The Future of Power System Protection, Control & Monitoring

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GE Digital Energy

April 7th 2009

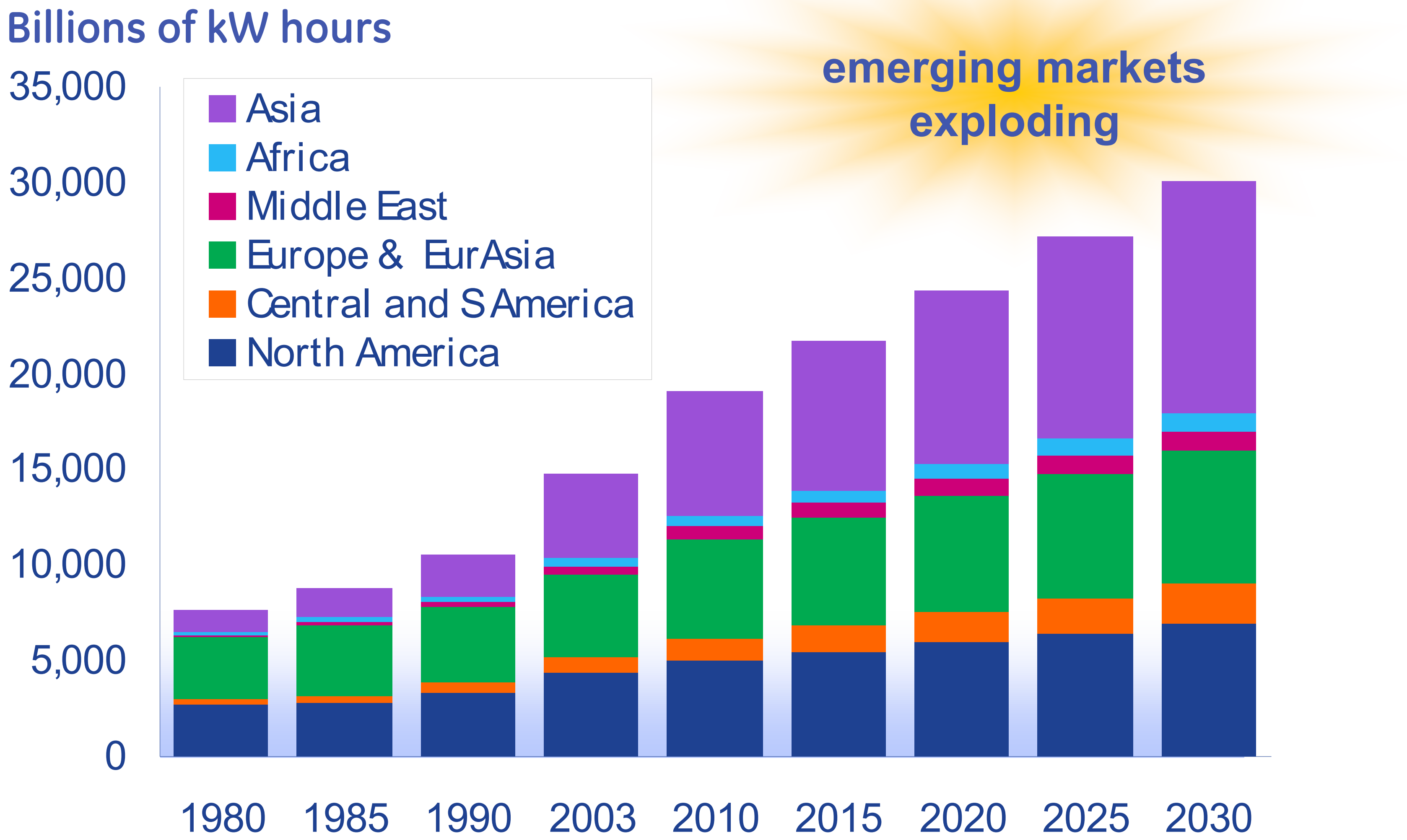
imagination at work

Power System Challenges

The worlds population is estimated at 6.76 B people


Electricity Demand….2x by 2030

Electricity demand … 2X by 2030



Sources: EIA-DOE International Energy Annual 2004 & International Energy Outlook 2006

Energy consumption growing

Electricity Demand….3x by 2040

source: U.S. Army Corps of Engineers EERDC/CERL TR-05-21

Today's Power System Challenges

Demand for electricity is growing

At an anticipated growth in demand of 2% per year, this works out to a 50% increase in demand over the next 20 years

Environmental Effect

50% increase in the amount of generating capacity required is also a 50% increase in environmental costs

Aging infrastructure

60% to 70% of the transformers, transmission lines, and circuit breakers nearing the end of their usable life

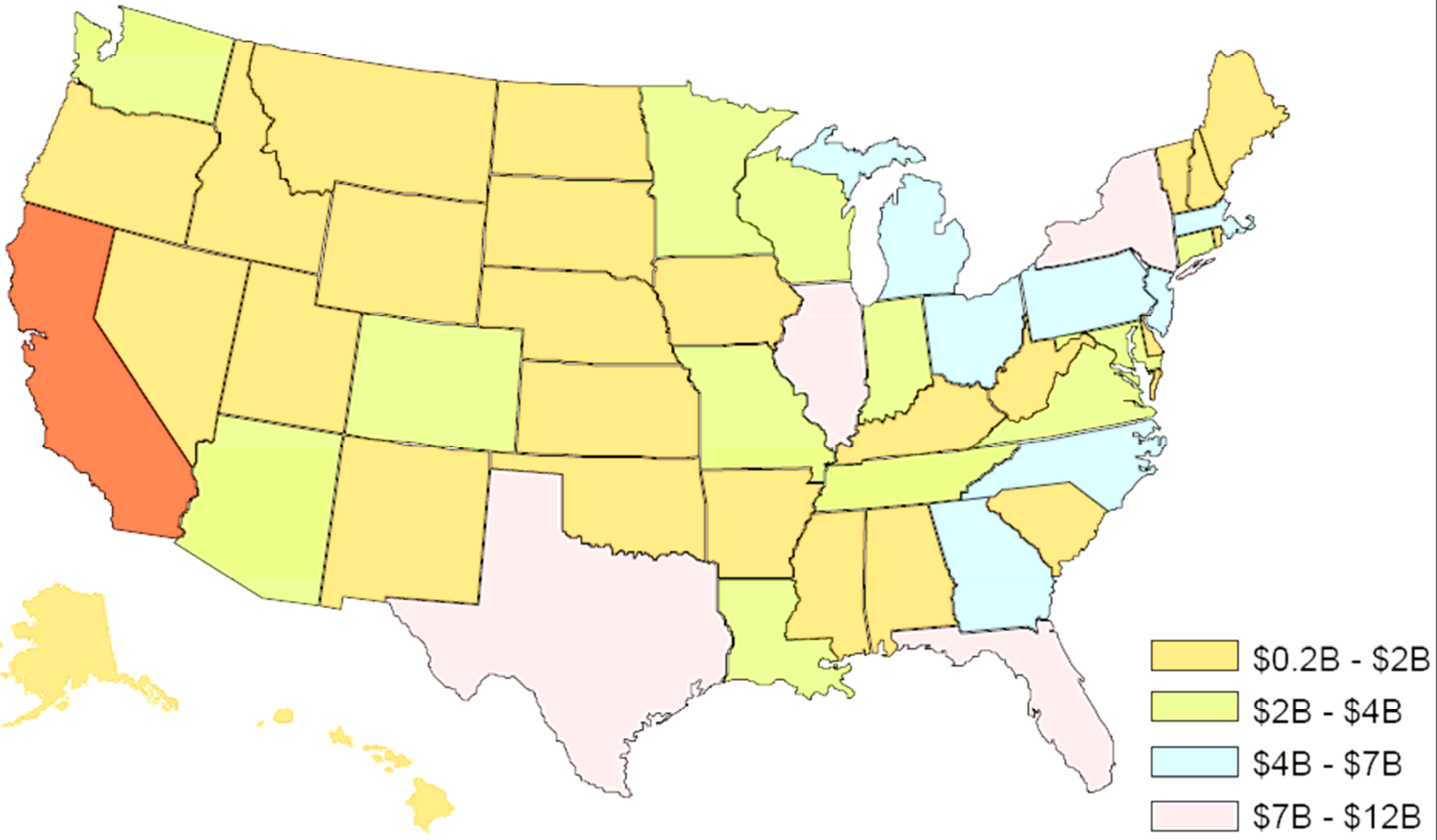
Safety Concerns

32,807 people were injured in ARC Flash incidents the U.S between the years of 1992 and 1998. The average economic impact to companies on each incident is between $8M-$10M in direct and indirect costs.

Economic Impact

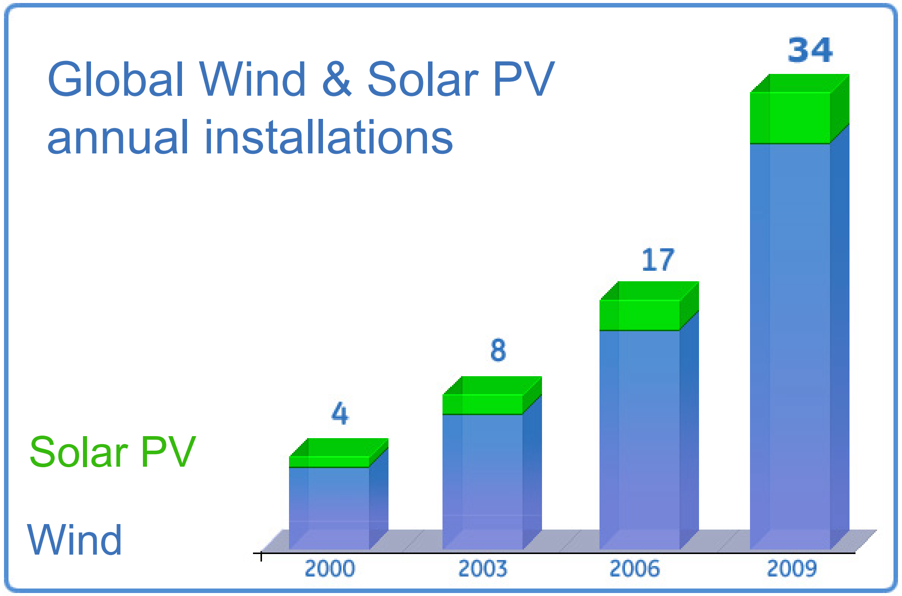
Power outage in the U.S has cost over $150B annually in productivity and lost business

Primen Study: $150B annually for power outages and quality issues



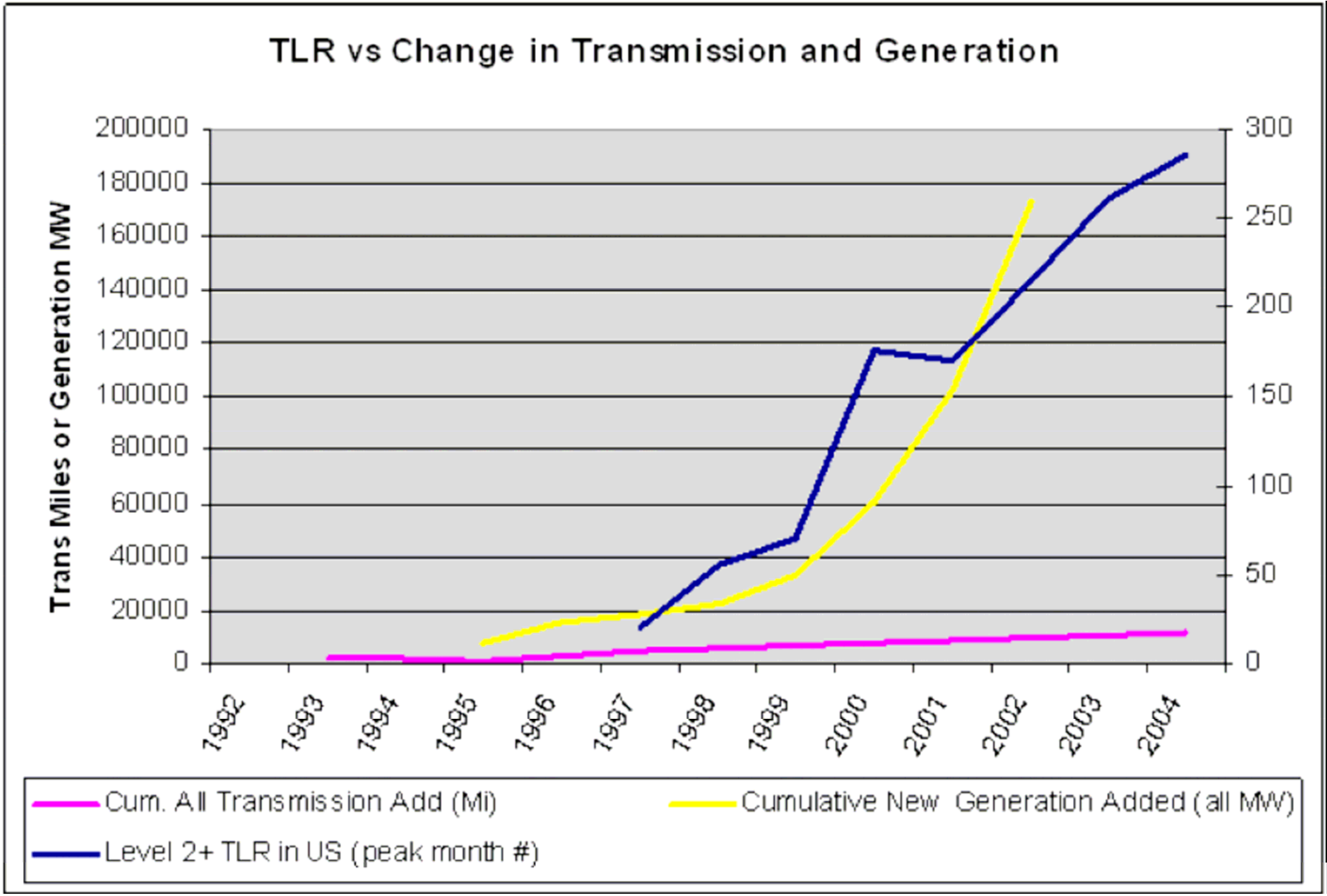
Renewable and Distributed Energy

- US Wind & Solar generation has tripled every year since ’02
- This still only accounts for a combined 34GW
- Trend expected to accelerate
- 12 Million new DER devices expected over next 20 years

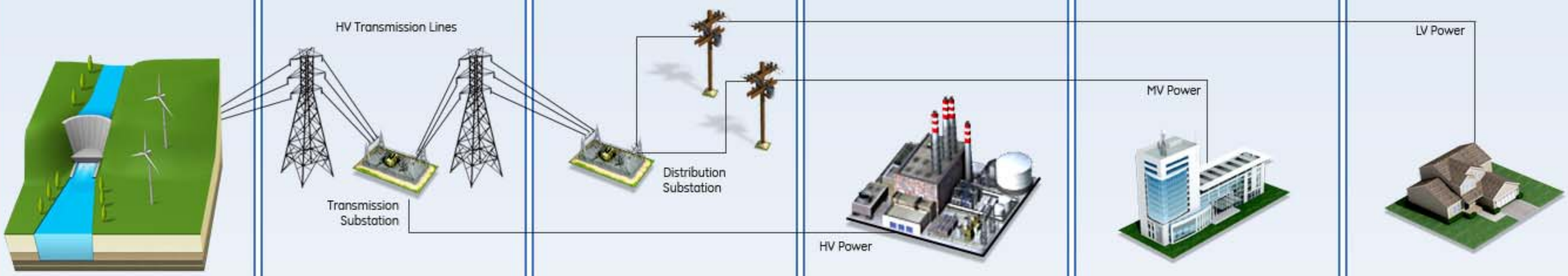


source: REN21 2007 update + EER

Transmission Loading Relief vs. Gen



Protection, Control, and Monitoring Technologies . . .



Generation

Examples:

Generator Protection & Control

Distributed Generation Management

Transmission

High Voltage Line Protection , Control, & Monitoring

Reliability Optimization

Digitizing Primary Equipment

Distribution

Transformer & Feeder Protection & Control

Power Distribution Safety

Distribution Automation

Fault Diagnostics & Analytics

Industrial

Feeder, Transformer & Motor Protection

Energy Management Systems

Plant Load Shedding & Peak Demand Mgmt

Asset Monitoring

Commercial

Emergency Backup Power

Sub Metering and Cost Allocation

Microgrid Control

Residential

Wireless Comms Enabling AMI, Demand Side Management & Direct Load Control

Protection and Control Spans the Electron Enterprise

Protection, Monitoring, and Control Challenges to Address (today):

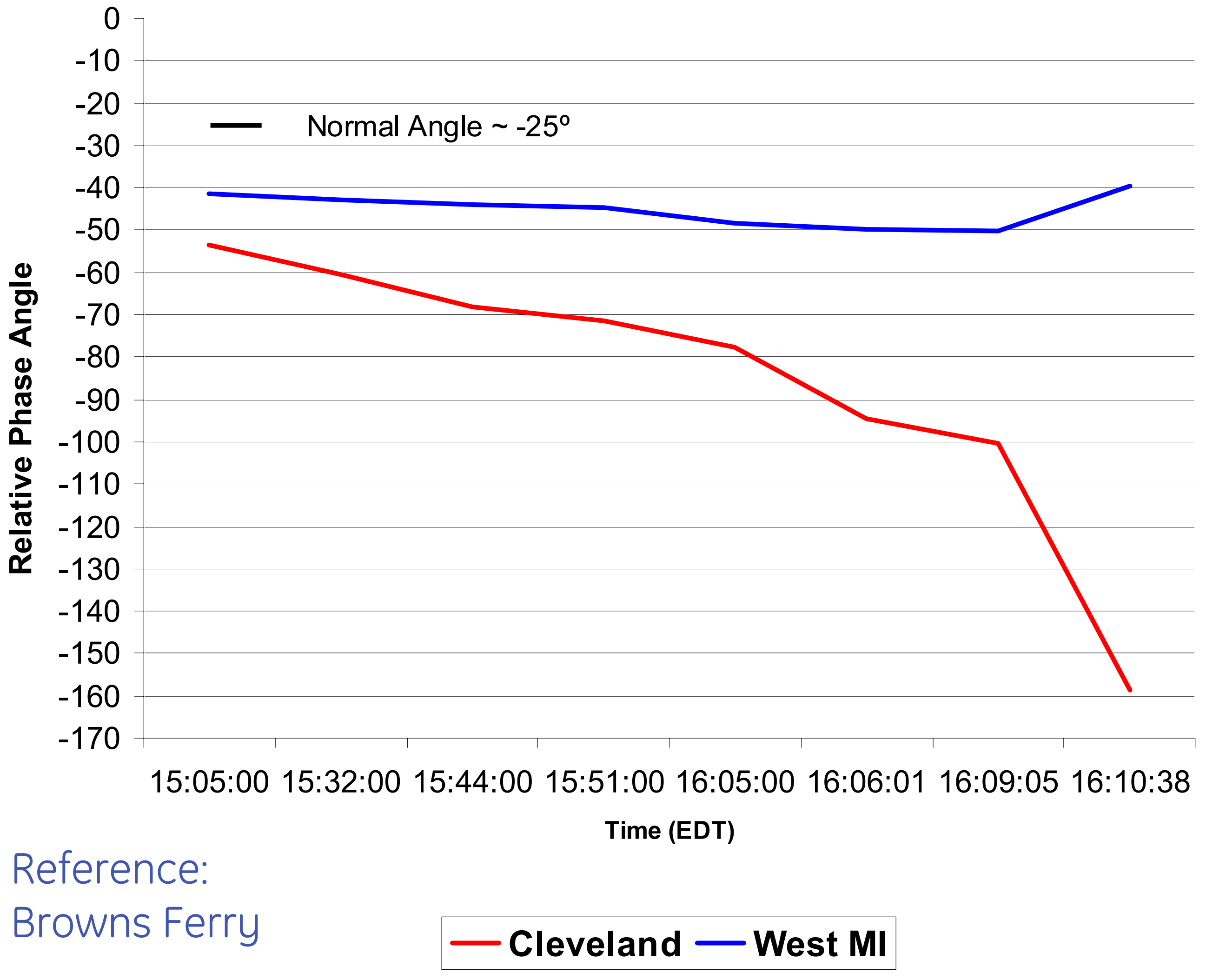
- Grid stability issues
- Extensive influx of Distributed Resources
  - Protection in a limited current environment
  - DR/MicroGrid Management
    - Optimal Dispatch
    - Tie Line Control
    - Load/Generation Shed
- Monitoring/Replacement of the aging P&C infrastructure

The Need for Wide-Area Measurements

- Following the east coast blackout, a federal commission was appointed
- Fault found with utility companies: no real-time knowledge of the state of the power system was available
- Recommendation made: establish a real-time measurement system and develop computer based operational and management tools

This Was after the 1965 blackout!

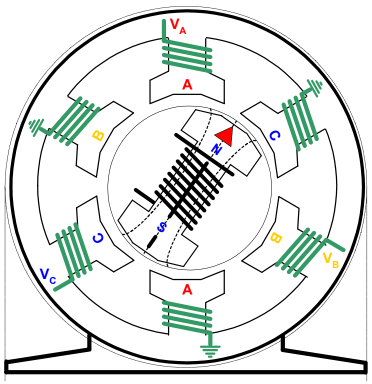
Cleveland Separation – Aug 14, 2003

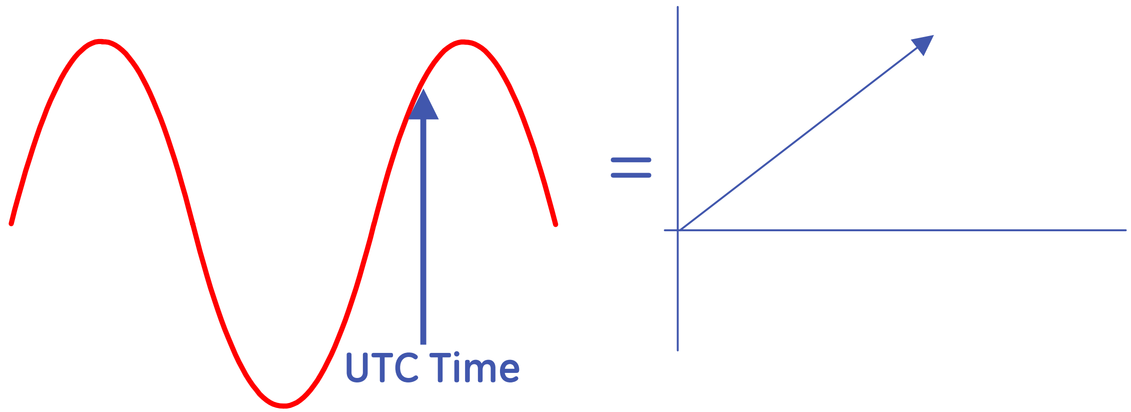


Reference:
Browns Ferry

Phasors → Synchrophasors

> Rotating rotors = alternate currents / voltages



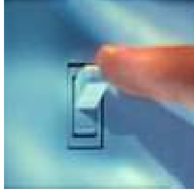


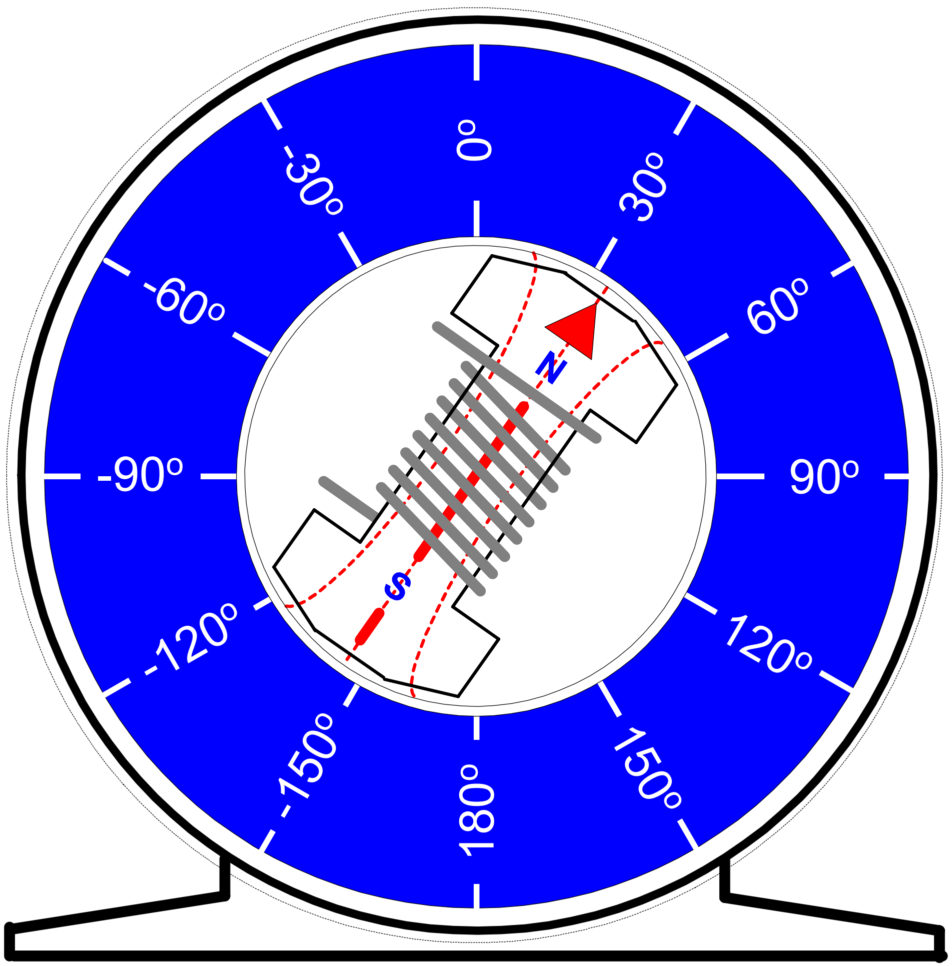
> Phasors are well established means of representing ac circuits

Charles Proteus Steinmetz (1865-1923)
Complex Quantities and their use in Electrical Engineering; Charles Proteus Steinmetz; Proceedings of the International Electrical Congress, Chicago, IL; AIEE Proceedings, 1893; pp.33-74.

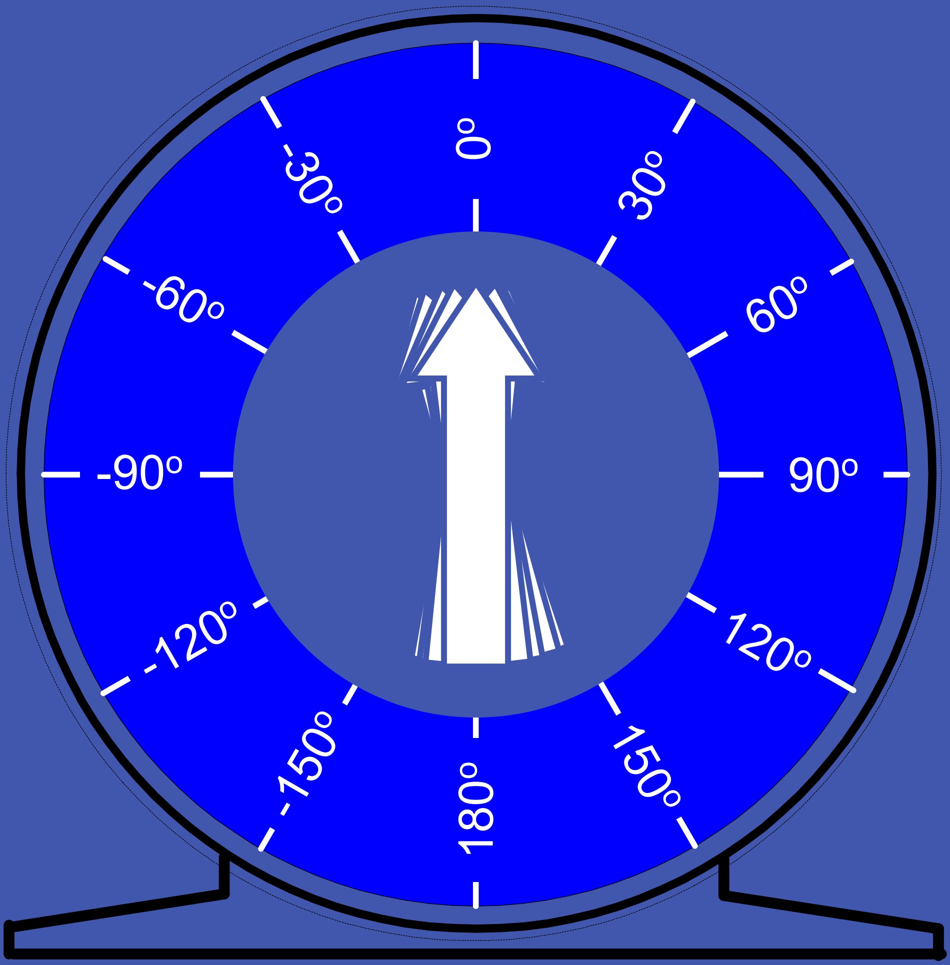
Synchrophasors

Strobe Light Analogy

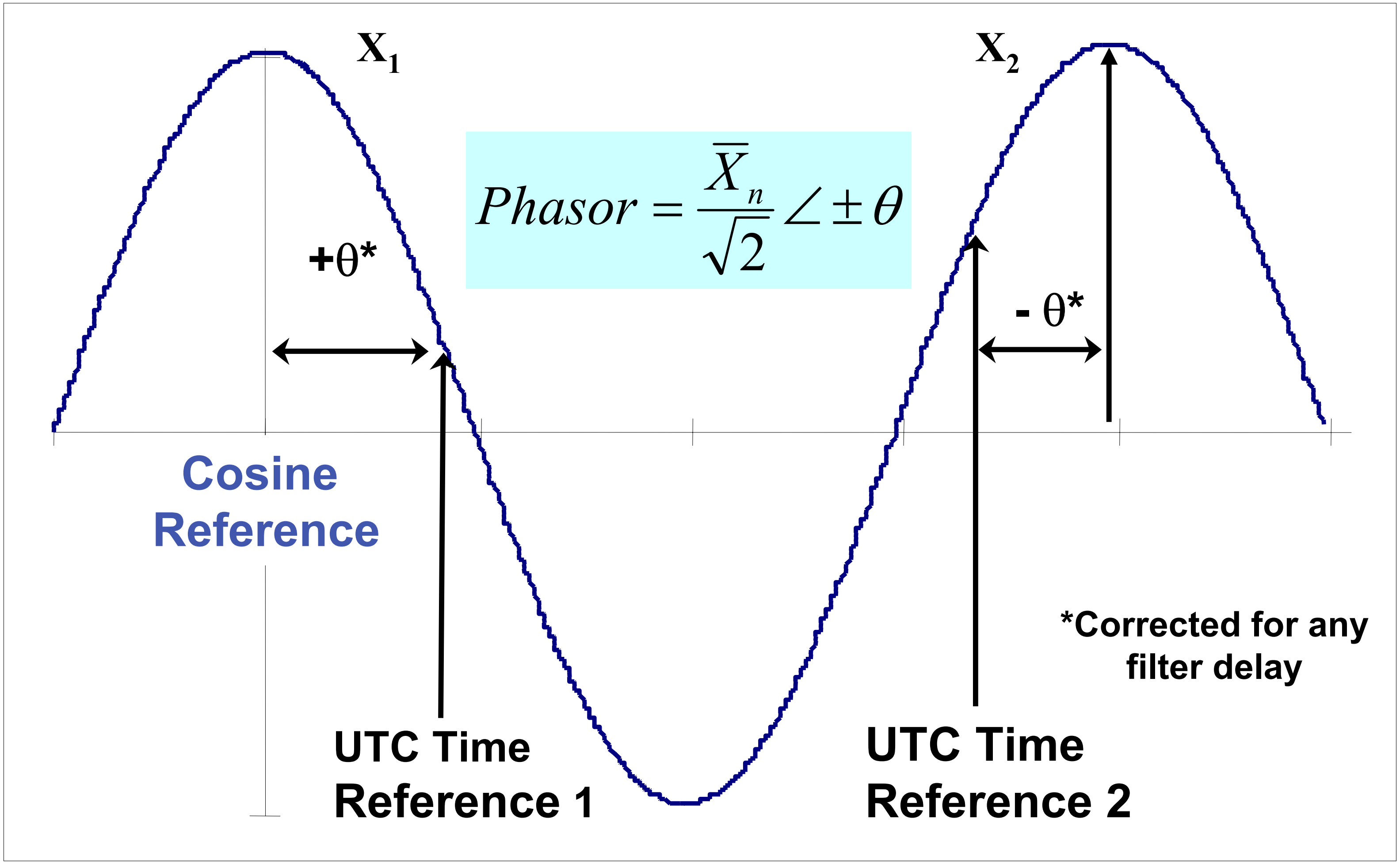




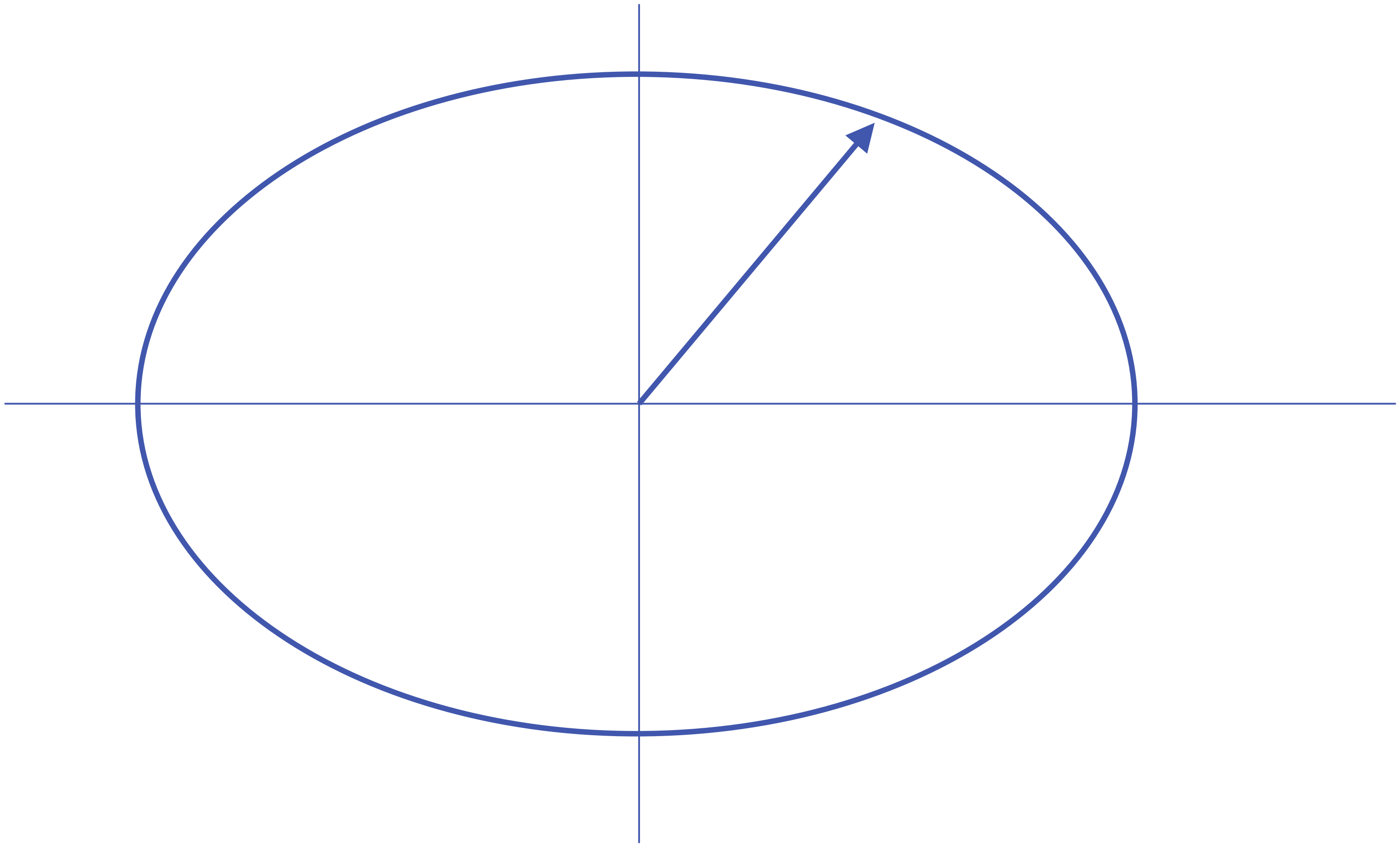
Strobe Light Analogy



IEEE C37.118 Synchrophasor Definition



Off-Nominal Frequency Response of the Fourier Transform



Mathematical Foundation

Phasor Model and Taylor Series Expansion of Model

$$x(t) \approx \sqrt{2}\,\mathrm{Re}\,al(\overline{X}(t) \bullet e^{j2\pi \bullet f \bullet t}) \approx \sqrt{2} \bullet \mathrm{Re}\,al((\overline{X} + \dot{\overline{X}} \bullet t) \bullet e^{j2\pi \bullet f \bullet t})$$

Traditional “Boxcar” Phasor Calculation

$$\overline{Y} = \frac{\sqrt{2}}{N} \sum_{n=-\frac{N}{2}}^{\frac{N}{2}-1} x(n) \bullet e^{-j(n+1/2)\frac{2\pi}{N}}$$

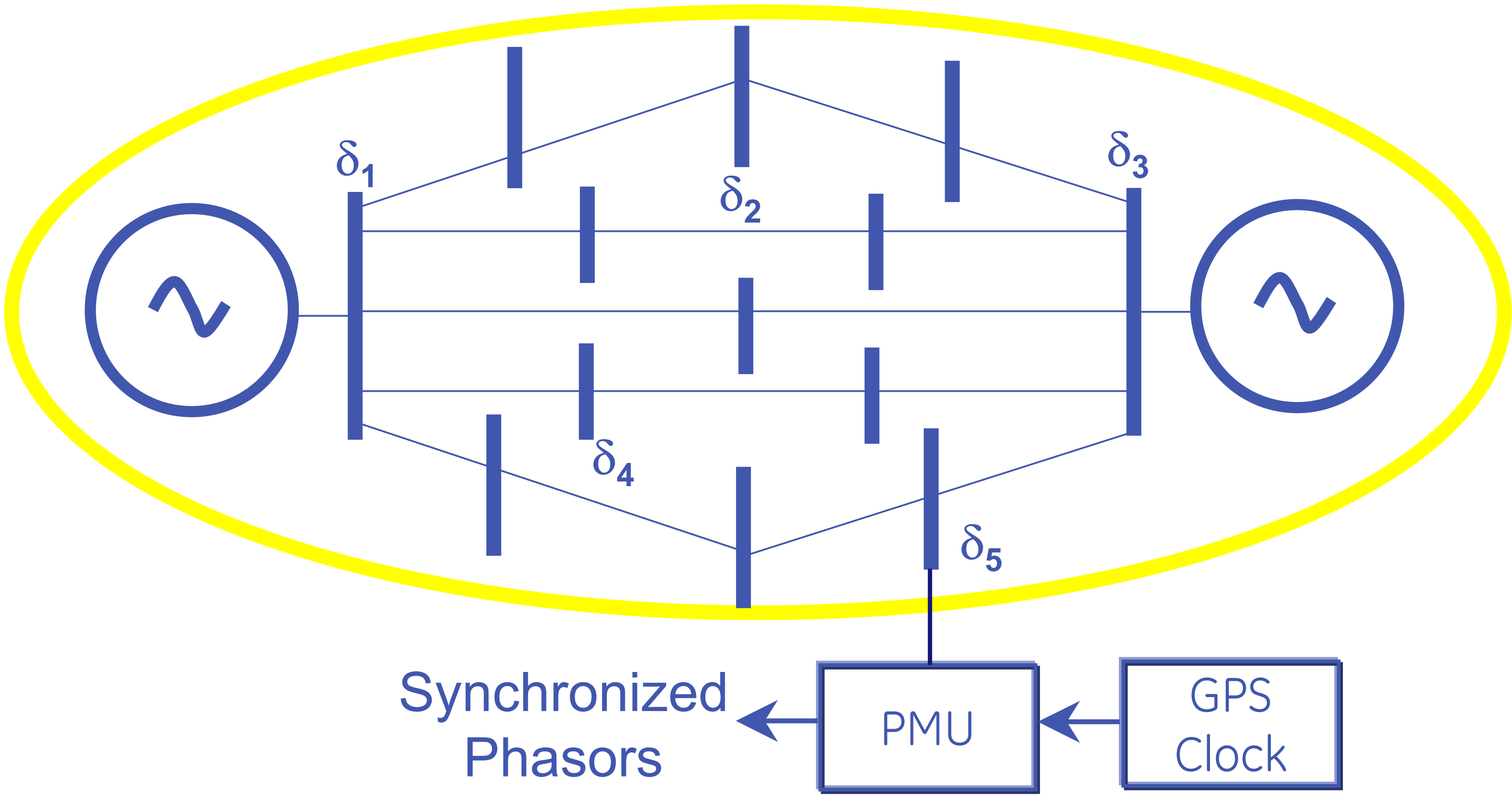
Compensated Synchronized Phasor[1]

$$\overline{X}_M \approx \overline{Y}_M - j \bullet \frac{(\overline{Y}_M - \overline{Y}_{M-1})}{2N \bullet \sin(\frac{2\pi}{N})}$$

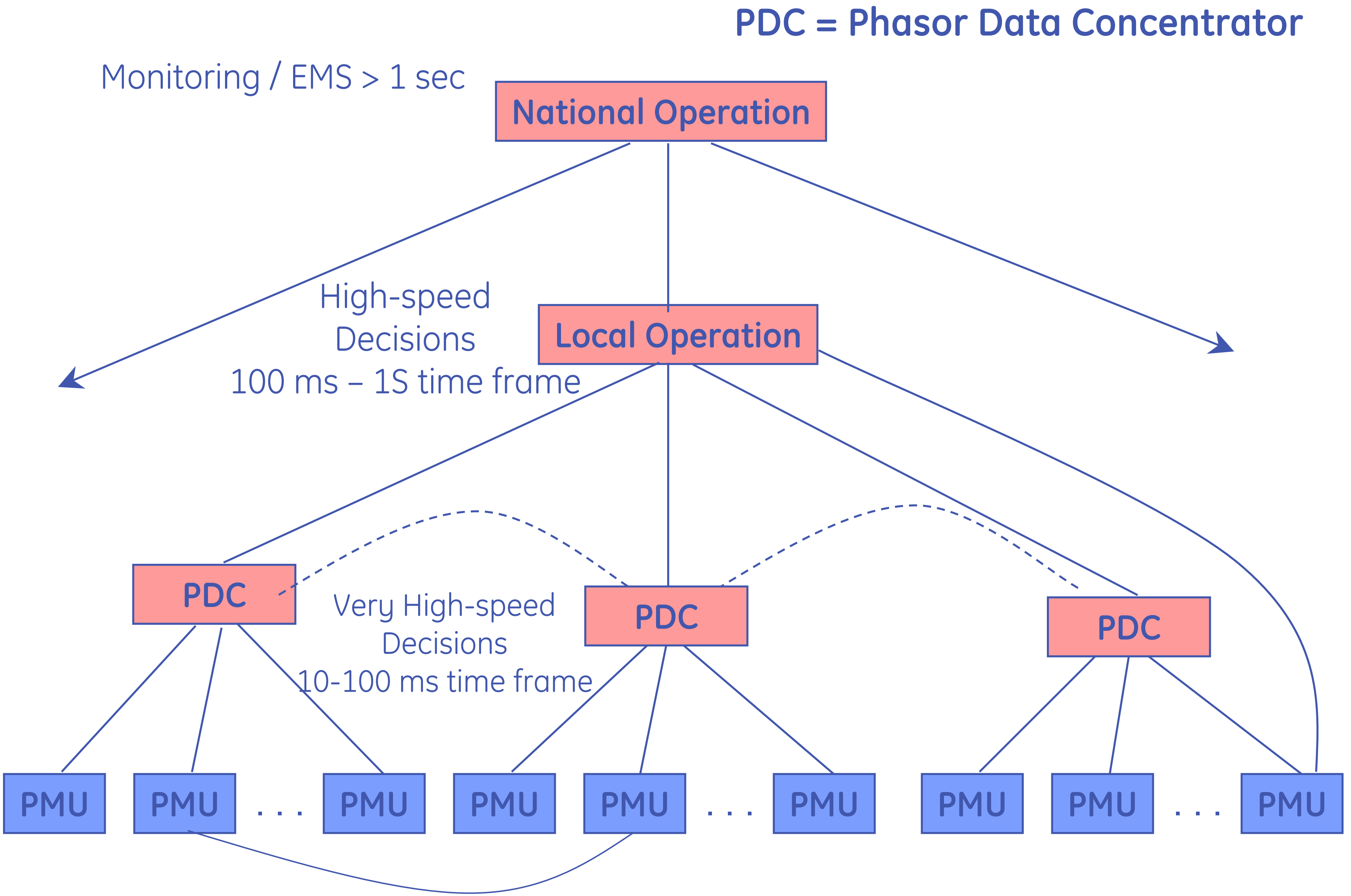
[1] Patented

PMU Implementation

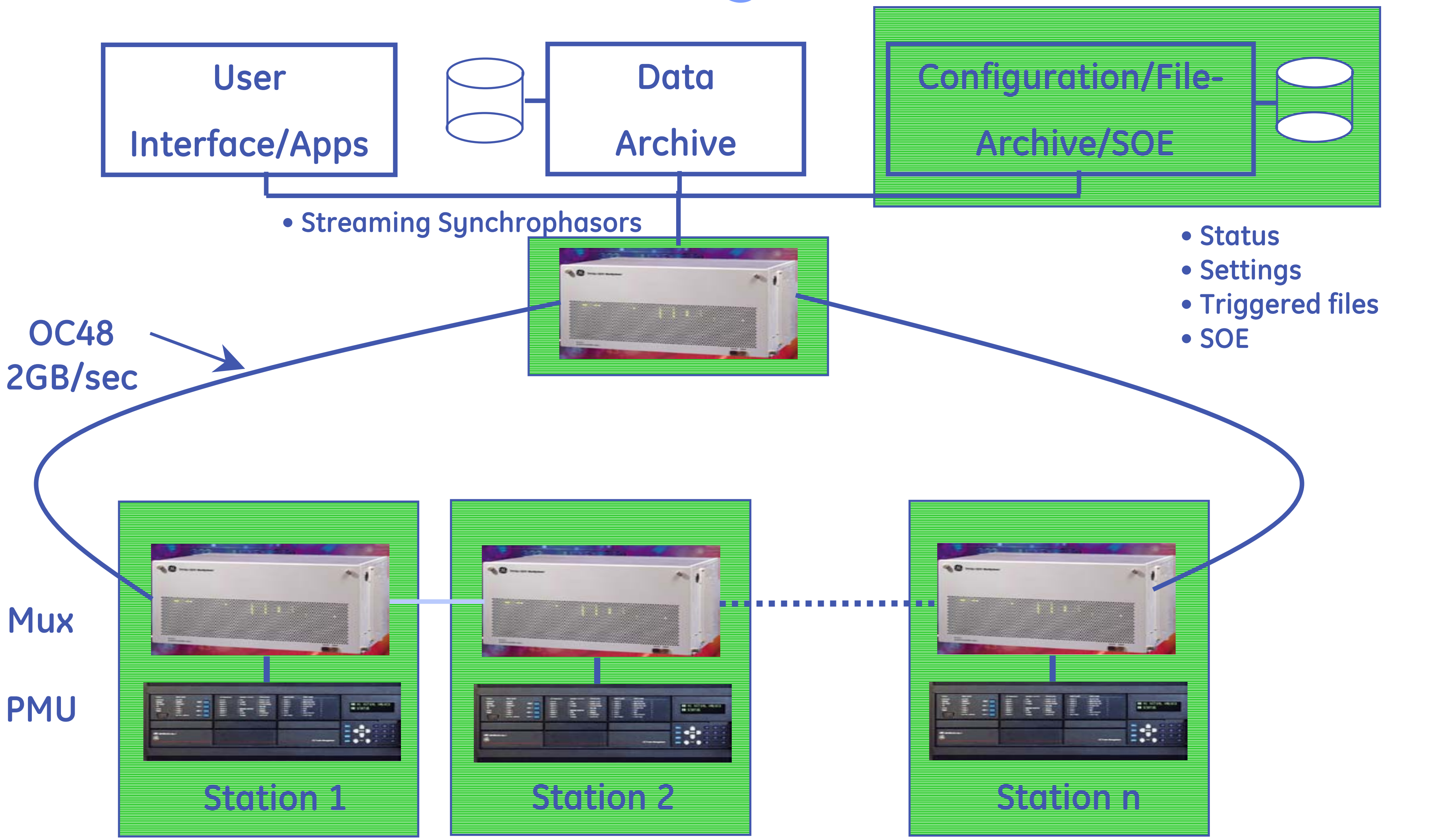
PMU = Phasor Measurement Unit



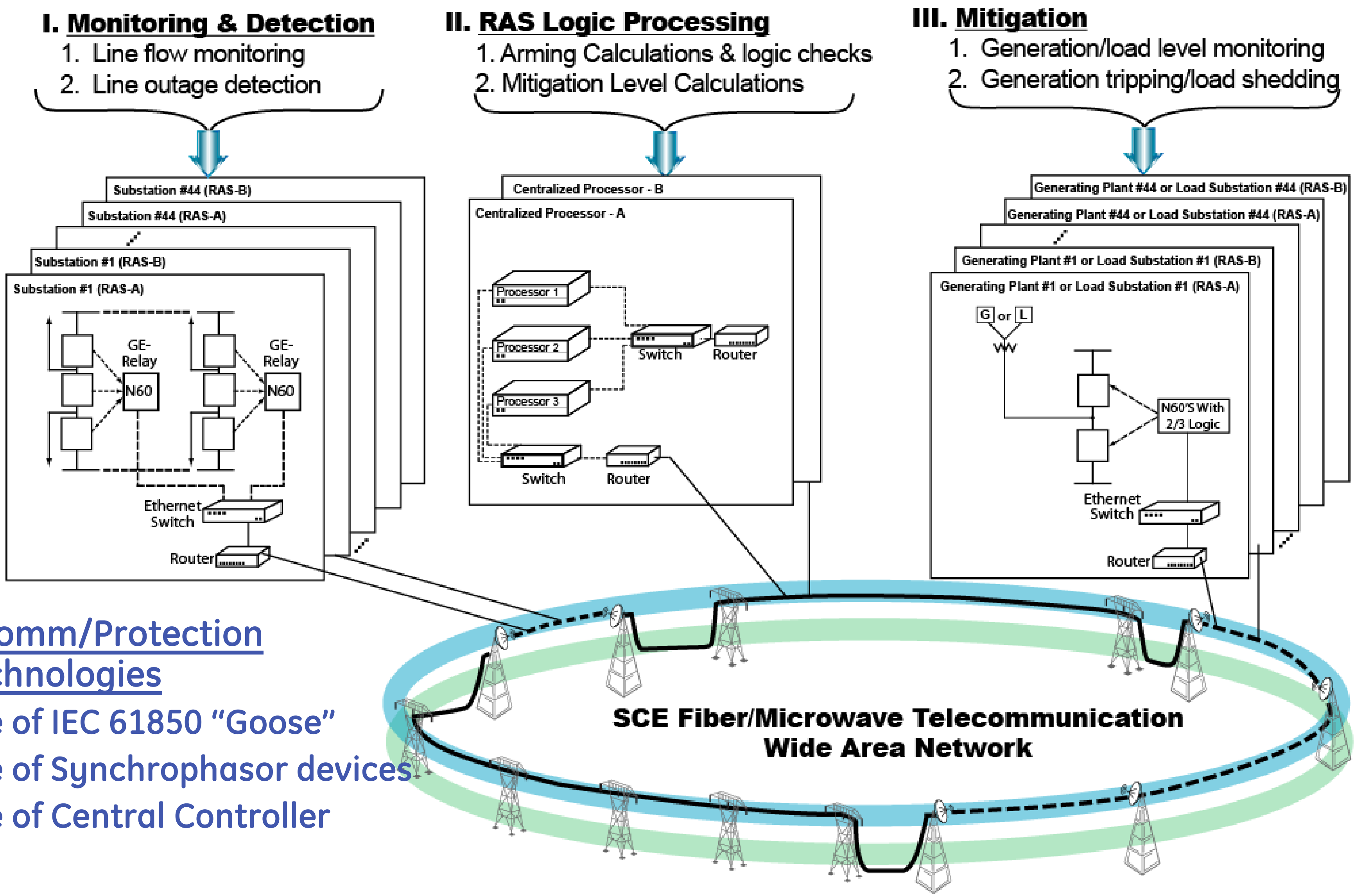
System Integrity Protection Schemes



Synchrophasor System Physical Architecture using SONET



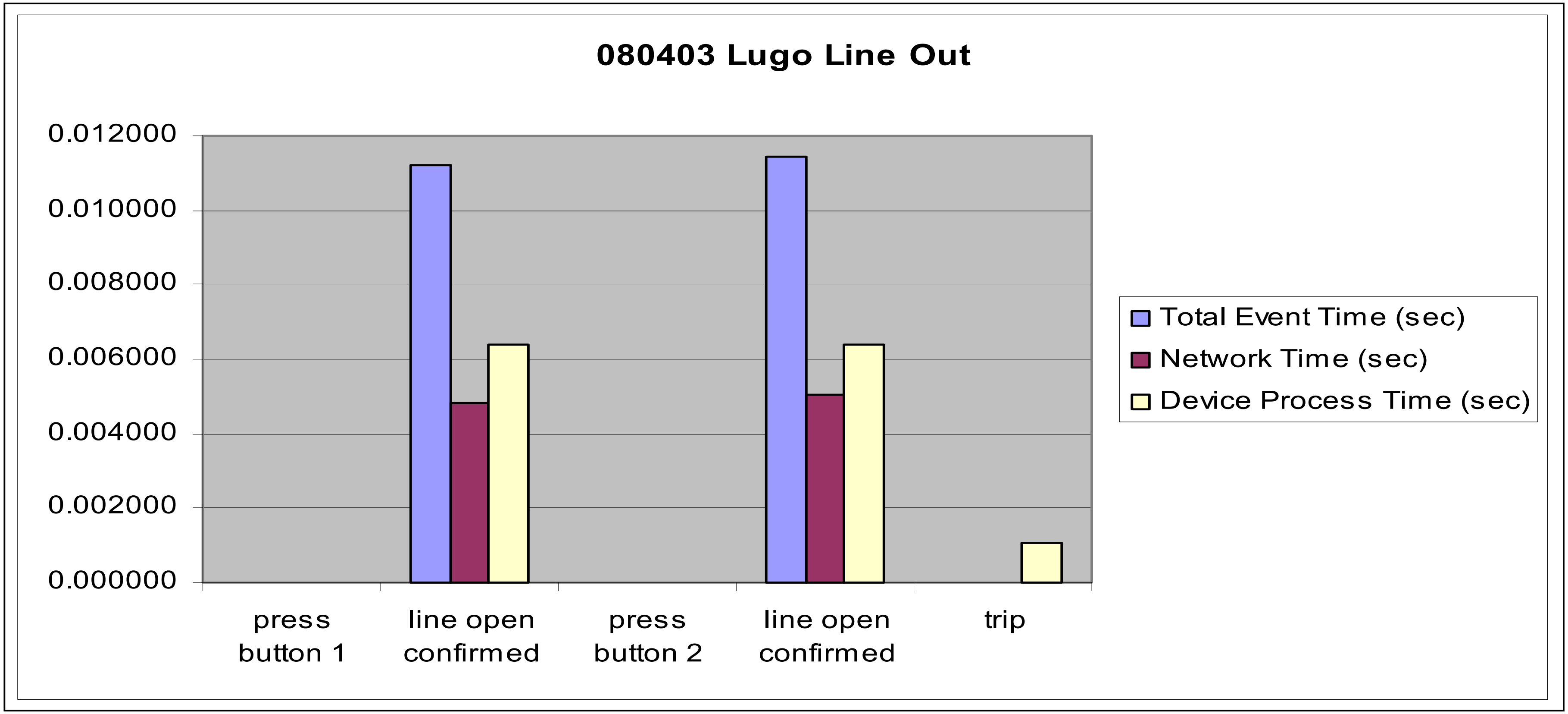
Architecture of the C–RAS Scheme



Telecomm/Protection Technologies

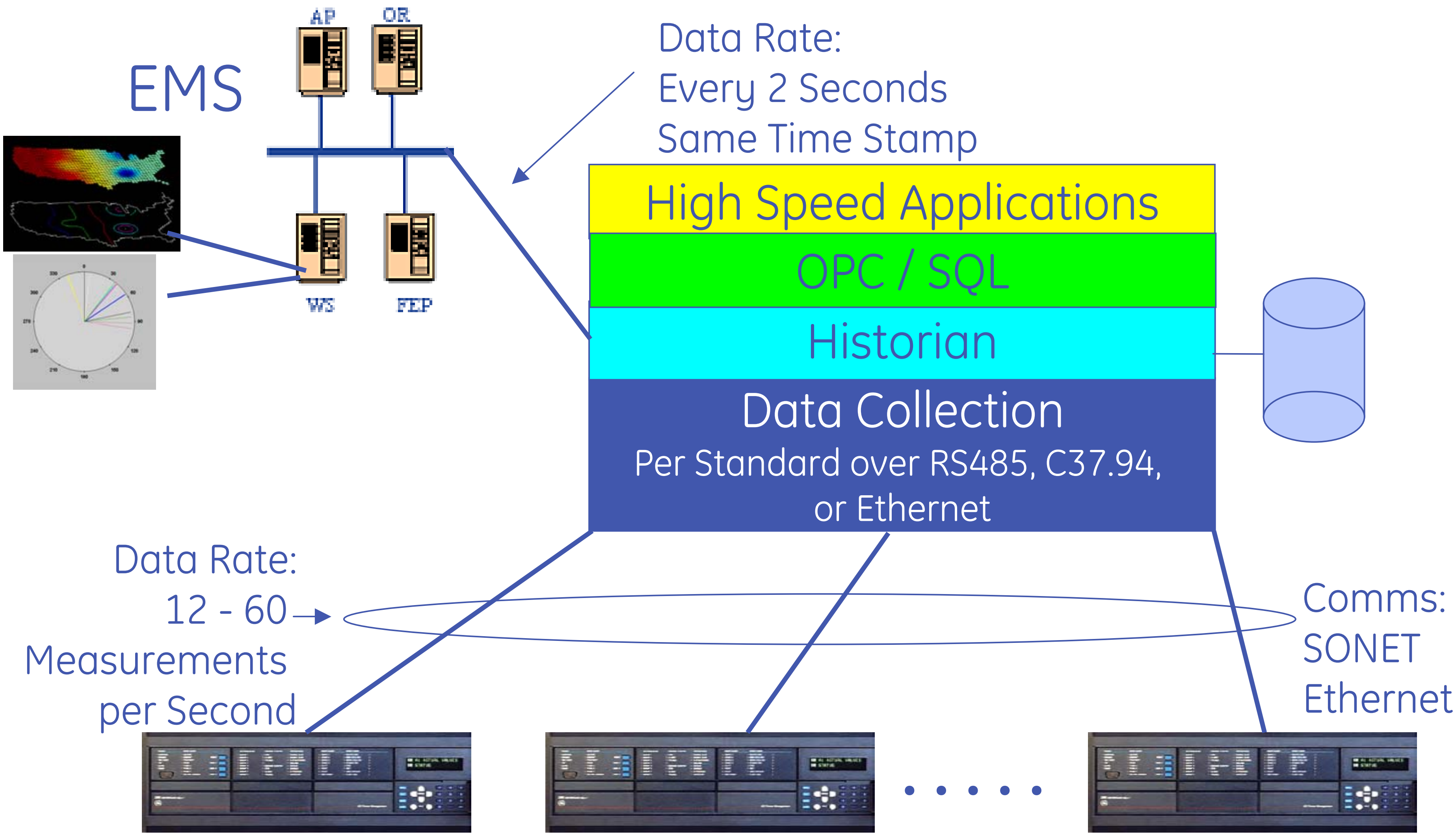
- Use of IEC 61850 "Goose"
- Use of Synchrophasor devices
- Use of Central Controller

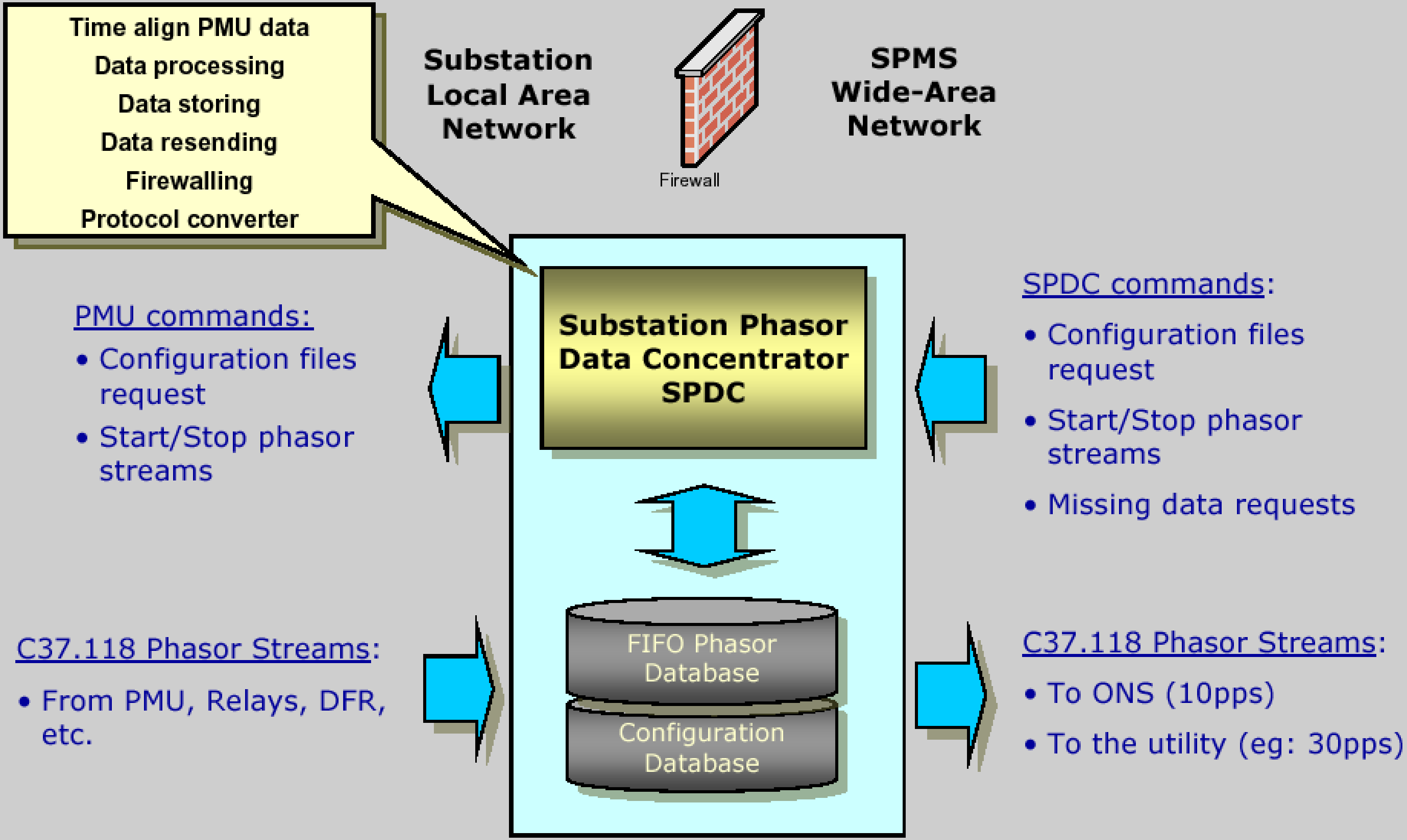
C-RAS Test Results



Less Than 12 ms Round Trip Execution Time

Wide Area Measurement Architecture




Time align PMU data
Data processing
Data storing
Data resending
Firewalling
Protocol converter
Substation Local Area Network
Firewall
SPMS Wide-Area Network
Substation Phasor Data Concentrator SPDC
FIFO Phasor Database
Configuration Database
PMU commands:
• Configuration files request
• Start/Stop phasor streams
SPDC commands:
• Configuration files request
• Start/Stop phasor streams
• Missing data requests
C37.118 Phasor Streams:
• From PMU, Relays, DFR, etc.
C37.118 Phasor Streams:
• To ONS (10pps)
• To the utility (eg: 30pps)

I. Visualization Applications

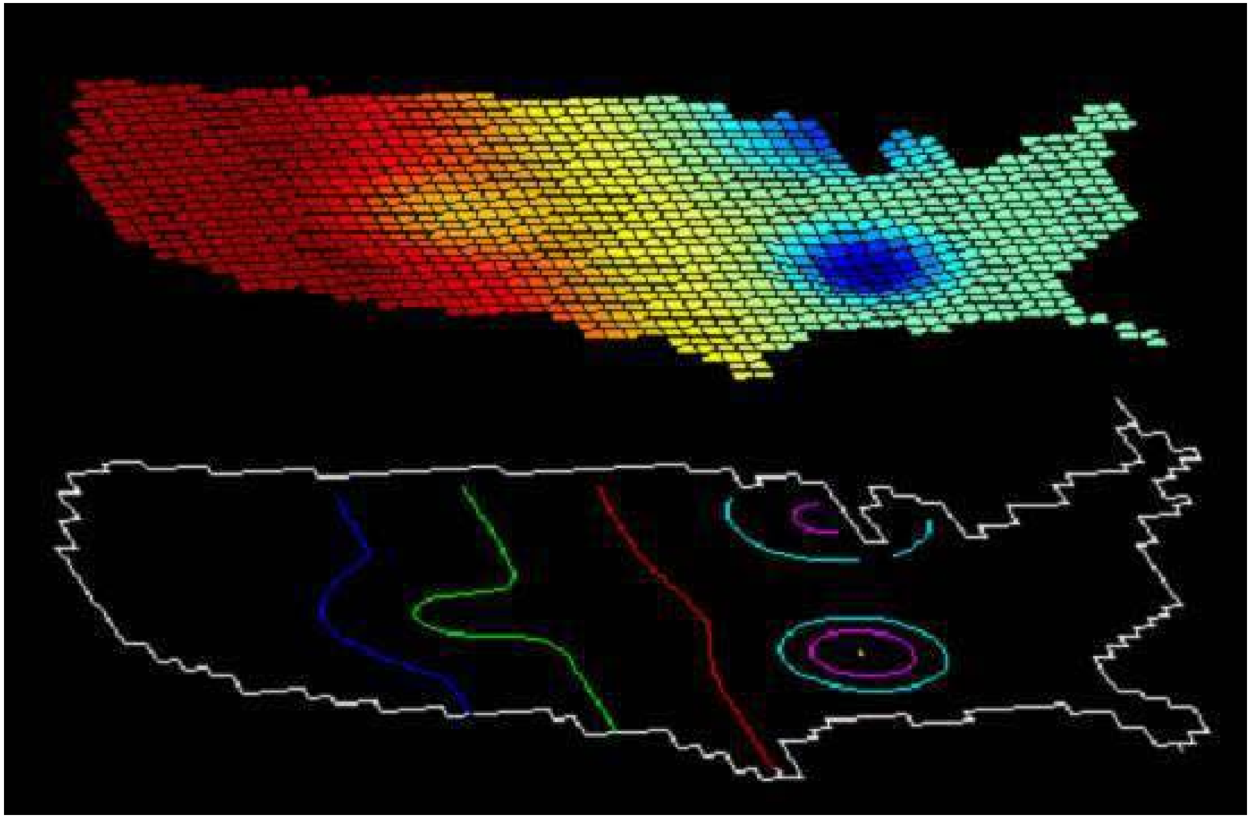
II. Analysis & Control Applications

imagination at work

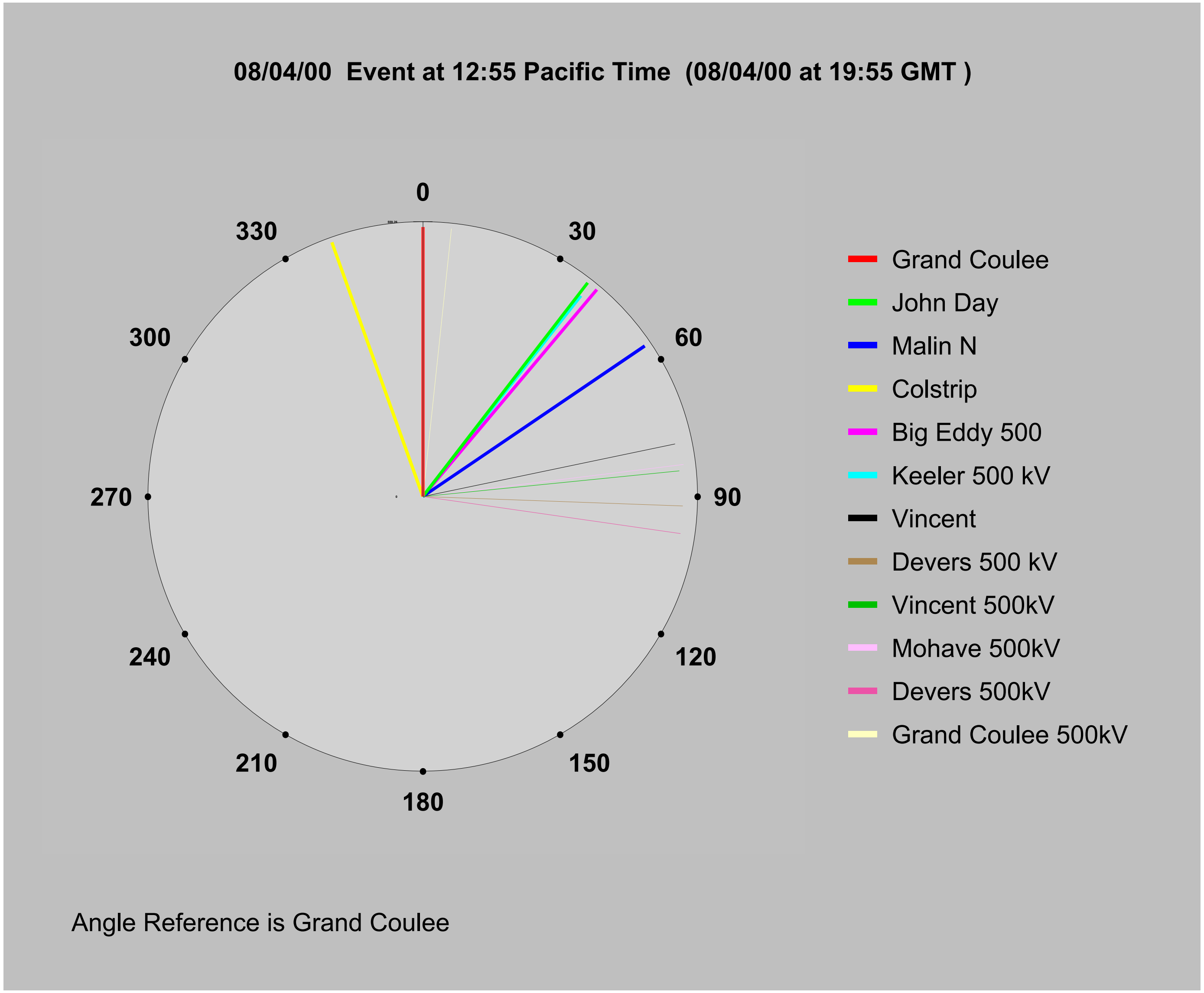
Wide Area System View

Phase Angle

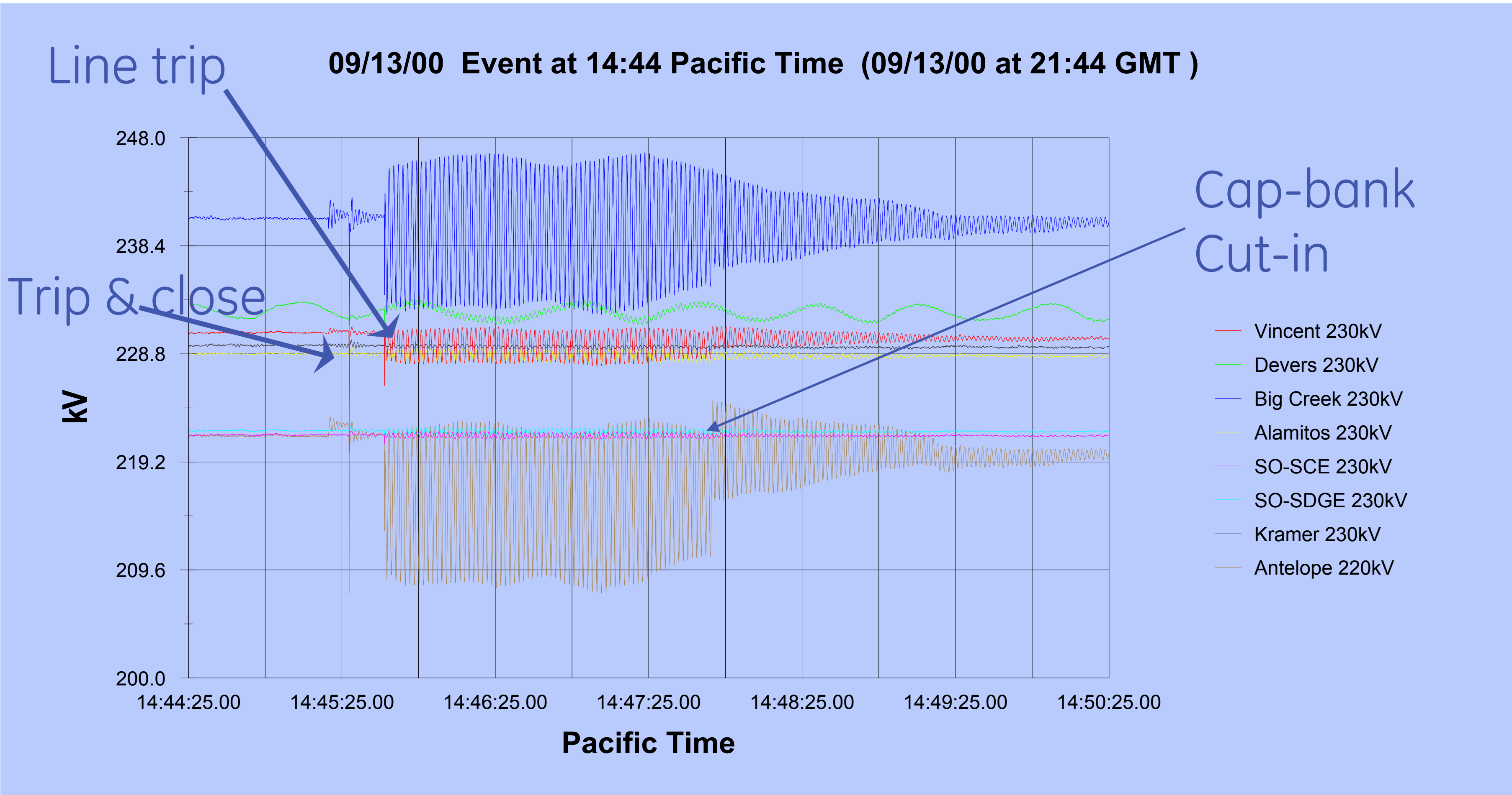
+30
+20
+10
+00
-10
-20
-30



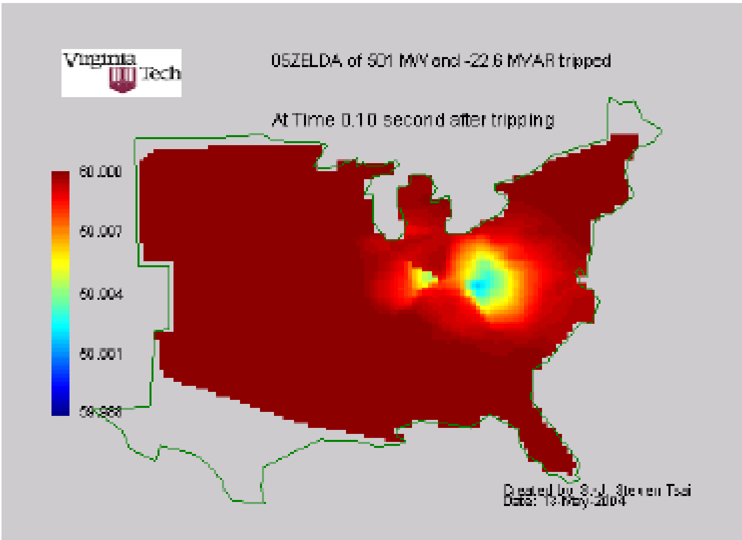
Phasor Viewing

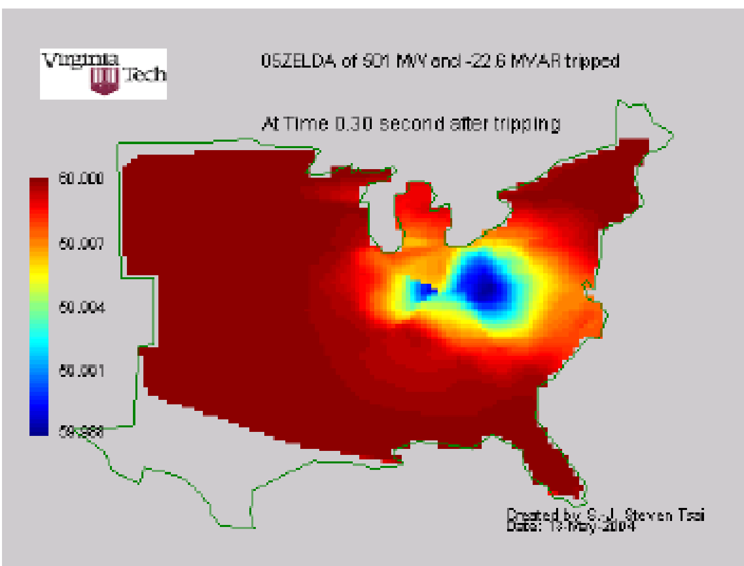


Big Creek System Oscillations of September 13, 2000
Voltage plots for 230 busses



System Frequency View



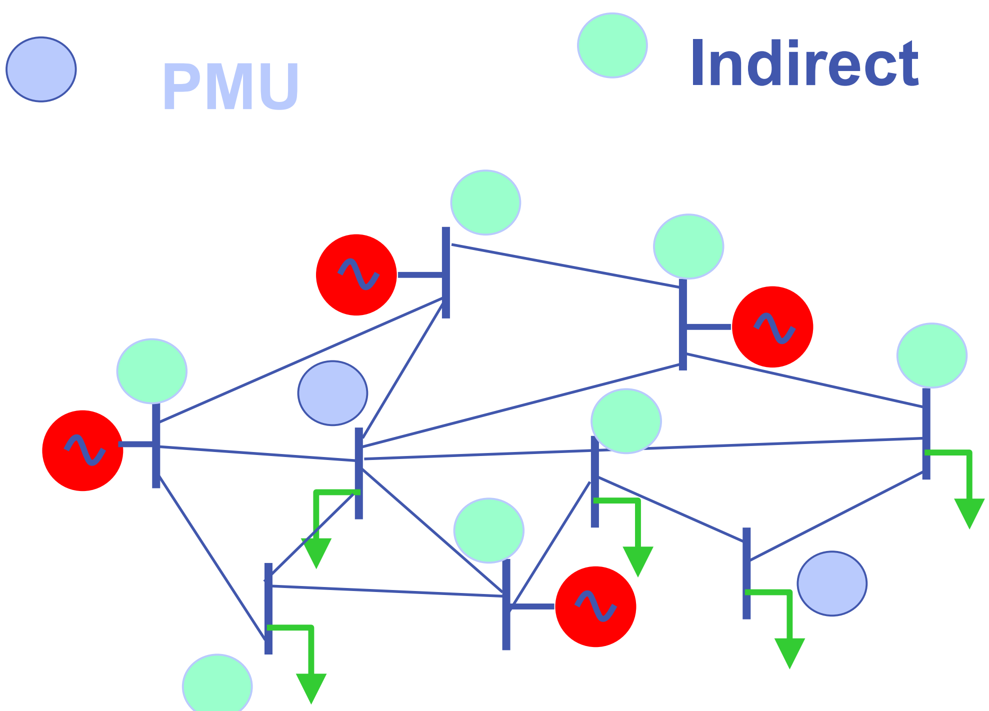


- Frequency – critical parameter for understanding system behavior
- FNET project at VaTech tracks frequency after an event
- Speed of Frequency Wave:
  - 350 Mi/Sec – East
  - 1100 Mi/Sec – WECC
- MW Lost ≈ $\Delta f * 31464$

I. Visualization Applications

II. Analysis & Control Applications

Synchrophasor-Based State *Measurement*

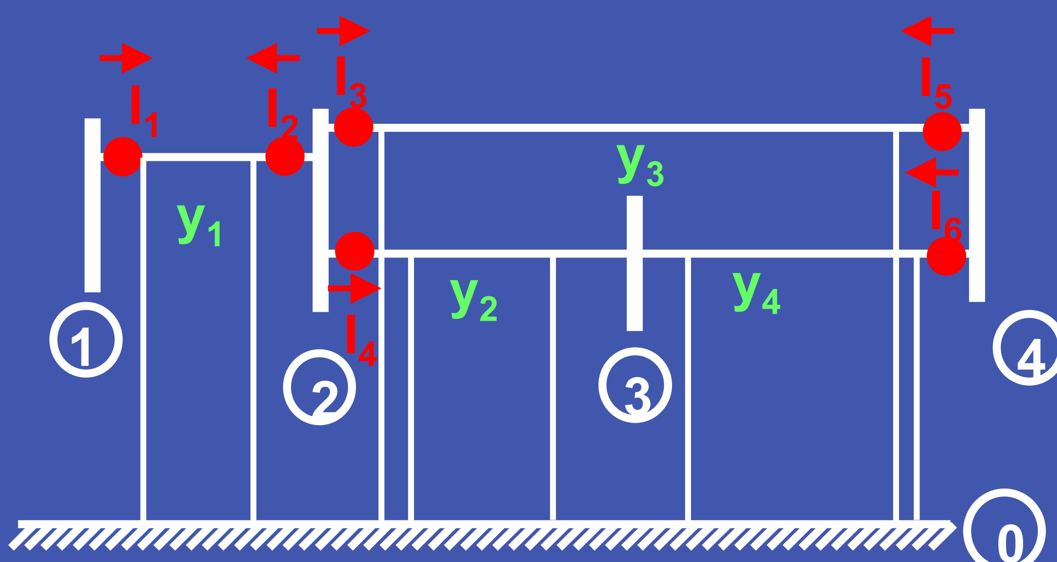


- Linear estimator
- True "simultaneous" measurements
- Complete observability requires PMUs at 1/3 buses
- Incomplete observability possible
- Dynamic update possible
- Foundation for "closed loop" control

State estimation with phasor measurements:

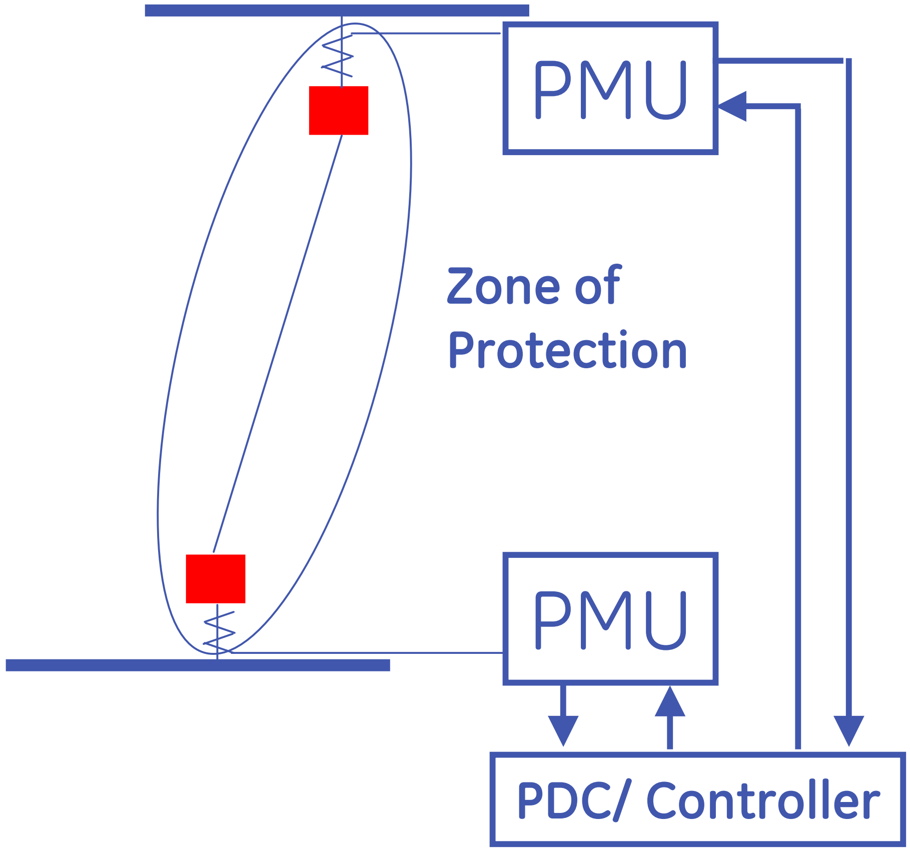
$$\begin{bmatrix} E_1 \\ E_2 \\ E_4 \\ I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ y_1+y_{10} & -y_1 & 0 & 0 \\ -y_1 & y_1+y_{10} & 0 & 0 \\ 0 & y_3+y_{30} & 0 & -y_3 \\ 0 & y_2+y_{20} & -y_2 & 0 \\ 0 & -y_3 & 0 & y_3+y_{30} \\ 0 & 0 & -y_4 & y_4+y_{40} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix}$$

which corresponds to the measurements on the network.



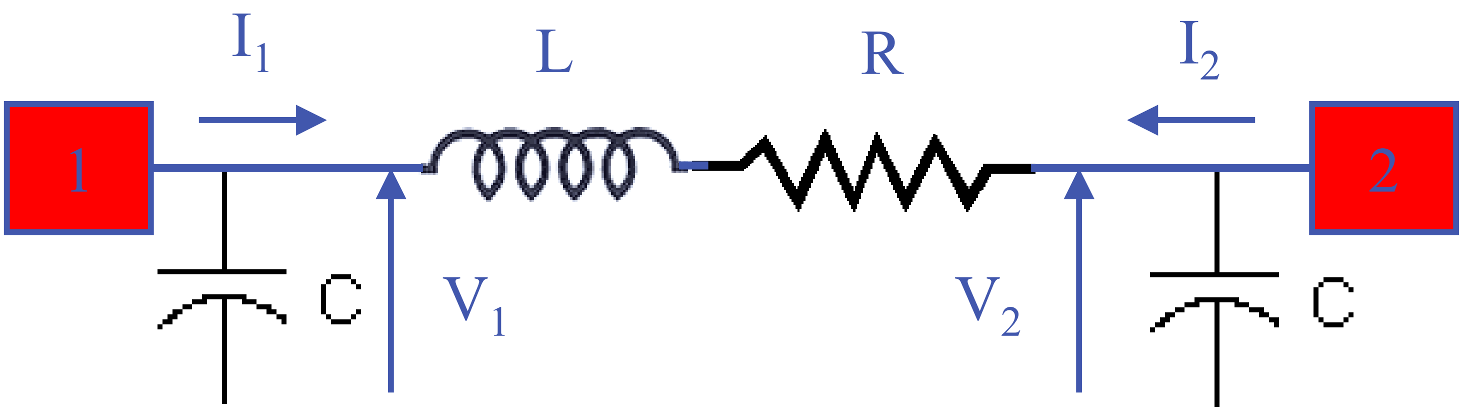
Synchrophasor Based Backup Current Differential

- Hi-Speed data streaming standardized (30-60 phasors/sec)
- Low Communication latency available (7ms as seen previously)
- Precise Zone isolation through current differential protection
- Positive Sequence Current based
- Bonus: Double ended fault location



Addresses NERC Z3 Issue

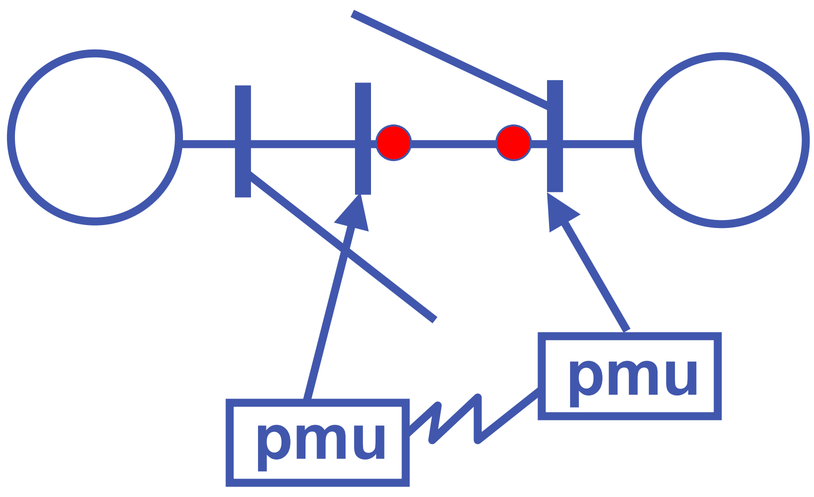
Line Parameter Calculation / Dynamic Line Loading

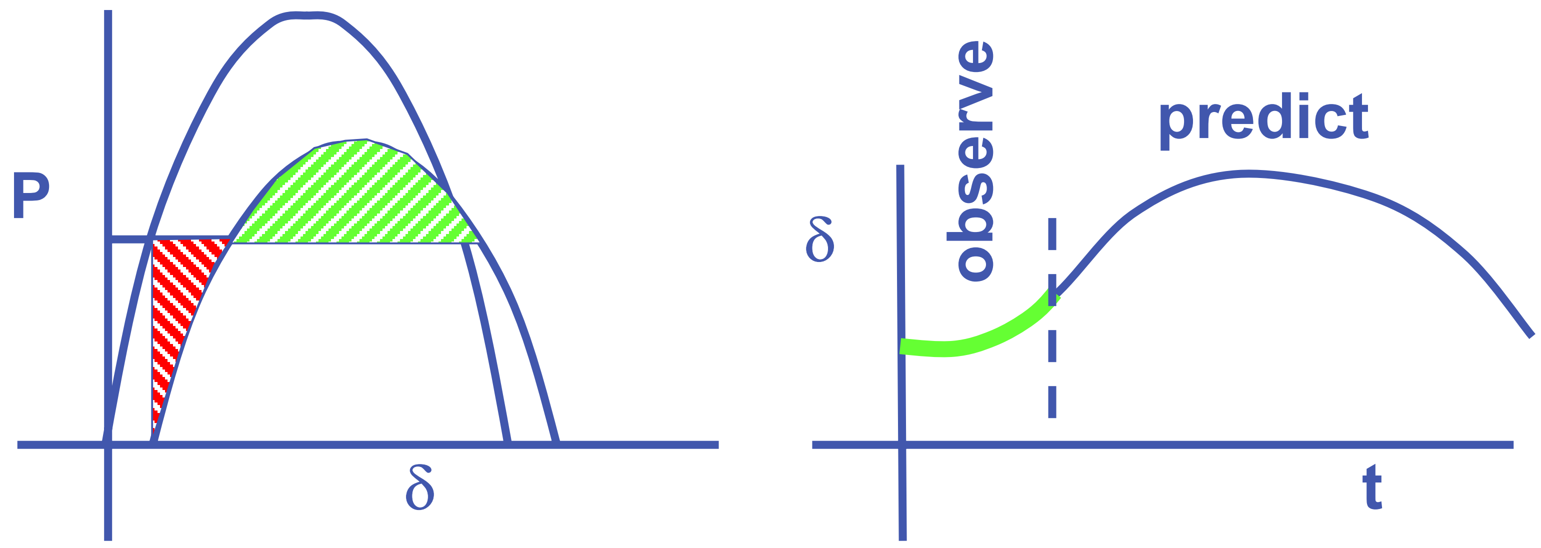


Measure: V_1, I_1, V_2, I_2, $T_{ambient}$
Compute: R, L, C, T_c

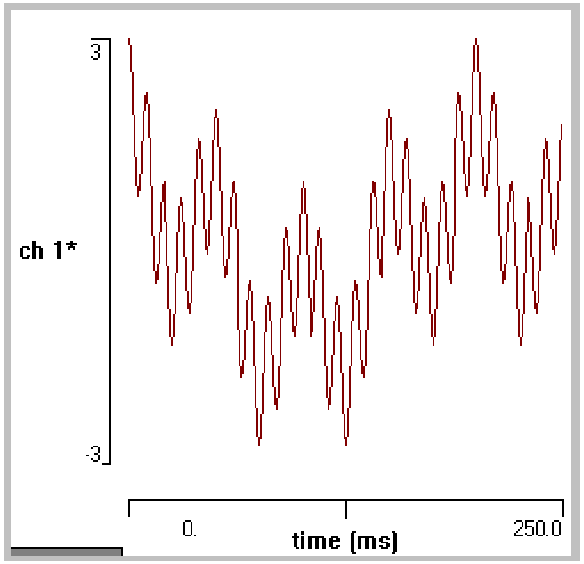
Simple Calculation…High Impact

Adaptive out-of-step relaying

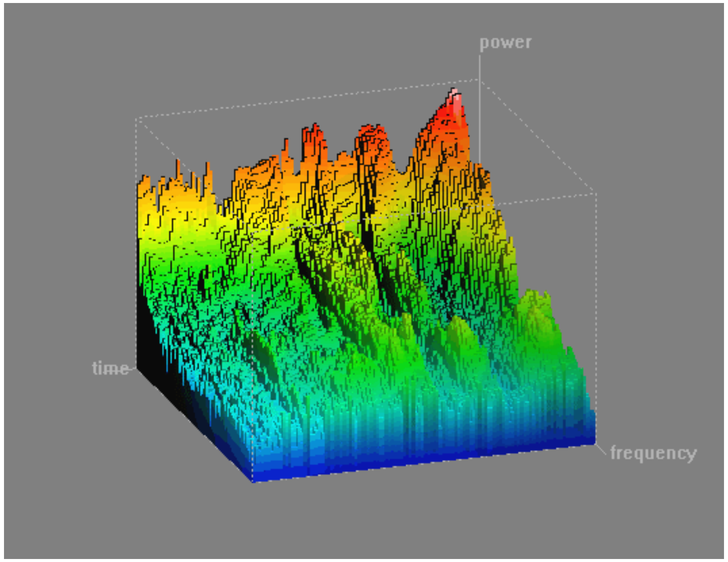




Synchrophasor Spectral Analysis



Fourier Transform

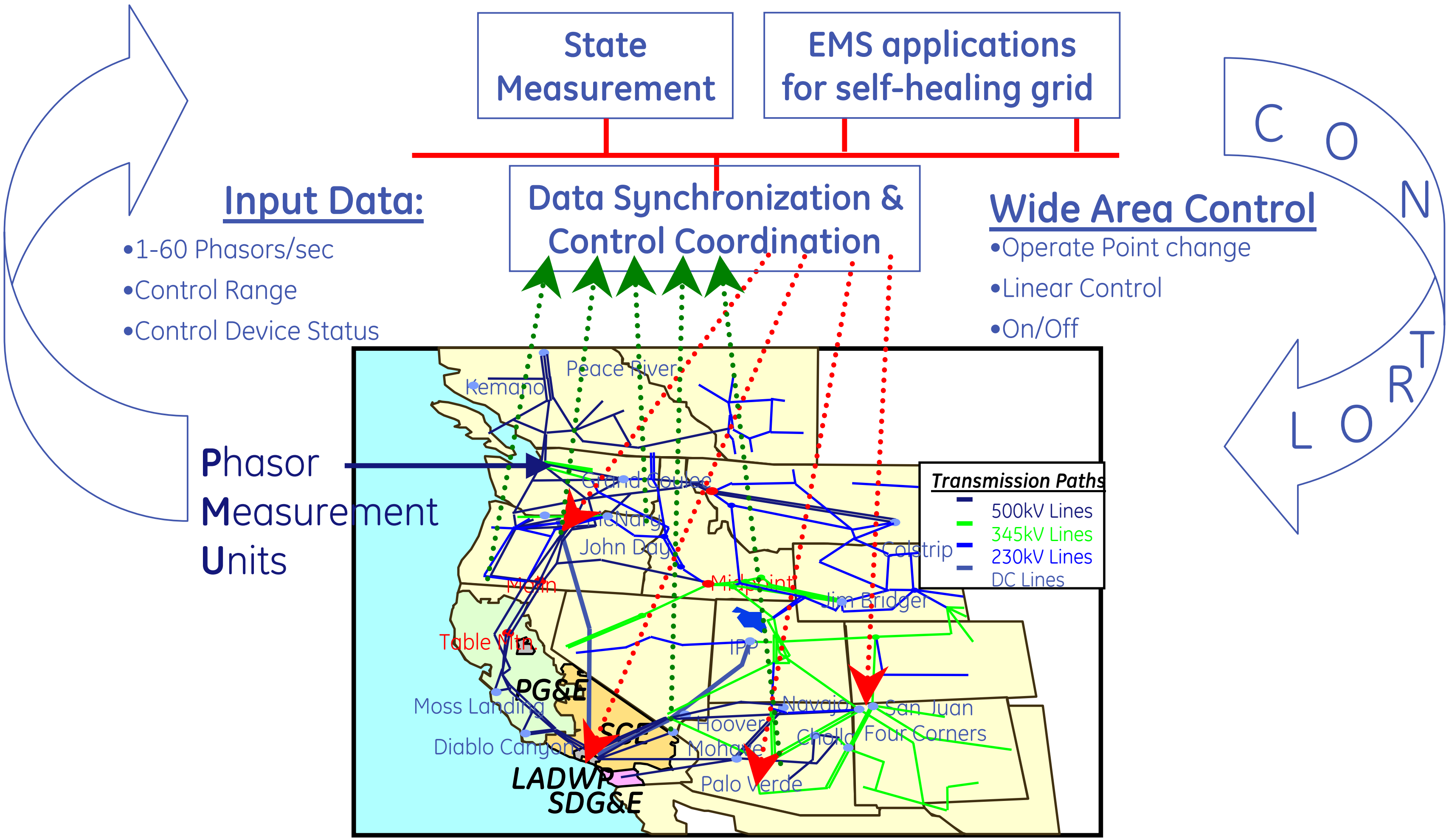


Input: Synchrophasors

Output: Sub-synchronous Modal Analysis

A View into the Pole and Zeros of the Power System

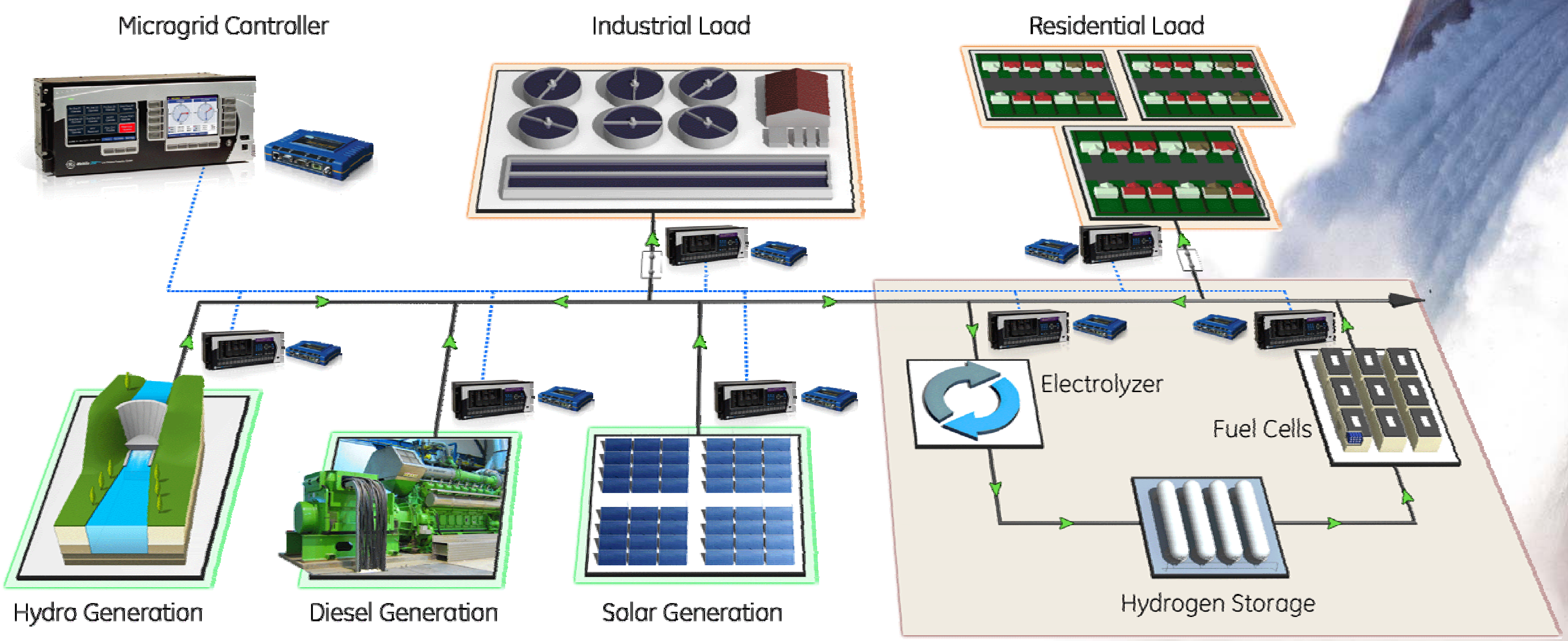
Wide Area Monitoring and Control



DER & Microgrid Control

Microgrid Controllers optimizes site generation

- Selects the most cost effective generation available to support the load
- Optimizes green power by dispatching power storage when excess generation is available
- Indicates amount of energy in storage (Fuel Cell and Diesel)



1.2MW Battery on the AEP System

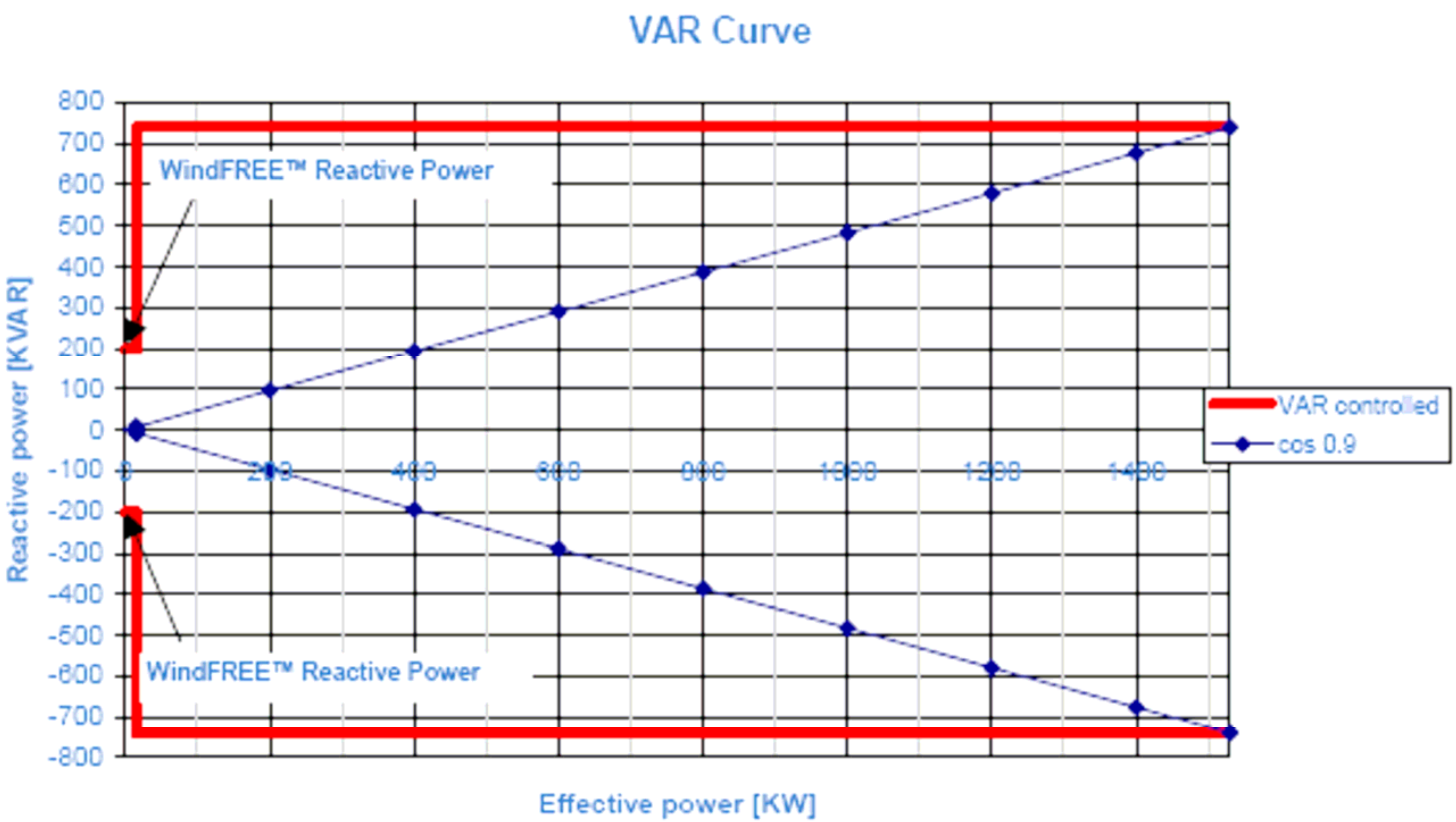
Challenge: Protection in an inverter-based environment

Protection of Inverter-based Sources Options:

- Require inverter current outputs capable of 3x load
  - Adds expense to the inverter
- Migrate to voltage-based protection
  - Issue on selectivity
- Migrate to directional Overcurrent protection
  - Requires a communication channel
- Incorporation of a MicroGrid Protection Coordinator

Adaptive Protection Provides the Most Flexibility

GE 1.5 MW Reactive Capability

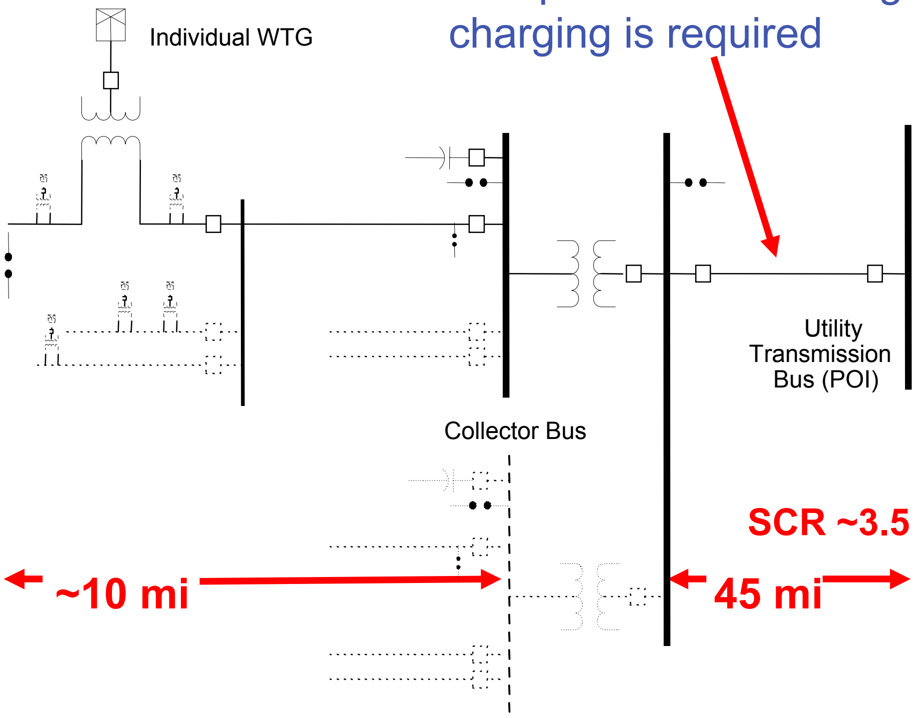


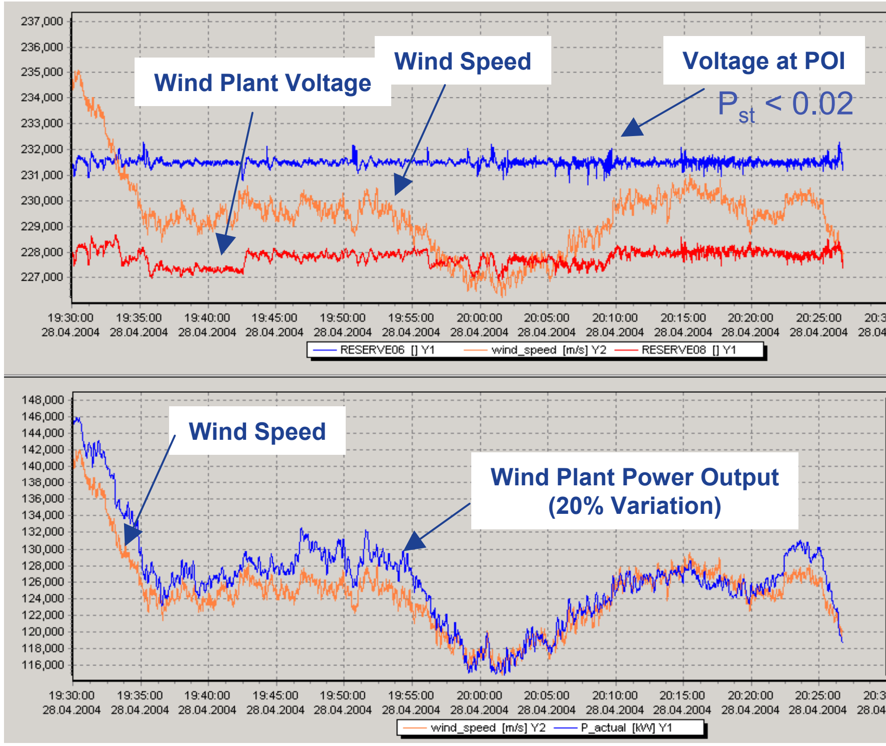
WindFREE™ option allows partial reactive capability when wind is below cut-in

Grid Voltage Regulation via Wind Control

Actual measurements from a GE 162MW wind power plant.

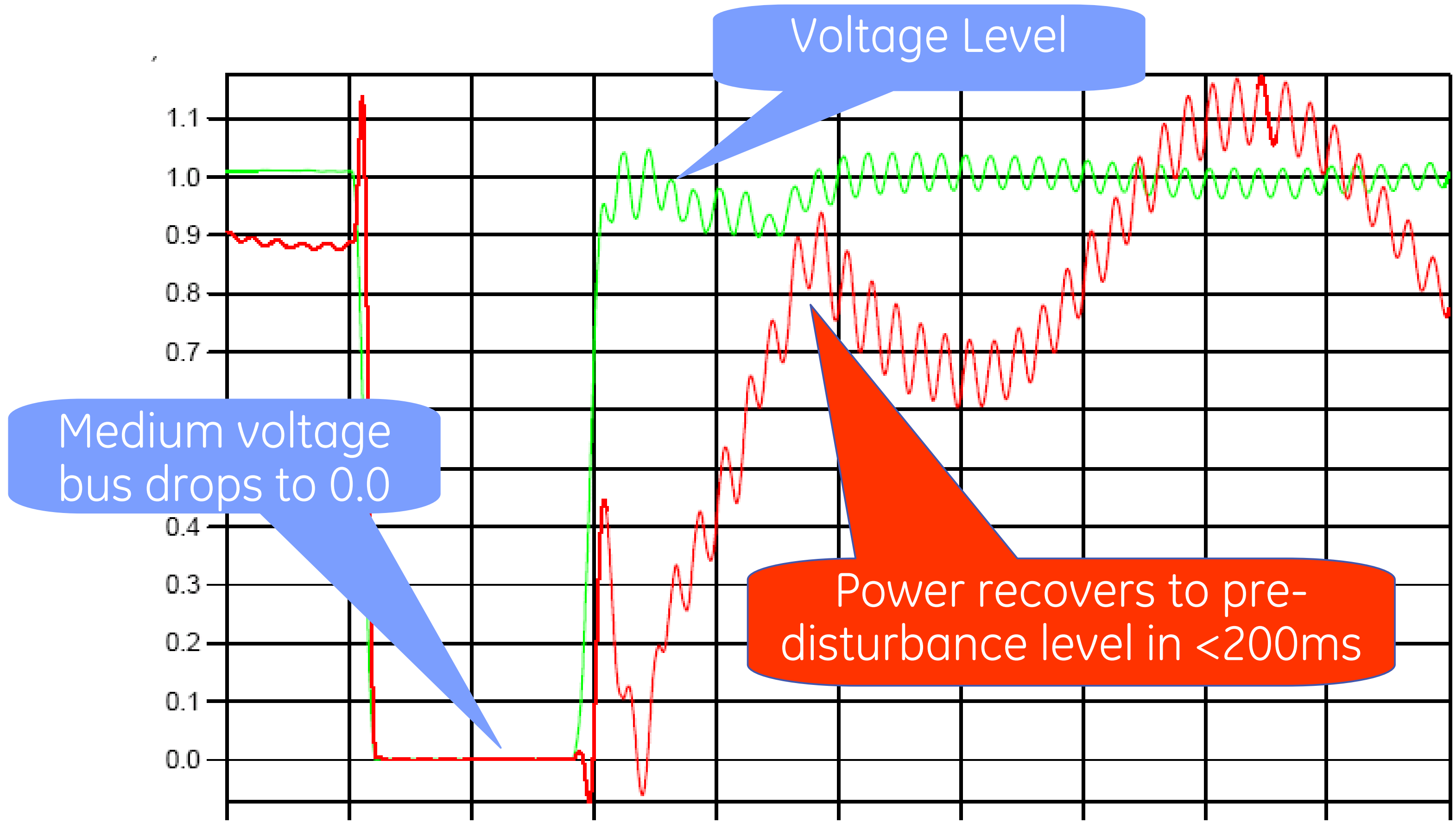
Compensation including charging is required





Control system coordinates wind turbine reactive output to regulate remote grid voltage

3-Phase, 200ms, Zero Voltage Fault

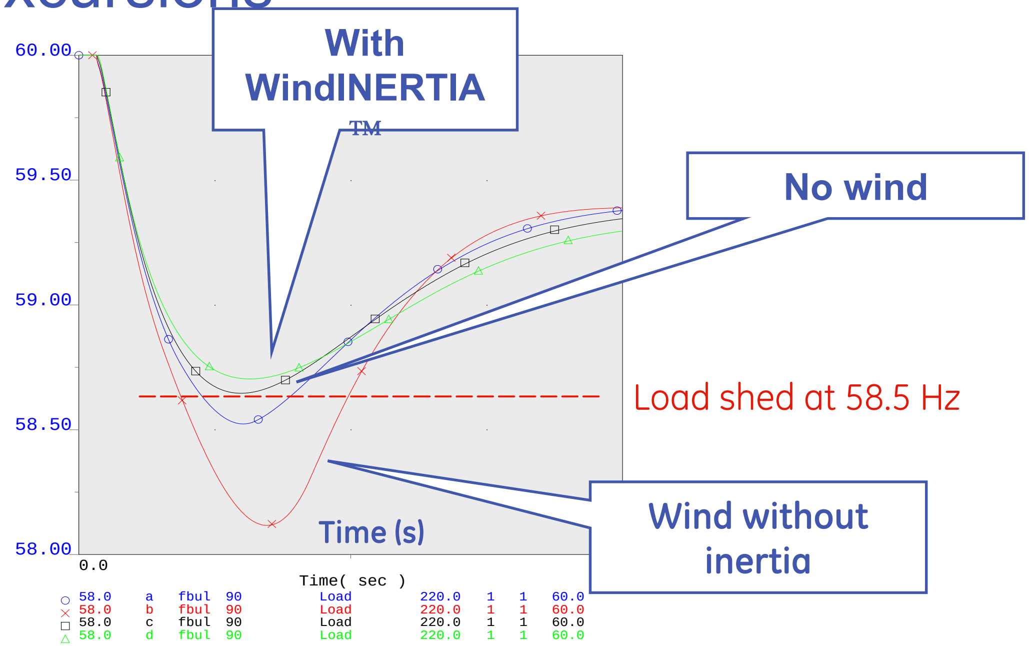


Active Power (delivered to Medium Voltage bus)

From WINDTEST report WT5491/06
Bexten Wind Plant
Three and Two Phase faults of various depths and durations

Wind Inertia

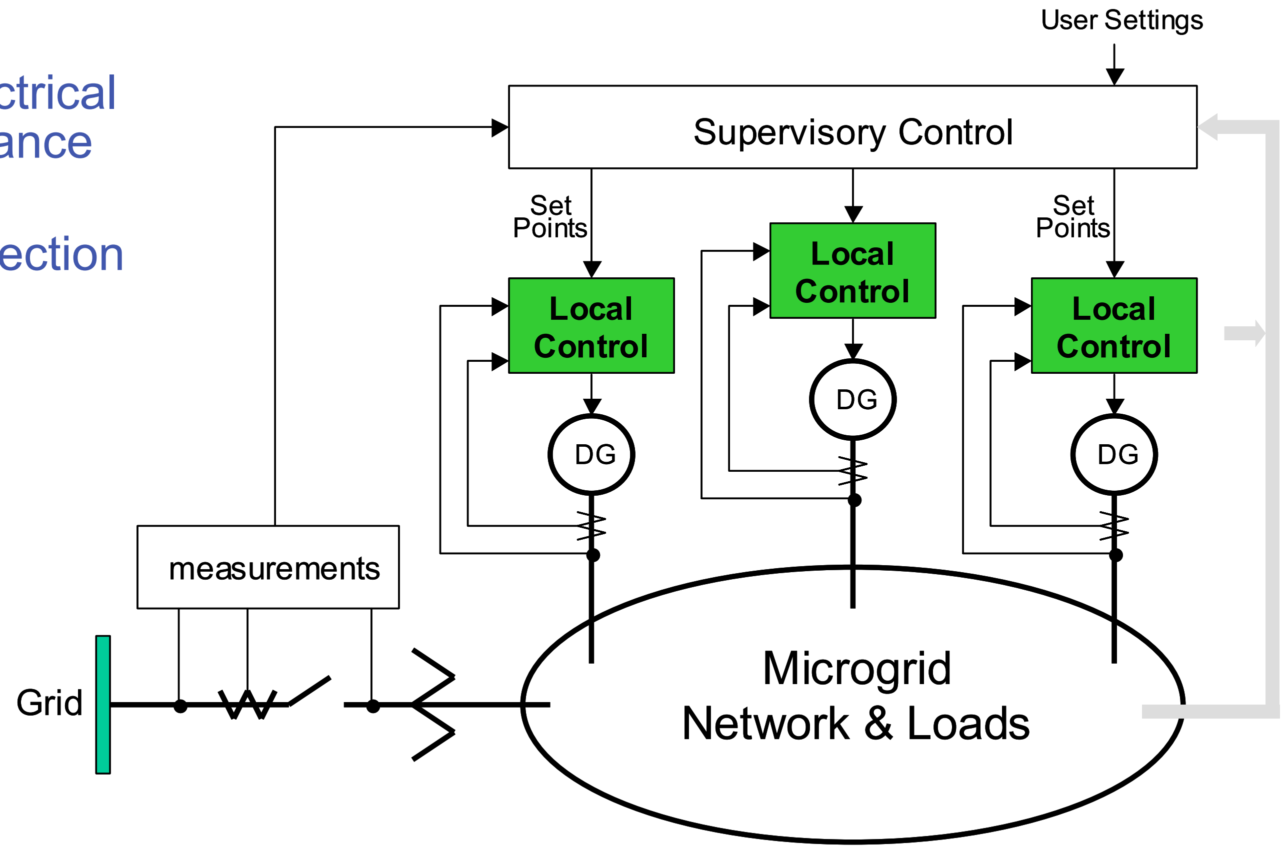
- > Controllable variable speed allows “borrowing” of energy stored drive train inertia
- > Programmed to appear to the grid as a “virtual inertia” of H = 3.5
  - – Power pulse of 5% - 10% of rated for up to 10 seconds
  - – Will only respond to large (-0.5 Hz) downward frequency excursions



Technical Approach

Supervisory Controls

- Used to optimize electrical and thermal performance and cost
- Manage feeder connection to bulk grid
- Manage renewable intermittency



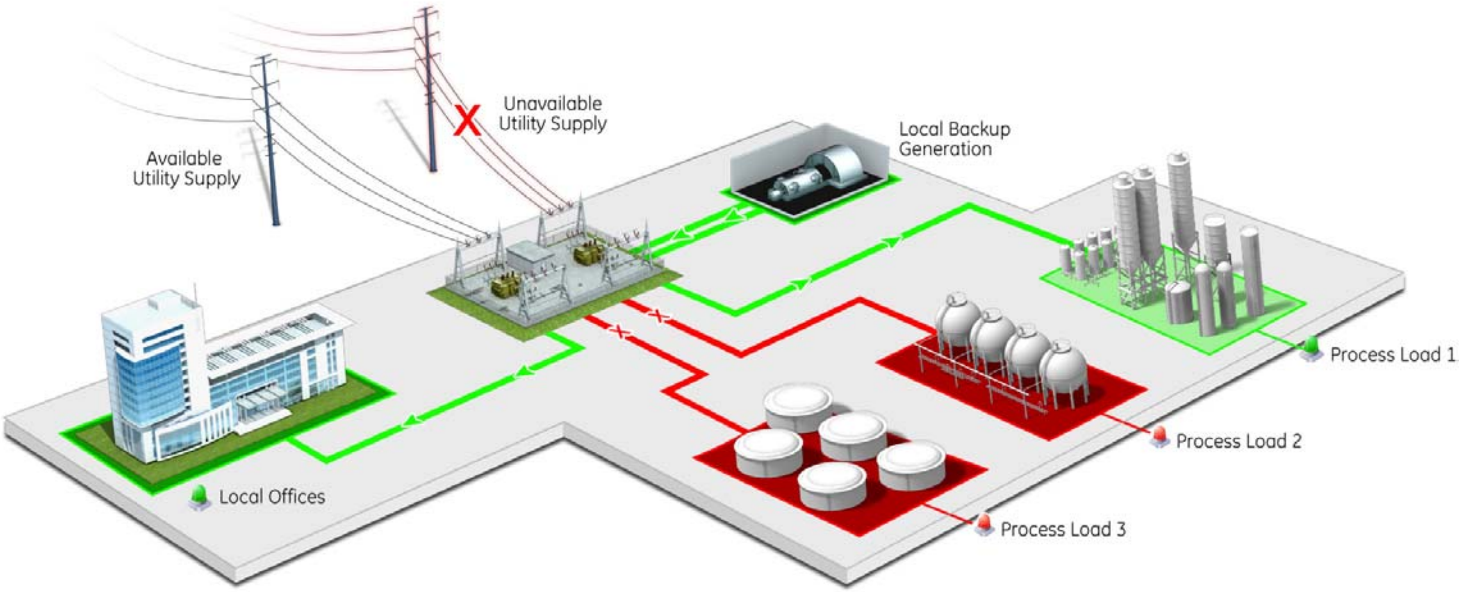
Local Controls

- Control response based on local measurements.
- Robust response to system disturbances and supervisory level commands.
- Provide inherent stability and load sharing for grid independent and grid interactive connections.

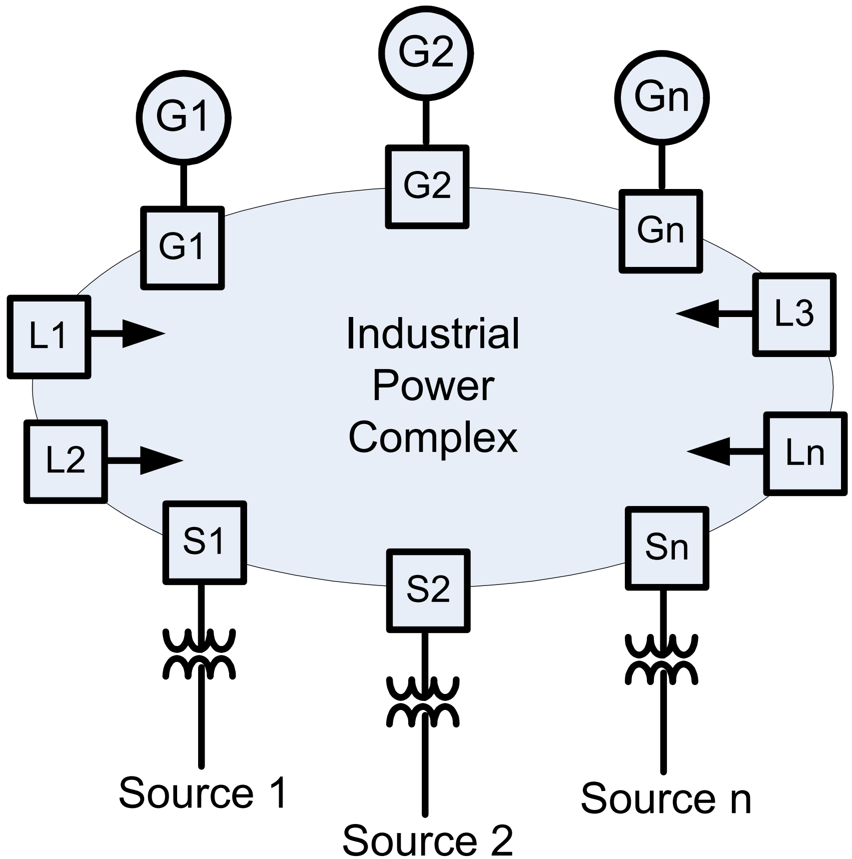
Industrial Load Shedding

Load Shedding solutions to keeps critical processes running

- Identifies when there is a lack of power to supply required load
- Dynamically sheds least critical loads to keep processes essential to the business running



Load Shed Model



$$Load = P_{G1} + P_{G2} + \ldots + P_{Gn} + P_{s1} + P_{G2} + \ldots + P_{Sn}$$

$$Generation = P_{G1} + P_{G2} + \ldots + P_{Gn}$$

$$Load\,(Generation)\,shed = Load - (Generation + Spinning\ \mathrm{Re}\,serve)$$

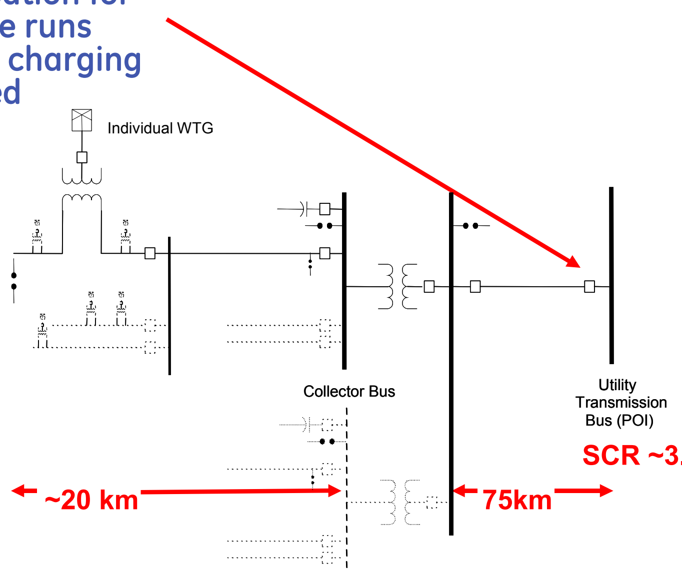
Microgrid Control System Features

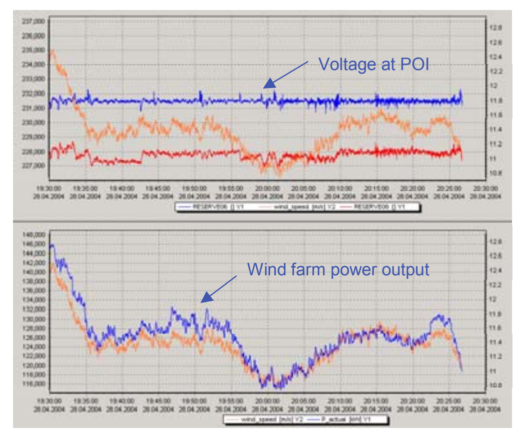
3. Tie Line Control – *Distributed Energy Resource Aggregation*

- Energy aggregation: To the grid, the aggregated distribution system looks like one well-behaved dispatchable energy resource
    - Active and reactive power
    - Power ramp rate limits
    - Ancillary services (voltage/VAR regulation, frequency droop…)

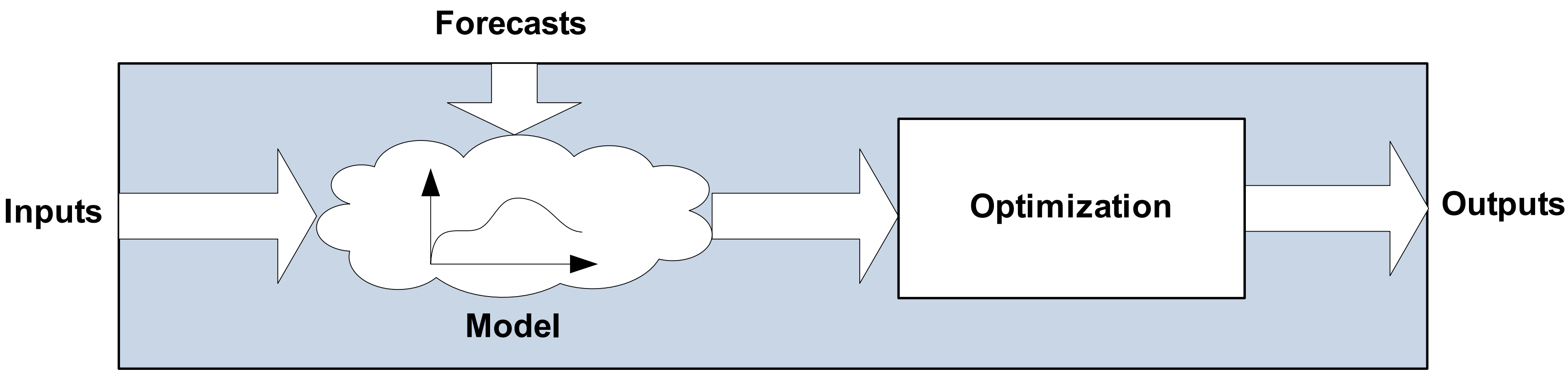
Example: Windfarm tieline Control

POI 75 KM away! Compensation for long cable runs including charging is required





Optimal Dispatch via Model Predictive Control



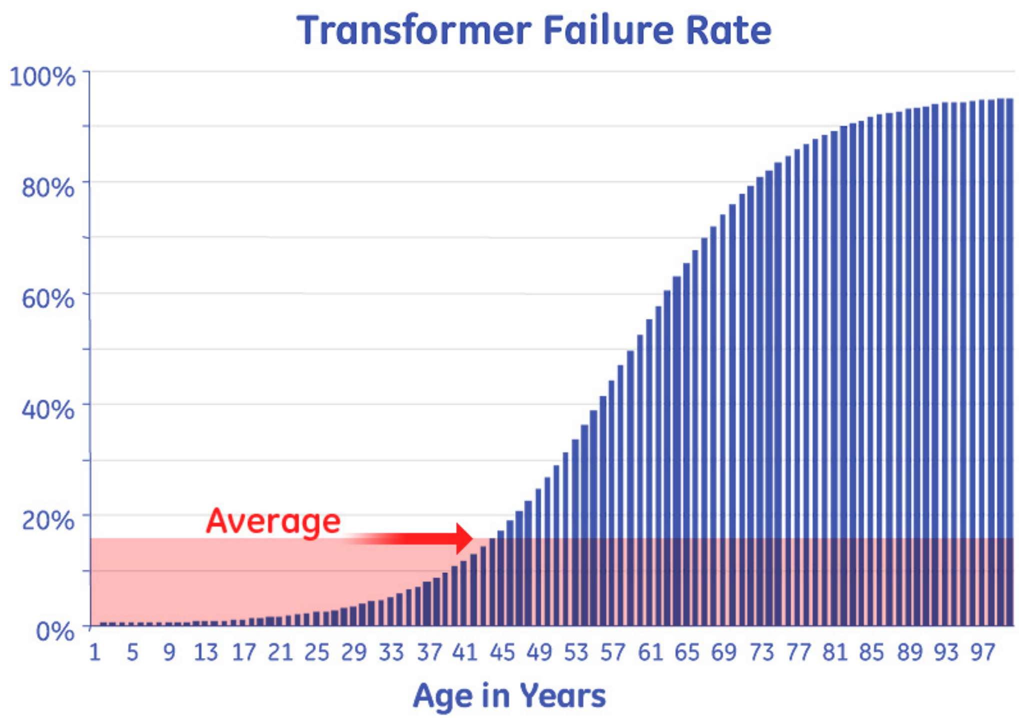
$$Cost = \sum_{n=1}^{N} \left(\sum_{i=1}^{I} Pd_{ni} \cdot \eta d_{ni} \cdot cd_{ni} + \sum_{j=1}^{J} Pso_{nj} \cdot \eta so_{nj} \cdot cso_{nj} + \sum_{k=1}^{K} Psi_{nk} \cdot \eta si_{nk} \cdot csi_{nk} \right)$$

Where: **Pd** is power out of a dispatchable generator
Pso is power out of a storage element
Psi is power into a storage element
η**d**, η**so**, and η**si** are efficiencies for each of the above
cd, **cso**, and **csi** are costs for each of the above

Technology Advancements

Aging infrastructure reduces reliability

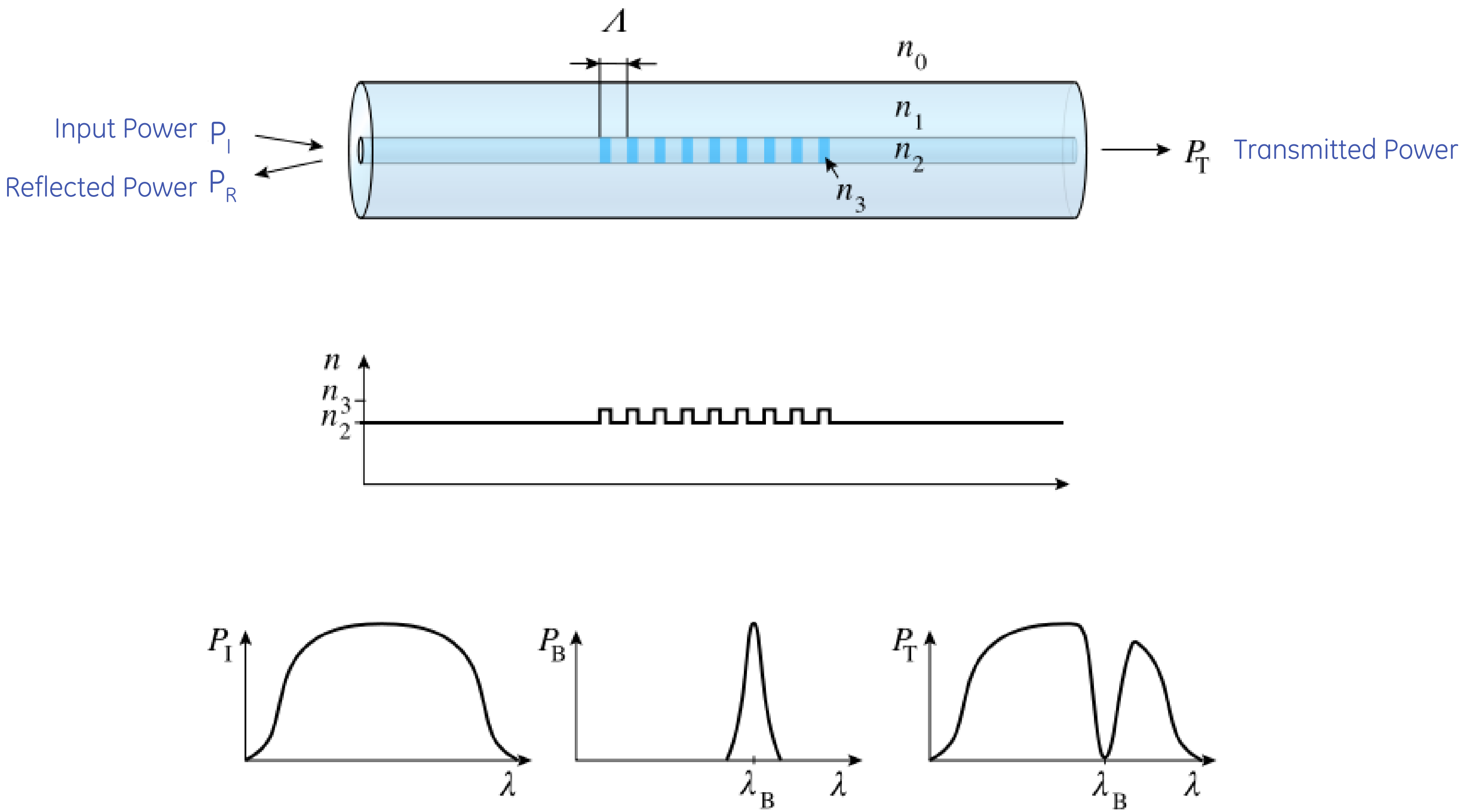
- The average transformers is 40 years old
- Transformer failure means a less reliable, less stable grid



source: William Bartley P.E. Hartford Steam Boiler Inspection & Insurance

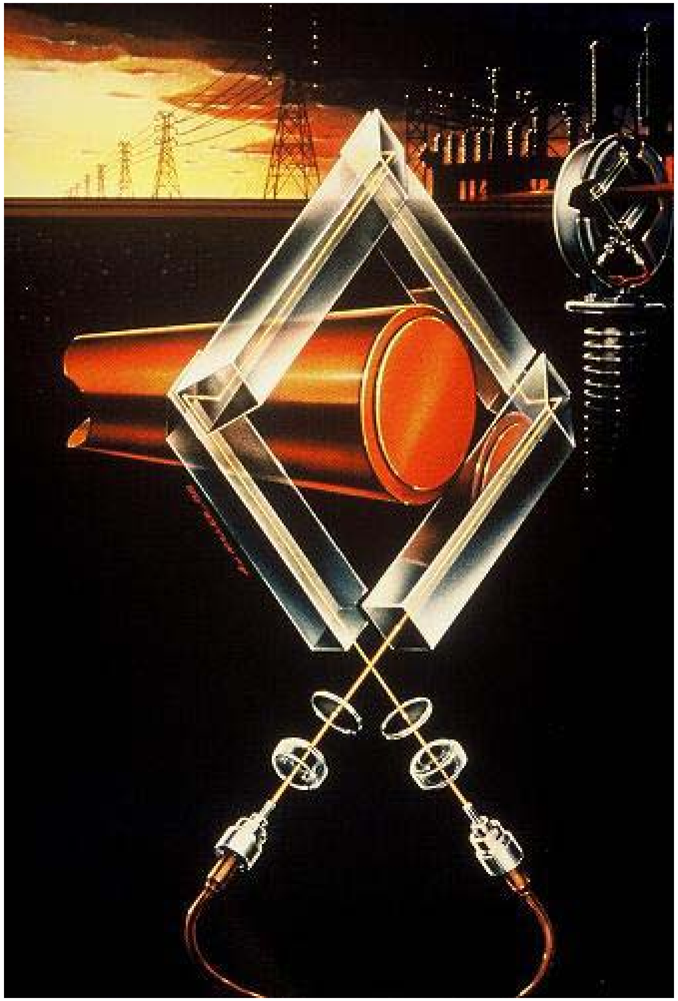
Major opportunity for Asset Monitoring

Temperature/Gas Monitoring via Bragg Grating



Reflected Wavelength is a Function of Temperature and/or Gas Type

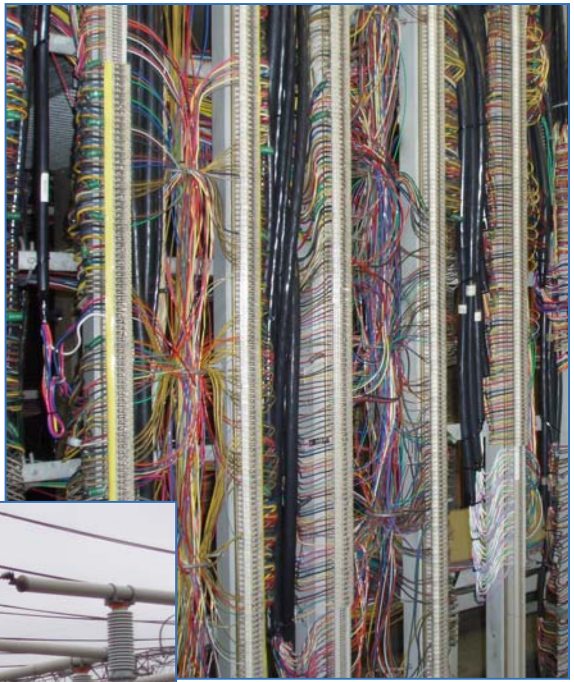
Stated Goal of 61850 Process Bus: Interface with Optical CTs/PTs



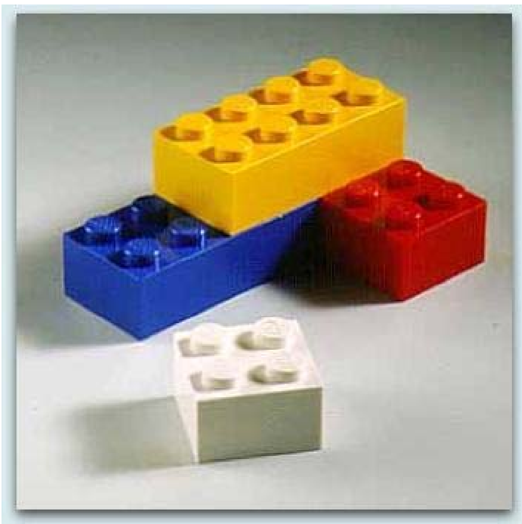
Reality: Copper Dominates the Landscape

Design objectives & constraints

- Maximum pre-connectorization
- Early and comprehensive acquisition of signals
- Fiber-based signaling
- Ruggedness and security paramount
- Risk mitigation with built-in redundancy

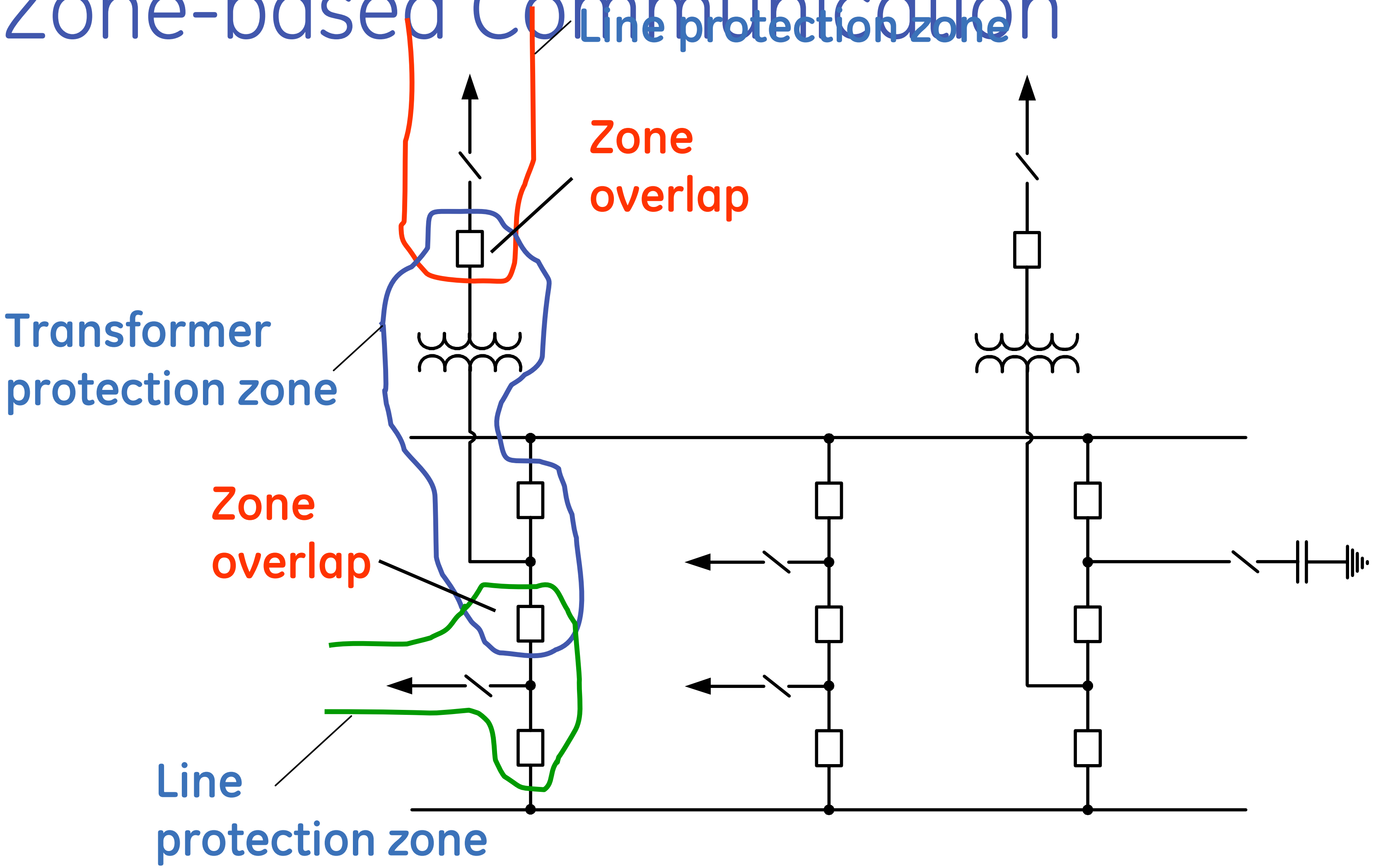


What is an Architecture?



The components of a system
and the rules for putting them together

IEC61850 Alternative Architecture 4: Zone-based Communication



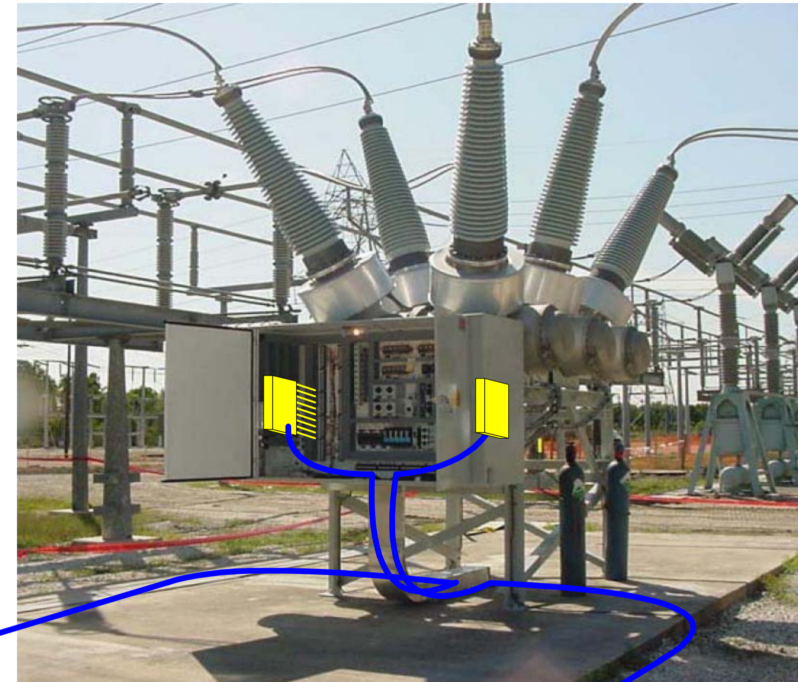
Observation: 90% of all Zones only require 4 input locations

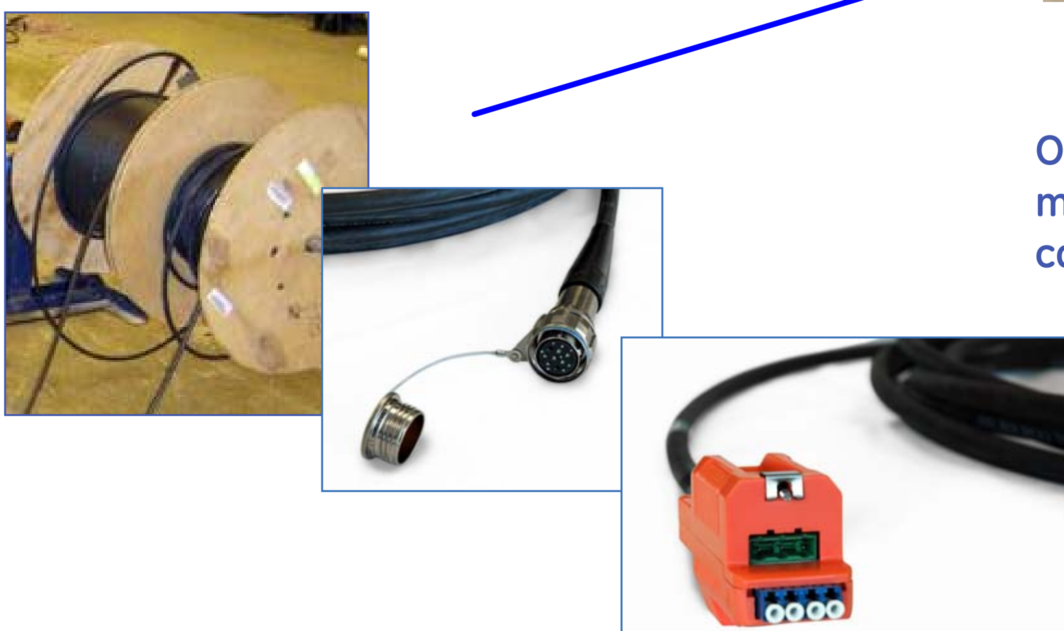
Optimized System Architecture

- **Remote I/O devices (process bus Merging Units - MU) installed in the switchyard to provide complete I/O capability for the system**
- ***Redundant* I/O for critical signals**
- **Data acquisition and outputs only, no processing (future-proof)**

Optimized System Architecture

- Connected via multi-fiber cables (star topology)
- Fiber cables in trenches, directly buried when required
- Powered via copper wires integrated in the fiber cable
- Pre-connectorized cables





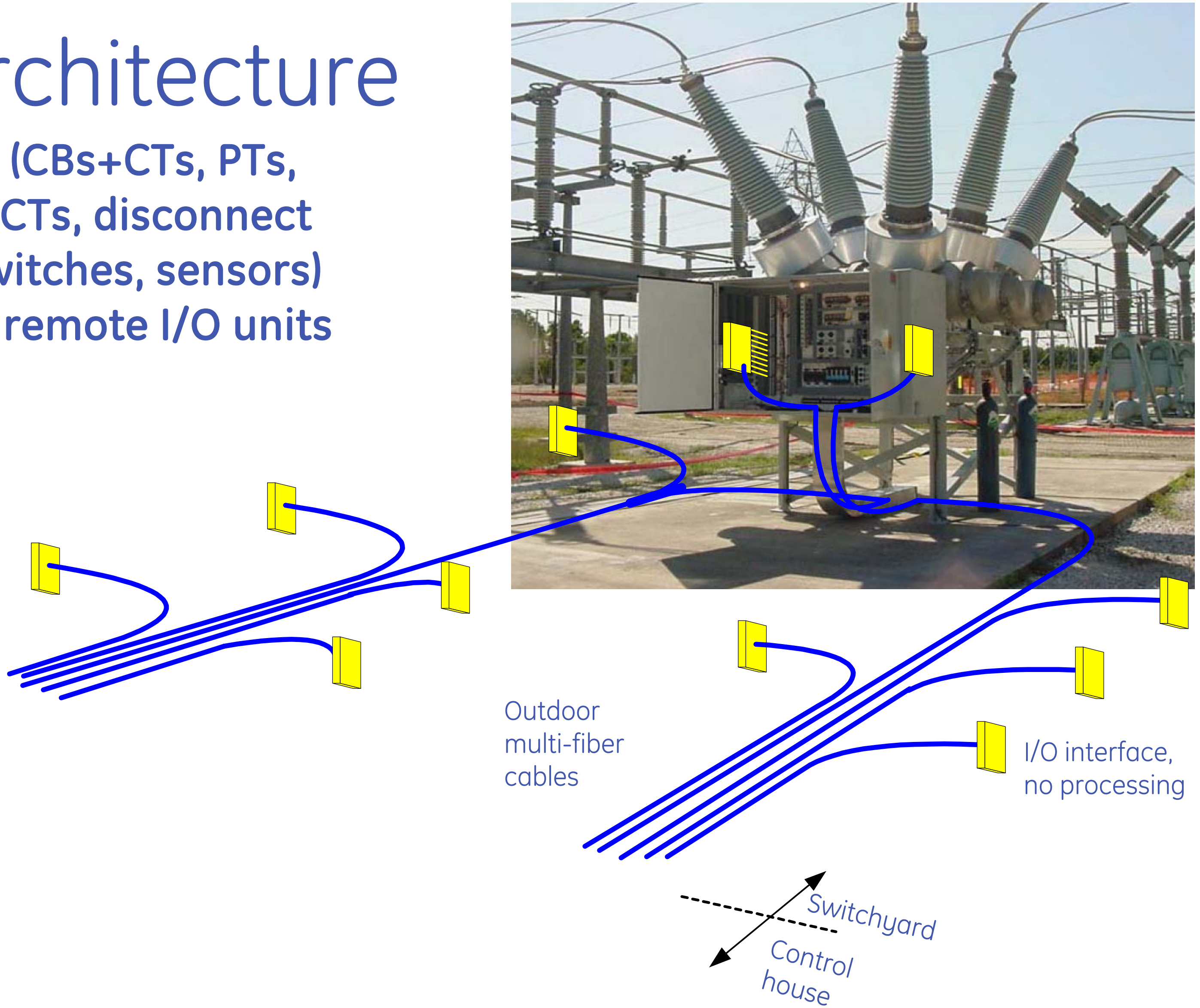
Outdoor multi-fiber cables

Switchyard

Control house

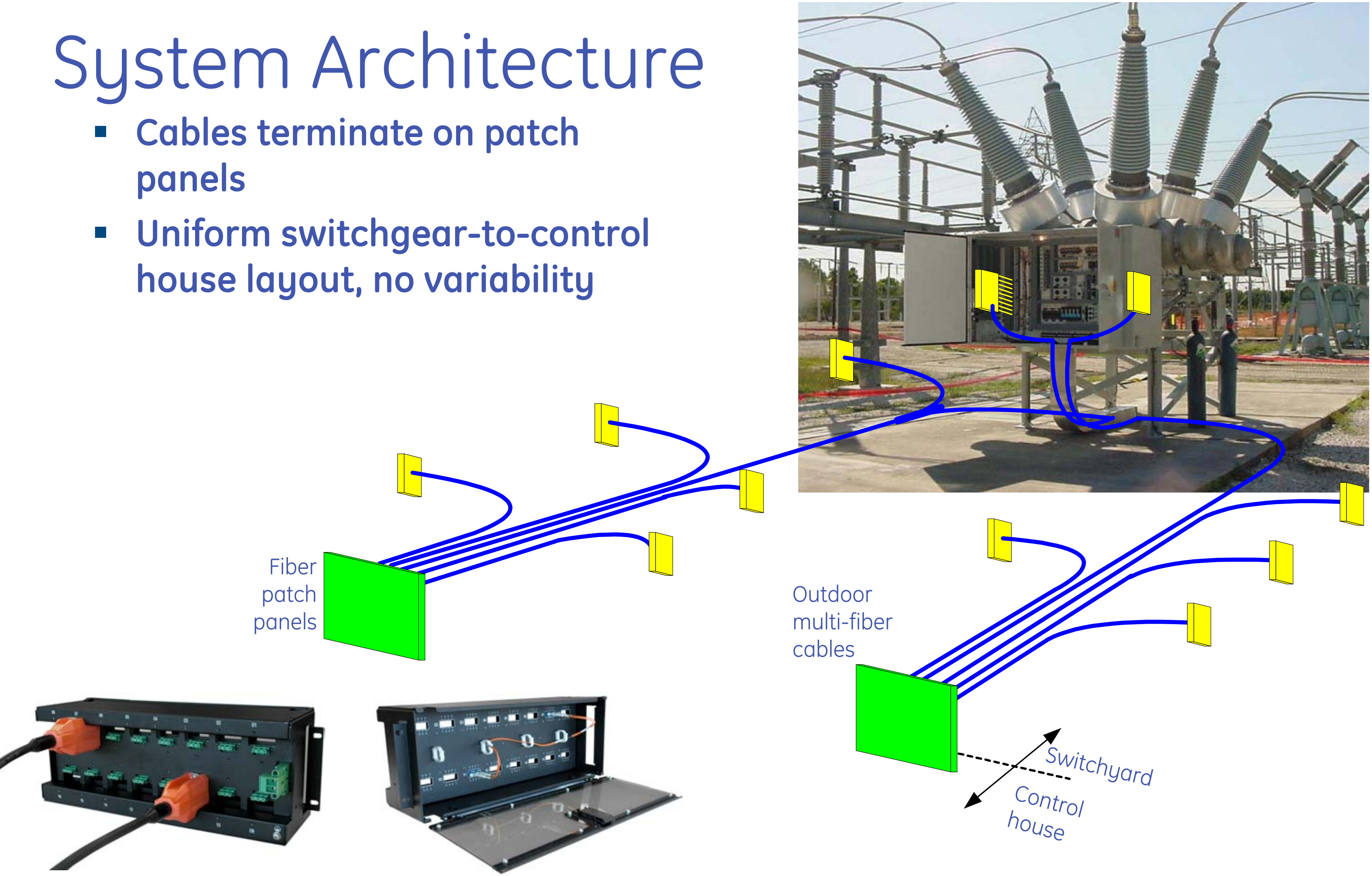
System Architecture

- **All switchgear (CBs+CTs, PTs, free-standing CTs, disconnect and ground switches, sensors) interfaced via remote I/O units**



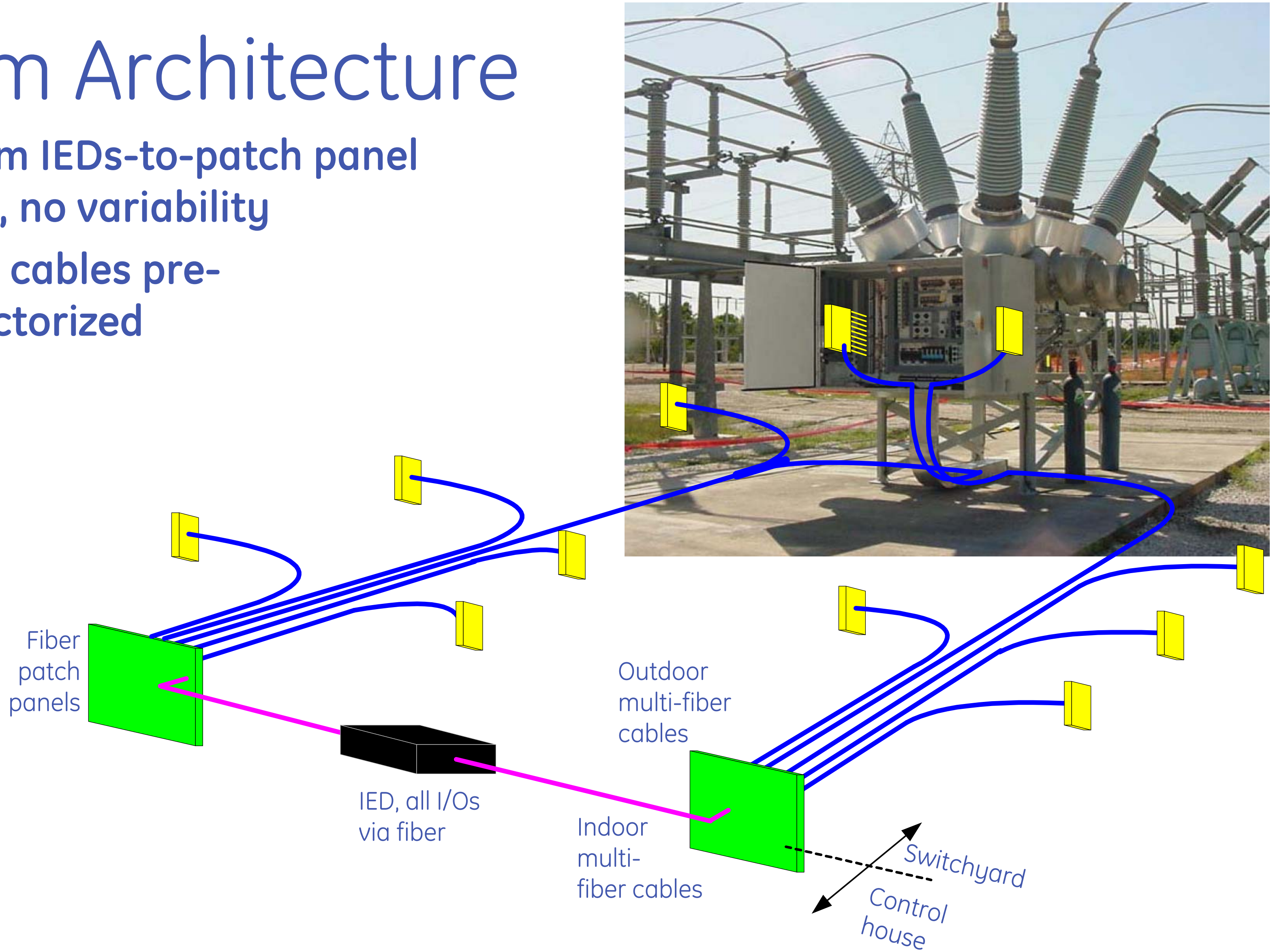
System Architecture

- **Cables terminate on patch panels**
- **Uniform switchgear-to-control house layout, no variability**

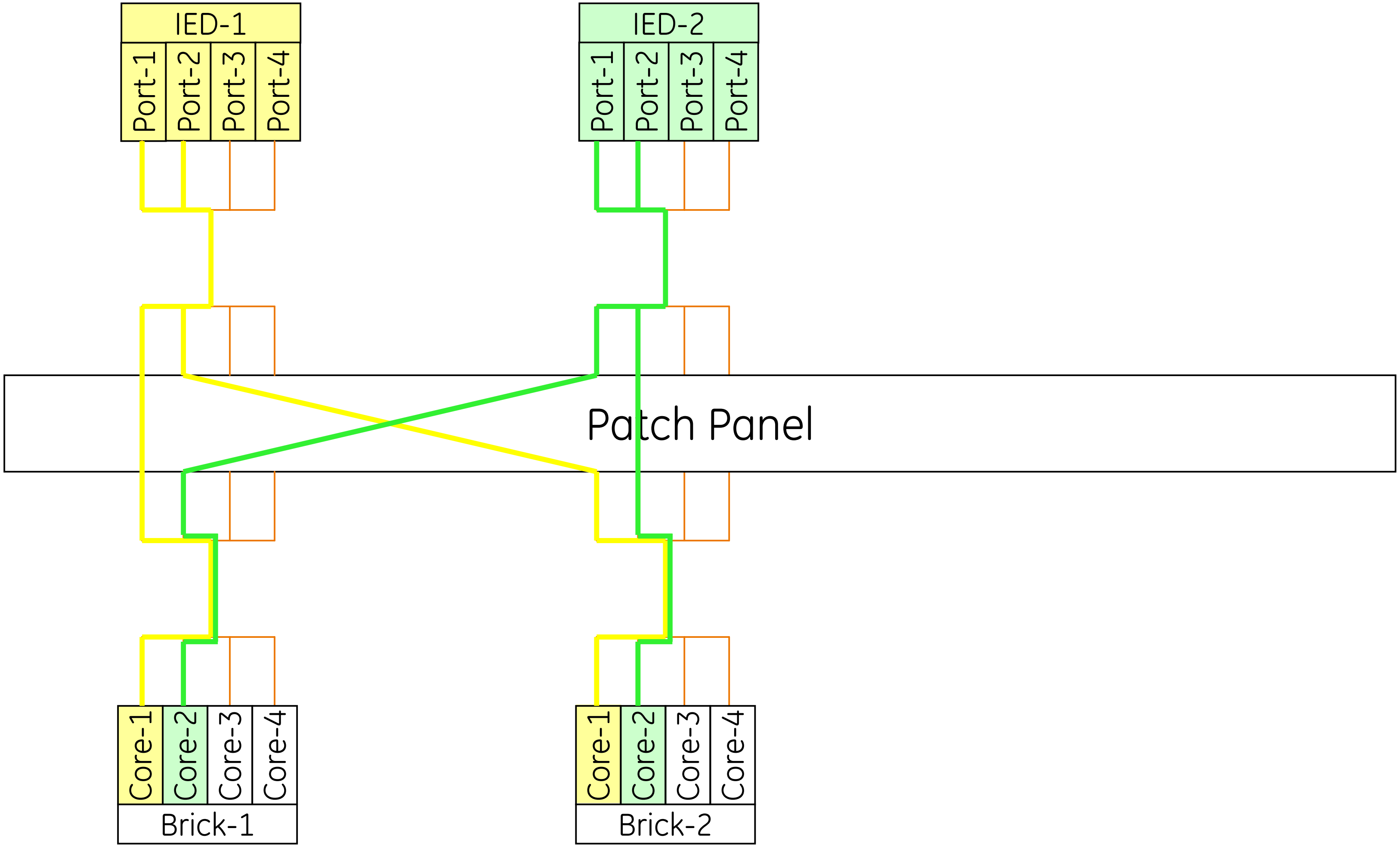


System Architecture

- **Uniform IEDs-to-patch panel layout, no variability**
- **Indoor cables pre-connectorized**



Making the Connection

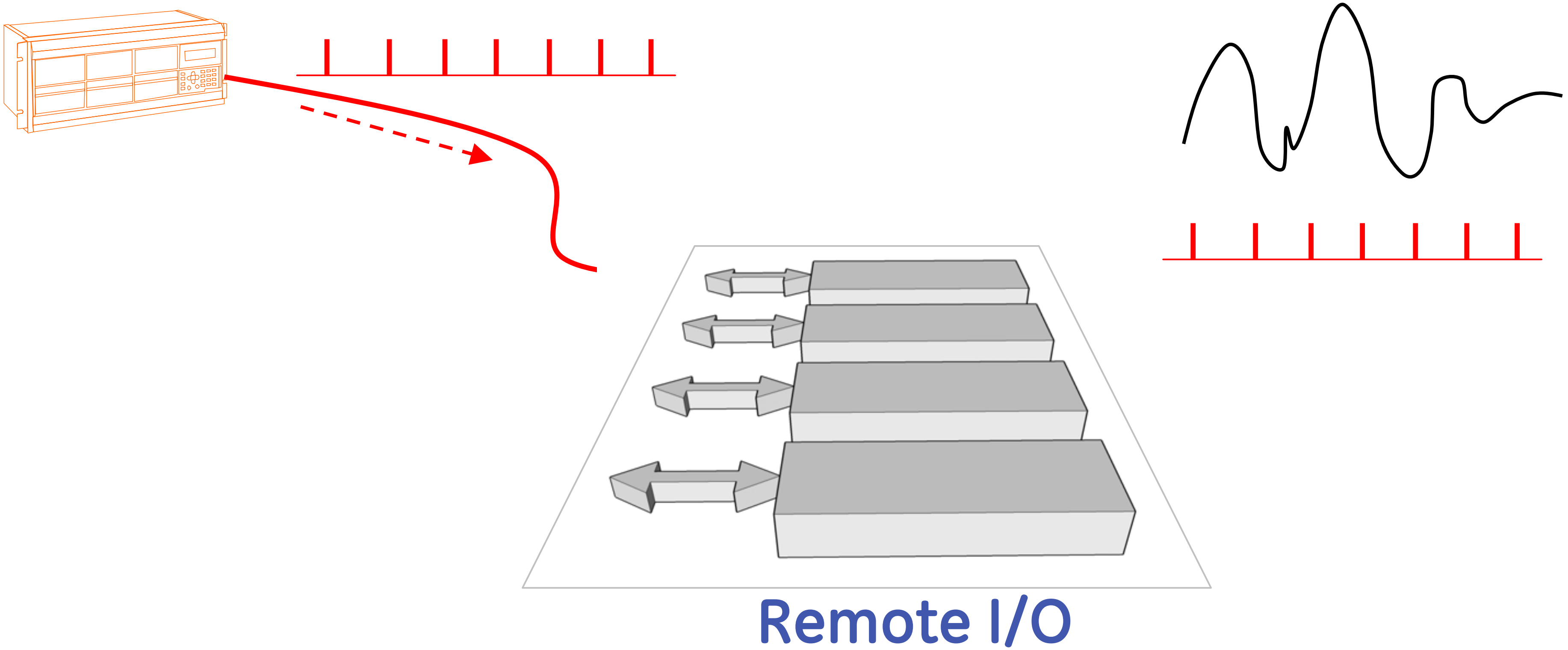


IEC 61850 Guidelines on Data Sampling Synchronization:

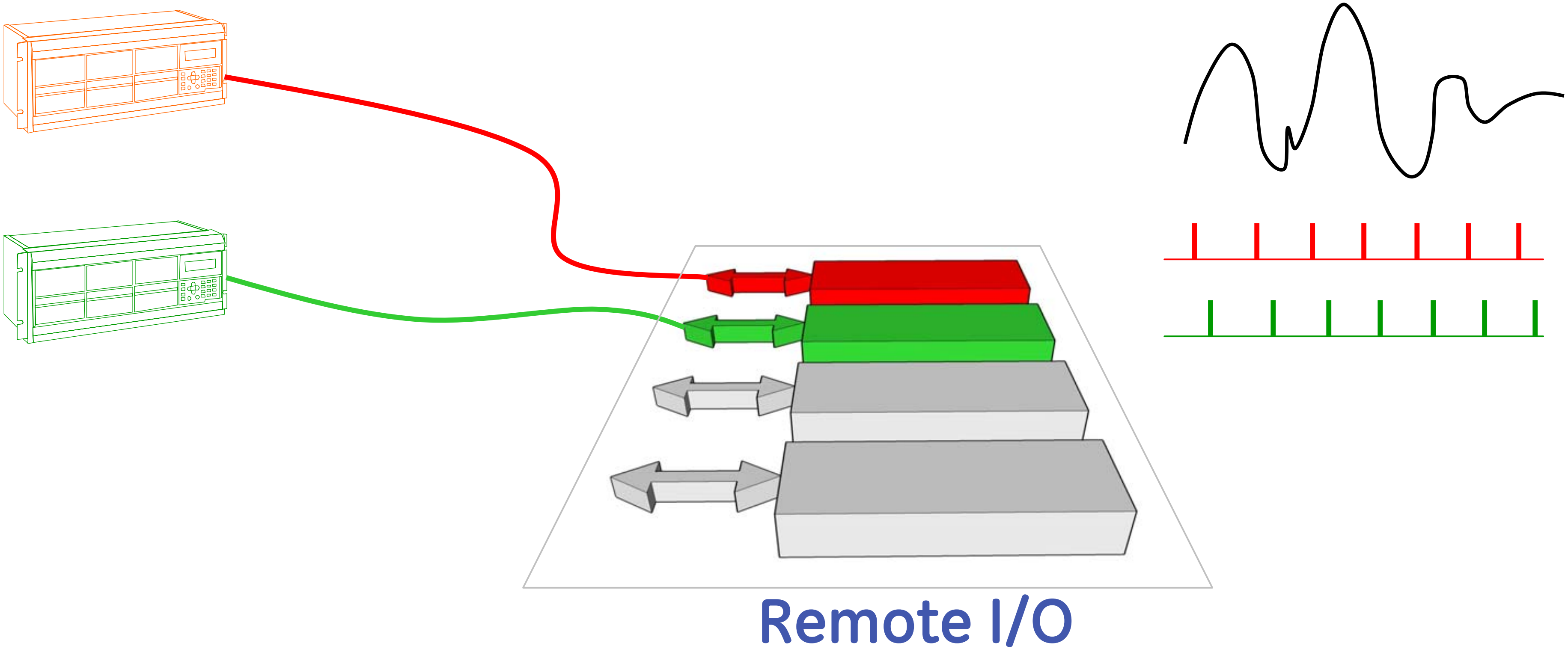
The synchronization of this sampling may be done internal or over the network.[1]

1 - IEC 61850 7-2 2004

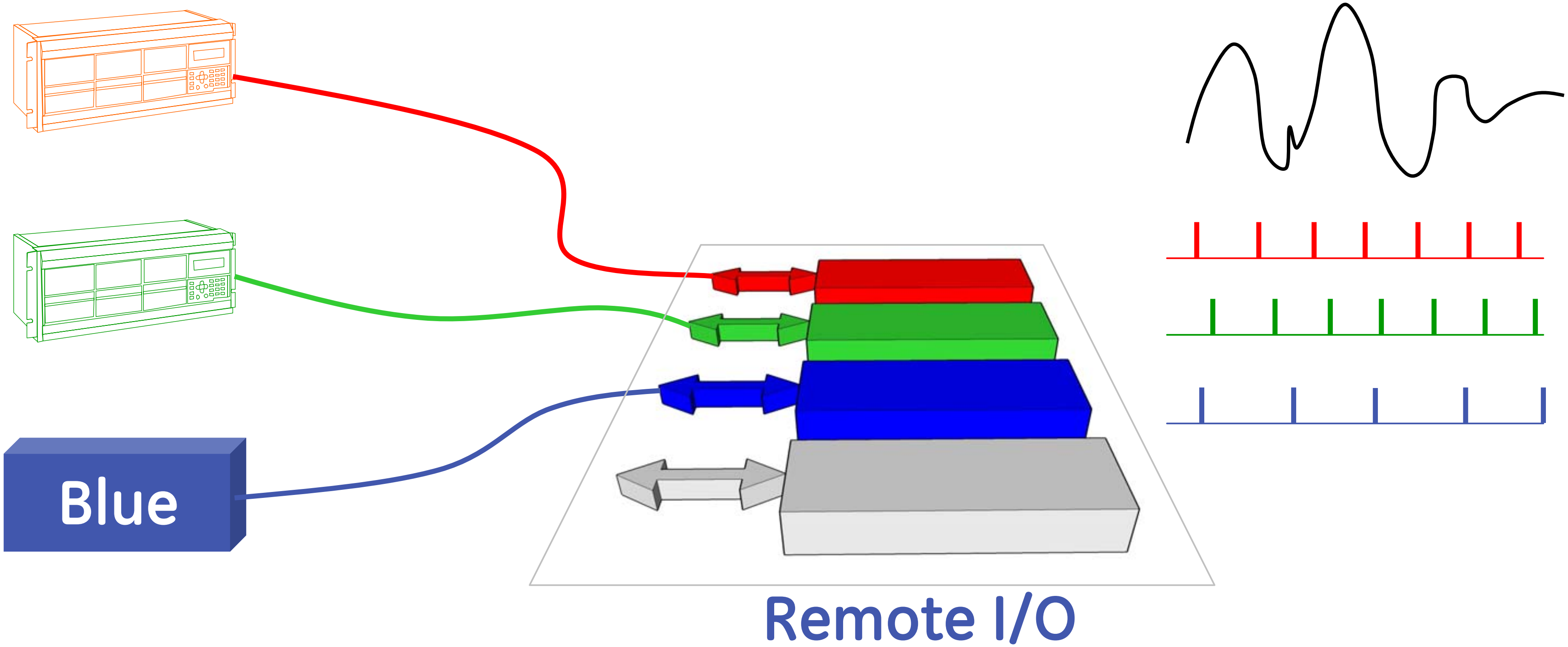
Synchronization



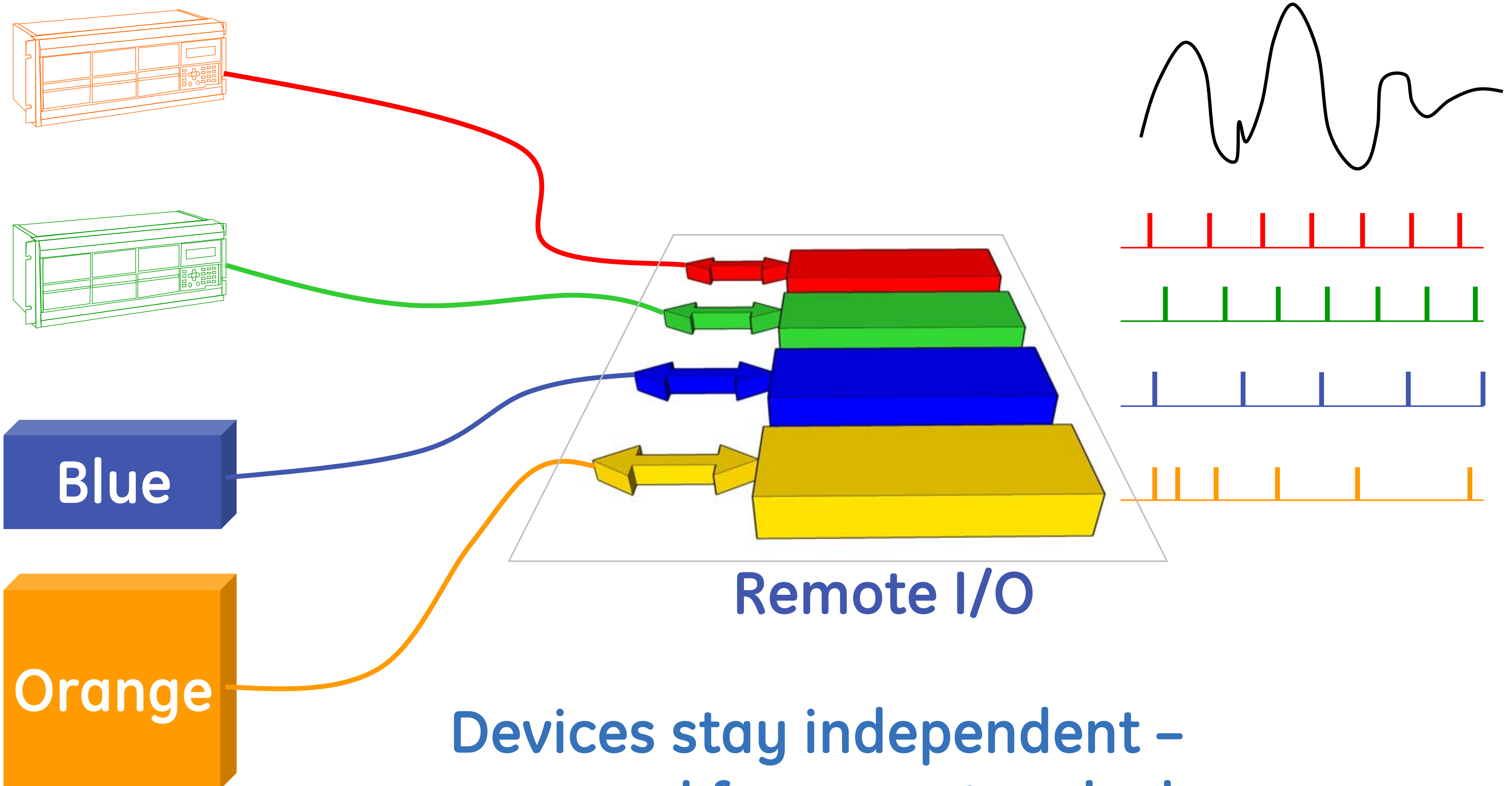
Synchronization



Synchronization

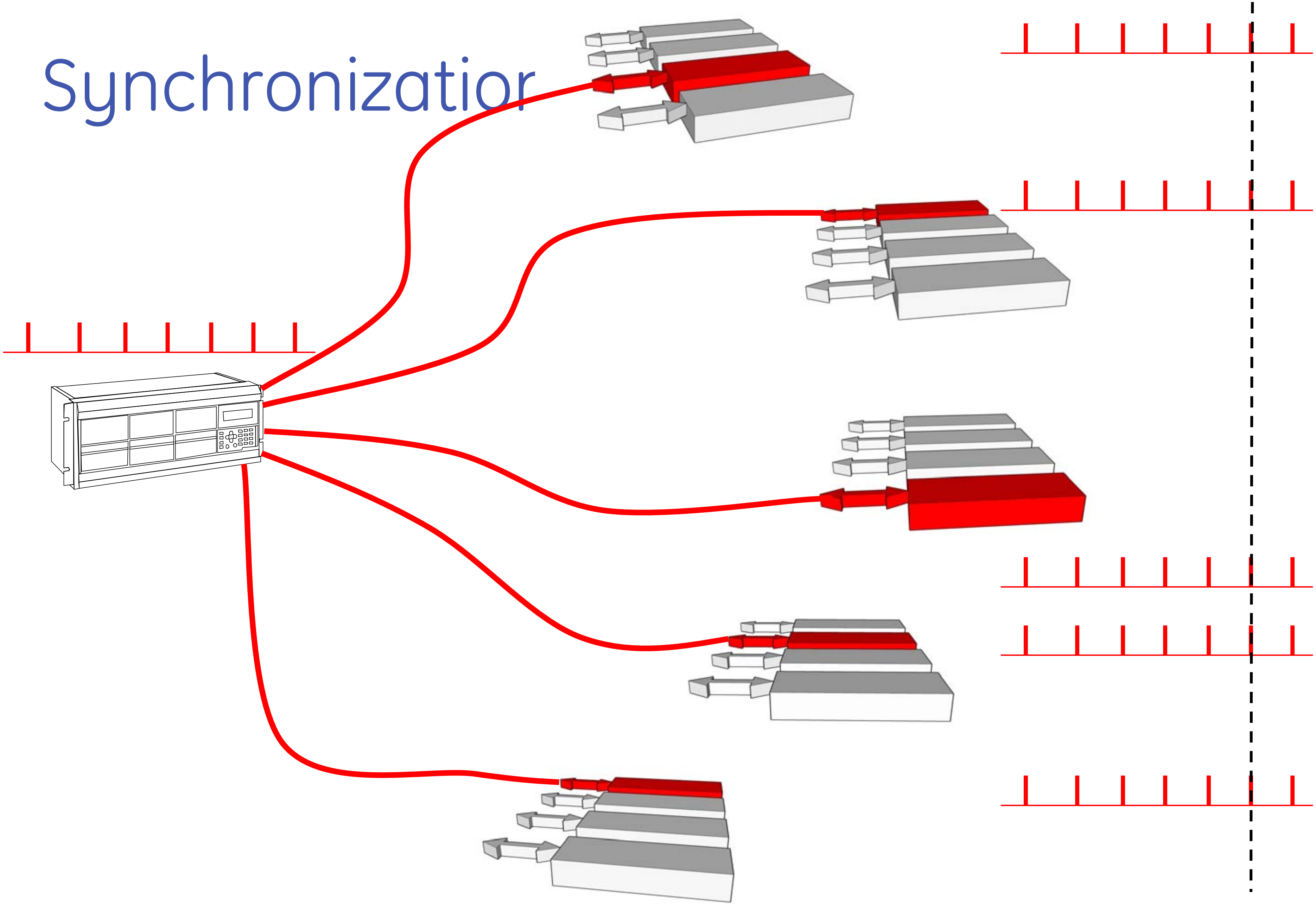


Synchronization



Devices stay independent –
- no need for a master clock

Synchronizatior



Sampling Variance: ±1μsec

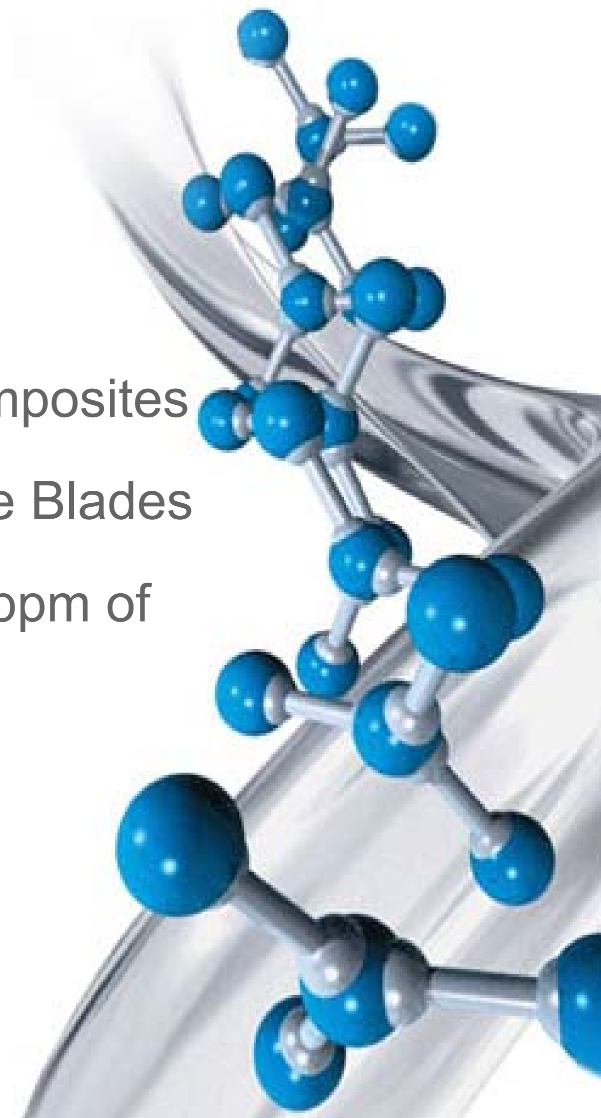
Nanotechnology in the Power System

Manipulating structure at the molecular level

Creating new materials

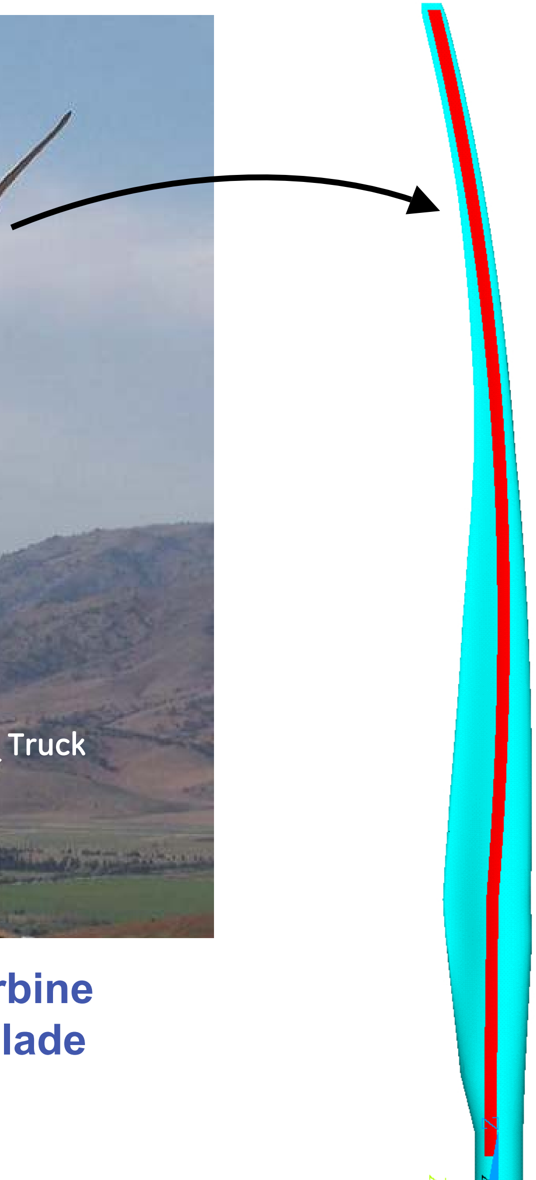
New Breakthroughs in Technology

- Nano-Materials: Carbon Nanotubes and new composites
  - Lighter/more efficient Windmill and Turbine Blades
- Nano-Detection: Nano Nose, detect as little as 1ppm of gas
  - Better detection of transformer gas in oil
- Nano-Coatings: Super-hydrophobic materials



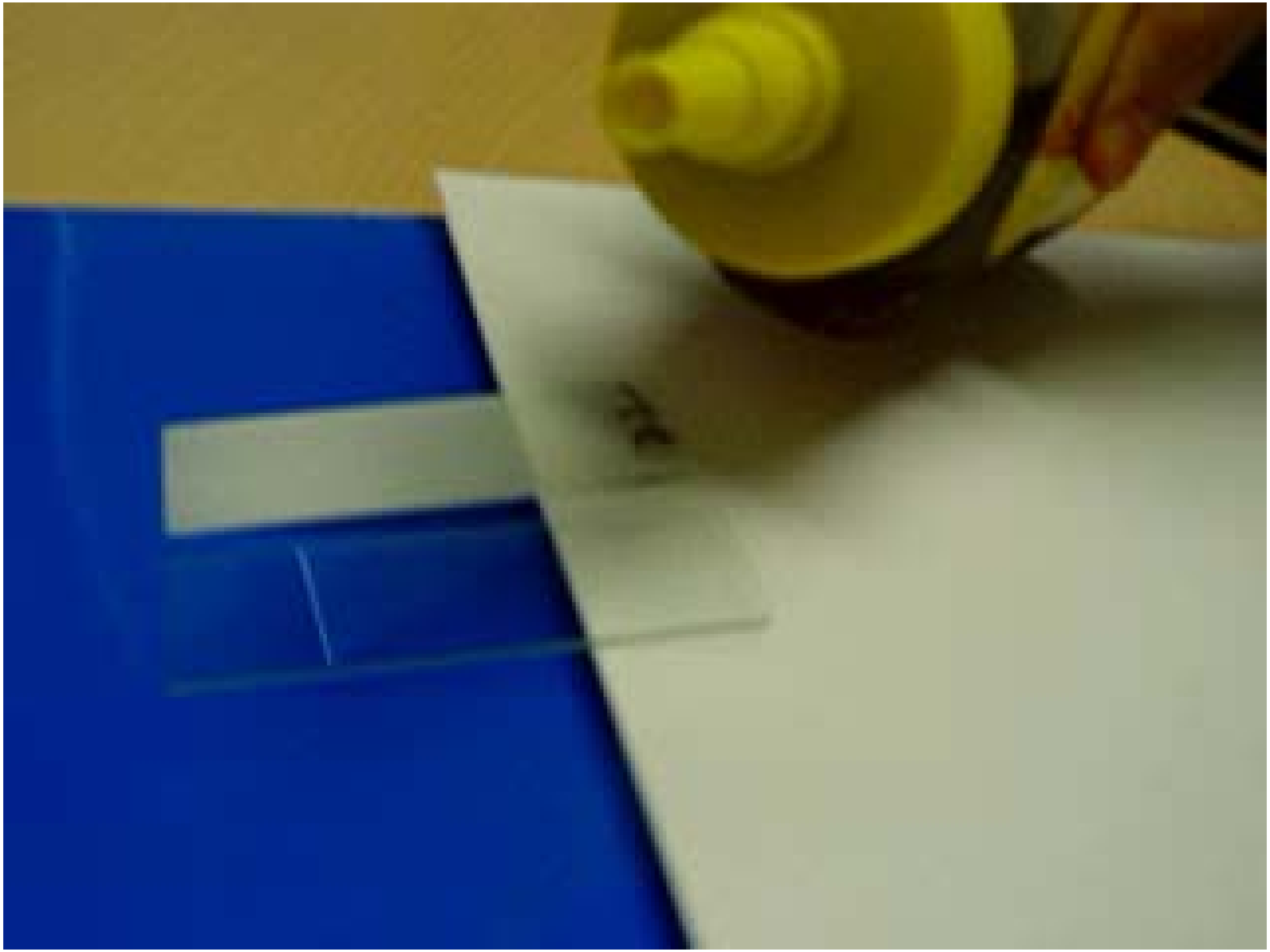
Accelerate new… wind

1.5-MW Turbine
40-Meter Blade



- 2.5-megawatt turbine with 55 meter advanced blades
- Advanced composite hybrid of carbon and fiberglass
- Aeroelastic tailored
- Creates higher efficiency and produces lower noise

NanoCoating Technology



Protection from the Elements

Super-Hydrophobic coatings so repellant that:

- Honey slides off it like mercury
- Water bounces and beads off

The Energy Sector Application

- New transmission & distribution line coating resists ice build-up
- New coatings protect coastal assets from salt damage
- New transformer winding material fights insulation breakdown

Increased Solar Energy Penetration

Low-cost silicon solution using next-gen nano materials

- Cost coming down
- Inverter interface into the Grid
- Self-limiting on fault current
- Intermittent – difficult to dispatch

Summary

The path is unfolding now, technology can help address:

- Increasing electrical demand
- Green power being more economical, viable and reliable
- Introduces new challenges and opportunities in the P&C world

Heavy lifting . . .

- Unprecedented levels of co-operation among the stakeholders
- Continued evaluation of new technology for additional benefits
- Vision to make the system predictive, self-healing and secure
- Continued investments from all stakeholders