Regional Grid Inertia Estimation Using Synthetic Ambient Synchrophasor Measurements - ComEd/Exelon Case Study

Presenter: Lin Zhu, lzhu@epri.com

Team:
1. EPRI: Evangelos Farantatos
2. Exelon: Ziping Wu, David Schooley

NASPI Work Group Meeting and Vendor Show
April 14, 2026 - April 15, 2026
Chicago, Illinois

Values of Inertia Estimation and Monitoring

- Situational awareness
  - Whether entire/regional grid has sufficient inertia?
  - Whether relays based on frequency nadir or RoCoF settings can be triggered under the largest N-1 contingency?
- Assist system operators to develop mitigation measures
  - Bring synchronous condensers into service
  - Redispatch synchronous generators
  - Procure inertia from inertia market, etc.

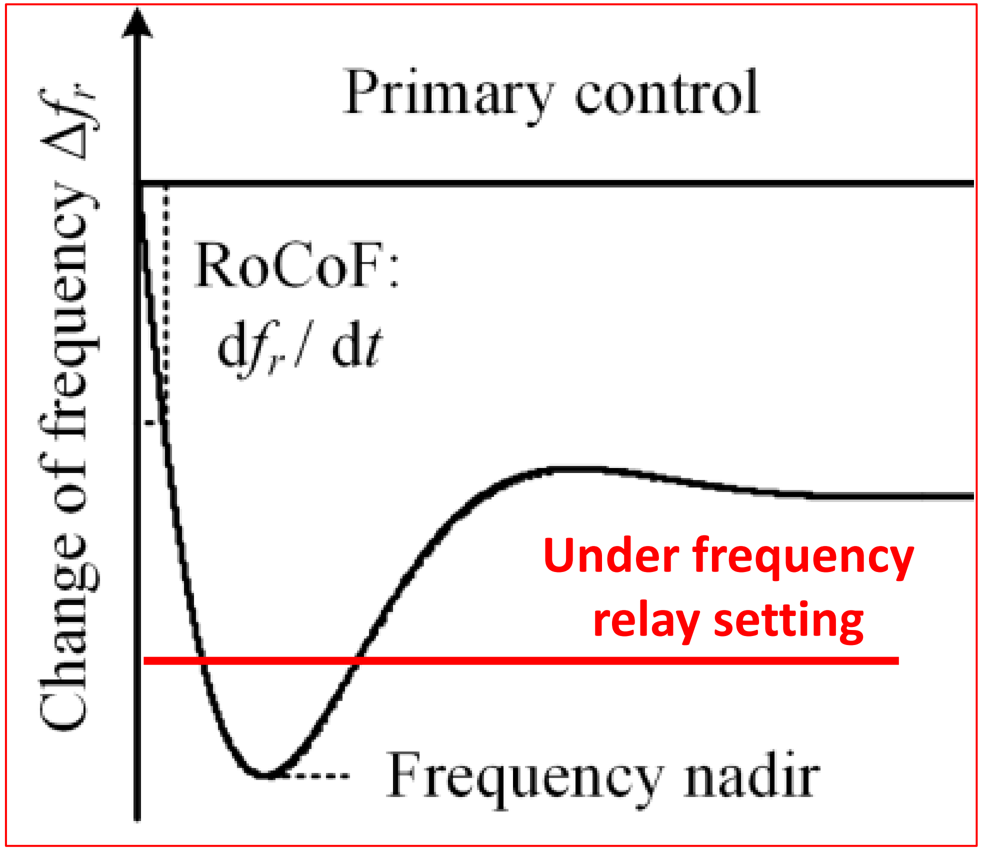


Figure source: Google

Revisit Definition of Grid Inertia

- IBRs' Fast Frequency Response (FFR) can inject active power to support grid frequency in the inertial timeframe
- Different types of active power injection according to IEEE 2800 - 2022 Std.
  - Step response
  - Proportional response (Proportional to Δf)
  - Derivative response (Proportional to RoCoF)
- Another type of "inertia", but does **NOT** follow the form of swing equation
  - Delay, deadband, and headroom, etc.
- IBRs' FFR can be treated as "artificial" fast governor

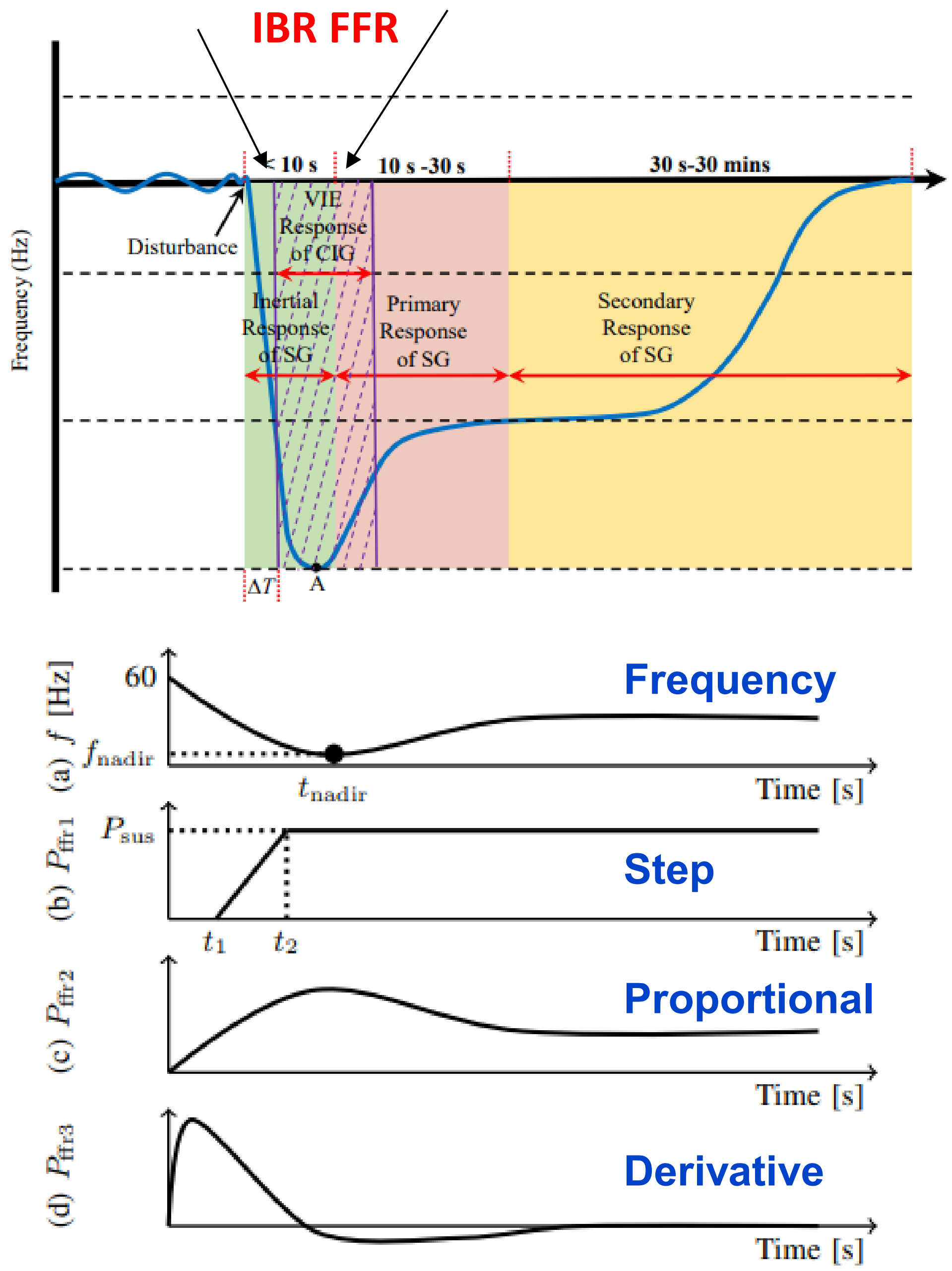


Figure source:

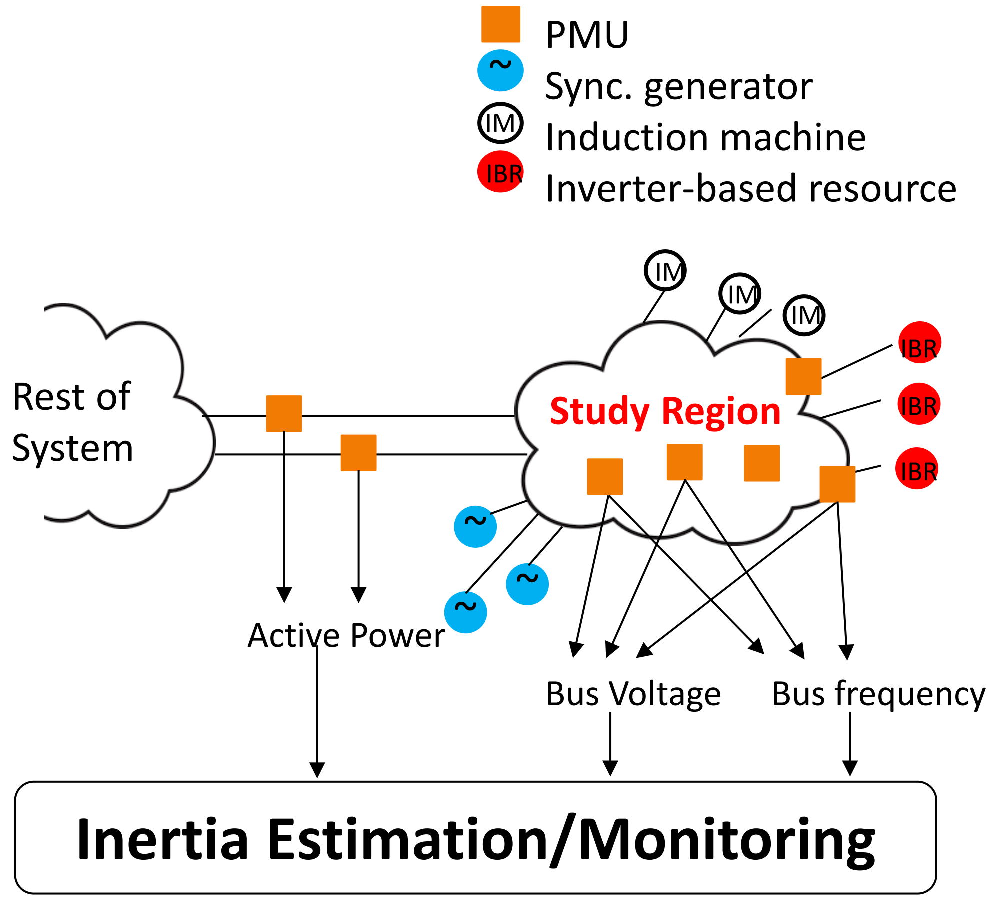
- Bendong Tan, Junbo Zhao, Marcos Netto, Venkat Krishnan, Vladimir Terzija, Yingchen Zhang, "Power System Inertia Estimation: Review of Methods and the Impacts of Converter-Interfaced Generations"
- L. Liu, W. Li, Y. Ba, J. Shen, C. Jin and K. Wen, "An Analytical Model for Frequency Nadir Prediction Following a Major Disturbance"

PMU-Based Regional Inertia Estimation/Monitoring

- PMUs within region and at interface lines
- Continuous inertia estimation and monitoring
  - Ambient PMU data
  - Does not rely on system events
- Consideration of IBRs’ contribution in inertial timeframe, e.g., Fast Frequency Response (FFR)
- Prediction of frequency nadir and RoCoF, and comparison with relay settings

Current practice: Estimated Inertia **vs.** Inertia Floor

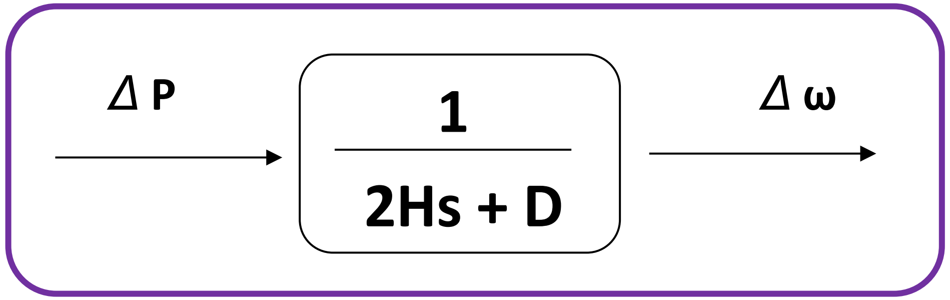
Approach in this work: Predicted RoCoF & Nadir **vs.** Relay Settings



PMU-Based Regional Inertia Estimation/Monitoring

- Synchronous generators' inertia
  - Swing equation-based inertia estimation
  - System identification technology
- IBRs' FFR
  - Consideration of IBRs' FFR in power imbalance estimation
  - Estimation based on known FFR parameters and frequency

Swing equation



ΔP estimation

Estimated by using governor model with droop and deadband

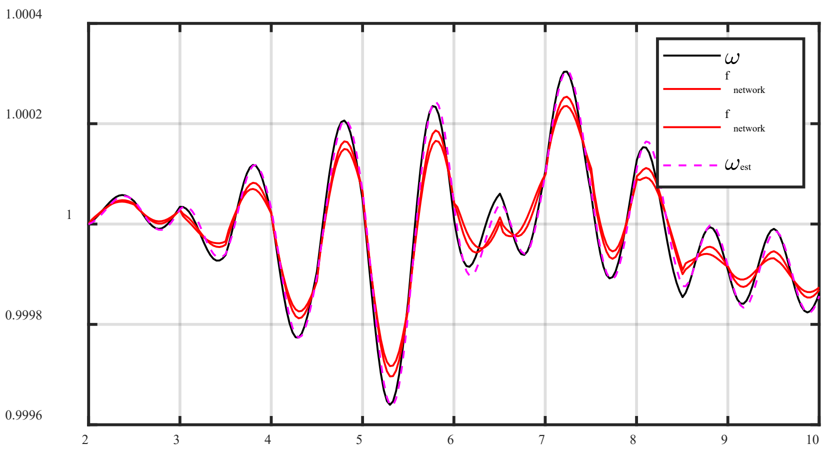
$$\Delta P = \Delta P_m - \Delta P_e = \Delta P_m - \Delta P\_line + \Delta P\_IBR - \Delta P\_load$$

Interface power (Measured by PMU)

IBR power (Measured by PMU or estimated)

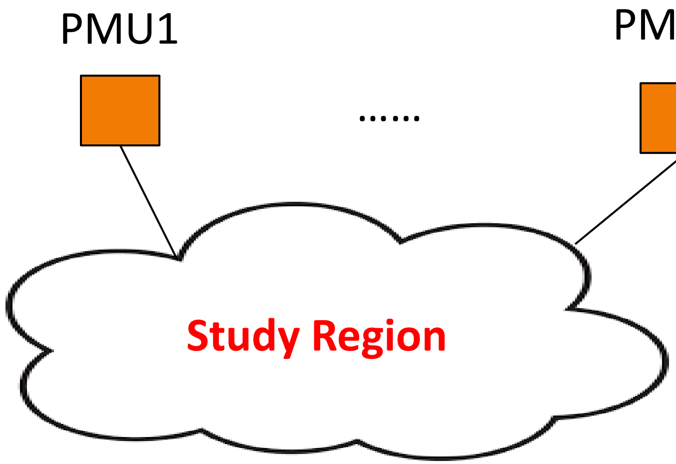
Load power (Estimated)

Δω estimation



Selected Regional Grid Model Within Exelon

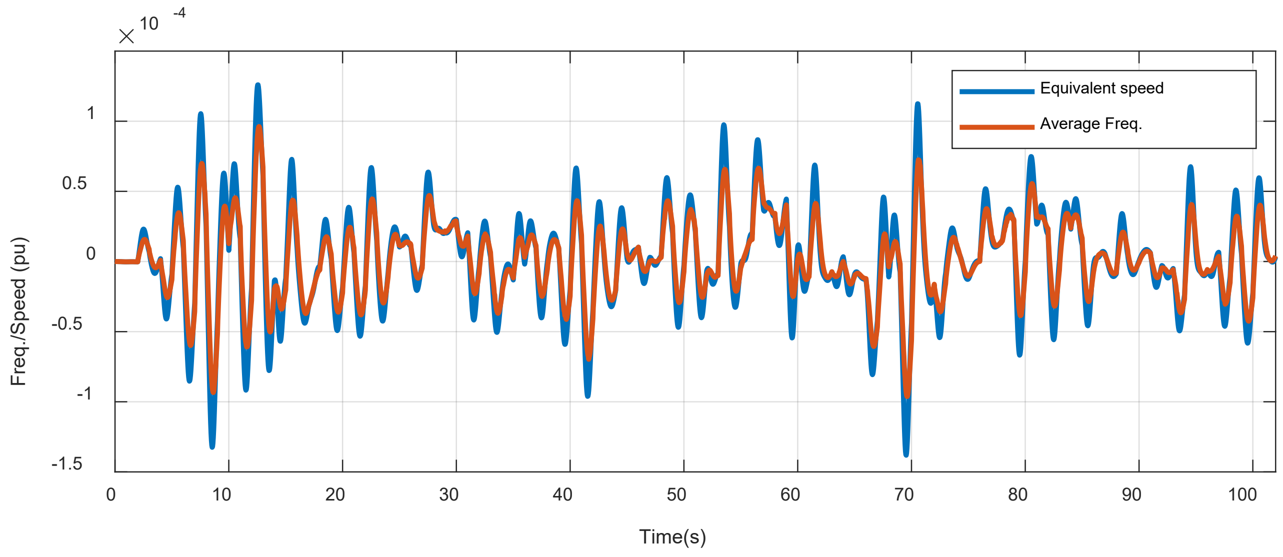
- PMUs deployed at all 13 interface lines
- Added +/- 36 mHz deadband to governor models
  - Nuclear units: +/- 100 mHz deadband (Do not respond to frequency deviation unless when necessary)
- Spring case & Summer case



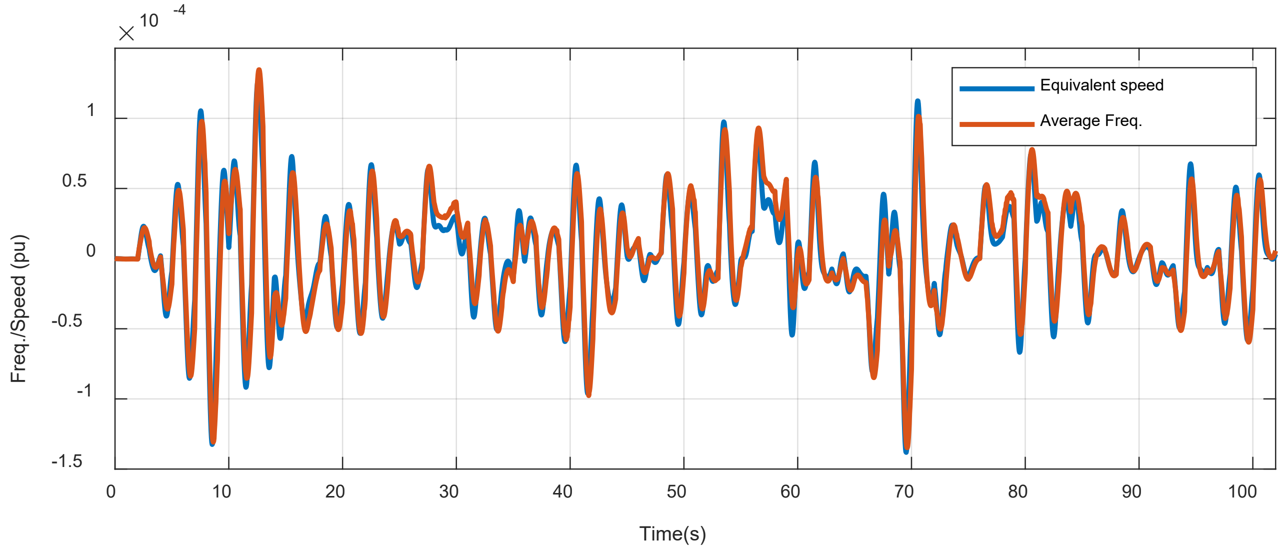
	Parameter	Spring Case	Summer Case
1	Total inertia	17,851 MWs	20,136 MWs
2	Total governor capacity	896 MW	1,304 MW
3	Equivalent governor droop	4.0 %	4.0 %
4	Equivalent governor deadband	+/- 36 mHz	+/- 36 mHz
5	Total wind	223.66 MW	102.21 MW
6	Total load	101.92 MW	212.87 MW

Rotor Speed Estimation

- It is observed that average frequency is almost in phase with equivalent rotor speed
- It is feasible to multiply a coefficient to approximate equivalent rotor speed



No coefficient



With coefficient = 1.4

Inertia Estimation with Estimated Rotor Speed

- With a fixed coefficient, inertia estimation error can be significantly reduced
- Inertia estimation results are close to those using weighed rotor speed

Spring Case: Inertia = 17,851 MWs

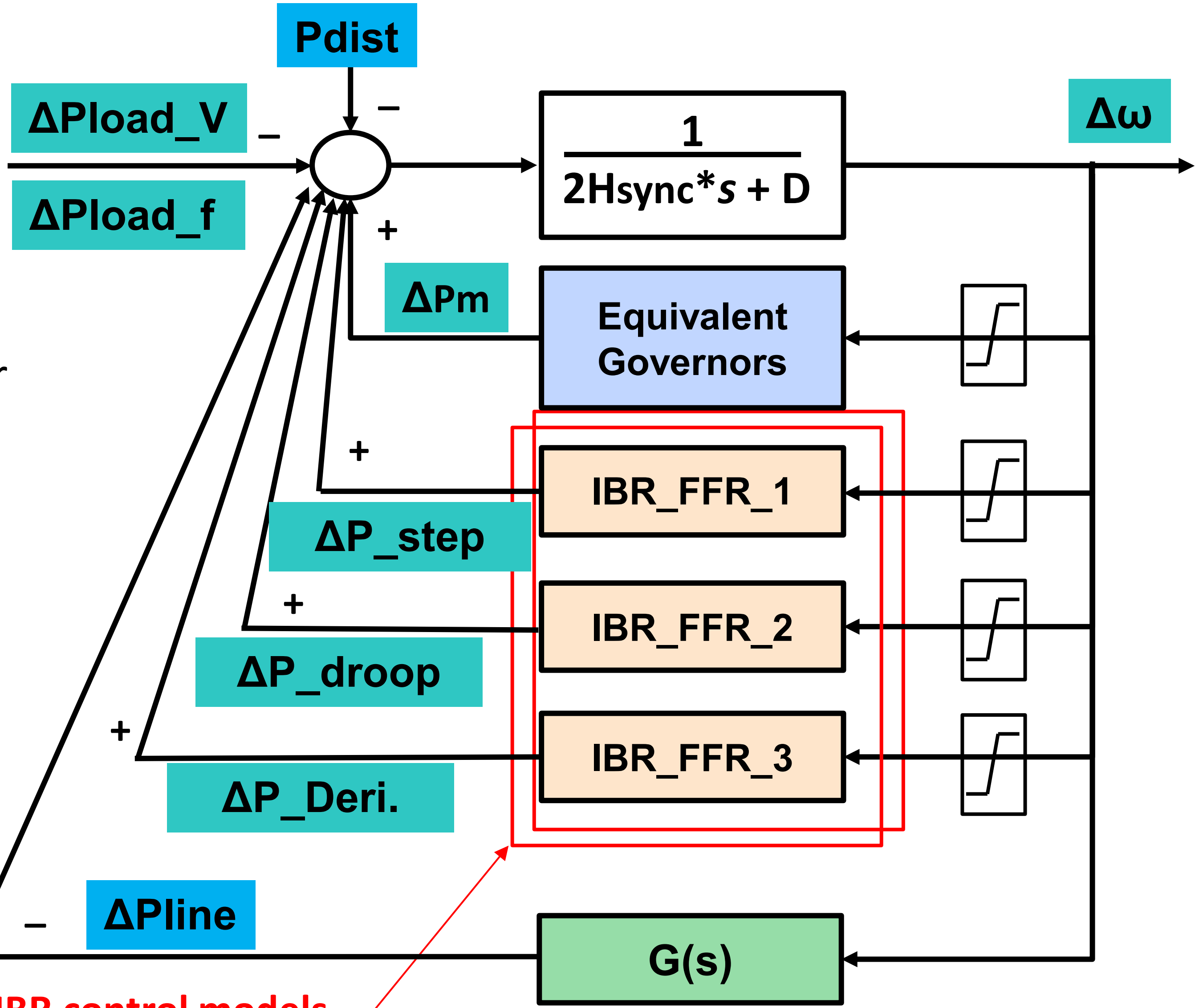
Input Signal #1	Input Signal #2	Estimated Inertia (MWs)	Error (%)
Est. ΔPm – Est. ΔPe	Weighted rotor speed	19,445	8.98
Est. ΔPm – Est. ΔPe	Average frequency	26,620	49.12
Est. ΔPm – Est. ΔPe	Average frequency x 1.4 (coefficient)	19,441	8.91

Summer Case: Inertia = 20,136 MWs

Input Signal #1	Input Signal #2	Estimated Inertia (MWs)	Error (%)
Est. ΔPm – Est. ΔPe	Weighted rotor speed	21,120	4.89
Est. ΔPm – Est. ΔPe	Average frequency	29,001	44.02
Est. ΔPm – Est. ΔPe	Average frequency x 1.4 (coefficient)	20,655	2.58

Frequency Nadir and RoCoF Prediction: Method

- Build a simple closed-loop system model, including:
  - Swing equation: Estimated inertia (Hsync)
  - Equivalent governor models
  - IBRs' FFR: Treated as "artificial" fast governor
  - Trained transfer function to estimate interface line power
- Analytical solution with a given disturbance to estimate frequency response
- Calculate frequency nadir and RoCoF

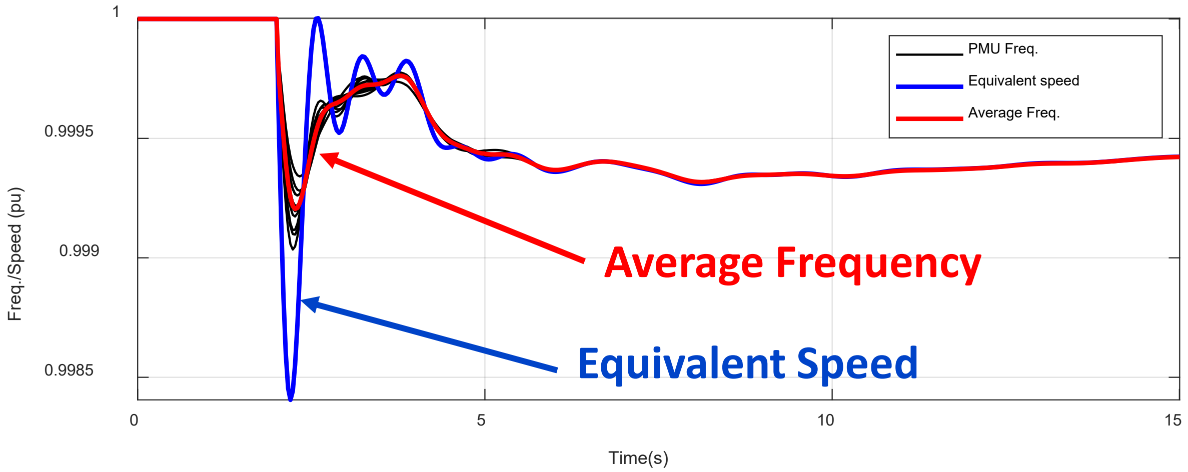


- Multiple IBR control models
- One model for each plant

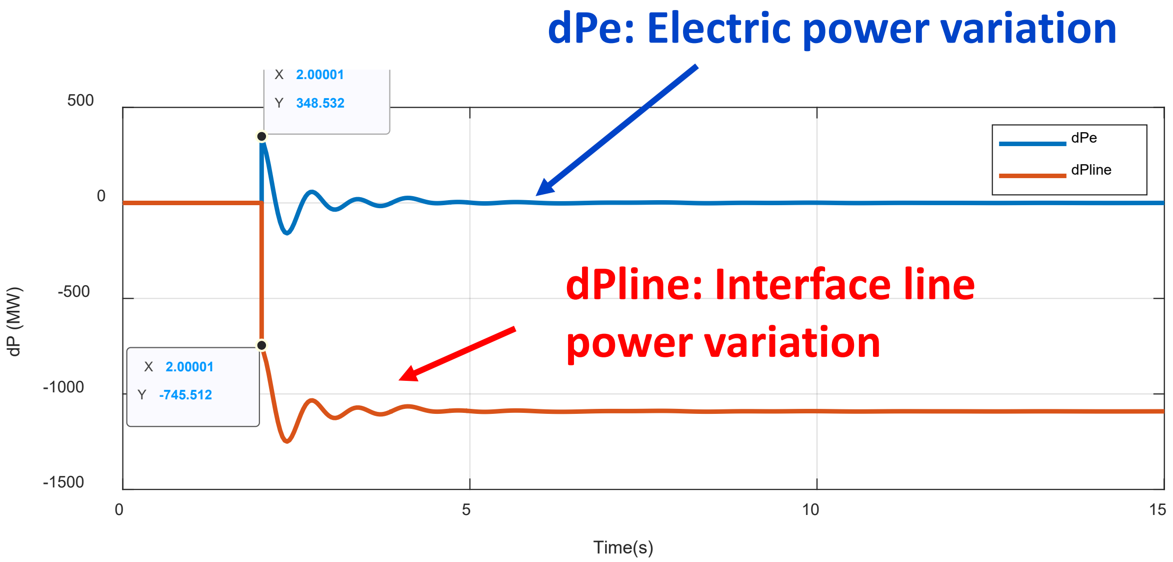
- Trained transfer function model to estimate interface line power

PSSE Simulation Results: Ground Truth

- Disturbance: Largest generation trip inside study region **1097 MW**
  - Discrepancy between weighted rotor speed and average frequency of all PMUs
  - Effective disturbance size: **348.53 MW** (1097 MW is applied to the entire system, **745.51 MW** power reduction on interface lines)



Frequency vs. Speed



dPe vs. dPline

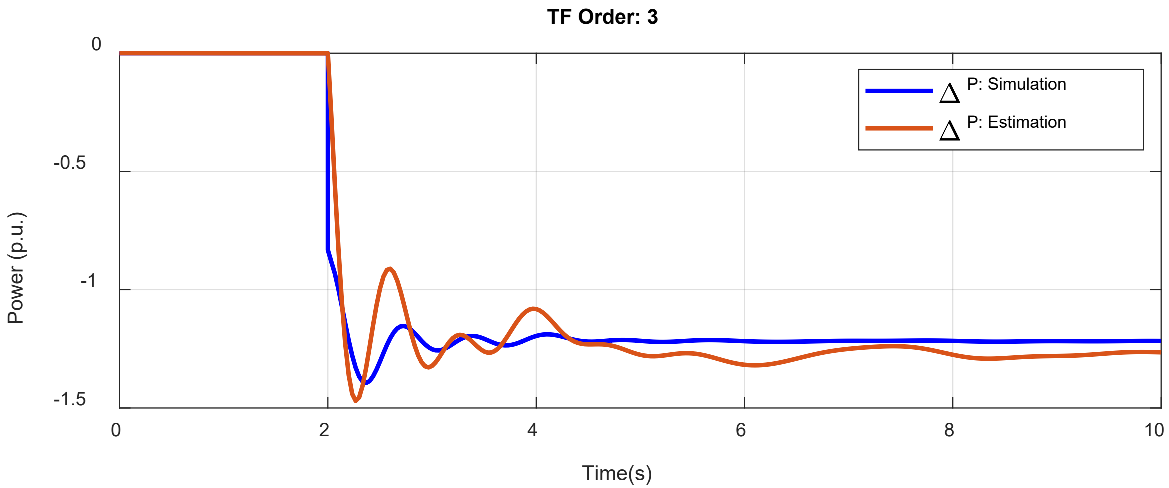
Trained Transfer Function to Estimate Interface Power

- Interface line power cannot be measured under a hypothetical disturbance
- Train a transfer function model to estimate interface line power
- Effective disturbance: 348.53 MW

Frequency →

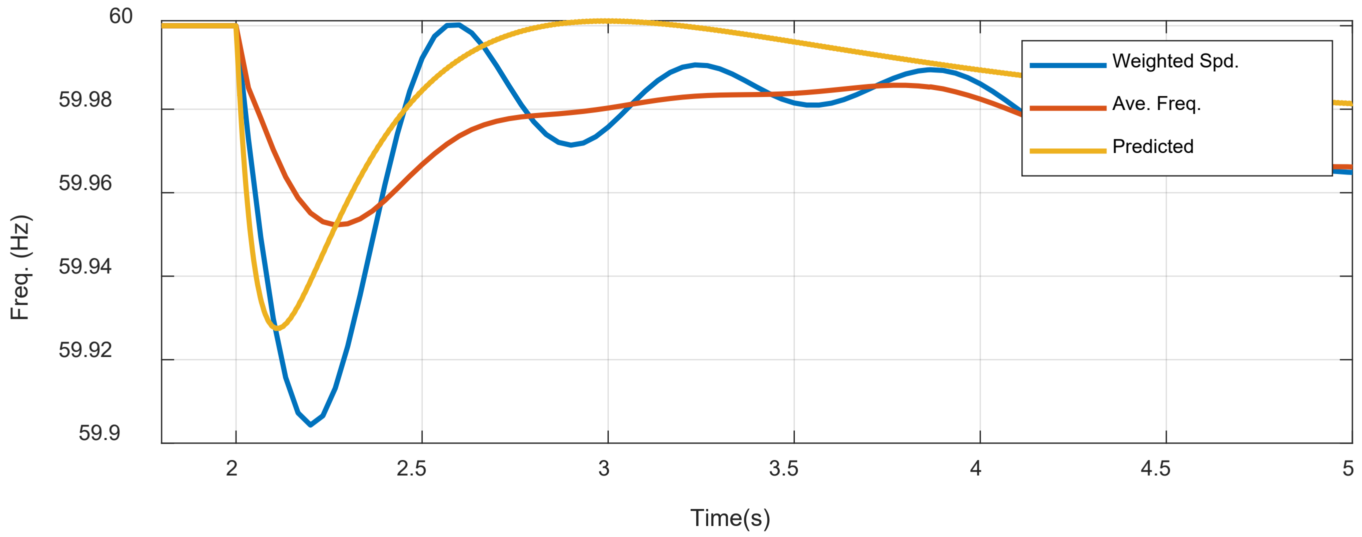
$$G(s) = \frac{-195.4\,s^2 - 626.7\,s - 471.1}{s^3 + 314\,s^2 + 98.56\,s + 244.6}$$

→ **Interface line power**



Frequency Nadir and RoCoF Prediction Results

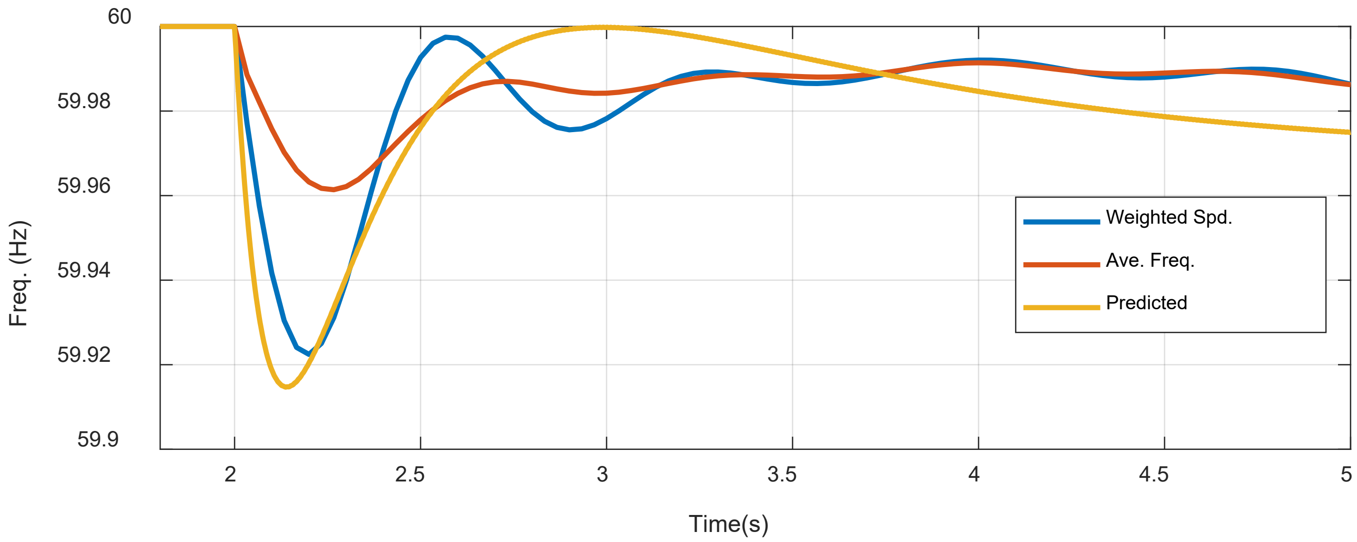
- Spring Case
  - Time window to calculate RoCoF: 0.1s (2.0s to 2.1s)
  - Prediction results are close to ground truth with weighted speed: Equivalent rotor speed is predicted



	Frequency Nadir (Hz)	RoCoF (mHz/s)
PSS/e Simulation (Ground truth): Weighted speed	59.904	-701.34
Prediction	59.928	-721.28

Frequency Nadir and RoCoF Prediction Results

- Summer Case
  - Time window to calculate RoCoF: 0.1s (2.0s to 2.1s)
  - Prediction results are close to ground truth with weighted speed: Equivalent rotor speed is predicted



	Frequency Nadir (Hz)	RoCoF (mHz/s)
PSS/e Simulation (Ground truth): Weighted speed	59.922	-583.21
Prediction: G(s) trained for Spring case	59.915	-812.17
Prediction: G(s) trained for Summer case	59.920	-783.74

Summary and Future Work

- Inertia estimation and monitoring using ambient PMU measurements
- Frequency nadir and RoCoF prediction
  - Consider inertia contribution from non-synchronous generators
  - Comparison between predicted frequency nadir & RoCoF and relay settings
- Case study on selected ComEd/Exelon regional grid with synthetic PMU measurements
- Future work
  - Case study with recorded ambient PMU measurements
  - Impacts of PMU data quality: Data loss, time synchronization error, PMU data unavailability, etc.

TOGETHER…SHAPING THE FUTURE OF ENERGY®

www.epri.com