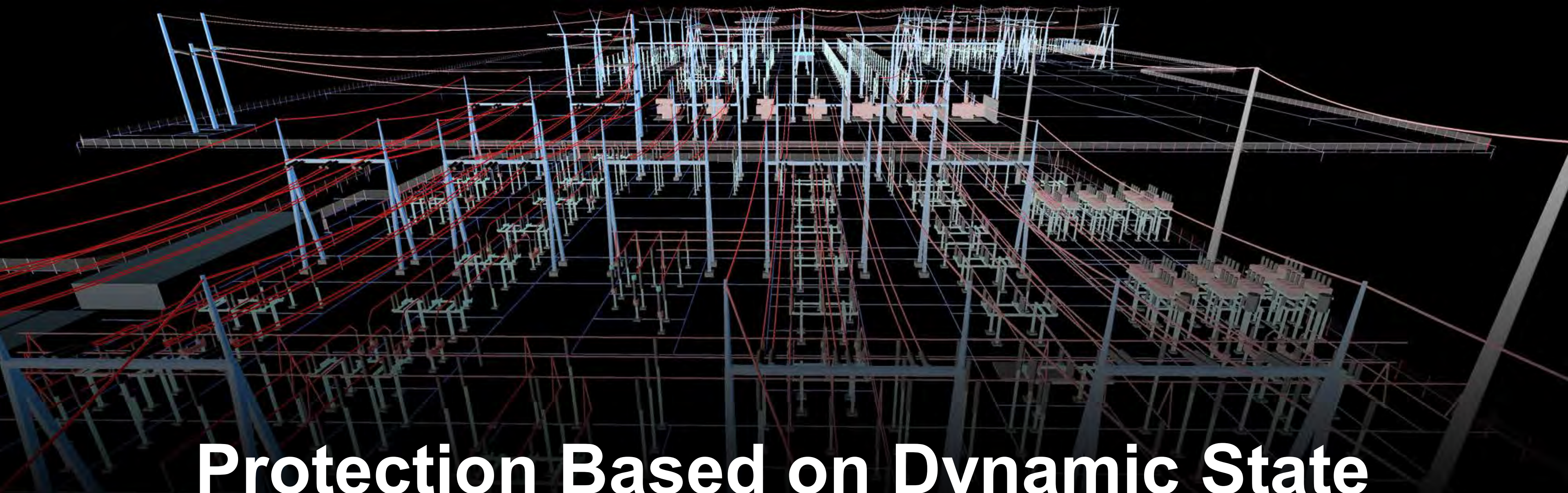

# Protection Based on Dynamic State Estimation (a.k.a. Setting-less Protection): Status and Vision

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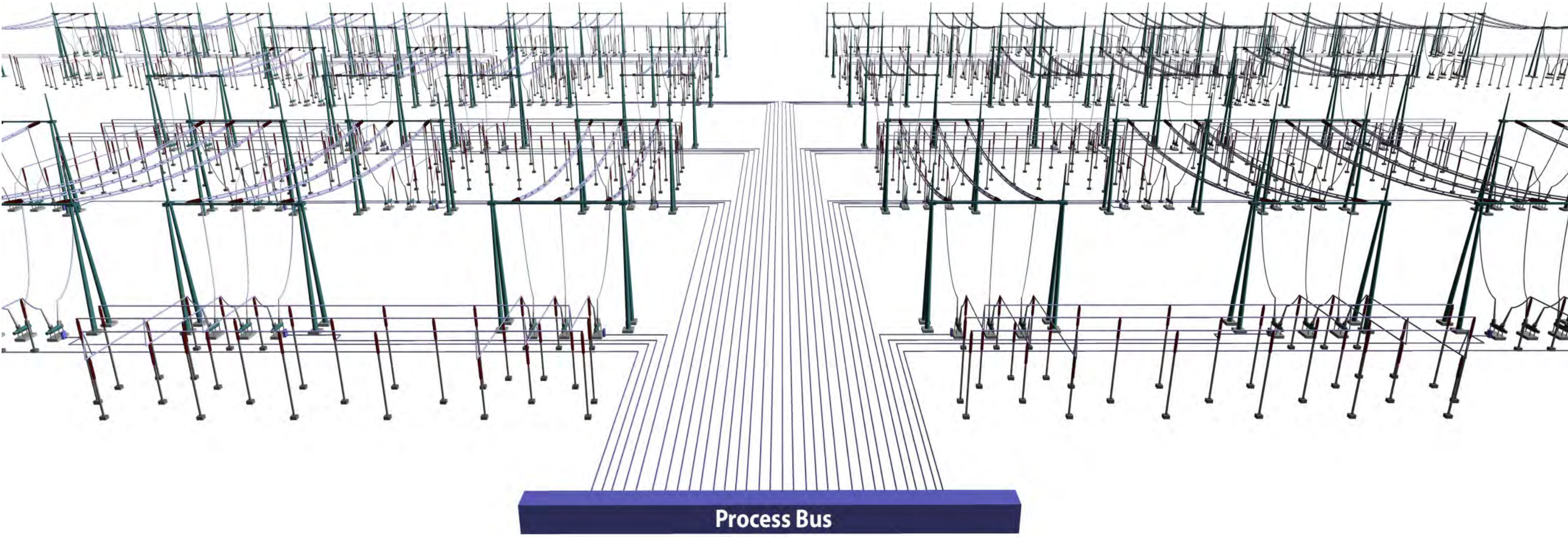
**September 16, 2014**

Georgia Tech Power Systems Control & Automation Laboratory
Georgia Tech
EPRI ELECTRIC POWER RESEARCH INSTITUTE
PSERC

# Contents

- History of Development
- DSE Based (aka Setting-less) Protection
- Examples of DSE Based Protection
- Laboratory Experimentation
- Integrated Protection & Control* Vision
- Dedicated Georgia Tech Laboratory

# History of Developments



# History of Developments

The Substation of the Future (2007-8, PSERC) (**INDUSTRY ADVISORS:** Floyd Galvan/Shannon Watts – ENTERGY, Raymond Vice – Southern Company, Bruce Fardanesh – NYPA, Lisa Beard – TVA, Paul Myrda – EPRI, Jamshid Afnan – ISO-NE, Simon Chiang – PG&E)

Advanced State Estimation Methods (2005-6, PSERC) (**INDUSTRY ADVISORS:** Floyd Galvan/Shannon Watts – ENTERGY, Raymond Vice – Southern Company, Bruce Fardanesh – NYPA, Lisa Beard – TVA, Paul Myrda – EPRI, Jamshid Afnan – ISO-NE, Simon Chiang – PG&E)

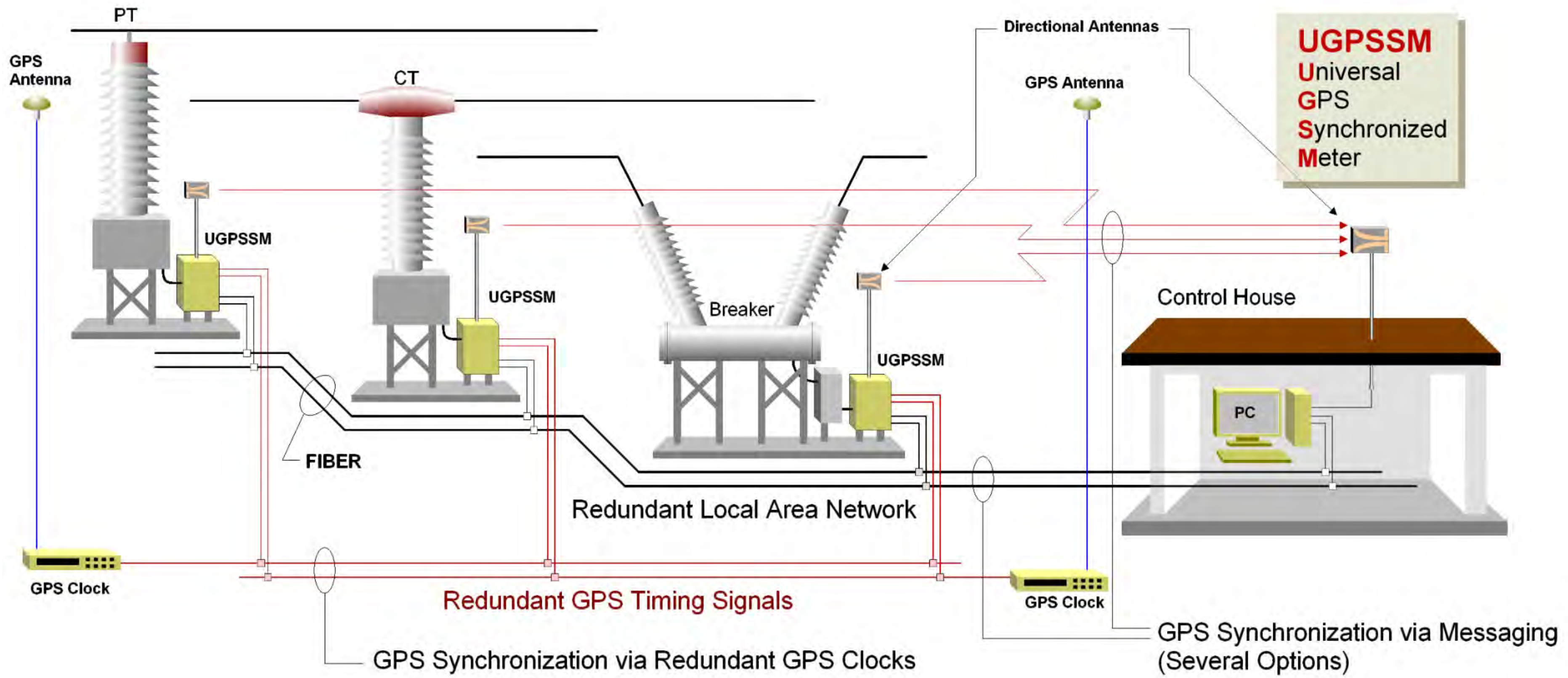
Distributed State Estimation (2009-13, DoE) (**COLLABORATORS:** USVI-WAPA, NYPA)

Grid Transformation (2011-present, EPRI) (**INDUSTRY ADVISORS:** Paul Myrda – EPRI, Floyd Galvan/Shannon Watts – ENTERGY, Raymond Vice – Southern Company, Bruce Fardanesh – NYPA, Lisa Beard – TVA, Jamshid Afnan – ISO-NE, Simon Chiang – PG&E)

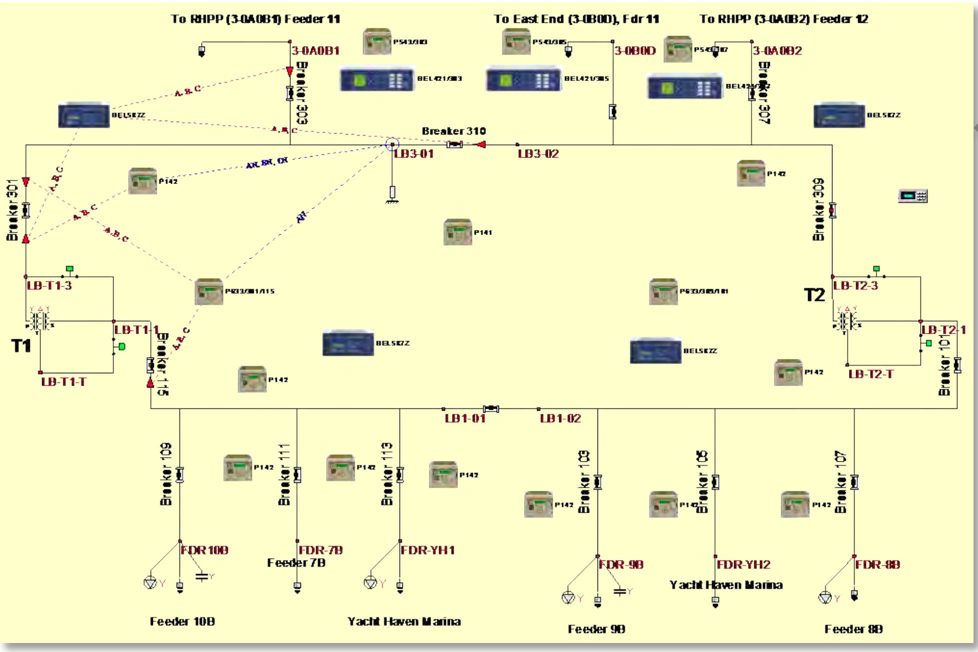
Cyber Security (2014-17, DoE): (**COLLABORATORS:** GTRI, USVI-WAPA, Southern Co., Burbank W&P)

# The Substation of the Future

## PSERC Project 2007-08

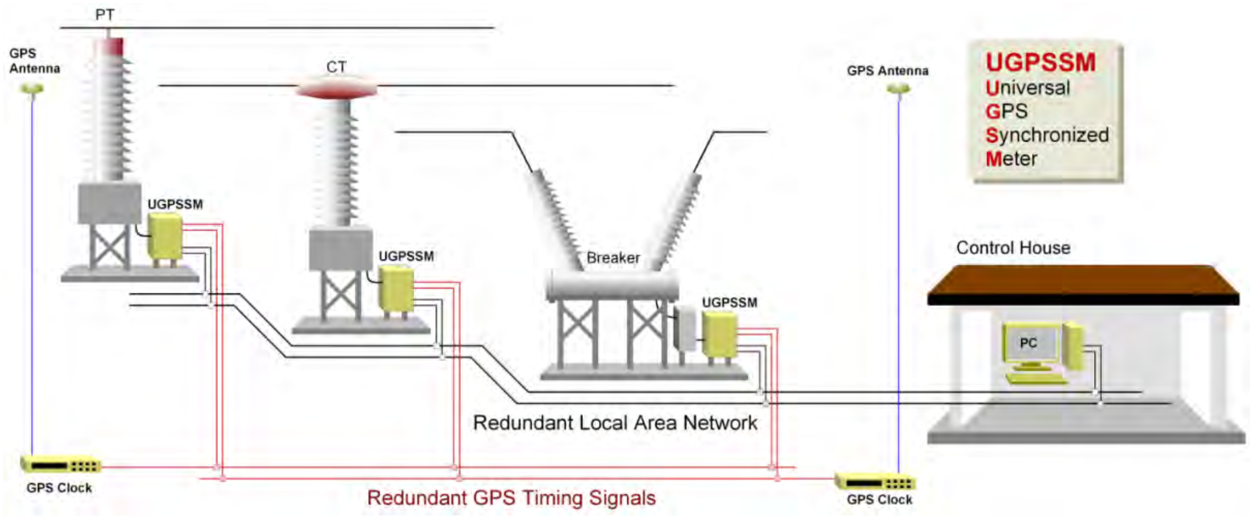


# Overall Approach




**From This**

**To This**



# Basic Questions

- Does it make sense to have separate SCADA system and Numerical Relays?
- Does it make sense to continue designing relays that rely on (typically) three currents and three voltages?
- Is it necessary for each relay to be equipped with data acquisition systems? Should DAQ be separate from relays?
- Present Systems and Technologies are Digital – They Provide Tremendous Flexibility – Are the capabilities of the technology used or we simply mimic E/M relays?
- Is the technology available to move from zone protection to subsystem (such as substation) protection?
- How do we deal with Increased Complexity?

# Traditional Component Protection

- Monitor Specific Quantity or Quantities (current, differential current, distance, voltage over frequency, etc.) and Act When the Quantity Enters a Specified Locus (settings).
- The Traditional Protection Approach Exhibits Limitations for the Simple Reason that the Specific Quantity that is Monitored Does not Always Represent the Condition of The Component Under Protection.
- NERC: #1 Root Cause of System Disturbances is Protection Relaying

# Complexity, Gaps & Challenges

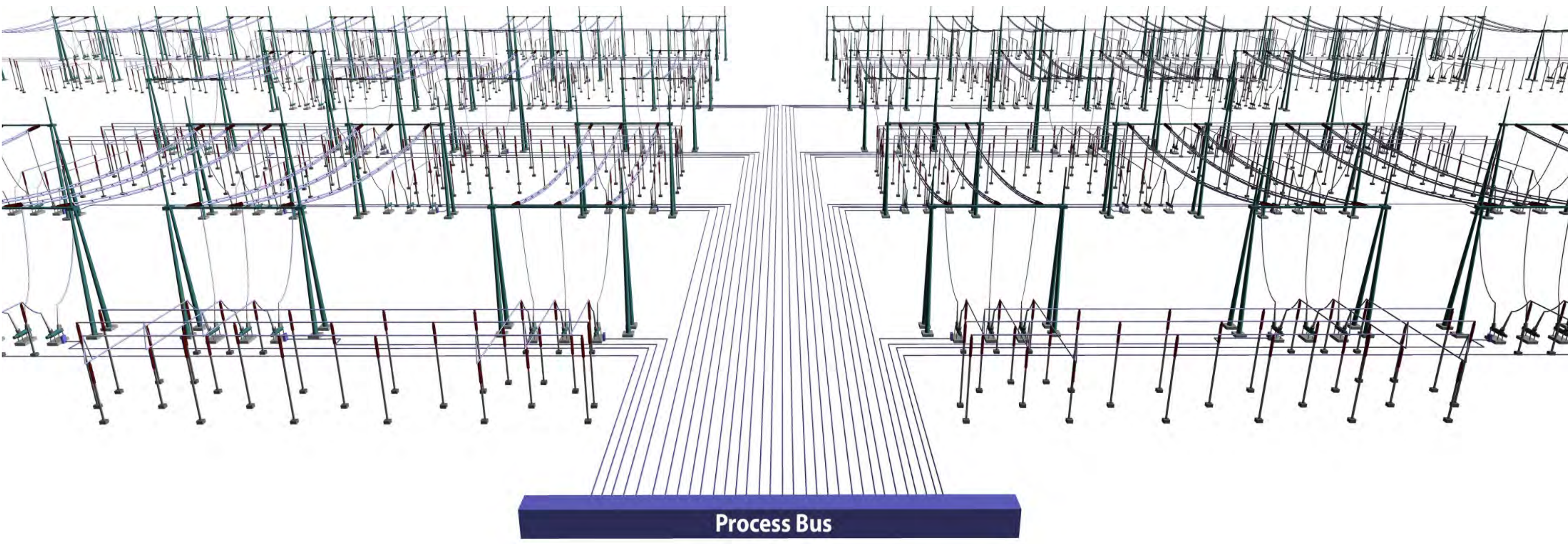
A Modern Substation May Have Tens of Numerical Relays, each relay has an average of 12 protection functions. Coordination of all these relay functions is quite complex. Experts (humans) and Expert Systems (computers) are needed…

Tools to validate coordination of complex protection schemes are at best inadequate.

Protection Gaps: HIF, Down Conductors, Faults Near Neutrals, Inverter Interfaced Generation, Faults in Series Compensated Lines, etc. etc.

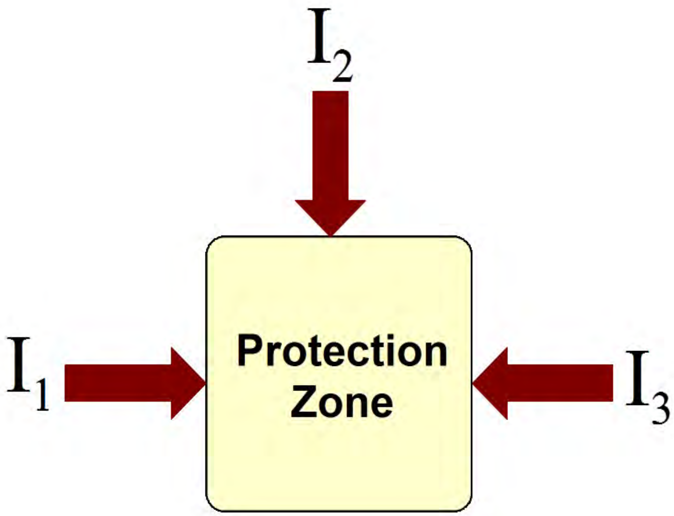
***Protection Gaps Result in Fatalities…***

# The Setting-Less Protection Method



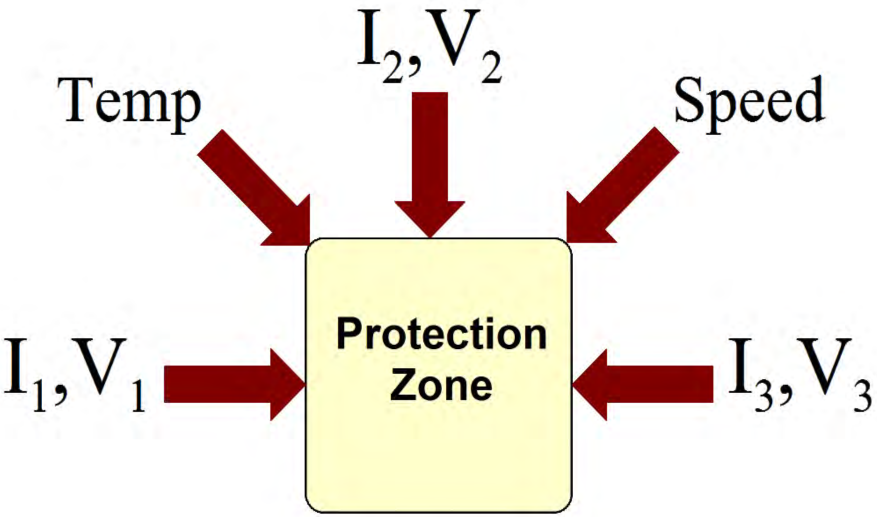
# In Search of Secure Protection

Setting-less Protection can be viewed as Generalized Differential protection




**Differential Protection**

(Monitors KCL Only)




**Setting-less Protection**

Monitors All Laws Applied to the Device
(KCL, KVL, Thermal Mechanical,
i.e. Complete Device Model)

**Analytics**: Dynamic State Estimation (systematic way to determine observance of physical laws)

# The Zone Setting-less Protection Approach

- Measure/Monitor as Many Quantities as Possible and Use Dynamic State Estimation to Continuously Monitor the State (Condition, Health) of the Zone (Component) Under Protection. Identify bad data, model changes, etc.
- Act on the Basis of the Zone (Component) State (Condition, Component Health).
- **Advantage**: No need to know what is happening in the rest of the system – no coordination needed.

# Key Elements of Approach

- "**Digitization**" Separate Data Acquisition from logic devices (relays, recorders, etc.) – Merging Unit Approach
- "**Objectify**" the model and measurements of each component: Starting Point: component physical model.
- "**Interoperability**" at all levels
  - Each logic device (IEDs) performs:

    **Protective functions for the component**
    **Validate the "model object"**
    **Perform parameter identification, if necessary**
    **Transmits model objects to any other stakeholder**
  - Extent this structure to the control center

# “Objectification”: The SCAQCF Model

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

**Compact Component Physical Model**

Set of Algebraic & Differential Linear & Nonlinear Equations & Inequalities

→

**Quadratized Model**

$$i(t) = Ax(t) + B\frac{dx(t)}{dt} + C$$

$$0 = Dx(t) + E\frac{dx(t)}{dt} + x^T(t)\langle \mathrm{F} \rangle \mathrm{x(t)}$$

Addition of State Variables

→

**State & Control Algebraic Quadratic Compact Form**

**(SCAQCF)**

$$i(t) = f_1\left(x(t), \mathrm{x(t_m)}, \mathrm{b_1(t-h)}\right)$$

$$0 = f_2\left(x(t), \mathrm{x(t_m)}, \mathrm{b_2}(t-h)\right)$$

$$i(t_m) = f_3\left(x(t), \mathrm{x(t_m)}, \mathrm{b_3}(t-h)\right)$$

$$0 = f_4\left(x(t), \mathrm{x(t_m)}, \mathrm{b_4}(t-h)\right)$$

Quadratic Integration

# "Objectification": Measurement Model

**Actual Measurements**

$$z_i(t) = h_{i1}\left(x(t), x(t_m)\right),\ \sigma_{meter}$$
$$z_i(t_m) = h_{i2}\left(x(t), x(t_m)\right),\ \sigma_{meter}$$

**Derived Measurements**

$$z_j(t) = h_{j1}\left(x(t), x(t_m)\right),\ \sigma_{meter}$$
$$z_j(t_m) = h_{j2}\left(x(t), x(t_m)\right),\ \sigma_{meter}$$

**Pseudo-Measurements**

$$z_k(t) = h_{k1}\left(x(t), x(t_m)\right),\quad \sigma = \text{large}$$
$$z_k(t_m) = h_{k2}\left(x(t), x(t_m)\right),\quad \sigma = \text{large}$$

**Virtual Measurements**

$$0 = h_{v1}\left(x(t), x(t_m)\right),\quad \sigma = 0$$
$$0 = h_{v2}\left(x(t), x(t_m)\right),\quad \sigma = 0$$

*All h equations are quadratic at most*

# "Objectification": Solution Method

**Quadratized Model**

**State & Control Algebraic Quadratic Compact Form**

**(SCAQCF)**

**Extended Kalman Filter**

**Unconstrained Optimization**

$$Min \sum_{\substack{Actual \\ Derived \\ Pseudo}} \left( \frac{z - h_m(x)}{\sigma} \right)^2 + \sum_{Virtual} \left( \frac{0 - h_v(x)}{0.1 \times \sigma} \right)^2$$

$$\Rightarrow x^{\nu+1} = x^{\nu} - \left( H^T W H \right)^{-1} H^T W \left( z - h(x) \right)$$

**Constrained Optimization**

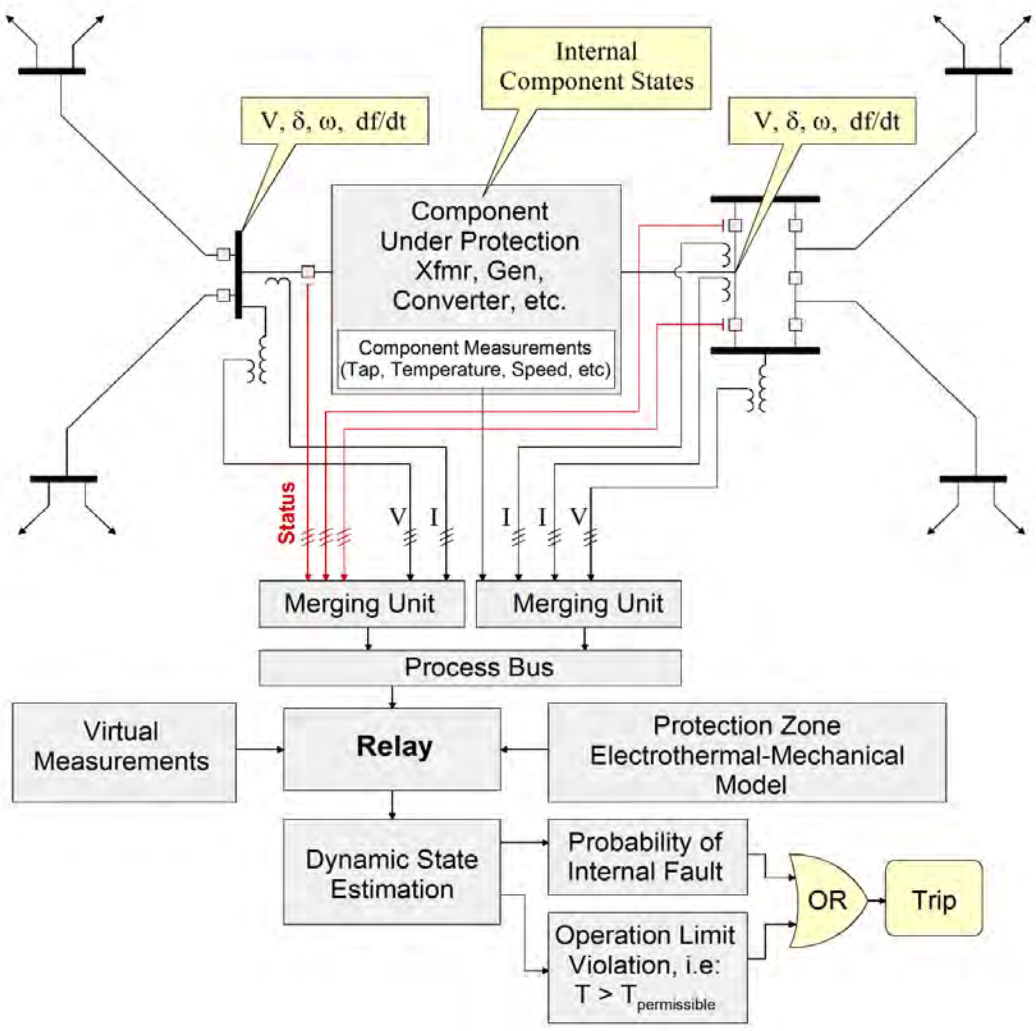
$$Min \sum \left( \frac{z - h_m(x)}{\sigma} \right)^2$$

$$S.T. \quad \mathrm{h}_v(x) = g(x) = 0$$

$$\Rightarrow \begin{bmatrix} x^{\nu+1} \\ \lambda^{\nu+1} \end{bmatrix} = \begin{bmatrix} x^{\nu} \\ \lambda^{\nu} \end{bmatrix} - \begin{bmatrix} H^T W H & G \\ G & 0 \end{bmatrix}^{-1} \begin{bmatrix} H^T W \left( h(x^{\nu}) - \mathrm{z} \right) + G^T \lambda^{\nu} \\ g(x^{\nu}) \end{bmatrix}$$

**Note**: For State Estimation the Controls are Treated as Known Parameters

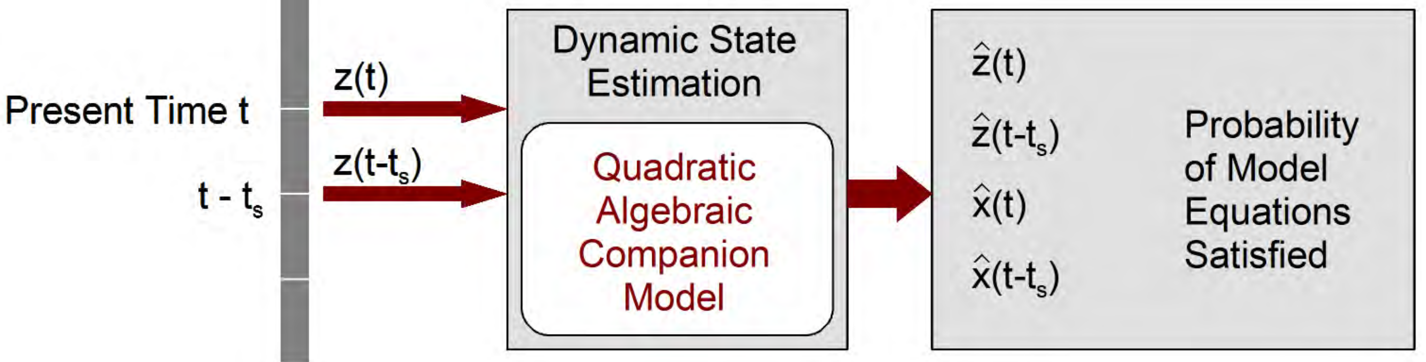
# Implementation Issues

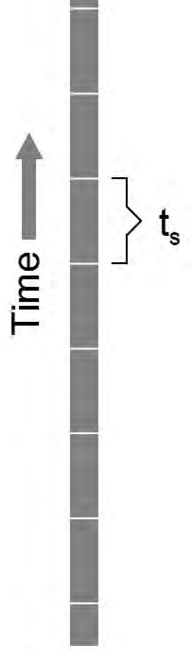



- The Component is Represented with a Set of Differential Equations (DE)
- The Dynamic State Estimator Fits the Streaming Data to the Dynamic Model (DE) of the Component
- Object Oriented Implementation

# Implementation Issues

Typical Sampling Rates → $t_s$ = 0.1 ms to 0.5 ms



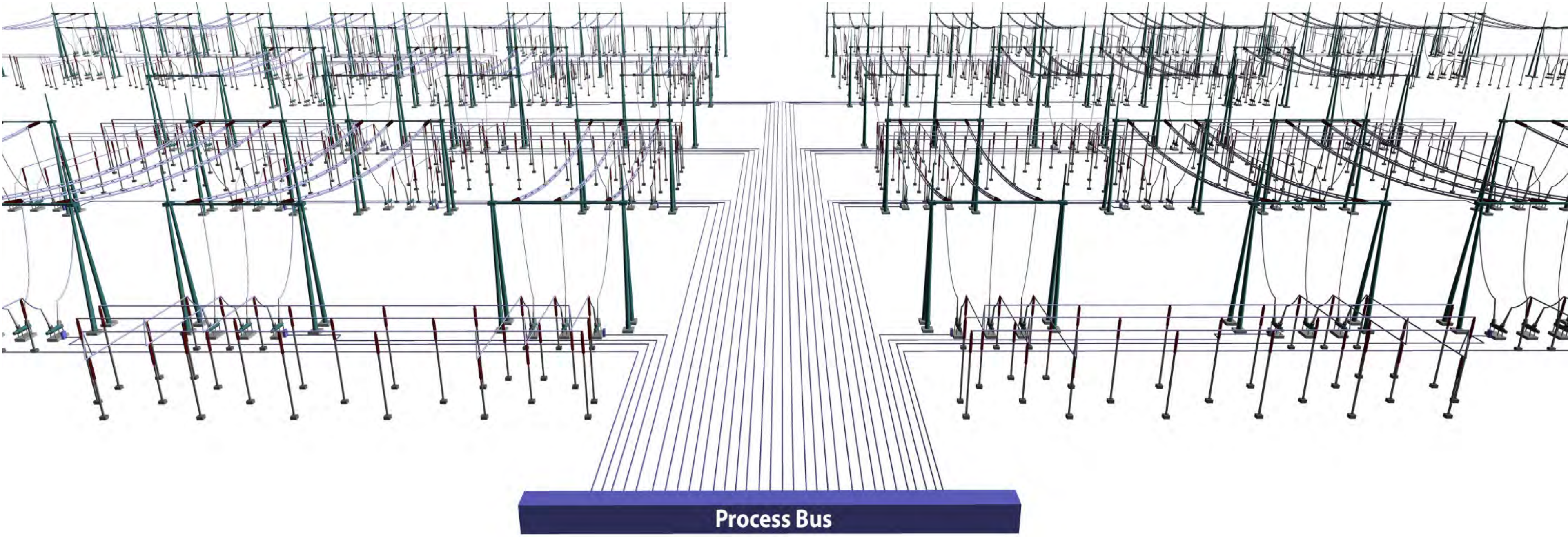




Challenges

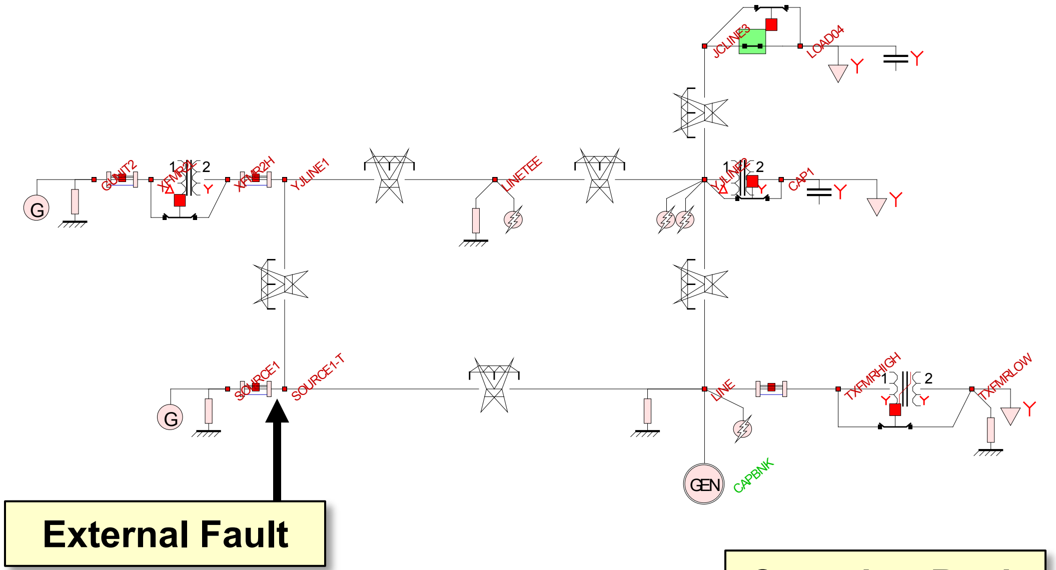
1. Perform the Analytics at time less than ($2t_s$)
2. Robust Operation of DSE requires accurate zone model
3. GPS Synchronized Measurements simplify Dynamic State Estimation (for linear zones it becomes a direct method)

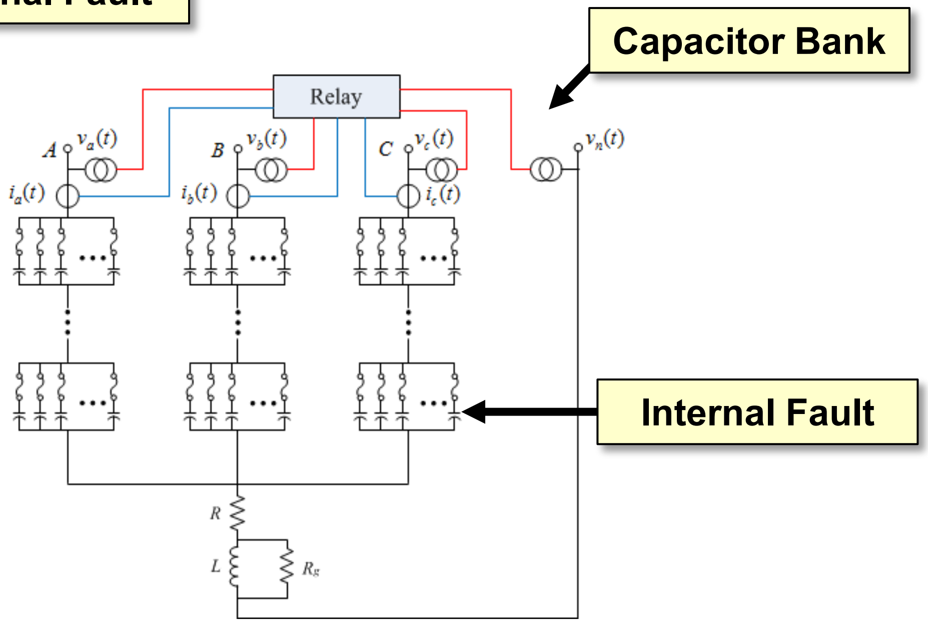
Example: Data Acquisition is performed 4 ks/s → Dynamic State Estimation is performed 2,000 times per sec.

# Examples of DSE Based Protection



# Capacitor Bank



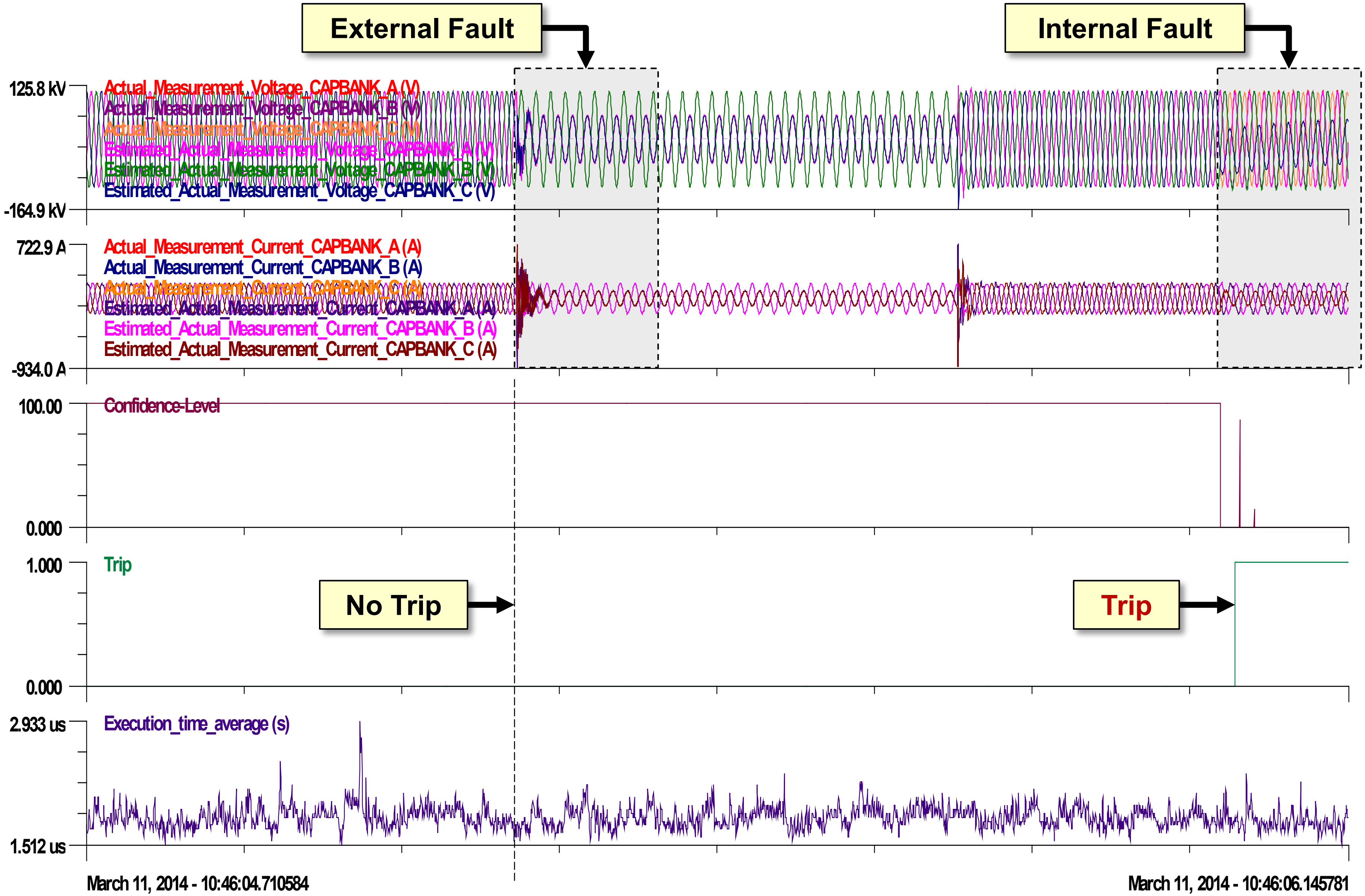

**Event:**

- 115 kV, 48 MVAr capacitor bank
- An external single phase to ground fault happened at 2.2 secs and last for 0.5 secs
- Followed by an internal fault in the capacitor bank at 3.0 secs, which changes the net capacitance of phase C from 4.8 μF to 2.4 μF.

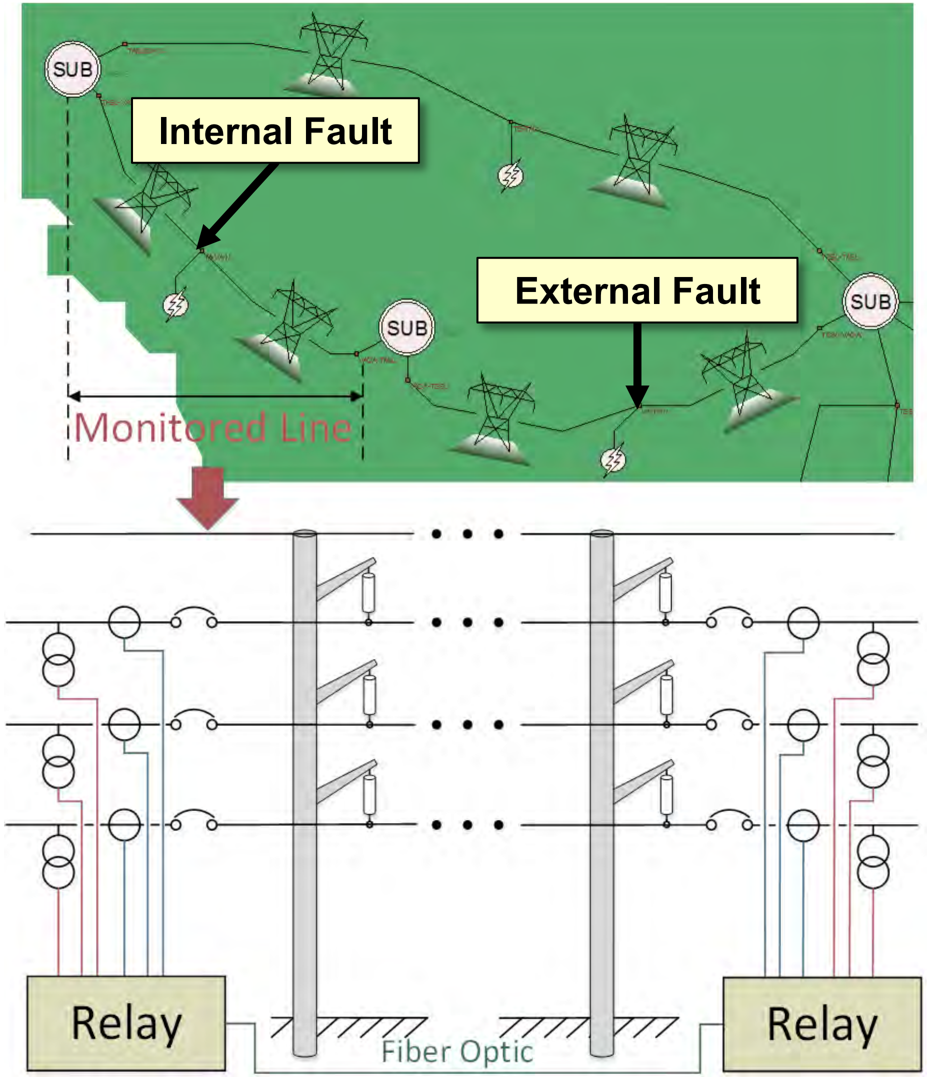
**List of Measurements:**

- Voltage of phase A-G
- Voltage of phase B-G
- Voltage of phase C-G
- Voltage at neutral point
- Current of phase A
- Current of phase B
- Current of phase C

# Capacitor Bank



# Protection of multi-section Lines



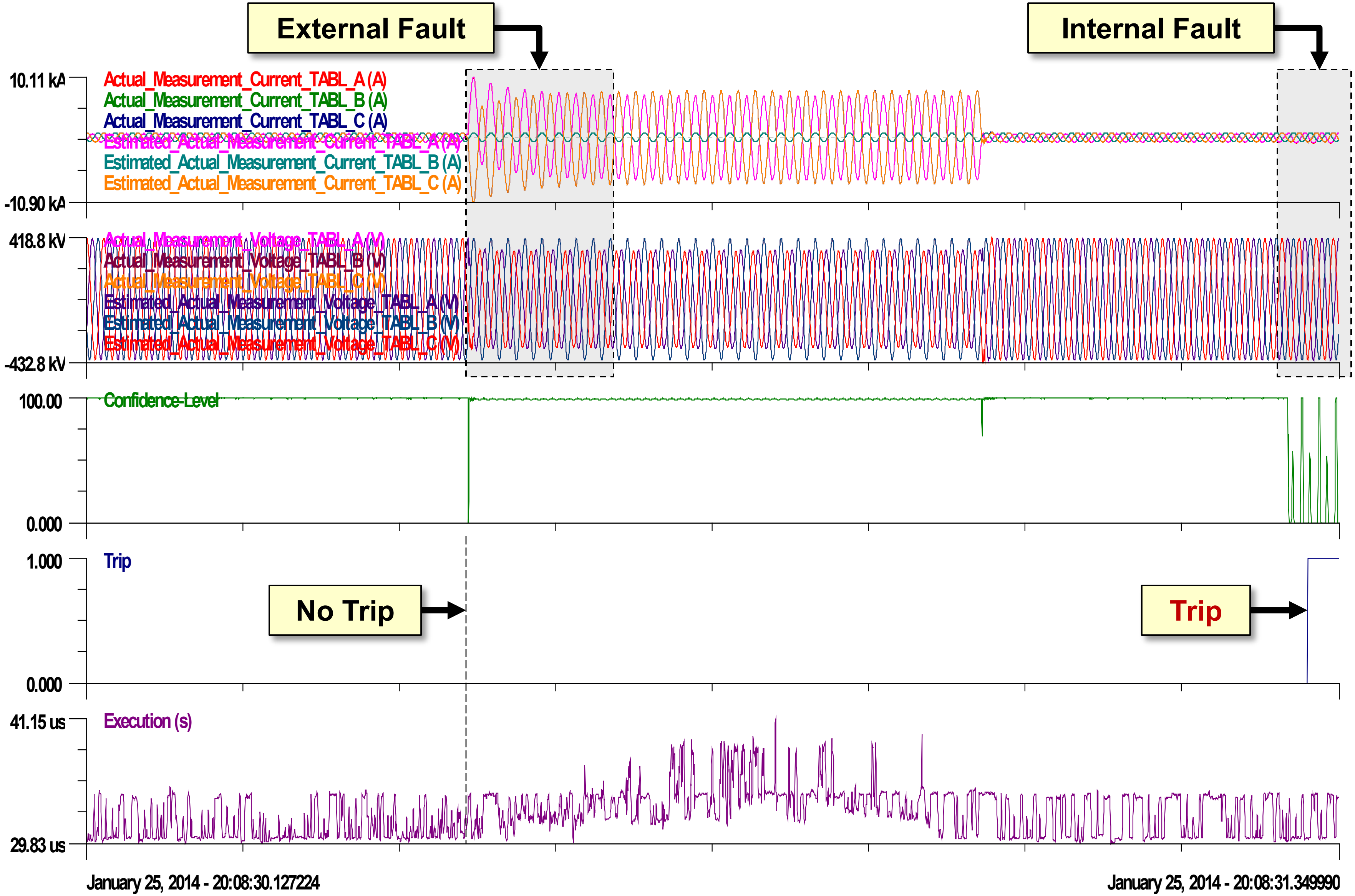

**Event:**

- 500 kV Transmission Line
- An external phase A-C fault happened at 0.5 secs and last for 0.5 secs
- Followed by an internal phase A-G fault in the transmission line at 1.3 secs, which is a 2kΩ high impedance fault.

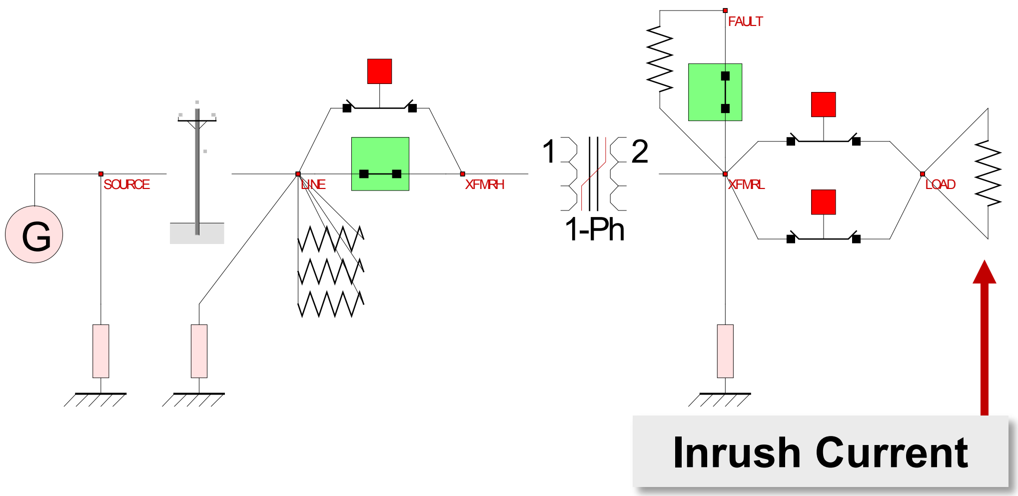
**List of Measurements:**

- Three-phase voltages at two sides
- Three-phase currents at two sides

# Protection of multi-section Lines

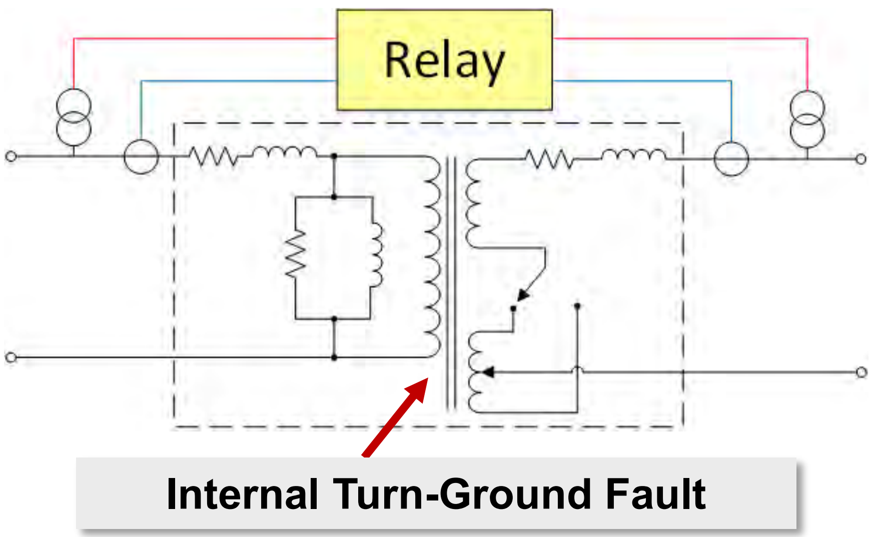


# Protection of Saturable Core Transformers




**Event:**

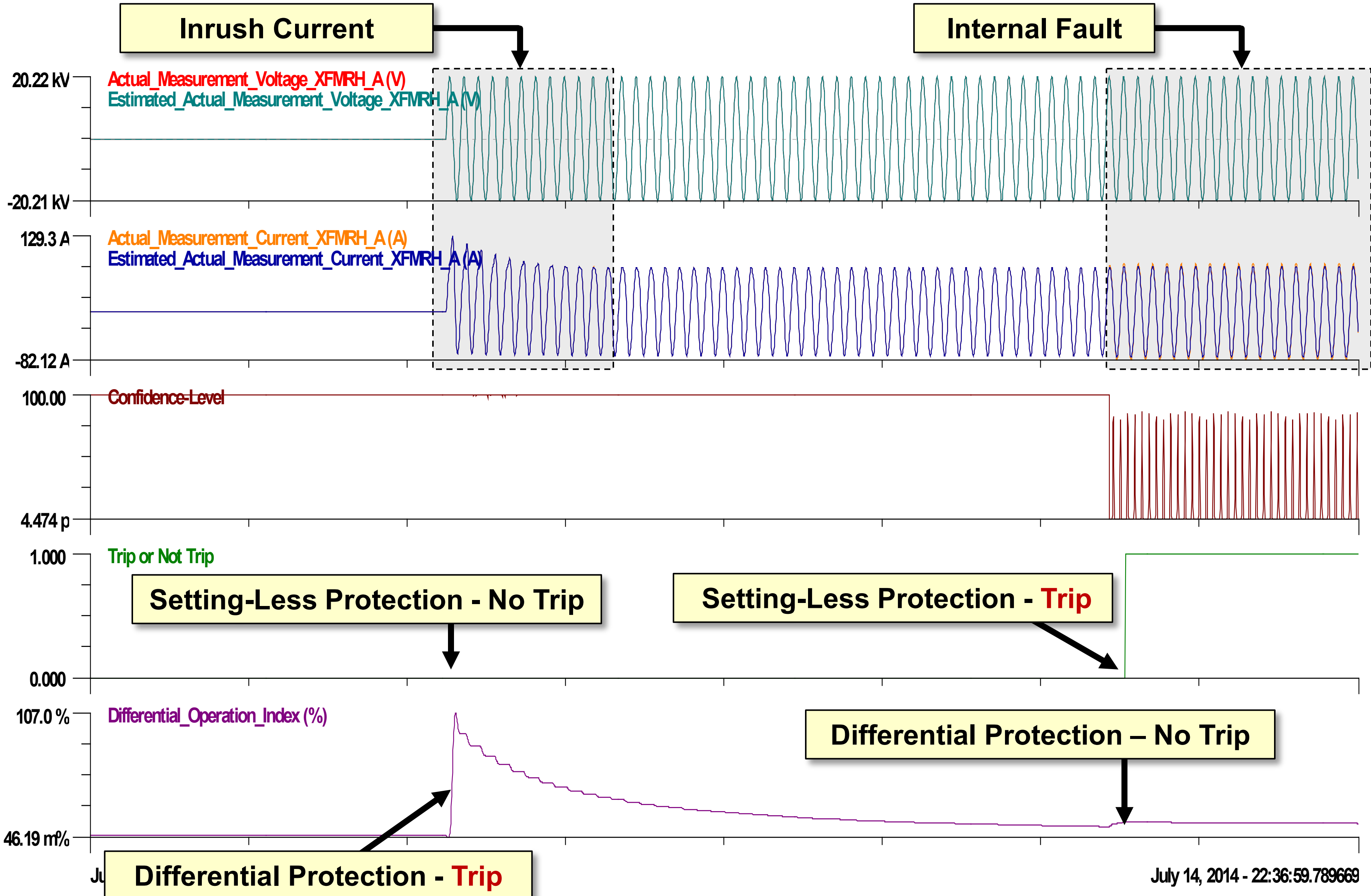
- 14.4/2.2kV, 1000 kVA single-phase saturable-core transformer
- A 800kW load connected to the system and generate inrush currents at 0.72 seconds
- Followed by a 5% turn-ground fault near neutral terminal of the transformer at 1.52 seconds



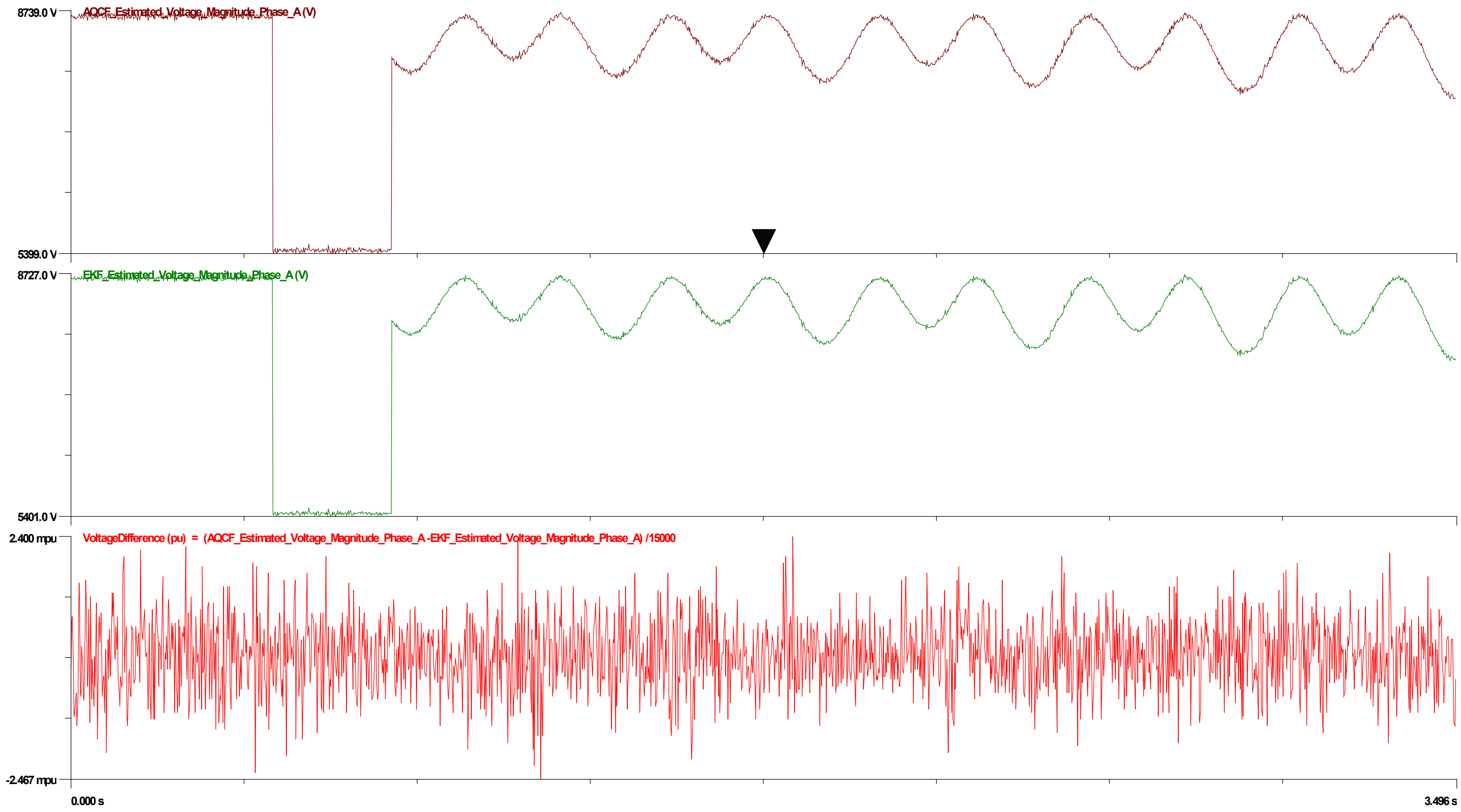

**List of Measurements:**

- Single-phase voltages at two sides
- Single-phase currents at two sides
- Temperature measurements at selected points

# Protection of Saturable Core Transformers



# Comparison of AQCF Based Solution and Extended Kalman Filter

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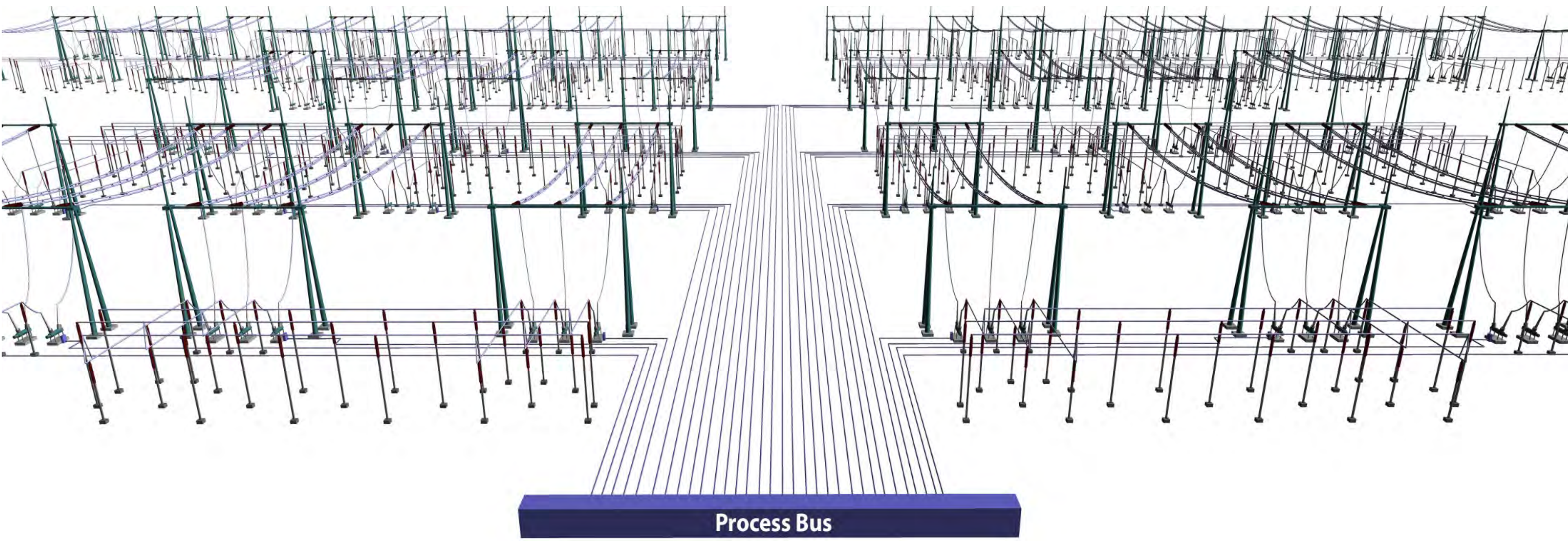
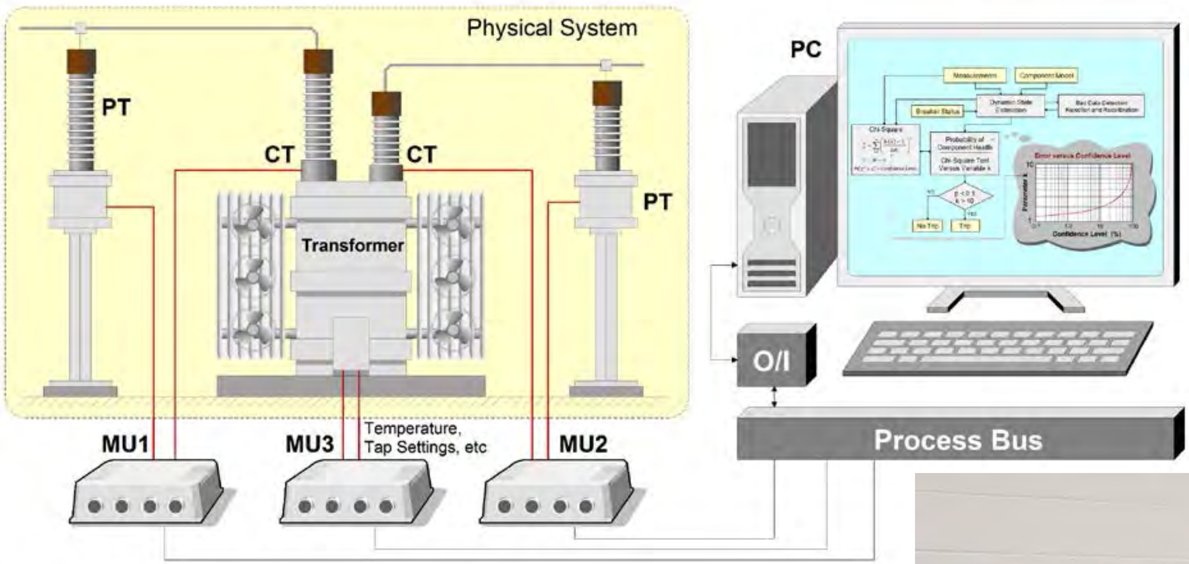
# Laboratory Experimentation



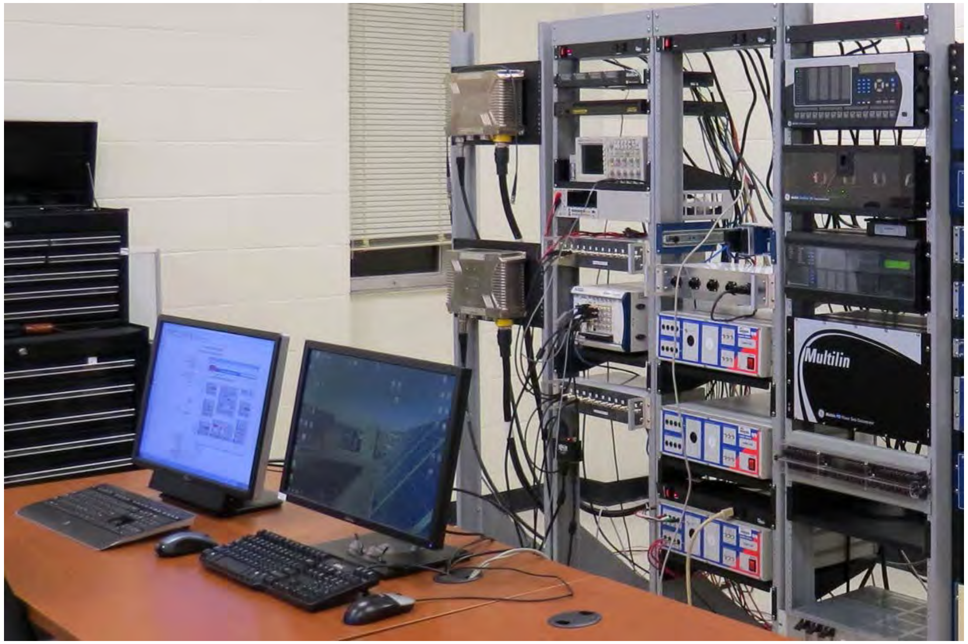
# Laboratory Implementation



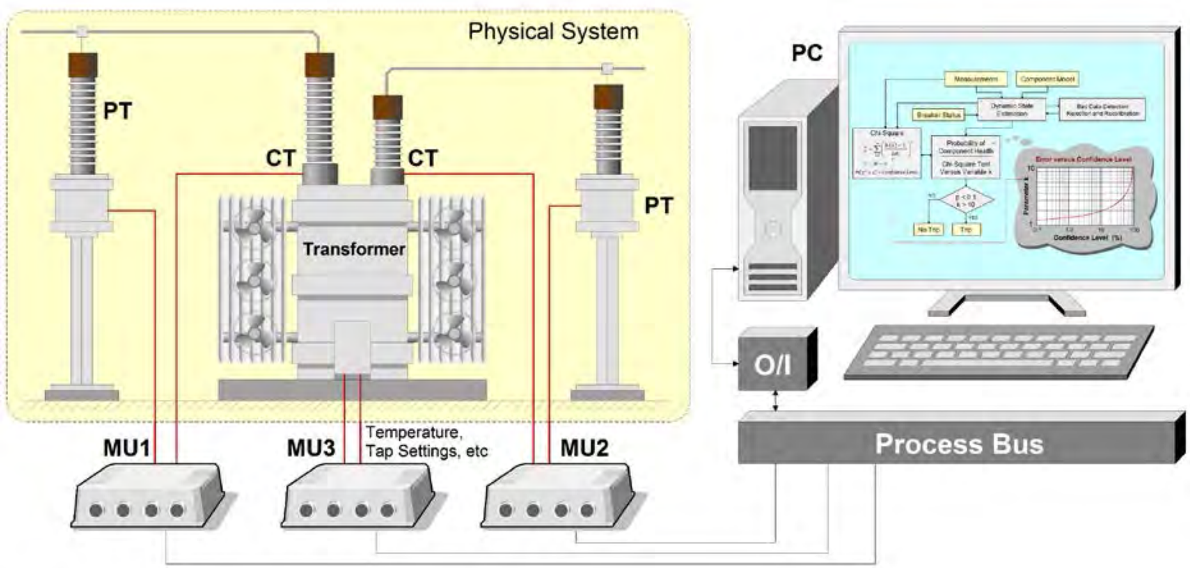

**Experimental Setup Block Diagram**

## Experimental Setup

- PC driven D/A Hardware (32 Chan.)
- Omicron Amplifiers (3)
- GE Hardfiber Merging Units (2)
- Reason MU (1)
- Protection PC with Optical Network Interface & IRIG-B Receiver
- Arbiter GPS Clock with IRIG-B output



# Laboratory Demonstration (Present Laboratory Capability)

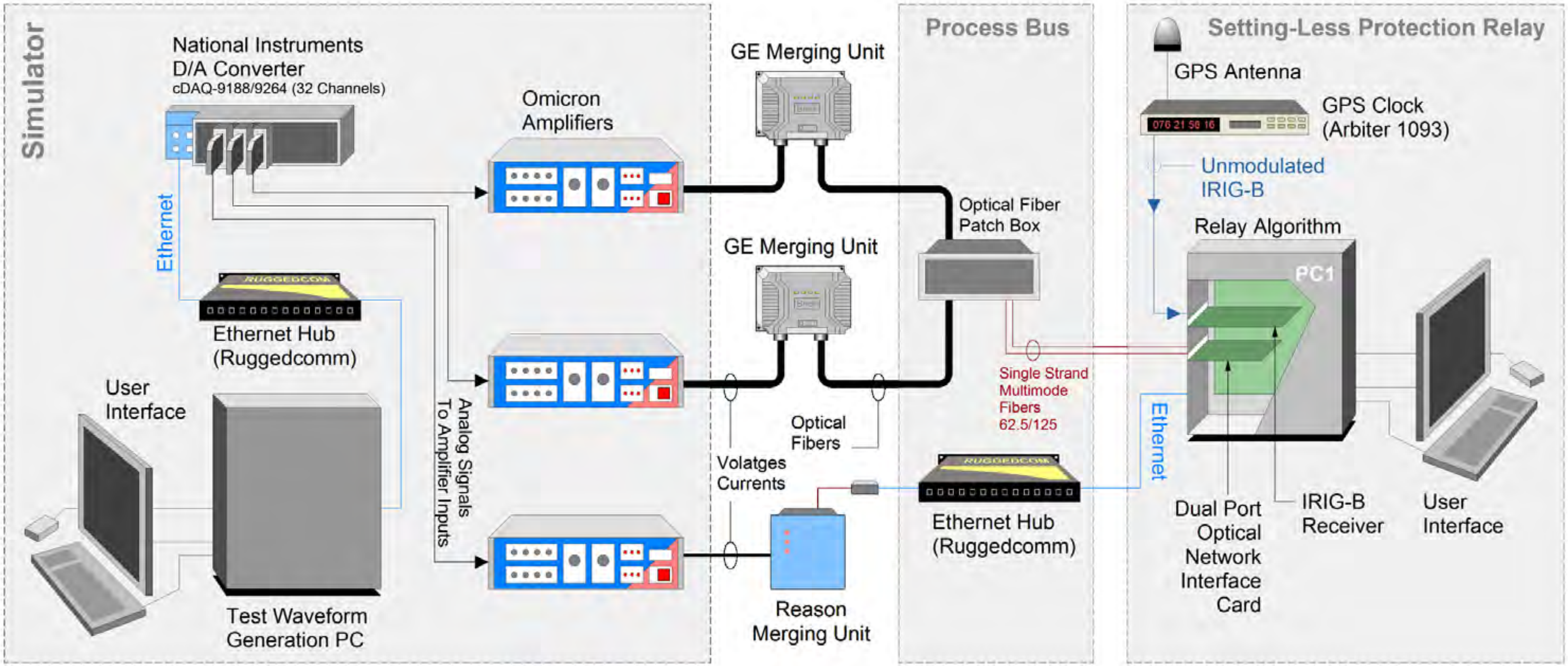




System Under Test consists of:

- Merging units to perform data acquisition
- A process bus, and
- A personal computer attached to the process bus

A personal computer executes the setting-less protection algorithm. The physical system is represented with a simulator, D/A conversion and amplifiers

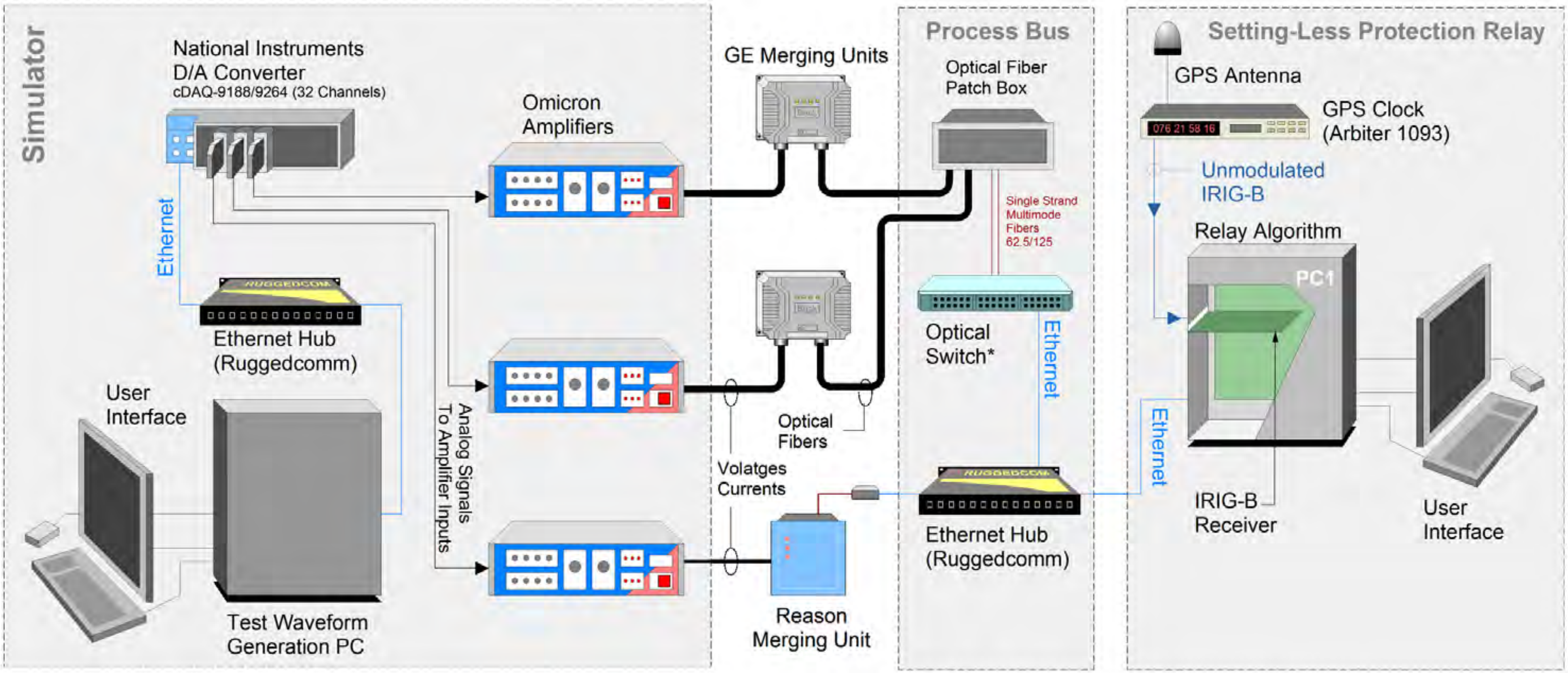
# Laboratory Instrumentation




Our Setting-less Relay is an 8-core $2k PC

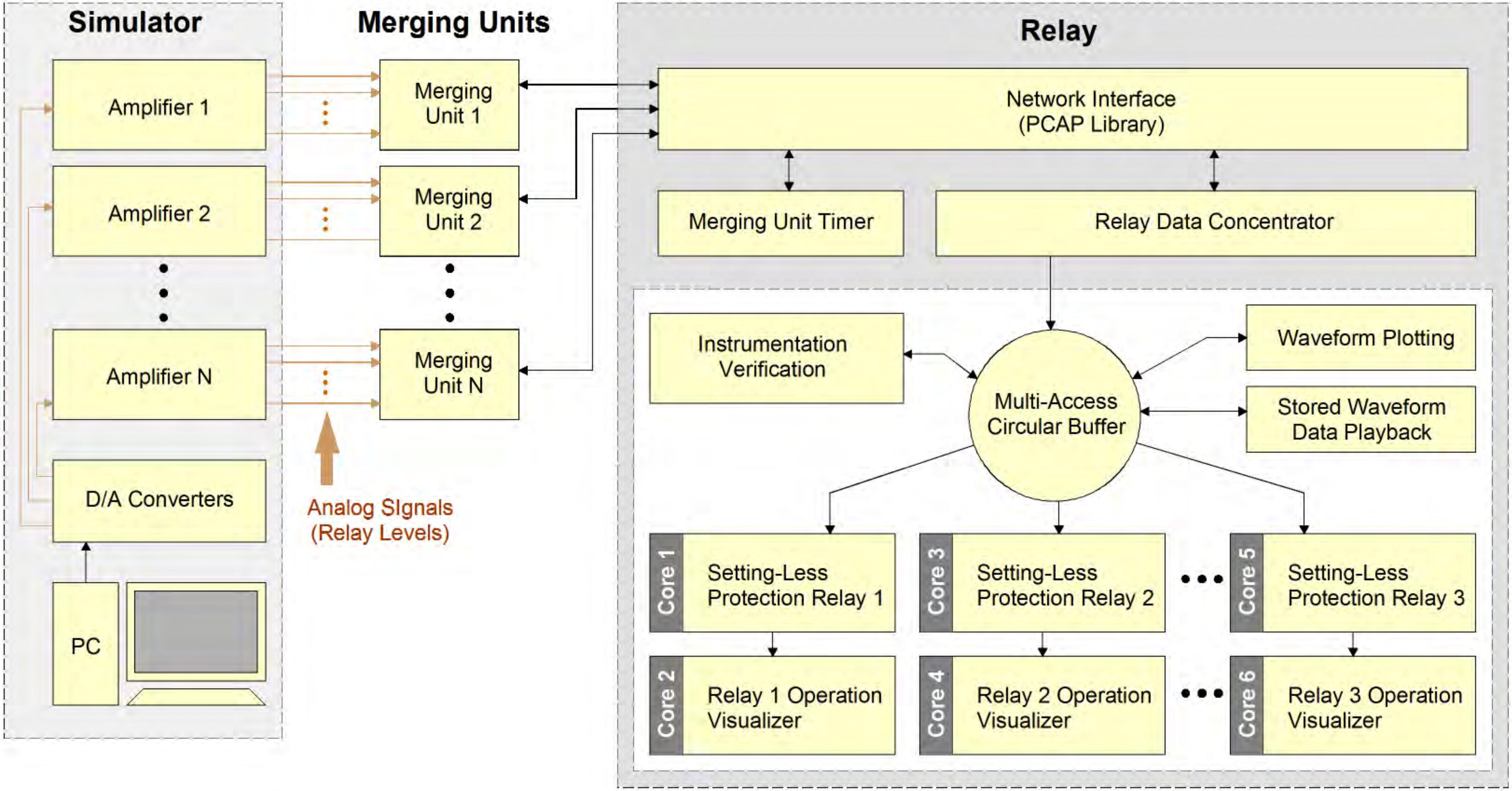
# Laboratory Instrumentation

## Alternate Configuration

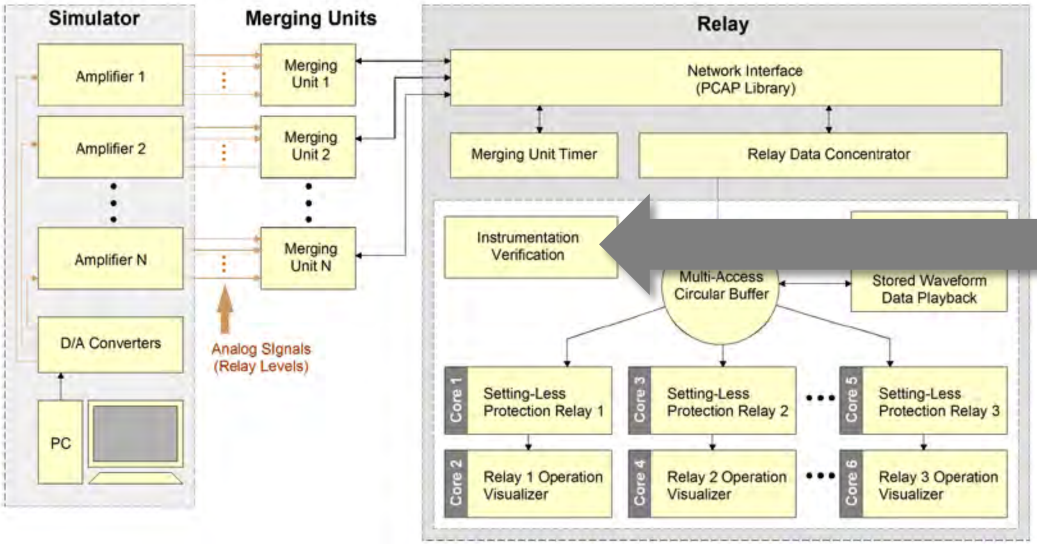



* CISCO CGS-2520-16S-8PC
Connected Grid Switch with SFP Optical Ports

# Object Oriented Implementation



# Instrumentation Verification




**Extremely Important New Capability**

## Identification of Hidden Failures

Blown Fuses

Wrong CT Ratio

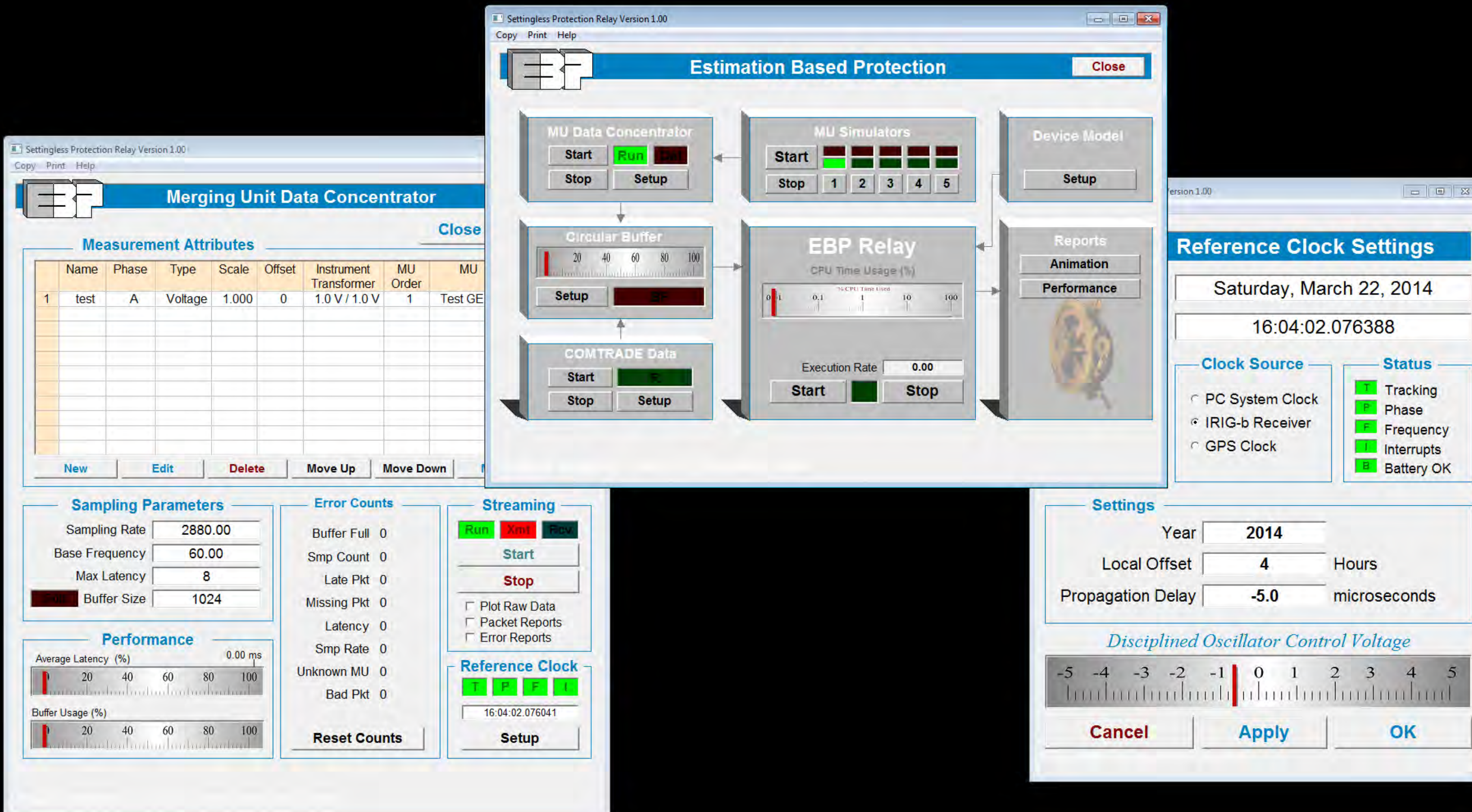
Etc., etc., etc.

## Handling of Hidden Failures

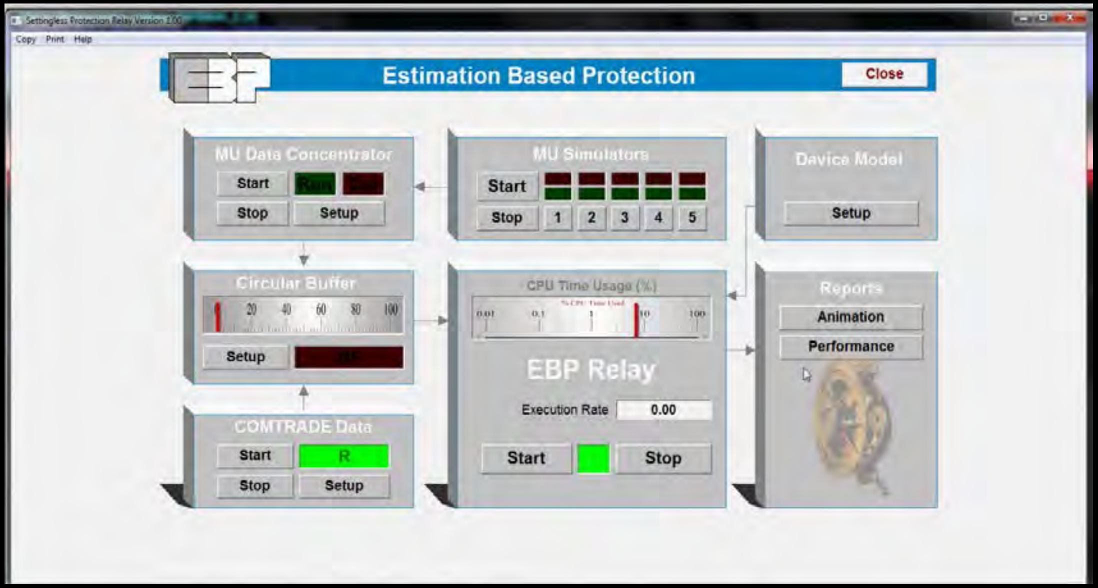
Issue alarms

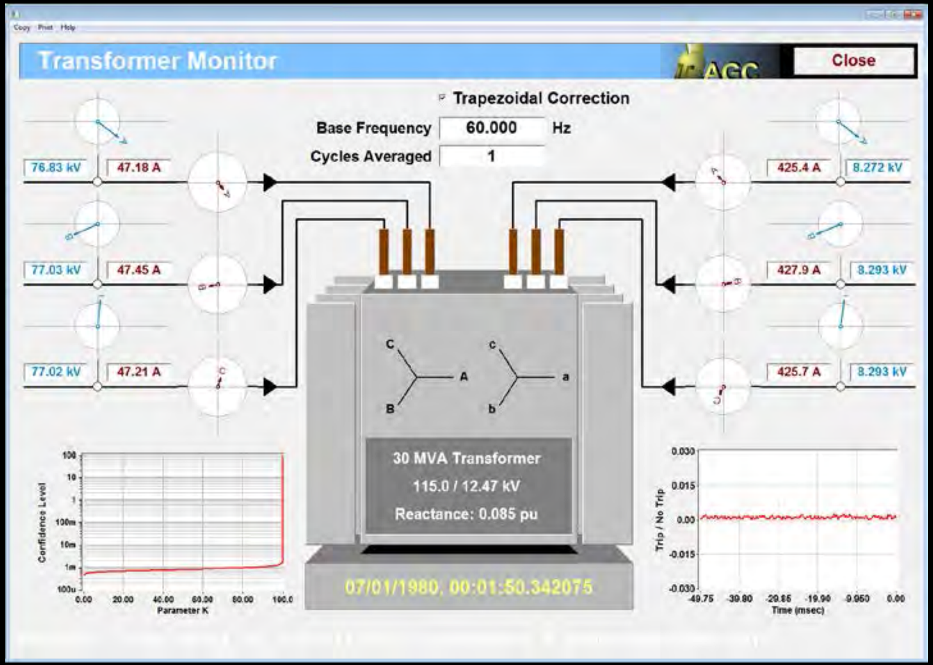
Label data as “bad”

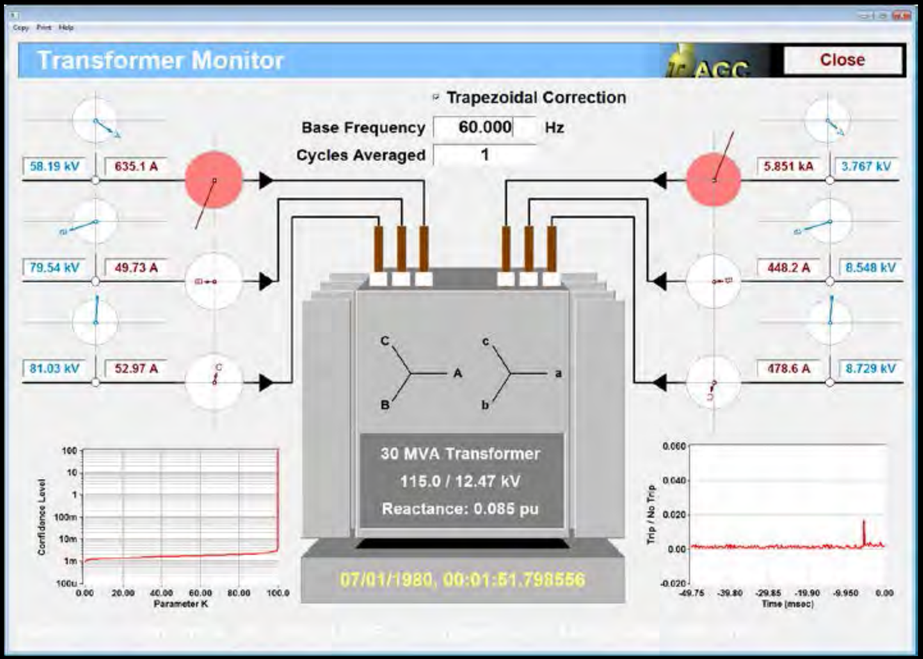
# Visualizations



# Laboratory Results



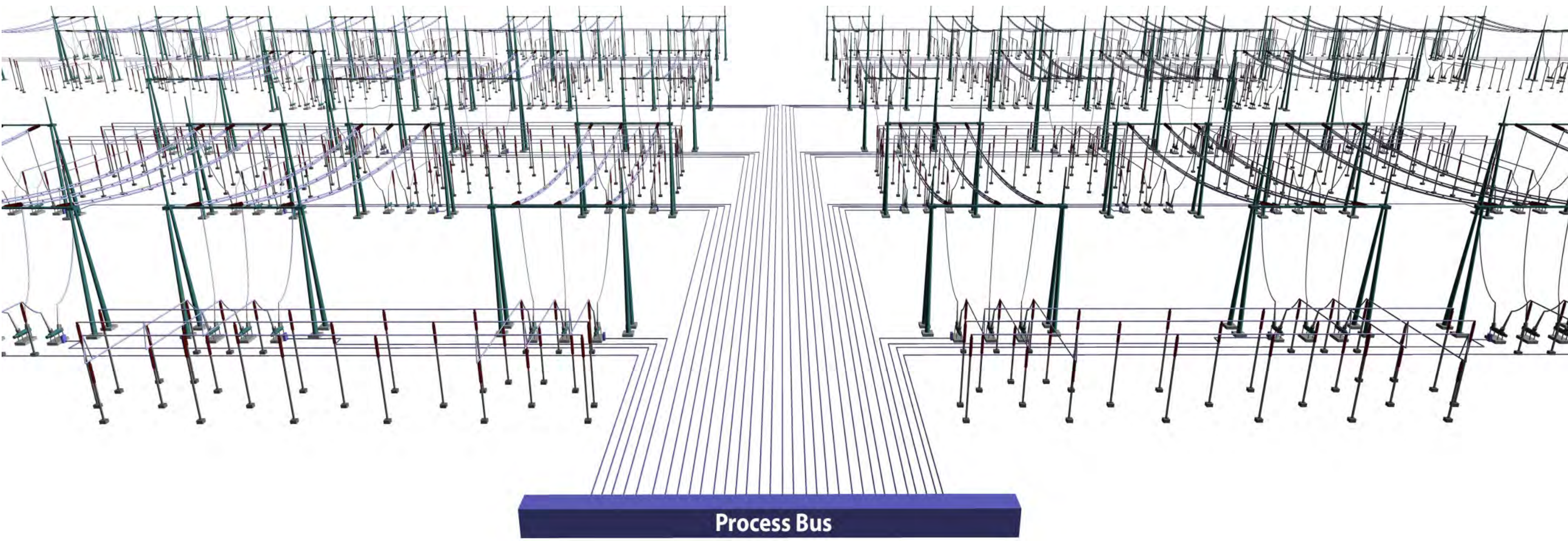



# Technology Issues - MU

- Use of Merging Units is preferable for the Dynamic State Estimation protection because MU data are of better quality and accuracy.
- Interoperability at the Process Bus Level ???
- Data Transmission Latencies may be significant and depend upon communication infrastructure organization and capabilities. Need additional work.
- Transmitted Data Organization Varies among Manufacturers, as IEC68150 does not specify “*Application Service Data Unit*” (ASDU) format
- The Process Bus implementation details vary greatly among Merging Unit manufacturers (eg: GE vs Reason/Alstom, Siemens, etc.)

# Integrated Protection & Control* Vision



# Additional Future Plans

**Work with forward looking utilities to develop and demonstrate a fully "digital" substation:**

- **Separated data acquisition systems from logic devices (merging units)**
- **DSE based protection (both zone and system)**
- **Integrate Substation Based State Estimation with DSE Protection**
- **EMS Integration (Seamless applications with SE model → controls → implementation)**
- **Provide integrated cyber security via the physical system / protection system co-model**

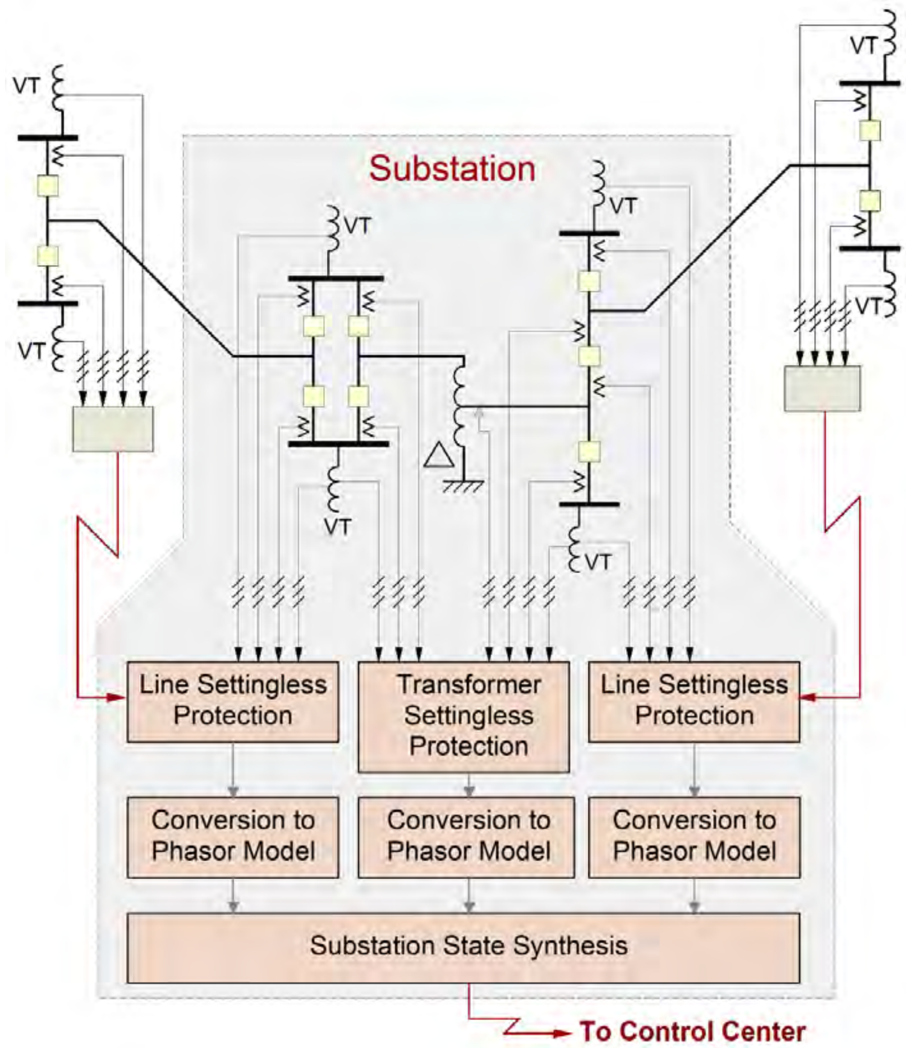
# Our Vision

Integrate Protection and State Estimation

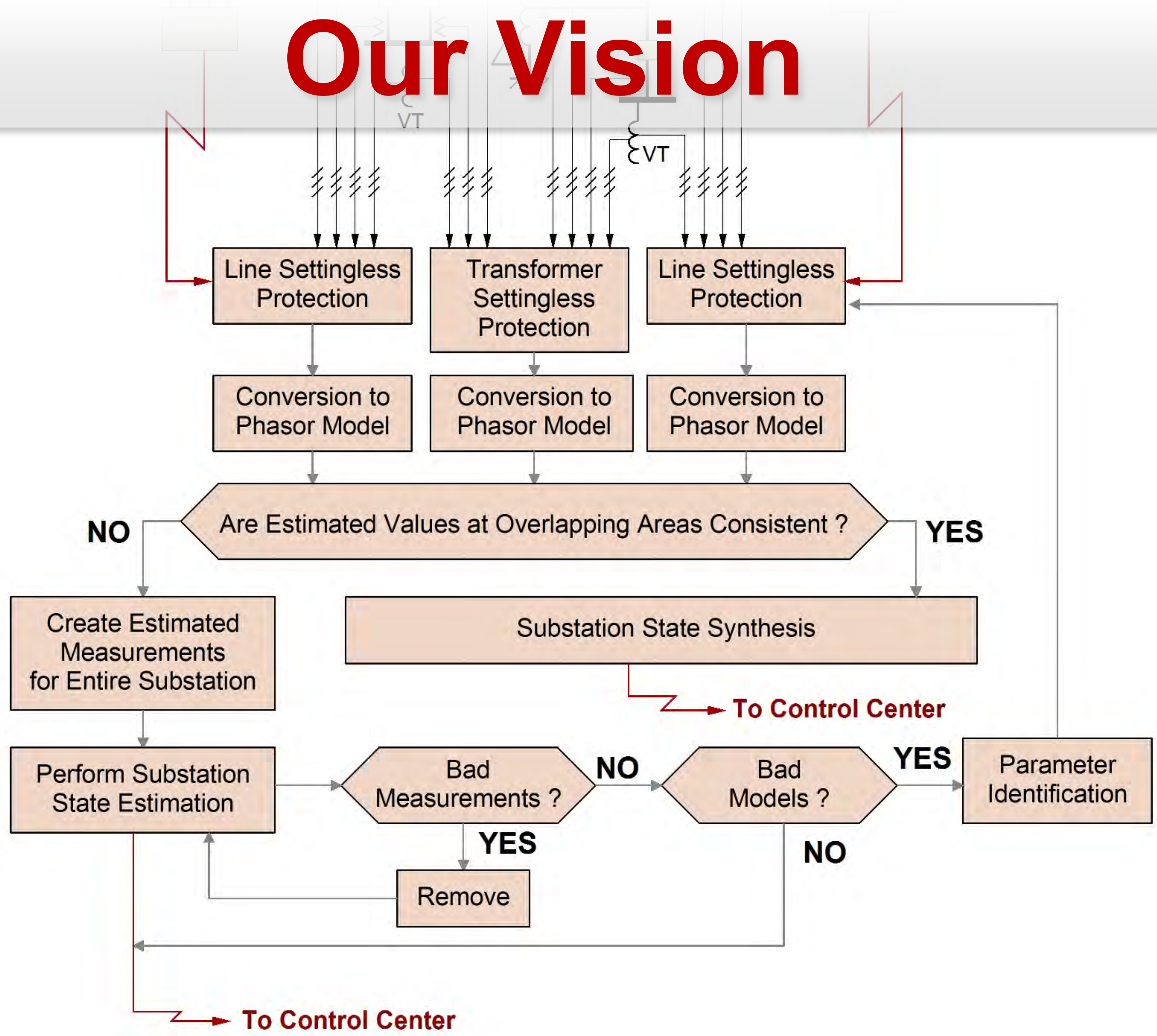
Perpetual Model Validation

Automated Substation State Estimation

Automated System Wide State Estimation



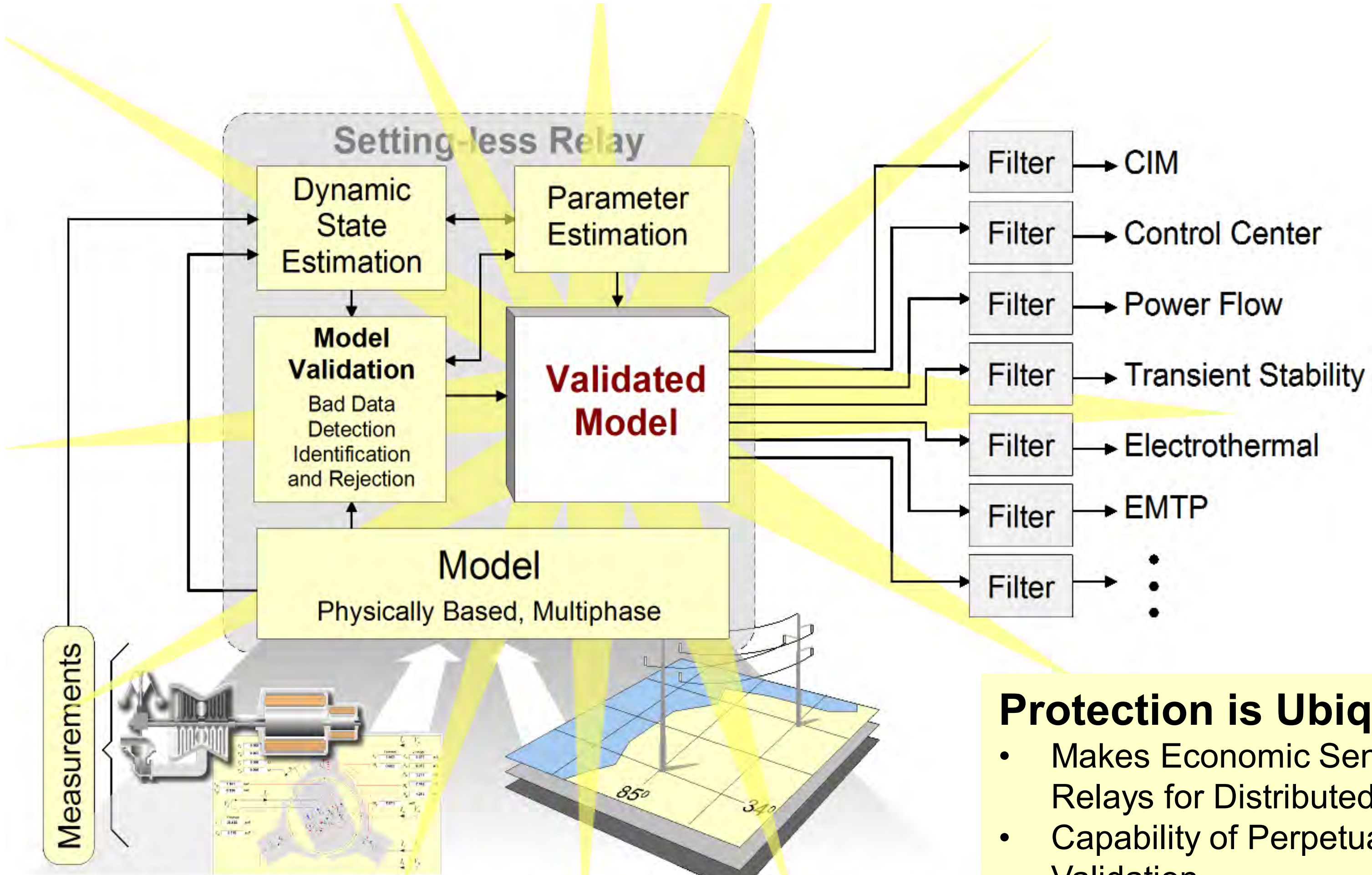
# Our Vision



VT
VT
Line Settingless Protection
Transformer Settingless Protection
Line Settingless Protection
Conversion to Phasor Model
Conversion to Phasor Model
Conversion to Phasor Model
NO
Are Estimated Values at Overlapping Areas Consistent ?
YES
Create Estimated Measurements for Entire Substation
Substation State Synthesis
To Control Center
Perform Substation State Estimation
Bad Measurements ?
NO
Bad Models ?
YES
Parameter Identification
YES
Remove
NO
To Control Center

# Perpetual Model Calibration and Validation

A Ubiquitous System for Perpetual Model Validation



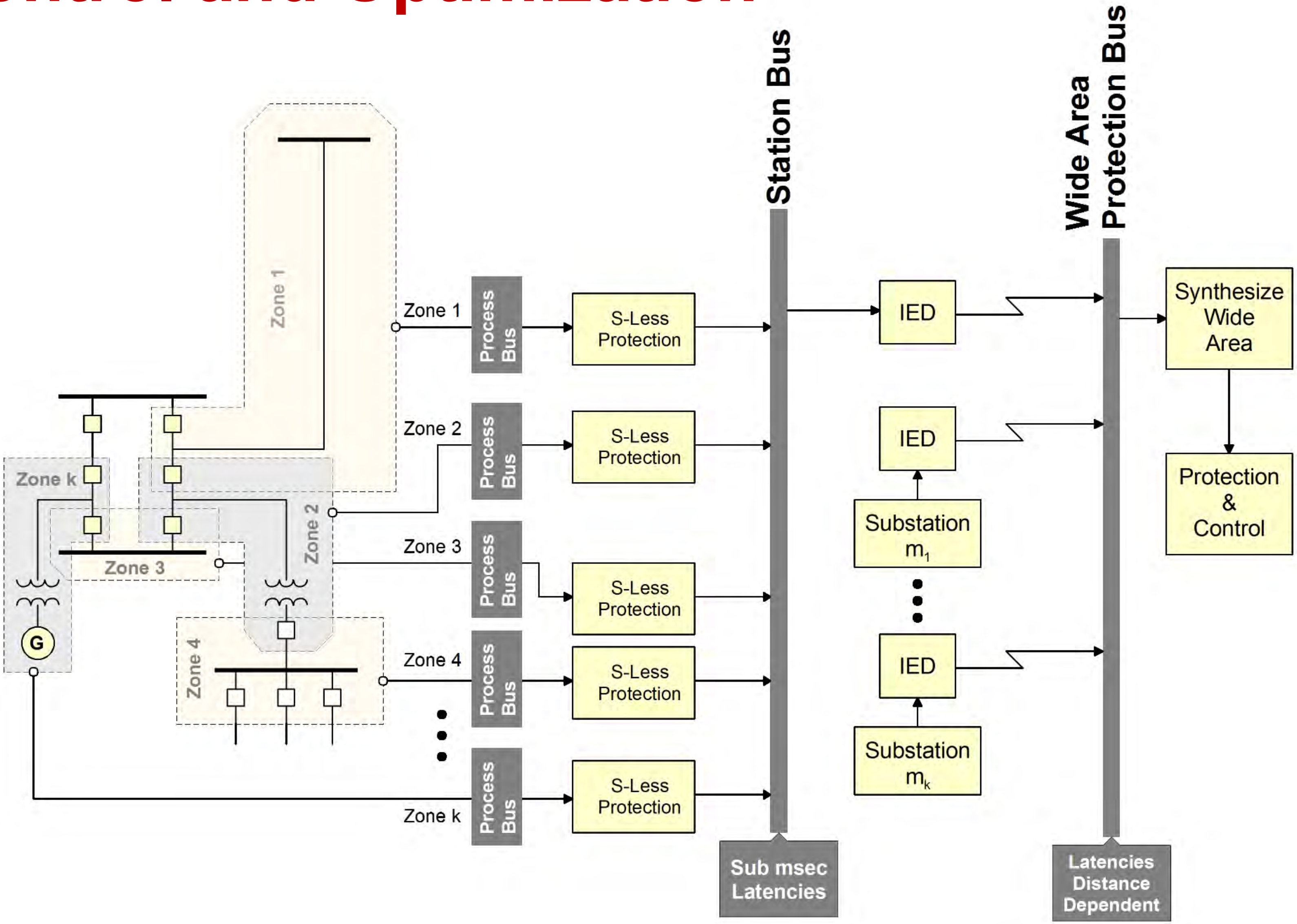

Physically Based Generator Model

GIS Based Transmission Line Model

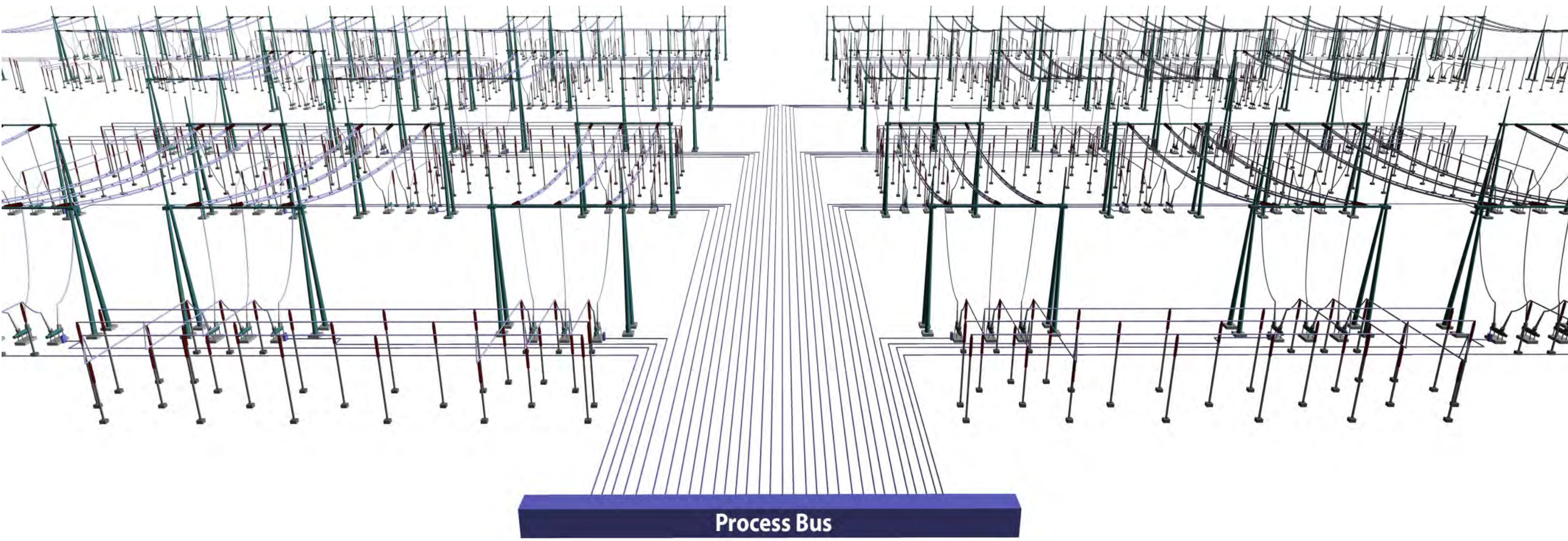
## Protection is Ubiquitous

- Makes Economic Sense to Use Relays for Distributed Model Data Base
- Capability of Perpetual Model Validation
- Component Real Time Model with GPS Time Stamp – enables distributed approaches

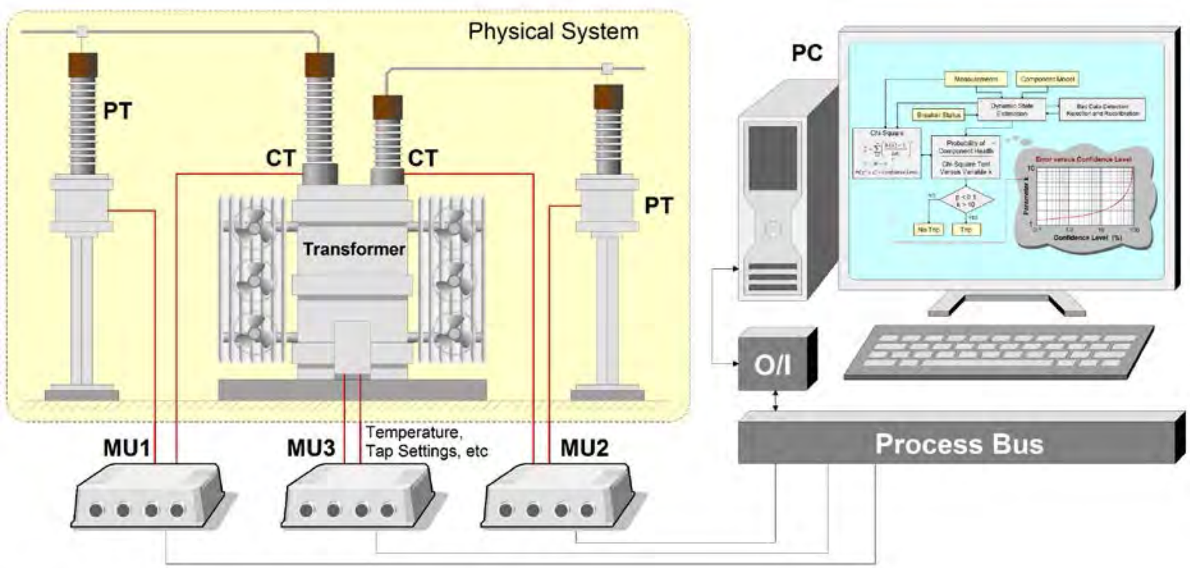
# Integrated Wide Area Modeling, Protection, Control and Optimization



# Dedicated Laboratory



# Laboratory Demonstration (Present Laboratory Capability)




System Under Test consists of:

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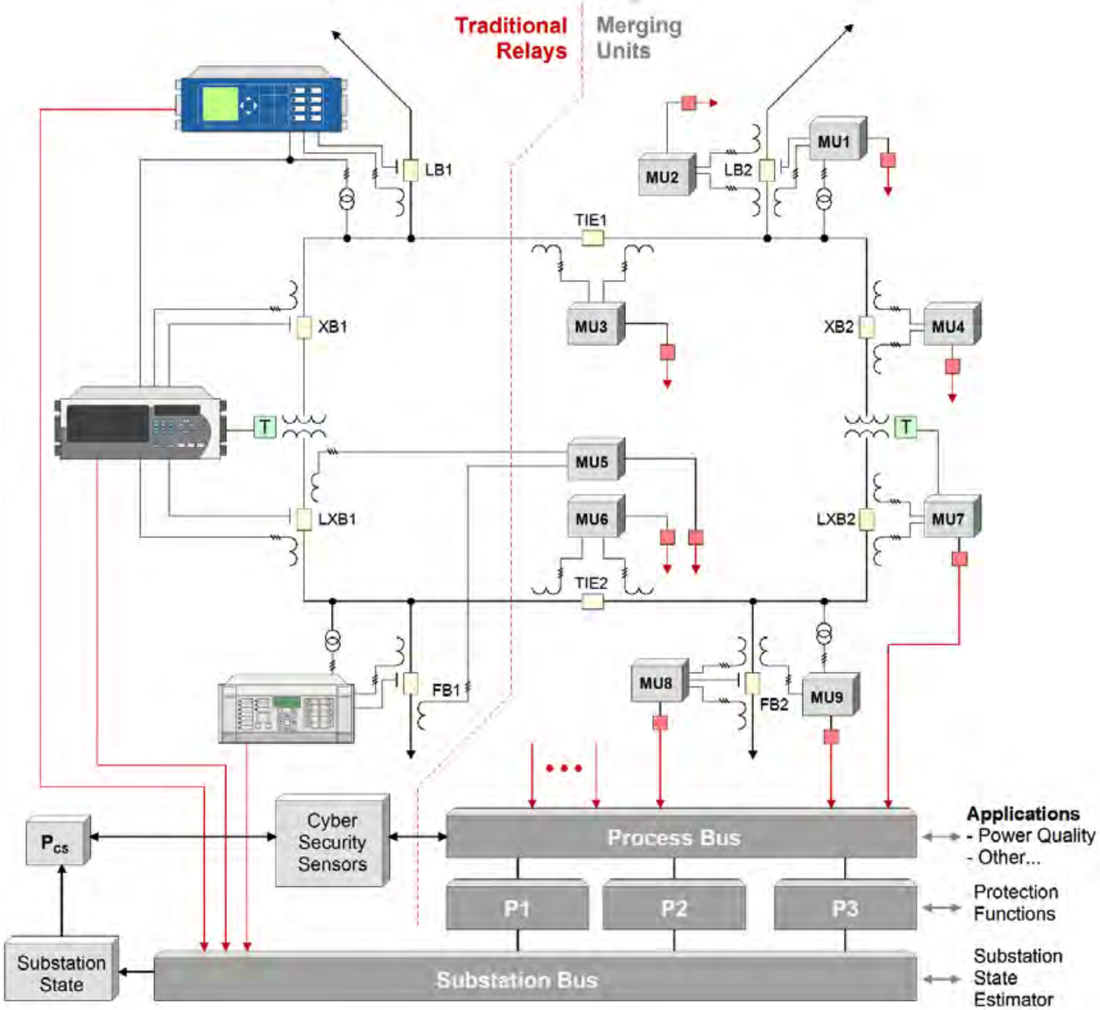
- A process bus, and
- A personal computer attached to the process bus

A personal computer executes the setting-less protection algorithm. The physical system is represented with a simulator, D/A conversion and amplifiers

# Planned Laboratory Expansion

## (Dedicated Lab for Protection, Control & Cyber Security Testing: Continuous Operation of Fully Automated Substation: To Be Used by Multiple GaTech Research Groups)




Configuration is a full replica of the IT infrastructure of a modern substation with multi-vendor equipment

It will be driven by a high fidelity simulator capable of reproducing real life conditions

Unique capability for simultaneous testing of **protection, control and cyber security**

# Acknowledgments

**We have collaborated with many folks over the years and it is impossible to list all.**

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Τέλος