

The Smart Grid Opportunity: from Automation to Autonomy



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Observations

Energy and Especially Electric Energy is the Fuel of Modern Economic Activity

Increased Energy Prices and Environmental Issues Have Elevated Energy Issues Among Top Concerns of Society

Electric Grid Failures Make News

Coal/Nuclear Closures and Increase of Renewables Make News

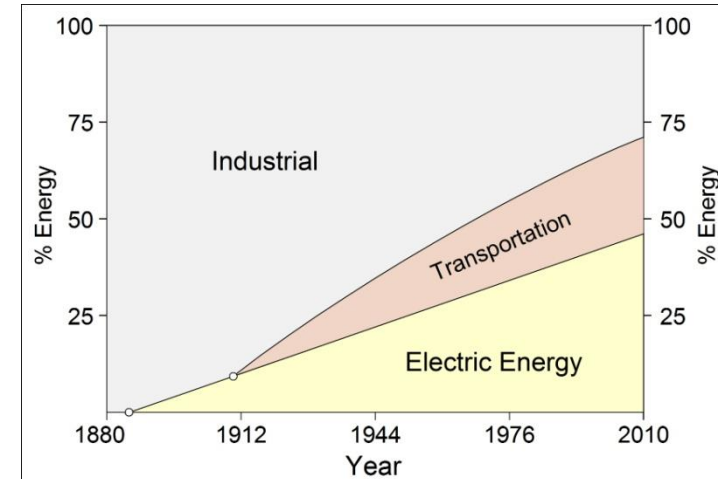
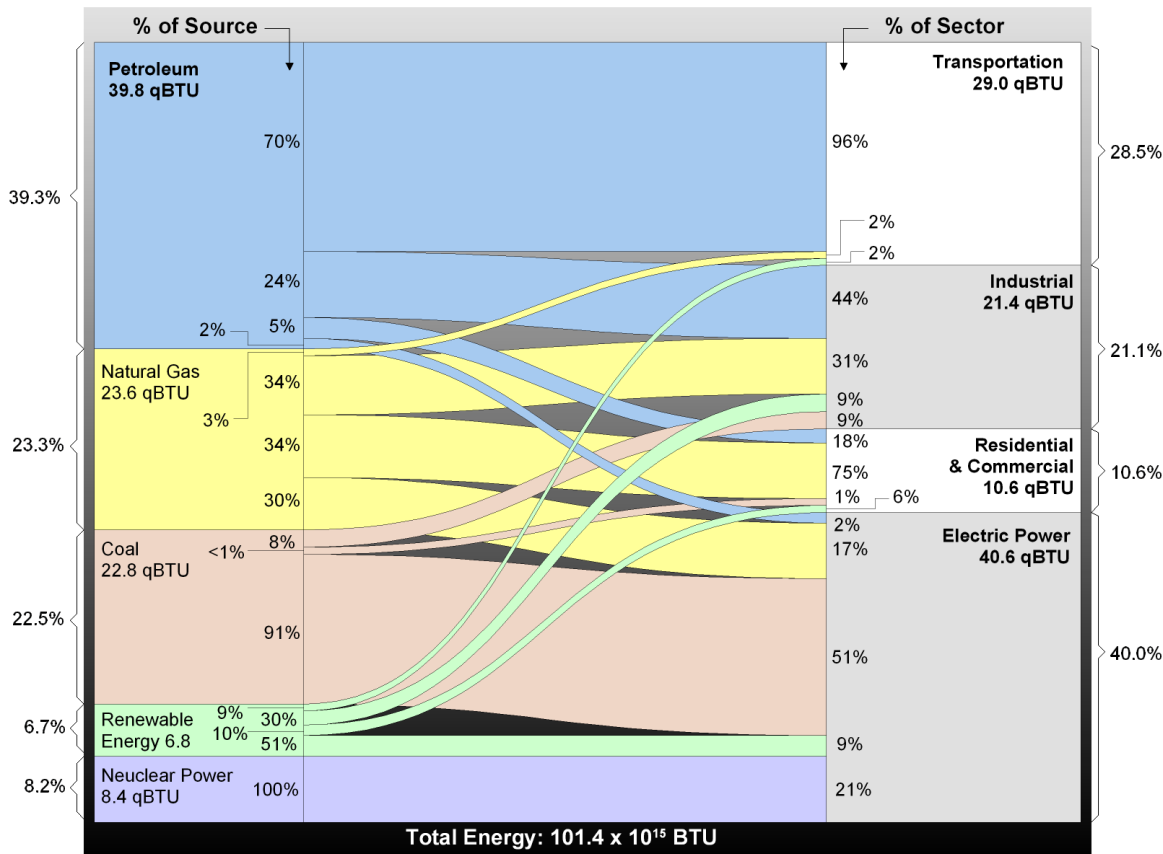
The Smart Grid is an Effort to Develop Enabling Technologies for:

- Increased Efficiency
- Increased Reliability
- Friendly Infrastructure for Renewable Resources



The Big Picture

Energy in 2007 (US DoE)



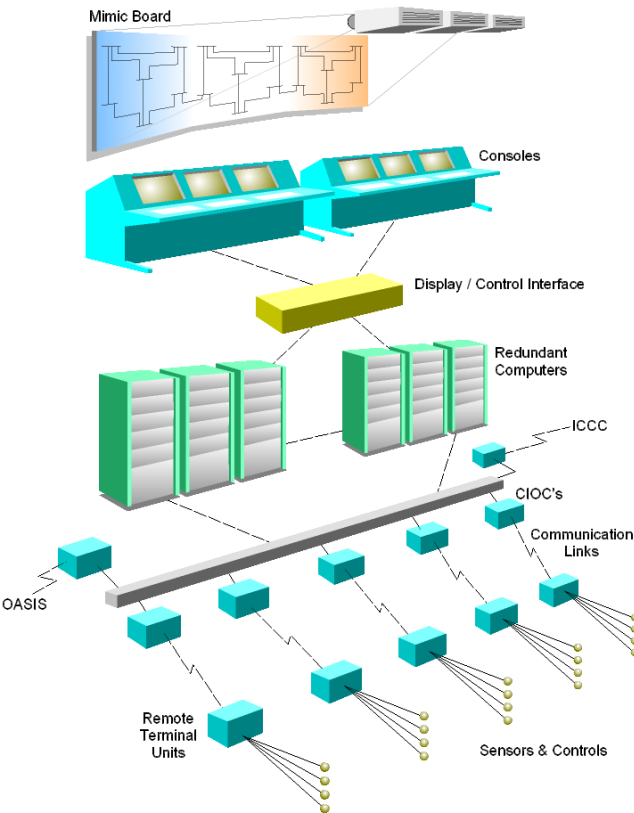
The US Electric Power Grid:

1,000,000 MW, Plus 350,000 MW customer owned
 Supplies 40% of total US energy consumption
 (about 40.6 quads = 11.9 Billion MWhrsT, 3.5 Billion MWhrsE)



Modern EMS: Present State of the Art: C&O and P&C

Control & Operation



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

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

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

Protection & Control

Component Protection

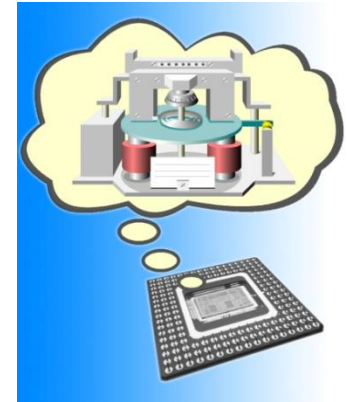
generators, transformers,
lines, motors, capacitors,
reactors

System Protection

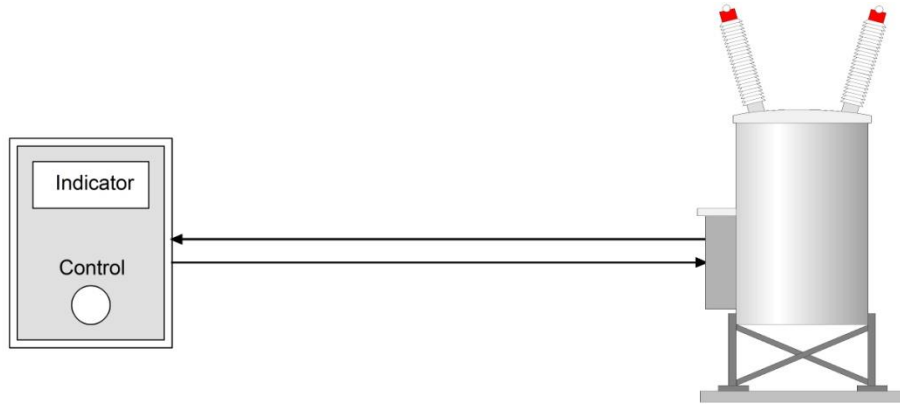
Special Protection
Schemes, Load Shedding,
Out of Step Protection, etc.

Communications

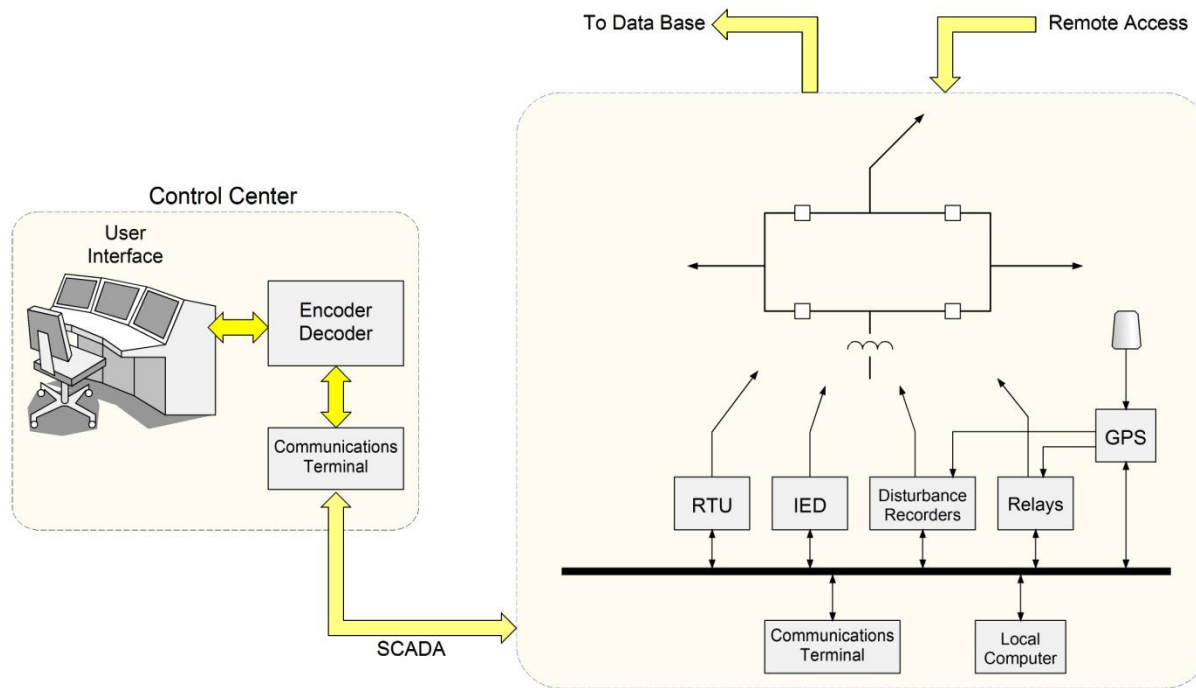
Substation Automation,
Enterprise, InterControl
Center



Role of Technology: SCADA Evolution



SCADA circa 1923

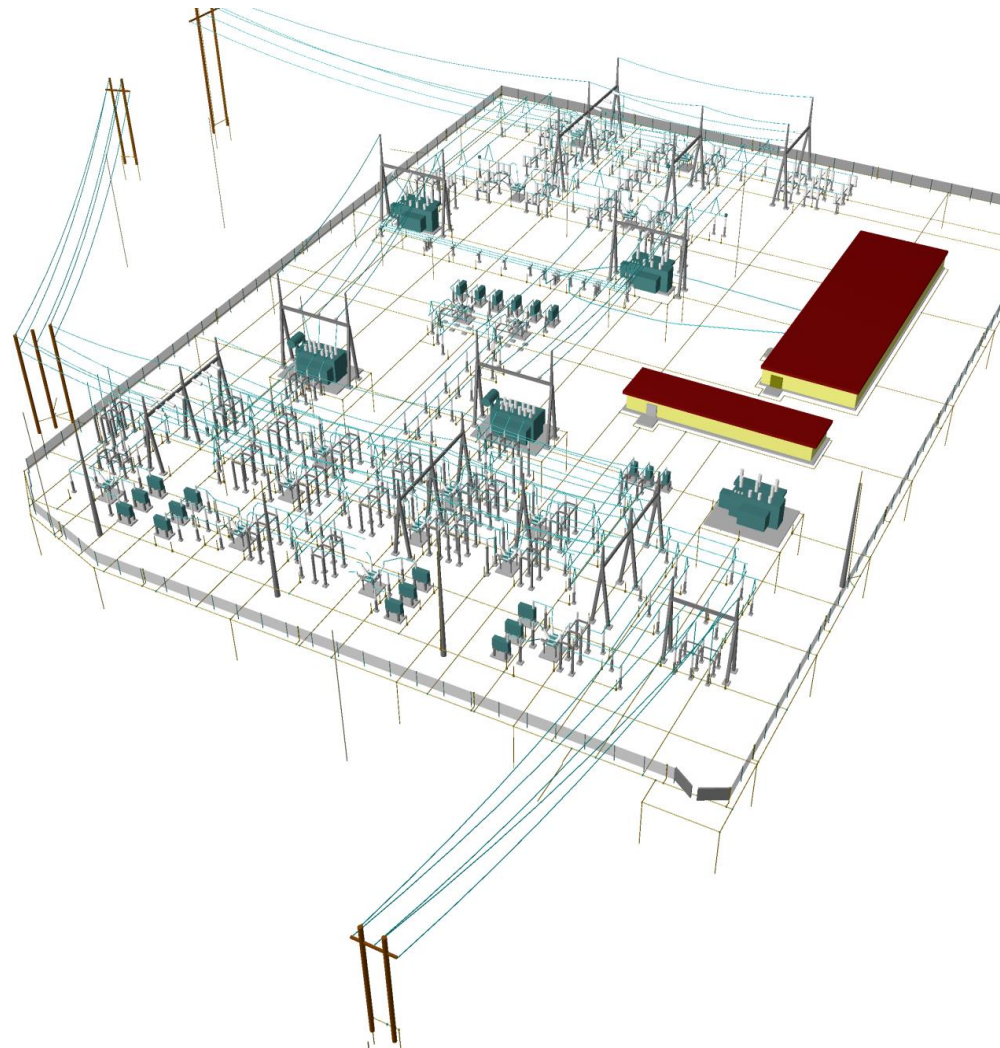


SCADA circa 2000

Communication Standards

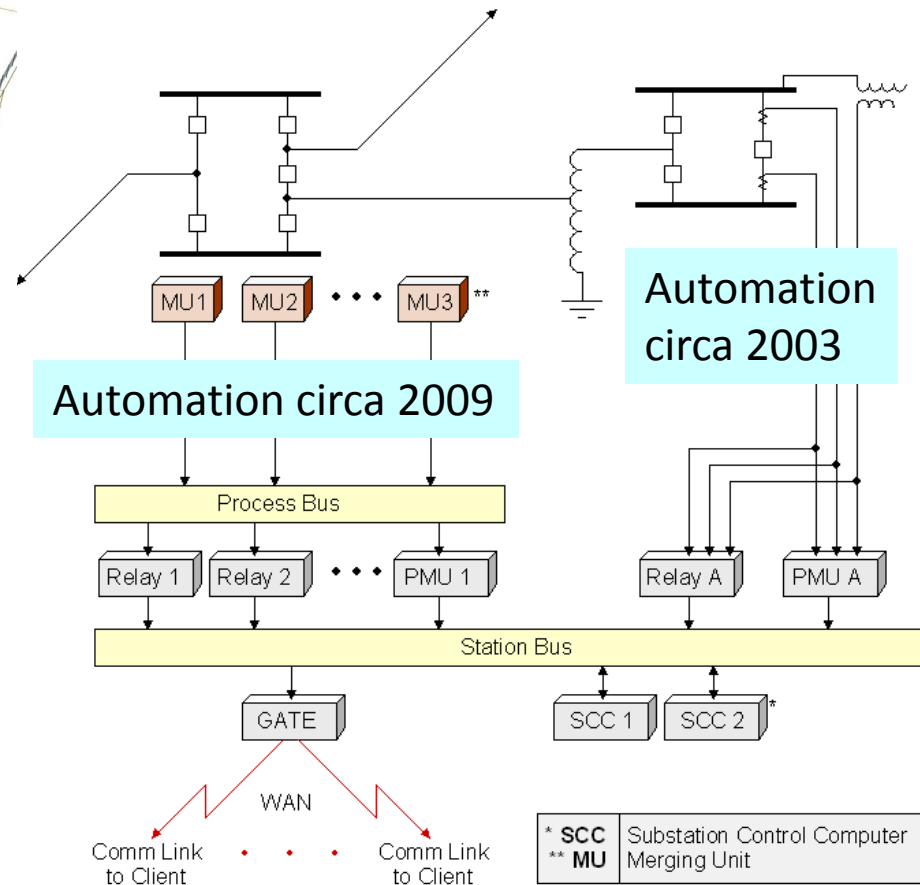


Present State of the Art: Smart Grid Infrastructure



Physical System

Protection, Control, Communications

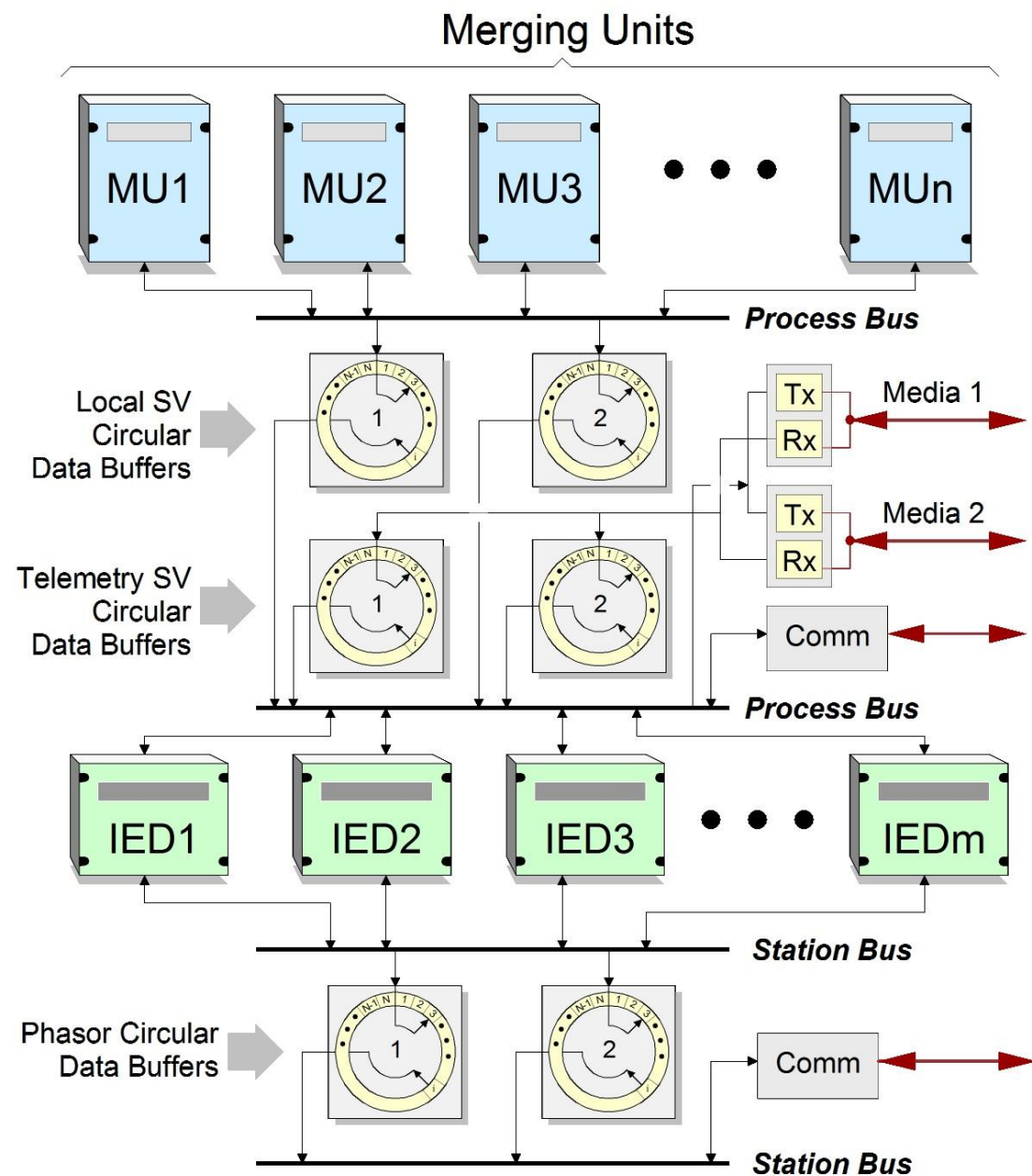


Near Future (now):

The Digital Substation

Data Acquisition Separated from Computing Devices

Analysis, Protection, Control & Operation in Cyber Space

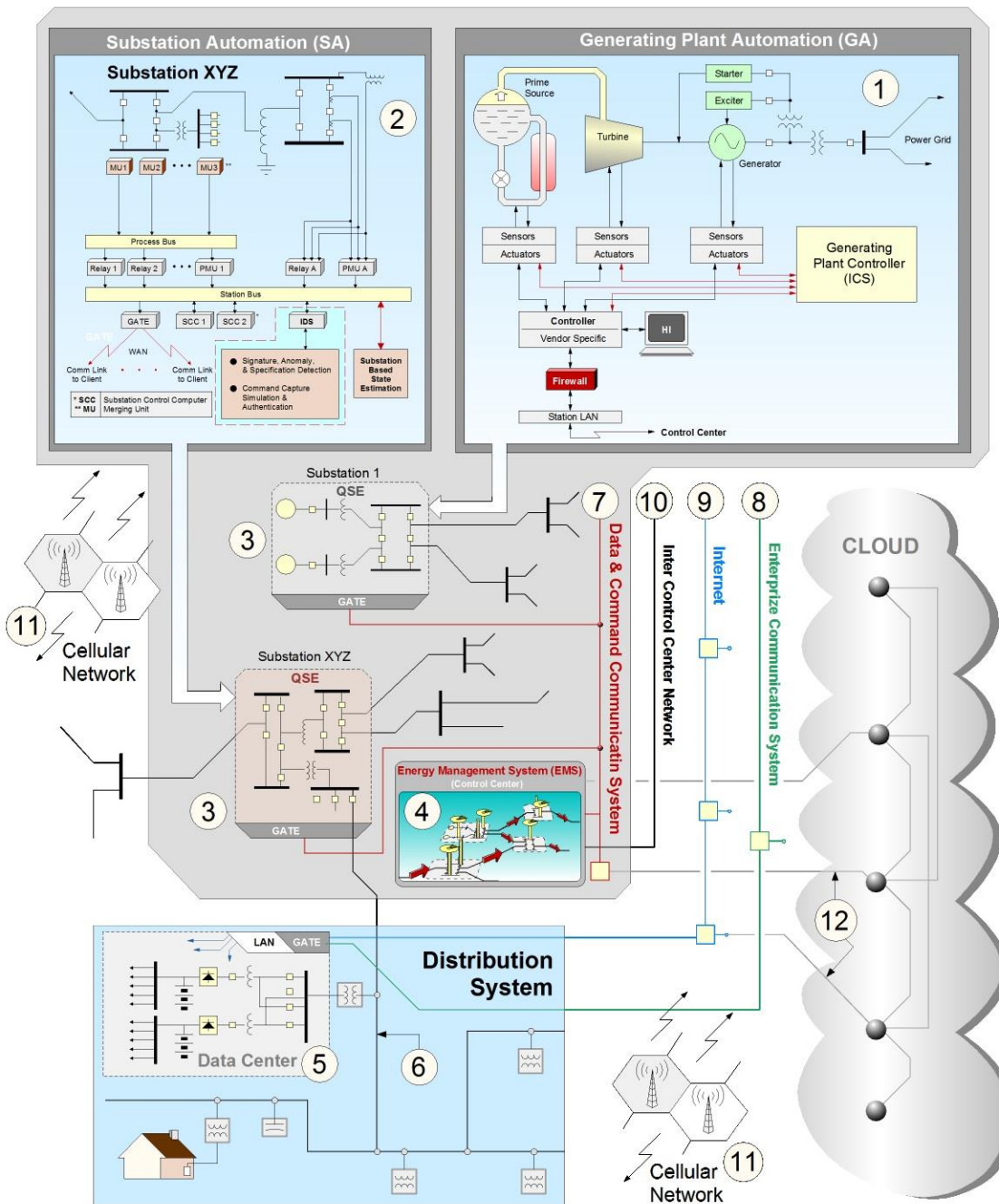


The Power System Cyber Landscape

Attacks Have Occurred Vulnerabilities Identified

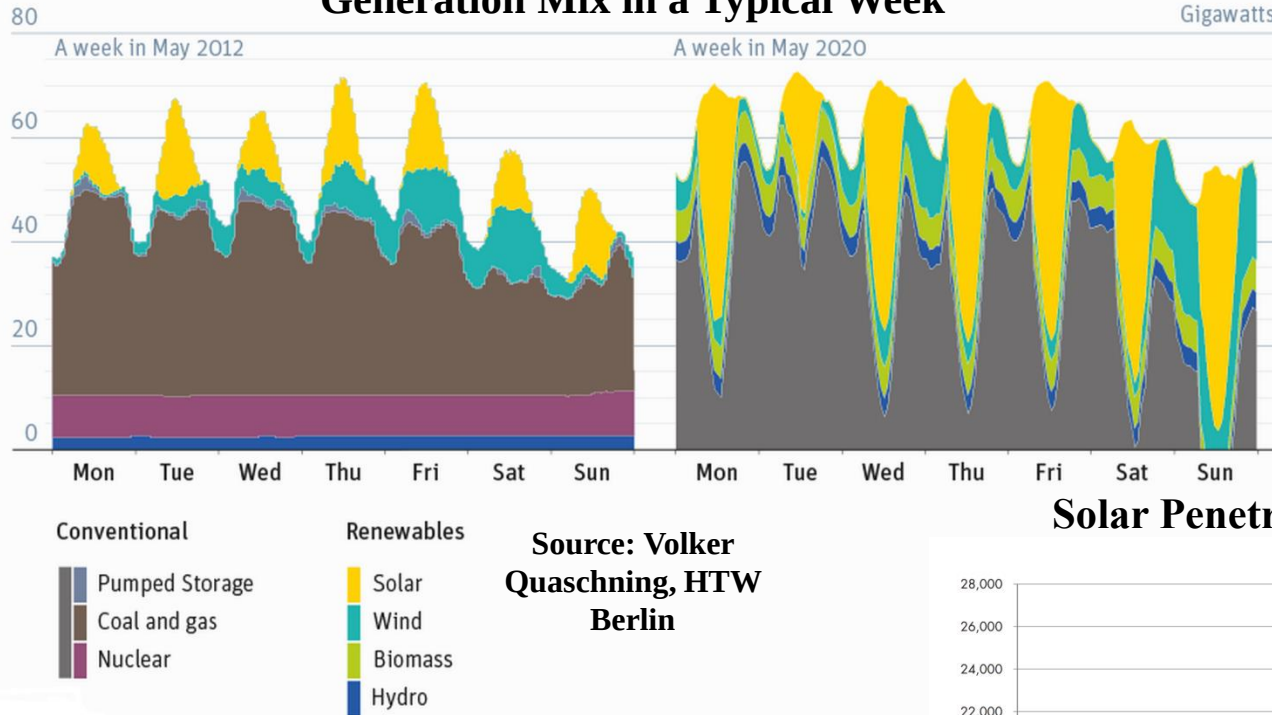
Aurora
Data/Settings Attacks
Malicious Commands
Etc.

Defenses are Developed



Challenges from Renewables

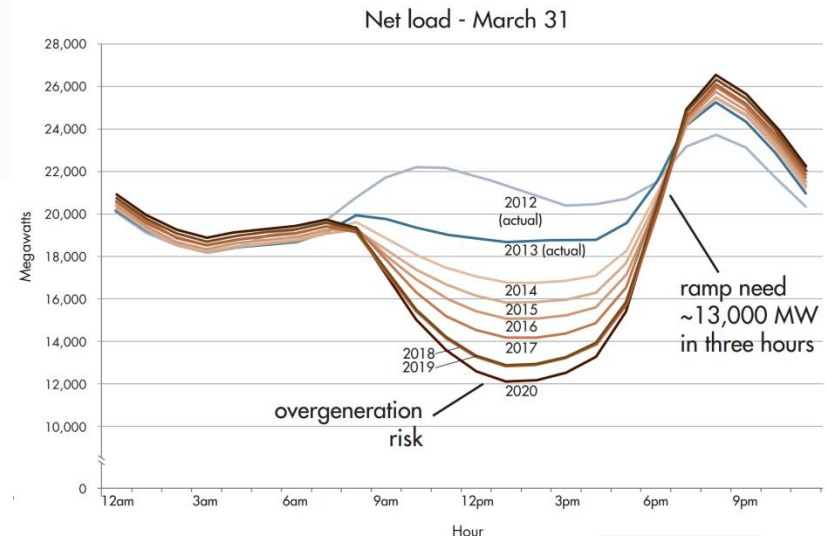
Generation Mix in a Typical Week



Need to rethink operational paradigm

1. Generation serving load
2. Load adjusting to generation

Solar Penetration: “Duck Chart”



Source: CAISO, “The Duck Curve”

Effects of changing generation mix

- Short, steep ramps
- Risk of over/under-generation
- Increased thermal unit cycling
- Decreased Frequency Response



The Renewable Challenge is Serious

It makes “business as usual” unworkable. “Business as Usual:” Balance Load by Generation

Recognition of New Need: Use end-use resources (customer) to help balance generation-load. Load contributes to balancing. Approaches:

- Demand Response (incentives, signal based)
- Coordinated Control (no customer inconvenience)

Customer Resources: Enough to Do the Job. Problem: Too Many, Too Small → need automation/autonomy



Transmission

Cost of Automation is Justified → Next Gen EMS

Distribution

Cost of Automation is Prohibitive → ADMS

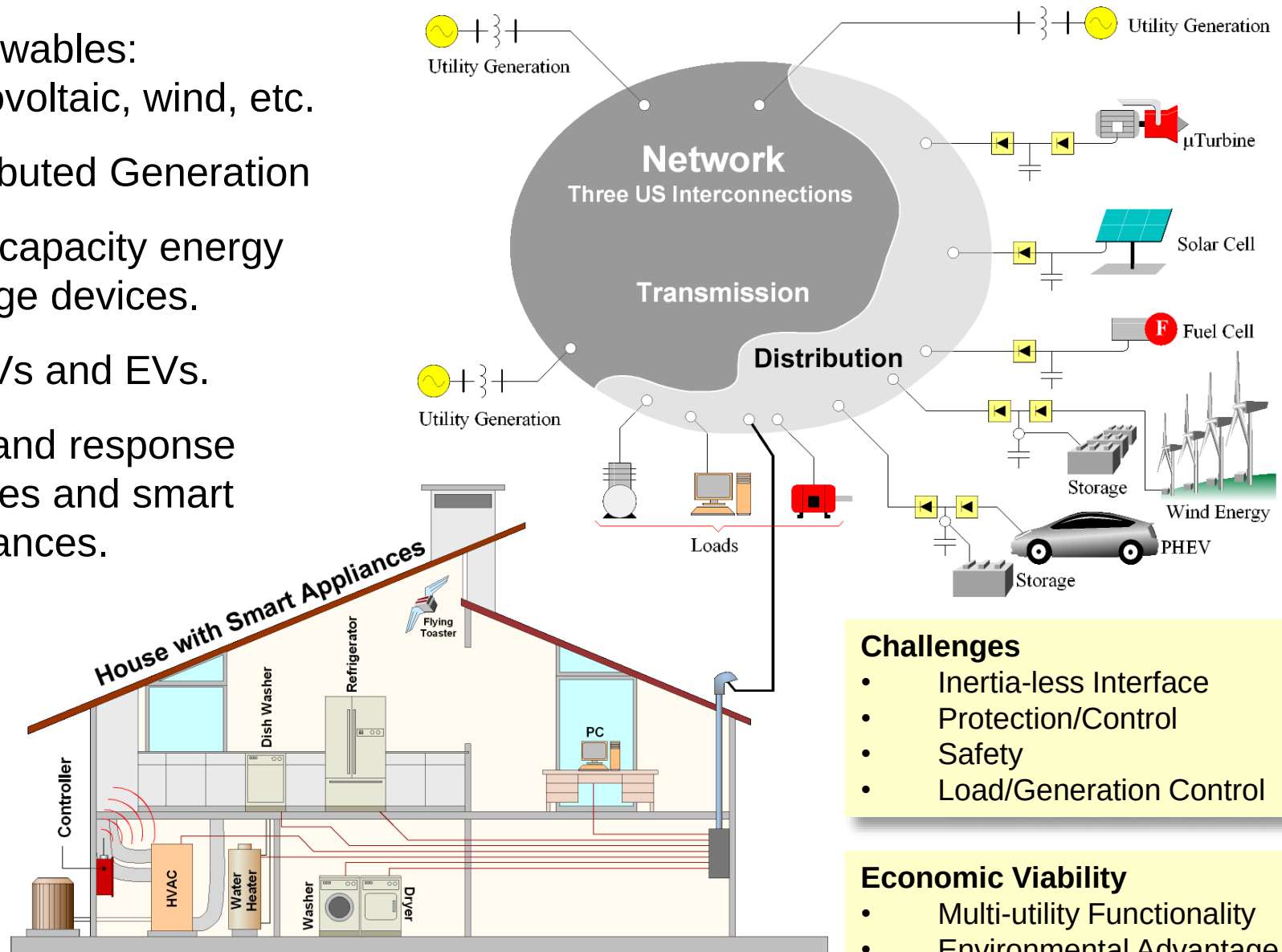
Renewables & Customer Resources, a New
Driving Force

Promising Approach → Autonomy



The Future Grid: Available Enabling Technologies

- Renewables: photovoltaic, wind, etc.
- Distributed Generation
- High capacity energy storage devices.
- PHEVs and EVs.
- Demand response devices and smart appliances.



Challenges

- Inertia-less Interface
- Protection/Control
- Safety
- Load/Generation Control

Economic Viability

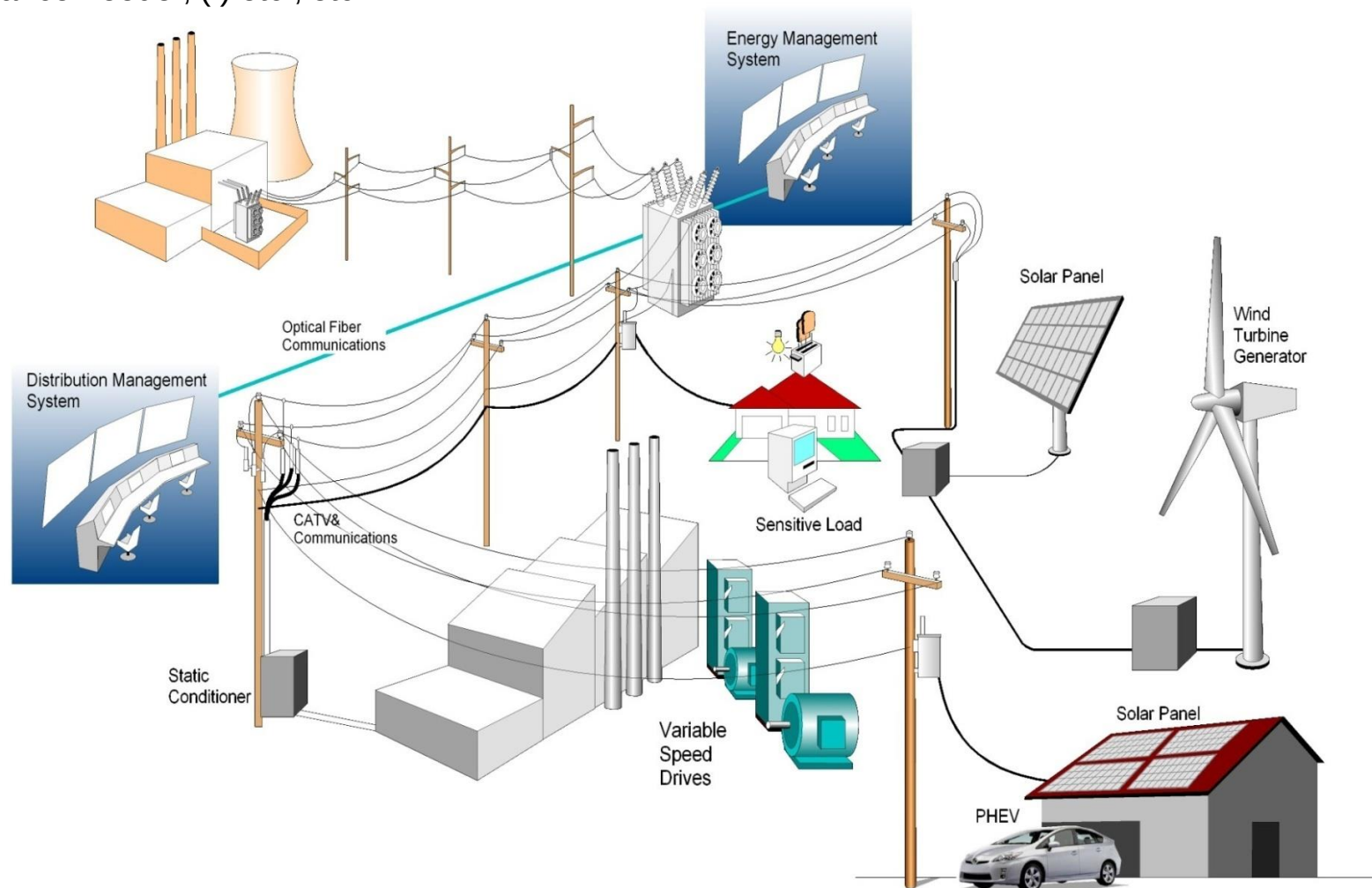
- Multi-utility Functionality
- Environmental Advantage



Active Future Distribution Systems (with distributed energy resources – solar, wind, PHEVs, fuel cells,...).

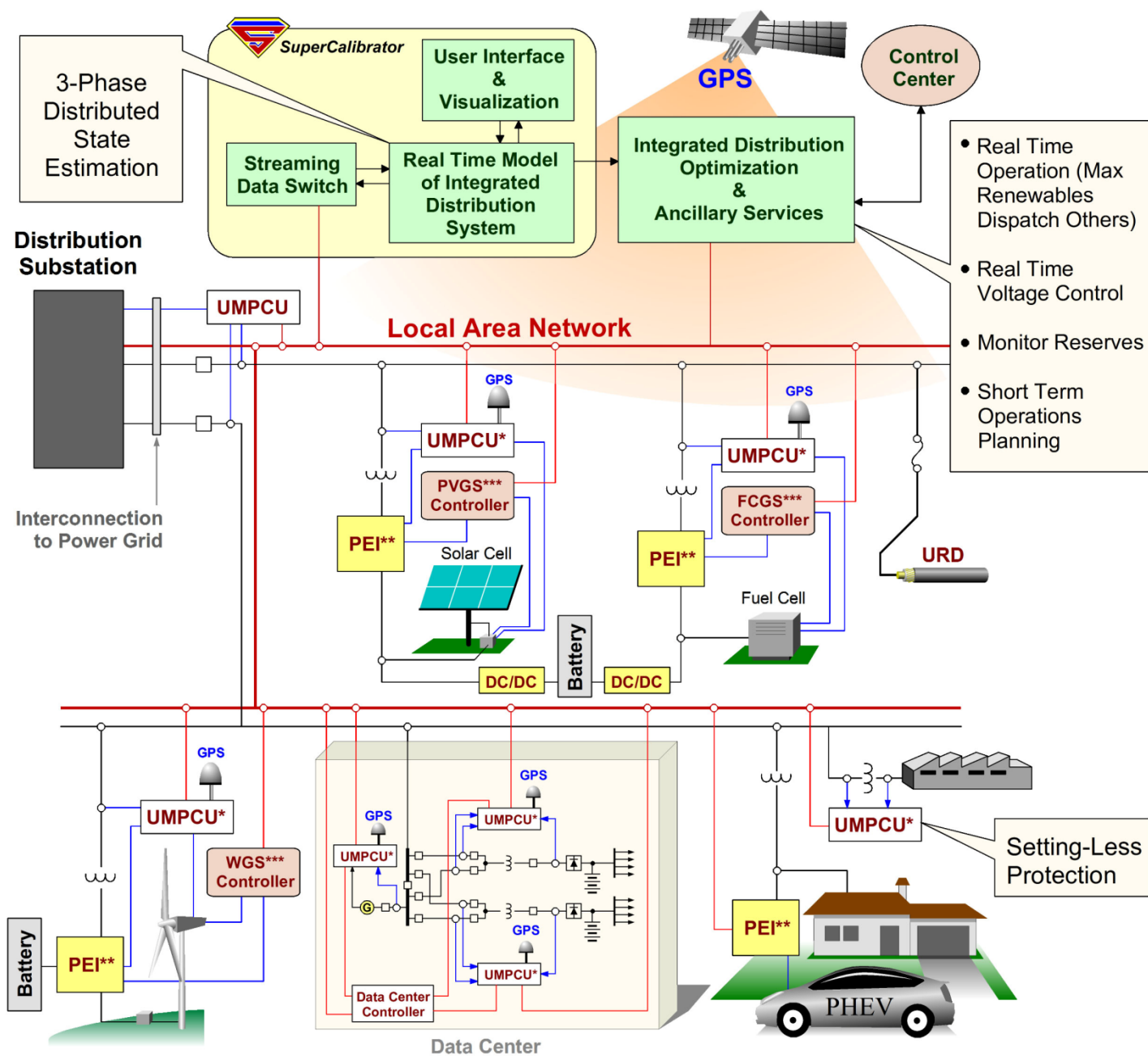
Smart Grid technologies: Distributed Monitoring, Control, Protection and Operations system. Target Speeds 10 times per second

Functions: (a) Optimal operation of the distribution system under normal operating conditions, (b) Emergency management in cases of faults and assist the power grid when needed, (c) Assist Voltage recovery, (d) Assist cold load pickup, (e) Balance Feeder, (f) etc., etc.



Design For Autonomy

Plug
and
Play...



Requirements for Autonomy

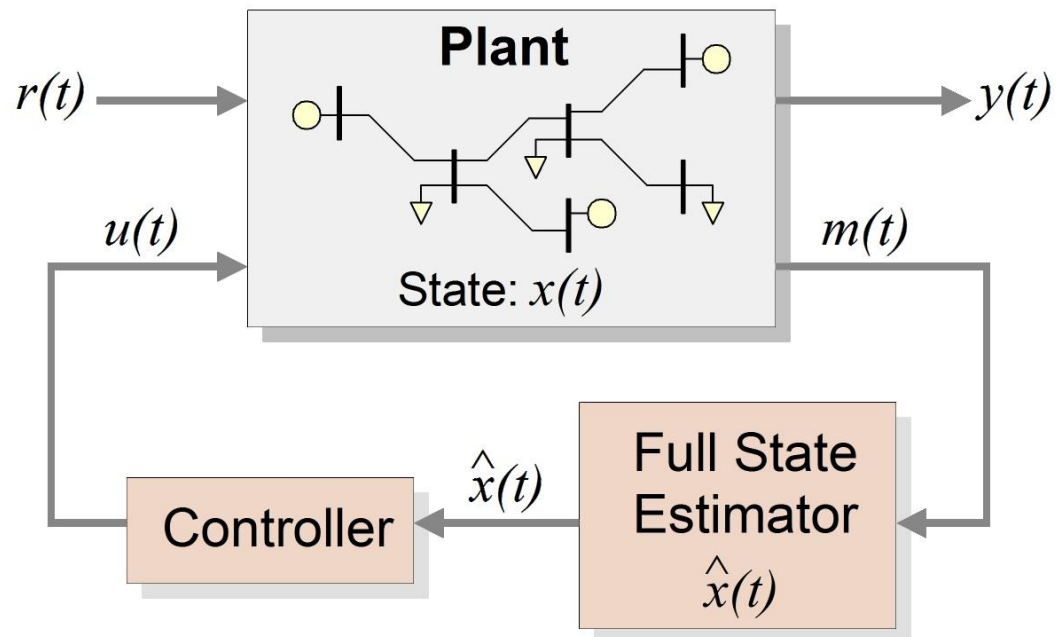
- **Autonomous Extraction of Real Time Model and State**
 - Setting-less Protection
- **Self Regulating**
 - Autonomous Frequency Control,
 - Autonomous Voltage Control
 - Other (Contractual Obligations, Environmental Control, etc.)
- **Self Managing (Operations Planning)**



Autonomous Extraction of Real Time Model and State

Power System Control and Operation: Model based Control

Basic Principles: Full State Feedback Control

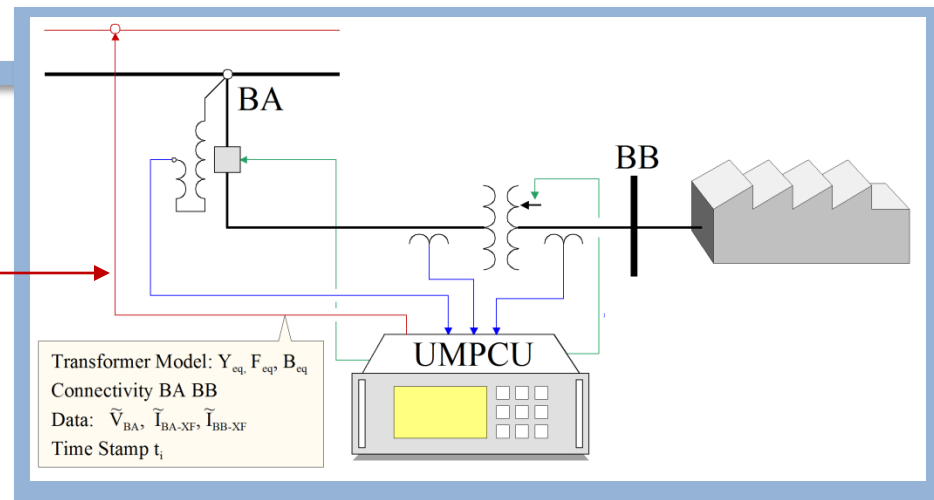
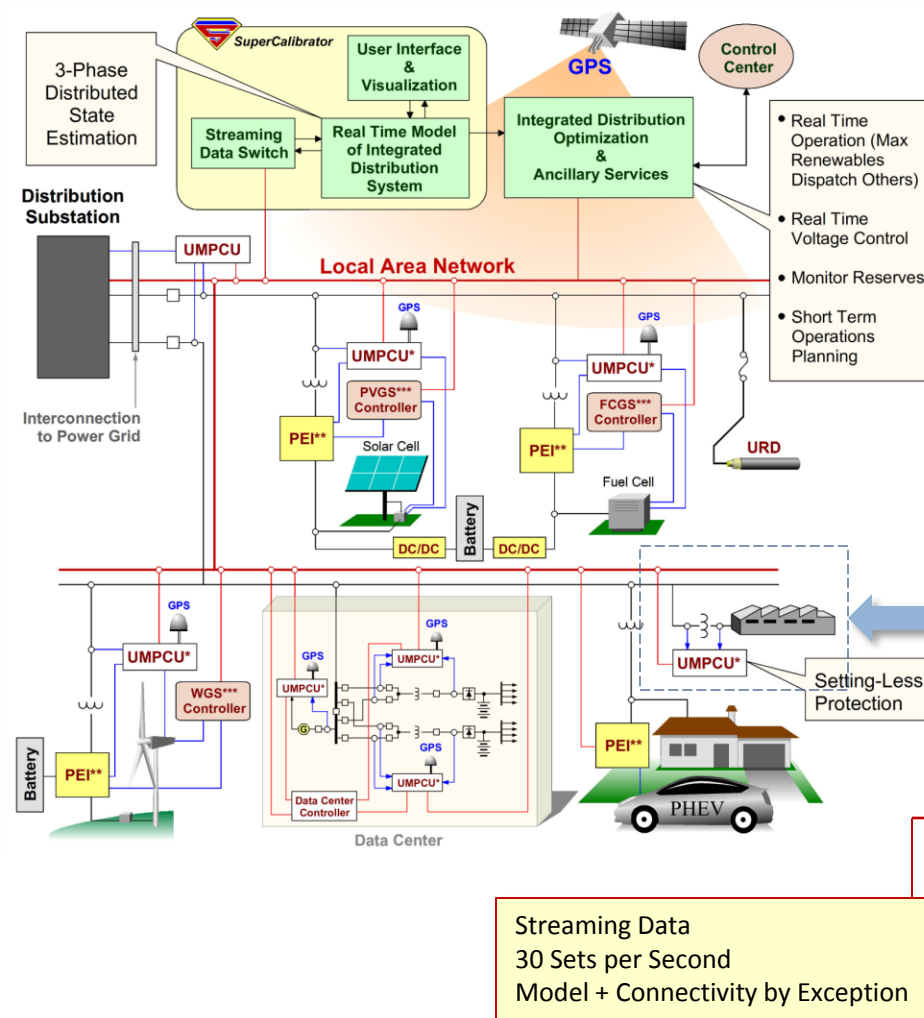


Autonomous State Estimation

Each component is equipped with what we named UMPCU (Universal Monitoring, Protection and Control Unit – high end relays with PMU capability can be programmed to provide these functions).

The UMPCU is a GPS synchronized data acquisition unit equipped with the capability to transmit via a physical communication layer the following information for the device that monitors:

- **device model,**
- **device measurements (in streaming fashion) and**
- **device connectivity information (connection pnt).**

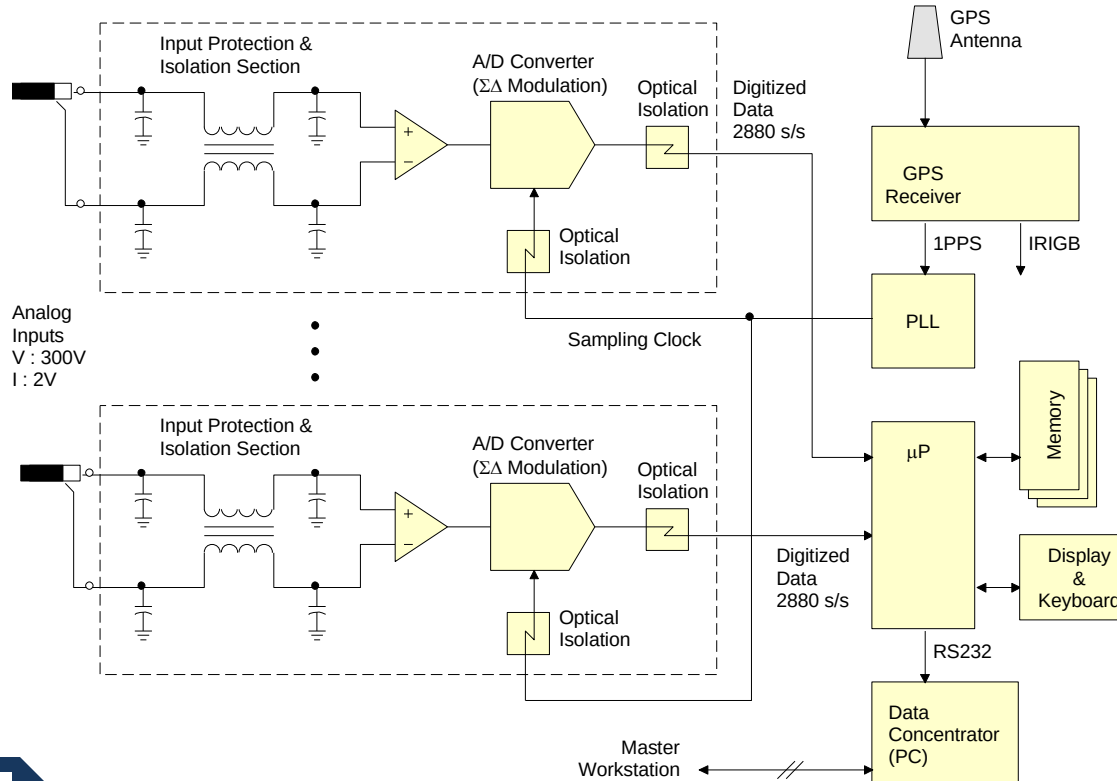


Enabling Technology

Macrodyne 1620 PMU

Released to Market January 1992

Jay Murphy (Macrodyne) Was First to Introduce
Term PMU: Phasor Measurement Unit



CHARACTERISTICS

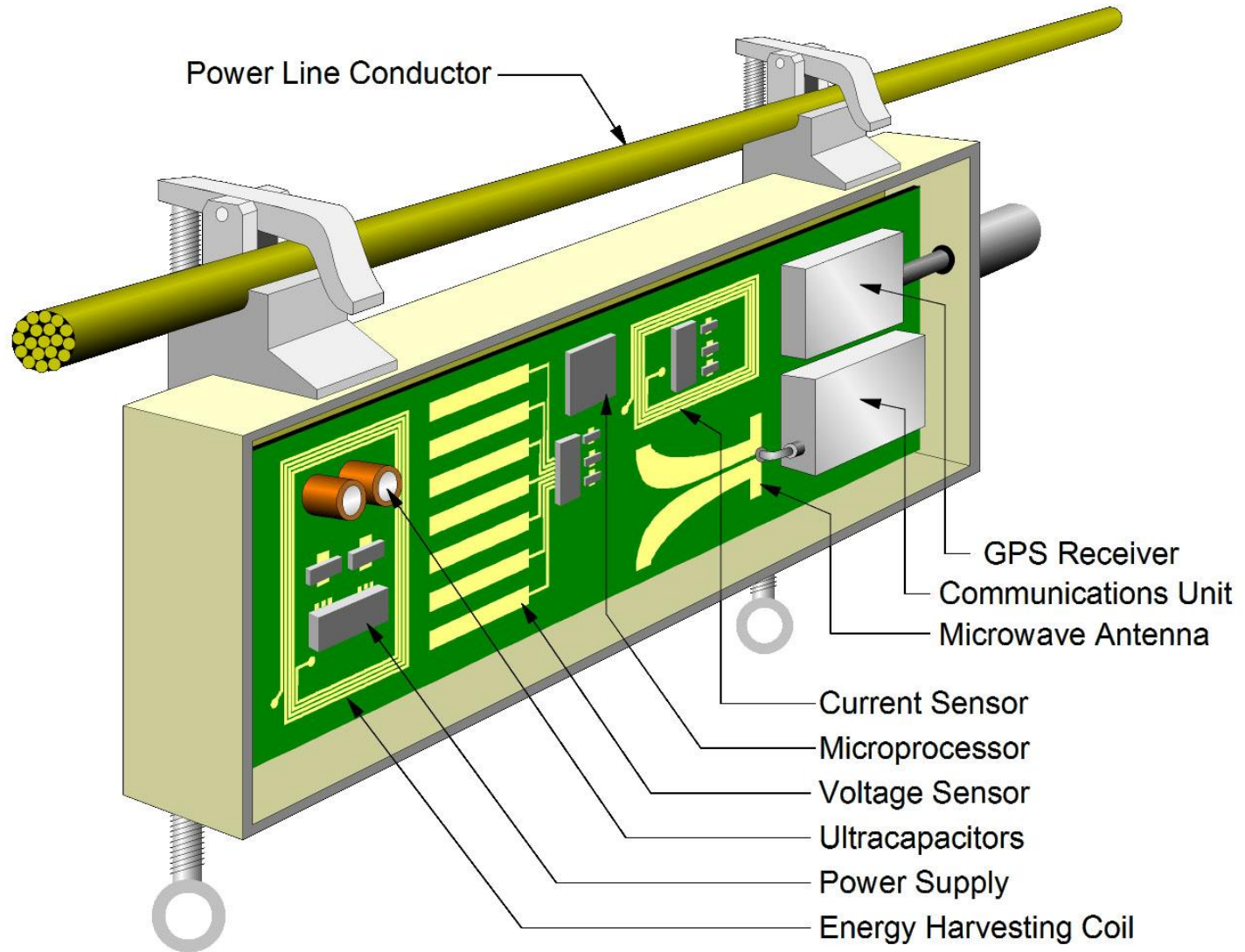
- Individually GPS Sync'd Channels
- Common Mode Rejection Filter with Optical Isolation
- 16 bit A/D $\Sigma\Delta$ Modulation

Time Accuracy 1 μ s
0.02 Degrees at 60 Hz



Other Realizations: The UMPCU

Universal Monitoring, Protection and Control Unit

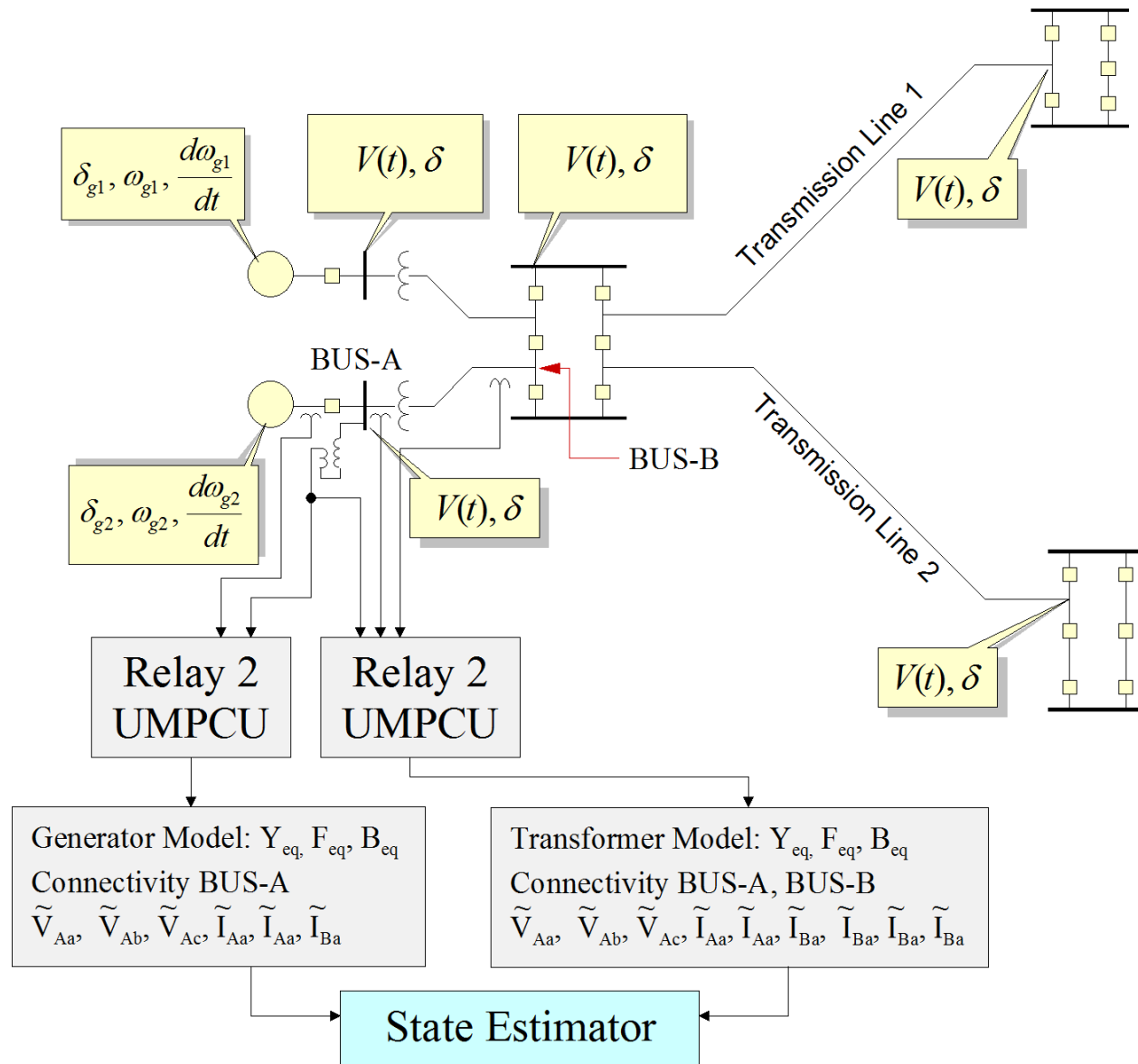


This is one possible implementation of the UMPCU

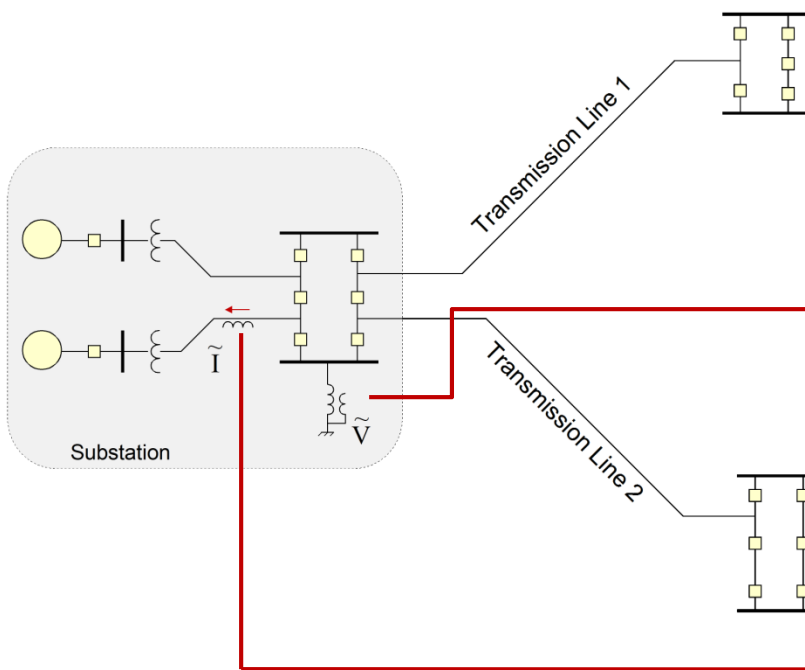
Georgia Tech Disclosure, 2009



Example Of Relay → State Estimator Data Flow



Object Oriented QSE



Across (Voltage) Measurement:

$$\tilde{z}_j(t) = \tilde{x}_j(t) + \eta_j$$

Through (Current, Torque, etc.) Measurement:
Measurement $\tilde{z}_j(t)$ represents a quality associated with one row of the Object oriented model

$$\tilde{z}_j(t) = \text{row } k \text{ of Object Oriented Model} + \eta_j$$

Object Oriented Model

$$\begin{bmatrix} \tilde{I}(t) \\ 0 \\ \tilde{I}(t_m) \\ 0 \end{bmatrix} = Y_{eq} \begin{bmatrix} \tilde{V}(t) \\ \tilde{Y}(t) \\ \tilde{V}(t_m) \\ \tilde{Y}(t_m) \end{bmatrix} + \begin{bmatrix} \tilde{V}^T(t) & \tilde{Y}^T(t) & \tilde{V}^T(t_m) & \tilde{Y}^T(t_m) \end{bmatrix} \cdot F_{eq} \cdot \begin{bmatrix} \tilde{V}(t) \\ \tilde{Y}(t) \\ \tilde{V}(t_m) \\ \tilde{Y}(t_m) \end{bmatrix} - B_{eq}$$

Row k

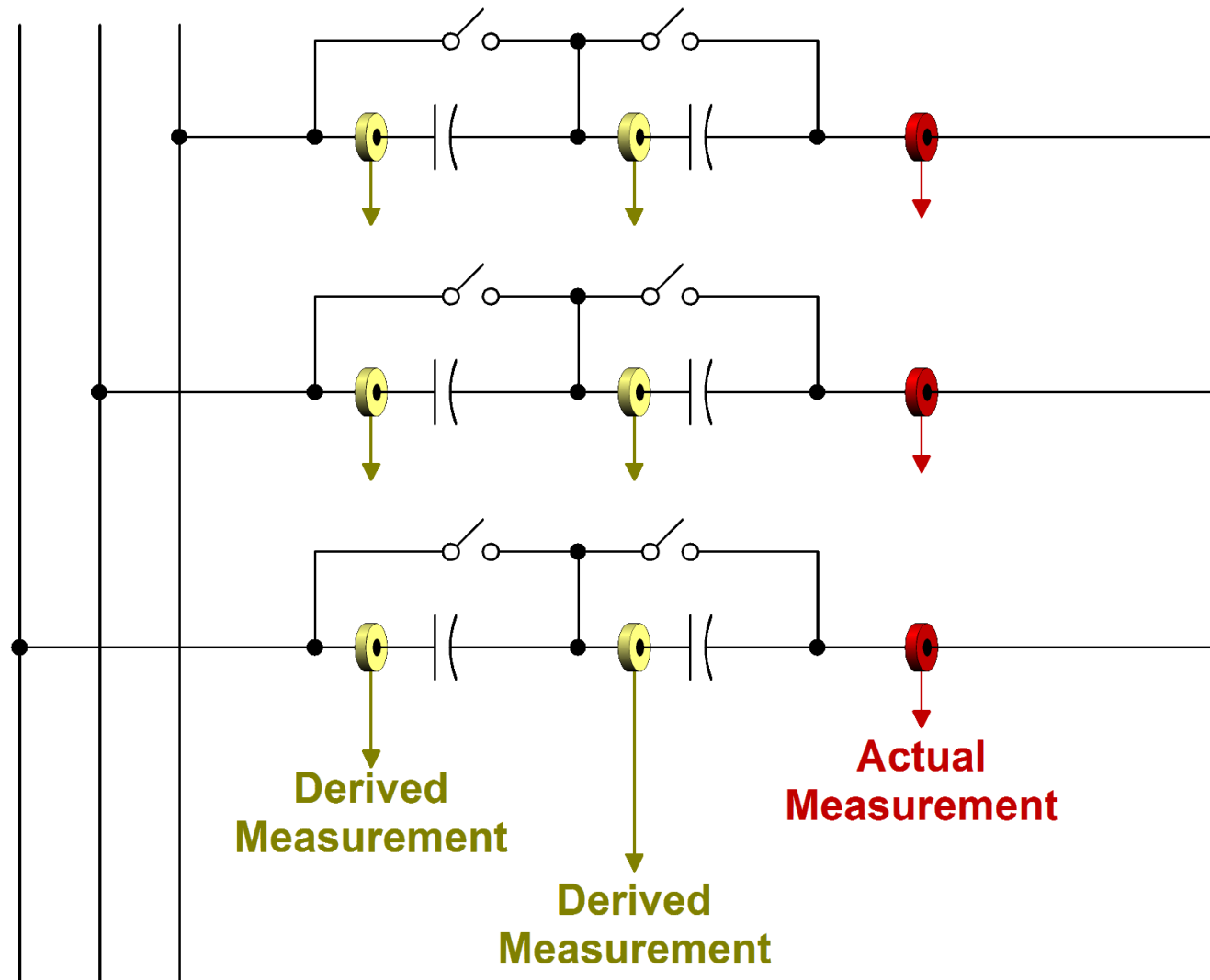
QSE states are
Phasors, Speed, etc

$$\text{where } B_{eq} = \sum_i A_i \cdot \begin{bmatrix} \tilde{V}(t-i \cdot h) \\ \tilde{Y}(t-i \cdot h) \end{bmatrix} + \sum_i B_i \cdot \begin{bmatrix} \tilde{I}(t-i \cdot h) \\ 0 \end{bmatrix} + C$$



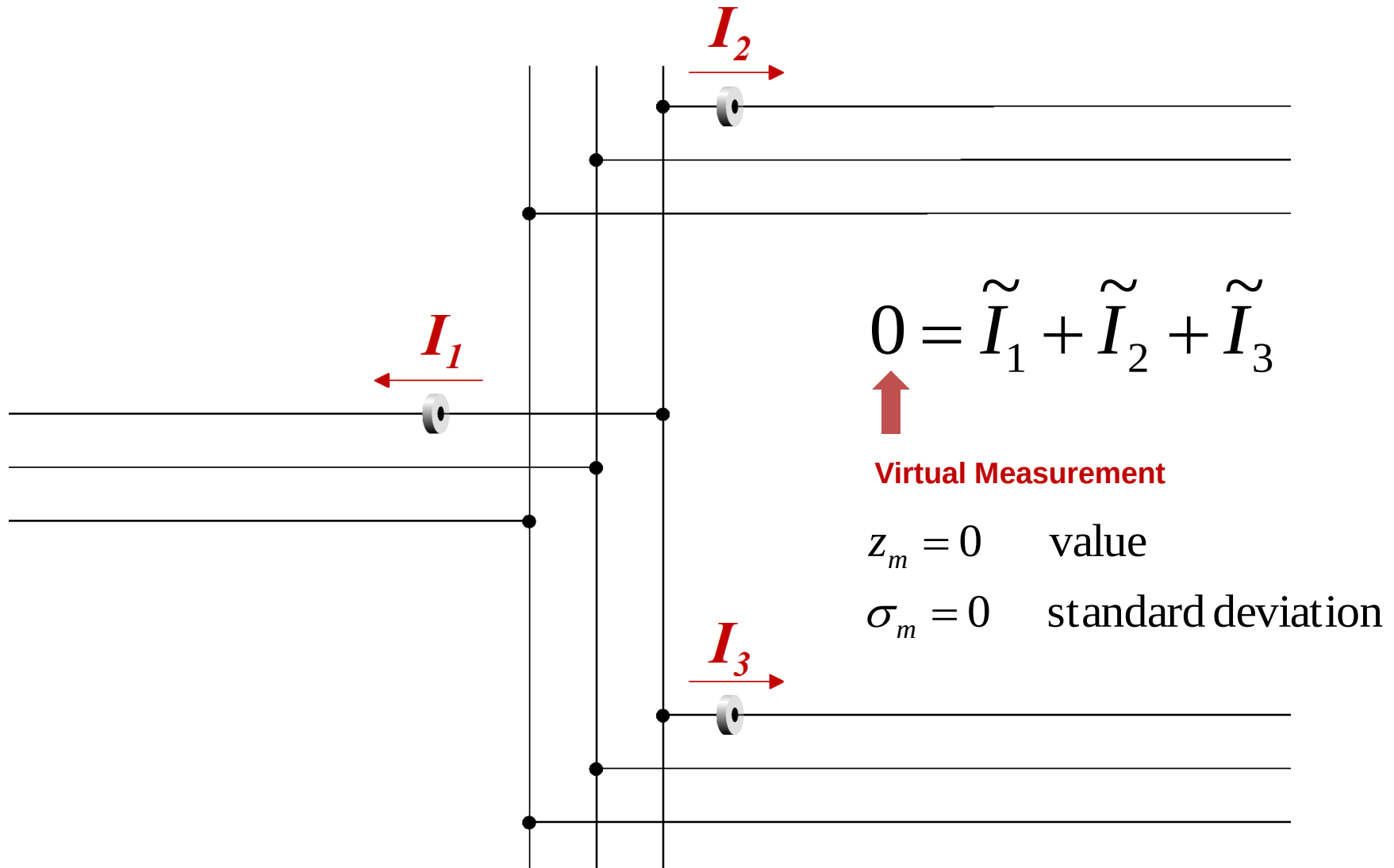
DSE: Autonomous Addition of Derived Measurements

Derived Measurements - Examples



DSE: Autonomous Addition of Virtual Measurements

Virtual Measurements - Examples



Autonomous DSE: Synchronization of Non-Synch Measurements

Non-GPS Synchronized IEDs provide phasors referenced on “phase A Voltage”. The phase A Voltage phase is ZERO. Same issue with PMUs that lost GPS clock.

The Autonomous DSE provides a reliable and accurate estimate of the phase A voltage phase.

$$\tilde{A}_{sync} = \tilde{A}_{meas} e^{j\alpha}$$

$$\begin{aligned} \tilde{A}_{sync} &= \tilde{A}_{meas} e^{j\alpha} = \\ &A_{real} \cos \alpha - A_{imag} \sin \alpha + \\ &j(A_{real} \sin \alpha + A_{imag} \cos \alpha) \end{aligned}$$

alpha is a synchronizing unknown variable

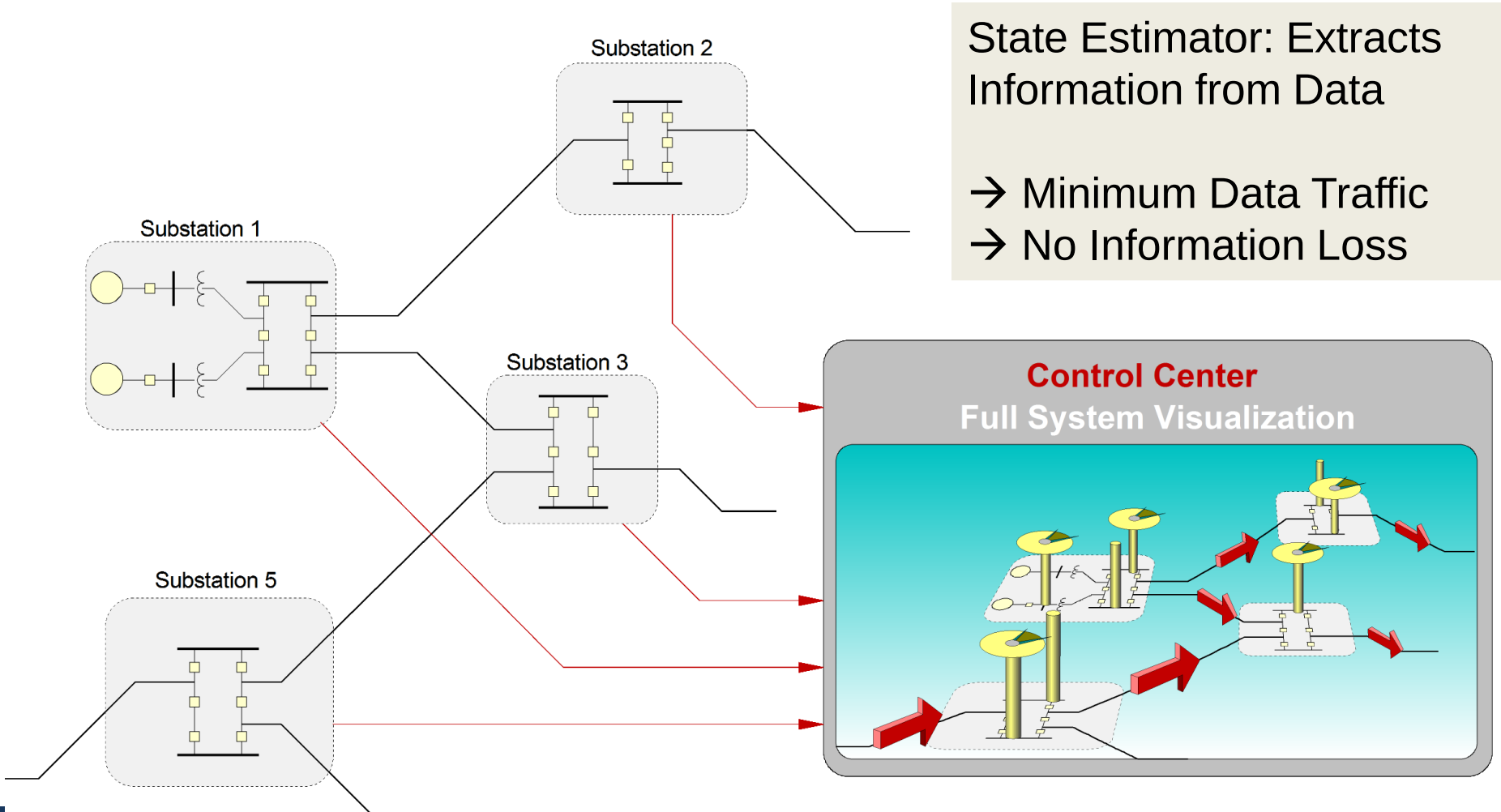
Cos and sin of alpha are unknown variable in the state estimation algorithm

There is one alpha variable for each non-synchronized relay

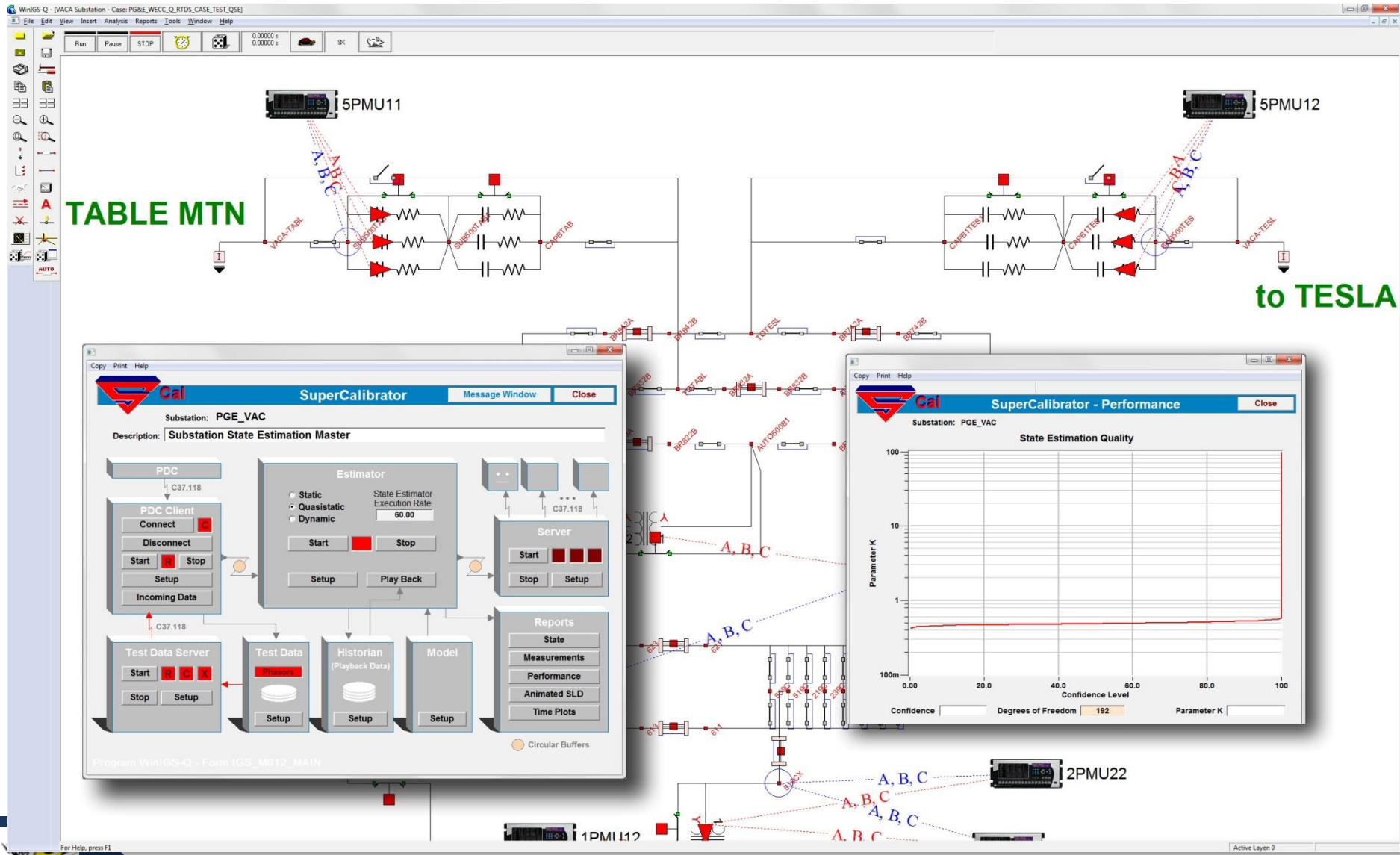


Distributed State Estimation

Synthesis of System Wide State (Control Center or SubArea)



Distributed State Estimation Visualization



Integration of State Estimation and Protection

Setting-less Protection



Setting-less Protection

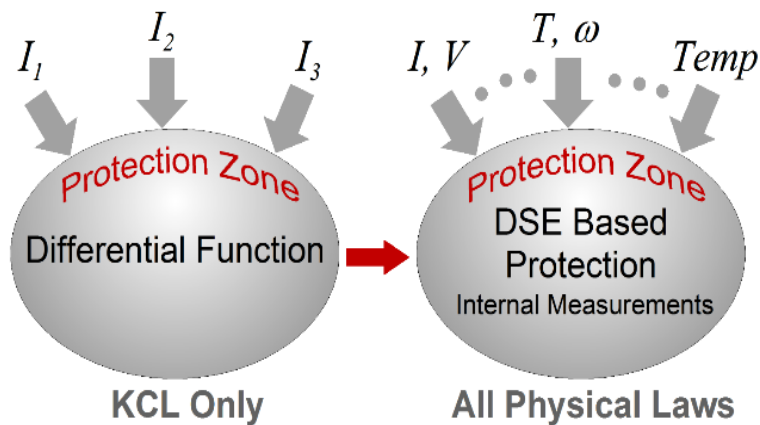
Why:

- Protection Settings Has Become a Complex Process ► Human Errors
- Resources with Power Electronic Interfaces Exhibit Fault Currents Comparable to Load Currents.
- Detection and Locating of Faults is Problematic.

New Approach:

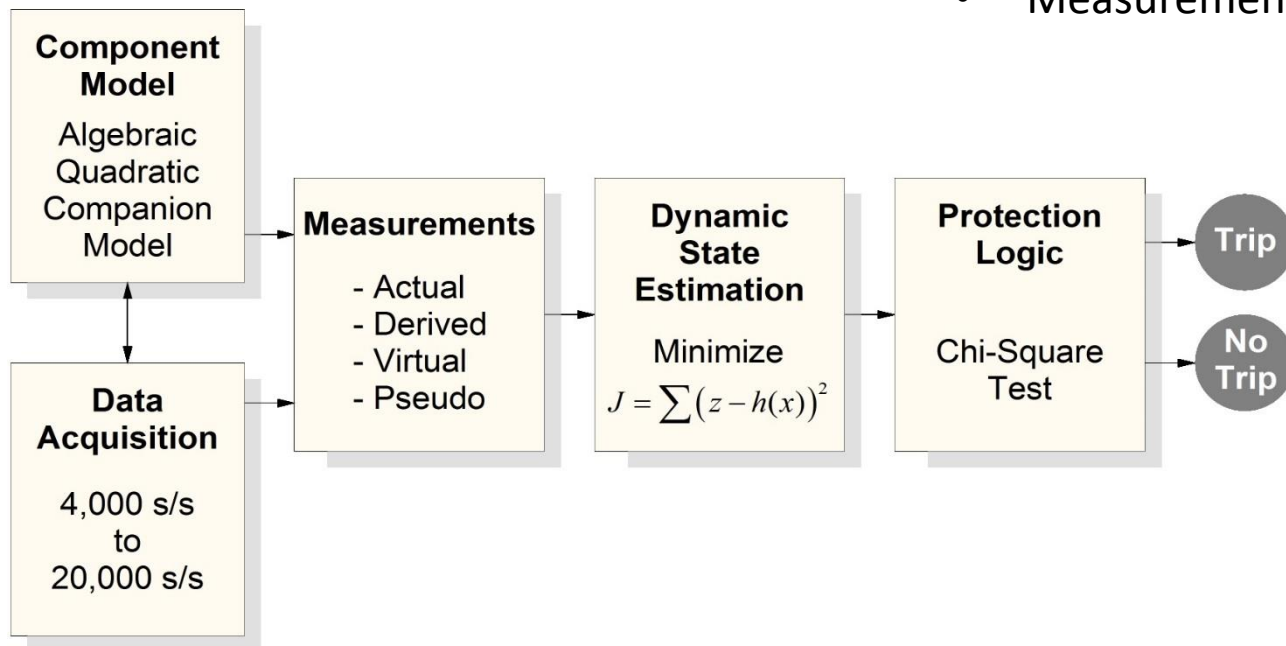
- Measure/Monitor as Many Quantities as Possible and Use Dynamic State Estimation to Continuously Monitor the State (Condition, Health) of the Component Under Protection.
- Act on the Basis of the Component State (Condition, Component Health).



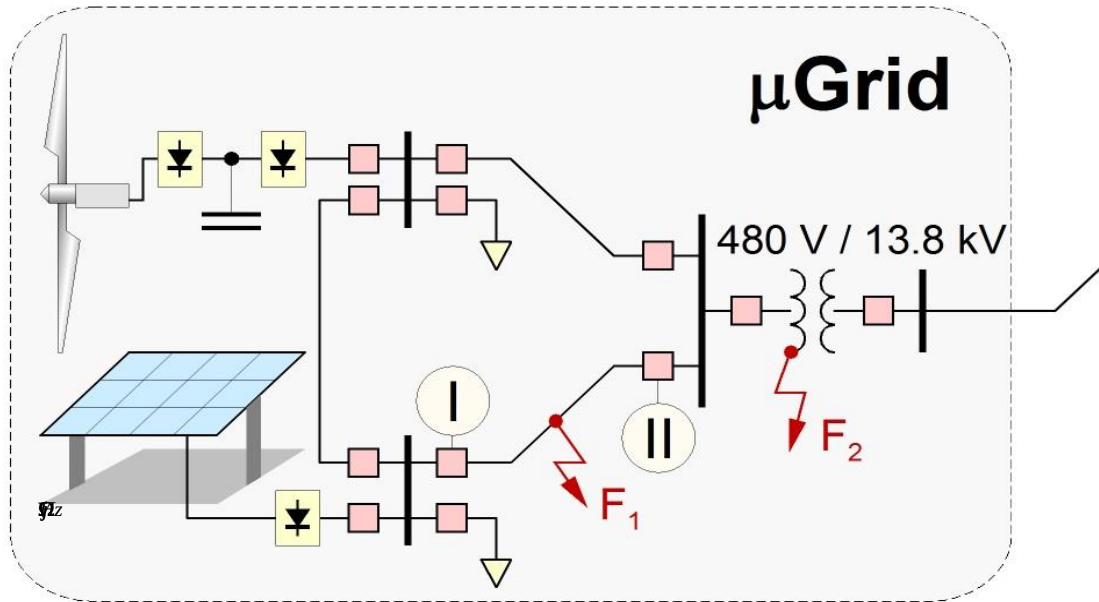


Dynamic State Estimation Based Protection

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



Example of Fault Detection: Comparison of Legacy Protection and DSE Based Protection



Protection of circuit I-II

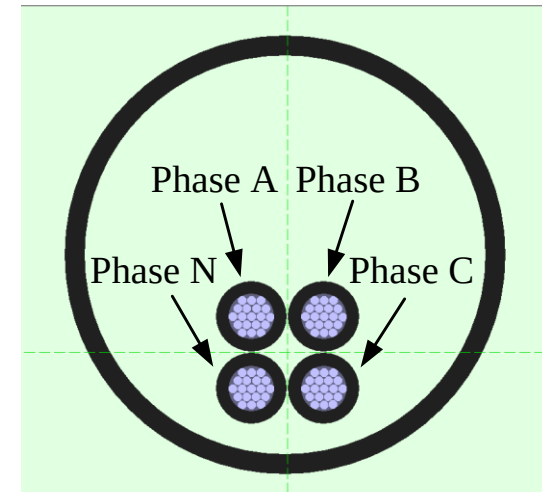
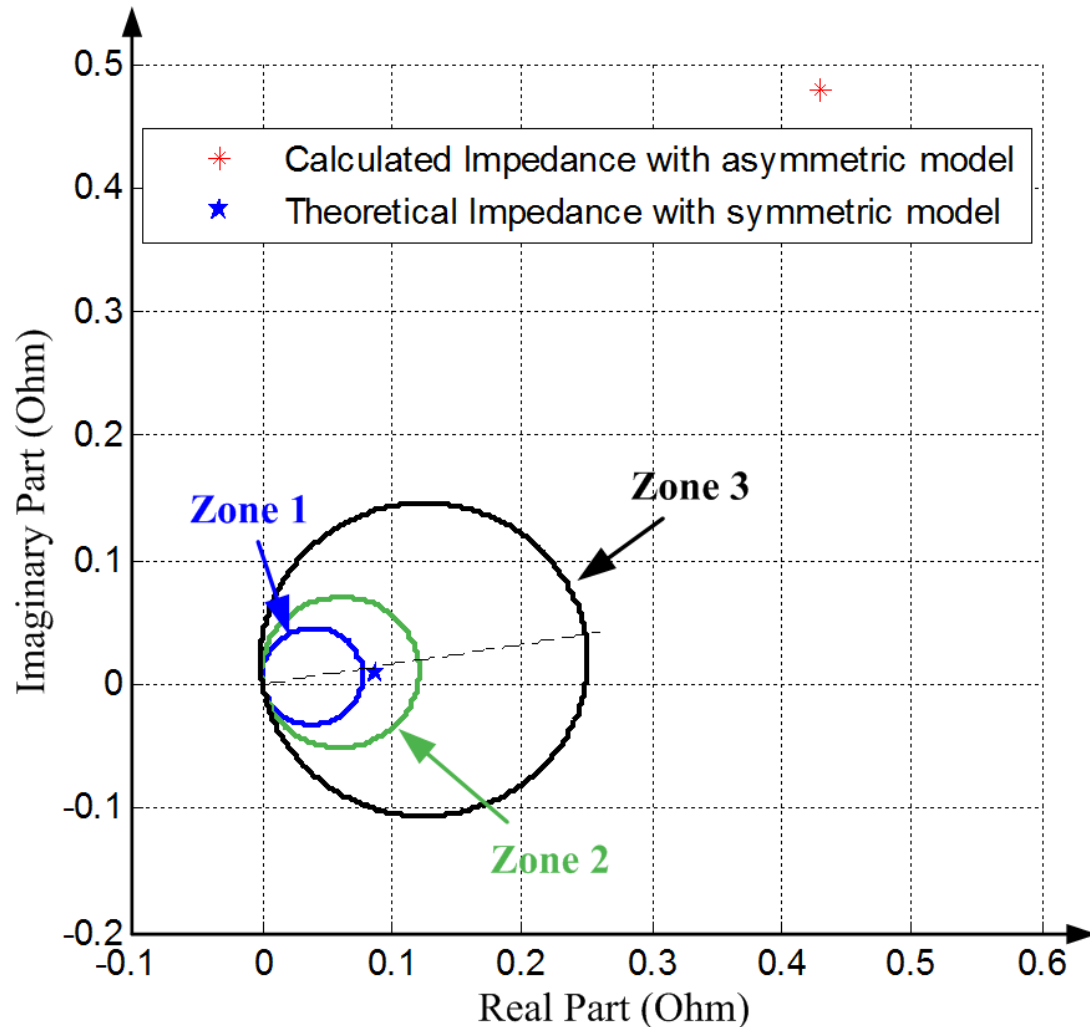


Table 1: Example μ Grid circuit parameters

Object	Parameter	Value
System	Line to line voltage	480 V
	Fundamental frequency	60 Hz
	Length of the monitored circuit	375 feet
Monitored Circuit	Positive (Negative) sequence	$0.0957 + j 0.0153 \Omega$
	Zero sequence	$0.2186 + j 0.1555 \Omega$

Legacy Protection: Distance Relay



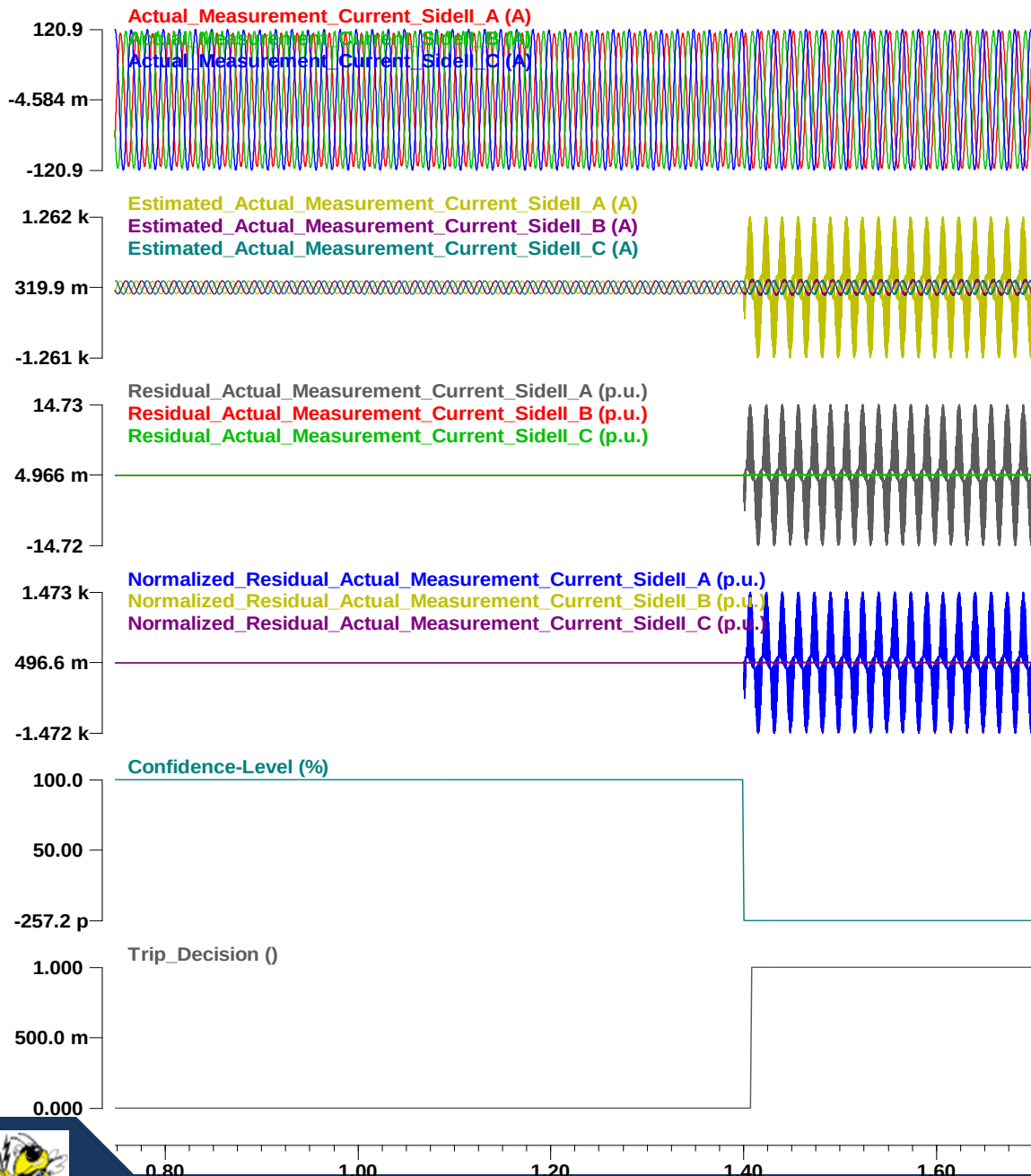
Performance of Legacy Protection Function

- Incorrect non-operation (misoperation)
- Inherent time delays due to phasor based detection circuit

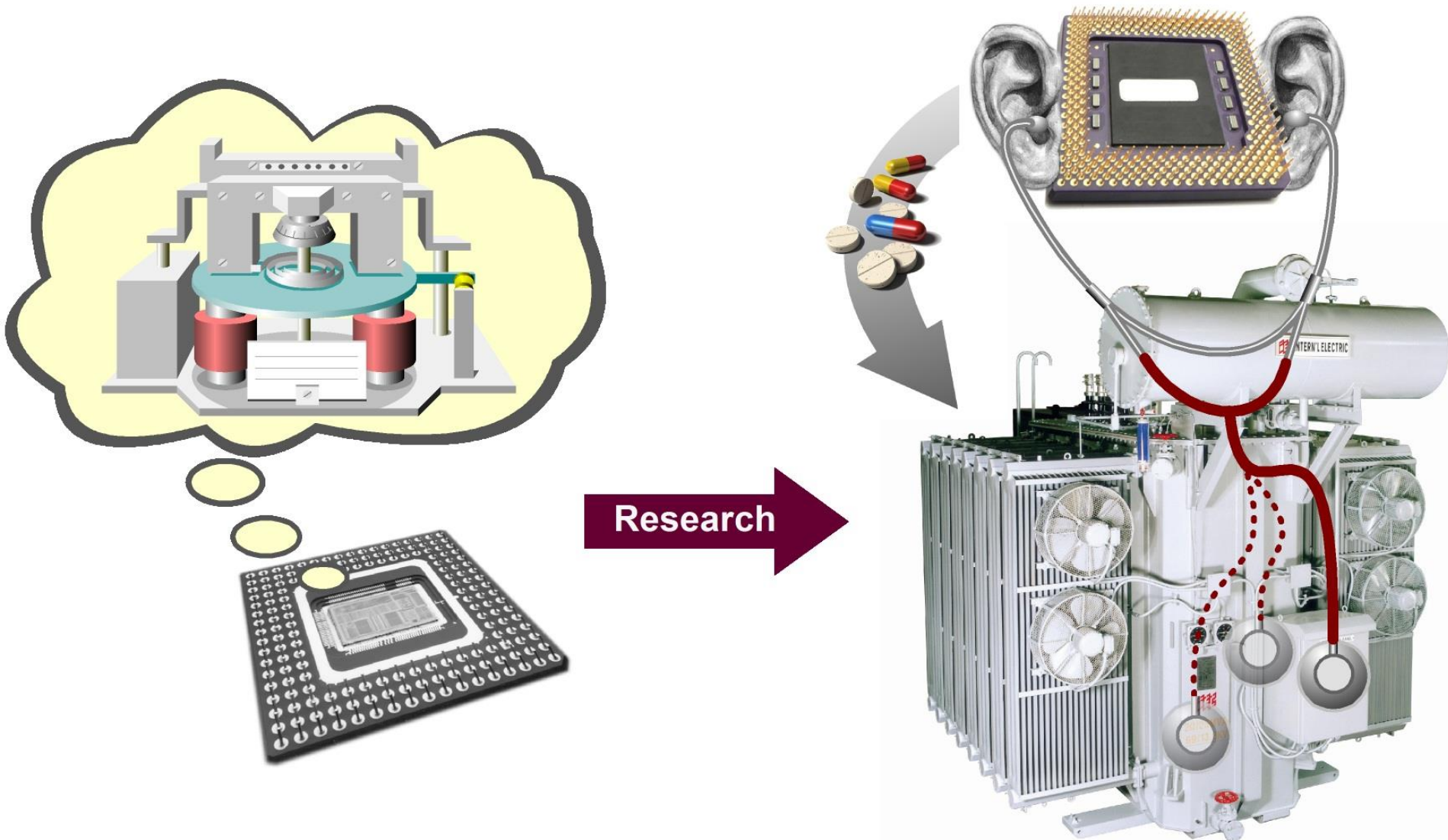


Performance of Setting-Less Protective Relay

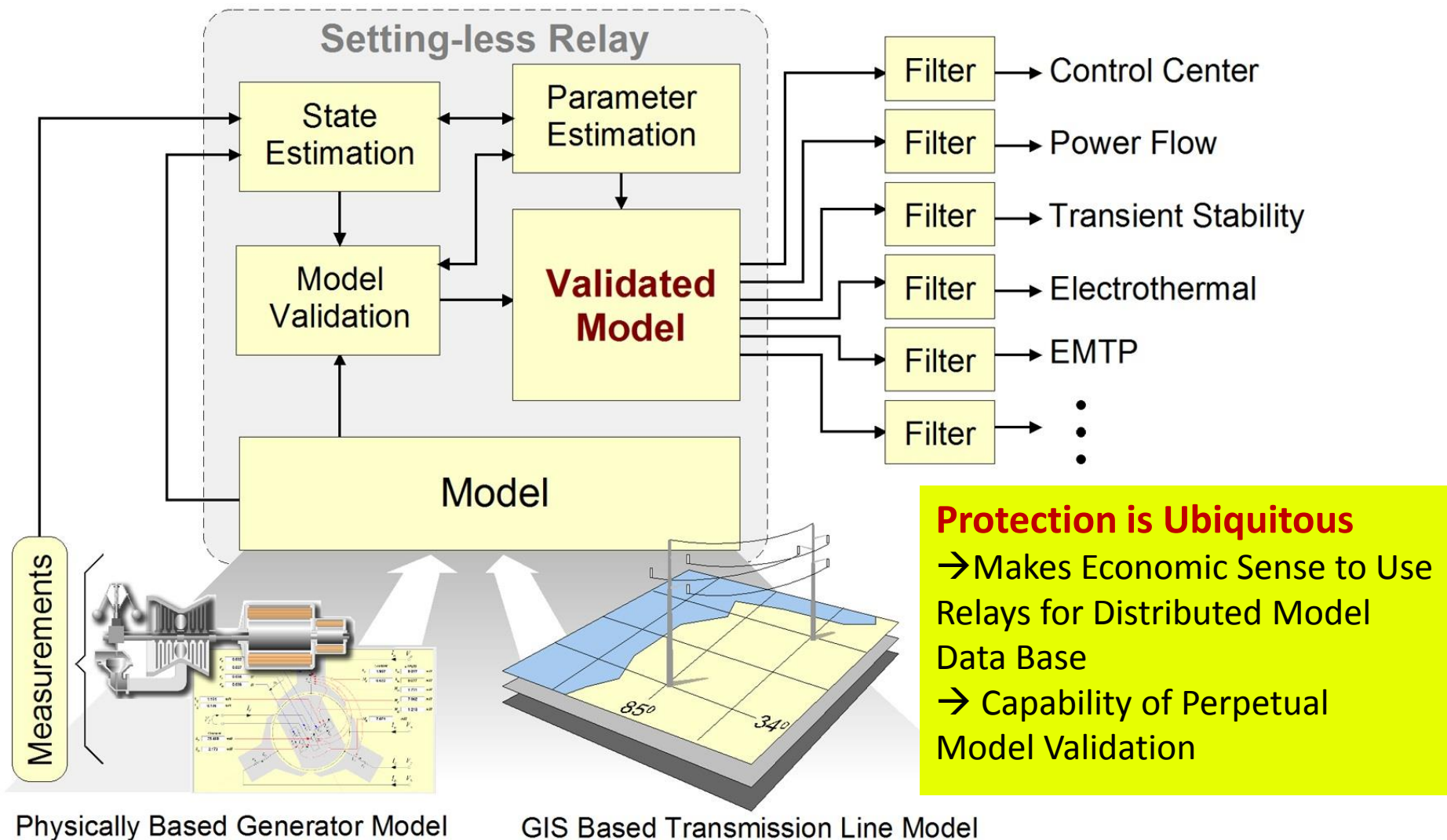
- Correctly detects the fault.
- Detection is achieved in less than 0.2 ms



Settingless Protection – Another View



Important Advantage/Side Benefits



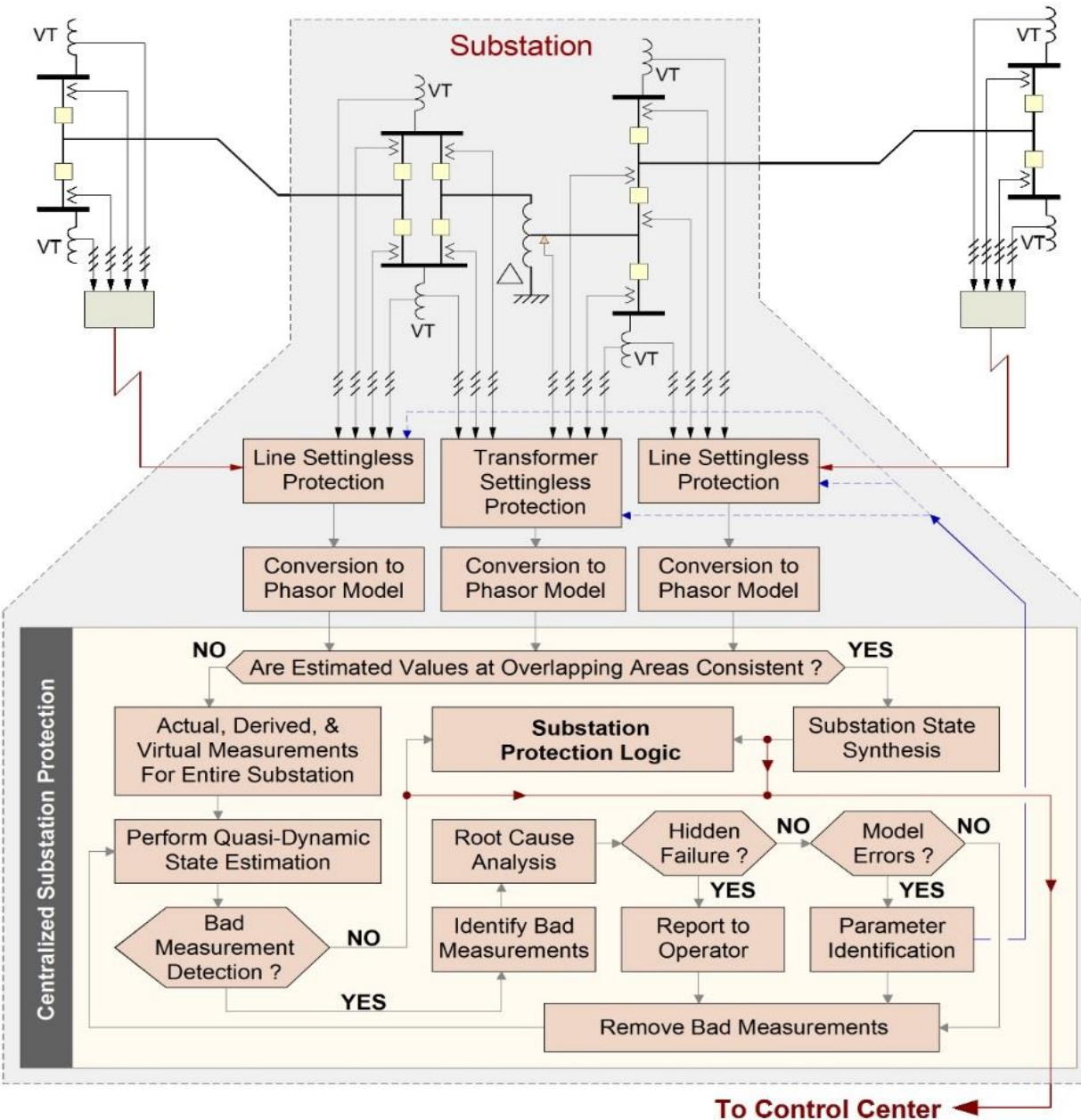
Integrated Dynamic State Estimation and Protection

Advantages

Detection of Hidden Failures

Centralized Substation Protection

Detection of cyber-attacks

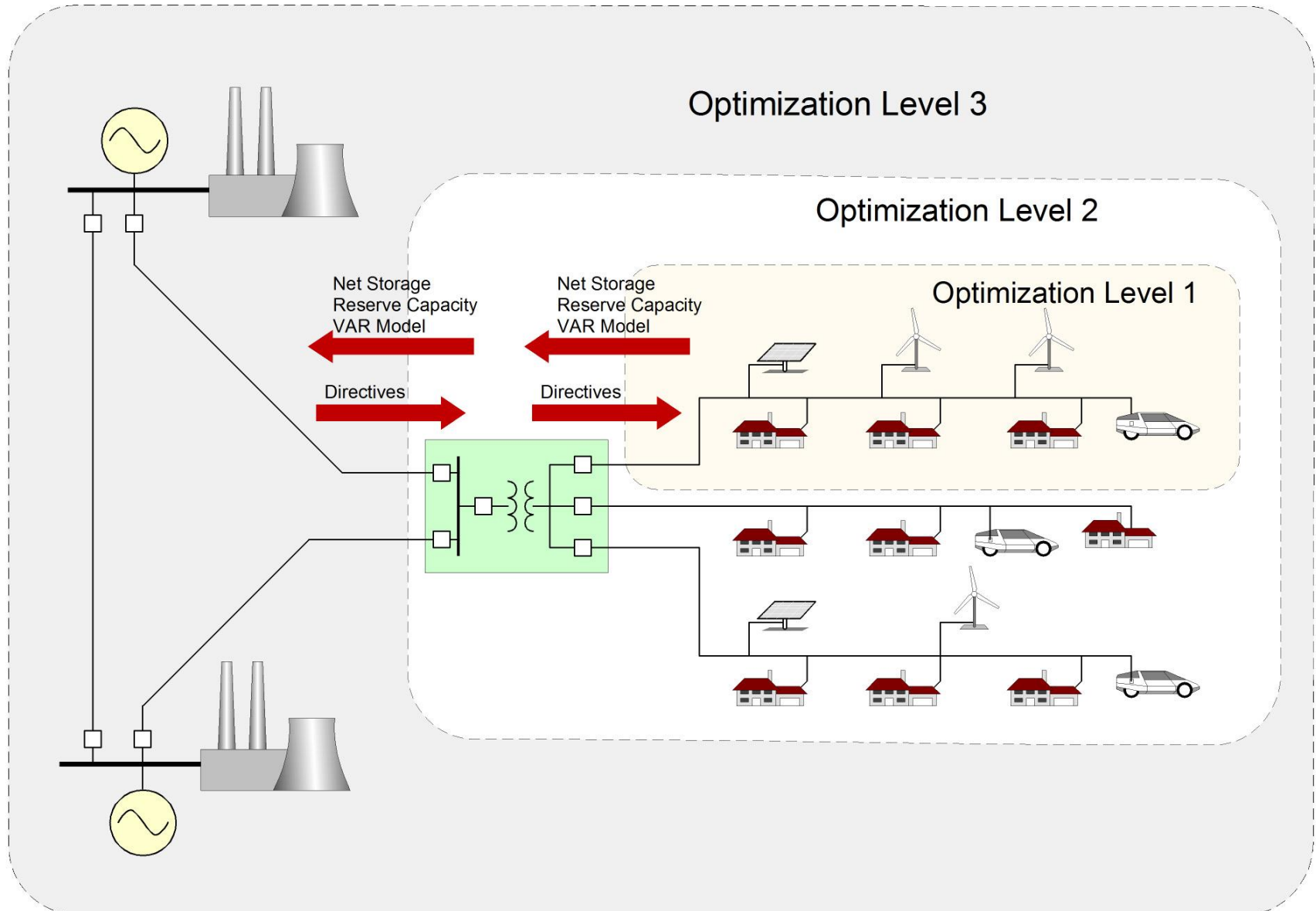


Requirements for Autonomy

- **Autonomous Extraction of Real Time Model and State**
 - Setting-less Protection
- **Self Regulating**
 - Autonomous Frequency Control,
 - Autonomous Voltage Control
 - Other (Contractual Obligations, Environmental Control, etc.)
- **Self Managing (Operations Planning)**

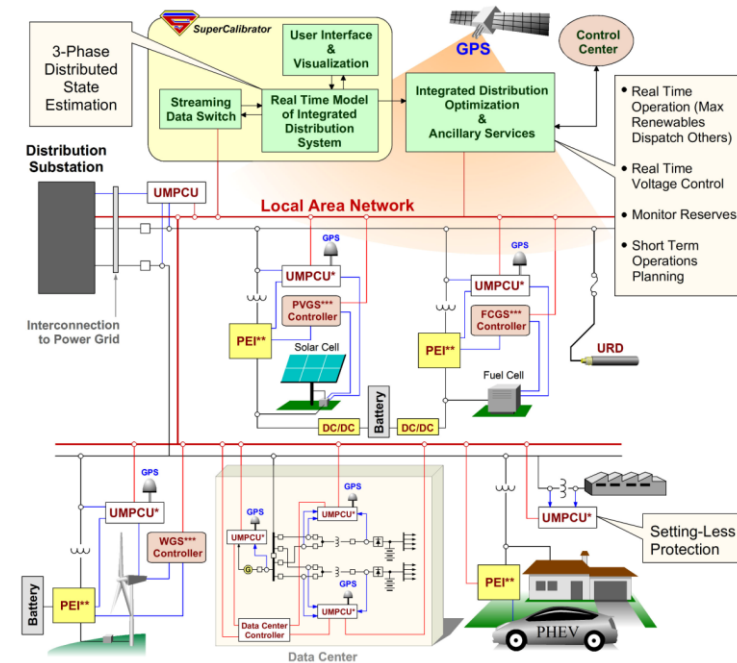
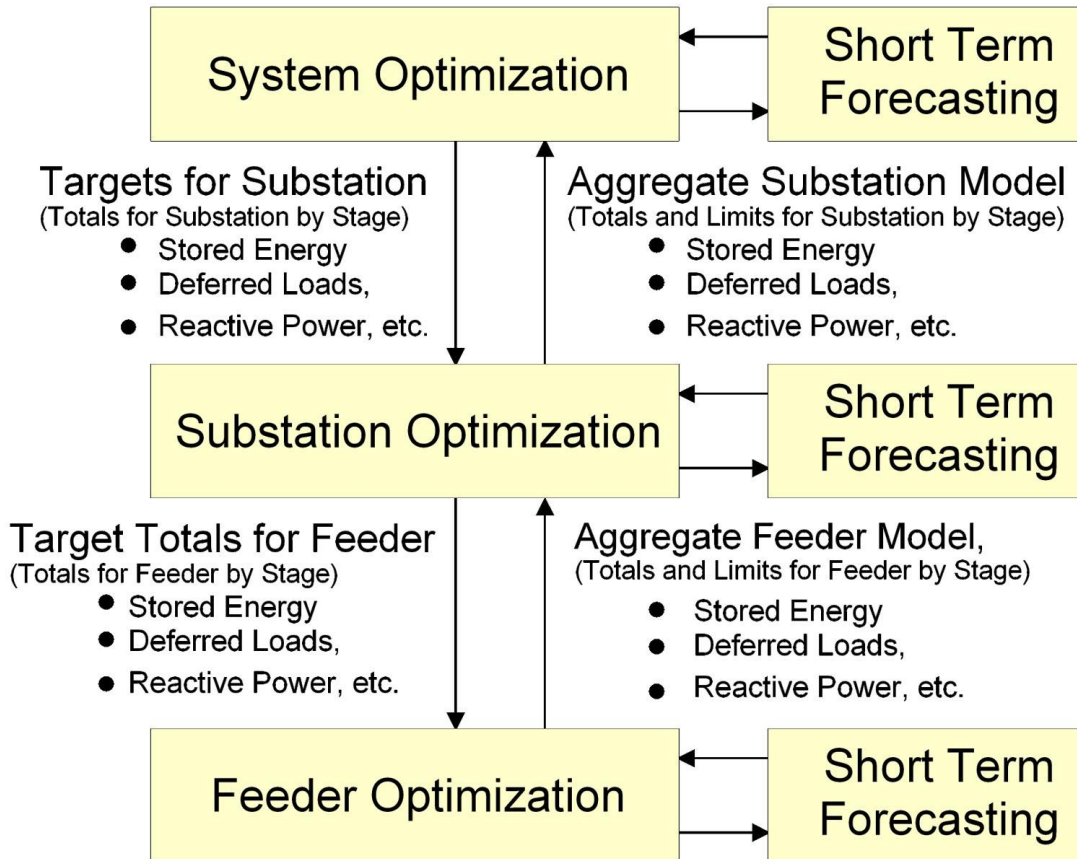


Hierarchical Optimization



Operations Planning

Hierarchical Optimization



Flexible Optimal Power Flow

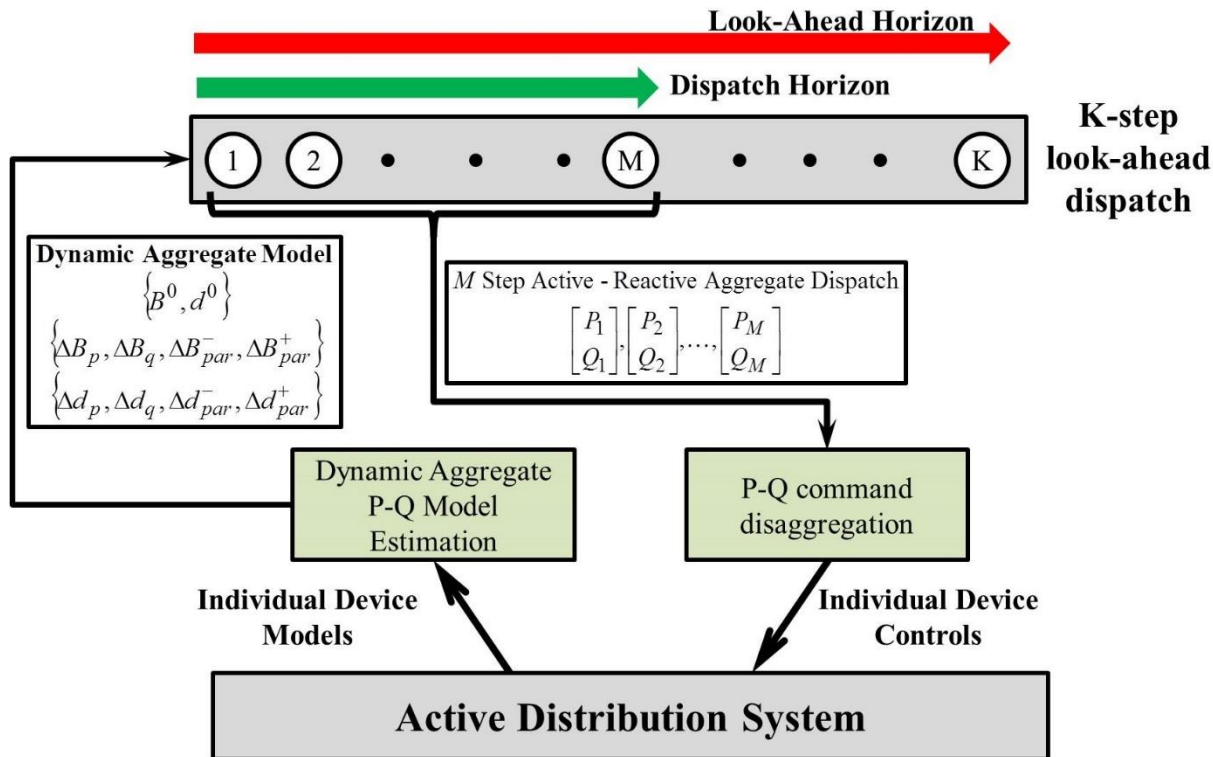
F-OPF:

Multi-Period Look-Ahead OPF & dynamic modeling of flexible resources

Problem Size: HUGE



F-OPF: AC-OPF Look-Ahead Dispatch



AC-OPF Look-Ahead Dispatch

- Multi-step AC-OPF problem with discretized device dynamics (five to ten minutes) – object oriented approach
- Stack of coupled AC-OPF problems
- Non-convex problem
- Accurate modeling of nonlinearities and full active-reactive dispatch
- Look-Ahead Horizon of 24 Hours
- Dispatch Horizon of one to two hours



Object Orientation: Device Model

Device Model Object at step k

The SCAQCF Standard

1. *Dynamics*
 2. *Model Quadratzation*
 3. *Controls & Limits*
- *Network Model*
→ *Optimization Model*

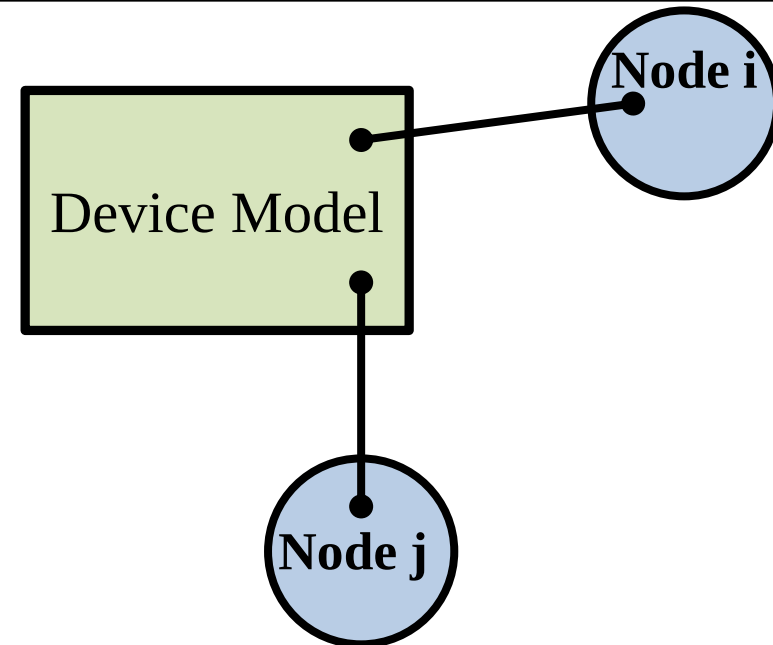
$$\begin{bmatrix} \mathbf{i}_k \\ \mathbf{0} \end{bmatrix} = \mathbf{g}(\mathbf{x}_{k-1}, \mathbf{u}_{k-1}, \mathbf{x}_k, \mathbf{u}_k | \mathbf{p}_k) = \mathbf{a}_{eq}(\mathbf{p}_k) + Y_{eqx}\mathbf{x}_k + Y_{equ}\mathbf{u}_k \\ + \begin{bmatrix} \vdots \\ \mathbf{x}_k^T F_{eqxx}^i \mathbf{x}_k^T \\ \vdots \end{bmatrix} + \begin{bmatrix} \vdots \\ \mathbf{u}_k^T F_{equu}^i \mathbf{u}_k^T \\ \vdots \end{bmatrix} + \begin{bmatrix} \vdots \\ \mathbf{x}_k^T F_{eqxu}^i \mathbf{u}_k^T \\ \vdots \end{bmatrix} - \mathbf{B}_{eq}^{k-1} \\ \mathbf{B}_{eq}^{k-1} = -N_{eqx}\mathbf{x}_{k-1} - N_{equ}\mathbf{u}_{k-1}$$

$$\mathbf{h}(\mathbf{x}_{k-1}, \mathbf{u}_{k-1}, \mathbf{x}_k, \mathbf{u}_k | \mathbf{p}_k) = \mathbf{a}_{ineq}(\mathbf{p}_k) + Y_{ineqx}\mathbf{x}_k + Y_{inequ}\mathbf{u}_k \\ + \begin{bmatrix} \vdots \\ \mathbf{x}_k^T F_{ineqxx}^i \mathbf{x}_k^T \\ \vdots \end{bmatrix} + \begin{bmatrix} \vdots \\ \mathbf{u}_k^T F_{inequu}^i \mathbf{u}_k^T \\ \vdots \end{bmatrix} + \begin{bmatrix} \vdots \\ \mathbf{x}_k^T F_{ineqxu}^i \mathbf{u}_k^T \\ \vdots \end{bmatrix} - \mathbf{C}_{ineq}^{k-1} \\ \mathbf{C}_{ineq}^{k-1} = -N_{ineqx}\mathbf{x}_{k-1} - N_{inequ}\mathbf{u}_{k-1}$$

$$\mathbf{h}(\mathbf{x}_{k-1}, \mathbf{u}_{k-1}, \mathbf{x}_k, \mathbf{u}_k | \mathbf{p}_k) \leq \mathbf{0}$$

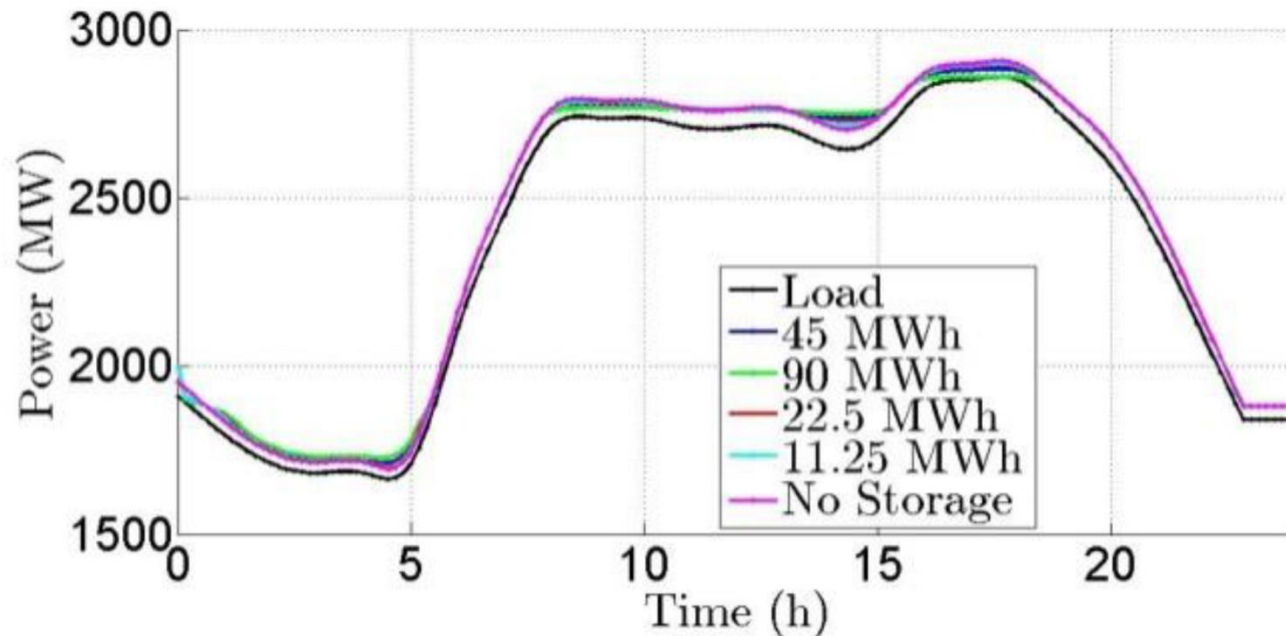
$$\mathbf{x}_{\min} \leq \mathbf{x}_k \leq \mathbf{x}_{\max}, \mathbf{u}_{\min} \leq \mathbf{u}_k \leq \mathbf{u}_{\max}$$

$$f(\mathbf{x}_k, \mathbf{u}_k) = \mathbf{a}_f + \mathbf{b}_{fx}^T \mathbf{x}_k + \mathbf{b}_{fu}^T \mathbf{u}_k + \mathbf{x}_k^T C_{fxx} \mathbf{x}_k + \mathbf{x}_k^T C_{fxu} \mathbf{u}_k + \mathbf{u}_k^T C_{fuu} \mathbf{u}_k$$



Example Results

IEEE 24 Bus System



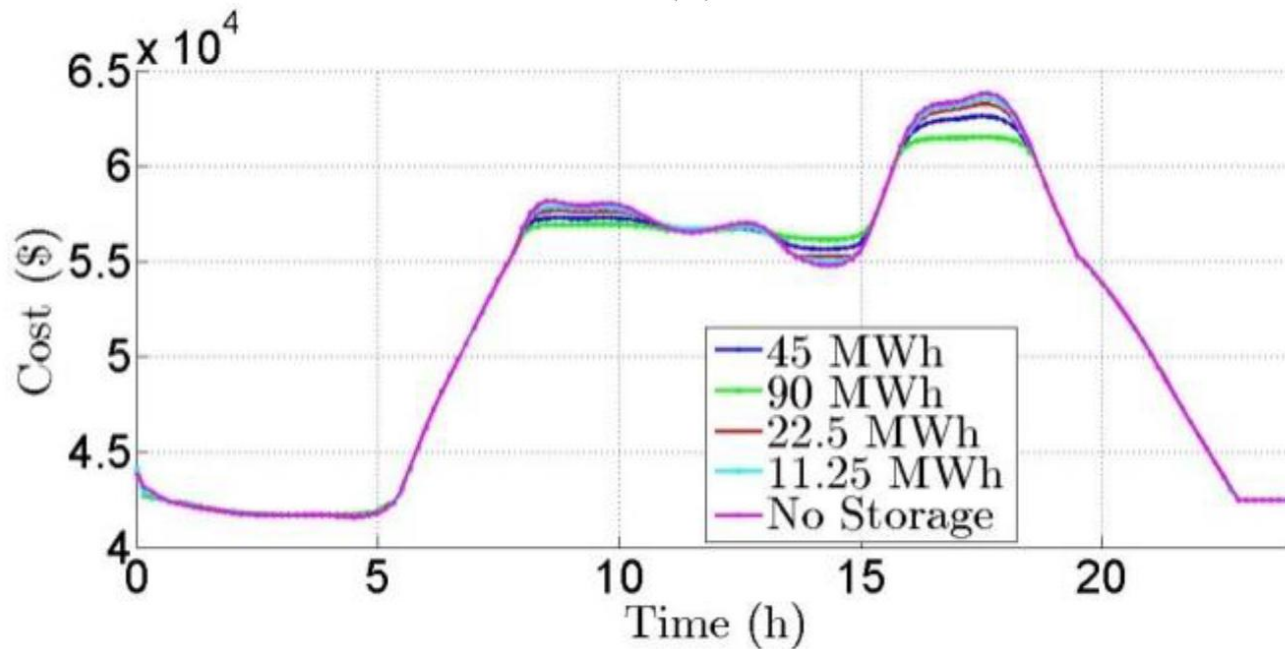
Conventional unit output for various storage penetration

- Reduction of generation at peak
- Storage Units charge at low-load periods



Example Results

IEEE 24 Bus System



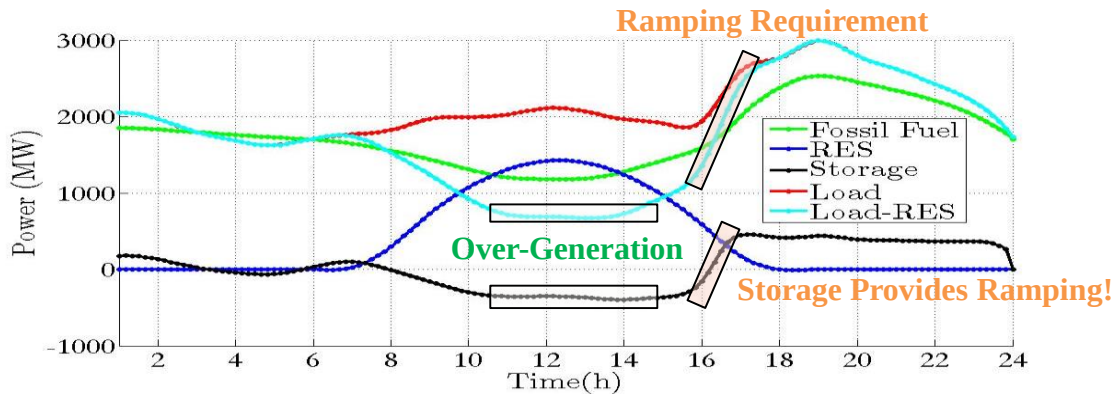
System Operating Cost Per Period

- Slightly higher costs in low-load period & lower costs in high load period

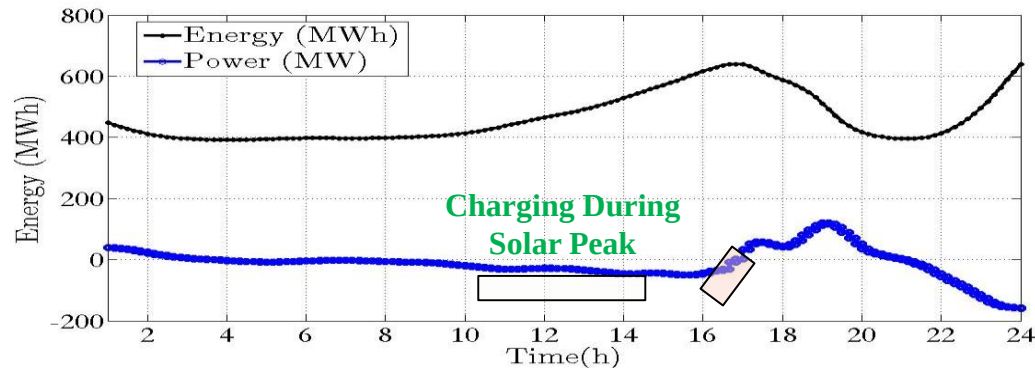


Sample Results: Storage Coordination

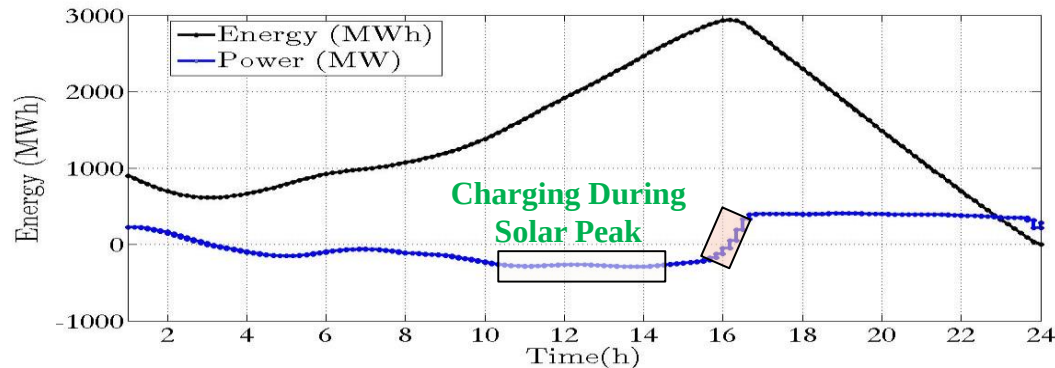
Generation
Mix
Schedule



PHEV
Charge/
Discharge
Schedule



Pumped
Hydro
Charge/
Discharge
Schedule

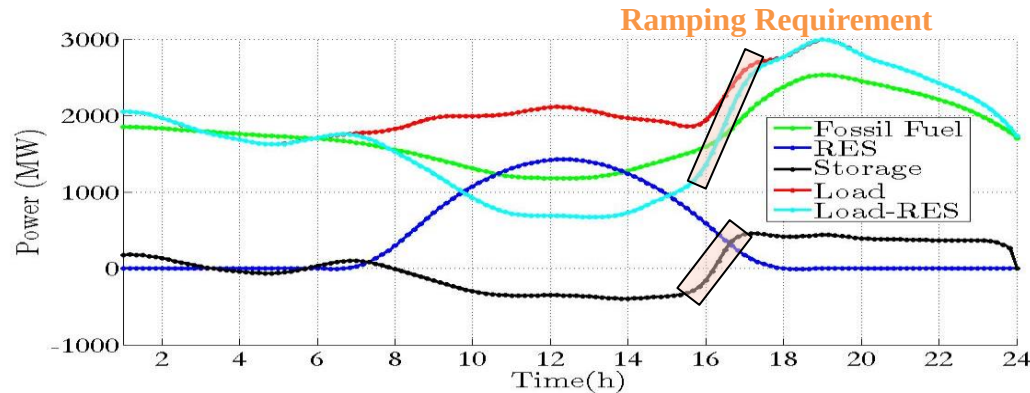


Storage
Provides
Ramping
Services &
Alleviates
Over-
Generation



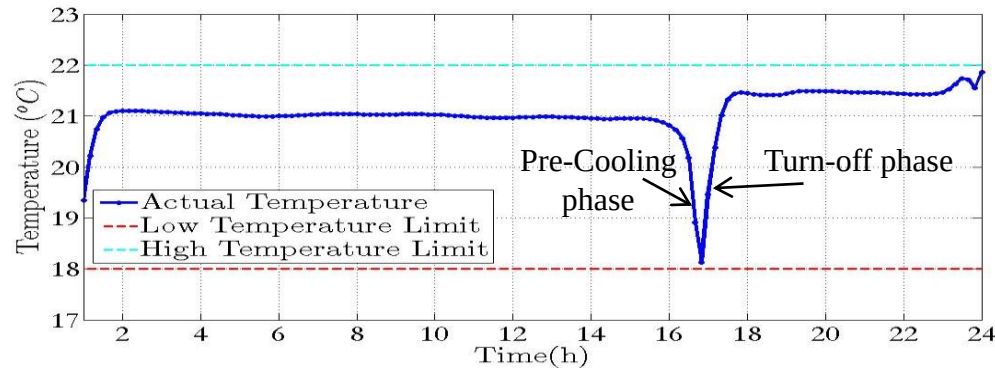
Sample Results: Responsive Load

**Generation
Mix
Schedule**



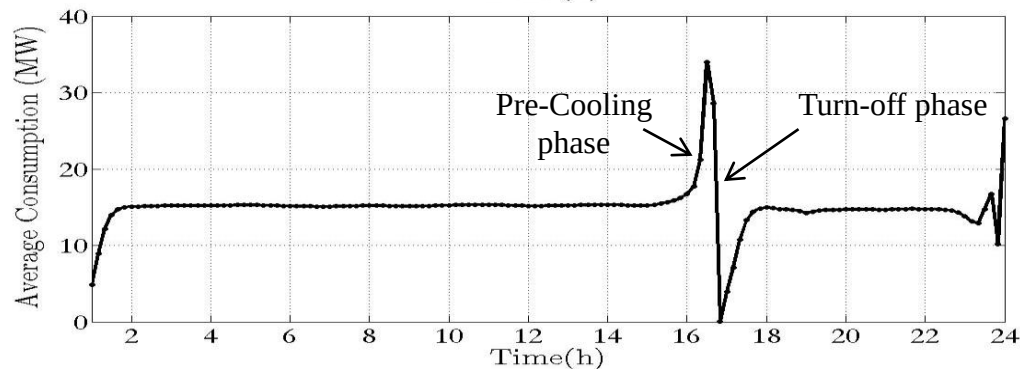
**TCL Provides
Ramping
Services** by
curtailing
consumption

**Thermostatic
Load**
Temperature of
Cooled Space



The F-OPF
guarantees
non-intrusive
load
scheduling &
considers
network effects

**Thermostatic
Load**
Average
Consumption
Per Period



Thank you for your Attention Questions?

