Effective Area Inertia:

Stability **Challenges**
PMU-Based **Metering**
& Machine Learning **Forecasting**

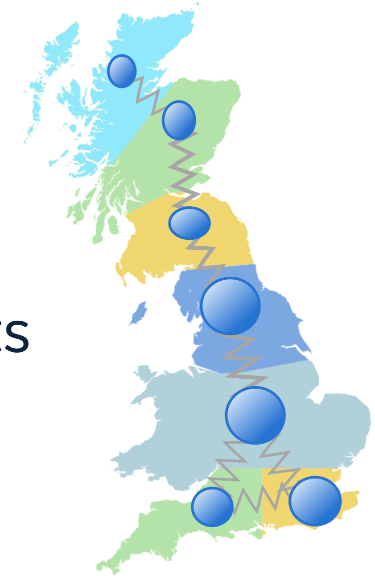
Background:
Inertia & Challenges

Power System Disturbances: **Centres of Inertia**

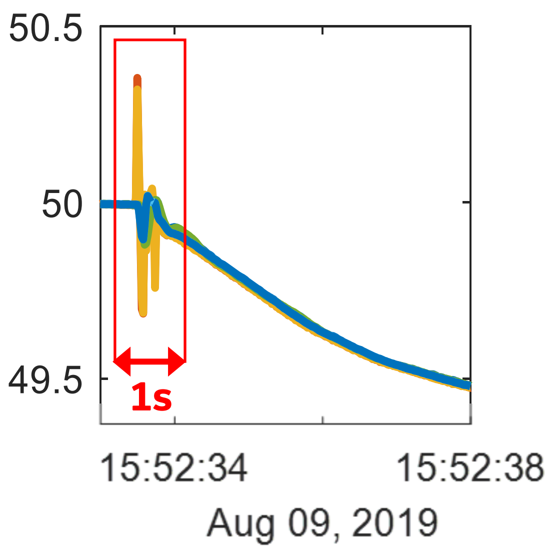
A power system behaves as area **centres of inertia** (“masses”) **linked by the network** (“springs”)

Significant spread of **Frequency & RoCoF** across a grid during events

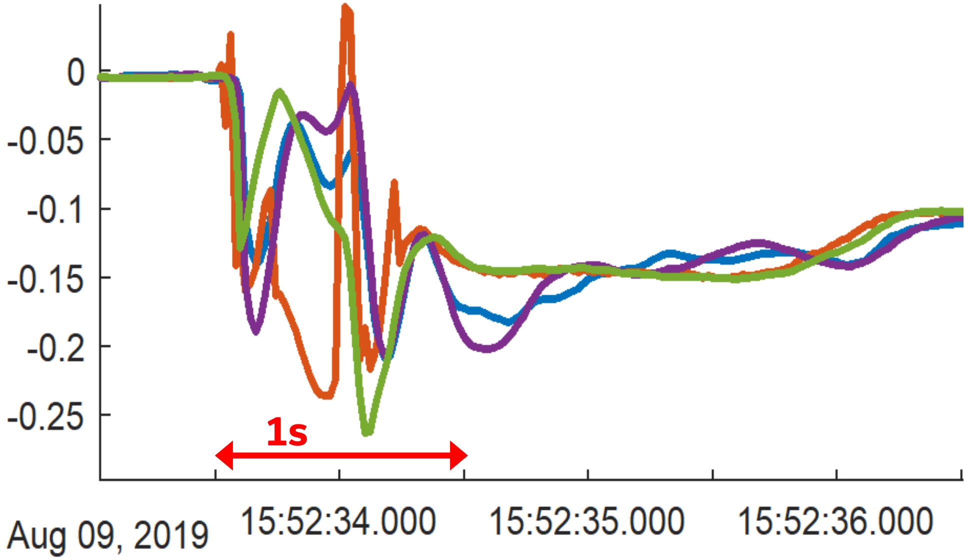
Example: Great Britain 9th August 2019

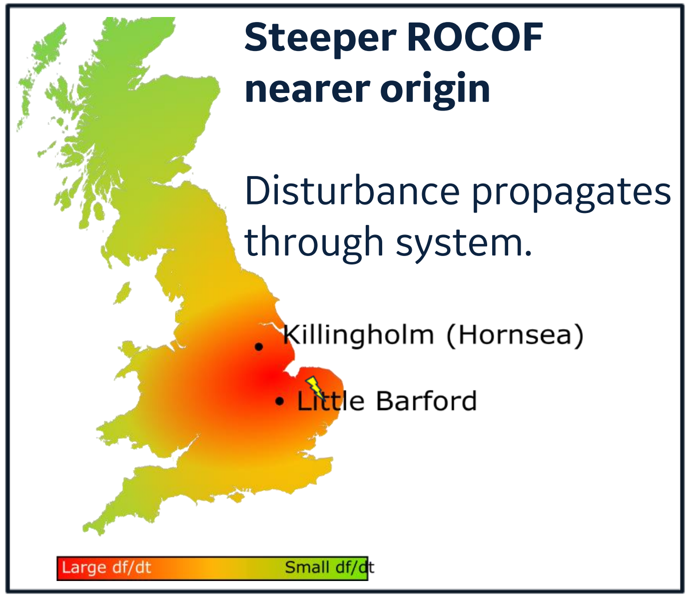


Frequency



Local Rate of Change of Frequency





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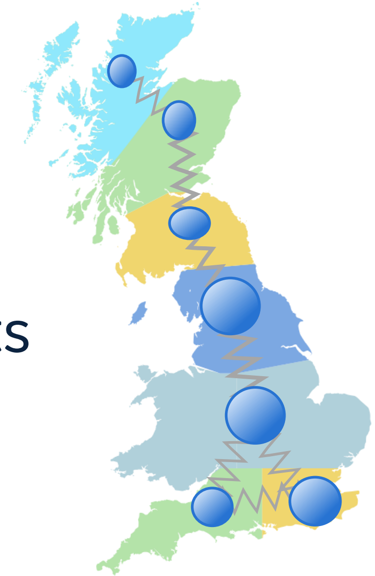
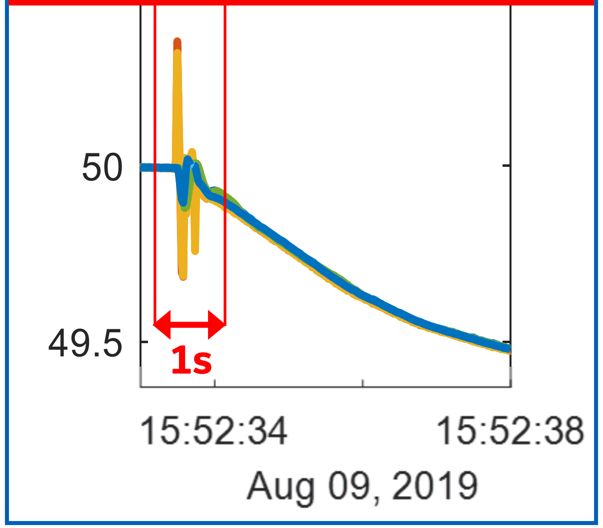


Significant spread of **Frequency & RoCoF** across a grid during events

Example: Great Britain 9th August 2019

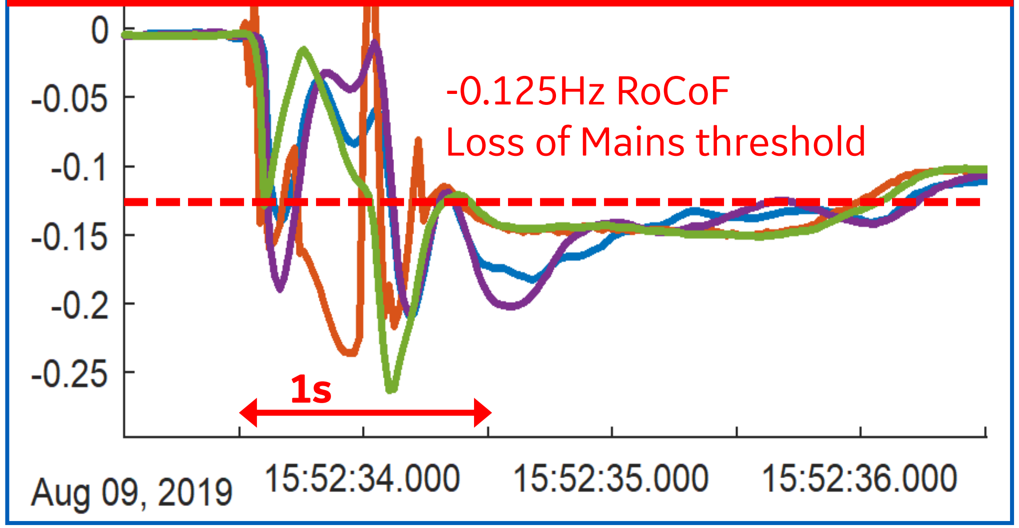
Frequency

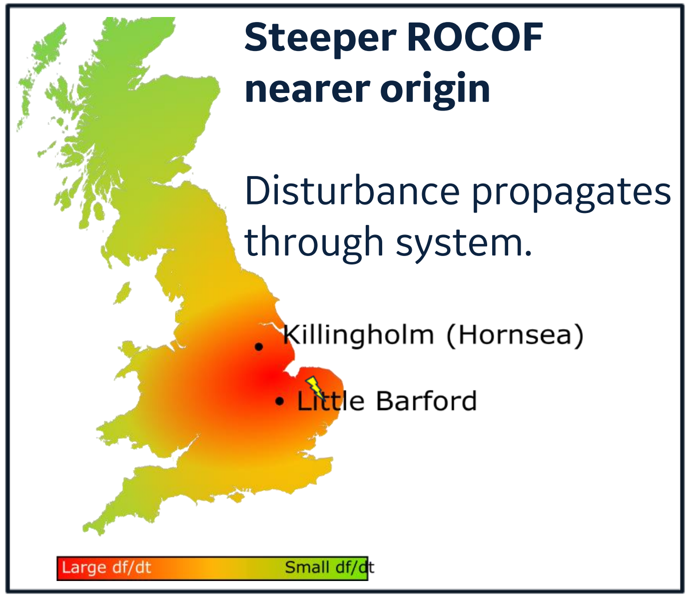
Risk: Centres of Inertia Separate



Local Rate of Change of Frequency

Risk: Embedded Generation disconnects - Loss of Mains



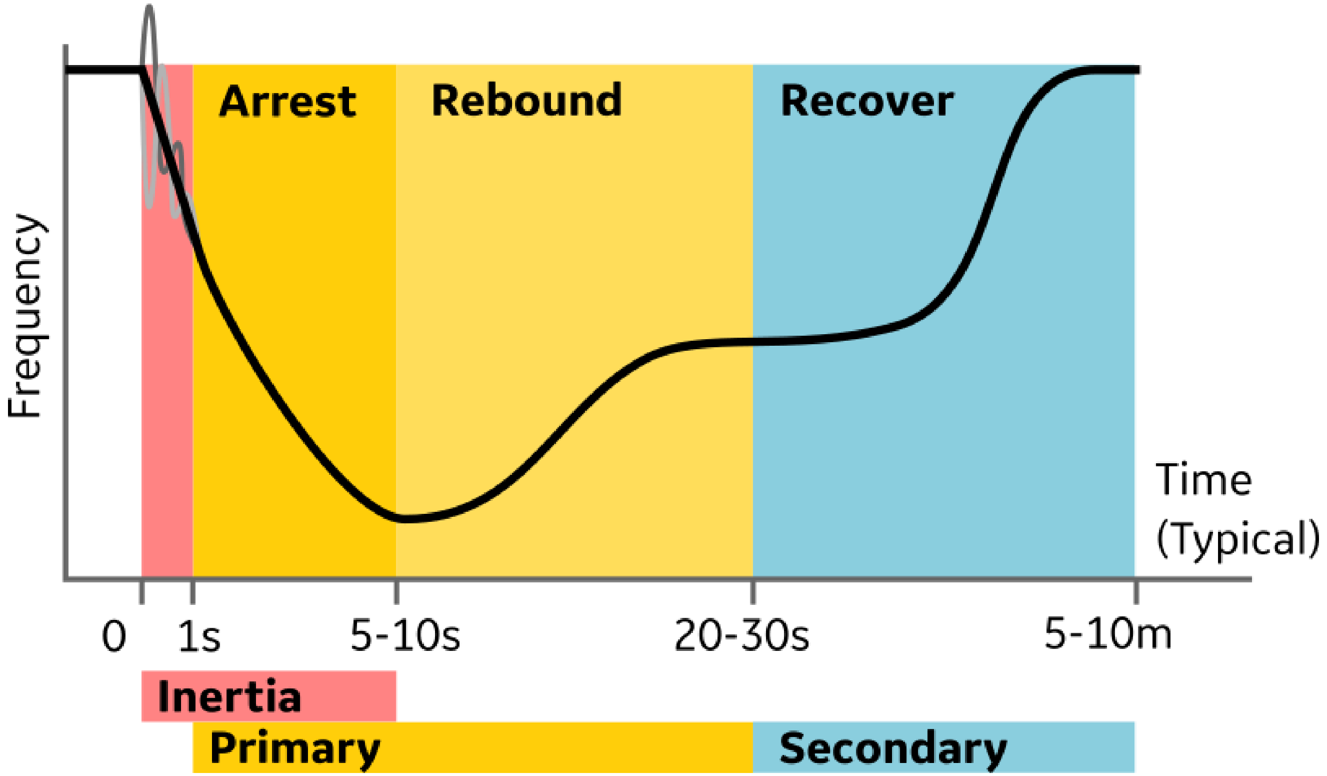


Effective Inertia

Relates **power imbalance** in a grid to the
rate of change of frequency that immediately results

Ability of a grid to
resist changing speed *due to a*
generation/demand ***imbalance***
or a ***fault***

"Grid" can be whole interconnection
or a coherent region
– a **centre of inertia**



Effective Inertia: **Why It Matters**

Low Inertia means in a disturbance:

- **Frequency falls faster & further**
  before primary response kicks in
- **Risk of Loss of Mains Disconnection**
  Embedded Generation disconnects at high RoCoF
- **Stability / Separation Risk**
  Area **angles move faster**
  Fast response in **wrong place** can **destabilize**

Resulting in **Additional Costs:**

- **Enhance Primary Response**
  larger volume and/or **faster delivery** needed
- **Procure Inertia**
  Generation trading or **dedicated 0 MW plant**
- **Tighten Constraints**
  Largest single potential loss of generation
  Inter-region flows for transient stability

Effective Inertia: **Sources**

Physical Rotating Inertia at Transmission
Steam/Hydro/Gas turbines
Synchronous Condensers

Well Known

Load
Rotating machines
Other passive/active behaviour

Inverter-Based Resources
Solar/Wind Generation
HVDC Links
Energy Storage

“Residual”
Less Known

Then / Now
High inertia
Neglect Residual

Now / Future
Low inertia
Residual significant

Measurement & Forecasting of Effective Inertia is becoming **critical** to grid operation

Effective Inertia: **Use Cases**

Constraining to Contain F & ROCOF

Contain system frequency within load shed limits by constraining largest infeed and/or minimum inertia

Contain regional ROCOF by constraining largest area loss w.r.t. area inertia & area coupling

Avoid imposing onerous generator ROCOF requirements

Locational Fast Response

Accept reduced inertia by **compensating loss without degrading stability** of angles and risk of islanding

Area inertia helps **relate system & area ROCOF to power imbalance**, leading to proportional response

Islanding Management

Improve islanding ride through capability by

- Identify **acceptable area imbalance** for islanding
- Incorporating **control** to improve island formation

Tune frequency control for island running → successful island operation Resynchronizing using **acceptable ΔF**

Infrastructure Planning

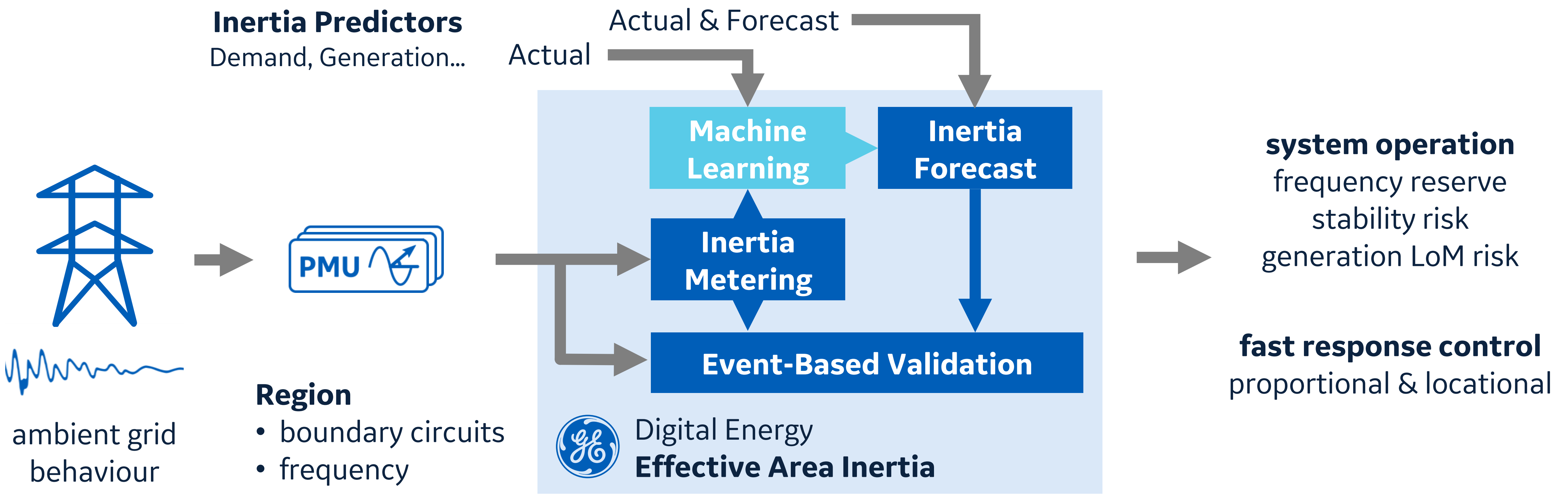
Assess the needs for physical inertia (e.g. Sync Comp with flywheel) compared with the area's effective inertia.

Avoid over-investment in capital assets while **ensuring sufficient** resources.

GE Solution:

Effective Area Inertia Metering, Forecast & Validation

Area Effective Inertia Metering, Forecast & Validation



no forced excitation

standard WAMS
measurements

scalable extensible secure
WAMS platform - premise or cloud

region + system inertia
real-time, forecast & event

Inertia Metering Using PMUs

Area Effective Inertia Metering Using PMUs

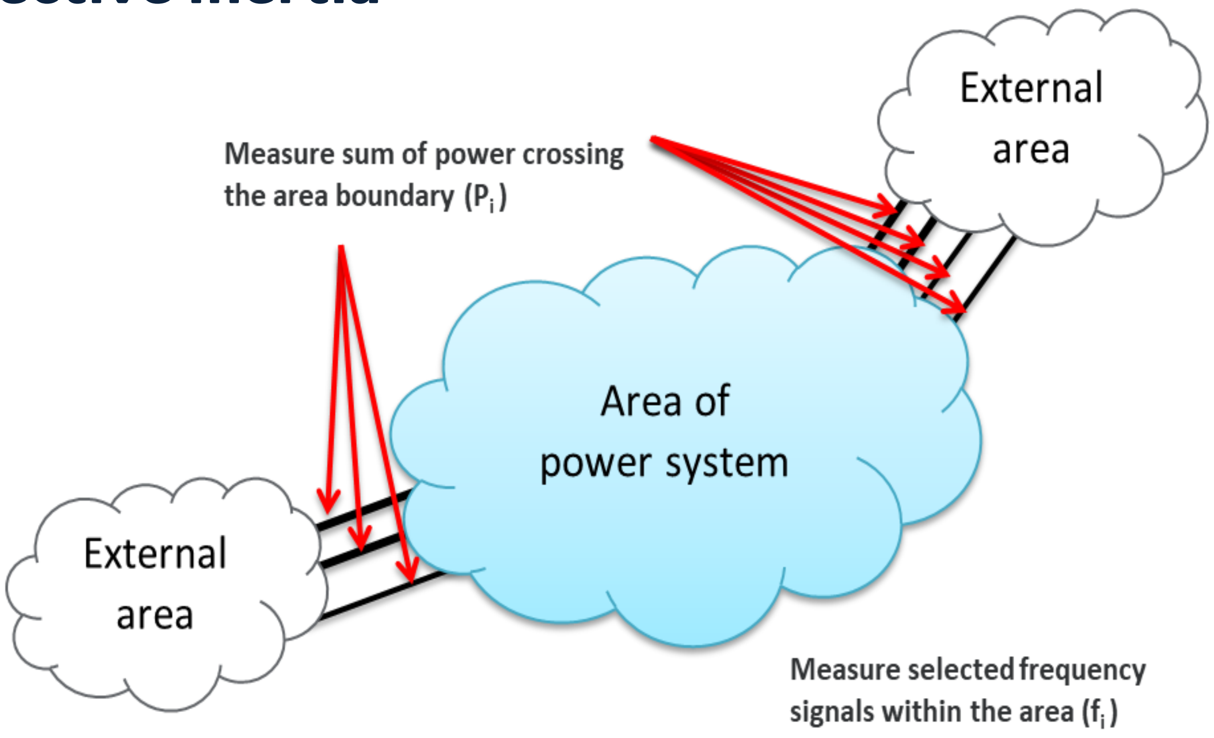
Continuous, passive metering of **Area Effective Inertia** using standard **PMU** measurements.

No deliberate excitation of system.

Only modest PMU measurements required:

- **Area boundary power:**
  V & I for transmission lines forming boundary

- **Area frequency:**
  Few key measurements within area (e.g. 3-4)
  To give representative area frequency

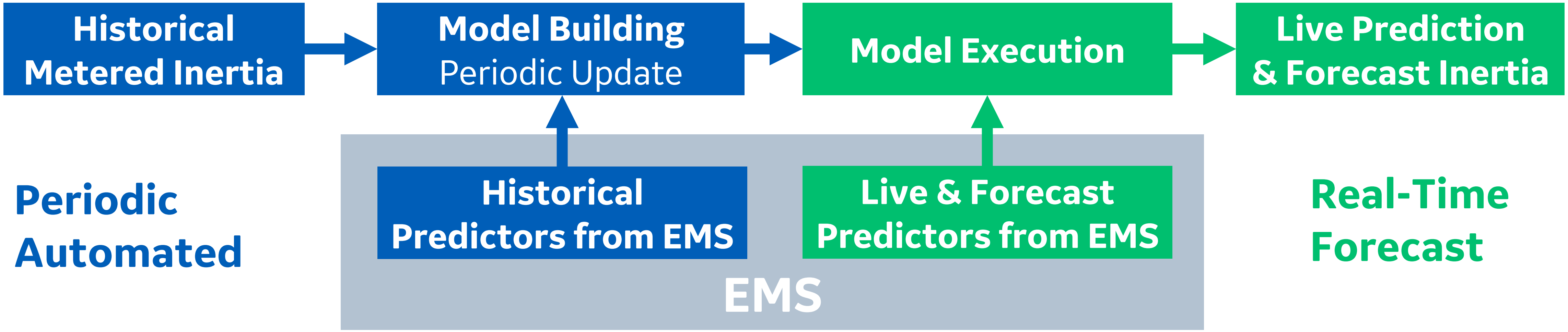


Sum Boundary Power $\Sigma P_b(t)$ → **Signal Analysis Process** → $H_{EA}(t)$

Weighted mean ROCOF $df_{area}/dt\ (t)$ → **Signal Analysis Process**

Inertia Forecasting

Area Effective Inertia Forecasting



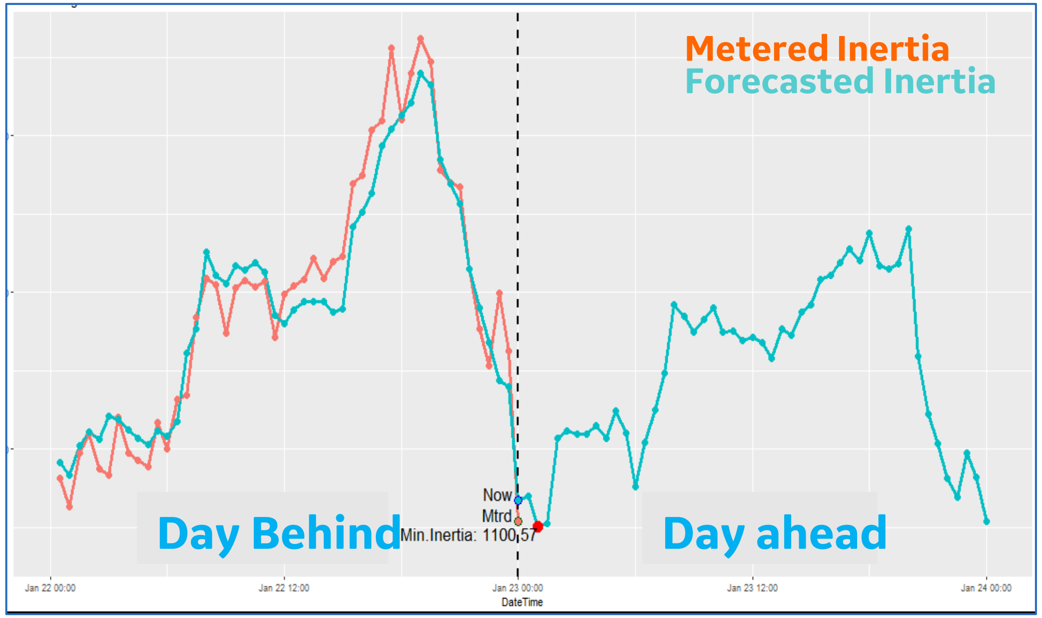
Machine Learning model links **inertia** to **predictor variables**, on a **per-area** basis:
E.g. *Demand, Synchronous Inertia, Wind, Solar*

Live Prediction based on measured predictors

- Backup & continuous validation with PMU-metered inertia

Forecast based on forecast predictors

Validated against metered and event inertia



Offline Field Testing: SP Energy Networks

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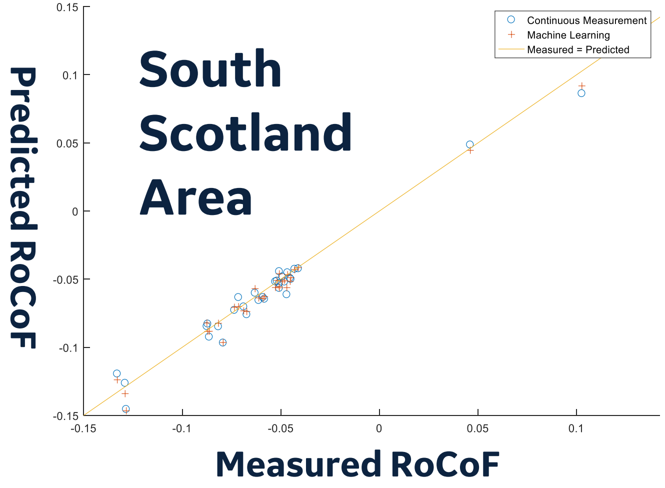
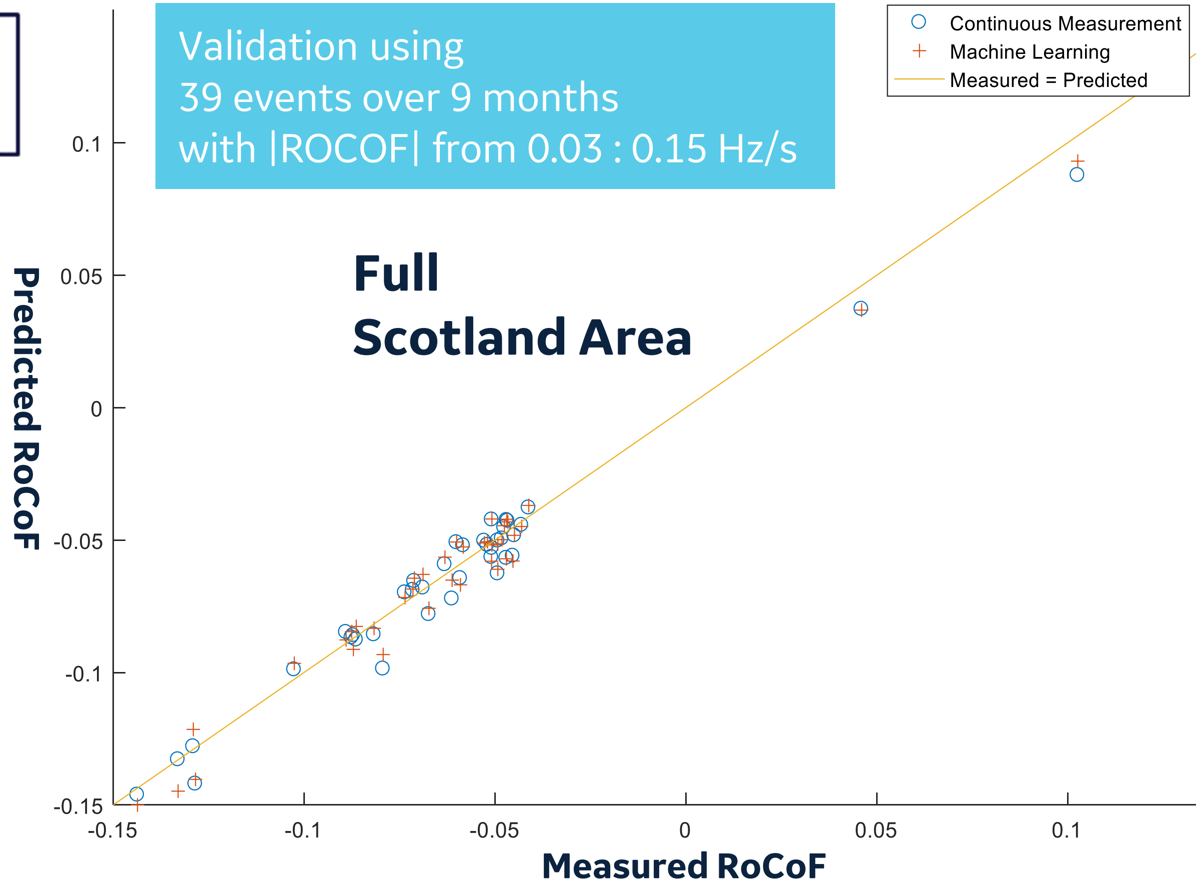
Inertia Metering & Forecast values for South Scotland and Full Scotland Areas

Validated Inertia-Predicted RoCoF vs real system RoCoF behaviour during events





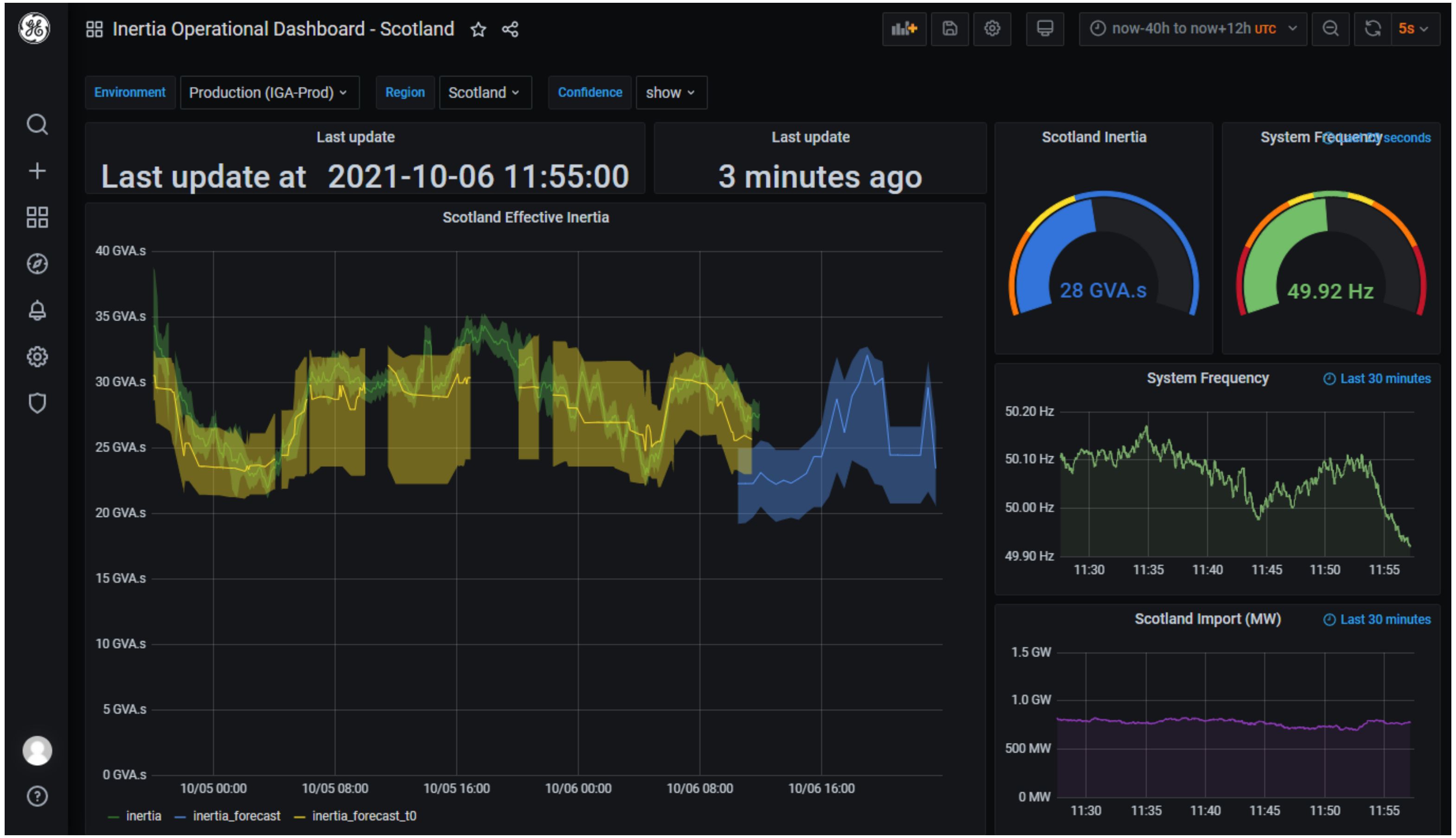
Operational Deployment: National Grid ESO, GB

National Grid ESO, GB: Operational Deployment

Inertia Metering

online for > 7months

- Continuous, real-time visibility of inertia in Scotland
- PMU connections under way to cover remaining regions of GB



Inertia Forecasting

online for >14 days

- Continuous real-time Forecast of inertia in Scotland
- Live prediction and Look-ahead Forecast

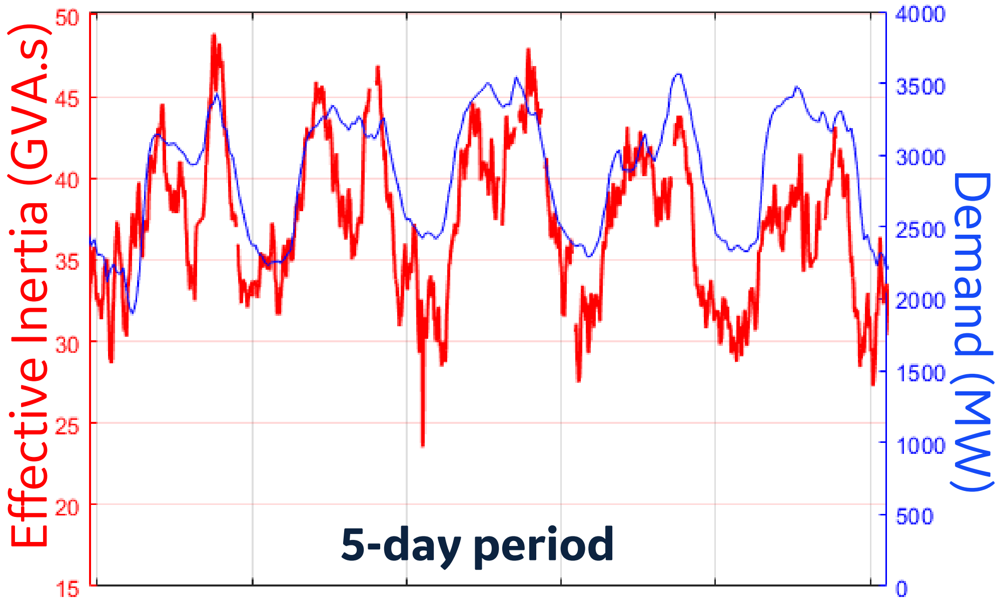
National Grid ESO, GB: Operational Experience

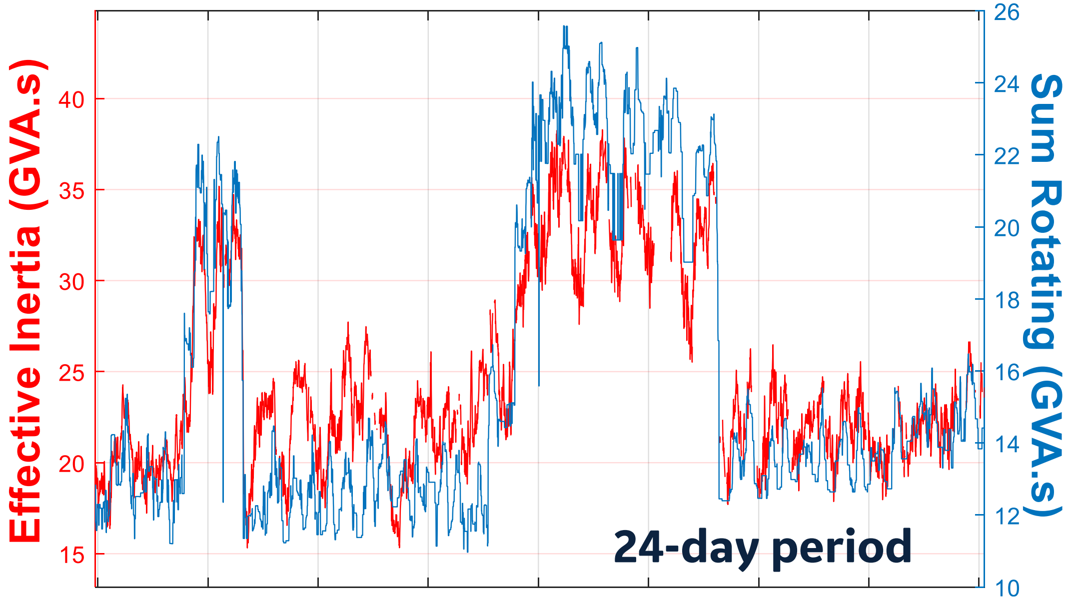
nationalgridESO

Metered Inertia:

Results match expectations: consistent with variations in demand & known rotating inertia

Example: Daily **correlation** with **Demand**	Example: Long term **correlation** with known **Rotating Inertia**

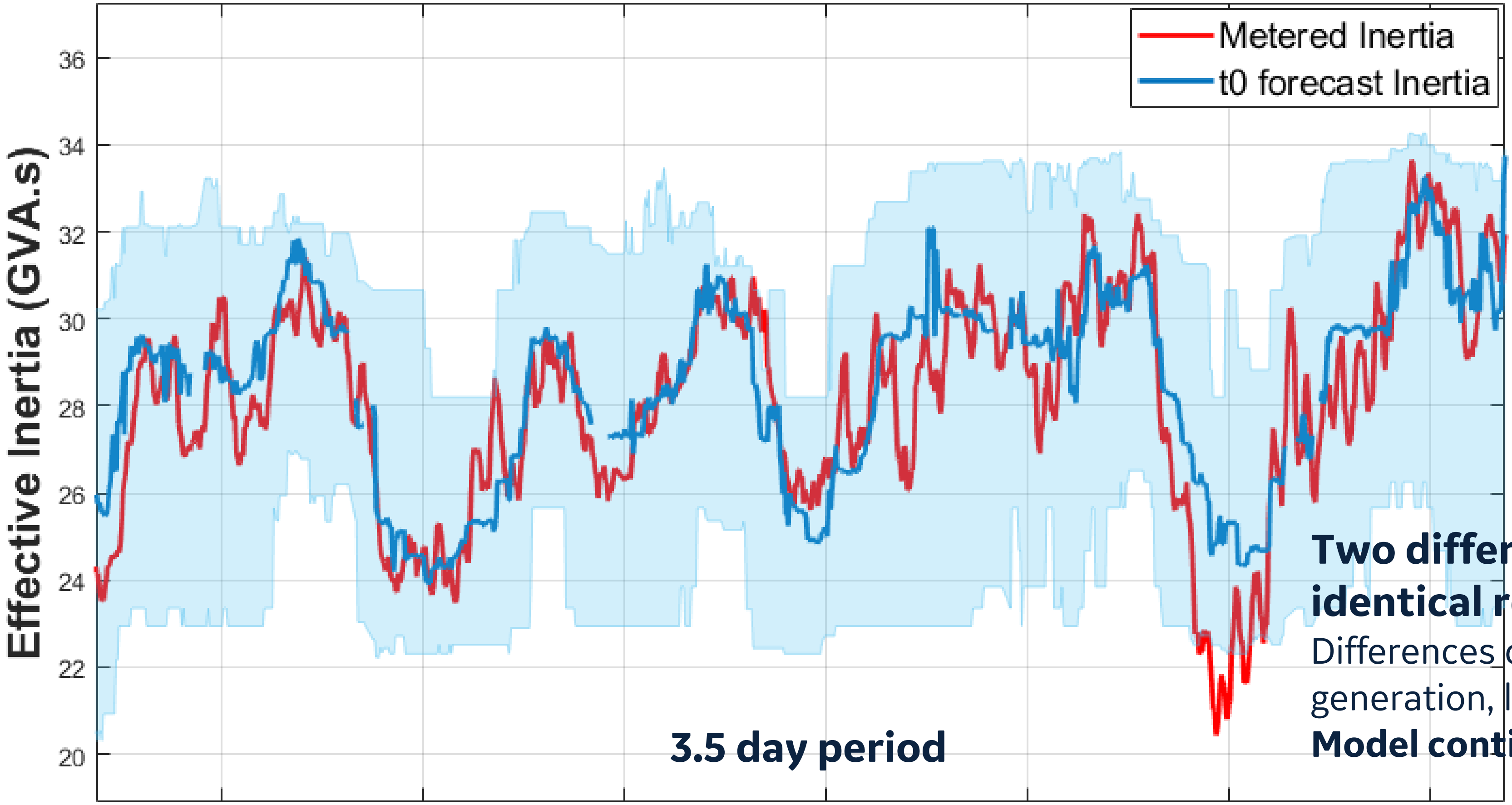




Regular automated validation against real system behaviour during events.

National Grid ESO, GB: Operational Experience

Live Inertia Prediction: backup & continuous sanity-check with PMU-metered inertia



Two different methods – not always identical results

Differences can occur, e.g. due to unmetered generation, load makeup...

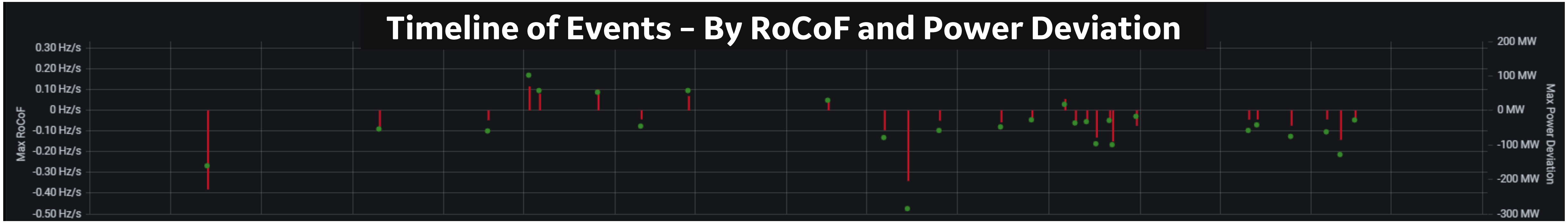
Model continuously improves

Regular automated validation against real system behaviour during events.

National Grid ESO, GB: Operational Experience

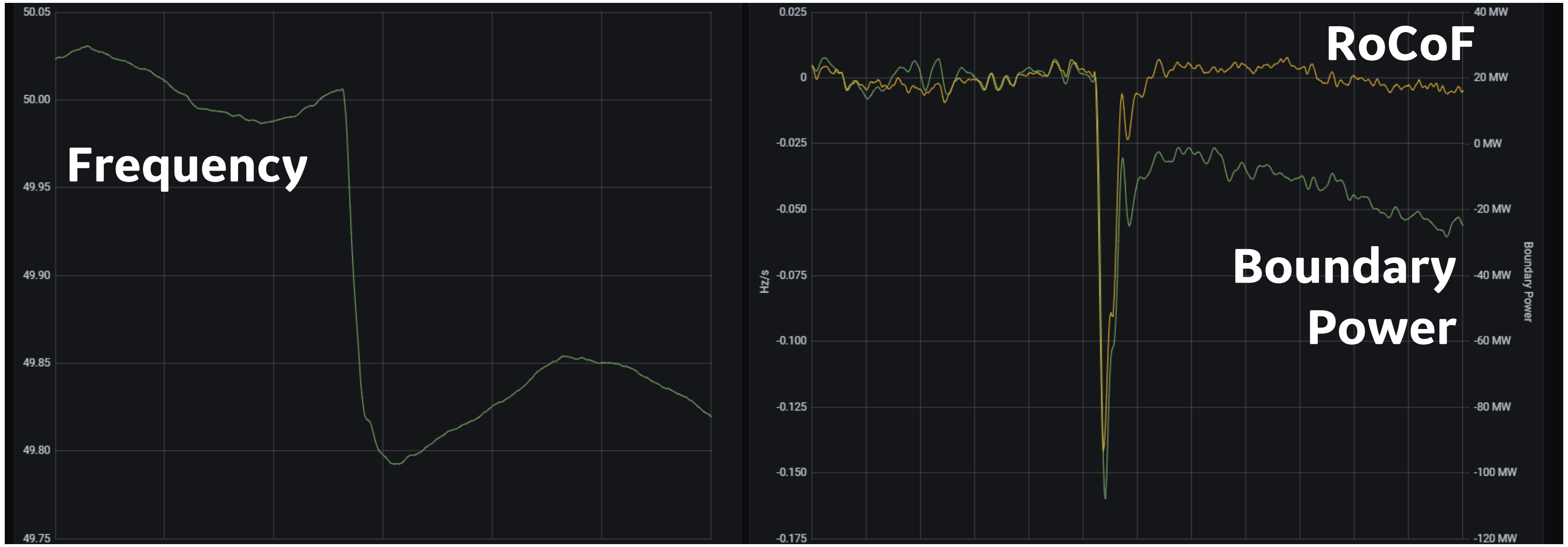
Automated event detection & inertia validation:

On-going validation against real system behaviour during events



Example Event

Inertia (GVA.s)	23
ΔP (MW)	-130
Predicted ROCOF (Hz/s)	-0.14
Observed ROCOF (Hz/s)	-0.14
ROCOF Prediction Error (%)	1



Conclusions

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1. **Inertia** is a **regionally distributed** parameter affecting **local RoCoF** and **stability**,
   not just system frequency

2. **Effective Inertia** covers all contributors to the **P-RoCoF relationship**,
   not just physical rotating transmission generation.

3. **PMU-based metering** of Effective Area Inertia is **passive**, uses standard PMU measurements, and is **in operation now**.
   Informs secure system operation, planning & analysis.
   Can feed **wide-area control** driven fast frequency response for islanding avoidance / ride-through.

4. **Machine Learning** yields **forecast of inertia – in operation now**
   Insight into system **inertia influencers**
   Backup and real-time validation of inertia metering
   Look-ahead forecast (e.g. day-ahead)