ERCOT WAMS System Architecture and Applications—Now and Future

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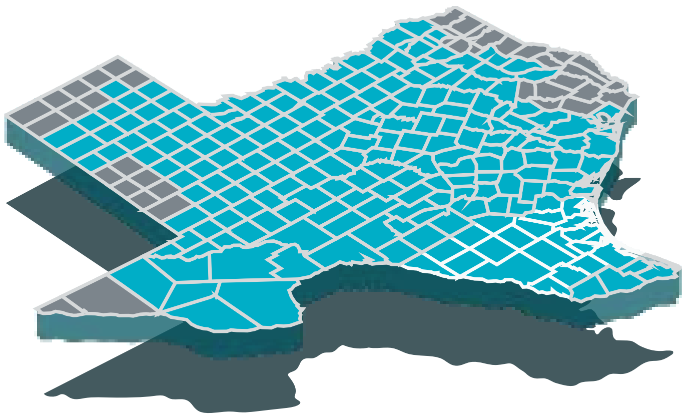
ERCOT Facts



27+ million customers in the ERCOT Region

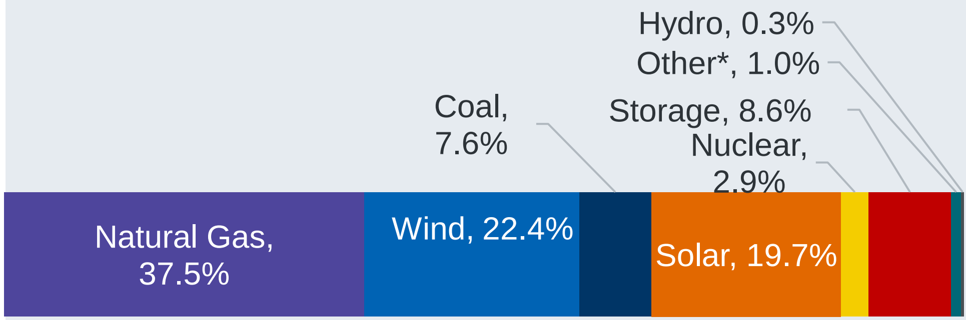
~$14 billion Transmission projects endorsed in 2025

1,460+ generating units, including PUNs

1,928+ active Market Participants that generate, move, buy, sell or use wholesale electricity

Summer 2026 Installed Capacity

Reflects operational installed capacity for Summer 2026 based on `December 2025 Capacity, Demand and Reserves report.



**Other includes biomass and Direct Current Tie capacity.*

2025 Energy Use

**Other includes solar, hydro, petroleum coke (pet coke), biomass, landfill gas, distillate fuel oil, net DC-tie and Block Load Transfer imports/exports and an adjustment for wholesale storage load.*

ERCOT Records

Peak Demand Record

85,508 MW
(August 10, 2023)

Weekend Peak Demand Record

85,116 MW
(August 20, 2023)

Expected Capacity for Summer 2026

104,850+ MW
(December 2025 *Capacity, Demand and Reserves report*)

1 MW of electricity is enough to serve about **250** residential customers during ERCOT peak hours.

Wind, Solar & Energy Storage by the numbers

40,739 MW
of installed wind capacity as of March 2026, the most of any state in the nation

28,751 MW
Generation Record (March 14, 2026)

69.15%
Penetration Record (April 10, 2022)

38,608 MW
of utility-scale installed solar capacity as of March 2026

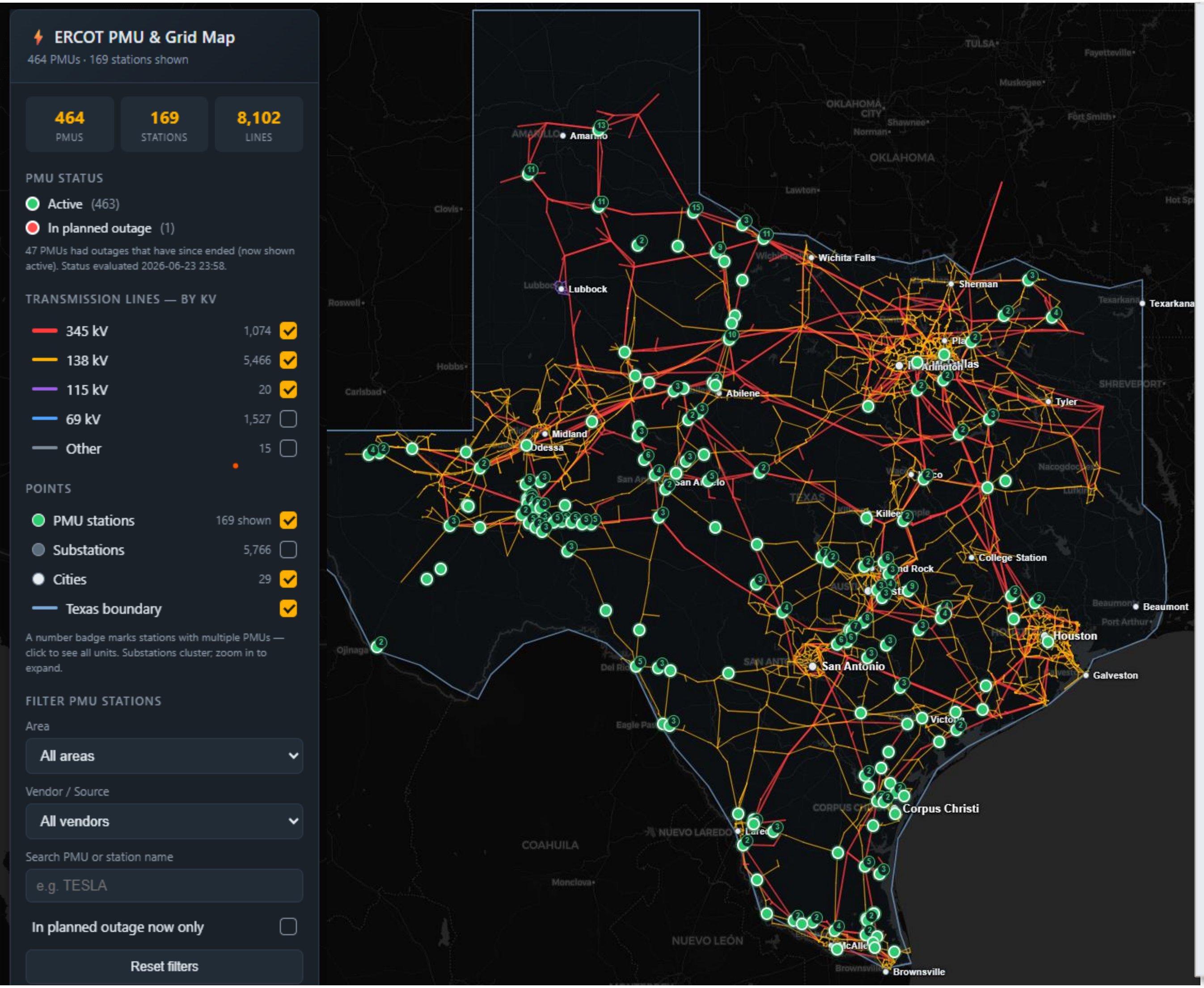
34,025 MW
Generation Record (May 2, 2026)

72.74%
Penetration Record (May 2, 2026)

19,693 MW
of installed energy storage capacity as of March 2026

10,515 MW
Energy Storage Generation Record (March 13, 2026)

ERCOT PMU Project Progress



First Phasor Measurement Unit (PMU) installation started around 2010, currently ERCOT receives 464 PMUs

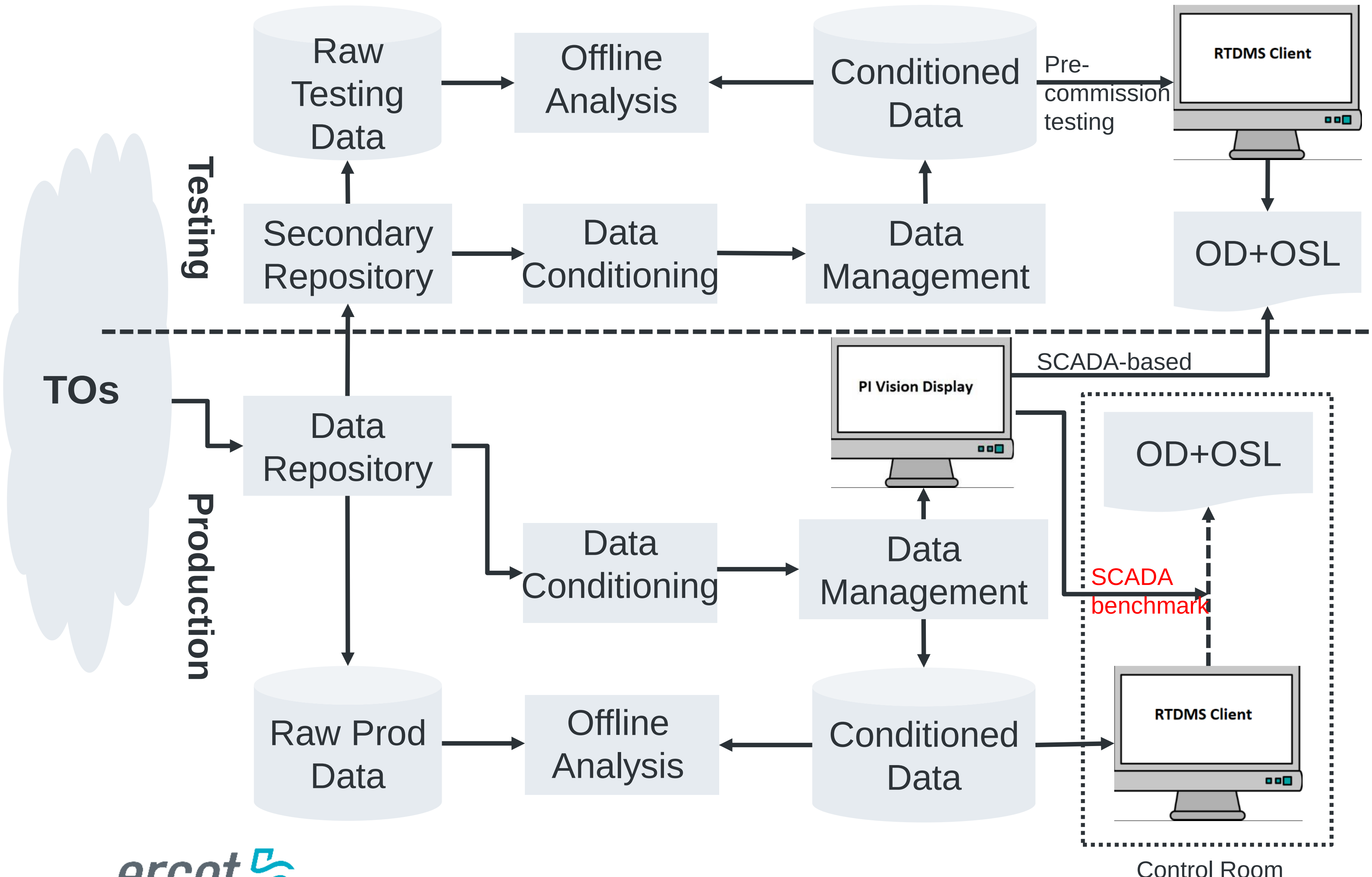
Active and reactive power Oscillation Detection(OD) enabled at 928 locations.

Mode monitoring is enabled to supervise inter-area oscillations.

Dissipating energy-based Oscillation Source Location (OSL) to be commissioned in production

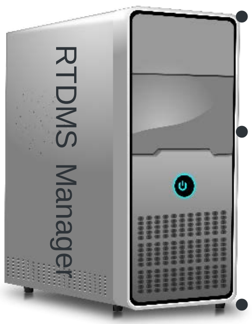
Real-time System strength and Inertia Monitoring under testing

ERCOT PMU Data Flow

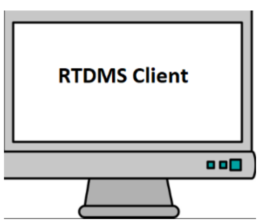


ERCOT PMU Property and Display

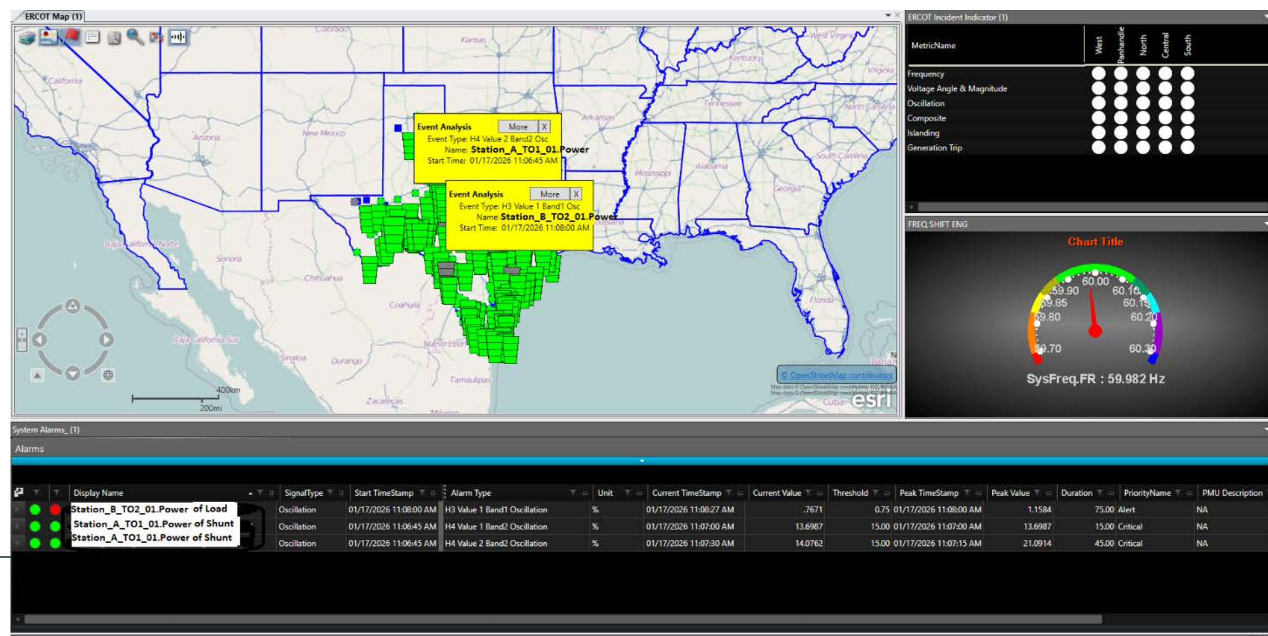
- Naming Convention: Label location and company information into names of PMUs streamed to ERCOT



- PMU and signal property : coordinates, description and outage information
- Aggregated signals: power, angle difference, system frequency and critical path
- Advanced data processing: mode monitoring, oscillation detection, islanding detection, *system strength and inertia monitoring (to be commissioned in 08/26)*
- Alarm configuration: frequency, voltage and composite alarm



- Oscillation map
- Alarm indicator
- System frequency



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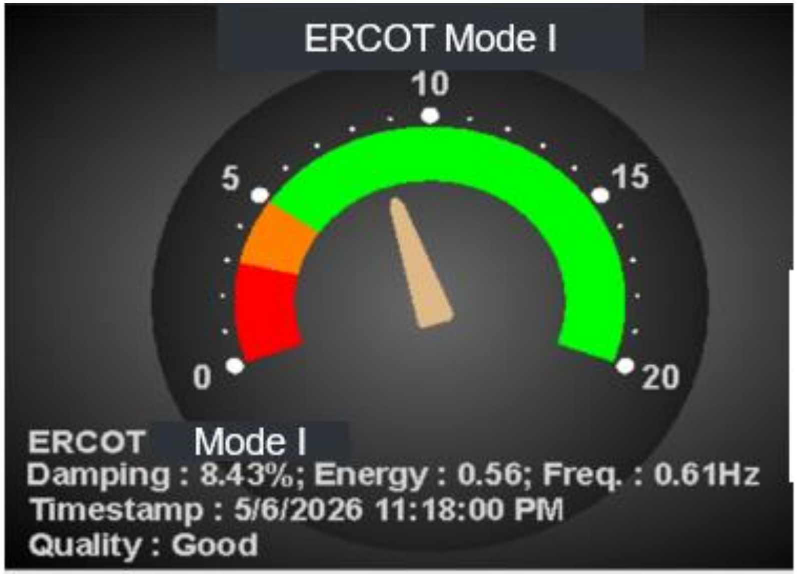
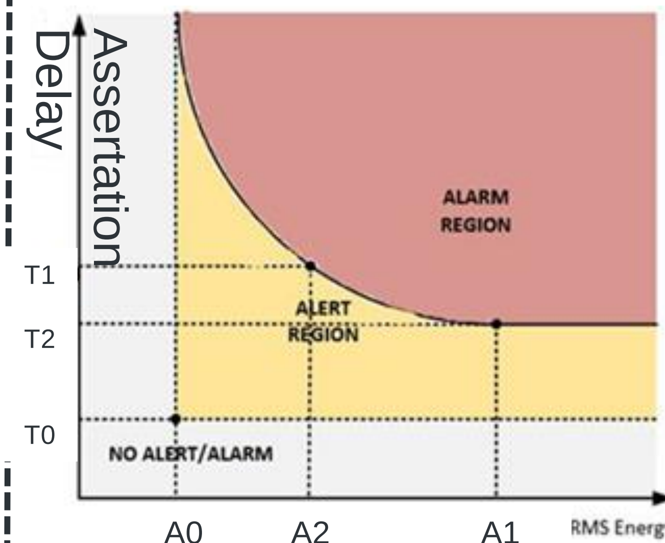
ERCOT Oscillation Monitoring

Mode Monitoring



Oscillation Detection



Band I thresholds on assertation delay and magnitude relaxed to avoid false alarm:

Band I <0.15hz Governor Response	**Band II** 0.15-1hz Inter-area Swing
Band III 1-5hz Local Swing	**Band IV** 5-15hz IBR Harmonics

SCADA-based OSL methodology

Iteratively expel noise and bad data using three-sigma rule

↓

Compute second derivatives as accelerations between consecutive samples

↓

Obtain oscillation score by aggregating absolute value of acceleration.

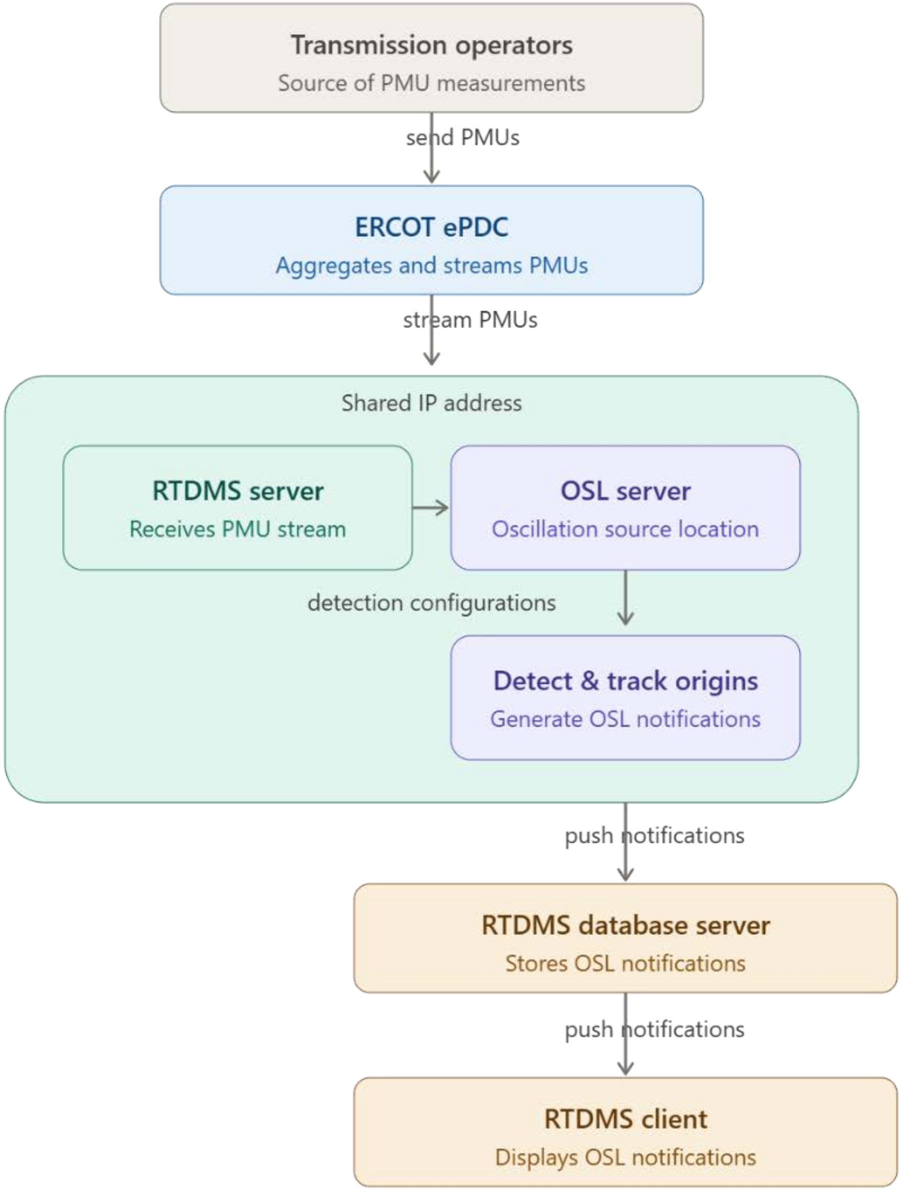
↓

A high score indicates that the unit's output underwent vigorous and repeated curvature — a pattern consistent with oscillatory behavior

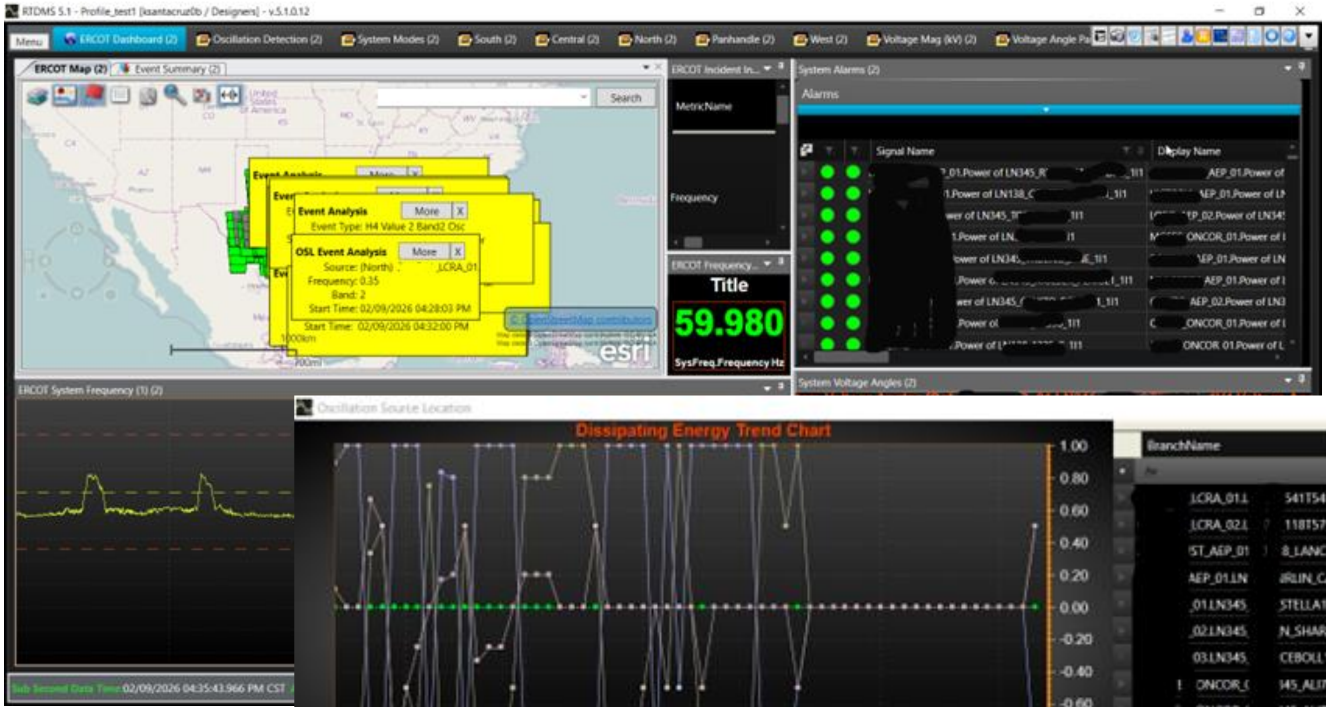
ERCOT OSL-SCADA based

Possible Source: Units exhibiting the largest cumulative acceleration between consecutive samples within the analysis window.

Dissipating Energy Based OSL Architecture



ERCOT OSL-Dissipating Energy-based



Dissipating energy calculated based on real power flows identifies oscillation source candidates

Directional DEF values points source of oscillation to closest PMUs

Proof of Concept-Real Time Estimation of System Strength and Inertia

System Strength Estimation – to evaluate grid voltage stability

Inertia Estimation - to ensure system frequency stability

Definition and Background

System strength (SC MVA): Capability to hold onto desired voltage during disturbances
Inertia (MW*s): Energy stored in power system to resist frequency change

Impact from IBR and large loads:
1) Inverter based generation instead of rotating machines: Reducing energy stored to resist frequency change---Decreasing Inertia.

2) Lower fault current: Typically, below 2.0 p.u. compared with 5-8 p.u. from rotating machines----Decreasing System Strength.

3) Limited low voltage ride-through capability--- Further decreasing System Strength.

Proof of Concept (POC)-Purpose and Goal

Testing if the real-time estimation of Inertia and System Strength are:

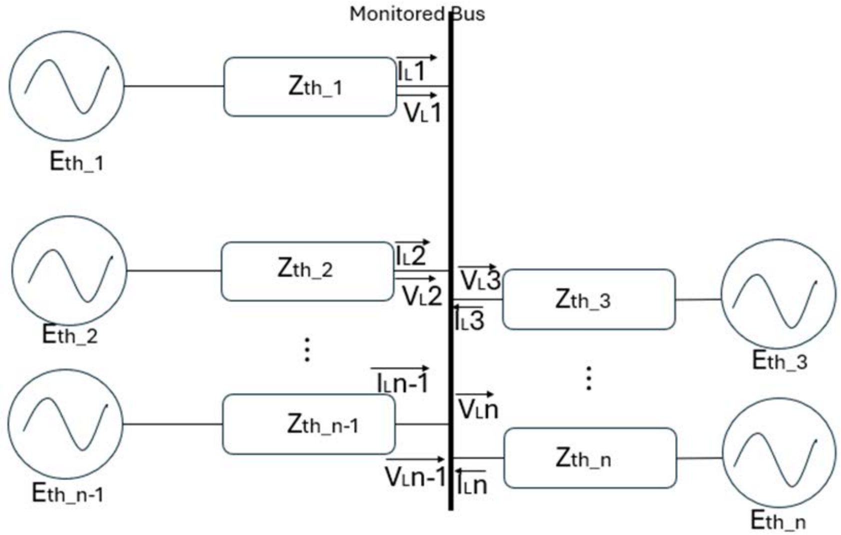
1. Accurate — yield results that are consistent, reliable and verifiable via independent means.

2. Robust — able to function with non-perfect PMU data quality and evolving system conditions.

3. Practical — Can be implemented in ERCOT without massive infrastructure enhancement.

POC Methodology-System Strength Estimation

Estimation



$$V_L = E_{th} - Z_{th} \cdot I_L$$

With monitored Bus short circuit V_L=0:

$$\overrightarrow{I_{SC_i}} = \frac{\overrightarrow{E_{th_i}}}{\overrightarrow{Z_{th_i}}} \qquad \overrightarrow{I_{sc}} = \sum_{i=1}^{n} \overrightarrow{I_{sc_n}}$$

$$S_{mva} = \sqrt{3} \cdot \left|\overrightarrow{I_{sc}}\right| \cdot \frac{\sum_{i=1}^{n} \left|\overrightarrow{E_{th\_i}}\right|}{n}$$

For high voltage transmission buses, X_{th} will be used to model contributed limit estimation error

ERCOT Verification:

1) SPWG Planning Studies using 03312025 case where:

I. Ignore Load, shunt and line charging
II. Ignore transient impedances and protection schemes
III. No outages in the system.

2) VSAT Short Circuit Analysis using operation snapshots with below built in assumption:

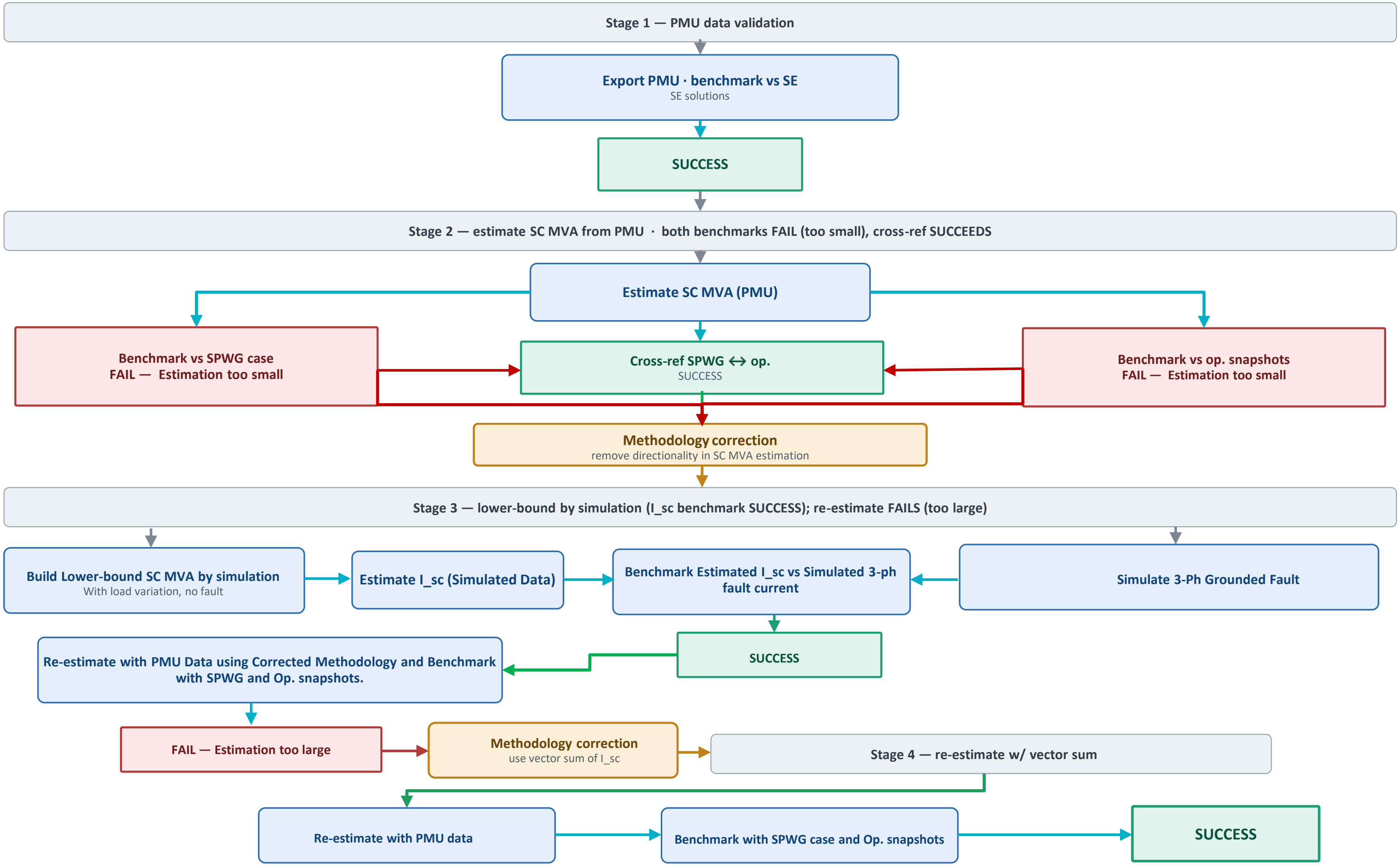
I. Ignore Load, shunt and line charging
II. Ignore transient impedances and protection schemes
III. Pre-fault Voltage assumed as 1.0 Pu

ERCOT Testing:
TSAT simulations using operation snapshots

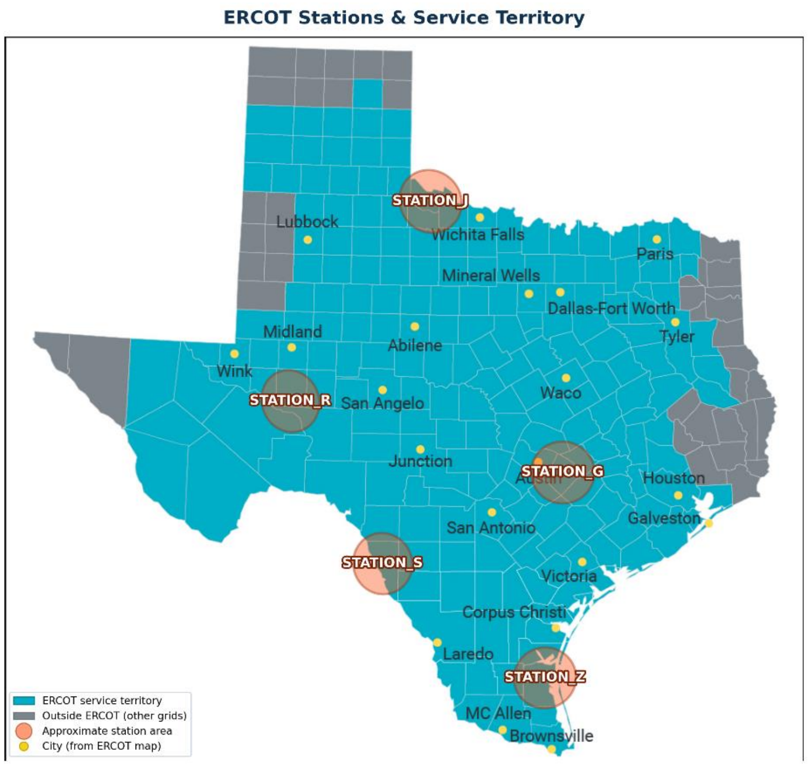
I. Provide a high sampling data with good quality that reflect (artificial) system variations
II. Establish a lower bound reference for system strength

POC Procedure-System Strength Estimation

PMU-based SC MVA estimation validated in four stages, with two methodology corrections



POC Results-System Strength Estimation



The selection reflects diverse grid conditions where:

- **STATION_G:** hosts on-site and interconnects nearby synchronous generations
- **STATION_J:** adjacent to a major load center and a HVDC tie with SPP
- **STATION_S/STATION_R:** connects multiple batteries and solar facilities
- **STATION_Z:** integrates wind generation exceeding 900 MVA

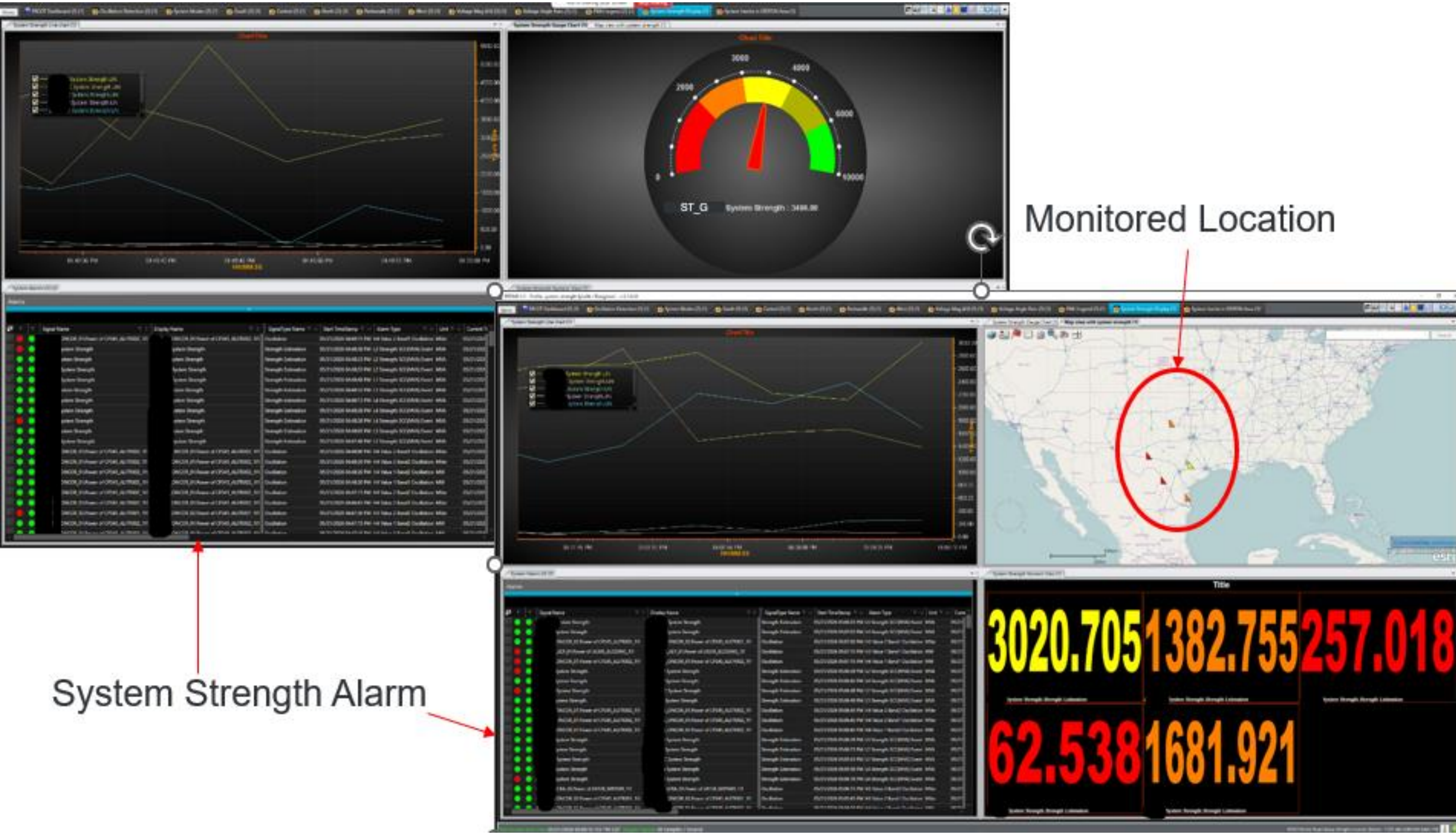
$$Error\% = \frac{|Estimation\ Average - Operation\ Snapshot\ Average|}{Operation\ Snapshot\ Average} \cdot 100\%$$

Coefficient of Variation% (CV) =std/average*100%

Station	KV	Steady-State Study		Estimation Mean MVA	Estimation Error%	Estimation STD	Coefficient of Variation%	Drop-out Rate	Data Distortion
		SPWG MVA	Operation Snapshot Average MVA						
G	138	6662	4268	4591.4	7.6%	607.8	13.2	3.1%	No
S	138	1191	1092	942.1	13.7%	85.98	9.1	3.1%	Yes
J	345	9119	8619	8611	0.0%	1591.2	18.4	0%	No
Z	345	5960	6082	5864	3.6%	831	14.2	0%	No
R	138	336	358	387	8.1%	53.5	13.8	3.1%	No

The methodology remains effective despite minor PMU data gaps and distortion.

Client Display- System Strength Estimation



PoC Summary and Action Items-System Strength Estimation

Summary

1. Estimation methodology delivered acceptable accuracy in estimating system strength even with non-perfect PMU data.

2. Current system strength estimation methodology demonstrated robustness in handling different grid conditions.

3. Real-time system strength estimation is achieved without requiring any upgrades to the existing server specifications.

Action items

1. Upgrades to the real-time estimation platform to support flexible estimation methods.

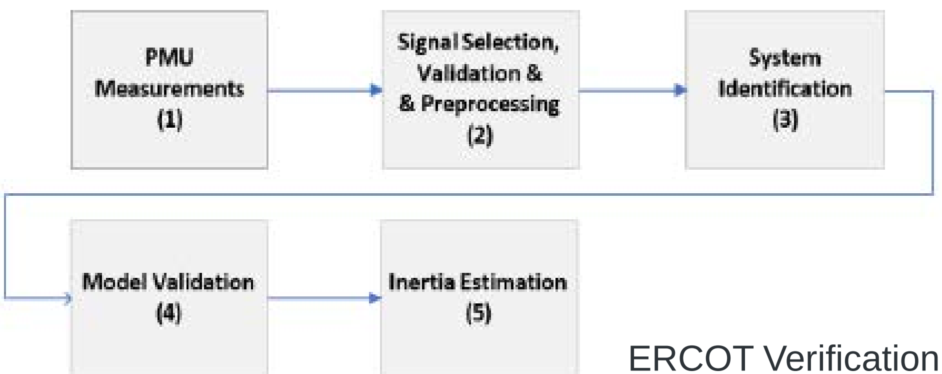
2. Baseline and configure real-time system strength alarms.

3. Methodology enhancements to maintain accuracy with PMU dropout rates more than 5%.

PoC Methodology - Inertia Estimation

Estimation:

1) Build $\Delta P_i(t)$ from selected flows and obtain $f_i(t)$ While calculating average of selected frequencies
2) Using the Numeric Subspace State-Space System Identification (N4SID) technique to build a data-driven model that captures the dynamic relationship between power and frequency.
3) Then excite the model with a sudden disturbance to extract inertia values.



For Local Inertia Estimation:

$$H_i = \frac{\Delta P_{i\,(t)} \cdot f_0}{2\,\frac{df_{i(t)}}{dt}}$$

For System-wide Inertia Estimation:

$$E_i = H_i \cdot S_i \qquad E_{total} = \sum_{i=1}^{n} W_i \cdot E_i$$

$$W_i = \frac{RMS(\Delta P_i)}{RMS\left(\sum_{i=1}^{n} \Delta P_i\right)}$$

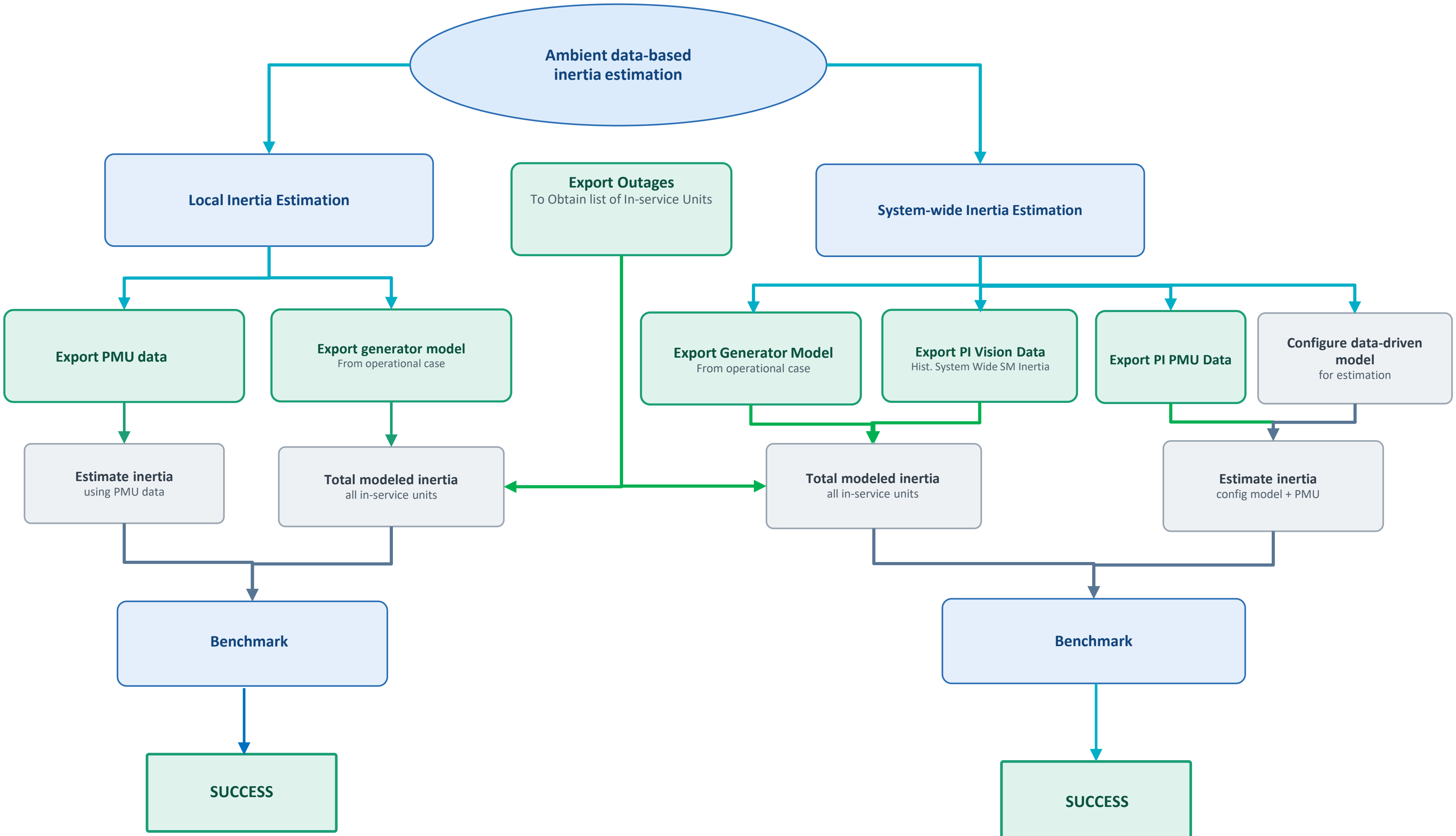
Where W_i is weight and S_i refers to total base MVA of nearby units.

ERCOT Verification:

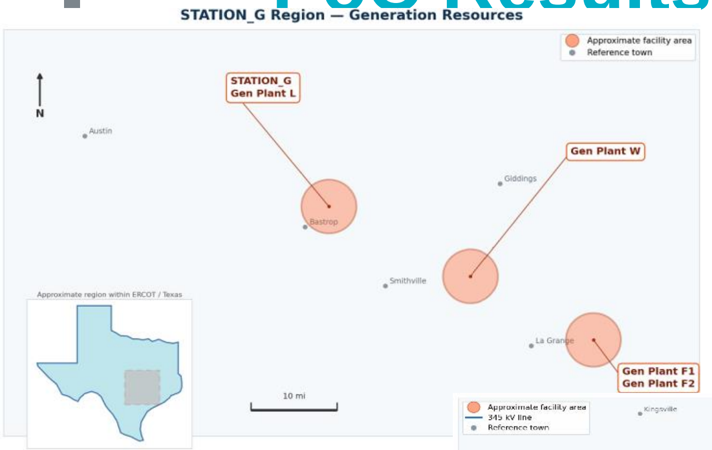
1. Using TSAT dynamic file to find modeled inertia constant of different units.
2. Refer to scheduled and forced outage databases to identify in-service units
3. Tally modeled inertia of in-service generators by summing the product of inertia constant H_i and rated MVA S_i.

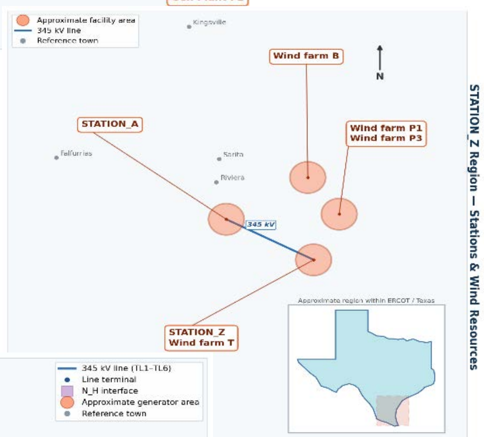
PoC Procedure - Inertia Estimation

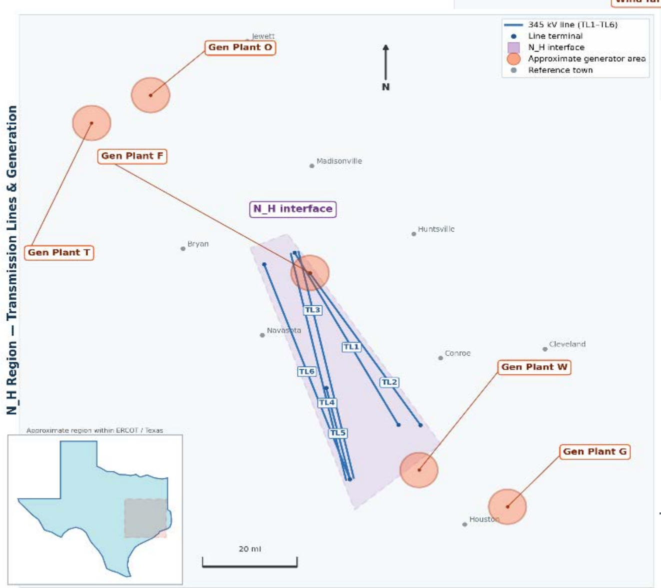
PMU-data and generator-model exports feed both local and system-wide inertia estimation; estimation benchmark with total modeled inertia tallied from in service units



PoC Results – Local Inertia Estimation







Local Inertia Estimation:

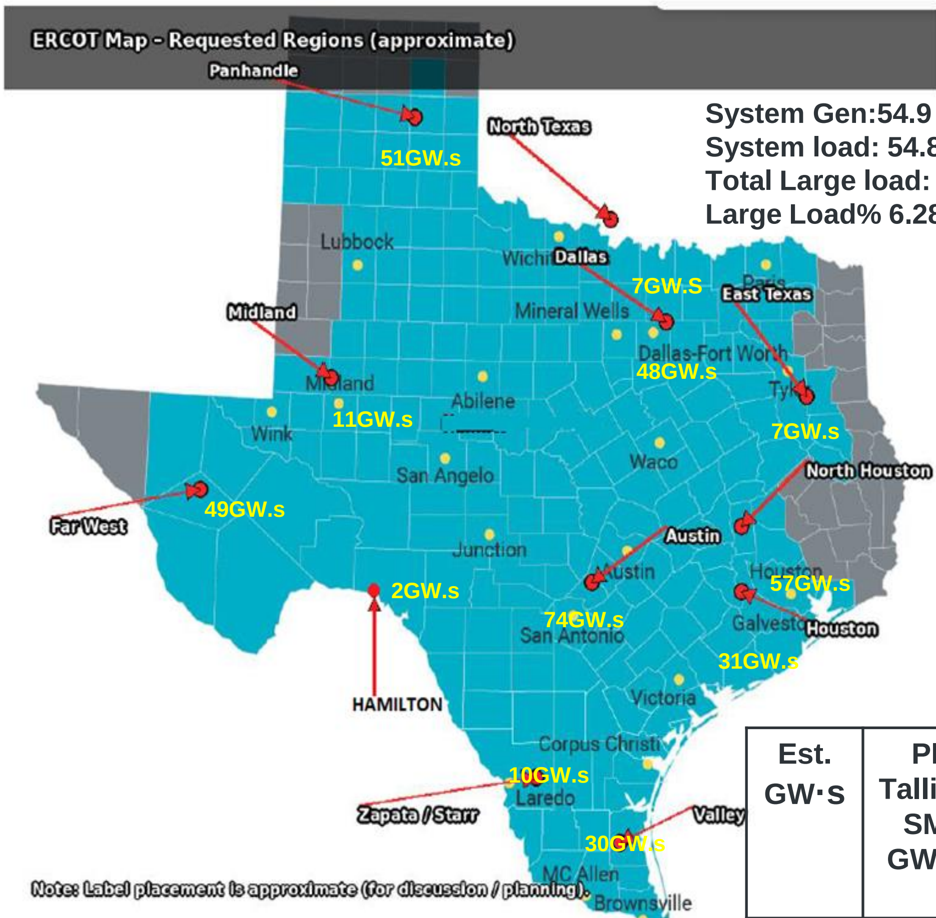
- **STATION_G:** all in service transmission lines selected to form the power path as for estimating inertia contributed by regional synchronous machines.
- **STATION_A:** STATION_A line to gulf coastal wind farms selected to form the power path for estimating inertia contributed by radial interconnected wind units.
- **Region N_H:** Critical path interconnecting 17 synchronous generation plants

Despite minor PMU data gaps and noise, the estimated inertia was within 8% of the tallied value.

Station	Units/Plants modeled	Units Online	Tallied Total MW·S	Estimated Average MW·S	Error Rate %
G	13	12	9504	10165	6.95
Z	7	6	5818	5396	7.25
N_H	17	13	53427	57000	6.74

$$Error\% = \frac{|Estimated\ Average - Tallied\ Total|}{Tallied\ Total} \cdot 100\%$$

PoC Results - System Wide Inertia Estimation



System Gen:54.9 GW
System load: 54.8GW
Total Large load: 3.44 GW
Large Load% 6.28%

Estimation used:
1. PMU data captured on an afternoon of January, dropouts <=5%
2. Power paths configuration consisting of 12 critical regions based on ERCOT GTC definitions

ERCOT verification used:
1. PI vision data which estimate inertia by tallying modeled H constant from all in-service synchronous machines
2. TSAT dynamic file that documents inertia constants of wind units
3. Outage database that recorded all in service wind units

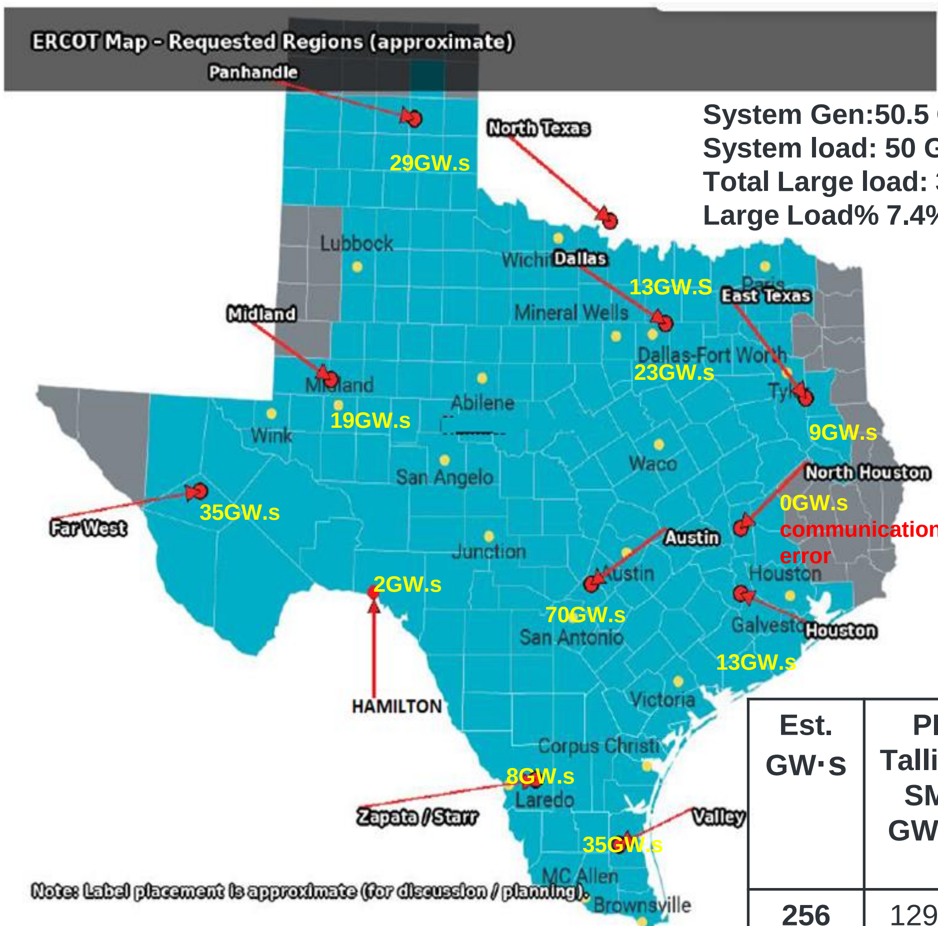
$$Error\% = \frac{|Estimated\ Average - Tallied\ Total|}{Tallied\ Total} \cdot 100\%$$

Estimation completed using 5-minute window

Est. GW·s	PI Tallied SM GW·s	Model Tally Type I and II Wind GW·s	Model Tally Type III Wind GW·s	Model Tally USDM GW.S	Model Tally Type IV Wind GW.S	Tallied Total	Error Rate
377	*283*	*16.8*	*28.6*	*25.2*	*18*	**372**	1.3%

60% of Type III plus 90% of Type IV wind units have plant control models
Estimated system-wide inertia matches well with tallied value despite PMU dropouts

PoC Results - System Wide Inertia Estimation



System Gen:50.5 GW
System load: 50 GW
Total Large load: 3.7 GW
Large Load% 7.4%

Estimation used:
1. PMU data captured on a high renewable penetration day in March, dropouts <=5%
2. Renewable penetration>80%

ERCOT verification used:
1. PI vision data which estimate inertia by tallying modeled H constant from all in-service synchronous machines
2. TSAT dynamic file that documents inertia constants of wind units
3. Outage database that recorded all in service wind units

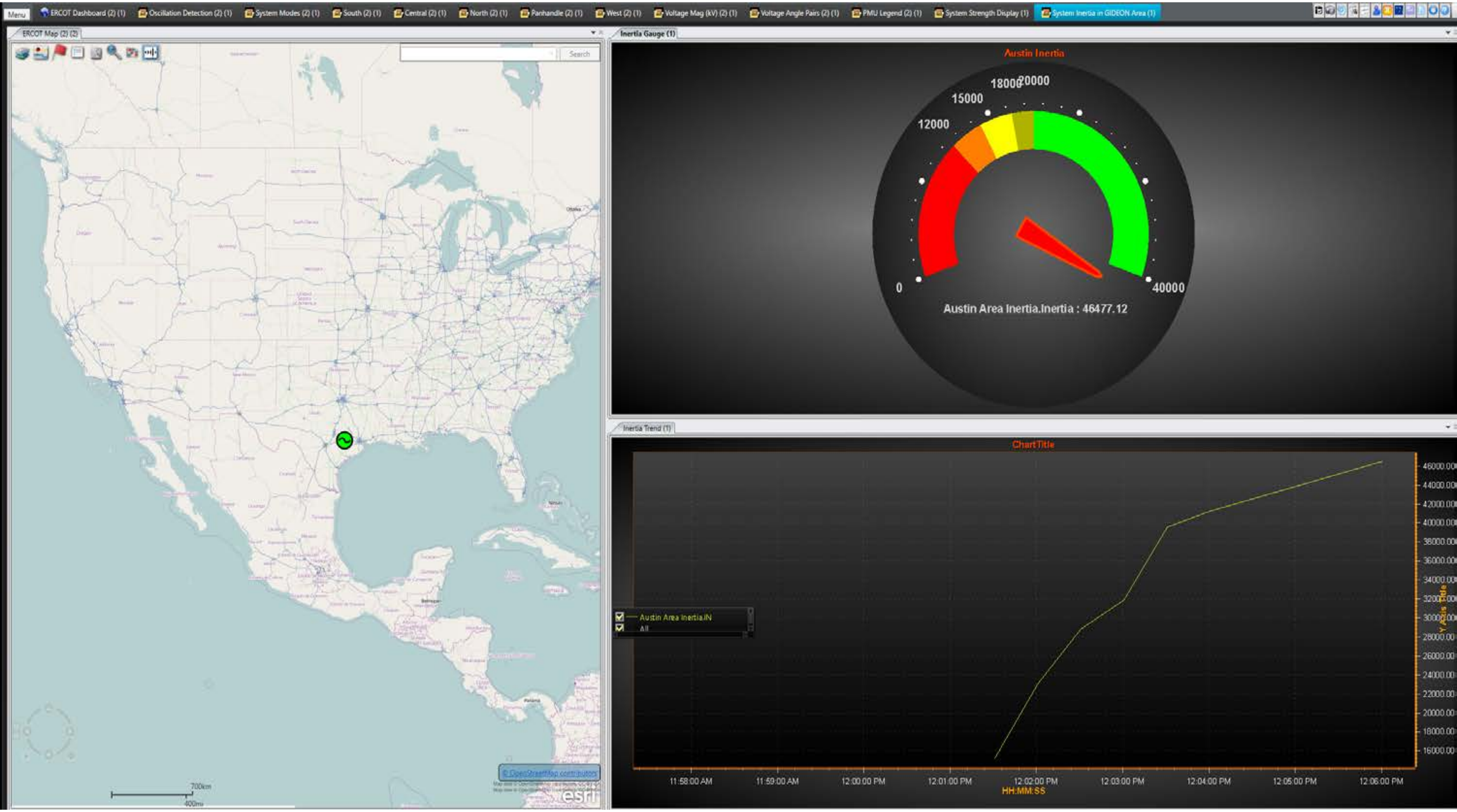
$$Error\% = \frac{|Estimated\ Average - Tallied\ Total|}{Tallied\ Total} \cdot 100\%$$

Estimation completed using 5-minute window

Est. GW·s	PI Tallied SM GW·s	PI tallied SM GW·s in N_H	SM GW·s minus N_H area	Model Tallied Wind GW·s	Total Tallied GW·s minus N_H area	Error Rate
256	129.5	21.9	*107.6*	*142.7*	**250.3**	2.3%

60% of Type III plus 90% of Type IV wind units have plant control models
Estimation excluded N_H region due to communication error
Estimated system-wide inertia matches well with tallied value despite PMU dropouts

Client Display-Real-time Inertia Estimation



PoC Summary and Action Items - Inertia Estimation

Summary

1. Without deploying extra PMUs, Inertia estimation methodology delivered robust and accurate results despite PMU data noises and dropouts.

2. Estimated system-wide inertia is slightly larger than tallied number due to inertia contribution from non-generator devices and purchased services.

3. Estimation included fast frequency response and droop response from Type III and Type IV wind farms and currently no way to separate them from synchronous inertia.

Action items

1. Hardware and software enhancements to allow constant real-time streaming and visualization of inertia estimation.

2. Baseline and configure real-time inertia alarms.

3. Methodology enhancements to ensure robust estimation under less ideal measurement conditions.

4. Explore means to differentiate torque inertia from synthetic inertia

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