Seamless Bulk Electric Grid Management:
A Platform for Designing the Next Generation EMS
PSERC Project S-62G

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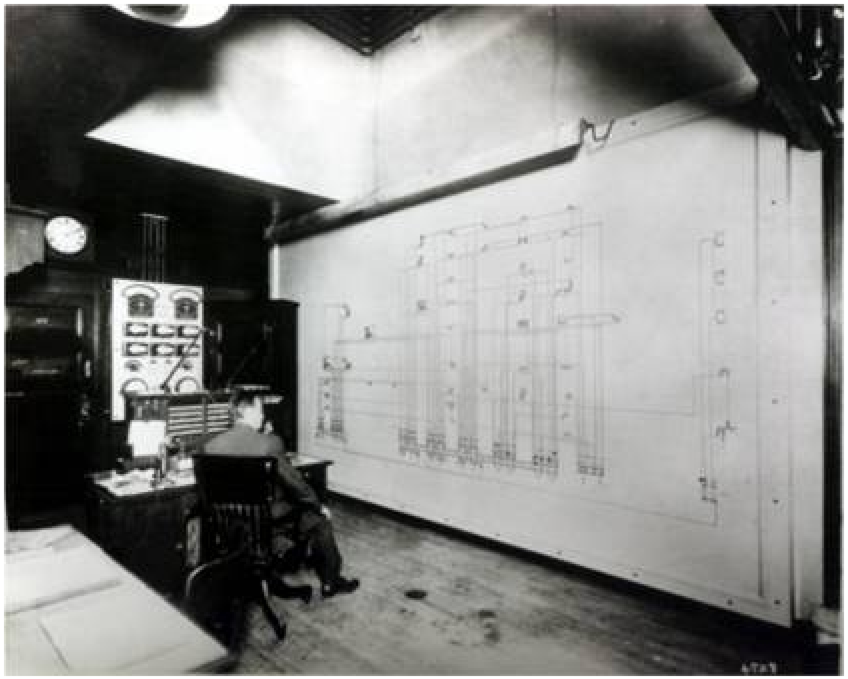
ELECTRIC POWER RESEARCH INSTITUTE

Project Overview

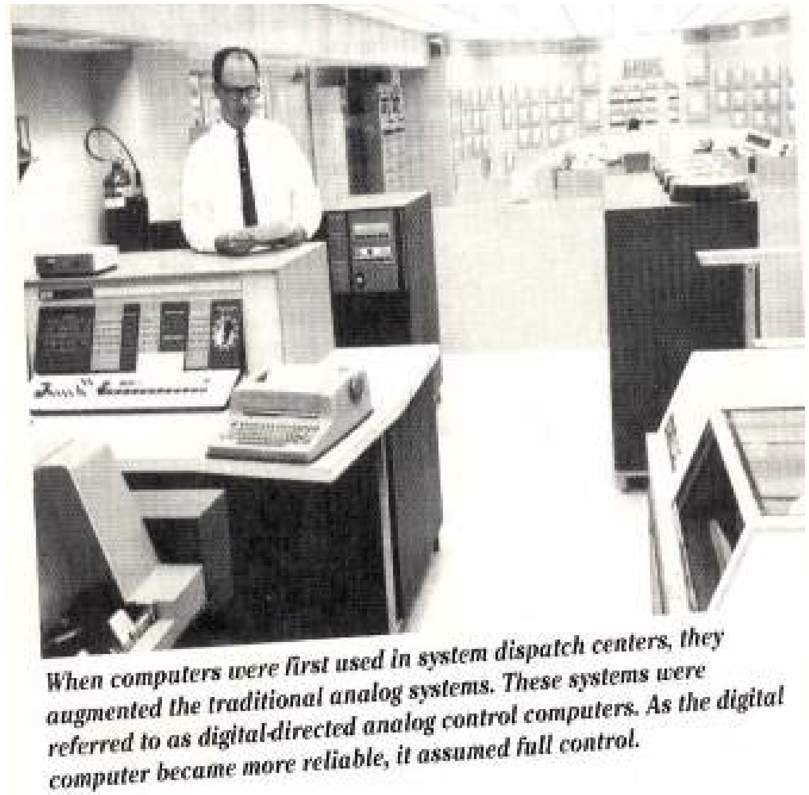
- The overall research objective is to develop a flexible platform in order to test the next generation EMS and associated analytics
  - Platform should be able to simulate different layers related to power grid operations including the system itself, its cyber infrastructure, various software applications
  - Platform should be flexible to allow different components to be included
  - Need to provide case study example systems

EMS Background

- The grid has long been a technology leader



Commonwealth Edison
Control Room Circa 1920



Utility Control Room, 1960’s

Source: W. Stagg, M. Adibi, M. Laughton, J.E. Van Ness, A.J. Wood, “Thirty Years of Power Industry Computer Applications,” IEEE Computer Applications in Power, April 1994, pp. 43-49

EMS Background

- And we are continually getting smarter!

PSE&G Control Center in 1988

ISO New England
Control Center

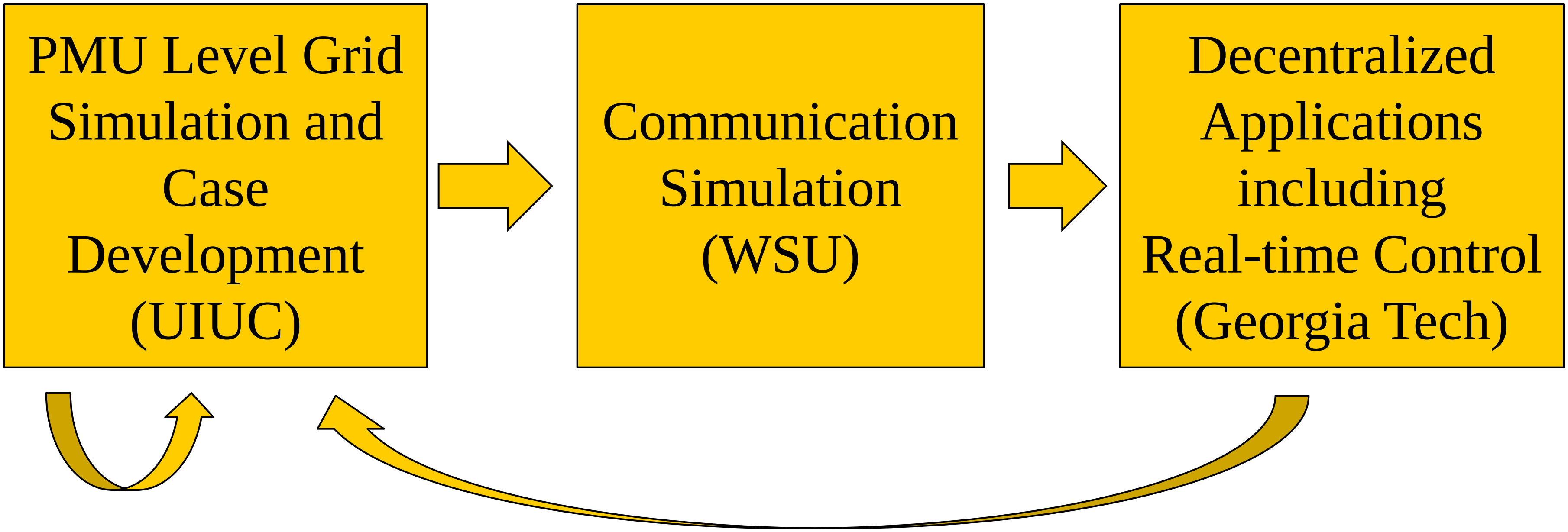
Source: J.N. Wrubel, R. Hoffman, "The New Energy Management System at PSE&G," IEEE Computer Applications in Power, July 1988, pp. 12-15.

Previous Work

- **Previous Work** under this project established a framework and requirements for next-generation Seamless Energy Management Systems.
- **Key Requirements** included:
  - Support for explicit modeling of the effects of imperfect communications in cyber-control.
  - Recognition of the need to manage faster and more dynamic effects in the system.
  - Trends and opportunities of decentralized control.
- Study requires simulation of a cyber-physical system.

Project Coordination

- Project involves coordinated work taking place at UIUC, WSU and Georgia Tech



Seamless Bulk Electric Grid Management (S-62G)

Part 1: PMU Level Grid Simulations and Cases (UIUC)

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PMU Level Simulations

- Traditionally the EMS has been driven by SCADA data
- Dispatcher Training Simulators have also used this time frame
  - Uniform frequency
- EMS of the future needs to work in the PMU (transient stability) timeframe, so this is required in the simulation
  - EMS is most important during stressed operation!

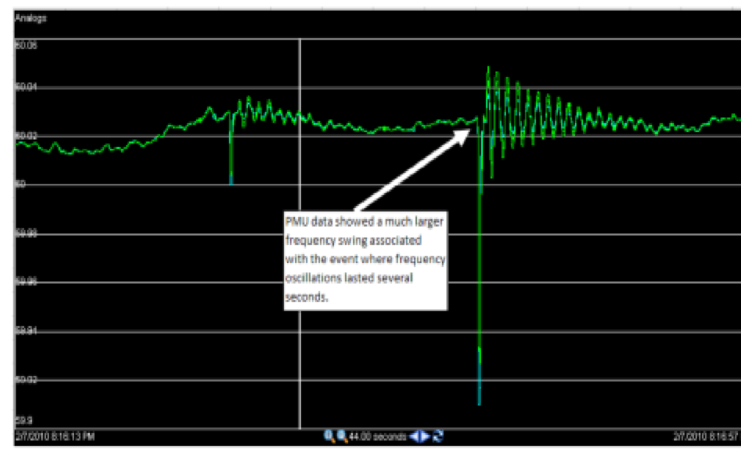
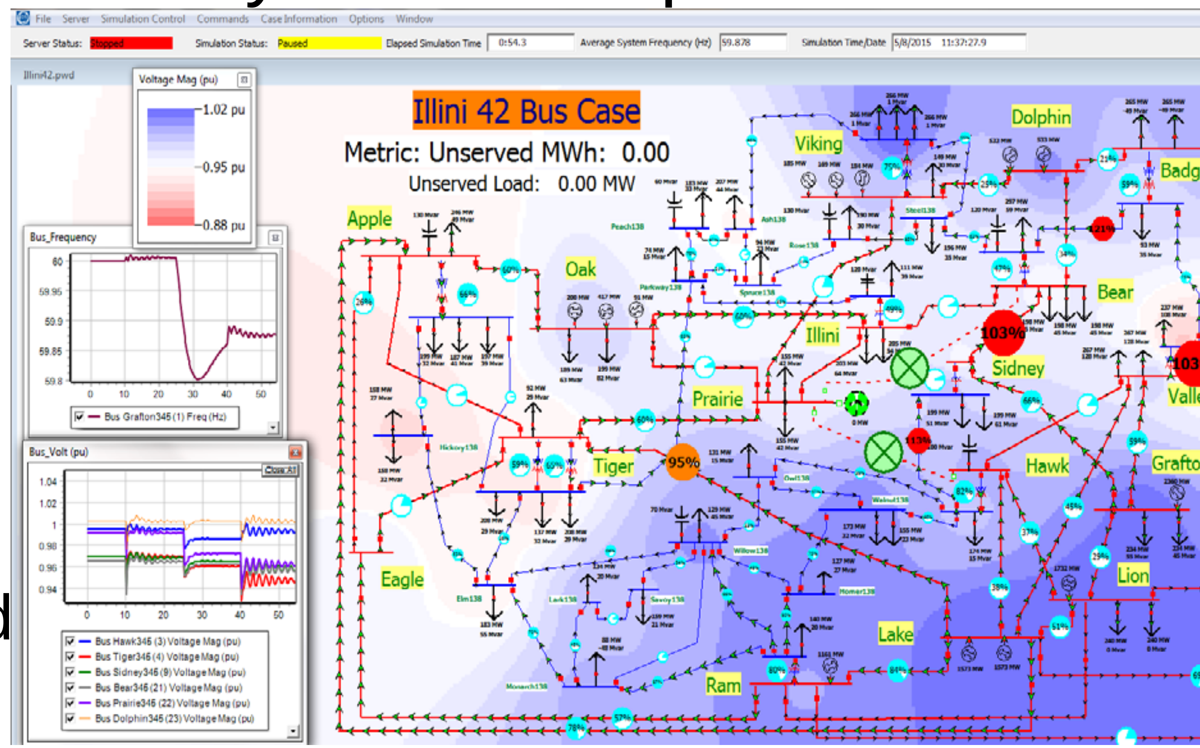


Image Source: Jay Giri (Alstom Grid), "Control Center EMS Solutions for the Grid of the Future," EPCC, June 2013

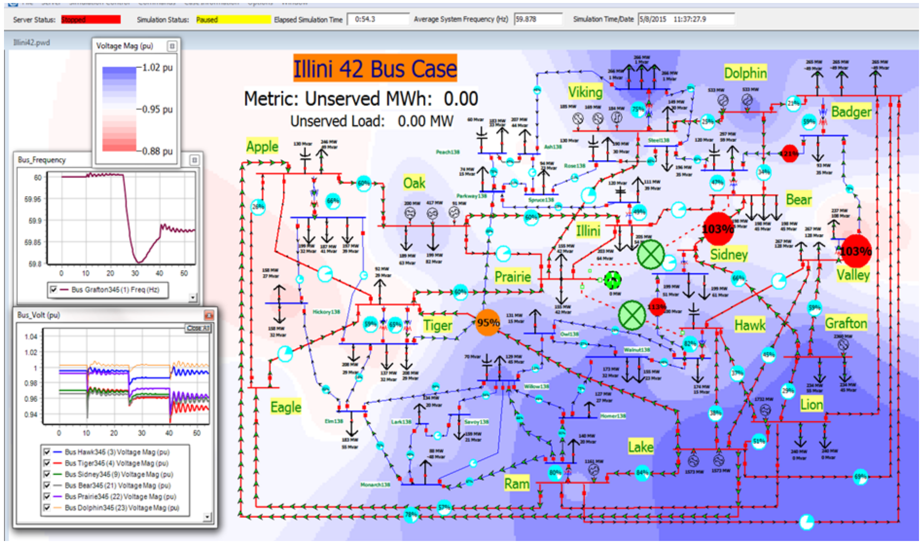
Real-time, PMU Level Simulation Environment

- Project leveraged commercial, interactive, real-time transient stability simulation platform
  - Data is exported in c37.118 format
  - Closed-loop control is also implemented
  - Standard transient stability models are used, including generator over excitation limiters and line relays



Case Development

- First case developed for this testing was a 42 bus, 345/138 kV, 11 GW of Generation/Load
  - Rather detailed dynamics models were included allowing for interactive, transient stability simulation
  - RTUs were modeled for each of the substations
  - Scenario considered was a tornado moving by a substation, taking out three 345 kV lines and 500 MW of generation
  - Case is public domain



Event scenario for 42 bus system

This is described as follows:

1.At 2.0 seconds, the system has a 3-phase ground fault at bus 15.
2.At 2.5 seconds, the line between buses 43 and 15 opens.
3.When control center receives fault data, it sends back control signal to trip the generator at bus 43.
4.The generator trip to keep system stable.

Each PMU data packet will have PDC processing delay when it goes through each substation or PDC, which varies and needed to be considered.

Seamless Bulk Electric Grid Management (S-62G)

Part 2: Communications (WSU)

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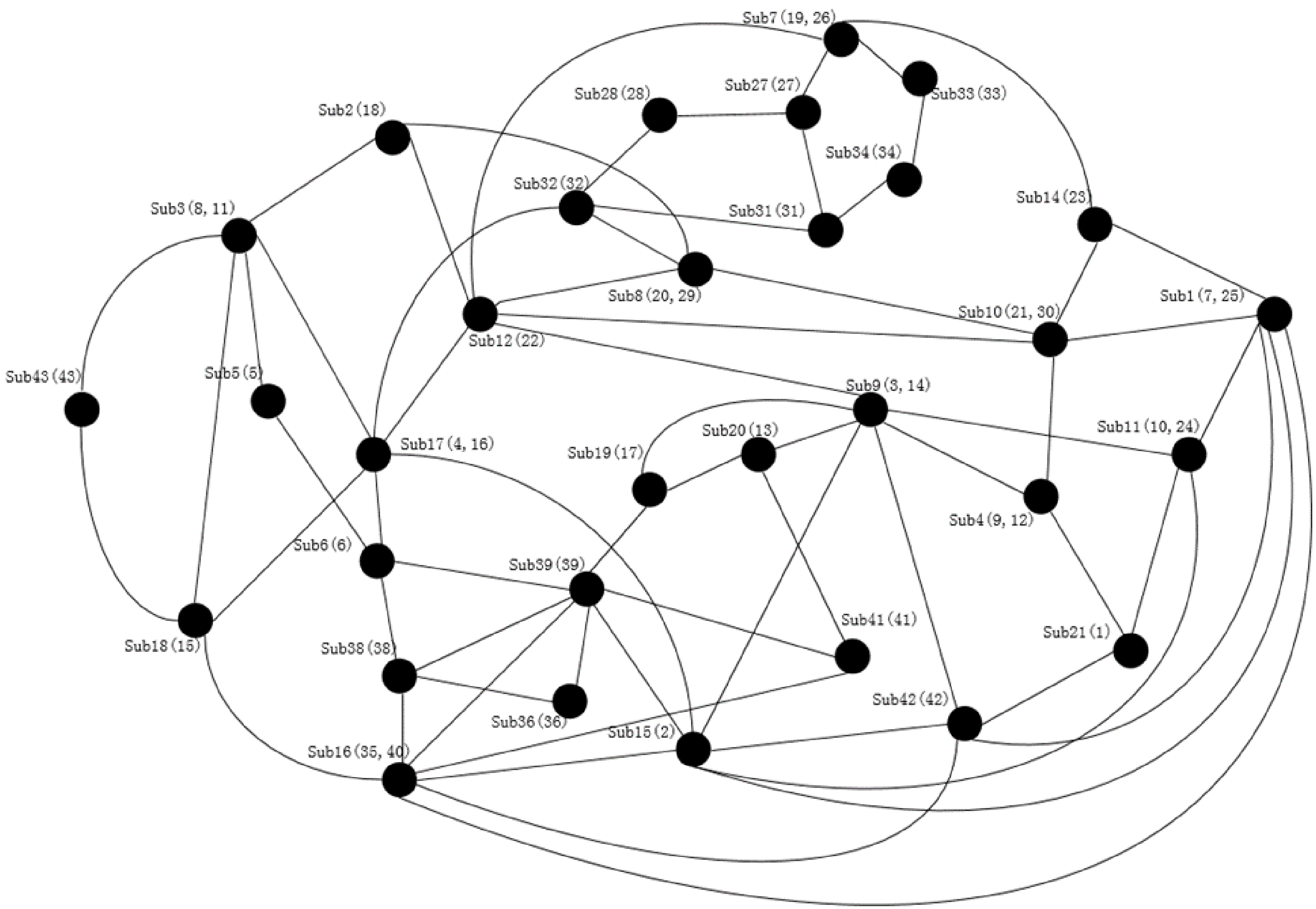
Communication simulation using NS3

I. Preparation of the communication network
- Communication network based on the power network
- Control center based near existing substation

II. Protocol Stack
- TCP or UDP? Why?

III. Communication network simulation and results
- NS3 used to calculate time delays in communication
- Output is PMU data plus time delays

Processing preparation



Communication network overlay for Illinois 42-bus system

Processing preparation, cont.

General rules in this case:

1. PMUs are installed at both ends of each transmission line, measuring voltage and current phasors both.
2. The sample rate for each PMU is 60 samples per second.
3. In each substation, phasor data concentrator (PDC) is collecting PMU measurements from PMUs connected to that substation.
4. PDCs are communicating each other over communication channels.

Our work is to compare different communication architectures to minimize communication delays.

Protocol stack

Communication network has 5-layer stacks according to TCP model.

- Application Layer: C37.118 is specifically designed for PMU messages exchanging.
- Transport Layer: Our choice is UDP but why?
  - UDP packet header is lighter thus transmit faster than TCP.
  - TCP protocol is complicated because it has many delivering-guaranteed mechanisms such as retransmission, congestion control, flow control.
- Network Layer: IPv4 (more common than IPv6).
- Link Layer: Ethernet.
- Physical Layer: Optical fiber.

Four different communication architectures with delay results

Two main kinds of communication network are presented: star and mesh networks.

- Star network: it defines a network in which all communication nodes communicate directly one node, in this case, control center.
- Mesh network: it defines a more flexile communication network in which communication links are along the same or similar right-of-way as the transmission lines.

Four different communication architectures with delay results, cont.

These four communication architectures have mesh and star networks both. They are:

1)Network along with the transmission lines. (Mesh)

2)Network divided by three areas. (Mesh)

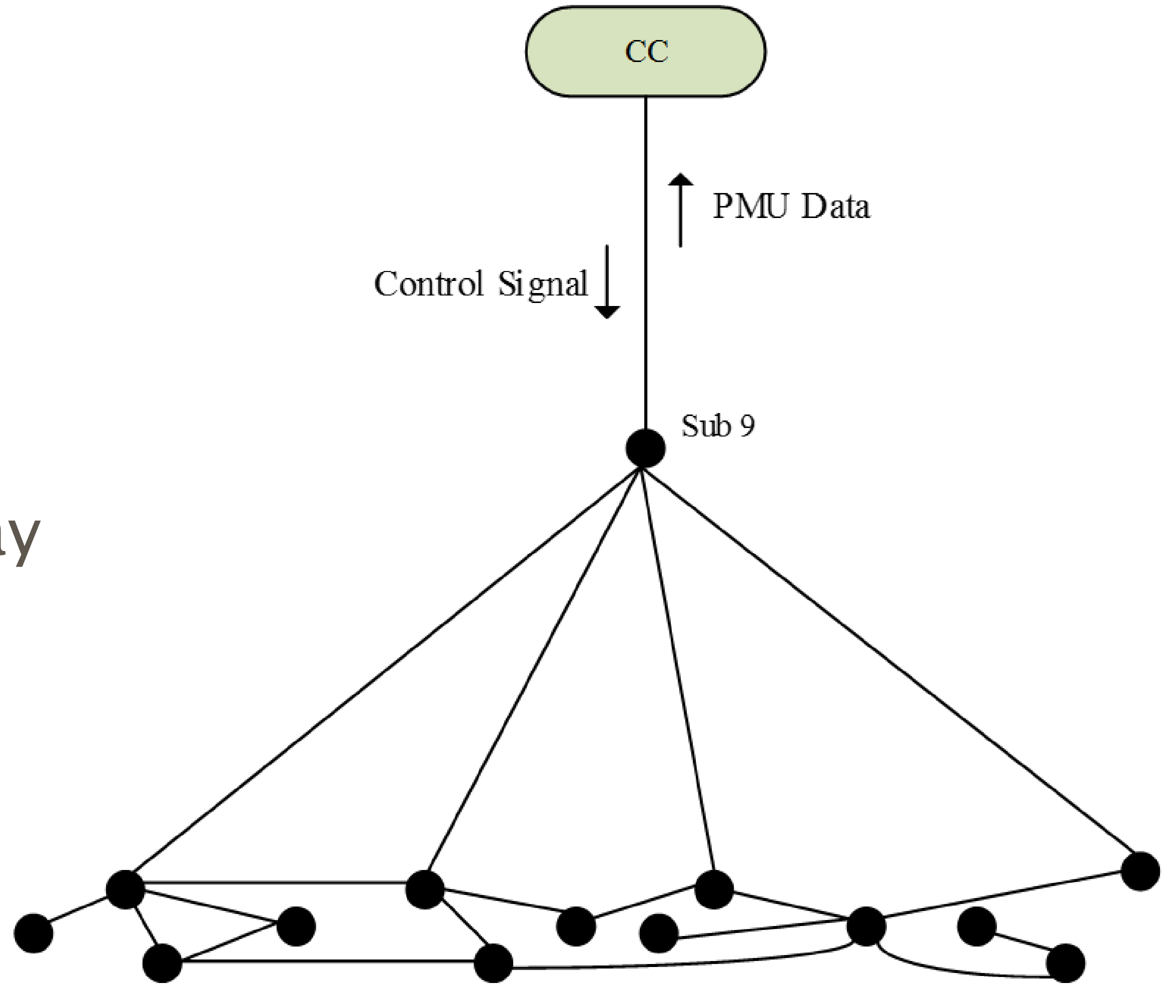
3)Centralized structure. (Star)

4)Decentralized structure. (Star)

The following slides describe them one by one, with delay results and demonstration on transient stability followed.

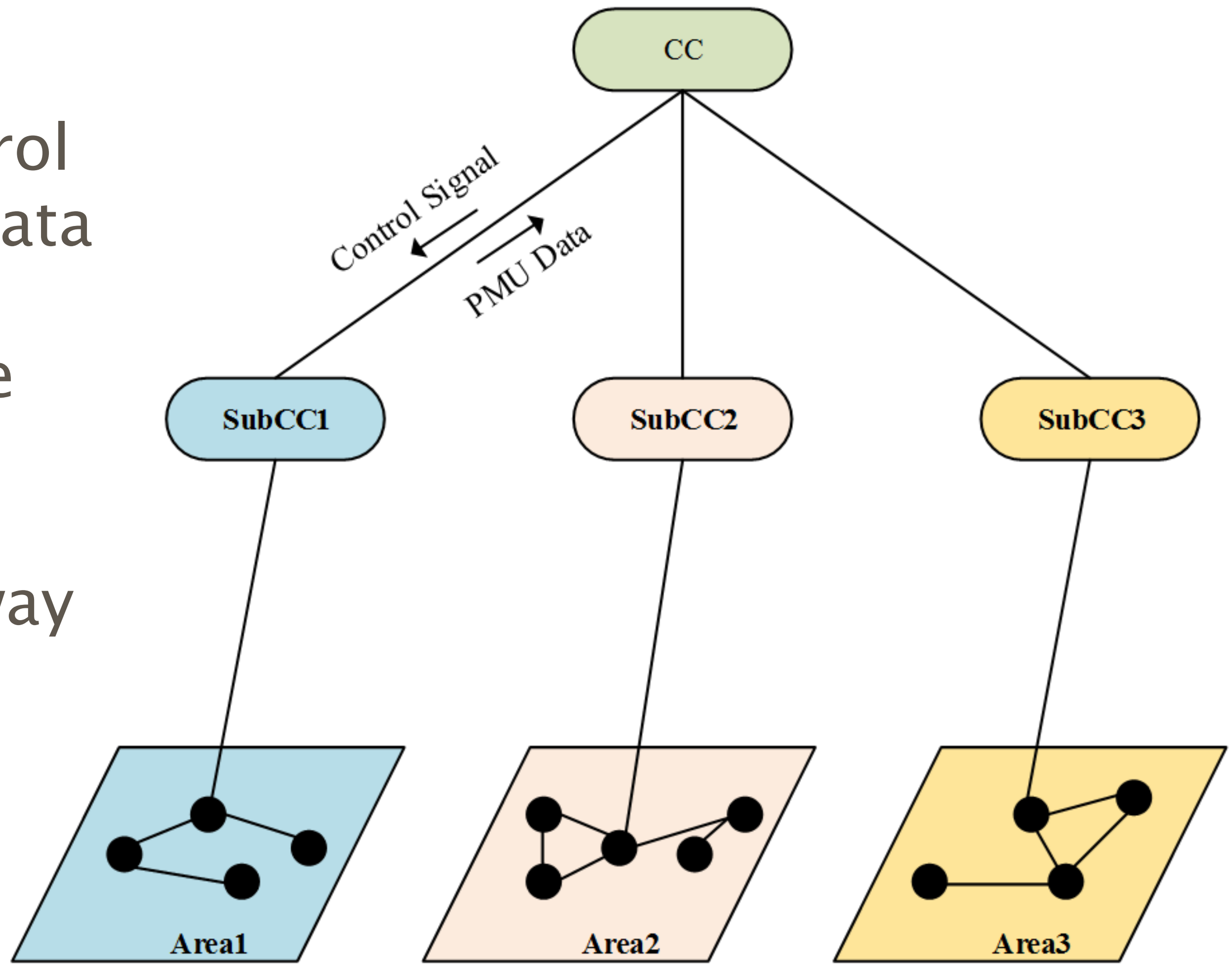
Network along with the transmission lines (network type 1)

One control center with communication lines along the same right-of-way as the power transmission lines.

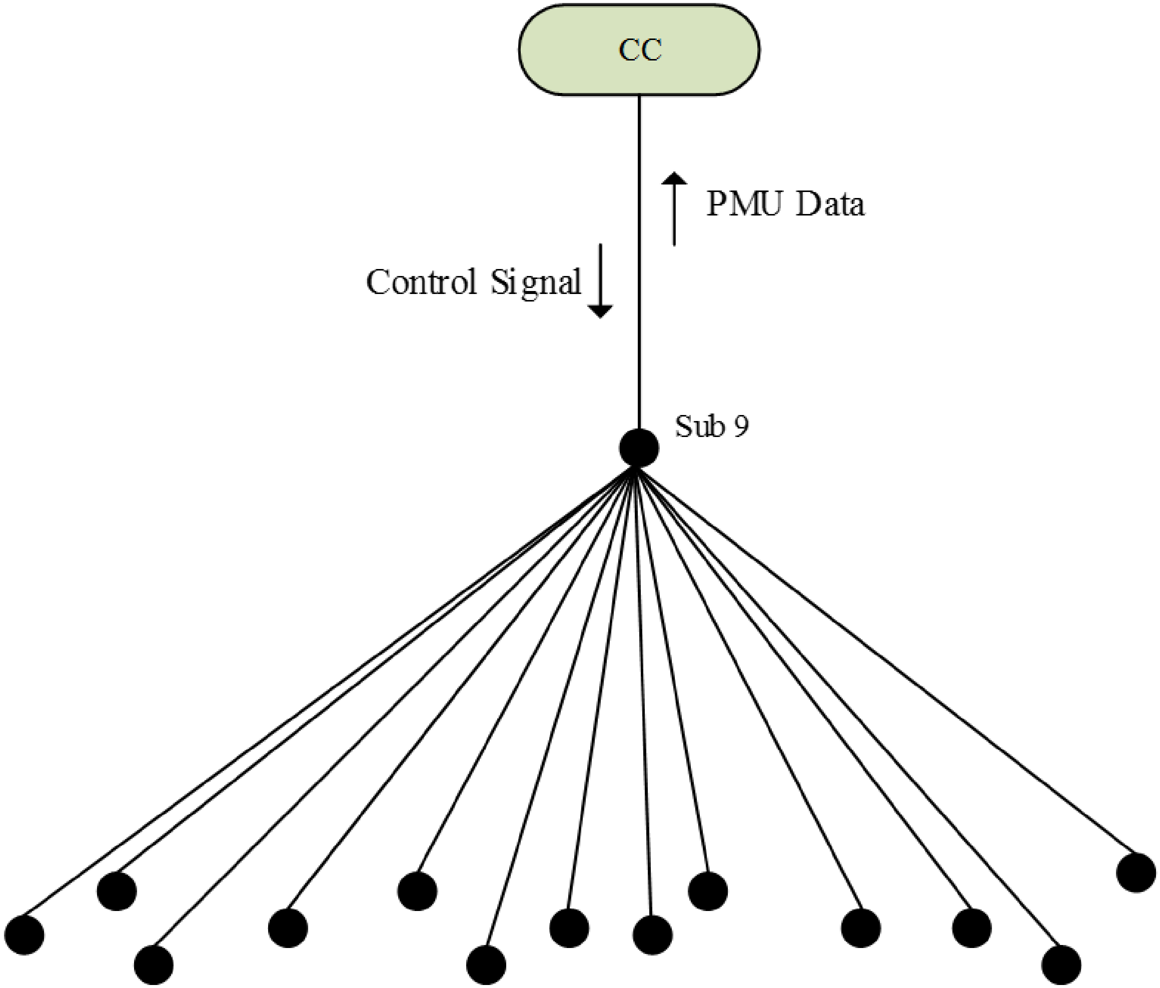


Network divided by three areas (network type 2)

Three sub-control can help PMU data routing.
In each area the communication links along the same right-of-way as the power transmission lines.

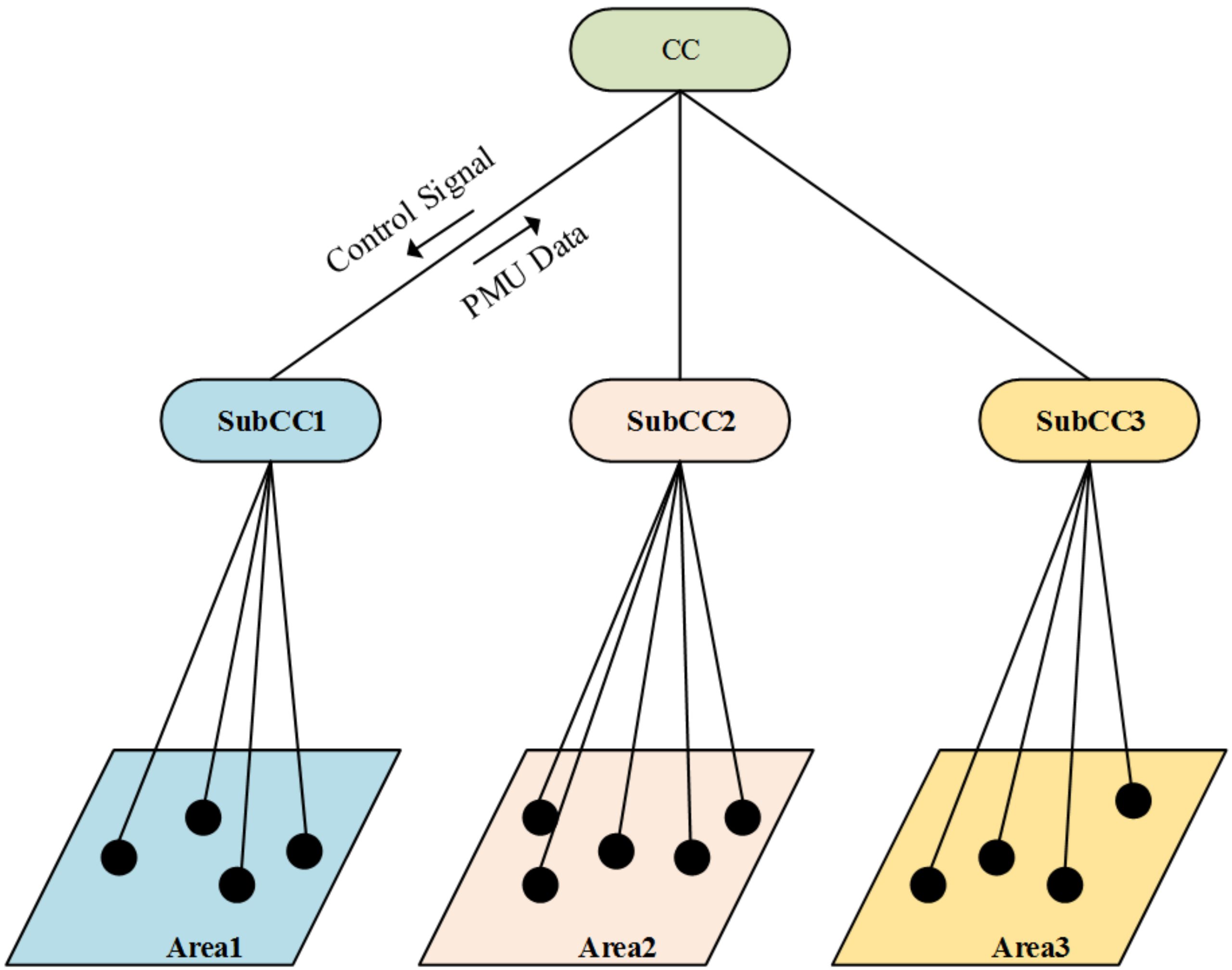


Centralized structure (network type 3)



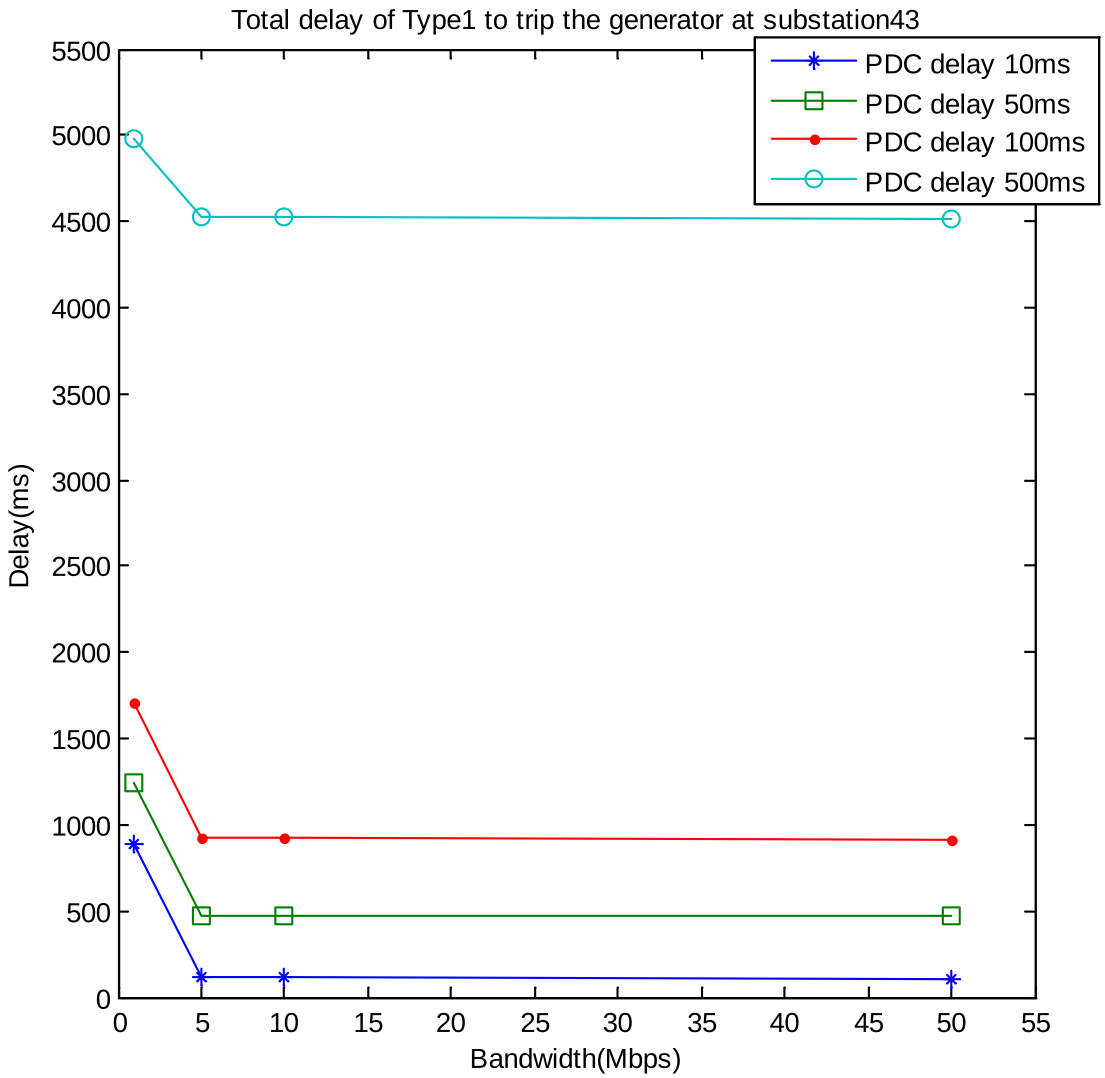
One control center through substation 9. Each substation is directly linked to Sub 9.

Decentralized structure (network type 4)



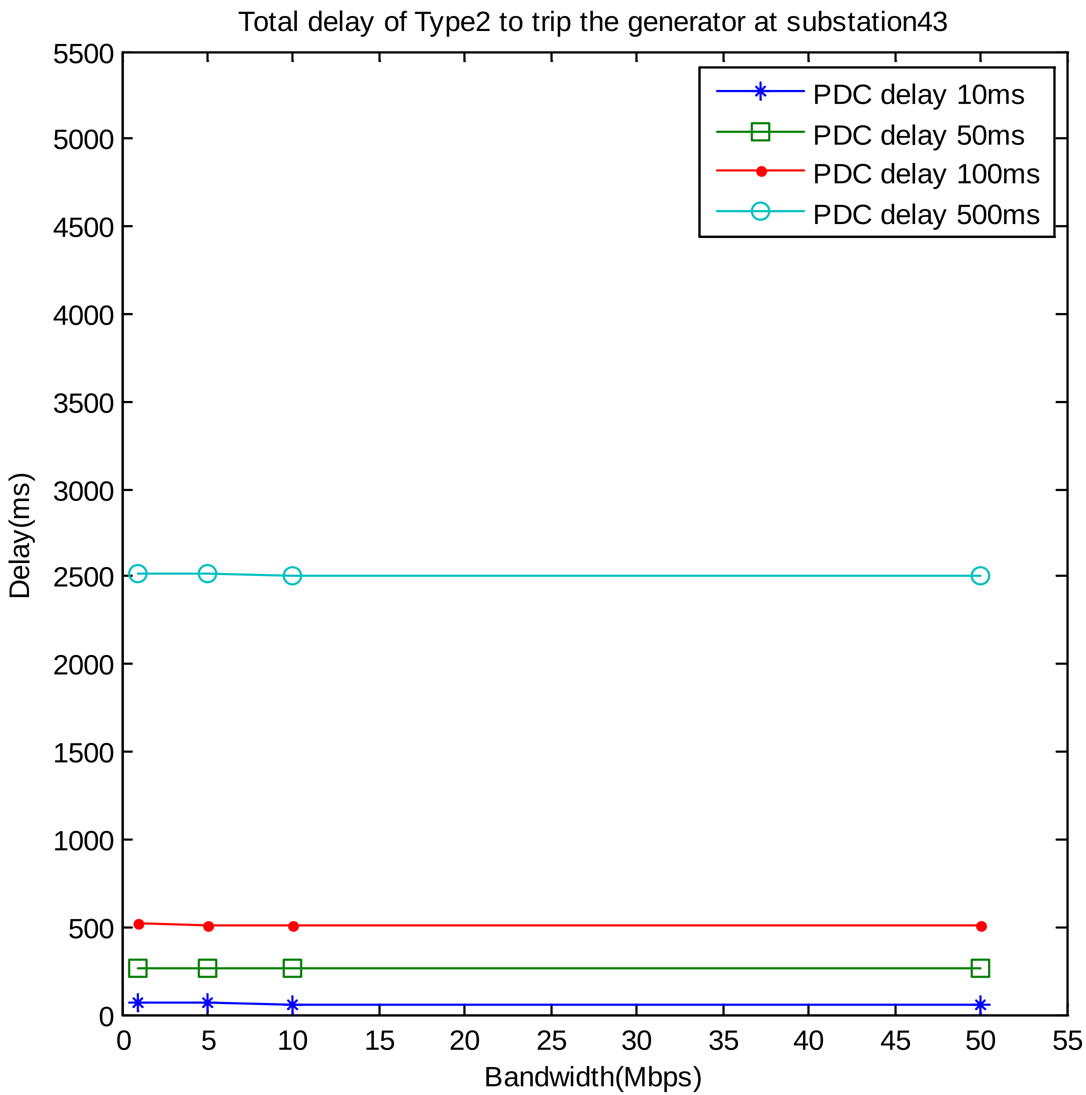
Similar to type 2 yet each substation link one sub-control center in its own area.

Type 1 delay results



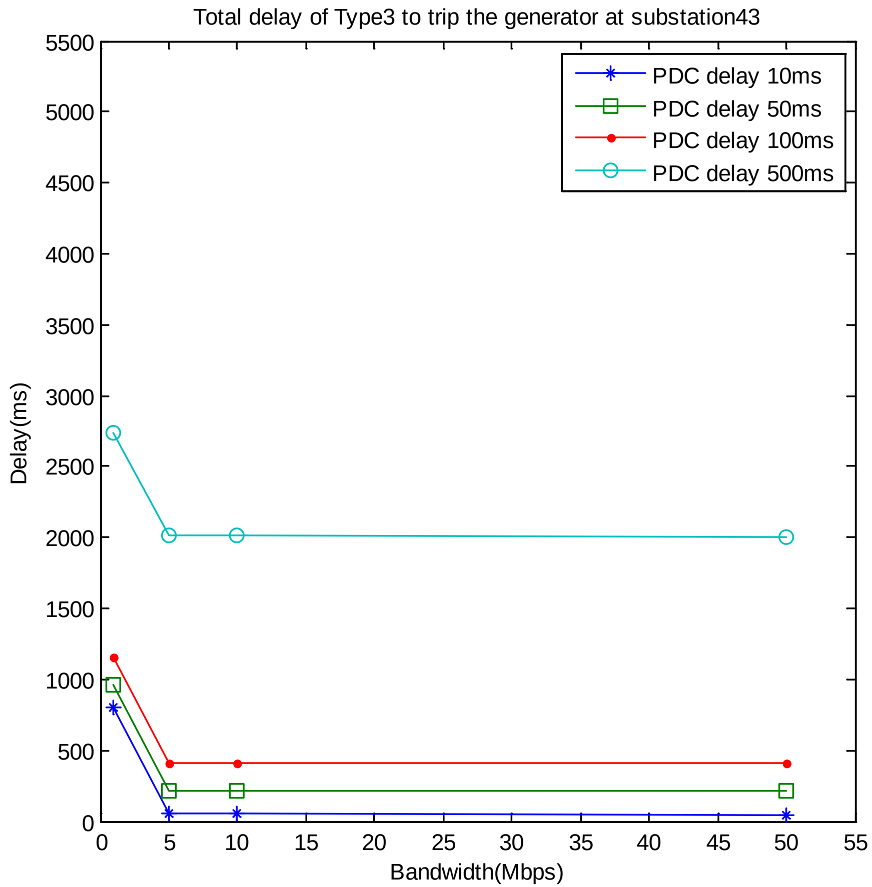
Different communication bandwidth considered. When the bandwidth is below 5Mbps, the queuing delay is increasing much.

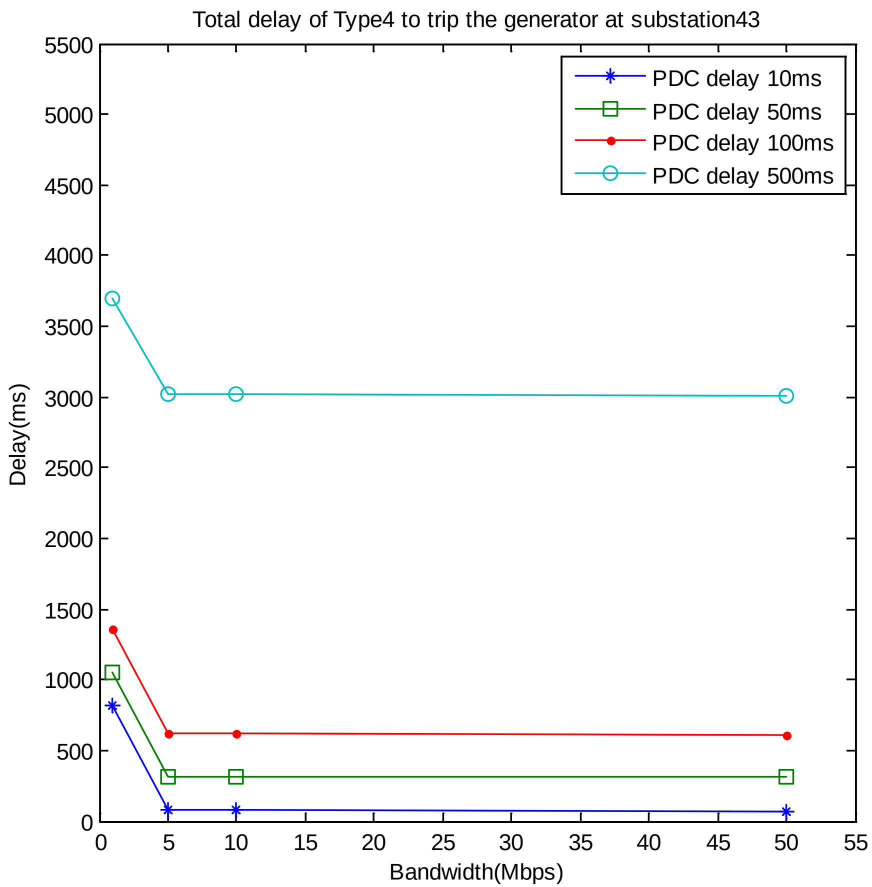
Type 2 delay results



The communication delays are almost "stable" even the communication transmission rate is below 5Mbps.

Type 3&4 delay results

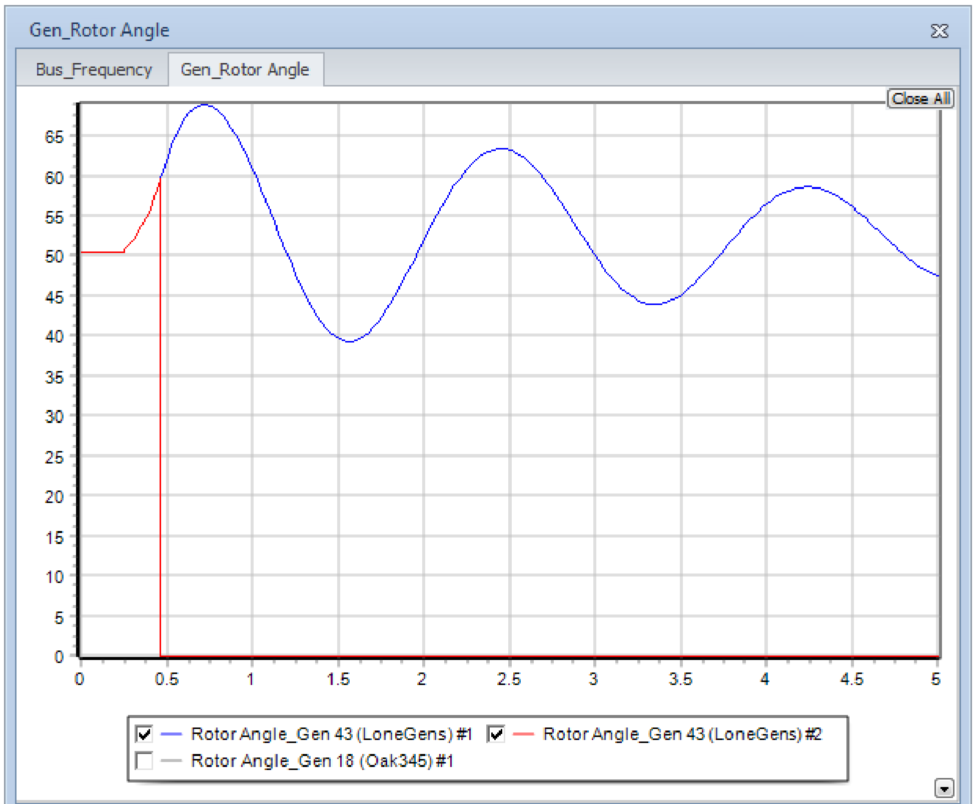




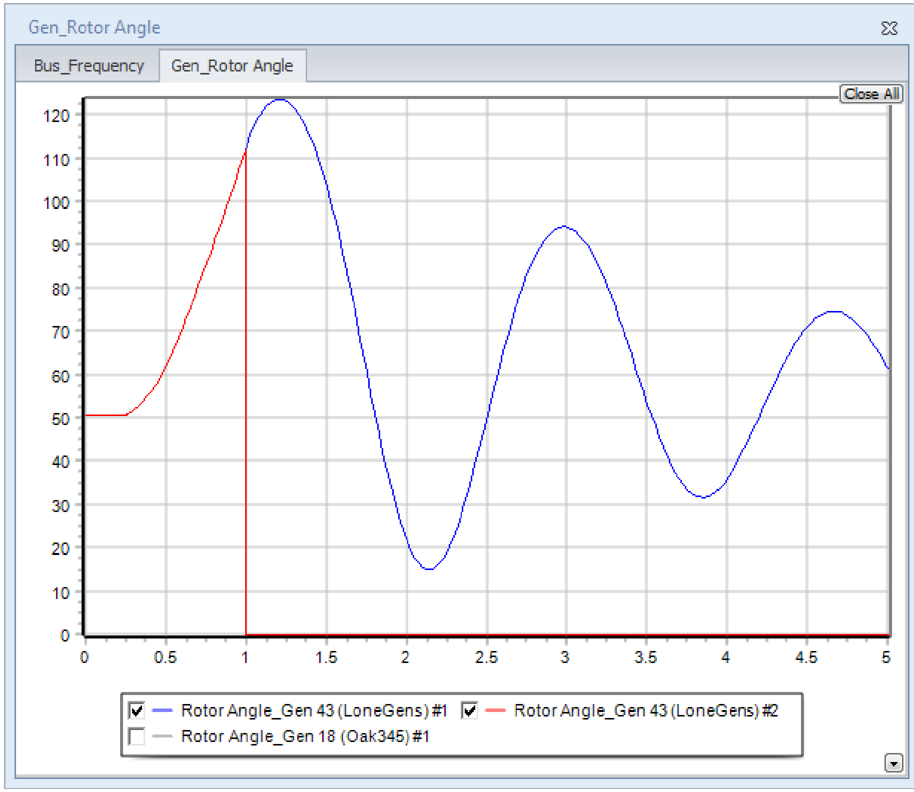
Similarly to type 1, rate as 5Mps can become a critical rate point, yet their delay values are different.

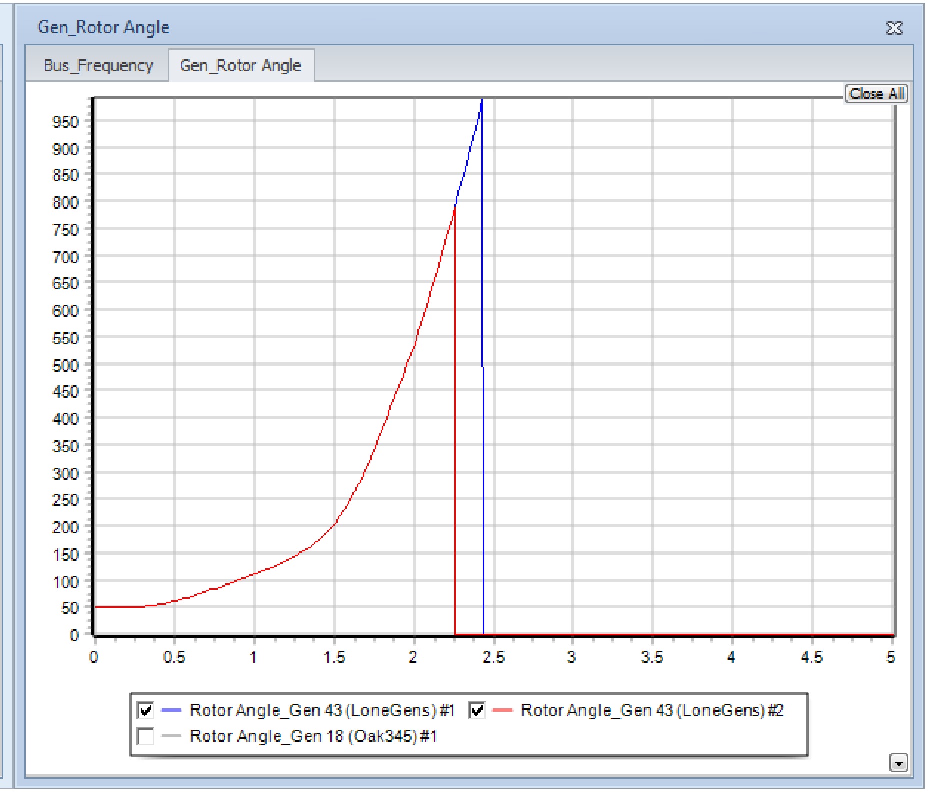
Communication results demonstration

Three circumstances are considered in power system transient stability: stability, critical stability and instability. This system has the critical delay point as 800ms approximately.



We examine the situation (case 1) in the first place where the generator is tripped in a very short time (<300ms). The rotor angle performances of two generators in substation 43 are shown here.





Critically stable case in which the generator is tripped after around 800ms. The maximum degree for oscillation is roughly 122 degree, which is greater than case 1.

Instability case in which the generator is tripped after a long time (>800ms). The system goes unstable even the generator is tripped.

Conclusions

In our work four different communication architectures are compared and studied. It's hard to say which one is the best and which one is the worst.
For those applications which don't have strict latency requirements, type 3, type 4 even type 1 might be a good choice. However, for those like real-time PMU-based applications, type 2 might meet the demands.

Seamless Bulk Electric Grid Management (S-62G)

Part 3:
Decentralized Applications (Georgia Tech)

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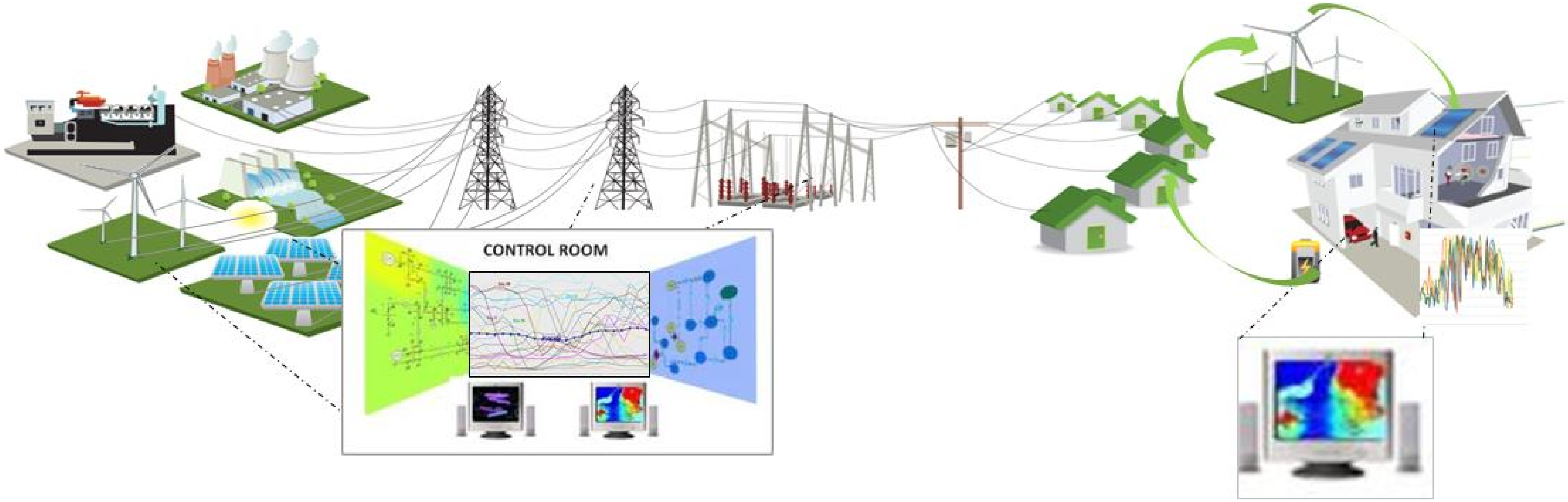
PSERC Industry-University Meeting
May, 2015

Motivation

- We need to integrate into the grid:
  - Large amounts of highly variable and spatially distributed renewable energy.
- Need much faster, better, tighter ***coordination*** across subsystems: ISO, utilities, microgrids, etc.



Motivation

- Various part of the grids are operated by EMS and DMS systems.
  - What happens in a region of the grid affects other regions.
  - Decentralized coordination issues must be addressed.
- A dynamics co-simulator could be used to test decentralized control applications including the effect of imperfect communication and delays.
- Use Cases:
  - ISO to ISO coordination within an interconnection
  - Distribution Utilities to ISO coordination

Example: Decentralized Power Agreement

- Assume that a region needs to change their reference production (net interchange) due to:
  - Power plant emergency
  - Contingency
  - Variation in renewables
- Each region has: $\widehat{p}_i$: Desired Power (ex-ante)

  $\tilde{p}_i$: Agreed-upon Power (algorithmic)

  p_i : Actual Power (ex-post)
- Can the regions agree on the needed levels of interchange to balance the system in a decentralized manner?

Decentralized Power Agreement

- Given desired power levels we want to:

$$\min \sum_{i=1}^{N} w_i \left\| \tilde{p}_i - \hat{p}_i \right\|^2$$

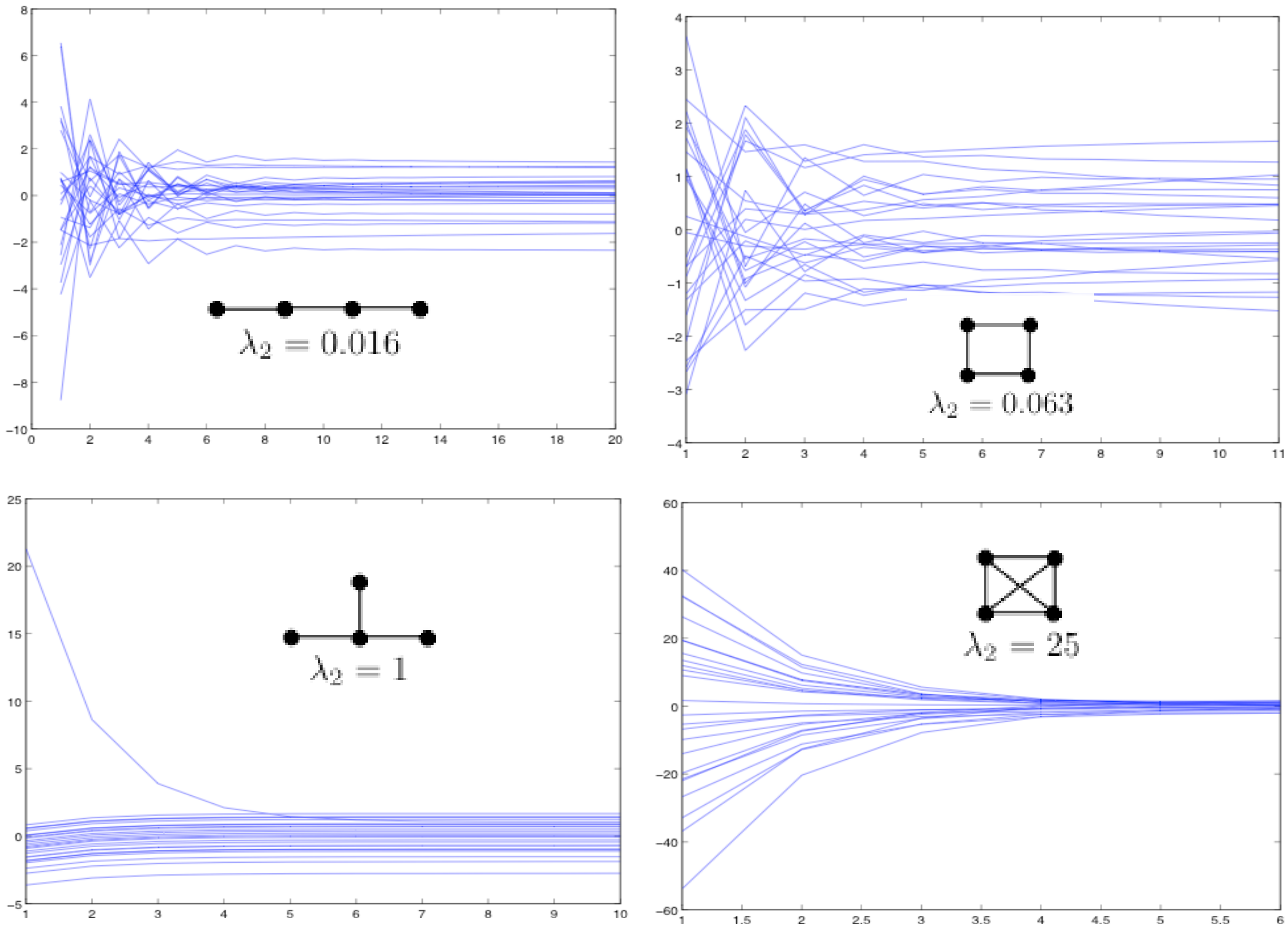
- An agreement dynamics, incorporating constraints, weights, and trust, is used by regions to agree on the power levels across the system in a decentralized fashion.

- How fast can an agreement be reached?

Ramachandran, Costello, Kingston, Grijalva, Egerstedt. Distributed Power Allocation in Prosumer Networks, *NecSys*, 2012.

Decentralized Agreement: Convergence

- Rate of converge depends on topology and connectivity
- Second eigenvalue of the communication graph Laplacian.



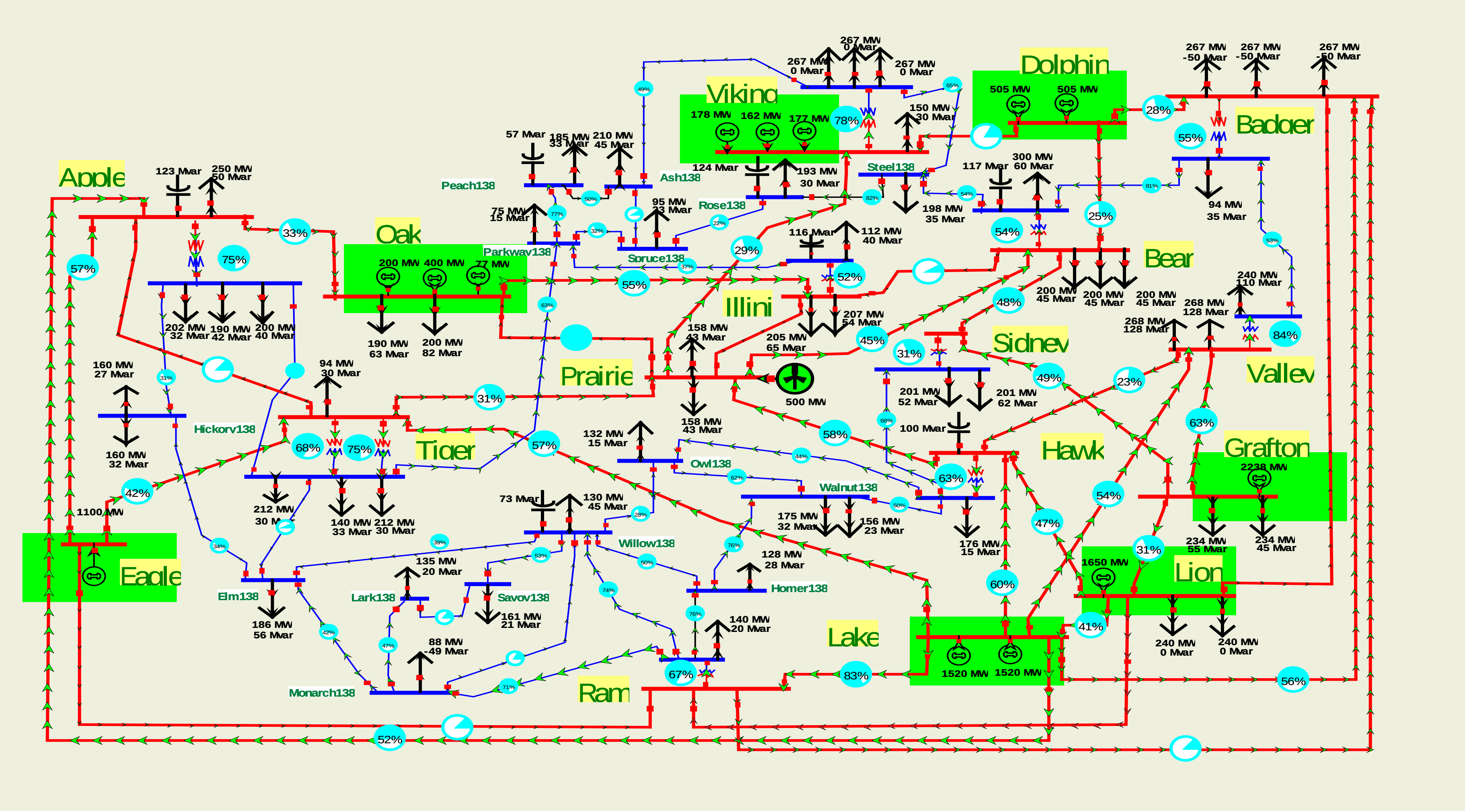
Example: Decentralized Power Agreement for Frequency Control

- Current frequency response is proportional to frequency deviation with respect to nominal.
- Current frequency regulation is unilateral and may cause inter-area oscillations.

- Question:
  - Can approaches be developed that can start correcting imbalances *before* frequency deviates?
  - Can agreement help drive the frequency closer to nominal after an imbalance?

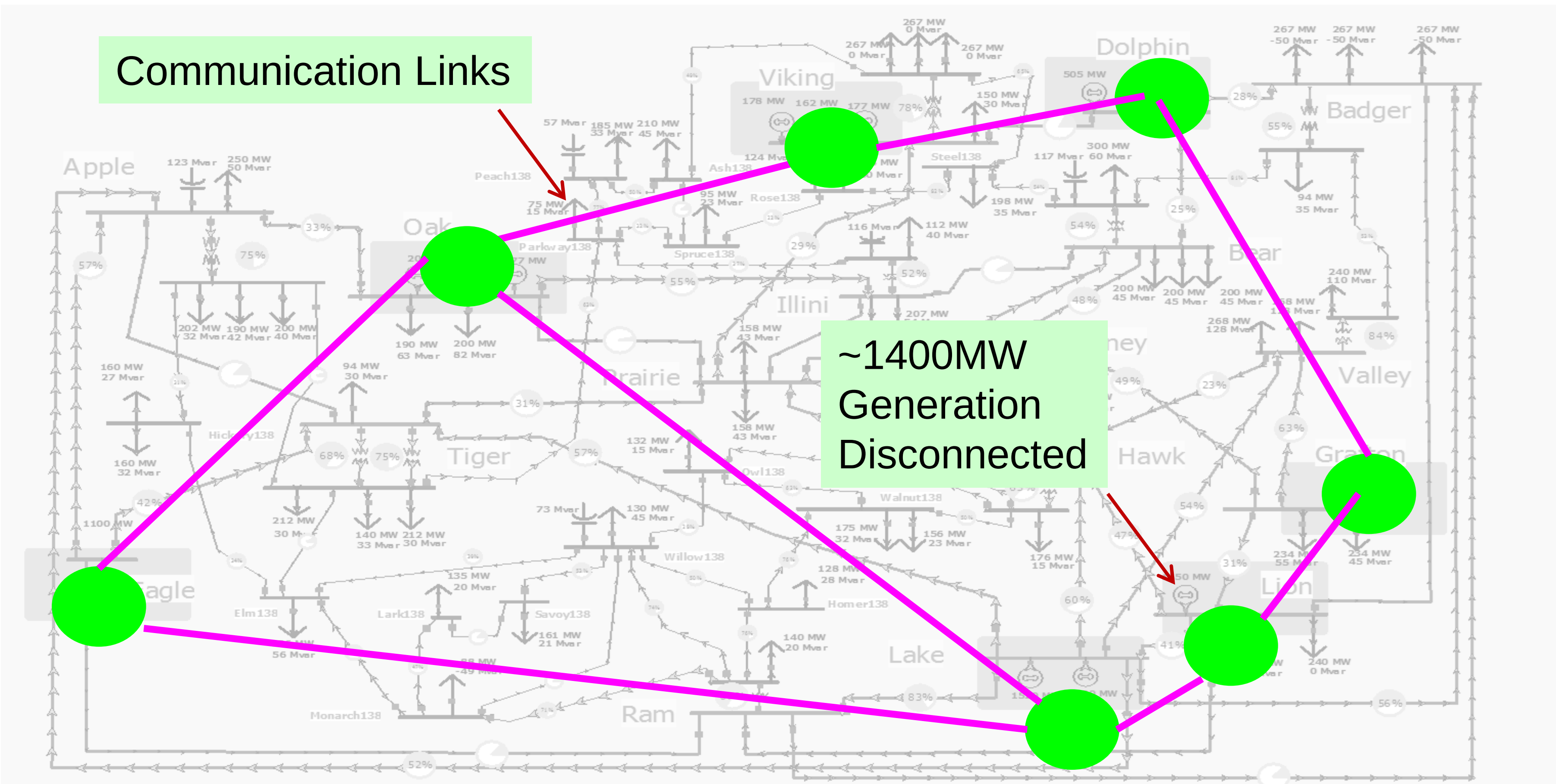
Small Case Simulation

- 42 bus system with dynamics.



Small Case Simulation

- System is partitioned into regions (e.g. control areas)
- No central agent, each region talks with neighbors.



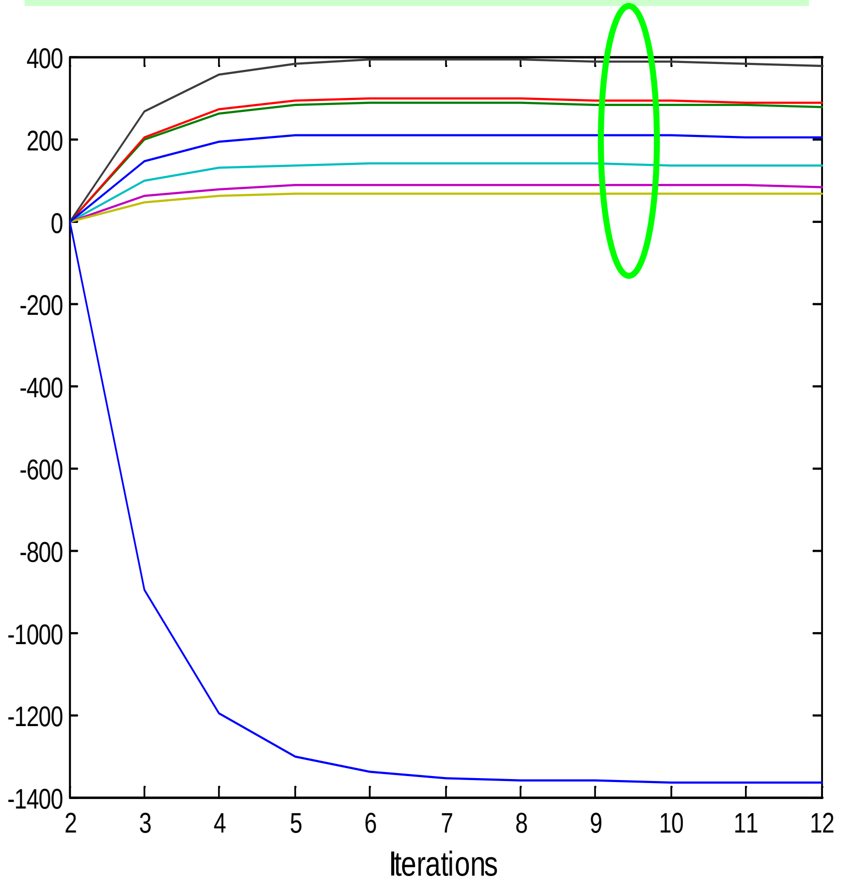
Small Case Simulation

- At time *t* a generator is disconnected in region *i* causing an imbalance equal to ΔP_i.
- As soon as the generator trips, power agreement is invoked to match the imbalance.

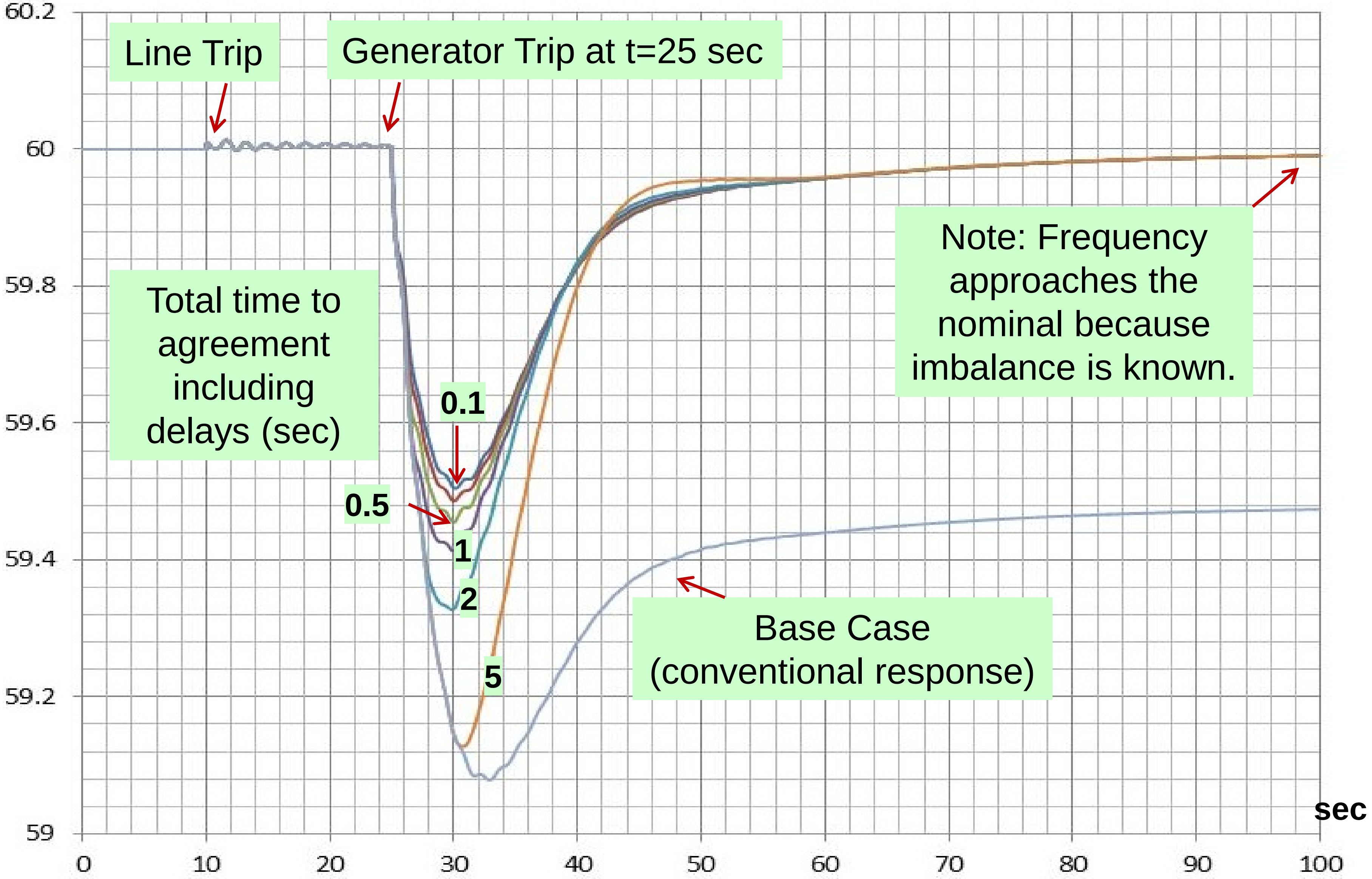
$$\sum_{j=1,\, j\neq i}^{N} \Delta P_j = \Delta P_i$$

- Regions reach agreement in a few iterations and take actions immediately.
- Performance depends on communication delays.

Regions determine (agree on) the power needed to compensate for generator trip



Frequency Response Performance



Summary

- Decentralized coordination methods can be of service in achieving scalable grid coordination.
- With appropriate communication system and small delays, fast applications such as frequency response can be improved.
- A co-simulation approach supports investigation of dynamic performance of decentralized control methods under imperfect communications.

Next Steps

- Development of larger cases for demonstrating additional and more realistic scenarios, and more closed-loop control
- Realistic modeling of communication delays using statistical simulator (WSU)
- More streamlined closed loop control
- Prototyping and assessment of improved visualizations utilizing the c37.118 data

Thank You!

Questions?

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