Regional Inertia Estimation Using Ambient Synchrophasor Measurements

CIGRE GOTF 2023

Lin Zhu, Evangelos Farantatos, Deepak Ramasubramanian,
Parag Mitra, Vikas Singhvi
Electric Power Research Institute
lzhu@epri.com

Mohamed Elnasry, Venkataramana Ajjarapu
Iowa State University

October 11, 2023
Kansas City, MO

What is Inertia?

- ***Inertia*- *Property* *of an object to stay in a state of motion or a state of rest (***Newton, 1686***)***
- ***What is measurable? 'Moment of Inertia' –*** *Dependent on mass and geometry*
  - Unit: kg-m^2

Swing Equation

$$2H\frac{d(freq)}{dt} = \mathrm{Pm} - \mathrm{Pe}$$

H: inertia constant (seconds)

Conventional generation plants

Generation	H
Nuclear	3.8-4.3
Coal	2.9-4.5
Combustion Turbine (Aero and Industrial)	1-10
Combined Cycle	1-9
Hydro	2-3

Motivation - Reducing Inertia

Increased Penetration of Inverter Based Renewables

Increasing integration of renewable generation displaces synchronous generation → system inertia reduction

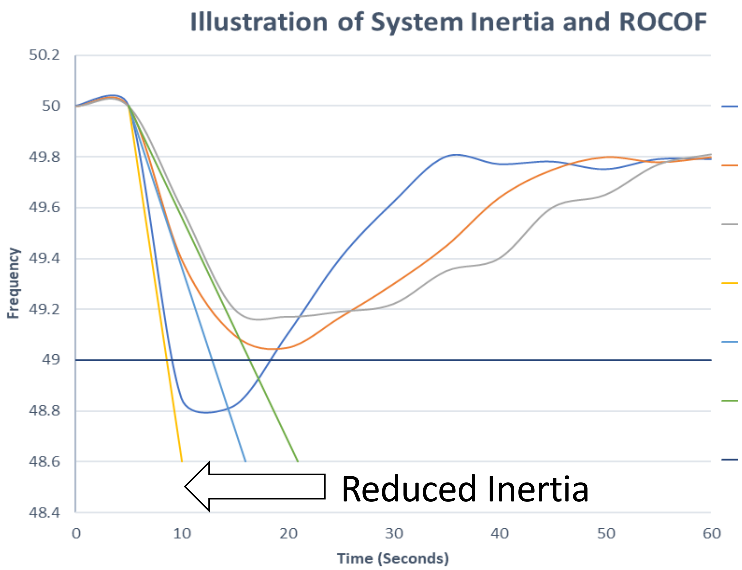
Challenges

Rate of Change of Frequency (RoCoF)

- Equipment Withstand
- Protection Maloperation
- Reserves Response Time

Frequency Nadir

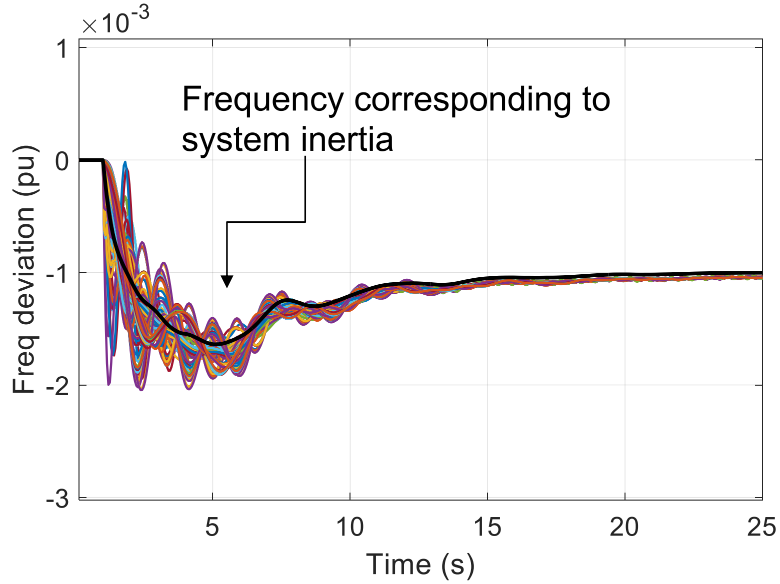
- Operational Security Standards
- Customer Load Shedding



Traditional Frequency Response Evaluation

- ✓ Most interconnections study the **inertial requirements** as well as the **frequency response** of the **entire interconnect** at once
- ✓ ***Event***: Largest generation/infeed loss event during a low inertia period for **the entire interconnect.**
- ✓ The **interconnected system inertia** has traditionally been measured as

$$Hsys = \sum_{All\ online\ units} MVA_i H_i$$



- ***Assumption: the interconnected system is*** ***somewhat strongly coupled and moves in unison***
- ***Does this assumption hold when the IBR penetration increases significantly?***

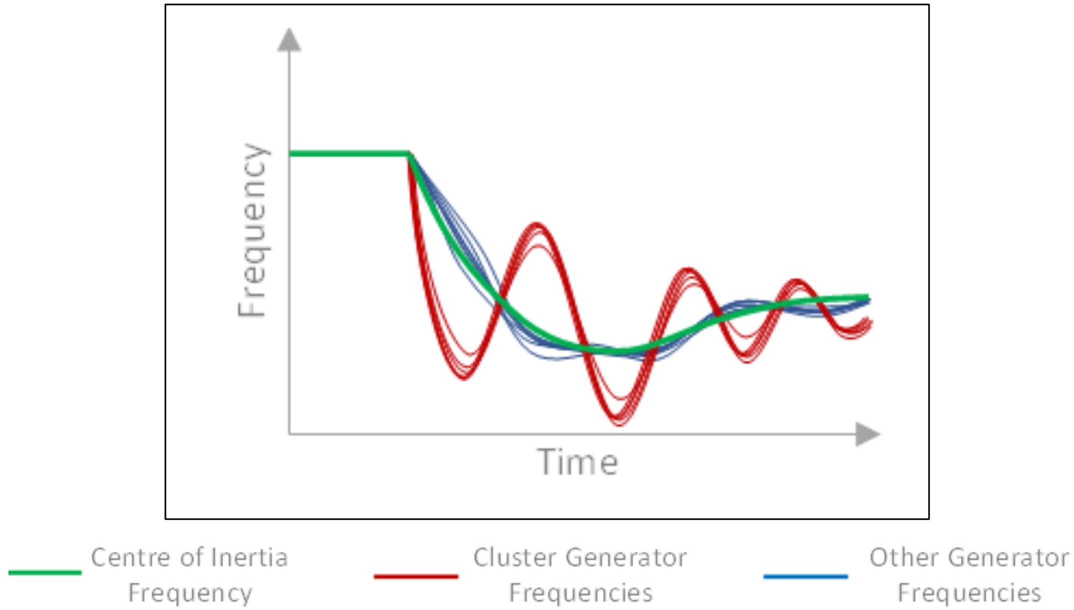
Regional Inertia

Regions of the system may emerge that have low inertia and are weakly coupled to the rest of the system and its inertia

Reduction in inertia is not spatially uniform, which can result in regions of disproportionately low inertia

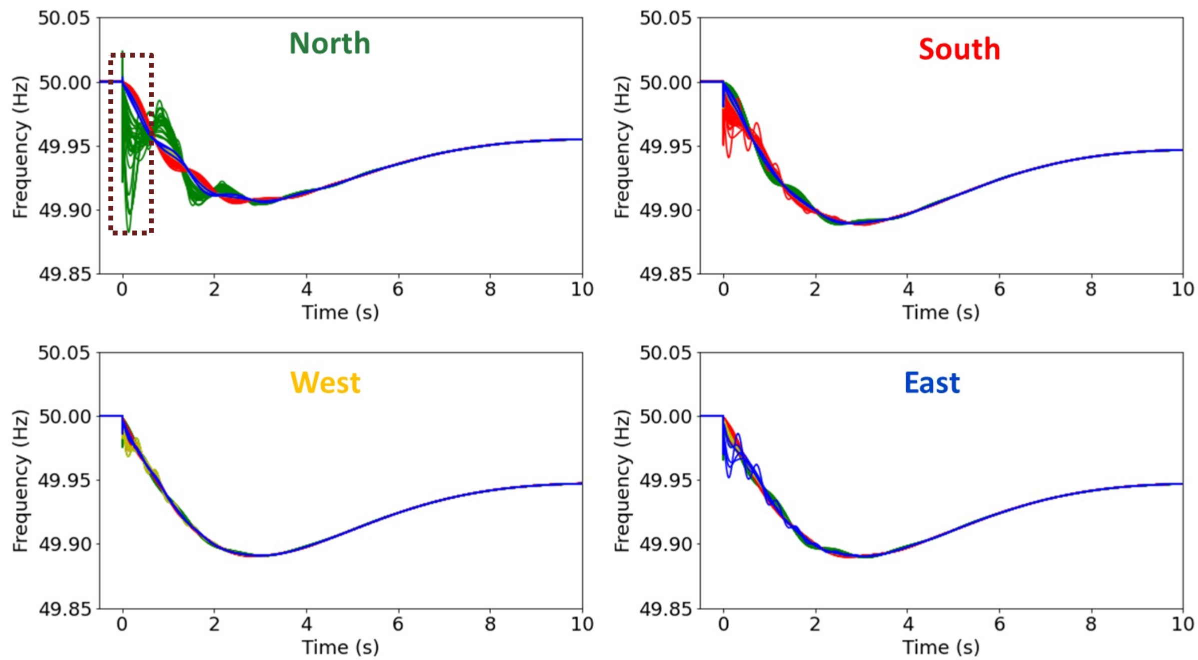
If low inertia regions are poorly coupled to the system, they will swing around the center of inertia frequency

Potential severe regional frequency and RoCoF response under local infeed loss



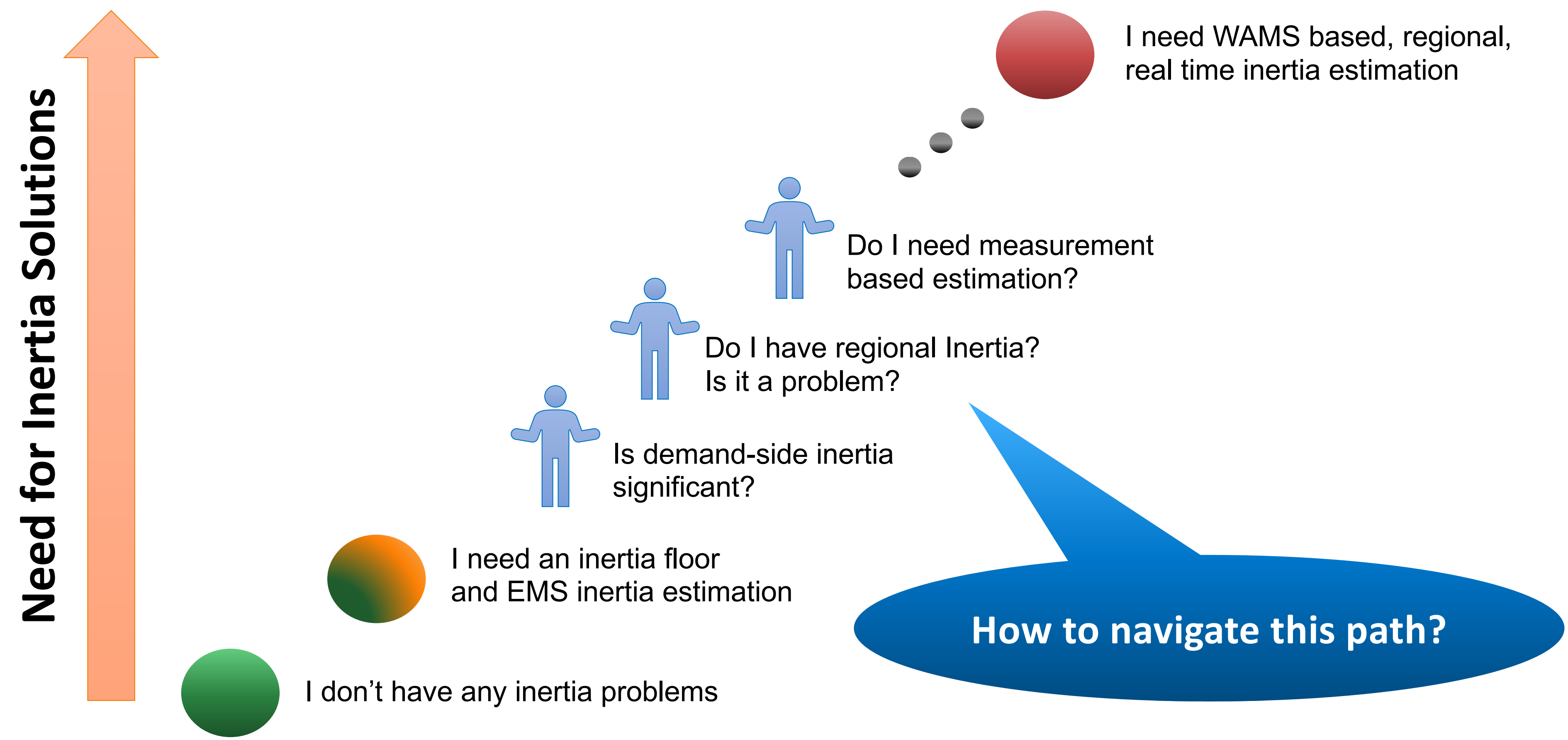
Example: Great Britain 36 Zone System

- Northern part of the system has **considerably low inertia**
- A **700 MW infeed loss** was simulated in all the four regions separately
- North experiences ROCOFs higher than **0.125 Hz/s and trip LOM protection**
- **Clearly a loss of 700 MW in other areas are not that impactful**
- **An interconnection level analysis may not reveal this**



How does one identify such regions?
Are these regions vulnerable?

Framework for Assessing Reduced System Inertia



Inertia Estimation Methods: Overview

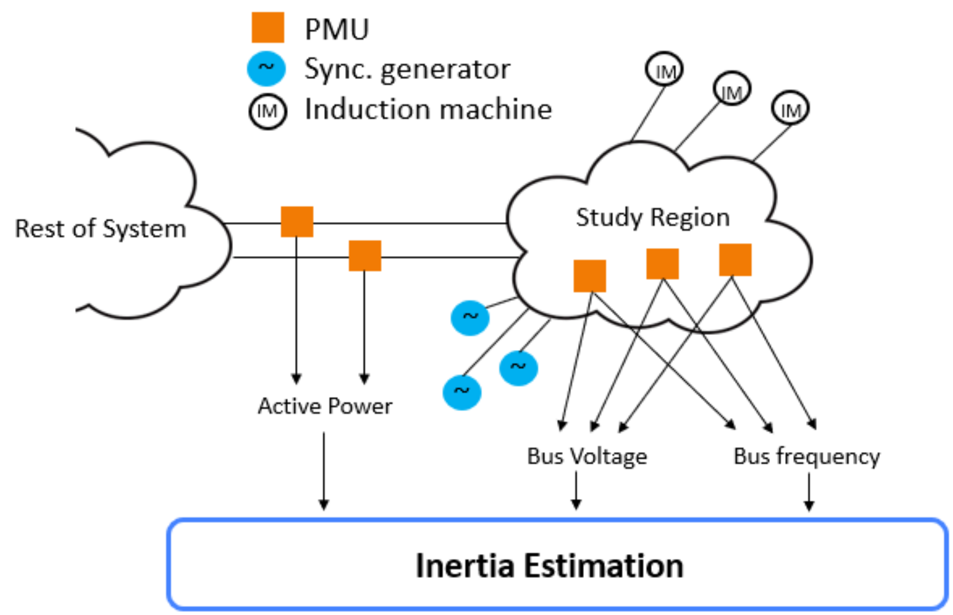
Method	Input Data				Synthetic Inertia?	Additional device?
	EMS	Frequency	Active power	Known Event		
Unit Commitment[1]	✓	✗	✗	✗	✗	✗
PMU Based: Ambient[2]	✗	✓	✓	✗	✓	✗
PMU Based: Stimulus/Probing[3]	✗	✓	✓	✗	✓	✓
PMU Based: Event (Large Disturbance)[4]	✗	✓	✓	✓	✓	✗
Machine Learning[5]	✗	✓	✗	✗	✓	✗

1. Sum of inertia contribution from each online synchronous generator
2. Continuous monitor ambient frequency and active power measurements, swing equation based approach to estimate regional or system inertia
3. Inject probing/stimulus signal to grid, swing equation based approach to estimate regional or system inertia
4. Large disturbance/event data for post-event analysis, swing equation based approach
5. A machine learning model to represent the system dynamics embedded in the ambient frequency measurements and system inertia

PMU Based Inertia Estimation

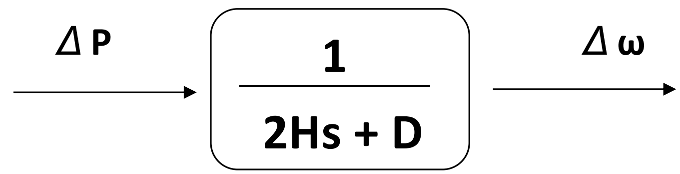
Regional PMU-Based Inertia Estimation

- Ambient PMU Measurement Based
- PMUs within region and at interface lines
- System Identification using ambient data: Depict the relationship between Δf and ΔP



PMU Based Inertia Estimation Method

- Swing equation-based inertia estimation algorithm
  - **Δ P** estimation
  - **Δ ω** estimation



Estimated by using governor model with droop and deadband

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

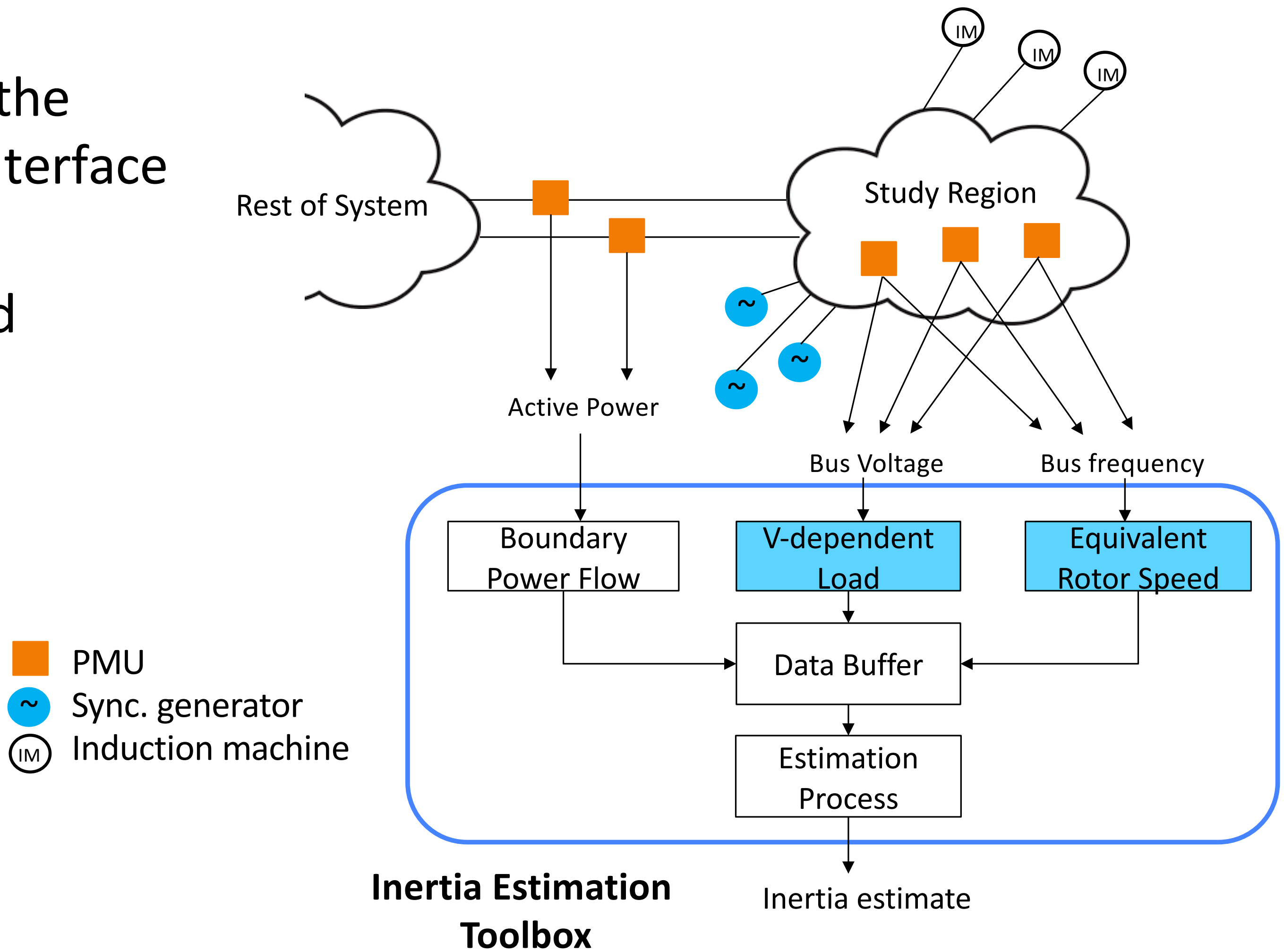
Tieline power (can be measured by PMU)

IBR power (can be measured by PMU)

Load power (can be estimated)

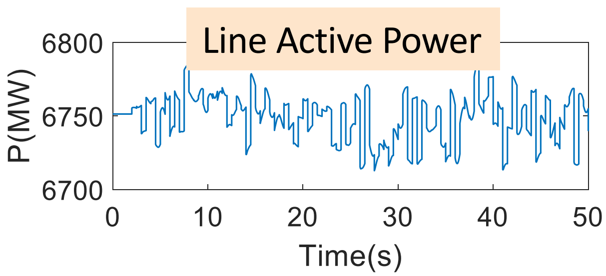
PMU Based Inertia Estimation Method

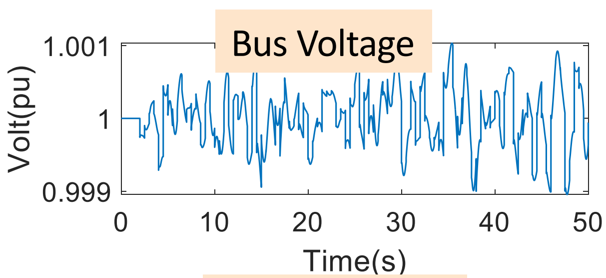
- PMUs deployed within the region (Δf, ΔV) and at interface lines (ΔP)
- Voltage-dependent load estimation
- Equivalent rotor speed estimation

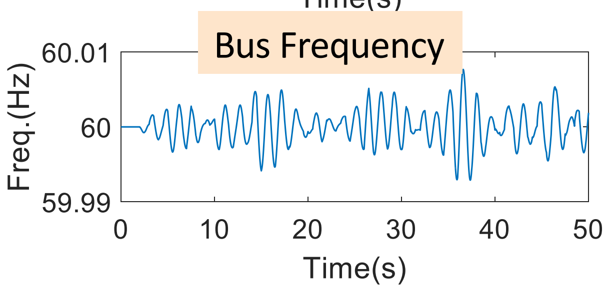


PMU Based Inertia Estimation Features

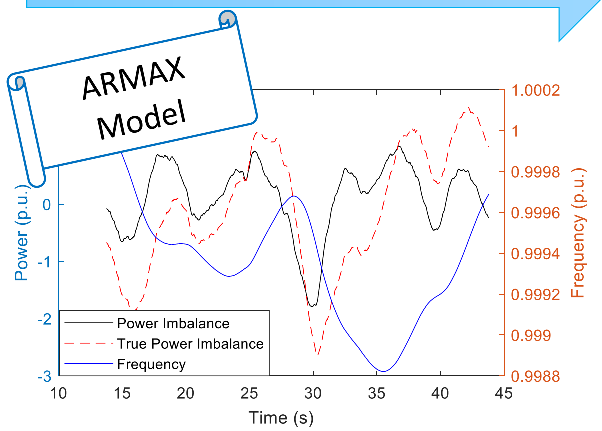
Ambient PMU Measurements







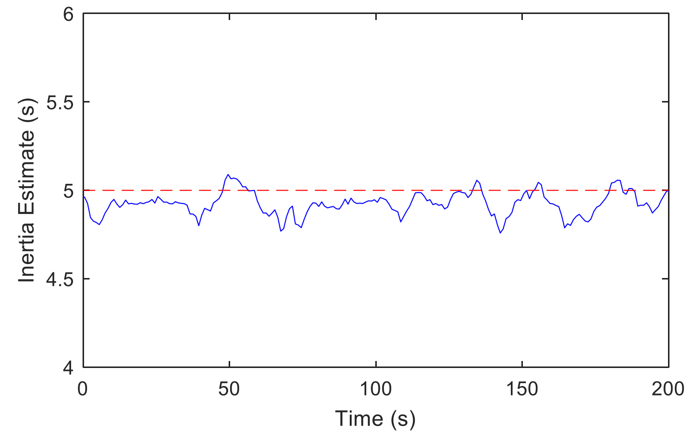
System Identification



Features

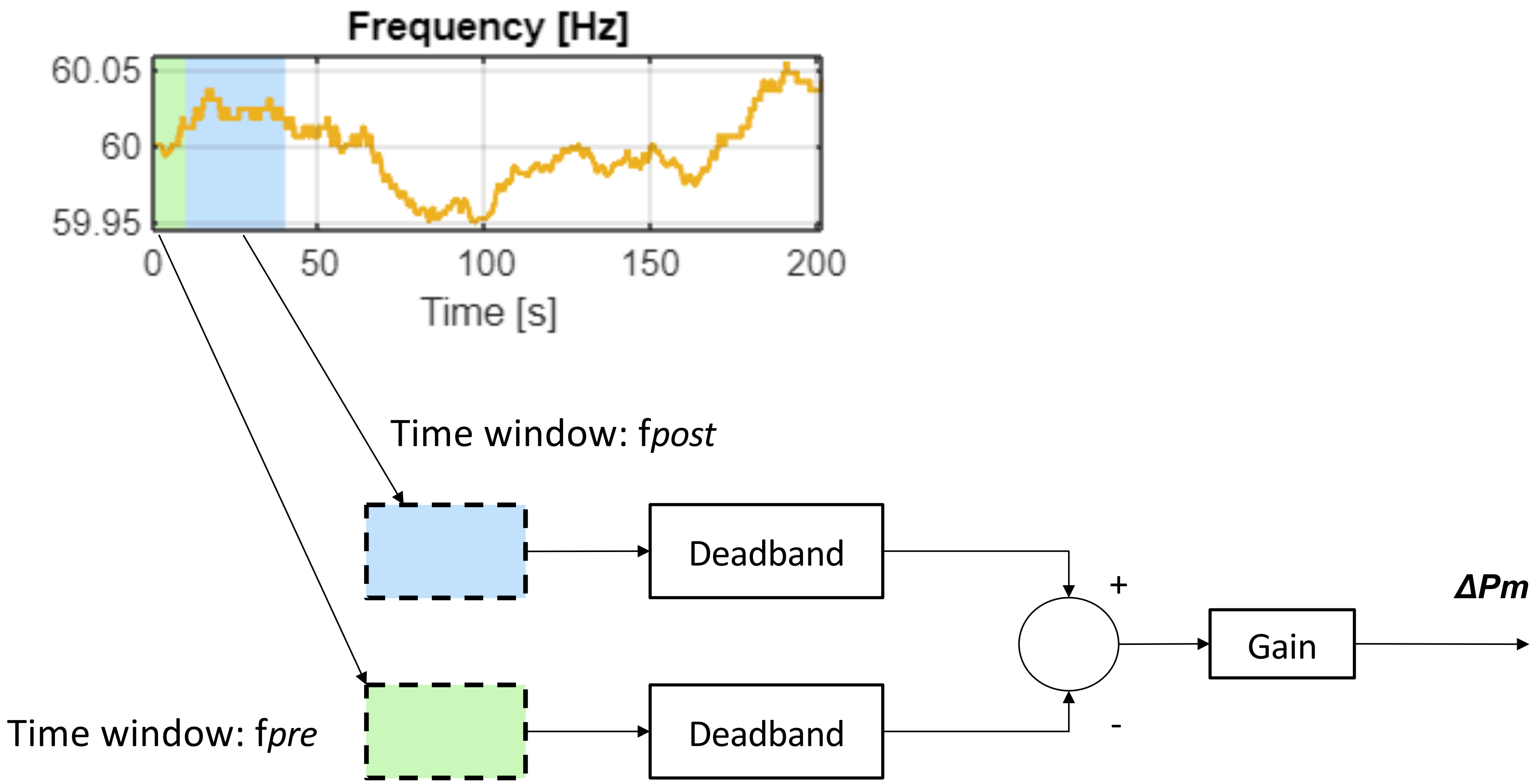
- ΔP Estimation
- Considers Governor Response
- V-dependent Load Estimation
- Rotor Speed Estimation
- RoCoF Estimation
- Sliding Windows

Inertia Estimation



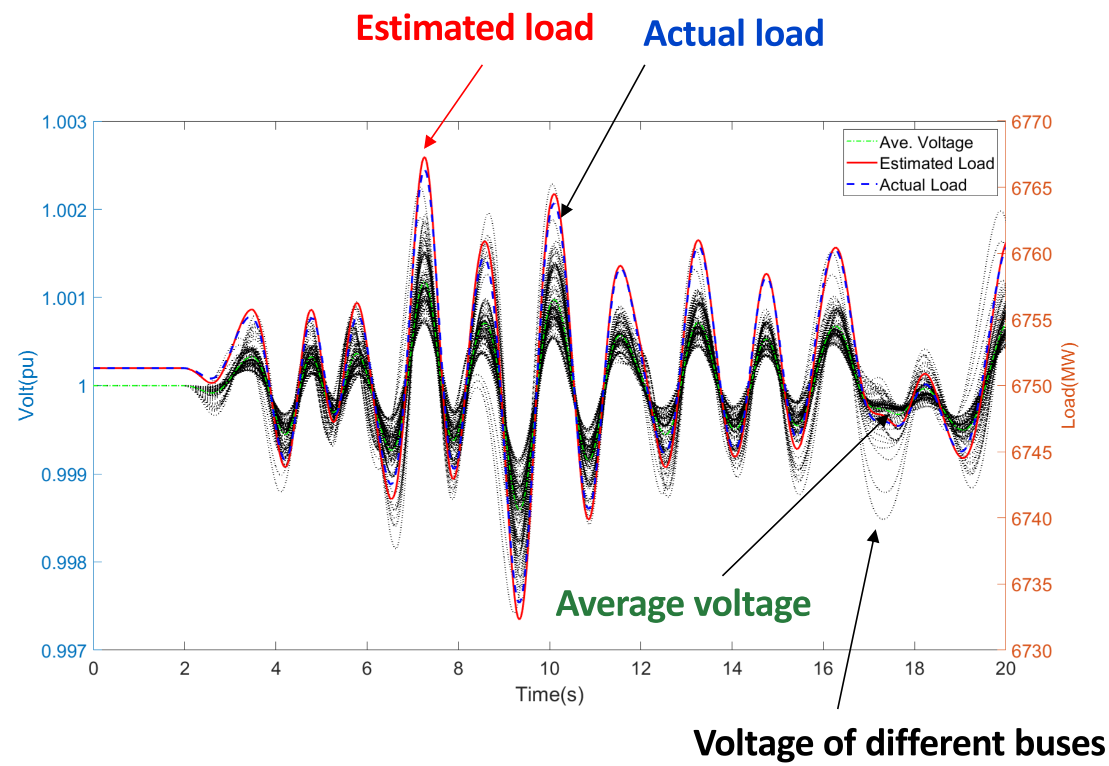
ΔPm Estimation

- Linear governor model considering deadband and droop



Voltage-Dependent Load Estimation

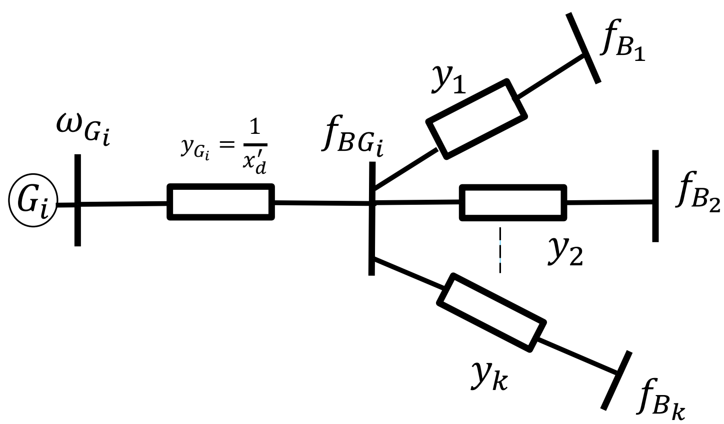
- Input:
  - Total steady-state load ($P_{load_{ss}}$)
  - Load type (ZIP) and percentage (P_P/ P_I / P_Z)
  - Voltage measurements from PMUs
- Output: Estimated voltage-dependent load ($P_{load_{est}}$)
- Algorithm:
  - $volt$: Mean value of normalized voltage measurements

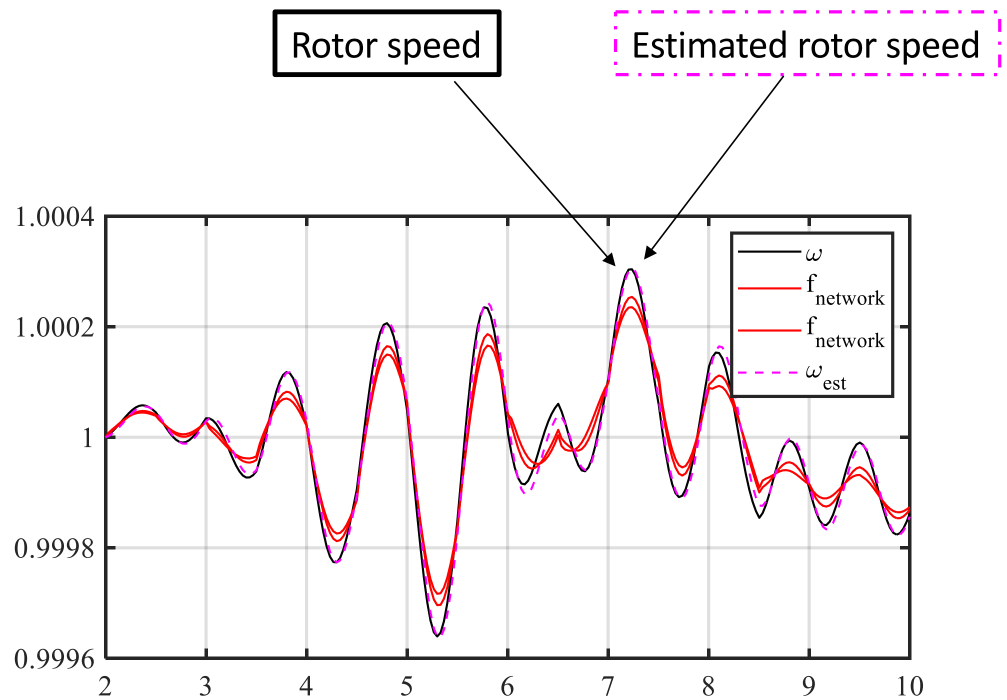


$$\sum P_{load_{est}} = P_P \sum P_{load_{ss}} + P_I \sum P_{load_{ss}} \times volt + P_Z \sum P_{load_{ss}} \times volt^2$$

Rotor Speed Estimation

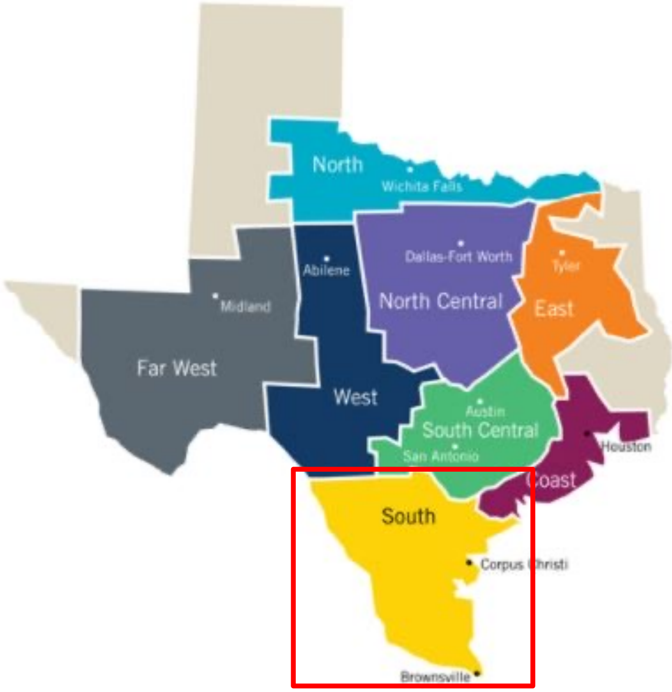
- Input:
  - Bus frequency measurements
  - Grid impedance matrix
  - Generator transient reactance
- Output: Estimated rotor speed





Case Study: 2000-Bus Synthetic Texas Model

- Study Region: South
  - 25 tielines between the study region (South) and its neighbor regions (West, South Central, and Coast)
  - 41 in-service synchronous generators: **7,448 MVA**
    - Governor model without deadband, droop = 4% to 5%
  - Total inertia = **34,610 MVAs**
- Ambient data creation
  - Applied white noise to a load outside the study region
  - PMU reporting rate = 30 Hz



Study Region

Simulation Scenarios

- Voltage-depend load estimation and rotor speed estimation can improve inertia estimation accuracy

Benchmark: 34,610 MWs

NO	Input Signal #1 (ΔP)	Input Signal #2 (Δω)	Estimated Inertia (MWs)	Error (%)
1	Tieline	Average rotor speed	25,967	**-24.97**
2	Tieline + Actual load	Average rotor speed	35,227	1.78
3	Tieline + Estimated load	Average rotor speed	35,707	3.17
4	Tieline + Actual load	Average bus frequency	43,624	**26.04**
5	Tieline + Actual load	Estimated rotor speed	38,284	10.62
6	Tieline + Estimated load	Estimated rotor speed	38,476	11.17

Summary and Next Steps

- Summary
  - Use voltage measurements of PMU inside study region to estimate load P variation
  - Estimate equivalent rotor speed using frequency measurements
  - The developed algorithm can accurately estimate inertia when **power imbalance (ΔP)** and **equivalent rotor speed (Δω)** are accurately estimated
- Next steps
  - Offline tool -> online tool


Together…Shaping the Future of Energy®