Situational Intelligence in Control Centers

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Outline

- Introduction
- Situational Awareness and PMUs
- Situational Intelligence (SI)
- Scalable Computing for SI

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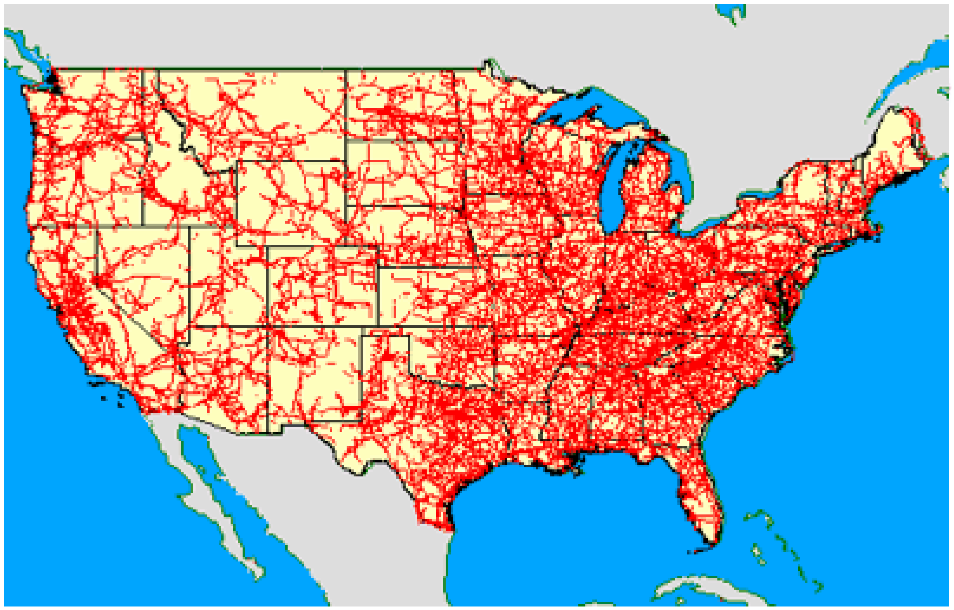
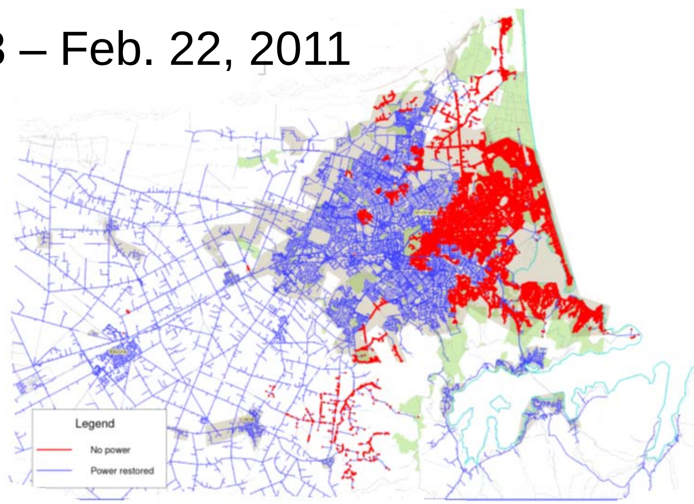
Power System Blackouts



M6.3 – Feb. 22, 2011



The Northeast blackout of 2003 (55 million people) is the third most widespread black in history (1999 Southern Brazil blackout – affected 97 million people, July 2012 Indian – affected ~670 million people).

630 millions of customer minutes not met – earthquake of M6.3 – February 22, 2011 (hours of weeks of power loss). The longest in the history of major natural events in Christchurch.

Power grid is the critical infrastructure of all critical infrastructures (including communication, water and gas distribution, and transportation).

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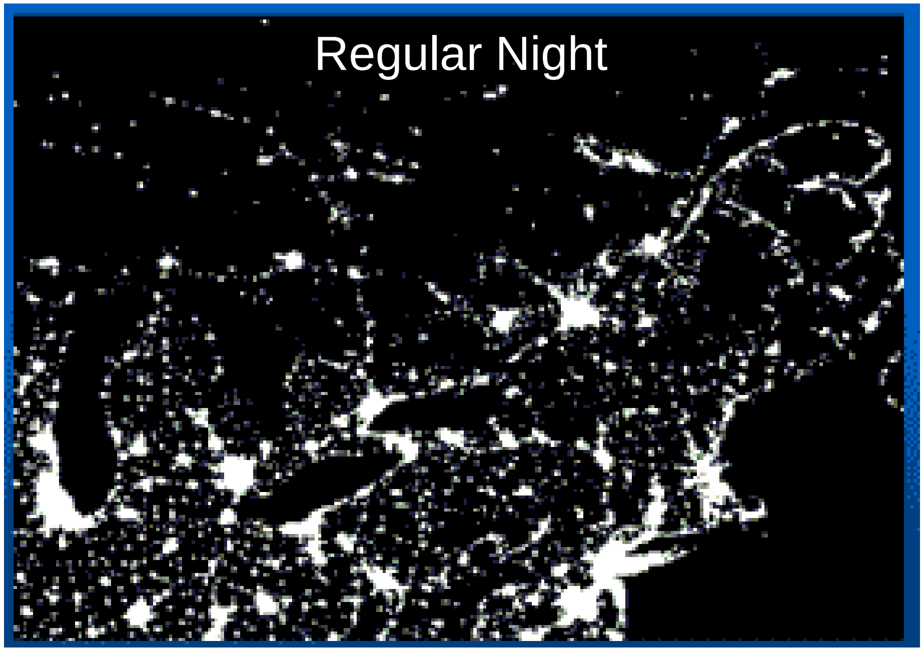
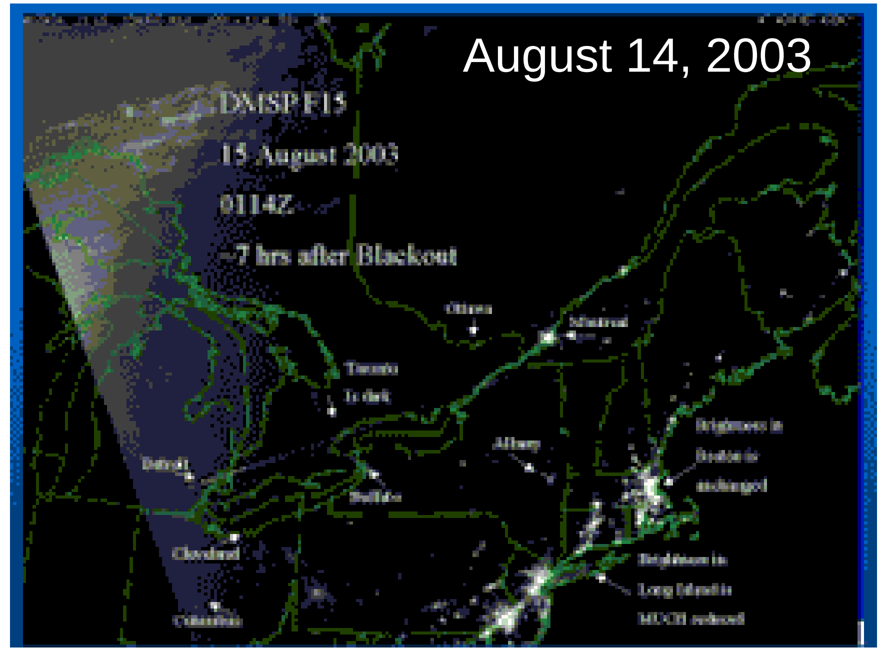
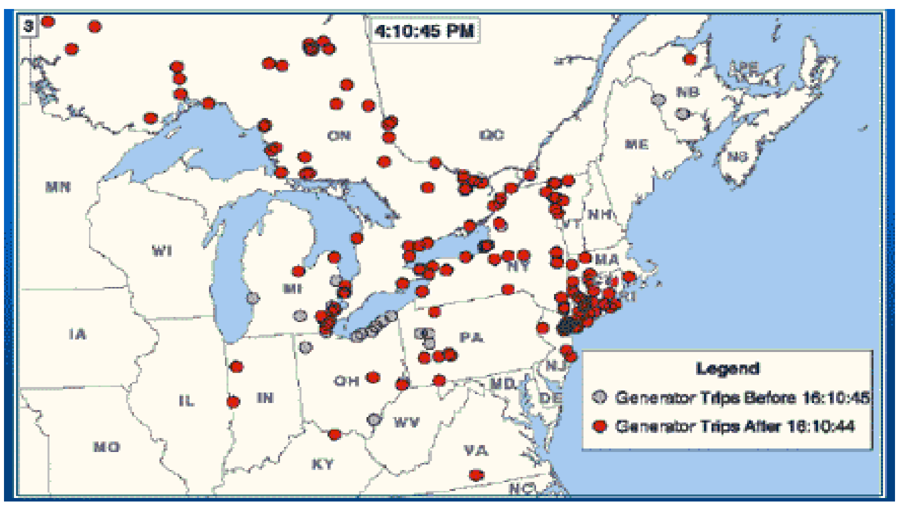
August 14, 2003 Blackout

IEEE Spectrum February 2005







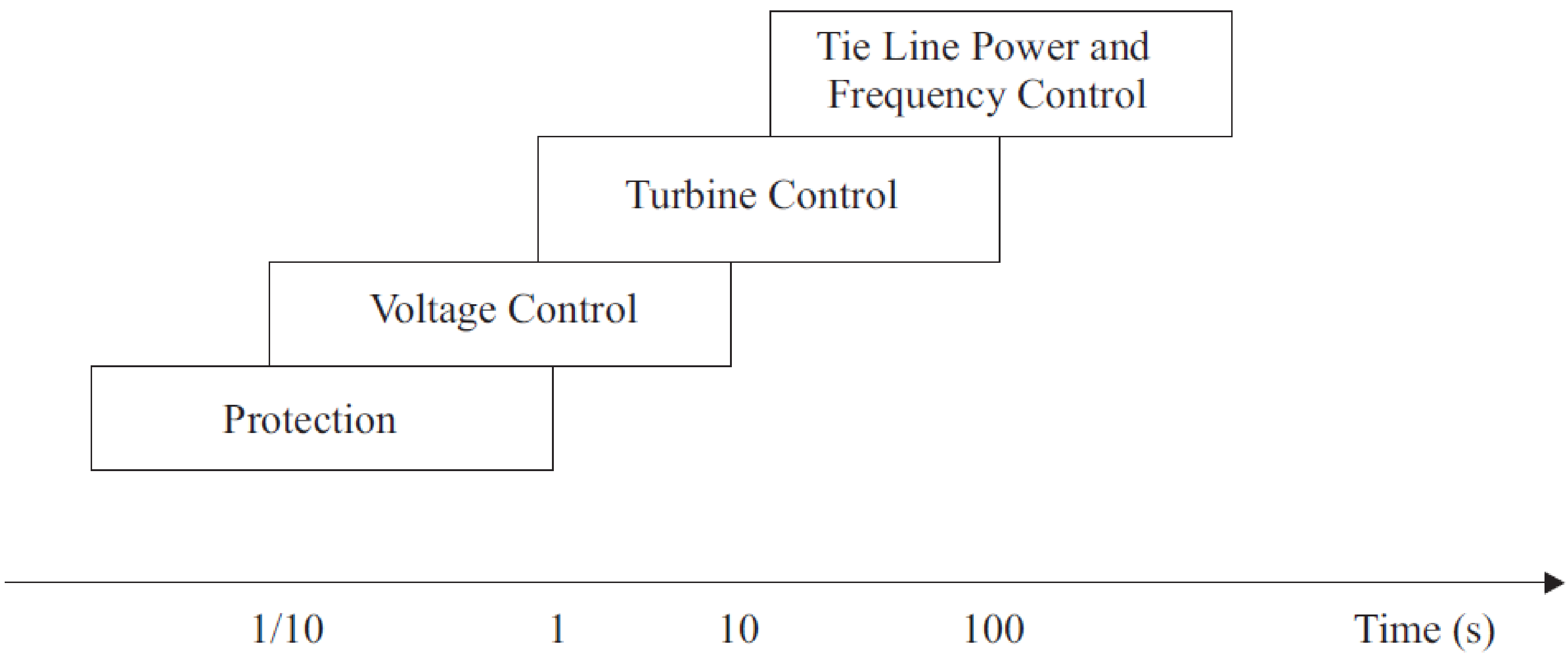
- > 60 GW of load loss;
- > 50 million people affected;
- Import of ~2GW caused reactive power to be consumed;
- Eastlake 5 unit tripped;
- Stuart-Atlanta 345 kV line tripped;
- MISO was in the dark;
- A possible load loss (up to 2.5 GW)
- Inadequate situation awareness.

Control Center Innovations

- Major blackouts have triggered outbursts of research that eventually led to significant technological breakthroughs.
- The real-time static security analysis tools were introduced in response to the Northeast blackout of 1965.
- The seminal paper[1] was written by the major blackout of 1978 in France.
- Real-time detection of the risk of instability can be traced to the wave of blackouts that US, UK, and the mainland Europe utilities in 2003.
- The online calculation of the loadability limits is essential for the effective and efficient utilization of a power system network, particularly in an open access environment.
- In the past, the computational capabilities were a bottle-neck, but now we have tons (tera-scale/peta-scale) of computing power.

[1] Barbier, C. and Barret, J. P., "An Analysis of Phenomena of Voltage Collapse on a Transmission Systems," *RGE*, special edition CIGRE, July 1980, pp. 3-21.

Time Scales for Power System Control



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Time Scales for Power System Control

• 0-5 seconds:	Automatic Voltage Regulation (AVR) Equipment Control Protection
• 5 s – 10 mins.:	Load Frequency Control (LFC) Automatic Generation Control (AGC)
• 10 mins. – 4 hours:	Economic Dispatch (ED)
• 5 sec.– 4 hours:	Security Assessment, Voltage and Frequency Stability
• 4 hours – 1 week:	Unit Commitment (UC)
• 1 week – 6 months:	Maintenance
• 6 months – years:	System Planning (Off Line)

Smart Grid

A smart grid must have certain basic functions for modernization of the grid (as indicated in the Energy Independence and Security Act (EISA) of 2007), including:

- Self-healing
- Fault-tolerant
- Dynamic integration of all forms of energy generation & storage
- Dynamic optimization of grid operation and resources with full cyber-security
- Demand-response, demand-side resources and energy-

Smart grid's growing complexity requires different approaches to traditional methods of modeling, control and optimization in power systems.

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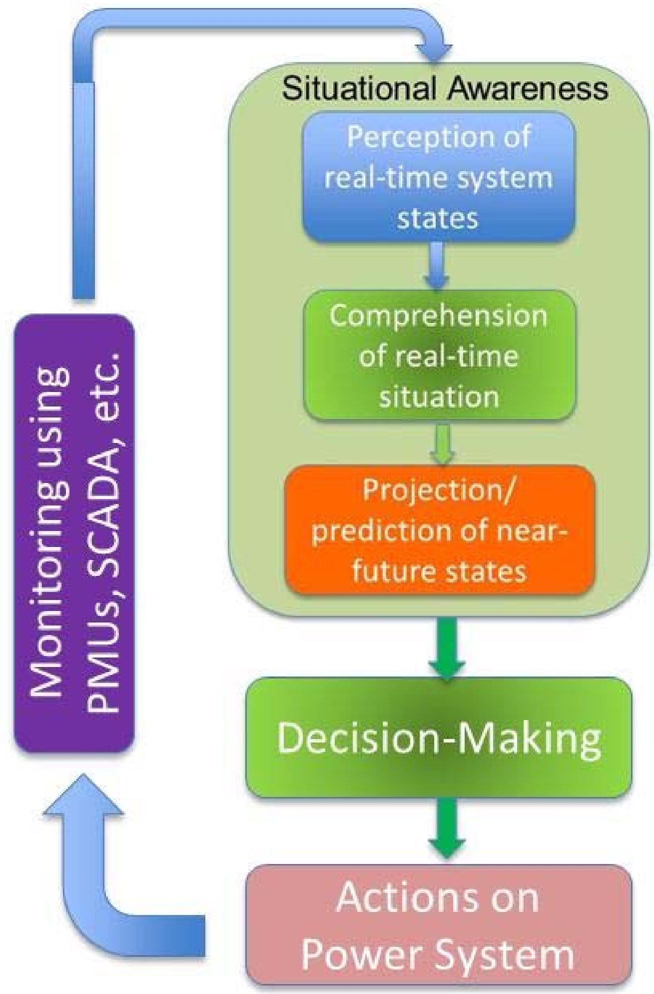
Situational Awareness (SA) in a Control Center

- When a disturbance happens, the operator is thinking:
  - **Received a new alert!**
    - **Is any limit in violation?**
      - **If so, how bad?**
  - **Problem location?**
    - **What is the cause?**
  - **Any possible immediate corrective or mitigative action?**
    - **What is the action?**
    - **Immediate implementation or can it wait?**
  - **Has the problem been addressed?**
    - **Any follow up action needed?**

- SA is aimed at looking into a complex system from many different perspectives in a holistic manner.

- Local regions are viewed microscopically and the entire system is viewed macroscopically.



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SA for Power Transmission Systems

- Dynamic model validation
- Online monitoring of system loading
- Load modeling – virtual real-time loads
- Real-time small signal analysis
- Real-time voltage stability assessment
  - Synchrophasor data
  - Model
- Transmission system stress – phase angle difference
- State estimation
  - Transmission system (bus voltage magnitude and angle)
  - Detection of bad PMU data (17% of 56 PMUs)
- Rea-time security indicators (nomograms)

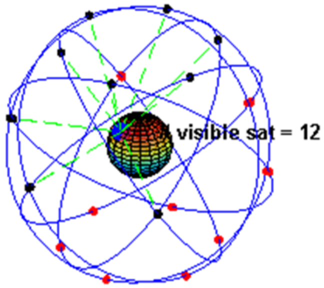
SA for Renewable Energy Systems

- Voltage sensitivity analysis
- Small signal analysis – low frequency oscillations and damping ratios
- Monitoring of renewable (wind and solar) generations
- Forecasting of renewable generations
- ‘Renewable’ stress – separate stress in the transmission system contributed by renewable generation plants
  - Real-time
  - Forecast
- Demand-response and improved grid reliability

PMU (Sensor) Placement

- Ideally - every bus of the grid but economically not practical
- Data requirements for multiple synchrophasor applications
- Guidelines:
  - HV substations
  - Large power plants
  - Major transmission corridors
  - Remedial action schemes based substations
  - Renewable generation plants





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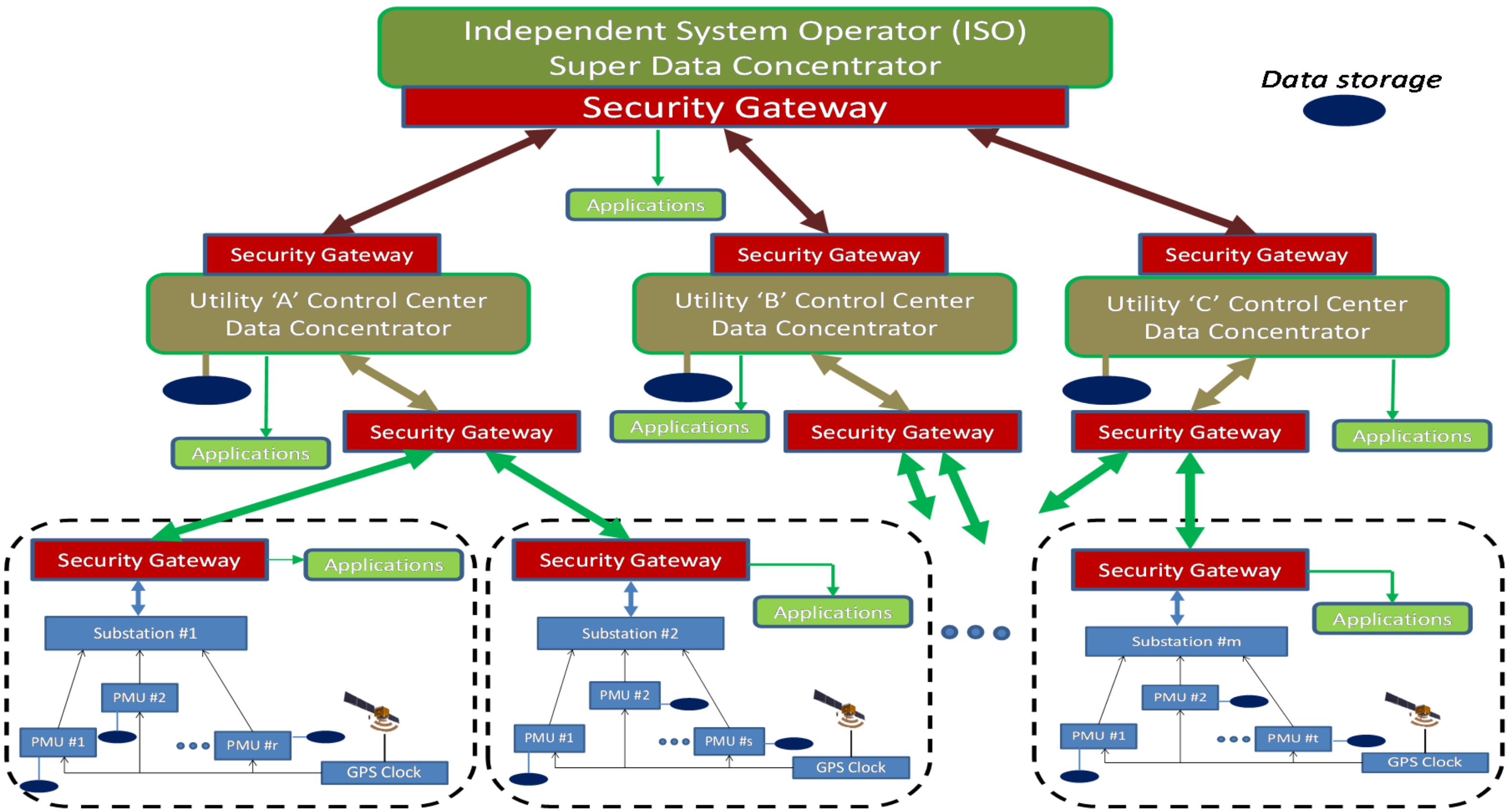
Hierarchy for PMU Systems

- Depending on applications, optimal locations of PMUs will be determined.
- PMUs, communication links, and data concentrators must exist in order to realize the full benefit of the PMU measurement system.



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Situational Intelligence

- Integrate historical and real-time data to implement near-future situational awareness

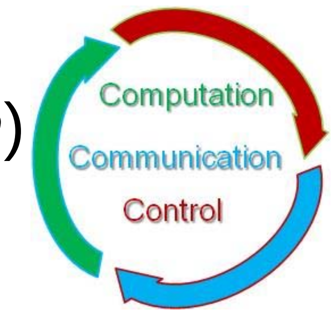
  Intelligence (near-future) =
  function(history, current status, some predictions)

- Predict security and stability limits
  - RT operating conditions
  - Oscillation monitoring
  - Dynamic models
  - Forecast load
  - Predict/forecast generation
  - Contingency analysis
- Advanced visualization
  - Integrate all applications
  - Topology updates and geographical influence (PI and GIS – Google earth tools)

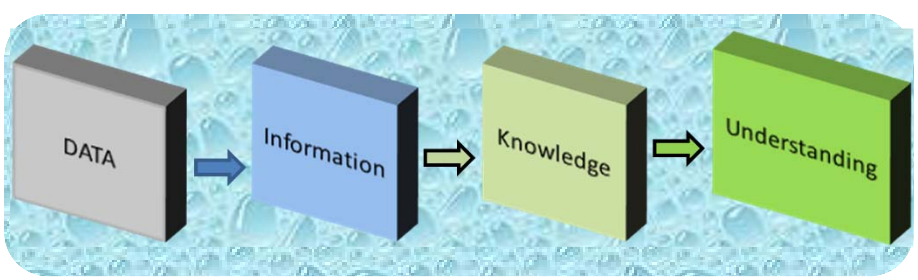
Predictions is critical for Real-Time Monitoring

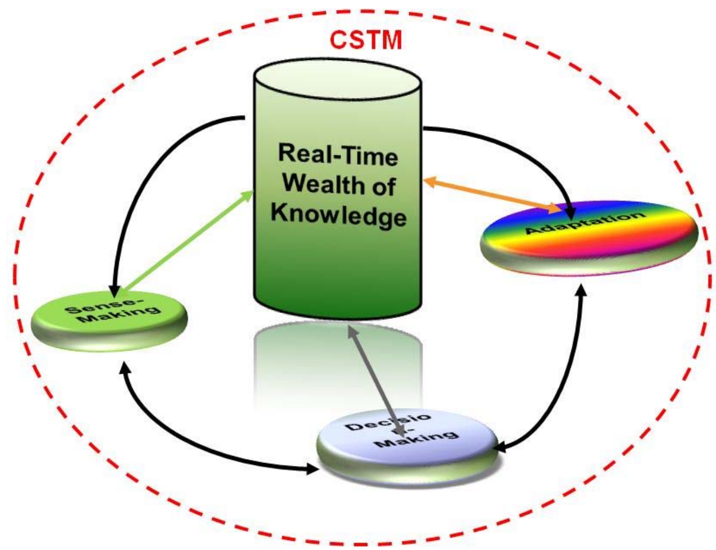
Computational Systems Thinking Machine (CSTM)

- To handle an evolving, uncertain, variable and complex smart grid – three strands of thinking are needed for
  - Sense-making
  - Decision-making (*Actionable Information*)
  - Adaptation



- In the center of all these strands exist a 'real-time wealth of knowledge'
  - Continuous refinement
  - Learns and unlearns

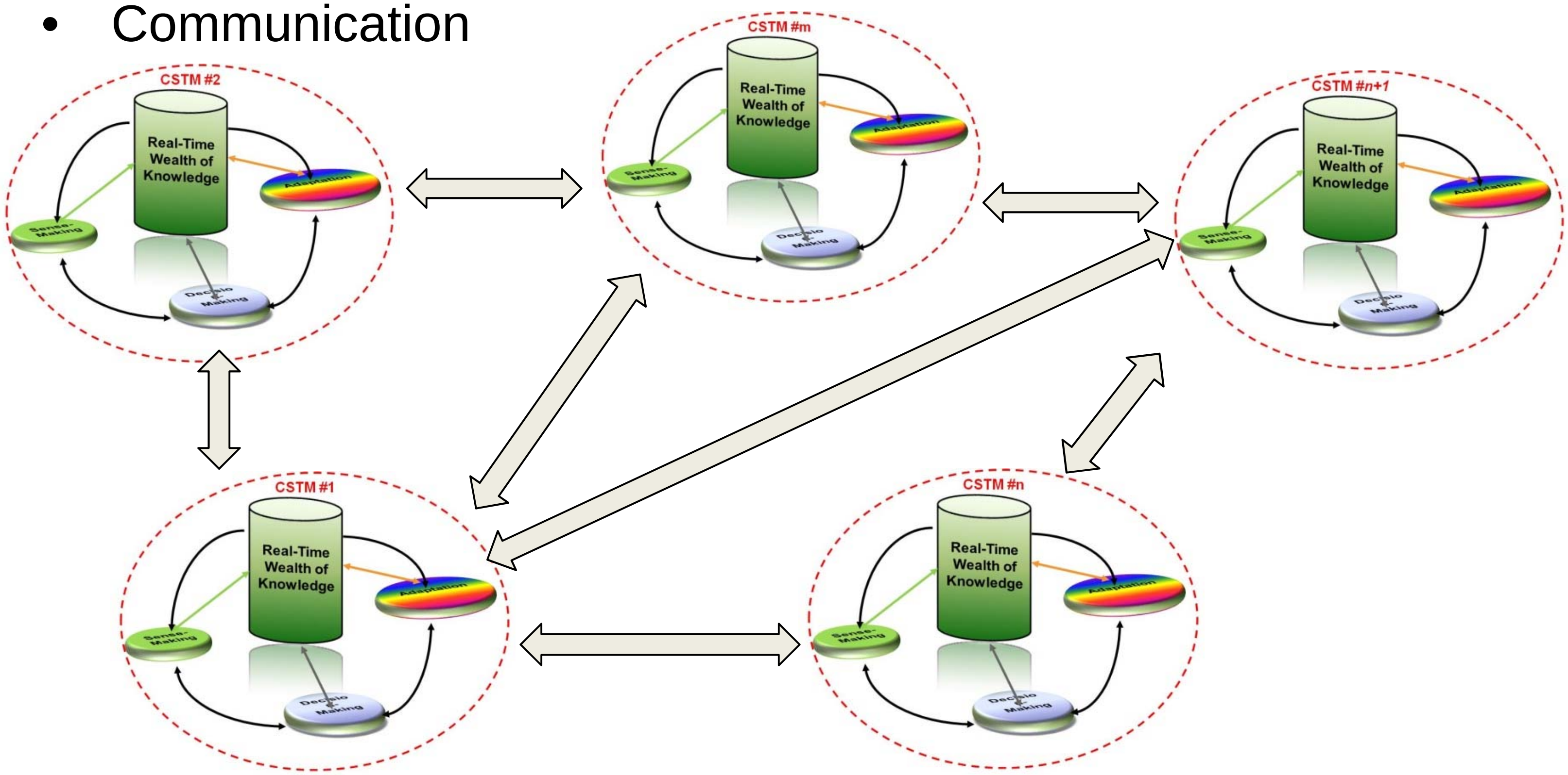




Co-existence of CSTMs

Co-existence of CSTMs is essential for smart grid operations

- Harmony
- Coordination
- Communication



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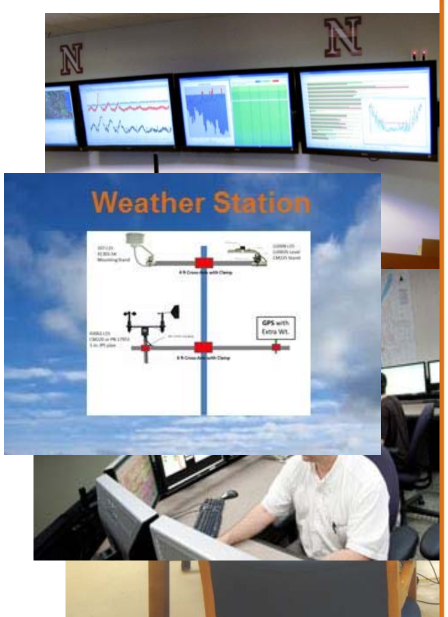
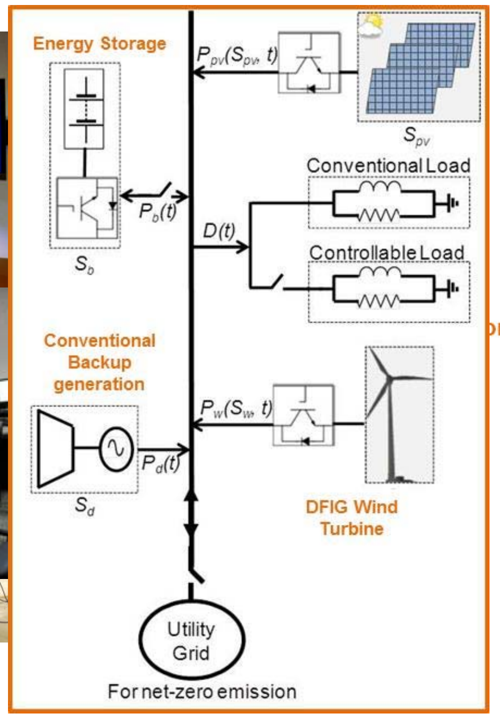
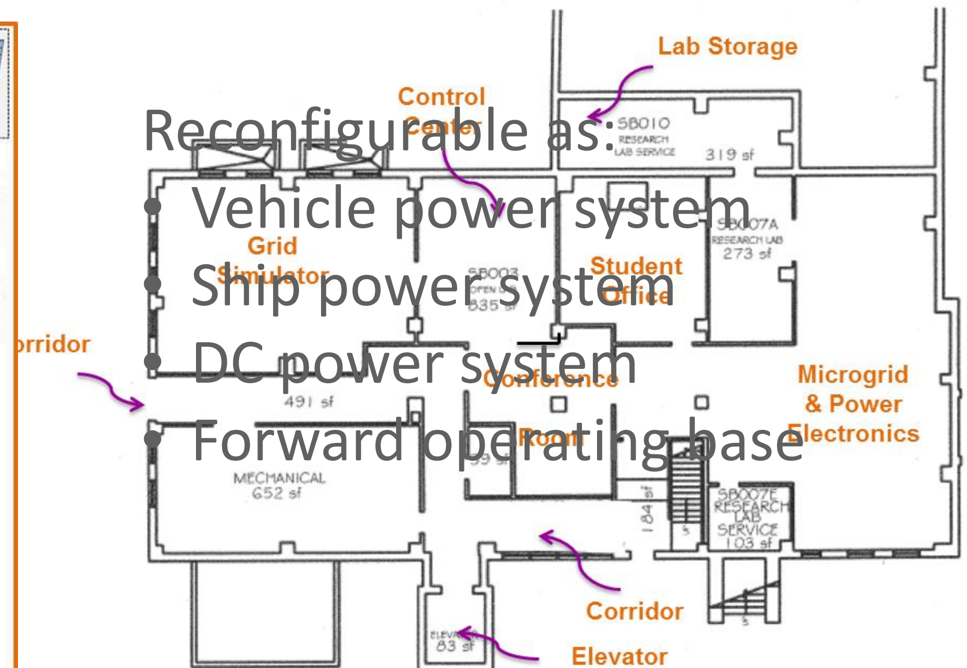
Real-Time Power & Intelligent Systems (RTPIS) Lab

- Real-Time Grid Simulation Lab.
- Situational Intelligence Lab.
- Microgrid and Power Electronics Lab.







Reconfigurable as:

- Vehicle power system
- Ship power system
- DC power system
- Forward operating base

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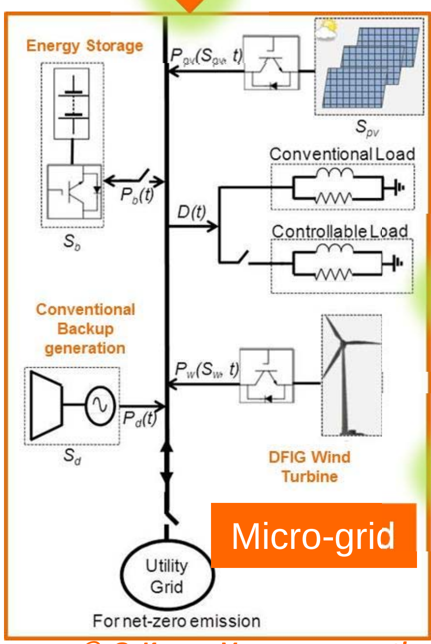
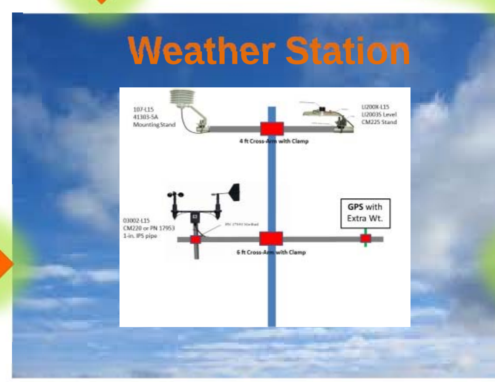
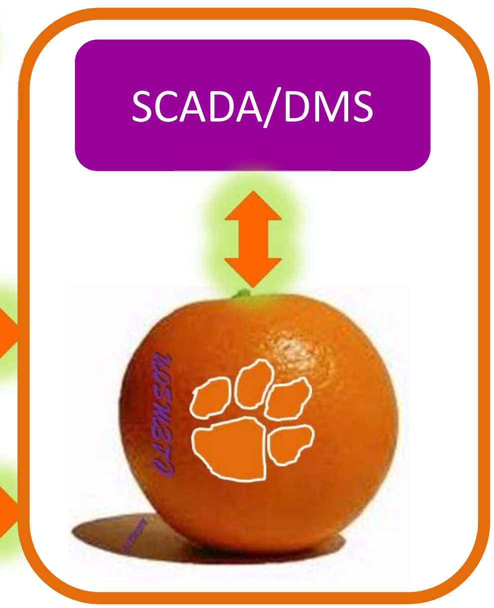
Real-Time Grid Simulation with Hardware-in-the-Loop Microgrid

- *Actual weather station/Any location operation*
- *Dedicated high-speed monitoring, control and communication*
- *Advanced sensor networks/IEDs*
- *SCADA/DMS*
- *ClemsonOrange platform*







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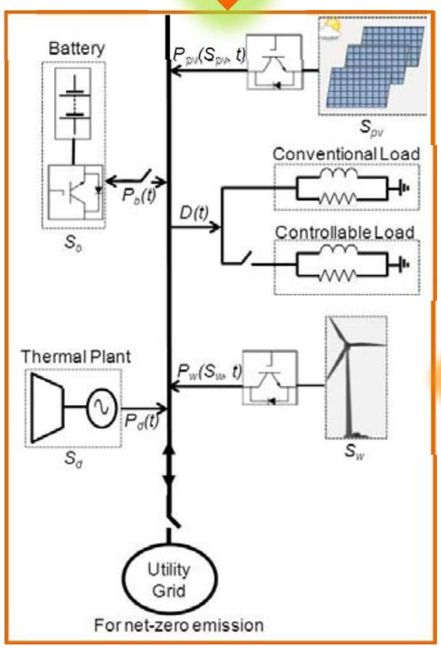
SIL Facilities

High-speed
1-10Gbit/s
fiber
link

High-speed
1-10 Gbit/s
fiber
link

Dedicated
fiber link

Micro-grid



High-speed
1-10 Gbit/s
fiber
link

High-speed
1-10 Gbit/s
fiber
link

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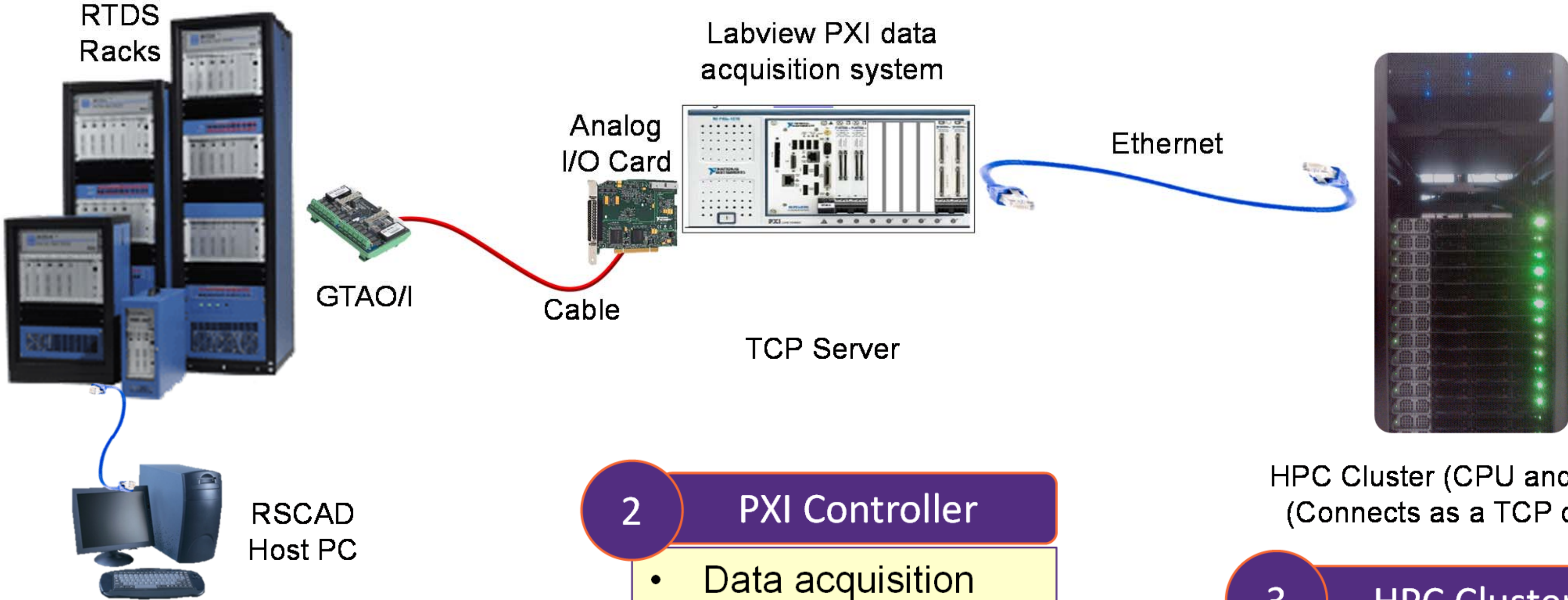
Platform - RT-HPC Platform

Real-Time High Performance Computing (RT-HPC) Platform



1 RTDS

- Simulates smart grid operation

2 PXI Controller

- Data acquisition system
- Interface between the RTDS and HPC Cluster

3 HPC Cluster

- Implements algorithms for monitoring and control

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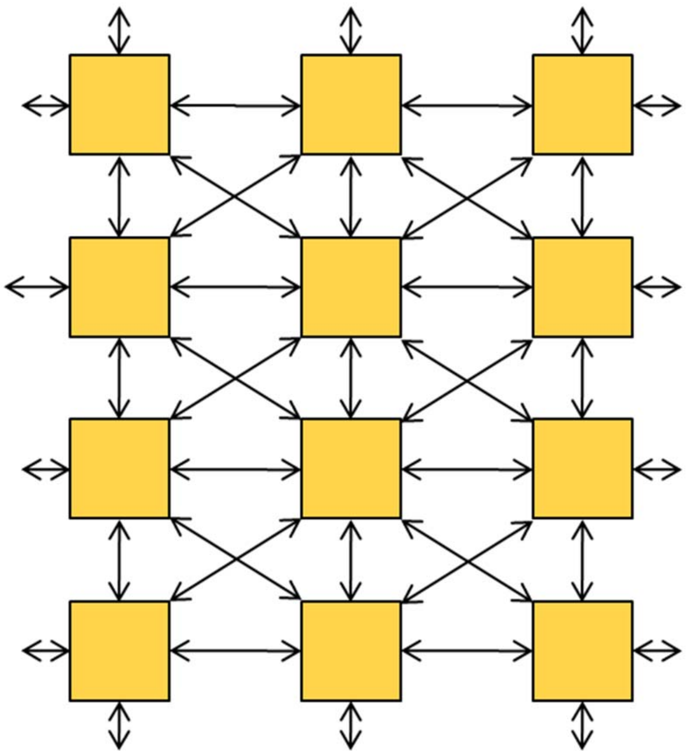
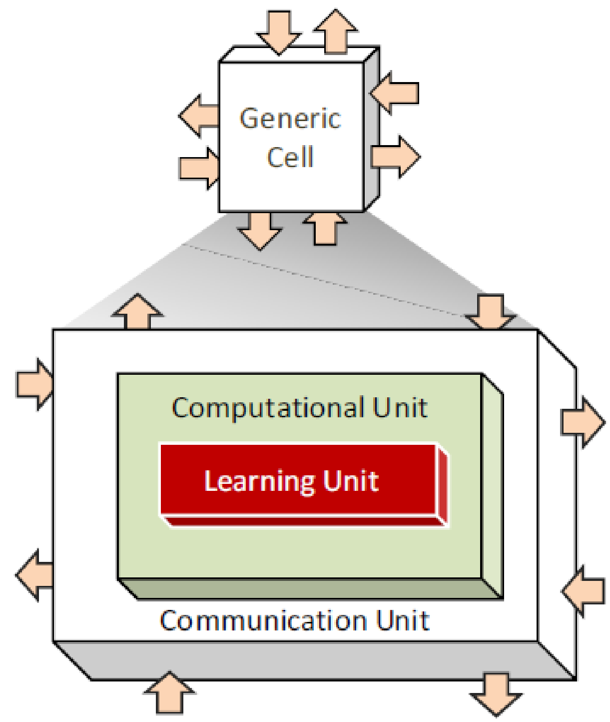
Cellular Computational Networks

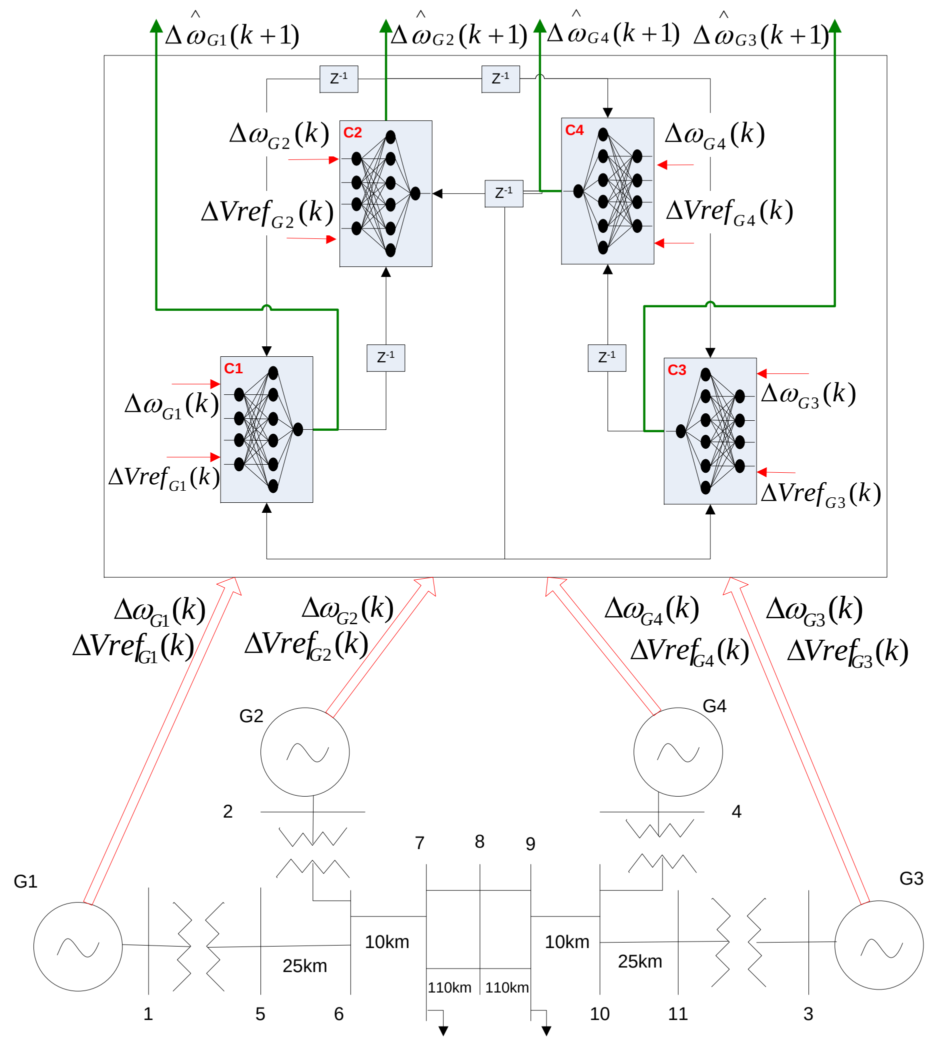
- Cellular computational networks (CCNs) generally mean computational units connected to each other.
- Cells are usually collocated and trained synchronously.





Wide Area Monitoring Systems (WAMS)

- Each cell represents one generator of a multi-machine power system - Each cell predicts speed. deviation of one generator
- The cells are connected to each other in the same way as the components in the physical system.
- Nearest neighbors topology is used (*n=2*) to reduce complexity.



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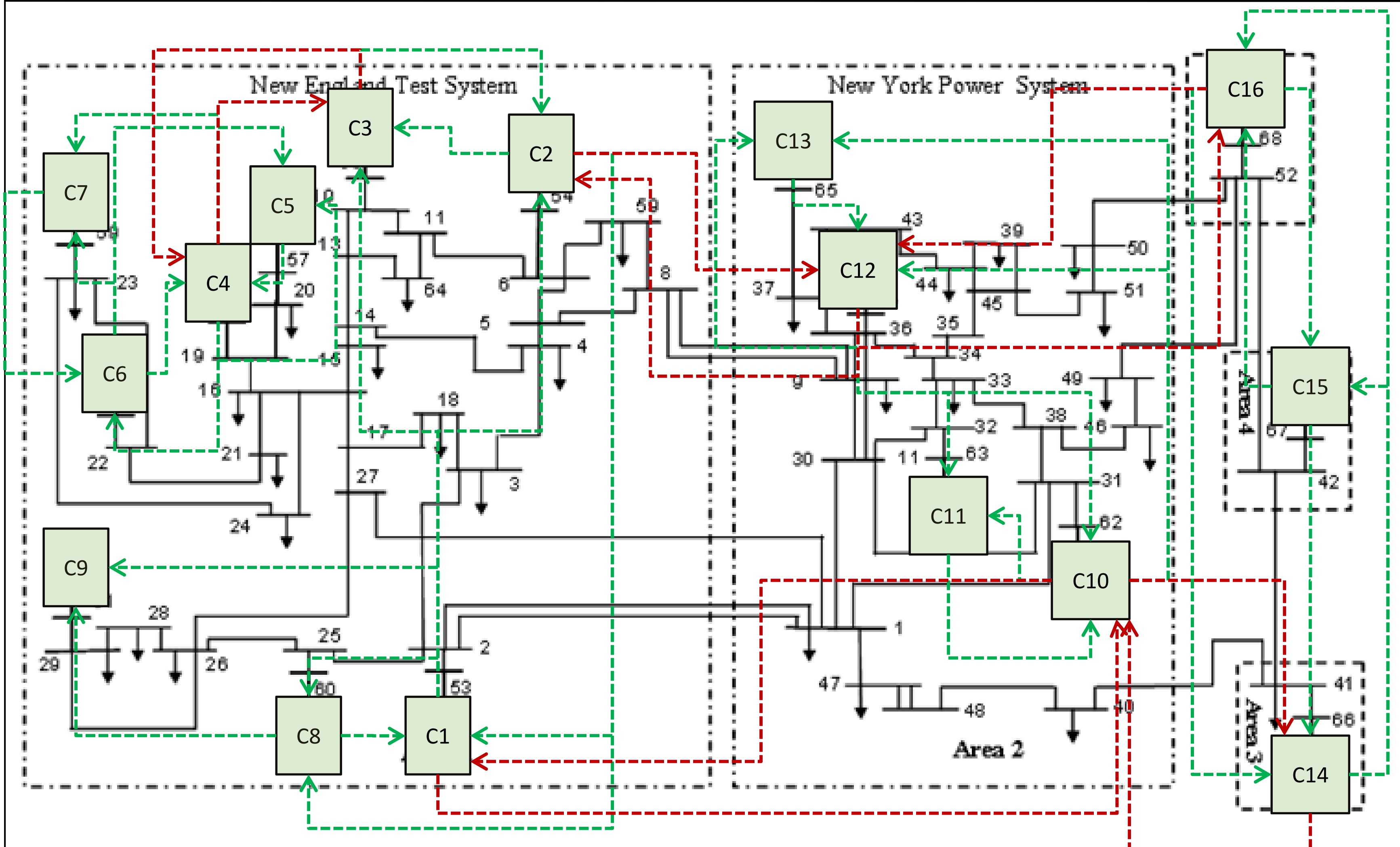
Scalable WAMS based on CCN



Luitel B, Venayagamoorthy GK, "Decentralized Asynchronous Learning in Cellular Neural Networks", *IEEE Transactions on Neural Networks*, to appear

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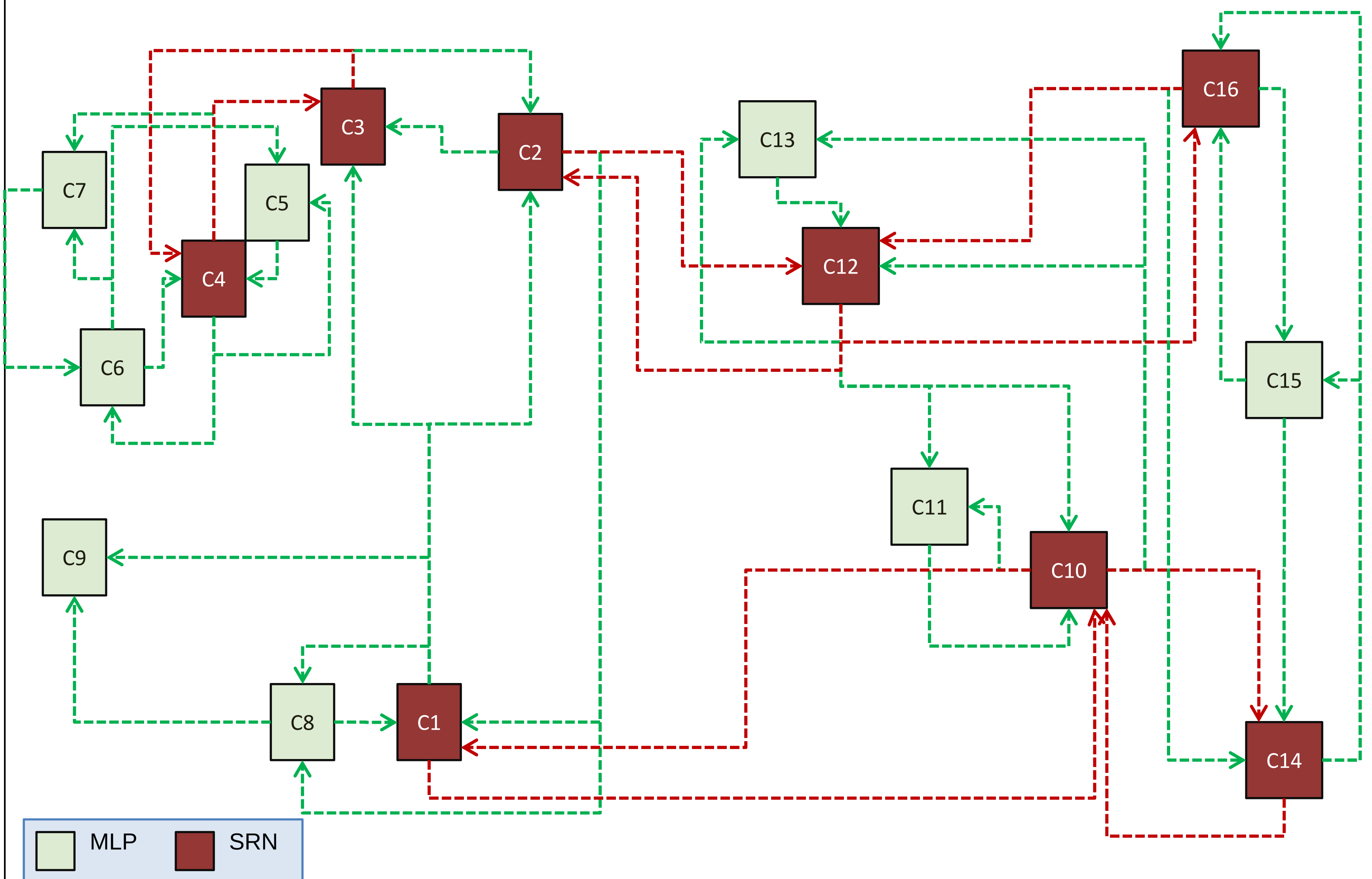
Scalable WAMS based on CCN



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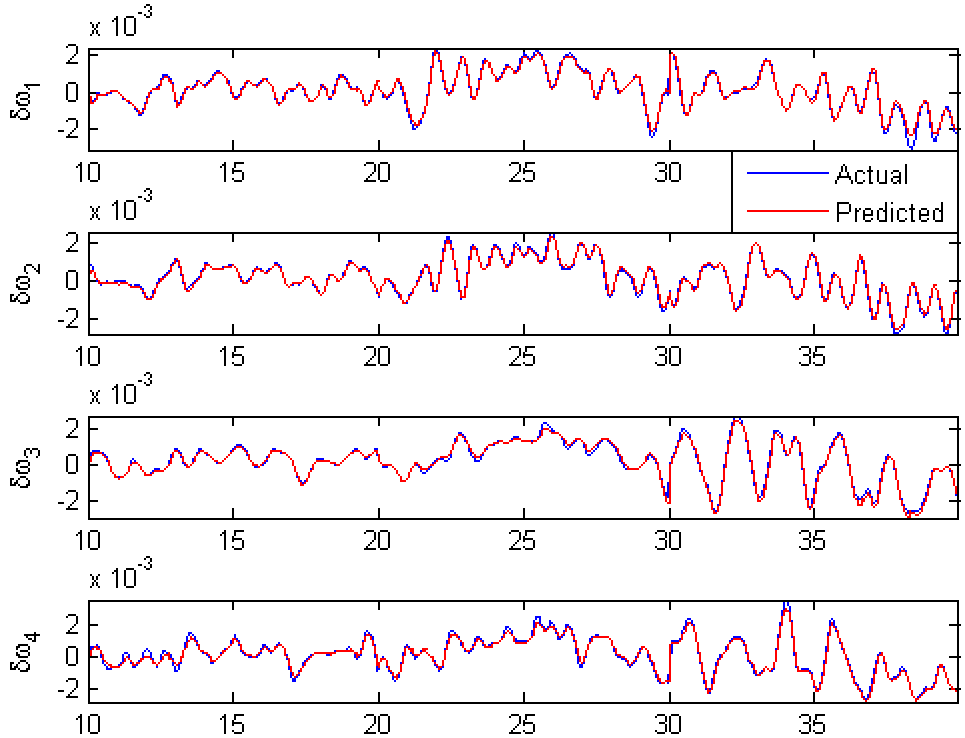
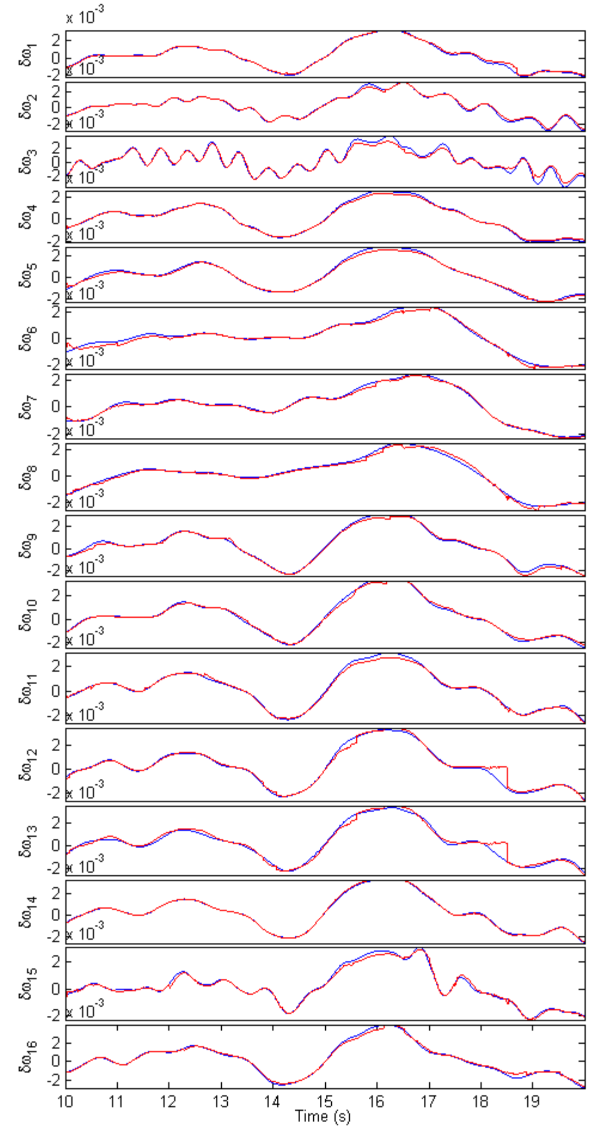
Scalable WAMS based on CCN





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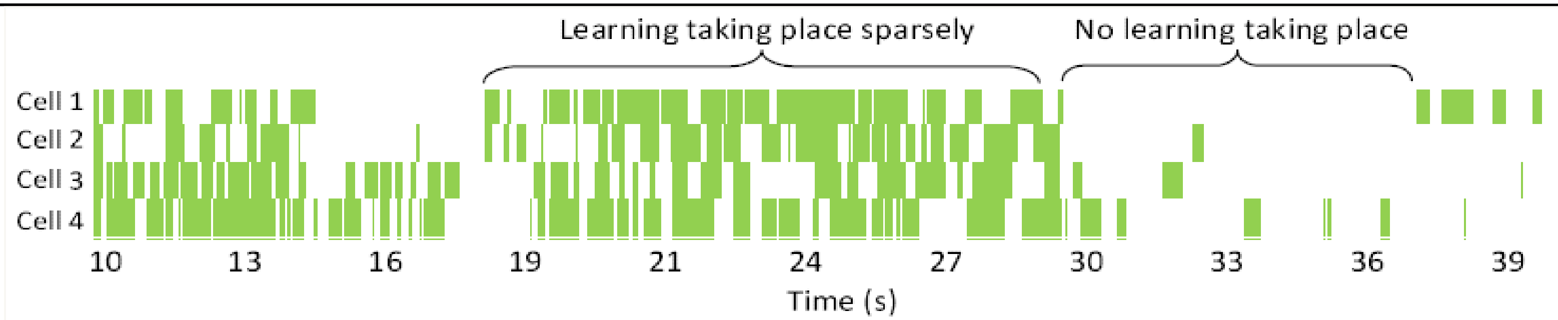
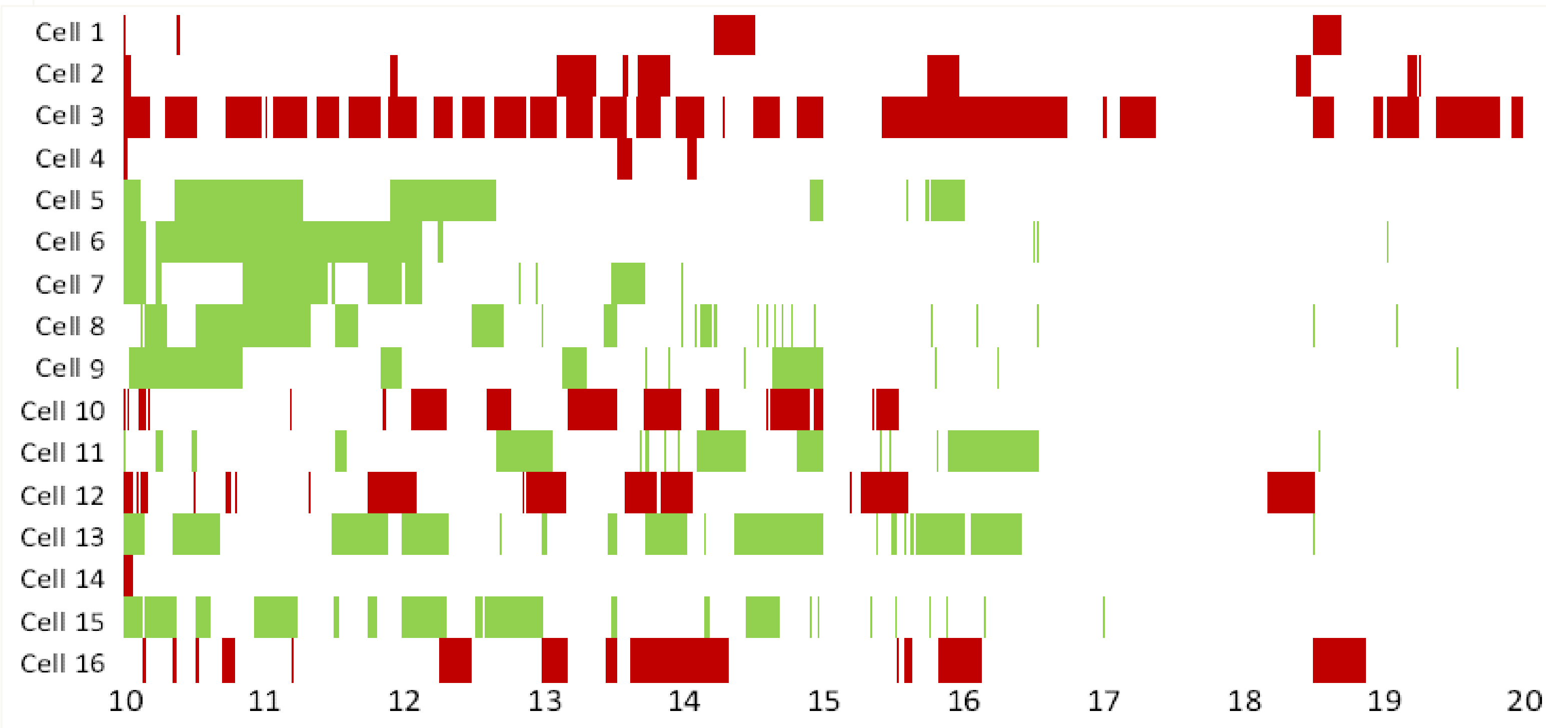
Asynchronous Learning in CCNs





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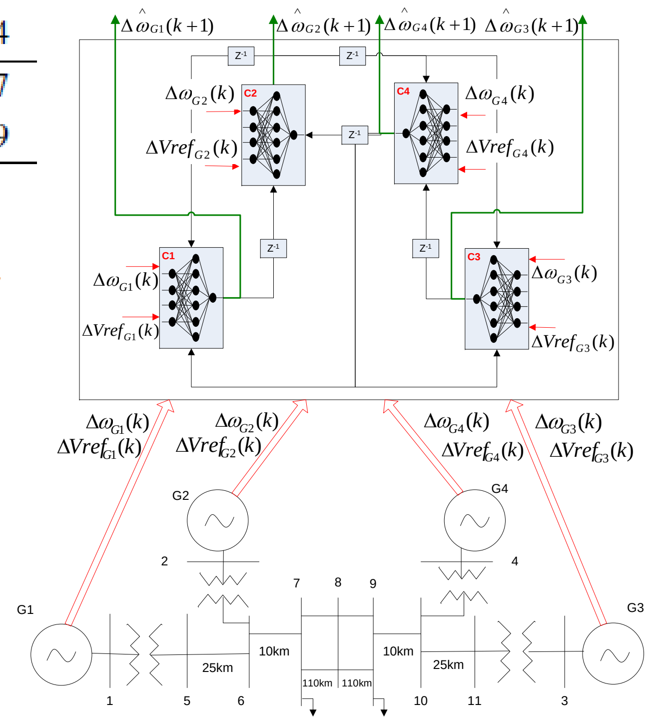
Frequency Modes from CCN Predictions

		Actual		Predicted		Error %	
		ω_N	ζ	$\hat{\omega_N}$	$\hat{\zeta}$	$E\omega_N$	$E\zeta$
G1	Mode 1	0.6023	0.1489	0.6035	0.1476	0.1992	0.13
	Mode 2	1.2075	0.1623	1.2026	0.1521	0.4058	1.02
G2	Mode 1	0.6023	0.1504	0.6039	0.1622	0.2657	1.18
	Mode 2	1.2482	0.1424	1.2298	0.1363	1.4741	0.61
G3	Mode 1	0.6036	0.1491	0.6059	0.1486	0.381	0.05
	Mode 2	1.251	0.1483	1.2311	0.1517	1.5907	0.34
G4	Mode 1	0.6036	0.1481	0.6051	0.1474	0.2485	0.07
	Mode 2	1.2196	0.1463	1.233	0.1802	1.0987	3.39

Natural frequencies and damping ratios obtained with Prony analysis on the actual generator outputs and predicted CCN outputs



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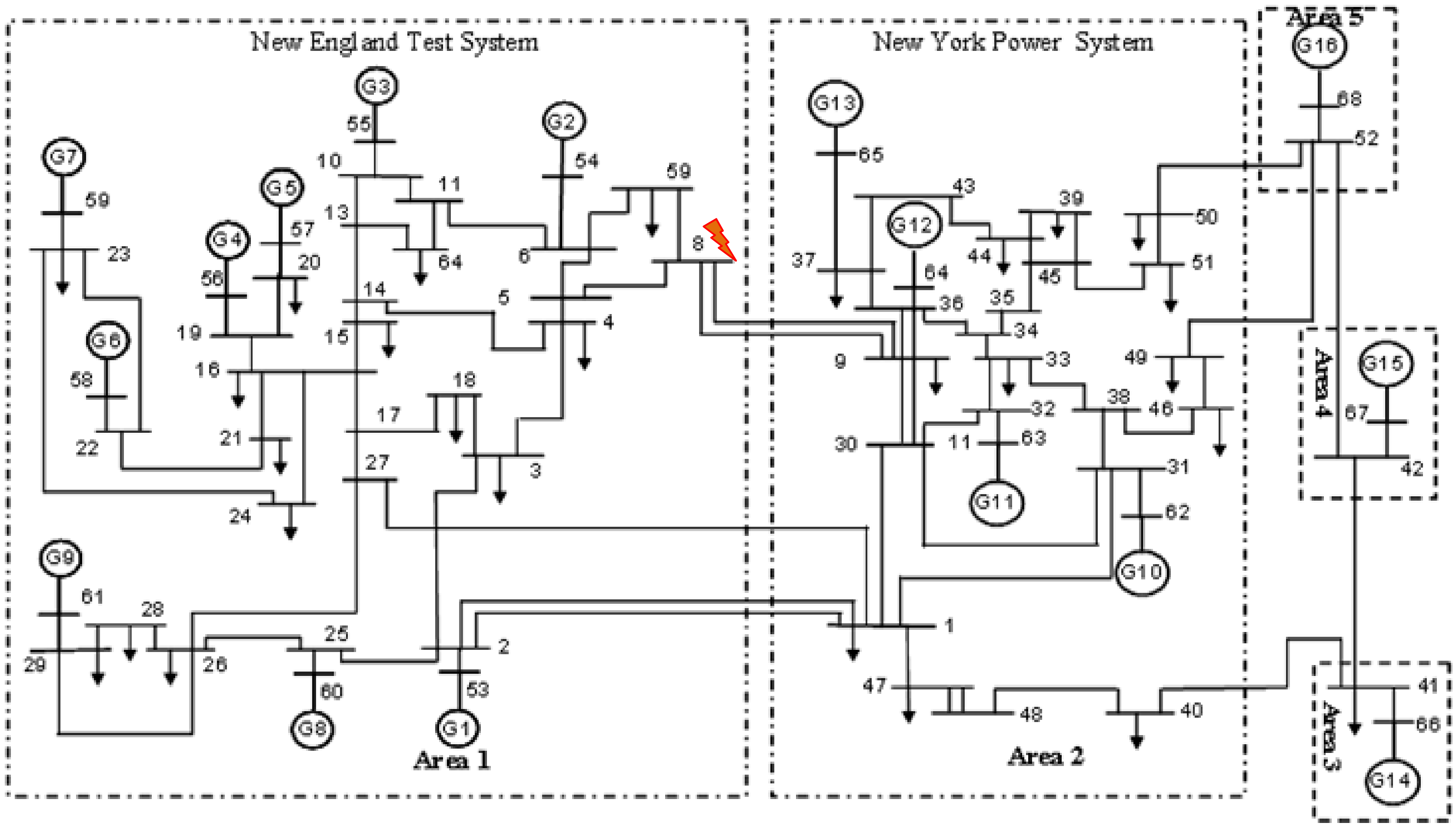
Online CCN based Monitoring Systems



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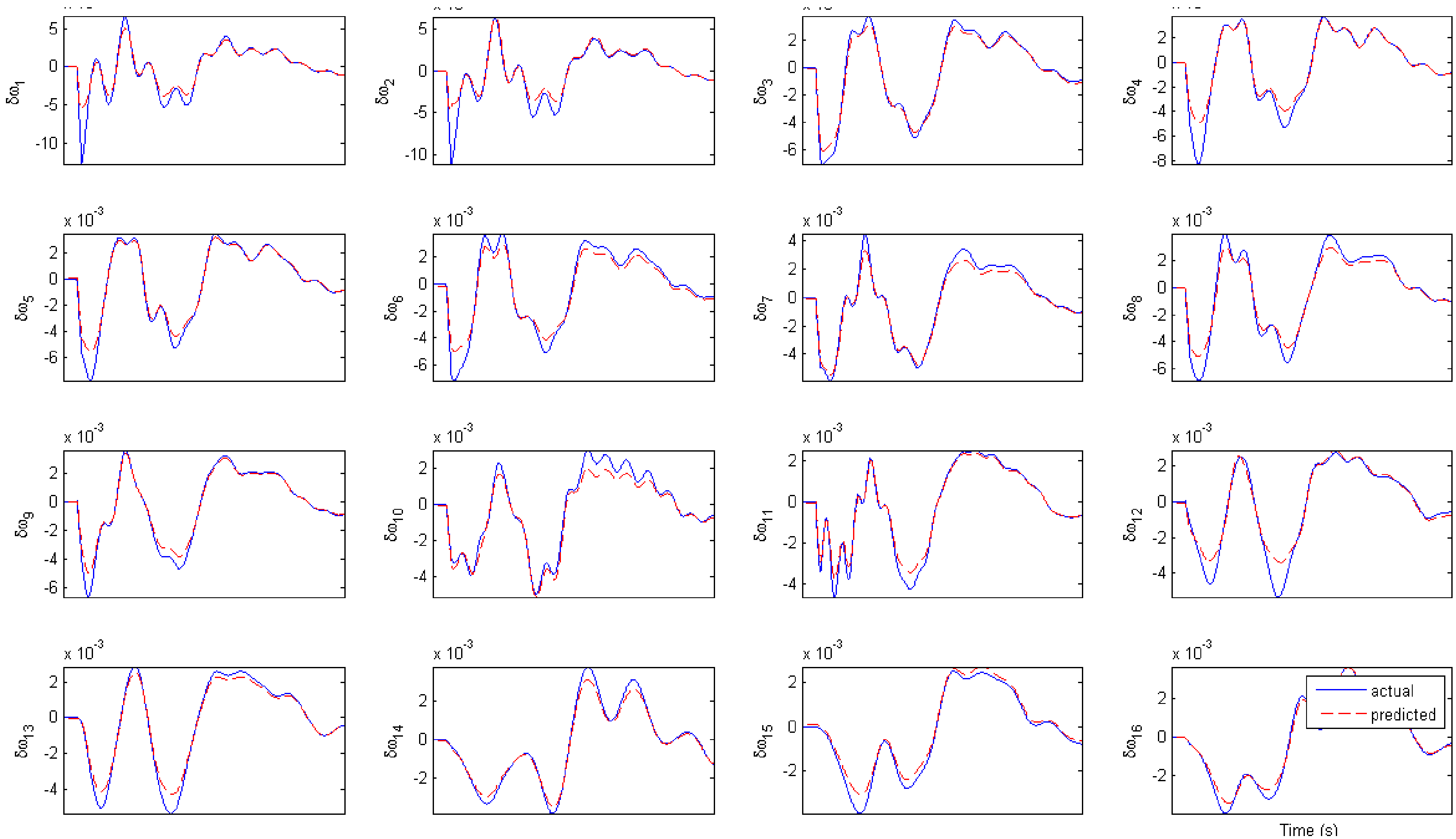


Online CCN based Monitoring Systems

G3			
0.1728	1	**0.1409**	**1**
0.2594	0.0549	**0.2625**	**0.0677**
0.2594	0.0549	**0.2625**	**0.0677**
0.6659	-0.0071	**0.5862**	**1**
0.6659	-0.0071	**0.6675**	**-0.0169**
0.8357	1	**0.6675**	**-0.0169**
1.0866	0.0382	**1.1102**	**0.0497**
1.0866	0.0382	**1.1102**	**0.0497**
1.5552	0.0614	**1.5753**	**0.0455**
1.5552	0.0614	**1.5753**	**0.0455**

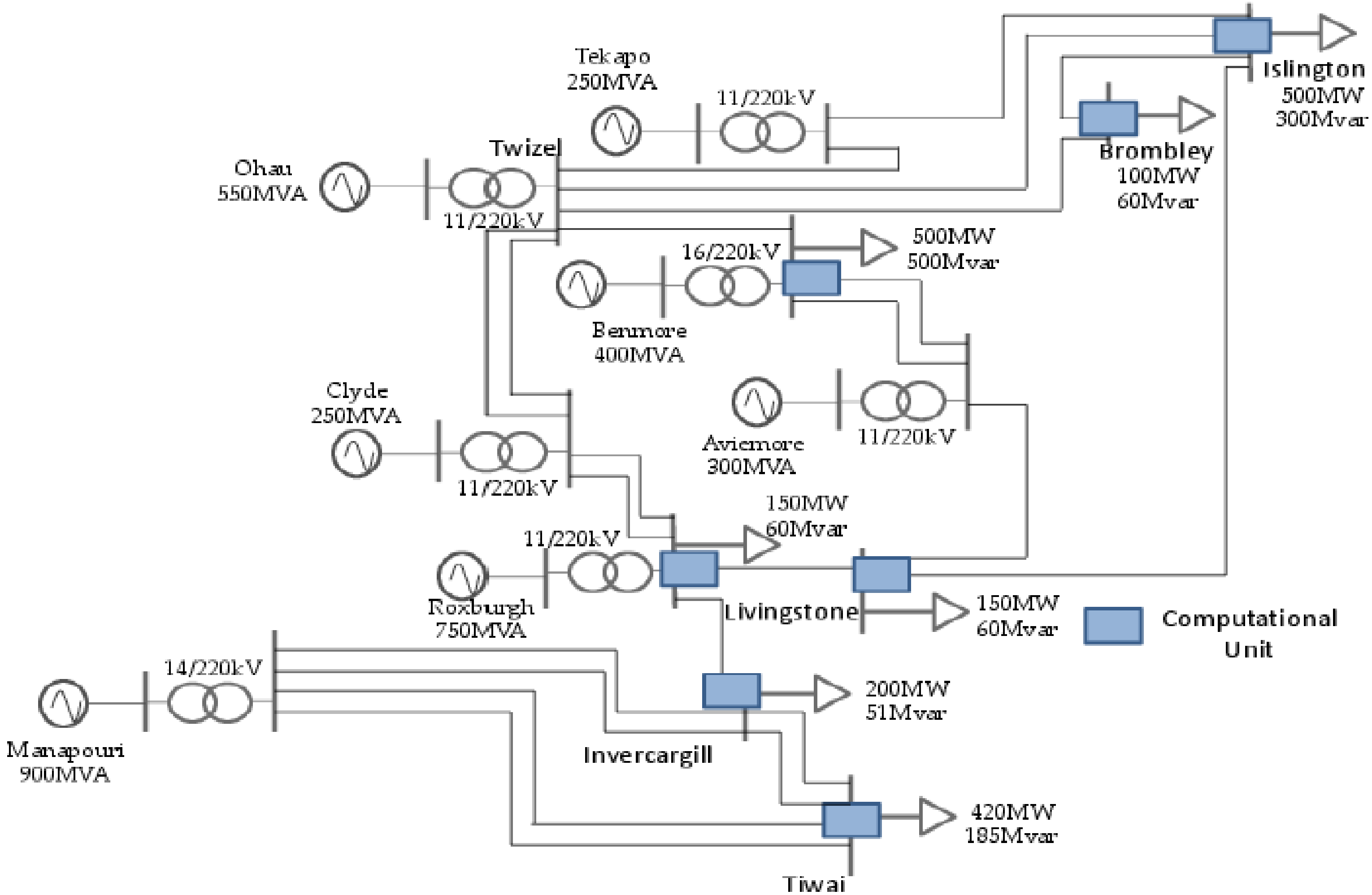
G4			
0.1258	1	**0.1166**	**1**
0.2671	0.0497	**0.2729**	**0.045**
0.2671	0.0497	**0.2729**	**0.045**
0.6606	0.0124	**0.642**	**0.0191**
0.6606	0.0124	**0.642**	**0.0191**
1.0977	0.0395	**1.102**	**0.0334**
1.0977	0.0395	**1.102**	**0.0334**

G12			
0.1626	-0.0588	0.1466	-0.3717
0.1626	-0.0588	0.1466	-0.3717
0.3911	0.161	0.3676	0.1189
0.3911	0.161	0.3676	0.1189
0.8112	0.6316	0.7301	0.0779
0.8112	0.6316	0.7301	0.0779
1.093	-0.04	1.1251	-0.0185
1.093	-0.04	1.1251	-0.0185
1.2984	-0.0368	1.4635	0.0008
1.2984	-0.0368	1.4635	0.0008

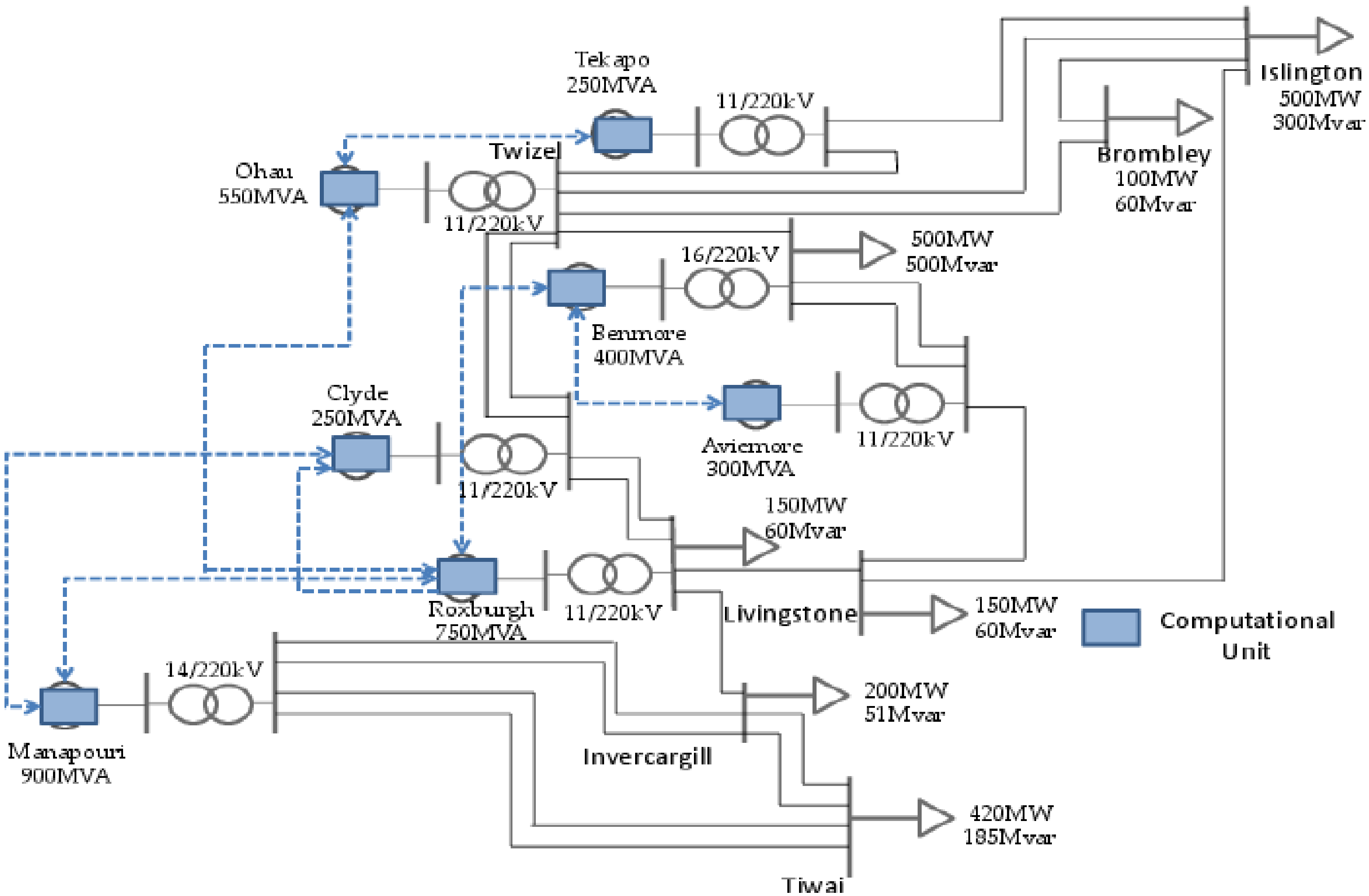
G6			
0.1159	1	**0.1072**	**1**
0.2678	0.0564	**0.2646**	**0.0748**
0.2678	0.0564	**0.2646**	**0.0748**
0.6478	0.0152	**0.6518**	**-0.0026**
0.6478	0.0152	**0.6518**	**-0.0026**
1.1176	0.0507	**1.1395**	**0.0495**
1.1176	0.0507	**1.1395**	**0.0495**
1.6009	0.0682	**1.4669**	**1**
1.6009	0.0682	**1.527**	**0.0462**
1.6891	0.2584	**1.527**	**0.0462**

G15			
0.0891	-0.4184	0.0973	-0.4306
0.0891	-0.4184	0.0973	-0.4306
0.4567	0.0318	0.4538	0.0203
0.4567	0.0318	0.4538	0.0203
0.7859	0.0801	0.8494	0.0384
0.7859	0.0801	0.8494	0.0384
0.8993	0.025	0.9144	0.1537
0.8993	0.025	0.9144	0.1537
1.2611	-0.0831	1.3902	0.0315
1.2611	-0.0831	1.3902	0.0315

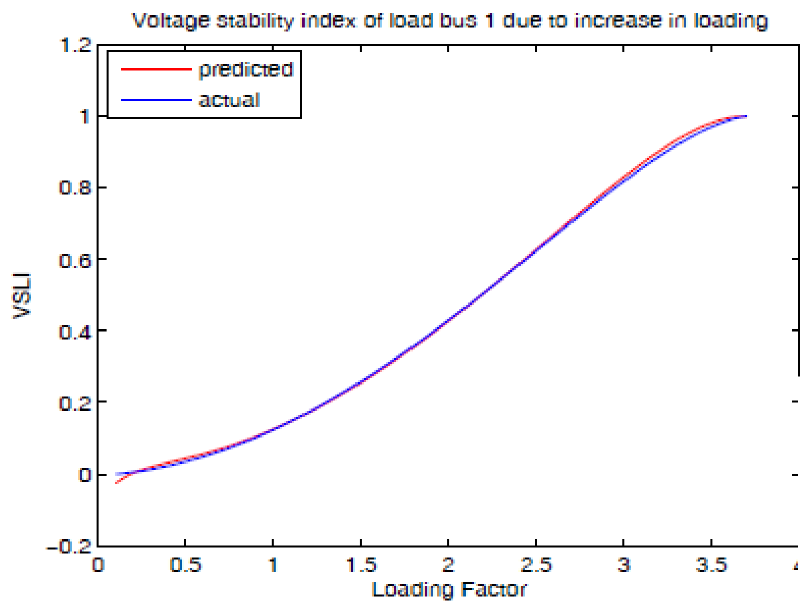
Situational Intelligence - VSLI

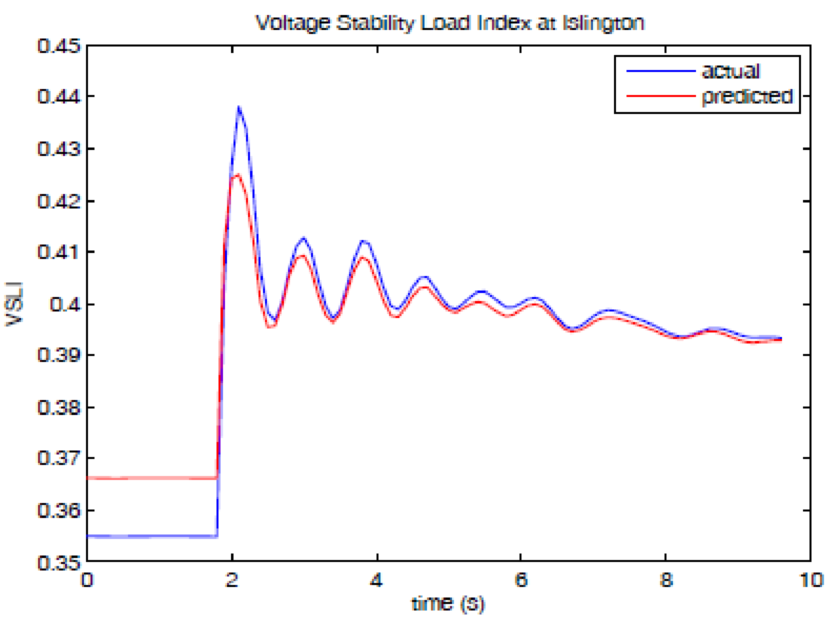


Situational Intelligence – TSM



Situational Intelligence - VSLI





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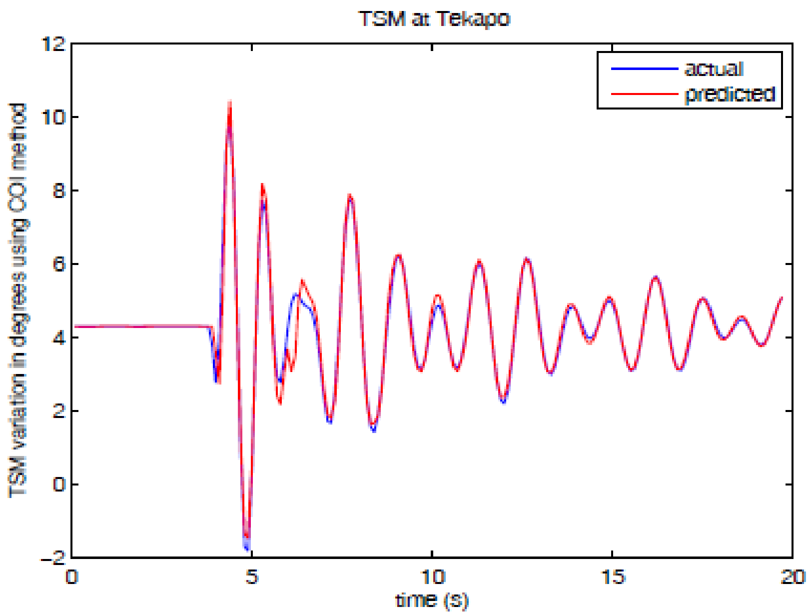

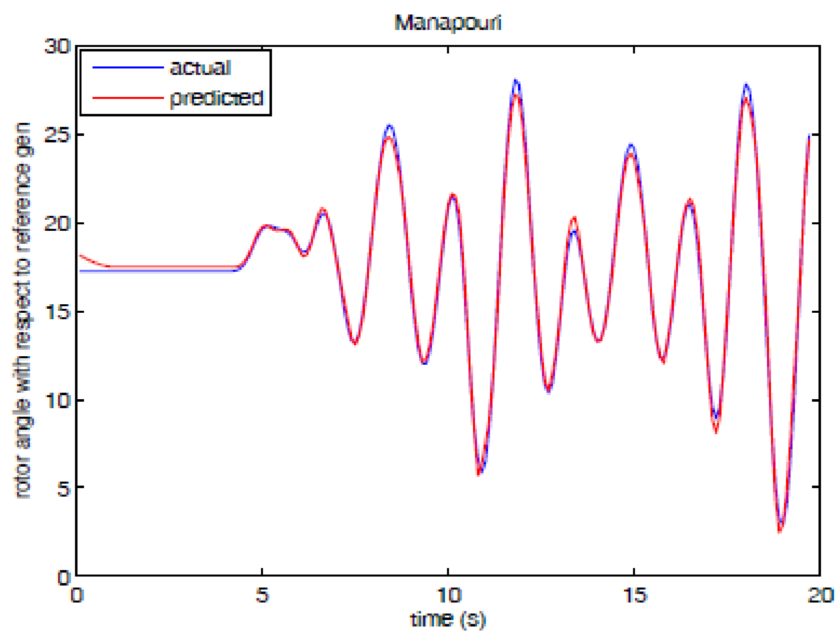

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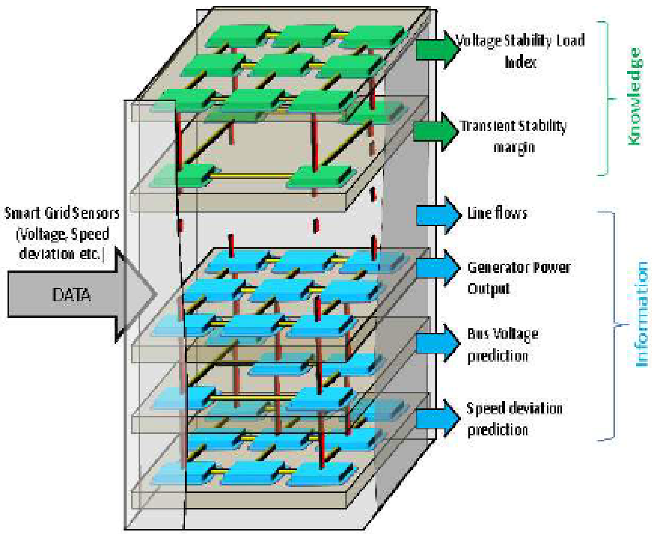
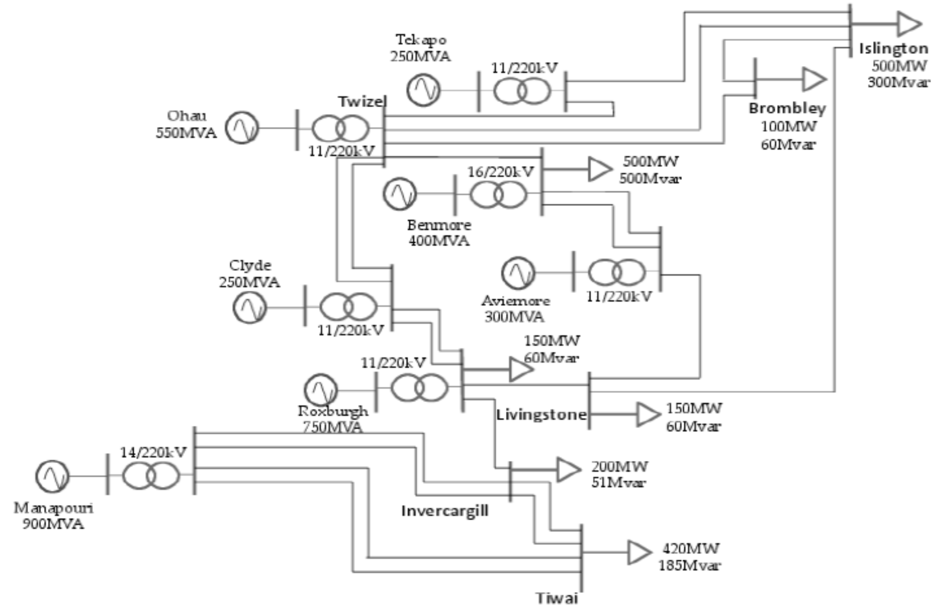
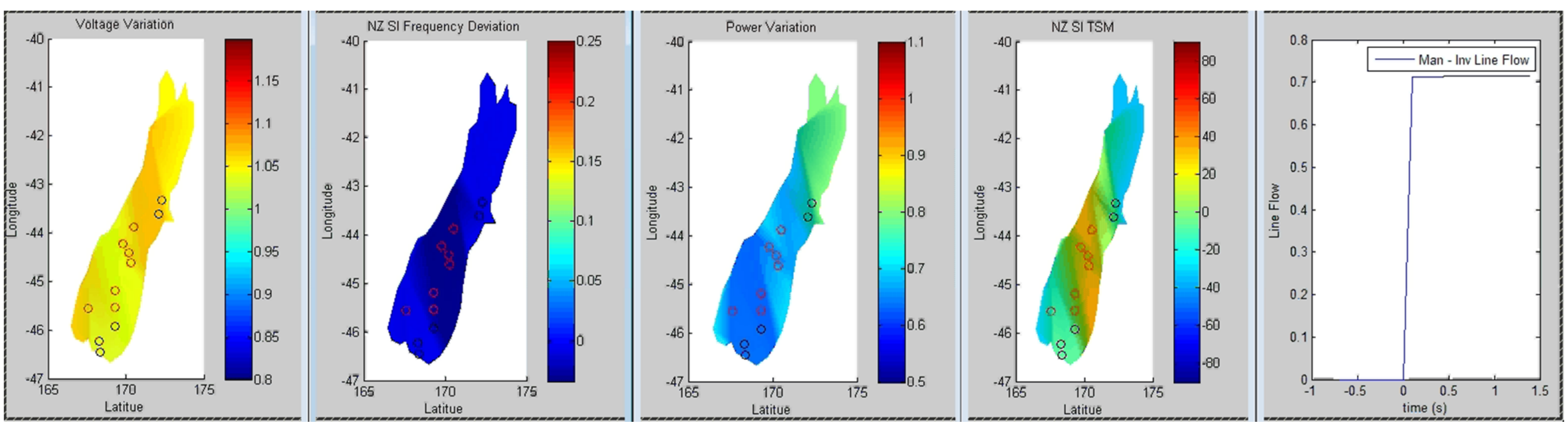
Online & Real-Time Situational Intelligence







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- Improved situational awareness at control centers
  - Power system operators
  - Regional reliability coordinators
- Improved and effective wide area system monitoring and visualization using real-time data
- Online assessment of system stress in respective regions
- Awareness of on-going disturbances
- Receive early warnings of potential stability-threatening events
- Pilot studies prior to deployment
- Educate students at Clemson in power system operations
  - Integrate into graduate research and teaching
  - Undergraduate research and senior design projects
- Certificate programs
- Short courses to utilities – power system dynamics, synchrophasors, system control procedures.

Thank You!

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