Inertia monitoring

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ENERGY SYSTEMS INTEGRATION GROUP

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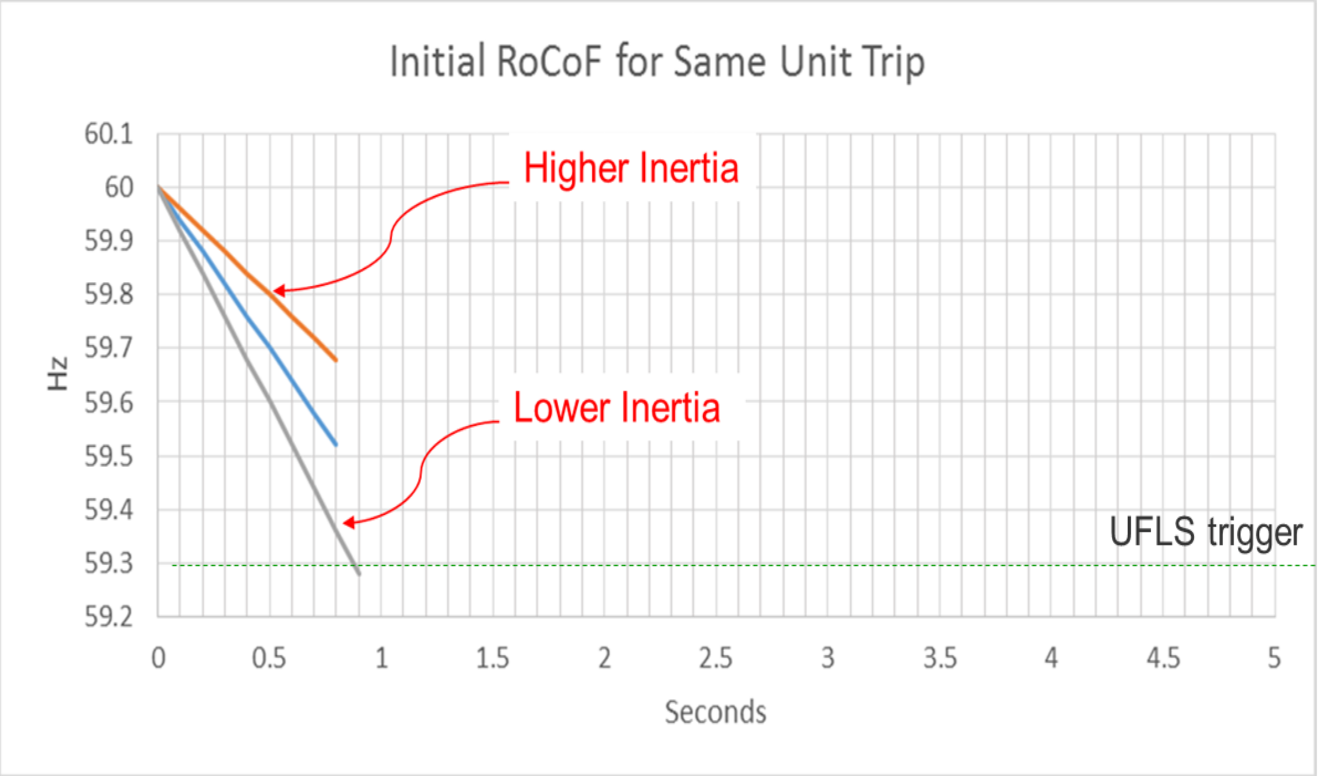
Role of Inertia



RoCoF – Rate of Change of Frequency

Issues with low inertia

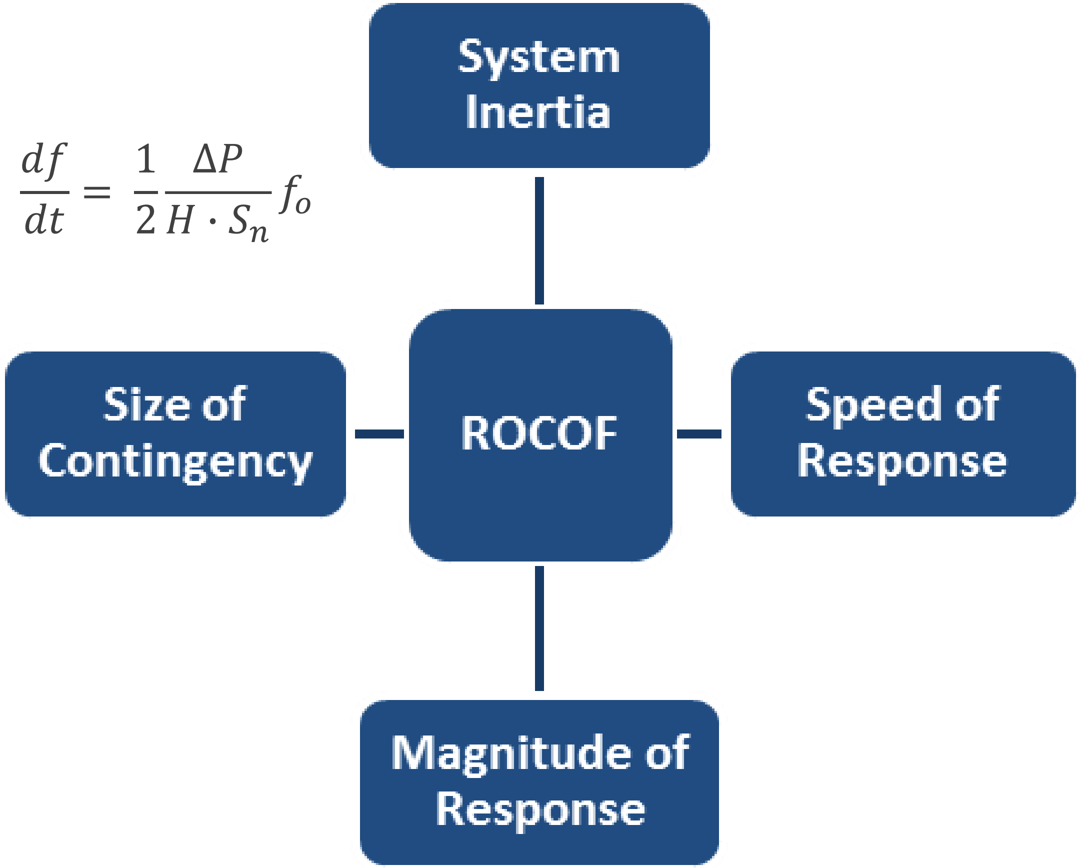
- Frequency declines faster, not sufficient time for frequency response and customer load shedding
- Loss of mains protection may disconnect additional distributed generation on high RoCoF
- Underfrequency Load Shedding (UFLS) relays may malfunction at high RoCoF
- Additional gas-fired generation may trip due to high RoCoF

For further information: Advisory on Equipment Limits associated with High RoCoF, prepared by GE Consulting for AEMO

How to Mitigate Low Inertia and High RoCoF

- Keeping sufficient number of synchronous generators online
  - Cons: minimum generation level, environmental impacts, costs
- Adding high inertia Synchronous Condensers with a flywheel
  - Pros: additional reactive/voltage support, locational
  - Cons: additional costs for additional asset
- Adjusting protection settings where possible
  - Pros: less inertia needed online
  - Cons: additional costs, time-consuming
- Reducing size of largest contingency:
  - Pros: less inertia needed online
  - Cons: costs of dispatching generation down out of market
- Implementing faster and/or more aggressive frequency response
  - Pros: less inertia needed online
  - Cons: additional costs, potentially stability issues
- Active power injection from IBRs in inertial timeframe (Grid Forming)
  - Pros: less inertia needed from synchronous machines, capability of a resource itself
  - Cons: additional costs, technology is still active area of R&D

$$\frac{df}{dt} = \frac{1}{2}\frac{\Delta P}{H \cdot S_n} f_o$$



Source: NERC White Paper: [Fast Frequency Response Concepts and Bulk Power System Reliability Needs]

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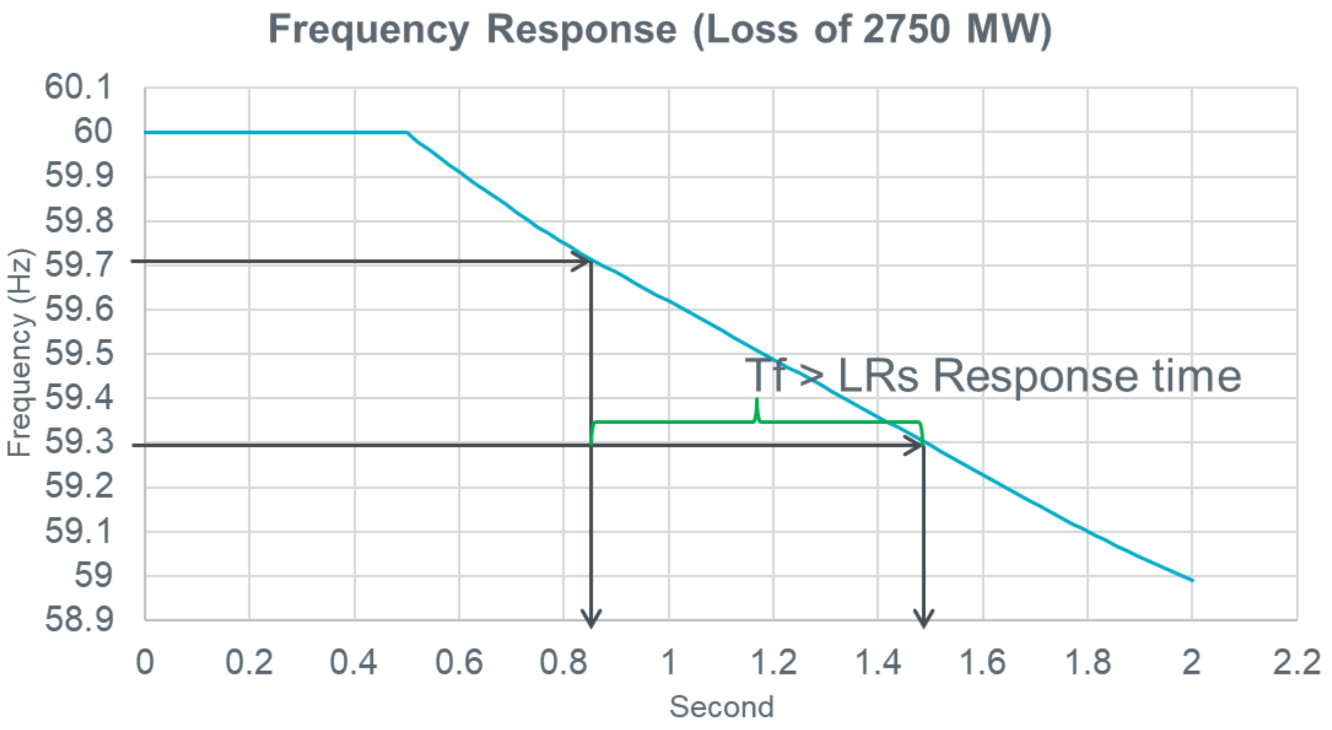
Inertia Floor or Critical Inertia

- Critical Inertia is the minimum level of system inertia at or below which a system cannot be operated reliably with existing frequency control practices.

- Criteria to determine critical inertia: The largest loss of infeed (e.g. generation trip or loss of importing interconnector) should not cause involuntary under frequency load shedding (UFLS).

ERCOT Example: Minimum level of system inertia that will ensure Load Resources (LR) have sufficient time to respond before frequency reaches 59.3 Hz (UFLS threshold)



Source: Inertia: Basic Concepts and Impacts on the ERCOT Grid

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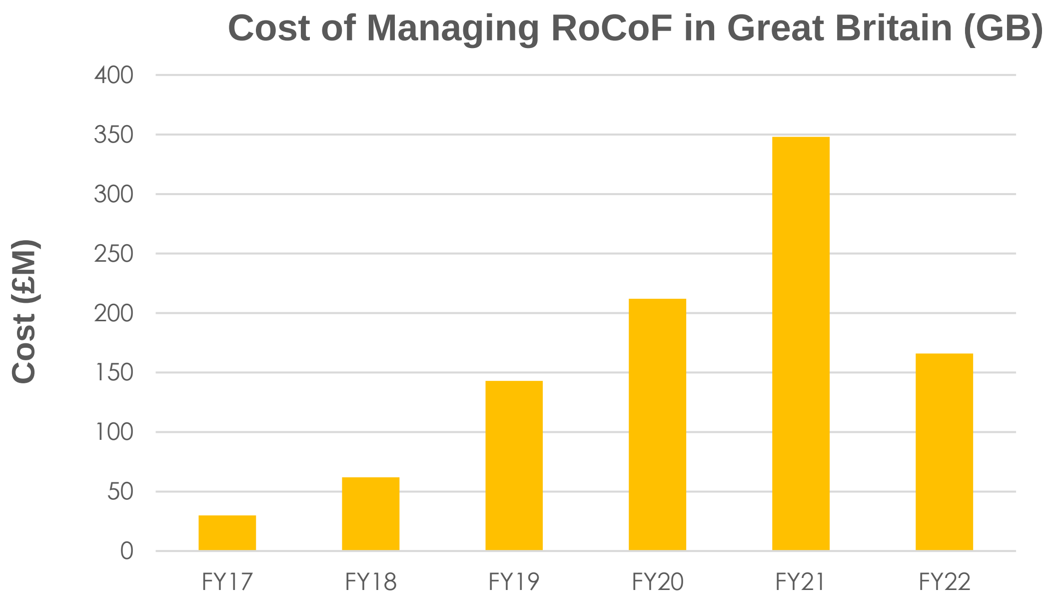
Why Monitor and Why Accuracy Matters?

Why Monitor Inertia?

- Inertia trending – to understand when additional mitigation measures should be introduced
- Situational awareness in real time - making sure inertia stays above critical level
- Understanding frequency reserve needs (e.g. based on historic inertia patterns)
- Situational awareness in real time - making sure speed and amount of available frequency reserves are sufficient at a given inertia level

Why Accuracy Matters?

- Less costs due to additional out of market synchronous generation commitments
- Less curtailments of clean and cheap power from renewables
- Less MW and/or slower frequency response reserves can be procured.



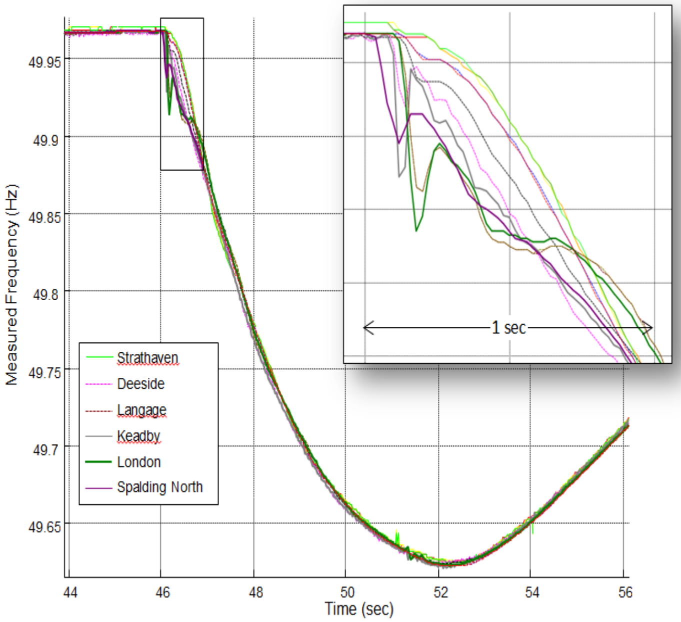
The cost includes costs to bring inertia online, the cost to reduce the largest loss as well as the costs of resultant renewable curtailment.

Note: Fiscal Year (FY) in GB is Apr to Mar. For example, FY21 is 4/20-3/21. Data for FY22 is incomplete and includes up to the end of Feb 2022.

Source: NASPI Webinar, System Inertia Monitoring National Grid ESO & communication with NGESO

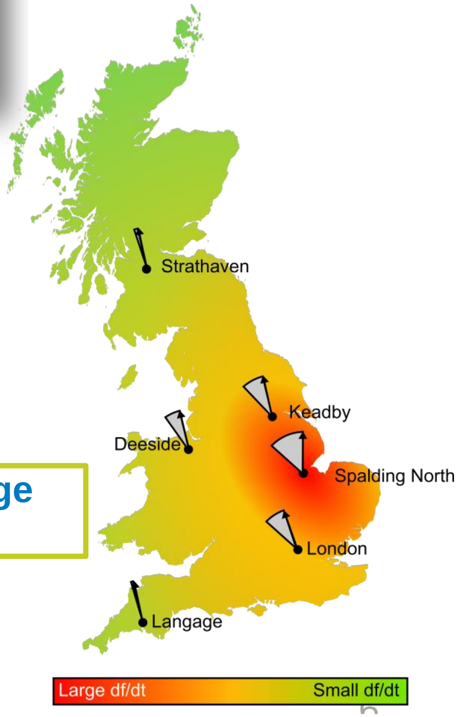
Regional Inertia

- For well interconnected systems with synchronous generation spread across the grid, all machines move in unison and monitoring system-wide inertia is sufficient.
- For "long and skinny" systems with pockets of synchronous generation, the power system behaves as regional centers of inertia ("masses") linked by network ("springs")
- Areas with lower regional inertia experience higher initial RoCoF
- Areas closer to the disturbance experience higher initial RoCoF
- Local RoCoF or frequency issues possible as a result
- In such systems it is recommended to identify coherent regions, determine critical inertia and appropriate mitigation in each region
- EPRI has developed a graph theory-based approach to identify and analyze these regions.
- Having Fast Frequency Response (FFR) in regions with low inertia may cause instability



Spread in frequency in first second

Phasor angles change across system

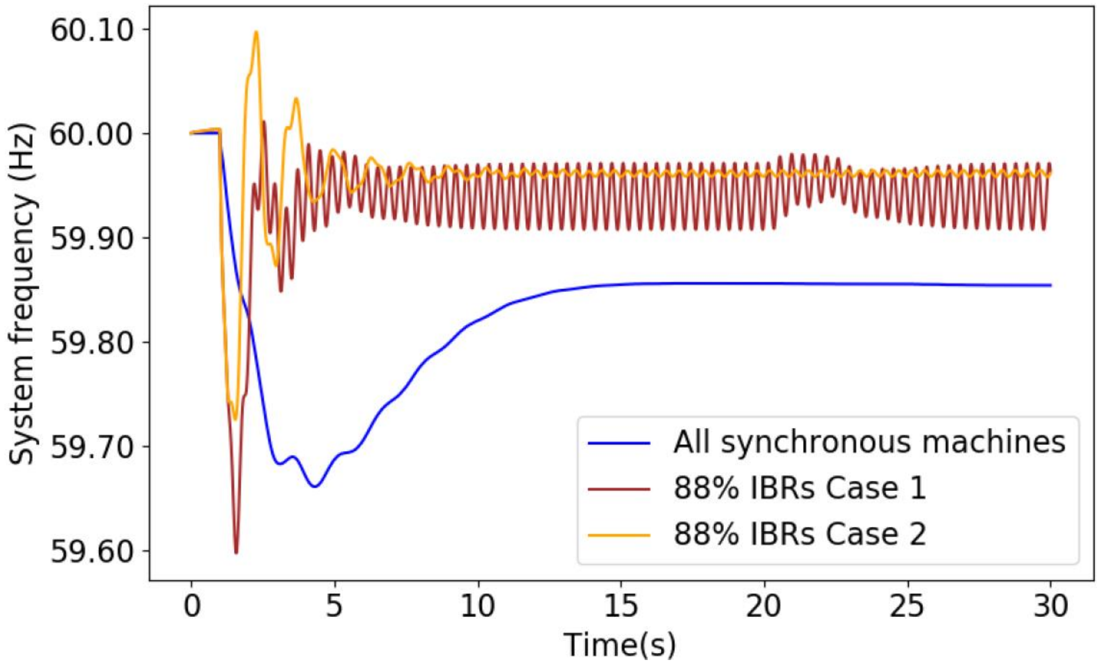


Source: EPRI, Real-time Inertia Estimation and Monitoring: Algorithm and Case Studies. EPRI, Palo Alto, CA: 2021. 3002021797

Source: [GE Power and National Grid, The Enhanced Frequency Control Capability Project]

Location of Delivery of FFR can be Important

- Location of response with regard disturbance is important to be considered
- At a given location, there can be a finite speed of FFR that is possible, while maintaining stability
- Fast frequency response provided by IBRs in remote areas can deteriorate the damping of local modes associated with electromechanical dynamics
- EPRI has developed analytical methods that can evaluate if delivery of FFR can deteriorate the system damping, and if so, what mitigation strategies are available



Case 1 – Only IBRs located electrically far away provide response
Case 2 – IBRs located nearby also provide response

Source: D. Ramasubramanian, P. Mitra, P. Dattaray, M. Bello, V. Singhvi, "Delivery of Primary Frequency Response over Weak Electrical Paths," *2021 IEEE Madrid PowerTech*, 2021

G. Misyris, D. Ramasubramanian, P. Mitra, and V. Singhvi, "Locational Aspect of Fast Frequency Reserves in Low-Inertia Systems," *2022 IREP Symposium*, Banff, Canada, 2022

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Inertia Monitoring Methods at Glance

Inertia Monitoring Method	Main Principles	Application
Unit Commitment	Sum of inertial contributions form online synchronous generators	Most system operators today use this method (ERCOT, EirGrid, AEMO etc.)
Unit Commitment + Adjustment Factor	Sum of inertial contribution form online synchronous generation plus factor estimating inertia contribution from distributed generation and load	National Grid ESO (Great Britain) This method is more suitable for areas with significant contribution from load and synchronous generation on the distribution level.
Continuous Frequency Measurement ("ambient" or with stimulus)	Real time inertia estimation based on "ambient" frequency changes or using known stimulus	Both are in final stages of implementation in National Grid ESO
Historic Disturbance Events	Historic analysis of large disturbance events	Not used for inertia monitoring as such but for calibration of other methods

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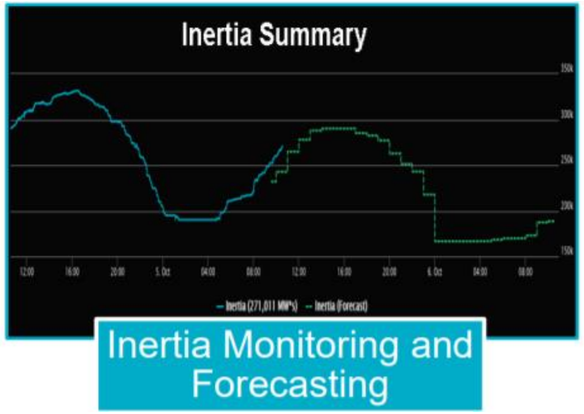
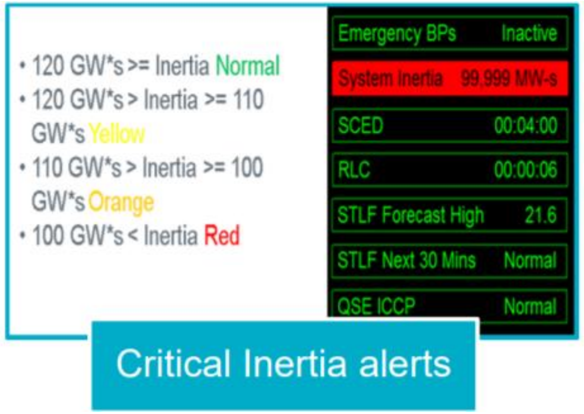
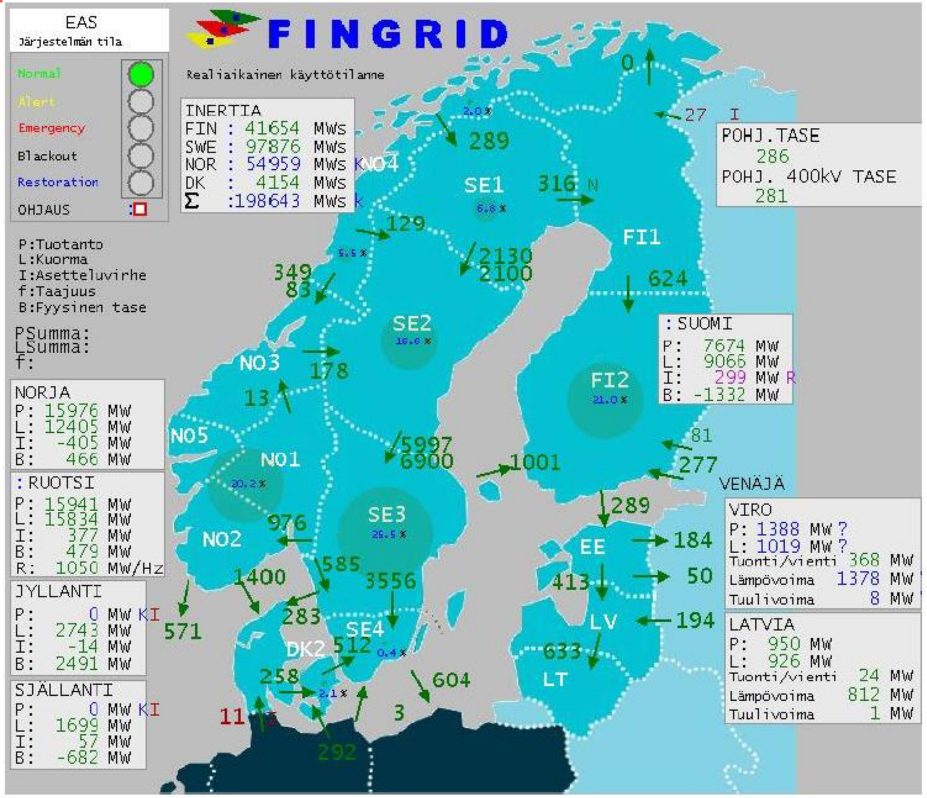
Unit Commitment-Based Inertia Monitoring

- Sum the nameplate inertia of all online synchronous generators
  - Simple and widely adopted
  - Good estimate of system inertia for most systems
  - Does not consider demand inertia without additional work/complexity (NG ESO in Britain use an uplift factor to include load and distributed generation inertia)
  - Inertia data from generators may not be accurate
- Convenient for real time monitoring, forecast and critical contingency estimates
  - Can be basis for alerts, determination of frequency reserves and sufficiency monitoring



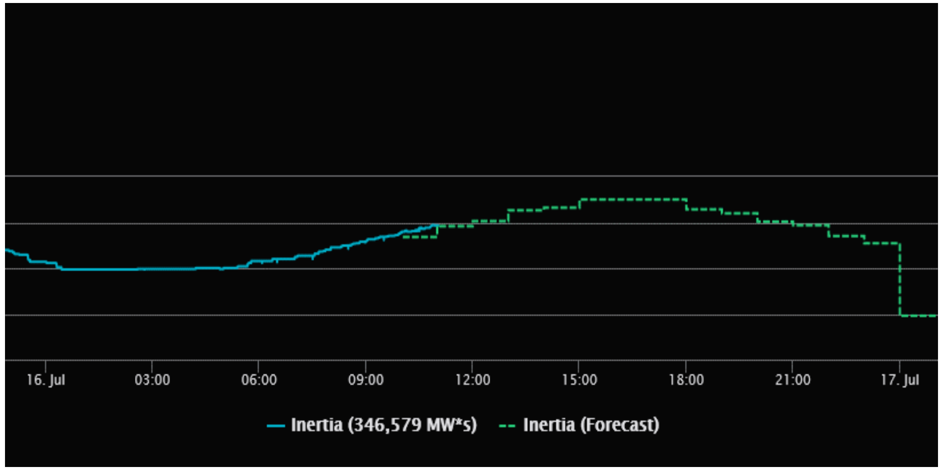


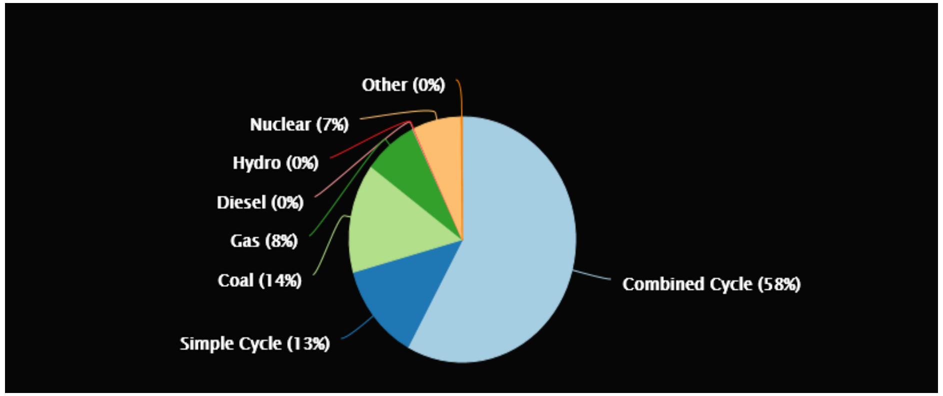


Source: Nordic report Future system inertia, 2018
https://docs.entsoe.eu/dataset/nordic-report-future-system-inertia

Source: CIGRE Academy Webinar: Impacts of High Share of Inverter-Based Resources on System Inertia and Frequency Control

ERCOT Inertia Monitoring Example





- ERCOT monitors inertia in real time based on generator status and inertia of each generator since 2016.
- Monitoring by generation type – useful for trend analysis
- Inertia forecasting, based on generators' Current Operating Plans submitted to the market every hour and spanning 168 hours ahead.
- ERCOT uses forecasted inertia to ensure inertia and frequency reserve sufficiency.

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Continuous inertia estimation based on frequency measurements

- Frequency is measured continuously, using high-speed measurements distributed across a power system
- Signal processing and swing equation for a single machine equivalent is used to estimate inertia

$$Inertia = \frac{1}{2}\frac{\Delta P}{\frac{df}{dt}} f_o$$

- System-wide or regional inertia estimation
- Change on flows between the regions is used to estimate ΔP during continuous small changes on the grid or
- Stimulus is used to “inject” known small ΔP into the grid
- This method captures inertia of load and distributed synchronous generation
- Impact from active power controls (e.g. FFR, governor response, etc.) can be estimated and removed from the estimated inertia, if needed.

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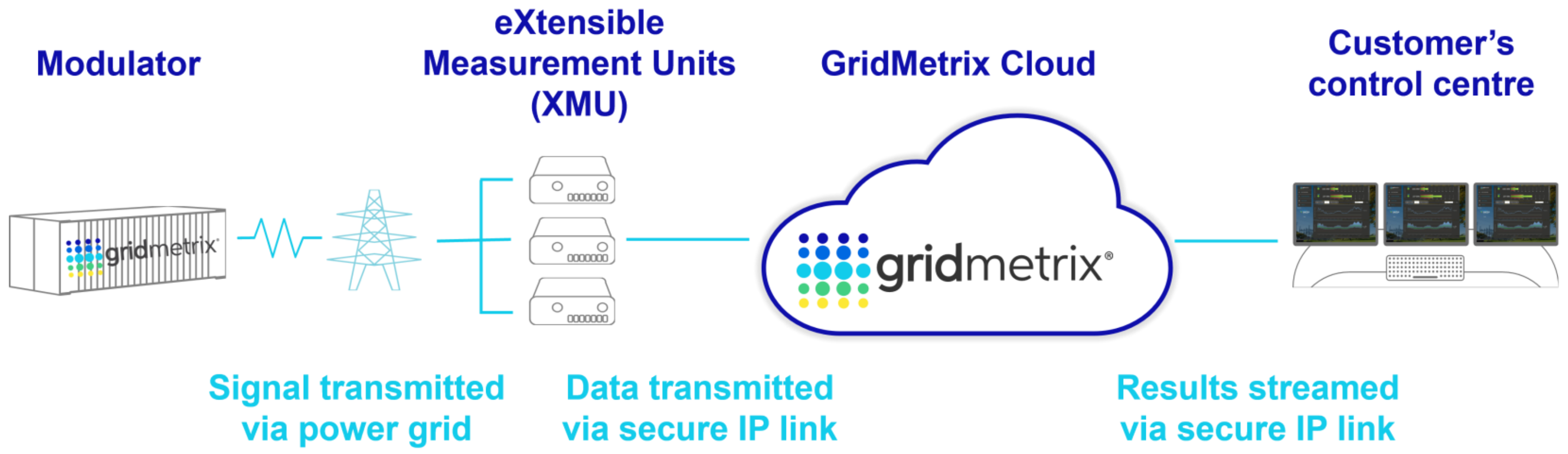
Reactive Technologies – Continuous Inertia Estimation using Stimulus



- Periodic small active power stimulus is introduced by a modulator (negligible effect on the grid)
- RoCoF is measured by Extensible Measurement Units (XMU)
- Extract signal from multiple locations using advanced signal processing techniques

5MW Ultracapacitor

- Calculate inertia using the swing equation with known ΔP and measured RoCoF
- Can be tuned to include or exclude active power control actions
- Can be costly due to need for modulator (though positive cost/benefit analysis)

Source: [NASPI Webinar, System Inertia Monitoring National Grid ESO]

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Reactive Technologies – Continuous Inertia Estimation using Stimulus

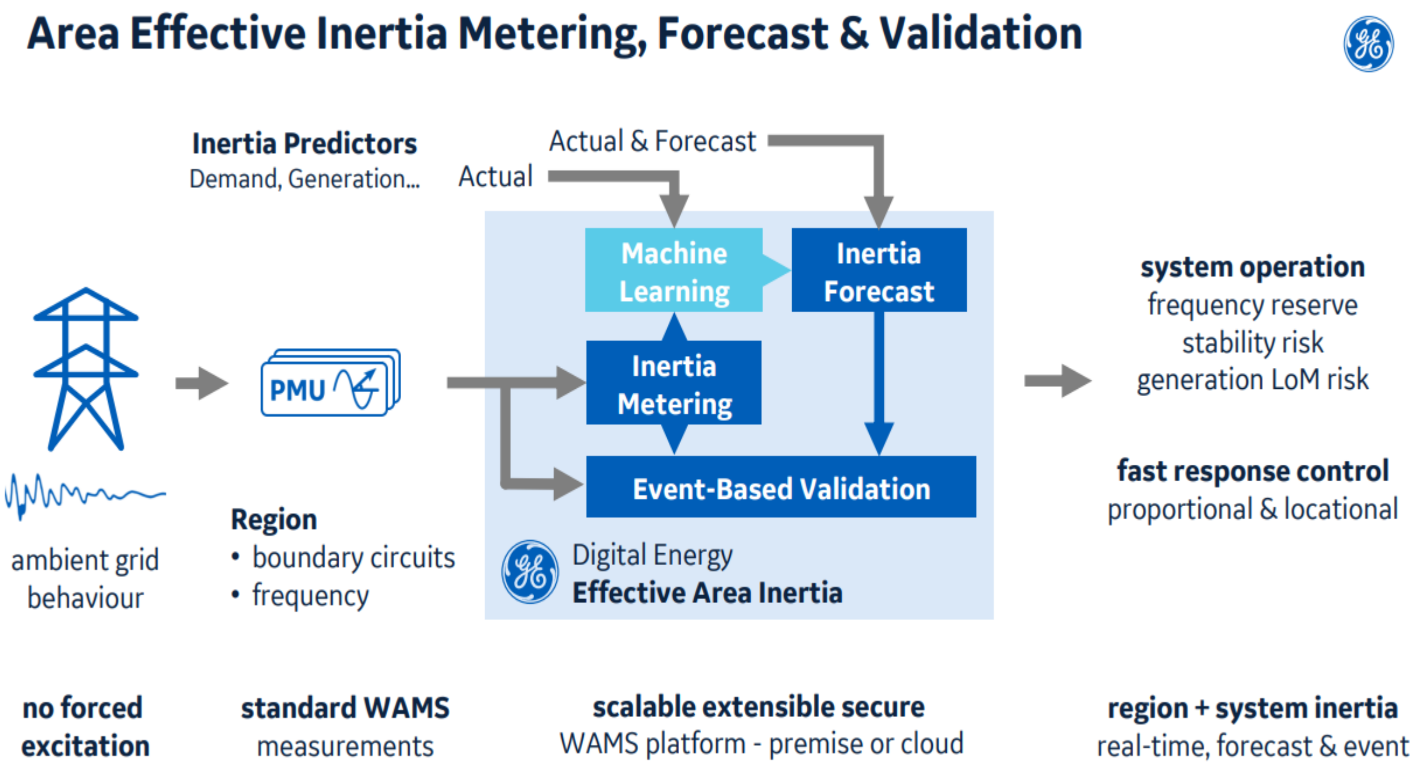
Validation in a number of trials

- Validated through power system simulations and pilot projects around the world. Most recently, 21-day trial in an islanded system in GB
- Used inertia and frequency measurements to estimate MW loss in the largest events.
- Demonstrated that the island system was not operating securely from the largest MW loss perspective

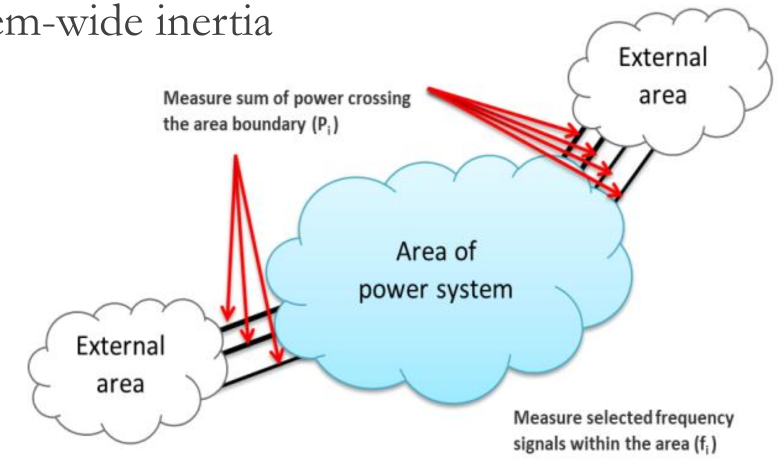
Current status

- Working on deployment in the GB system
- Testing has been underway over recent weeks and final improvements are being planned.
- The system will go live in the next 1-2 months
- NG ESO will then be assessing the data with the aim of introducing it to the Control Room later this summer.

GE - Effective Area Inertia



- Uses "ambient" changes in system frequency
- Captures combined inertia of generation, load and active generator controls
- Modest number of PMUs is needed
- Frequency in each region with a few key measurements
- Measuring power over transmission lines between the regions and
- Estimates and forecasts both regional and system-wide inertia

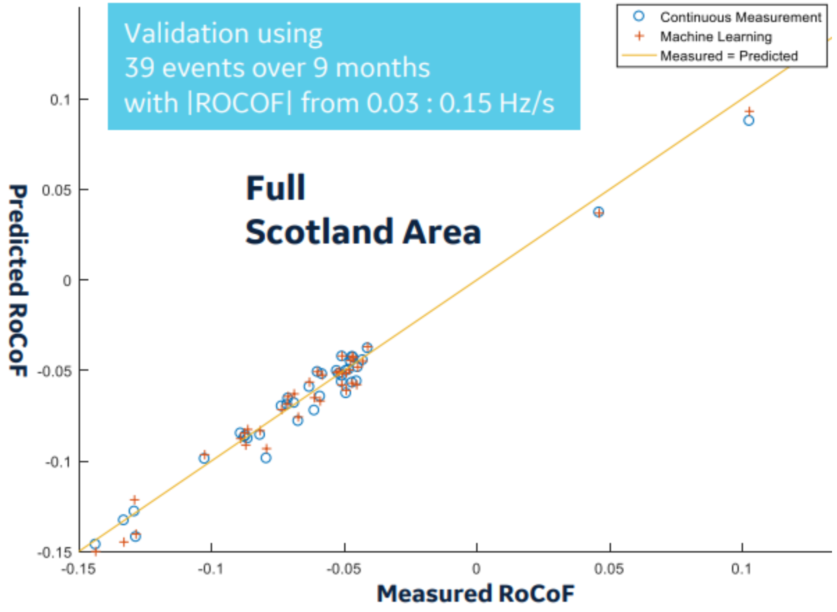


Source: NASPI Working Group Meeting, [GE Effective Area Inertia: Stability Challenges, PMU-Based Metering & Machine Learning Forecasting]

GE - Effective Area Inertia

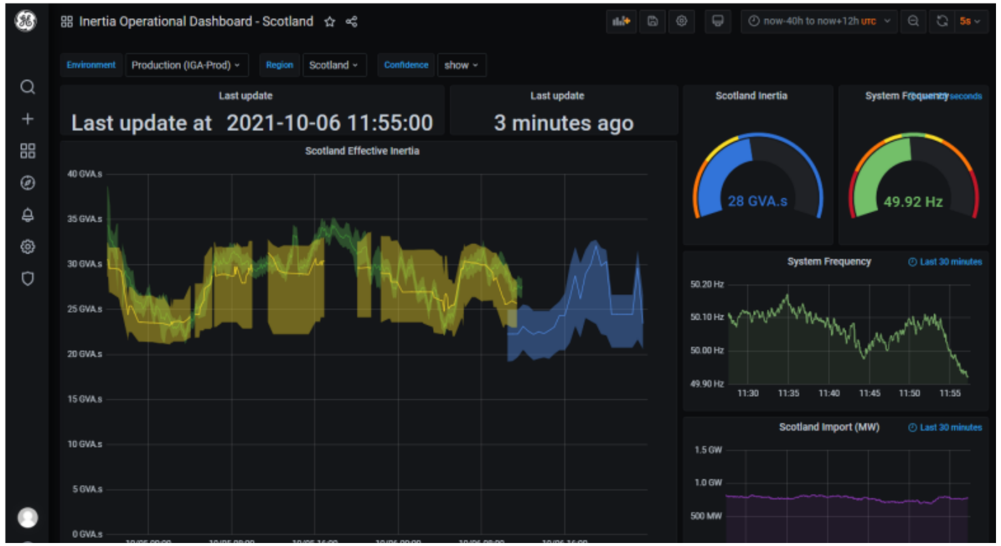
Validation in Scotland based on frequency events

- Estimated & Forecasted inertia before event and Boundary Power Change during event is used to calculate RoCoF
- Calculated RoCoF is compared to RoCoF observed in the event.
- Good accuracy is demonstrated both for estimated and forecasted inertia



Current status

- Inertia metering online and forecasting > 1 year for Scotland
- PMU deployment underway for the rest of GB
- Inertia forecasting went live in Oct and will be rolled out in the control room ahead of summer.

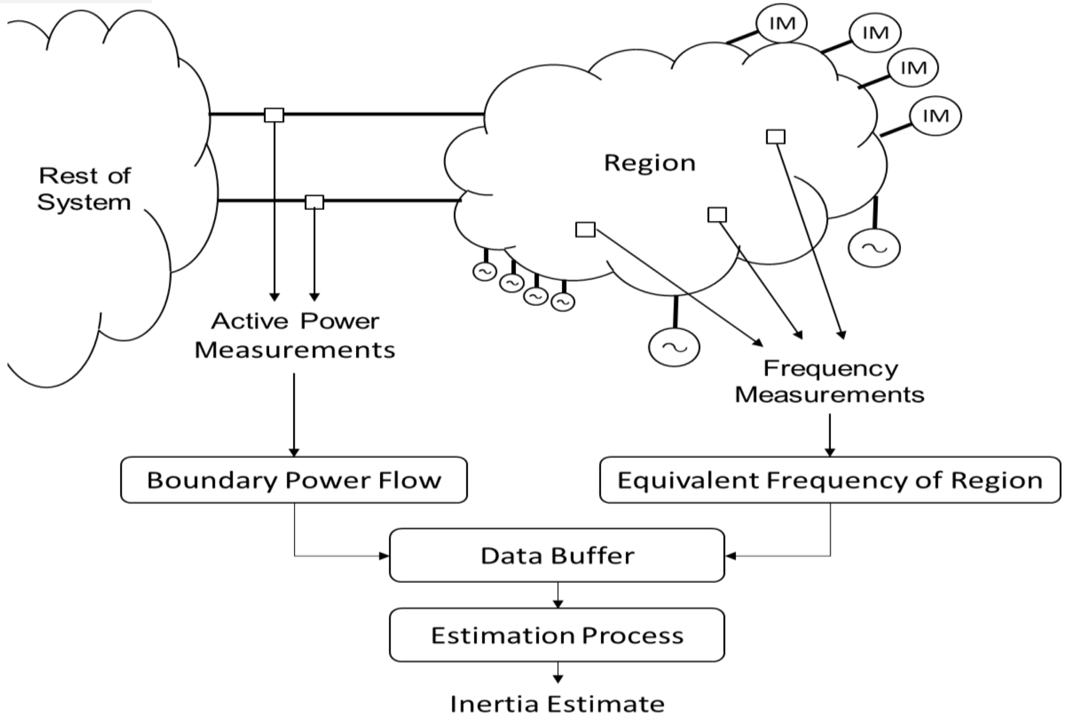


Source: NASPI Working Group Meeting, [GE Effective Area Inertia: Stability Challenges, PMU-Based Metering & Machine Learning Forecasting]

EPRI – PMU Measurement Based Inertia Estimation

Regional PMU-Based Inertia Estimation

- PMU Measurement Based
- PMU within region and at interface lines
- System identification using “ambient” data
- Captures regional load impact
- Tested with simulated data on IEEE test system

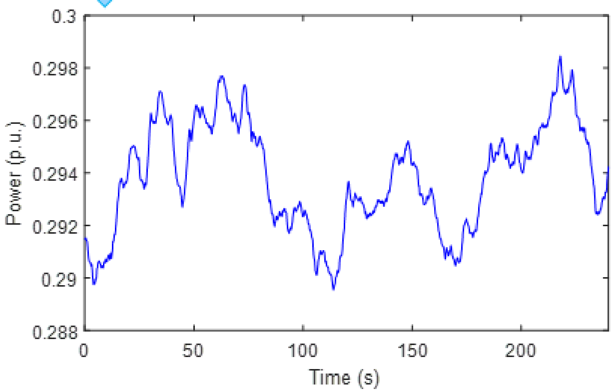


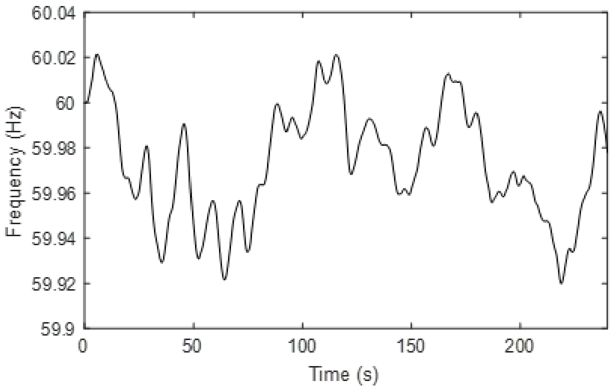
Source: ERPI, Real-time Inertia Estimation and Monitoring: Algorithm and Case Studies. EPRI, Palo Alto, CA: 2021. 3002021797.

EPRI – PMU Measurement Based Inertia Estimation

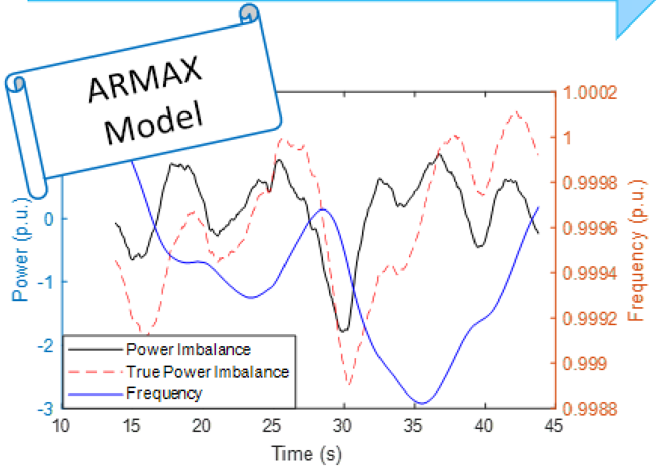
EPRI

Ambient PMU Measurements





System Identification



Features

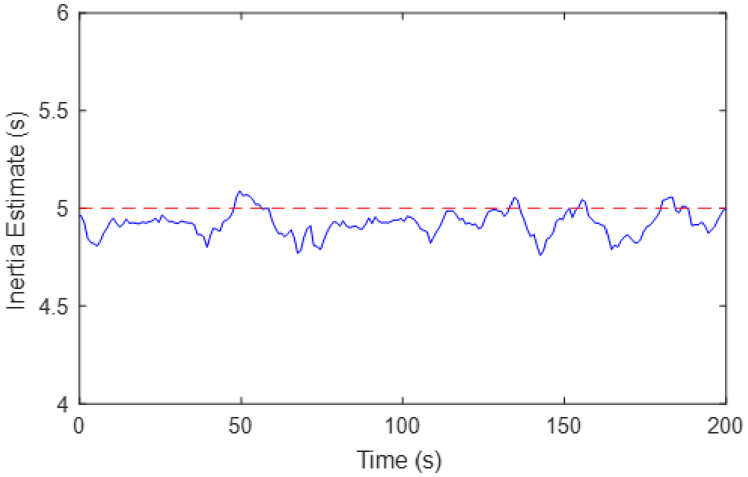
ΔP Estimation

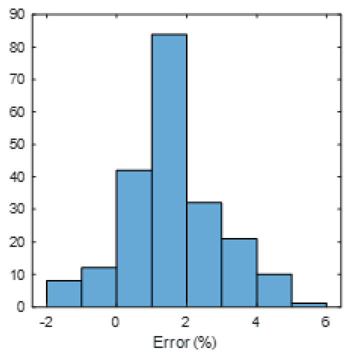
RoCoF Estimation

Sliding Windows

Considers governor response

Inertia Estimation





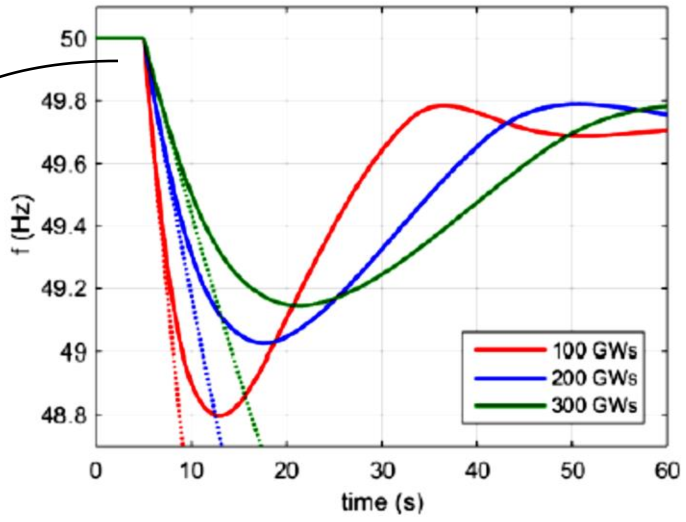
Source: ERPI, Real-time Inertia Estimation and Monitoring: Algorithm and Case Studies. EPRI, Palo Alto, CA: 2021. 3002021797.

Inertia Estimation Based on Historic Disturbance Events

- Treat system as a single equivalent machine
- Use frequency measurements to estimate the initial RoCoF
- Assumes constant mechanical power and only the disturbance changes to electrical power, this is only strictly true for instant of disturbance, so error prone
- RoCoF is difficult to estimate especially during a disturbance
- Difficult to identify exact time of disturbance
- Requires a large number of "clean" events across a year

$$Inertia = \frac{1}{2}\frac{\Delta P}{\frac{df}{dt}} f_o$$

Known Disturbance
ΔP and time of the event



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Summary of Inertia Monitoring

	Input Data				When	Estimates Rotating Inertia?	In Use?	New Monitoring equipment*	Modulator	Basis for Forecasts^	Includes Load Inertia
	EMS^	Frequency	Active Power	Known Event(s)							
Unit Commitment	✓	✗	✗	✗	Real Time	✓	✓	✗	✗	✓	~
Event Driven System	✗	✓	✗	✓	Post Mortem	✓	✓	✗	✗	~	✓
Continuous Signal - Ambient	✗	✓	✓	✗	Real Time	✓	✓	✓	✗	✓	✓
Continuous Signal – Stimulated	✗	✓	✗	✓	Real Time	✓	✓	✓	✓	✓	✓

^EMS data required for forecasting or contingency estimates
*Assuming some PMUs in place

Source: EPRI White Paper: Online Inertia Estimation & Monitoring: Industry Practices & Research Activities', 000000003002016195

So, what does it mean for my system?

1. Is inertia declining?
2. Synch. gen. inertia trending
3. What are RoCoF or Freq. constraints?
4. Unit commit. inertia monitoring & forecasting
5. RoCoF mitigation, FFR, Dyn. Reserve
6. Is load & distributed gen. inertia significant?
7. Cost savings with more accurate monitoring?
8. Continuous inertia monitoring & forecasting
9. Regional inertia?
10. Risk in each region?
11. Continuous regional inertia monitoring & forecasting
12. Is my FFR in the right region?

Things to keep in mind

- Periodic re-assessment
- Continuous benchmarking and parameter calibration based on events
- Load inertia and distributed gen. inertia may change
- Region definitions may change

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THANK YOU

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