Real-Time Inertia Monitoring Using Synchrophasors

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NASPI – Inertia Panel Presentation

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Outline

- Need for Inertia Monitoring
- Understanding of Inertial Response of Modern Power Grids
- Using Synchrophasors for Real-Time Inertia Monitoring
- Approach and Methods
- Case Studies and Simulation Results
  - > Moving Window Method
  - > System Identification Method (ARMAX)
- Summary
- Q&A, Discussion

Need for Inertia Monitoring

- **Penetration of renewable generation is increasing** – concerns for inadequate inertia
- **Inadequate inertia –** events can lead to high ROCOF, excessive frequency drop, under-frequency load shedding, blackouts
- **Real-Time Inertia Monitoring -** assess risk to grid stability and plan for adequate spinning reserves for secure operation

NERC Recommendations and Guidelines

- **NERC BAL-003-1 Standard** [1] requires sufficient Frequency Response from the Balancing Authority (BA)
- Monitoring of synchronous inertia and frequency deviation recommended by NERC ERSTF as industry best practices [2]
  - > **Measure 1: Synchronous Inertial Response at an Interconnection Level**
  - > **Measure 2: Initial Frequency Deviation Following Largest Contingency**
  - > **Measure 3: Synchronous Inertial Response at BA Level**

[1] NERC Reliability Standard BAL-003-1.1 — Frequency Response and Frequency Bias Setting
https://www.nerc.com/pa/Stand/Reliability%20Standards/BAL-003-1.1.pdf

[2] NERC Essential Reliability Services Task Force (ERSTF) Measures Framework Report, November 2015
https://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERSTF%20Framework%20Report%20-%20Final.pdf

August 9, 2019 UK Blackout – low inertia a contributing factor

ofgem

Making a positive difference
for energy consumers

9 August 2019 power outage report

Publication date:	3 January 2020	**Contact:**	Simon Wilde
		Team:	Systems and Networks
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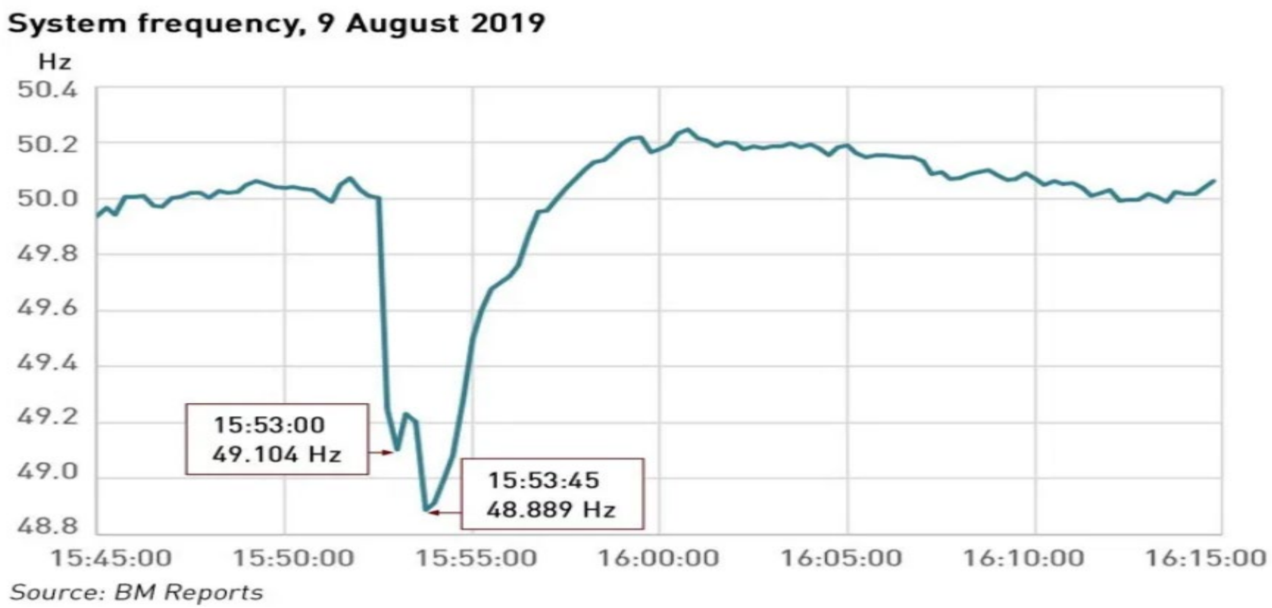
This report sets out the key findings to date, outcomes and next steps from our investigation into the power outage that occurred on 9 August.

In the report we:

- identify the circumstances and causes of the outage;
- set out our assessment of the key issues, and the outcomes of our investigation into certain licensed parties' compliance with their obligations;
- identify the lessons to be learned by the energy sector to improve the resilience of Great Britain's electricity network; and
- recommend actions to implement the lessons learned.

Source: Ofgem 9 August 2019 power outage report

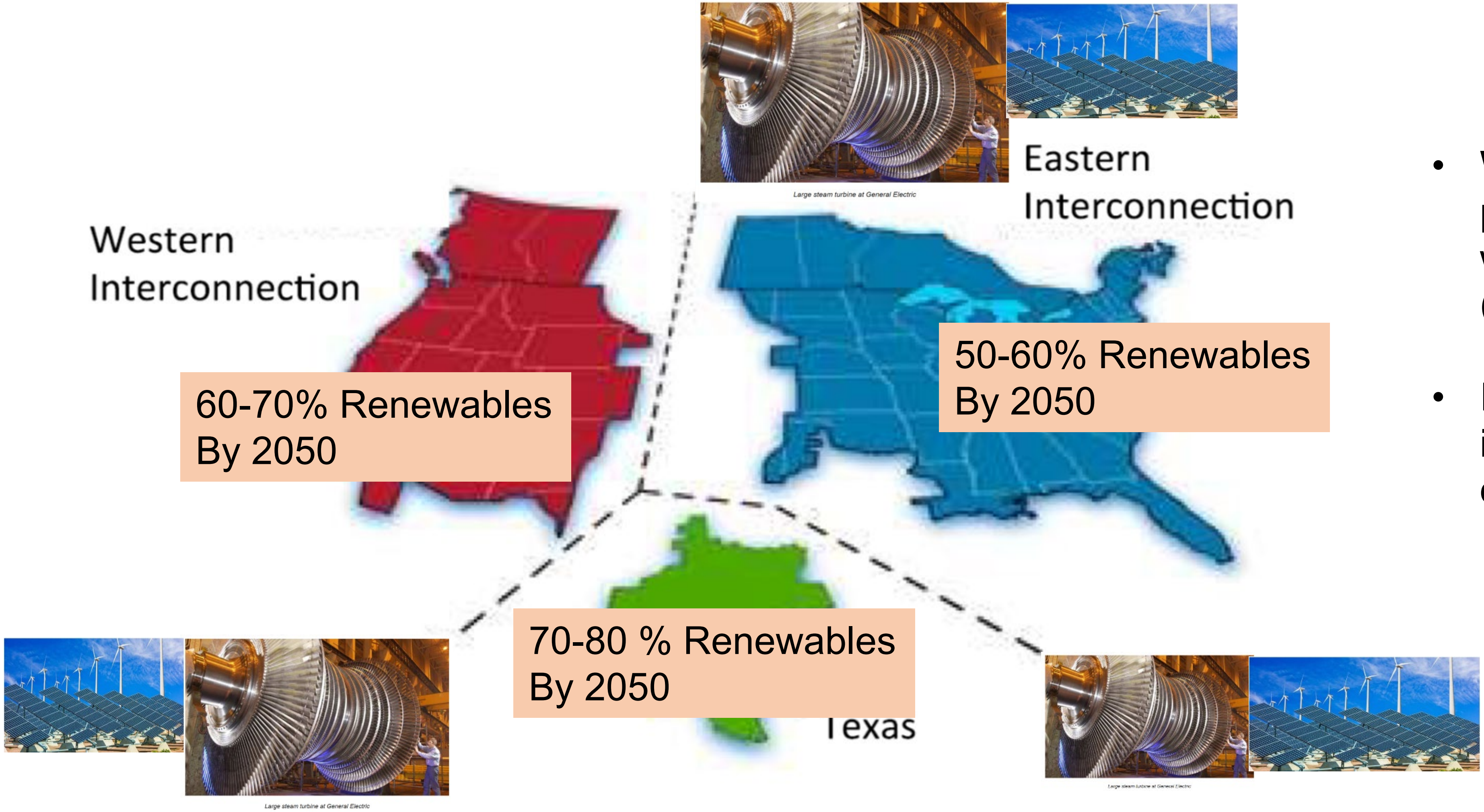
- System Operating with large penetration of Renewables (> 30% Wind)
- Lightning Strike and Fault caused two large generators and large amount of distributed generation to trip
- Frequency Drop (ROCOF) above 125 mHz/sec
- Under-frequency Load Shedding Triggered below 48.8 Hz and affected 1.15 million customers
- Low Inertia and inadequate frequency response was a factor in blackout



Understanding Inertial Response of Modern Power Grids

Background

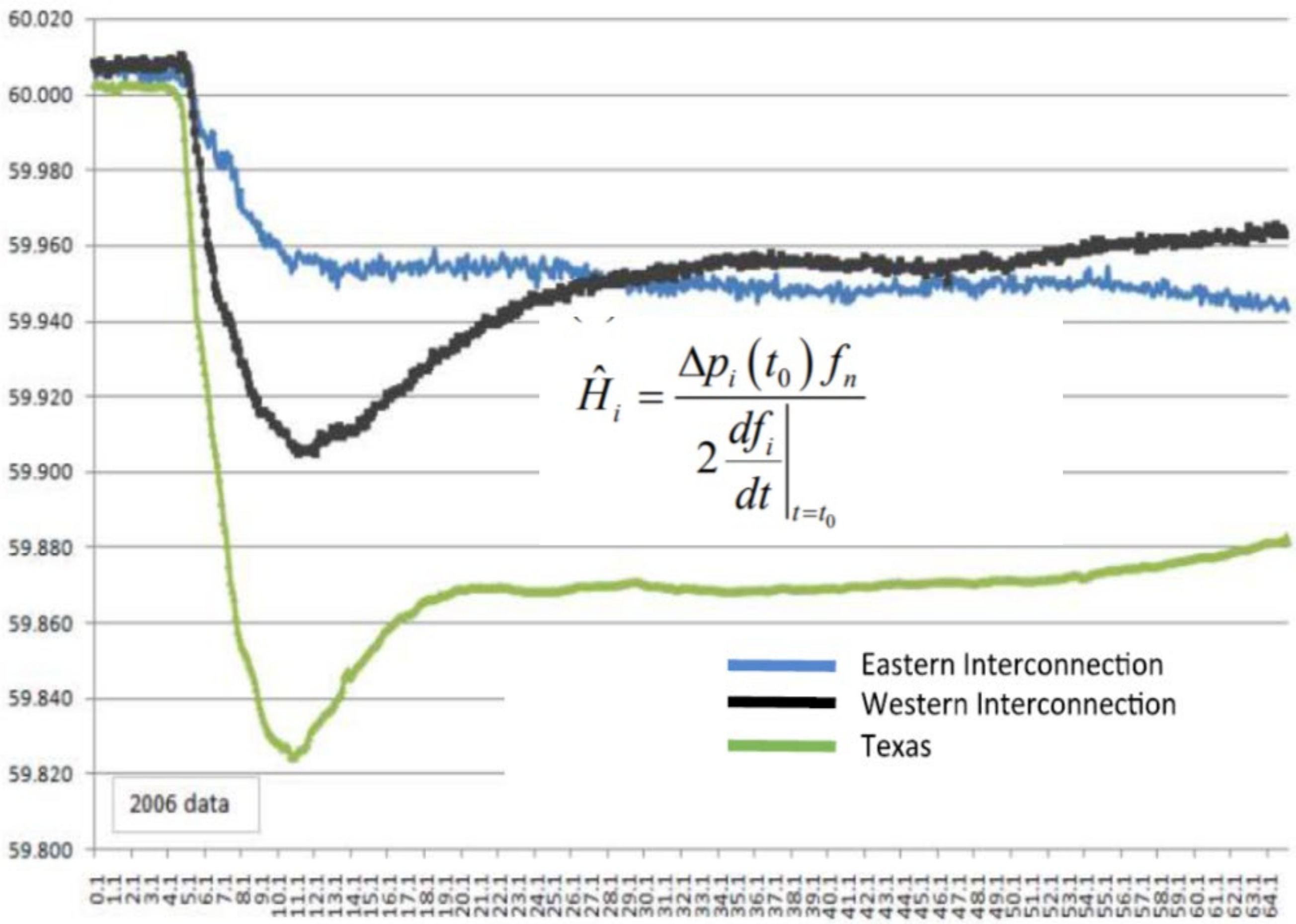
Inertial Support Decreasing in All Interconnections West, East & Texas



- Within each interconnection, penetration of renewables with Inverter Based Systems (IBRs) is growing
- Inertial support within interconnections is decreasing

Reference: NREL 2019 Standard Scenarios Report: A U.S. Electricity Sector Outlook

Inertial Response By Interconnection



$$\hat{H}_i = \frac{\Delta p_i(t_0) f_n}{2 \left. \frac{df_i}{dt} \right|_{t=t_0}}$$

Interconnection	Highest UFLS Trip Frequency (Hz)	NERC Recommended IFRO (MW/0.1 Hz)
Eastern	59.5	-1015
Western	59.5	-858
ERCOT	59.3	-425
Quebec	58.5	-179

Source: NERC Report, 2019 Frequency Response Annual Analysis, November 2019

Impact of Low Inertia on System Response to Events

- **Frequency Drop -** Larger
- **Rate of Change of Frequency (ROCOF)** - Higher
- **Critical Clearing Time (CCT)** – Lower
- **Oscillation Characteristics** – Change

Rate of Change of Frequency (ROCOF) - Higher

60 MW generation loss occurs in a 60 Hz system with 1000 MW generation/load in the steady state

	Case	ROCOF after generation loss*
1	All Synchronous Generation	0.45 Hz/s
2	80% Synchronous Generation and 20% Wind Generation	0.56 Hz/s
3	20% Synchronous Generation and 80% Wind Generation	2.25 Hz/s

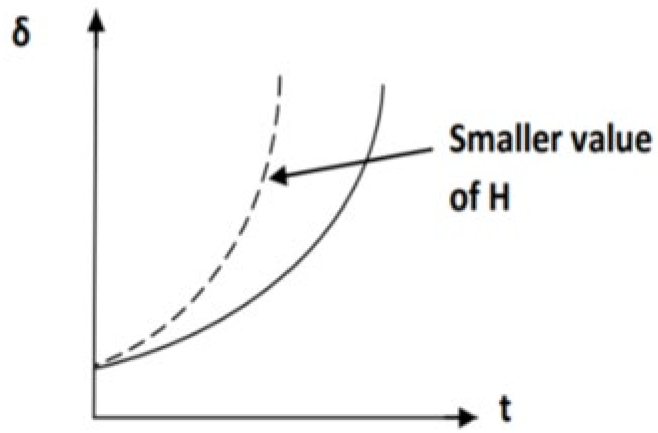
With increase in wind generation and the resultant reduction in system inertia, the frequency drops at a faster rate after a disturbance: Deterioration in Frequency Stability

* Calculation factors:

- Each SG with 100 MVA rating and H = 4 s
- Each WG with 5 MVA rating and H = 0
- Case 1: 10 SGs, 0 WGs
- Case 2: 8 SGs, 40 WGs
- Case 3: 2 SGs, 160 WGs
- $\frac{df}{dt} = \Delta P \frac{f}{2(n_{SG}S_{SG}H_{SG}+n_{WG}S_{WG}H_{WG})}$

Critical Clearing Time (CCT) - Lower

Lower Critical Clearing Time Reduces Transient Stability of synchronously connected grid



$$t_c = \sqrt{\frac{2H(\delta_c - \delta_0)}{\pi f P_{max} \sin \delta_0}}$$

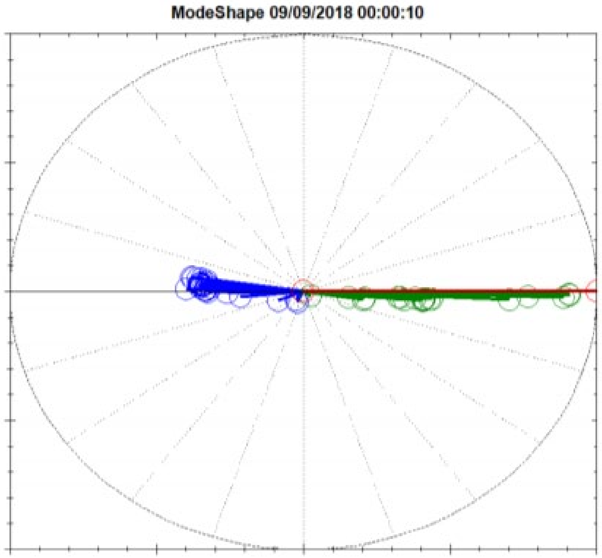
$$\Delta\delta_{(n)} = \Delta\delta_{(n-1)} + \frac{P_{a(n-1)}}{M} (\Delta t)^2$$

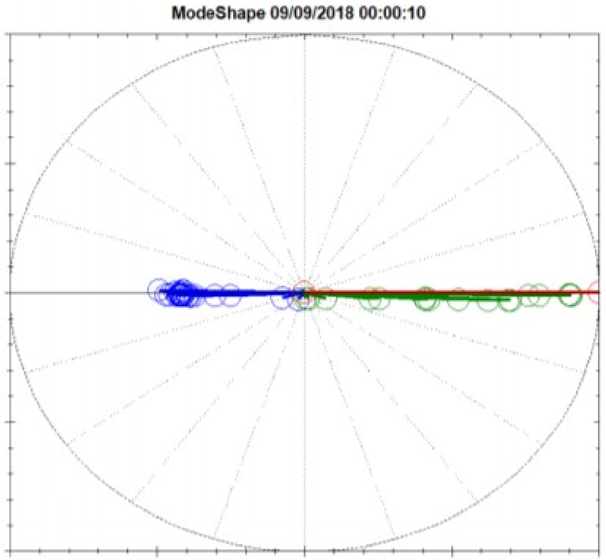
$$M(pu) = \frac{H}{\pi f} \ s^2/\text{elect rad}$$

Oscillation Characteristics - Change

- Change in Inter-area mode characteristics – Frequency, Damping

	Base Case Simulation (204.8 GVA*s)			Lower Inertia Simulation (191.5 GVA*s)		
	Frequency (Hz)	Damping Ratio (%)	Relative Energy (%)	Frequency (Hz)	Damping Ratio (%)	Relative Energy (%)
Mode 1	0.72	9.21	100	0.79	7.15	100





Source: NERC Report, Interconnection Oscillation Analysis, July 2019

Current Practices for Inertia Calculation

- Estimate Inertia based on information from EMS/SCADA
- Use of Generator breaker status information to include/exclude the Inertia of each machine based on the design value
- Does not accurately consider the impact of embedded generations (Wind, Solar, Battery backup etc.,) and other rotating devices (loads)
- Assumes linear relationship between system inertia and demand variation

Real-Time Inertia Monitoring Using Synchrophasors

Inertia Monitoring

- Inertia is Time Varying – Varies with topology, resource mix
- Inverter-based resources such as solar PV, Batteries provide no inertia
- Wind asynchronously connected – Provides no inertia
- Individual Generator Inertia and System Inertia are different
- Inertia calculation is used to Estimate Rotational Kinetic Energy Reserve to predict system response to events
- To determine system inertia High-speed time-synchronized data is required

Individual Machine Inertia

$$\hat{H}_i = \frac{\Delta p_i(t_0) f_n}{2 \left.\frac{df_i}{dt}\right|_{t=t_0}}$$

Total Area/System Inertia

$$H_{tot} = \frac{\sum_{i=1}^{N} H_i S_{B_i}}{\sum_{i=1}^{N} S_{B_i}}$$

Rotational Kinetic Energy (KE) Reserve

KE = G x H, where G= System rating in MVA,
H = Inertia constant in second(s)

Benefits of using Synchrophasor Measurements

- Provides time-synchronized measurements over a wide area of the grid
- Provides high-resolution data for real time monitoring of dynamic conditions
- Rate of change of frequency (part of the synchrophasor protocol) is directly available to evaluate the inertial response
- Time synchronized phase angles readily available for the online estimation of inertia constant

Approach

- Real time estimation of area wise inertia constant using wide area synchrophasor measurements.
- Evaluate Total inertia constant using the individual area inertia constant.
- Determine Area wise rotational kinetic energy reserve.
- Estimate Total rotational kinetic energy reserve.
- Real time visual display of the inertial response summary
  - which includes various parameters to assist the operators to have better inertial situational awareness by estimating total / area wise rotational kinetic energy reserve along with other metrics such as voltage, frequency etc.

Real Time Inertia Monitoring - Methods

- Moving Window Method
  > Uses disturbance measurement data

  > Based on swing equation

- System Identification Method
  > Uses ambient measurement data

  > Based on System Identification using ARMAX technique

Moving Window Method

Moving Window Method - Estimation of Generator Inertia

The dynamic swing equation defines the inertial response of a rotating machine or a group of machines to a power system disturbance.

$$2\frac{H}{f_n}\frac{df}{dt} = P_m - P_e = \Delta P$$

Estimate the inertia constant of a generator:

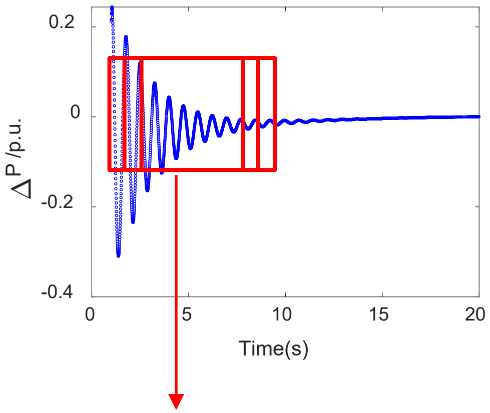
$$H = \frac{\Delta P f_n}{2\frac{df}{dt}}$$

The total inertia constant of the power system can be given by:

$$H_{tot} = \frac{\sum_{i=1}^{N} H_i S_{B_i}}{\sum_{i=1}^{N} S_{B_i}}$$

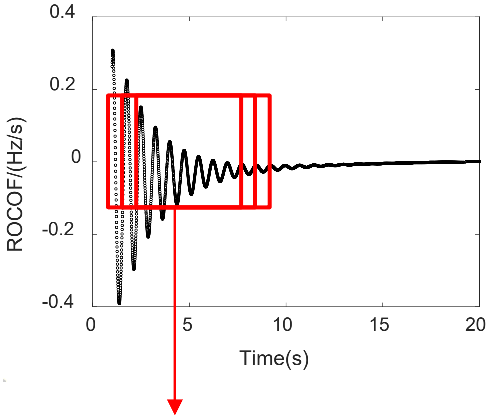
Moving Window Method – Time Window

Change of active power (ΔP)



Average value within the selected time window

Rate of Change of Frequency (RoCoF)



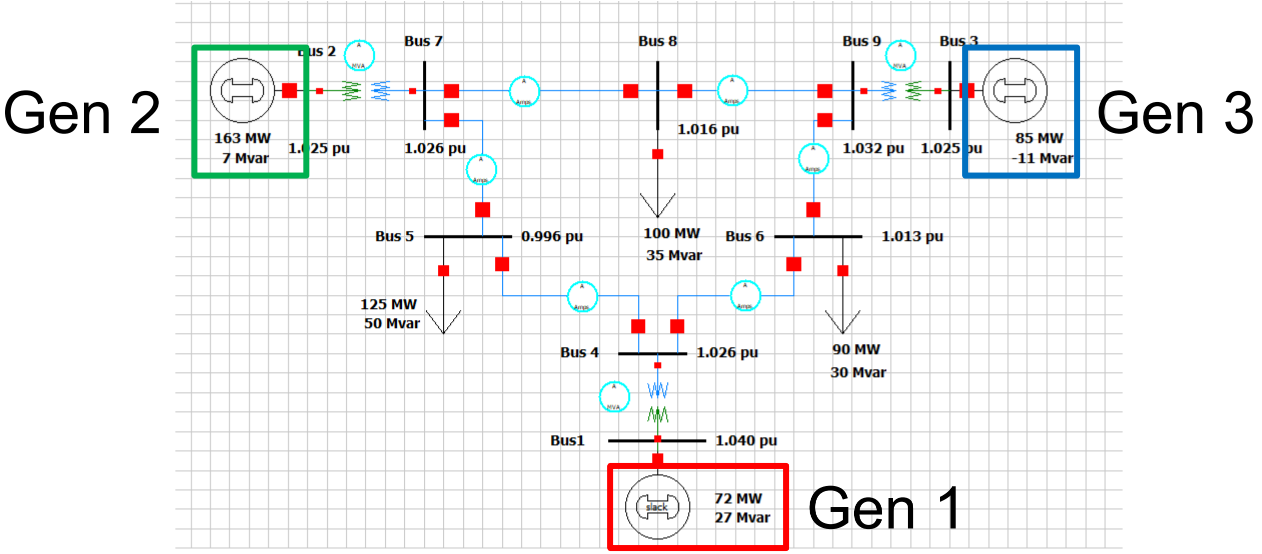
Average value within the selected time window

Define a time window length T, for the data points of ΔP and RoCoF within T, calculate the average values of ΔP and RoCoF, remarked by ΔP_{ave} and $[\frac{df}{dt}]_{ave}$, respectively. Then estimating the generator inertia as:

$$H = \frac{\Delta P_{ave} f_n}{2[\frac{df}{dt}]_{ave}}$$

Case Study

System: WSCC 3-machine, 9-bus
Model: GENROU; Governor models (TGOV1) are disabled.
Disturbance: Load on bus 5 is tripped at 0.7s and recovered at 1s, simulation step size: 0.005 seconds (200 samples/second)

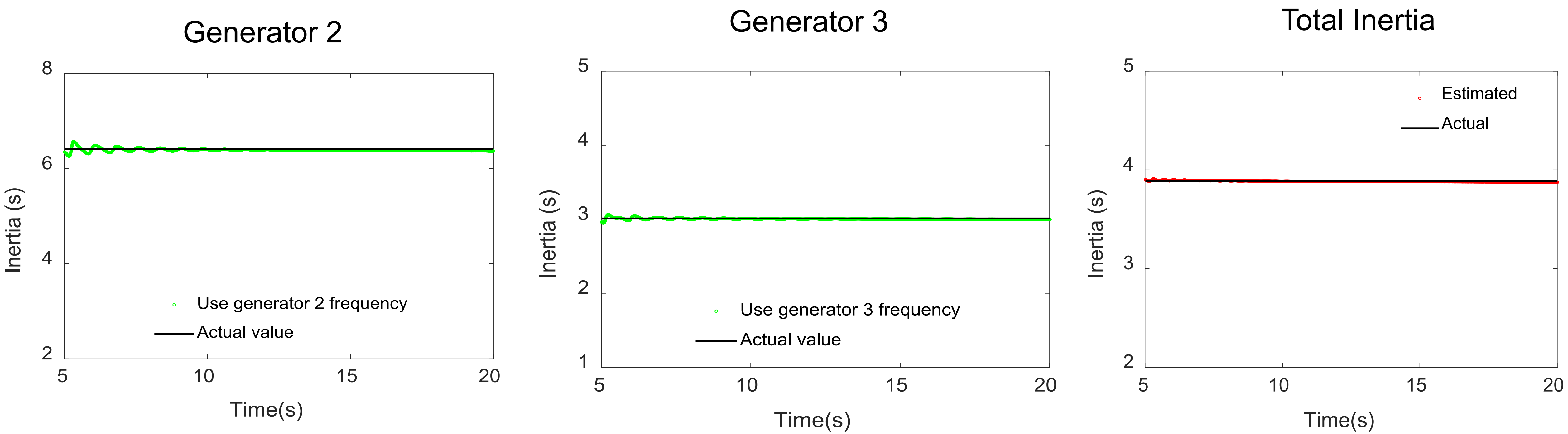


Actual Values

Generator Number	Inertia Constant (s)
Generator 1	23.64
Generator 2	6.41
Generator 3	3.01

Note: the inertia value of generator is converted into the system base (100MVA)

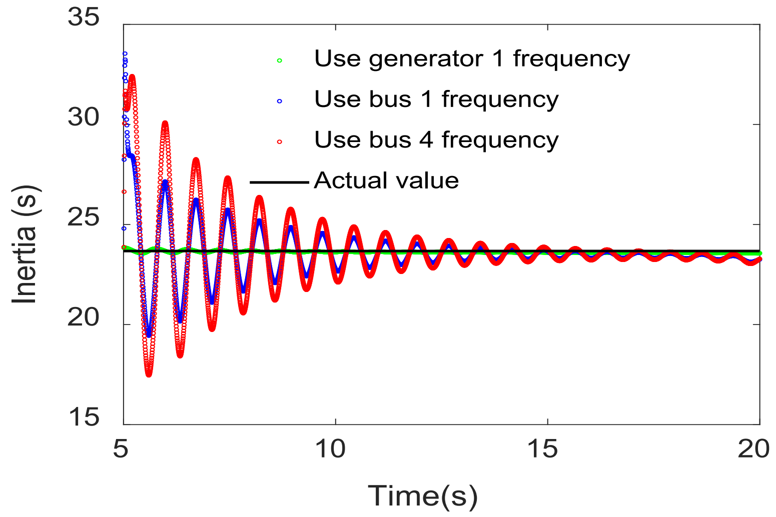
Estimated Inertia for Other Generators and Total Inertia



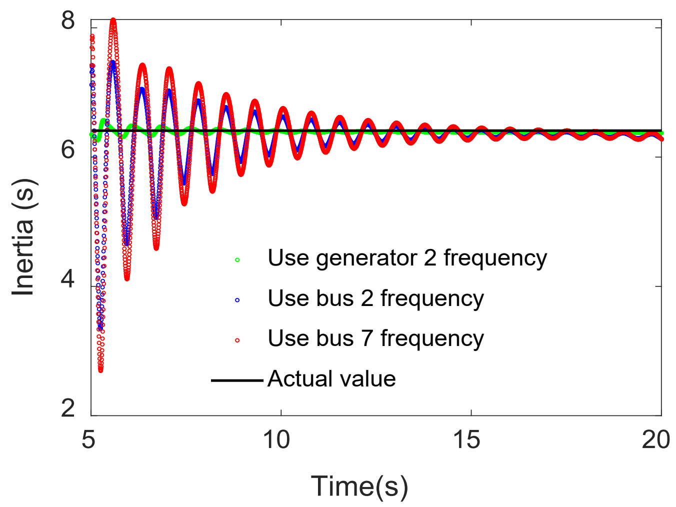
Observation: The moving window approach shows good performance for estimating generator inertia since match between estimated and actual values is good

Comparison of Estimated Inertia Using Different Frequency Signals

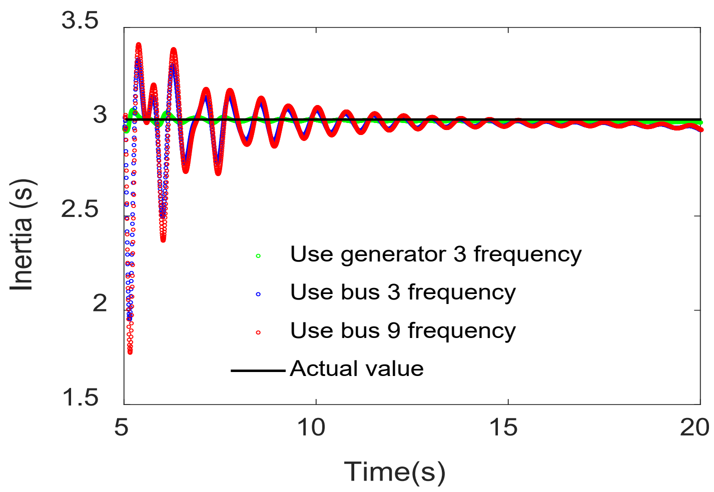
Take generator 1 as the example, the frequency of generator 1 and the frequencies obtained from buses 1 and 4 are used independently to estimate the inertia value. Bus 1 is closer to generator 1 when compared with bus 4.



Generator 1



Generator 2



Generator 3

Observation: We can see that moving window approach shows good performance for estimating generator inertia when we compare those green dots with the black line. And the closer the bus frequency used for estimation, the smaller the estimated error for generator inertia.

Key Considerations

- Measurements near generator locations
- Accurate detection of the event (start of the disturbance) with proper data conditioning
- Impact of Data Quality
- The selection of the window size for calculation which may vary for different events

System Identification Method

System Identification Method

For a single generator *i*, the swing equation is

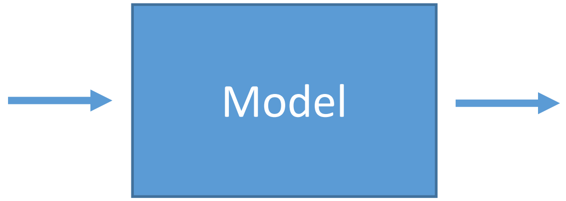
$$\frac{\mathrm{d}f_i}{\mathrm{d}t} = \frac{P_{iM} - P_{iE}}{2H_i S_{in}} f_n$$

For an area *j,* an equivalent equation is

$$\frac{\mathrm{d}f_j}{\mathrm{d}t} = \frac{P_{jM} - P_{jE}}{M_j} = \Delta P_j / M_j$$

M_j is the effective inertia

Input: ambient load variations



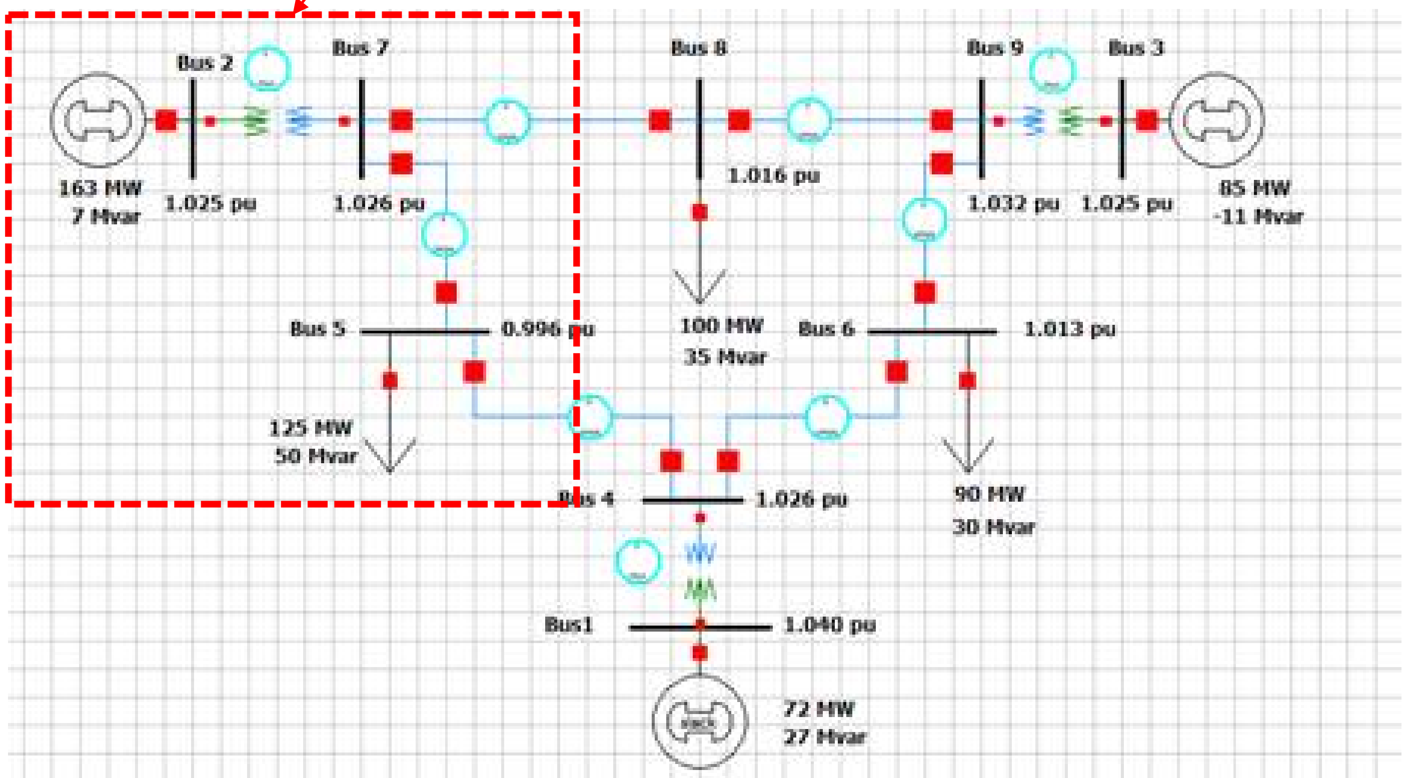
Output: frequency deviations

The identified model characterizes the dynamics between load changes and resulting frequency deviations. The effective inertia M_j can be extracted from the identified models [3].

[3] K. Tuttelberg, et al, "Estimation of power system inertia from ambient wide area measurements", *IEEE Trans. Power System*, vol. 33. no. 6, pp. 7249-7257, Nov. 2018.

Case Study on WSCC System

Study area---the inertia of generator 2 needs to be estimated.



Load variation: Random small load variation on load bus 5 every second

Input: Approximate load variation of the study area

Output: The average frequency deviation from buses (2, 5, and 7)

- Enable all the governors and exciters
- Simulation length is 90s

Results for System Identification Method

- System identification was applied so that ARMAX models of orders 9 to 28 were identified, i.e., 20 models with different model orders.
- Average value for different orders of models is taken as the effective inertia.

Theoretical value of the effective inertia is calculated as: $M_i = 2H_i S_{in} / f_n$

Effective Inertia	Unit (MWs^2)
Theoretical Value	53.41
Estimated Value	59.96

Converting the unit to *s* in the generator MVA base

Inertia	Unit (s)
Theoretical Value	6.41
Estimated Value	7.19

Conclusions and Summary

Conclusions

- Monitoring Real-Time Inertia allows operators to have situational awareness of the frequency response along with the rotational inertial reserve
- Allows operators to plan better generation dispatch
- Total kinetic energy reserve available will help better forecast of minimum reserve necessary for stable operation of the grid
- Helps in re-evaluating the interconnection frequency response obligation (IFRO) factor – NERC term

Summary

- Inertia constant
  - > Affects frequency drop and frequency response (ROCOF)
  - > Varies with Time – Variable Generation due to renewables
  - > Affects Grid Stability – Critical Clearing Time, Natural system modes
- Real time estimation of inertia constant benefits operators to plan better generation dispatch and use of spinning reserve, planners to validate their models, and protection engineers to re-evaluate their ROCOF, and UF/OF settings
- Synchrophasors data is suitable for real-time measurement of inertia of the power system, which includes the contributions from embedded generations and loads connected to the grid

Q&A, Discussion

- Q&A
  - > Suggestions/Comments

For detailed discussion and more information, please contact: narendra@ElectricPowerGroup.com

Thank you for participating!

If you have any questions regarding any part of the webinar, please contact us at Contact@electricpowergroup.com

http://electricpowergroup.com

Thank you!

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