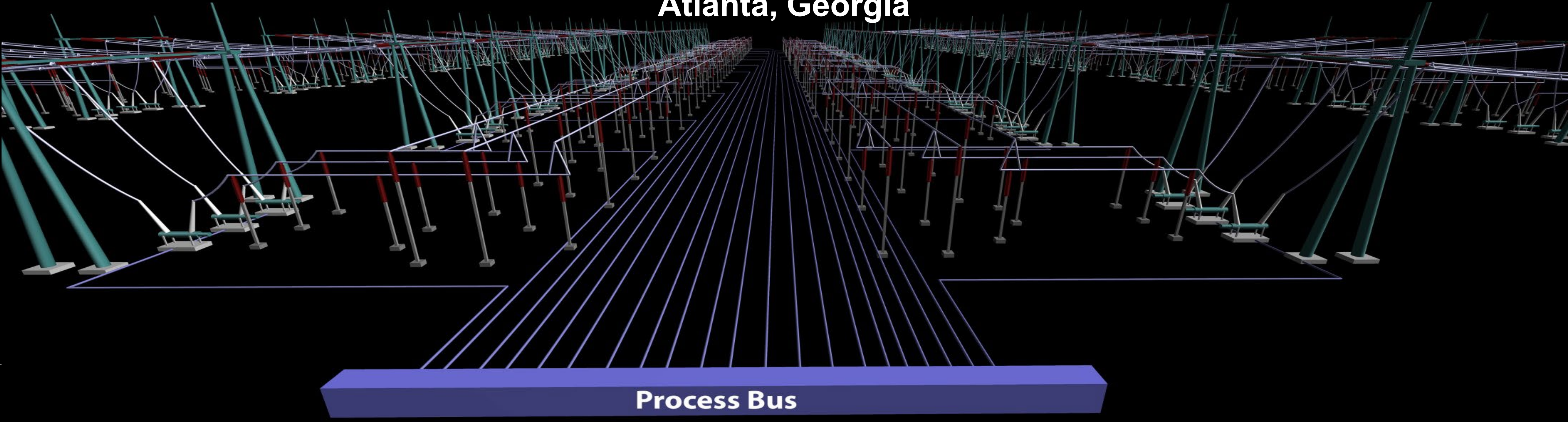
From Automation to Autonomy: Infrastructure for intelligent protection, control, optimization and operations

Sakis Meliopoulos

Georgia Power Distinguished Professor
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia



Contents

Introduction & Background

Rapidly increasing number of new controllable devices with new characteristics at the transmission and distribution level as well as third party resources. Utility size Wind and PV plants, as well as a plethora of customer owned resources (PV rooftops, EV, TCL).

Controllable Resources Advantages:

(a) Increases Flexibility and enables adjusting load to generation

(b) Tremendous storage capability

Controllable Resources Challenges:

(a) Variability and impact on system operations: need to use inherent flexibility

(b) Reduced fault current levels, impact on protection: Need new methods.

Present centralized architectures and tools have serious shortcomings.

Dealing with these issues requires increased automation and better yet autonomy

Automation and Autonomy

- Automation in any engineering system goes back to ancient times.
- Let’s take a look at the milestones occurred in power systems that led to automation. History is the best teacher.

History of Automation in PS

Automation before computers in mechanical systems of electric energy systems:

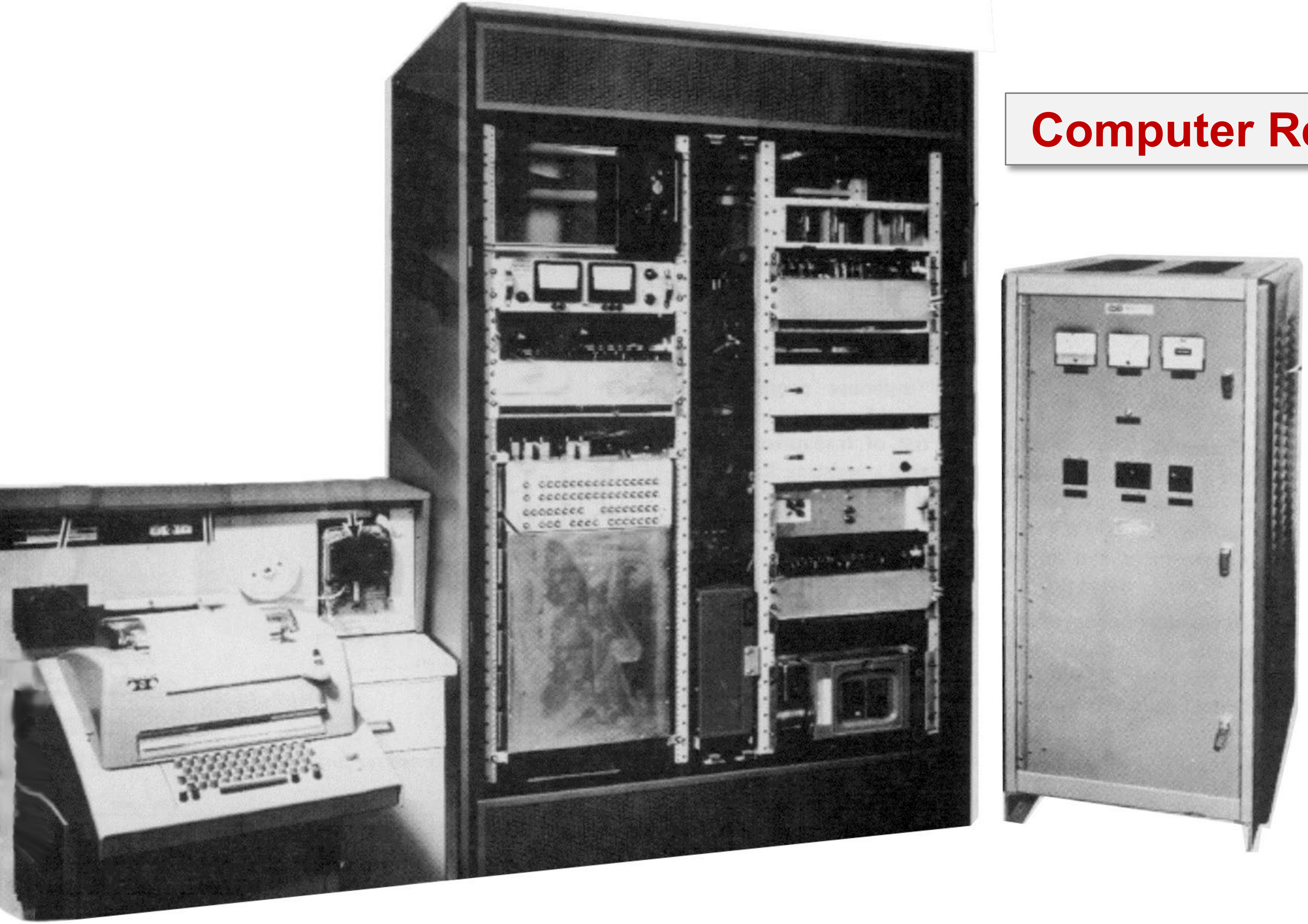
- Frequency Control,
- Voltage Control, etc.

Some of these systems still in use.

Digital systems brought a revolution in automation. Some specific milestones:

- Computer relaying (PRODAR 1970)
- Microprocessor based relaying (SEL, 1984) – introduced digital communications
- OSI seven layer communications protocol (1984, ISO 7498)
- GPS synchronized measurements (Jay Murphy, Microdyne PMU, 1992)
- Merging units (GE hardfiber, 2009)
- UCA project (EPRI, 1986)
- IEC 61850 (2003 – proposed in IEC 1995)

With digital systems, the sky is the limit.



Computer Relaying (PRODAR 1970)

- G. B. Gilcrest
- G. D. Rockefeller
- E. A. Udren

Microprocessor Based Relaying

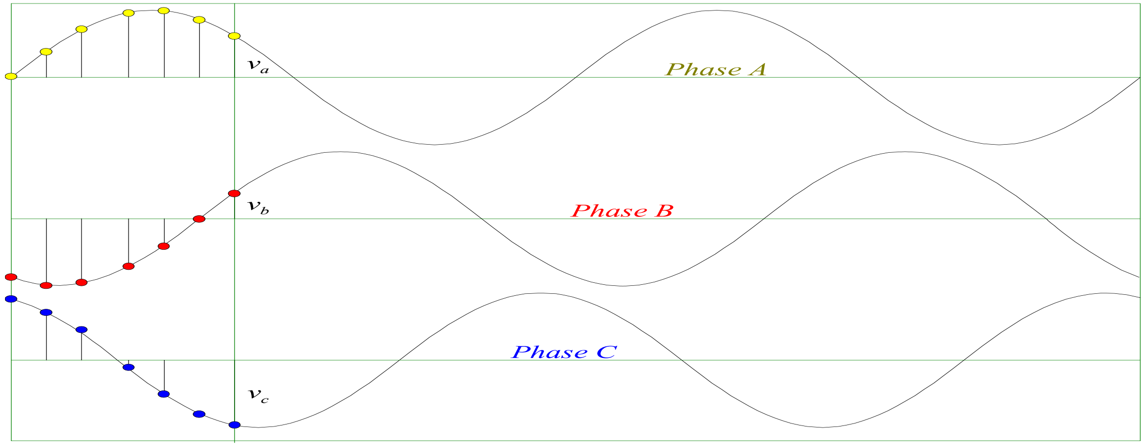
(SEL, 1984) – Introduced Digital Communications

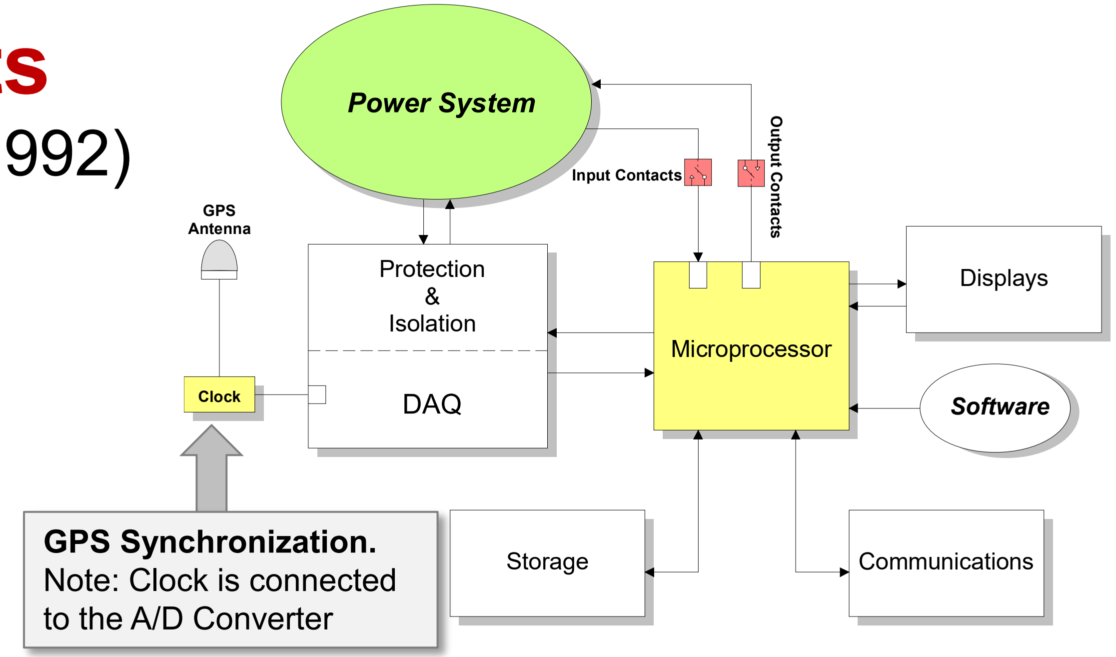
OSI Seven Layer Communications Protocol
(1984, ISO 7498)

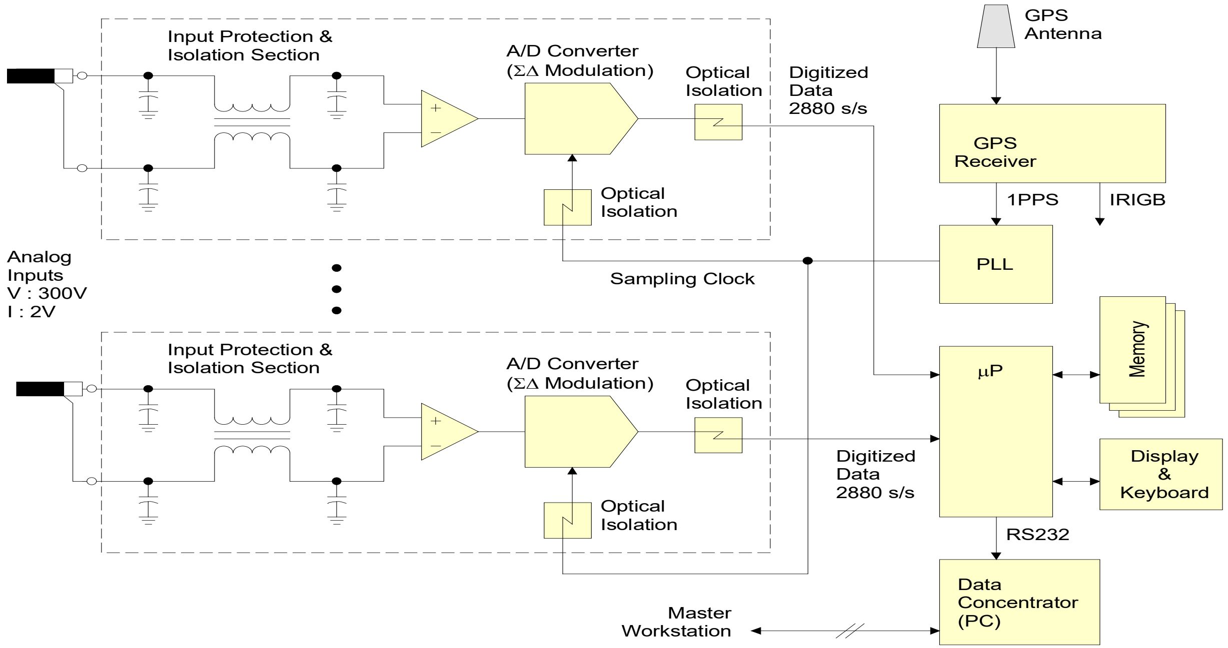
Open Systems Interconnection model (OSI model)			
	OSI Layer	**TCP/IP**	**Datagrams are called**
Software	**Layer 7** Application	HTTP, SMTP, IMAP, SNMP, POP3, FTP	**Upper Layer Data**
	Layer 6 Presentation	ASCII Characters, MPEG, SSL, TSL, Compression (Encryption & Decryption)	
	Layer 5 Session	NetBIOS, SAP, Handshaking connection	
	Layer 4 Transport	TCP, UDP	**Segment**
	Layer 3 Network	IPv4, IPv6, ICMP, IPSec, MPLS, ARP	**Packet**
Hardware	**Layer 2** Data Link	Ethernet, 802.1x, PPP, ATM, Fiber Channel, MPLS, FDDI, MAC Addresses	**Frame**
	Layer 1 Physical	Cables, Connectors, Hubs (DLS, RS232, 10BaseT, 100BaseTX, ISDN, T1)	**Bits**

GPS Synchronized Measurements

(Jay Murphy, Macrodyne 1620 PMU, January 1992)



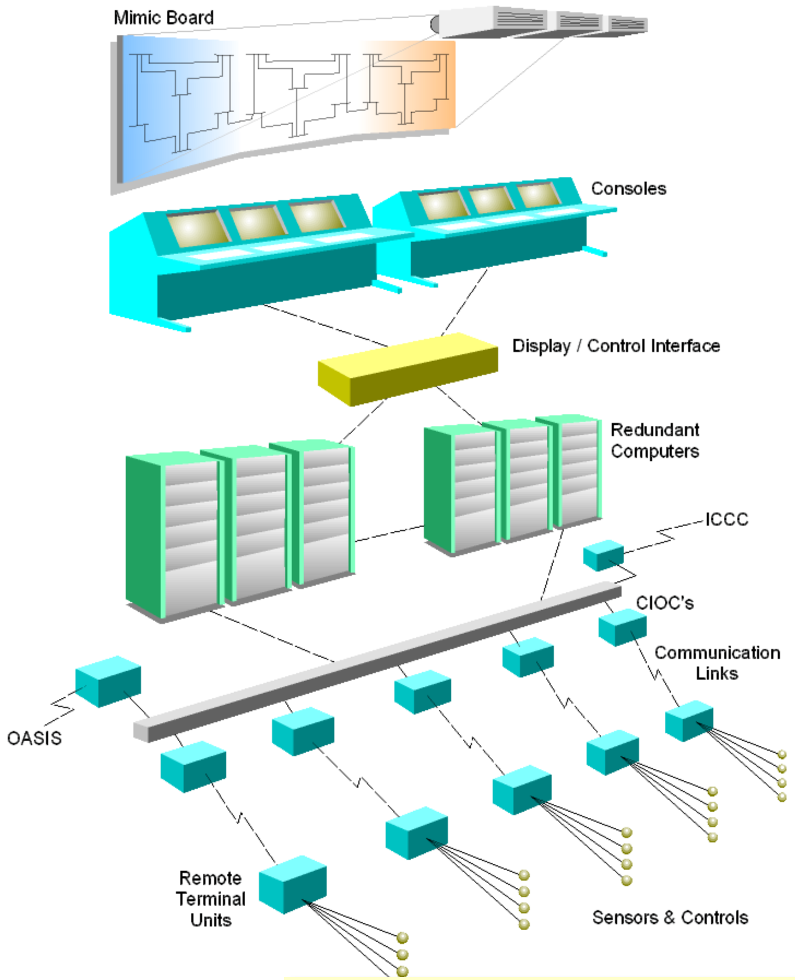




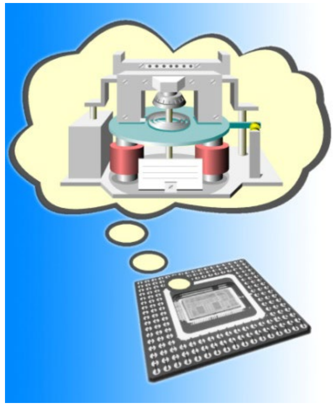
Merging Units

Present State of the Art: Centralized C&O/Function Based P&C

Control & Operation



Protection & Control



Real Time Model
State Estimation

Applications (MB)
Load Forecasting
Optimization (ED, OPF)
VAR Control
Available Transfer capability
Security Assessment
Congestion Management
Dynamic Line Rating
Transient Stability
EM Transients, etc.
Visualizations

Markets:
Day Ahead, Power Balance, Spot Pricing, Transmission Pricing (FTR, FGR), Ancillary Services

Component Protection
generators, transformers, lines, motors, capacitors, reactors

System Protection
Special Protection Schemes, Load Shedding, Out of Step Protection, etc.

Communications
Substation Automation, Enterprize, InterControl Center

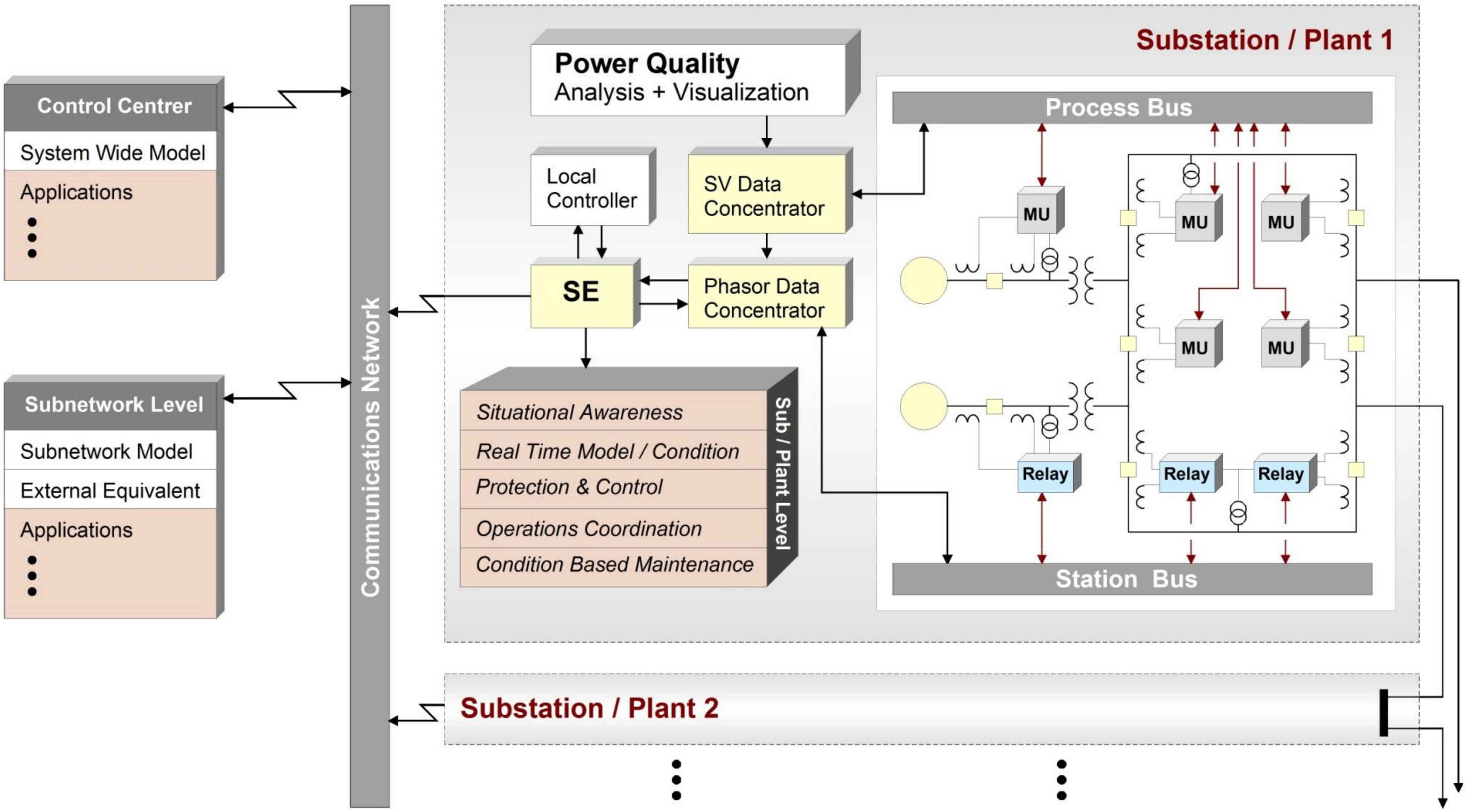
A Large Number of Standards – Examples:
OASIS: Open Access Same-Time Information System
UCA: Utility Communication Architecture
ICCP: Inter-Control Center Communications Protocol
C37.118, IEC 61850, DNP3.0, ..
CCAPI: Control Center Application Program Interface
CIM: Common Information Model

Smart Grid Focus: Real Time Model, Component and System Protection, Communications

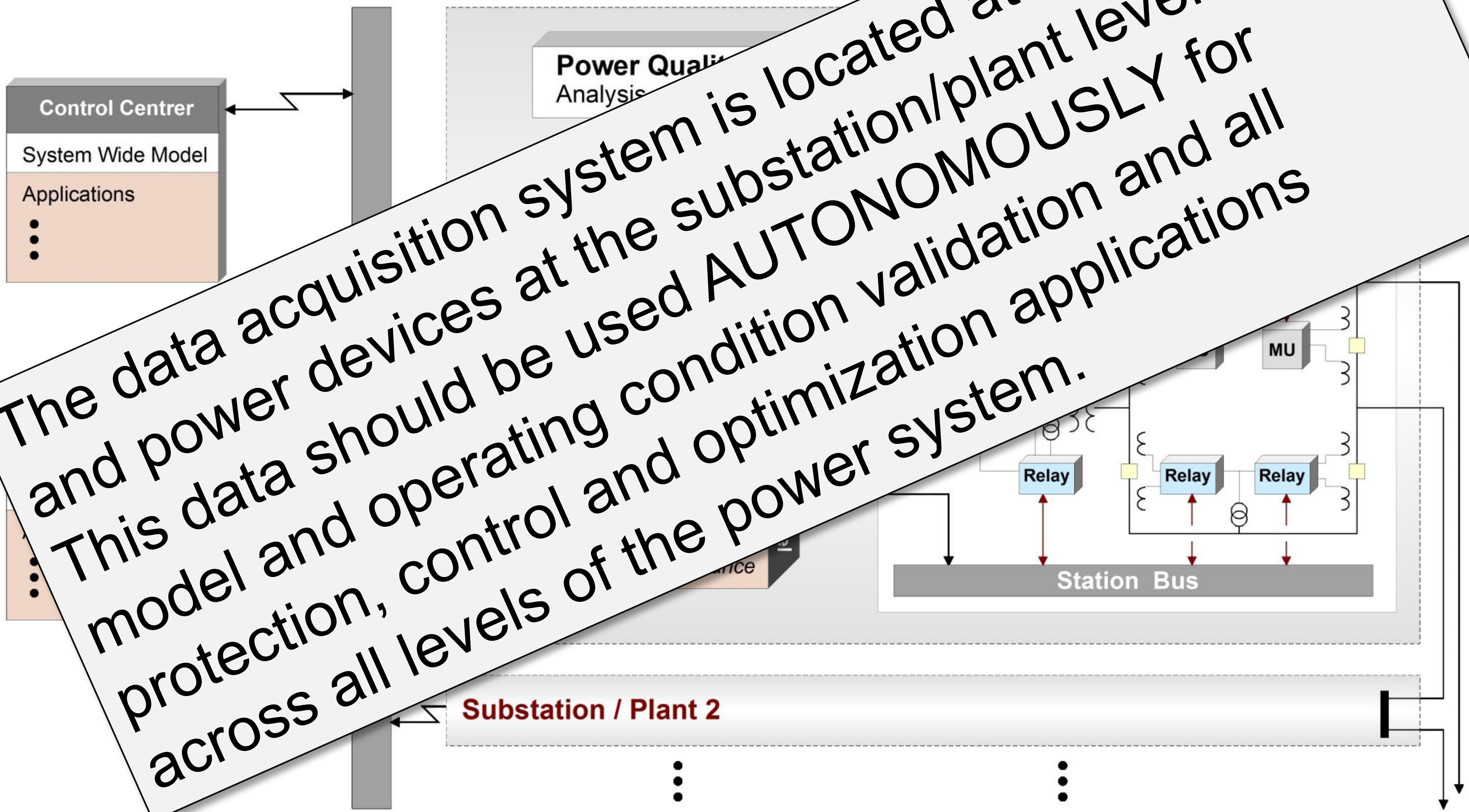
Observations and Comments

Observation	Comment
All control, optimization and operations functions are model based	Many times models are error laced. Need an automated model validation process
All control, optimization and operations functions are feedback based	Feedback is presently measurement based and/or partial state using static state estimation. Full dynamic state feedback needed to deal with new challenges.
All zone protection functions are independent. Protection system represents a ubiquitous measurement and monitoring system. Gradually, relays are used to provide SCADA. Vulnerability to hidden failures/attacks	Seamless integration of protection, control and operation. New technology enables relays to become providers of validated models and data and full dynamic state feedback. They can also detect hidden failures/attacks

Overall Decentralized Infrastructure
(Substation/Plant Level, Subnetwork, System)



Overall Decentralized Infrastructure (substation/plant level, subnetw... m)



The data acquisition system is located at the breakers and power devices at the substation/plant level. This data should be used AUTONOMOUSLY for model and operating condition validation and all protection, control and optimization applications across all levels of the power system.

Delivering Accurate Data to All

This is Extremely Important

- Calibration
  - Traditional Approaches are Tedious, Expensive and at Off-Line
  - New Technologies allow automation and continuous real time
  - Examples will follow

- Health of Data Acquisition and Protection & Control System
  - Protection & Control Critical for System Reliability
  - Vulnerable to faults, hidden failures and cyber attacks
  - New technologies offer the capability to monitor the health of the system in real time.

Requirements for Autonomy

- Autonomous Extraction of Real Time Model and State
  - Model Objectification
  - Setting-less Protection
  - Integrated Autonomous Dynamic State Estimator
  - Intrusion Detection – secure operation
  - Autonomous Parameter Identification
- Self Regulating
  - Autonomous Frequency Control
  - Autonomous Voltage Control
  - Other (Contractual Obligations, Environmental Control,….)
- Self Managing (Operations Planning)

Model Objectification – Beyond CIM

The SCAQCF: (**S**tate, **C**ontrol & **P**arameter **A**lgebraic **Q**uadratic **C**ompanion **F**orm)

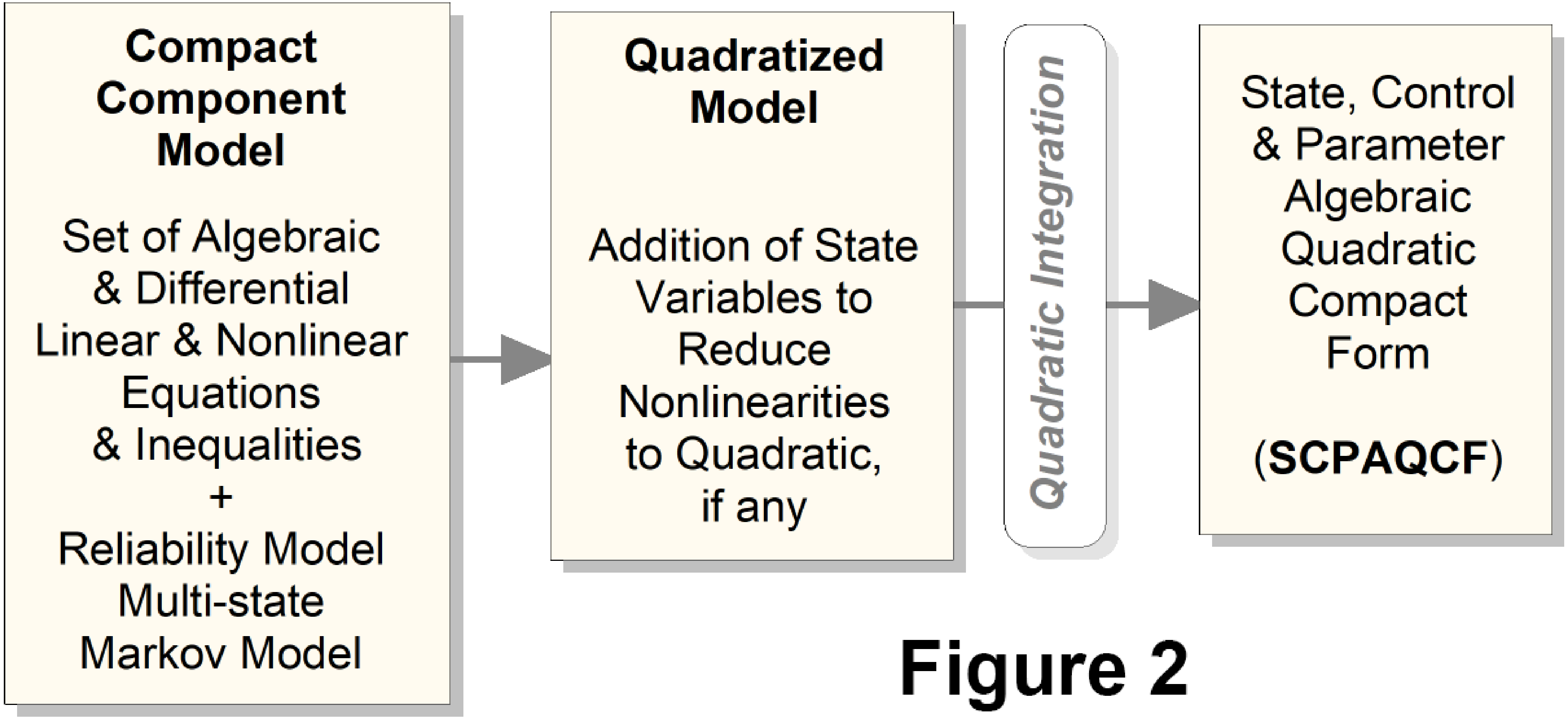


Figure 2

The SCPQDM Model

(**S**tate, **C**ontrol & **P**arameter **Q**uadratized **D**evice **M**odel)

The Only User Input: State, Control & Parameter Quadratized Device Model

$$i(t) = Y_{eqx1}\mathbf{x}(t) + Y_{equ1}\mathbf{u}(t) + Y_{eqp1}\mathbf{p}(t) + D_{eqxd1}\frac{d\mathbf{x}(t)}{dt} + C_{eqc1}$$

$$0 = Y_{eqx2}\mathbf{x}(t) + Y_{equ2}\mathbf{u}(t) + Y_{eqp2}\mathbf{p}(t) + D_{eqxd2}\frac{d\mathbf{x}(t)}{dt} + C_{eqc2}$$

$$0 = Y_{eqx3}\mathbf{x}(t) + Y_{equ3}\mathbf{u}(t) + Y_{eqp3}\mathbf{p}(t) + \begin{Bmatrix} \vdots \\ \mathbf{x}(t)^T \left\langle F^i_{eqxx3} \right\rangle \mathbf{x}(t) \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}(t)^T \left\langle F^i_{equu3} \right\rangle \mathbf{u}(t) \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{p}(t)^T \left\langle F^i_{eqpp3} \right\rangle \mathbf{p}(t) \\ \vdots \end{Bmatrix}$$

$$+ \begin{Bmatrix} \vdots \\ \mathbf{u}(t)^T \left\langle F^i_{equx3} \right\rangle \mathbf{x}(t) \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{p}(t)^T \left\langle F^i_{eqpx3} \right\rangle \mathbf{x}(t) \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}(t)^T \left\langle F^i_{equp3} \right\rangle \mathbf{p}(t) \\ \vdots \end{Bmatrix} + C_{eqc3}$$

Connectivity: Terminal Node Names

$$\mathbf{h}(\mathbf{x},\mathbf{u},\mathbf{p}) = Y_{feqx}\mathbf{x} + Y_{fequ}\mathbf{u} + Y_{feqp}\mathbf{p} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T \left\langle F^i_{feqxx} \right\rangle \mathbf{x} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}^T \left\langle F^i_{fequu} \right\rangle \mathbf{u} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{p}^T \left\langle F^i_{feqpp} \right\rangle \mathbf{p} \\ \vdots \end{Bmatrix}$$

$$+ \begin{Bmatrix} \vdots \\ \mathbf{u}^T \left\langle F^i_{fequx} \right\rangle \mathbf{x} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{p}^T \left\langle F^i_{feqpx} \right\rangle \mathbf{x} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}^T \left\langle F^i_{fequp} \right\rangle \mathbf{p} \\ \vdots \end{Bmatrix} + C_{feqc}$$

$$subject\ to: \quad \mathbf{h}_{\min} \le \mathbf{h}(\mathbf{x},\mathbf{u}) \le \mathbf{h}_{\max}$$

$$\mathbf{u}_{\min} \le \mathbf{u} \le \mathbf{u}_{\max}, \quad \mathbf{x}_{\min} \le \mathbf{x} \le \mathbf{x}_{\max}$$

The SCPAQCF Model

(**S**tate, **C**ontrol & **P**arameter **A**lgebraic **Q**uadratic **C**ompanion **F**orm)

SCPQDM → Numerical Integration → SCPAQCF (Automated Process)

$$\begin{Bmatrix} i(t) \\ 0 \\ 0 \\ i(t_m) \\ 0 \\ 0 \end{Bmatrix} = Y_{eqx}\mathbf{x}(t) + Y_{equ}\mathbf{u}(t) + Y_{eqp}\mathbf{p}(t) + \begin{Bmatrix} \vdots \\ \mathbf{x}(t)^T \left\langle F_{eqxx}^i \right\rangle \mathbf{x}(t) \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{p}(t)^T \left\langle F_{eqpp}^i \right\rangle \mathbf{p}(t) \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}(t)^T \left\langle F_{equu}^i \right\rangle \mathbf{u}(t) \\ \vdots \end{Bmatrix}$$

$$+ \begin{Bmatrix} \vdots \\ \mathbf{u}(t)^T \left\langle F_{equx}^i \right\rangle \mathbf{x}(t) \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}(t)^T \left\langle F_{equp}^i \right\rangle \mathbf{p}(t) \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{p}(t)^T \left\langle F_{eqpx}^i \right\rangle \mathbf{x}(t) \\ \vdots \end{Bmatrix} - B_{eq}$$

$$B_{eq} = -N_{eqx}\mathbf{x}(t-h) - N_{equ}\mathbf{u}(t-h) - N_{eqp}\mathbf{p}(t-h) - M_{eq}i(t-h) - K_{eq}$$

Connectivity: Terminal Node Names

subject to: $\mathbf{h}_{\min} \le \mathbf{h}(\mathbf{x},\mathbf{u}) \le \mathbf{h}_{\max}$

$\mathbf{u}_{\min} \le \mathbf{u} \le \mathbf{u}_{\max}, \quad \mathbf{x}_{\min} \le \mathbf{x} \le \mathbf{x}_{\max}$

$$\mathbf{h}(\mathbf{x}(t),\mathbf{u}(t),\mathbf{p}(t)) = Y_{feqx}\mathbf{x}(t) + Y_{fequ}\mathbf{u}(t) + Y_{feqp}\mathbf{p}(t) + \begin{Bmatrix} \vdots \\ \mathbf{x}(t)^T \left\langle F_{feqxx}^i \right\rangle \mathbf{x}(t) \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}(t)^T \left\langle F_{fequu}^i \right\rangle \mathbf{u}(t) \\ \vdots \end{Bmatrix}$$

$$+ \begin{Bmatrix} \vdots \\ \mathbf{p}(t)^T \left\langle F_{feqpp}^i \right\rangle \mathbf{p}(t) \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}(t)^T \left\langle F_{fequx}^i \right\rangle \mathbf{x}(t) \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{p}(t)^T \left\langle F_{feqpx}^i \right\rangle \mathbf{x}(t) \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}(t)^T \left\langle F_{fequp}^i \right\rangle \mathbf{p}(t) \\ \vdots \end{Bmatrix} + C_{feqc}$$

The SCPAQCF Model

Properties

Given a System or Sub-system Consisting of n devices and the SCPAQCF of each device

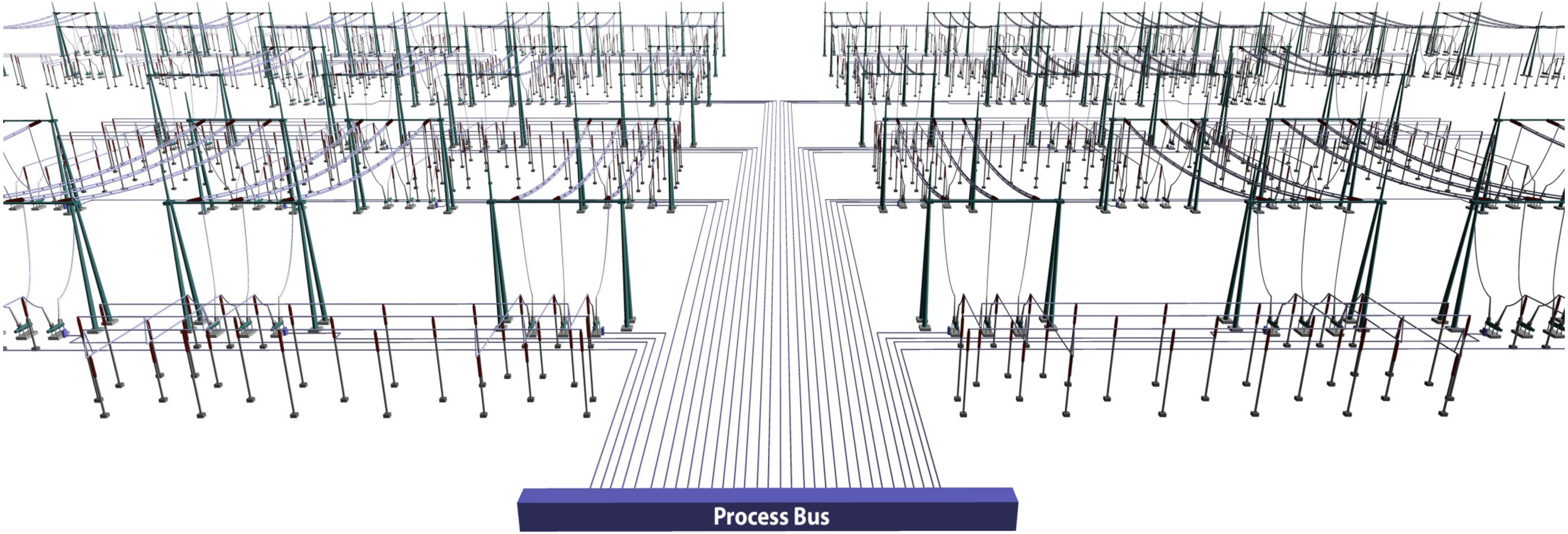
- *The system or subsystem model is in the SCPAQCF form. It can be constructed with a relatively simple algorithm. Large scale system algorithms must be employed.*

Given a measurement (datum) expressed as a function of x, u and p of a device

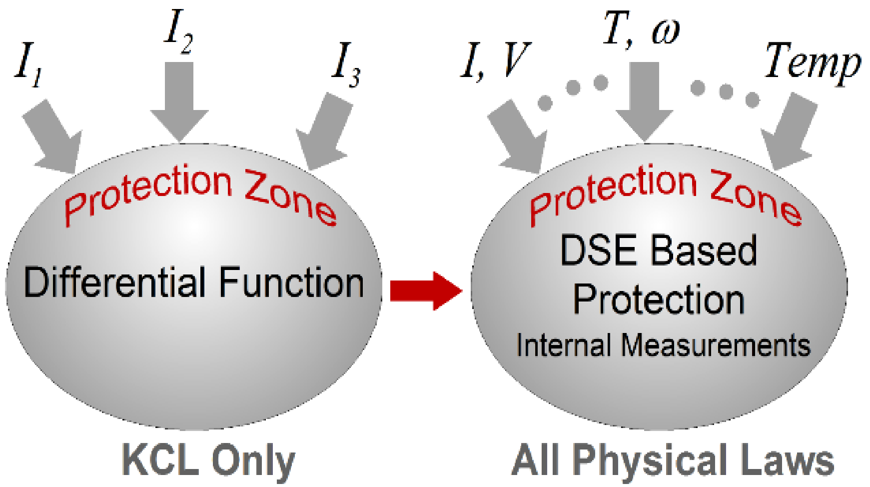
- *The measurement (datum) can be also expressed as a function of x, u and p of the system or subsystem SCPAQCF. This is a relatively simple mapping algorithm.*

Protection & Control of IBR Dominated Power Systems

Adaptive Protection or New Protection Approaches?

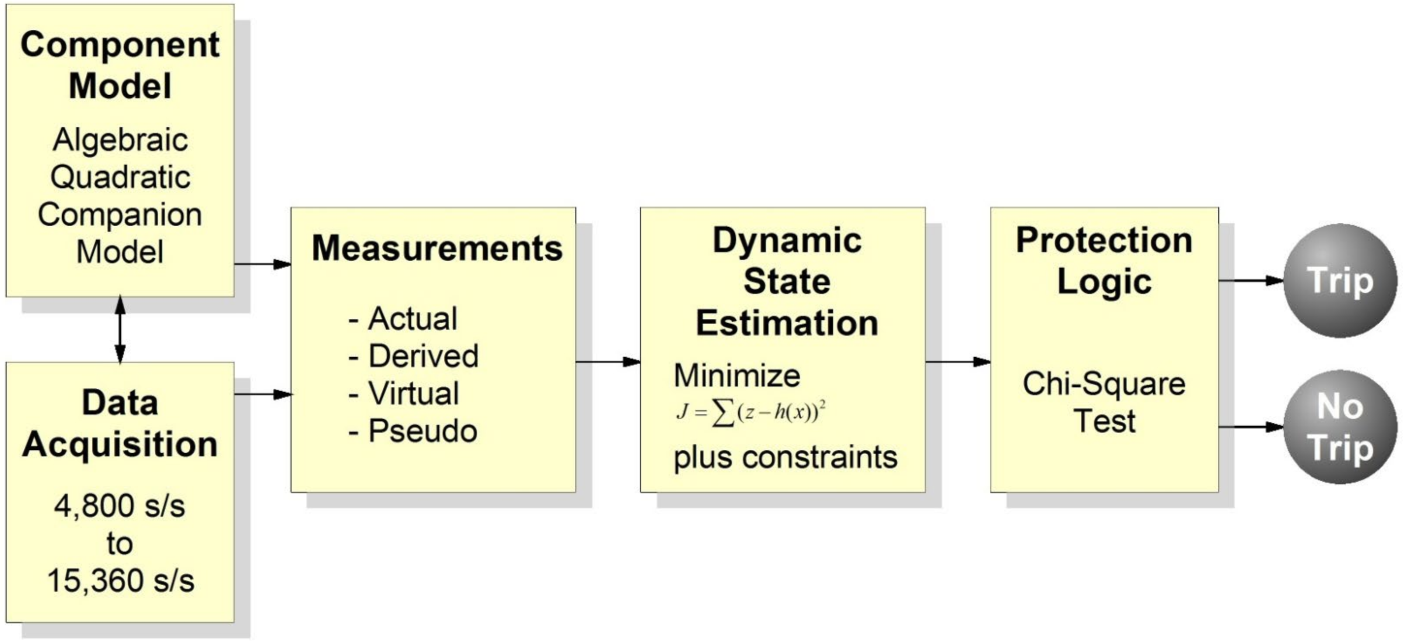


SCPAQCF Application



Dynamic State Estimation Based Protection

- Setting-less protective relay
- Sampled Value based dynamic state estimation
- Fast fault detection (sub ms)
- Measurement of frequency
- Measurement of ROCOF



State Estimation Based Protection

Parameter Identification

- The method is dependent on a high-fidelity protection zone model
- For most devices/components we can construct a high-fidelity model from first principles
- If certain parameters are suspect of inaccuracy, augment state estimation problem by moving the suspected parameters into the state. Then, these parameters are estimated from measurements. Model Parameter identification.

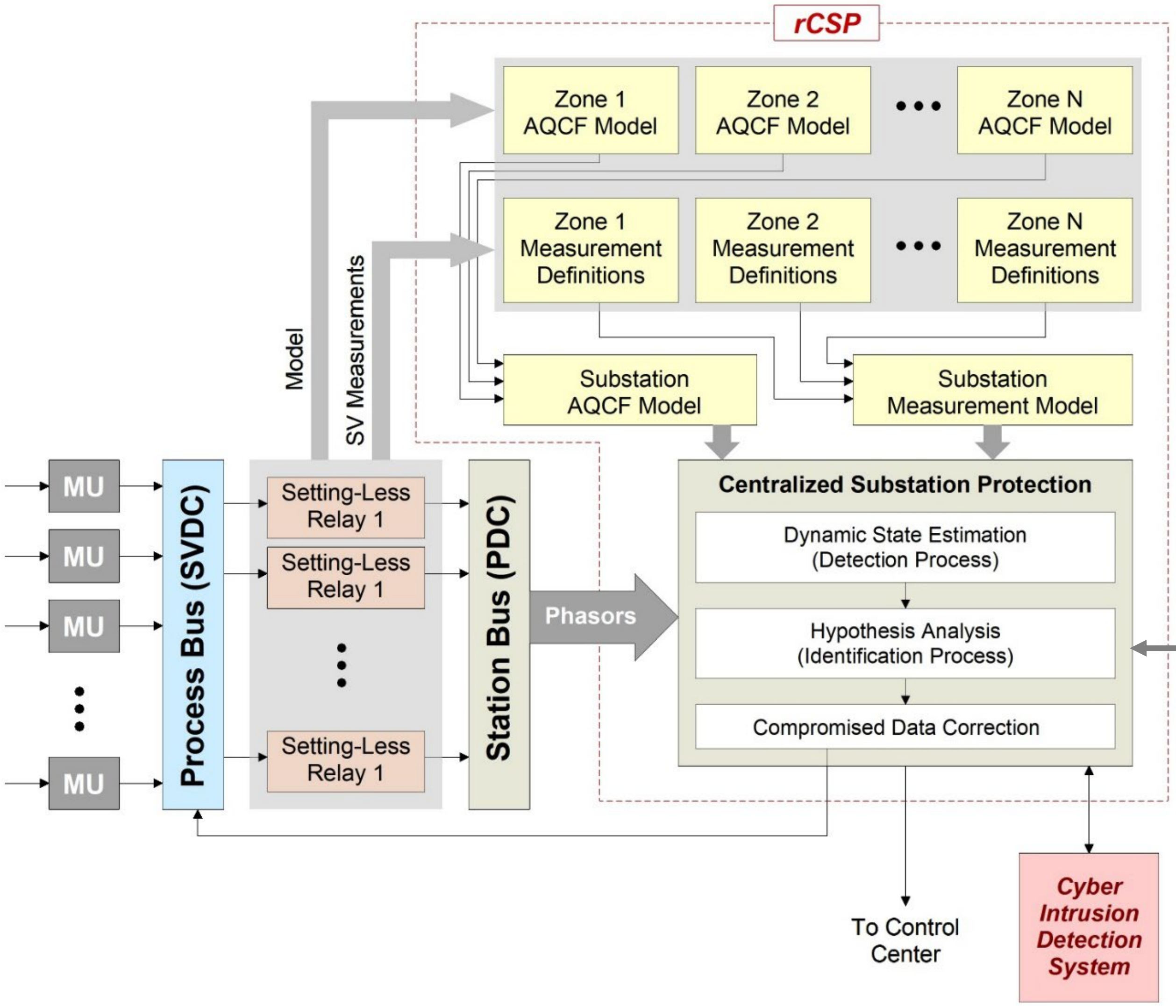
Dynamic State Estimation Based Protection
Hidden Failures

- As any protection and control system, the estimation-based protective relay is also dependent upon an instrumentation system that provides reliable measurements to the relay. Failures in instrumentation or malfunction of instrumentation will cause relay mis-operation and affect reliability.

- The answer is: provide a supervisory system to guarantee validated input data to each relay. How can this be achieved? Use of substation based dynamic state estimation methods.

Substation DSE, Anomaly Detection and Identification

Basic Functions in Absence of Anomalies



Provide the full state of the system with minimal delay for optimal full state feedback control.

Detect Anomaly: Easy Part.

Identify Source Anomaly via Hypothesis Testing:

- Bad data, hidden failures, power faults
- Cyber-attacks (false data and/or malicious control injection) and identify the source

Running Quasi-Dynamic State Estimator Using Phasor Data, Once per Cycle (*16,666* μs)

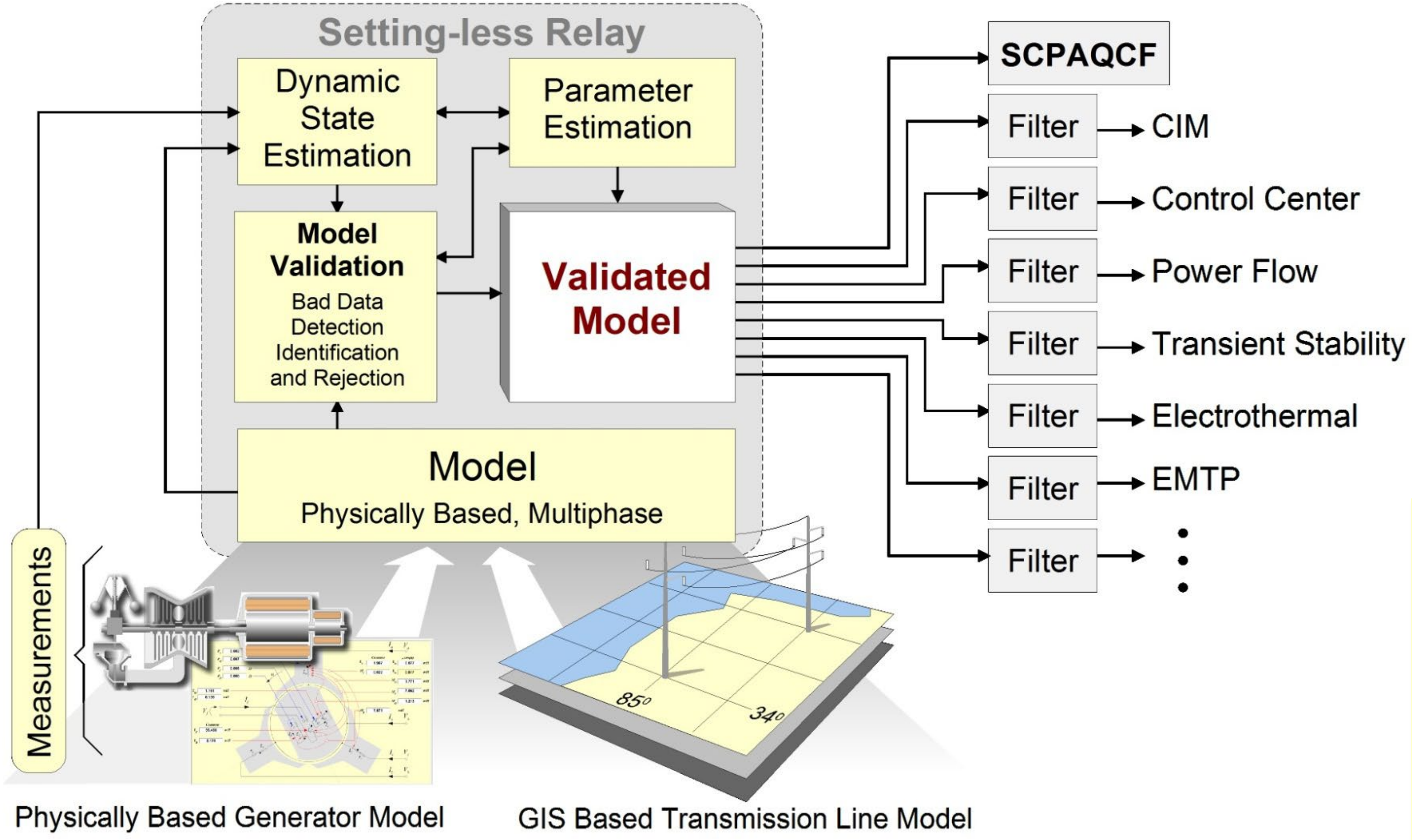
Running Dynamic State Estimator Using SV Data, Once per 416 μs

Relies on the tremendous redundancy of data at substation.

State Estimation Based Protection

Makes the Relay the Gatekeeper of the Model (validated)

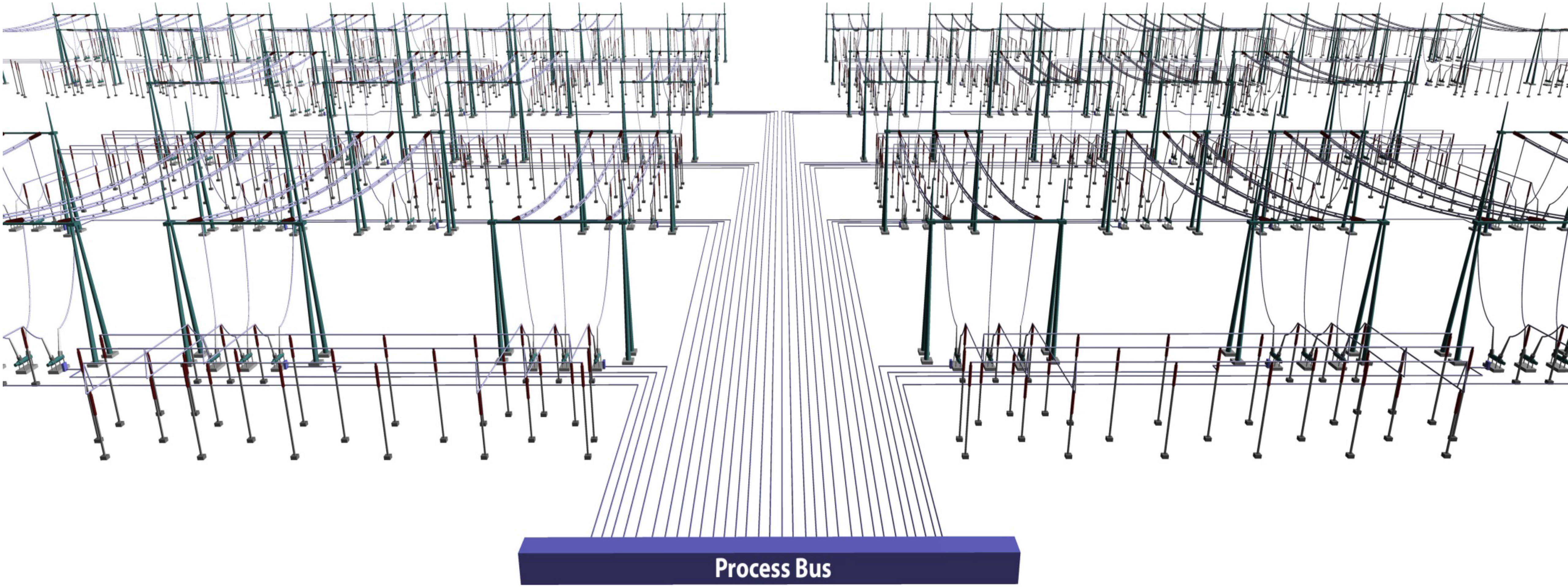
Relays: a Ubiquitous System for Perpetual Model Validation



Protection is Ubiquitous

- Makes Economic Sense to Use Relays as Keepers of Component Models
- Capability of Perpetual Model Validation in Estimation Based Relays
- Provide Other Level Models as Needed.

Self-Calibration and End-to-End Testing



Self-Calibration and End-to-End Testing: Real time self calibrating and end-to-end testing. Equivalent to primary injection testing. Guaranteed health of protection and control.

System Wide Dynamic State Estimation: update rate of once per cycle, high resolution situational awareness.

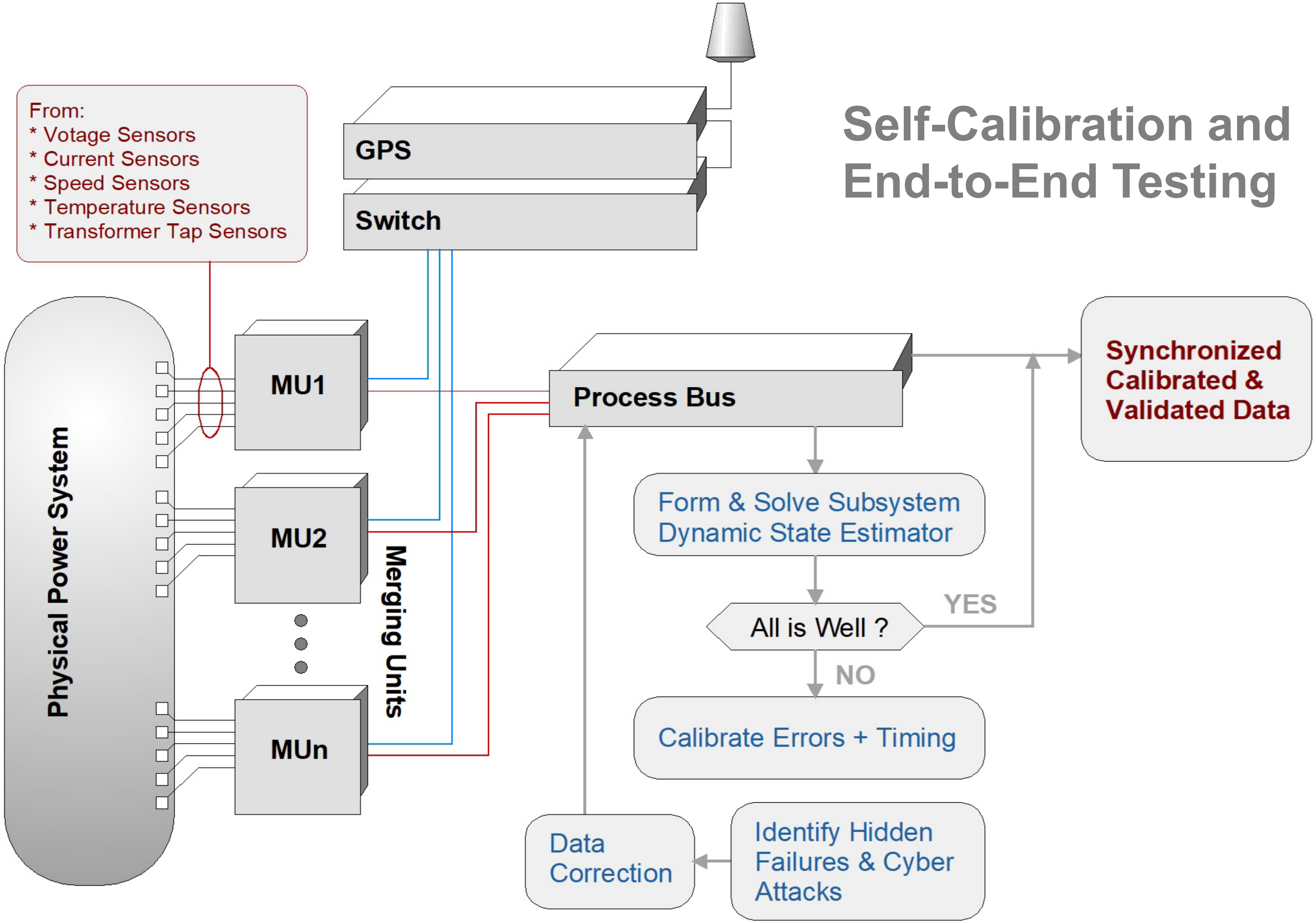
Monitoring of the Protection and Control Health: detection of hidden failures, detection of cyber-attacks.

Self-healing of the Protection and Control System: provides continuity of protection and situational awareness, alerts operator to perform repairs.

END RESULT

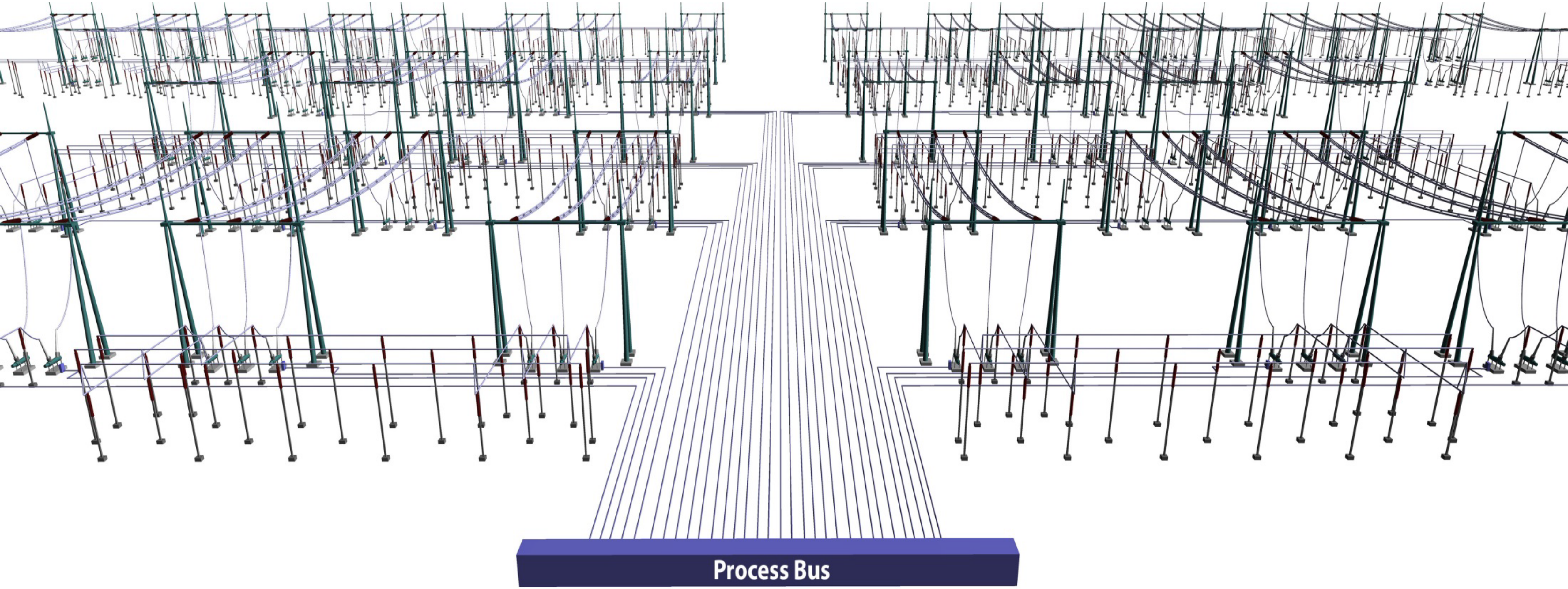
- Real time assessment of the health of the Protection and Control System
- Guarantee that all data are validated

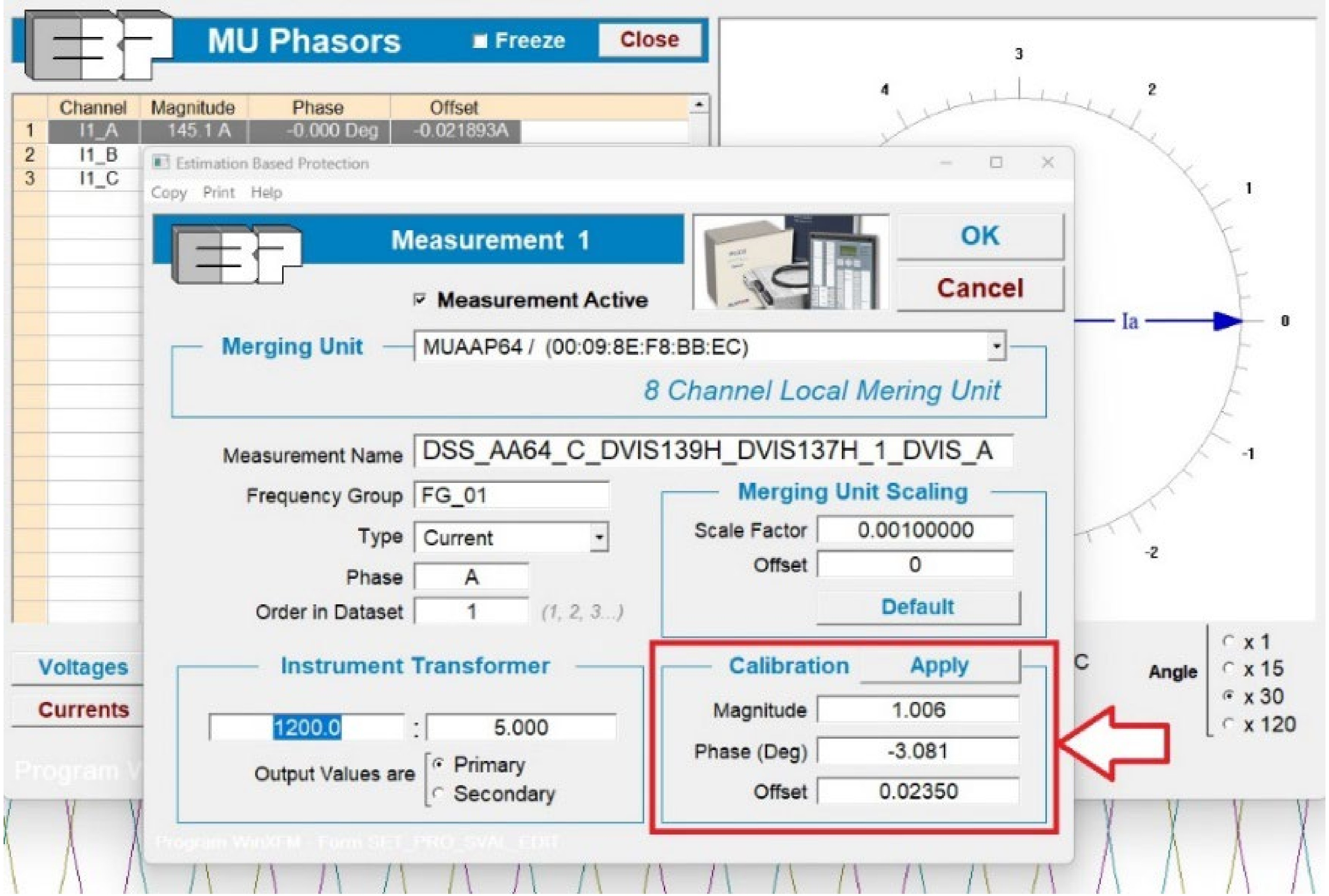
Basic Approach of Self-Calibration and End-to-End Testing



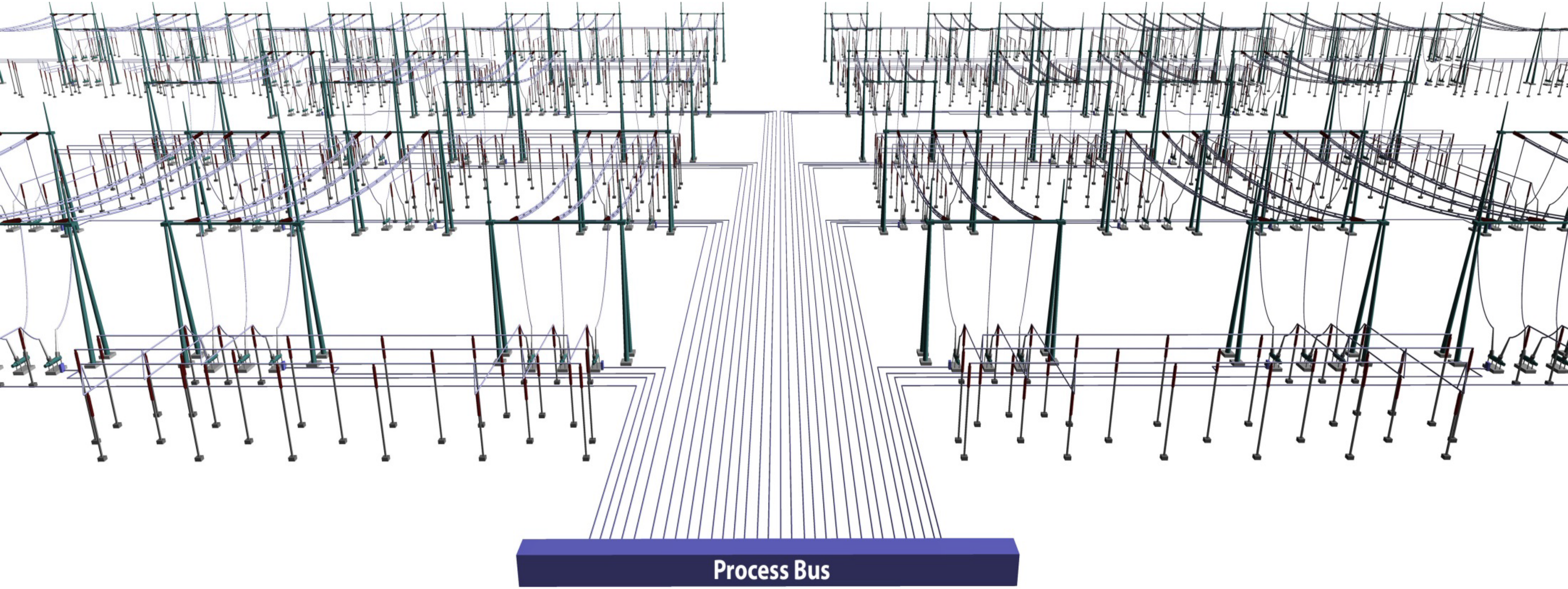
Self-Calibration and End-to-End Testing

Data Acquisition, Calibration and Validation



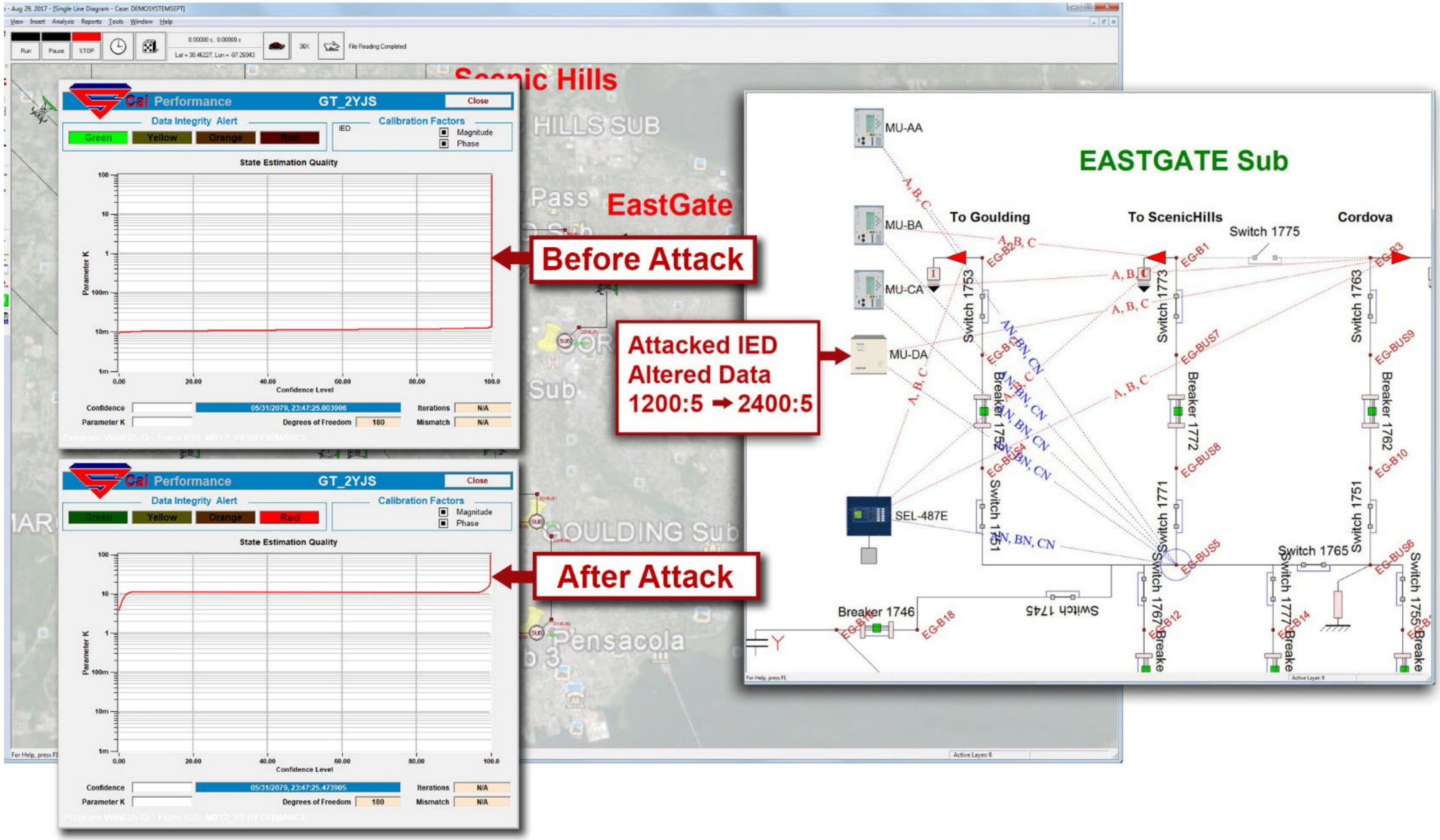

MU Phasors
Freeze
Close
Channel
Magnitude
Phase
Offset
1
I1_A
145.1 A
-0.000 Deg
-0.021893A
2
I1_B
3
I1_C
Estimation Based Protection
Copy Print Help
Measurement 1
OK
Cancel
Measurement Active
Merging Unit
MUAAP64 / (00:09:8E:F8:BB:EC)
8 Channel Local Mering Unit
Measurement Name
DSS_AA64_C_DVIS139H_DVIS137H_1_DVIS_A
Frequency Group
FG_01
Type
Current
Phase
A
Order in Dataset
1
(1, 2, 3...)
Merging Unit Scaling
Scale Factor
0.00100000
Offset
0
Default
Instrument Transformer
1200.0
5.000
Output Values are
Primary
Secondary
Calibration
Apply
Magnitude
1.006
Phase (Deg)
-3.081
Offset
0.02350
Voltages
Currents
Ia
Angle
x 1
x 15
x 30
x 120

Identification of Hidden Failures / Cyber Attacks



Substation QDSE, Anomaly Detection

Immediate Detection of Anomaly



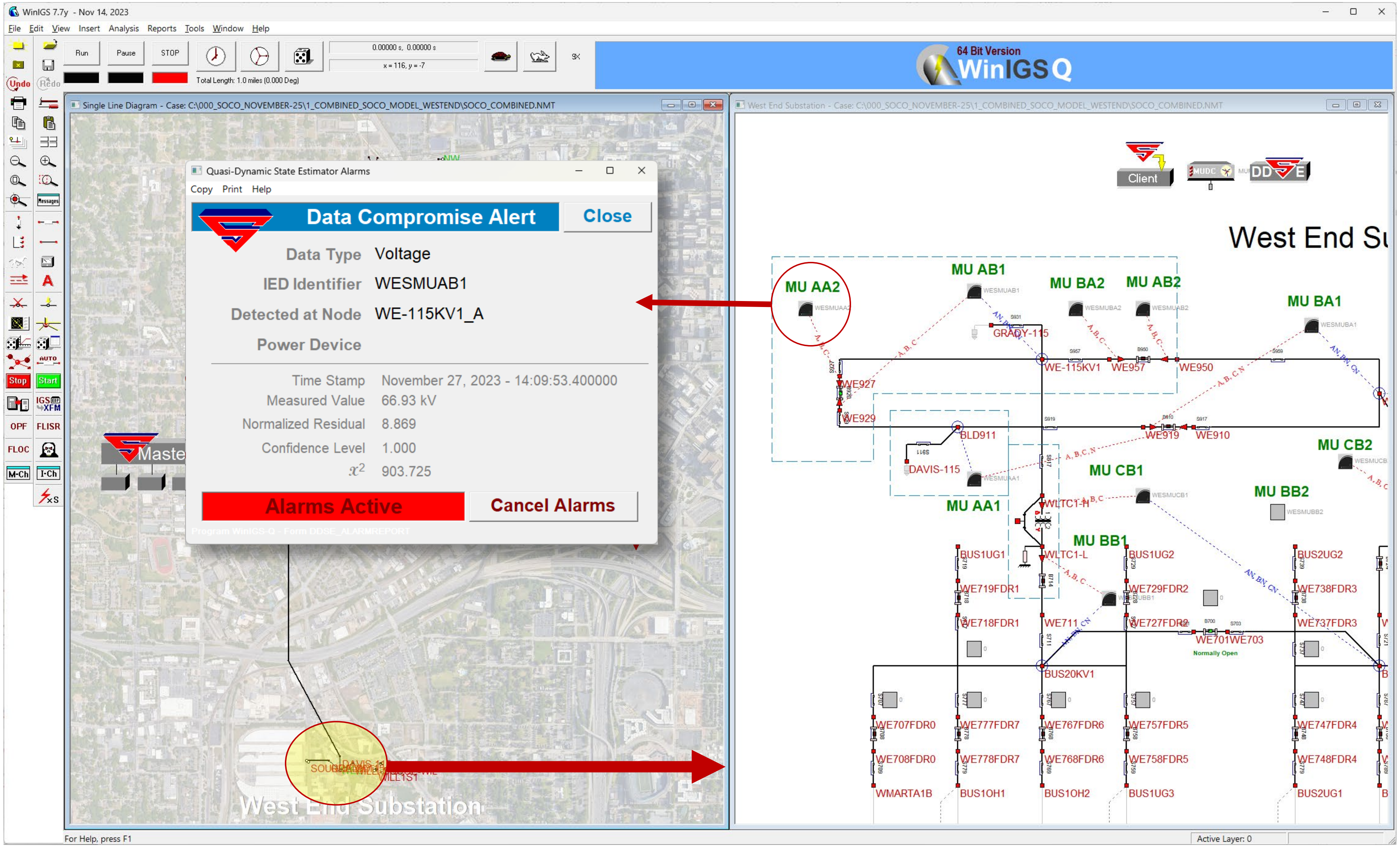
An intruder stages an attack by altering data as shown.

***Attack:* Change MU-DA Settings: from 1200:5 to 2400:5**

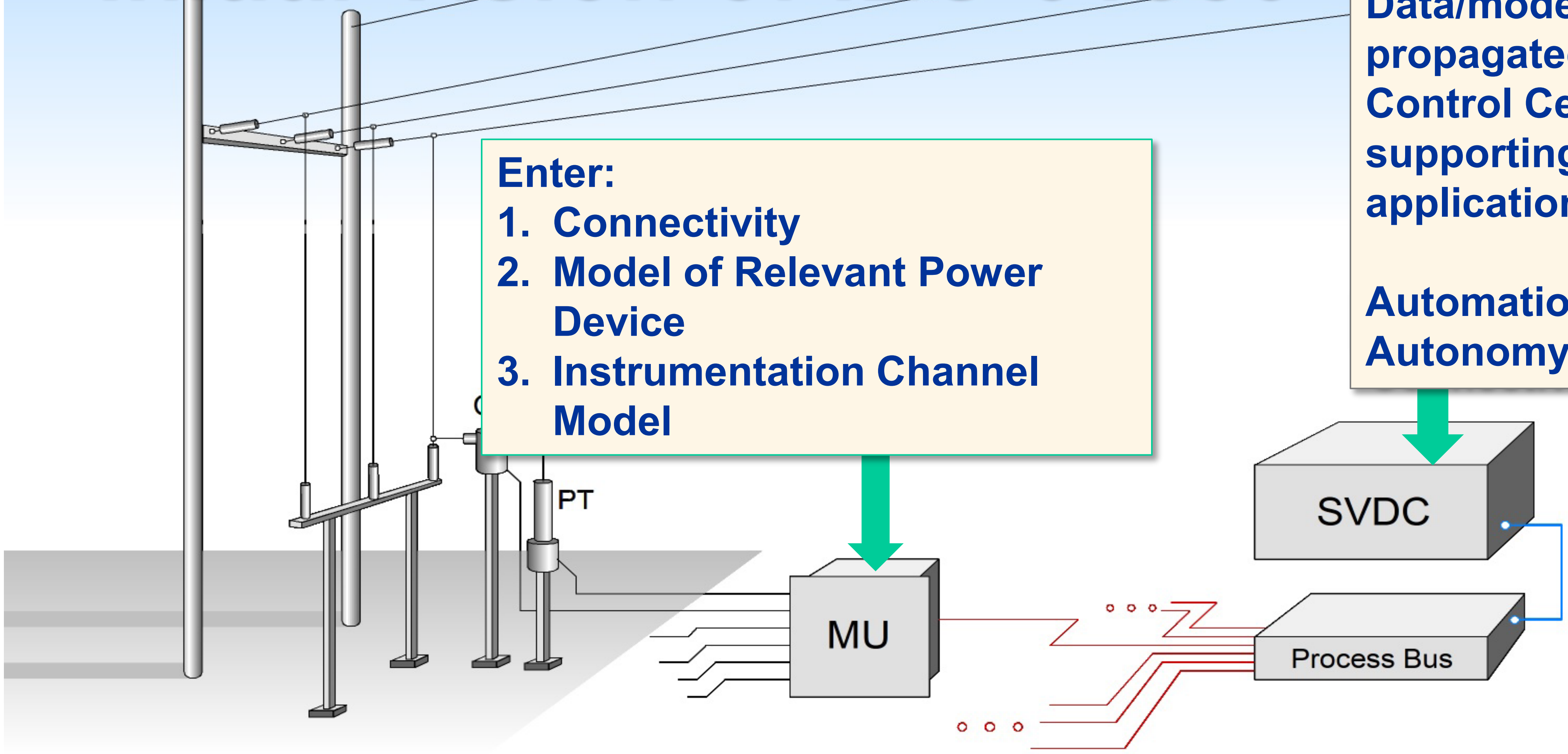
Dynamic state tracking detects the event immediately.

Identification: it is more complex to be discussed later.

Compromised Data Alerts



SUMMARY:
Initial Vision of IEC 61850



Enter:
1. Connectivity
2. Model of Relevant Power Device
3. Instrumentation Channel Model

Only Human Entry: Data are entered at the merging level.

Data/models are propagated from MU to Control Center supporting ALL applications in-between.

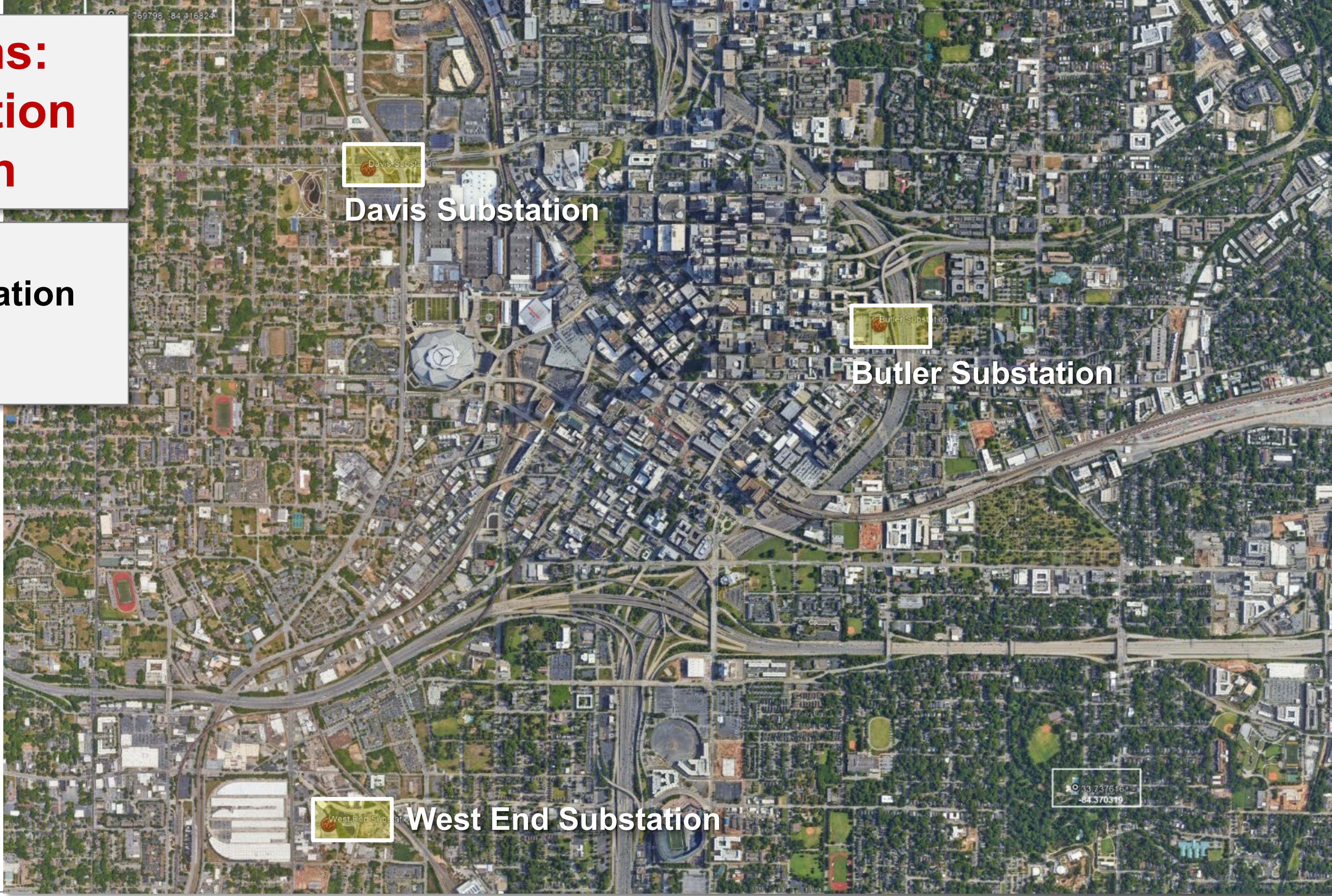
Automation → Autonomy

I want to make the point:

All of this is possible today

Pilot Programs: Field Verification and Validation

Integrated 3-Substation System Model



Example of one utility in the Atlanta area

Example Pilot Project

Each Installation Runs the Following Functions (Technology Summary)

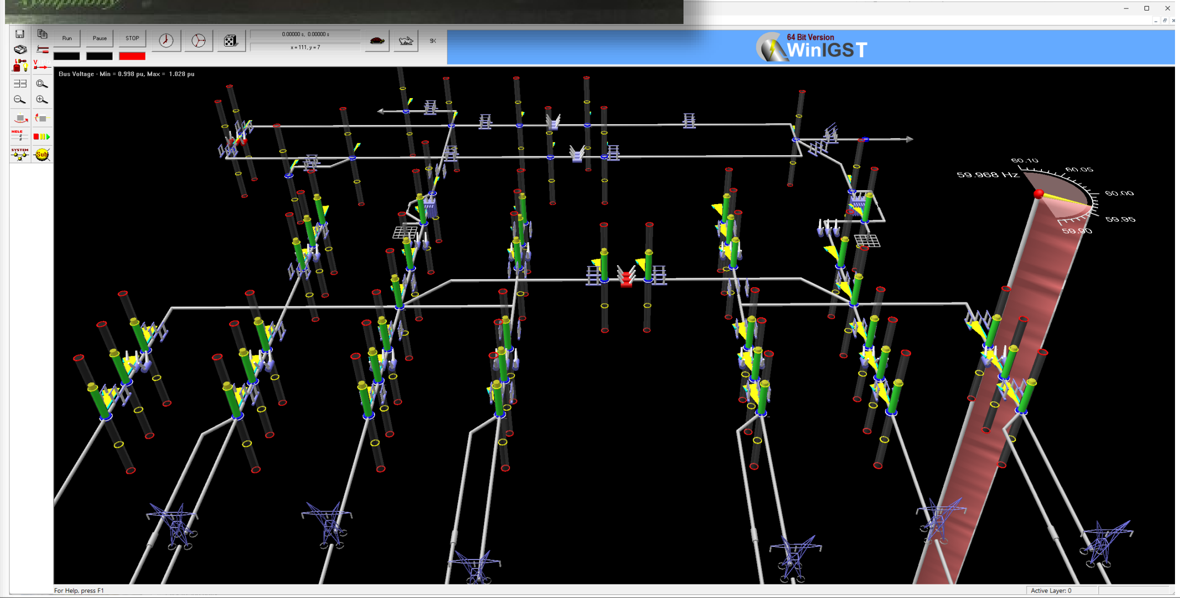
- Dynamic State Estimation Based protection.
- Substation centralized protection.
- Hidden failure detection and self-healing.
- False data and malicious control detection, isolation and disinfection - real time cyber security
- Full state feedback control (Closed Loop OPF)

Master

- System Wide Dynamic State Estimation

Front Panel View

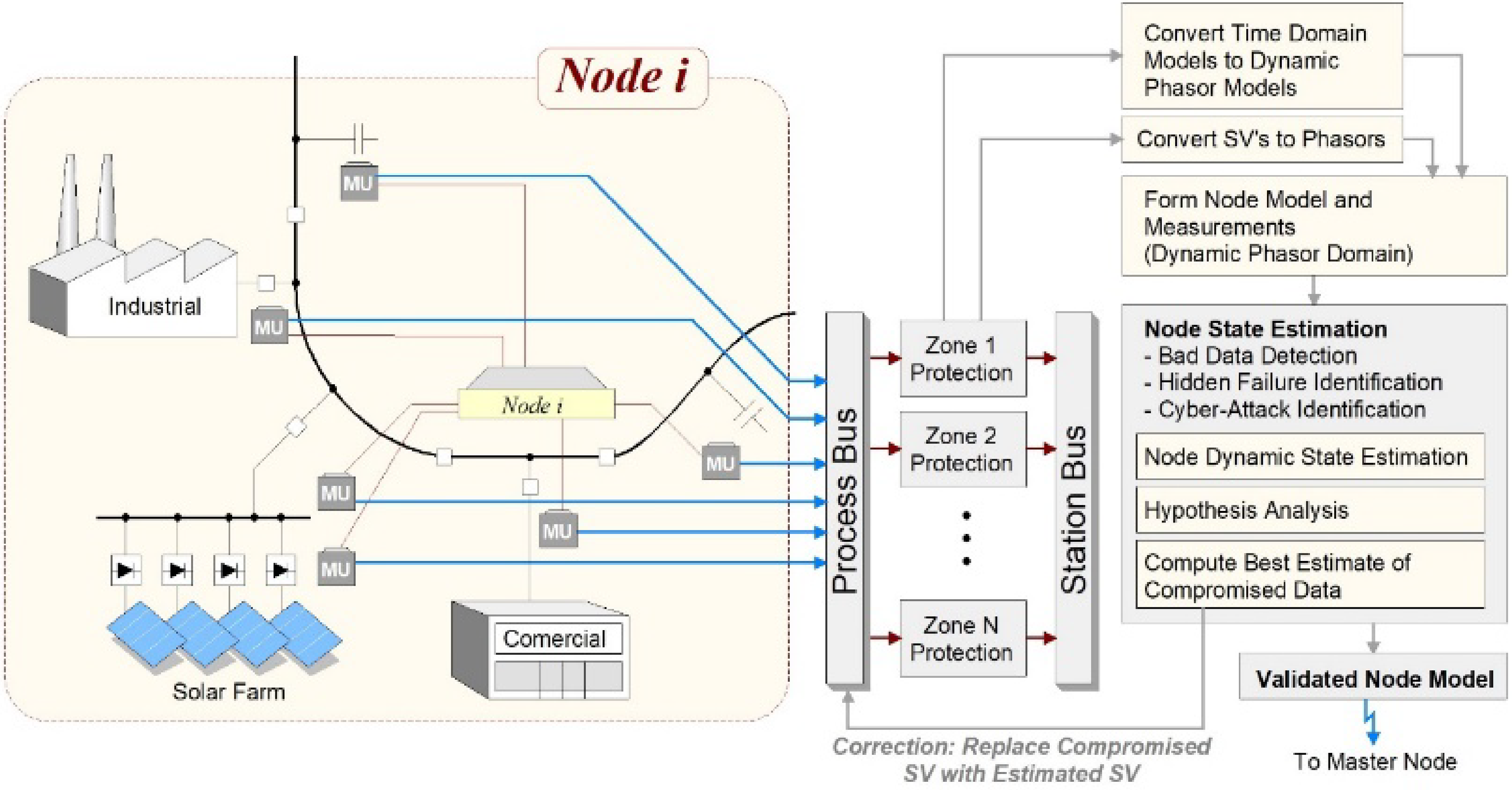
Example Visualization Substation Operating Conditions



Extension to Active Distribution Systems

SETO Project a2SDP

Motivation and Acknowledgement:
The method has been developed as a real time application in the a2DSP (autonomous, adaptive Distribution System Protection) sponsored by SETO.



Applications

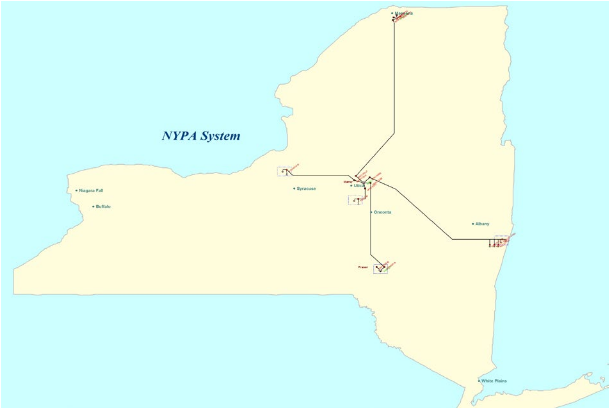
- Optimization – (via full state feedback)
  - Voltage / VAR Control
  - Dispatch / Network controls
  - Integration of customer flexibility
- Network Reconfiguration
- Intrusion Detection
- Inertia meter / Frequency Response
- Etc…. Etc….

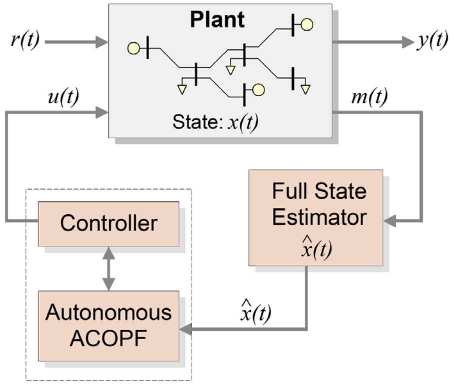
Application

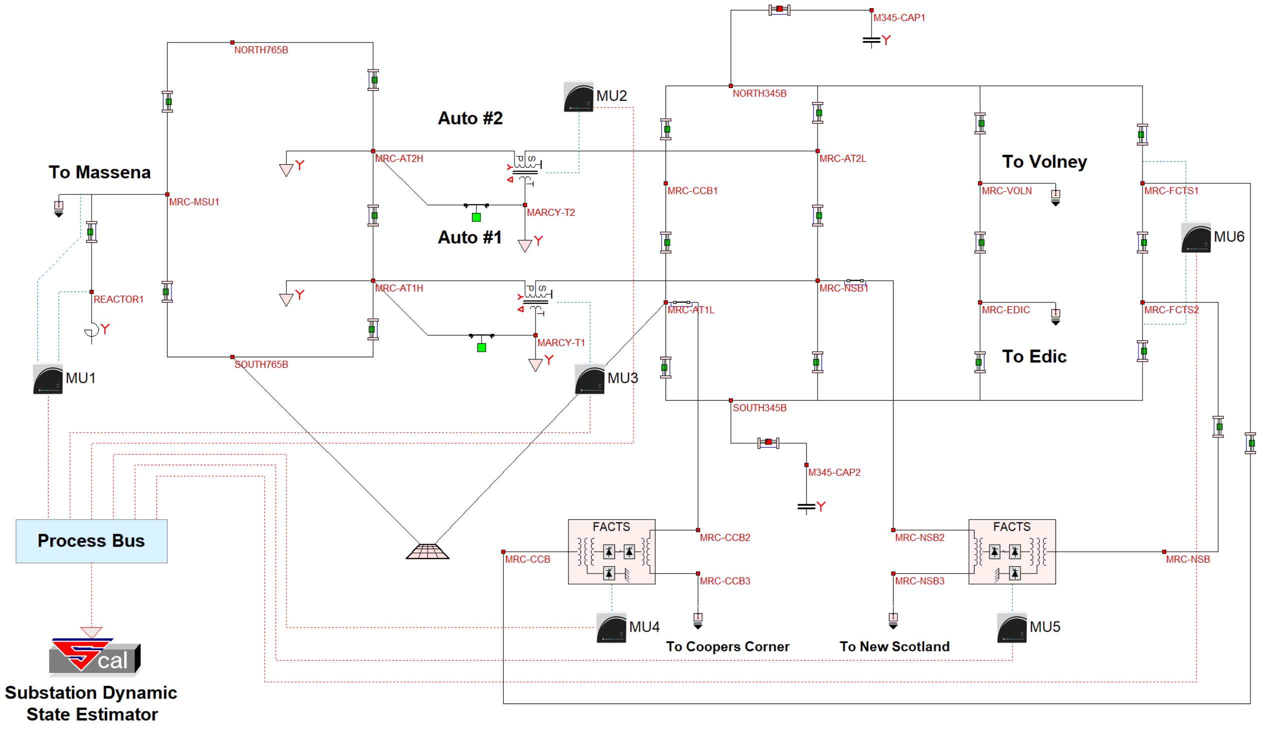
Optimization – (via full state feedback)

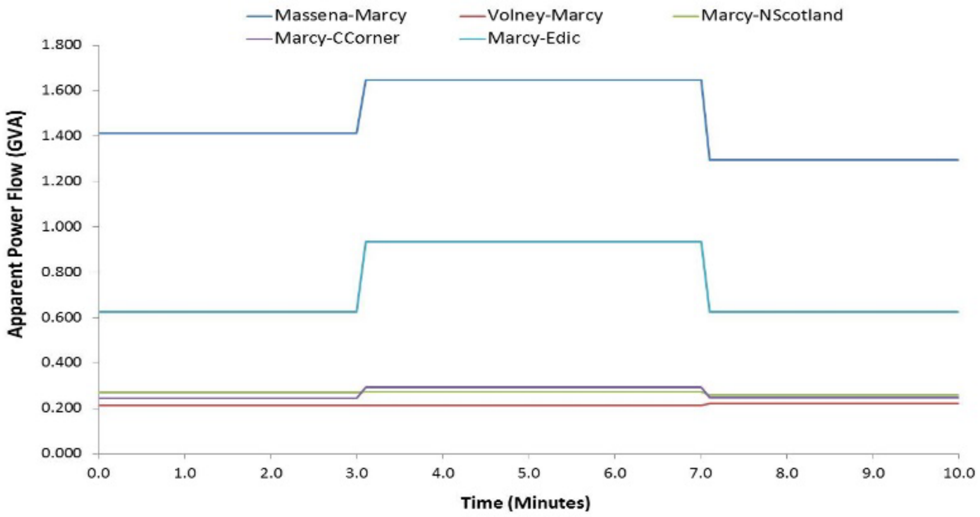
Example: **Volt/VAR Control**

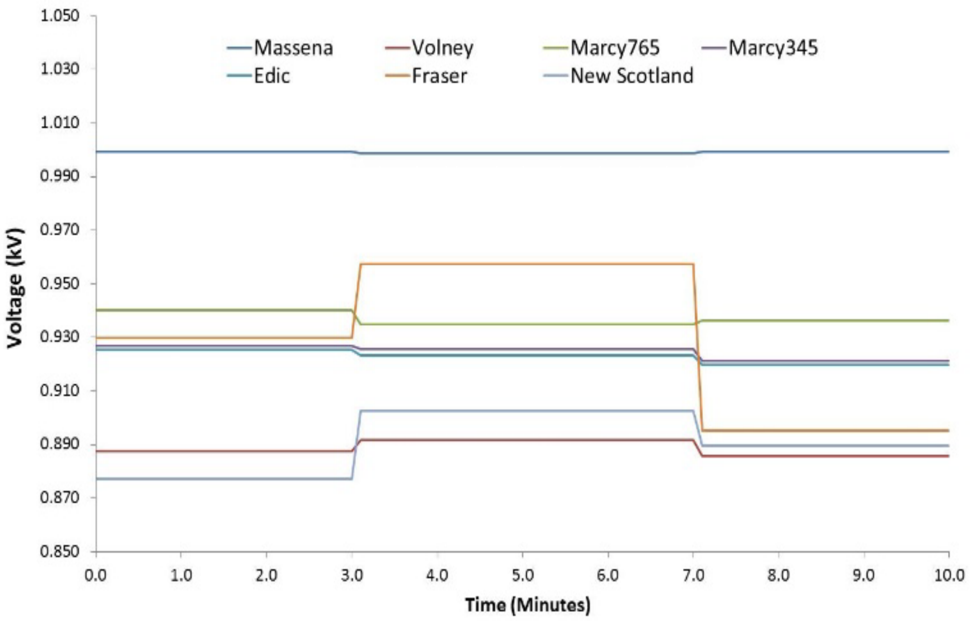
Example of Full State Feedback Control











Modeling and Implementation of Autonomous OPF

Formulate OPF as a Quadratic OPF

Solution Method:

(a) Convexify Quadratic OPF,

(b) Solve Convexified Quadratic OPF,

(c) Compute final solution of Quadratic OPF with SLP (initial conditions defined from step (b))

Quadratic OPF

Objective Function Generation

The Objective Function is the Weighed sum of:
Interchange through the MSU, Line Voltage levelization, Flow levelization on two key circuits

$$J = w_1\left(P_{MSU} - P_{sche,\text{int}}\right)^2 + \sum_{i\in S_{bus}}\left(\frac{V_{i,mag} - V_{i,tar}}{\alpha_i V_{i,tar}}\right)^2 + \sum_{i\in S_{cc}}\left(\frac{I_i - I_{i,t}}{0.05 I_{i,t}}\right)^2$$

The quadratic objective function is expressed in SCPAQCF syntax:

$$J\left(\mathbf{x},\mathbf{u},\mathbf{p}\right) = Y_{objx}\mathbf{x} + Y_{obju}\mathbf{u} + Y_{objp}\mathbf{p} + \mathbf{x}^T F_{objxx}\mathbf{x} + \mathbf{u}^T F_{objuu}\mathbf{u} + \mathbf{p}^T F_{objpp}\mathbf{p} + \mathbf{x}^T F_{objxu}\mathbf{u} + \mathbf{u}^T F_{objup}\mathbf{p} + \mathbf{p}^T F_{objpx}\mathbf{x} + C_{objc}$$

Quadratic OPF

Constraints

$$f_1 : I(t) = Y_{eqx1}\mathbf{x} + Y_{equ1}\mathbf{u} + Y_{eqp1}\mathbf{p} - B_{eq1}$$

$$f_2 : 0 = Y_{eqx2}\mathbf{x} + Y_{equ2}\mathbf{u} + Y_{eqp2}\mathbf{p} - B_{eq2}$$

$$0 = Y_{eqx3}\mathbf{x} + Y_{equ3}\mathbf{u} + Y_{eqp3}\mathbf{p} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T F^i_{eqxx3}\mathbf{x} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}^T F^i_{equu3}\mathbf{u} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{p}^T F^i_{eqpp3}\mathbf{p} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T F^i_{eqxu3}\mathbf{u} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}^T F^i_{equp3}\mathbf{p} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{p}^T F^i_{eqpx3}\mathbf{x} \\ \vdots \end{Bmatrix} - B_{eq3}$$

$$f_3 : I(t) = Y_{eqx4}\mathbf{x} + Y_{equ4}\mathbf{u} + Y_{eqp4}\mathbf{p} - B_{eq4}$$

$$f_4 : 0 = Y_{eqx5}\mathbf{x} + Y_{equ5}\mathbf{u} + Y_{eqp5}\mathbf{p} - B_{eq5}$$

$$0 = Y_{eqx6}\mathbf{x} + Y_{equ6}\mathbf{u} + Y_{eqp6}\mathbf{p} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T F^i_{eqxx6}\mathbf{x} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}^T F^i_{equu6}\mathbf{u} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{p}^T F^i_{eqpp6}\mathbf{p} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T F^i_{eqxu6}\mathbf{u} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}^T F^i_{equp6}\mathbf{p} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{p}^T F^i_{eqpx6}\mathbf{x} \\ \vdots \end{Bmatrix} - B_{eq6}$$

$$B_{eq\_i} = -N_{eqx\_i}\mathbf{x}(t-h) - N_{equ\_i}\mathbf{u}(t-h) - N_{eqp\_i}\mathbf{p}(t-h) - M_{eq\_i}\mathbf{i}(t-h) - K_{eq\_i}$$

$connectivity: \quad node1, node2, \ldots\ldots, nodeN$

$$subject\ to: \quad h_{\min} \le h(\boldsymbol{x}, \boldsymbol{u}) \le h_{\max}$$

$$\boldsymbol{u}_{\min} \le \boldsymbol{u} \le \boldsymbol{u}_{\max}$$

$$h(\mathbf{x},\mathbf{u},\mathbf{p}) = Y_{feqx}\mathbf{x} + Y_{fequ}\mathbf{u} + Y_{feqp}\mathbf{p} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T F^i_{feqxx}\mathbf{x} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}^T F^i_{fequu}\mathbf{u} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{p}^T F^i_{feqpp}\mathbf{p} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{x}^T F^i_{feqxu}\mathbf{u} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}^T F^i_{fequp}\mathbf{p} \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{p}^T F^i_{feqpx}\mathbf{x} \\ \vdots \end{Bmatrix} - C_{feqc}$$

Convexify Quadratic OPF

Why Convexification? And How?

In the last 2-3 decades, there is a serious activity towards convexified OPF formulations and solutions.

There are many extremely efficient solvers for convex OPF problems.

Examples: **Gurobi, GAMS,** etc. as well as open-source software, **OPT++, IPOPT.**

Convexification Mechanics of the Quadratic OPF

Given a quadratic OPF with hessian matrix H (symmetric without loss of generality)

$$H^{+} = H + \mathbf{d}^{T}\mathbf{I}$$

The entries of vector d are obtained by solving the following minimization problem:

$$\text{Min} \quad \sum_{i} |d_i|$$

$$\text{Subject To:}$$

$$\text{leading principal minor k of } \left(H + \mathbf{d}^{T}\mathbf{I}\right) \geq 0, k = 1,..n$$

Convexification Example 1

Given the quadratic system below

$$0.1x^2 + 0.2u^2 + 0.45xu$$

What is the convex system with minimal changes?

$$0.1x^2 + 0.2u^2 + 0.45xu + ax^2 + bu^2$$

$$Min \quad |a| + |b|$$

$$subject\ to:$$

$$a + 0.1 \geq 0$$

$$ab + 0.2a + 0.1b - 0.23 \geq 0$$

$$Solution:$$

$$a = 0.125, \quad b = 0.025 \quad \rightarrow \quad 0.225x^2 + 0.225u^2 + 0.45xu$$

Quadratic OPF Convexification

Original QACOPF problem

$$\begin{aligned} &\text{Minimize} \quad J(\mathbf{x},\mathbf{u},\mathbf{p}) \\ &\text{Subject to:} \; g(\mathbf{x},\mathbf{u},\mathbf{p}) = 0 \\ &\qquad h(\mathbf{x},\mathbf{u},\mathbf{p}) \le 0 \\ &\qquad \mathbf{u}_{\min} \le \mathbf{u} \le \mathbf{u}_{\max} \end{aligned}$$

Symmetrized QACOPF problem

Convex QACOPF problem

Transformation to make Hessian matrix of the system symmetric

Make **minimal** additions to nonlinear equation so that the Hessian matrix of the system will be positive semidefinite

$$y^T F y \;\rightarrow\; \frac{1}{2} y^T \left(F + F^T\right) y$$

Quadratic Convex problem:

Handling of Quadratic Equality Constraints

Given the convexified quadratic equality constraint

$$\mathbf{x}_i + \mathbf{x}_j + a_2\mathbf{x}_i + b_2\mathbf{x}_m + (a_k\mathbf{x}_k + b_m\mathbf{x}_m)^2 + \mathbf{u}_v^2 + c = 0$$

Substitution of quadratic terms with new variables

Equivalent linearized equation

$$\mathbf{x}_i + \mathbf{x}_j + a_2\mathbf{x}_i + b_2\mathbf{x}_m + y_1 + y_2 + c = 0$$

+

Companion quadratic equations

$$(a_k\mathbf{x}_k + b_m\mathbf{x}_m)^2 - y_1 = 0$$

$$\mathbf{u}_v^2 - y_2 = 0$$

$$y_1, y_2 \geq 0$$

Introduction of slack variables

quadratic convex inequalities

$$(a_k\mathbf{x}_k + b_m\mathbf{x}_m)^2 - y_1 + s_1 \leq 0$$

$$\mathbf{u}_v^2 - y_2 + s_2 \leq 0$$

$$y_1, y_2, s_1, s_2 \geq 0$$

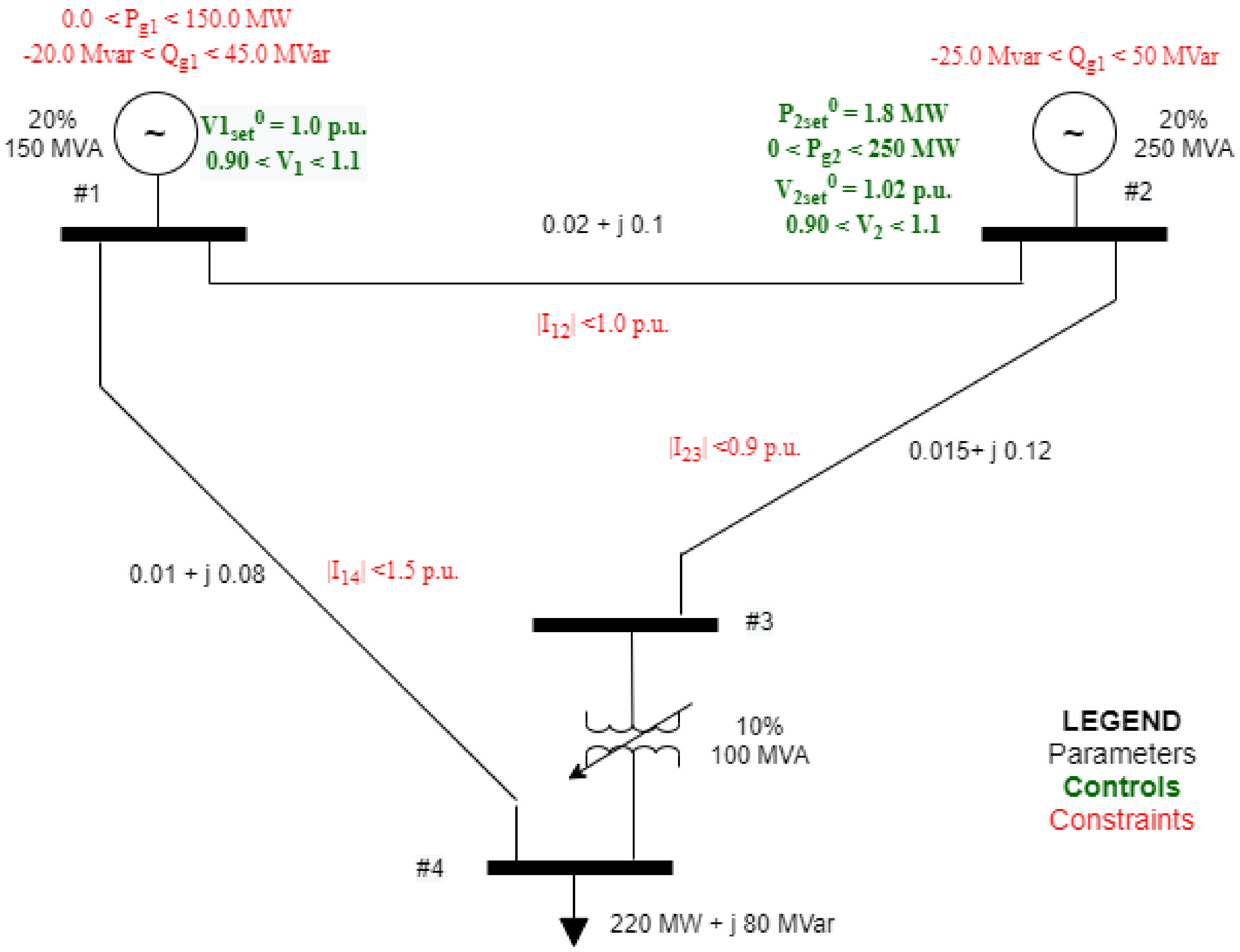
Constraints added to the convexified OPF problem

Overall Solution Approach

The solution of the convexified QACOPF problem represents a solution of an approximated model. It may or may not be feasible.

To compute the final optimal and feasible solution of the not-approximated ACOPF, a SLP approach is applied to the QACOPF.

Example Test System – Four-Bus System



$$f_1 : i(t) = Y_{eqx1}\mathbf{x}(t) + Y_{equ1}\mathbf{u}(t) + C_{eqc1}$$ *SCAQCF* Standard

$$f_2 : 0 = Y_{eqx2}\mathbf{x}(t) + Y_{equ2}\mathbf{u}(t) + C_{eqc2}$$

$$f_3 : 0 = Y_{eqx3}\mathbf{x}(t) + Y_{equ3}\mathbf{u}(t) + \begin{Bmatrix} \vdots \\ \mathbf{x}(t)^T \left\langle F^i_{eqxx3} \right\rangle \mathbf{x}(t) \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}(t)^T \left\langle F^i_{equu3} \right\rangle \mathbf{u}(t) \\ \vdots \end{Bmatrix} + \begin{Bmatrix} \vdots \\ \mathbf{u}(t)^T \left\langle F^i_{equx3} \right\rangle \mathbf{x}(t) \\ \vdots \end{Bmatrix} + C_{eqc3}$$

$$\mathbf{u}_{hmin} \le \mathbf{u}(t) \le \mathbf{u}_{hmax}$$

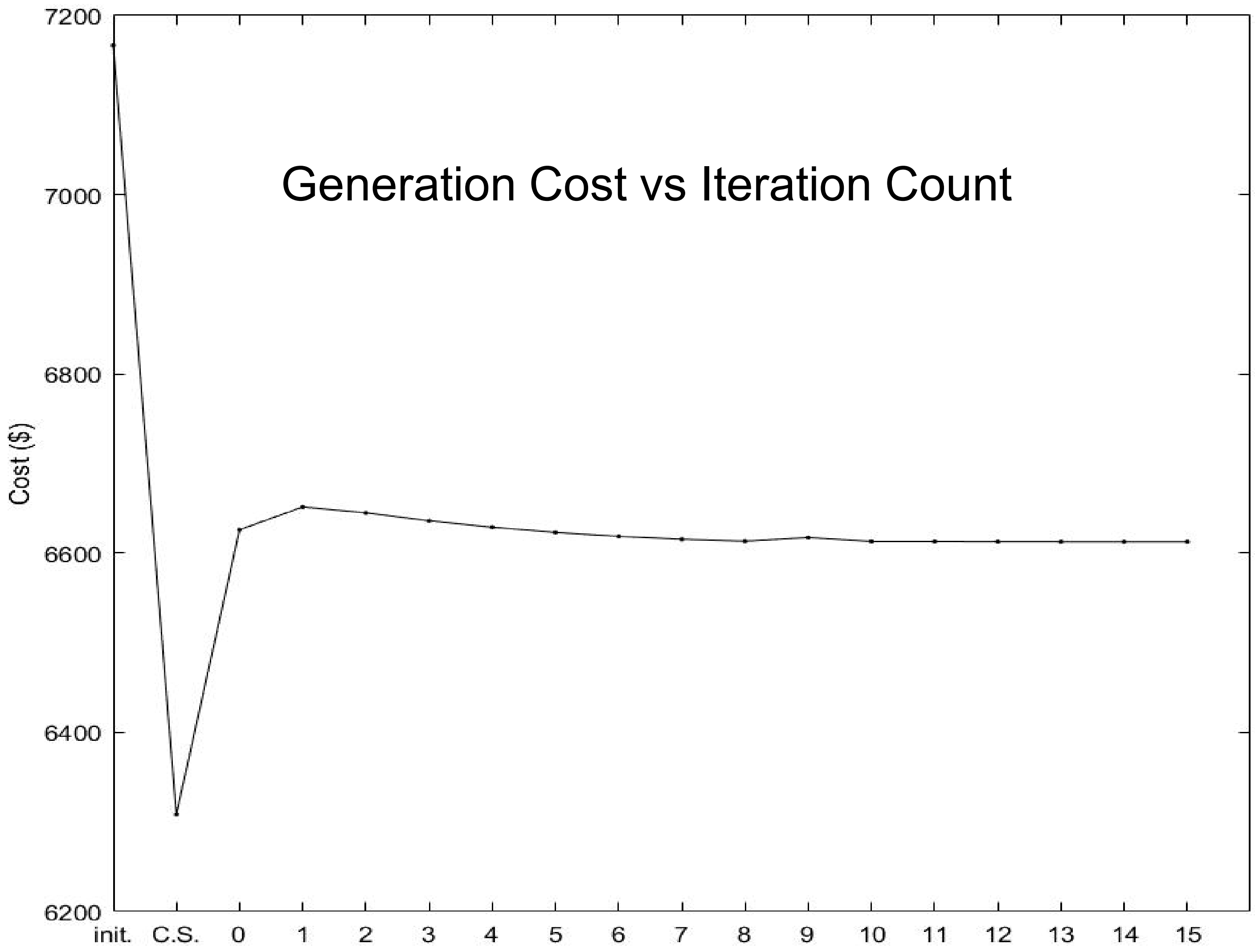
KCL-based Quadratized Formulation

35 States, 4 Controls

Equality Constraints (Power Flow):
- 18 linear equations
- 17 quadratic equations

Inequality (Functional) Constraints:
- 8 linear equations
- 6 nonlinear equations

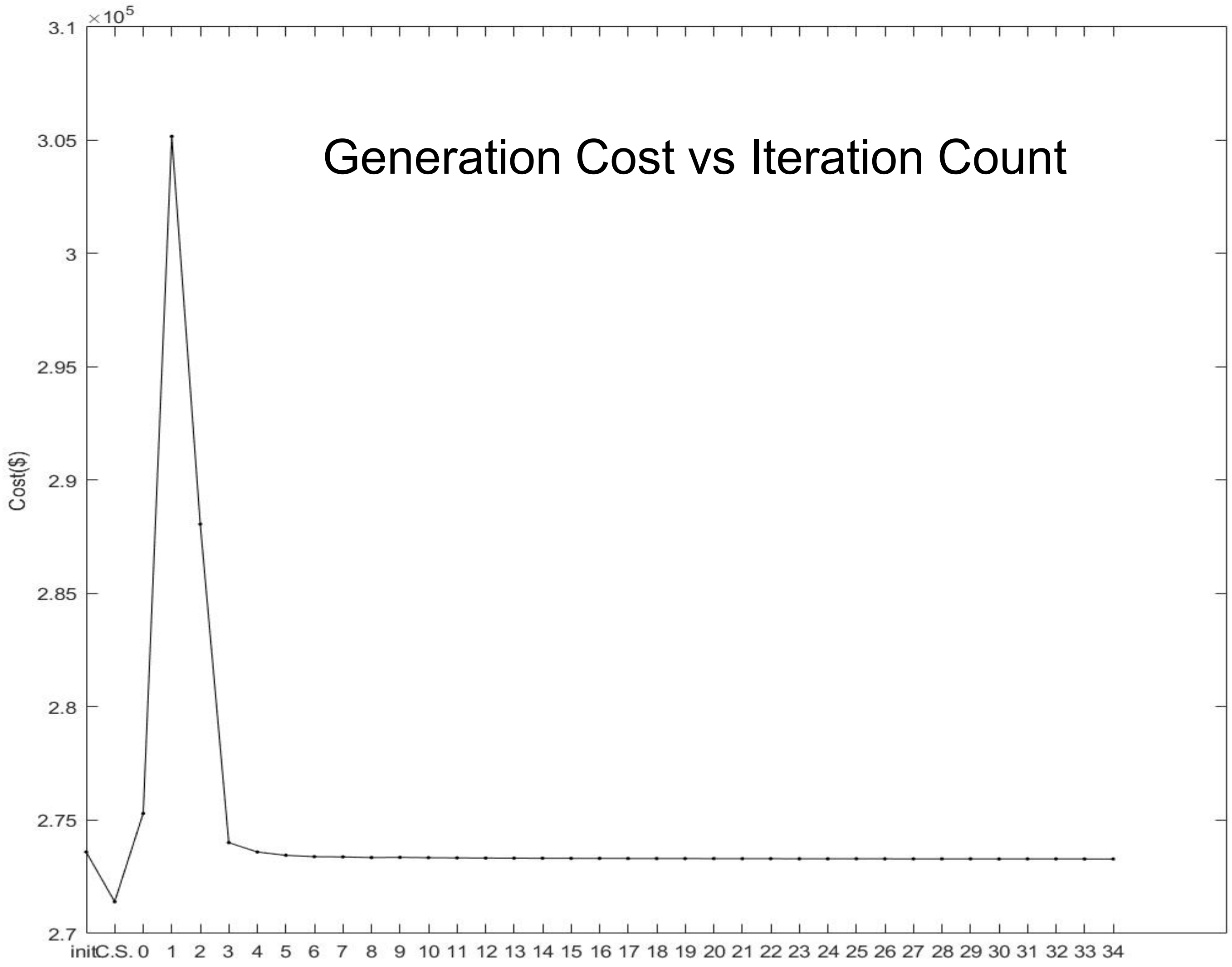
Results for Four-Bus System



The lowest cost of $6308.51 corresponds to the solution to the convexified problem. Correction of convexification error with SLP result in the optimal generation cost of $6612.85 and no violation in any of the functional constraints.

The largest number of model constraints is 5 and the largest number of violated model constraints is 3, or respectively 35.7% and 21.4% of the total number of functional constraints.

Results for final event Network_02*-173



The lowest cost of $271401.97/hr corresponds to the solution to the convexified problem. Correction of convexification error with SLP result in the optimal generation cost of $273289.62/hr and no violation in any of the functional constraints.

The largest number of model constraints is 113 and the largest number of violated model constraints is 53, or respectively 5.58% and 2.62% of the total number of functional constraints.

Application

Optimization – (via full state feedback)

Example: **Active Distribution System Reconfiguration**

Introduction & Background

Network topology optimization as a means to increase reliability and meet optimization objectives has gain attention for both Transmission and Distribution systems.

While for transmission systems some folks has raised concerns, for distribution systems there is general acceptance of the value of network topology optimization.

Introduction & Background

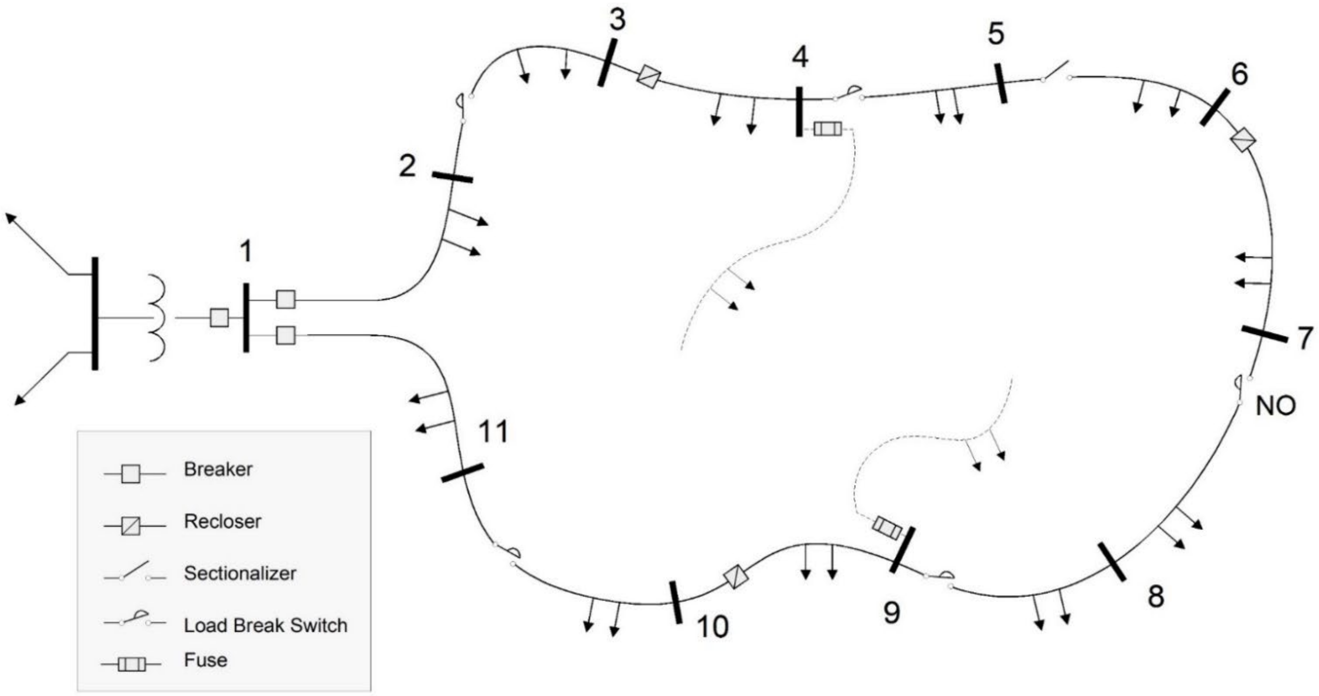
Back in the 1980's we introduced transmission switching as a means for remedial actions during emergency or restorative actions:

See: A. G. Bakirtzis and A. P. Meliopoulos, "Incorporation of Switching Operations in Power System Corrective Control Computations," *IEEE Transactions on Power Systems*, vol. PWRS-2, no. 3, pp. 669-676, August 1987.

When we discussed with a group of utilities of extending the work for optimization of the transmission system under normal conditions, there was a lot of pushback, captured in two arguments: (a) gains are minimal, and (b) wear and tear on breakers may increase cost.

Distribution System Reconfiguration in Real Time

OFR: Optimal feeder reconfiguration - normal conditions
FLISR: Fault Locating Isolation & Service Restoration – after a fault



Objectives

Feeder optimization OR Fast restoration of system services

Optimality of switching sequence and observance of physical limitations

Minimization of customers affected

Distribution System Reconfiguration in Real Time

Dynamic Programming Based Approach: Addresses Two Problems

1. OFR: Optimal feeder reconfiguration - normal conditions
2. FLISR: Fault Locating Isolation & Service Restoration - fault

OFR: In normal operation, the feeder connections are optimally configured through controlling the states of switches with the objective of minimizing the system operating loss

$$Optimal\ \mathrm{Re}configuration - Normal\ Operation$$

$$Min \quad J = \sum_{all\ circuits\ k} \left(P_{ij}(k) + P_{ji}(k) \right)$$

Distribution System Reconfiguration in Real Time

Dynamic Programming Based Approach: Addresses Two Problems

1. OFR: Optimal feeder reconfiguration - normal conditions
2. FLISR: Fault Locating Isolation & Service Restoration - fault

FLISR: After a fault, based on the fault locating information provided by protection system, the method can isolate the minimum part of the system affected by the fault in a real-time fashion, and generate an optimal switching operation sequence to help to restore the service to customers, thus minimizing the unserved power in the system.

$$\textit{Optimal Reconfiguration} - \textit{After A Fault}$$

$$Min \quad J = \sum_{all\ loads\ i} P_{load,i}$$

Important Consideration in OFR

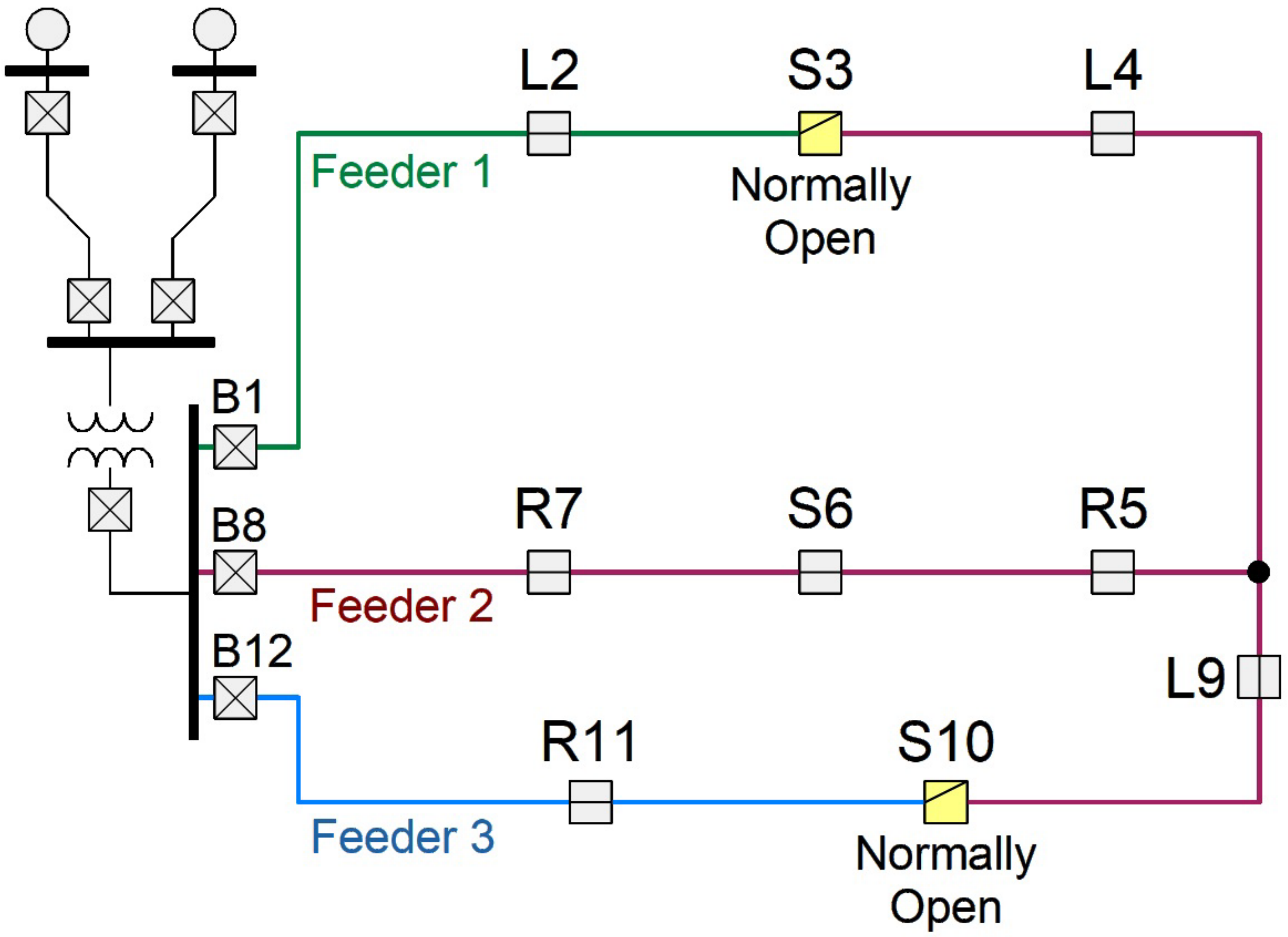
Dynamic Programming is Extremely Flexible in Incorporating Many Other Issues:

- Optimal Control of DERs and Coordination with Storage
- Voltage Control
- Include Customer Flexibility
- Coordination with Transmission
- Beware of the “Curse of Dimensionality”

Solution for Efficiency

- Successive Dynamic Programming

Example OFR Results



Example OFR Results

Step 1: Power flow analysis on initial system topology and conditions
12.66kV System with 3 Feeders, 58 Buses, and 12 Switches
Total load: 15MW; Initial system loss: 1081.52kW (7.333% of total load)

Optimal Switching Operation Sequence

Switch 9 opens → Switch 5 opens → Switch 3 closes → Switch 10 closes

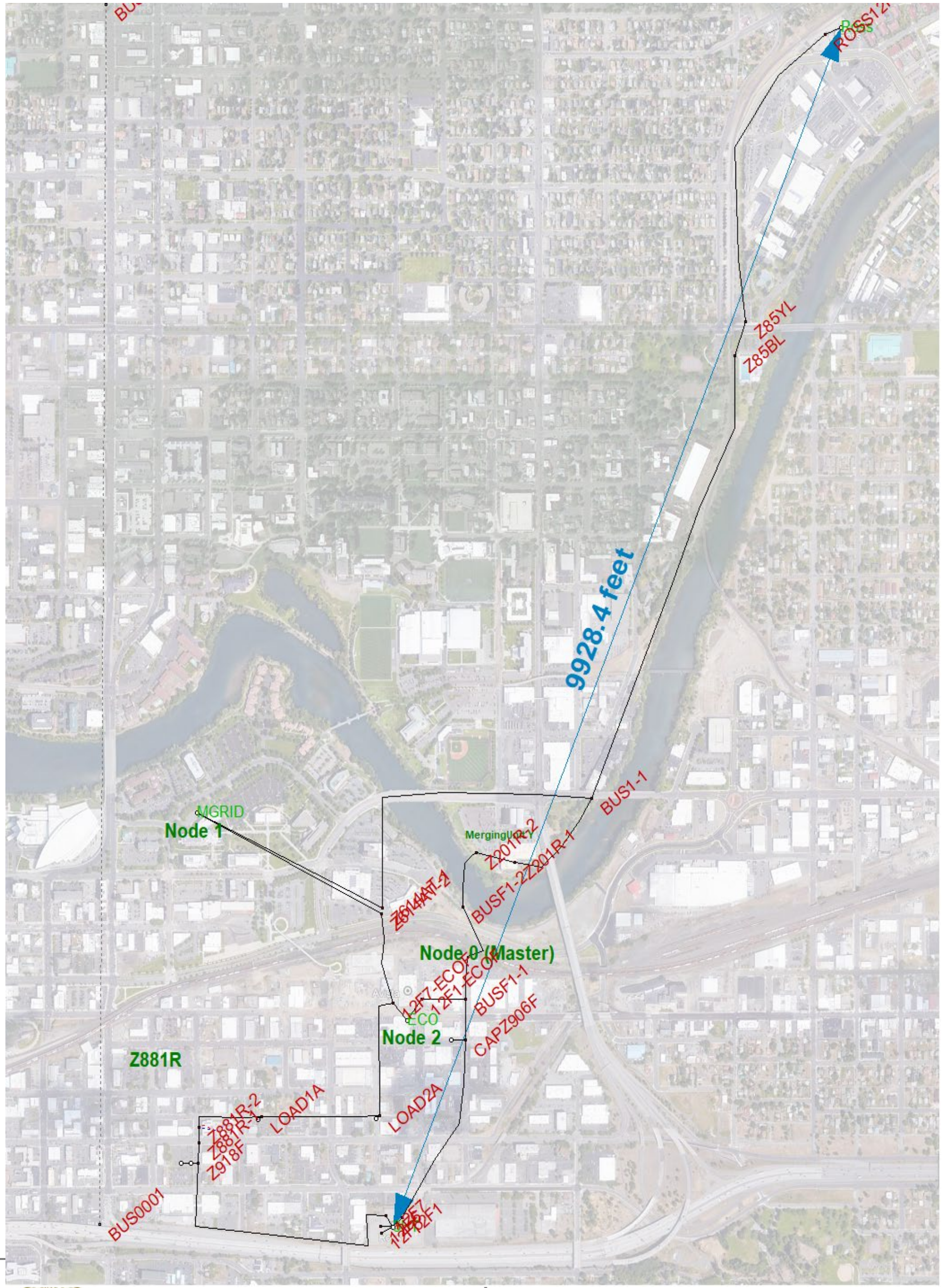
Performance

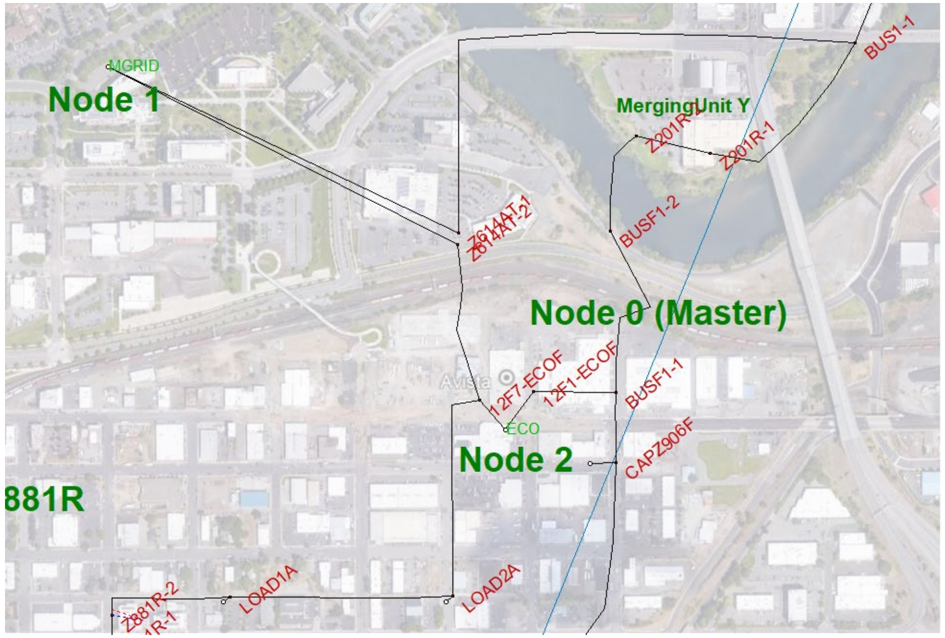
Original System Loss: 1081.52kW (7.333% of total load)
Final System Loss: 432.36kW (2.88% of total load)

I want to make the point:

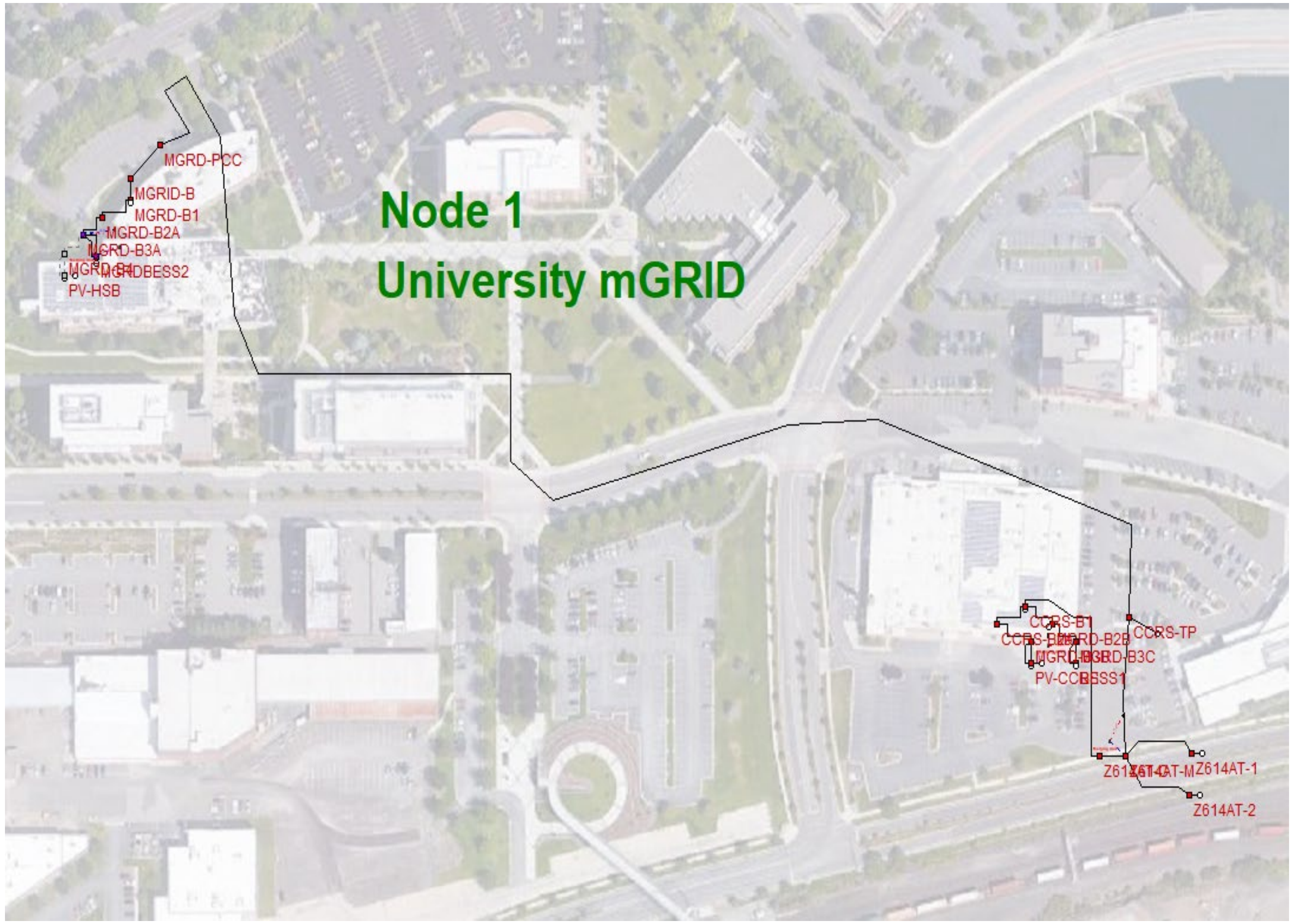
All of this is possible today

Option 2 Two Node System (Microgrid + EcoDistrict) Plus the Master Node (Node 0)

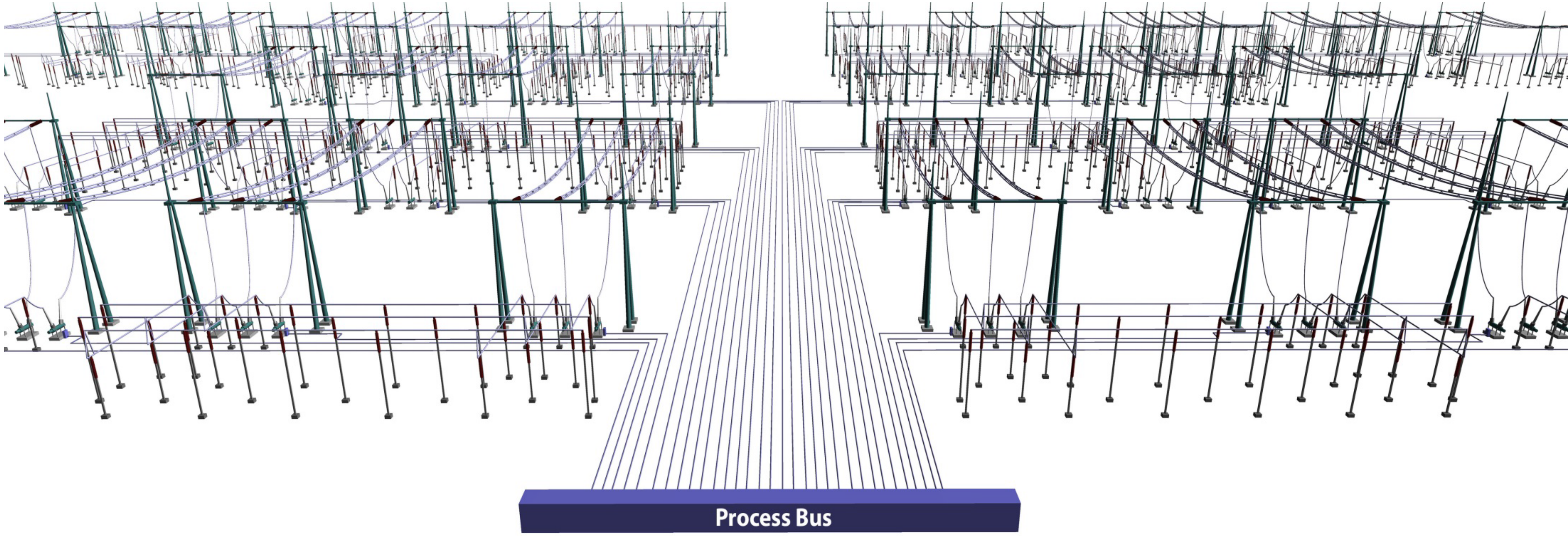




Laboratory Setup: Node 1



Inertia Meter: Real-Time Frequency Response Meter



Importance of Frequency Response

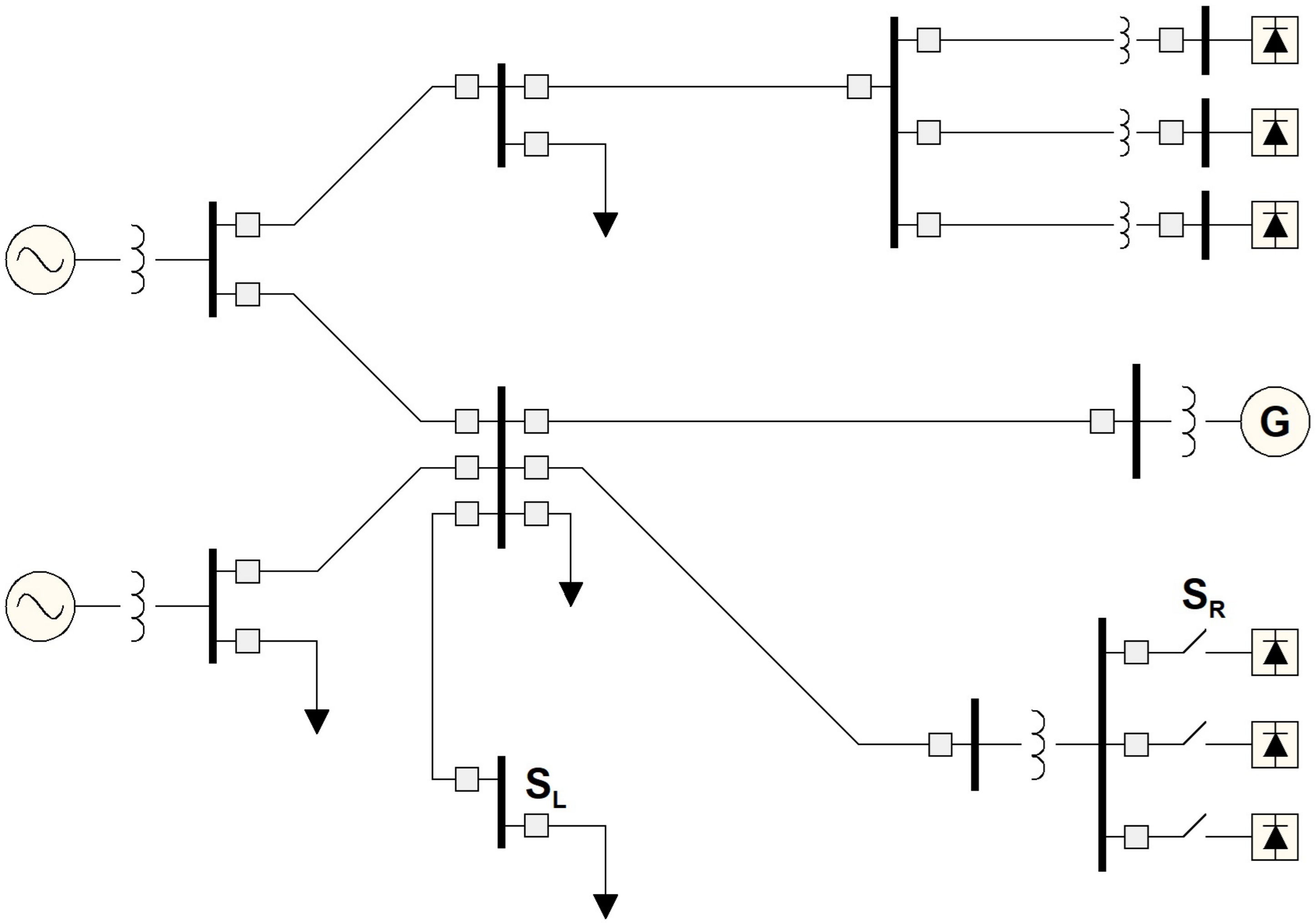
A very important issue affecting system operations and reliability.

It affects operation of renewables who are inverter-based resources. Sudden changes in frequency affect the operation of the controller, increase probabilities of misfiring and shutting down operation.

There is concern that sudden changes in frequency can cause massive imbalances in IBR dominated power systems.

Inertia Meter: Real-Time Frequency Response Meter

The Experimentalist Approach



- Apply disturbance: Open **SL** or open **SR**
- Measure frequency at all substations.
- Report frequency response

Problem:

Frequency measurement with practical disturbances is unreliable

Example: for my local utility I need a disturbance of 4,000 MW to cause a frequency deviation of 100 mHz.

Inertia Meter: Real-Time Frequency Response Meter

Model Based Approach

Use model of the system to compute frequency response:

Models should include: (a) generators with exciters and governor models, dead-bands, frequency dependent and their controls, (b) inverter models with their controls – both continuous and triggered controls, (c) all models should be high fidelity.

Advantages: Analysis can provide:

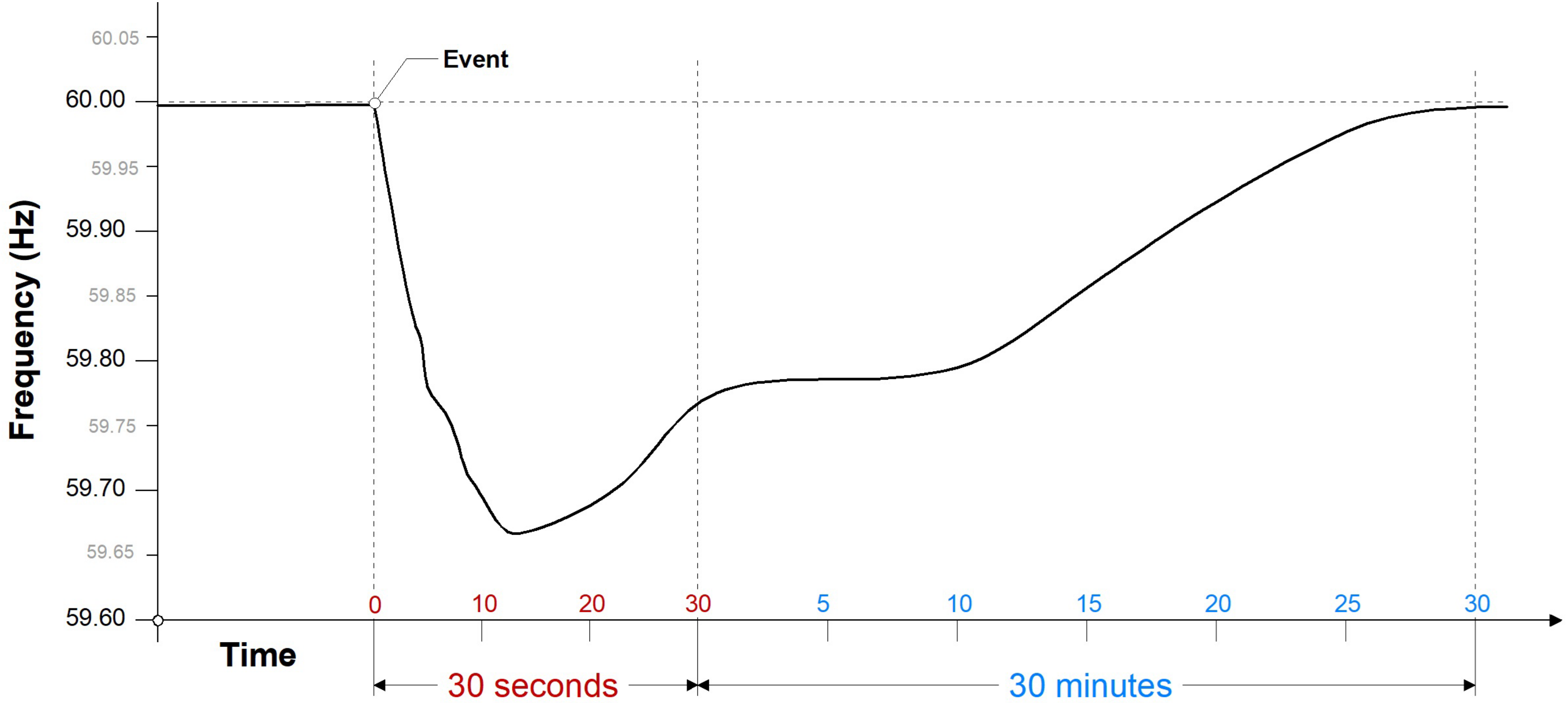
(a) Small signal frequency response, and
(b) Large scale frequency response

Important Issue: Model must be valid, accurate and real time

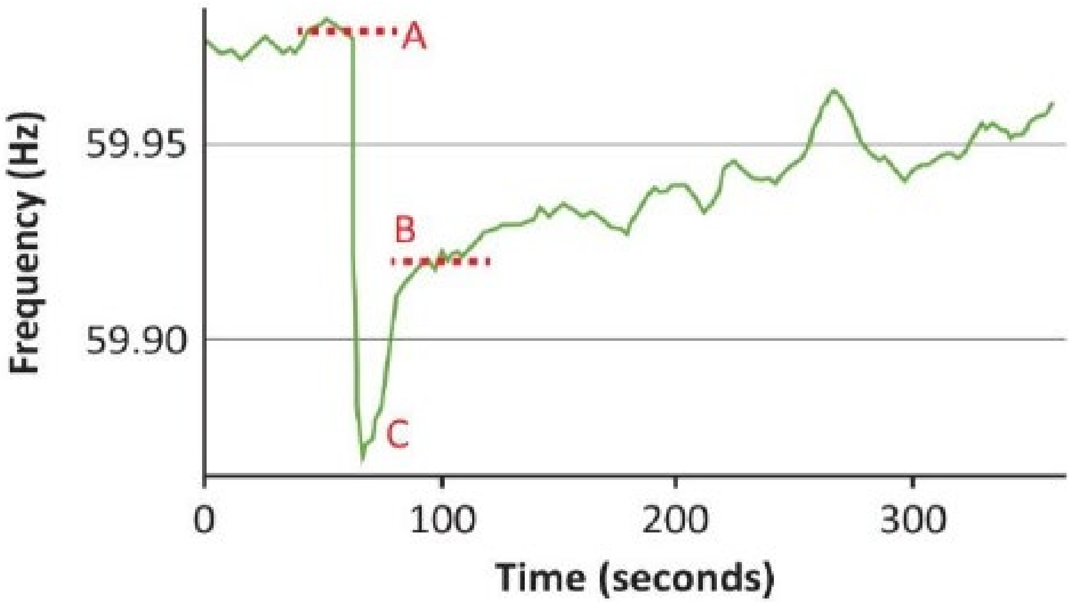
***Note**: Described system provides this information*

Typical Frequency Response using this Method

Model Based Approach

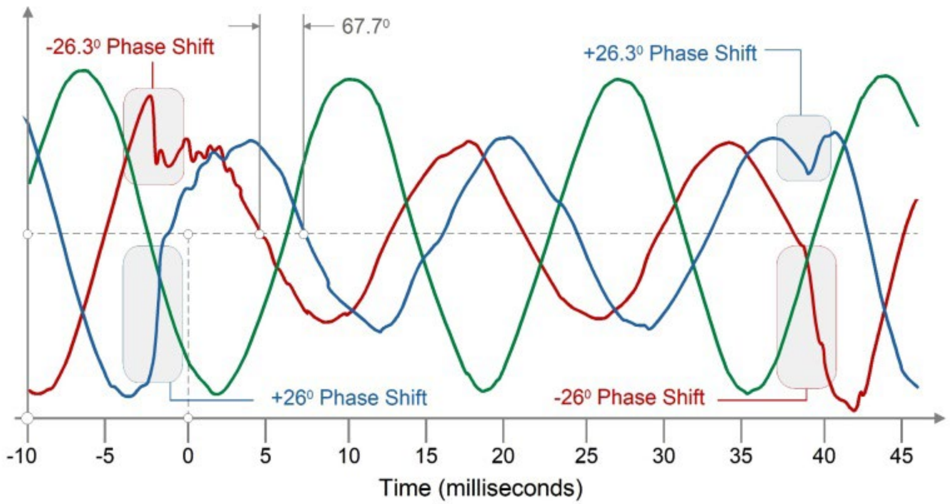


Post-Mortem Recreation of the Frequency Response
Model Based Approach



Note a 110 mHz deviation for a 1300 MW loss of renewables and an unknown imbalance caused by the fault.

Note a phase shift during the fault condition. The phase shift had a negative effect of the inverter controllers.



Inertia Meter: Real-Time Frequency Response Meter

Model Based Approach

This is a straightforward application of the digital substation

This is Dipylon (two leaf door)

Imagine it.

If you wanted to visit Athens in ancient times, you have to enter Athens here.