MANAGING GRID STABILITY IN LOW-INERTIA ENVIRONMENTS: PRACTICAL APPROACHES USING REAL-TIME PMU MEASUREMENTS

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Electric Power Group

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EPG INTRODUCTION

- ***Founding:*** Motivation came from 1996 WECC Blackout – Founder was a Senior Executive at SCE who led investigation of Blackout
- ***Mission***: Provide industry leading applications to prevent blackouts by monitoring real time grid dynamics including WAMS, Oscillations, Phase Angles using time synchronized high-speed Synchrophasor data from PMUs
- ***Company***: Established in 2000 – HQ in Pasadena, CA, USA
- ***Team***: Experienced and internationally acknowledged industry experts in phasor technology
- ***Solutions Portfolio***: Most comprehensive portfolio of WAMS and Advanced Applications for Real-time and Off-line Analytics including Oscillations, Inertia, System Strength, LSE, RTCA
- ***Deployments***: Leader in large-scale WAMS deployments at more than 40 Grid Operators and Transmission Utilities Globally

AGENDA

- **Introduction**
- **Low Inertia Environments**
  - Frequency Response
  - Is Inertia a local or a global phenomena ?
- **Major Blackout Events Due to Low Inertia**
- **Real Time Inertia Measurements Using PMUs**
- **Utilization of FFR for Low Inertia Mitigation**
- **Conclusions**
- **Q&A**

INTRODUCTION

OVER VIEW & CONTEXT, LOW INERTIA REGIONS & FREQUENCY RESPONSE

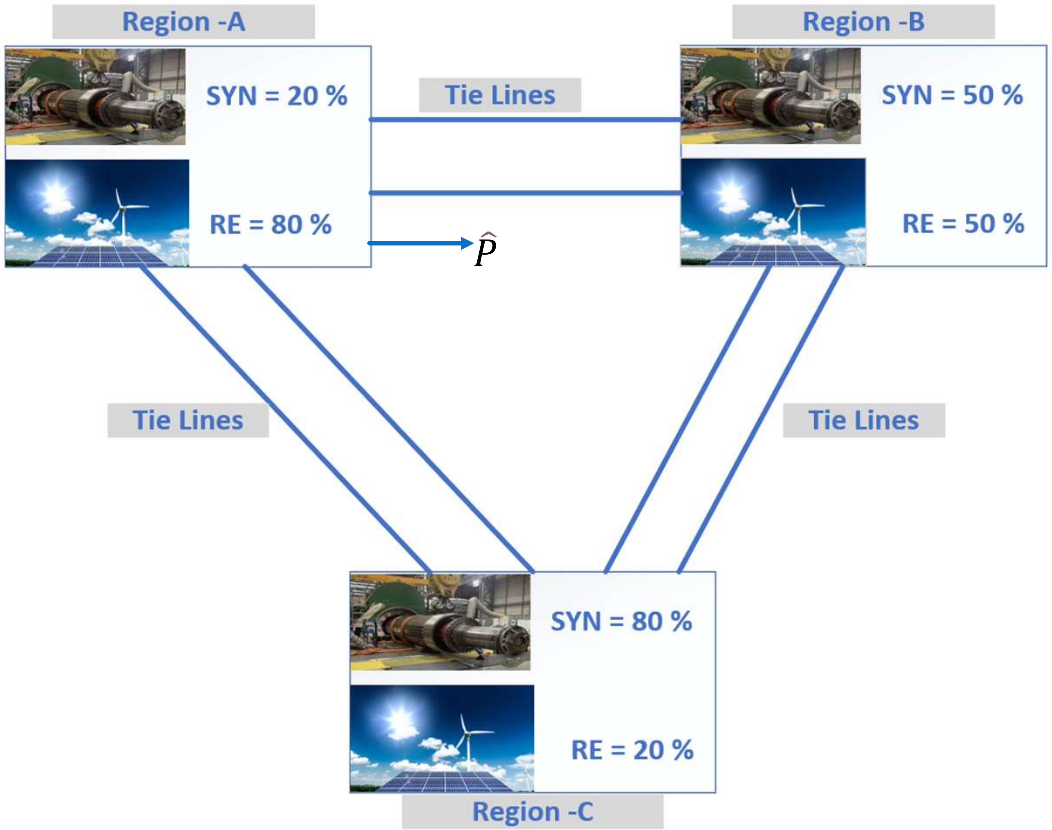
OVERVIEW & CONTEXT

Why Real Time Inertia Measurement Matters?

- **Inertia is the First Line of Defense**
  - Instantaneous stability depends on the kinetic energy from synchronous machines
- **Grids Are Losing Natural Inertia**
  - Displacing synchronous units with IBRs reduces system resilience
- **Not All Inertia Is Equal**
  - Operators must distinguish local weak zones from global averages
- **Frequency Stability Needs Real-Time Insight**
  - ROCOF is local — and must be monitored regionally, not just system-wide
- **Global Shift Toward Regional Inertia Mandates**
  - Utilities worldwide are enforcing minimum inertia and ROCOF thresholds
- **Dispatch Without Inertia Visibility is a Risk**
  - Economic decisions must factor in inertia to avoid operational surprises
- **Operators Need Actionable Tools**
  - PMU-based, real-time estimation is essential for tracking, alarming, and responding to low inertia conditions

Key Message:
"Frequency Stability in Modern Grid = ***Low Inertia Awareness in Real Time"***

INERTIA PHENOMENA IS BOTH LOCAL AND GLOBAL IN NATURE



Power Impact= $\hat{P}$

Common Rotor Angle = $\Delta\partial$ → All Sync M/C

$\hat{P} = \Delta P1 + \Delta P2 .... \Delta Pn$

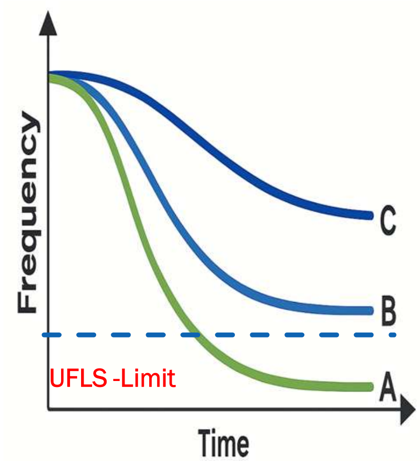
$\Delta P_j = Ps_j * \Delta\partial$

$$\Delta P_j = \frac{Ps_j}{\sum Ps}\hat{P}$$

$$P_j = \frac{KE_j}{\sum KE}\hat{P}$$

$$\partial_j = \frac{KE_j}{\sum KE}\frac{\hat{P}}{Ps_j}$$

$\partial_j > \Delta\partial$ or $\partial_j < \Delta\partial$



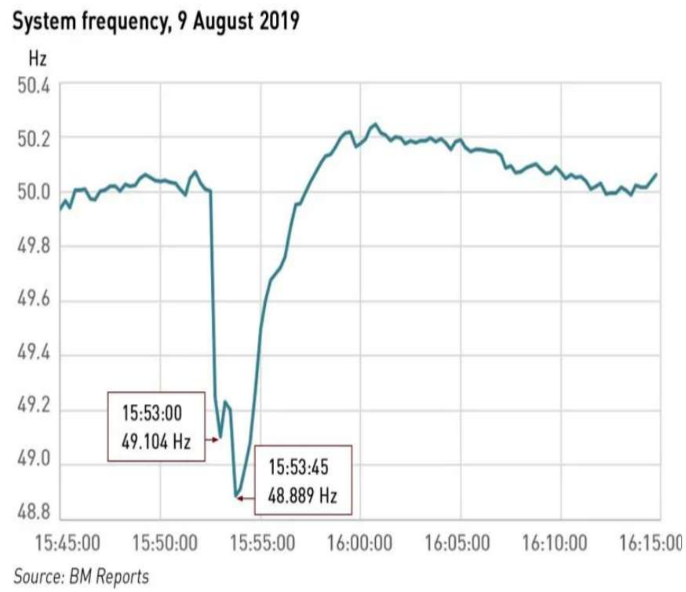
$$\mathrm{ROCOF} = \frac{df}{dt} = \frac{f_0}{2H}\cdot\Delta P$$

MAJOR BLACKOUT EVENTS - LOW INERTIA A CONTRIBUTING FACTOR

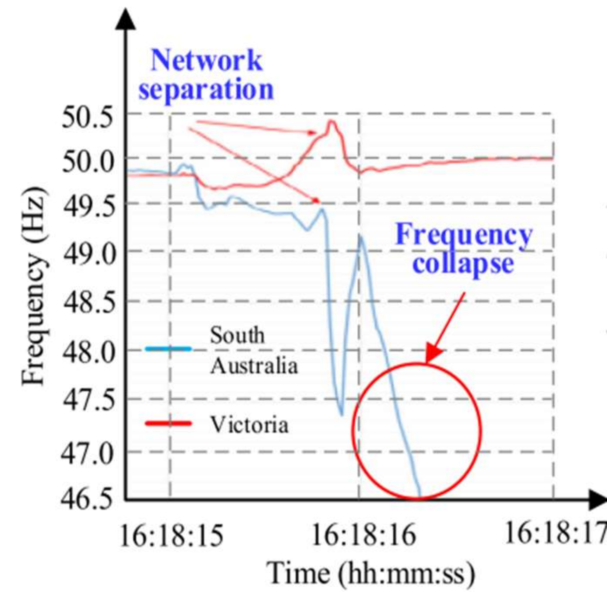
BLACK OUTS : SPAIN, UK , & AUSTRALIA

MAJOR BLACKOUT: LOW INERTIA CONTRIBUTING FACTOR

Spain - 2025



UK - 2019



Australia - 2016

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KEY TAKEAWAYS FROM THE BLACKOUTS

- Inertial response starts locally, driven by synchronizing power and kinetic energy in each region
- It evolves into a global response across the interconnected grid
- ROCOF is a local phenomenon and varies by region based on local inertia
- Maintaining healthy local ROCOF is critical to avoid false trips and instability
- Operators need real-time visibility of inertia both regionally and system-wide
- Frequency stability cannot rely solely on global inertia—localized inertia monitoring is essential
- PMUs provide time-synchronized, high-resolution frequency and active power data suitable for real time Inertia monitoring

EPG's REAL TIME INERTIA ESTIMATION USING PMUs

OVERVIEW , CAPABILITIES, PMU LOCATION, VALIDATION, MANAGING LOW INERTIA ALARMS

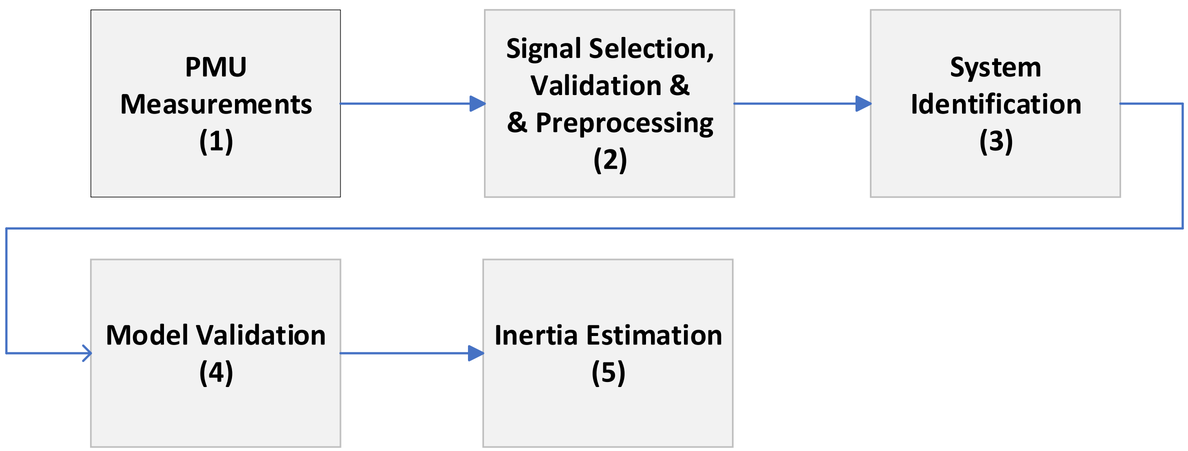
EPG'S INERTIA MONITORING SOLUTION OVERVIEW

- **Centralized Software Based Solution –** Inertia is estimated from wide-area PMU data aggregated into a single software platform
- **Leverage Existing PMUs** – Solution with Existing PMUs deployed in your grid
- **Field Measurement Devices** – Not Required
- **Scalable** - Software Based Solution
- **Flexible** – Handles Changes in Resource Mix and Topology without need for Additional PMUs
- **Additional PMUs** – Enhance Better Inertial Situational Awareness
- **Operational Intelligence** – Visualization of Real Time Inertia Estimation by Region / Specific Bus location
- **Operating Procedures** – Guidelines for operator action and user defined logic based operating guidelines
- **Deployed at** – Electra Net (Australia), TPC (Taiwan), OETC (Oman), IESO (Canada), ERCOT (USA – deployment is in progress)

PMU LOCATIONS FOR INERTIA ESTIMATION

Location Type	PMU Objective
Synchronous Generation Areas	Capture actual frequency and phase angle response from inertia-rich synchronous units
IBR-Dominant Regions	Detect rapid frequency drop, validate synthetic inertia/FFR injection
Load Centers	Assess load-side frequency sensitivity, support UFLS scheme design
Tie-Line and Inter-Zone Buses	Observe inter-area oscillations and power exchange (synchronizing power / torque behavior)
Isolated or Weak Grids	Monitor local inertial response, improve situational awareness in islanded areas

REAL TIME SYSTEM INERTIA IMPLEMENTATION & DATA FLOW



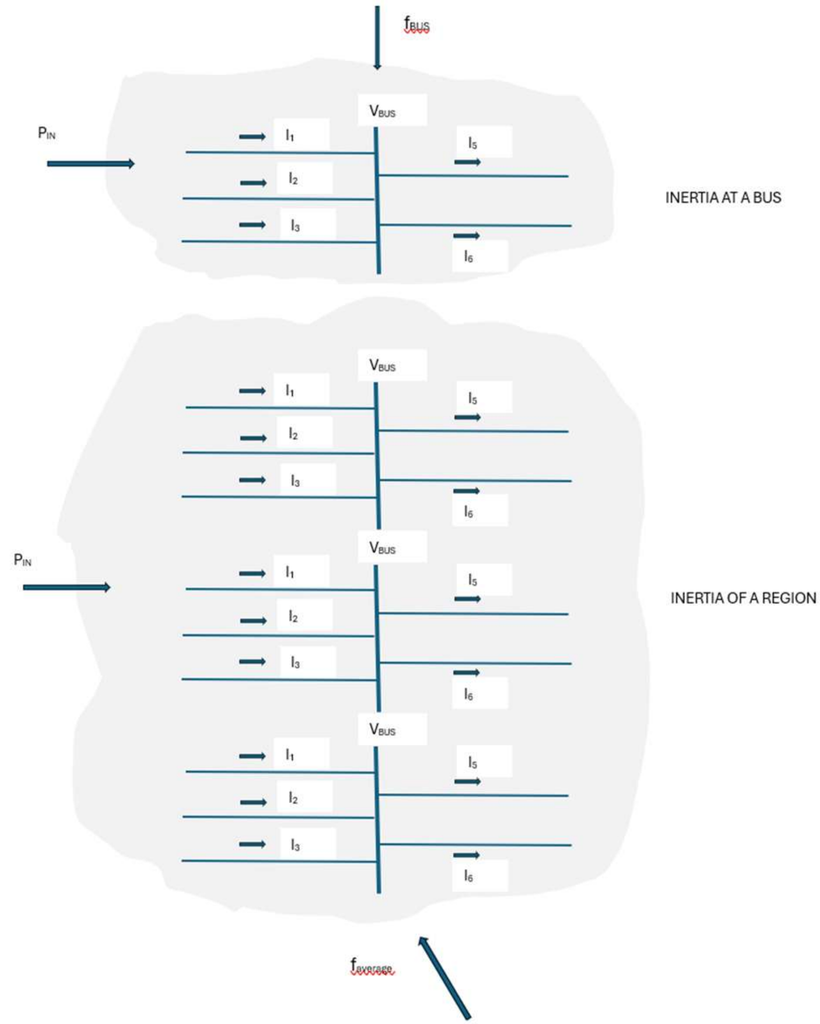
1. Acquire data (V,I) from PMUs

2. Estimate Active Power and Bus Frequency (or Area Frequency), and Convert the signals to Per Unit, Detrend, apply Low-pass Filter etc.

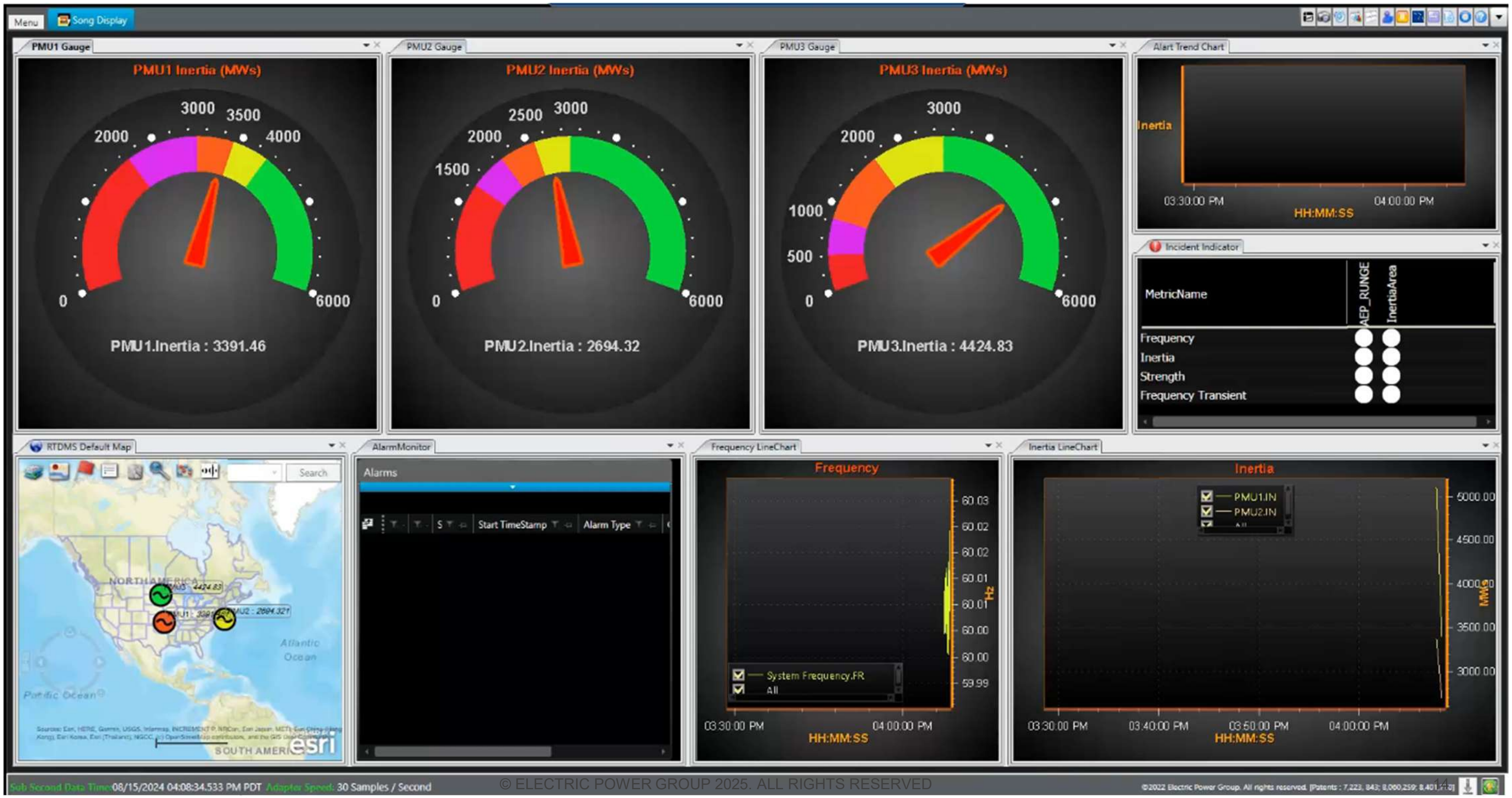
3. N4SID algorithm , and State Space Model $H \propto \frac{1}{2*ROCOF}$

4. Validate Order of the Identified Model and check for accuracy

5. Evaluate System Inertia



REAL TIME INERTIA PROFILE DASHBOARD

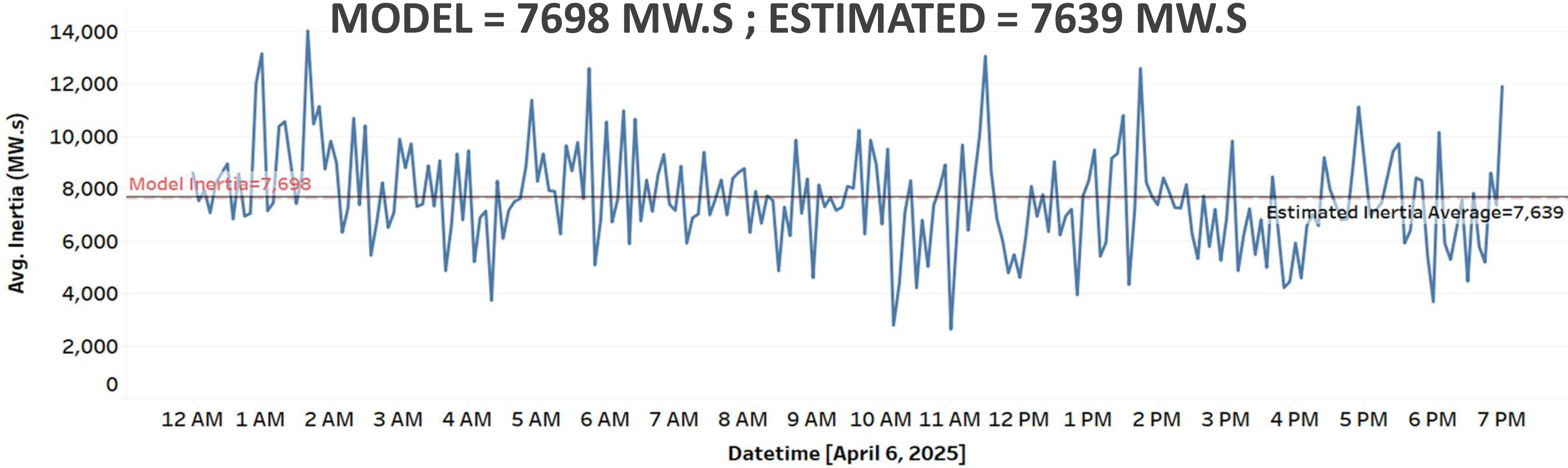


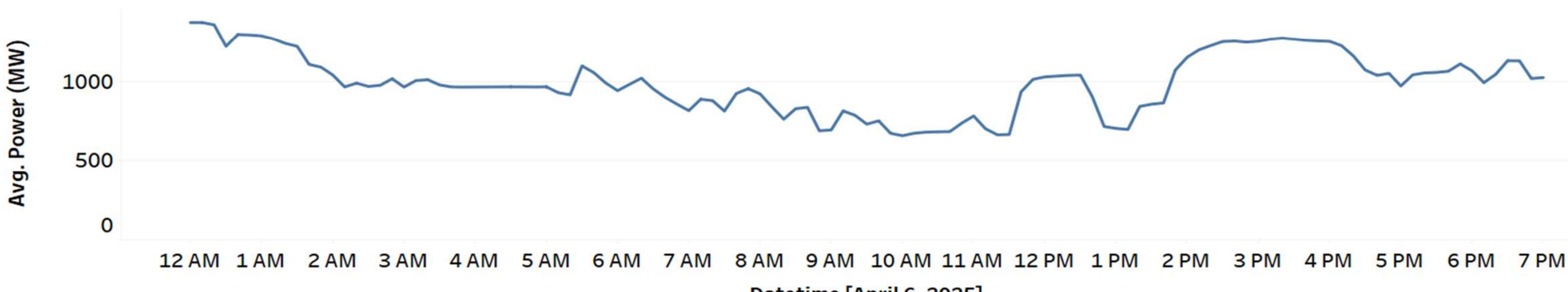
INERTIA VALIDATION PROCEDURE USING EPG's TOOL

- **Step 1: Validate at Synchronous Generator Buses**
  - Use PMUs at high-side terminals of major synchronous machines to estimate local inertia based on measured active power and frequency response
- **Step 2: Assess Multiple Synchronous-Rich Areas**
  - Compare inertia measurements across different synchronous zones to identify localized strengths and weaknesses
- **Step 3: Monitor PCCs (Ponit of Common Coupling) of Large Renewable Injection**
  - Use PMUs at renewable hubs (>100 MW) to detect low-inertia signatures and observe high ROCOF behavior in real time
- **Step 4: Analyze Tie-Line ROCOF and Inertia Transfer**
  - Use tie-line PMUs to assess how inertia varies across regions and how disturbances propagate spatially.
- **Step 5: Evaluate Inertia Impact at Critical Loads**
  - Monitor ROCOF near sensitive infrastructure (e.g., data centers) to ensure frequency resilience and event survivability
- **Step 6: Generate System-Wide Inertia View**
  - Aggregate all PMU data and compute global inertia, enabling system-wide stability awareness

UTILITY 1- REAL TIME INERTIA FIELD VALIDATION – GENERATION BUS

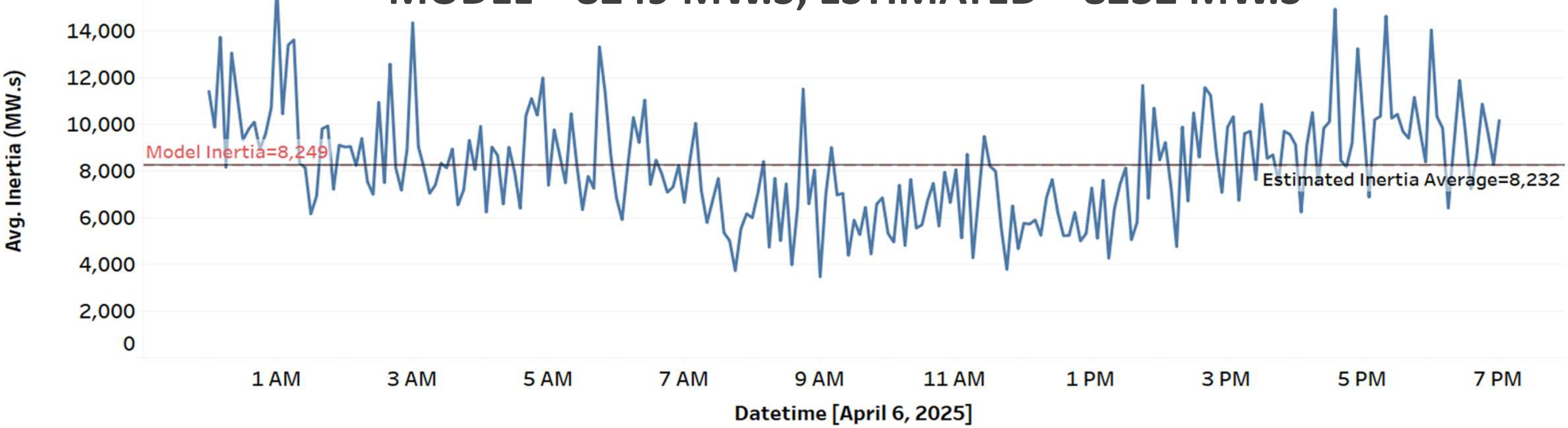
MODEL = 7698 MW.S ; ESTIMATED = 7639 MW.S

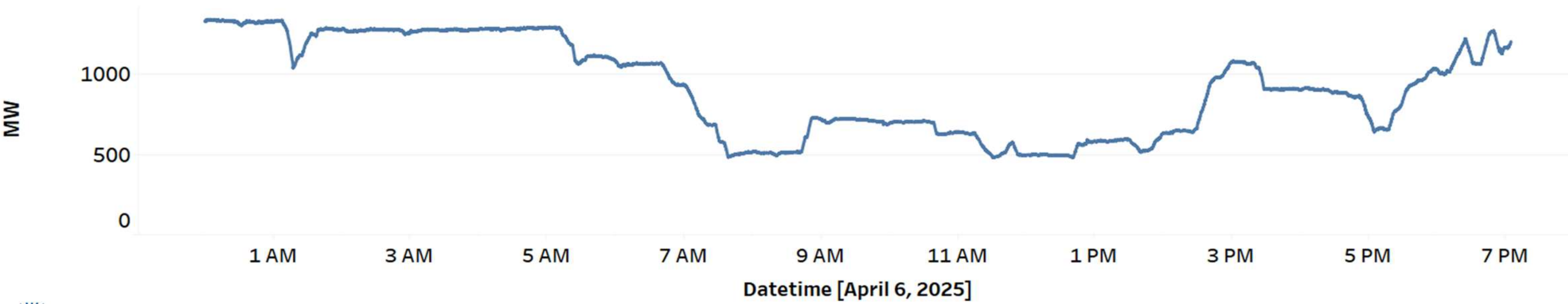




UTILITY 2- REAL TIME INERTIA FIELD VALIDATION – GENERATION BUS

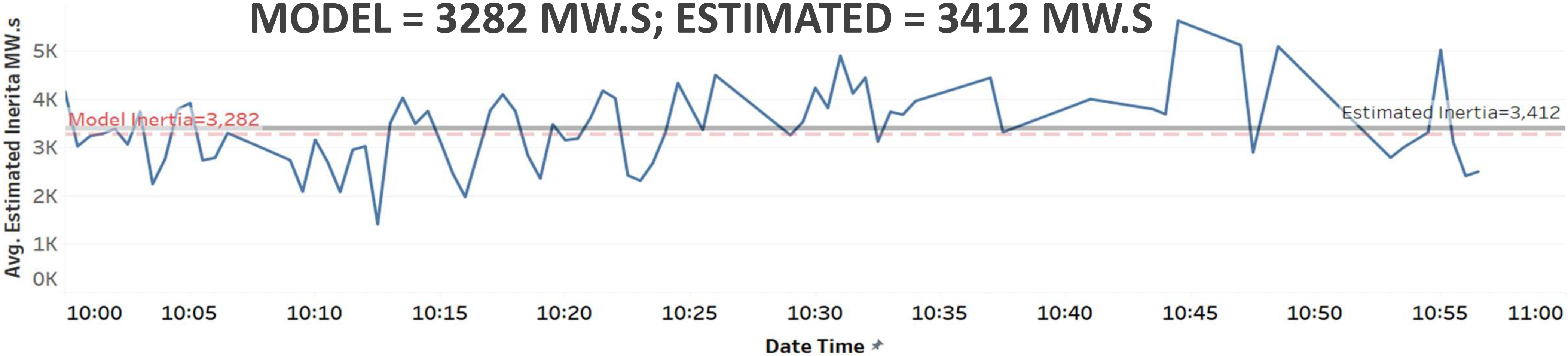
MODEL = 8249 MW.S; ESTIMATED = 8232 MW.S

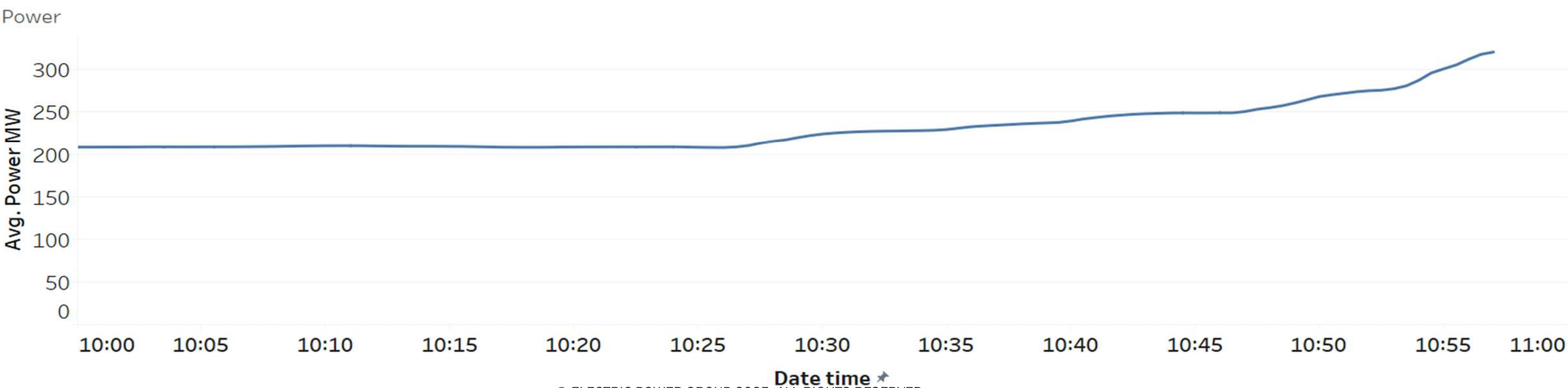




UTILITY 3- REAL TIME INERTIA FIELD VALIDATION – GENERATION BUS

MODEL = 3282 MW.S; ESTIMATED = 3412 MW.S





RESPONDING TO LOW INERTIA ALARMS FROM EPG'S TOOLS

- **Step 1 : Confirm the Alarm**
  - Identify region, timestamp, and alarm level (Threshold-1 or Threshold-2)
  - Verify PMU data quality and Inertia Tool's measurement integrity
- **Step 2: Assess Real Time Conditions**
  - Monitor frequency, ROCOF, and generation mix (Synchronous vs. IBR)
  - Check AGC status, major tie-line flows, and contingency exposure
- **Step 3: Evaluate FFR / Synthetic Inertia Readiness**
  - Identify available FFR/BESS/Grid-forming inverters
  - Confirm FFR settings and recent activation records

OPERATOR ACTIONS AND COORDINATION

- **Step 4 : Preventive Operator Action**
  - Increase commitment of synchronous generators
  - Re-dispatch generation to increase online kinetic energy
  - Coordinate with adjacent regions if system risk is regional
- **Step 5 : Validation & Logging**
  - Log alarm event; validate Inertia Estimate to confirm the inertia reduction
  - Record FFR impact and validate performance for compliance/audits
- **Step 6 : Use Inertia Trends for Situational Awareness**
  - Track hourly/daily inertia to identify vulnerable periods
  - Alert operators during low-demand/high-IBR windows

UTILIZATION OF FFR TO MITIGATE LOW SYSTEM INERTIA

FFR DEVICES & OPERATOR STRATEGY

BENEFITS OF REAL TIME PMU MEASUREMENTS AT FFR LOCATION

- **Confirm Actual FFR Power Injection**
  - PMUs provide high-speed (30–60 Hz) power & frequency data
  - Validates whether FFR delivered the right magnitude power and timing.
- **Assess Response Timing and Duration**
  - Tracks key FFR metrics: **onset time, hold period, and ramp down.**
  - Evaluates ability to arrest ROCOF and stabilize frequency
- **Differentiate Inertial vs. FFR Response**
  - PMUs help separate natural inertia (first 0.5s) from FFR-triggered control
  - Crucial for event attribution and performance tuning
- **Enhance Planning and System Studies**
  - Real event validation feeds model tuning and system reliability assessments
  - Refines FFR deployment strategies
- **Prove Grid Code Compliance**
  - Confirms FFR meets activation time, MW delivery, and response windows
  - Fulfills regulatory and performance obligations

OPERATOR STRATEGY FOR MITIGATING LOW INERTIA USING FFR DEVICES

Region Type	Typical IBR Share	FFR Devices	Operator Strategy
High-IBR Regions (Wind/Solar >70%)	Very High	BESS, Grid-Forming Inverters, Wind (Synthetic Inertia)	Deploy fast-acting FFR (BESS), validate timing, ensure coordination with sync zones
Wind-Dominant Areas	Moderate to High	Wind Turbines with Synthetic Inertia, Synchronous Condensers	Use wind torque injection + sync condensers to buffer ROCOF and support local voltage
Weak Grid or Low Inertia Zones	Low–Moderate Sync	Synchronous Condensers, Grid-Forming Inverters	Validate inertia floor, deploy inertia-like support for UFLS avoidance
Urban/Critical Load Centers	Varies	Responsive Industrial Loads, BESS	Leverage load curtailment or fast injection to protect sensitive infrastructure
Cross-Border / Intertie Corridors	Regional	HVDC with FFR Mode	Use HVDC for inertia-like power flow response and coordinated multi-area frequency control

CONCLUSIONS

KEY TAKEAWAYS ON EPG's LOW INERTIA SOLUTIONS

KEY TAKEAWAYS ON EPG's LOW INERTIA SOLUTION

- **Real-Time Inertia Awareness** is critical for grid stability in high-renewable, low-inertia environments

- **No New Hardware Needed** – EPG's software uses existing PMUs for fast, scalable deployment

- **Regional Insights Matter** – Inertia and ROCOF vary locally; visibility at bus, region, and system levels helps prevent false trips and blackouts

- **Actionable Intelligence** – Operators get alarms, inertia trends, and operating guidelines to support real-time decisions

- **Utilization of FFRs** – PMUs verify actual BESS/inverter response timing and MW delivery during events

- **Supports Grid Codes & Planning** – Enables inertia threshold tracking, FFR tuning, and informed dispatch strategies

- **Field Validated -**Utilities worldwide have adopted and validated EPG's Inertia Tool

TECHNICAL DISCUSSION

THANK YOU

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