REAL-TIME INERTIA AND SYSTEM STRENGTH MEASUREMENT AND INTELLIGENCE FOR IMPROVING CONTROL ROOM OPERATIONS AND GRID RELIABILITY

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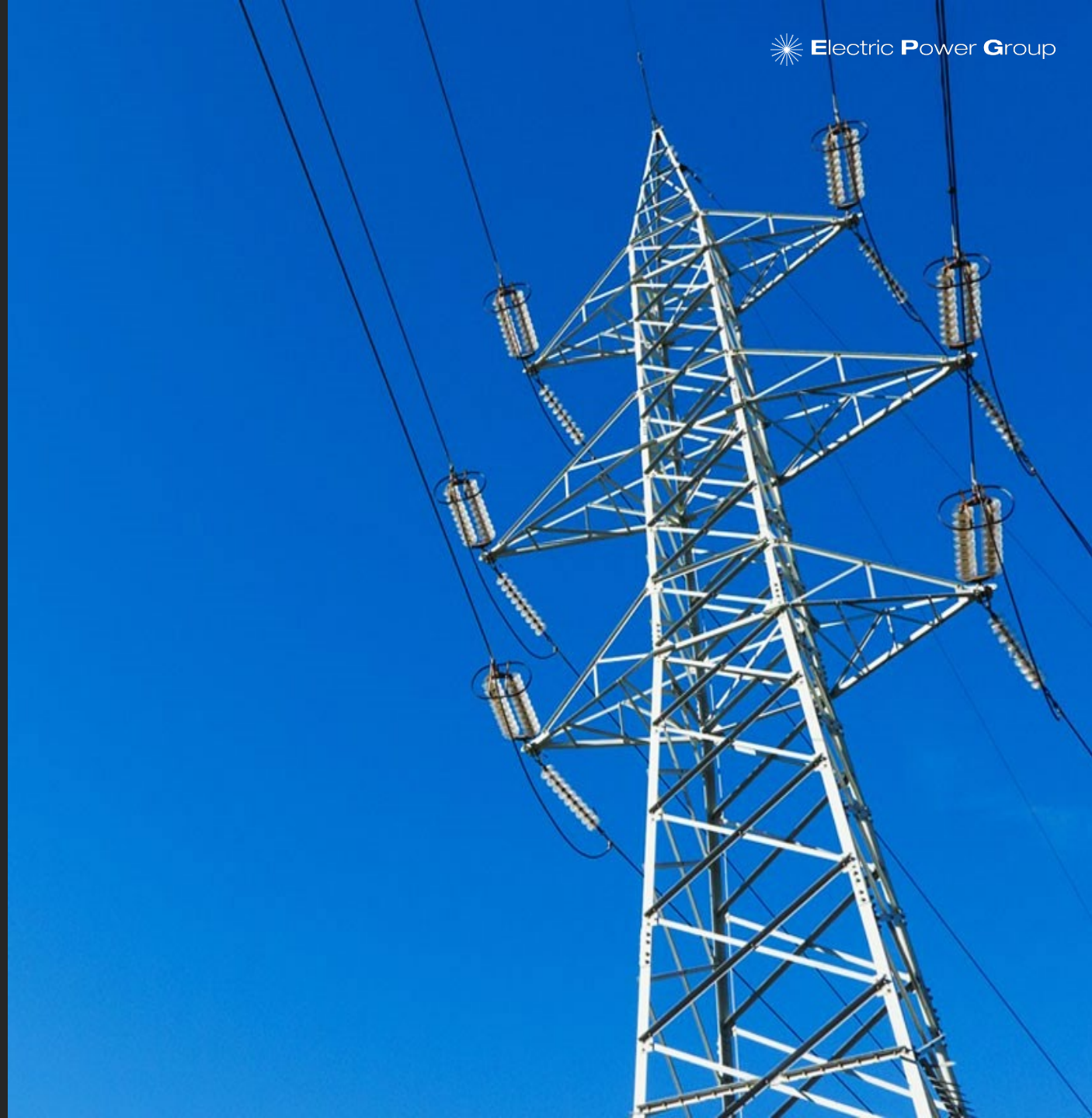


OUTLINE

- Introduction
- Inertia and System Strength - Concept
- EPG’s Inertia and System Strength Solution - Overview
  - Capabilities, Visualization, Monitoring, Forecasting, Actions
  - Example Dashboards and Results
- Summary
- Questions and Discussion

INTRODUCTION

- Grid Operators Rely on System Strength and Inertia from Rotating Machines for Reliability and Stability
- Synchronous Rotating Machines (Coal, Nuclear) in Grids are Decreasing
- Penetration of Inverter Based Resources (IBRs) is Increasing
  - Consequences are:
    - Low System Strength - Weaker Grids, Voltage Instability
    - Reduced System Inertia – Frequency Instability
    - Dynamic changes of System Impedance due to control & operational characteristics
- Operators Need Real Time Intelligence on System Strength and Inertia to Maintain Grid Stability and Reliability
- High Resolution PMU data enables System Strength and Inertia Estimation in Real Time
- Operators can use real time intelligence for:
  - Improved Situational Awareness
  - Monitor Trends and Alarms of Low System Strength & Inertia
  - Take Pre-Emptive Actions for Improved Reliability and Stability
  - Comply with Grid Codes to meet Reliability Performance Requirements

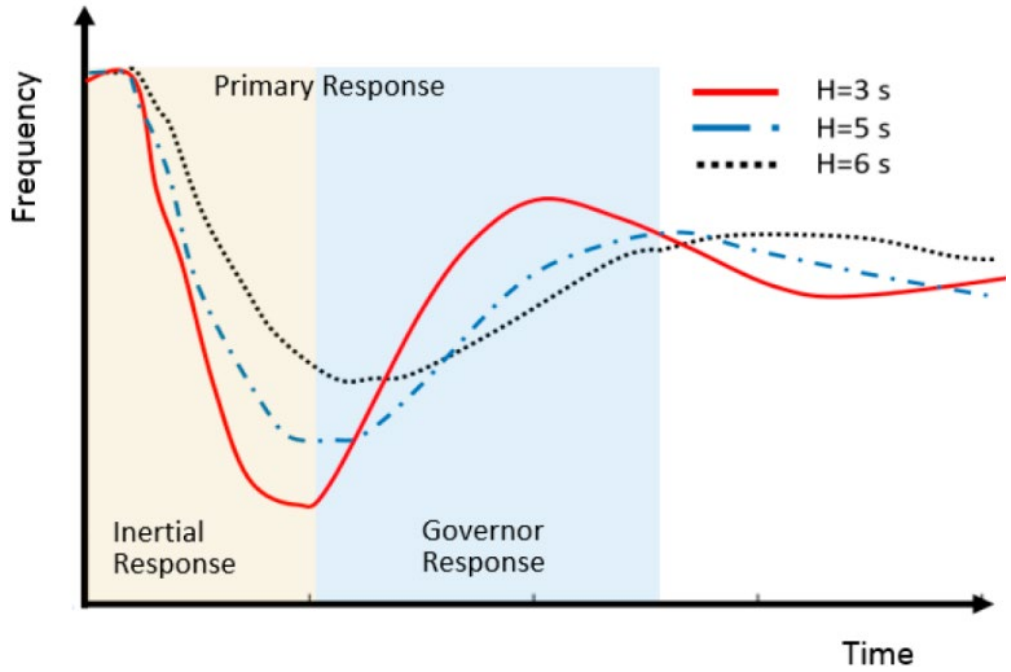
INERTIA MONITORING- CONCEPT

- What is System Inertia?
  - Refers to the ability of a power system to resist changes in frequency due to disturbances, such as sudden changes in load or generation
  - The ability to resist the change will be automatically provided by the Kinetic Energy Stored in the synchronously rotating mass of the Generating System
  - Unit of measurement is in Seconds or MW Seconds

- How is it Calculated?
  - $H_{sys} = (\sum H_i \times S_i)/S_b$

  Where H_{sys} = System Inertia in (s), H_i = Individual Generator Inertia (s), S_i= Individual Generator Rating (MVA) , and S_b=Base Power (MVA)

- Consequences of Low Inertia:
  - Frequency Instability
  - Poorer Disturbance Response
  - Impacts Critical Clearing Time
  - Voltage Fluctuations
  - Change of system oscillation modes
  - Increased risk of system separation and blackouts



SYSTEM STRENGTH - CONCEPT

- What is System Strength?
  - Ability of a power system to maintain stable voltage levels and support large power flows under various operating conditions, ensuring reliable and secure Grid Operation (also known as Network or Grid Strength)
  - Generally Measured with Short Circuit Capacity (SCC) and Short Circuit Ratio (SCR) Metrics
- What is Short Circuit Capacity (SCC)?
  - SCC is a measure of the capacity of the system to supply power/current during faults – this is crucial for maintaining system stability
  - Unit of measurement is MVA or Per Unit (pu)
  - Calculation:
    - $SCC = E^2_{TH}/Z_{th}$ Where, E_{TH} = Pre-fault voltage or Thevenin's Voltage , and Z_{th} =Thevenin's Impedance,
- What is Short Circuit Ratio (SCR)?
  - Ratio of SCC at a particular bus to the rated capacity of a connected generator or IBR at that bus.
  - While SCC provides an absolute measure and SCR provides relative measure of System Strength
  - Calculation :
    - $SCR = SCC / P_{IBR}$, Where SCC=short circuit capacity at a bus, and P_{IBR} = Rate Power of the IBR resource
- Consequences of low System Strength :
  - Reduced Grid Strength
  - Voltage Instability
  - Delayed Fault Voltage Recovery
  - Lower Fault current contributions due to IBRs
  - Requires large reactive power support
  - Increased risk of oscillations

EPG'S INERTIA MONITORING AND SYSTEM STRENGTH SOLUTION - OVERVIEW

- PMU measurement-based solution
  - Captures impact of synchronous machines, renewable energy resources and IBRs, loads, controllers and other system dynamics
  - Does not require grid injection devices/modulators
- Key functions and features
  - Real-time Monitoring – 24/7 assessment of system inertia and system strength
  - Uses both ambient PMU data as well as event data during disturbances
  - Real-Time Displays - geographical map, trends, frequency contours, graphs, charts, alarms etc.
  - Alarms and Events
  - Historical Replay of data, alarms and events
  - Automated Reporting
  - Forecasting Using Machine Learning / AI
- Current and Planned Deployments
  - ElectraNet, Australia
  - OETC, Oman
  - Taiwan Power Company, Taiwan
  - IESO, Canada
  - Red Sea Global, Kingdom of Saudi Arabia
  - ISOs and Utilities in USA
- Solution available stand-alone or integrated into EPG WAMS

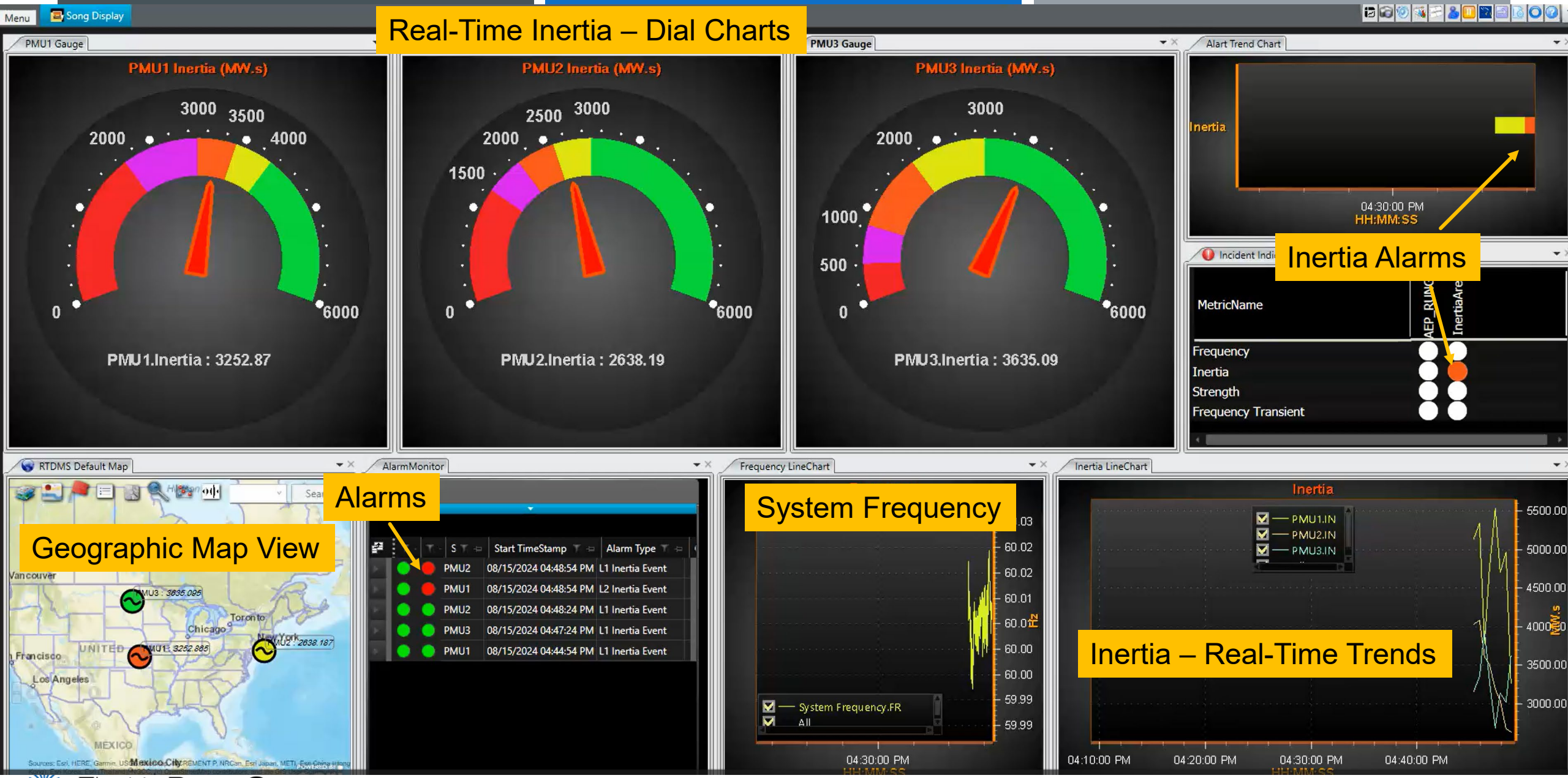
EPG'S SYSTEM STRENGTH & INERTIA SOLUTION - SUMMARY

Capabilities	System Strength	System Inertia
Objective	• Real Time System Strength Monitoring at any Bus	• Real Time System Inertia Monitoring at any Bus, Region wise or system level
Data Required	• PMU measurements for voltages and currents at a bus	• PMU measurements for Power Flows and frequency at a bus

Methodology	• Thevenin Equivalent Impedance based Method	• Combination of two approaches
		  • Ambient Data – System Identification method
		  • Event Data – Polynomial Approximation

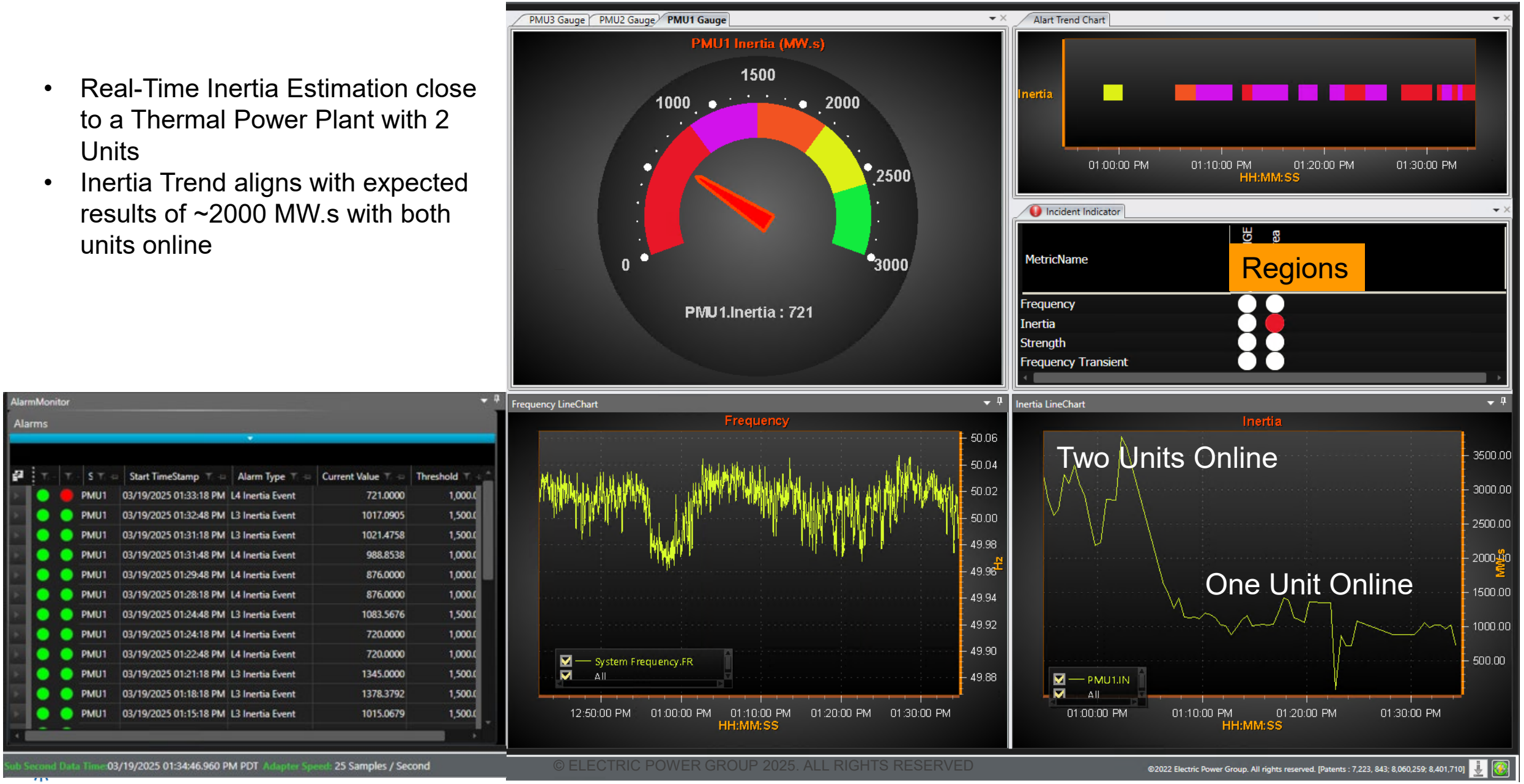
Situational Awareness	• SCC values on Geographical Map, Trends, Alarms, Reports	• Inertia values on Geographical Map, Trends, Alarms, Reports
Alarms	• Four level alarms of System Strength Metric based on SCC with customizable thresholds	• Four level alarms on System Inertia Metric (Bus, Region or System Level) with customizable threshold
Results	• Real-Time Trend charts of SCC etc.	• Trend charts of active power, frequency, Inertia, etc.
Forecasting	• Real time forecasting of System Strength based on incremental machine learning	• Real time forecasting of Inertia based on incremental machine learning
Replay	• Replay historical data, results and alarms	• Replay historical data, results and alarms
Reports	• Automated Report Generation – Trends, Daily/Weekly/Monthly reports	• Automated Report Generation – Trends, Daily/Weekly/Monthly reports

REAL-TIME INERTIA MONITORING – SAMPLE DASHBOARD

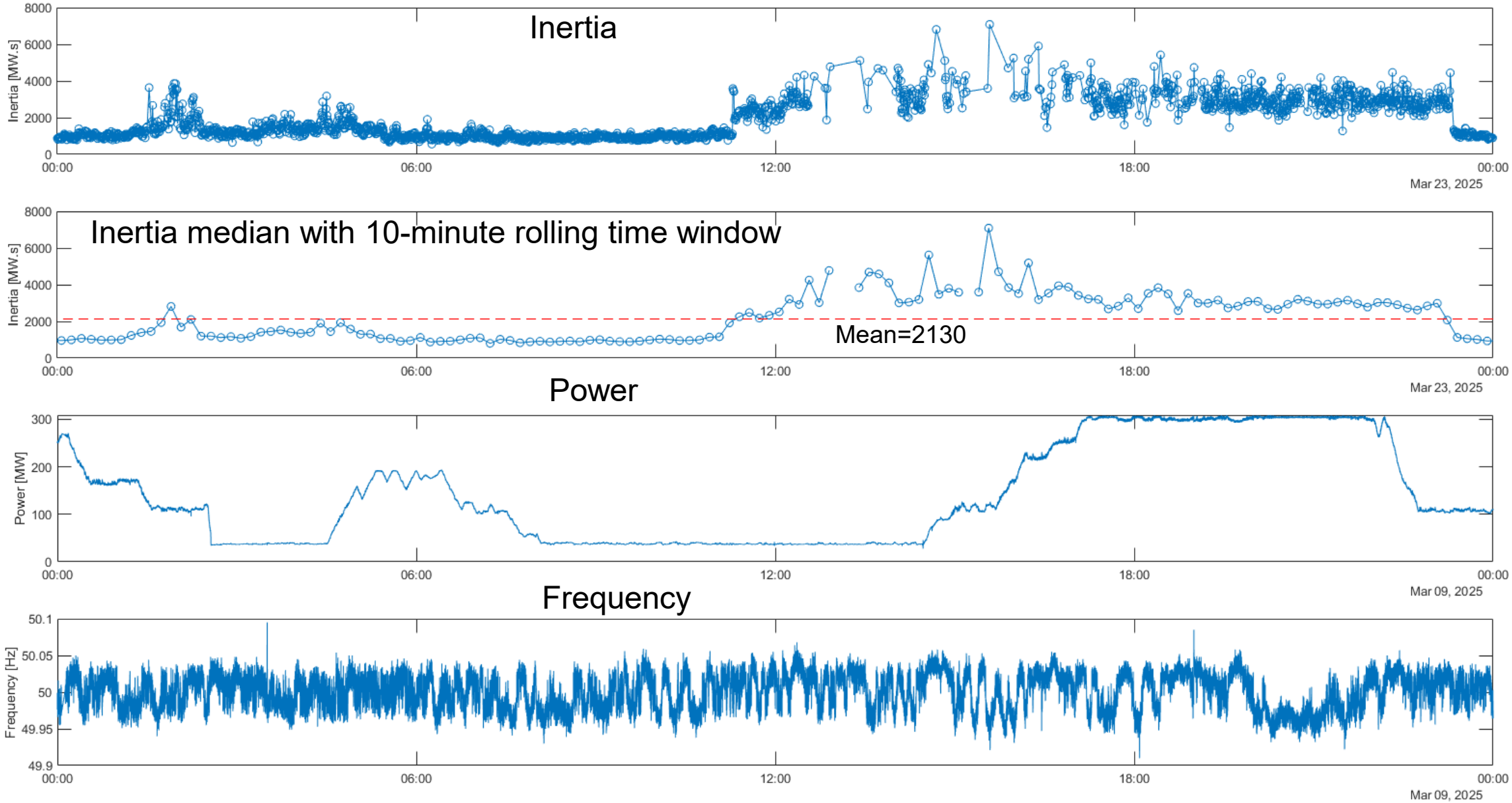


REAL-TIME INERTIA RESULTS – EXAMPLE

- Real-Time Inertia Estimation close to a Thermal Power Plant with 2 Units
- Inertia Trend aligns with expected results of ~2000 MW.s with both units online



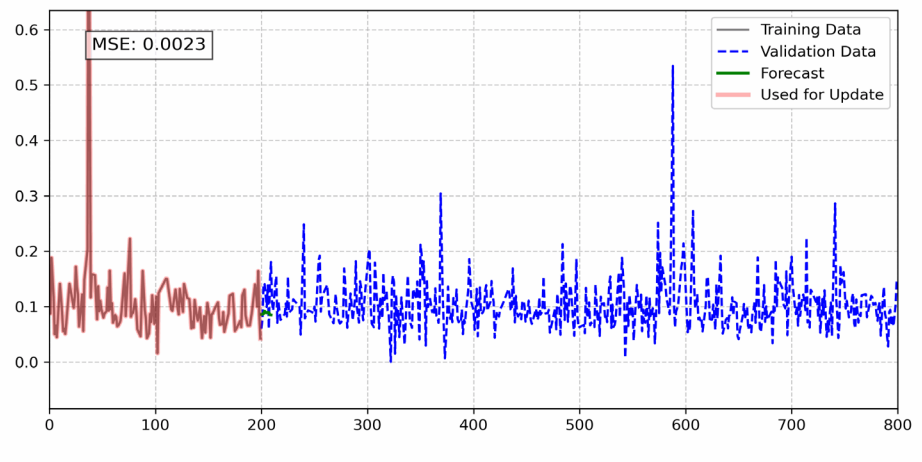
INERTIA TREND OVER 24 HOURS

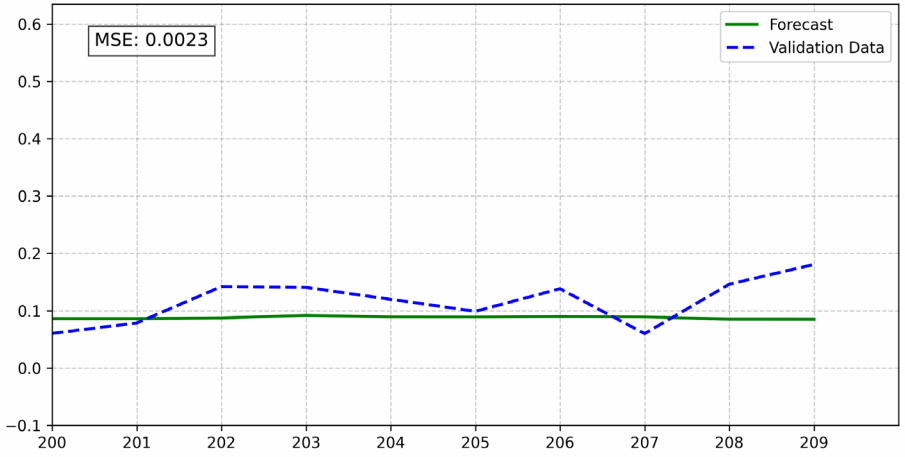


SYSTEM STRENGTH – SAMPLE DASHBOARD

MACHINE LEARNING BASED FORECASTING

- EPG solution provides real-time forecasts for inertia and system strength based on historical PMU data and calculation results
- Utilizes a Long Short-Term Memory (LSTM) model to capture temporal dependencies in time-series forecasting
- Utilizes Incremental Learning that enables the model to adapt to changing grid conditions every hour while capturing longer term trends
- Initial results produce forecast values within a 5% Mean Squared Error. Results depend on historical data availability and quality.
- Provides users flexibility to update the model, forecast horizon and parameters





Example illustration of inertia forecasting – shows normalized results

MANAGING SYSTEM STRENGTH AND INERTIA - SUMMARY

- PMU measurements provide high-resolution and time-synchronized data
- PMU data is used for estimating inertia and system strength in real time
- Existing PMU installations and WAMS are used to provide operators with actionable intelligence
- No new field devices are required
- Key Capabilities of EPG's System Strength and Inertia Solutions
  - Enables Monitoring of System Strength/Inertia continuously in Real-Time
  - Provides real time Visualization of results in different formats
  - Presents operators with Warnings via Alarms and Notifications
  - Enables Operators to Verify Alarms, Assess Grid Vulnerability, and initiate required actions via operating procedures
  - Provides day ahead forecasts

DISCUSSION AND Q&A

THANK YOU

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