

Scalable Implementation and Deployment Of RTLSE and RTLSE-based Contingency Analysis for Transmission Systems

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Outline

- ✓ Introduction

- ✓ Real-time State Estimator
 - ✓ Overall view
 - ✓ Scalability and Robustness
 - ✓ Results and displays

- ✓ RTLSE complementary tools
 - ✓ Contingency Analysis
 - ✓ Optimal PMU Placement

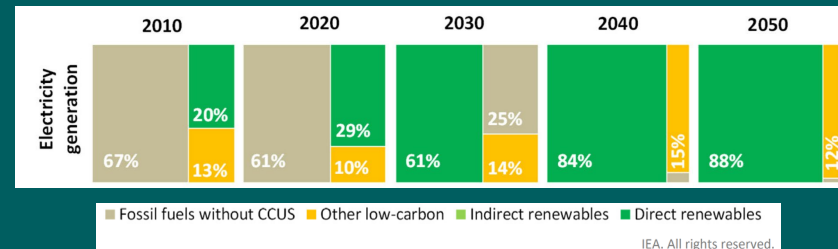
- ✓ Conclusion

INTRODUCTION

Landscape Change- Need for Scalability and High-Performance Platforms

Higher Renewables Penetration

- ✓ Need for higher resolution visibility and faster agility to monitor and manage the grid.
- ✓ Greater and regional variability in frequency (due to reduced/sparse inertia)
- ✓ Grid operating closer to its stability limits (frequency and voltage)



Need for Better Visibility and Higher Agility

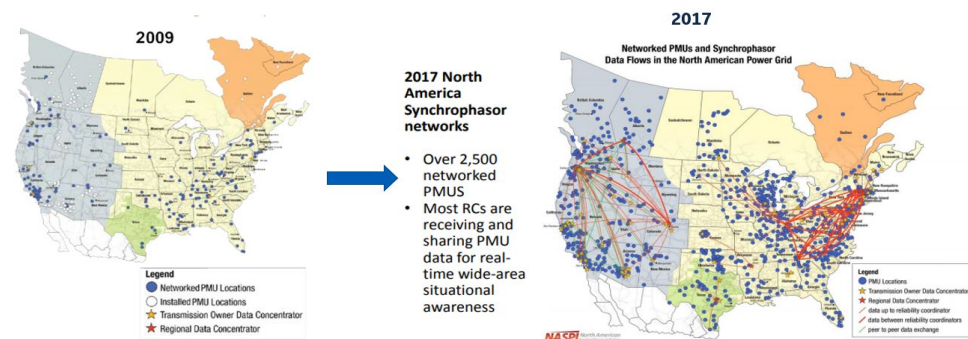
Accelerated Adoption of WAMS sensors

- ✓ Customer field installations growing from 100s → 1000s (e.g. ONS, Brazil 1000+ ; PowerGrid, India 2500+)
- ✓ Multifunctional IEDs (such as Relays & Fault Records) capable of providing WAMS data.

There is a need for application with:

- Higher Performance
- Scalability
- Flexibility and Agility
- Modularity and Extensibility
- Additive Solution

Changing Landscape



200 Sensors → 2500+ Networked Capable Devices

REAL-TIME STATE ESTIMATOR

Real-time Linear State Estimator

Comply with **NERC IRO-008-2 R4** and **TOP-001-4 R13** as **back-up** to existing **EMS State Estimation**.

- Tertiary real-time assessment solution
 - Leveraging WAMS -> Independent of data from EMS
 - Solves at incoming WAMS data rate; built-in error processing to ensure solution robustness
- Extends WAMS observability beyond existing infrastructure
- Detect and correct for erroneous/missing WAMS data

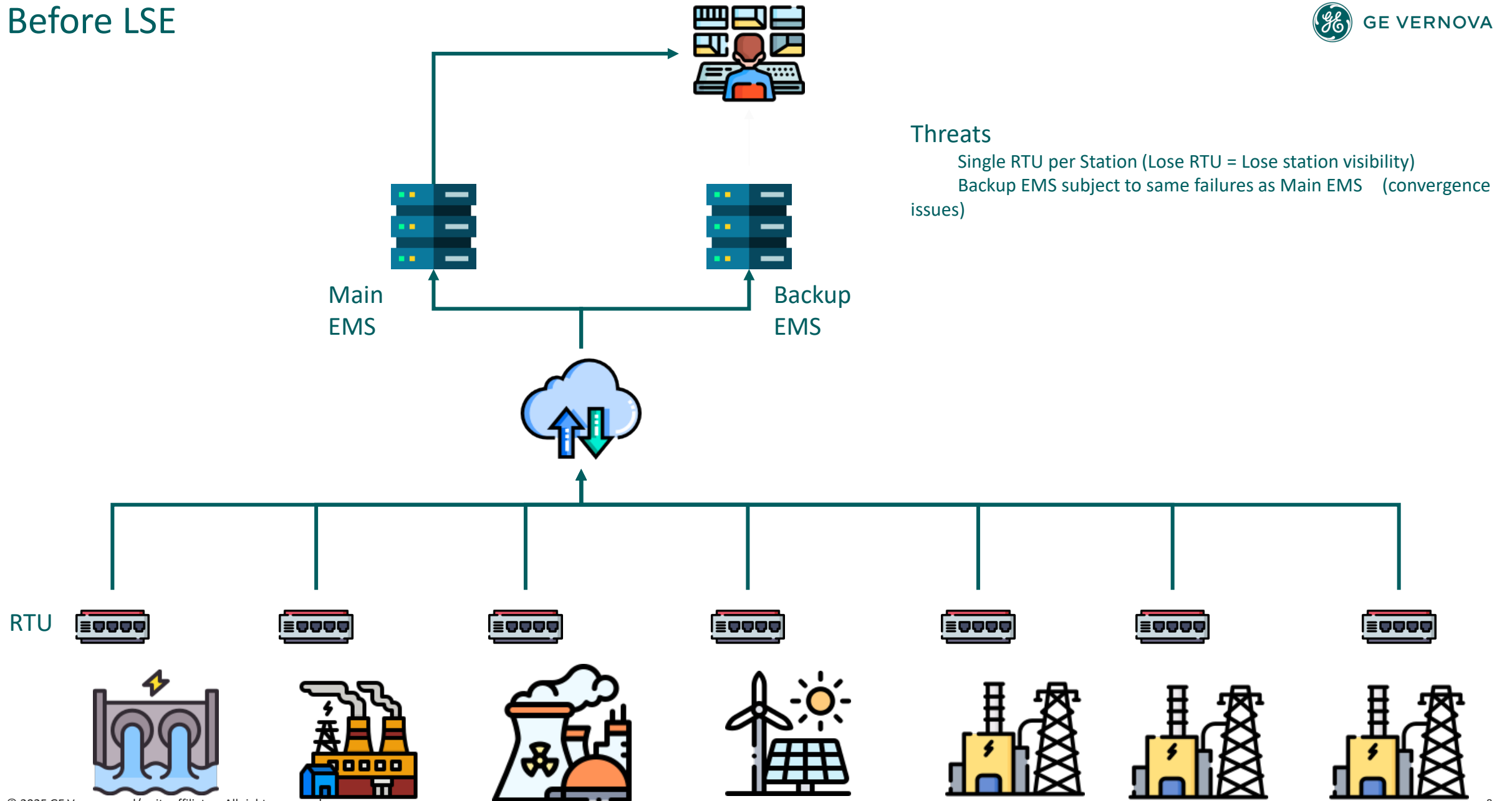


LSE versus Classic SE

Features	Linear State Estimator	Traditional State Estimator
100% Convergence	✓	
Linear Solution	✓	
Iterative Solution		✓
Sub-second results	✓	
Time synchronized measurements improving solution quality	✓	
Alternative data source for CA and Dynamic Stability Assessment	✓	
Official data source for CA and Dynamic Stability Assessment		✓

- Approximately 30~40% PMU coverage needed to achieve observability
- LSE can be restricted to observability pockets or grid voltage levels for lower PMU coverage

Before LSE

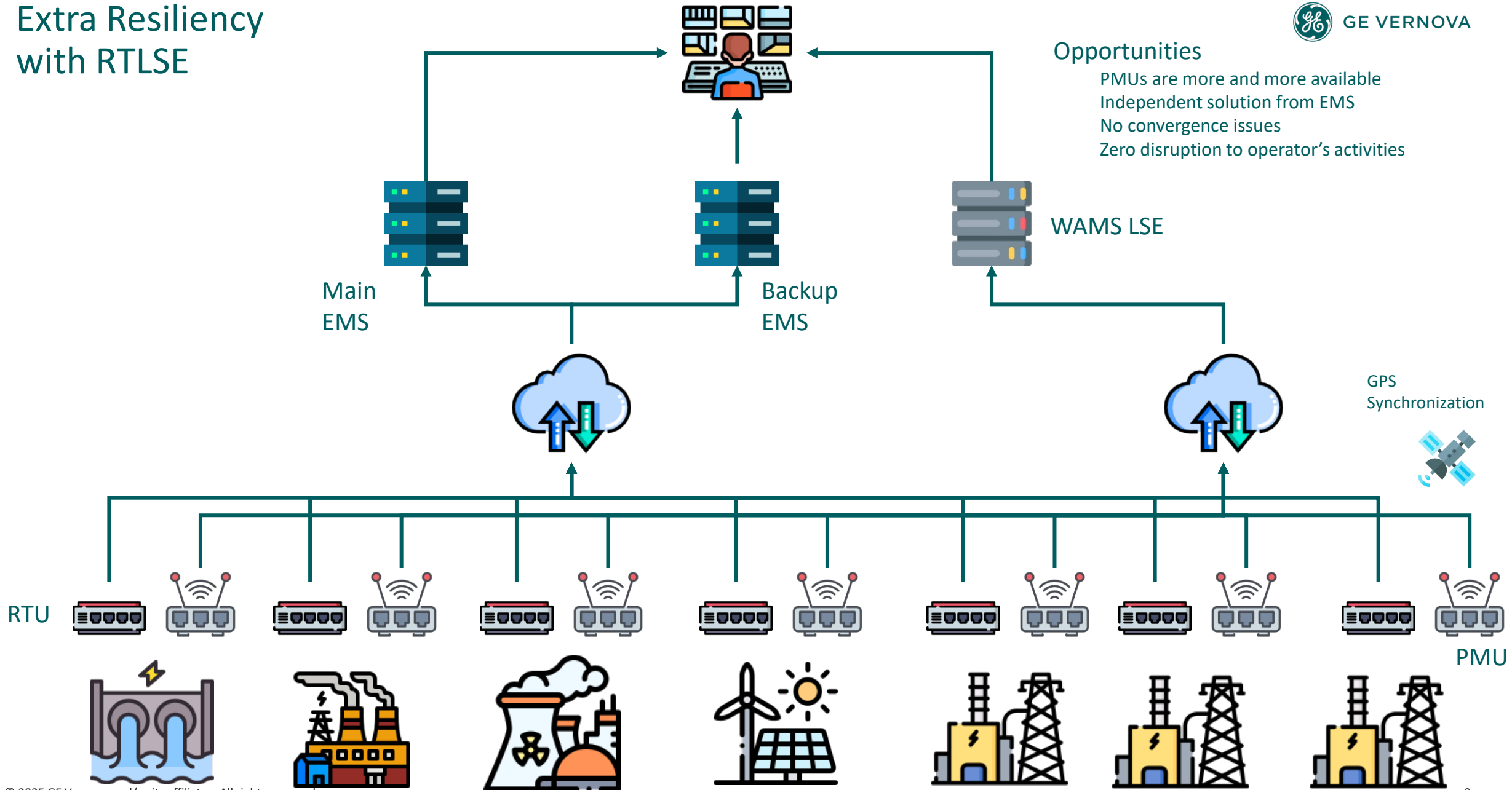


Threats

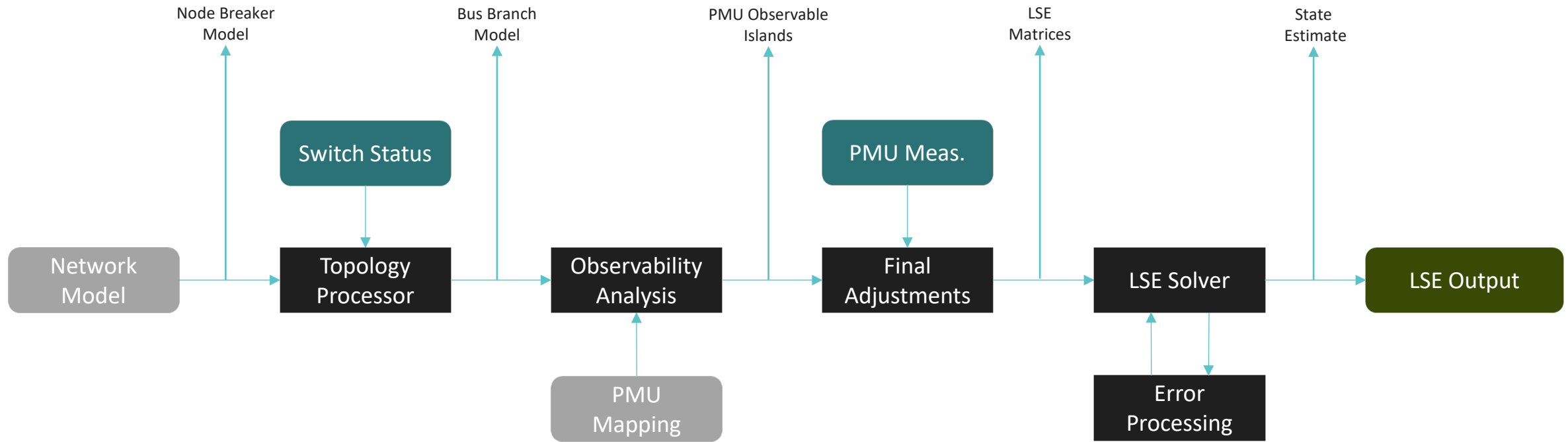
Single RTU per Station (Lose RTU = Lose station visibility)

Backup EMS subject to same failures as Main EMS (convergence issues)

Extra Resiliency with RTLSE

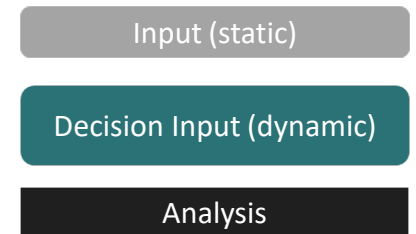


LSE Solution Workflow



Generic LSE Solution Workflow

- ✓ Utilizes phasor measurements from PMUs
- ✓ Linear Problem, non-iterative solution
- ✓ State estimates obtained at sub-second intervals



Scalability and Robustness



Architecture

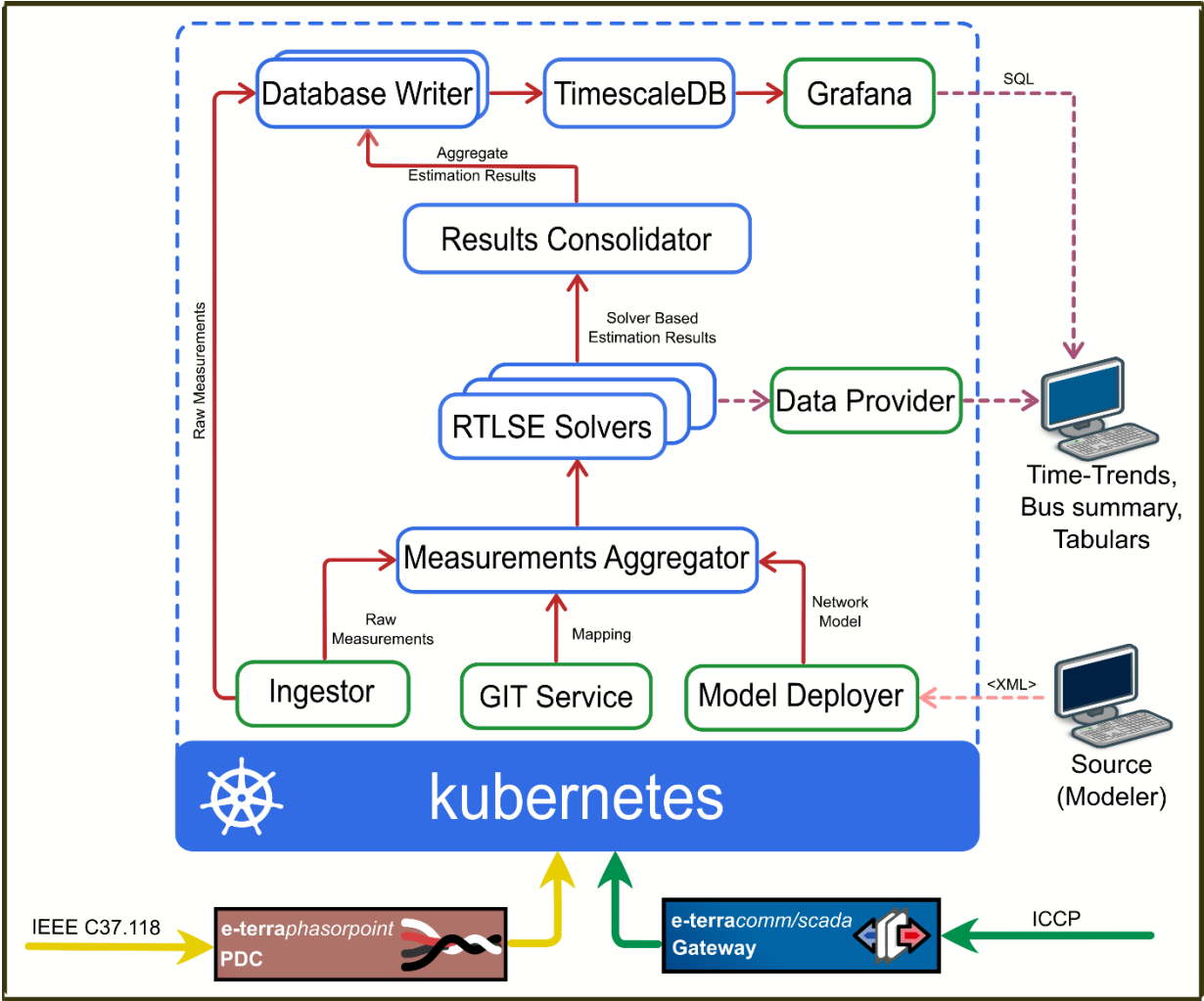
- Solution offered as a set of microservices
- Orchestration of services is handled by Kubernetes
- Horizontally scalable, individually upgradable
- Parallelization

Highlights

- Speed : Keeping up with real-time PMU streaming rate
- Robustness : Efficient and thorough error processing
- Backup to EMS classic State Estimator

Performance:

- Successfully validated sub-second performance with large-scale utility model.
- Deployed (and in process of deployment) for multiple customers
- Parallelization- Scale up LSE solvers to keep up with increasing PMU deployments
- Different Run-Time Optimizations



RTLSE Architecture

RT-LSE Results (major US ISO)

PMU Datasets

Three datasets were created based on provided PMU data –

- **Set A:** PMU Data As Is
- **Set B:** Cleaned data after removing 14 phasors with highest number of gaps
- **Set C:** Subset of data (timestamp based) with no data quality changes

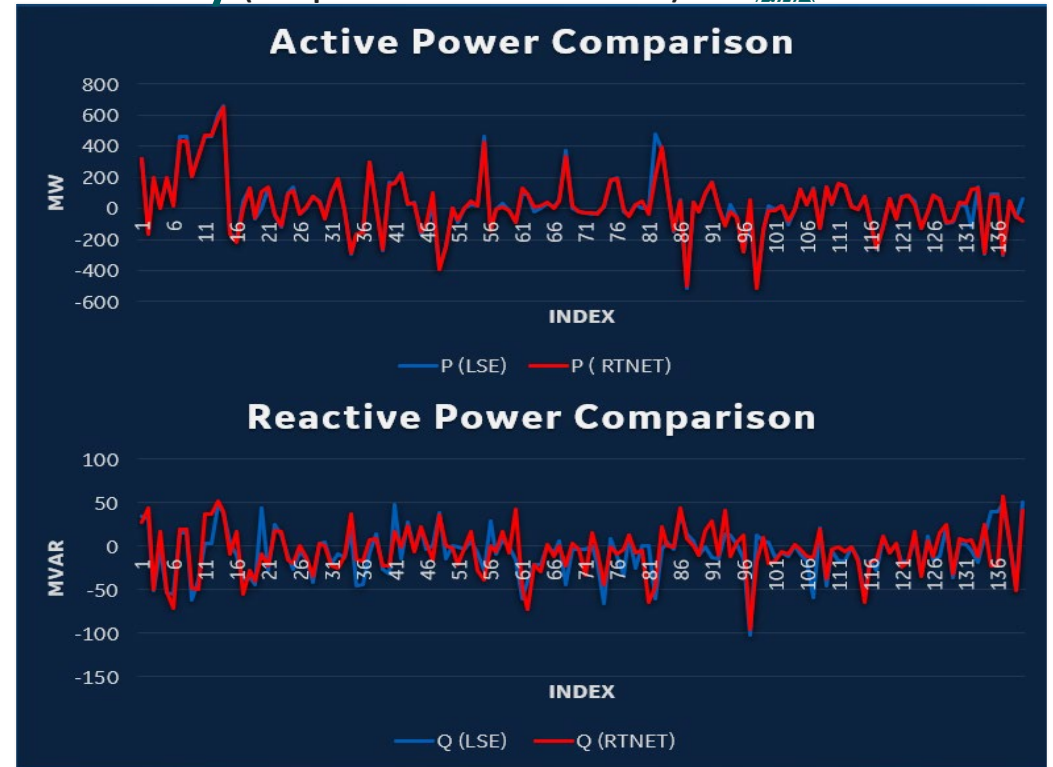
Performance

Dataset	Set A	Set B	Set C
No. of input phasors	396	382	396
Total Time	783.335 (s)	520.460 (s)	297.115 (s)
Avg. Time / Cycle	43.542 (ms)	28.930 (ms)	16.515 (ms)
Avg. Cycles / Second	22.966	34.566	60.551

Machine Specifications → Operating System: Windows 10 Pro, Processor: Intel® Xeon® E-2176M CPU @ 2.70 GHz 2.71 GHz, Installed Memory (RAM): 64.0 GB

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Accuracy (Comparison of LSE with EMS SE)



Customers with RTLSE in their GridOS WAMS Portfolio:



LSE Displays

Navigation Tabs (Summary, Violations, Observability, Trends)

Network Violation Summary

Network Observability Summary

Solution Cost Index

Application Health Indicators

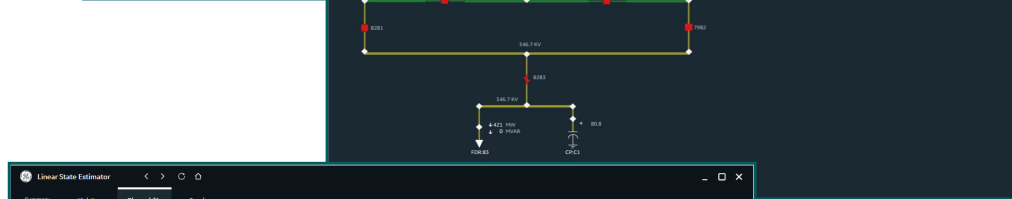
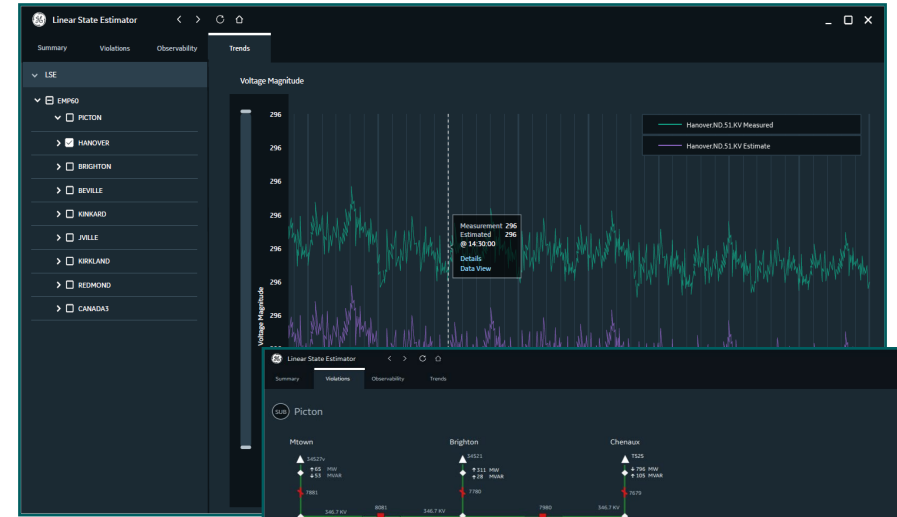
Alarm Messages

Bus	Line	Transformer	Interface
9	13	8	2

Island No.	Topological Island	Observable Buses	Voltage Measurements	Current Measurements	Error Processing Success
1	1	85	76	92	True
2	1	23	21	28	False

Measurement Type	Total Mapped	Data Quality Bad	Used	LSE Bad
1	1	85	76	92
2	1	23	21	28

High	Medium	Low
3	2	2



Filter Name	Company	Island Topological	Observable	Status	Base Voltage	Device Type	Device Name	Phase Name	Measured Magnitude	Estimated Magnitude	Measured Angle	Estimated Angle
Company 1	1	1	Beville	500	Bus	NR12	Voltage Phasor - NR12	506.32	505.74	-12.28	-12.67	
Company 1	1	1	Beville	500	Bus	BR10	Voltage Phasor - BR10	482.17	505.74	-12.14	-12.67	
Company 1	1	1	Beville	345	Bus	C2	Voltage Phasor - C2	344.67	345.27	-11.98	-11.74	
Company 1	1	1	Beville	345	Bus	Z1	Voltage Phasor - Z1	344.11	345.27	-11.71	-11.74	
Company 1	1	1	Beville	118	Bus	IR5	Voltage Phasor - IR5	118.74	118.74	-15.06	-15.06	
Company 1	1	1	Beville	14	Bus	BR51	Voltage Phasor - BR51	11.27	11.55	-14.71	-14.38	
Company 1	1	1	Beville	500	Bus	BR2	Voltage Phasor - BR2	118.54	345.27	-14.71	-14.38	

RTLSE COMPLEMENTARY TOOLS

RT-LSE Based Contingency Analysis

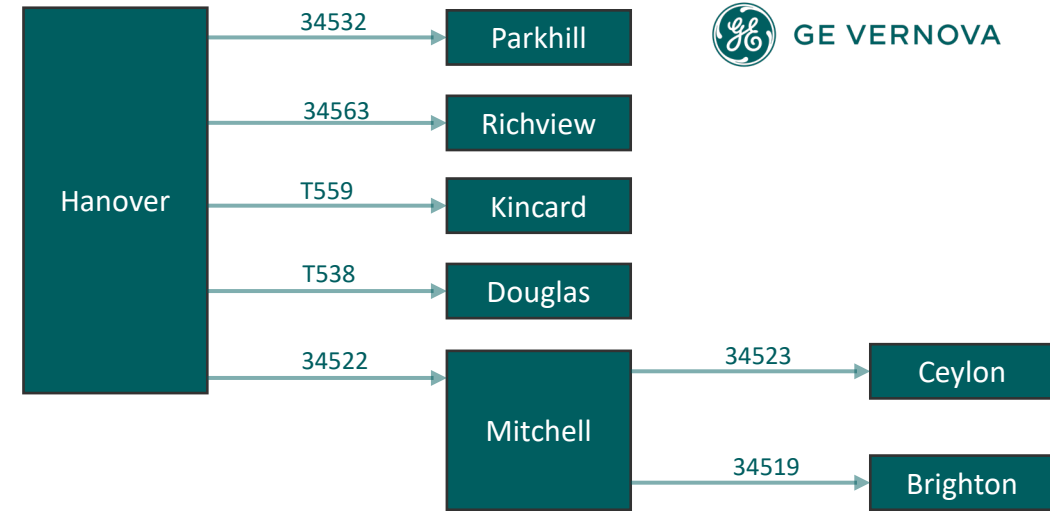
Key Challenges

- Limited PMU based observability – Often, only high KV level network observable
- Leads to incomplete basecase for traditional full Contingency Analysis
- Heavy network equivalencing needed to run CA → negative impact on the quality of the solution

Solution

- Sensitivity based contingency analysis
- No need of network equivalencing
- Automatically adjusts to PMU-observable region of the network

Local Network Connectivity



Results Comparison for Contingent Line 34532

Observed Element (Line)	Pre-Contingent MW Flows	Post-Contingent MW Flow		
		RT-LSE + Sensitivity Based	Power Flow Result	Delta (%)
34563	38.71	84.35	83.9	0.53
T559	-324.94	-324.94	-319.7	1.61
T538	-185.52	-185.52	-188.1	-1.39
34522	-131.12	-84.91	-83.9	1.19
34523	96.31	121.25	122.1	-0.70
34519	-227.58	-206.31	-206.1	0.10

All flows are reported on FROM side.

RT-LSE Based Contingency Analysis

Q Search or jump to... ctrl+k

Home > Dashboards > LODF Results

~ LSE - LODF

LODF Results

timestamp	contingency_equip	monitored_equipment_id	pre_mw	lodf	post_mw	observable	violation_level	violation	last_topology_run	model_version
2025-04-04 12:45:00	ddbe7d9b-89cf-4ce7-81b10d9a-217f-4dc2-80b9-4f044a46a615	81b10d9a-217f-4dc2-80b9-4f044a46a615	531	-0.0600	503	true	EMERGENCY_LOW	600	2025-04-04 08:45:11	WamsCommonModel_
2025-04-04 13:21:00	81b10d9a-217f-4dc2-80b9-4f044a46a615	ddbe7d9b-89cf-4ce7-a855-59ae767122a2	-450	-0.0903	-497	true	LOADSHED_LOW	300	2025-04-04 08:45:11	WamsCommonModel_
2025-04-04 13:21:00	81b10d9a-217f-4dc2-80b9-4f044a46a615	ddbe7d9b-89cf-4ce7-a855-59ae767122a2	452	-0.0903	405	true	UNKNOWN	0	2025-04-04 08:45:11	WamsCommonModel_
2025-04-04 13:21:00	81b10d9a-217f-4dc2-80b9-4f044a46a615	d1c9f5c5-4f06-4f2e-aef3-e85292172711	-195	0.0449	-171	true	LOADSHED_LOW	500	2025-04-04 08:45:11	WamsCommonModel_

Contingency Elements

mrid	composite_id	name	type
81b10d9a-217f-4dc2-80b9-4f044a46a615	NEPOOL.EAST.T559.1	1	AC_LINE_SEGMENT
ddbe7d9b-89cf-4ce7-a855-59ae767122a2	NEPOOL.NORT.34532.1	1	AC_LINE_SEGMENT

Monitored Elements

mrid	composite_id	name	type
072bff3f-87f7-4924-9f0c-e9293f90dfd8	NEPOOL.EAST.34591.1	1	AC_LINE_SEGMENT
81b10d9a-217f-4dc2-80b9-4f044a46a615	NEPOOL.EAST.T559.1	1	AC LINE SEGMENT

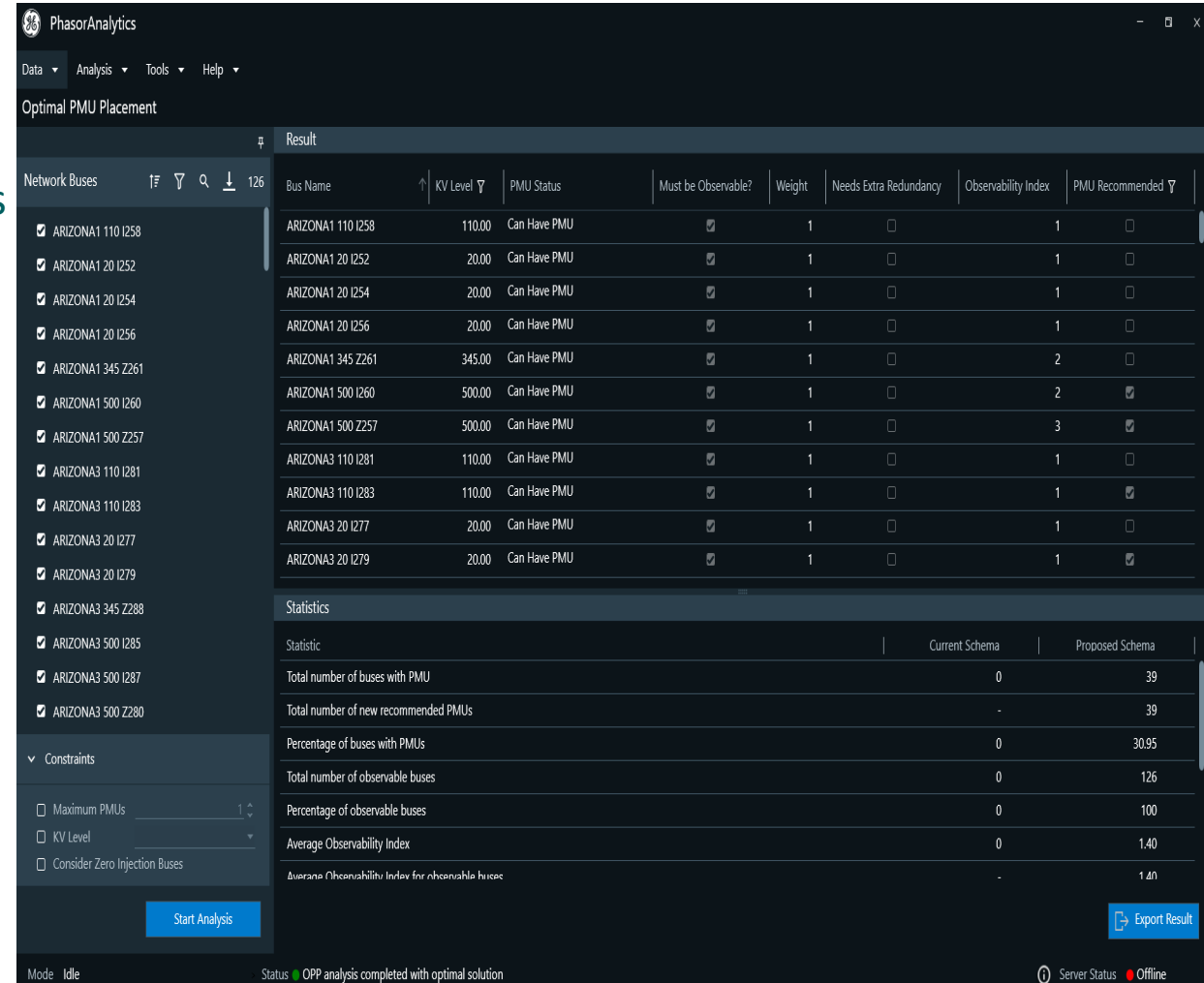
Results

Contingency List

Observable elements

Optimal PMU Placement

- Aims to achieve complete power system network observability with minimum number of PMUs
- Considers existing PMU placement in the solution process (*or prohibited buses*)
- Considers additional conditions like required level of redundancy for a particular network equipment
- Inputs:
 - Network Model (CIM16/PSSE)
 - Existing PMU deployment mapping information
- Output:
 - Number and location of new PMUs for complete system observability



Network Buses	Result							
	Bus Name	KV Level	PMU Status	Must be Observable?	Weight	Needs Extra Redundancy	Observability Index	PMU Recommended
<input checked="" type="checkbox"/> ARIZONA1 110 I258	ARIZONA1 110 I258	110.00	Can Have PMU	<input checked="" type="checkbox"/>	1	<input type="checkbox"/>	1	<input type="checkbox"/>
<input checked="" type="checkbox"/> ARIZONA1 20 I252	ARIZONA1 20 I252	20.00	Can Have PMU	<input checked="" type="checkbox"/>	1	<input type="checkbox"/>	1	<input type="checkbox"/>
<input checked="" type="checkbox"/> ARIZONA1 20 I254	ARIZONA1 20 I254	20.00	Can Have PMU	<input checked="" type="checkbox"/>	1	<input type="checkbox"/>	1	<input type="checkbox"/>
<input checked="" type="checkbox"/> ARIZONA1 20 I256	ARIZONA1 20 I256	20.00	Can Have PMU	<input checked="" type="checkbox"/>	1	<input type="checkbox"/>	1	<input type="checkbox"/>
<input checked="" type="checkbox"/> ARIZONA1 345 Z261	ARIZONA1 345 Z261	345.00	Can Have PMU	<input checked="" type="checkbox"/>	1	<input type="checkbox"/>	2	<input type="checkbox"/>
<input checked="" type="checkbox"/> ARIZONA1 500 I260	ARIZONA1 500 I260	500.00	Can Have PMU	<input checked="" type="checkbox"/>	1	<input type="checkbox"/>	2	<input checked="" type="checkbox"/>
<input checked="" type="checkbox"/> ARIZONA1 500 Z257	ARIZONA1 500 Z257	500.00	Can Have PMU	<input checked="" type="checkbox"/>	1	<input type="checkbox"/>	3	<input checked="" type="checkbox"/>
<input checked="" type="checkbox"/> ARIZONA3 110 I281	ARIZONA3 110 I281	110.00	Can Have PMU	<input checked="" type="checkbox"/>	1	<input type="checkbox"/>	1	<input type="checkbox"/>
<input checked="" type="checkbox"/> ARIZONA3 110 I283	ARIZONA3 110 I283	110.00	Can Have PMU	<input checked="" type="checkbox"/>	1	<input type="checkbox"/>	1	<input checked="" type="checkbox"/>
<input checked="" type="checkbox"/> ARIZONA3 20 I277	ARIZONA3 20 I277	20.00	Can Have PMU	<input checked="" type="checkbox"/>	1	<input type="checkbox"/>	1	<input type="checkbox"/>
<input checked="" type="checkbox"/> ARIZONA3 20 I279	ARIZONA3 20 I279	20.00	Can Have PMU	<input checked="" type="checkbox"/>	1	<input type="checkbox"/>	1	<input checked="" type="checkbox"/>
<input checked="" type="checkbox"/> ARIZONA3 345 Z288								
<input checked="" type="checkbox"/> ARIZONA3 500 I285								
<input checked="" type="checkbox"/> ARIZONA3 500 I287								
<input checked="" type="checkbox"/> ARIZONA3 500 Z280								

Statistic	Current Schema	Proposed Schema
Total number of buses with PMU	0	39
Total number of new recommended PMUs	-	39
Percentage of buses with PMUs	0	30.95
Total number of observable buses	0	126
Percentage of observable buses	0	100
Average Observability Index	0	1.40
Average Observability Index for observable buses	-	1.40

Conclusion

- The increasing number of deployed PMUs highlights the need for scalable and high-performance applications in modern power systems.
- RTLSE can serve as a backup to the traditional EMS state estimator, offering enhanced visibility and reliability.
- A scalable and high-performance implementation of RTLSE can be achieved through a Kubernetes-based microservices architecture, enabling flexibility and efficient resource utilization.
- RTLSE has been tested and is either deployed or in the process of being deployed by various utilities and ISOs.
- Complementary tools such as contingency analysis and optimal PMU placement further enhance the value and effectiveness of RTLSE.

THANK
YOU!
QUESTIONS?