

Distributed Dynamic State Estimator: Extension to Distribution Feeders

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IEEE-PES General Meeting
Vancouver, BC, Canada
July 21-25, 2013



Outline

DS-SE Challenges

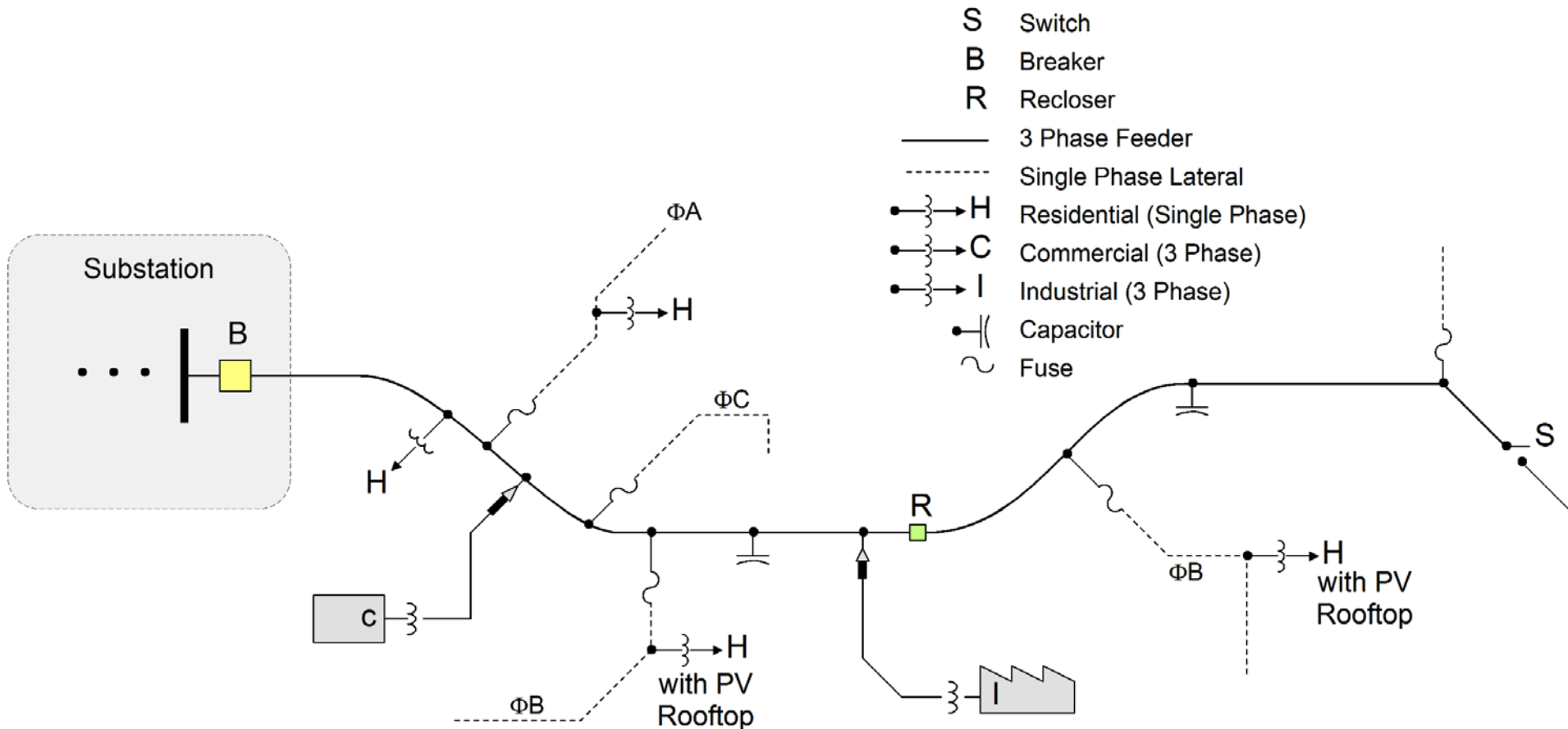
Basic Background Technology: Distributed State Estimation

Distribution System State Estimation Implementation

State Estimation of generation resources along distribution circuits

Conclusions

DS-SE Challenges



Special Issues and Challenges

Available Measurements in Distribution Feeders

Substation Data

Recloser Data

Capacitor Control Data

Smart Meter data (secondary)

Customer Owned Distributed Resources with Metering

State Estimation is Extended to Customer Systems

Other

Typically not Enough for Full Observability

Feeder Sections May Be not Observable

Implementation Approaches Become Important

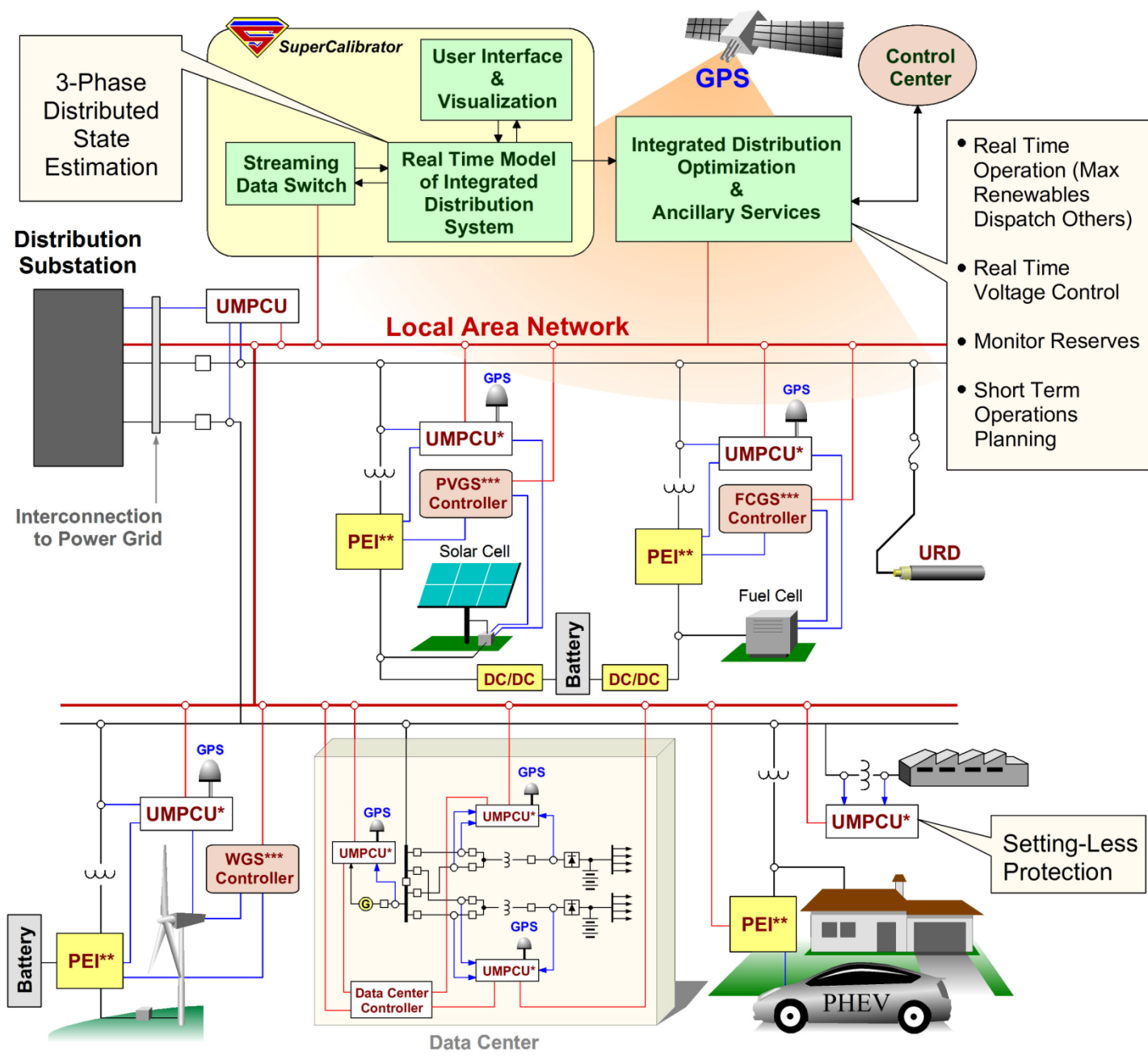
Multiphase Modeling is a Necessity

Many More Power Devices than Transmission Systems

DMS

Design For Autonomy

Plug and Play...



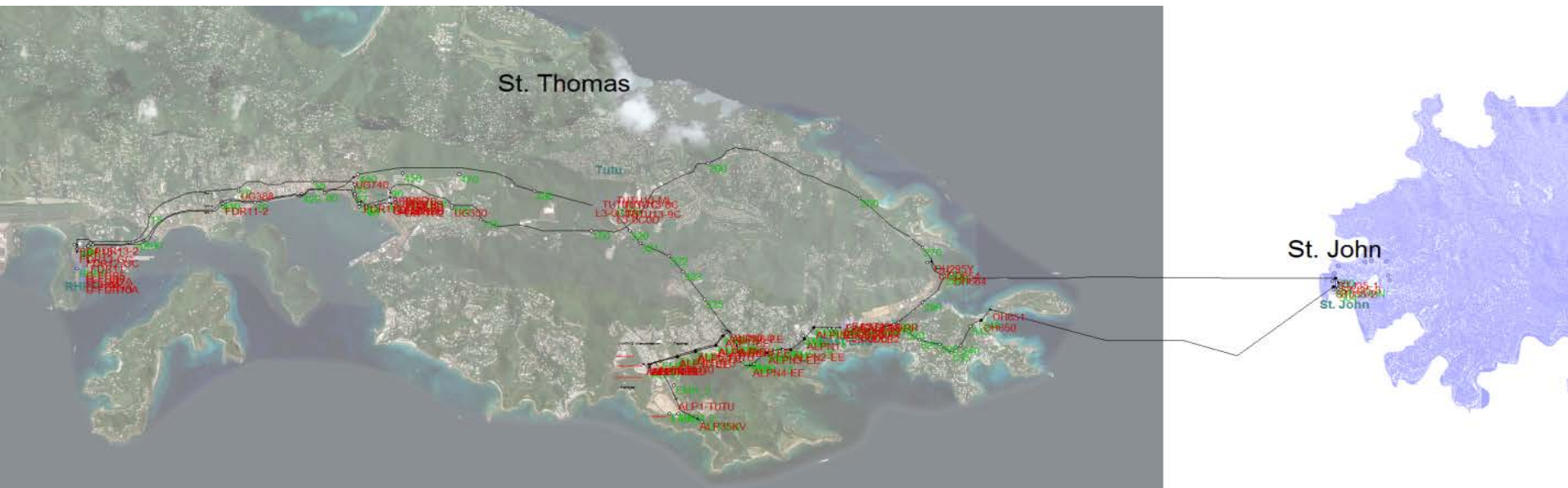
Background: USVI-WAPA

Installation of the Distributed Dynamic State Estimator on the USVI WAPA system.

Demonstration and Field Experience with the operation of the Distributed State Estimator on the USVI-WAPA

Demonstration: August 1-2, 2012

Extension to Distribution System – Compelling Reasons



Distributed Dynamic State Estimation

State of Technology: provides a high fidelity real time model of the system at speeds of 60 times per second.

Demonstration projects at several utilities have been implemented for field evaluation

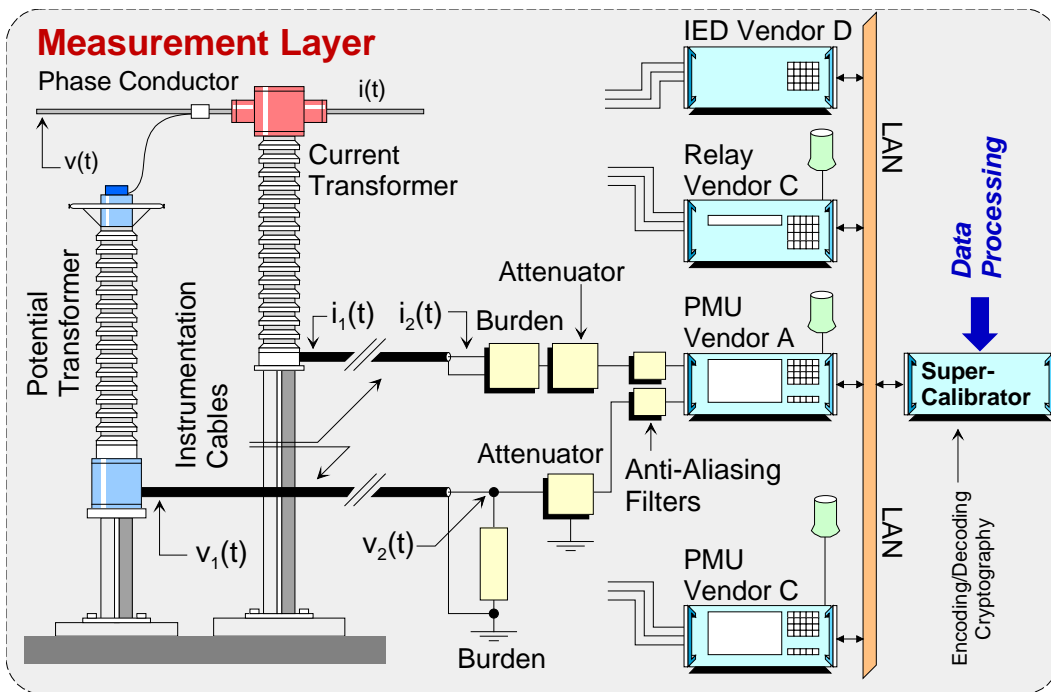
How: distributed dynamic state estimation using (a) synchrophasor technology, (b) numerical relays, and (c) physically based models

The SuperC Concept (Distributed SE)

The SuperC is conceptually very simple:

- Utilize all available data (Relays, DFRs, PMUs, Meters, etc.)
- Utilize a detailed substation model (three-phase, breaker-oriented model, instrumentation channel inclusive and data acquisition model inclusive).
- Use “Derived” and “Virtual” Measurements by Application of Physical Laws
- At least one GPS synchronized device (PMU, Relay with PMU, etc.) → Results on UTC time enabling a truly decentralized State Estimator

Distributed Dynamic State Estimation Implementation



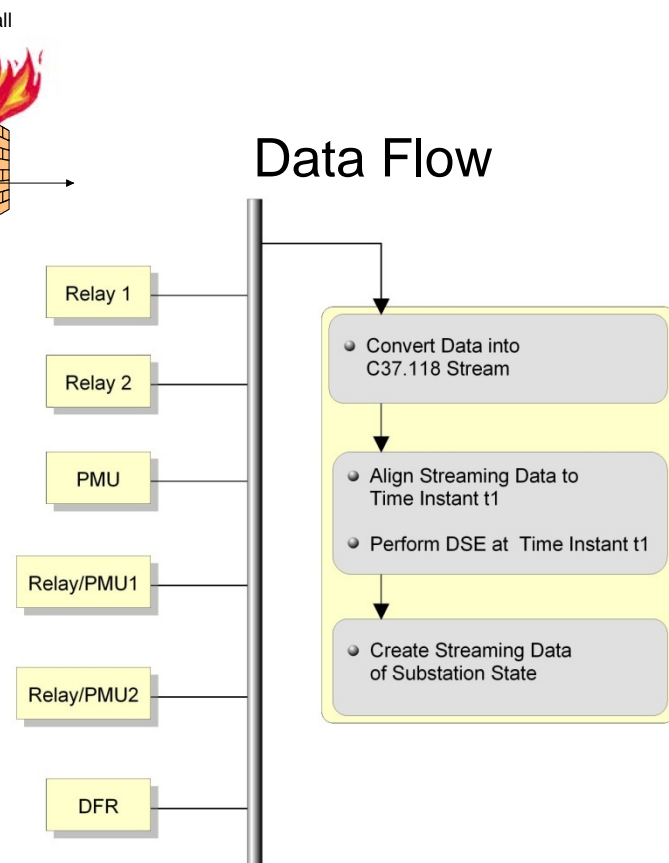
Physical Arrangement

Data Flow

Data/Measurements from all PMUs, Relays, IEDs, Meters, FDRs, etc are collected via a Local Area Network in a data concentrator.

The data is used in a dynamic state estimator which provides the validated and high fidelity dynamic model of the system.

Bad data detection and rejection is achieved because of high level of redundant measurements at this level.



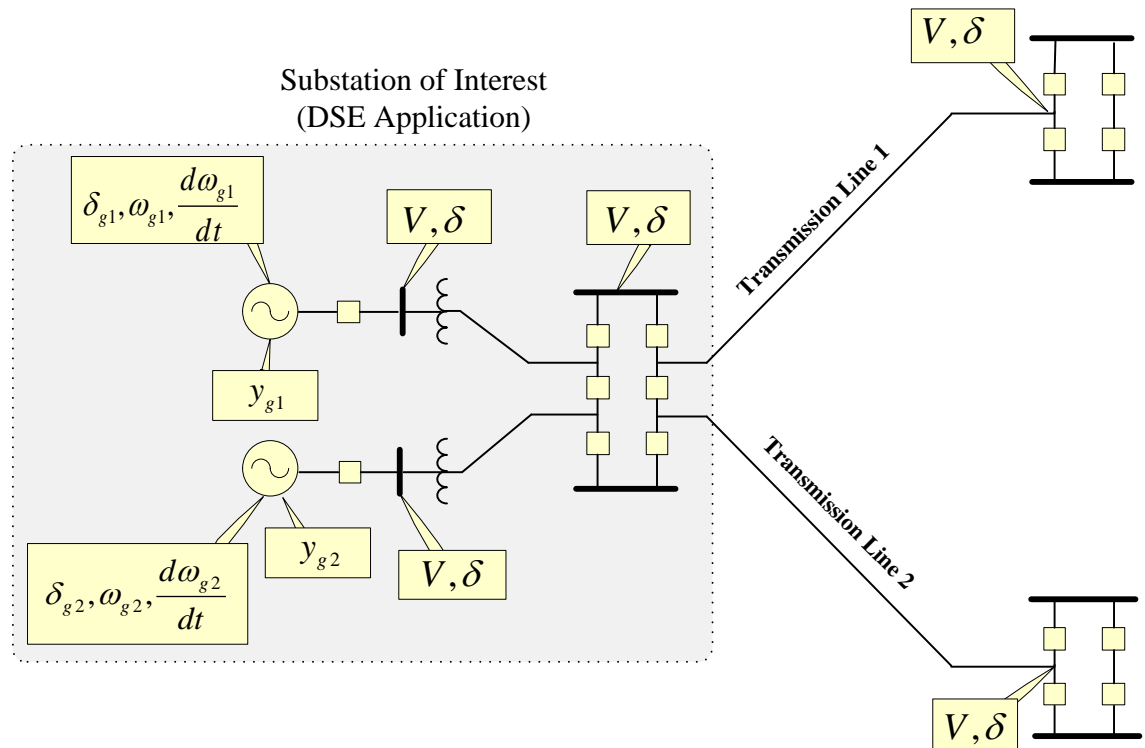
Distributed Dynamic State Estimation Implementation

The Estimator is Defined in Terms of:

- Model
- State
- Measurement Set
- Estimation Method

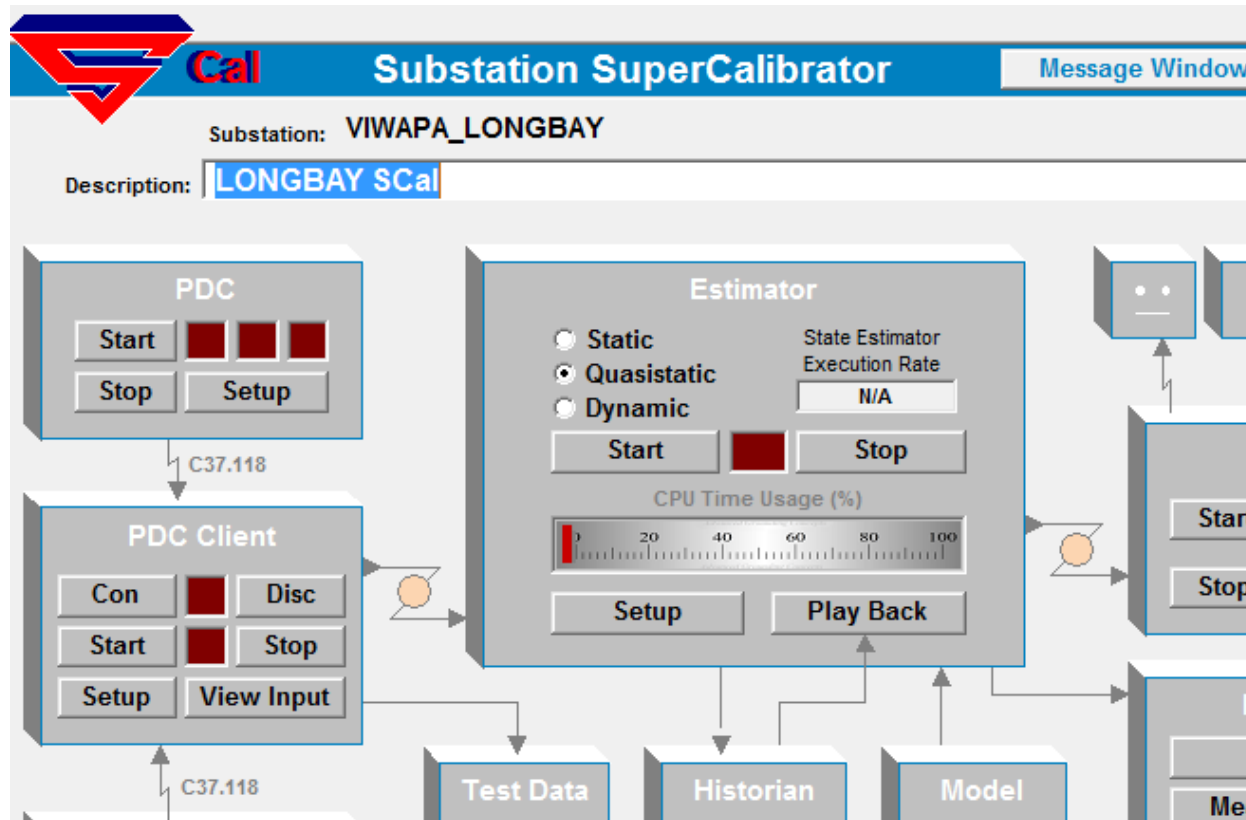
Observability

Redundancy



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

Performance Evolution: Distributed State Estimation Execution Time Monitor

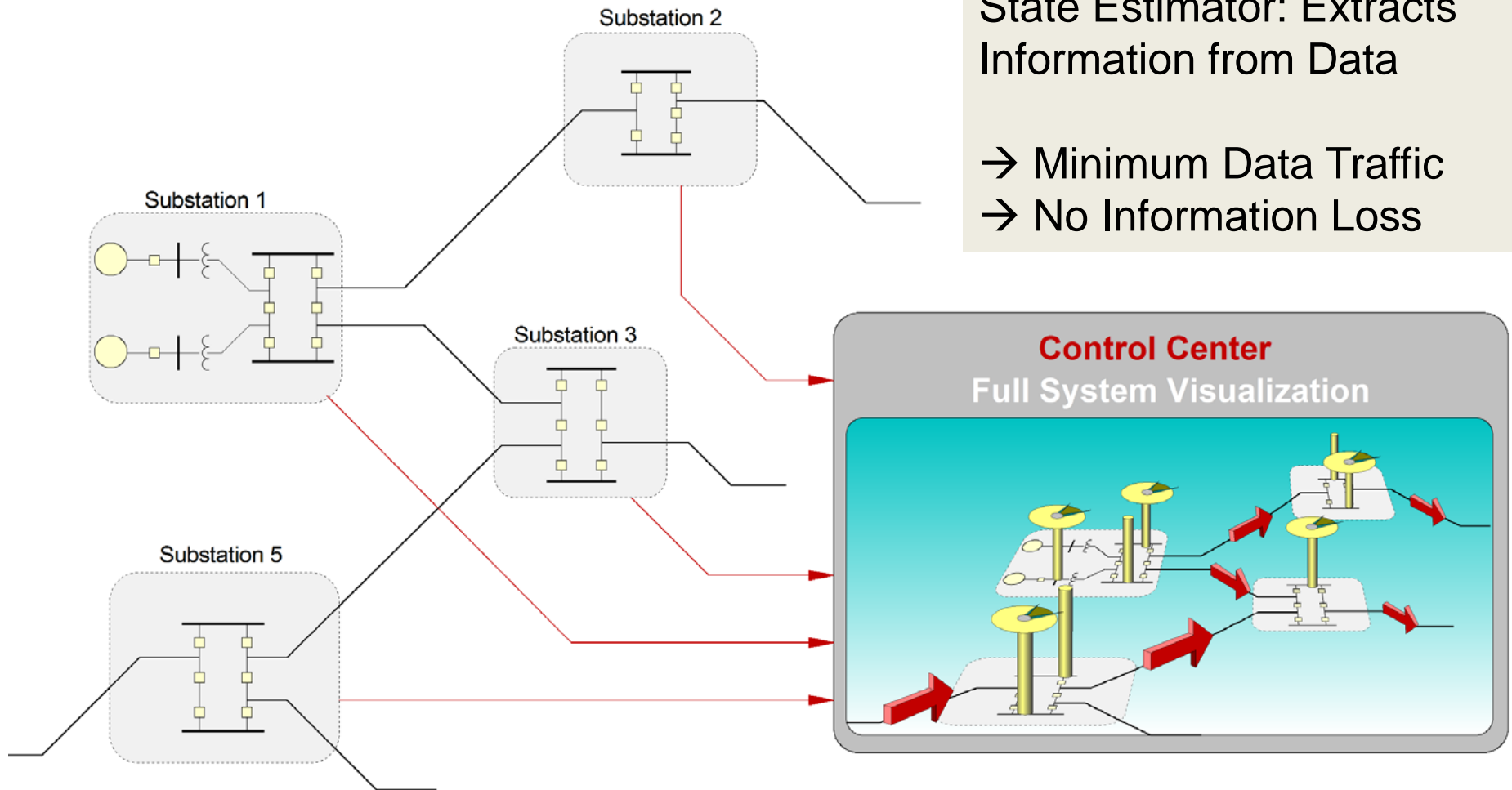


CPU Time Usage Indicates in Real Time the Portion of the Time Used by the SE Calculations.

100%=Time Between Two Successive SE Computations.
example: if SE is set to execute 60 times per second, then
100%=16.6 ms

Distributed State Estimation

Synthesis of System Wide State at the Control Center



Summary

- Distributed State Estimation Enables State Estimation at Each Cycle (Sixty Times per Second).
- The Approach Requires a Detailed Three Phase Substation Model and **at Least One PMU Device**.
- Four Demonstration Projects Have Provided and Will Provide Tremendous Experience.
- The Approach Has Enabled a New Disturbance Play Back Which Has Proven to be Very Useful.

Object Oriented DS-SE Formulation

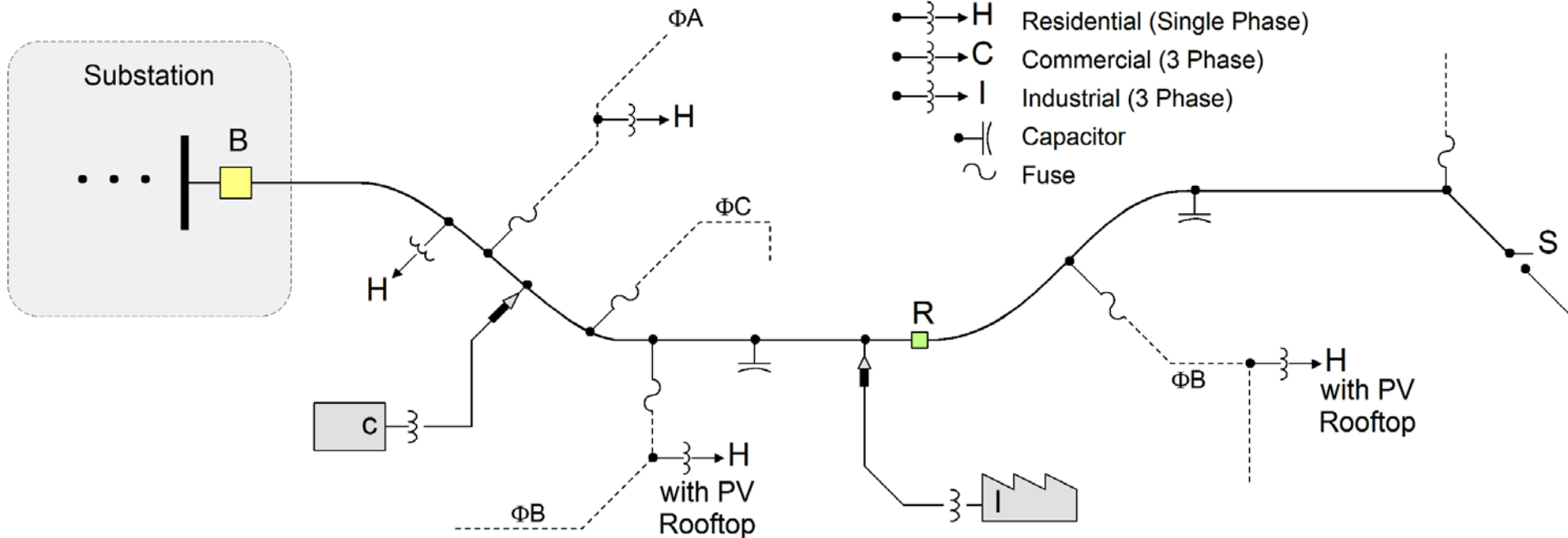
Use Existing Measurements
Supplement with

Virtual
Derived
Pseudo-measurements

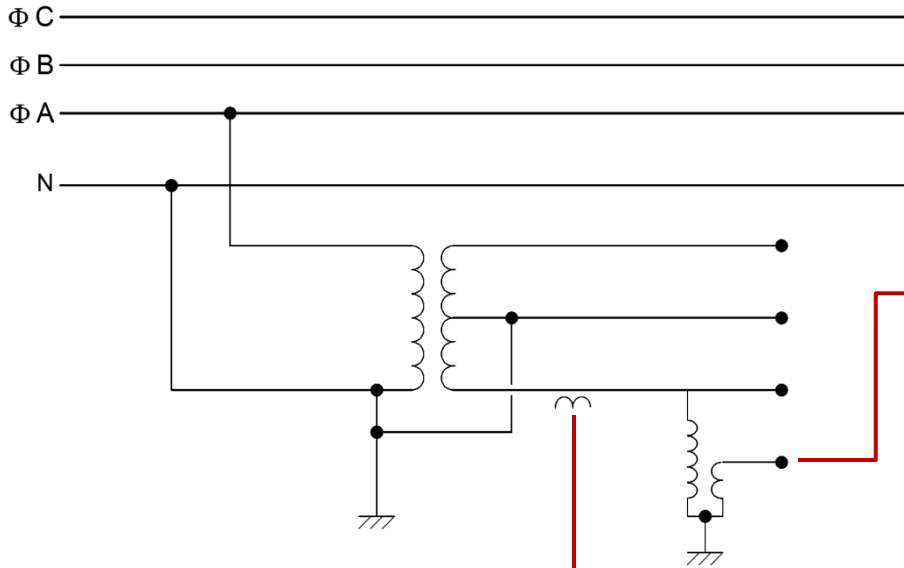
Apply to a DS Section with
At Least one GPS Sync Meas

Formulation

- S Switch
- B Breaker
- R Recloser
- 3 Phase Feeder
- - - Single Phase Lateral
- } → H Residential (Single Phase)
- } → C Commercial (3 Phase)
- } → I Industrial (3 Phase)
- () Capacitor
- ~ Fuse



Object Oriented DS-SE



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

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

Object Oriented Model

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

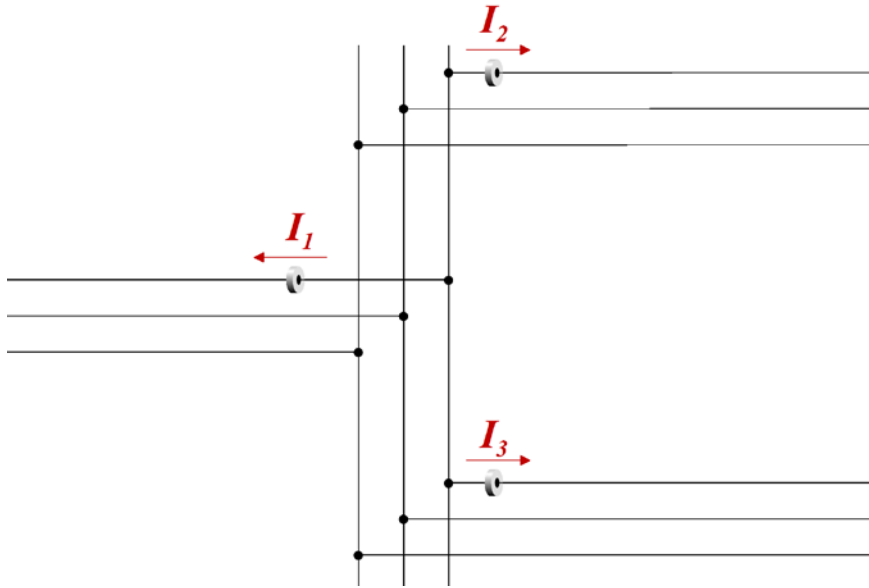
Row k

QSE states are
Phasors, Speed, etc

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

Distributed State Estimation

Virtual Measurements - Examples



Any Equation of a Model Used in the State Estimation

Example: The Equation for the Transformer Internal Voltage

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



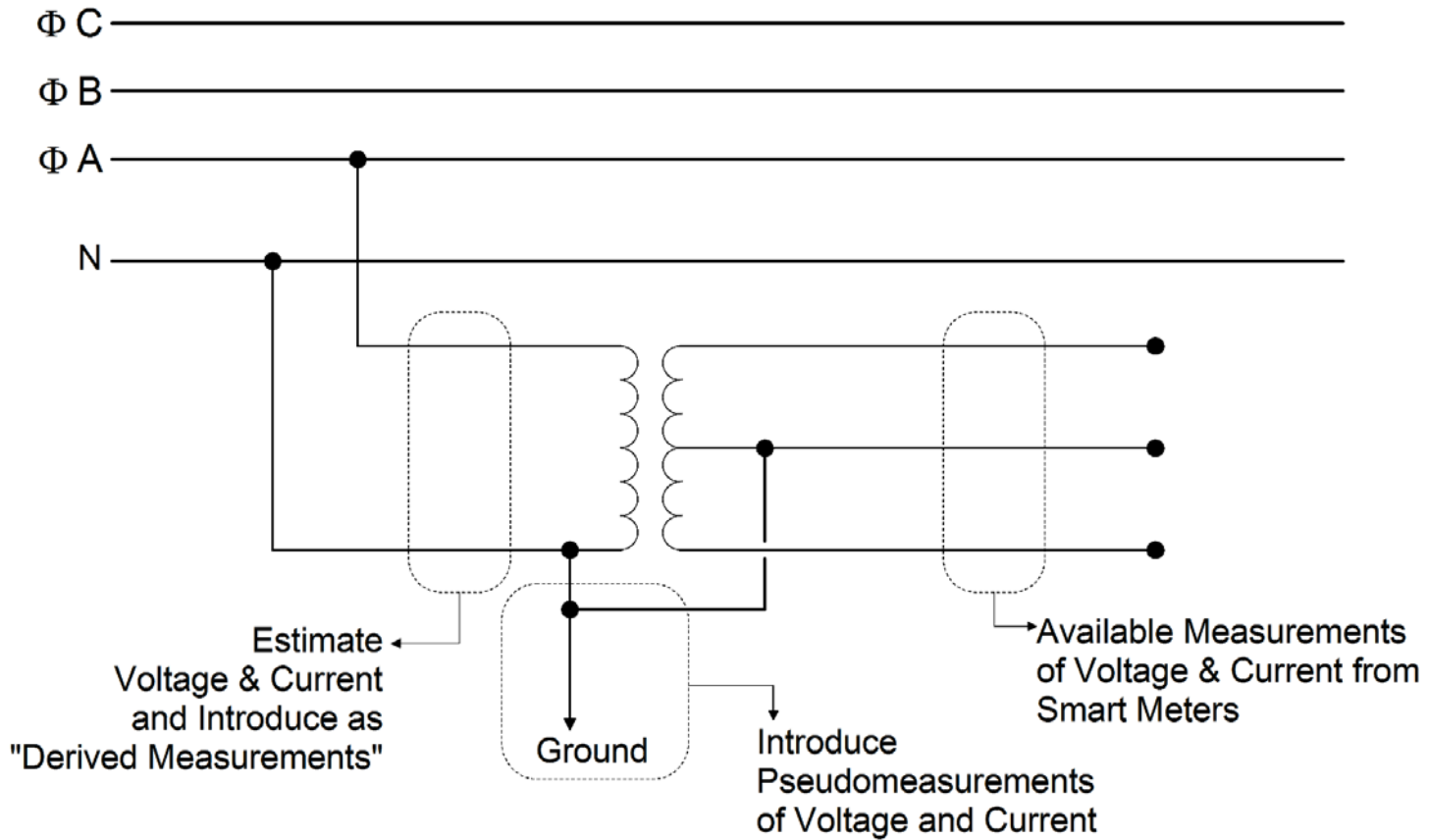
Virtual Measurement

$z_m = 0$ value

$\sigma_m = 0$ standard deviation

Distributed State Estimation

Derived and Pseudo-Measurements - Examples



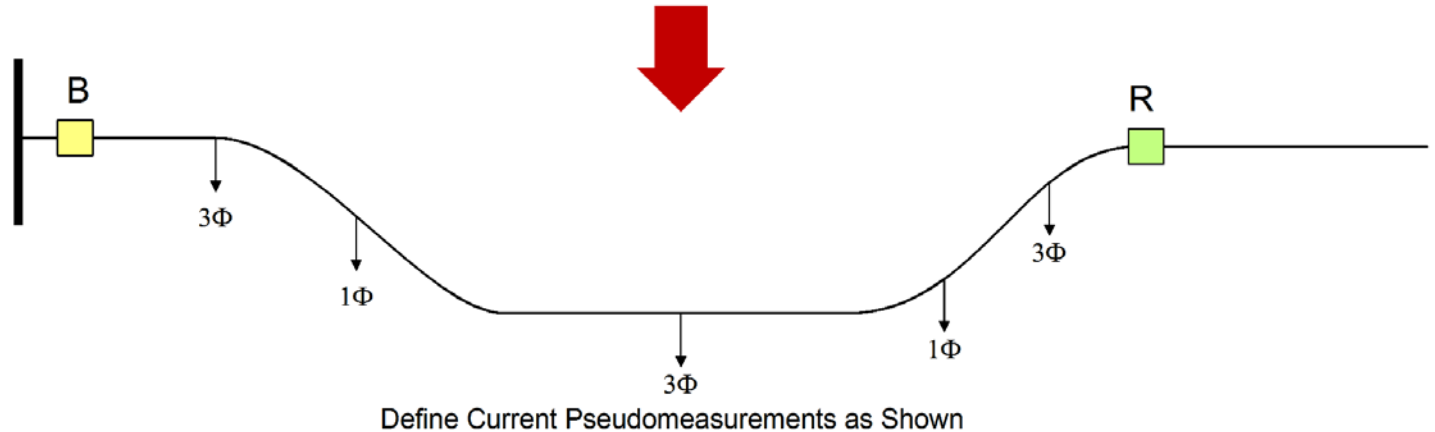
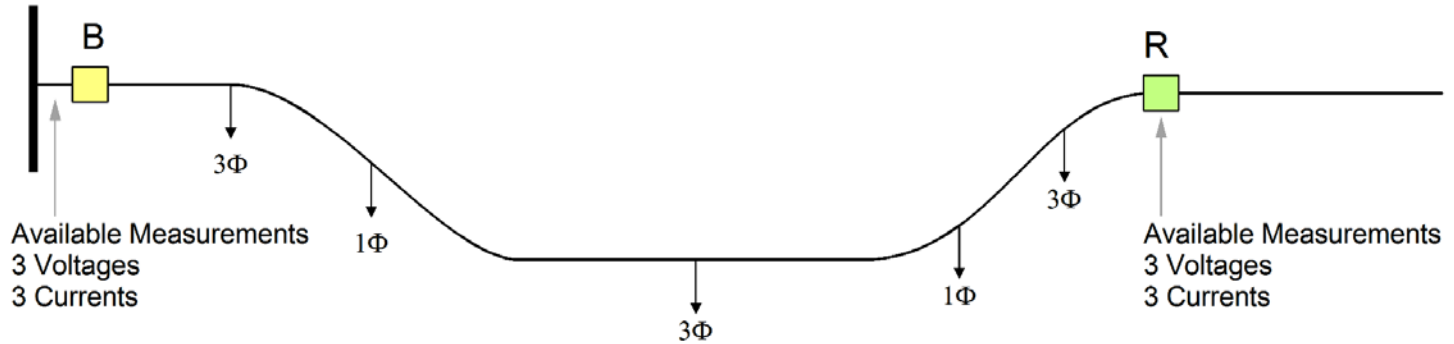
Distributed State Estimation

Pseudo-Measurements - Examples

In a Feeder, there may be sections without instrumentation

Pseudo-Measur. Can Provide the Link Towards Full Observability

An example is shown



Pseudomeasurement Values : Distribute the Current Difference from Breaker to Recloser to the Loads / Phases

Uncertainty : High

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.

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

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

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

DS-SE: Algorithm

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

Solution

$$x^{v+1} = x^v + A[z - h(x)]$$

where: $A = [H^T W H]^{-1} [H^T W]$

Efficiency

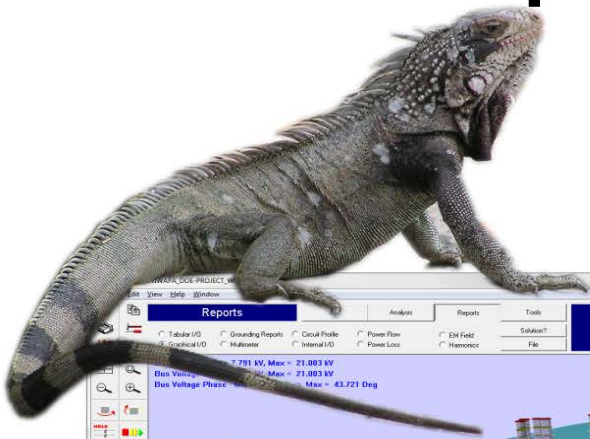
Demonstrated the ability to execute the state estimator 60 times per second for substantial size substations.

There is still space for improved computational efficiency.

Demonstration: USVI-WAPA

The USVI-WAPA System

Expansion Plans



The screenshot displays the Win ICS F software interface. The main window shows a 3D model of a power substation with several green and yellow towers connected by lines. The interface includes a menu bar with 'Reports', 'Analysis', and 'Tools'. Below the menu, there are several buttons and checkboxes for various reports and analyses. The 'Win ICS F' logo is visible in the top right corner of the main window.

Overlaid on the bottom right is the 'SuperCalibrator' control panel. It features a 'POC' section with a 'POC Client' and 'POC Server' status, and a 'Server' section with 'Start' and 'Stop' buttons. The 'Estimator' section includes 'Static', 'Quasi-Static', and 'Dynamic' options, along with 'Start', 'Stop', 'Setup', and 'Play Back' buttons. The 'Test Data Server' section has 'Start', 'Stop', and 'Setup' buttons. The 'Historian (Playback Data)' and 'Model' sections also have 'Setup' buttons. The 'Reports' section includes 'State', 'Measurements', 'Performance', 'Animated SLD', and 'Time Plots' options. The 'SuperCalibrator' window title is 'Substation: NIA' and 'Description: Substation State Estimation Master'.

Demonstration Projects

Application to PV Farms (1.16 MW Array)



What is Monitoring via State Estimation?

Implementation

System is Represented with a Set of Differential Equations (DE) in terms of the system state

SYSTEM STATE: Voltages at each node of the system (see example system)

The State Estimator Fits the Streaming Data to the Model of the System via a least square approach.

END RESULT: Best estimate of system state, i.e. voltages at each node

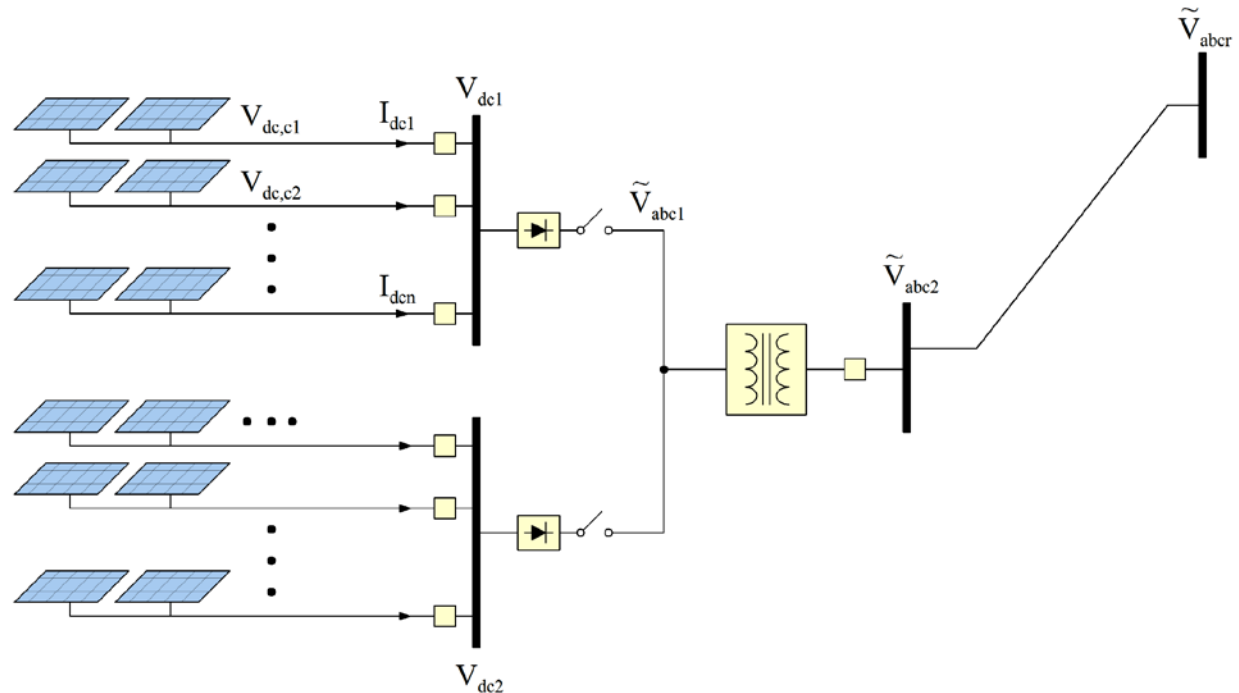
The Estimator is Defined

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Observability

Redundancy



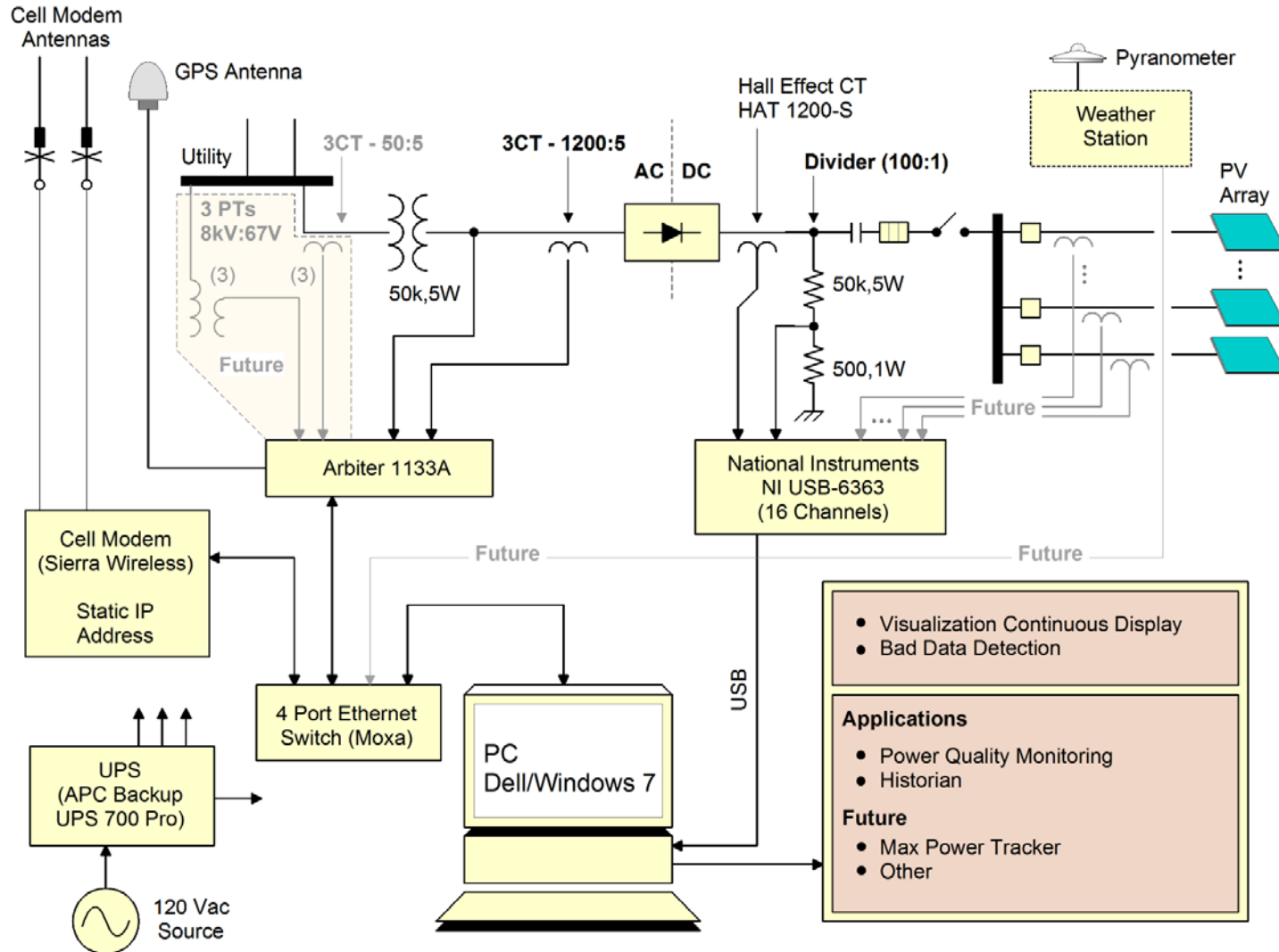
1.16 MW PV Array

4224 Panels (270-280W)
2 Solarex Inverters (500kW each)
10 Combiners per Inverter



Field Demonstration

1.16 PV Array



Model Overview

PV Interconnection



Switch Gear



PV Panels



Substation

Buckman PV Array WinIGS Model

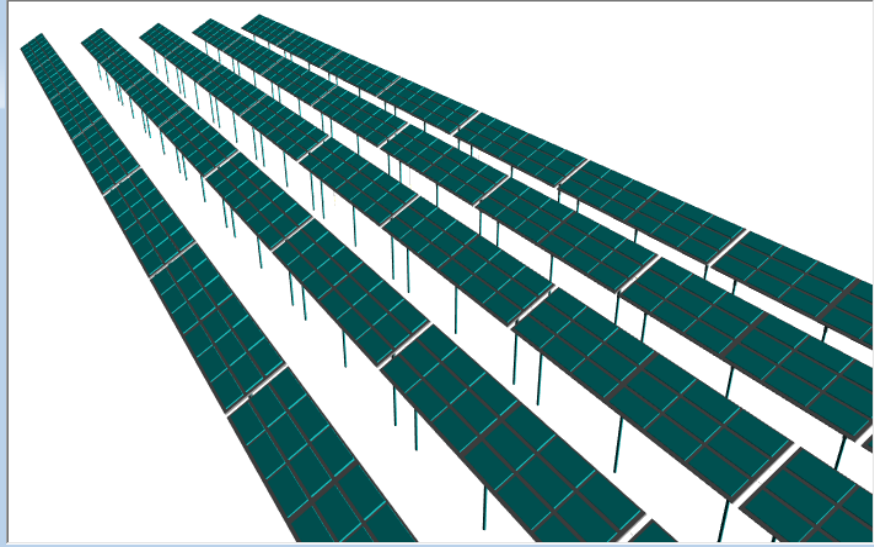
WinIGS-Q

File Edit View Help Window

Run Pause STOP 0.00000 s 0.00000 s 128X

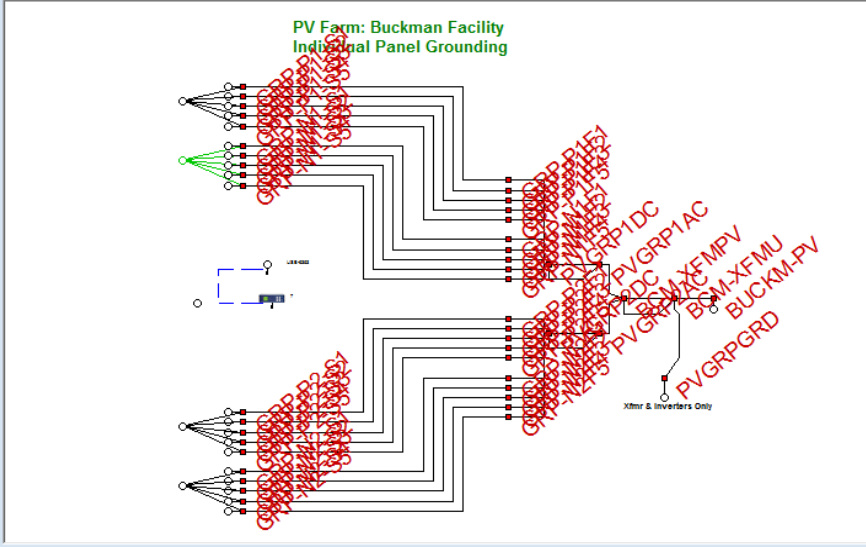
Grounding System 0.5 MW PV Farm Module, Code 139, ID = 32, File = BUCKMAN-DEVELOPMENT.003

Grounding System 0.5 MW PV Farm Module - Case: BUCKMAN-DEVELOPMENT



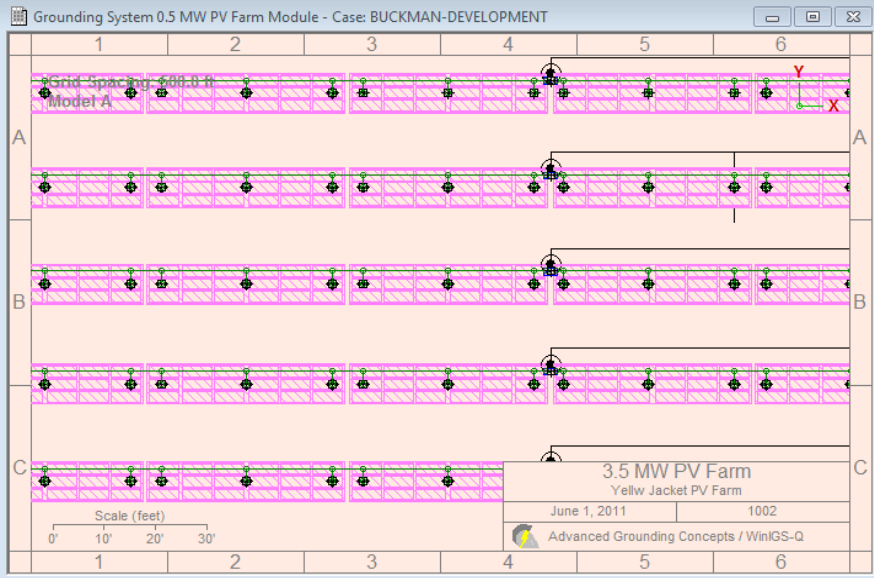
Buckman PV Array - Case: BUCKMAN-DEVELOPMENT

PV Farm: Buckman Facility
Individual Panel Grounding



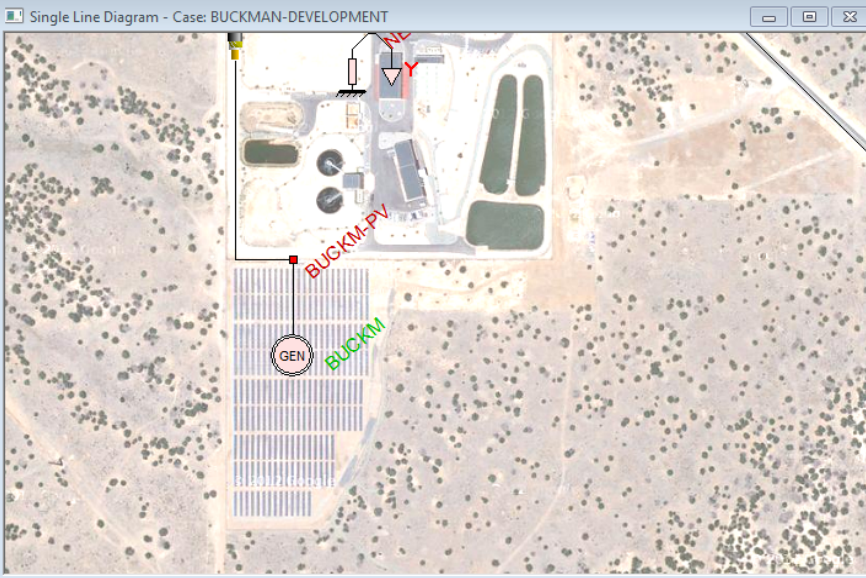
Grounding System 0.5 MW PV Farm Module - Case: BUCKMAN-DEVELOPMENT

Grid Spacing: 500.0 ft
Model A



3.5 MW PV Farm
Yellow Jacket PV Farm
June 1, 2011 1002
Advanced Grounding Concepts / WinIGS-Q

Single Line Diagram - Case: BUCKMAN-DEVELOPMENT



GEN BUCKMAN BUCKMAN-PV

For Help, press F1

Active Layer: 0

Buckman PV Array WinIGS Model

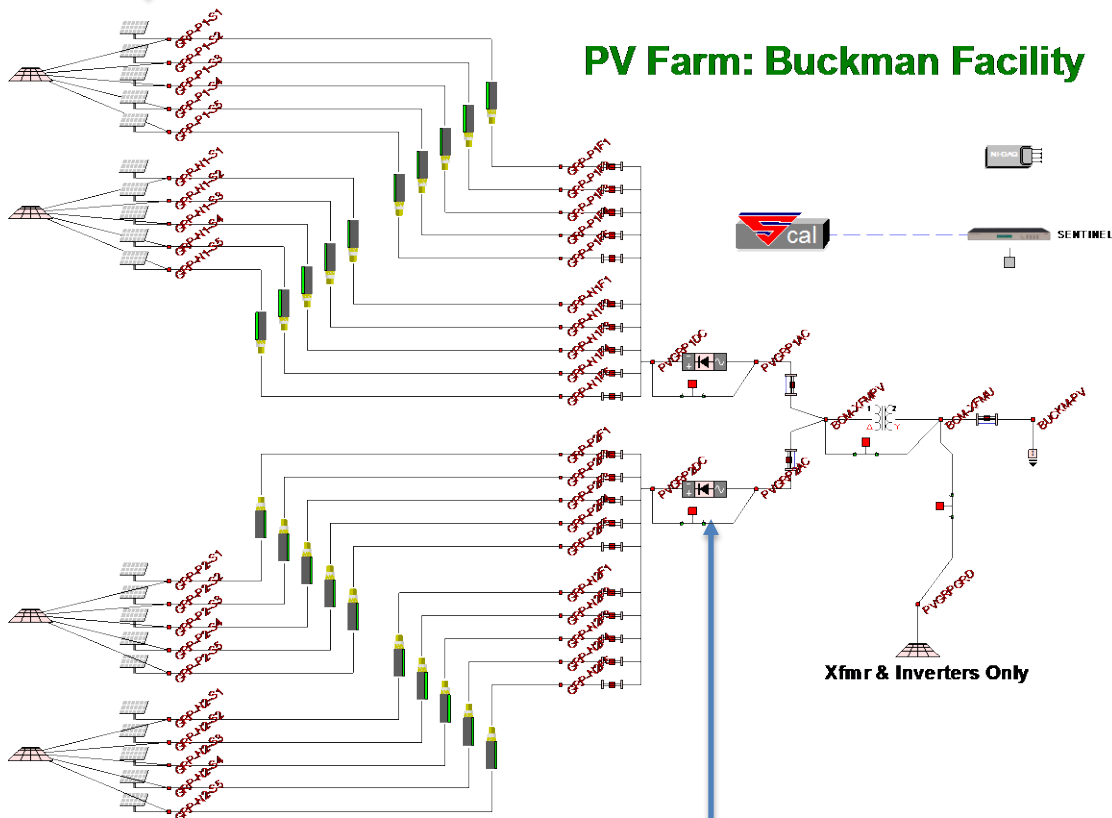


Buckman PV Array WinIGS Model

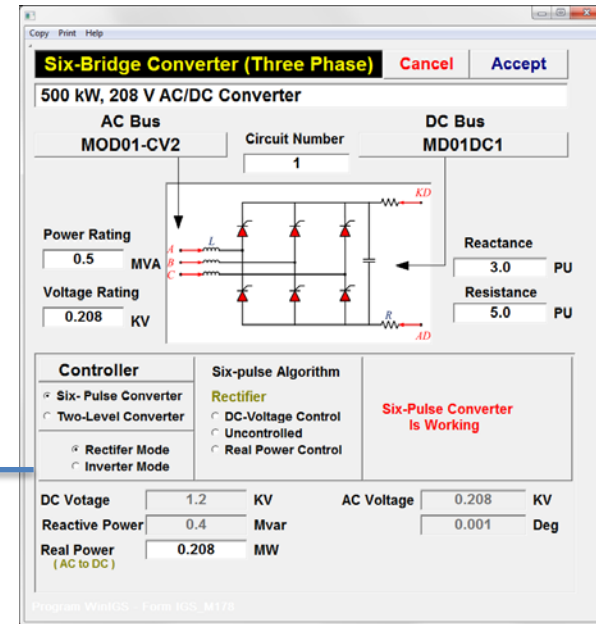
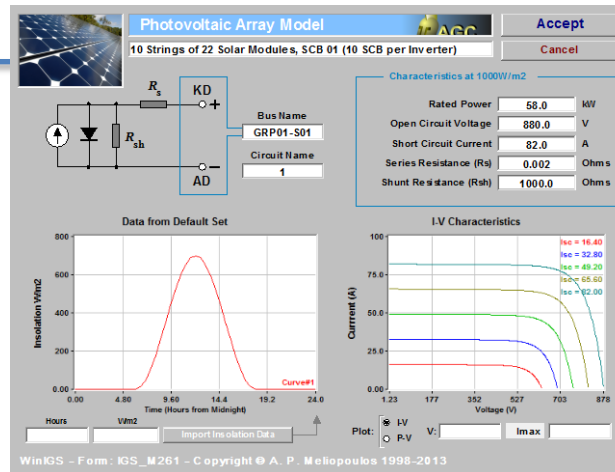
PV Module Model: PV Strings, PV String model, Converter Model

Photovoltaic Array Model

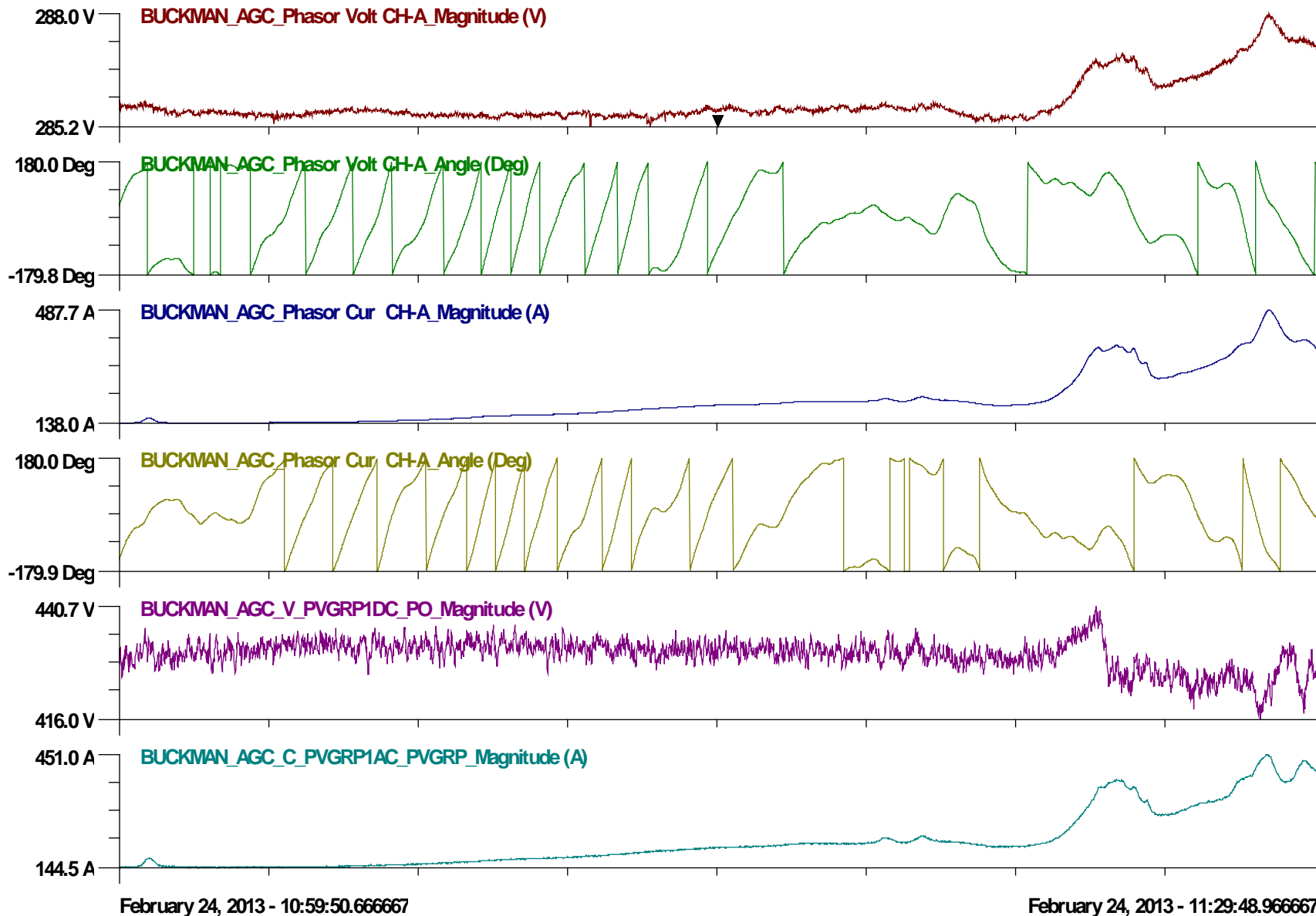
PV Farm: Buckman Facility



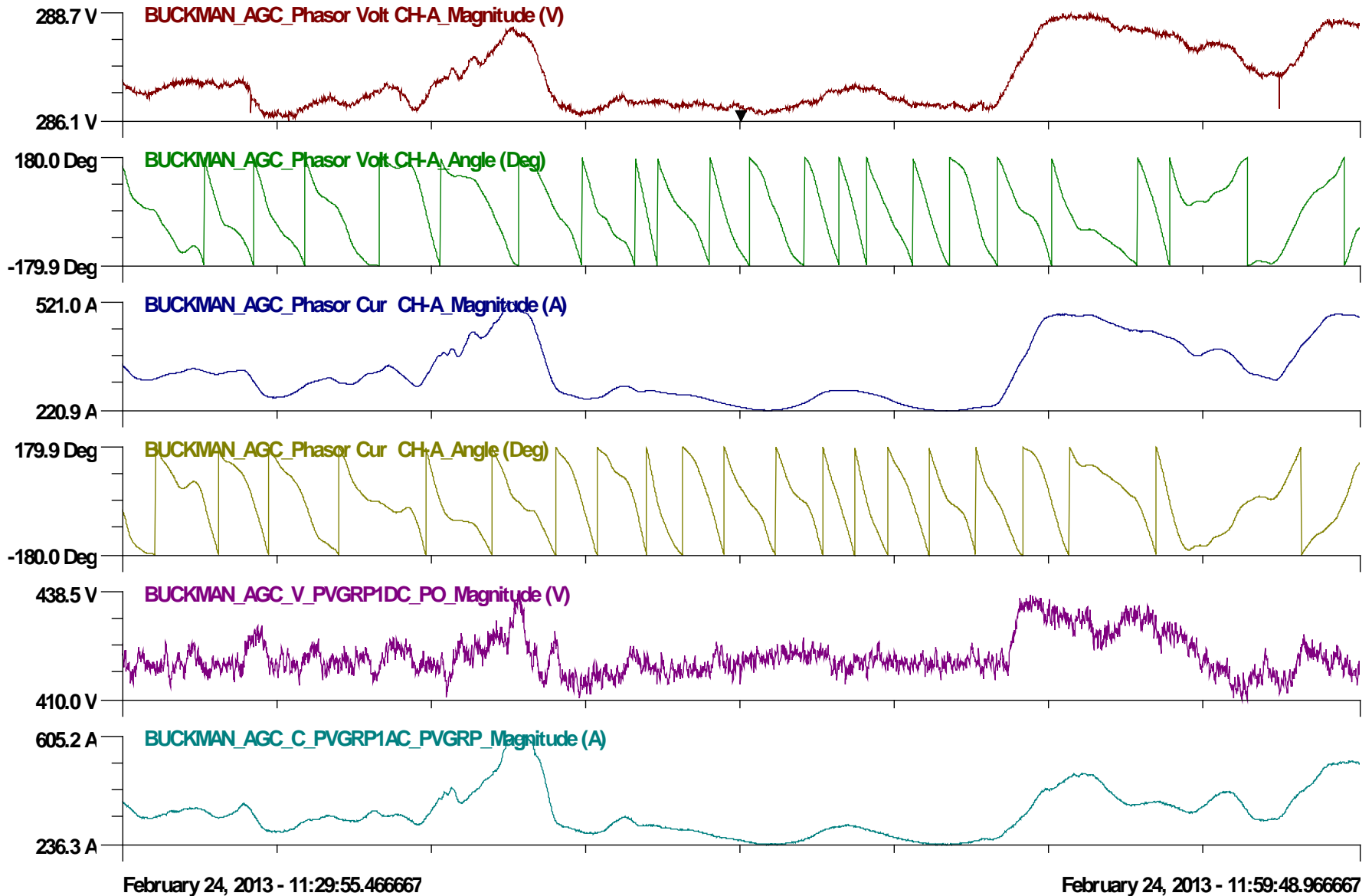
Inverter Model



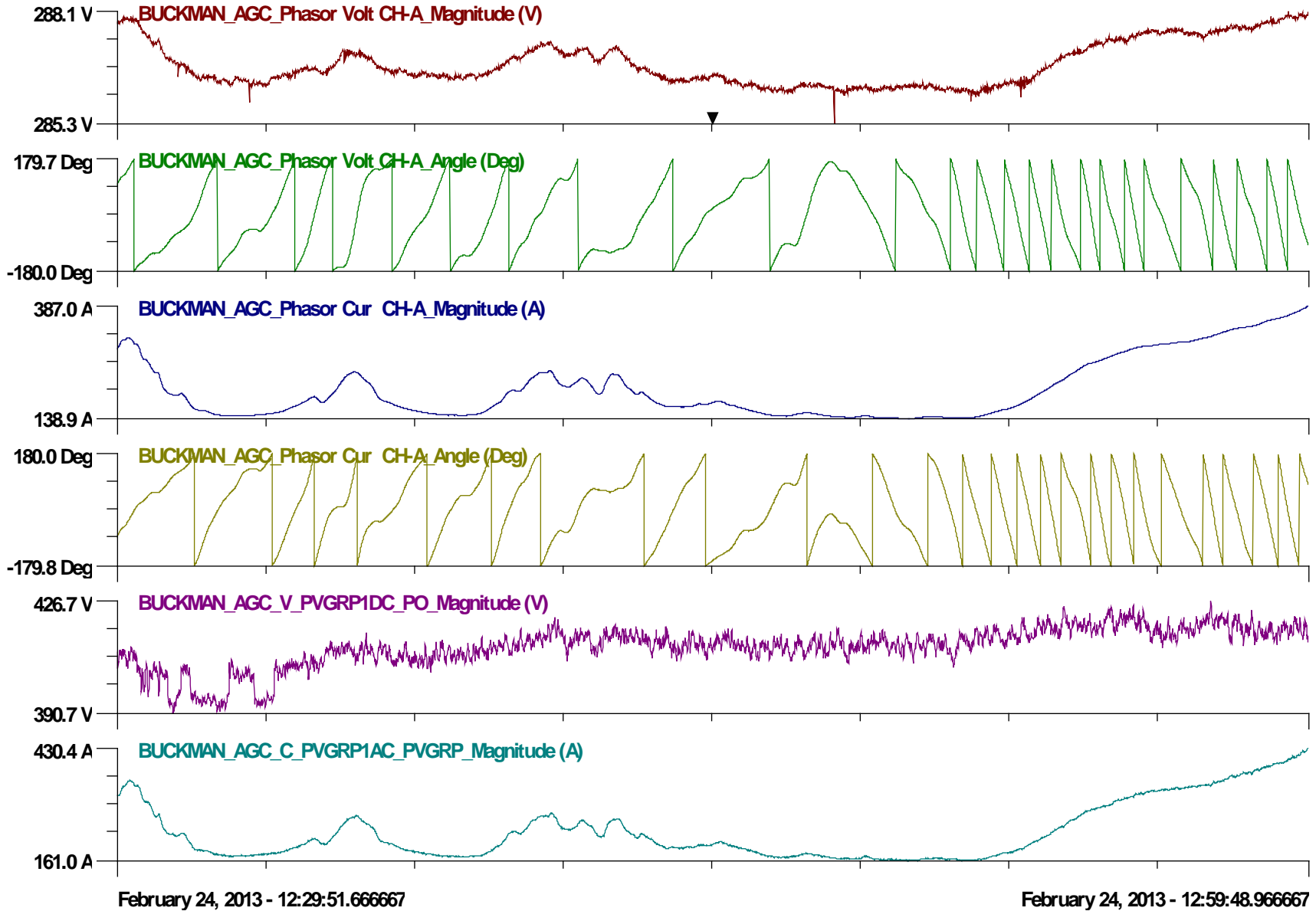
Field Data – 9:00 – 9:30 am (30 Samples / Sec)



Field Data – 9:30 – 10:00 am (30 Samples / Sec)



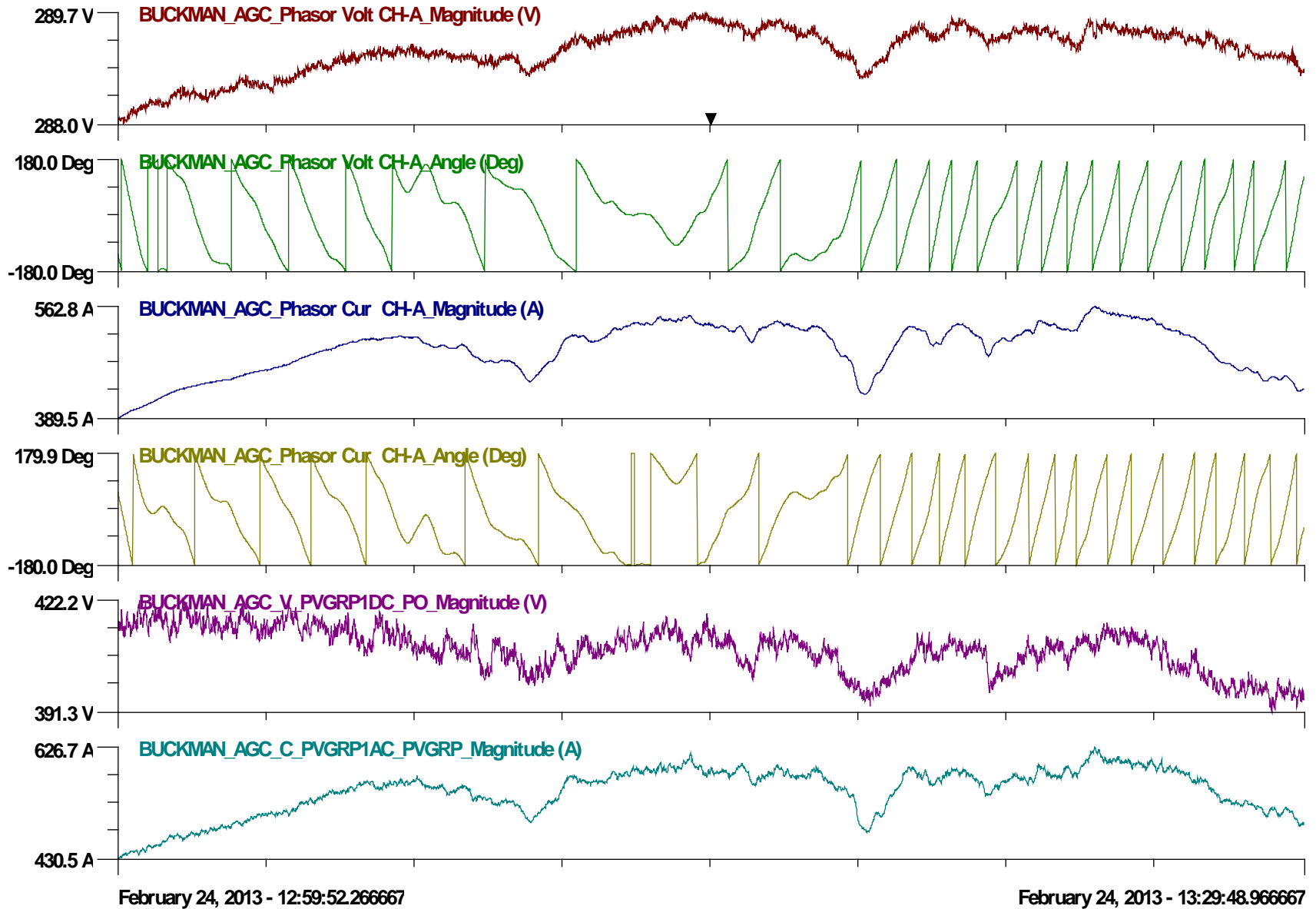
Field Data – 10:30 – 11:00 am (30 Samples / Sec)



February 24, 2013 - 12:29:51.666667

February 24, 2013 - 12:59:48.966667

Field Data – 11:00 – 11:30 am (30 Samples / Sec)



February 24, 2013 - 12:59:52.266667

February 24, 2013 - 13:29:48.966667

Synchrophasor Field Data Snapshot

Substation: YJC_BUCKM

Communication Parameters

Rescan Local IP Address: 192.168.0.102
 Local Port Number: 2000
 Outstation IP Address: 192.168.0.102
 Outstation Port Number: 2003
 Outstation ID: 10

Connect Start
 Disconnect Stop
 Frame Window Copy CFG
 Set Rate 60
 Buffer Usage 0.00 %

Protocol
 TCP
 UDP-1
 UDP-2
 TCP/UDP

Autostart
 Adjust Clock

Save Stream to File buckman

Phasor Diagram

F = 60.0219 Hz Time: 12:14:32.533333

DF/DT = 0.0201 Hz/sec Rate = 30.0000 fps

Program WinIGS-Q - Form IGS_MC

Phasors				
	Name	Type	Magnitude	Phase (Degrees)
0	Phasor Volt CH-A	Voltage	288.8389	123.4191
1	Phasor Cur CH-A	Current	435.2258	-58.5011
2	Phasor Volt CH-C	Voltage	289.0181	-116.4568
3	Phasor Cur CH-C	Current	444.2625	62.1891
4	Phasor Volt CH-B	Voltage	288.8625	3.3638
5	Phasor Cur CH-B	Current	441.4685	-179.7037
6	V_PVGRP1DC_PO	Voltage	395.0335	0.0000
7	C_PVGRP1AC_PVGRF	Current	494.9604	0.0000

Program WinIGS-Q - Form IGS_M007_DATA_WIN

Conclusions: Technology Capabilities

An Object Oriented Implementation of a Distribution System State Estimation Enables Full Observability of the Distribution System and Customer Owned Resources. State Estimation enables: (a) validation of data, and (b) extent the observability of the distribution system beyond the existing instrumentation. The DS-SE enables many applications:

Utility

- Optimize voltage along feeder by
 - cap control
 - distributed resource control, etc.

Customer/Third Party Resources

- Example: PV Model Validation
- Identify Panel Deterioration, Faulty Panels, etc.
- Determine root cause of disturbances