Update On Distributed Dynamic State Estimators: Hybrid Inputs (PMUs, MUs, Numerical Relays) and Correction of Instrumentation Errors

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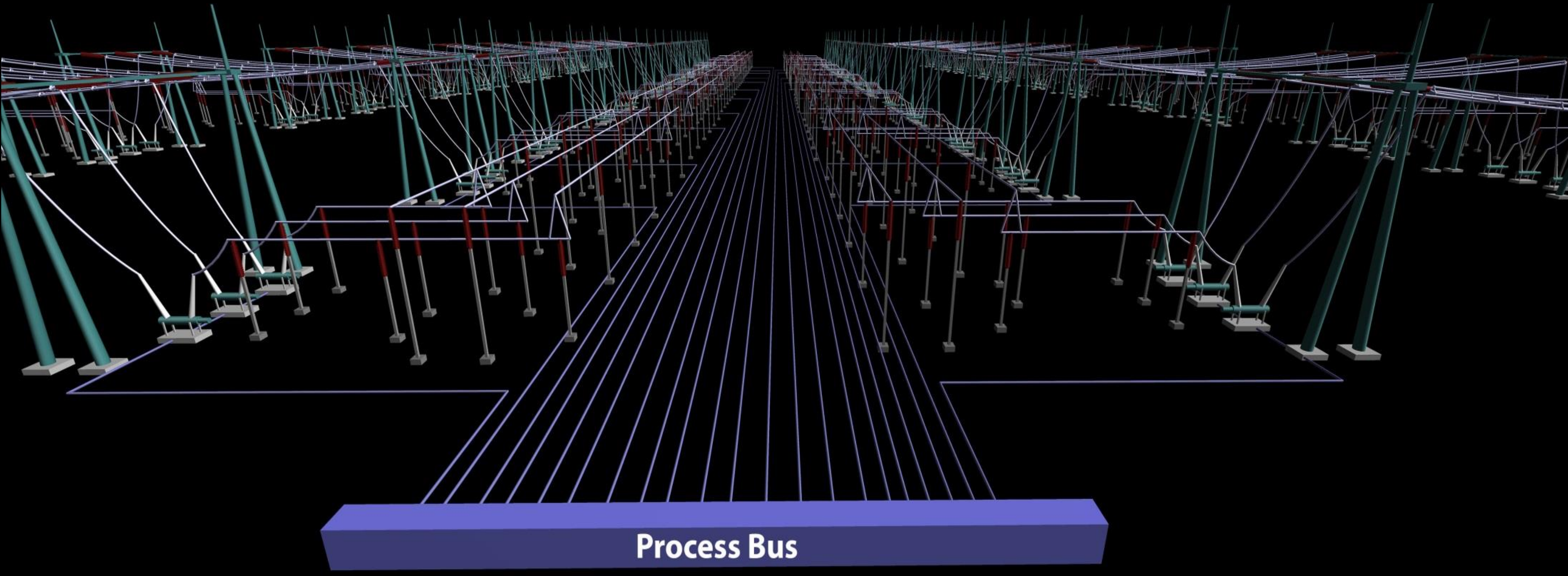


Outline

- **Legacy State Estimators**
- **New Technologies: The Changing SCADA System**
  - Relays provide SCADA
  - Merging Units
  - GPS Synchronization
- **Distributed Dynamic State Estimators**
  - Integrated with Protection System
- **Error Correction**
- **Directions / Future Work**

Legacy State Estimator

Introduced After the 1965 Blackout

Centralized State Estimator – Long Response (min)
Model Biased State Estimator

Power System SE: Basic Assumptions

- Positive Sequence Model
- P, Q, V measurement set
- Near-Simultaneous Measurements
- Single Frequency

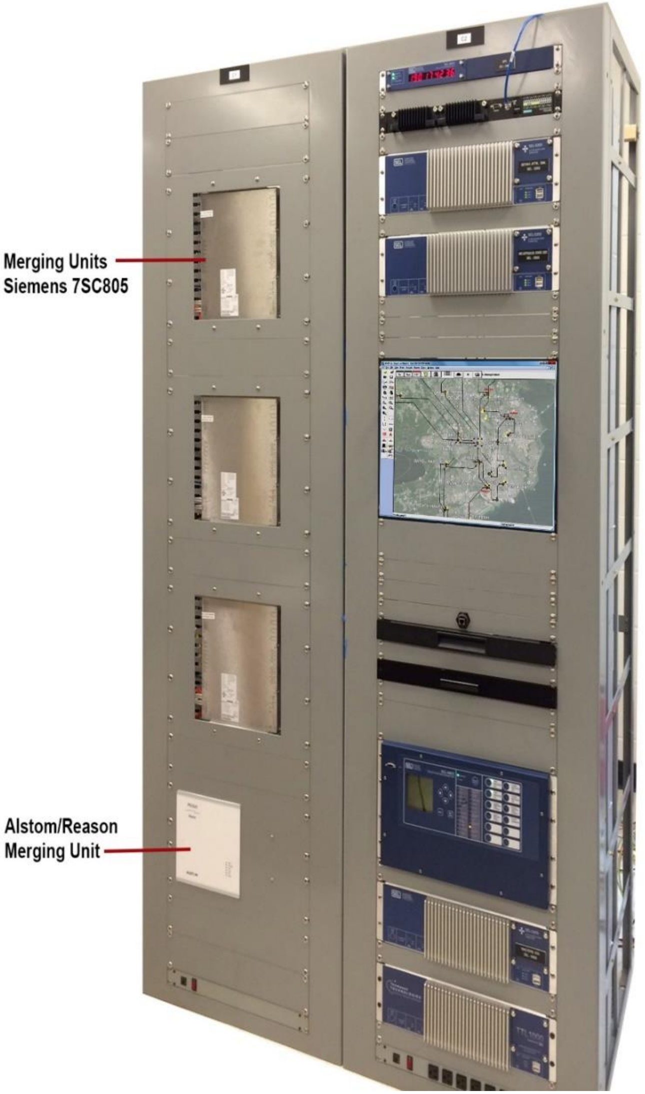
Implications:

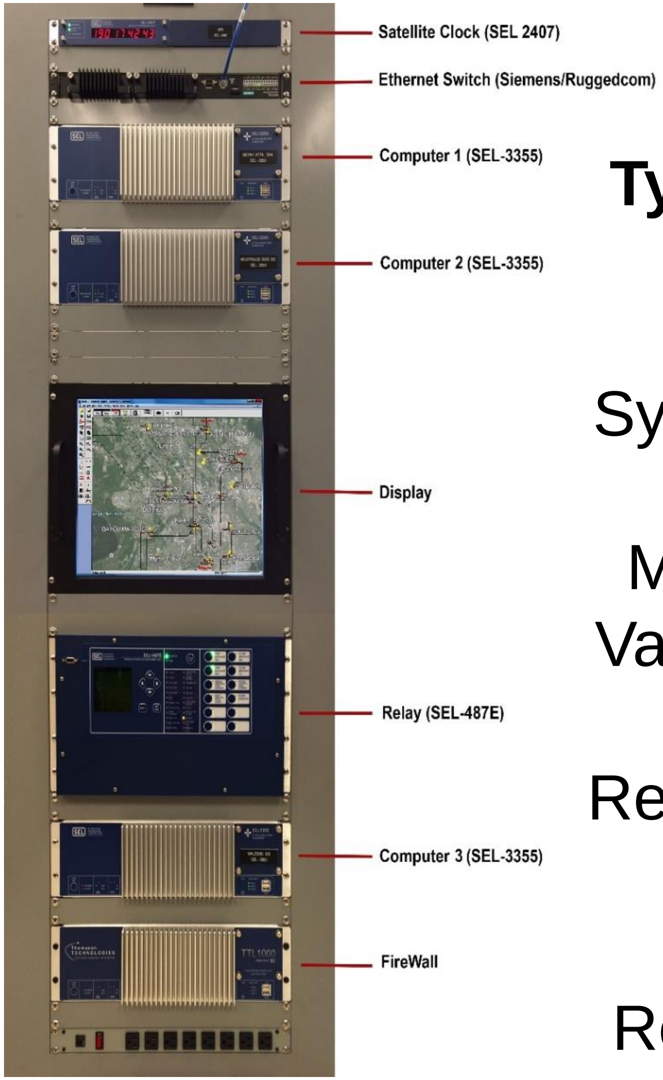
- Balanced Operation
- Symmetric Power System
- Biased SE
- Iterative Algorithm

Present Technologies Enable Removal of these Assumptions and Transition from Static to Dynamic State Estimators

Present Technologies

Relays/Merging Units provide 3-Phase GPS Synchronized SCADA





Typical Specs

GPS Synchronization

MU: Sampled Values at 80 s/c

Relays: Phasors at one s/c

Reality: Hybrid

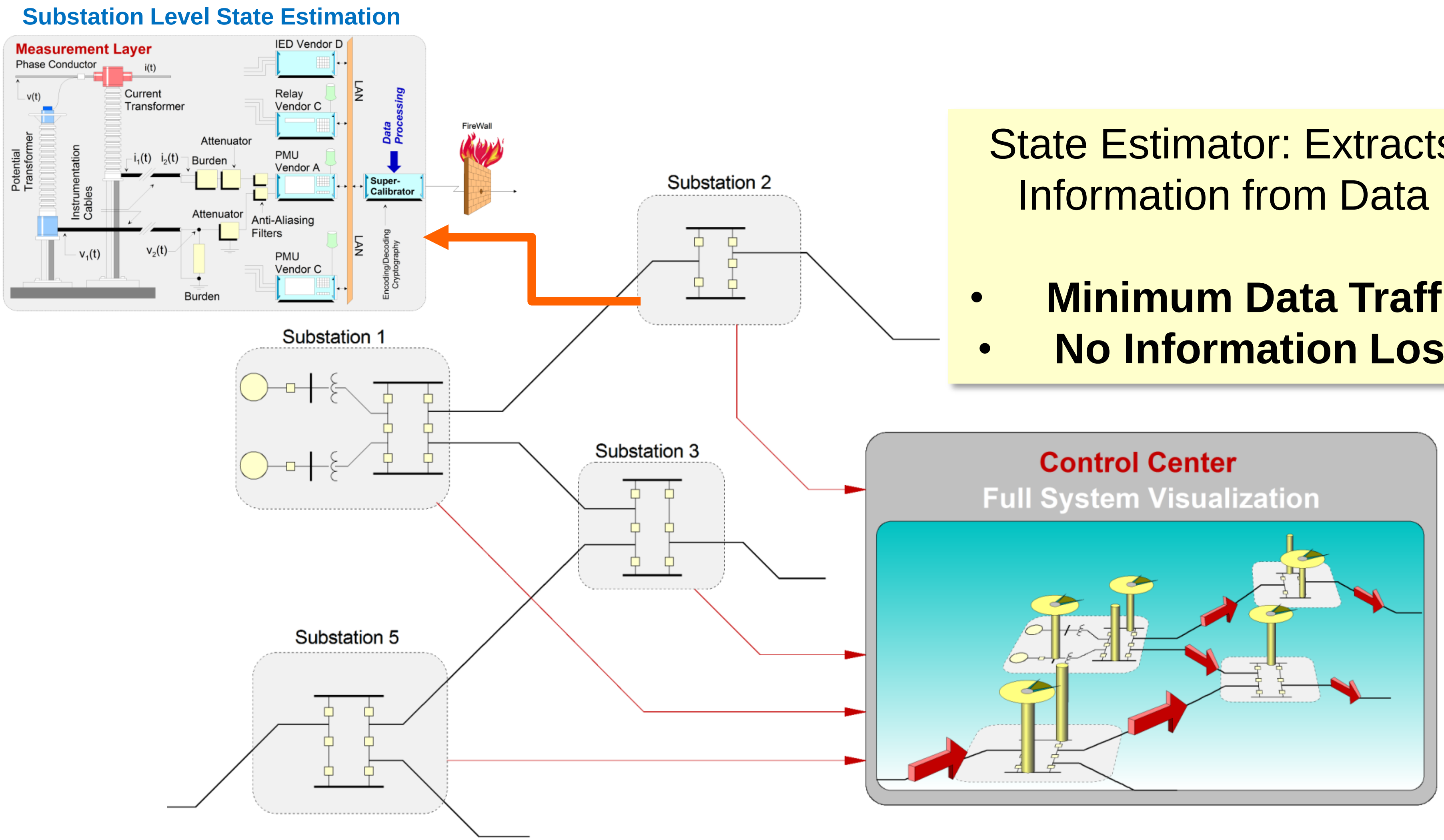
Present Technology Enables Transition from Static State Estimators to Dynamic State Estimators.

- Dynamic State Estimators: Objective, Model (dynamic), Measurements
- Quasi-Dynamic State Estimators: Model Captures Slow Dynamics. Fast Electrical Dynamics are Ignored (Suitable for Operations).
- Dynamic State Estimators: Model Captures Slow and Fast Dynamics (Suitable for Protection).

Distributed Quasi-Dynamic State Estimation

Substation Level SE → Synthesis of System Wide State at the Control Center

Enabling Technology: GPS-Synchronized Measurements



State Estimator: Extracts Information from Data

- **Minimum Data Traffic**
- **No Information Loss**

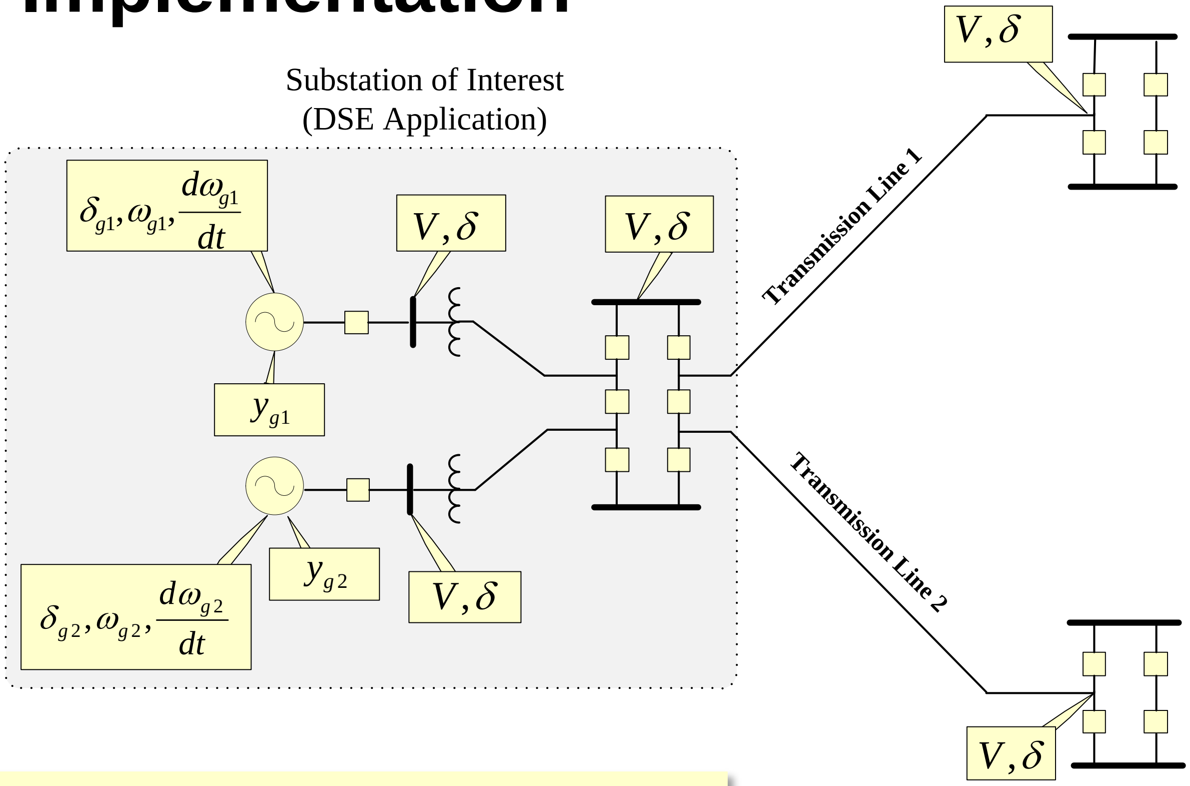
Distributed Quasi-Dynamic State Estimation

Implementation

The Estimator is Defined in Terms of:

- Model (Q-D)
- State
- Measurement Set
- Estimation Method

Observability Redundancy



System is Represented with a Set of Differential Equations (DE)
The Quasi-Dynamic State Estimator Fits the Streaming Data to the Quasi-Dynamic Model (QDE-slow dynamics) of the System

Distributed SE Measurement Set

- Any Measurement at the Substation from Any IED

    (Relays, MU, Meters, FDR, PMUs, etc.)

- Data From at Least one GPS-Synchronized Device
- Augmentation of Data Set
    - Derived Measurements

      Based on Topology

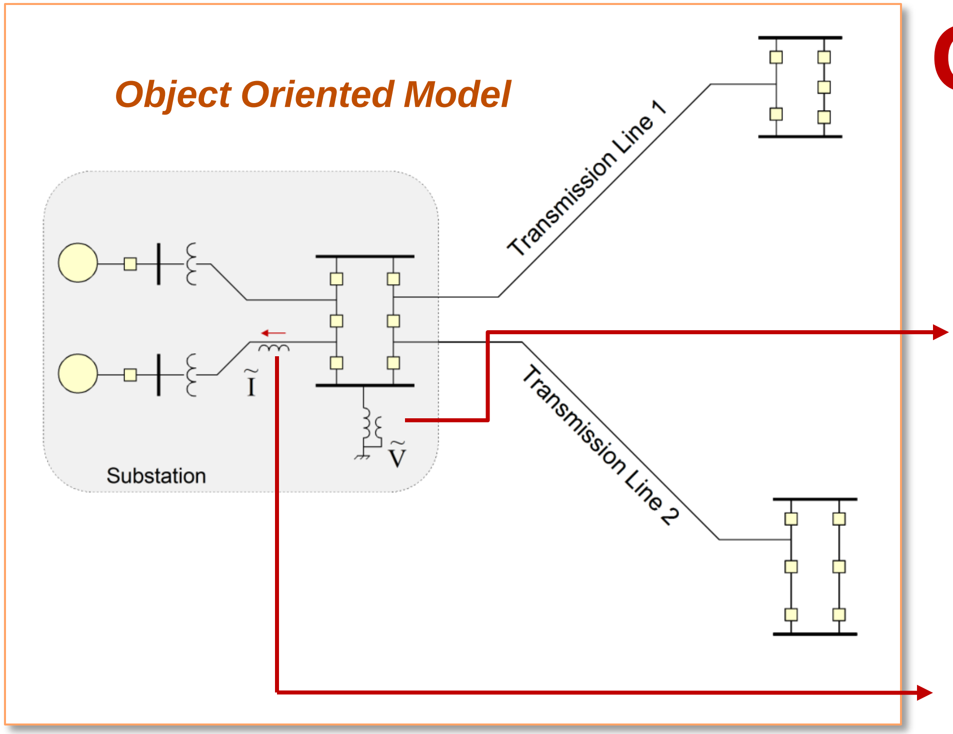
    - Virtual Measurements

      Kirchoff’s Current Law
      Model Equations

    - Pseudo-Measurements

      Missing Phase Measurements
      Neutral/Shield Current Measurement
      Neutral Voltage

Object Oriented QSE



Across (Voltage) Measurement:

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

Through (Current, Torque, etc.) Measurement:
Measurement $z_j(t)$ represents a quality associated with one row of the Object oriented model

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

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

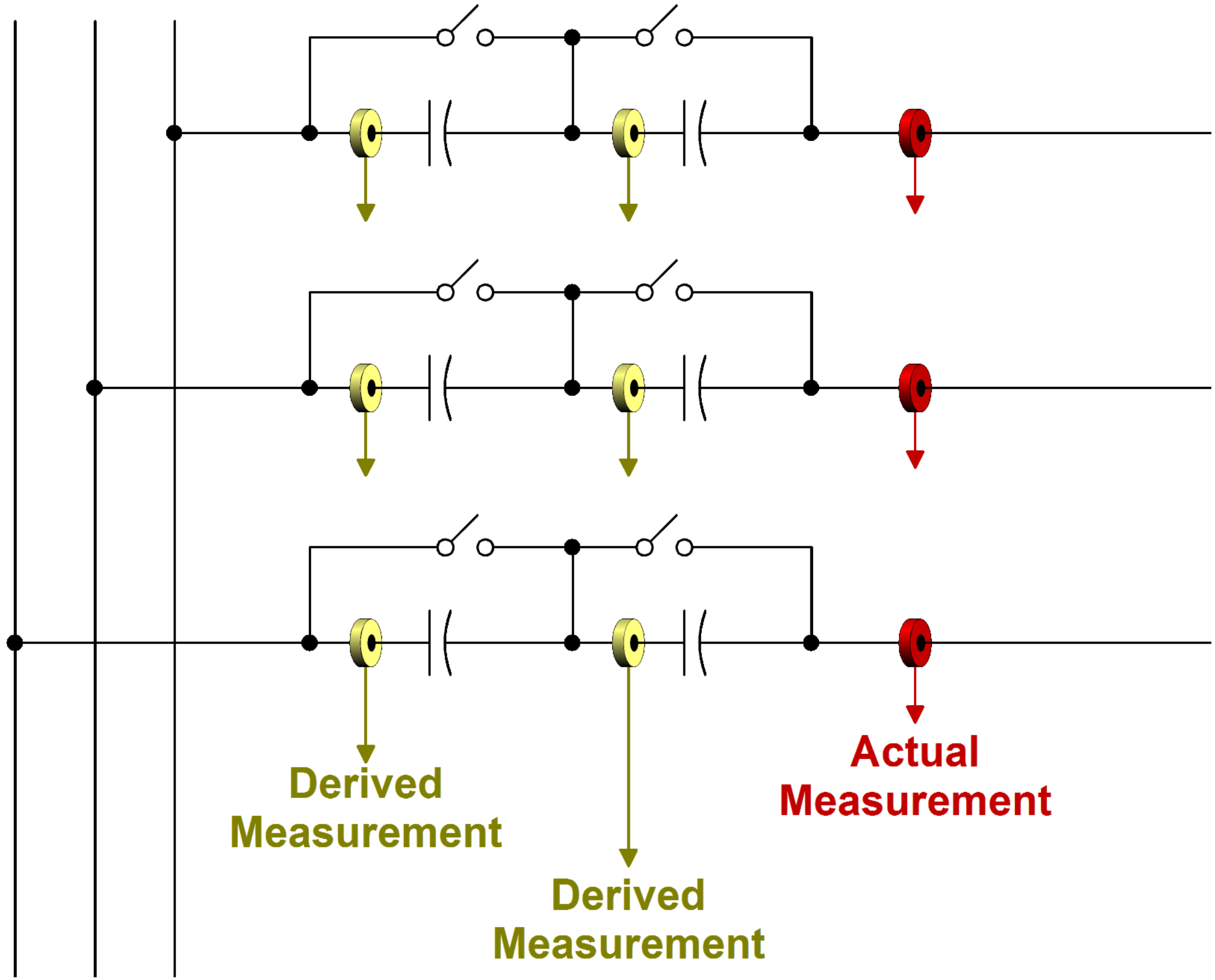
Row k

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

QSE states are
Phasors, Speed, etc

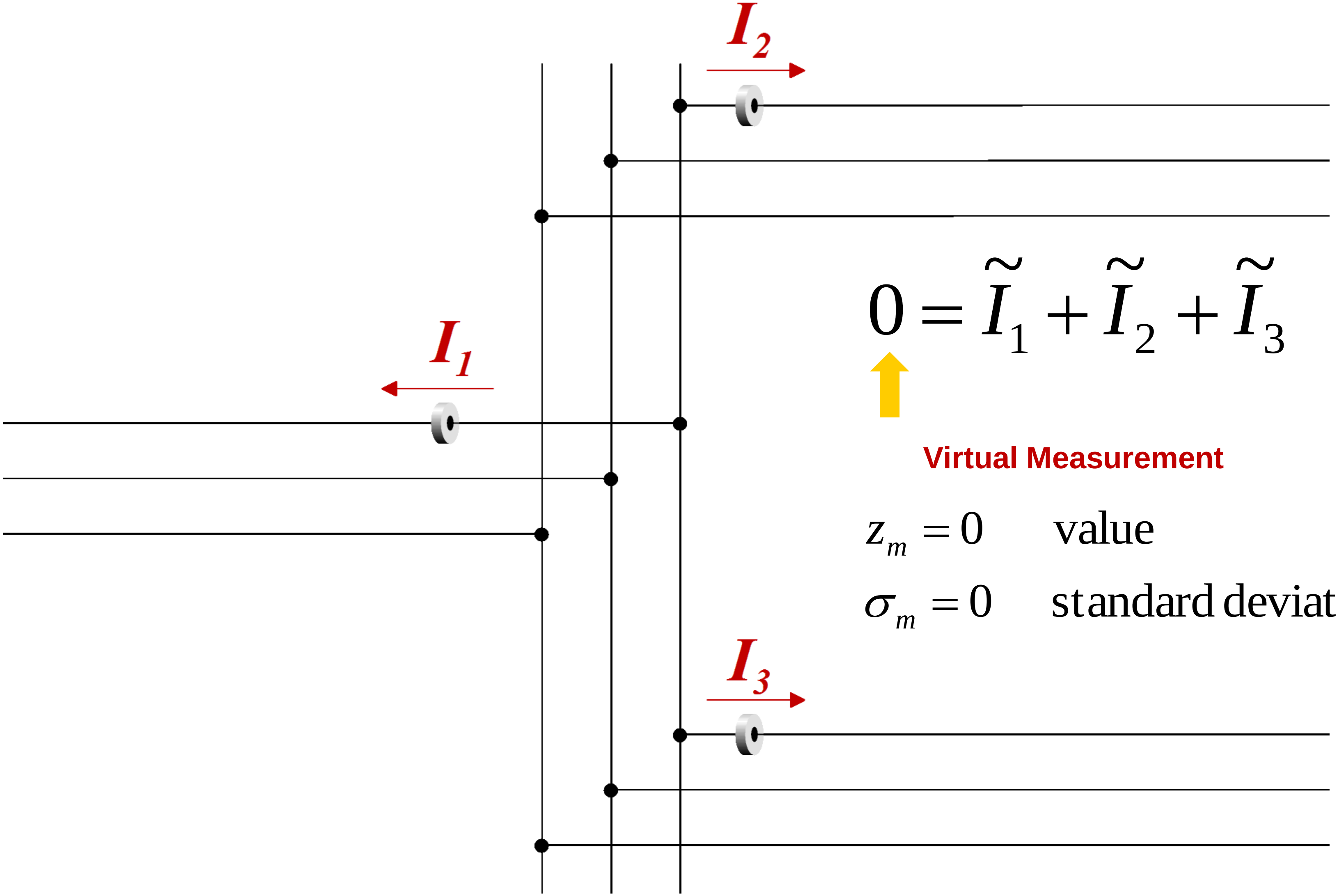
Distributed State Estimation

Derived Measurements - Examples



Distributed State Estimation

Virtual Measurements - Examples



$$0 = \tilde{I}_1 + \tilde{I}_2 + \tilde{I}_3$$

Virtual Measurement

$z_m = 0$ value

$\sigma_m = 0$ standard deviation

Distributed SE Measurement Set

Non-Synchronized Measurements

Non-GPS Synchronized Relays provide phasors referenced on “phase A Voltage”. The phase A Voltage phase is ZERO.

The SuperC provides a reliable and accurate estimate of the phase A voltage phasor.

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

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

α is a synchronizing unknown variable.

$cos(\alpha)$ and $sin(\alpha)$ are unknown variables in the state estimation algorithm.

There is one α variable for each non-synchronized relay.

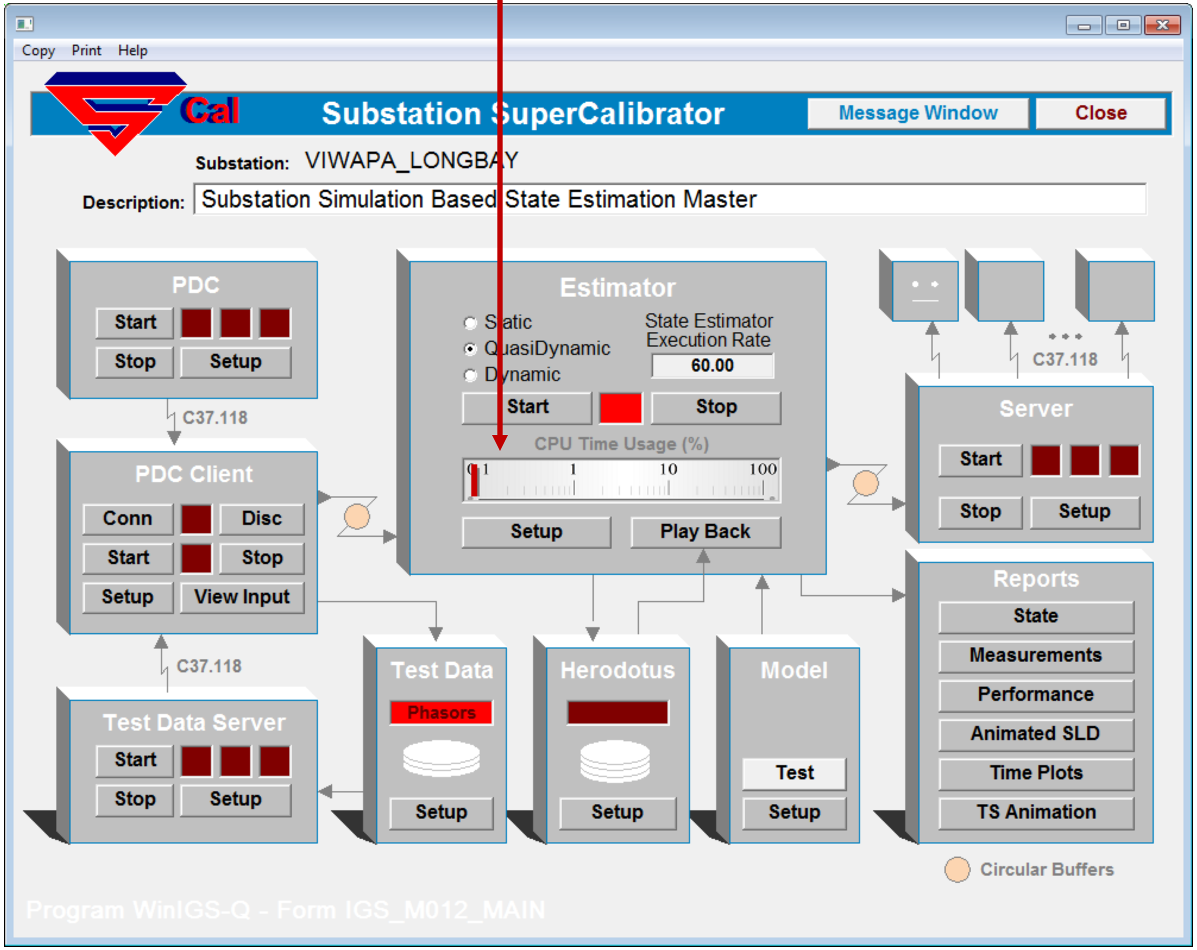
Distributed Quasi-Dynamic SE Algorithms

- Unconstrained WLS,
- Constraint WLS,
- Extended Kalman Filter
  (Provides Model Uncertainty)

***Important Observation**: Data and Model Fidelity is most important requirement for best performance*

Performance Evolution: Distributed State Estimation

Execution Time Monitor



Substation: VIWAPA_LONGBAY

Description: Substation Simulation Based State Estimation Master

Estimator: ● QuasiDynamic

State Estimator Execution Rate: 60.00

CPU Time Usage Indicates in Real Time the Portion of the Time Used by the SE Calculations.

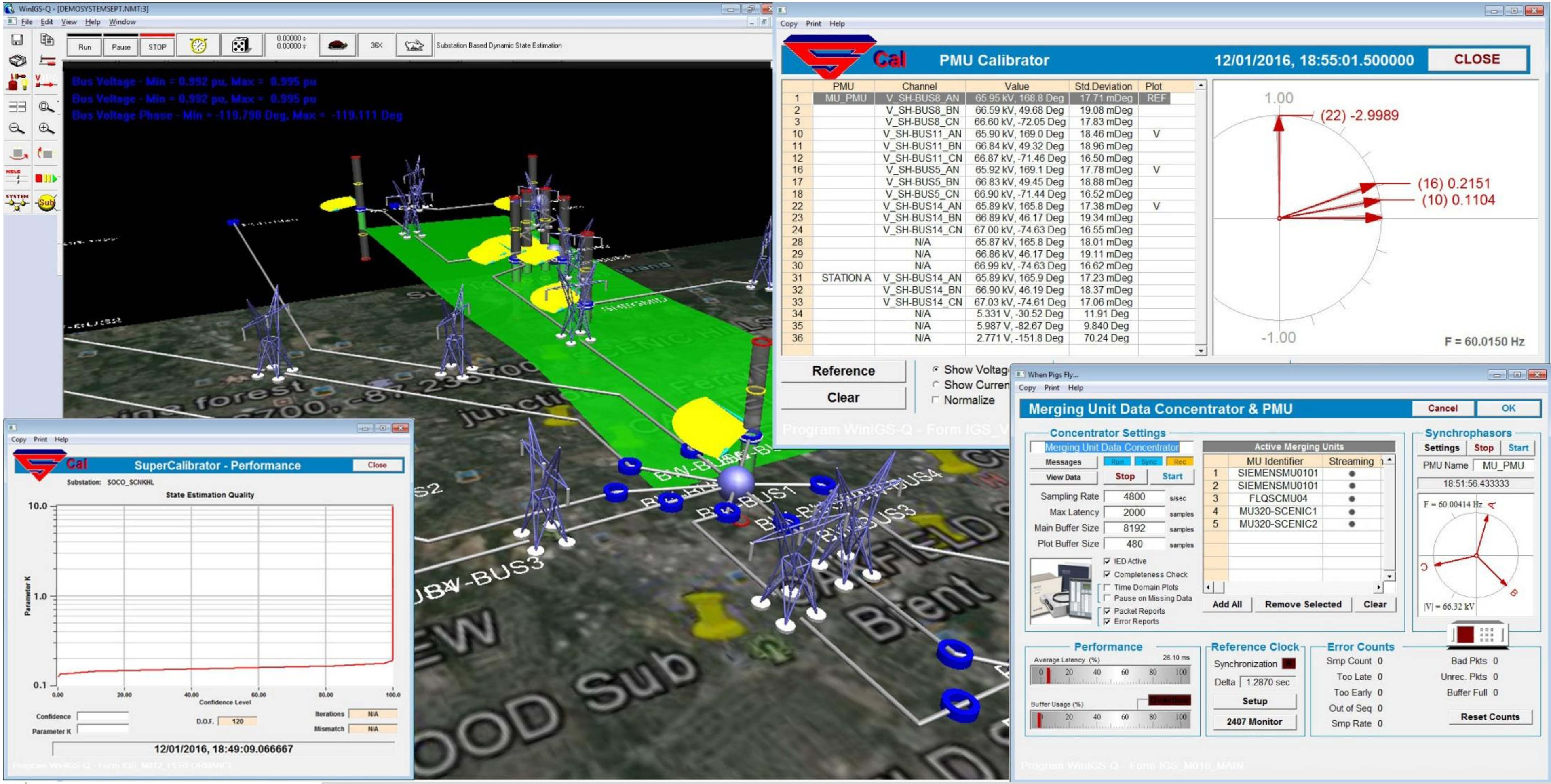
100% corresponds to the time between two successive SE computations.

Example: if SE is set to execute 60 times per second, then:

100% → 16.6 ms

Implementation and Field Demonstrations

Snapshot of system:
(a) visualization of system operation updated once per cycle
(b) metric of data validity
(c) displays of phasors and errors.



WinIGS-Q - [DEMOSYSTEMSEPT.NMT:3]

Bus Voltage - Min = 0.992 pu, Max = 0.995 pu
Bus Voltage - Min = 0.992 pu, Max = 0.995 pu
Bus Voltage Phase - Min = -119.798 Deg, Max = -119.111 Deg

PMU Calibrator 12/01/2016, 18:55:01.500000

	PMU	Channel	Value	Std.Deviation	Plot
1	MU_PMU	V_SH-BUS8_AN	65.95 kV, 168.8 Deg	17.71 mDeg	REF
2		V_SH-BUS8_BN	66.59 kV, 49.68 Deg	19.08 mDeg	
3		V_SH-BUS8_CN	66.60 kV, -72.05 Deg	17.83 mDeg	
10		V_SH-BUS11_AN	65.90 kV, 169.0 Deg	18.46 mDeg	V
11		V_SH-BUS11_BN	66.84 kV, 49.32 Deg	18.96 mDeg	
12		V_SH-BUS11_CN	66.87 kV, -71.46 Deg	16.50 mDeg	
16		V_SH-BUS5_AN	65.92 kV, 169.1 Deg	17.78 mDeg	V
17		V_SH-BUS5_BN	66.83 kV, 49.45 Deg	18.88 mDeg	
18		V_SH-BUS5_CN	66.90 kV, -71.44 Deg	16.52 mDeg	
22		V_SH-BUS14_AN	65.89 kV, 165.8 Deg	17.38 mDeg	V
23		V_SH-BUS14_BN	66.89 kV, 46.17 Deg	19.34 mDeg	
24		V_SH-BUS14_CN	67.00 kV, -74.63 Deg	16.55 mDeg	
28		N/A	65.87 kV, 165.8 Deg	18.01 mDeg	
29		N/A	66.86 kV, 46.17 Deg	19.11 mDeg	
30		N/A	66.99 kV, -74.63 Deg	16.62 mDeg	
31	STATION A	V_SH-BUS14_AN	65.89 kV, 165.9 Deg	17.23 mDeg	
32		V_SH-BUS14_BN	66.90 kV, 46.19 Deg	18.37 mDeg	
33		V_SH-BUS14_CN	67.03 kV, -74.61 Deg	17.06 mDeg	
34		N/A	5.331 V, -30.52 Deg	11.91 Deg	
35		N/A	5.987 V, -82.67 Deg	9.840 Deg	
36		N/A	2.771 V, -151.8 Deg	70.24 Deg	

F = 60.0150 Hz

● Show Voltag
○ Show Curren
☐ Normalize

SuperCalibrator - Performance

Substation: SOCO_SCNKHL

Confidence
Parameter K
D.O.F. 120
Iterations N/A
Mismatch N/A

12/01/2016, 18:49:09.066667

When Pigs Fly...

Merging Unit Data Concentrator & PMU

Sampling Rate 4800 s/sec
Max Latency 2000 samples
Main Buffer Size 8192 samples
Plot Buffer Size 480 samples

☑ IED Active
☑ Completeness Check
☐ Time Domain Plots
☐ Pause on Missing Data
☑ Packet Reports
☑ Error Reports

Active Merging Units

	MU Identifier	Streaming
1	SIEMENSMU0101	●
2	SIEMENSMU0101	●
3	FLQSCMU04	●
4	MU320-SCENIC1	●
5	MU320-SCENIC2	●

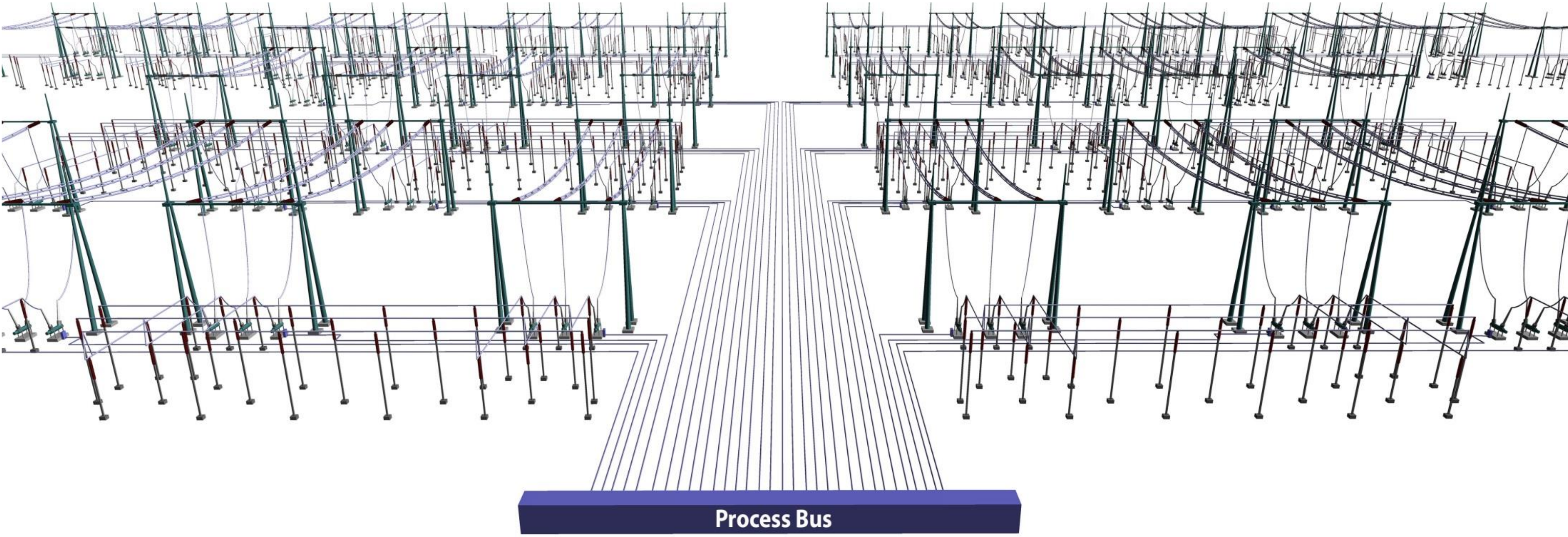
PMU Name MU_PMU
18:51:56.433333
F = 60.00414 Hz
|V| = 66.32 kV

Synchronization
Delta 1.2870 sec

Smp Count 0
Too Late 0
Too Early 0
Out of Seq 0
Smp Rate 0
Bad Pkts 0
Unrec. Pkts 0
Buffer Full 0

Data Integrity

Instrumentation Channel Error Correction



Effects of Input Data Accuracy

Quality of Data is Affected from:

- *(a) Instrumentation Channel Errors,*
- *(b) Hidden Failures and*
- *(c) Cyber data attacks.*

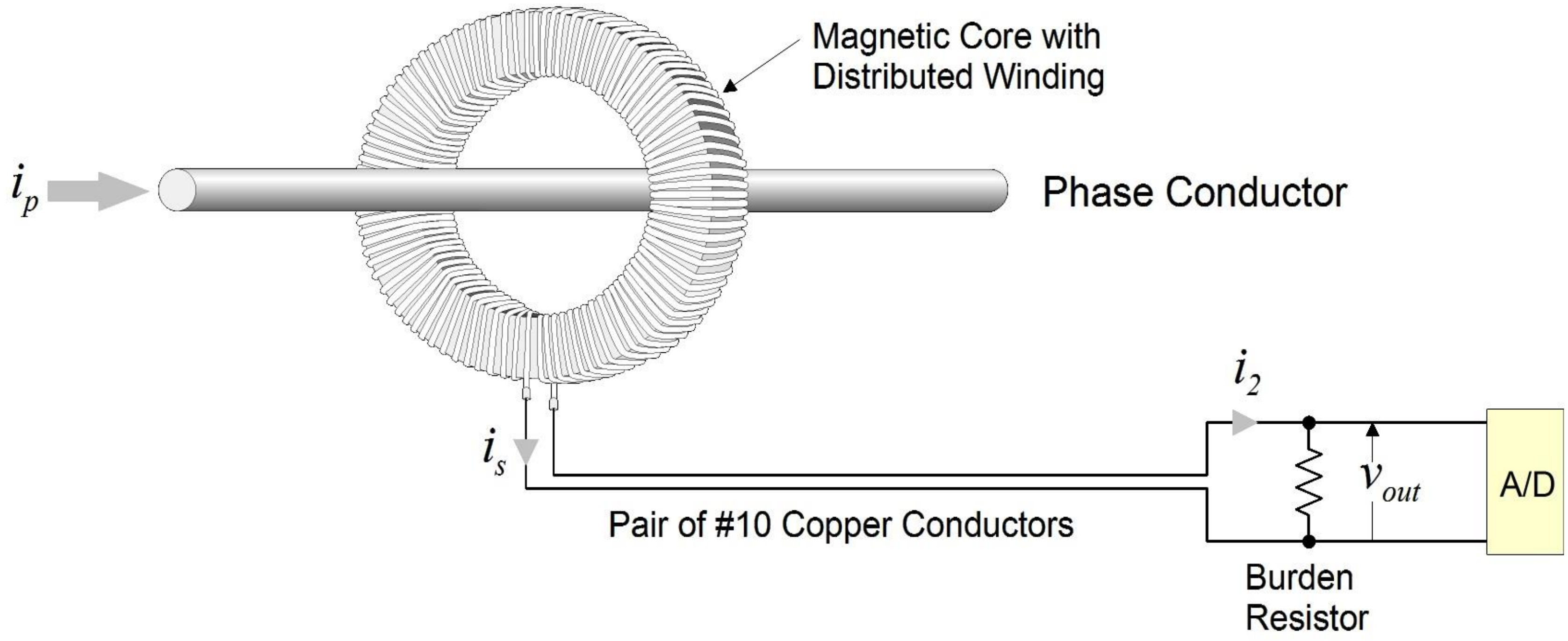
All Affect Performance of Protection and State Estimation.

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.

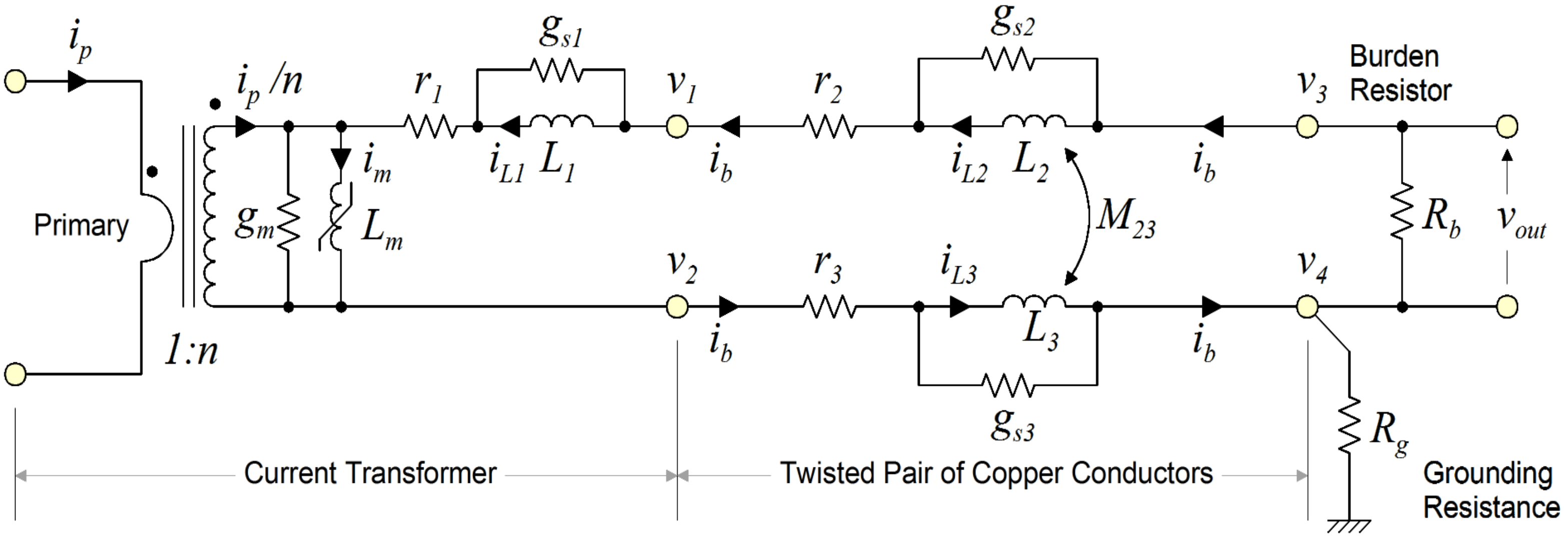
Basic Question



- 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

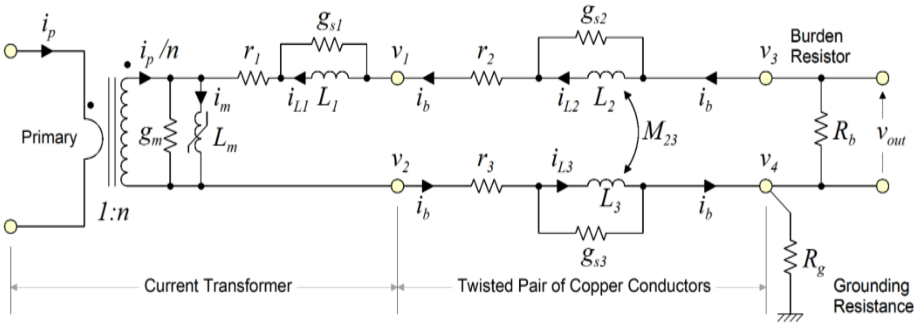
(c) pseudo measurements

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

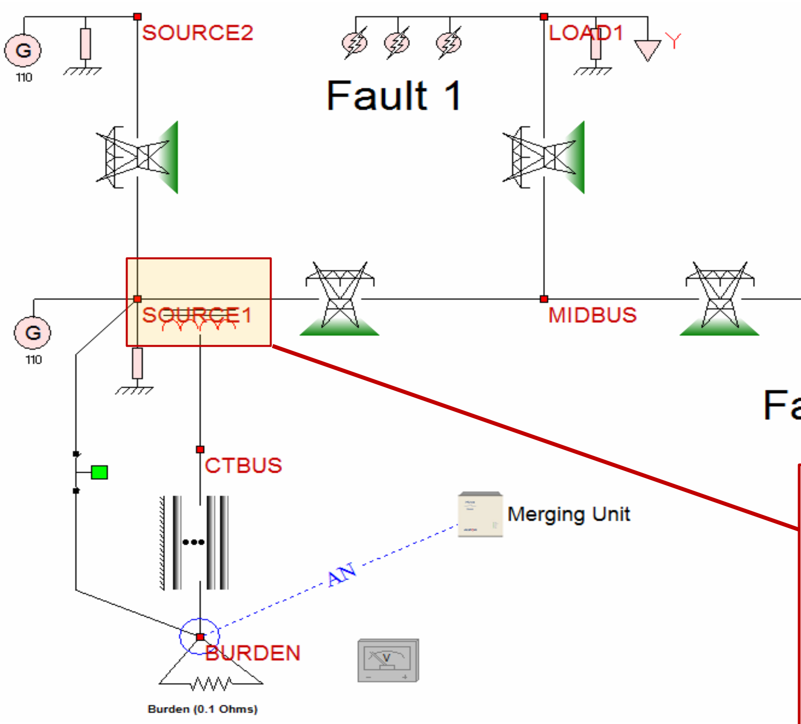
Example Pseudo Measurement: $0^m = v_4(t)$

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

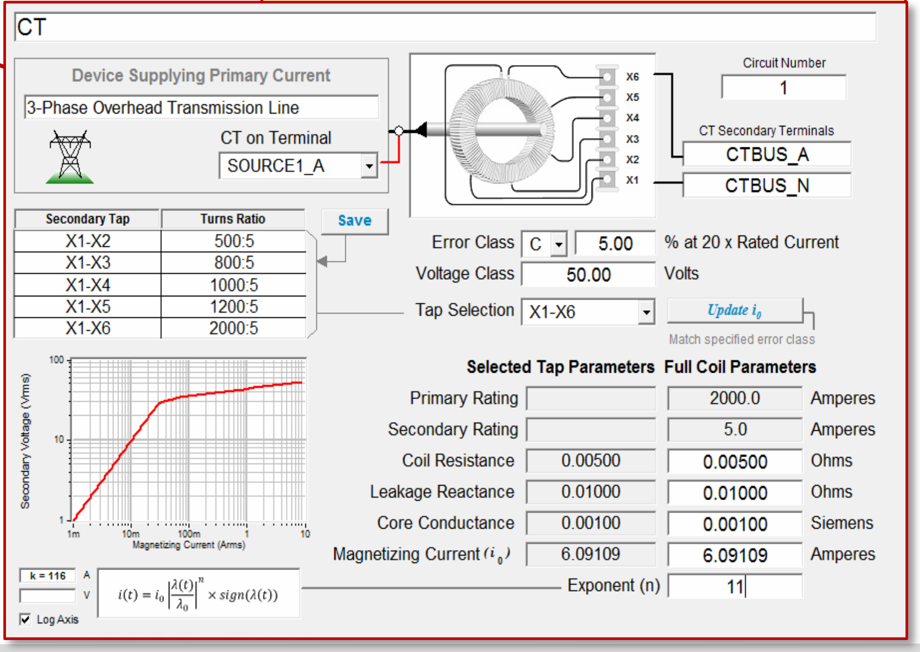
Error class: 10C100.

CT instrumentation cable: #10 copper

Instr. cable length: 96 meters

Burden resistance: 0.1 Ω

Current Transformer Parameters



CT

Device Supplying Primary Current: 3-Phase Overhead Transmission Line

CT on Terminal: SOURCE1_A

Circuit Number: 1

CT Secondary Terminals: CTBUS_A, CTBUS_N

Secondary Tap	Turns Ratio
X1-X2	500:5
X1-X3	800:5
X1-X4	1000:5
X1-X5	1200:5
X1-X6	2000:5

Error Class: C 5.00 % at 20 x Rated Current

Voltage Class: 50.00 Volts

Tap Selection: X1-X6

Match specified error class

	Selected Tap Parameters	Full Coil Parameters	
Primary Rating		2000.0	Amperes
Secondary Rating		5.0	Amperes
Coil Resistance	0.00500	0.00500	Ohms
Leakage Reactance	0.01000	0.01000	Ohms
Core Conductance	0.00100	0.00100	Siemens
Magnetizing Current (i_0)	6.09109	6.09109	Amperes
Exponent (n)		11	

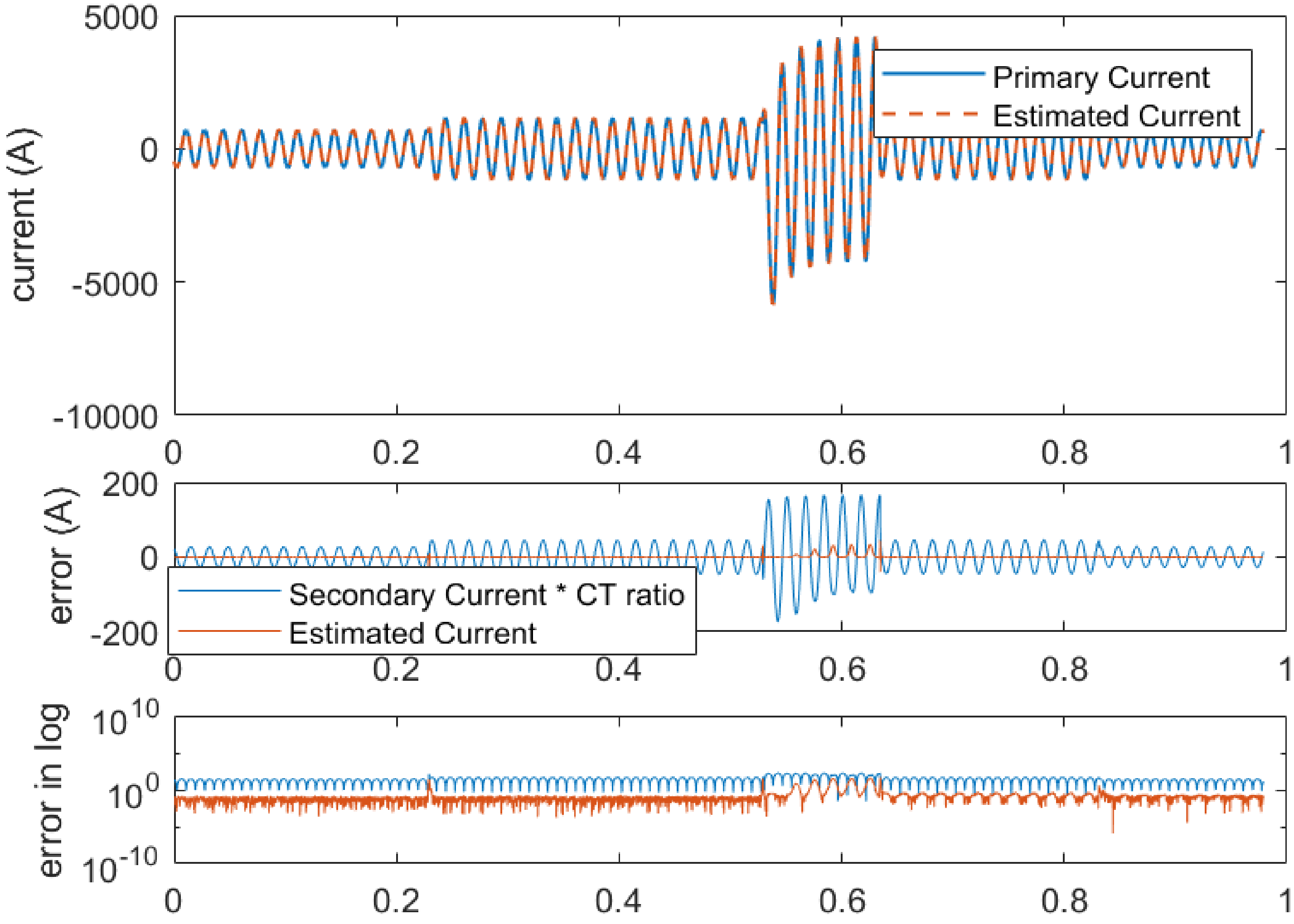
k = 116 A

V

☑ Log Axis

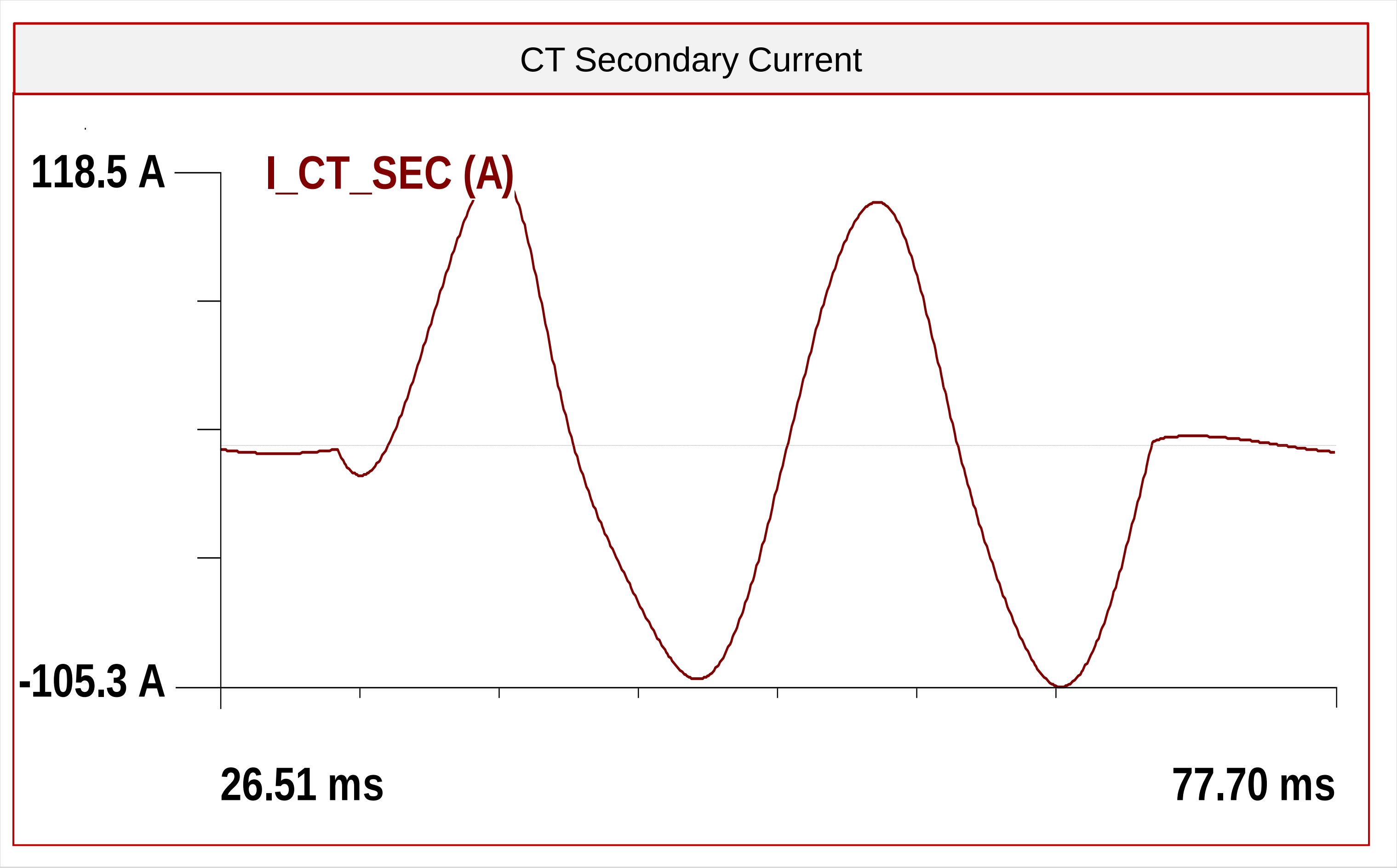
$$i(t) = i_0 \left|\frac{\lambda(t)}{\lambda_0}\right|^n \times sign(\lambda(t))$$

Example System Results



Example System Results – Mild CT Saturation

Simulated CT Secondary Current Waveform



Phase A to ground fault at “MIDBUS”

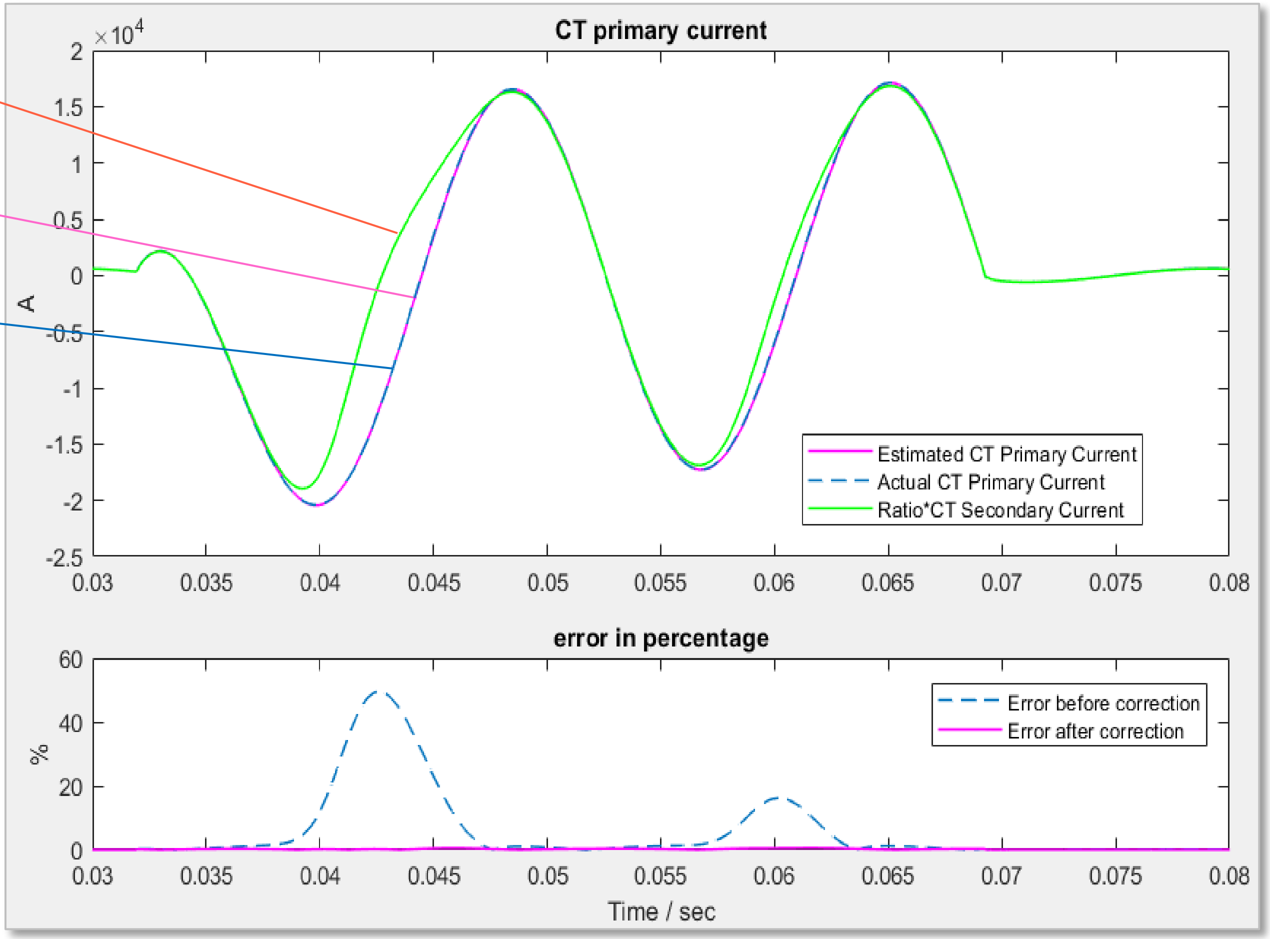
Example System Results – Mild CT Saturation

Error Correction Performance

Secondary Current x CT Ratio

Estimated Primary Current

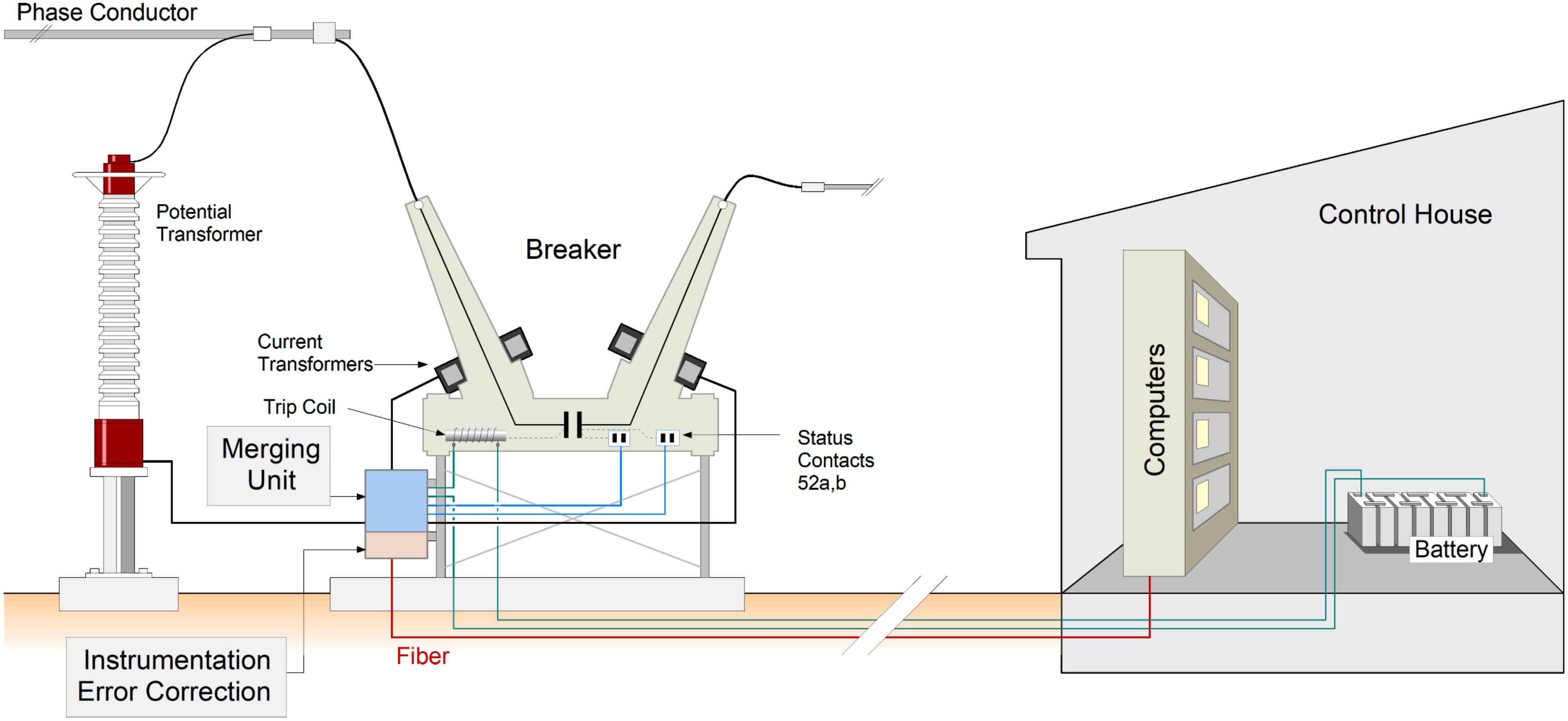
Actual Primary Current



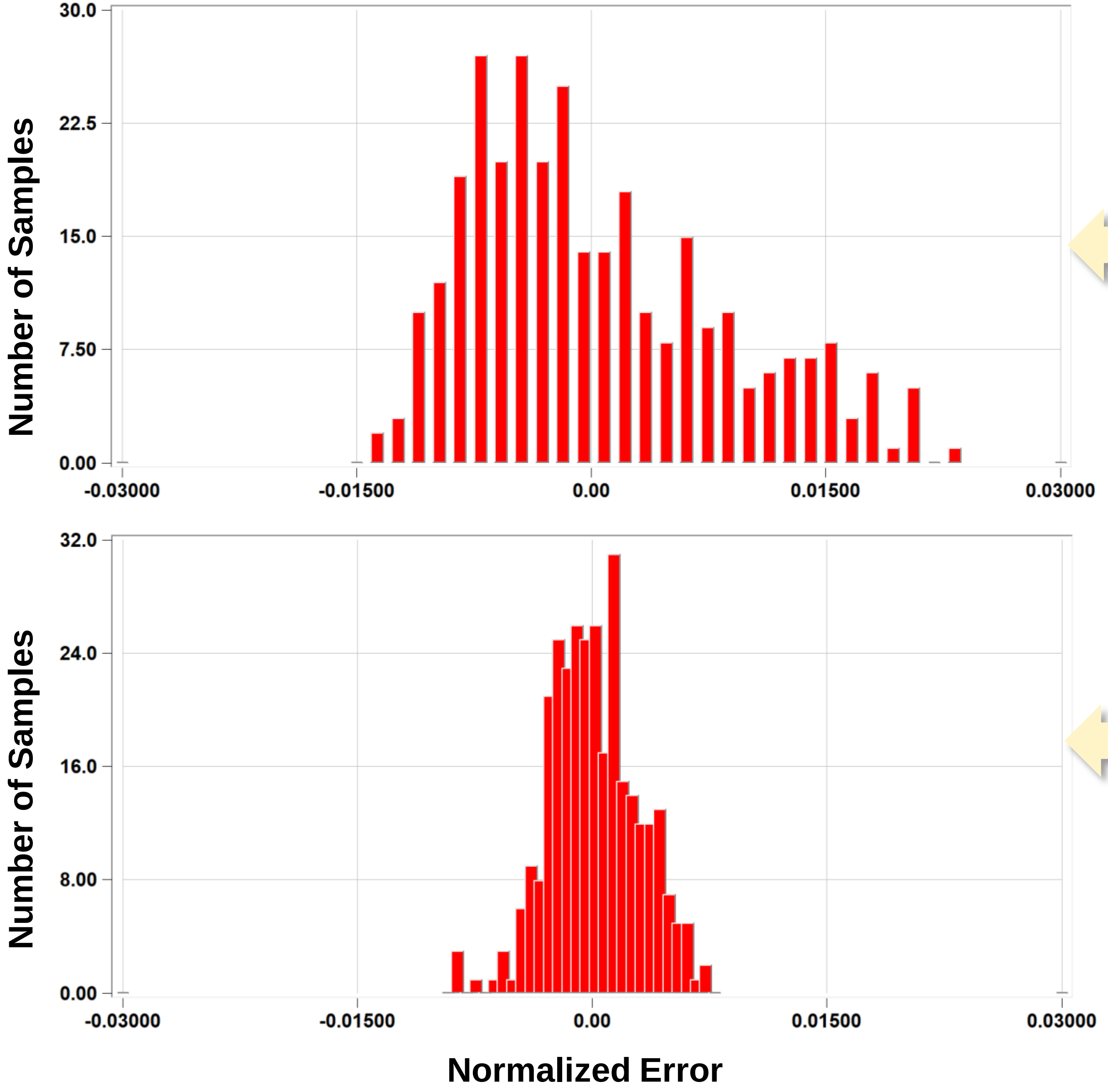
Estimated results match actual primary current with less than 1% error

Intelligent Merging Units Provide Corrected Primary Values

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



Residual Analysis with/without Instrumentation Error Correction



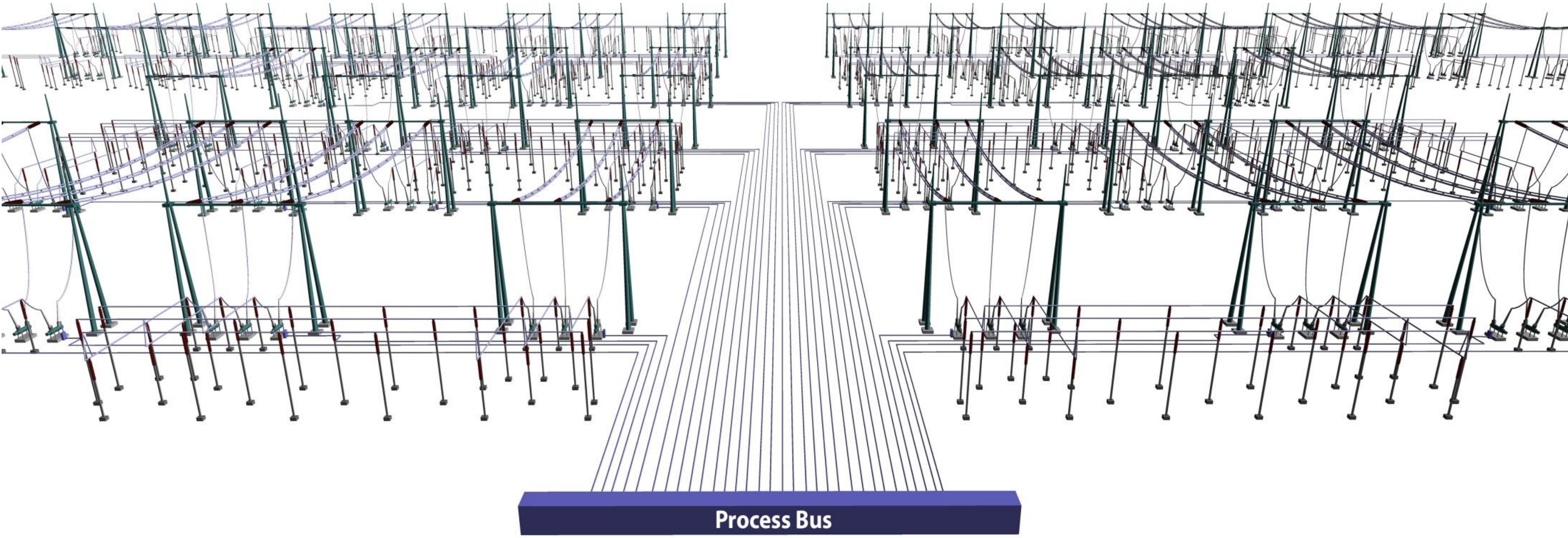
Histogram of Residuals without Correction (300 SE Executions)

Histogram of Residuals with Correction (300 SE Executions)

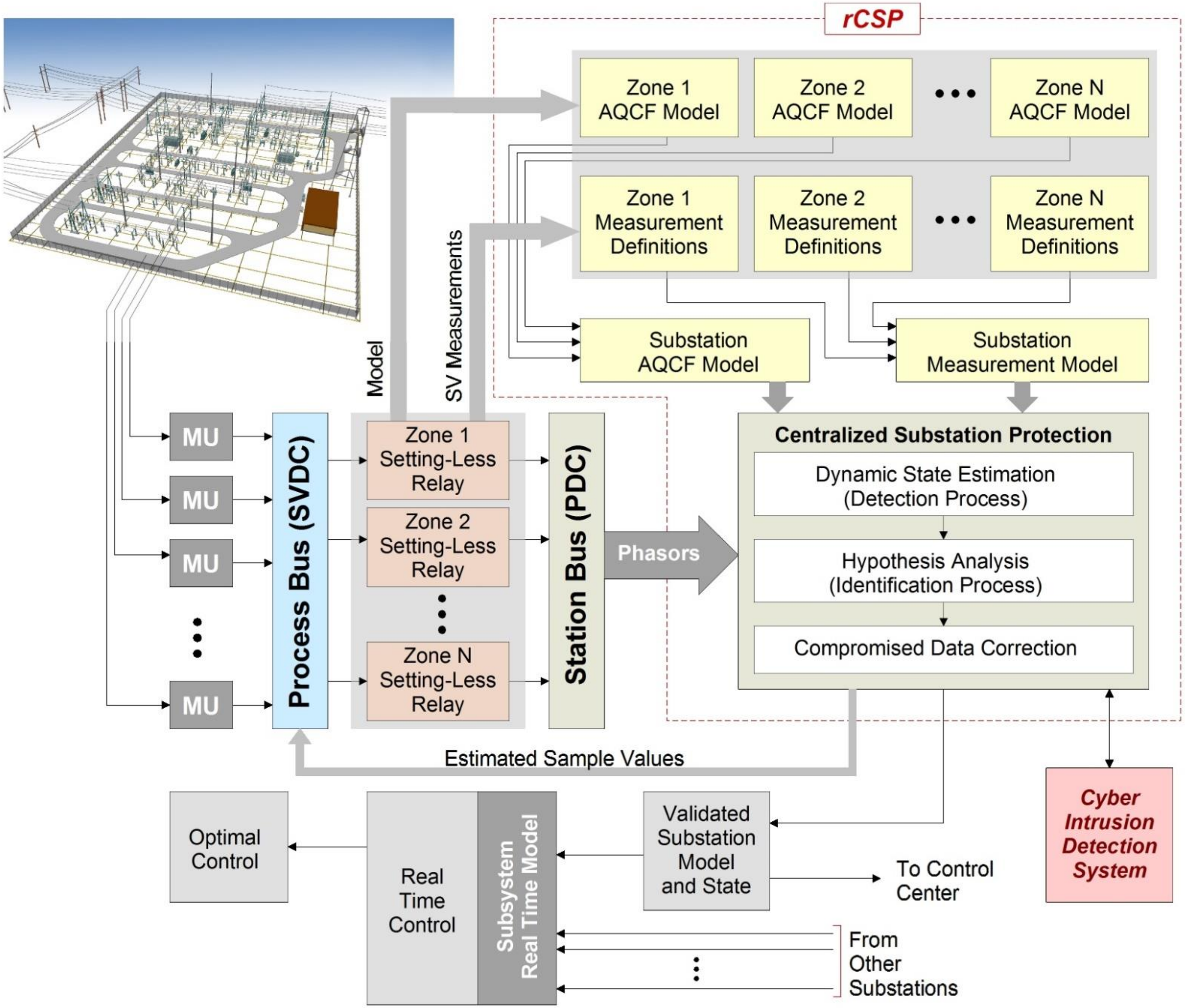
The Future

The Digital Substation

Integration of Protection and State Estimation



Dynamic State Estimation Based Centralized Protection Scheme



Resilient
Centralized
Substation
Protection
(**rCSP**)

Concluding Remarks

IEEE and CIGRE Efforts Move Towards the DIGITAL SUBSTATION.

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

Awareness: Automatic provision of substation dynamic state.

Asset Management: Automated testing and in-line testing of active substation protection and control systems.