Control and Protection Paradigms of the Future

A PSERC Future Grid Initiative Progress Report – Thrust 2

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PSERC Webinar Series
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Fundamental Objective for Thrust 2

Original Thrust proposal stated its goal as:

"Define the overall concept for hierarchical coordinated control and protection of the smart grid."

Today, place this in context of an overall objective PSERC's Future Grid Initiative supported by DOE, that of enabling higher penetrations of renewable generation and other future technologies into the grid, while enhancing grid stability and reliability.

(see http://www.pserc.org/research/FutureGrid.aspx)

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Thrust 2 Tasks

- Task 1: Requirements for Hierarchical Coordinated Control and Protection of the Smart Grid
(Anjan Bose)

- Task 2: Hierarchical Coordinated Control of Wind Energy Resources and Storage for Electromechanical Stability Enhancement of the Grid
(Chris DeMarco)

- Task 3: Hierarchical Coordinated Protection of the Smart Grid with High Penetration of Renewable Resources
(Mladen Kezunovic)

Control and Protection: Overview of Challenges and Opportunities

Many challenges to present-day control and protection practice come with growing penetration of distributed and renewable generation.

- Greater volatility in injections/operating conditions

- Less clear boundary between roles at bulk transmission level versus distribution level. More generation and storage at distribution level, more participants impacting protection & control.

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Control and Protection: Overview of Challenges and Opportunities

Rapid improvements in grid communication and sensor technologies offer opportunities to manage new resources, but also present challenges.

- Need a well-organized architecture to coordinate flow of data that informs grid control and protection. Must carefully consider latency and bandwidth requirements, as well as security.

Control and Protection: Overview of Challenges and Opportunities

Similarly, tremendous opportunities in expanded computational and signal processing power available to distributed controllers and protection devices, but new design challenges here as well.

- Need coordinated hierarchy, balancing greater ability to operate locally, enabled by more powerful local computation, with opportunities to use select wide-area measurements available via high-bandwidth communication.

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Task 2 of Thrust: Control Architectures for the Future Grid

Task 2: “Hierarchical Coordinated Control of Wind Energy Resources and Storage for Electro-mechanical Stability Enhancement of the Grid.”

- Focus on characteristics of power-electronically coupled wind, and on battery storage. This gave structure to the work, producing control designs specifically useful for these technologies.

  Goal today: show that it also produced a more broadly applicable control architecture.

Future Grid Control: Motivation

- New technologies contributing to generation, and to grid control, present dramatically different interconnection characteristics than traditional synchronous generators.

- Widespread recognition that power electronically coupled generation (without advanced controls) lack inertia characteristic of synchronous machines. Inertia is typically a stabilizing effect, so grid stability challenged when it decreases.

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Future Grid Control: Motivation

- More generally, the future grid will have a much wider variety of technologies contributing to its control, with much wider variety of characteristics. In terminology of control design, we will have a much more diverse set of ***actuators***.

- Some wind controllers today seeks to make new “actuator” behave like the old – to mimic traditional machines’ inertia. **Better approach**: optimize for new characteristics, don’t mimic old.

Future Grid Control Architectures

- **Question:** In thinking about control architectures, suited to widely diverse control resources, how to rigorously describe the characteristics that define different actuators?

- **Our Answer:** bandwidth, and very importantly, limits on the range of available control action.

  At risk of oversimplification, we'll motivate by similar to challenges in home theater design!

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Why Grid Control is Like Home Theater: Bandwidth and Saturation

- A speaker is a multi-actuator device, with goal of controlling sound pressure delivered to listener's ear.
- Each actuator is responsible for different portion of audible range (woofer, mid-range, tweeter).
- Each actuator has different hard limits on its mechanical excursion/ saturation ("long-throw" on woofer, less than ±1 mm on tweeter)

Why Grid Control is Like Home Theater: Bandwidth and Saturation

- Lower-end speakers use relatively simple linear filtering (crossover network) to direct ***different portion of the control signal bandwidth to different actuators.***

- Higher-end devices use bi-amplification, to apply separate, appropriate power levels to each actuator***, to respect each one's saturation limits.***

Why Grid Control is Like Home Theater: Bandwidth and Saturation

- Project used industry standard models of the pitch power control of type-3 wind turbines, characterizing control response bandwidth and saturation limits (commanded change in power as input, achieved change in active electrical power as output). Similar concept for speed-based power control.

- Project also used SAFT International models for high power lithium-ion batteries with power electronic interface, characterizing response from commanded power as input, to grid-interface power as output.

Bandwidth and Saturation Issue in Future Grid Control Architectures

- This project used Linear Quadratic (LQ) Optimal control design, to make best effective use of each actuator, in contributing to formal objective of stable grid frequency regulation.

- Our LQ control design used recent advances in the control system literature, that allow optimal design within the hard constraints of limits on the control actuators. For grid examples, limits included charge/discharge rate of batteries, battery energy storage limits, max/min limits on wind turbine blade pitching.

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Importance of Estimation – Grid vs. Home Theater Analogy again…

- Home theater designers recognize actuators operate into a network that greatly impacts performance in controlling sound pressure to listener's ear: the room.

- Traditional designs involved picking fixed designs that were robust to a range of rooms, and engineering rules of thumb to tune to specific installation. Perhaps not unlike traditional grid control design.

- Modern home theater includes microphones to measure room response, estimate its parameters, and tune amplifier/speaker characteristics to suit the room.

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Importance of Estimation in Future Grid Control

- Similar challenge in optimizing grid control action effected through widely diverse resources exercising control: need estimate of system ***dynamic*** state.

- High sampling rate, synchronized phasor measurements (PMUs) open the door to make such estimation possible.

- But even with PMUs, need caution in making fast time scale controls dependent on large number of wide-area sensors. In coordination with Task 1 of this Thrust, need to treat communication bandwidth, latency, and security.

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Importance of Estimation in Future Grid Control

- Work in Task 2 developed multiple, distributed dynamic state estimators/"observers."

- To keep communication needs modest (and to allow for graceful degradation when remote measurements not available), each observer seeks to estimate just low degree of freedom dynamic behavior, not full state (observe and control small number of system "modes").

- We developed model-based measures of observability, to decide which sensors to best "feed" a given controller (will also allow decision when communication loss makes a given mode no longer observable).

Summary: Task 2 Contributions to Future Grid Initiative

- Developed control designs to make best use of generation and control resources with widely diverse terminal characteristics. Demonstrated on Type-3 wind turbines and lithium-ion batteries as test cases, with a design architecture that is broadly applicable.

- Complemented controllers with a distributed estimation architecture: a local state observer for each controller. Each uses local measurements, plus (when available) very modest number of remote PMU measurements.

- Methodology for quantifying modal-based observability, for measurement selection and graceful degradation.

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Publications

- Baone, C.A.; C.L. DeMarco. “Observer-based distributed control design to coordinate wind generation and energy storage.” *Proceedings of the 2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*, Gothenburg, SWEDEN, Oct. 2010.
- Baone, C.A.; C.L. DeMarco. “Saturation-bandwidth tradeoffs in grid frequency regulation for wind generation with energy storage.” *Proceedings of the 2011 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT)*, Anahiem, CA, Jan 2011.
- Baone, C.A.; C.L. DeMarco. “Distributed control design to regulate grid frequency and reduce drive train stress in wind systems using battery storage.” *Proceedings of the 2012 American Control Conference,* Montreal, CANADA, June 2012.

Requirements for Hierarchical Coordinated Control and Protection of the Smart Grid

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PSERC Webinar Series
February 5, 2013

IT Overlay for the Power Grid

- **Measurements**
  - **PMU (transmission, high rate)**
  - **AMI (distribution, high volume)**
- **Communications**
  - **High bandwidth**
  - **Middleware for QoS**
- **Computers**
  - **Ubiquitous**
  - **Amenable to distributed analytics and data**

What should the architecture be?

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Architecture Considerations

- **Data at substations and applications – volume and rate**
- **Where is this data needed and at what rate?**
- **Depends on the applications**
- **Applications can be located conveniently**
- **Applications (and data) can be distributed**

The resulting design will depend on the applications and the measurements (location, volume, rate)

How can the design be developed?

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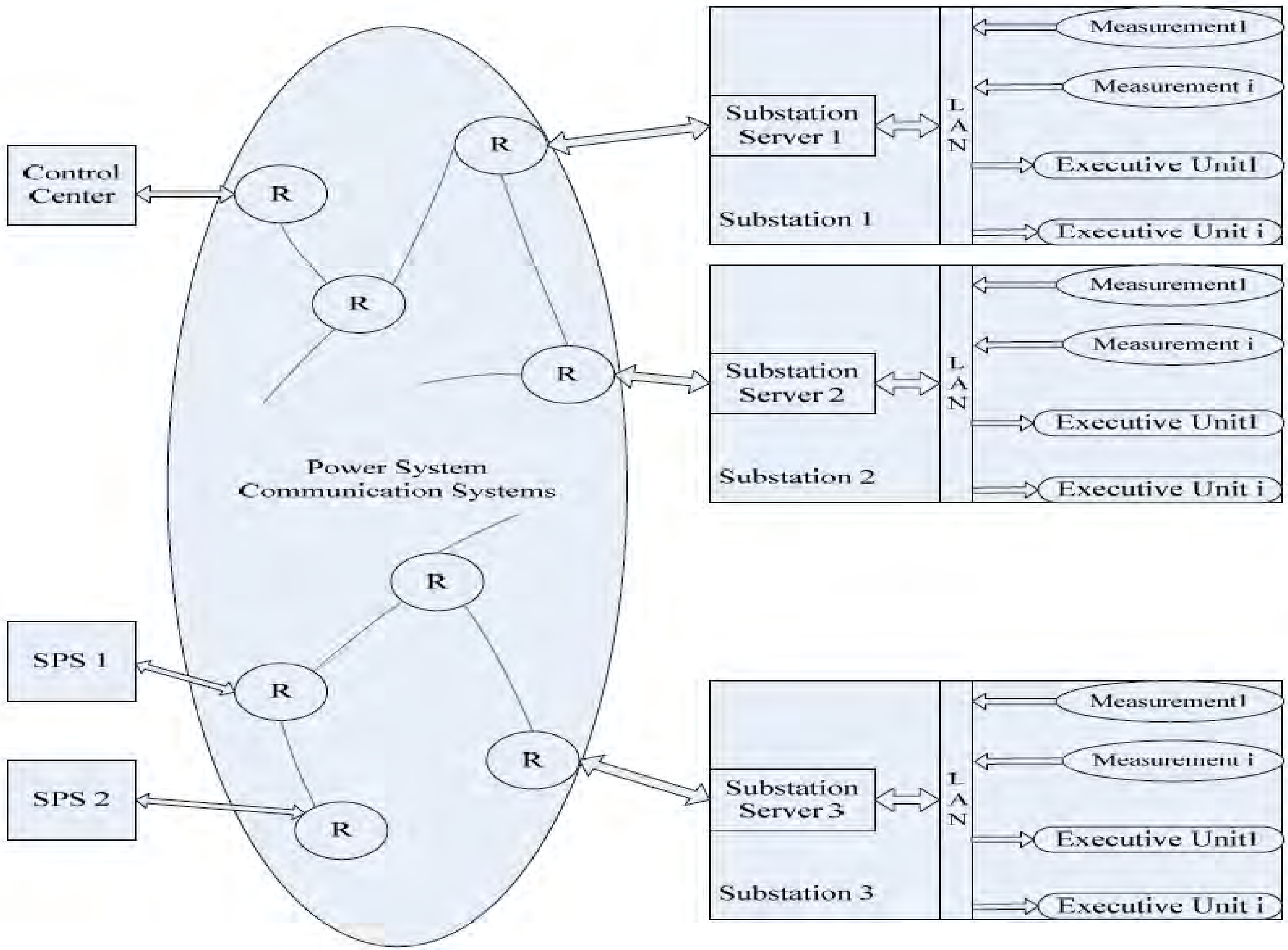
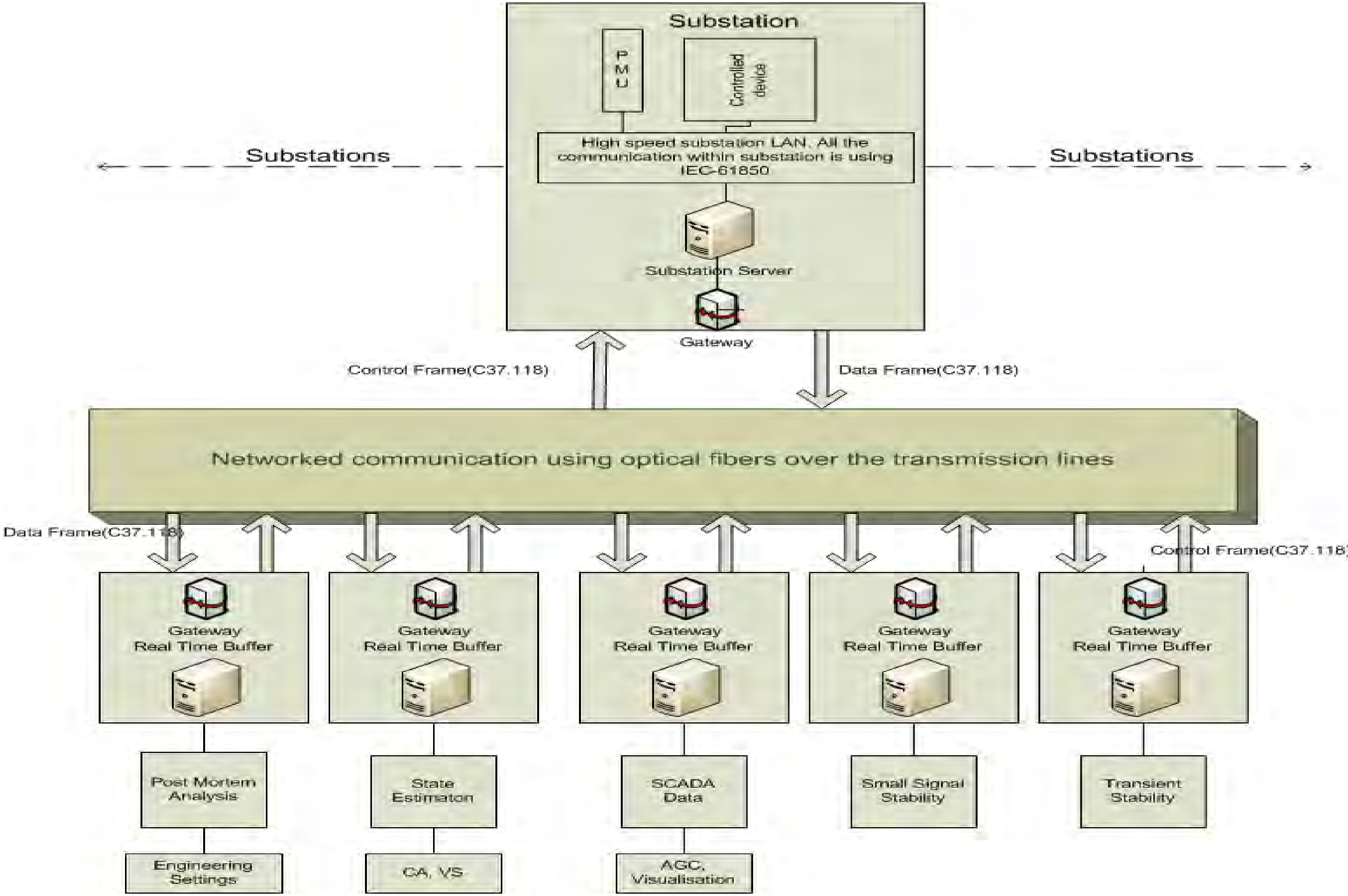
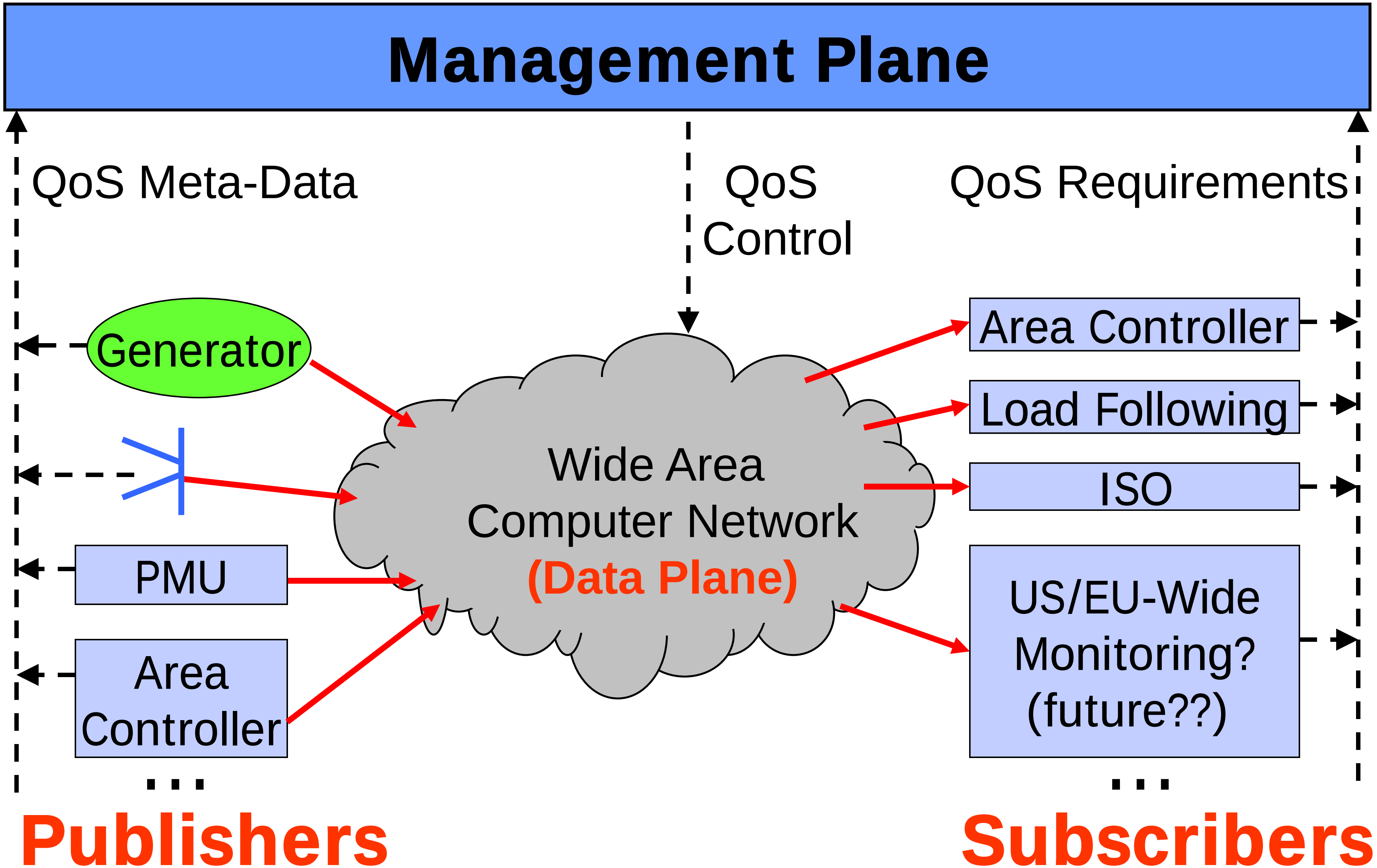
Proposed IT Infrastructure



Communication Architecture



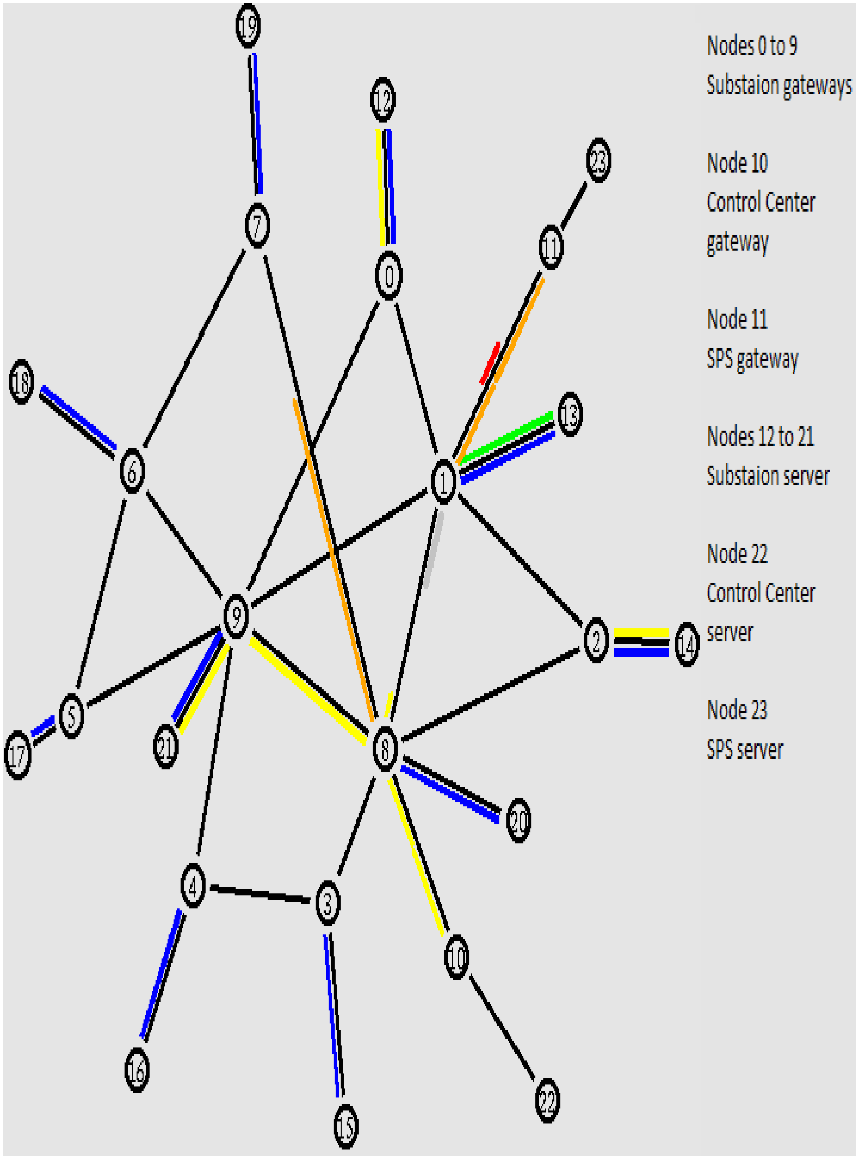
Basic GridStat Functionality



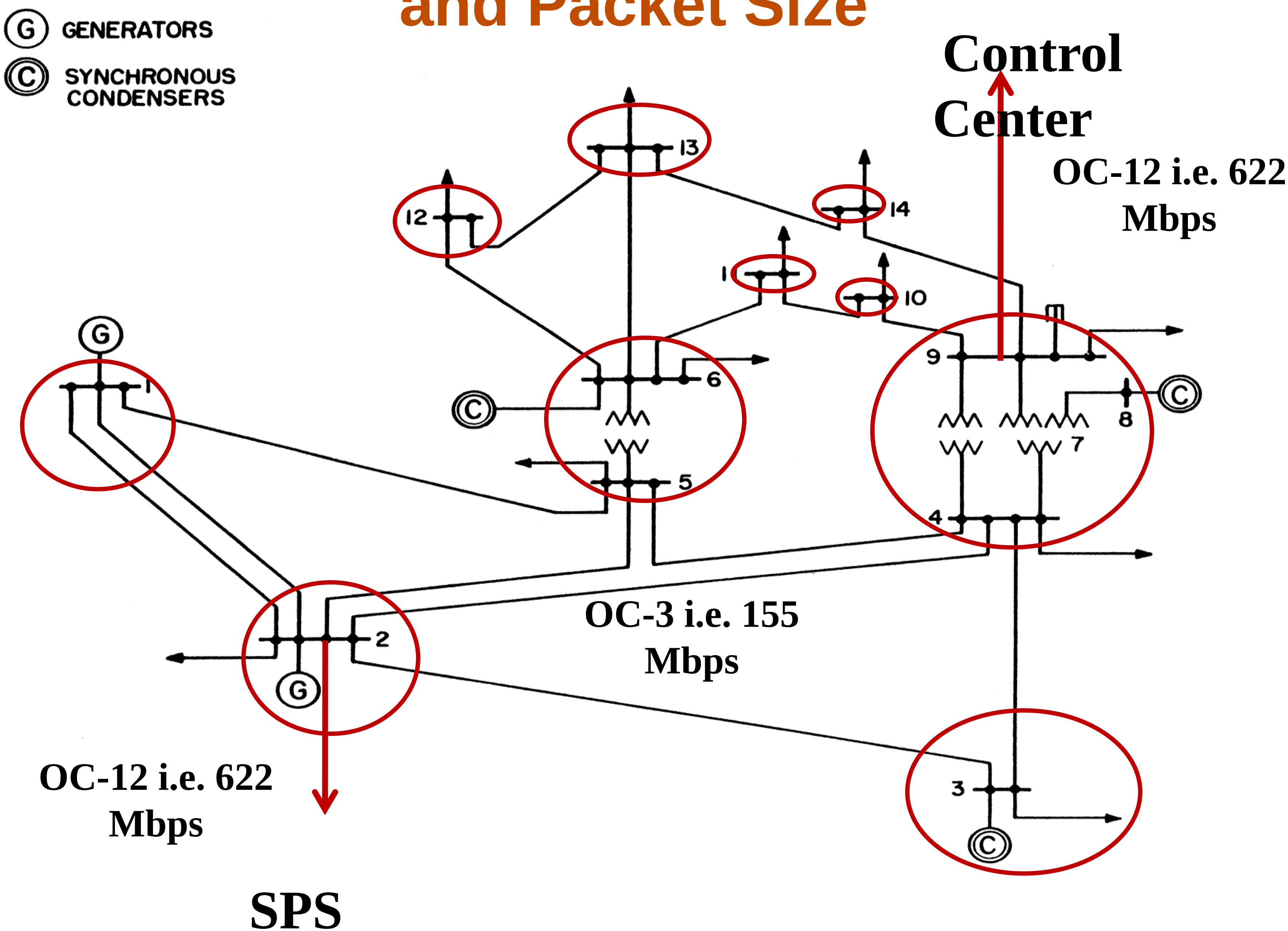
Simulation Set-up

- Ns2: An event based, open source communication network simulator
- Matlab, Python, Tcl and Awk scripts to do the analysis
- 6 basic traffics in the network as follows:

1. All the Substation to Control Center [Blue]
2. Control Center to Control Substation (Generating stations and Substation having control units like transformers and reactors) [Yellow]
3. SPS substation to SPS [Red]
4. SPS to SPS substation [Orange]
5. Generating substation to Generating substation [Green]
6. SPS to Control Center[Grey]



Traffic Sources /Destinations and Packet Size



Communication Delays

The communication delays on the network:

1. Transmission delays: packet size (1 to 10 kb) divided by link bandwidth (10 to 100 Mbps). Around 0.1ms (maximum) on each link
2. Propagation delays: Distance/Speed of communication. Assume it as 0.7c
3. Processing delays: Router processing time. Hard to quantify, we assume it as 10-100 microsecond for Grid-Stat kind of communication
4. Queuing delays: This is where we need to run the simulation using software

Communication Data Format

- Wide Area Communication-C37.118
- C37.118 describes 4 types of frames:

  -Header Frame

  -Configuration Frame: Is sent when configuration of the system changes

  -Data Frame: Sent during the normal system operations from PMU to PDC

  -Command Frame: Sent from PDC to PMU in normal operation
- In normal operation only two types of frames are communicated i.e. Data Frame and Command Frame
- It is important to know the Data formats to exactly figure out how much data is being generated in bytes at each substation

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Communication Protocol

Layer	Protocol
Application	CBR
Transportation	UDP
Network	IP
Data	Ethernet
Link	Ethernet (Optical fiber)

- CBR (Constant Bit Rate) : Given that PMUs and Control frames are sent out at a constant rate it looks reasonable
- UDP

  -Given the latency requirement and CBR as application layer, UDP is a natural choice

  -UDP is a no frill service. Packet reordering can be implemented at application layer (in case)

  -Given the huge data generated dropping a packet should not be a concern

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Some Assumptions

- Simulation for 14, 30, 57 bus, WECC 225 bus, Polish system (2383 bus)
- Connect control center and SPS to busiest nodes
- CBR over UDP setting MTU size as 1500 bytes
- Shortest path (No. of Hops) and static routing
- System is under normal operation and only Data frames are being communicated
- Processing delays (10-100 microseconds) are assumed to be zero at all levels
- Sampling rate is assumed to be 60samples/sec for all traffic type
- Propagation delay: Convert Reactance to distance
- Queue size as 5000: No packet drop and long delays
- TTL to 64 hops
- One SPS per 10 substations and 1CC for a zone

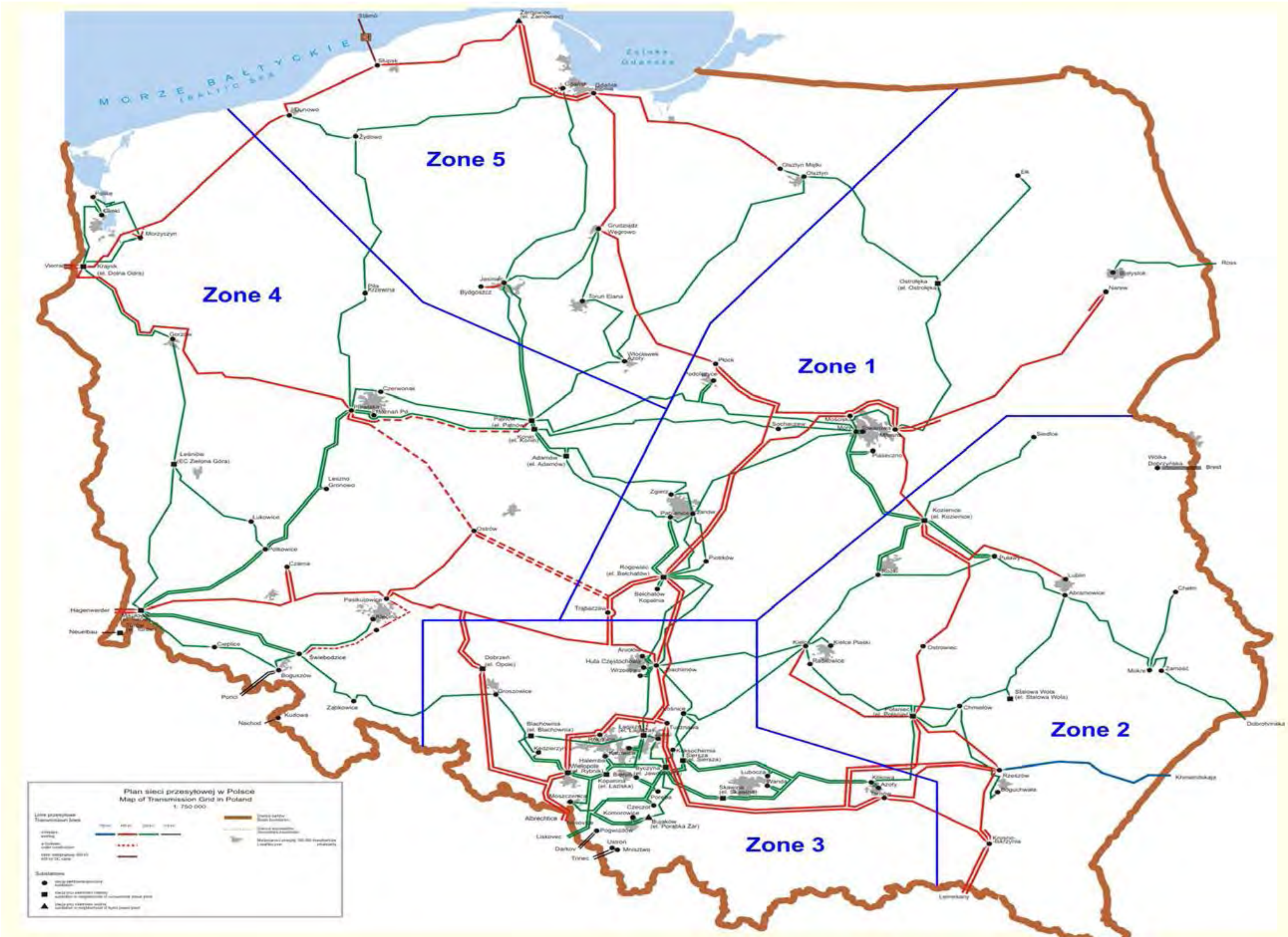
Packet Size for Type-1 Traffic

- Calculated number of feeders in each substation
- Assuming breaker and half scheme, we calculated number of current, voltages and CB status in each substation
- Assuming each PMU has 9 analog and 9 digital channels, we calculated number PMUs
- So given number of PMUs and number of Phasors & CB status in a given substation, we calculated the packet size of C37.118 data frame sent-out from the substation
- Packet size from Control center and from SPS assumed to be 250 bytes

Parameters for 225 Bus System

S.No.	*Parameter*	*Value*
1	Buses	225
2	Substations	161
3	Control Center	1
4	SPS	16
5	Generating S/S	31
6	Control S/S	58
7	SPS SS	160

Poland Grid 2383 Bus System



Parameters for Polish System

Parameter	Zone1	Zone2	Zone3	Zone4	Zone5
Substations	343	259	831	515	268
Control	1	1	1	1	1
SPS	34	25	83	51	26
Generating S/S	42	36	88	92	47
Control S/S	56	51	104	112	63
SPS SS	340	250	830	510	260
CC links	5	5	7	7	5

Packet Size for Type-1 Traffic

Zone	*Maximum (Bytes)*	*Minimum (Bytes)*	*Average (Bytes)*	*Median (Bytes)*
1	1438	148	290.7	262
2	1204	160	303.1	262
3	1540	148	265.6	262
4	1426	148	281.2	262
5	1078	148	293.8	262

Average Link Bandwidth Usage

Max. of used links (Mbps)	*Min. of used links (Mbps)*	*Average of used links (Mbps)*	*Median of used links (Mbps)*	*% of unused Gw2Gwlinks*
126.77	0.09	4.68	0.94	2.96

Maximum Delays in Traffic Using Two Times the Actual Bandwidth from Base Case

Zone	*S/s to C/c (ms)*	*S/s to SPS (ms)*	*G.S/s to G.S/s (ms)*	*C/c to Con S/s (ms)*	*SPS to S/s (ms)*	*SPS to C/c (ms)*
1	12.4	22.2	23.6	11.5	28.7	11.9
2	12.7	19.7	25.3	10.8	24.6	10.2
3	14.2	25.4	25.9	13.6	27.9	11.2
4	12.5	18.0	25.8	11.6	22.9	10.2
5	15.4	26.3	21.0	11.1	26.6	10.0

Number of Hops

Zone	*Max*	*Min*	*Average*	*Median*
1	18	2	7.23	7
2	15	2	7.23	7
3	20	2	8.12	8
4	20	2	7.71	8
5	15	2	6.85	7

As expected

Conclusions

- Methodology for simulating the performance of the communication network for Power Systems
- Many assumptions, results would change as these assumptions are modified. Assumptions should reflect the actual design parameters of the communication infrastructure
- Propagation delays changes with topology. Queuing delay and transmission delays changes with bandwidth.
- Average link bandwidth needed for smart grid applications should be in range of 5-10 Mbps for communication within one control area and 25-75Mbps for inter control center communications.
- Using meshed topology delays can be contained within the 100ms latency requirement satisfying all applications.
- Packets traversing just 8-10 hops processing delays at routers should not be a problem.

Publications

1. Kansal, P.; A. Bose. *Smart Grid Communication Requirements for the High Voltage Power System*. IEEE Power Engineering Society General Meeting, Detroit, MI, July 2011.
2. Kansal, P. *Communication Requirements for Smart Grid Applications in Power Transmission Systems*. MS Thesis, Washington State University, Pullman, WA, December 2011.
3. Kansal, P.; A. Bose. *Bandwidth and Latency Requirements for Smart Transmission Grid Applications*. IEEE Transactions on Smart Grid, vol. 3, no. 3, pp. 1344-1352, September 2012.

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Hierarchical Coordinated Protection of the Smart Grid with High Penetration of Renewable Resources

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PSERC Future Grid Webinar
February 5, 2013

Outline

- Current Needs and Study Goals
- Study Focus and Proposed Solutions
- Proposed Approach
- Study Case: Cascading Events Detection and Mitigation
- Study Case: Anti-islanding Protection

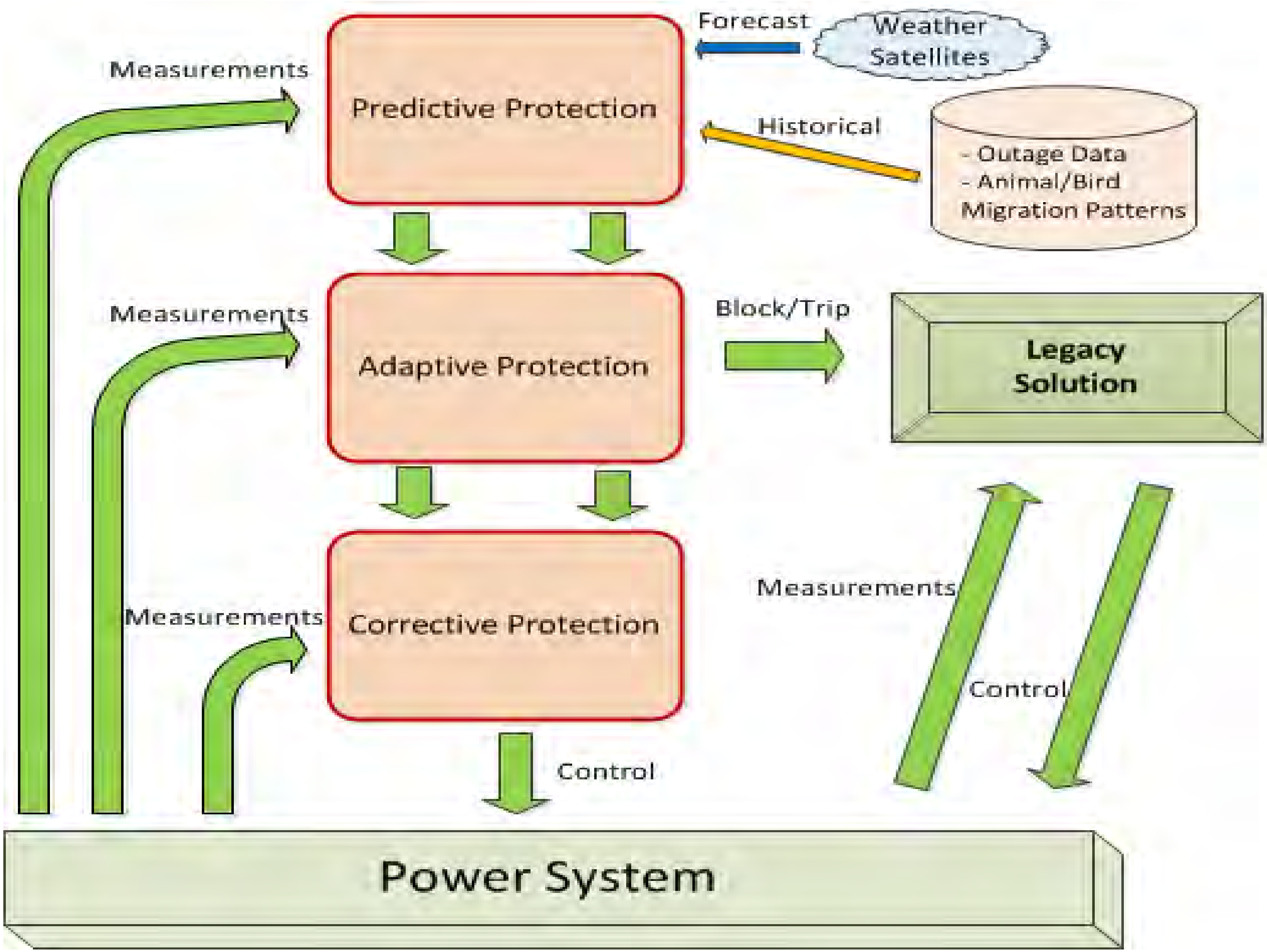
Current Needs and Study Goals

1. Define protection issues and network conditions that current solutions cannot handle well
2. Specify new protection requirements associated with high penetration of renewable sources
3. Outline criteria for the design of new protection solution that can improve efficiency and reliability
4. Propose conceptual solution for the hierarchically coordinated protection (HCP) scheme
5. Describe each of the three HCP protection layers and explain how they may be implemented
6. Present overall HCP solution using some modeling and simulation, as well as real-life examples
7. Assess major benefits of the new solution when compared to the legacy solution

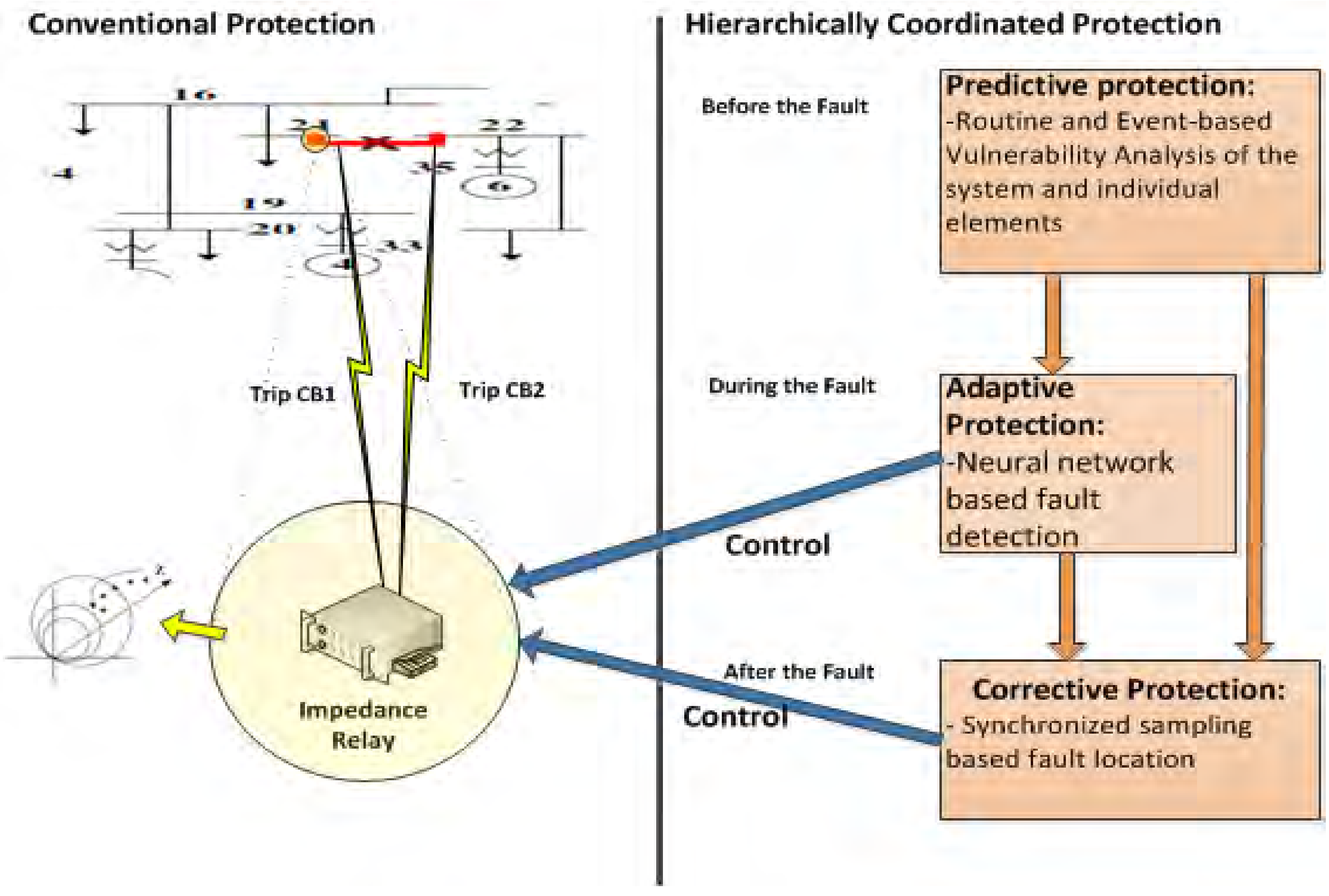
Study Focus and Proposed Solutions

- **New Requirements:**
  - flexibility in protection operation (dependability vs security)
  - robustness of protection that has not been expected before
  - self correction and verification
- **Proposed Layout:**
  - **Predictive Protection:**
    - provides “breathing time” for protection system to achieve flexibility (adjust bias between dependability and security)
    - conditions leading to major disturbances are recognized
  - **Adaptive Protection:**
    - provides robustness in protection behavior using setting-less protection
    - Enables learning from data to analyze disturbances
  - **Corrective Protection:**
    - Uses additional time to achieve higher accuracy
    - makes available verification tool for protection operation
- **New Applications:**
  - cascading event detection and mitigation
  - anti-islanding protection

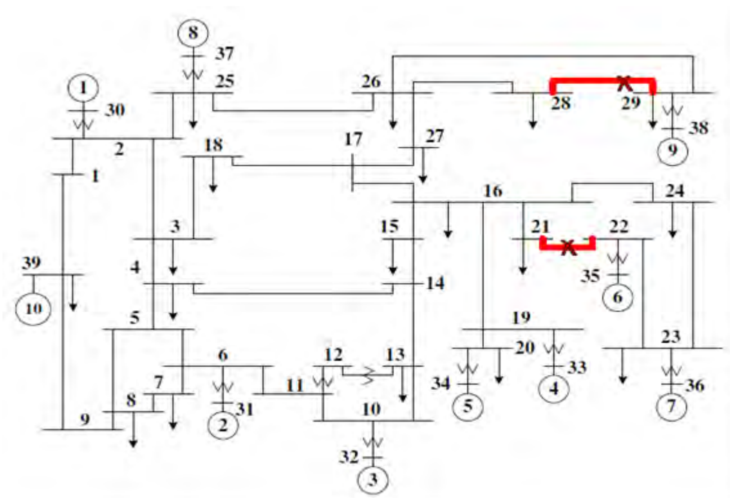
Proposed Approach

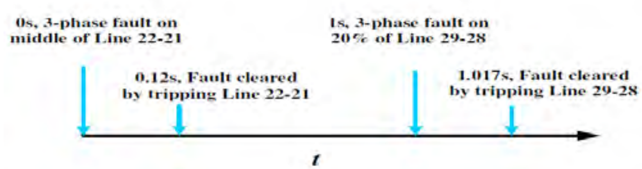


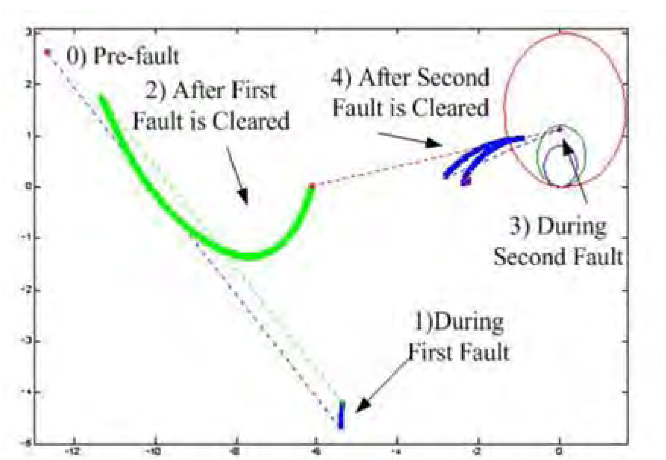
Cascading Event Detection and Mitigation



Cascading Event Detection and Mitigation





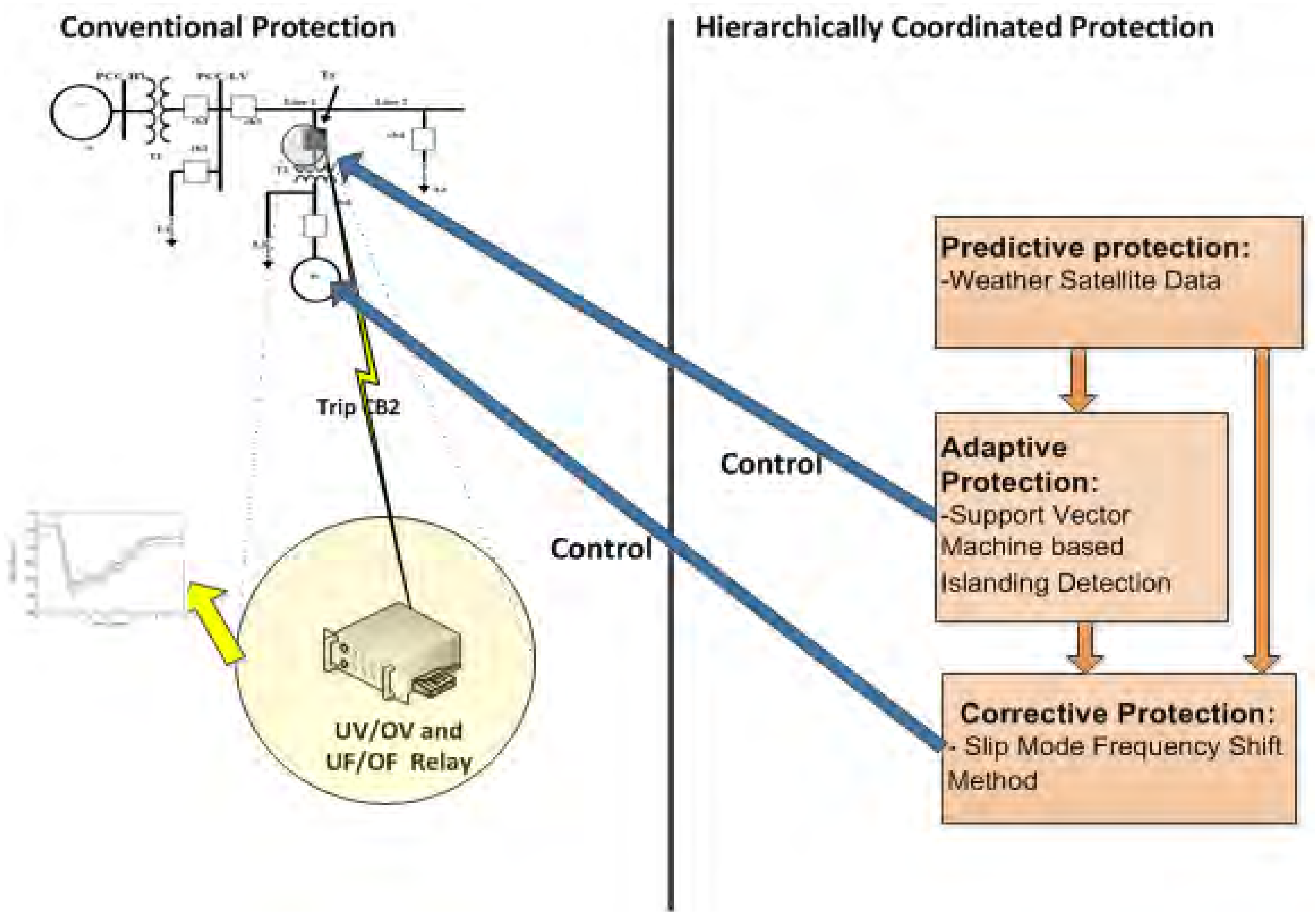


- **Predictive Protection**
  - Finds the most vulnerable lines
  - Triggers corrective layer to closely monitor relay operation
- **Adaptive Protection**
  - Neural network based fault detection
  - sends block/trip signal to distance relay
- **Corrective Protection**
  - Synchronized sampling based fault location
  - Verifies fault location or restore line

Benefits:

- Make a way for adaptive protection to be accepted as a alternative to conventional protection principle
- Several layers for disturbance verification
- Prevents line tripping due to overloading, swing…

Anti-Islanding Protection



Anti-Islanding Protection

- **Predictive Protection**
  - Non-conventional data, data from weather satellites may be used for prediction indices calculation, which are are sent to trigger corrective part of the approach.
- **Adaptive Protection**
  - The features from current and voltage signals are continuously extracted and compared to the models obtained in the offline training. In case OV/UV and OF/UF relays mis-operation to detect island, trip signal is sent to circuit breaker at point of common coupling (PCC).
- **Corrective Protection**
  - At the corrective layer an active anti-islanding method is used (Slip Mode Frequency Shift). The corrective layer will sent block / trip signal to the circuit breaker at PCC.

Benefits:

- Negative effect of active anti-islanding method to power quality is reduced
- Has high accuracy and it is robust to switching events in the grid
- Make way for adaptive protection to be accepted as a alternative to conventional protection principle

Conclusions

- New protection requirements are identified
- The new approach is proposed that :
  - has superior performance when compared to the existing solutions
  - co-exists with the legacy solutions and only supplements its normal operation
  - has self-corrections and verification tools
  - make a way for adaptive protection to be accepted as a alternative to conventional protection principle

Publications

1. Kezunovic, M.; Y. Dong. "Information Exchange Needs for New Fault Location Applications in T&D Systems." *Proceedings of the 16th IEEE Mediterranean Electrotechnical Conference*, *MELECON 2012, Tunisia,* 2012.
2. B. Matic-Cuka, M. Kezunovic, "Improving Smart Grid Operation with New Hierarchically Coordinated Protection Approach," *The 8th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER 2012)*, Cagliari, Italy, October 2012.

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