A High-Fidelity Real-Time Cyber-Power Operation Testbed for Grid Resiliency and Security

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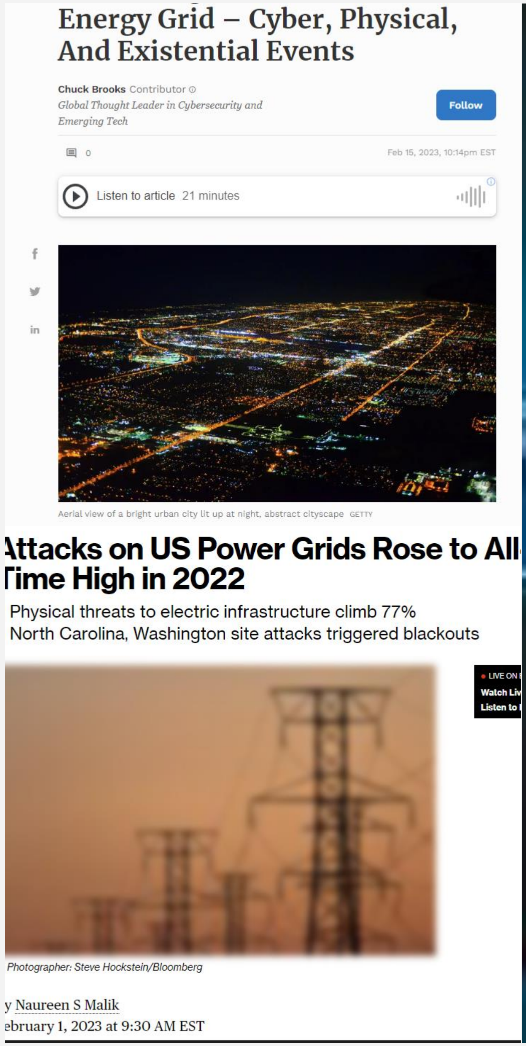
Real-time, **data-driven tools** supporting **wide-area monitoring and** providing **decision support to control room operators toward** better grid performance.

A grid that is resilient to adverse cyber-events


Energy Grid – Cyber, Physical, And Existential Events

Chuck Brooks Contributor
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Aerial view of a bright urban city lit up at night, abstract cityscape GETTY

Attacks on US Power Grids Rose to All-Time High in 2022

Physical threats to electric infrastructure climb 77%
North Carolina, Washington site attacks triggered blackouts

Photographer: Steve Hockstein/Bloomberg

y Naureen S Malik
ebruary 1, 2023 at 9:30 AM EST

TO IMPROVE RESILIENCY OF GRID

Tools for Cyber Resiliency

- Algorithms and tools for cyber anomaly detection, classification, localization, root cause analytics, and resiliency analysis

Testbed

- Validate algorithms and tools for deployment

AGENDA

- Physical Power System modelling
- Communication Network over Power system base layer
- Data Generation for machine learning and tool development
- Summary

POWER SYSTEM MODELING

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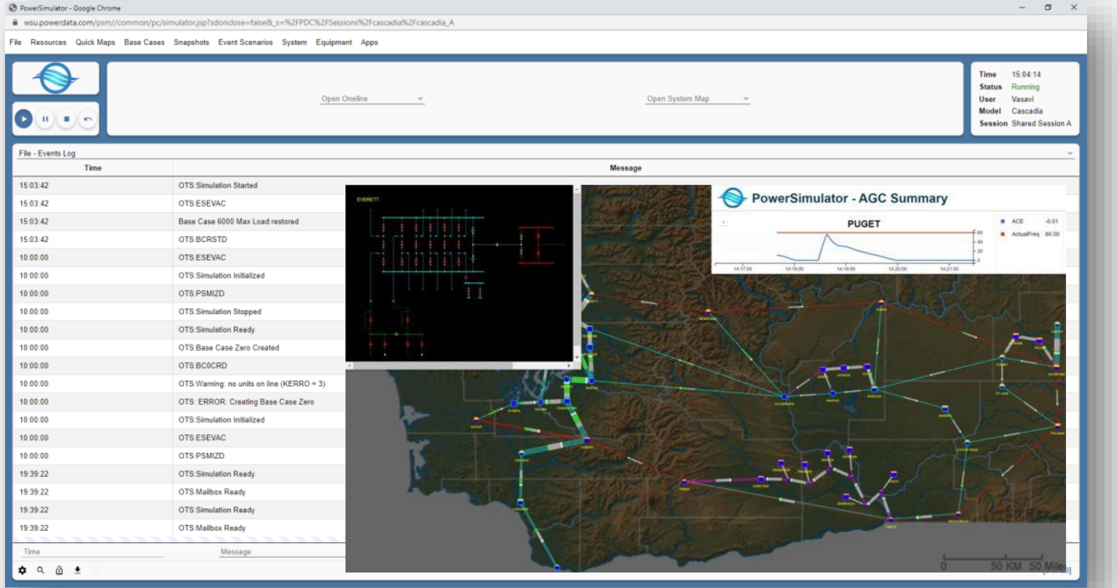
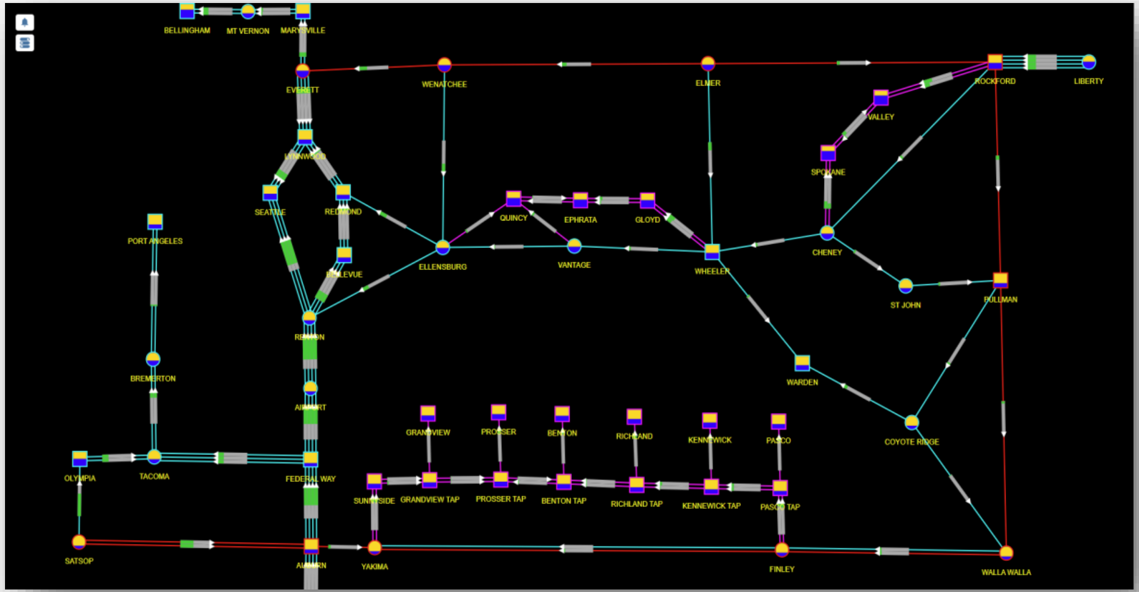
- Dynamic Model to Represent Field System: Electromagnetic model developed in RTDS
- Realistic Long-Term Dynamic Model in Control Room using PowerSimulator®– A realistic platform for power system operation and control developed by IncSys and PowerData.
- About PowerSimulator®: The Modeling and Simulation Solution with an Operator Training Simulator (OTS).
- Cascadia Test System: A power system model, congruent to the actual grid of Washington State with suitable modifications is also being developed in RTDS.



PowerSimulator® web user interface

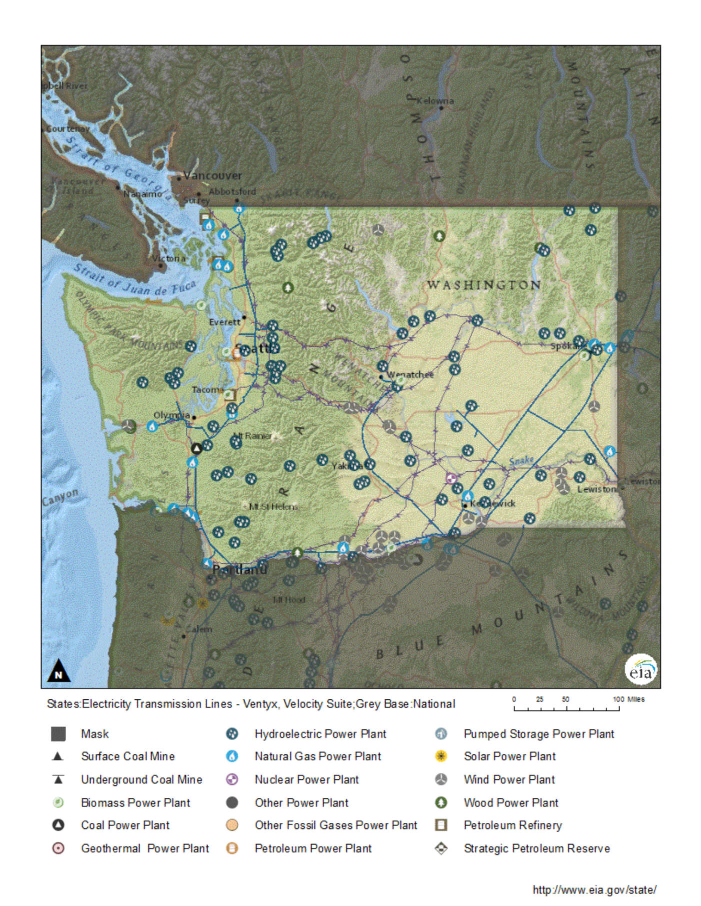


System Schematic-Cascadia power system model

CASCADIA POWER SYSTEM

HIGHLIGHTS

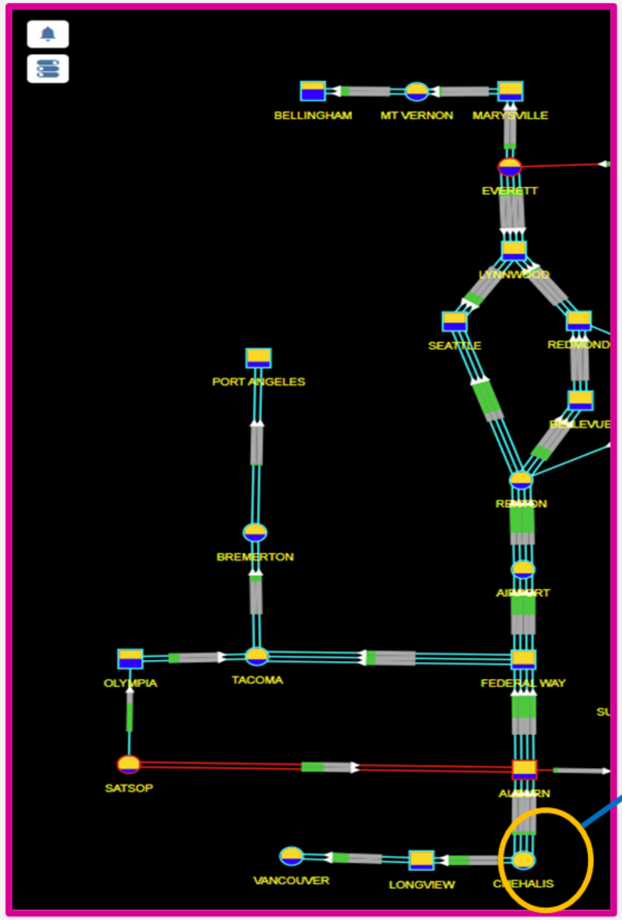
- Total number of sub-stations: 54
- With an overall 21 generating stations (mainly Hydro, Thermal, and Natural Gas)
- The Cascadia deals with power transfer through 115 KV, 230 KV, and 525 KV lines.
- Satsop is the largest generator and is set as the slack bus due to its power generation quantity of 2400 MW.
- The high-power flowlines of Cascadia are Auburn – Satsop (1877 MW), Airport- Renton (1503 MW) and etc.



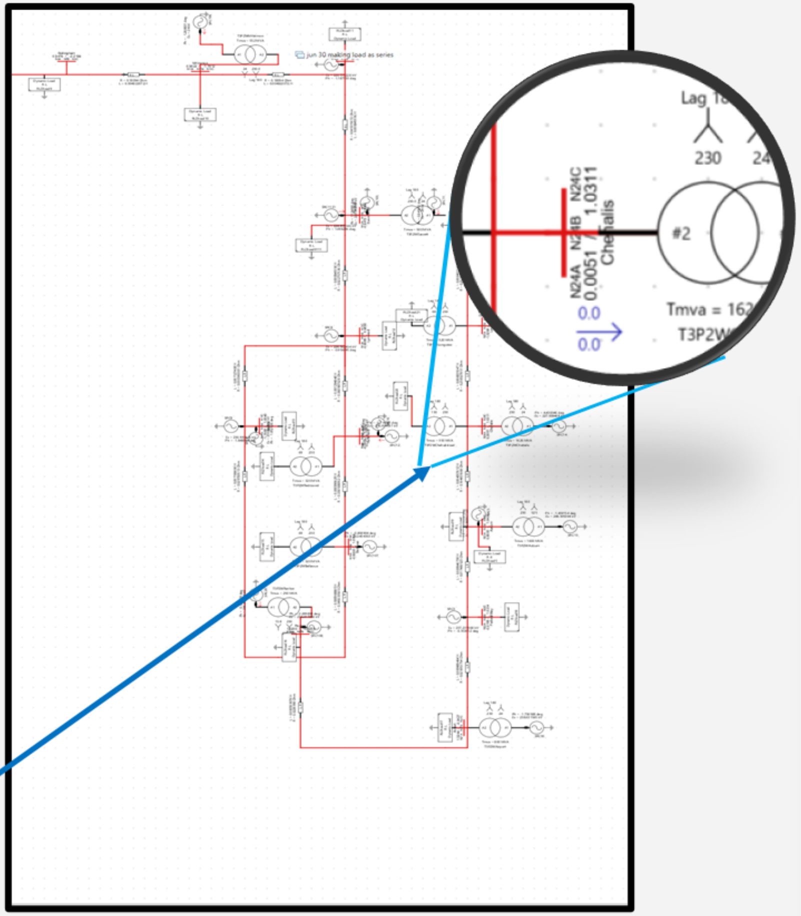
Test System Representing Washington State Area

WESTERN REGION OF CASCADIA MODELLED IN RTDS

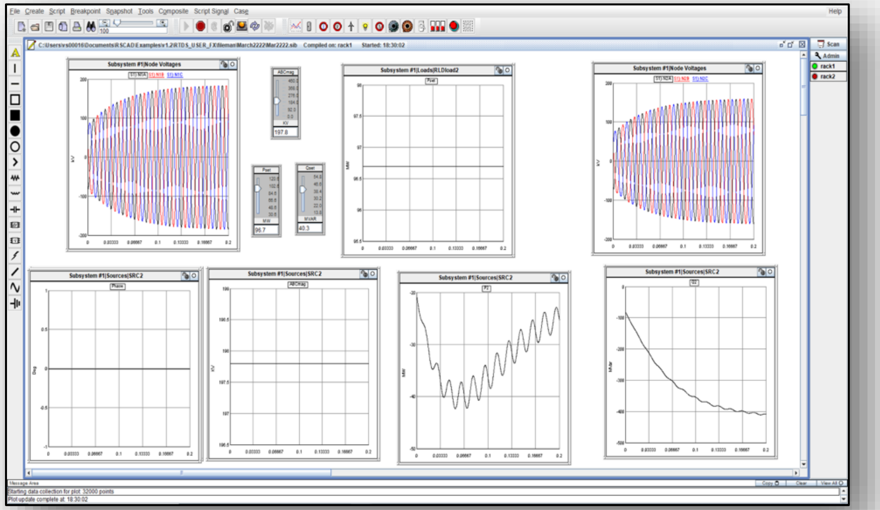
- The Power Flow converges after 6 iterations
- Real Power flow achieved identical to PowerSimulator®



Puget Region of Cascadia on PowerSimulator



Cascadia(Puget) on RTDS via RsCad Fx

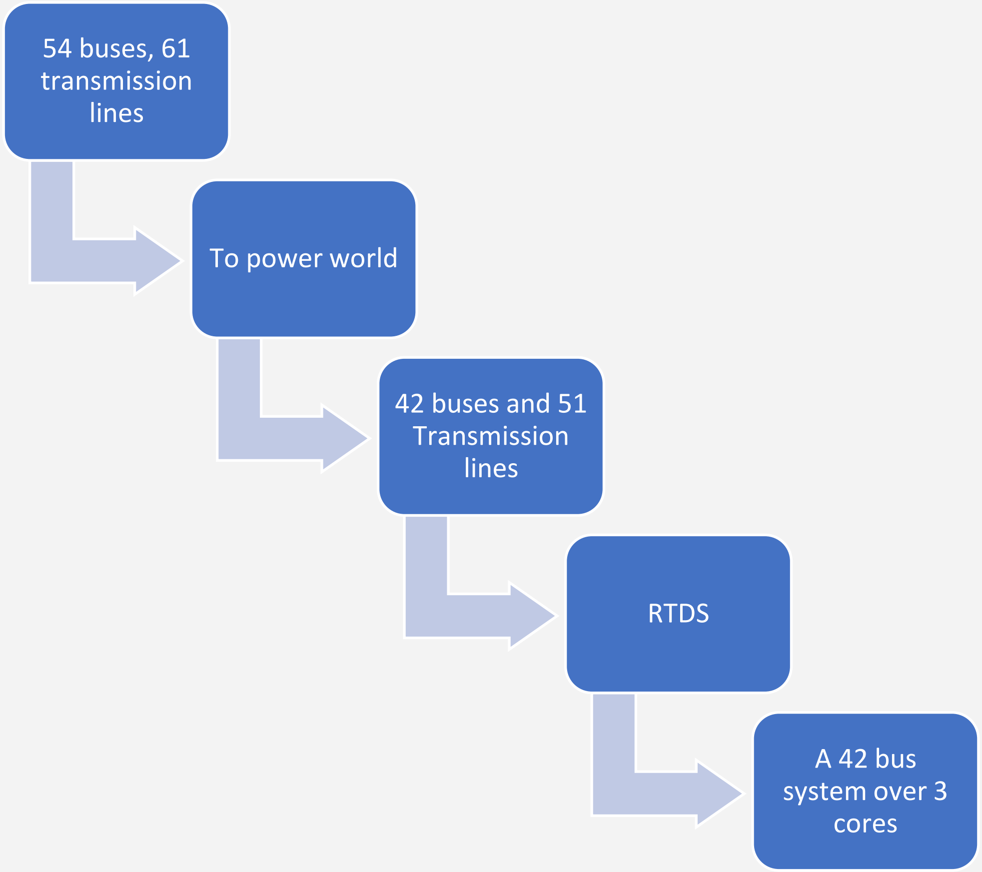


Voltage and Power wave forms from Mt Vernon substation in PUGET model on RTDS

COMPLETE SYSTEM MODEL WITH MODEL REDUCTION IN RTDS WITHOUT CHANGE IN SYSTEM SIMULATION OUTPUT

Challenge: System Model in RTDS should be same as System Model in Energy Management System (EMS)

Constraints: Limited Computing capability in RTDS

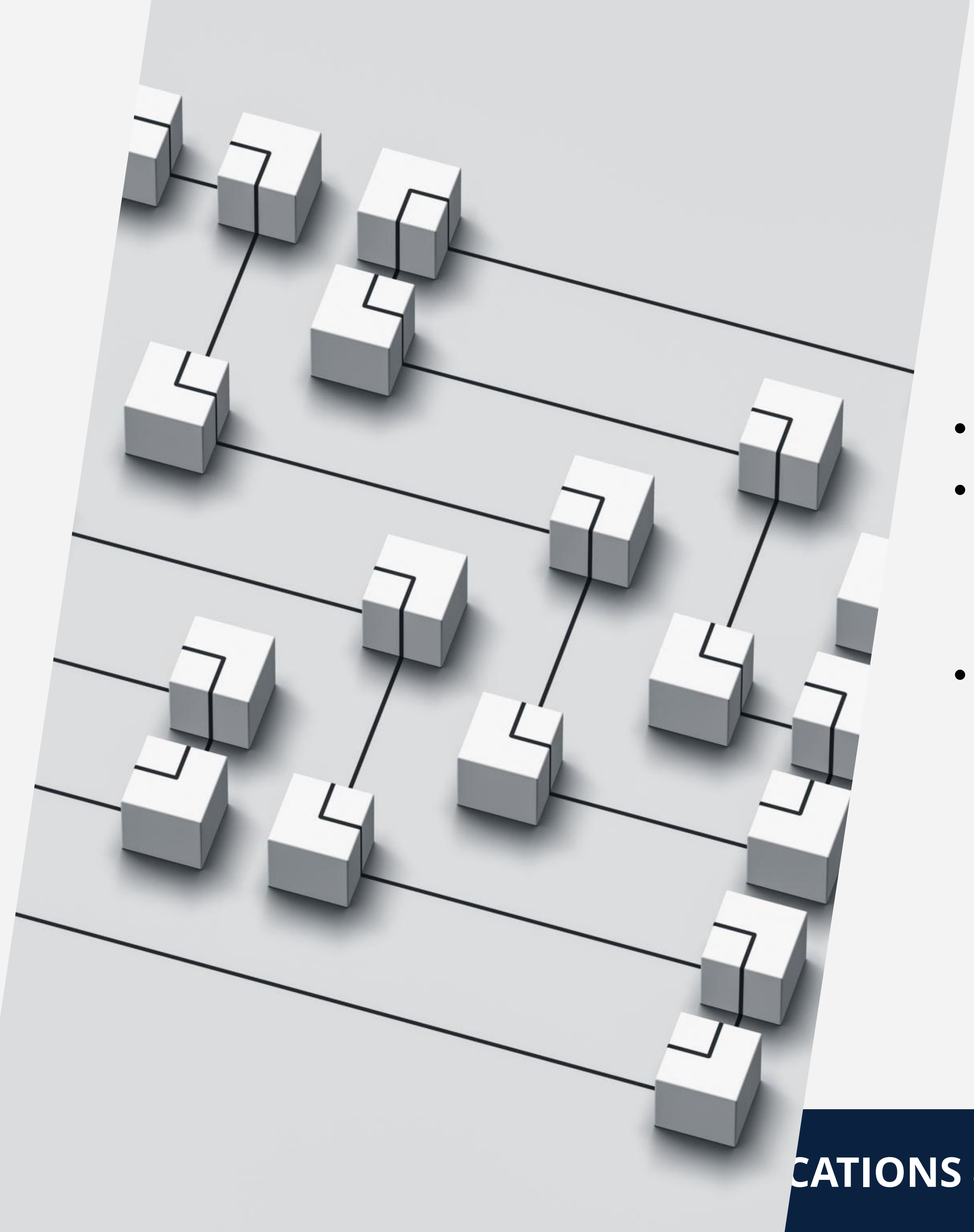


WHY A REDUCED MODEL ?

Having all buses at the same voltage level makes it easier to model on RTDS.

It avoids the insertion of transformers there by saves a lot of core space.

This reduced model is created in such a way that it exactly matches with the original(Incsys), yet it is much simpler.



HOW IT WAS REDUCED ?

- All parallel lines are eliminated
- Equivalent lines of 115 kV, 230kV and 525 kV is created and the base is kept at 230kV.
- Equivalent lines for all 115kV-230kV and 230kV-525kV transformers is introduced in the place of transformers.

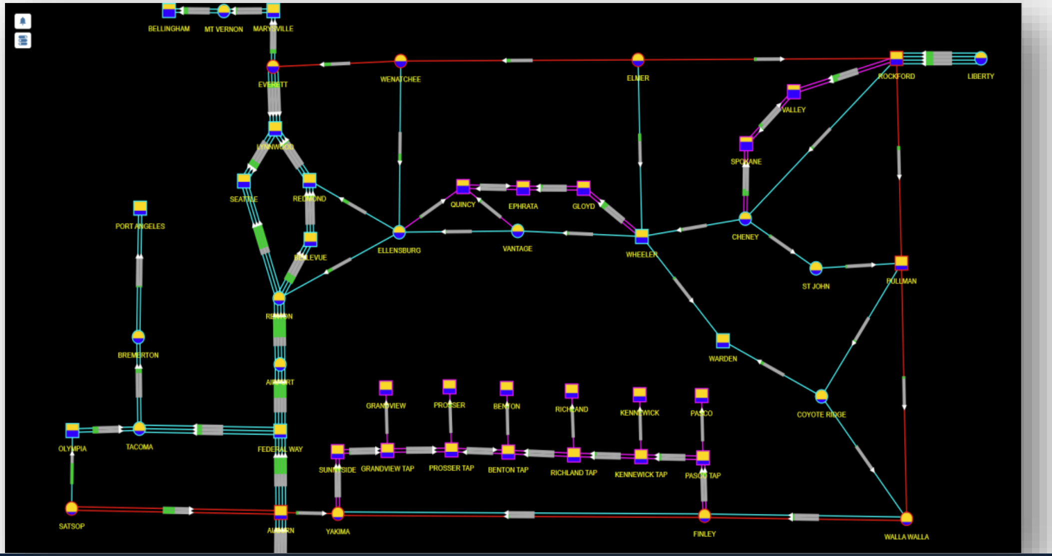
REDUCED CASCADIA MODEL ON RTDS

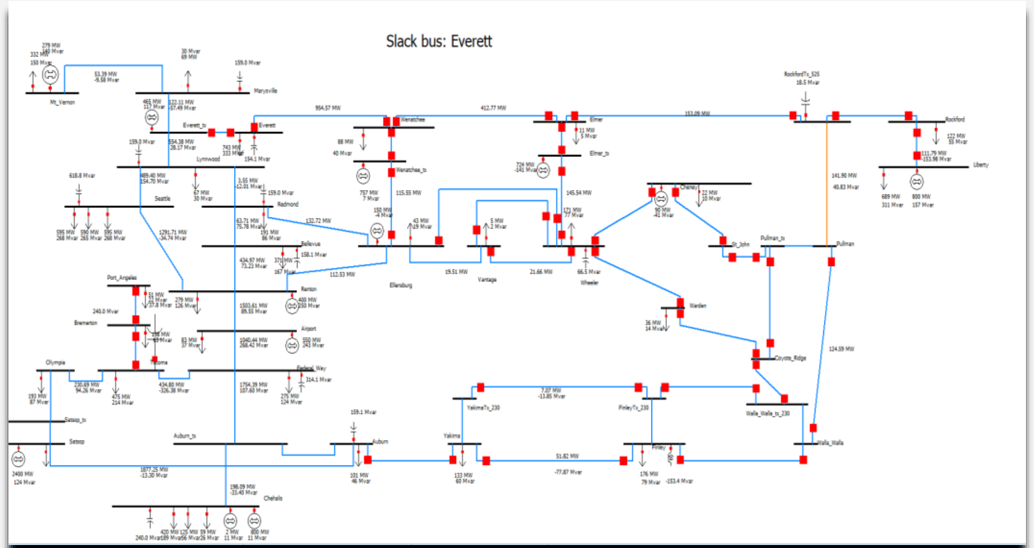
Challenge :

The reactive power limit was not strictly enforced in Incsys which led to power flow discrepancy.

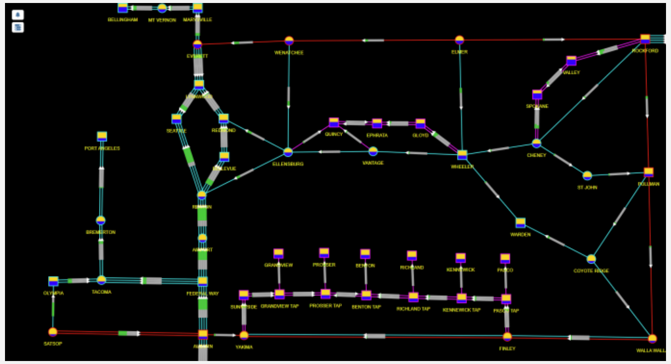
Solution :

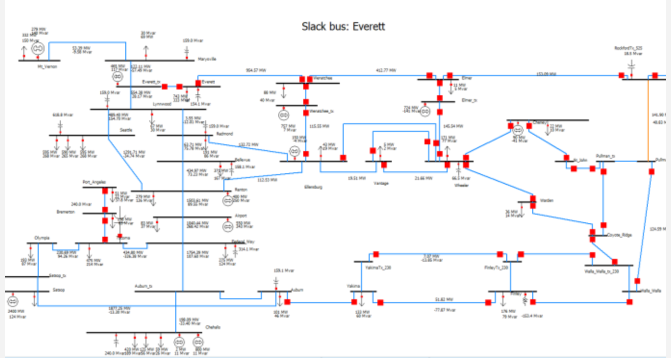
System modified and reduced for power flow matching between Incsys and Power World.

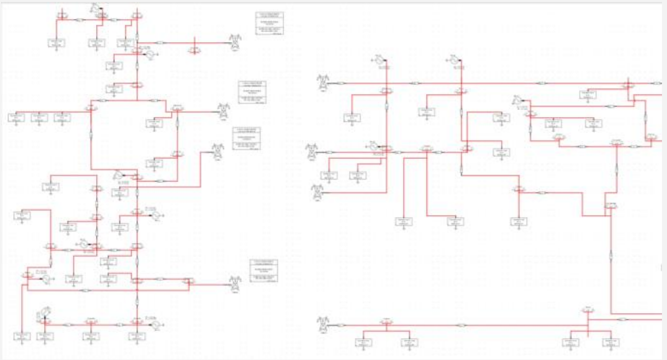




CASCADIA ON RTDS



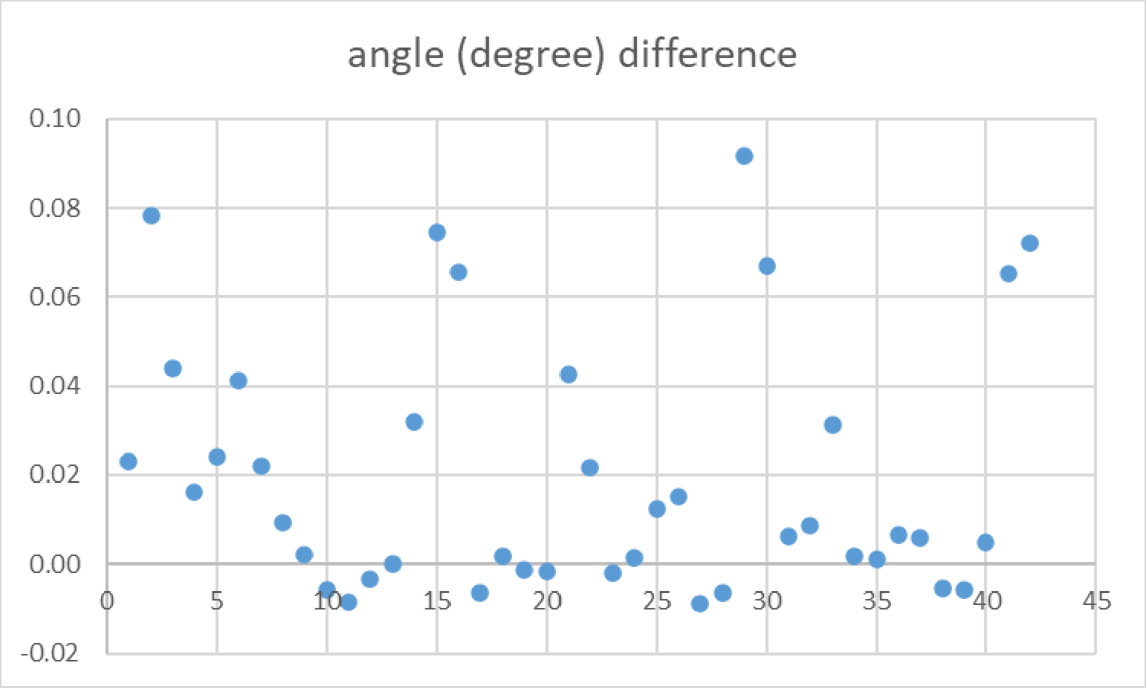


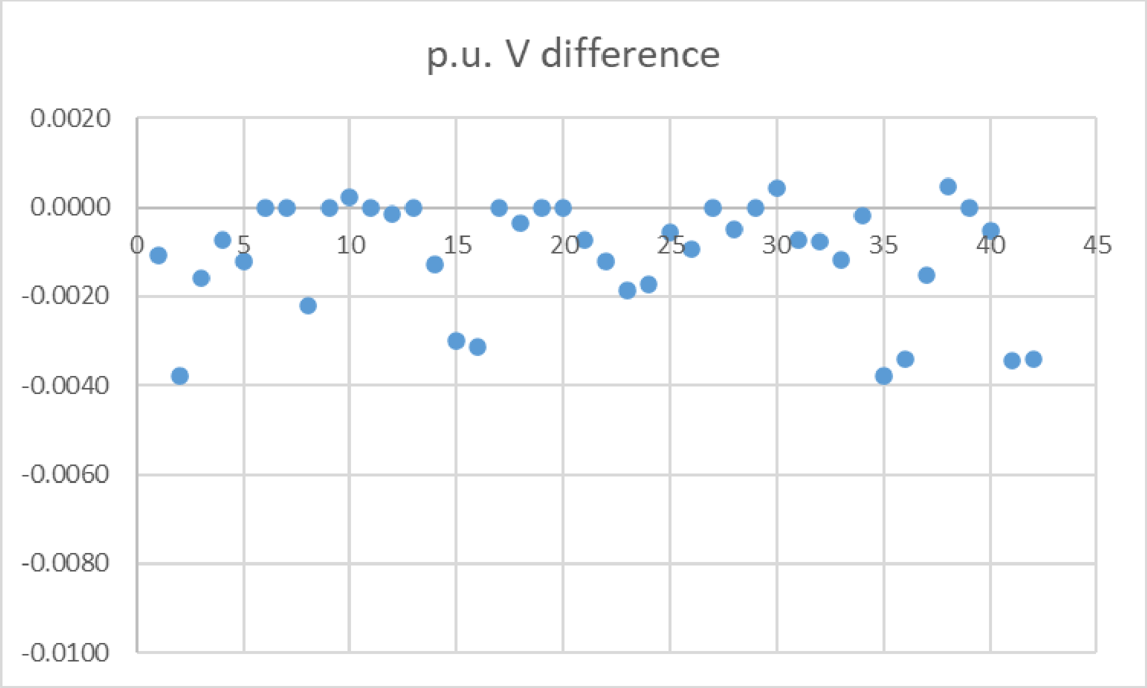


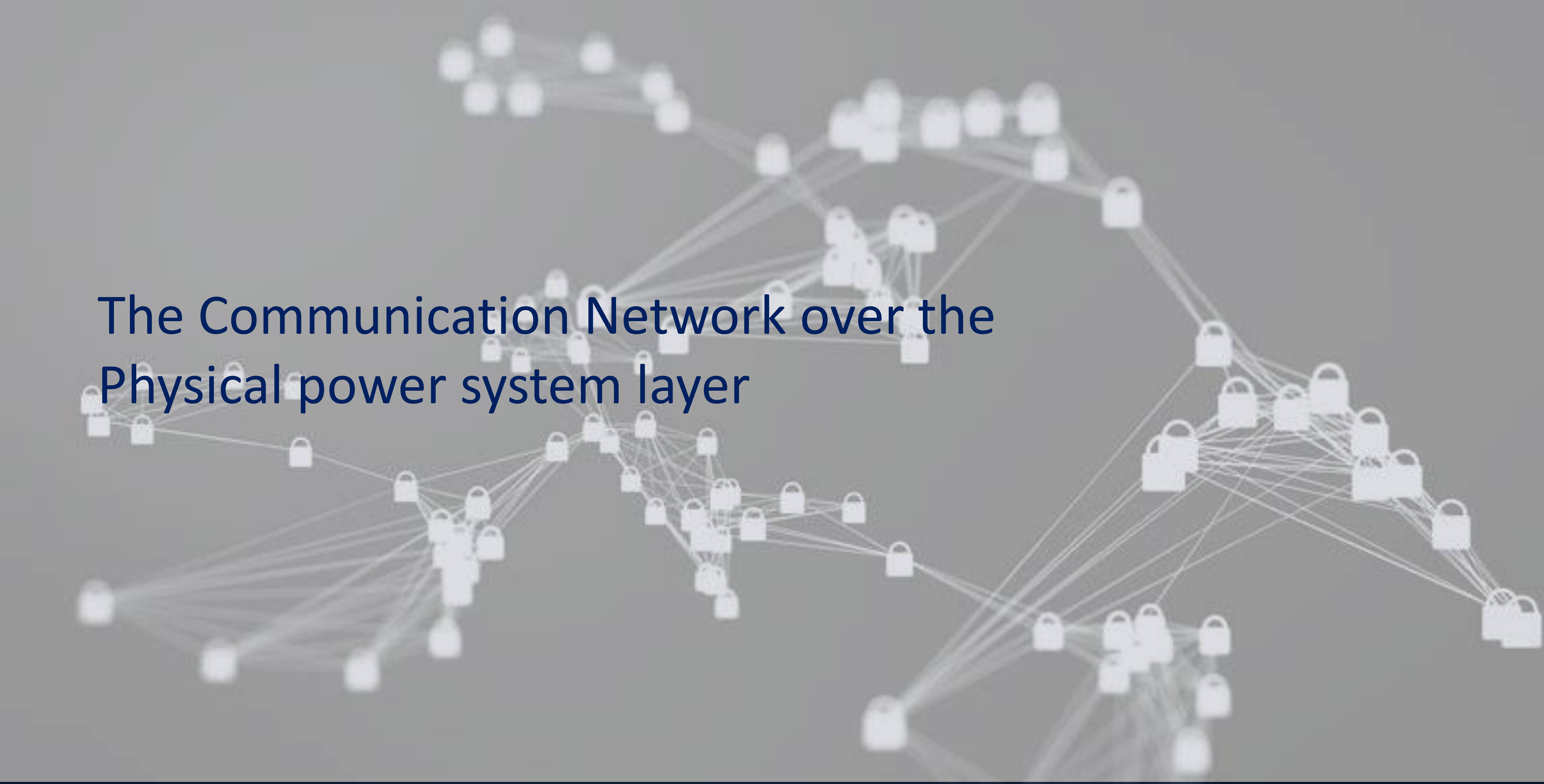
- Reduced 42 bus Cascadia system over 2-racks (3cores), using rack changing components.
- Actual values calculated from P.U values inputed into RTDS
- Real and Reactive power flow matched up to 2 decimal points.

PLOT INDICATING THE DIFFERENCE IN VOLTAGE AND ANGLE

- The differences between the original Cascadia and Reduced Cascadia lie on and around zero

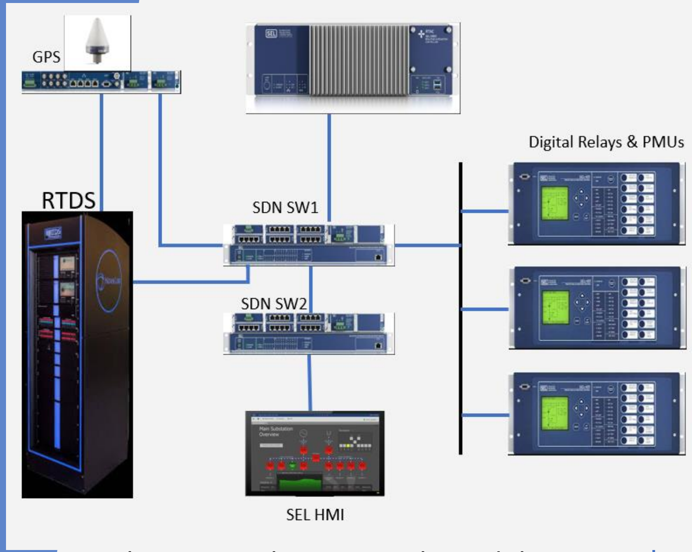




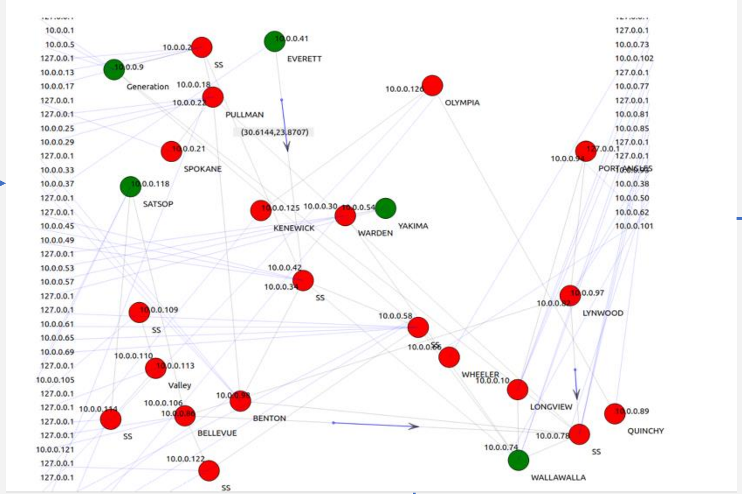


The Communication Network over the Physical power system layer

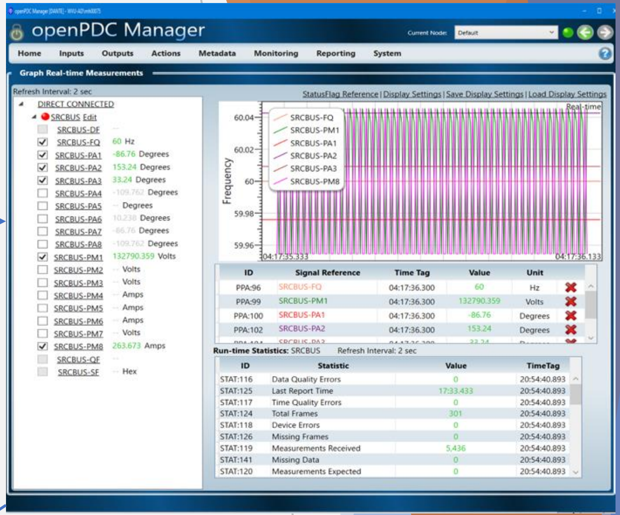
END TO END DATA CONNECTIVITY, FROM SUBSTATION TO CONTROL CENTER USING NS3



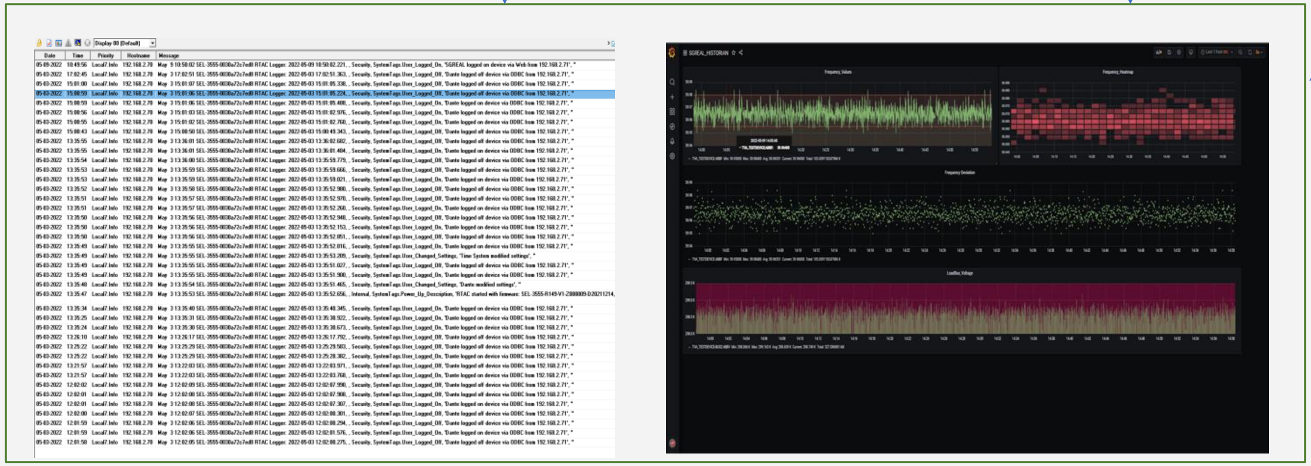
Substation Cyber Network Modeling



NS3 communication network for multiple substation



OpenPDC receiving data from substation to control center



Logging and Archiving from Substation, NS3 and Control center

SUBSTATION CYBER NETWORK MODEL ENSEMBLE AT SG-REAL LAB

Real-Time Digital Simulator Running Cascadia Model

Real Time Automation & Controller (RTAC), Working as Local PDC and local historian

Software Defined Networking (SDN) Switches connecting substation network

Substation Workstation and local HMI

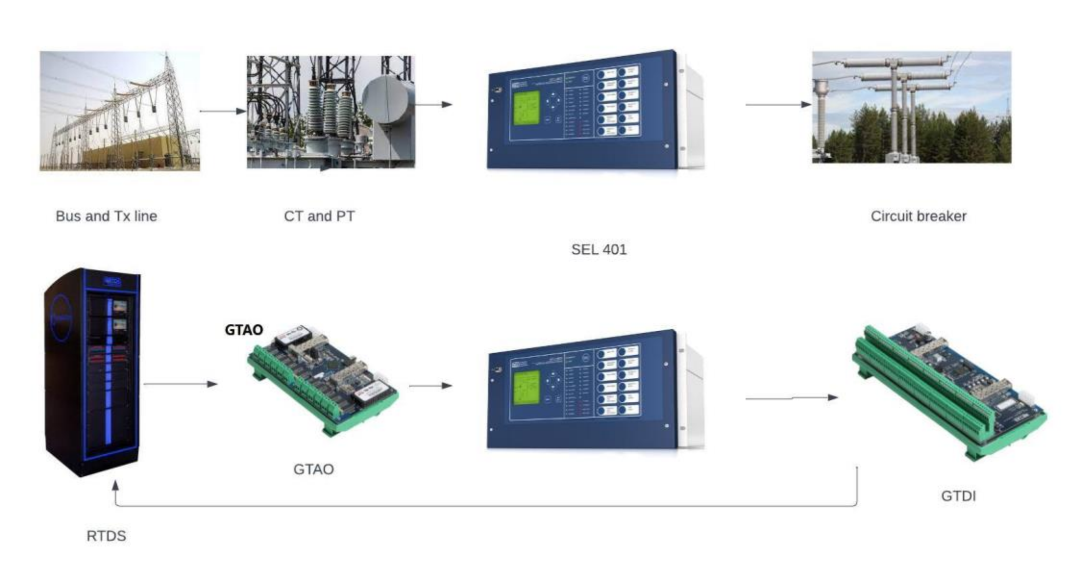
SEL Relays and PMUs connecting RTDS

SEL GPS for time synchronization

Substation communication is developed using a combination of both RTDS software PMU/Relay and SEL hardware PMU/relays

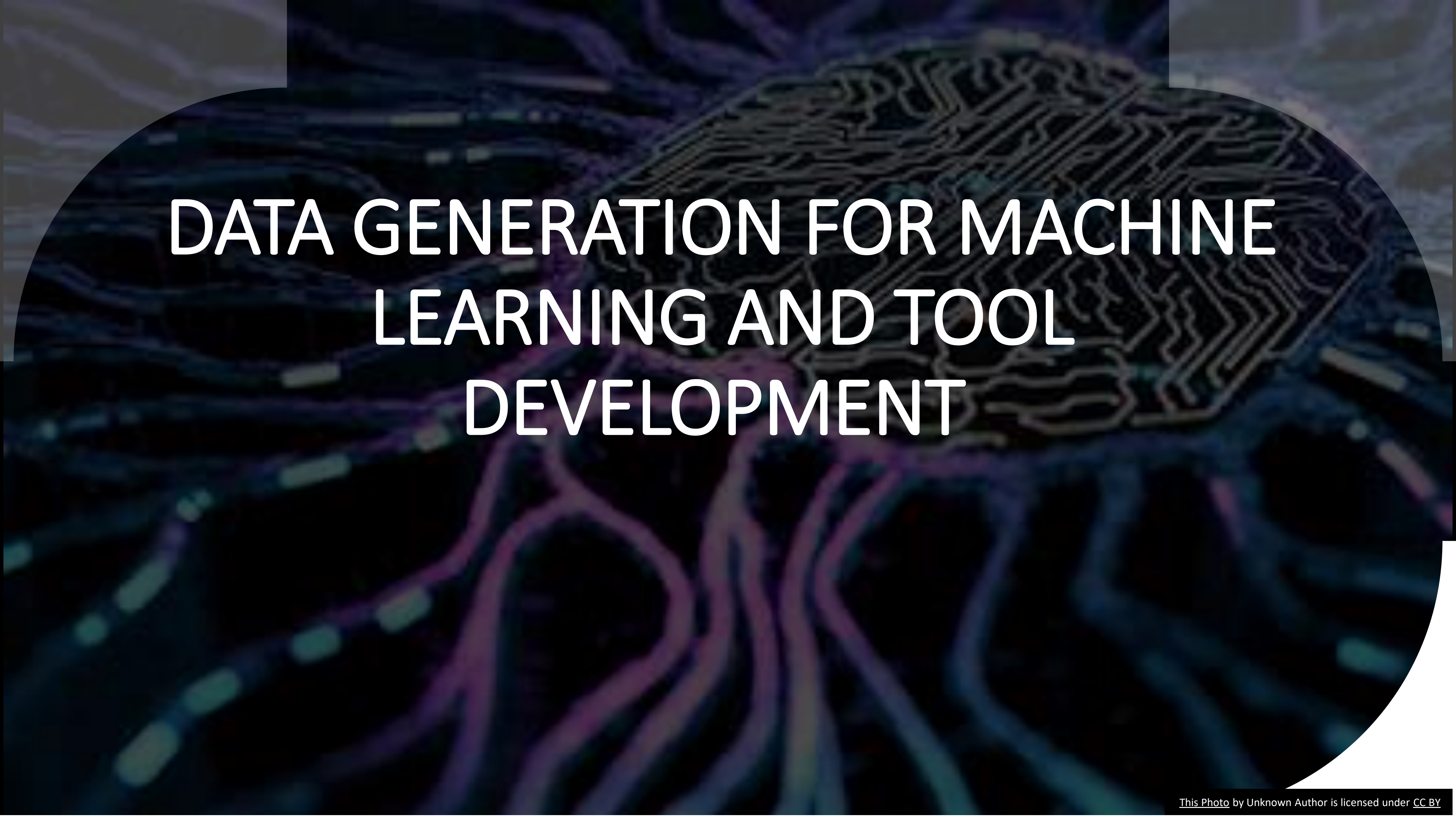
AN ENSEMBLE OF S.S DEVICES CONNECTED VIA A NETWORK AND PHYSICAL COUPLING

- Apart from devices connected through NS3, the test bed is also incorporated with the SEL 401 merging unit.
- The coupling with the power system is done using the CVT and CT embedded into the SEL 401.
- The output from the physical system is sent to the merging unit using the GTAO card.
- And the relay is looped back into the physical system using the GTDI input configured with distance protection for the transmission line.



CHALLENGES IN CYBER-POWER SIMULATIONS AND POSSIBLE SOLUTIONS

Challenge	Solution
Synchronization between dynamic power system and discreet cyber network system	Developed Hardware-In-The-Loop testbed using NS3 & SEL SDN switches to exchange data in real time
Interfacing multi vendor hardware & software components	Worked with SEL, RTDS & GPA products to come up with common supporting standards and protocol
Developing logging & data storage system involving both power and cyber data	Used a combination of MySQL and Cloud Database along with Splunk to create a real-time logging system
Creating real-time cyber-power scenarios to validate monitoring and control tools	Developing different cyber attack and power system events to create real-time cyber-power scenarios

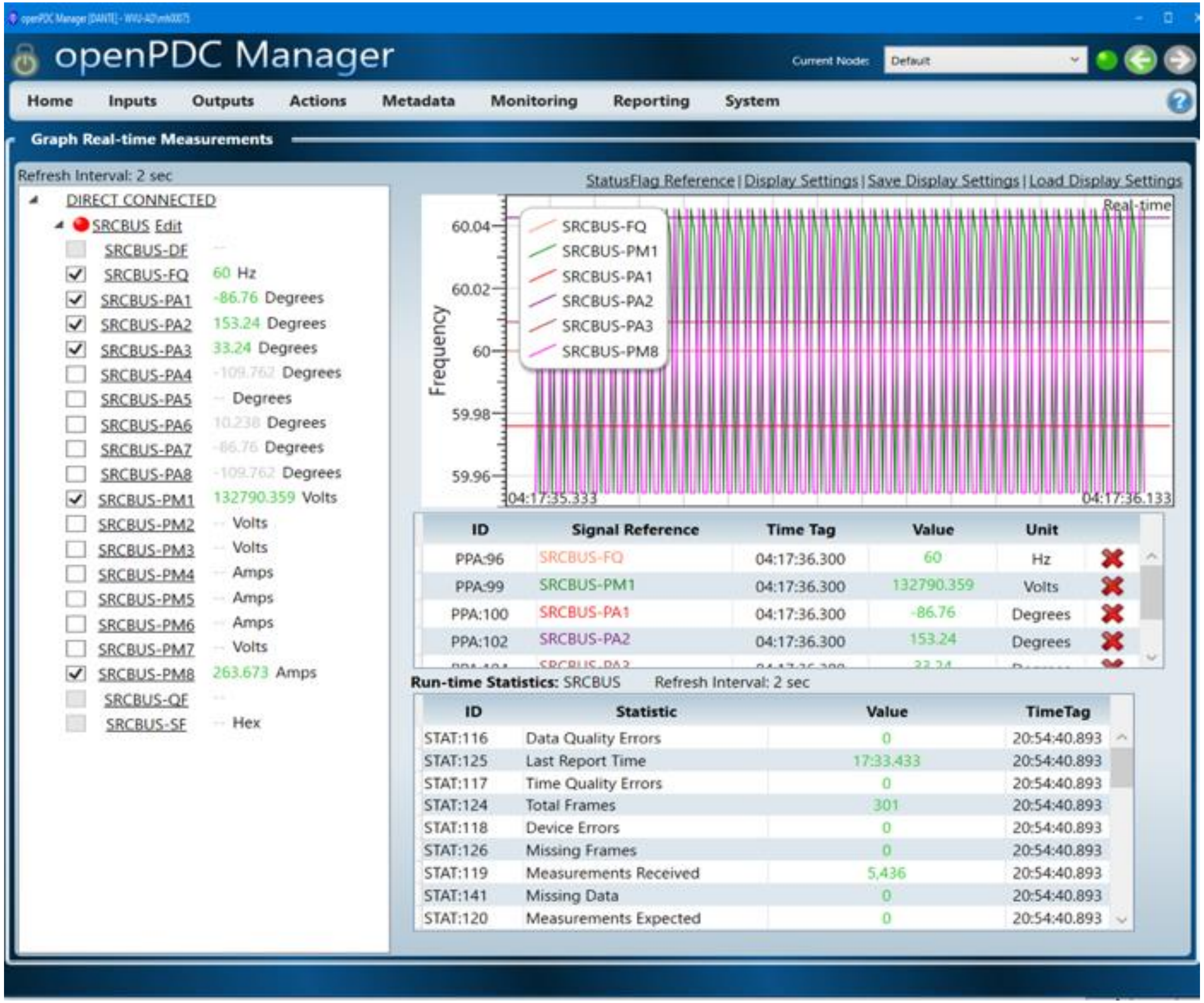


DATA GENERATION FOR MACHINE LEARNING AND TOOL DEVELOPMENT

DATA GENERATION FOR MACHINE LEARNING AND TOOL DEVELOPMENT

- Data generation from IEEE 14 bus, 39 bus, and Cascadia system.
- Data generation for control data and various events and switch operations.
- Switch operations to emulate unsolicited access and attacks.
- Data used in various data analytics and physics involved machine learning algorithms to identify cyber-attacks from rest of the events and operations

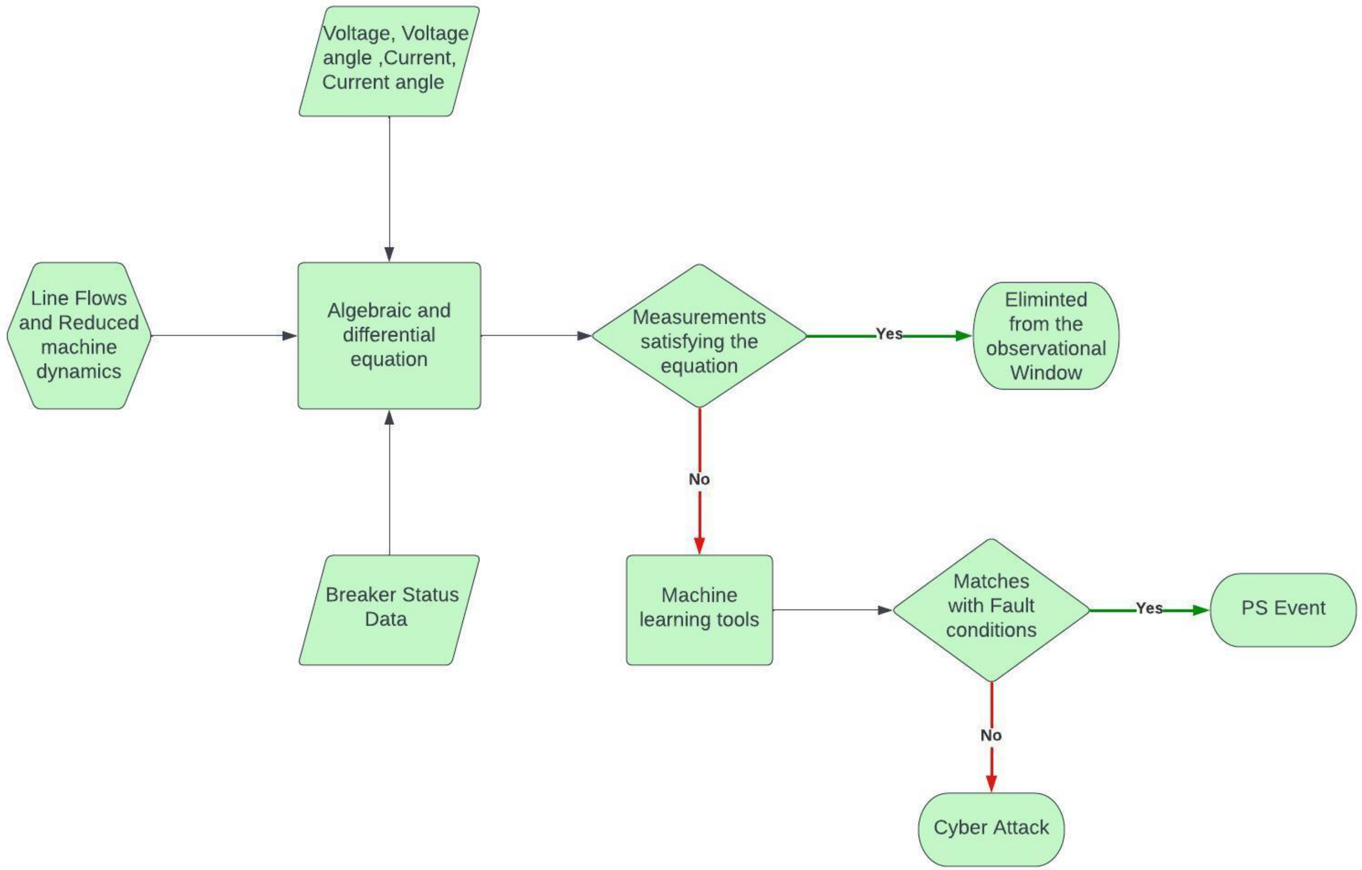
TIME SYNCED DATA STREAMED TO OPEN PDC



SAMPLE OF GENERATED DATA

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Time	Subsystem #1|PMU|PMU|PMU1|IAp4-1an	Subsystem #1|PMU|PI	Subsystem #1|PMU|PI	Subsysten	Subsysten	Subsysten	Subsysten	Subsysten	Subsysten	Subsysten	Subsysten	Subsysten	Subsysten	Subsysten	Subsysten	Subsysten	Subsysten	Subsysten
2	0	0.326680055	2829.875101	-1.767717554	2829.877	2.421073	2829.87	0.833333	59.94869	-1.28E-04	0.50598	11066.76	-1.58842	11066.76	2.600374	11066.73	0.788613	4717.73	-1.30578
3	8.00E-04	0.326680055	2829.875101	-1.767717554	2829.877	2.421073	2829.87	0.833333	59.94869	-1.28E-04	0.50598	11066.76	-1.58842	11066.76	2.600374	11066.73	0.788613	4717.73	-1.30578
4	0.0016	0.326680055	2829.875101	-1.767717554	2829.877	2.421073	2829.87	0.833333	59.94869	-1.28E-04	0.50598	11066.76	-1.58842	11066.76	2.600374	11066.73	0.788613	4717.73	-1.30578
5	0.0024	0.326680055	2829.875101	-1.767717554	2829.877	2.421073	2829.87	0.833333	59.94869	-1.28E-04	0.50598	11066.76	-1.58842	11066.76	2.600374	11066.73	0.788613	4717.73	-1.30578
6	0.0032	0.326680055	2829.875101	-1.767717554	2829.877	2.421073	2829.87	0.833333	59.94869	-1.28E-04	0.50598	11066.76	-1.58842	11066.76	2.600374	11066.73	0.788613	4717.73	-1.30578
7	0.004	0.326680055	2829.875101	-1.767717554	2829.877	2.421073	2829.87	0.833333	59.94869	-1.28E-04	0.50598	11066.76	-1.58842	11066.76	2.600374	11066.73	0.788613	4717.73	-1.30578
8	0.0048	0.326680055	2829.875101	-1.767717554	2829.877	2.421073	2829.87	0.833333	59.94869	-1.28E-04	0.50598	11066.76	-1.58842	11066.76	2.600374	11066.73	0.788613	4717.73	-1.30578
9	0.0056	0.326680055	2829.875101	-1.767717554	2829.877	2.421073	2829.87	0.833333	59.94869	-1.28E-04	0.50598	11066.76	-1.58842	11066.76	2.600374	11066.73	0.788613	4717.73	-1.30578
10	0.0064	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
11	0.0072	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
12	0.008	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
13	0.0088	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
14	0.0096	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
15	0.0104	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
16	0.0112	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
17	0.012	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
18	0.0128	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
19	0.0136	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
20	0.0144	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
21	0.0152	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
22	0.016	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
23	0.0168	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
24	0.0176	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
25	0.0184	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
26	0.0192	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
27	0.02	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
28	0.0208	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
29	0.0216	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
30	0.0224	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
31	0.0232	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
32	0.024	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
33	0.0248	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
34	0.0256	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
35	0.0264	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
36	0.0272	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653
37	0.028	0.315932069	2829.870836	-1.778460676	2829.874	2.410327	2829.878	0.866667	59.94869	-1.39E-04	0.495233	11066.73	-1.59916	11066.76	2.589627	11066.76	0.777867	4717.716	-1.31653

METHODOLOGY TO IMPLEMENT PIML



SUMMARY

- Used Real-Time Digital Simulator (RTDS) as a dynamic power system simulator to feed SCADA/PMU data to sensor, network and EMS
- Generating Synthetic but realistic data for validation of the algorithms/ tools.
- Performing Cyber attacks and creating power events to understand the nature of interdependency within cyber-power system.
- Developing Advanced Tools to help operators with better decision making and situational awareness


Any
Questions