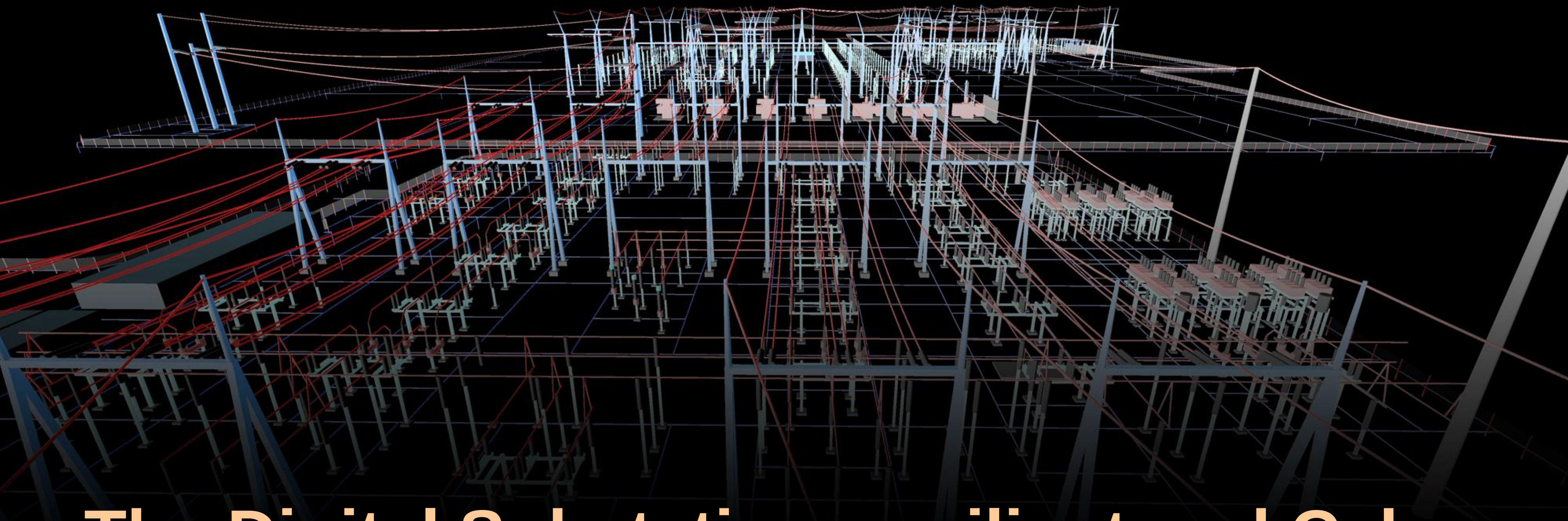


The Digital Substation: resilient and Cyber Secure Protection and Control

Sakis Meliopoulos

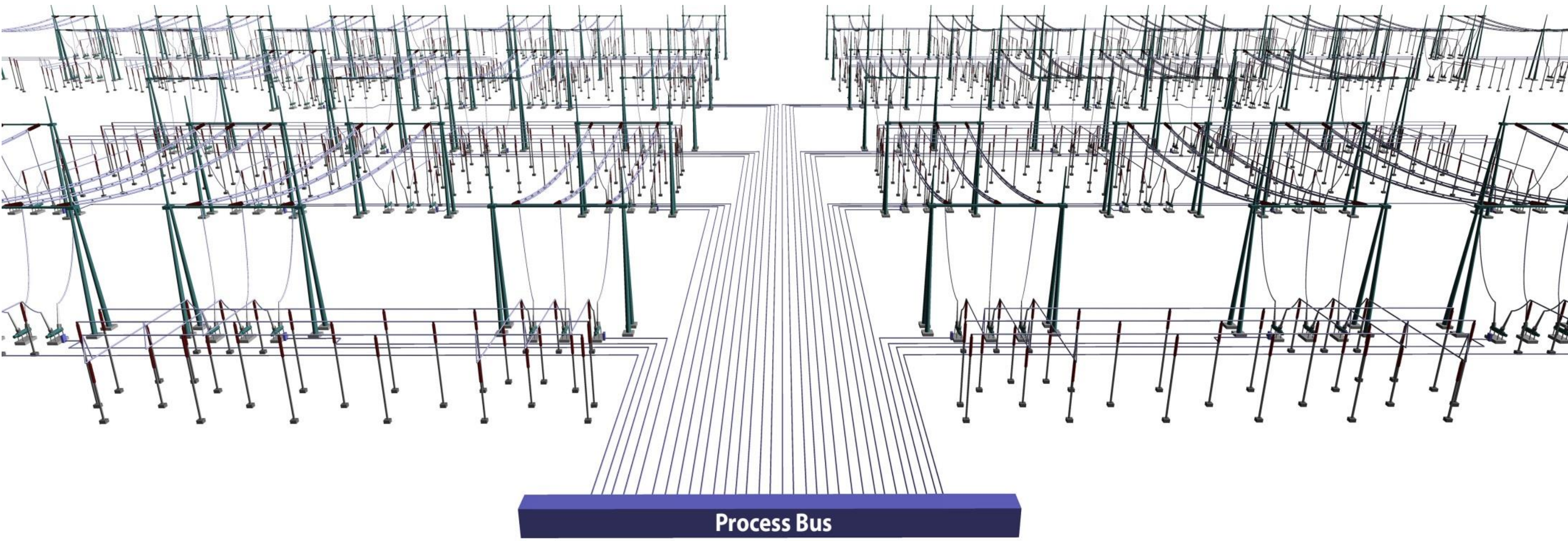
Georgia Institute of Technology, Atlanta, Georgia USA

Presentation Outline

- Protective Relaying Status & Challenges: Performance Statistics
- Perennial Issues: Data Integrity, Hidden Failures, Complexity and now cyber attack concerns
- The digital substation concept
- Relevant Technologies
  - Setting-less relays
  - Error Correction within Merging Units
  - Substation Centralized Protection Scheme
  - Detection of Hidden Failures and cyber attacks
- Real Time Autonomous Self Healing
- Concluding Remarks

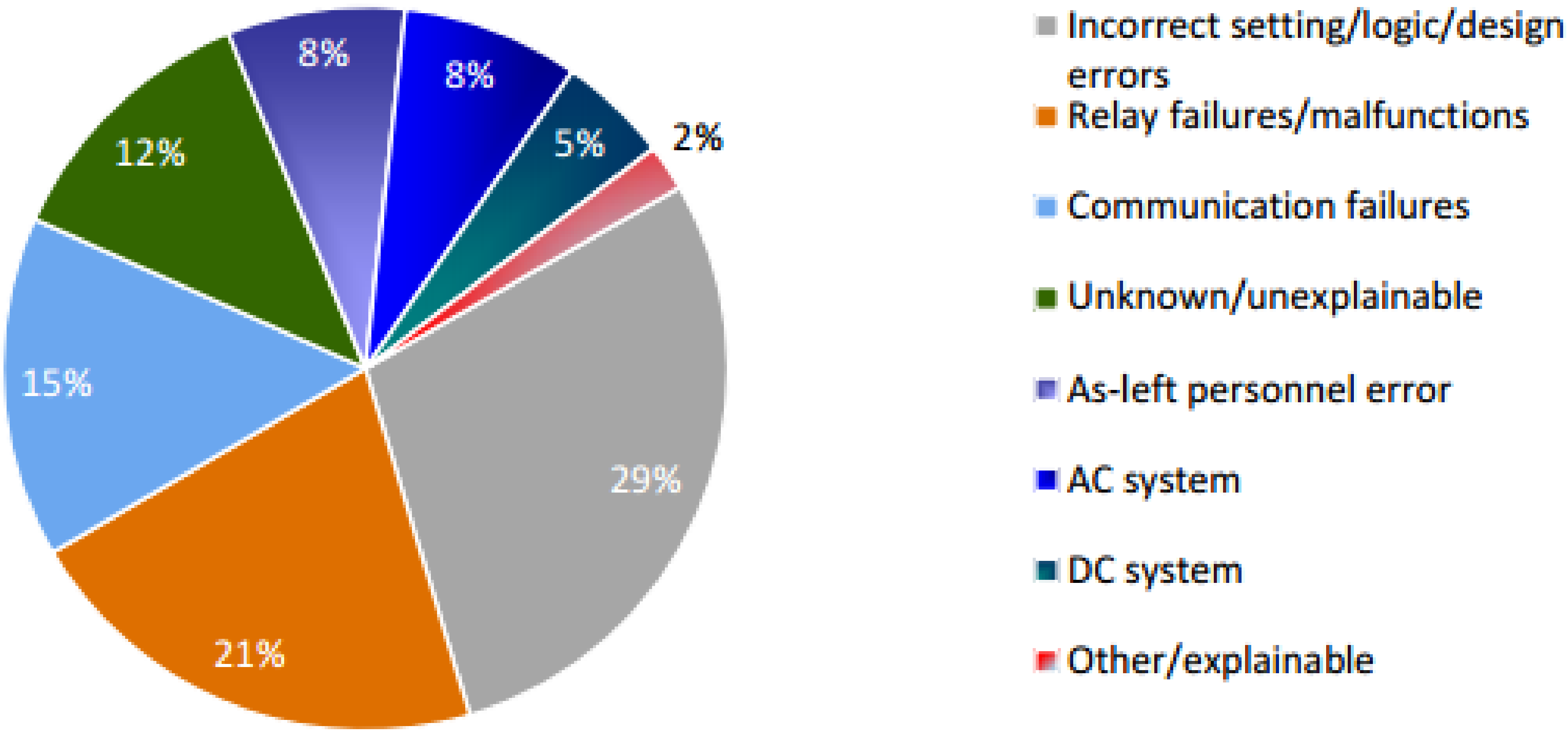
Performance Statistics

Mis-Operations & Protection Gaps



Performance Statistics: DoE

Relay Mis-operations: 10%
Of These 65% are related to hidden failures



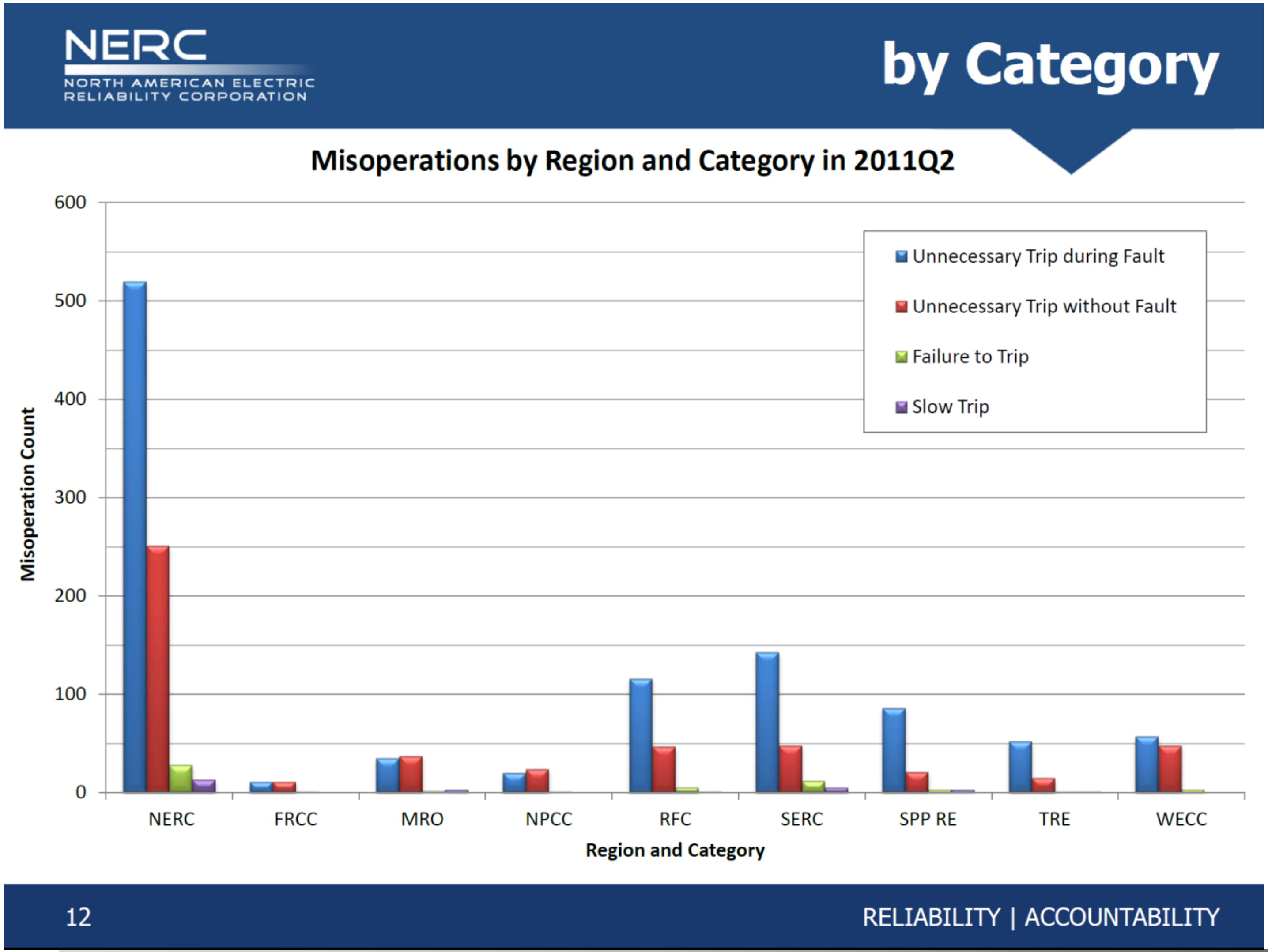
Sample Statistics

For the Brazilian National Grid, the ISO collects yearly the data about the performance of protection systems. The following graph shows the percent of success in operation of protection of transmission lines, transformers and buses, for the whole Brazilian grid, in 3 years.

Brazil	2008	2009	2010
Line	97.42	96.3	96.8
Transformer	86.3	87.3	91.2
Bus	86.8	86.2	83.0

Statistics

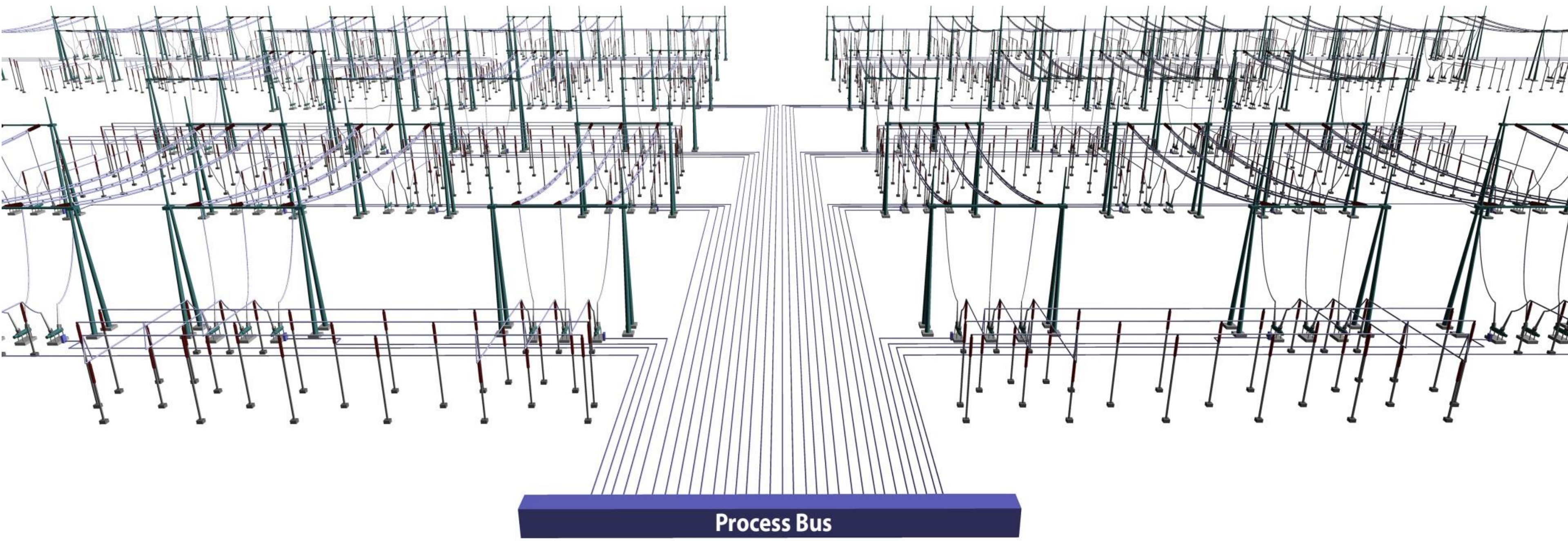
Protection Systems Misoperations Identified as
#1 NERC Reliability Issue in 2010



Causes of Mis-Operation

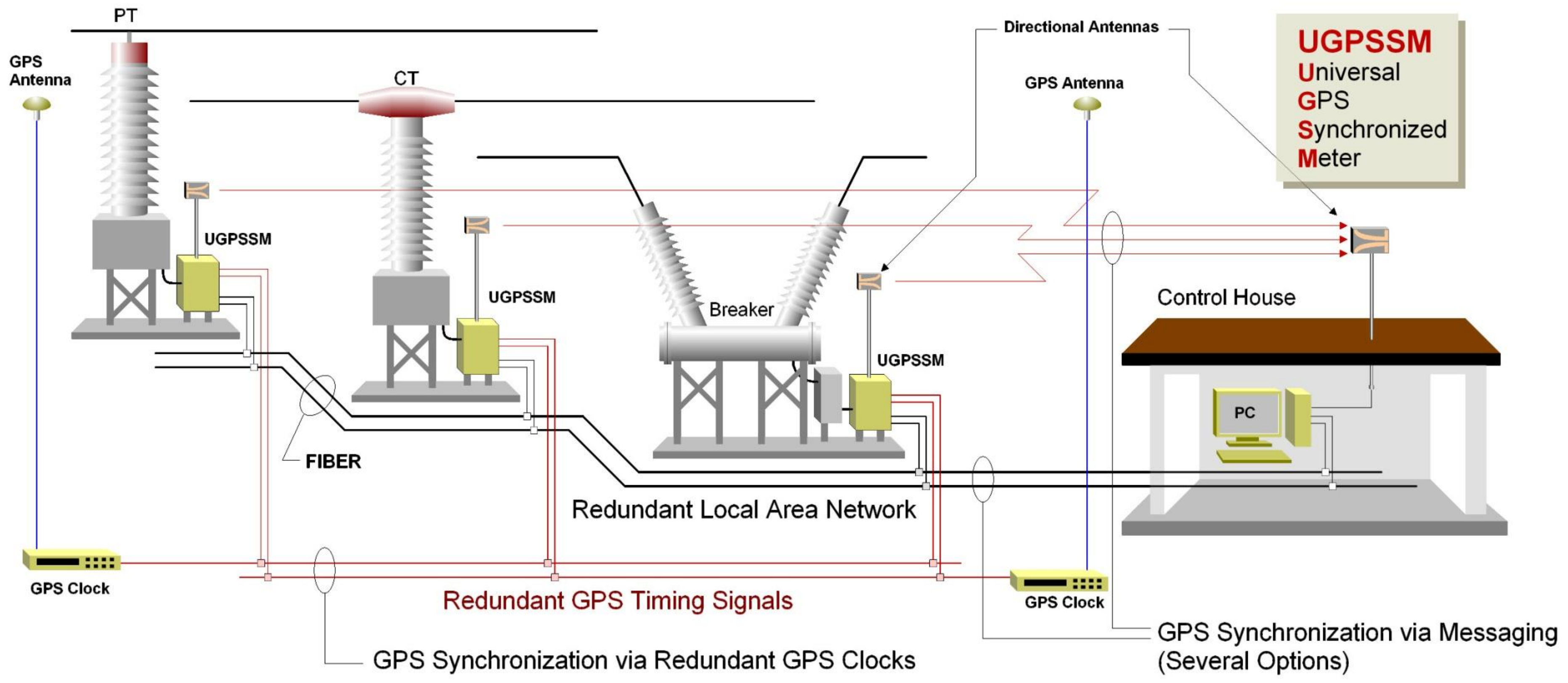
- **Complexity**
  Relay Settings
  Coordination Issues
- **Data Integrity**
- **Hidden Failures**
- **Cyber Attacks**
- **Protection Gaps**
  (HIF, Faults near neutrals, etc.)
- **Unusual Events**

Relevant Technologies

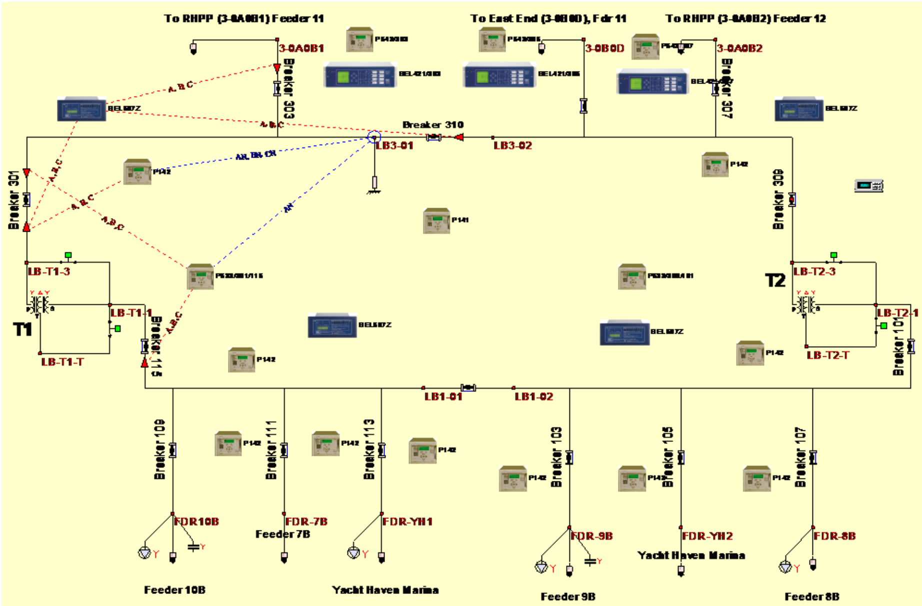


The Substation of the Future

PSERC Project 2007-08 (Meliopoulos, Bose)

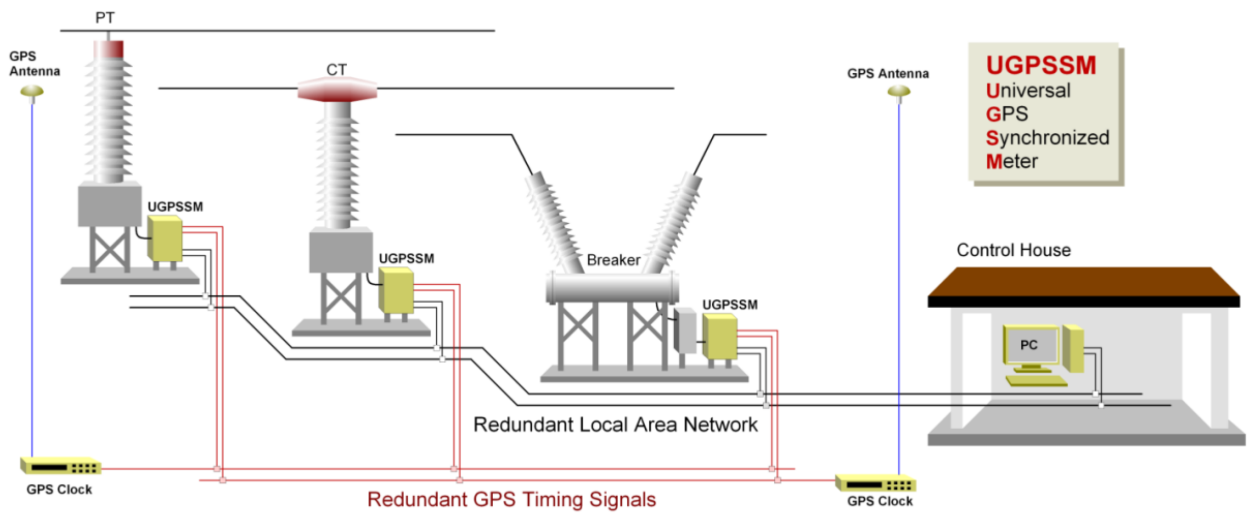


Overall Approach



From This

To This



Present Day Technology

Merging Units were Introduced by 2009:

- *Hardfiber by GE.*

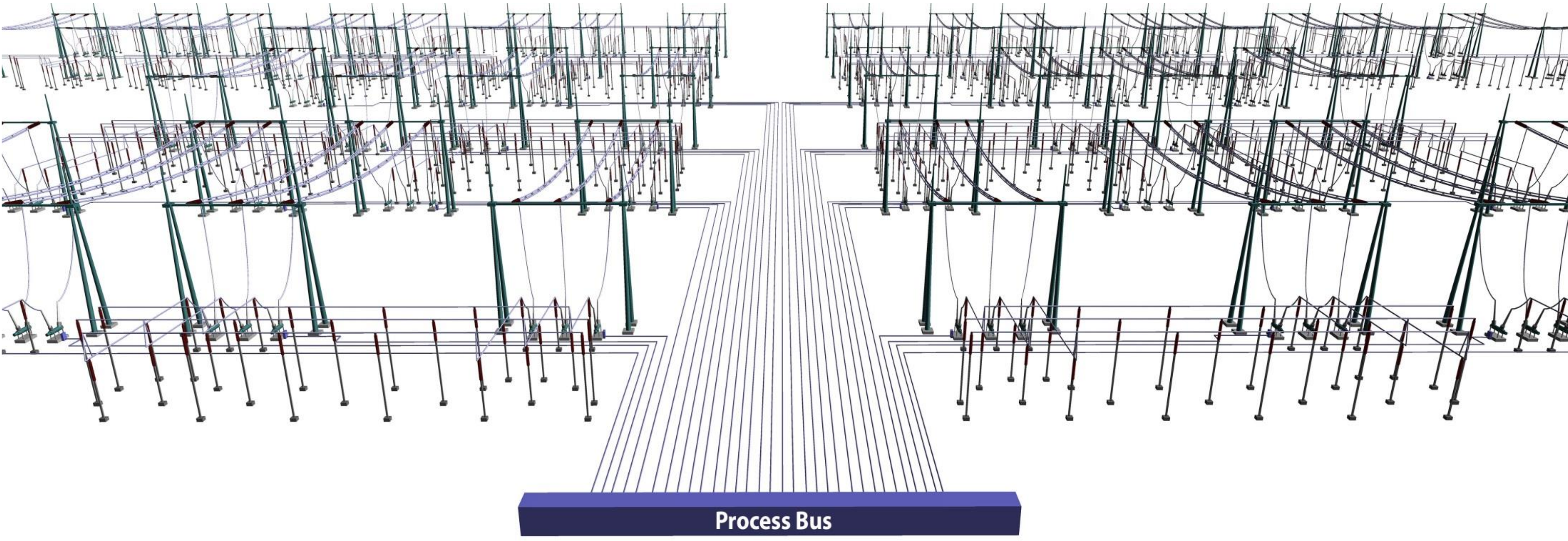
Today many manufacturers offer free standing merging units

and

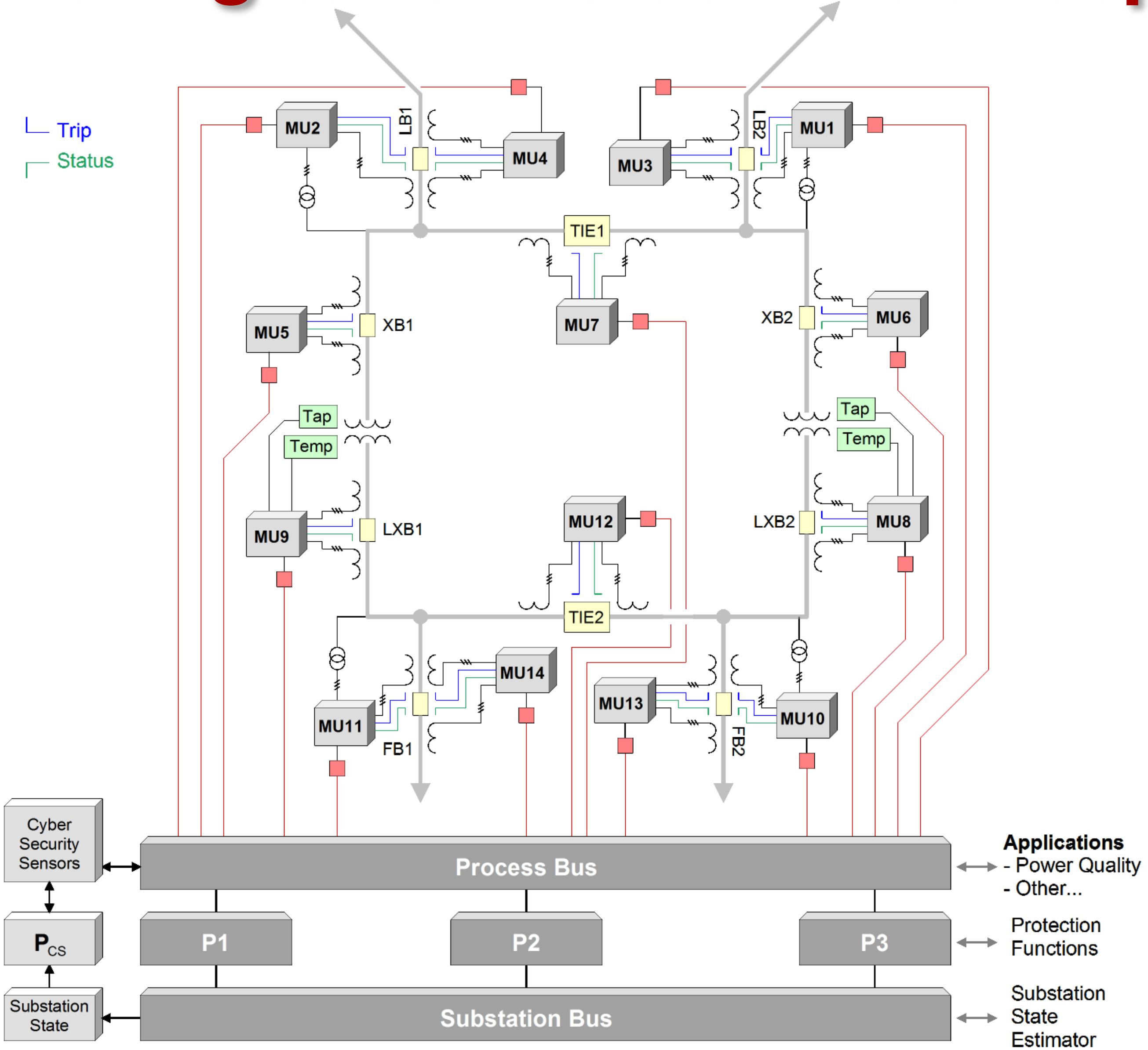
NCIT (Non-Conventional Instrument Transformers)

Standardization is quite advanced

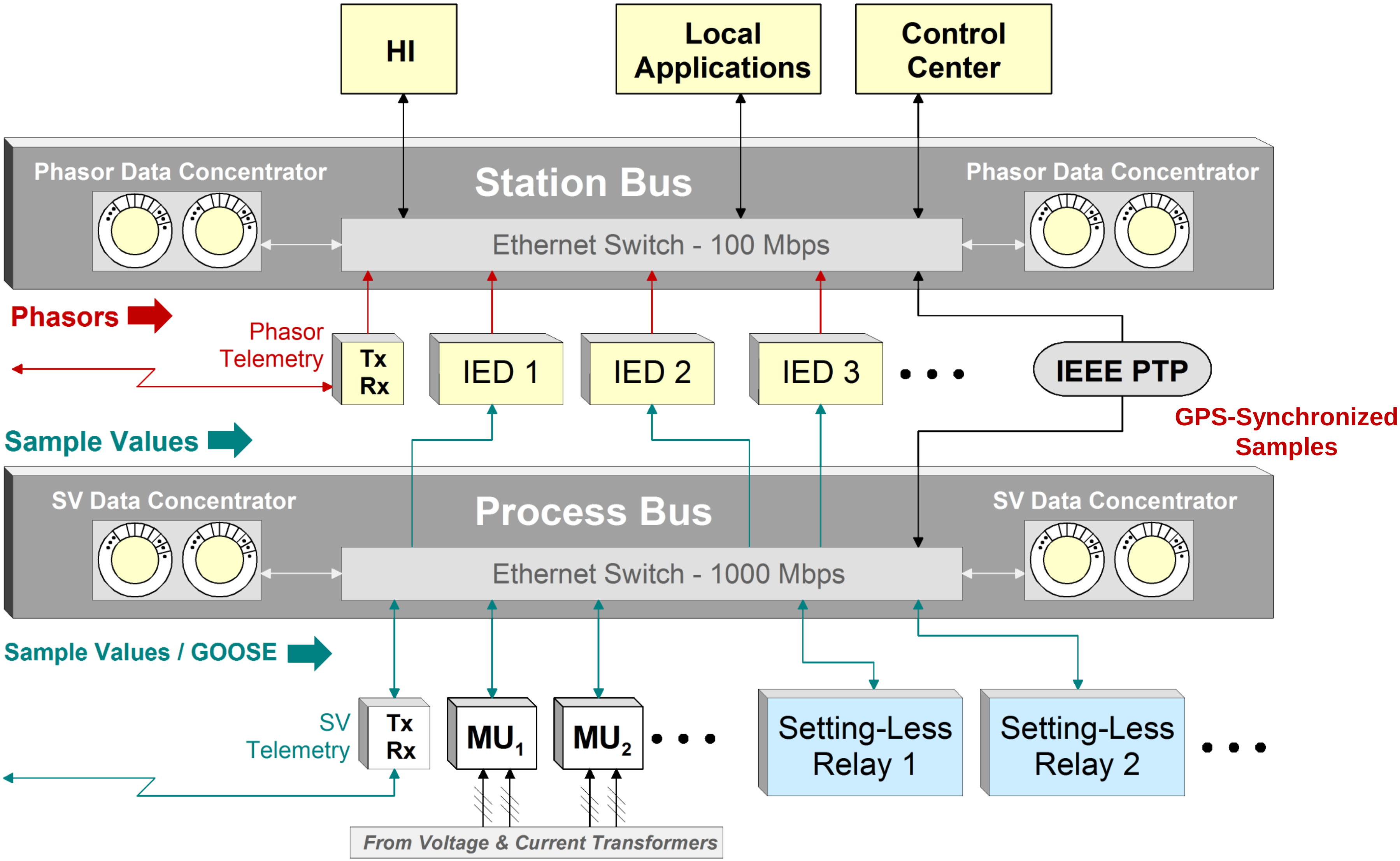
The Digital Substation Concept



The Digital Substation Concept

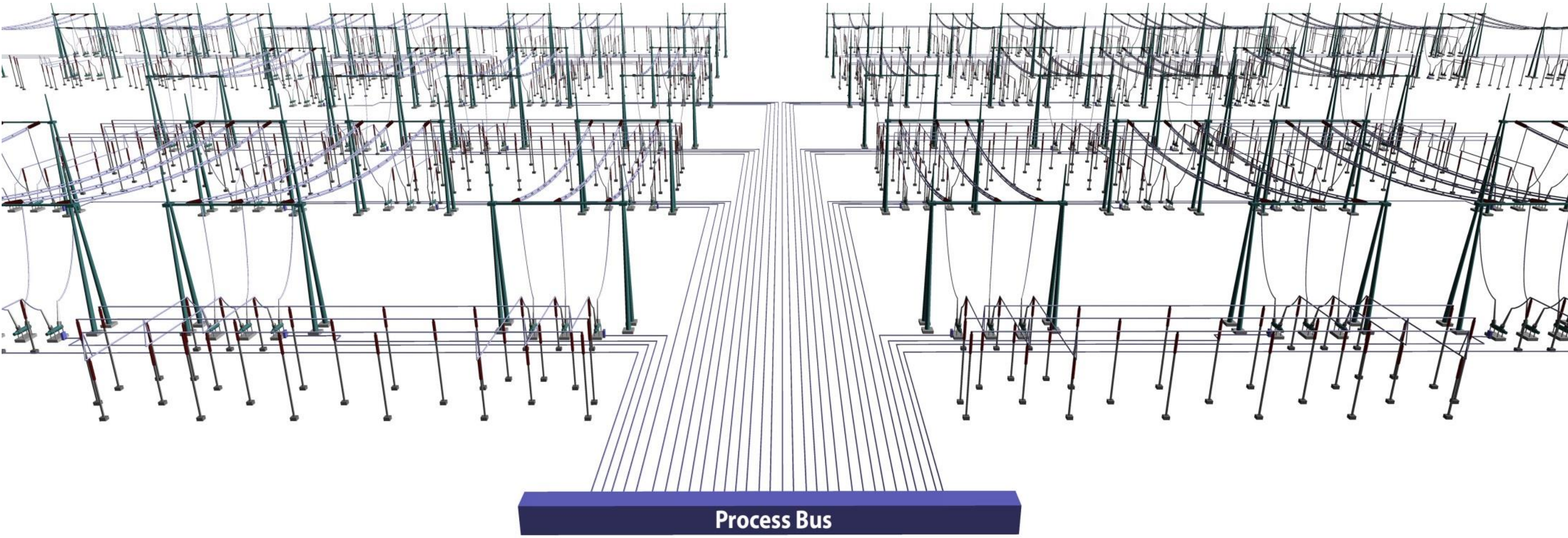


Architectural Notes



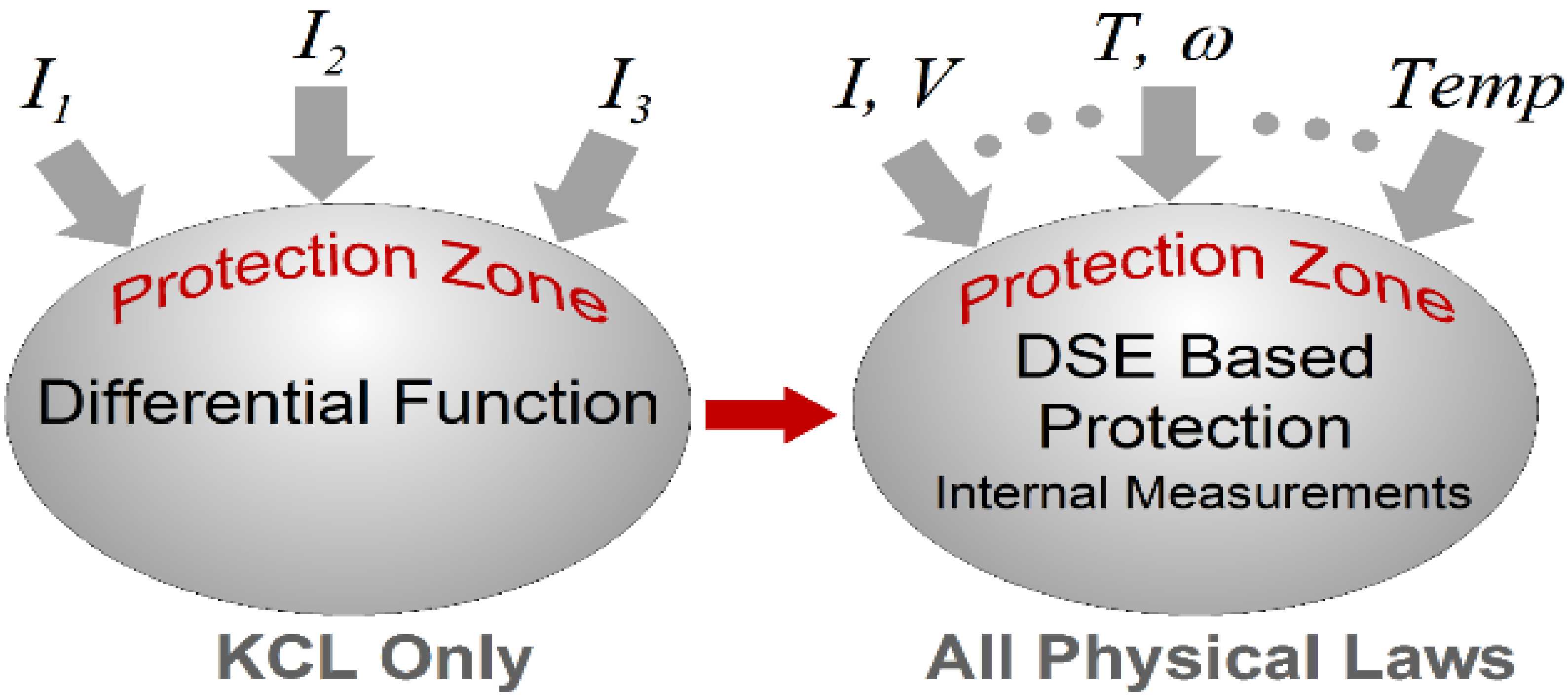
The Setting-Less Protection Method

Complexity and Protection Gaps



DSE Motivation: In Search of Secure Protection

Setting-less Protection has been inspired from Differential protection



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

The Setting-Less Protection Method
(Dynamic State Estimation Based Protection)

Protection Zone State x(t): Minimum Number of Variables that Completely Define the Operating Condition of the Protection Zone, i.e. Voltages, Flux, Speed, etc.

Measurements z(t): Any Measurement Can be Expressed as a Function of the State x(t), i.e. z(t)=h(x(t)).

State Estimation: Compute x(t) that will make the difference: z(t)-h(x(t)) as small as possible. Note z(t) are Sample Values

$$Min\ J = \sum_{i=1}^{m} \left(\frac{z_i(t) - h_i(x(t))}{\sigma_i} \right)^2$$

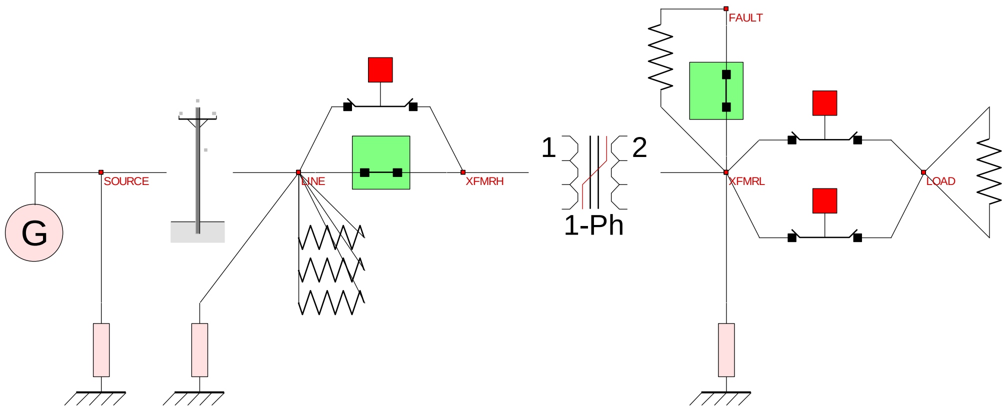
The Setting-Less Protection Method
(Dynamic State Estimation Based Protection)

If Protection Zone is Free of Faults, the distance $(z(t)-h(x(t)))$ is very small – comparable to Measurement Error.

If Protection Zone is Free of Faults and there are faults outside the protection zone, the distance $(z(t)-h(x(t)))$ is very small – comparable to Measurement Error.

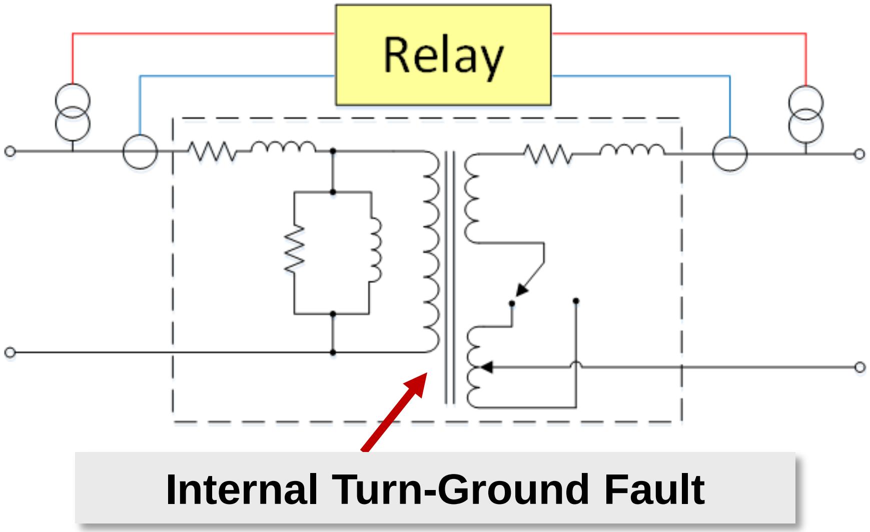
If Protection Zone experiencing an internal Fault, the distance $(z(t)-h(x(t)))$ becomes large.

Protection of Saturable Core Transformers



Event:

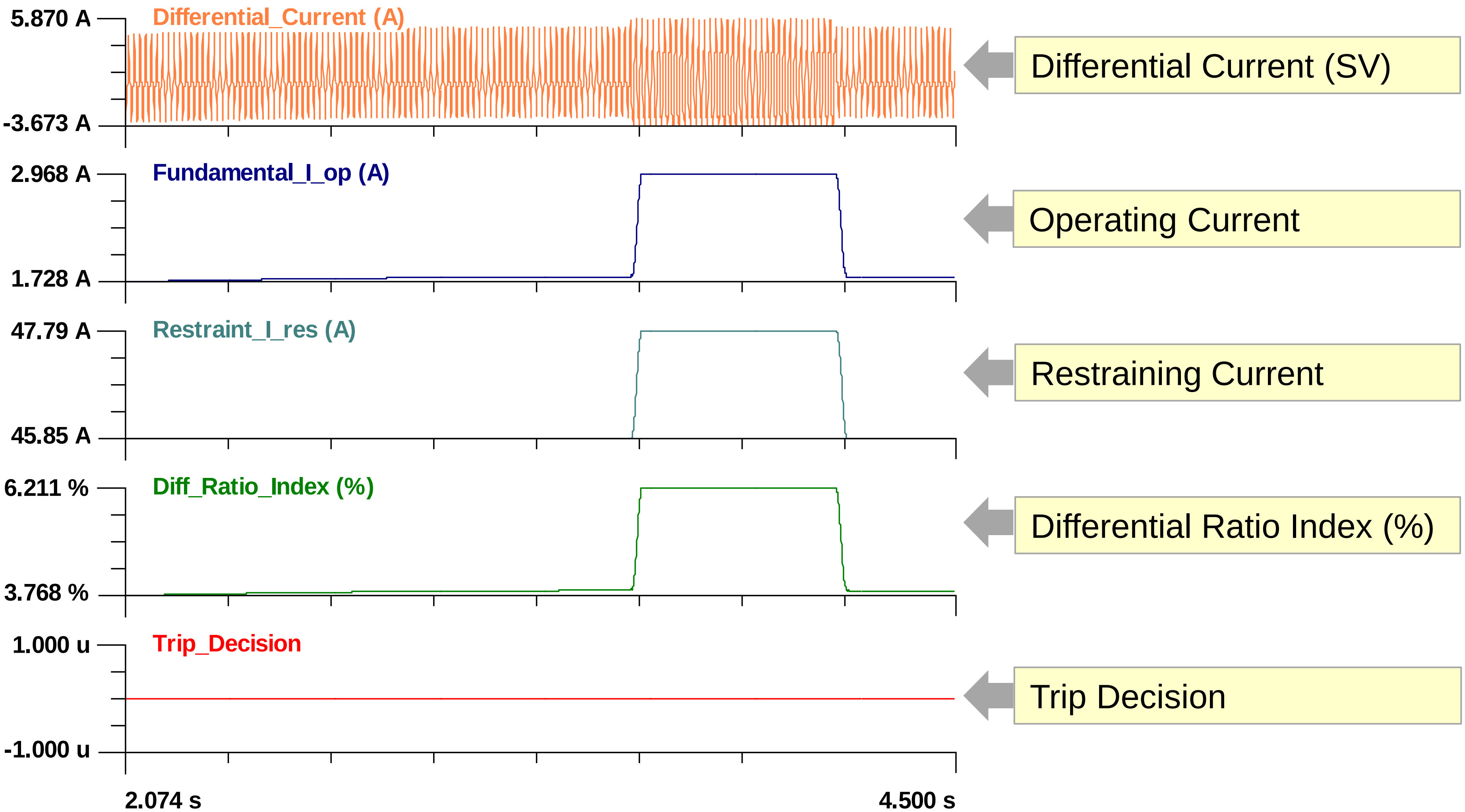
- 14.4/2.2kV, 1000 kVA single-phase saturable-core transformer
- A 800kW load connected to the system, generating transients and inrush currents at 0.72 seconds
- Followed by a 5% turn-ground fault near neutral terminal of the transformer at 1.52 seconds



List of Measurements:

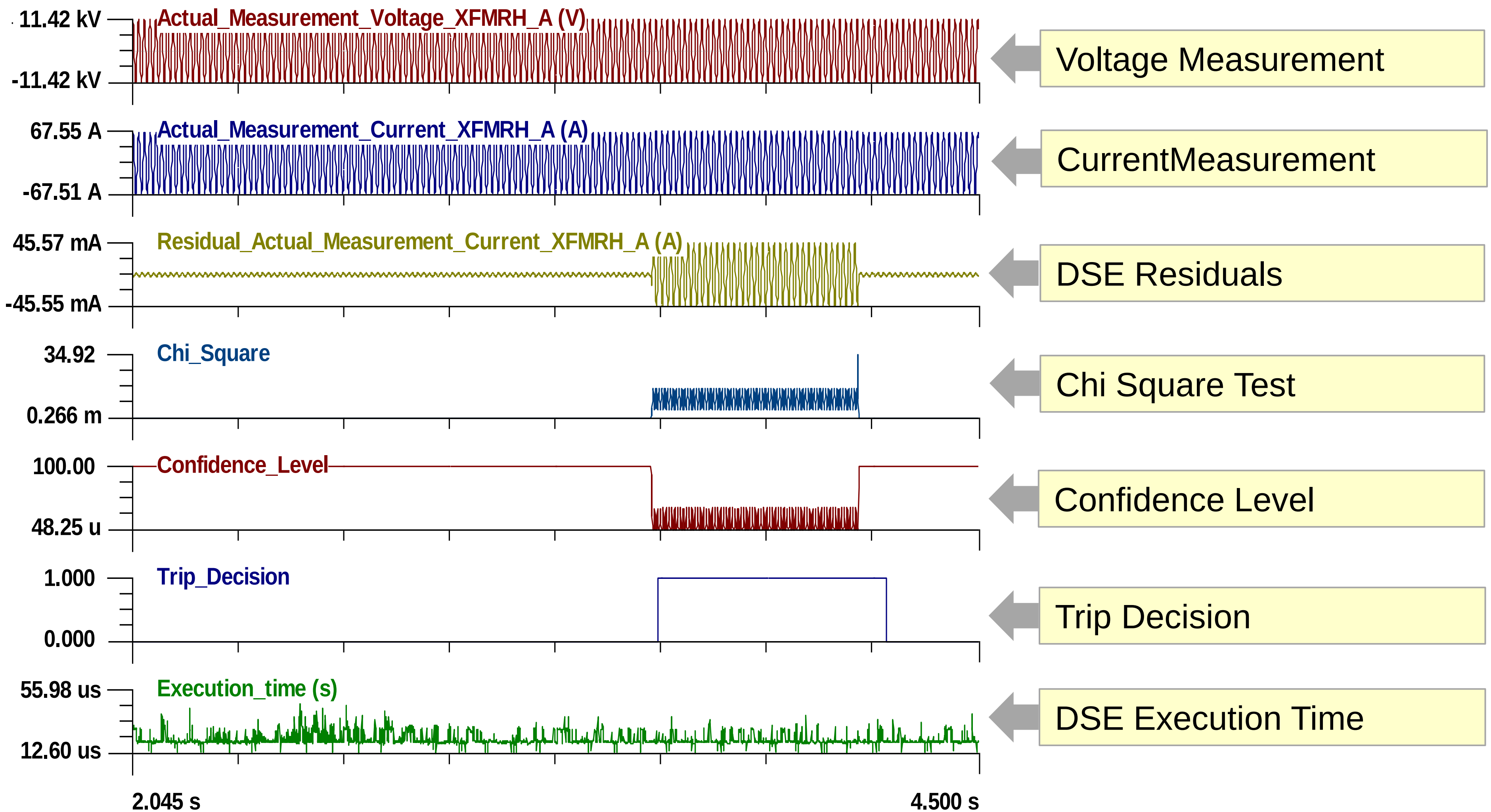
- Single-phase voltages at two sides
- Single-phase currents at two sides
- Temperature measurements at selected points

Differential Protection for Turn-ground Fault 5% from Neutral



Legacy Differential Protection MISSES the Fault

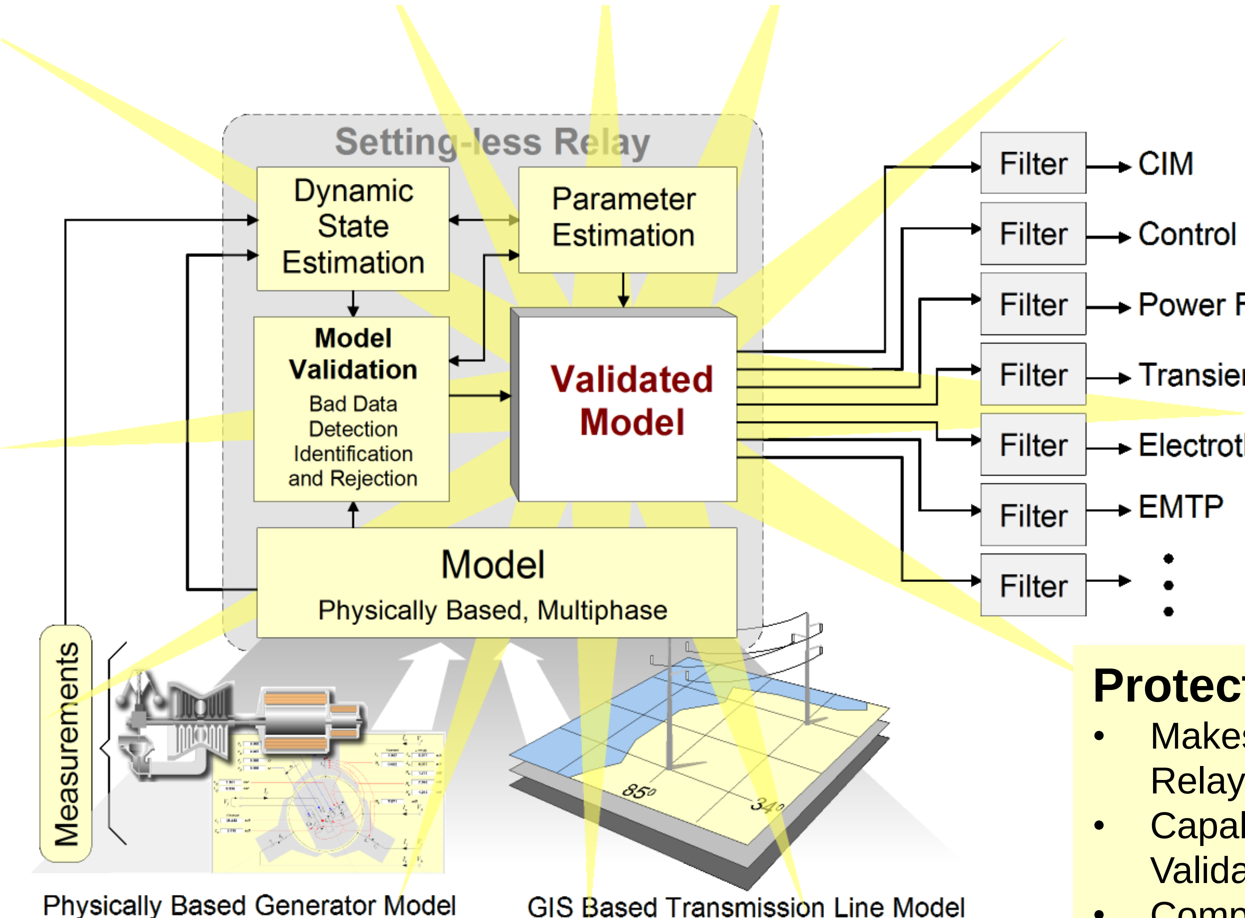
Setting-less Protection for Turn-ground Fault 5% from Neutral



Setting-Less protection detects fault in sub-msec time and trips within a fraction of a cycle.

Major Additional Benefit: Perpetual Model Calibration and Validation

A Ubiquitous System for Perpetual Model Validation

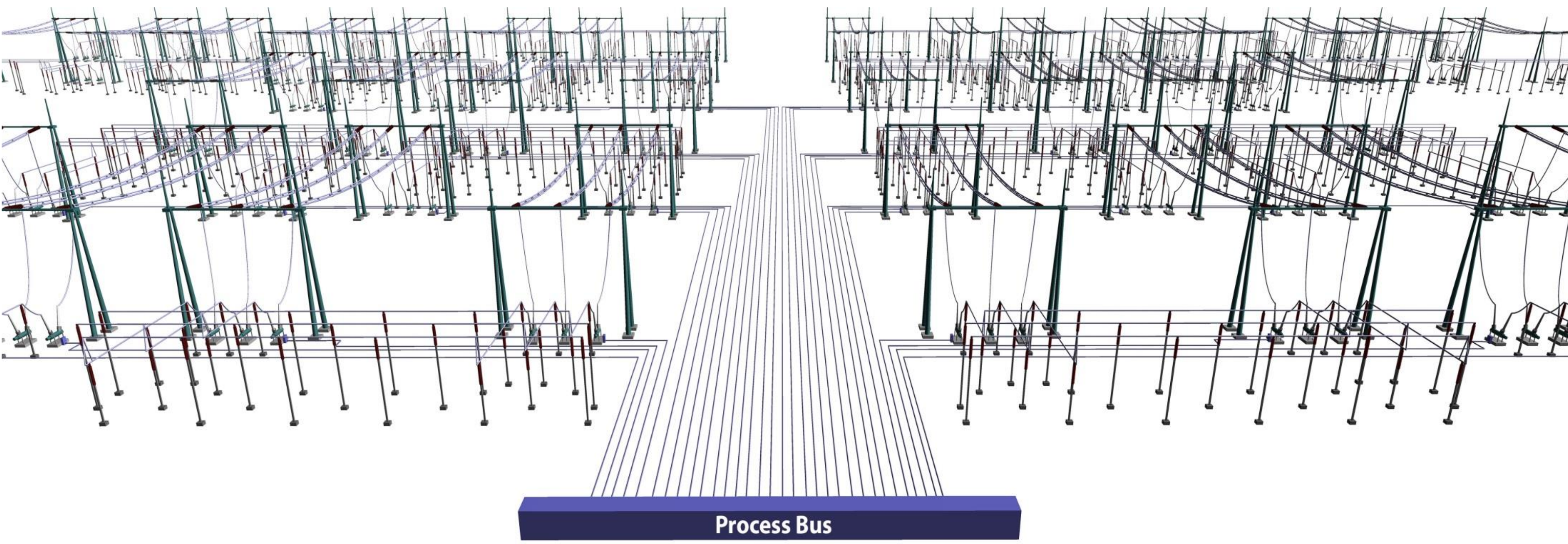


Protection is Ubiquitous

- 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

Data Integrity

1. **Instrumentation Channel Errors**
2. Hidden Failures
3. Cyber Data Attacks



Effects of Input Data Accuracy

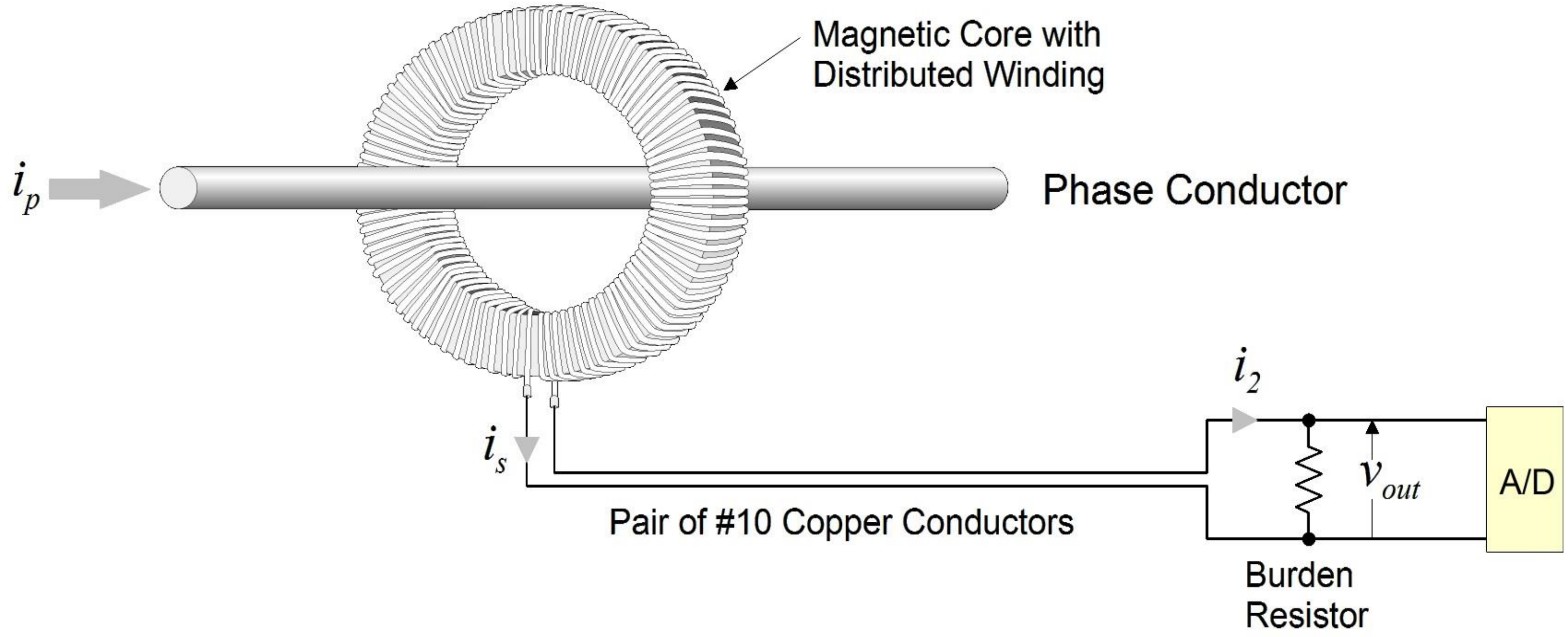
Quality of Data is Affected from (a) Instrumentation Channel Errors, (b) Hidden Failures and (c) cyber data attacks. All Affect Performance of Setting-less relays as any other legacy relays.

Relays and merging units are becoming more accurate by using higher resolution in data acquisition and higher sampling rates.

Errors from instrumentation channels remain practically the same. Instrumentation channel errors have been much higher than the errors introduced by the data acquisition even in earlier generations of sensor less systems.

Merging Units offer a unique opportunity to perform error correction within a merging unit → MU provides corrected data in primary quantities.

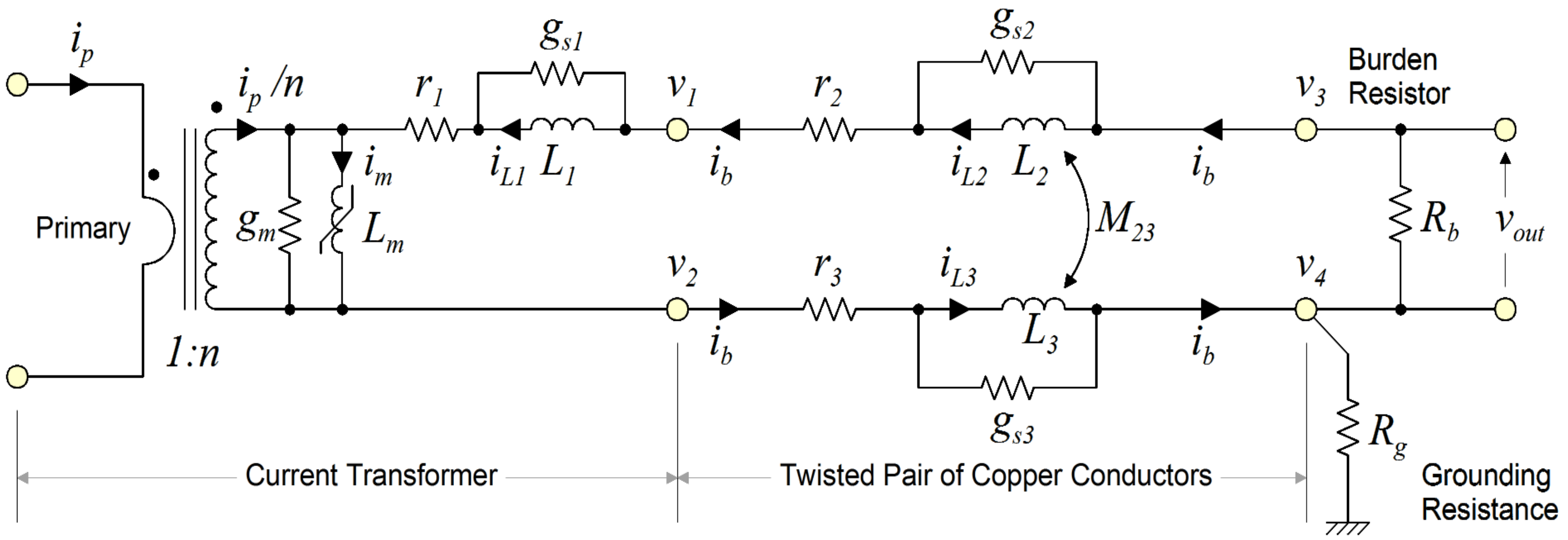
Basic Question



- Given a measurement at the secondary of an instrumentation channel, can we extract the correct value of the primary quantity?
- Can it be done on a sample by sample basis?

Basic Approach to Error Correction

Construct the mathematical model of the instrumentation channel: Example CT Channel



Use actual measurements and augment with:

(a) virtual measurements,

(b) derived measurements, and

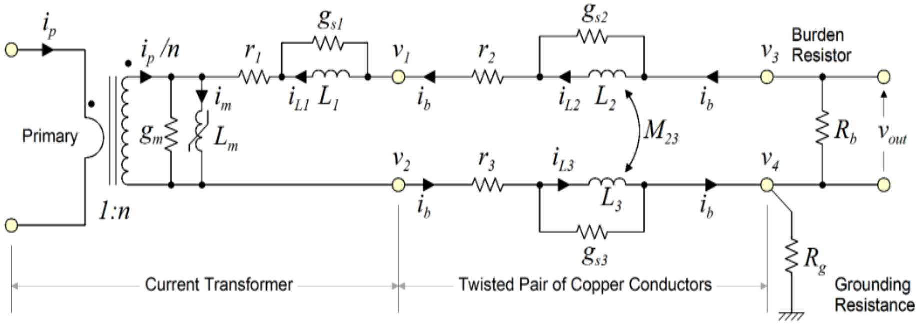
(c) pseudo measurements

Redundant Measurements.

Perform dynamic state estimation → ***Best Estimate Of Primary Current***

Dynamic State Estimation

CT Channel math Model



Measurements

Actual: - Voltage or Current at Burden

Add: -Virtual,

-Derived, and

-Pseudo-Measurements

Example Virtual Measurement: $0 = -g_m e(t) - i_m(t) + \frac{1}{n} i_p(t) + \mathrm{i}_{L_1}(t) + g_{s1} L_1 \frac{di_{L_1}(t)}{dt}$

Example Derived Measurement: $i_b^m(t) = \mathrm{i}_{L_1}(t) + g_{s1} L_1 \frac{di_{L_1}(t)}{dt}$

Example Pseudo Measurement: $0^m = v_4(t)$

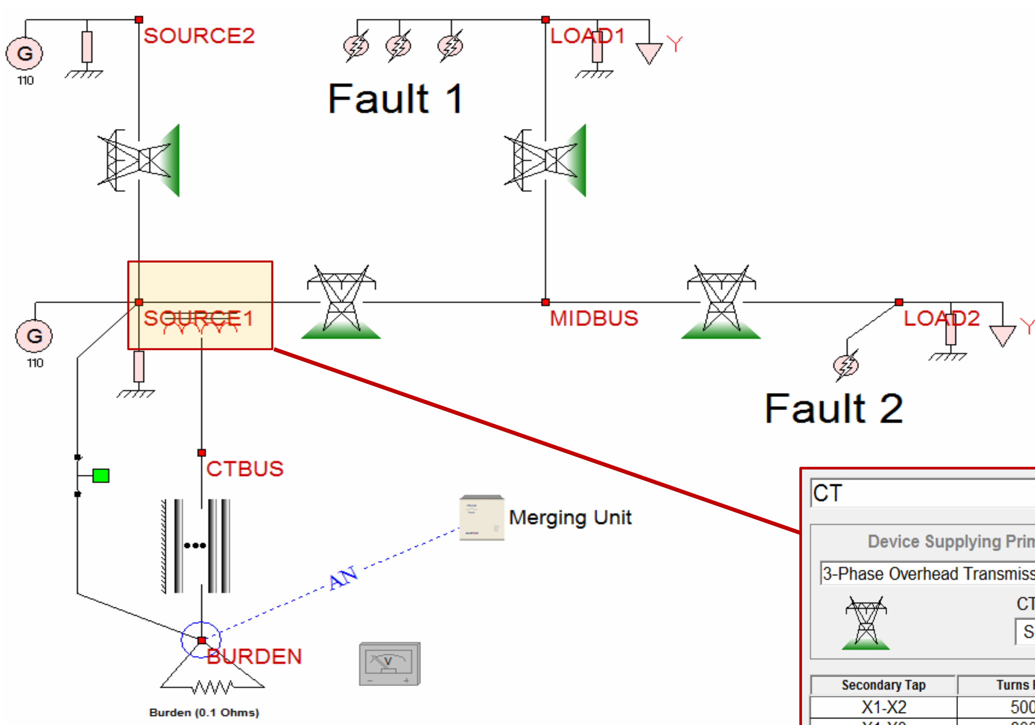
States: 15

Actual Measurements: 1
Virtual Measurements: 14
Derived Measurements: 5
Pseudo measurements: 1

21 Equations in 15 unknowns.

One of the unknowns is the Primary Current

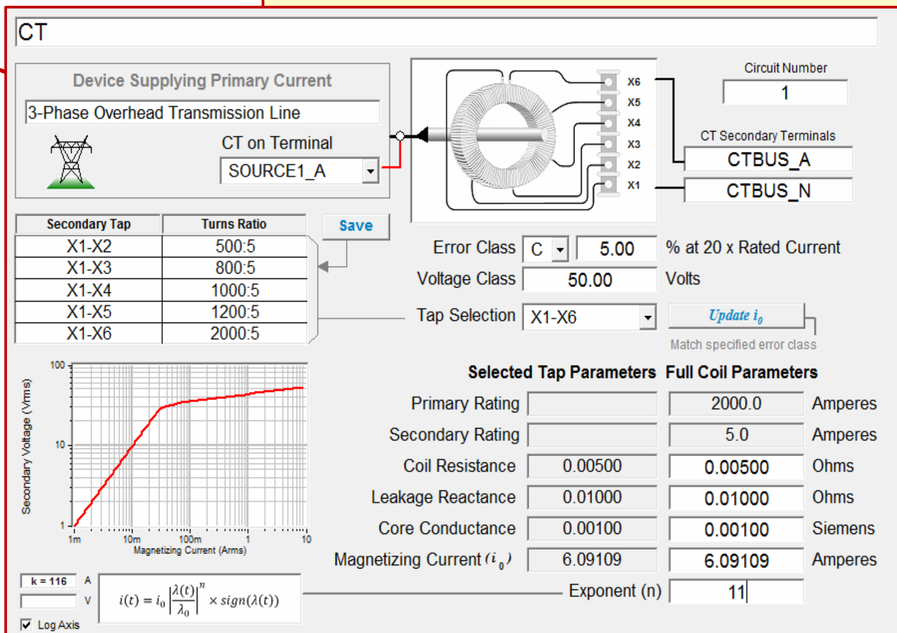
Example System



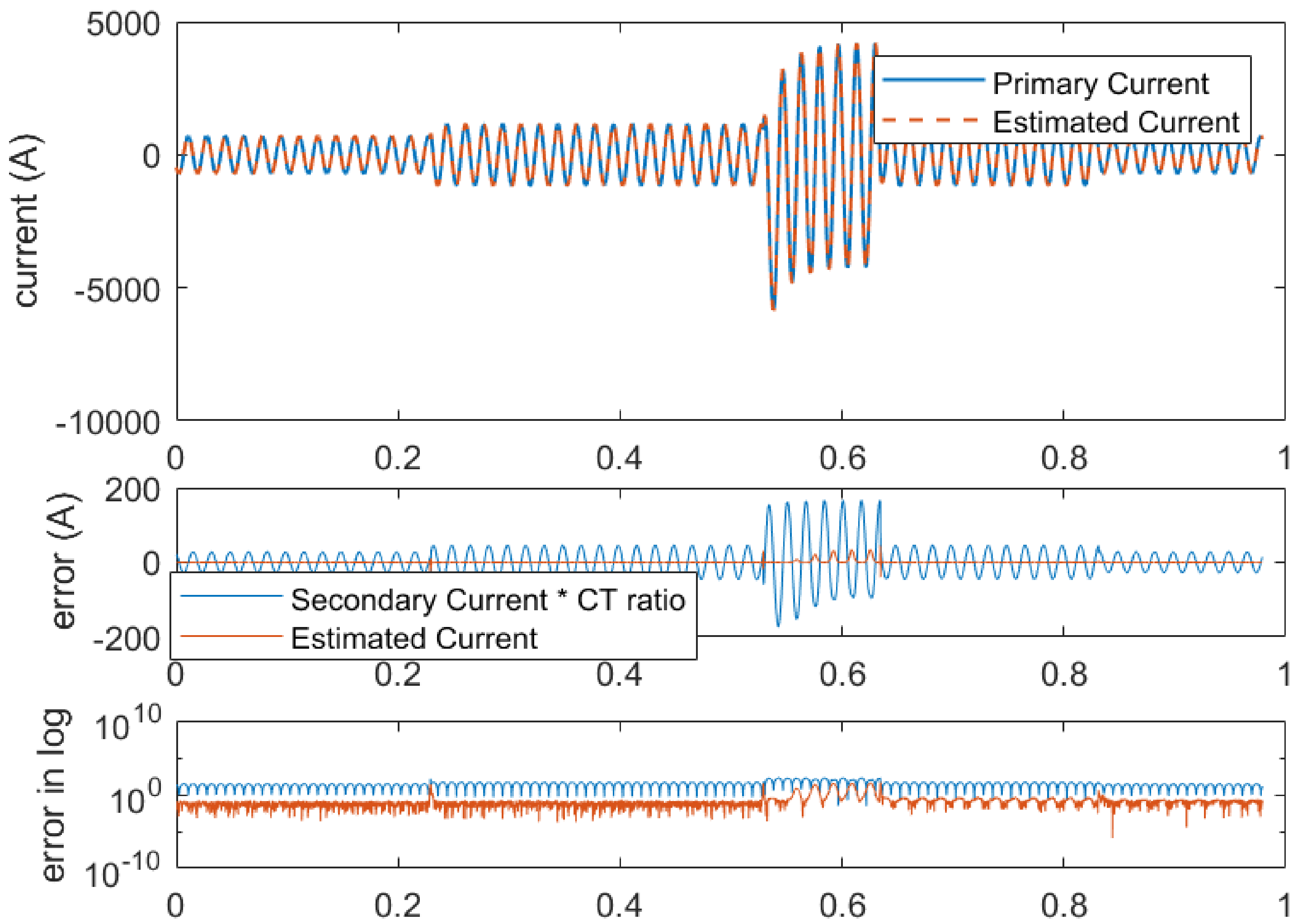
Example System Parameters

115-kV transmission system.
Current transformer on phase A
CT ratio is 800:5A
Error class: 10C100.
CT instrumentation cable: #10 copper
Instr. cable length: 96 meters
Burden resistance: 0.1 Ω

Current Transformer Parameters

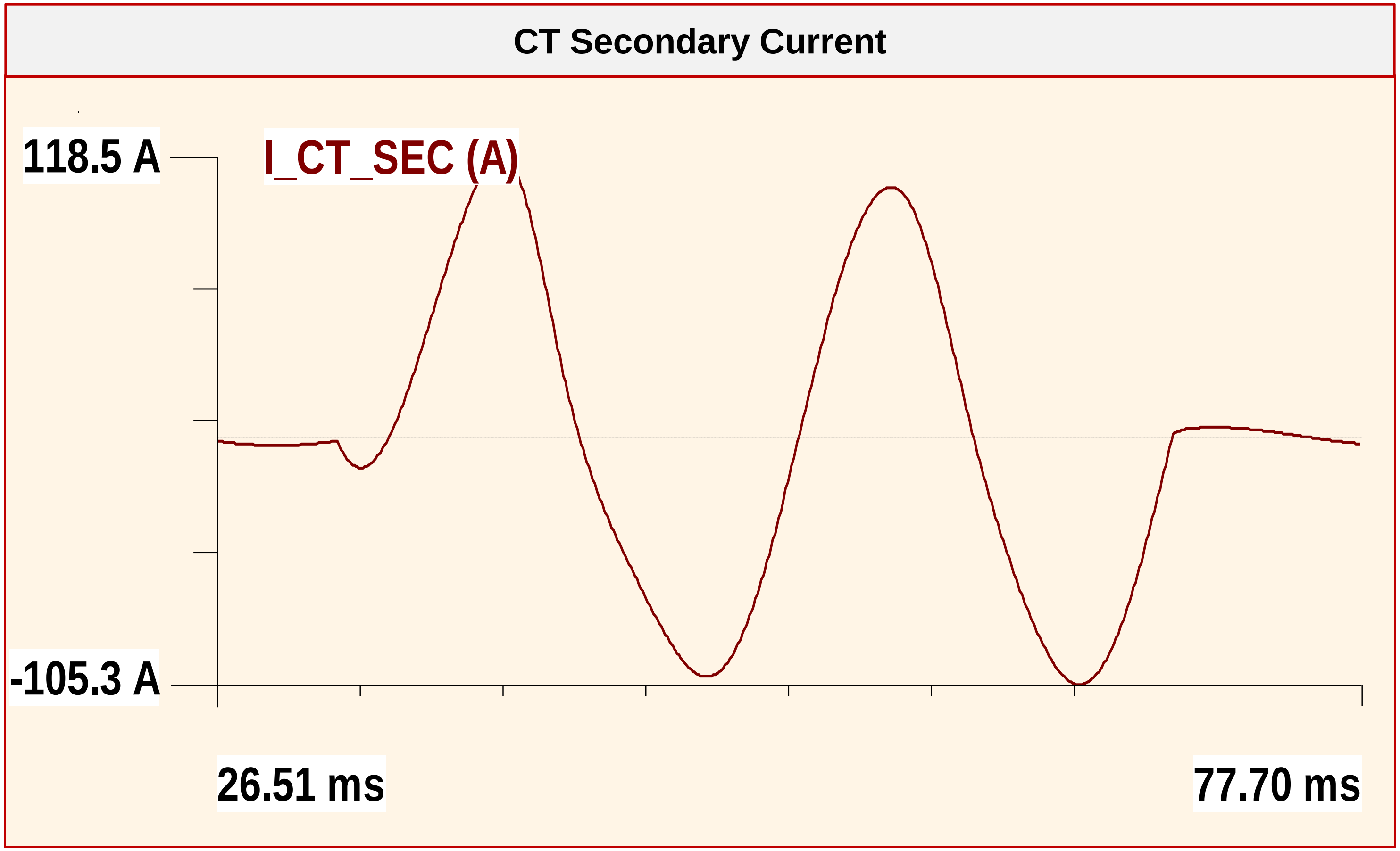


Example System Results



Example System Results – Mild CT Saturation

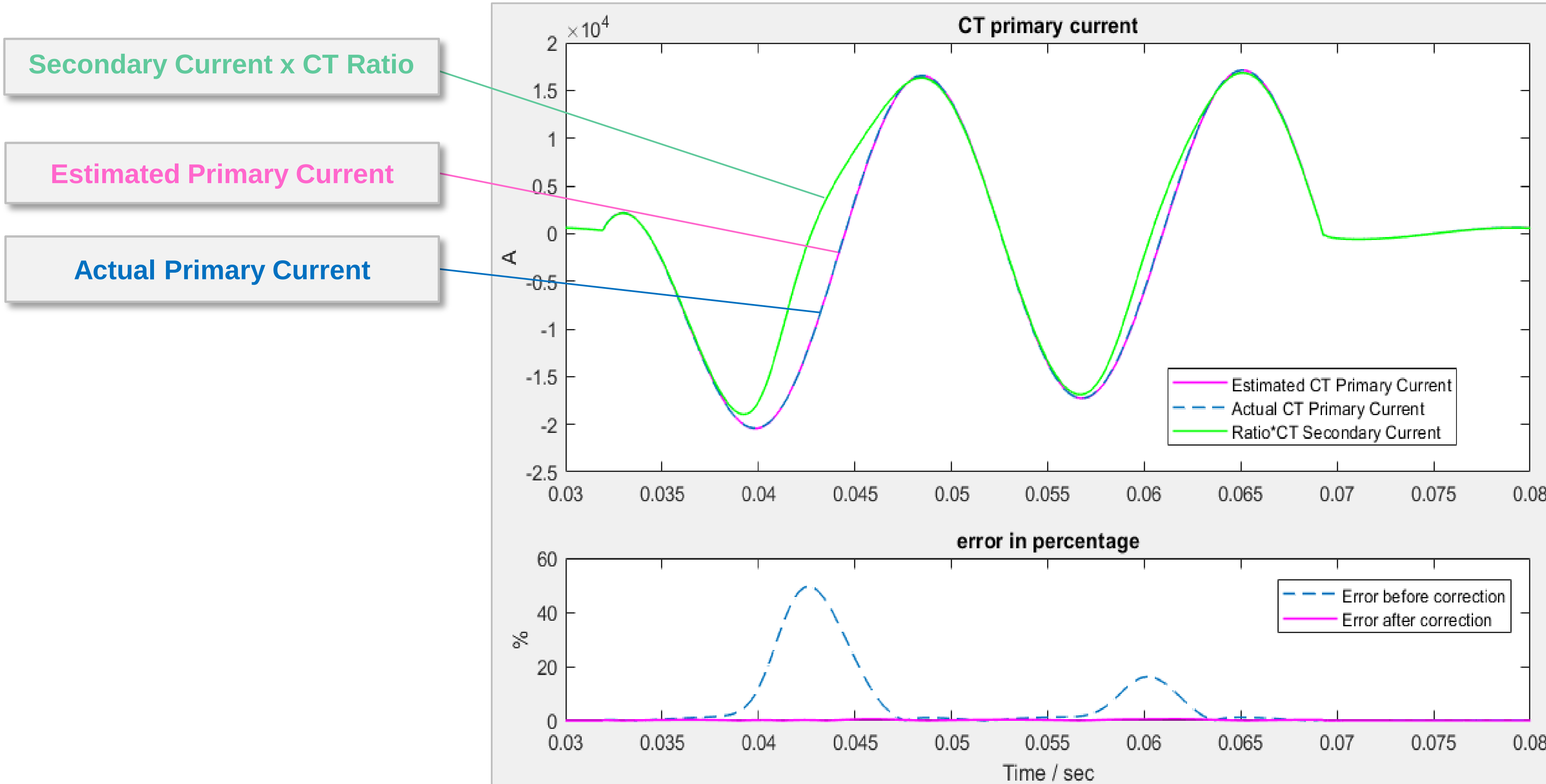
Simulated CT Secondary Current Waveform



Phase A to ground fault at "**MIDBUS**"

Example System Results – Mild CT Saturation

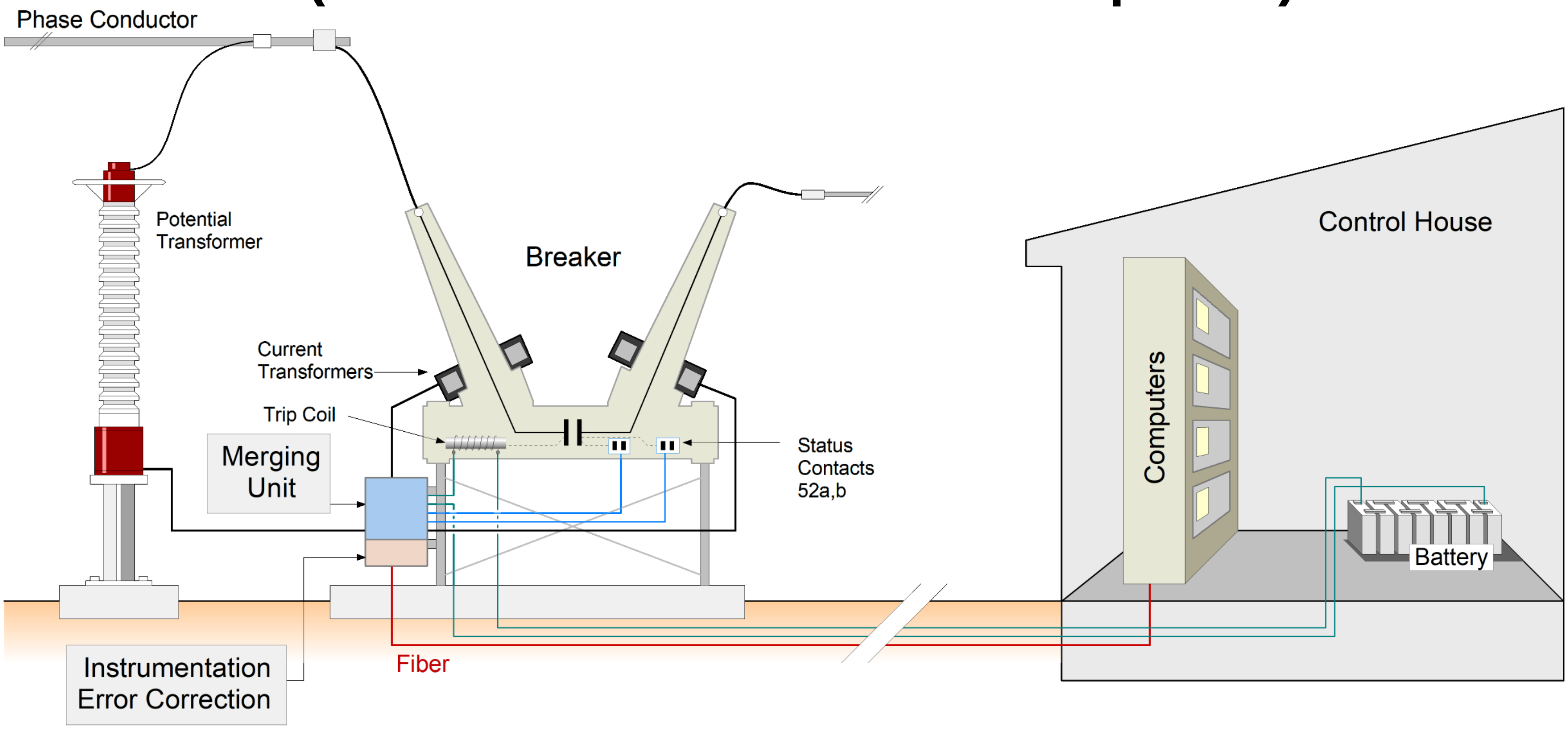
Error Correction Performance



Estimated results match actual primary current with less than 1% error

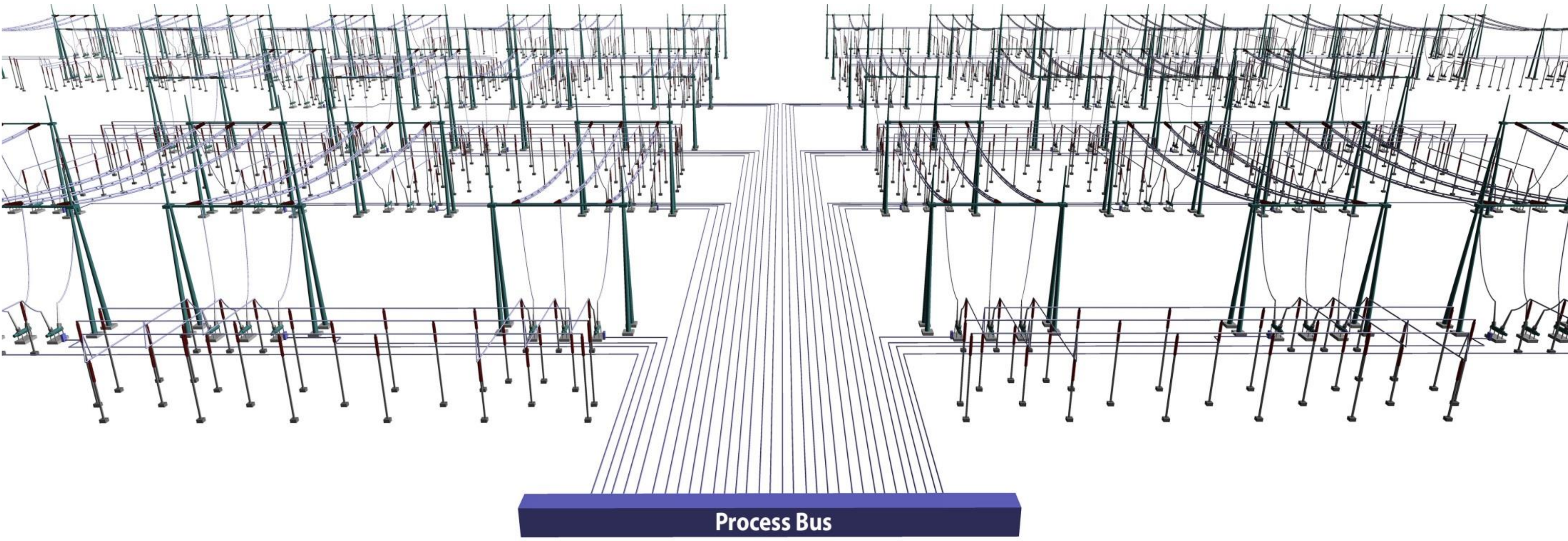
Intelligent Merging Units Provide Corrected Primary Values

Error Correction Integrated into Merging Units (alternative: in substation computers)



Data Integrity

1. Instrumentation Channel Errors
2. **Hidden Failures**
3. **Cyber Data Attacks**



Impact of Hidden Failures/Cyber Attacks

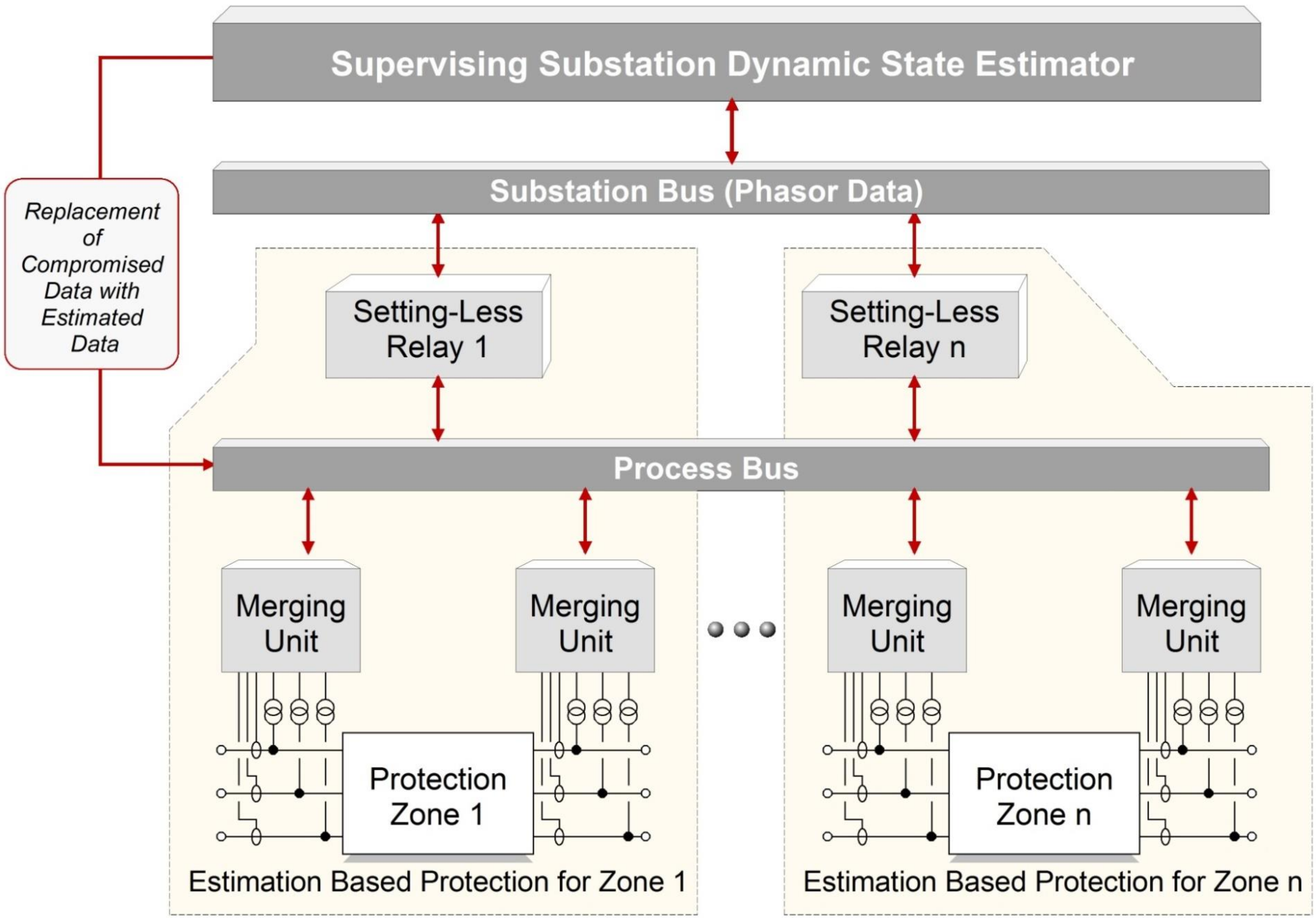
Hidden failures and cyber attacks corrupt the data “seen” by a relay, legacy relay or setting-less protective relay.

Hidden failures/cyber attacks will cause relay mis-operation whether it is a legacy protective relay or a setting-less relay.

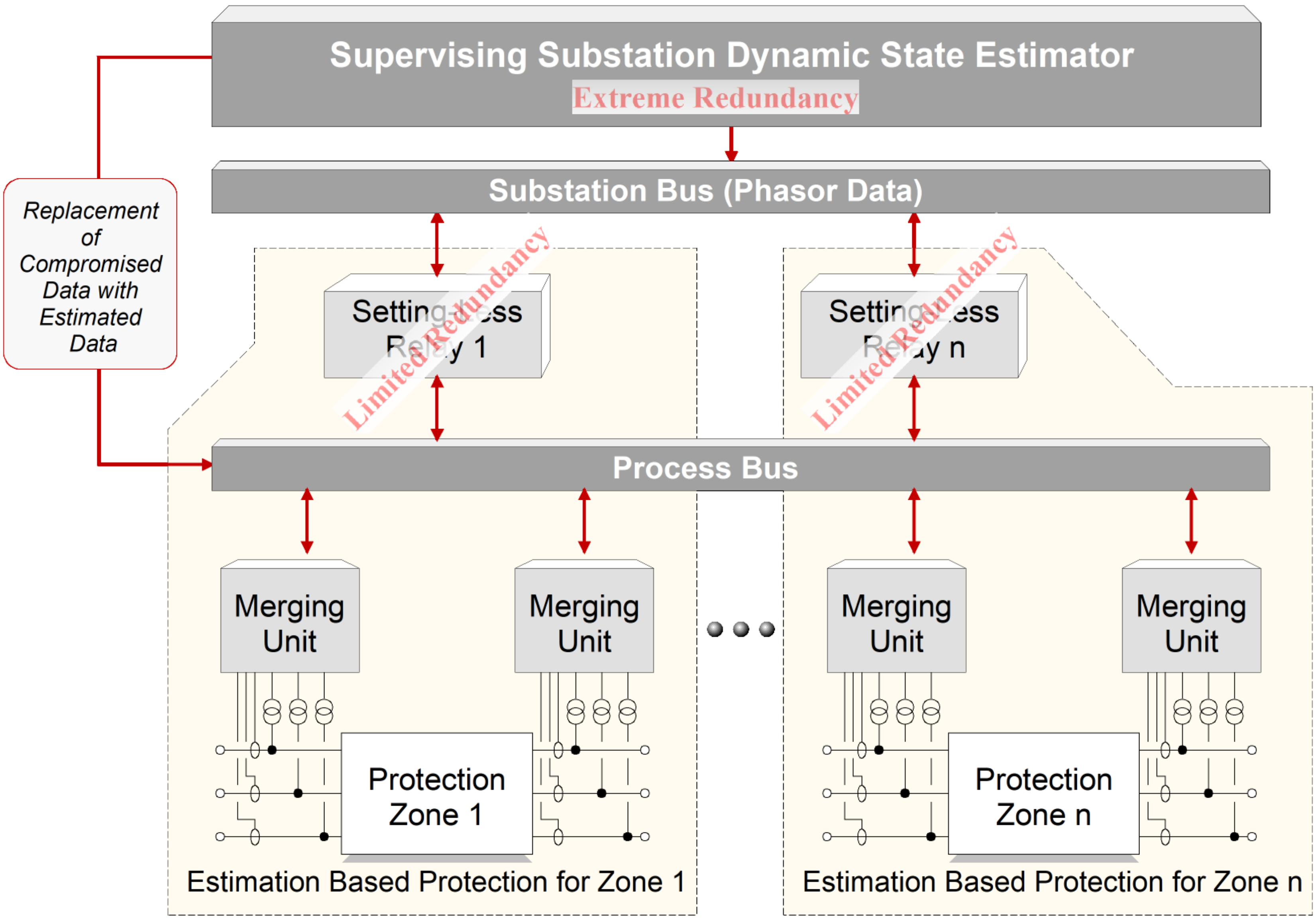
Need to identify hidden failures/cyber attacks and avert relay mis-operations.

Present State of Art: Some legacy relaying schemes can identify some hidden failures and inhibit relay operation. No capability to take corrective action.

Proposed Method for Securing Data

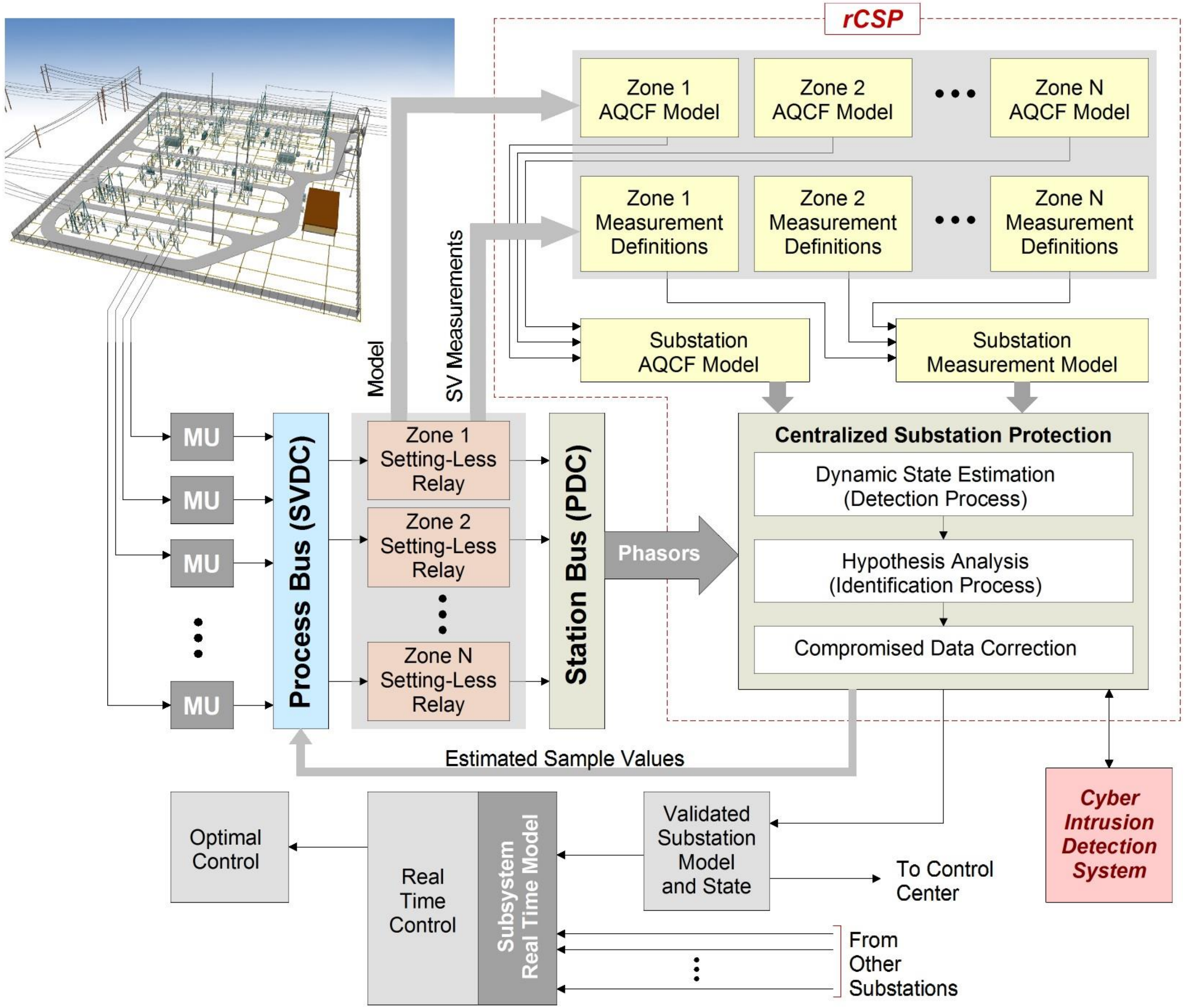


Proposed Method for Securing Data



Dynamic State Estimation Based Centralized Protection Scheme

Resilient Centralized Substation Protection (rCSP)



Dynamic State Estimation Based Centralized Protection Scheme (rCSP)

Hypothesis Testing: Observations

- At substation level redundancy is high (over 2000%)
- System is continuously running.
- Probability of simultaneous failure events is low

Hypothesis Testing: Mechanics

- Identify suspect measurements from residuals
- Group suspect data with certain criteria (see paper)
- Determine “faulted devices” from setting-less relays output

Dynamic State Estimation Based Centralized Protection Scheme (rCSP)

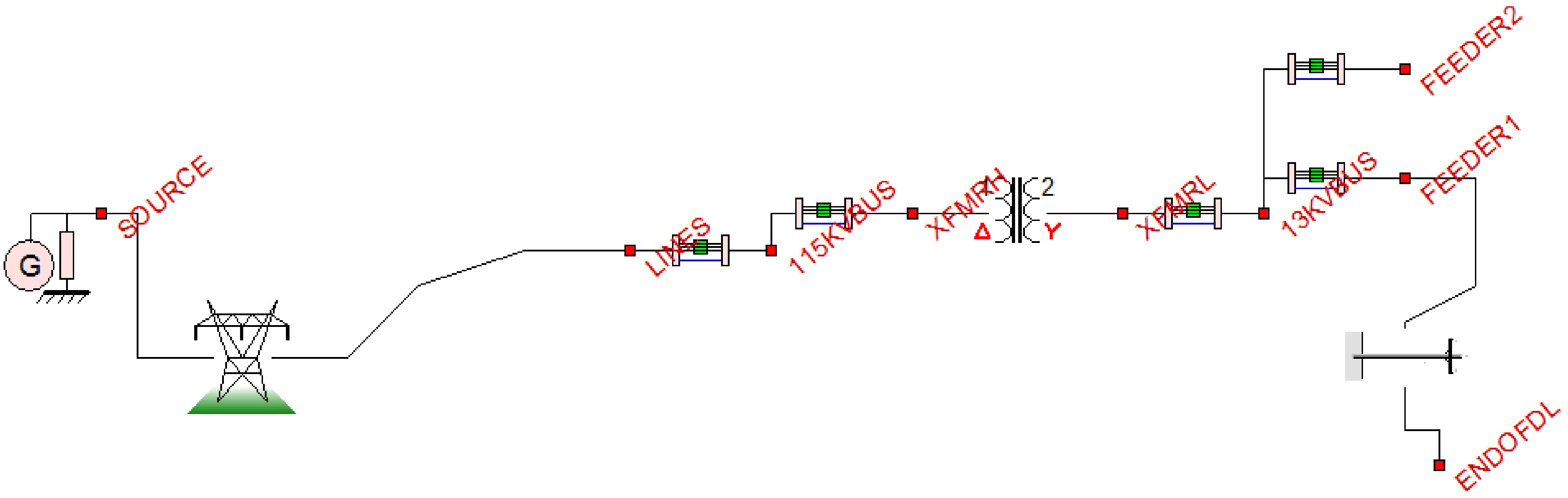
Hypothesis Type 1 (H1): Remove suspect measurements and rerun DSE. If probability high → removed measurements are bad → identify root cause → issue diagnostics → replace bad data with estimated values. End hypothesis testing. Otherwise go to **H2**.

Hypothesis Type 2 (H2): (determine if a fault decision is correct). For the reported faulted device, remove all internal device measurements and remove the faulted device model from the substation model. Then rerun DSE. If probability high → the device is truly experiencing an internal fault. Allow zone relay to trip the faulted device. End hypothesis testing.

Hypothesis Type 3 (H3): This test combines type 1 and type 2 hypothesis testing to cover the case of a simultaneous fault and a hidden failure.

Numerical Example

Case Study:

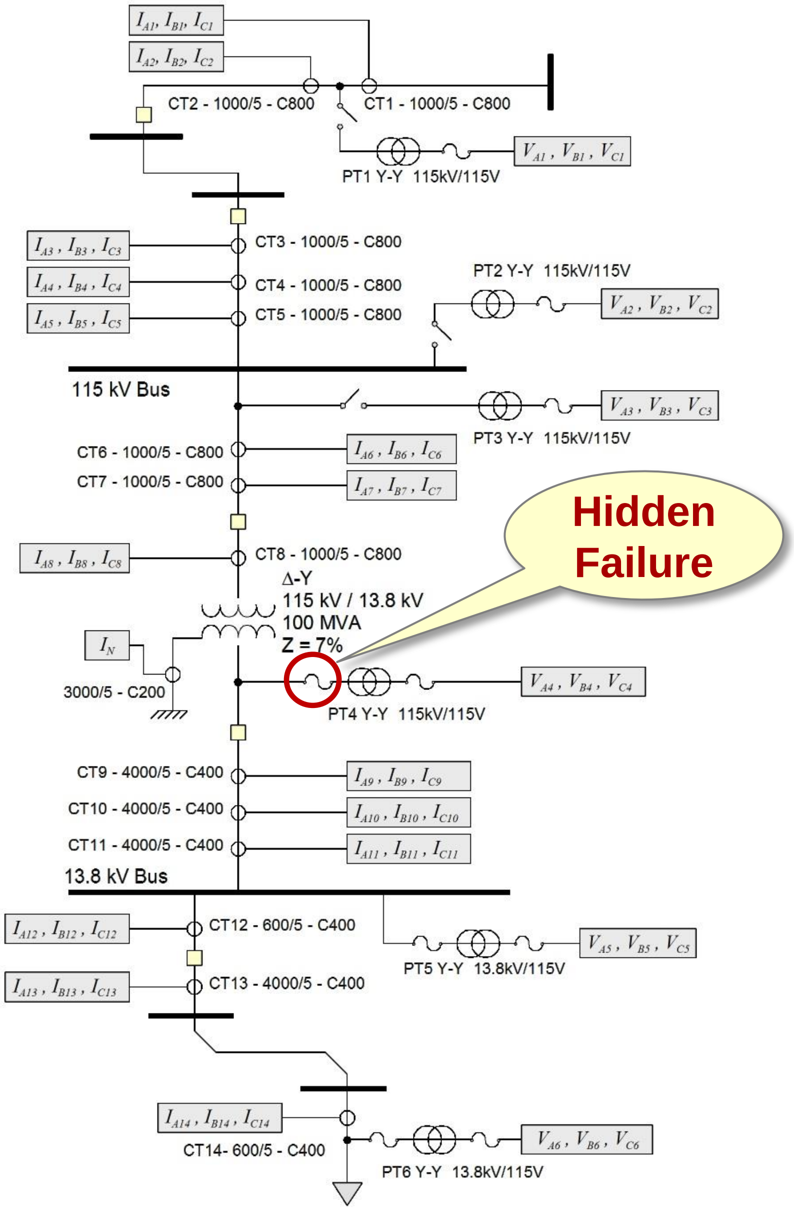


5 Protection Zones:

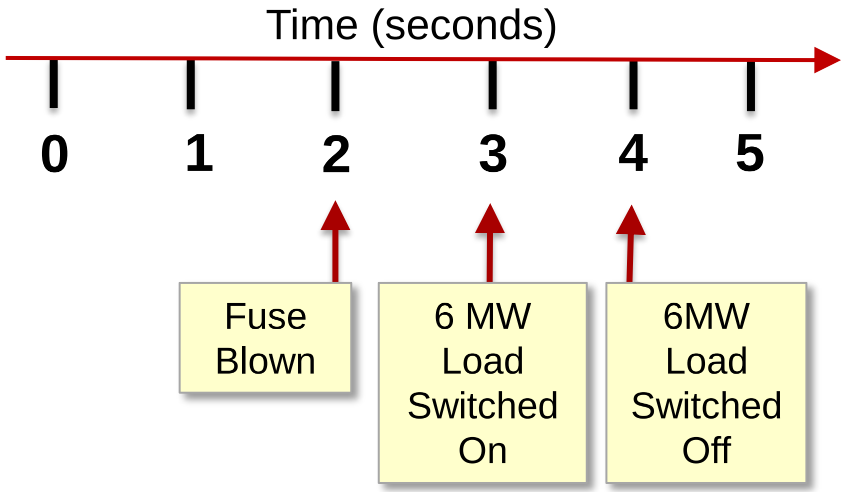
- 115 kV Transmission Line
- 115 kV Bus
- 115/13.8 kV , 36 MVA Transformer
- 13.8 kV Bus
- 13.8 kV Distribution Line (one of the two)

Numerical Example

Case1: Primary Fuse Blown Y-Y, PT-4A



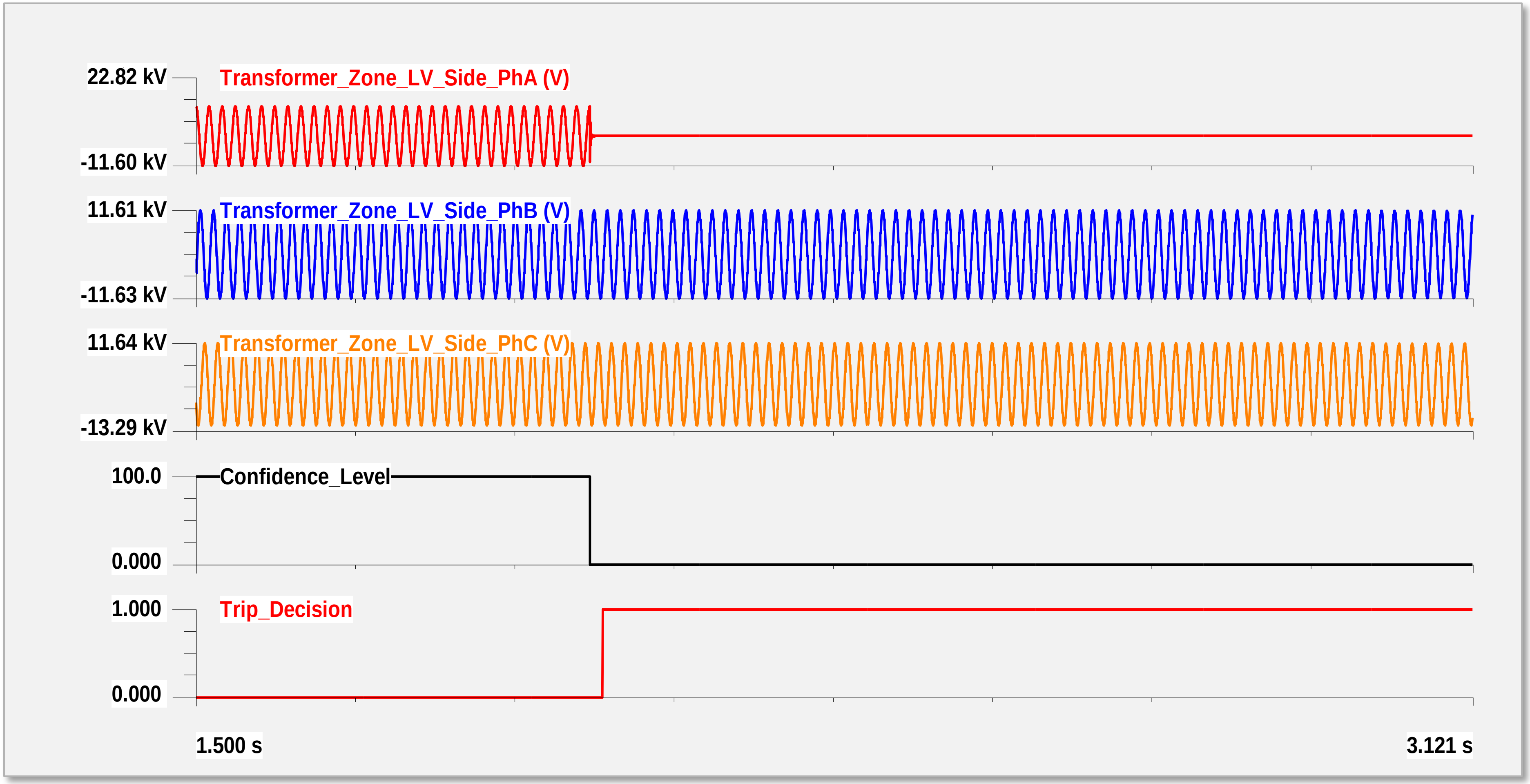
Sequence of Events



Numerical Example

Case1: Primary Fuse Blown Y-Y, PT-4A

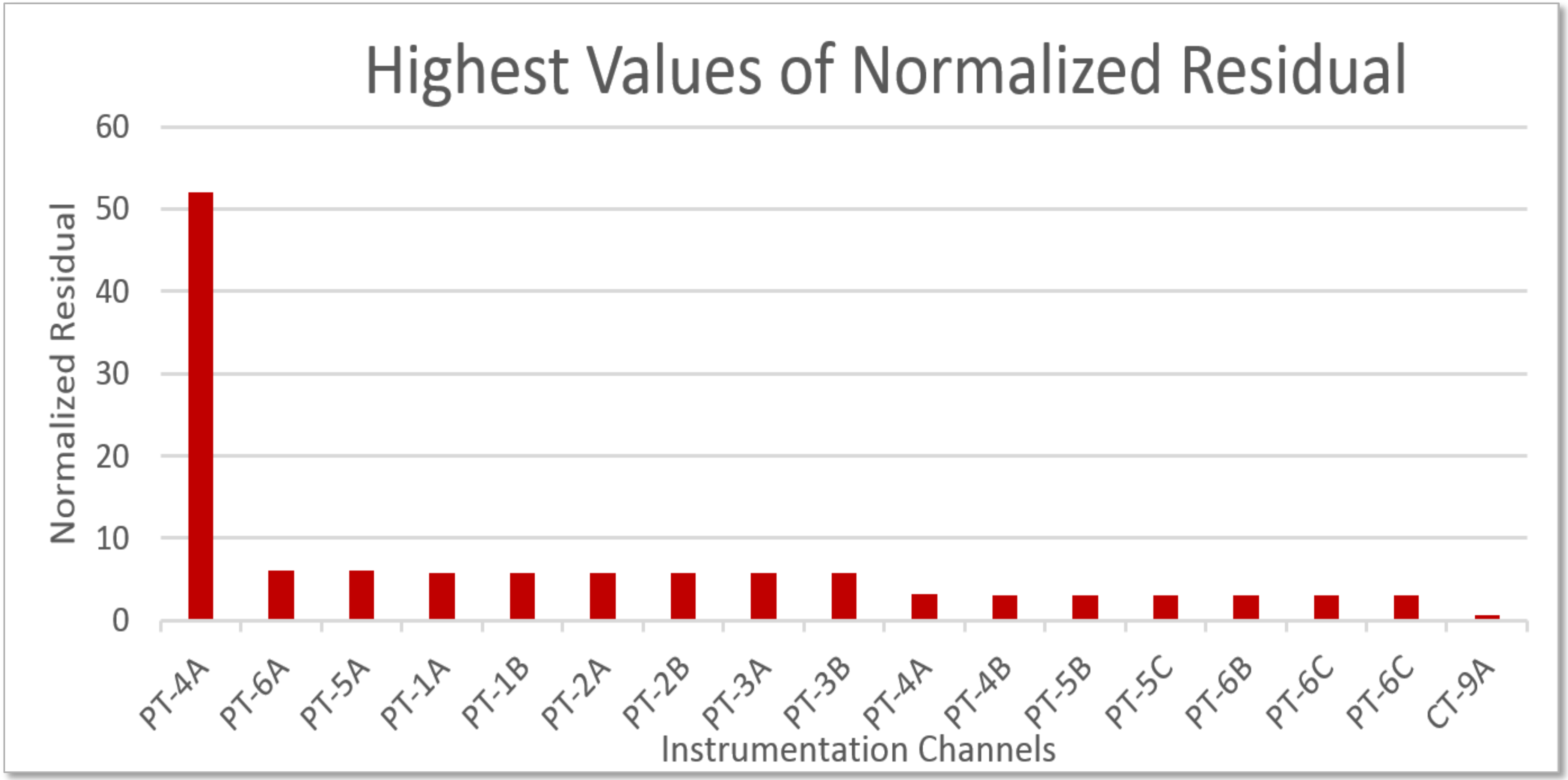
Setting-less Relay of Transformer Zone:



Numerical Example

Case1: Primary Fuse Blown Y-Y, PT-4A

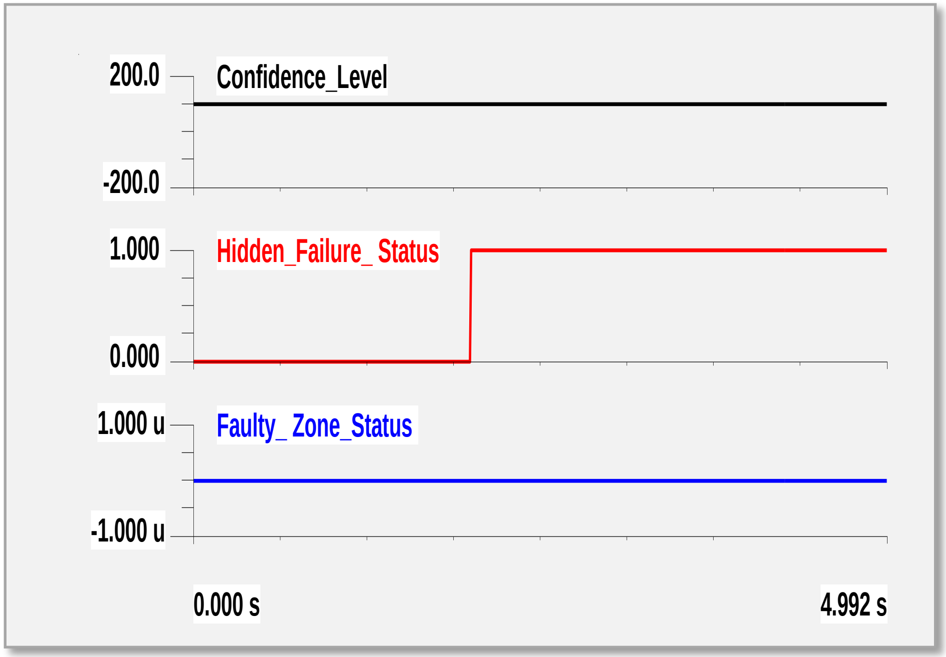
Centralized Protection Scheme :

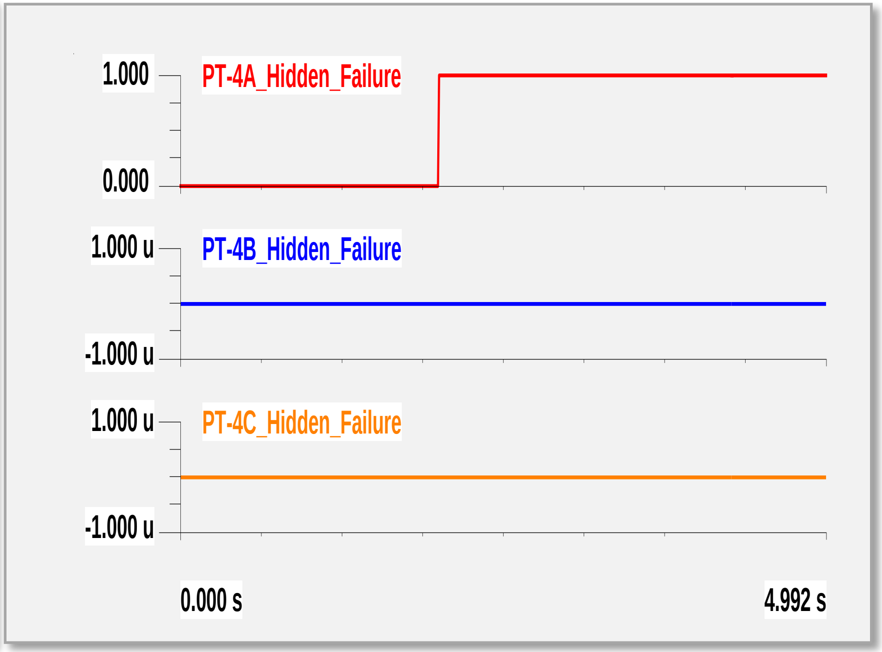


Numerical Example

Case1: Primary Fuse Blown Y-Y, PT-4A

Centralized Protection Scheme :

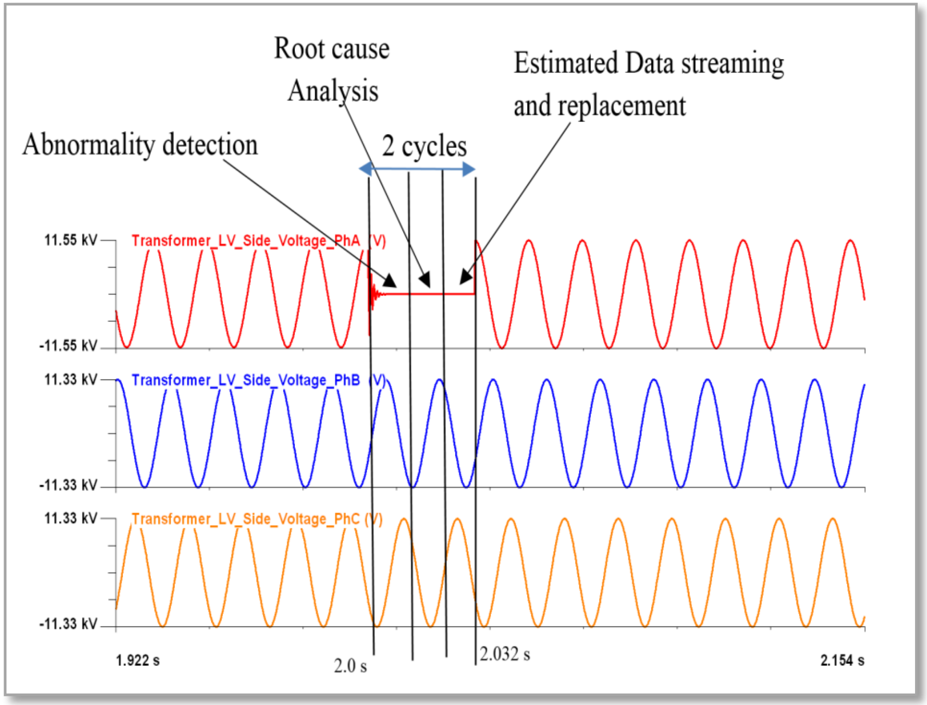


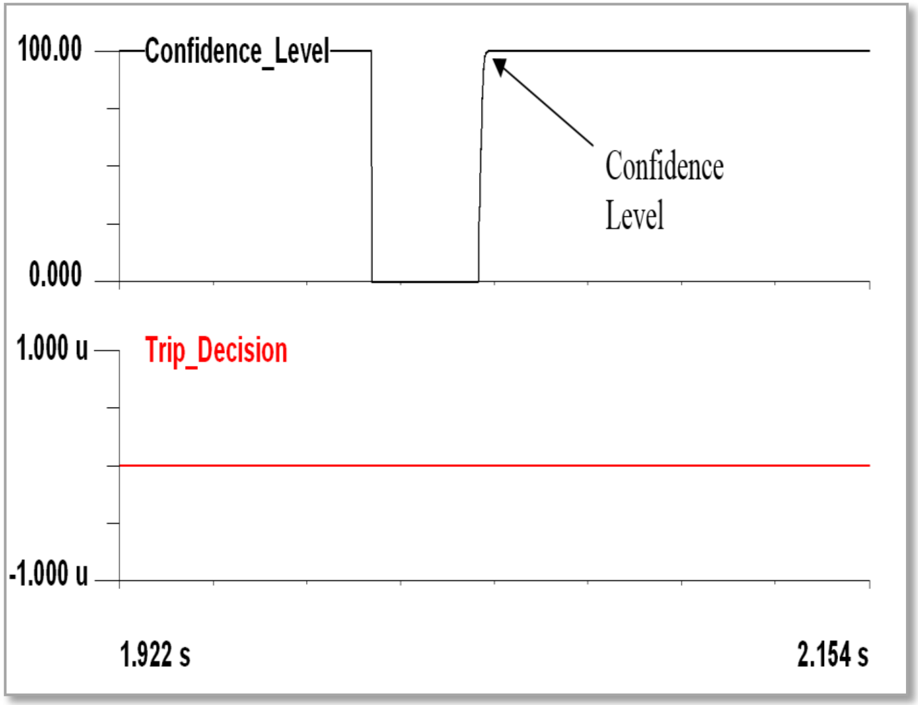


Numerical Example

Case1: Primary Fuse Blown Y-Y, PT-4A

Compromised Data Correction :





Concluding Remarks

Centralized Substation Protection innovations:

Innovation 1: Setting-less Protective Relay

Innovation 2: Merging Units can provide corrected primary values via instrumentation error correction embedded in intelligent Merging Units

Innovation 3: Supervision of protection functions (logical nodes) to determine that hidden failures do not exist. In case of hidden failures use real time dynamic model to replace compromised data with estimated data → enable resiliency

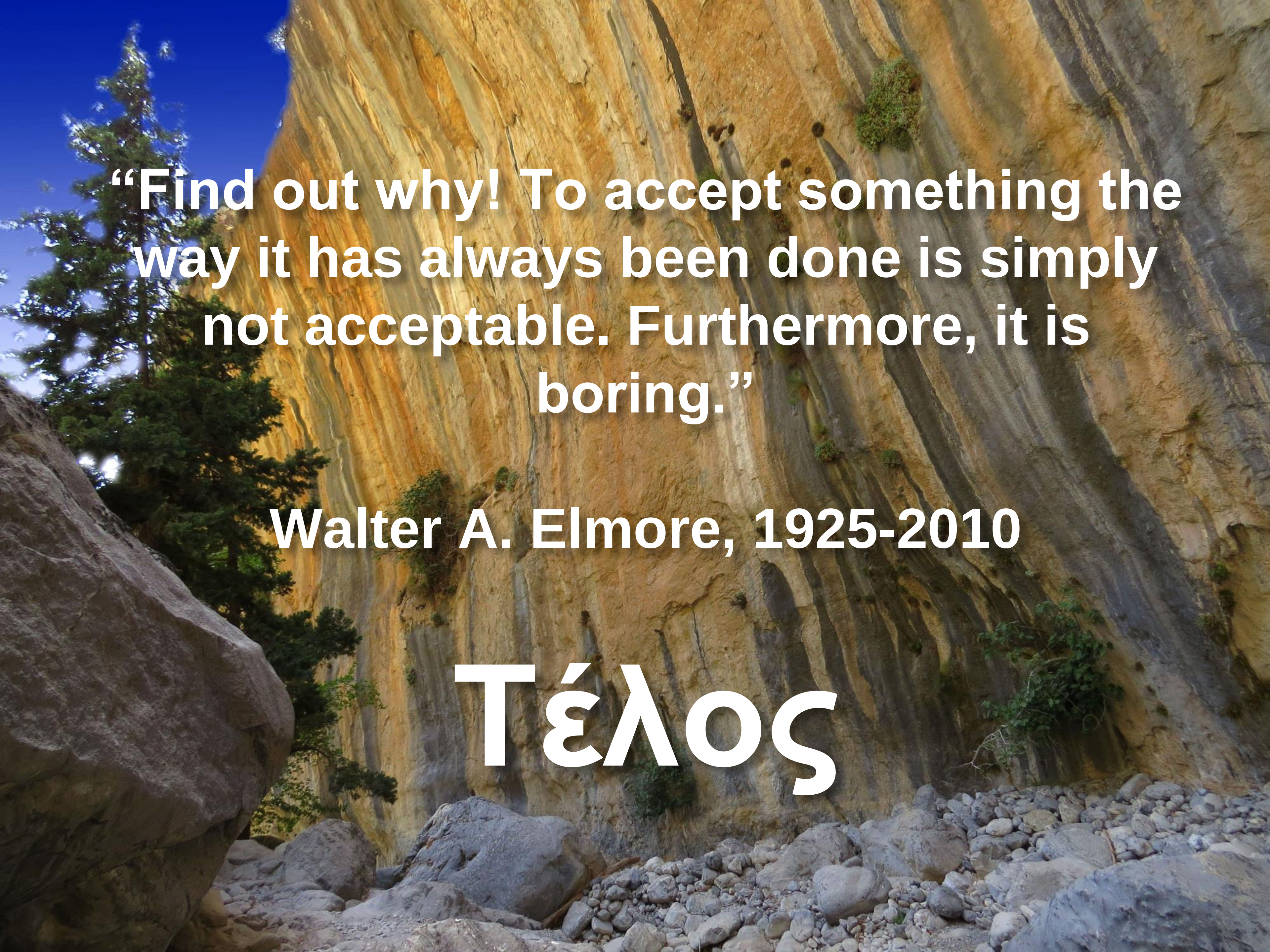
Innovation 4: Supervision of data integrity to determine data attacks. In case of cyber data attack, use real time model to replace false data → enable resiliency.

Concluding Remarks

IEEE and CIGRE Efforts Move Towards the DIGITAL SUBSTATION.

The entire process should be automated with self healing capabilities against data errors, hidden failures and cyber attacks.

Automated testing and in-line testing of active substation protection and control systems. The technology exists. We need to continue developments to bring these approaches to a practical level.


"Find out why! To accept something the way it has always been done is simply not acceptable. Furthermore, it is boring."
Walter A. Elmore, 1925-2010
Τέλος