Distributed State Estimation

With Application to Alarm Processing

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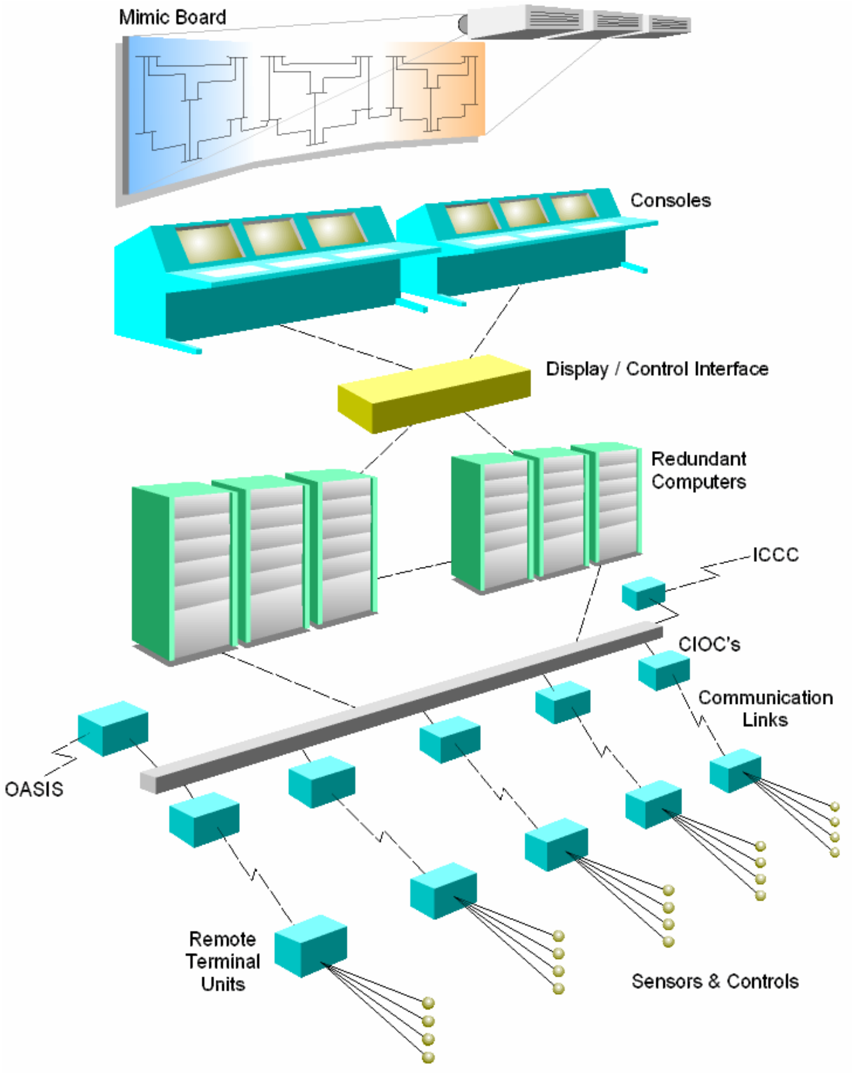
Project Summary

State estimation and meaningful alarm analysis are extremely important for increasing the “visibility” and situational awareness in control centers. Yet the average reliability of the state estimator in the US industry is only 95% (the 5% unreliability occurs when the state estimator is mostly needed). We propose a distributed state estimation based on the “supercalibrator” approach (state “measurer”) integrated with a model predictive alarm processing. There are two distinct main goals of the proposed research: (a) we expect to achieve 100% reliability of the state estimator and (b) identification of the **root cause event** of alarms. There are other additional advantages: (a) fast identification and detection of bad data and topology errors; (b) increased precision of the real time model and (c) minimization of data traffic. The proposed tools will be demonstrated in several substations of the collaborating utilities.

Motivation: Present Operating Model



Real Time Model

State Estimation

Applications

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

Basic Operational Tool

August 14, 2003 Report: **Lack of Situational Awareness**

Power Grid Visibility

Basic Tools: **SCADA** (unfiltered) and **SE** (filtered)

The objective of **SE** is to provide a reliable real time model

How well is it done?

Historical performance of SE suggests an

Average reliability of 95%

Is this performance acceptable?

Motivation

We Should be Moving from State Estimation to State “Measurer”

Terry Boston, April 2005

Traditional State Estimation

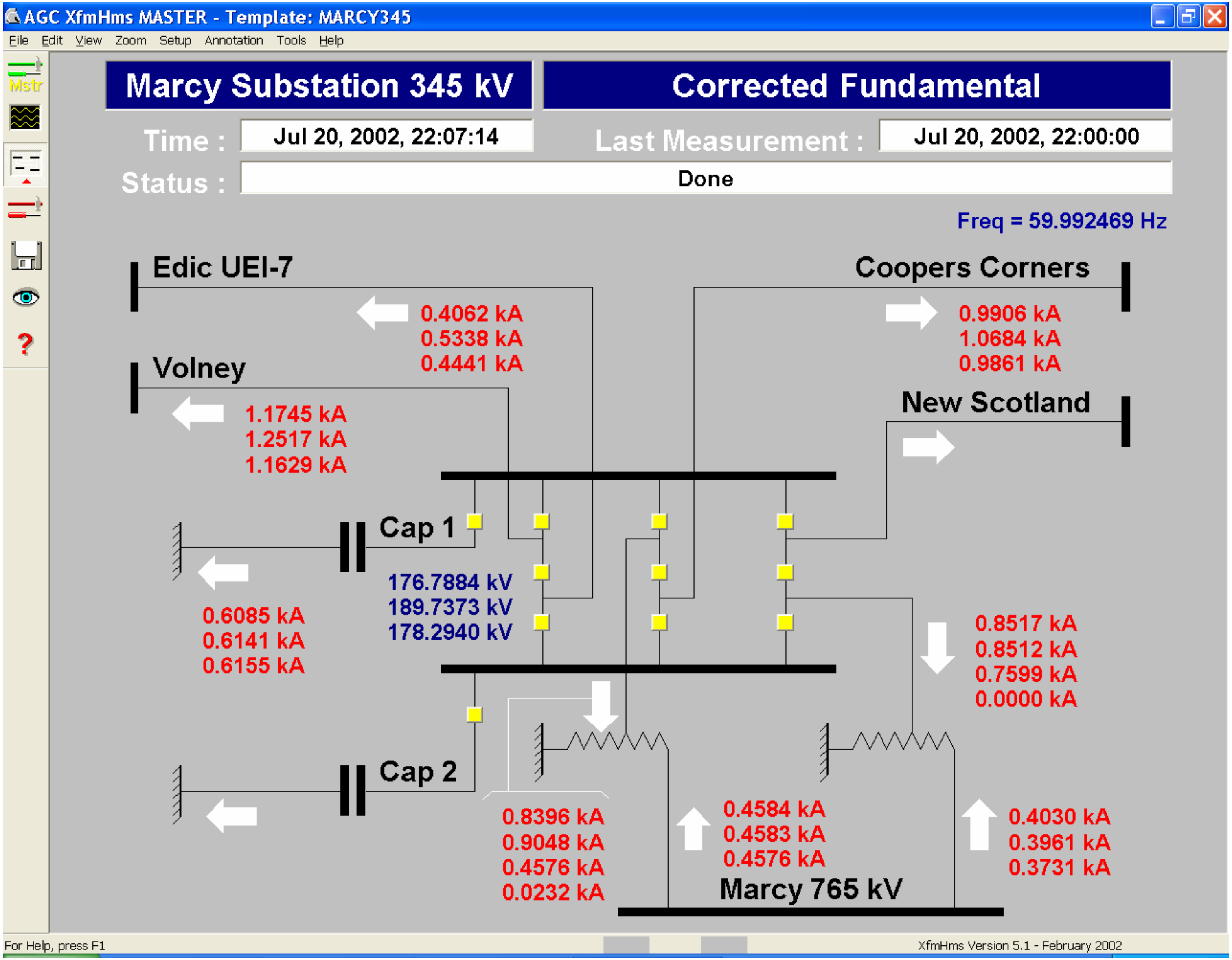
Power System SE: Basic Assumptions

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

Implications:

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

Errors from Imbalance and Asymmetry



Marcy Substation 345 kV

Corrected Fundamental

Time : Jul 20, 2002, 22:07:14

Last Measurement : Jul 20, 2002, 22:00:00

Status : Done

Freq = 59.992469 Hz

Instrumentation Errors:

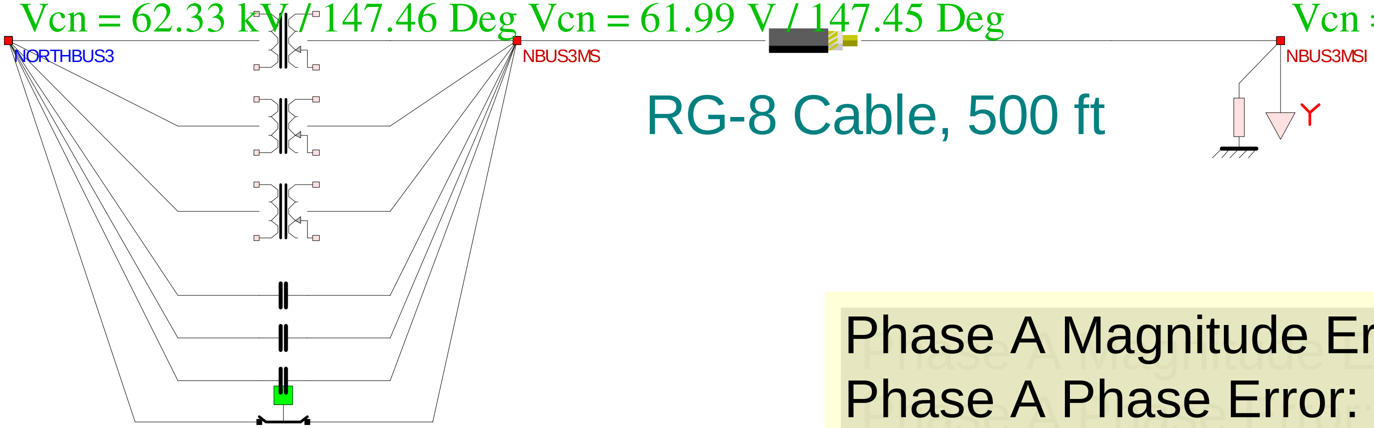
Voltage Measurement Example

Voltage Measurement IC
Substation A, 115 kV Bus

Van = 62.53 kV / 27.52 Deg
Vbn = 62.96 kV / -92.68 Deg
Vcn = 62.33 kV / 147.46 Deg

Van = 62.19 V / 27.51 Deg
Vbn = 62.61 V / -92.70 Deg
Vcn = 61.99 V / 147.45 Deg

Van = 61.63 V / 27.11 Deg
Vbn = 63.09 V / -92.85 Deg
Vcn = 61.72 V / 148.00 Deg



RG-8 Cable, 500 ft

Phase A Magnitude Error: 1.46%
Phase A Phase Error: 0.41 degrees

69kV:69V Wound Type VT

GPS-Synchronized Equipment Help but…

Keeping Things in Perspective…

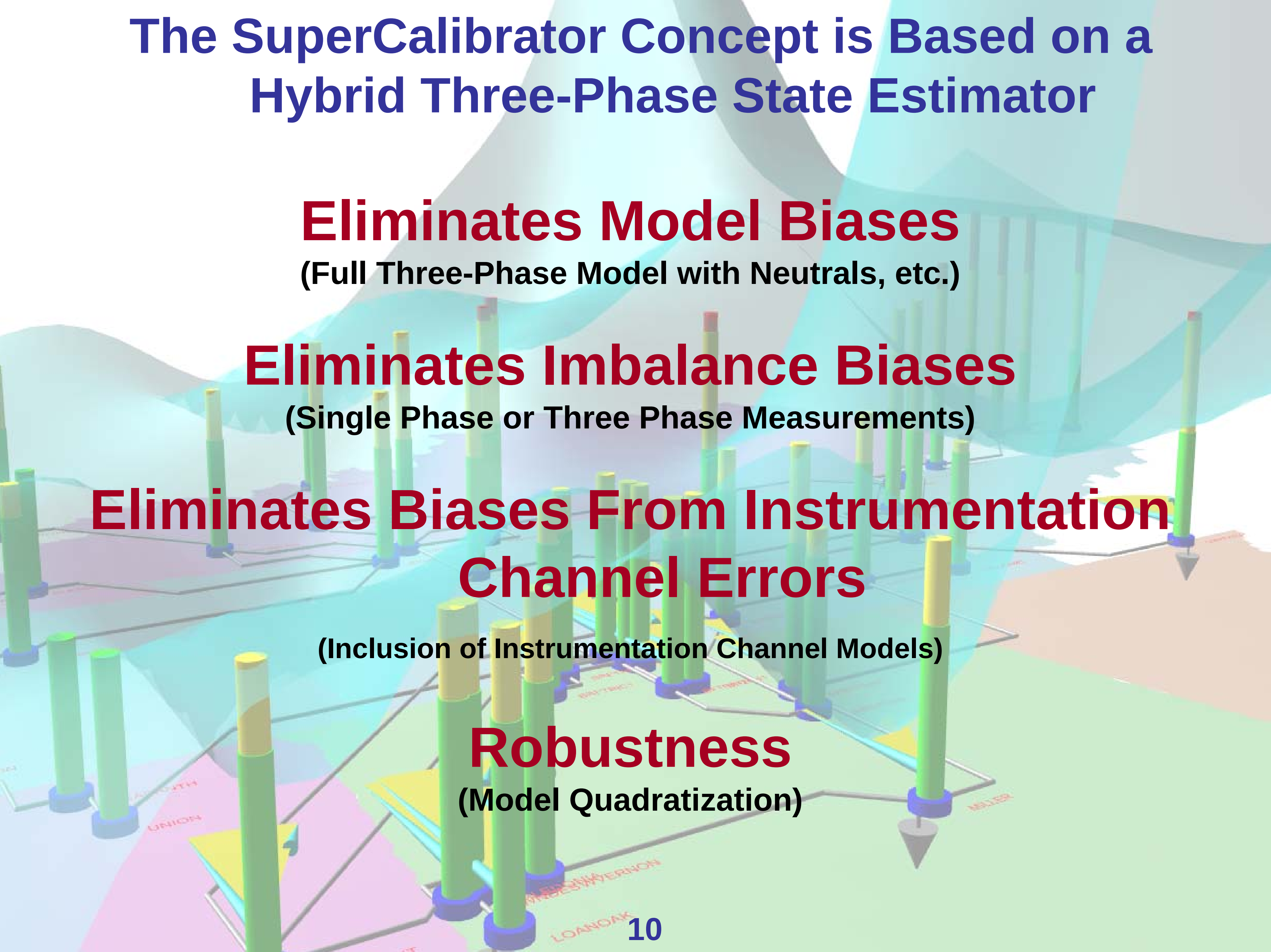
(a) GPS-Synchronized Equipment: Magnitude 0.1% to 1%, Phase: 0.01 to 0.05 Degrees at 60 Hz.
(Systematic Errors Can Be Easily Accounted for)

(b) System Asymmetries (4 to 6% differences among phases)

(c) System Imbalance (0 to 12% among phases – based on personal observations)

(d) Instrumentation Channel Errors (0.02 to 3%)

The SuperCalibrator Concept is Based on a Hybrid Three-Phase State Estimator



Eliminates Model Biases

(Full Three-Phase Model with Neutrals, etc.)

Eliminates Imbalance Biases

(Single Phase or Three Phase Measurements)

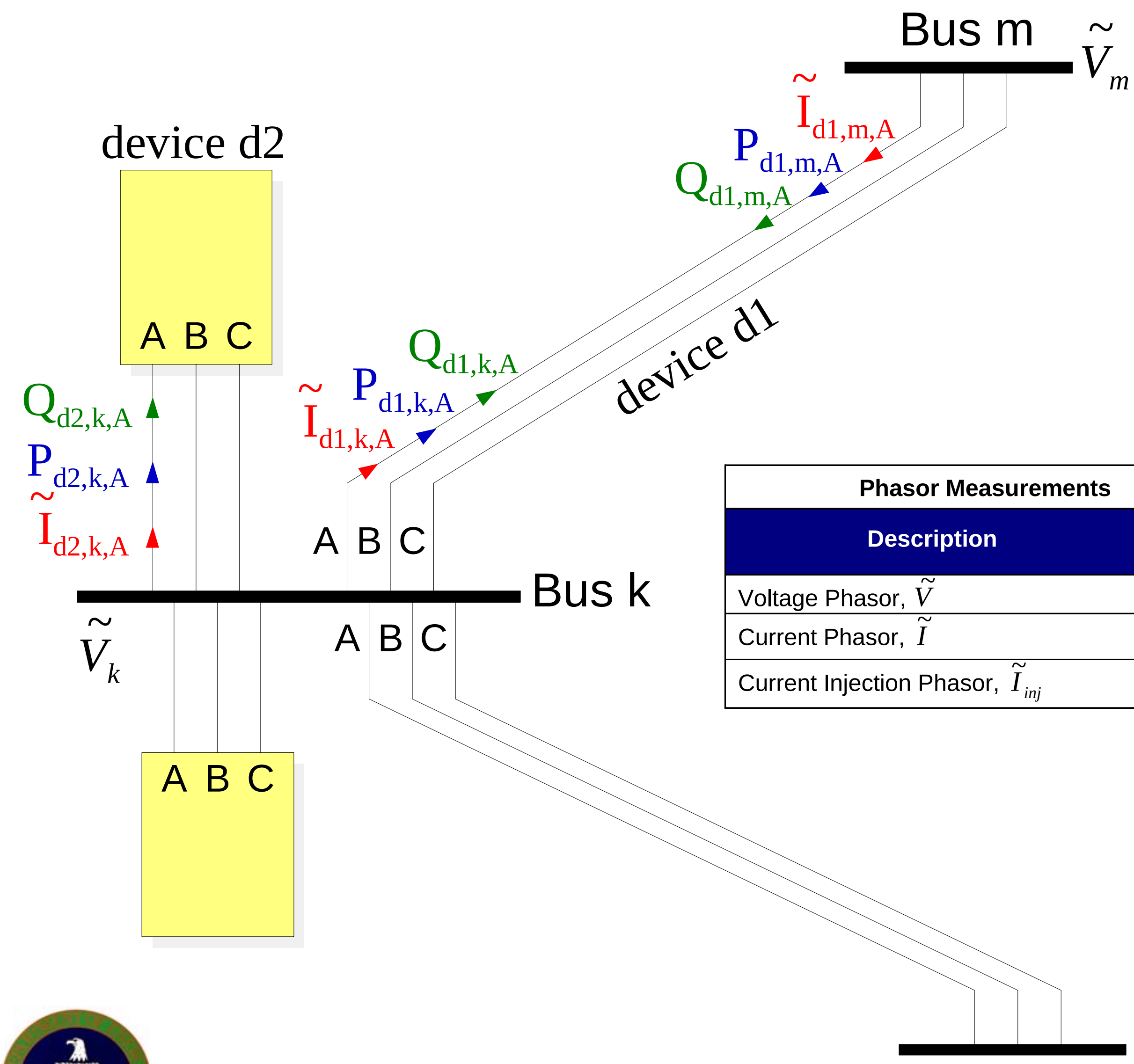
Eliminates Biases From Instrumentation Channel Errors

(Inclusion of Instrumentation Channel Models)

Robustness

(Model Quadratization)

SuperCalibrator Approach: Available Data



Phasor Measurements		Non-Synchronized Measurements	
Description	**Type Code**	**Description**	**Type Code**
Voltage Phasor, $\tilde{V}$	1	Voltage Magnitude, V	4
Current Phasor, $\tilde{I}$	2	Real Power Flow, P_f	5
Current Injection Phasor, $\tilde{I}_{inj}$	3	Reactive Power Flow, Q_f	6
		Real Power Injection, P_{inj}	7
		Reactive Power Injection, Q_{inj}	8

QPF-SE Approach: Hybrid SE Formulation

$$Min \quad J = \sum_{v\in phasor} \frac{\tilde{\eta}_v^{*}\tilde{\eta}_v}{\sigma_v^2} + \sum_{v\in non-syn} \frac{\eta_v\eta_v}{\sigma_v^2}$$

GPS-Synchronized Measurements

Voltage Phasor

$$\tilde{z}_v = \tilde{V} \quad \tilde{V}$$

Curren

$$\tilde{z}_v = \tilde{I}_{d1,k,A} + \eta_v = C_{d1,k,A}^T \begin{bmatrix} \tilde{V}_{k,C} \\ \tilde{V}_{m,A} \\ \tilde{V}_{m,B} \\ \tilde{V}_{k,C} \end{bmatrix} + \tilde{\eta}_v$$

Non-Synchronized Measurements

V

$$)^2 + 2\eta_v$$

$$z_v = P_{d1,k,A} + \eta_v = \mathrm{Re}\left\{ \tilde{V}_{k,A} \left(C_{d1,k,A}^T \begin{bmatrix} \tilde{V}_{k,A} \\ \tilde{V}_{k,B} \\ \tilde{V}_{k,C} \\ \tilde{V}_{m,A} \\ \tilde{V}_{m,B} \\ \tilde{V}_{k,C} \end{bmatrix} \right)^{*} \right\} + \eta_v$$

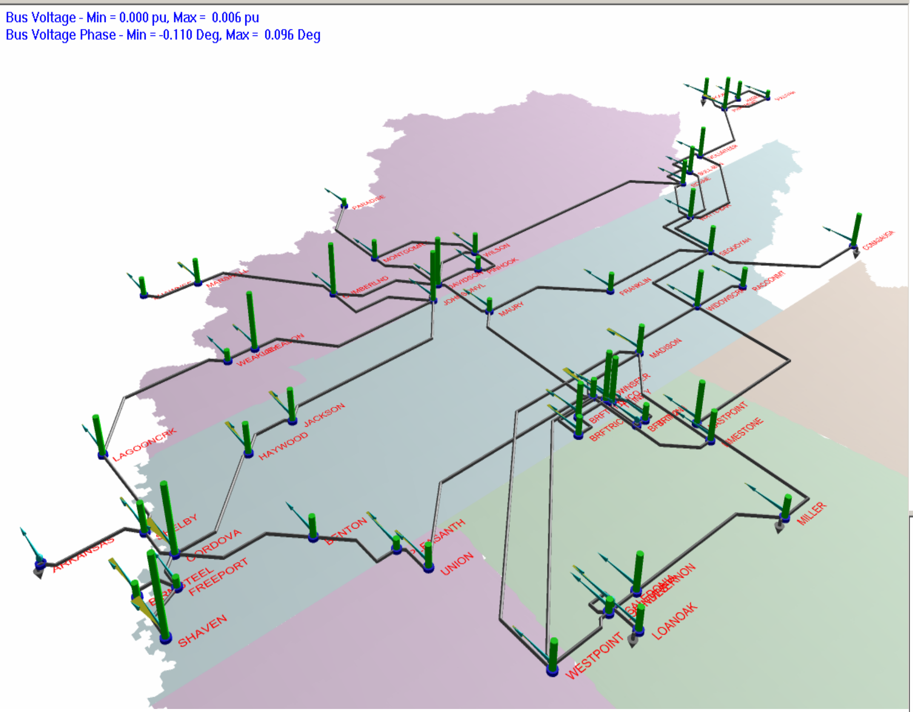
NOTE

Synchronized Measurement Model

is LINEAR

Bus Voltage Magnitude and Phase Errors – Estimated minus Measured Value

Magnitude is Normalized, Phase is Magnified 100 times



Bus Voltage - Min = 0.000 pu, Max = 0.006 pu
Bus Voltage Phase - Min = -0.110 Deg, Max = 0.096 Deg

Measurement Data: Phase A Only

Displayed Data: Phase A

Max magnitude error: 0.006 pu

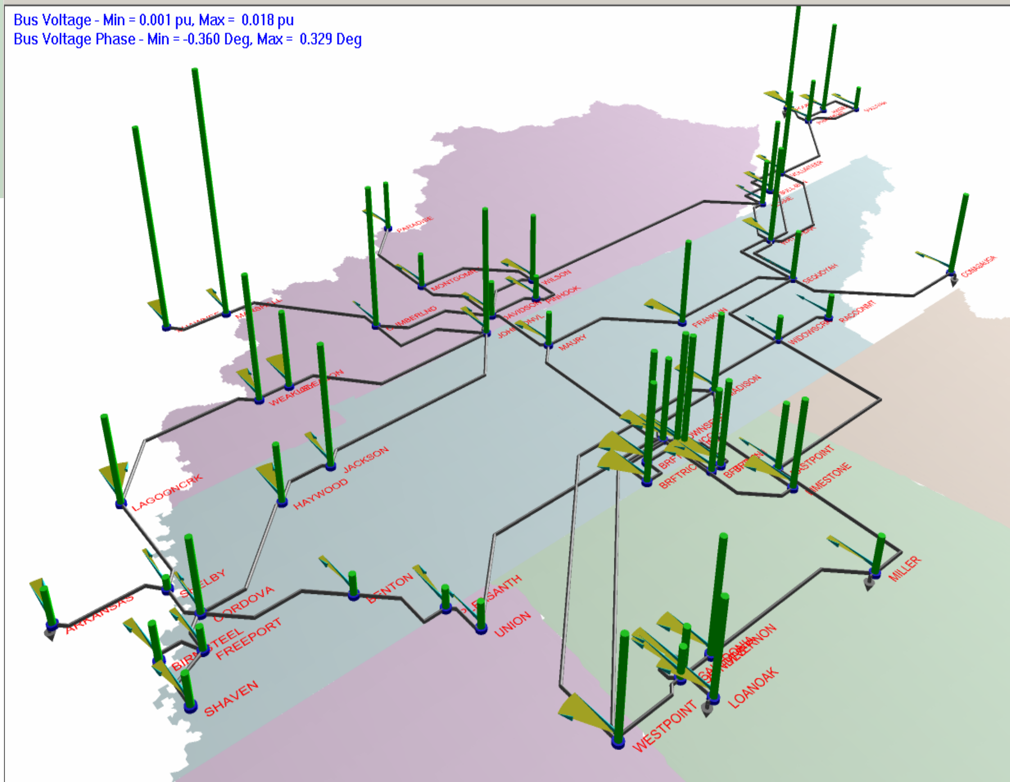
Phase error: (-0.110 to 0.096)

Measurement Data: Phase A Only

Displayed Data: Phase B

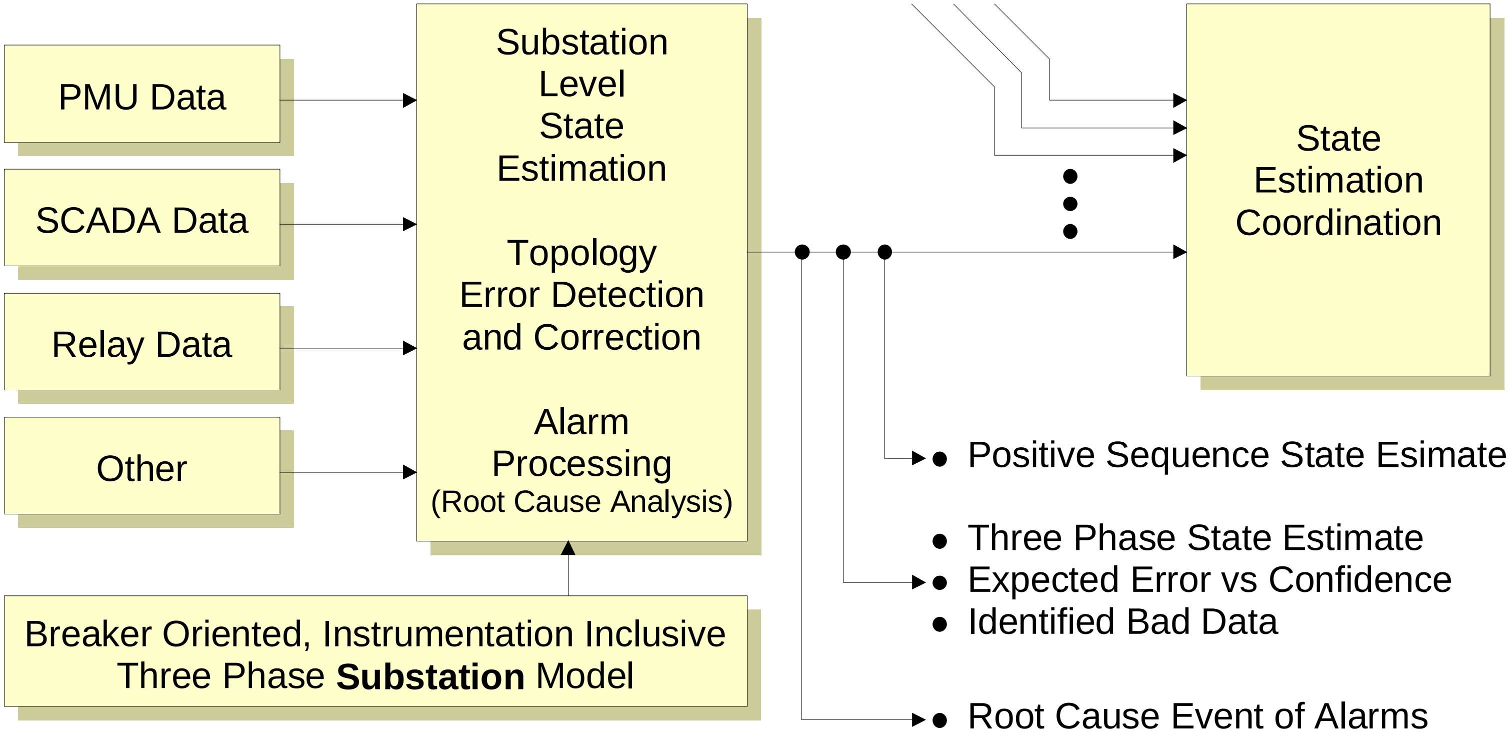
Max magnitude error: 0.018 pu

Phase error: (-0.360 to 0.329)



Bus Voltage - Min = 0.001 pu, Max = 0.018 pu
Bus Voltage Phase - Min = -0.360 Deg, Max = 0.329 Deg

The SuperCalibrator is a Suit of State Estimators (Static & Dynamic) Operating on the Three-Phase, Breaker-Oriented, Instrumentation Inclusive Model



PMU Data

SCADA Data

Relay Data

Other

Substation Level State Estimation

Topology Error Detection and Correction

Alarm Processing (Root Cause Analysis)

Breaker Oriented, Instrumentation Inclusive Three Phase **Substation** Model

State Estimation Coordination

- Positive Sequence State Esimate

- Three Phase State Estimate
- Expected Error vs Confidence
- Identified Bad Data

- Root Cause Event of Alarms

Real time validation of relay data, CTs, and PTs

Important Side Benefit: Use real time model for

Verification of relay settings

Assess Protection Reliability

Advantages of Super-Calibrator

- Utilization of All Data – Relay, SCADA, PMU
- Operates on Streaming Data at the Substation Level – Distributed SE
- Quantifies Data Accuracy – Remote Calibration
- Minimizes Data to be Transferred (very important)
  - - Communication of Information not Raw Data
  - - Improve Latencies

State Estimator → “State Measurer”

The SuperCalibrator is the “State Measurer”

Quantification of SuperCalibrator Output Accuracy

- Chi-Square Test provides a measure of how well the measurements “fit” the model on a probabilistic basis. Equations omitted

- The SuperCalibrator provides a measure of the uncertainty of the estimated states. Equations omitted.

- The SuperCalibrator provides a measure of Measurement error – to be used for remote calibration. Equations omitted.

SuperCalibrator

Implementation
&
Demonstration

High Fidelity Power System Model

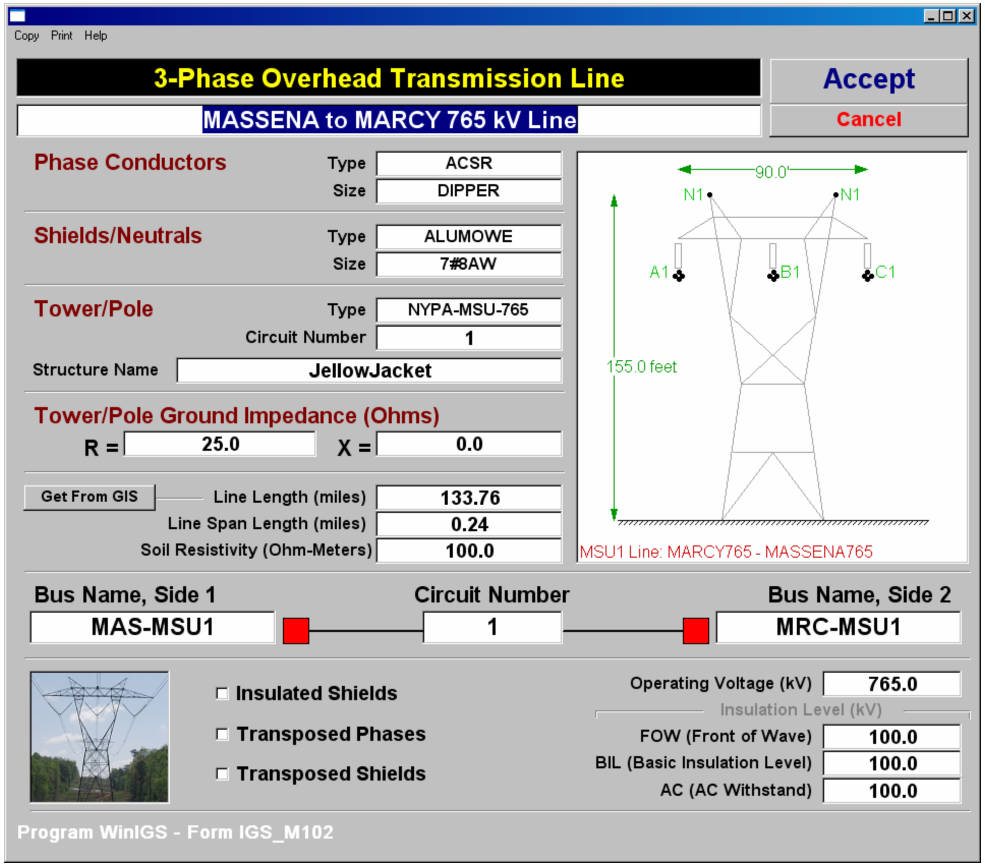
- Physically Based Power System Modeling
- Explicit Representation of Phase Conductors, Neutrals, Ground Conductors and Grounding – accounts for ground potential rise
- Explicit Representation of Breakers, Switches
- Explicit Representation of Instrumentation and Relay/PMU/DFR/RTU Inputs Integrated with the Power System
- All Models are Linear or Quadratic
- Solvers Are Based on Quadratic Models (robust), capability to model abnormal conditions such as “stuck pole”.
- Visualization and Animation

High Fidelity Power System Simulator

Physically Based Models

Example: Three Phase Power Line – MSU1

Physically Based Model



3-Phase Overhead Transmission Line

MASSENA to MARCY 765 kV Line

Phase Conductors
Type: ACSR
Size: DIPPER

Shields/Neutrals
Type: ALUMOWE
Size: 7#8AW

Tower/Pole
Type: NYPA-MSU-765
Circuit Number: 1

Structure Name: JellowJacket

Tower/Pole Ground Impedance (Ohms)
R = 25.0 X = 0.0

Line Length (miles): 133.76
Line Span Length (miles): 0.24
Soil Resistivity (Ohm-Meters): 100.0

MSU1 Line: MARCY765 - MASSENA765

Bus Name, Side 1	Circuit Number	Bus Name, Side 2
MAS-MSU1	1	MRC-MSU1

☐ Insulated Shields
☐ Transposed Phases
☐ Transposed Shields

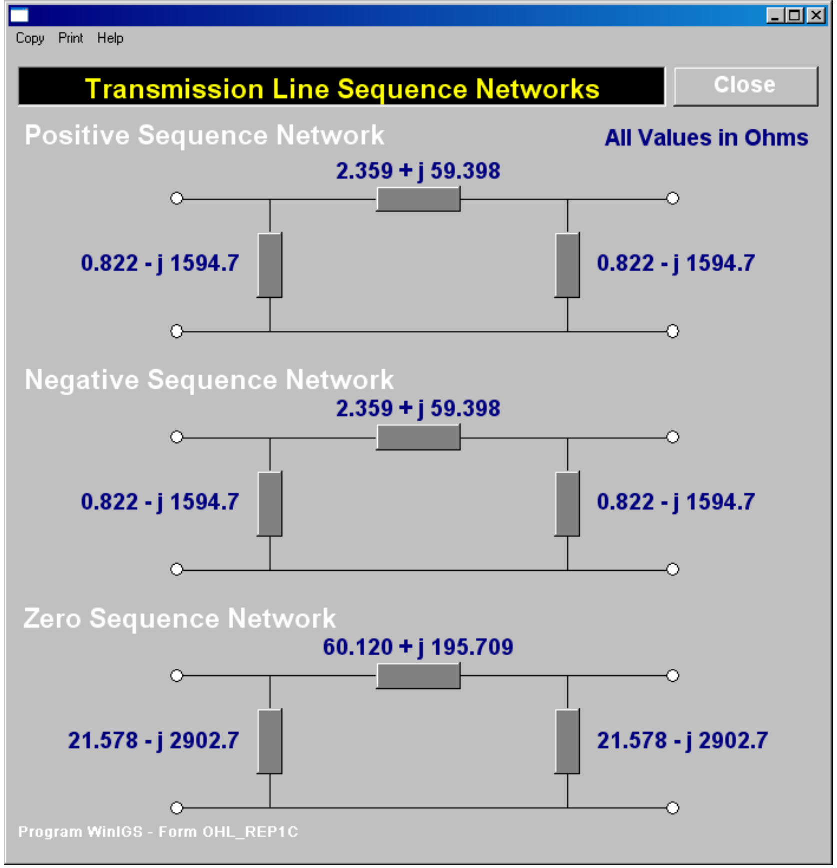
Operating Voltage (kV): 765.0

Insulation Level (kV)
FOW (Front of Wave): 100.0
BIL (Basic Insulation Level): 100.0
AC (AC Withstand): 100.0

Program WinIGS - Form IGS_M102

Sequence Parameter Model

Not Used – for Info Only



Transmission Line Sequence Networks

All Values in Ohms

Positive Sequence Network
Series: 2.359 + j 59.398
Shunt: 0.822 - j 1594.7 | 0.822 - j 1594.7

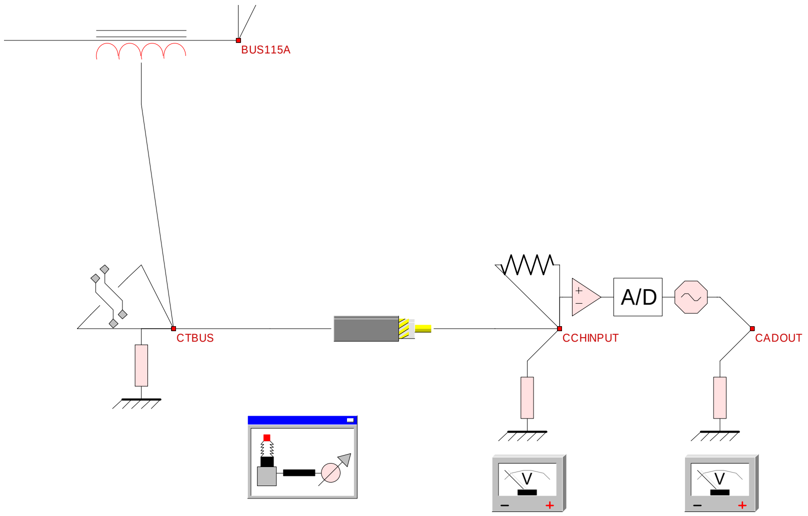
Negative Sequence Network
Series: 2.359 + j 59.398
Shunt: 0.822 - j 1594.7 | 0.822 - j 1594.7

Zero Sequence Network
Series: 60.120 + j 195.709
Shunt: 21.578 - j 2902.7 | 21.578 - j 2902.7

Program WinIGS - Form OHL_REP1C

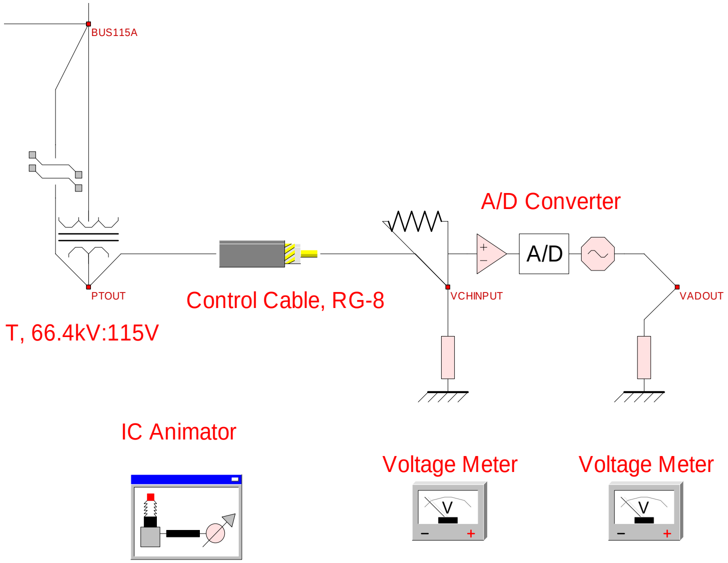
High Fidelity Power System Simulator

Instrumentation Channel Model



Current

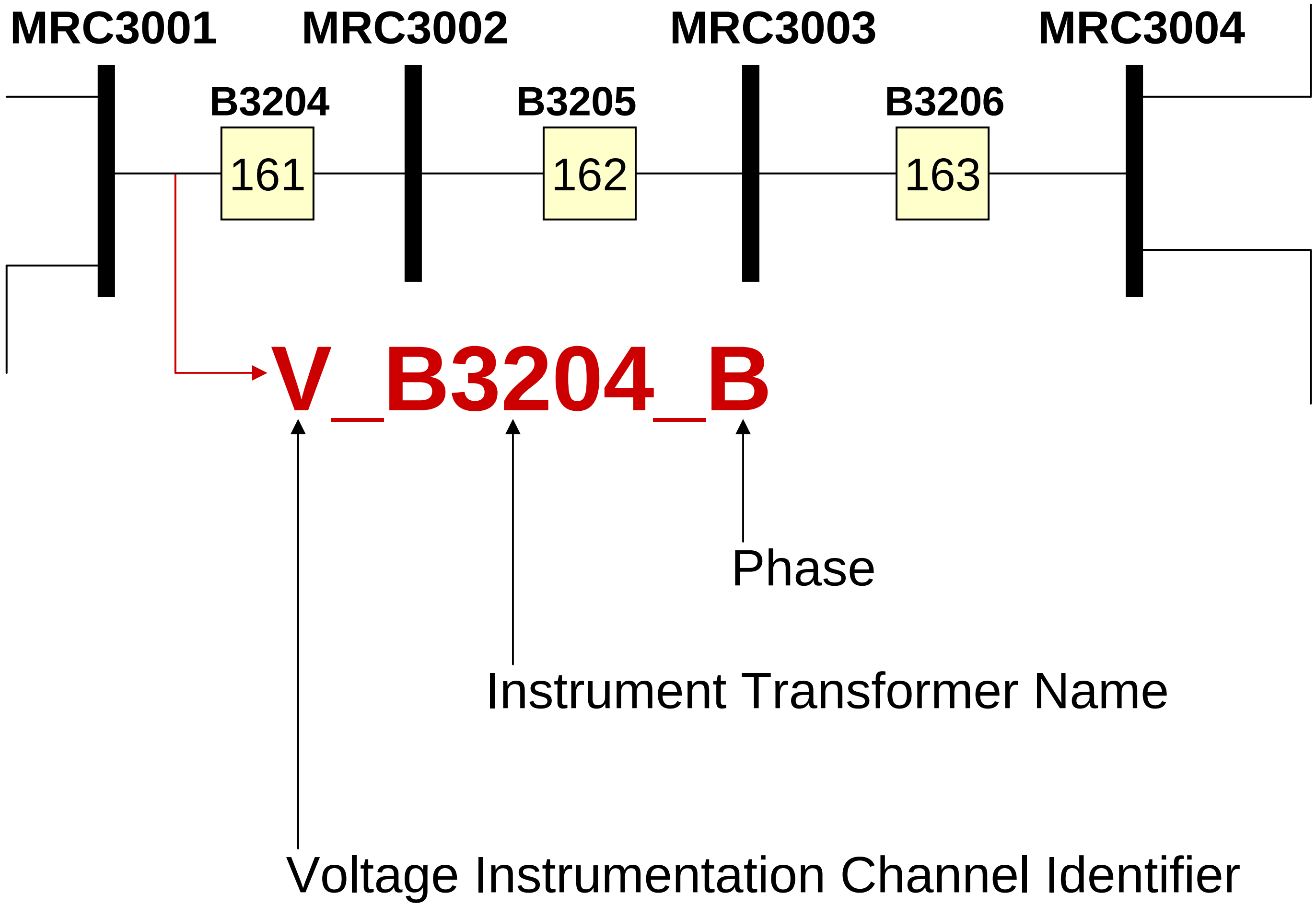
$$g_{j,i}\left(f\right)=\frac{\tilde{I}_{out}\left(f\right)}{\tilde{I}_{in}\left(f\right)}$$



Voltage

$$g_{j,v}\left(f\right)=\frac{\tilde{V}_{out}\left(f\right)}{\tilde{V}_{in}\left(f\right)}$$

Naming Example: Voltage Instrumentation Channel



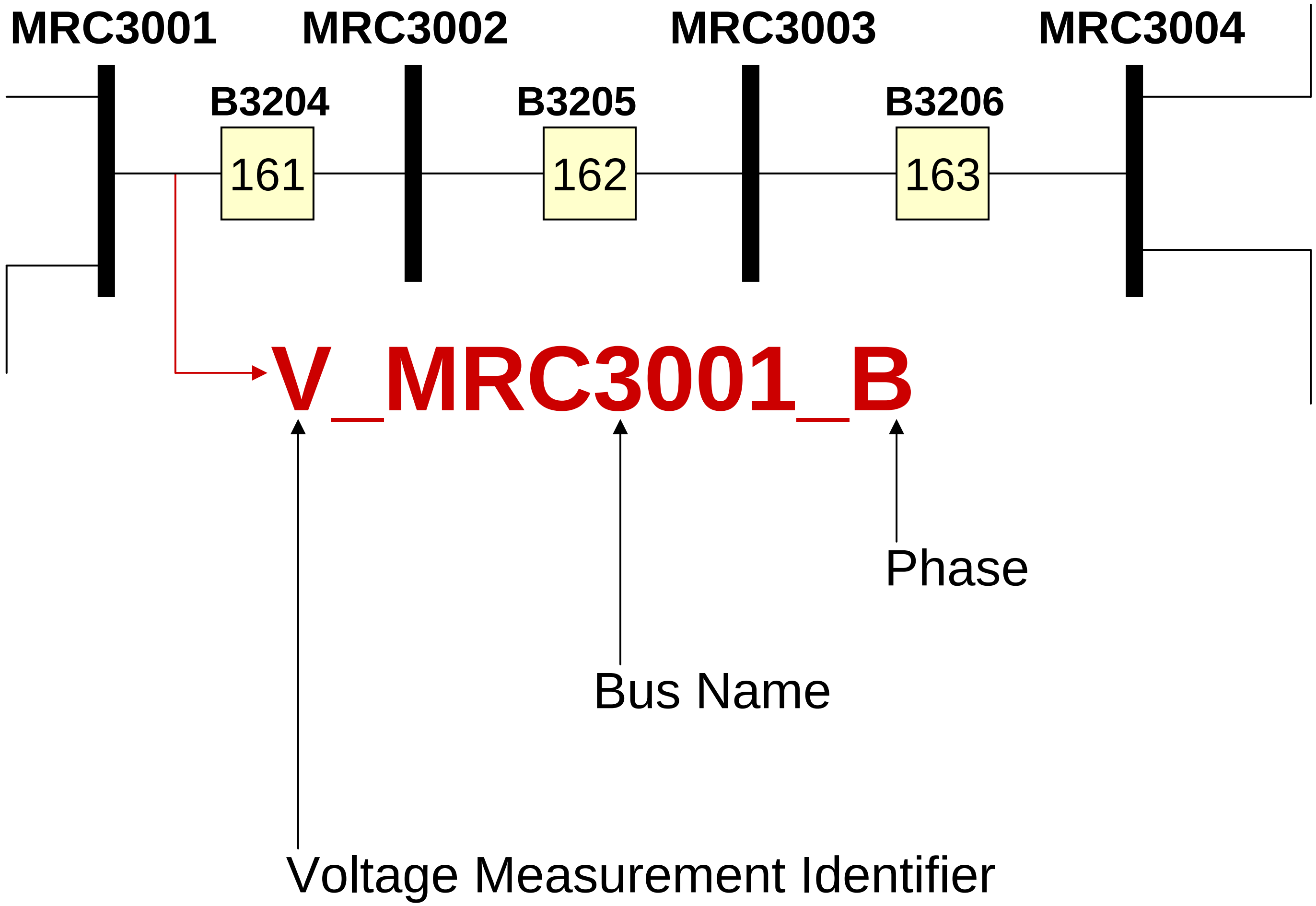
V_B3204_B

Phase

Instrument Transformer Name

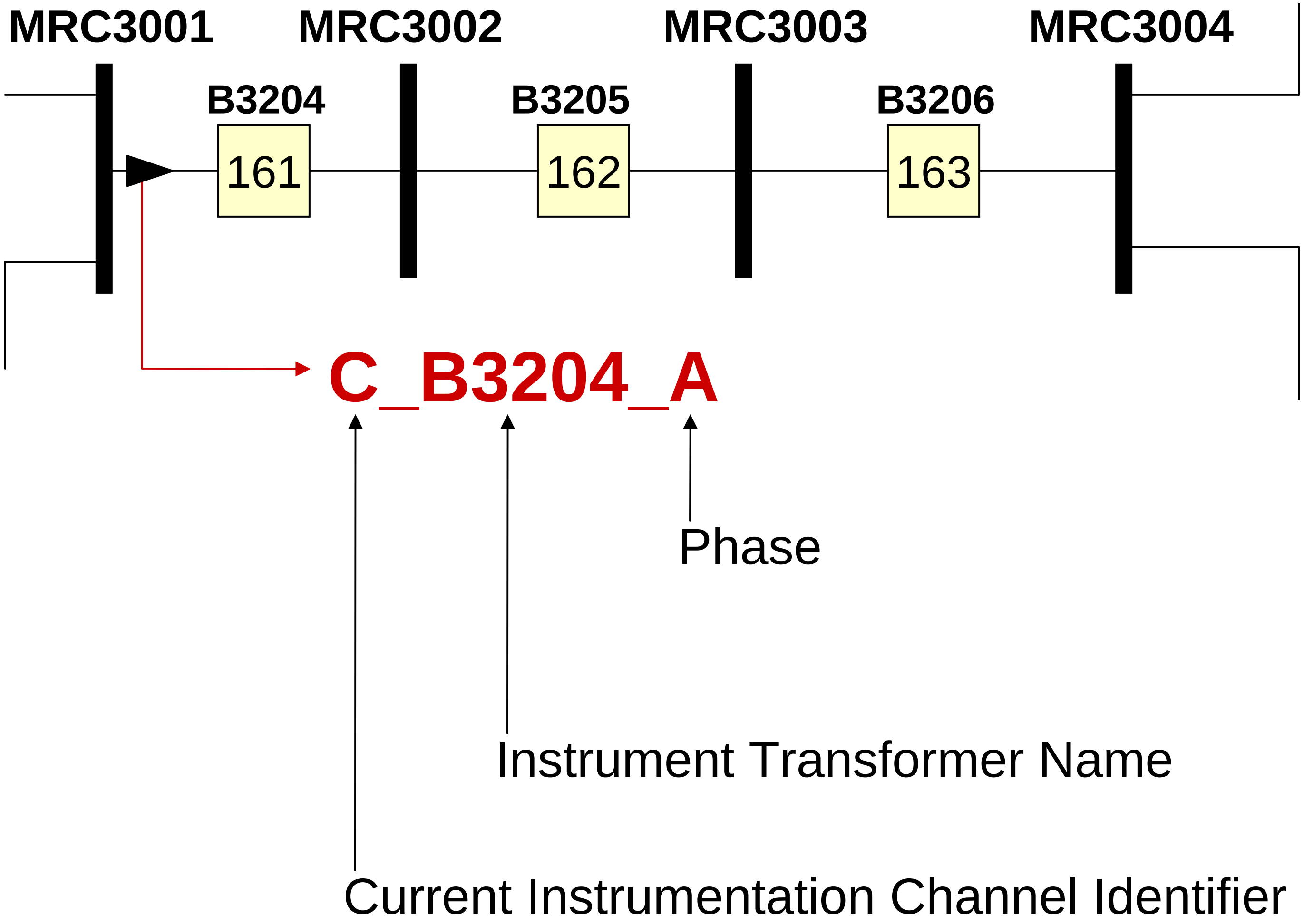
Voltage Instrumentation Channel Identifier

Naming Example: Voltage Measurement



V_MRC3001_B

Naming Example: Current Instrumentation Channel



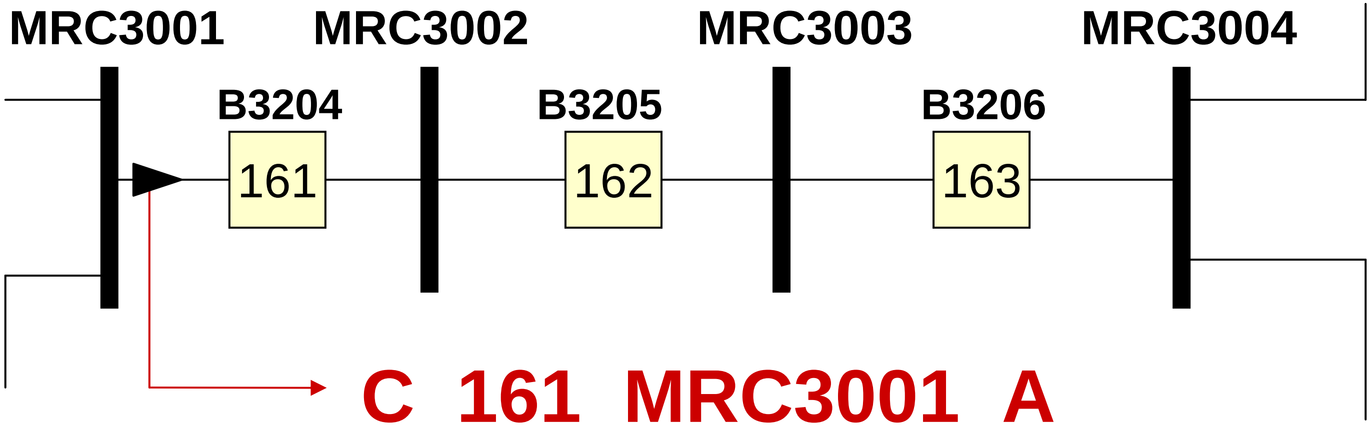
C_B3204_A

Phase

Instrument Transformer Name

Current Instrumentation Channel Identifier

Naming Example: Current Measurement



C_161_MRC3001_A

Phase

Bus Name

Power Device ID

Current Measurement Identifier

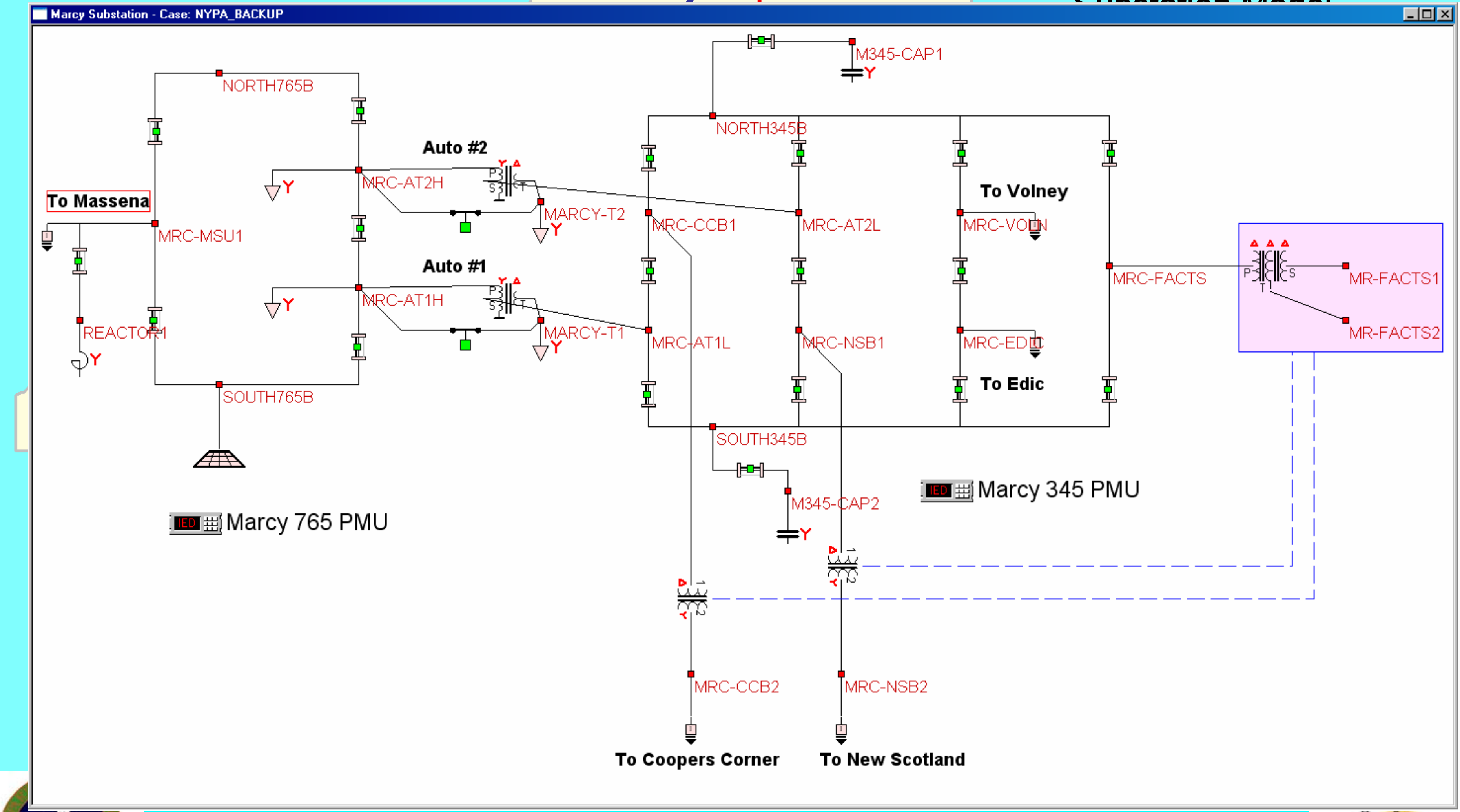
SuperCalibrator Demonstration

Test Systems

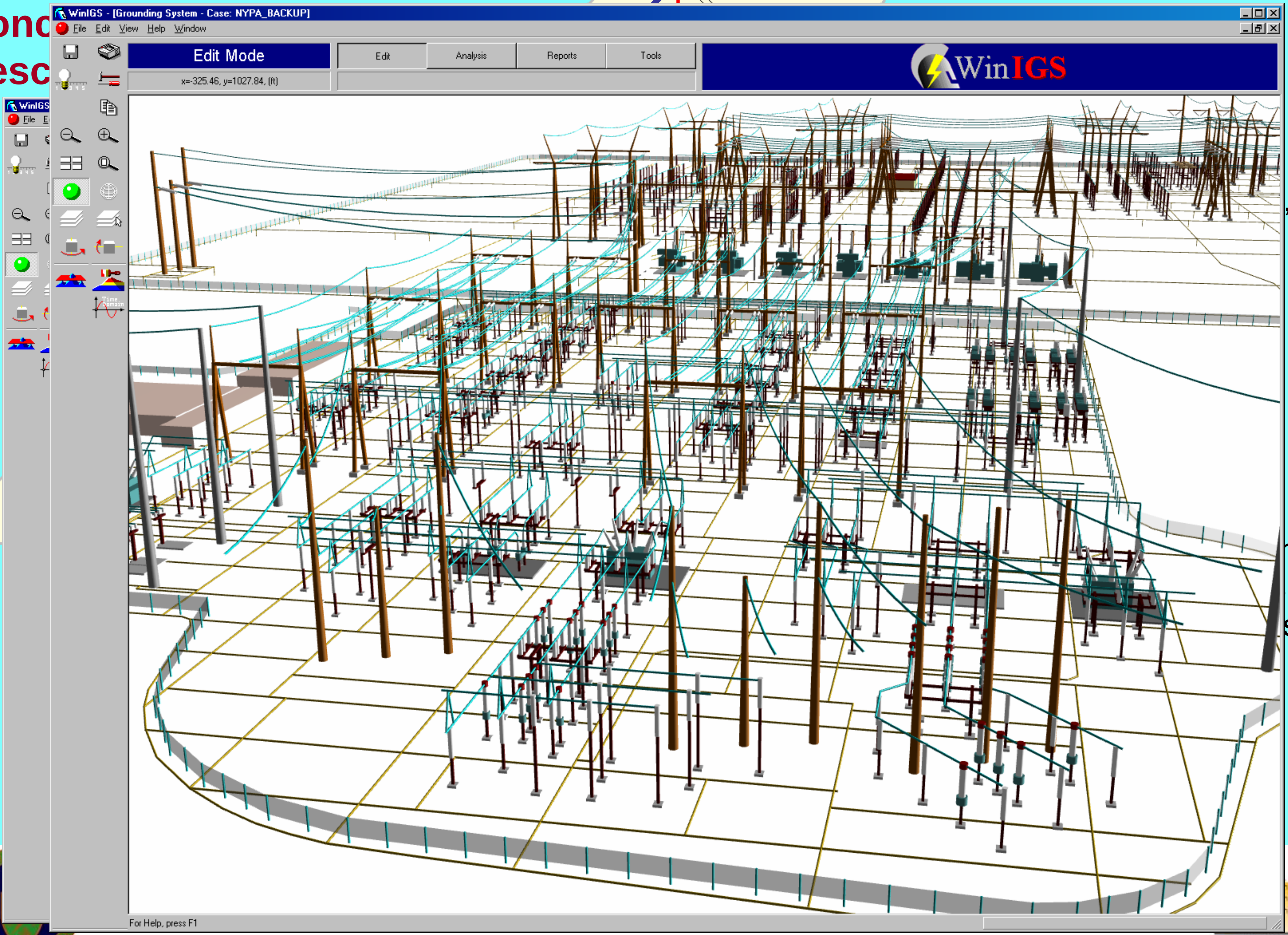
- NYPA (Two Interconnected Subs)
- ENTERGY
- METC

The SuperCalibrator Concept Description

Substation Model



The SuperCalibrator
Conc
Desc

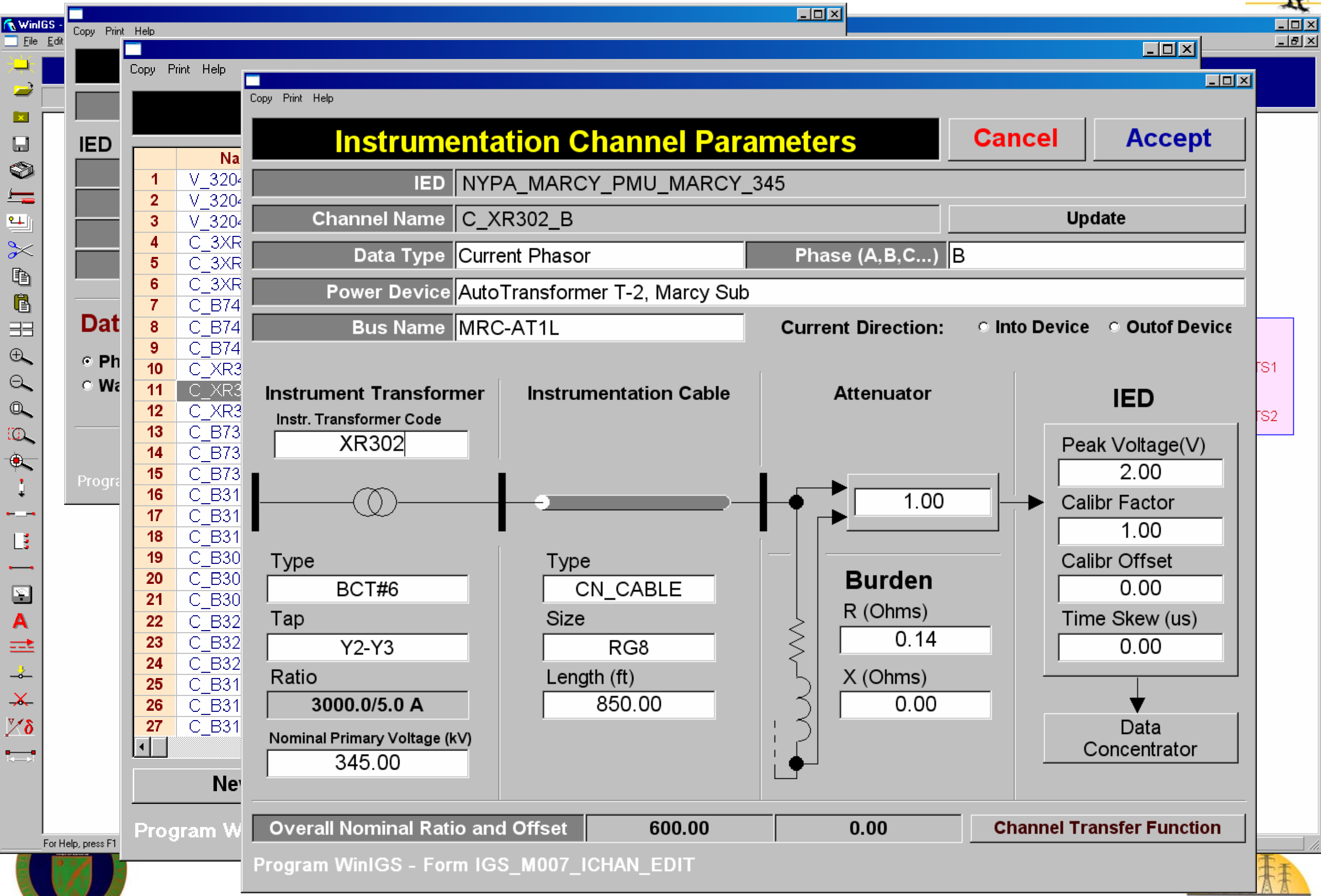


WinIGS - [Grounding System - Case: NYPA_BACKUP]

x=-325.46, y=1027.84, (ft)

For Help, press F1

Integrated Power System and Instrumentation Model



Instrumentation Channel Parameters

IED: NYPA_MARCY_PMU_MARCY_345

Channel Name: C_XR302_B

Data Type: Current Phasor

Phase (A,B,C...): B

Power Device: AutoTransformer T-2, Marcy Sub

Bus Name: MRC-AT1L

Current Direction: ○ Into Device ○ Outof Device

Instrument Transformer

Instr. Transformer Code: XR302

Type: BCT#6

Tap: Y2-Y3

Ratio: 3000.0/5.0 A

Nominal Primary Voltage (kV): 345.00

Instrumentation Cable

Type: CN_CABLE

Size: RG8

Length (ft): 850.00

Attenuator

1.00

Burden

R (Ohms): 0.14

X (Ohms): 0.00

IED

Peak Voltage(V): 2.00

Calibr Factor: 1.00

Calibr Offset: 0.00

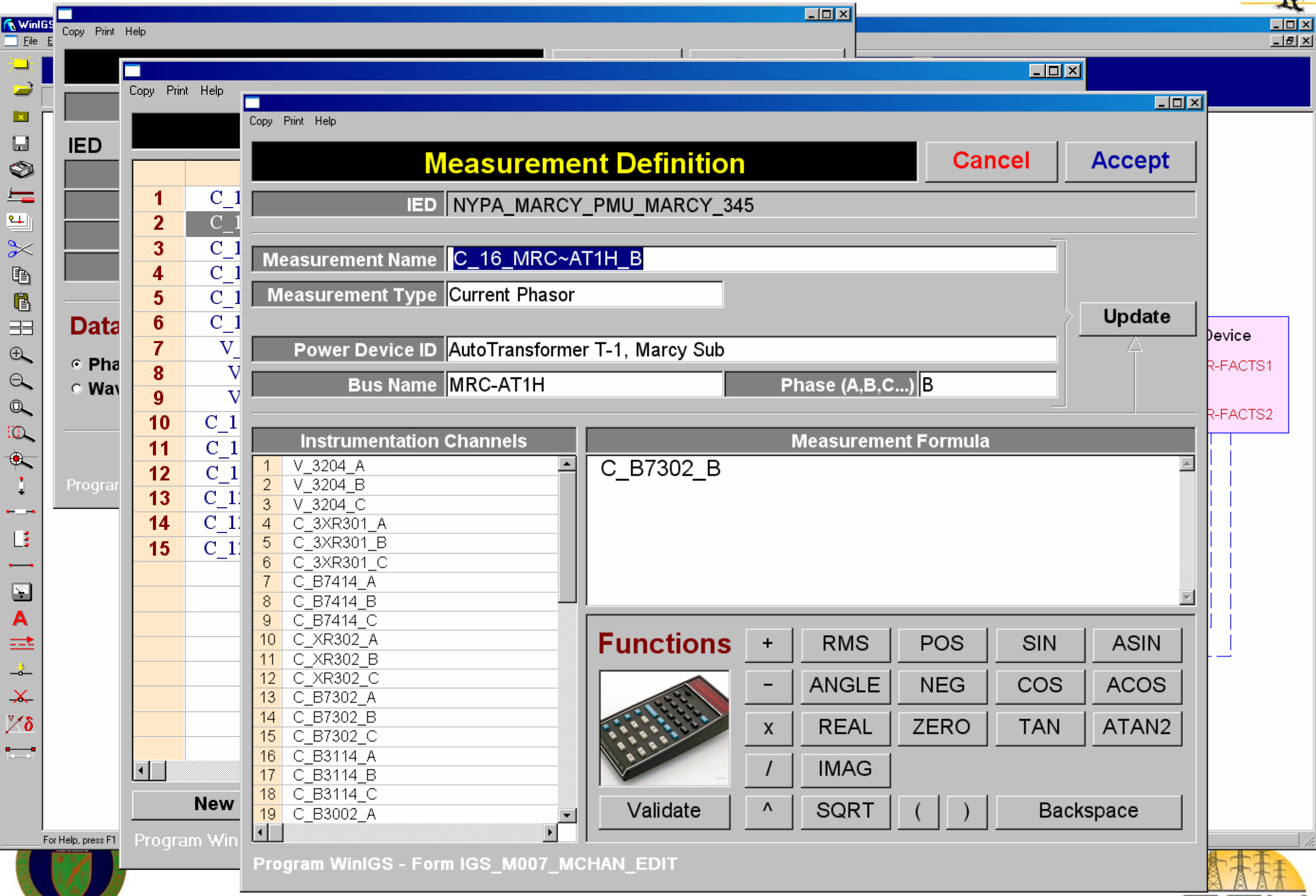
Time Skew (us): 0.00

Data Concentrator

Overall Nominal Ratio and Offset: 600.00 | 0.00

Program WinIGS - Form IGS_M007_ICHAN_EDIT

Integrated Power System and Instrumentation Model



Measurement Definition

IED	NYPA_MARCY_PMU_MARCY_345
Measurement Name	C_16_MRC~AT1H_B
Measurement Type	Current Phasor
Power Device ID	AutoTransformer T-1, Marcy Sub
Bus Name	MRC-AT1H
Phase (A,B,C...)	B

Instrumentation Channels

1	V_3204_A
2	V_3204_B
3	V_3204_C
4	C_3XR301_A
5	C_3XR301_B
6	C_3XR301_C
7	C_B7414_A
8	C_B7414_B
9	C_B7414_C
10	C_XR302_A
11	C_XR302_B
12	C_XR302_C
13	C_B7302_A
14	C_B7302_B
15	C_B7302_C
16	C_B3114_A
17	C_B3114_B
18	C_B3114_C
19	C_B3002_A

Measurement Formula

C_B7302_B

Program WinIGS - Form IGS_M007_MCHAN_EDIT

Demonstration: March 2007 on Location

NYPA Substation
(North of Utica, NY)

Demonstration will consist of Processing Collected Data:

(A)Via the SuperCalibrator for Two Subs Separately
(B) State Estimation on Combined Two Sub System
(C)Compare Results

Future Plans

Implement the SuperClalibrator
on a 61850 Environment

Implementation on a Multi-Substation System

Extension to Monitoring and
Evaluation of Relays
((a) Settings Validation and (b) Hidden Failures Identification)

Applications Are Only Limited by Our Imagination