function (TF) as a measure of risk of shaft oscillation magnification

- At each f , the plot indicates the magnitude of shaft-torque oscillation that would result from 1 p.u oscillation in generator output power caused by AI load fluctuation
- Peaks at torsional modes
- A larger value is indicative of higher risk**

Sensitivity Analysis on Torsional Interaction Risk

- The shape of the transfer function response is influenced by the generator and turbine parameters
 - Sensitivity studies to identify how parameter choices (or different hydro-generator designs) impact risk

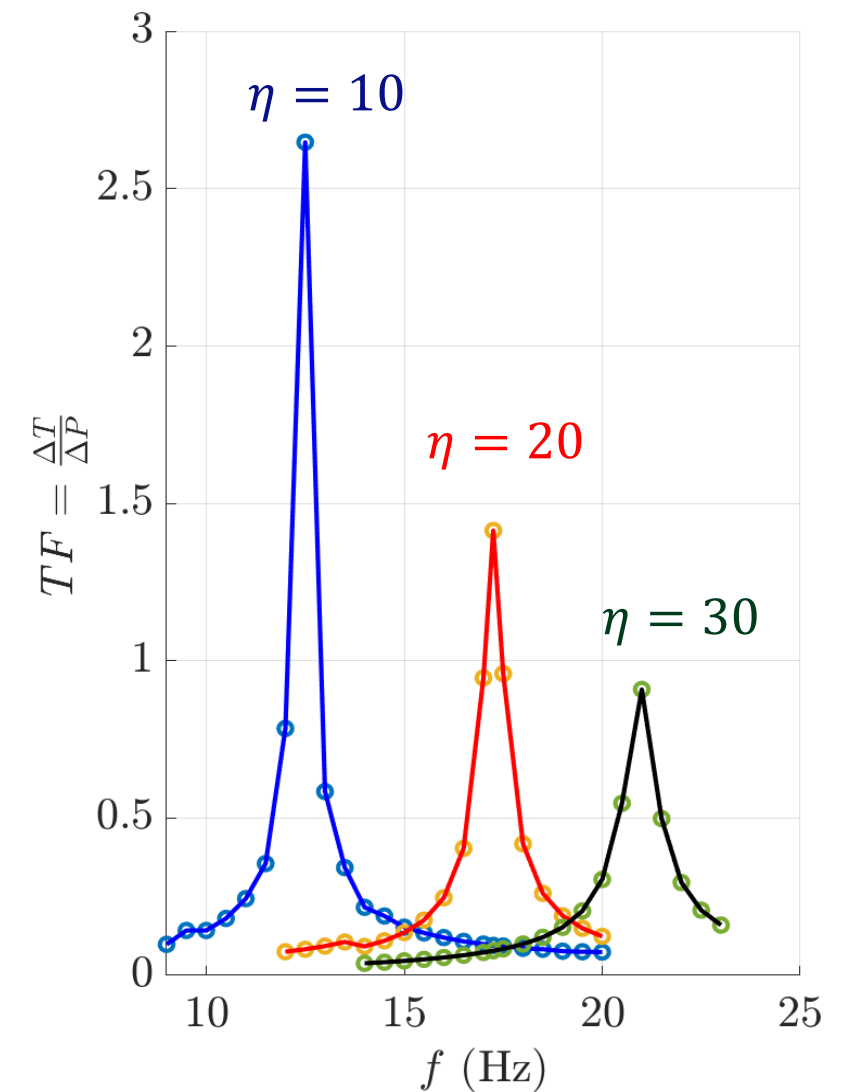
- **Example: Impact of generator-to-turbine inertia ratio**

$$\eta = \frac{\text{Generator Inertia}}{\text{Turbine Inertia}}$$

- In simulation, fixing the generator inertia, we vary the turbine inertia

Lower generator-to-turbine inertia
 ⇒ Higher amplitude shaft torque oscillation
 ⇒ Greater risk of shaft stress/fatigue from AI load FO

- Generator-to-turbine inertia ratio is often correlated with turbine type
 - Francis vs. Kaplan – risk metric may be used to suggest what units (based on inertia/turbine type) may be at more risk



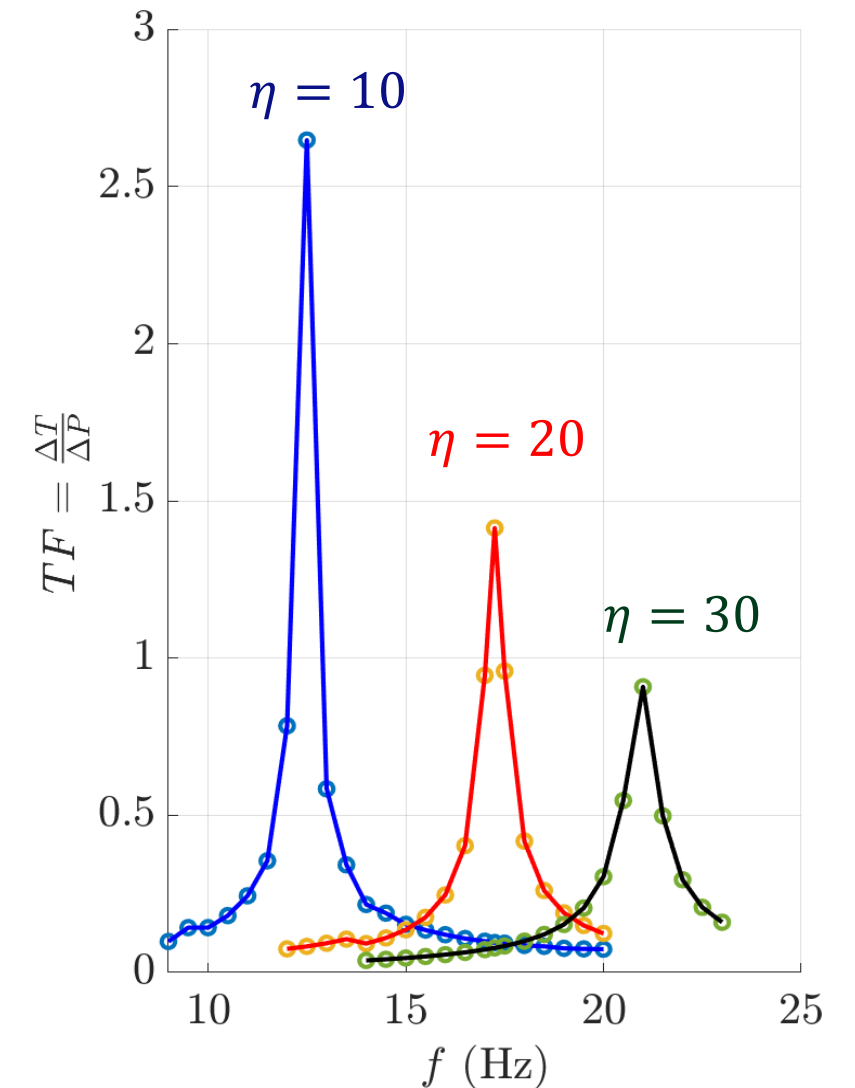
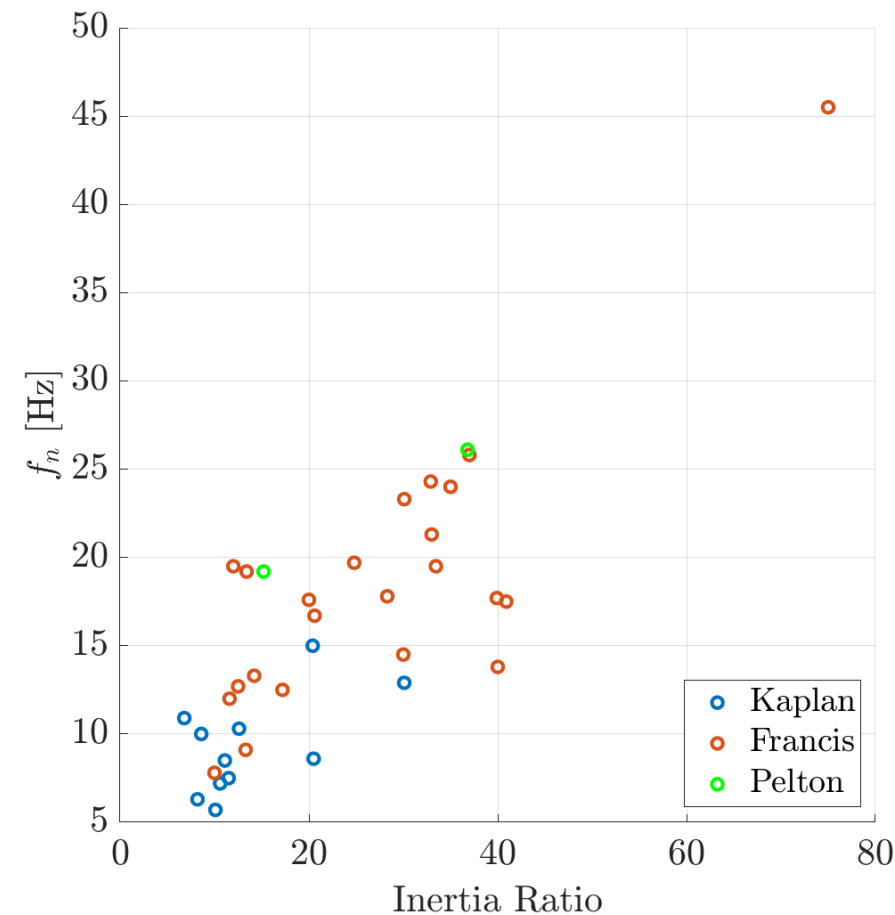
Sensitivity Analysis on Torsional Interaction Risk

Example: Impact of generator-to-turbine inertia ratio $\eta = \frac{\text{Generator Inertia}}{\text{Turbine Inertia}}$

Lower generator-to-turbine inertia
⇒ Greater risk of shaft stress/fatigue from AI load FO

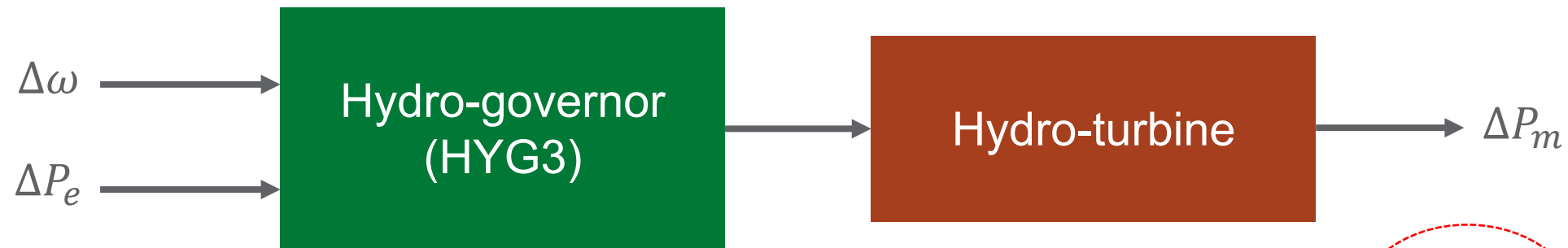
- Correlation between inertia ratio, resonant frequency, and turbine type

- Kaplan turbines typically have low η and lower frequencies torsional modes
- **Low inertia ratio Kaplan turbine systems may be more susceptible to AI-load induced oscillations**
- Some Francis turbines are also in the risk zone
 - Other factors may be involved
 - Further analysis required – ongoing work

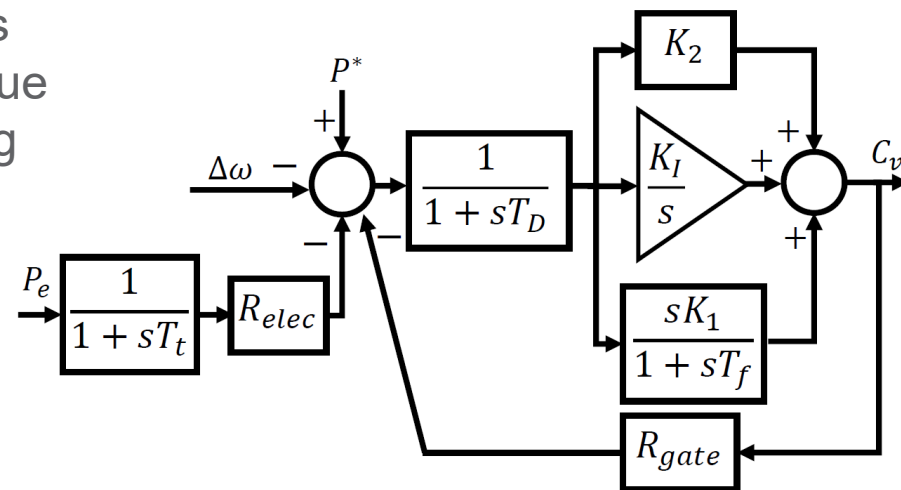


Risk Assessment for Governor Interactions

- Assess how AI-training oscillations seen in the feedback quantities of the hydro-governor are amplified in mechanical power due to governor and turbine parameters



Electrical power at POI sees oscillations due to AI training



$$H_t(s) = \frac{P_m(s)}{C_v(s)} = \frac{1}{s} \frac{K_g}{1 + sT_p} \frac{1 - sT_w}{1 + sT_w/2}$$

Water time-constant T_w introduces a non-minimum phase system that may negatively impact oscillations

- Study the magnitude response of the transfer function $TF = \Delta P_m / \Delta P_e$ as a measure of risk of oscillation amplification

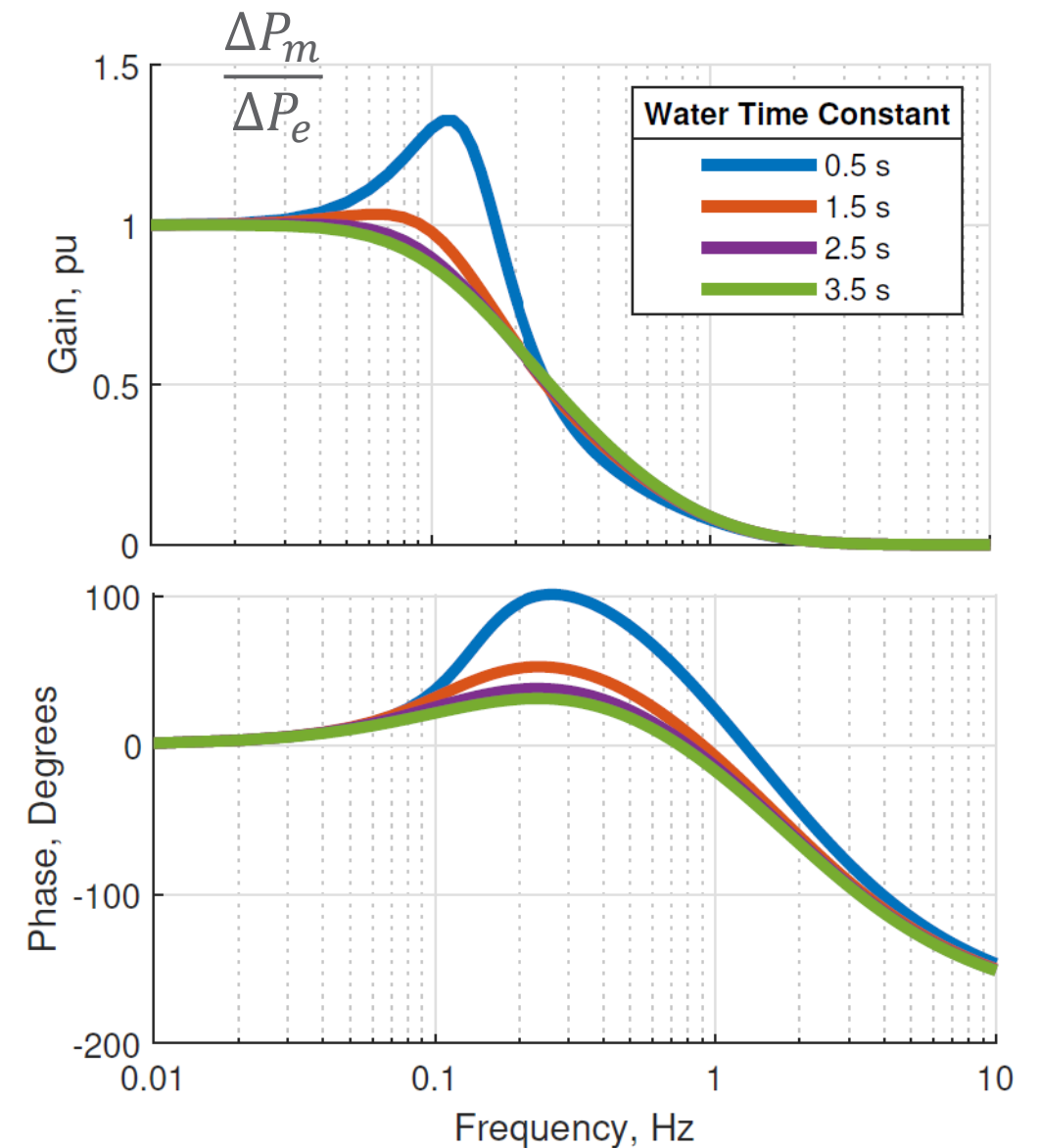
Sensitivity Analysis on Governor Interaction Risk

- The transfer function response (i.e., the risk measure) is influenced by governor and turbine parameters
- Risk analysis for different water time constant values

- For smaller T_w values, magnitude response is large at lower frequencies indicating risks of oscillation amplification in mechanical power
- Factors that determine water time constant: water head (H_w), flow velocity (U_w), and penstock length (L)

$$T_w = \frac{LU_w}{a_g H_w}$$

- In plants with shorter penstock, in seasons with high water head, T_w could small increasing risks of oscillation amplification
- Risks can be managed by tuning governor parameters



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Thank you

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