Distributed Dynamic State Estimator: Extension to Distribution Feeders

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Outline

DS-SE Challenges

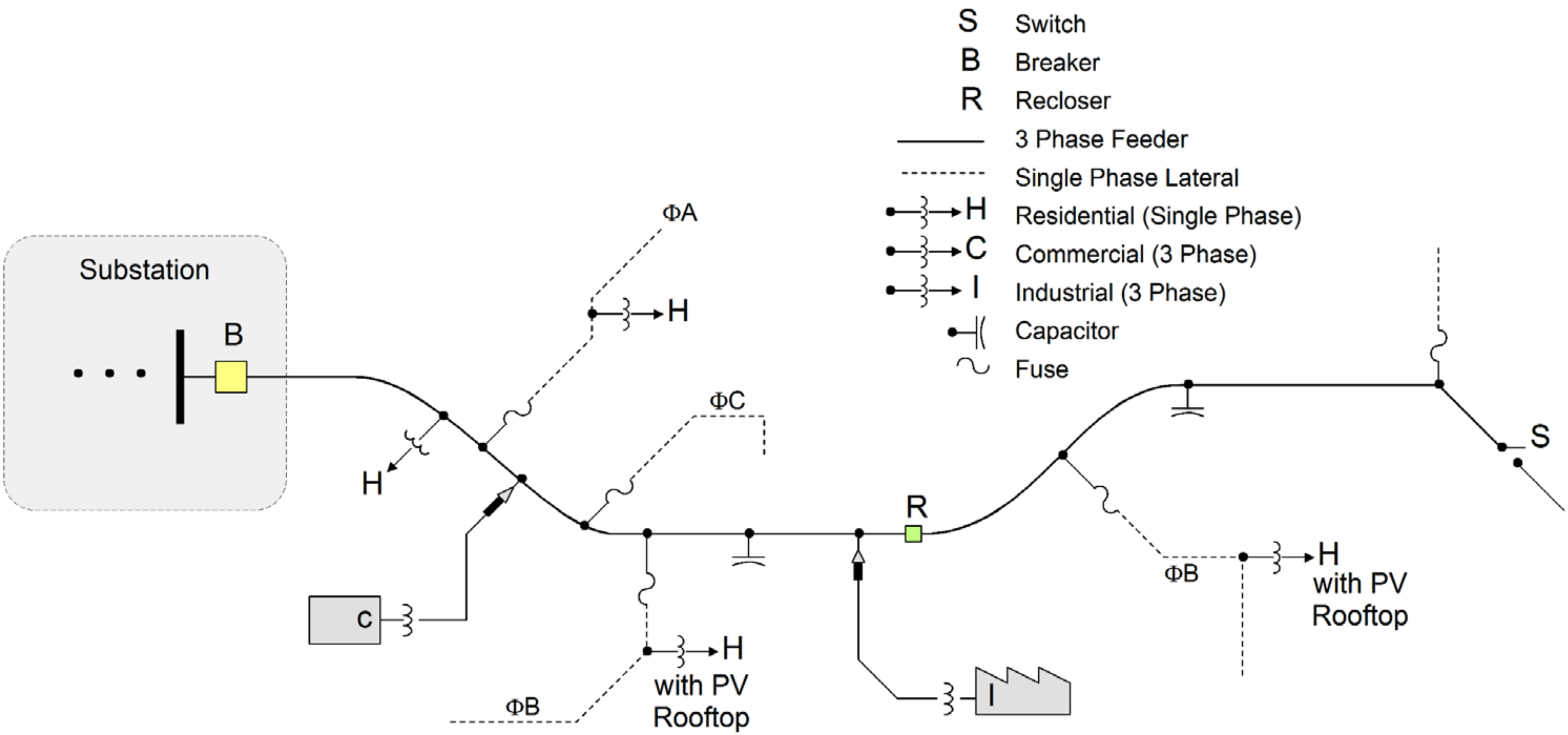
Basic Background Technology: Distributed State Estimation

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

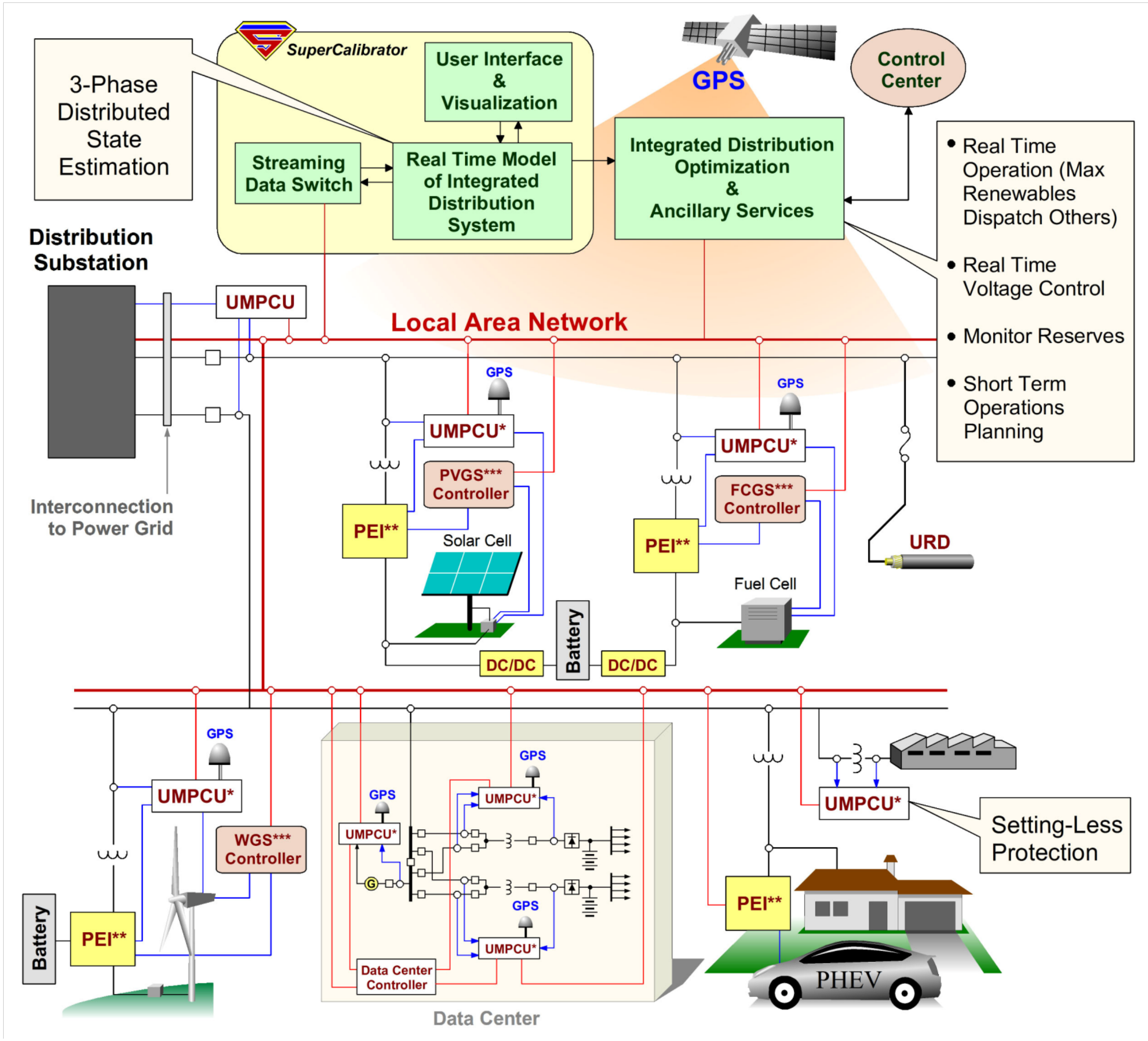
- Feeder Sections May Be not Observable

Implementation Approaches Become Important

- Multiphase Modeling is a Necessity
- Many More Power Devices than Transmission Systems

DMS

Design For Autonomy



Plug and Play…

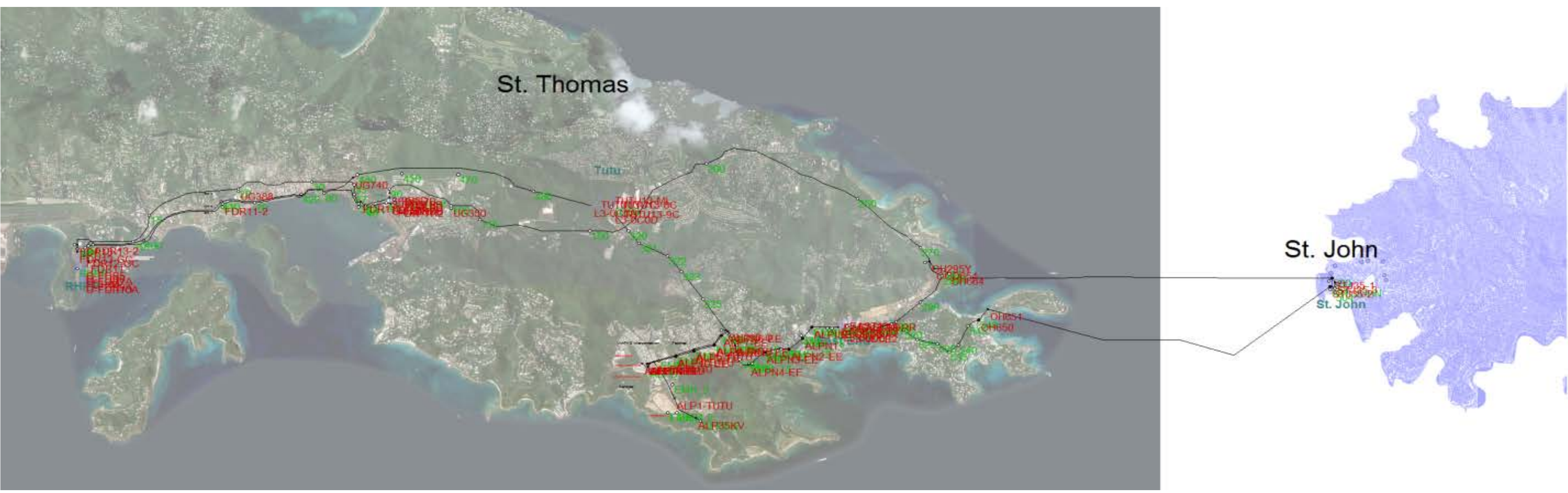
Background: USVI-WAPA

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



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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

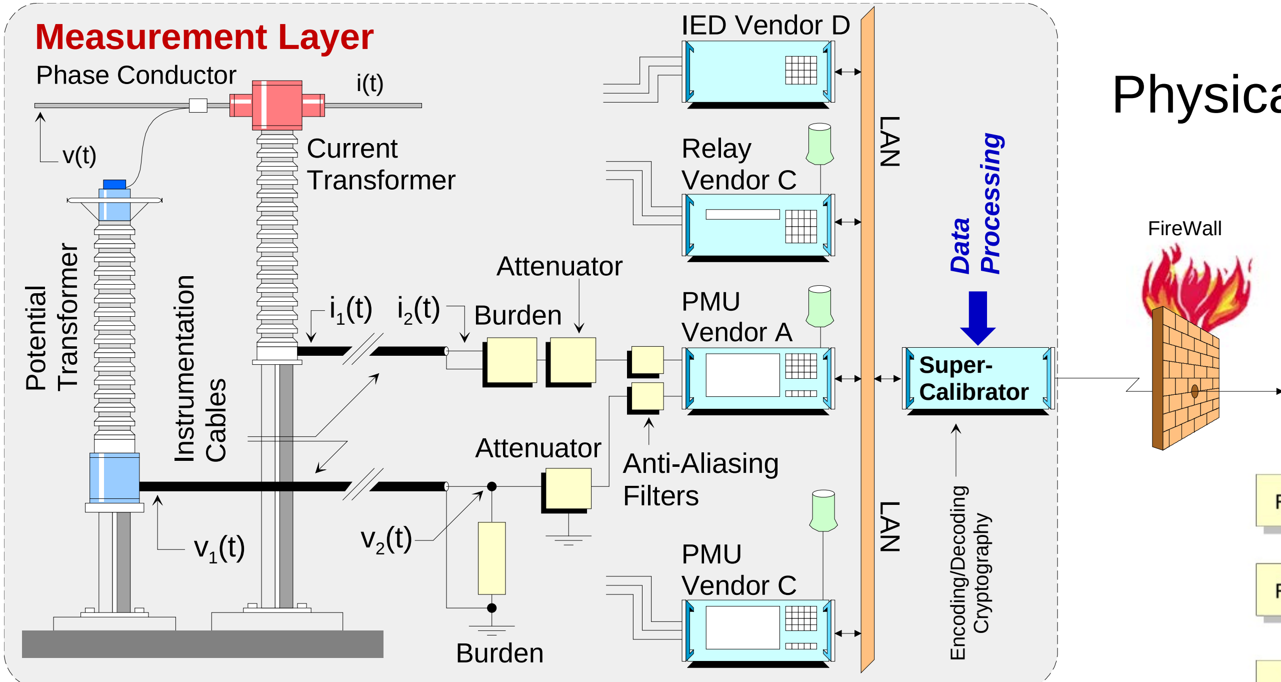
The SuperC Concept (Distributed SE)

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

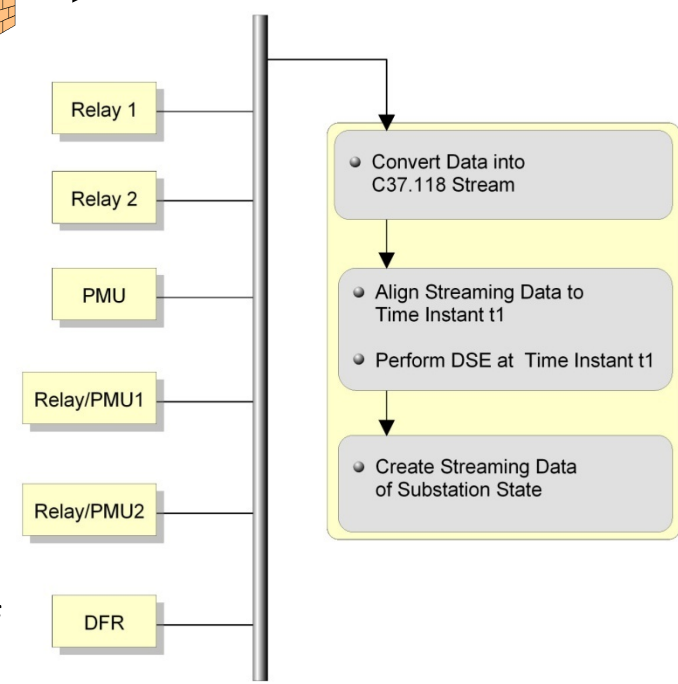
Distributed Dynamic State Estimation

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

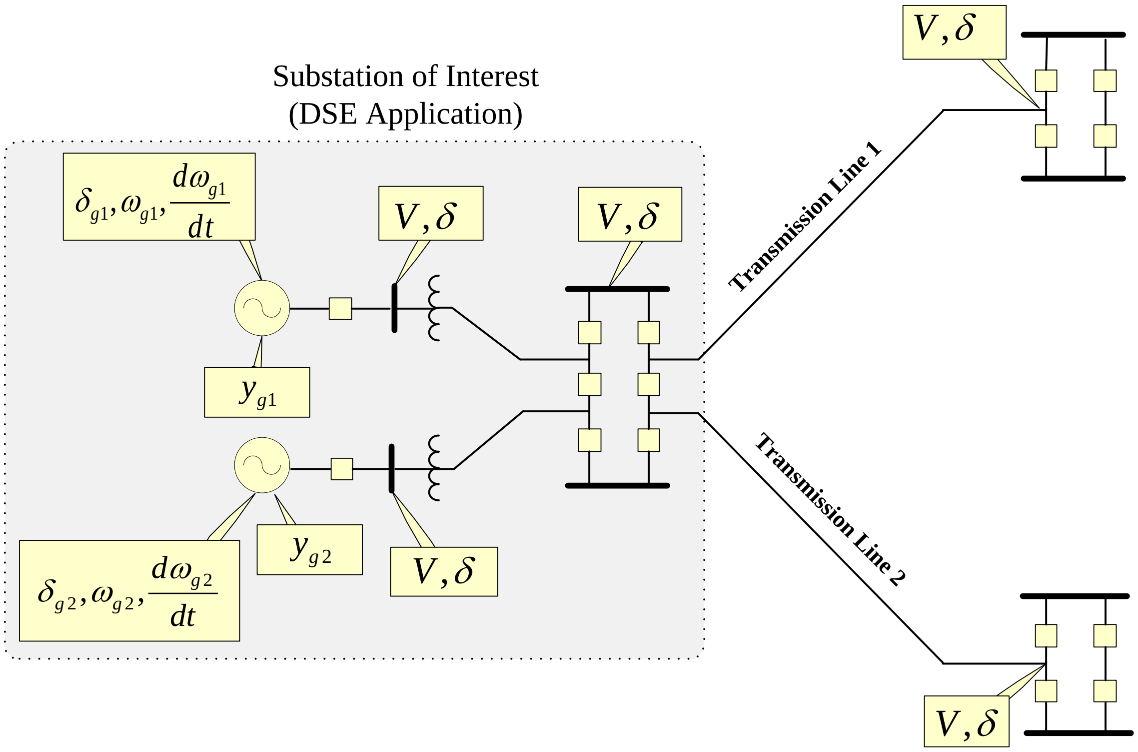
Implementation

The Estimator is Defined in Terms of:

- Model
- State
- Measurement Set
- Estimation Method

Observability

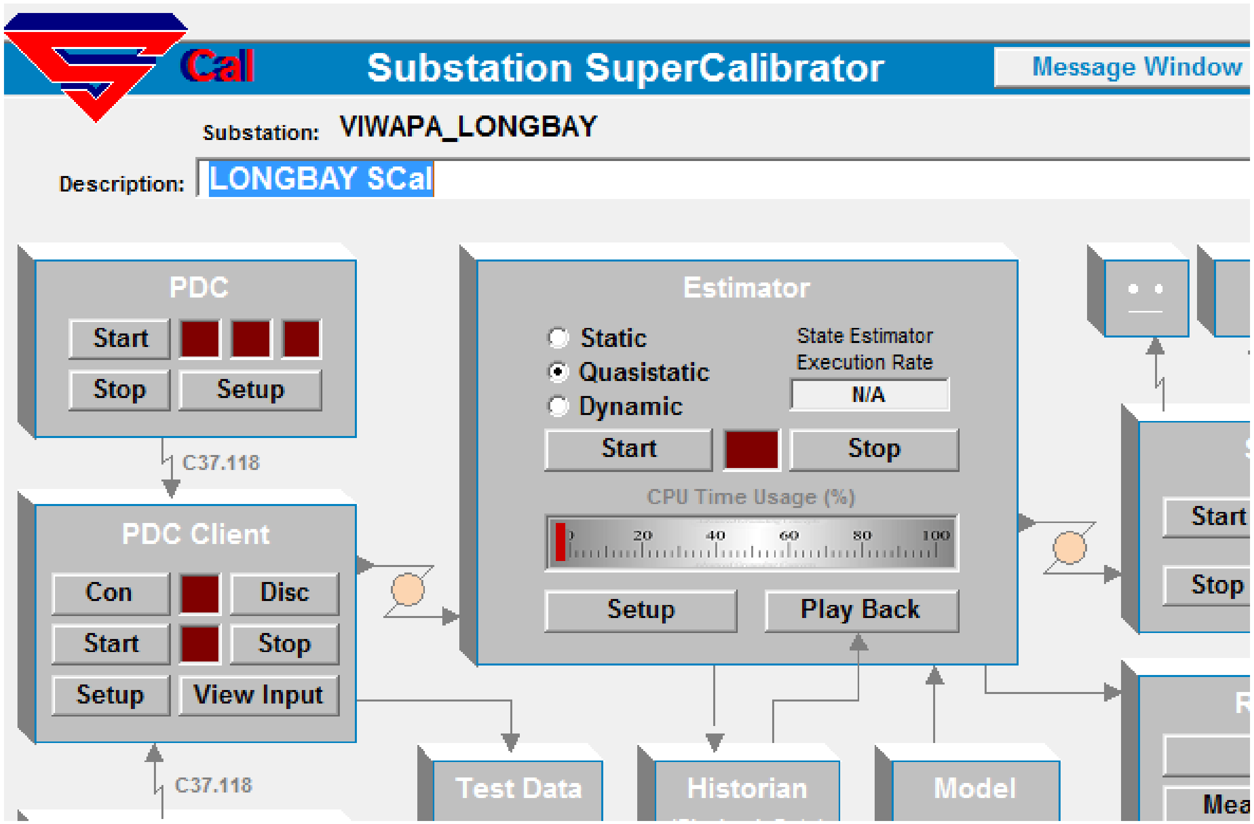
Redundancy



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.

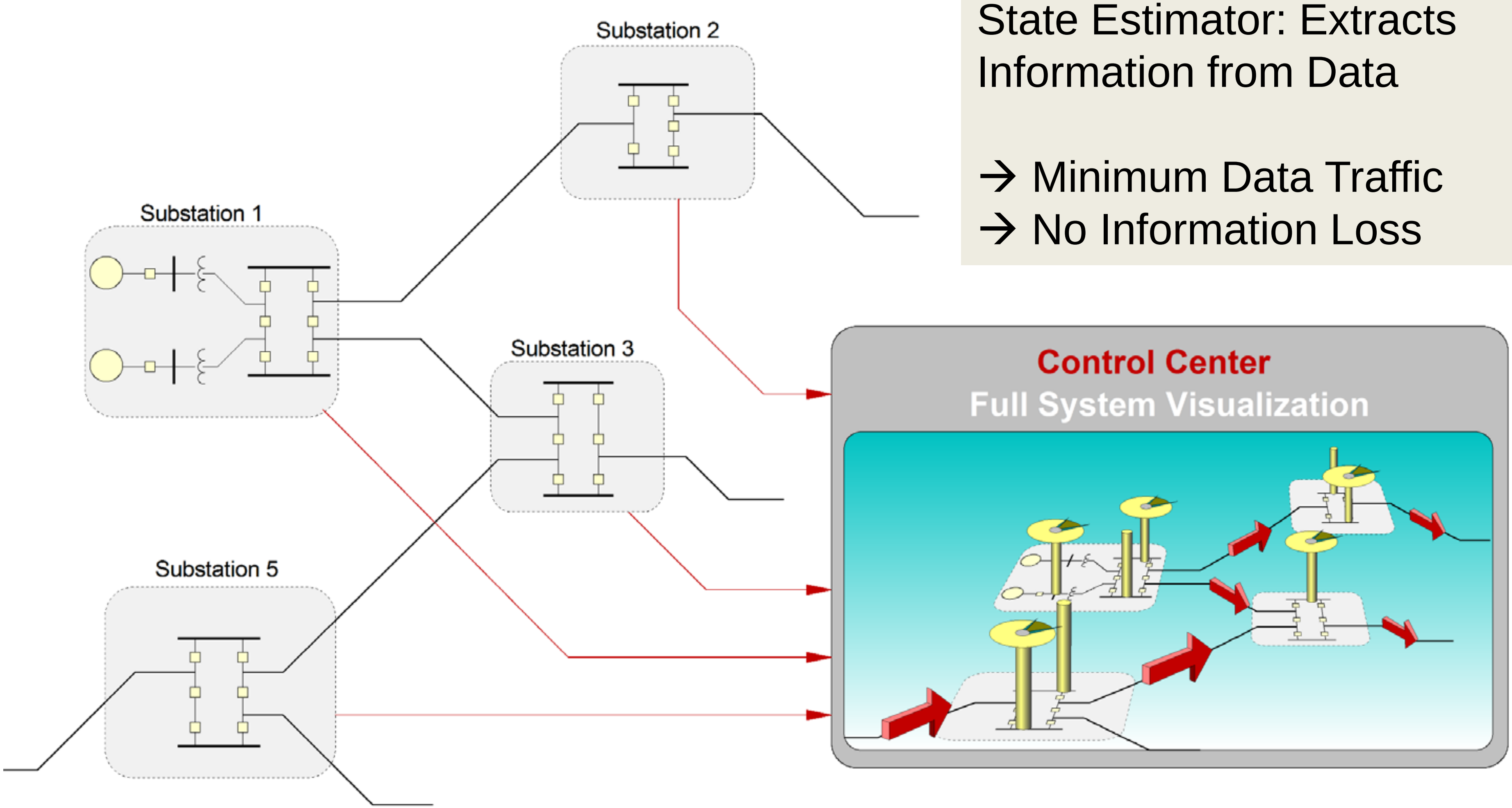
100%=Time Between Two Successive SE Computations. example: if SE is set to execute 60 times per second, then 100%=16.6 ms

Distributed State Estimation

Synthesis of System Wide State at the Control Center

State Estimator: Extracts Information from Data

→ Minimum Data Traffic
→ No Information Loss



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.

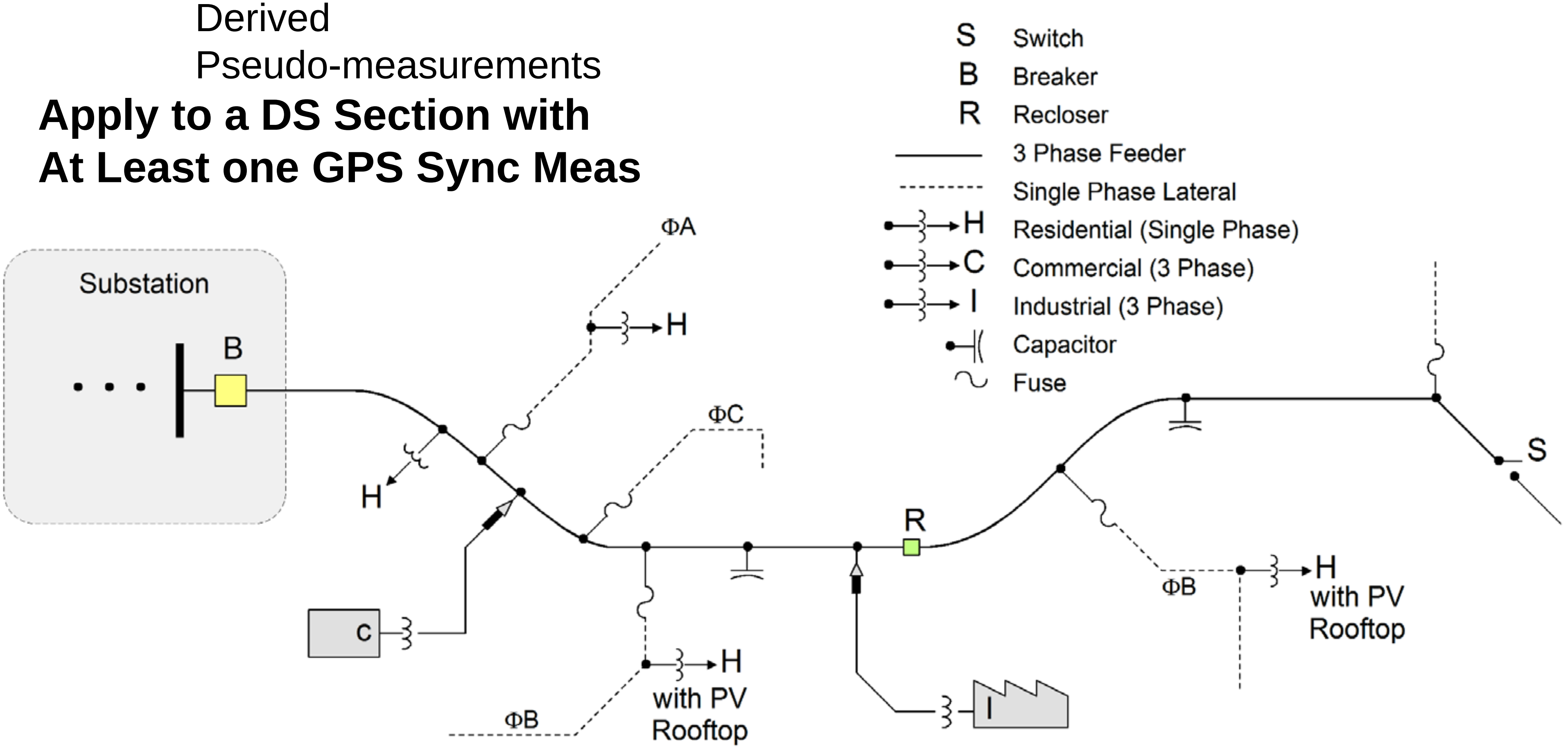
Object Oriented DS-SE Formulation

Use Existing Measurements

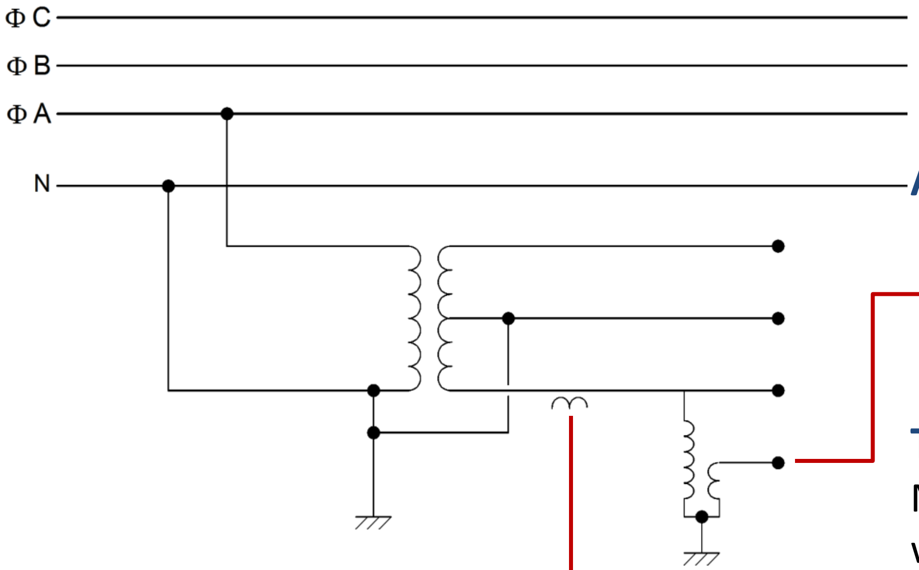
Supplement with

- Virtual
- Derived
- Pseudo-measurements

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



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

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

Object Oriented Model

Row k

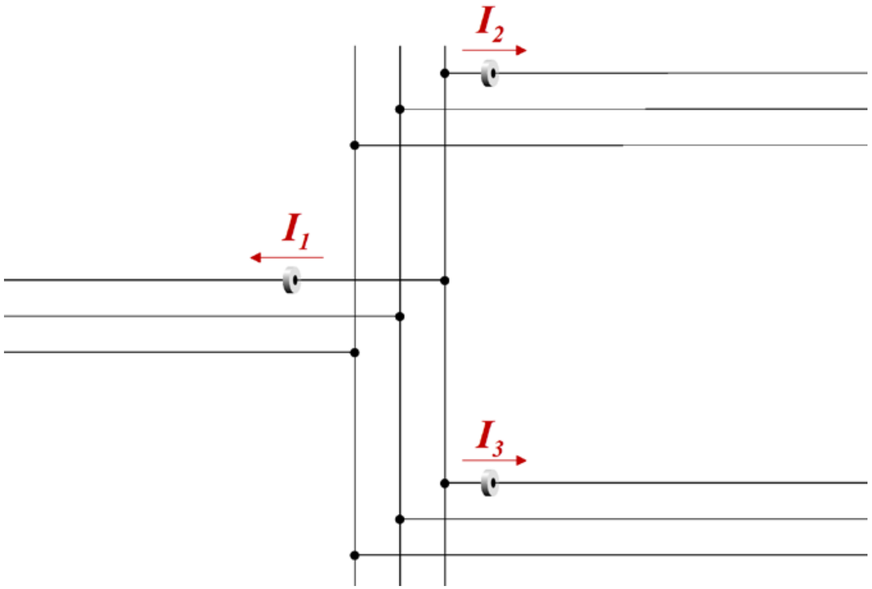
$$\begin{bmatrix} \tilde{I}(t) \\ 0 \\ \tilde{I}(t_m) \\ 0 \end{bmatrix} = Y_{eq} \begin{bmatrix} \tilde{V}(t) \\ \tilde{Y}(t) \\ \tilde{V}(t_m) \\ \tilde{Y}(t_m) \end{bmatrix} + \left[\begin{bmatrix} \tilde{V}^T(t) & \tilde{Y}^T(t) & \tilde{V}^T(t_m) & \tilde{Y}^T(t_m) \end{bmatrix} \cdot F_{eq} \cdot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

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

QSE states are
Phasors, Speed, etc

Distributed State Estimation

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

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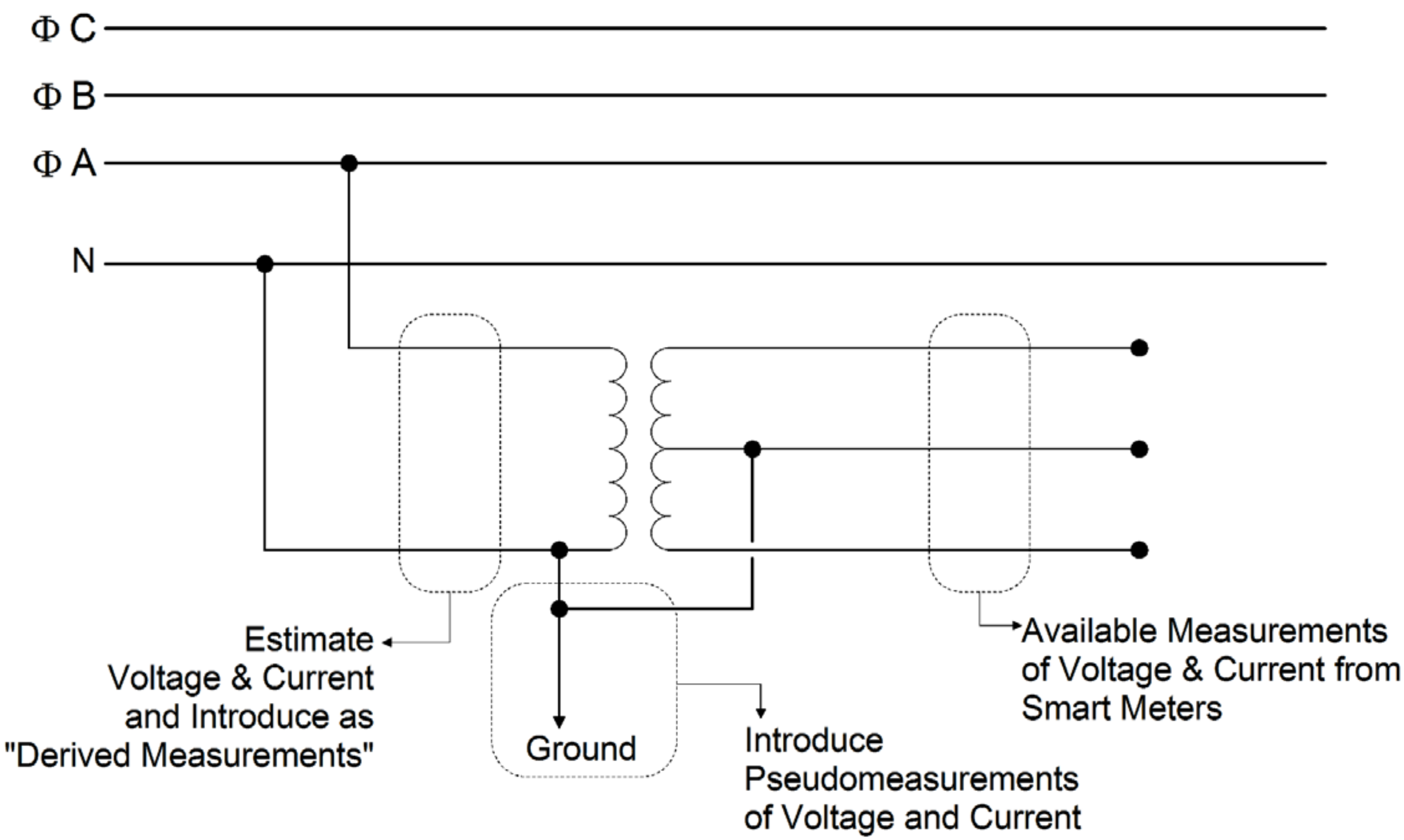
Distributed State Estimation

Derived and Pseudo-Measurements - Examples



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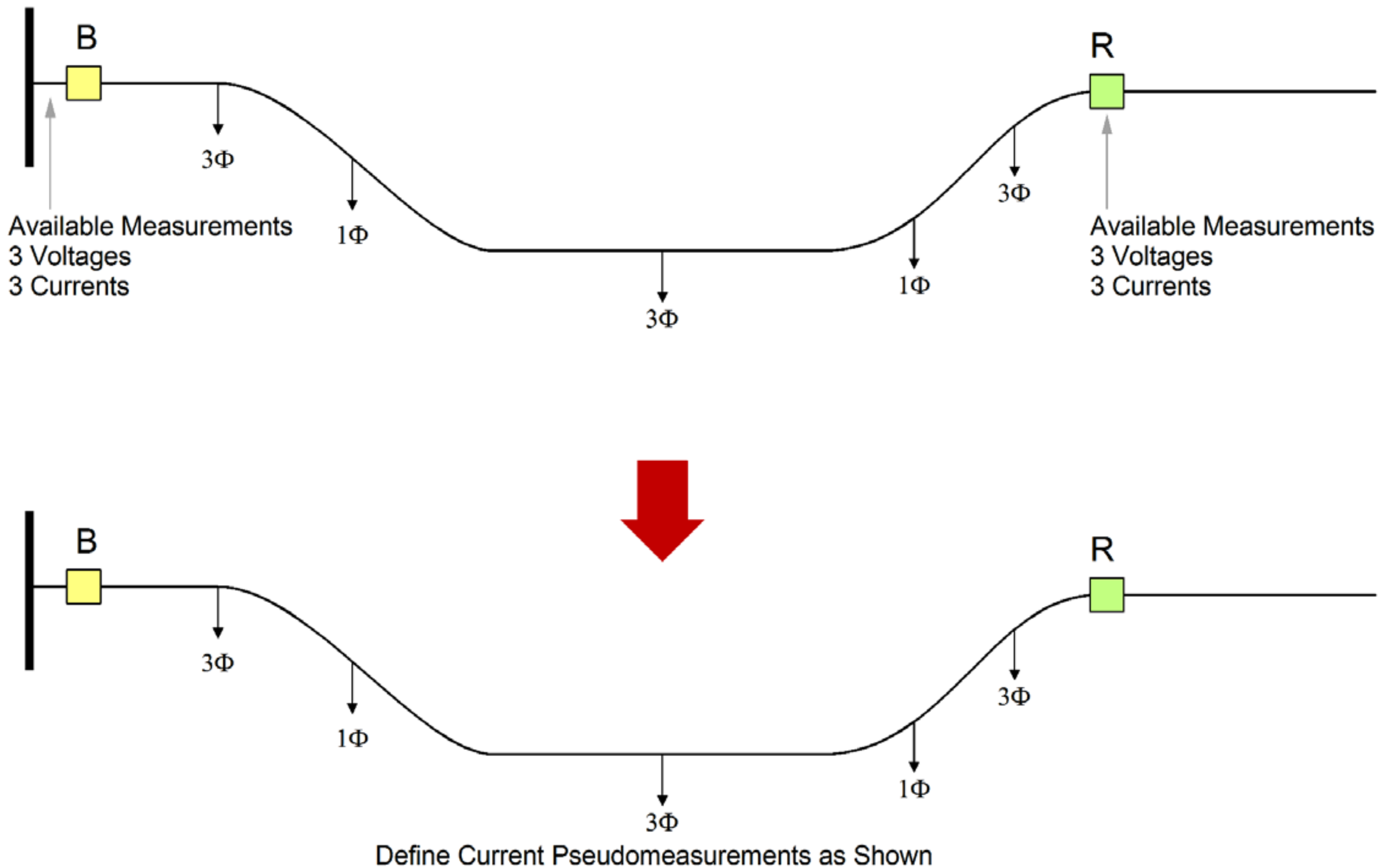
Distributed State Estimation

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.

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

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

α is a synchronizing unknown variable

cos(α) and sin(α) are unknown variables in the state estimation algorithm

There is one α variable for each non-synchronized relay

DS-SE: Algorithm

$$Min \quad J = \sum_{\nu \in phasor} \frac{\tilde{\eta}_\nu^* \tilde{\eta}_\nu}{\sigma_\nu^2} + \sum_{\nu \in non-syn} \frac{\eta_\nu \eta_\nu}{\sigma_\nu^2}$$

Solution

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

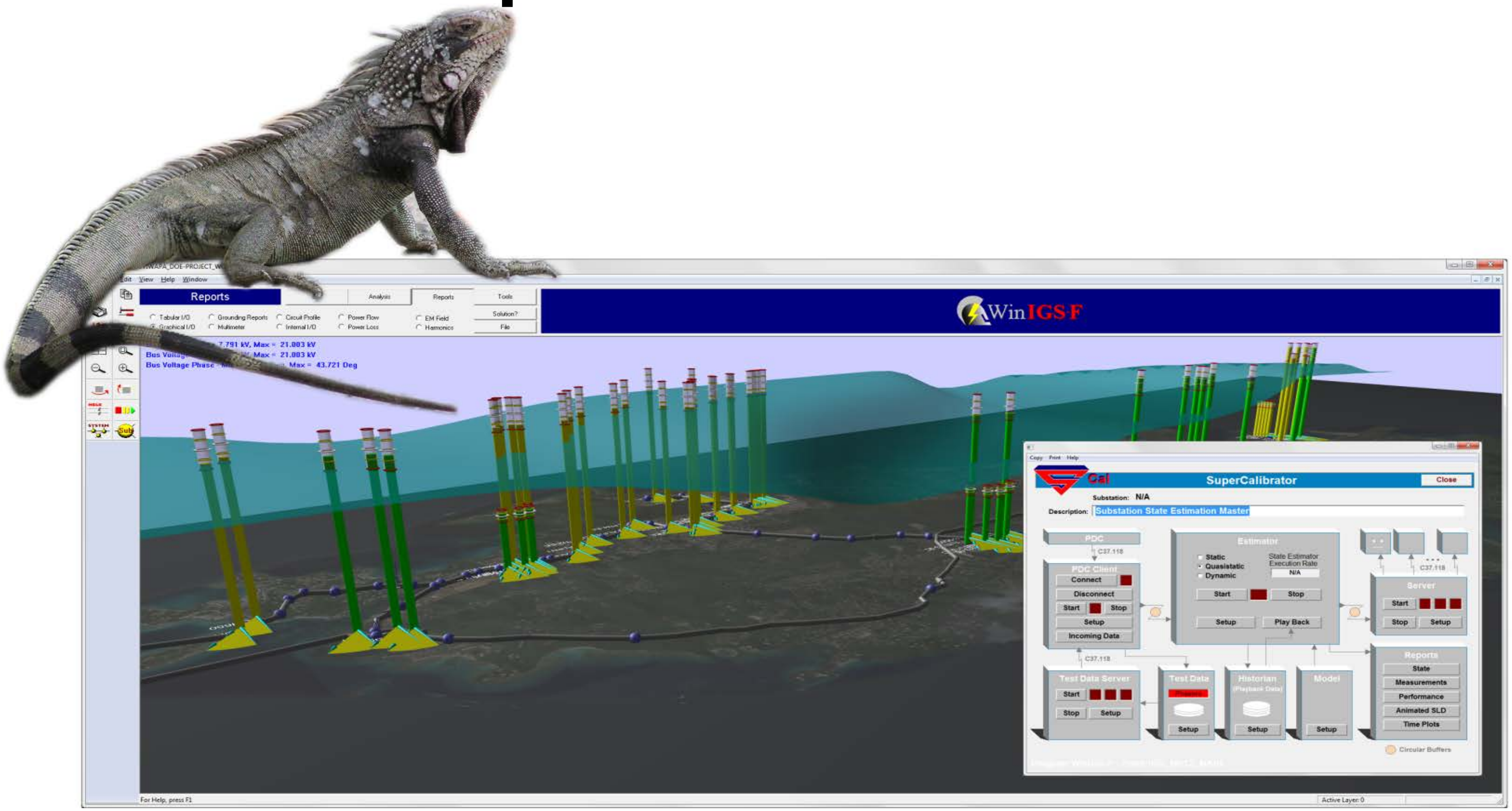
where: $$A = \left[H^T W H\right]^{-1}\left[H^T W\right]$$

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.

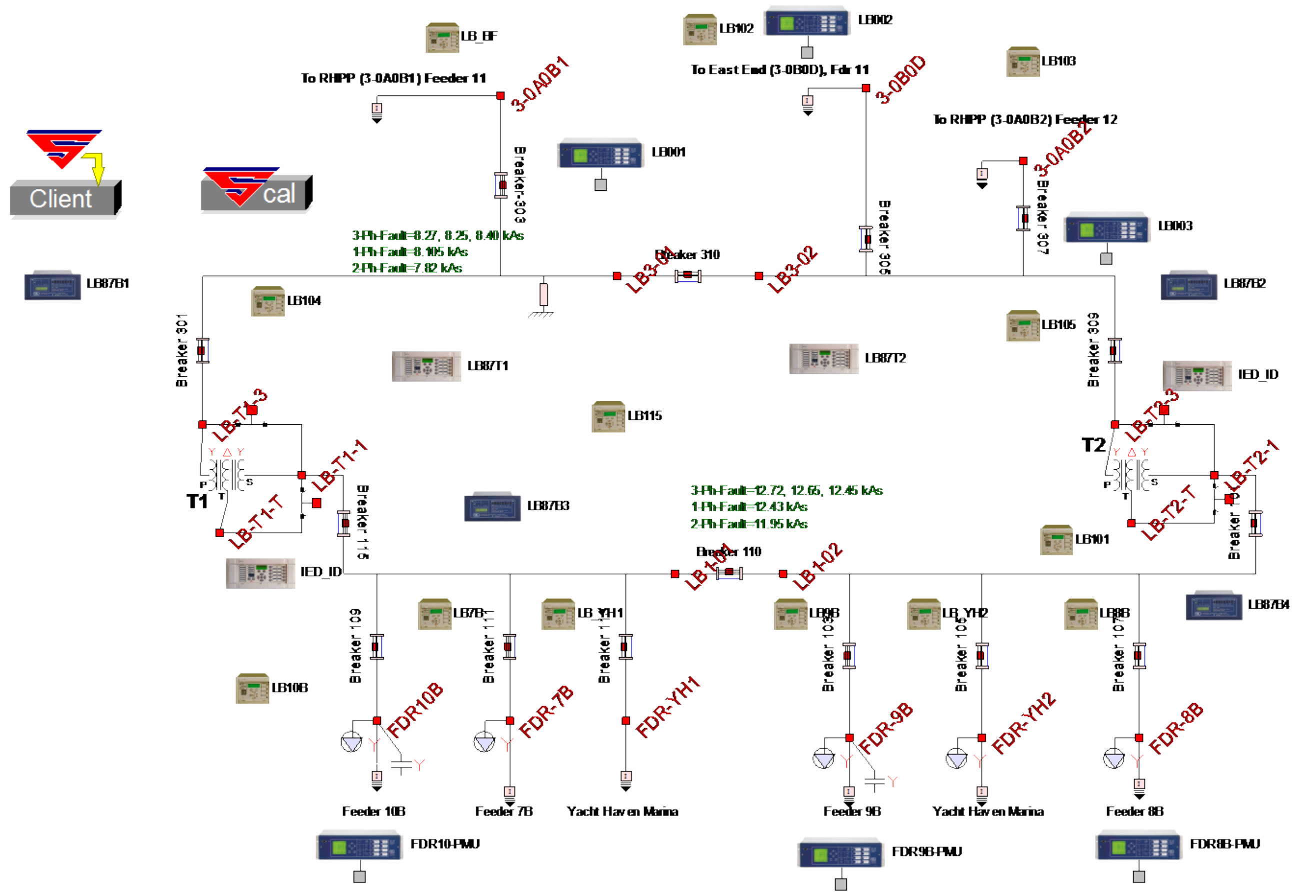
Demonstration: USVI-WAPA

The USVI-WAPA System Expansion Plans



The USVI-WAPA System

Present Project: Extension to Feeders and PV Farms



Addition of PMUs on the Feeder

Extend Substation Based State Estimator to Feeders

Demonstration Projects
Application to PV Farms (1.16 MW Array)

What is Monitoring via State Estimation?

Implementation

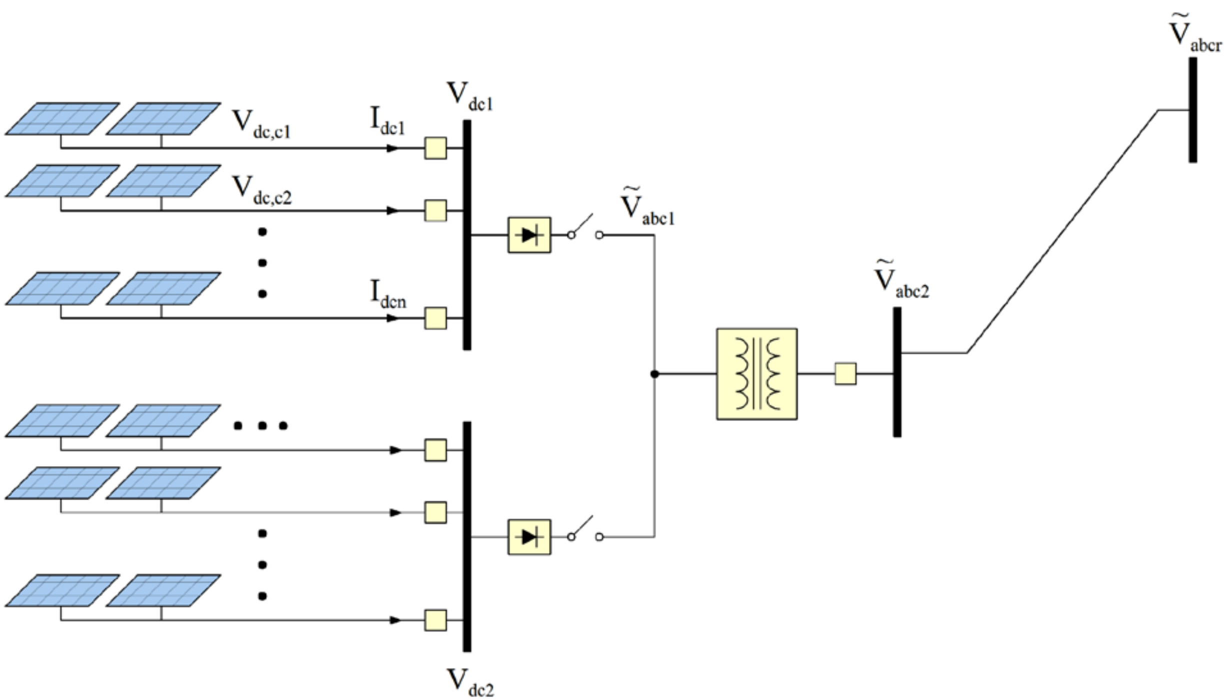
System is Represented with a Set of Differential Equations (DE) in terms of the system state
SYSTEM STATE: Voltages at each node of the system (see example system)
The State Estimator Fits the Streaming Data to the Model of the System via a least square approach.
END RESULT: Best estimate of system state, i.e. voltages at each node

The Estimator is Defined in Terms of:

- Model
- State
- Measurement Set
- Estimation Method

Observability

Redundancy

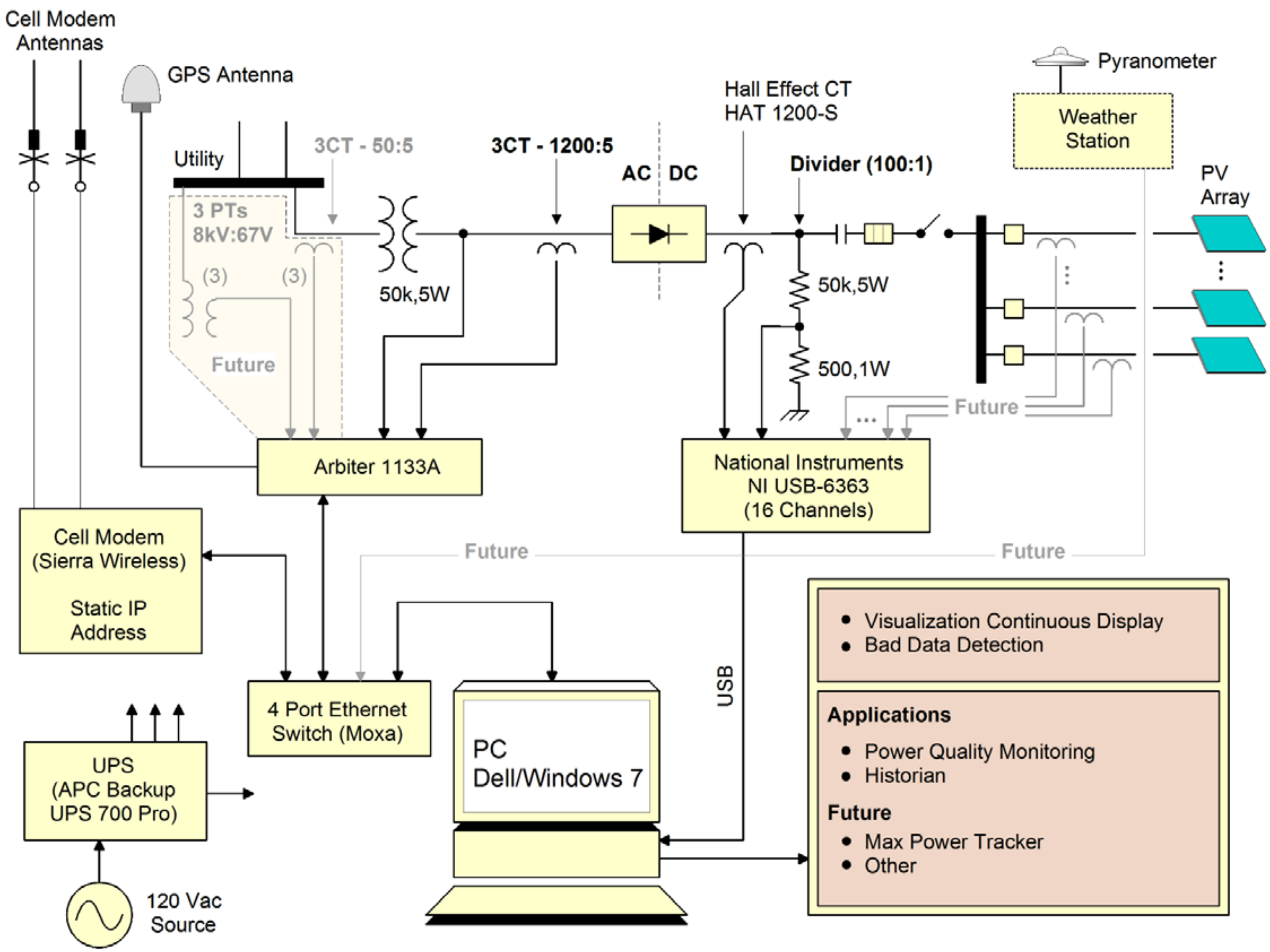


1.16 MW PV Array

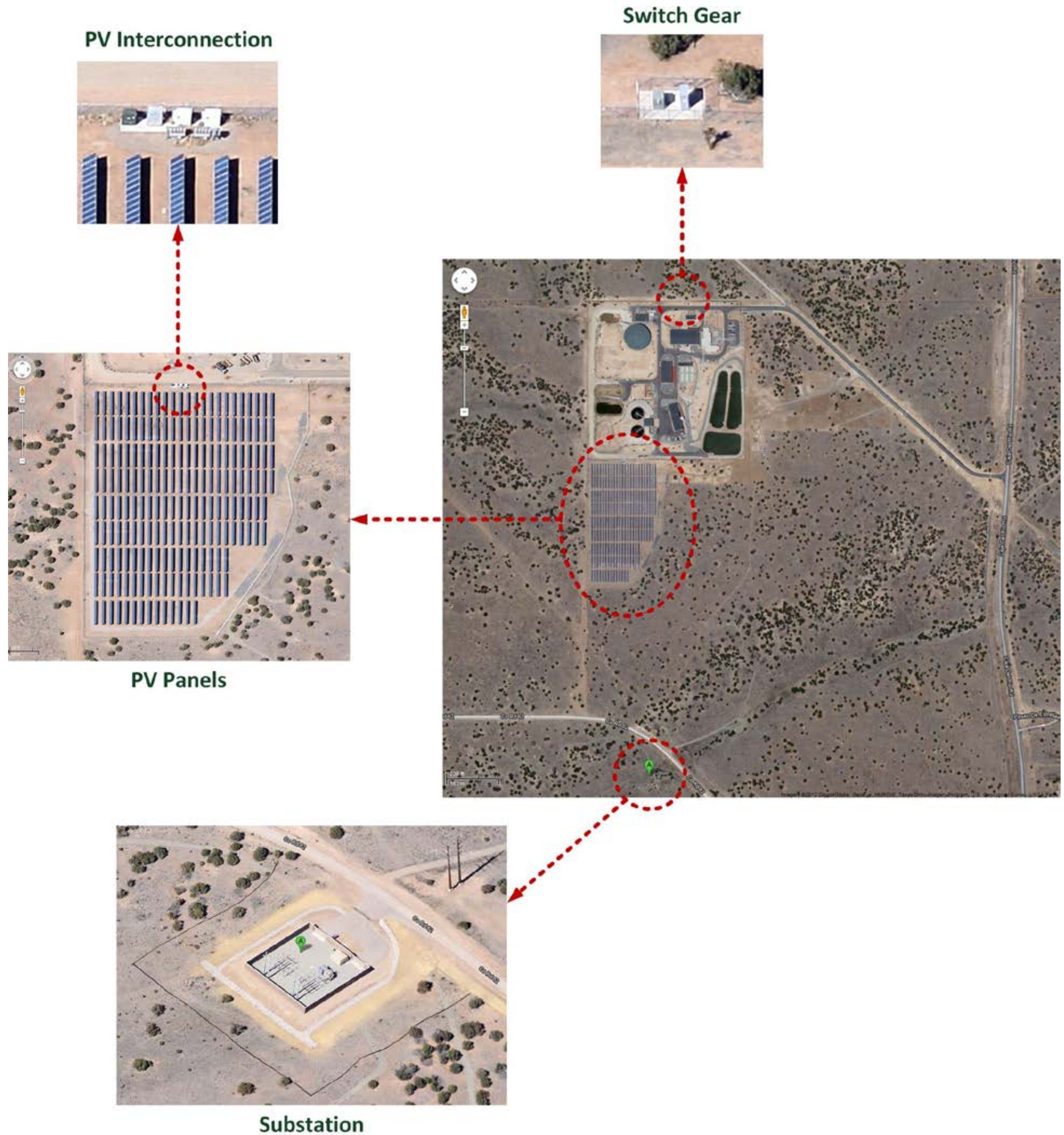
4224 Panels (270-280W)
2 Solarex Inverters (500kW each)
10 Combiners per Inverter

Field Demonstration

1.16 PV Array



Model Overview



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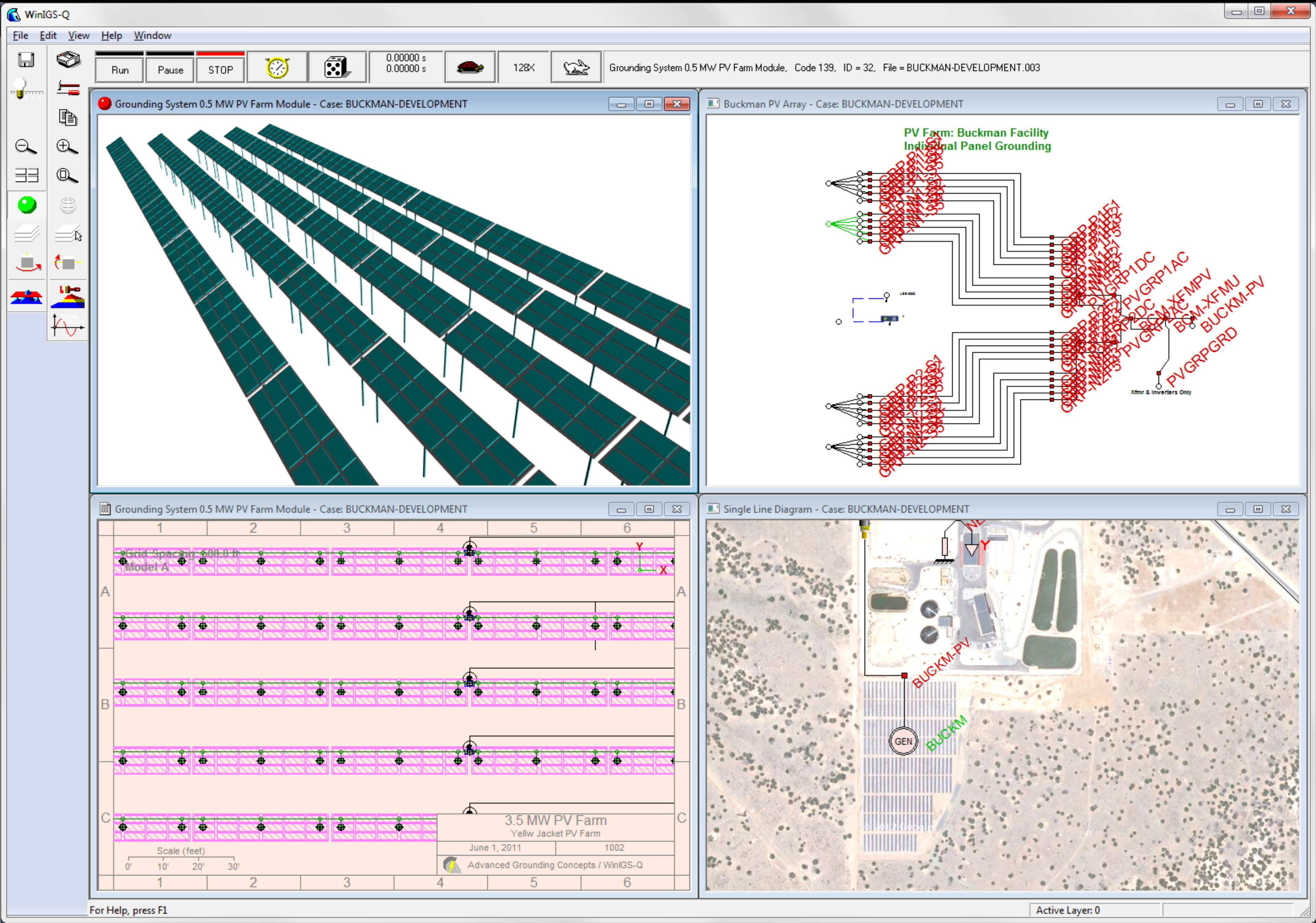
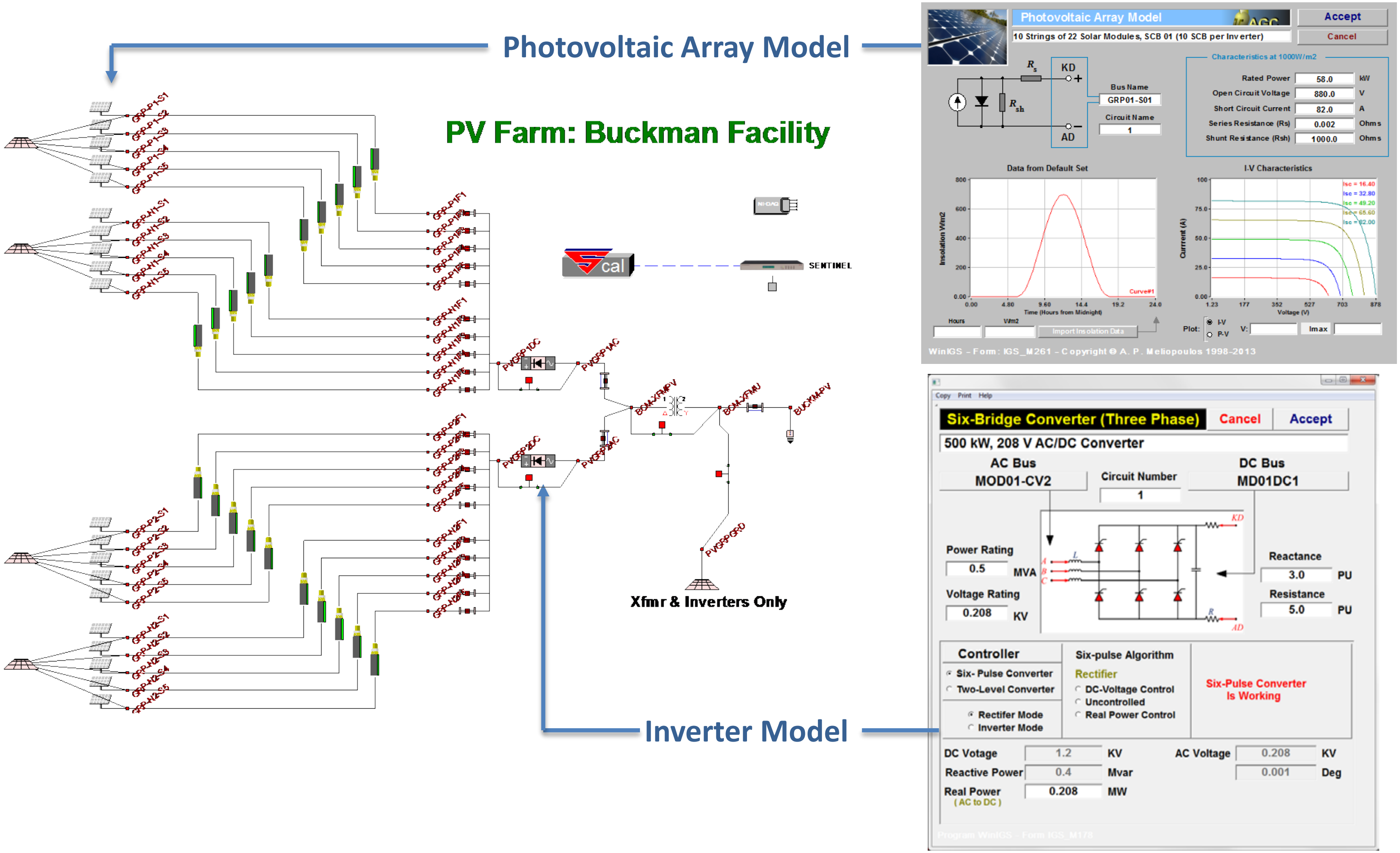
Buckman PV Array WinIGS Model



Buckman PV Array WinIGS Model

Buckman PV Array WinIGS Model

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



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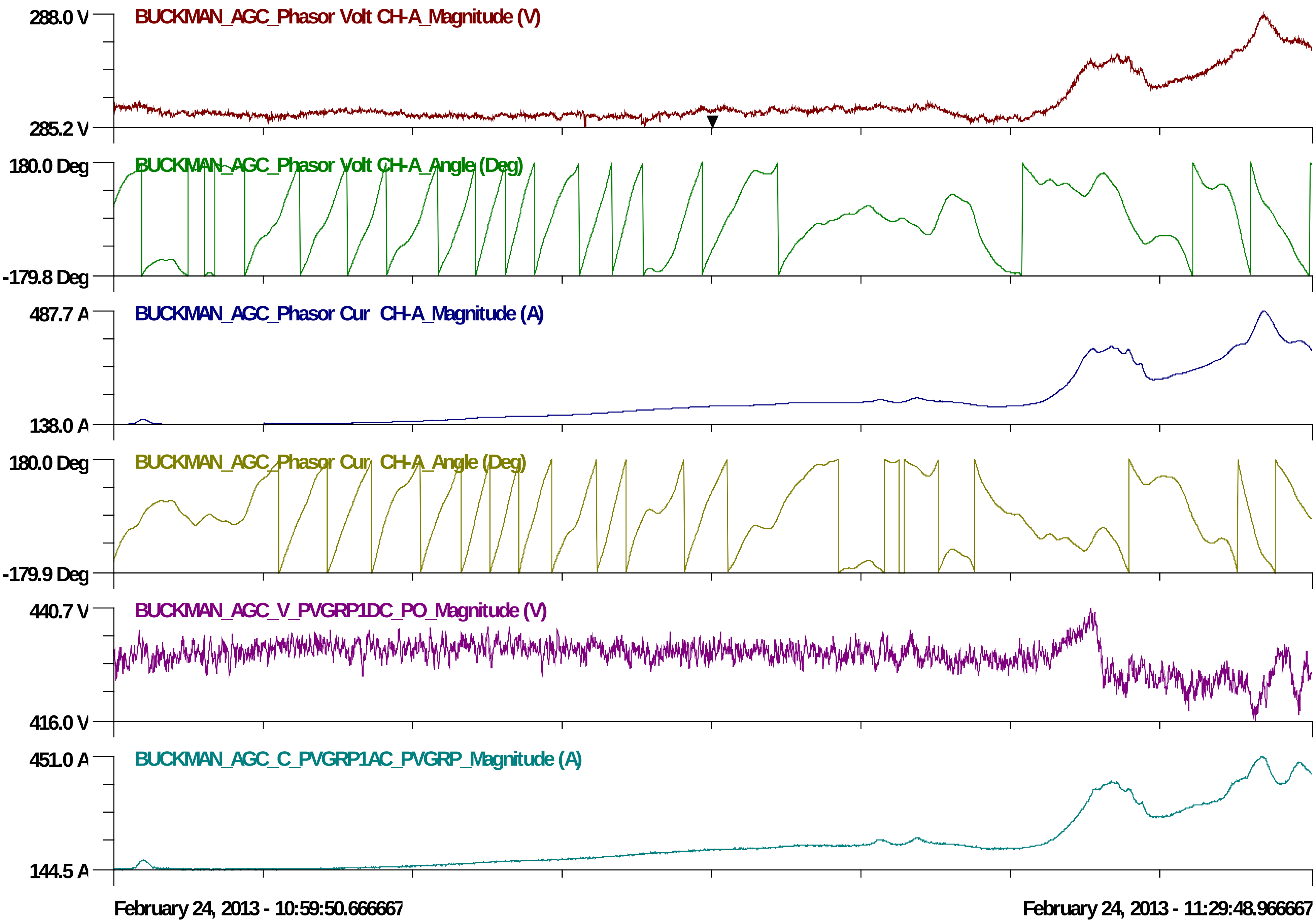
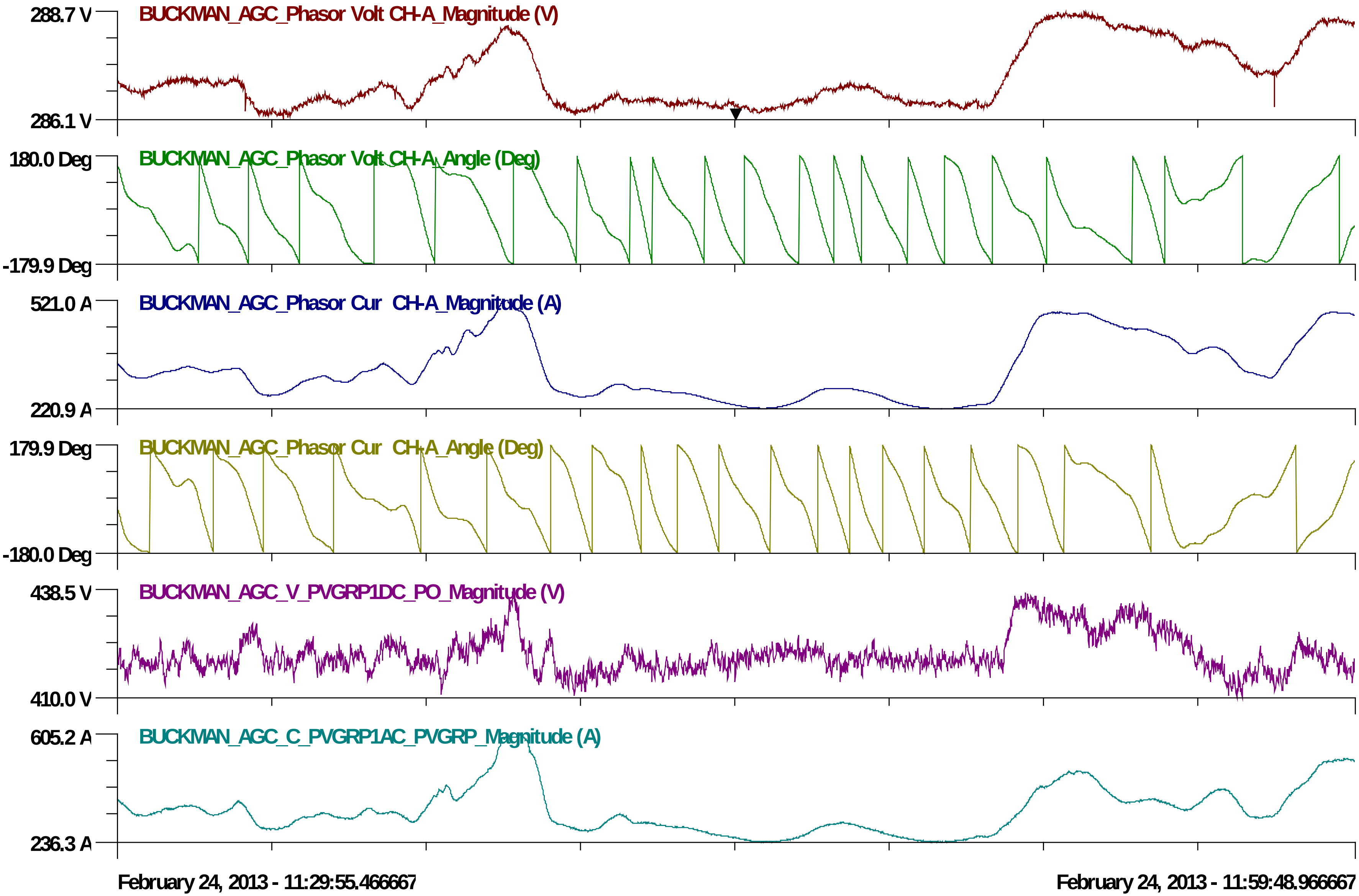
Field Data – 9:00 – 9:30 am (30 Samples / Sec)



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



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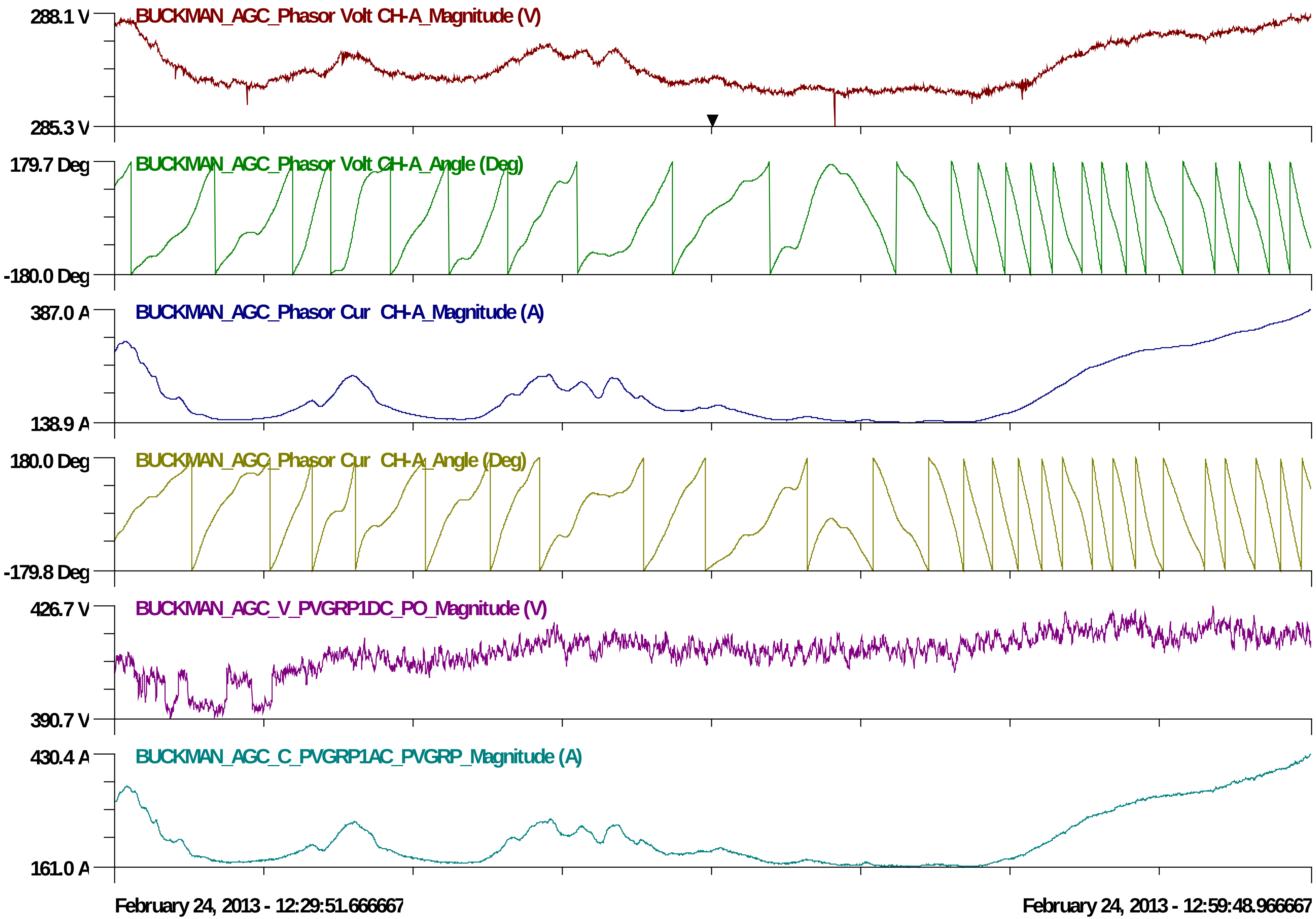
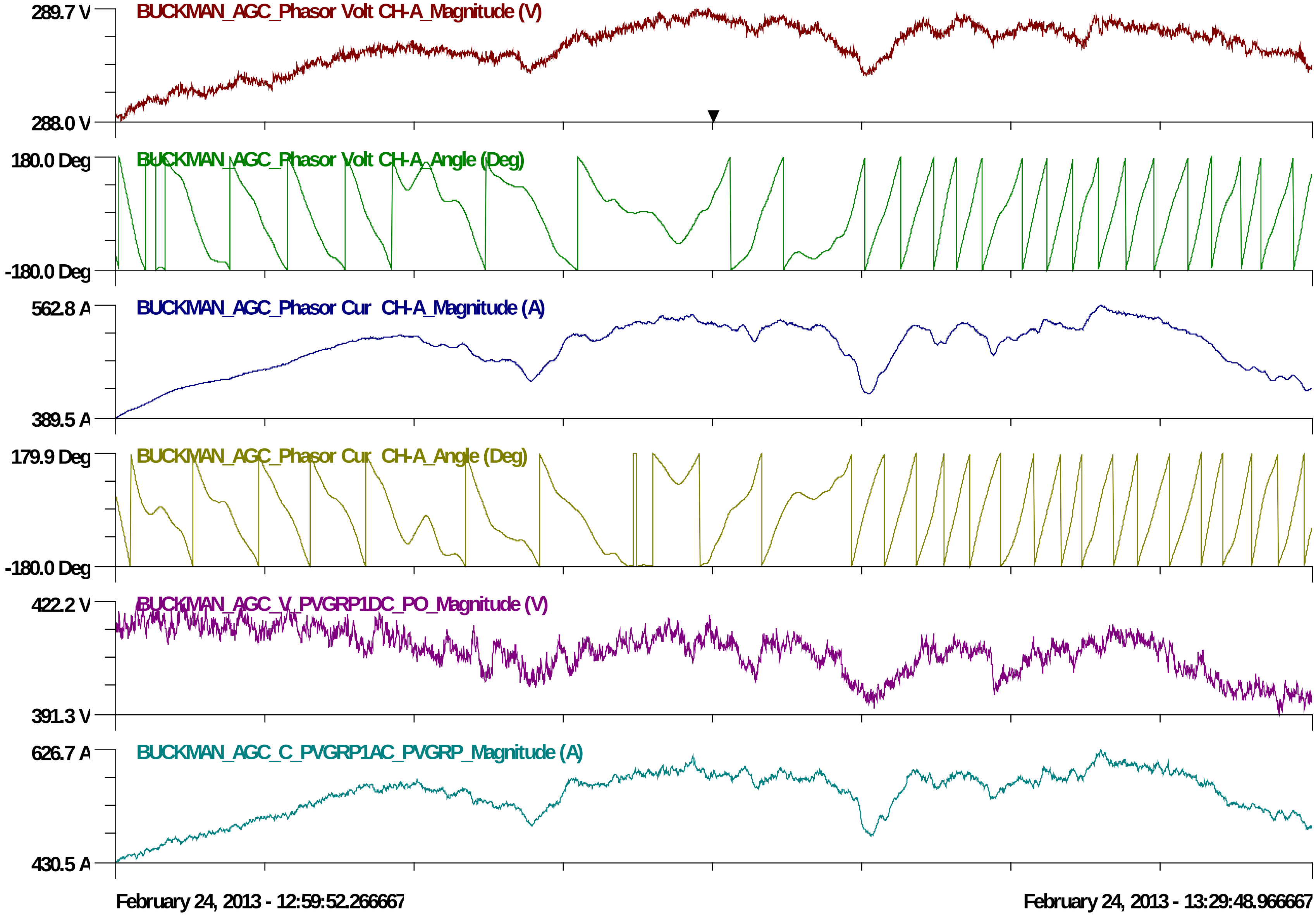
Field Data – 10:30 – 11:00 am (30 Samples / Sec)



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



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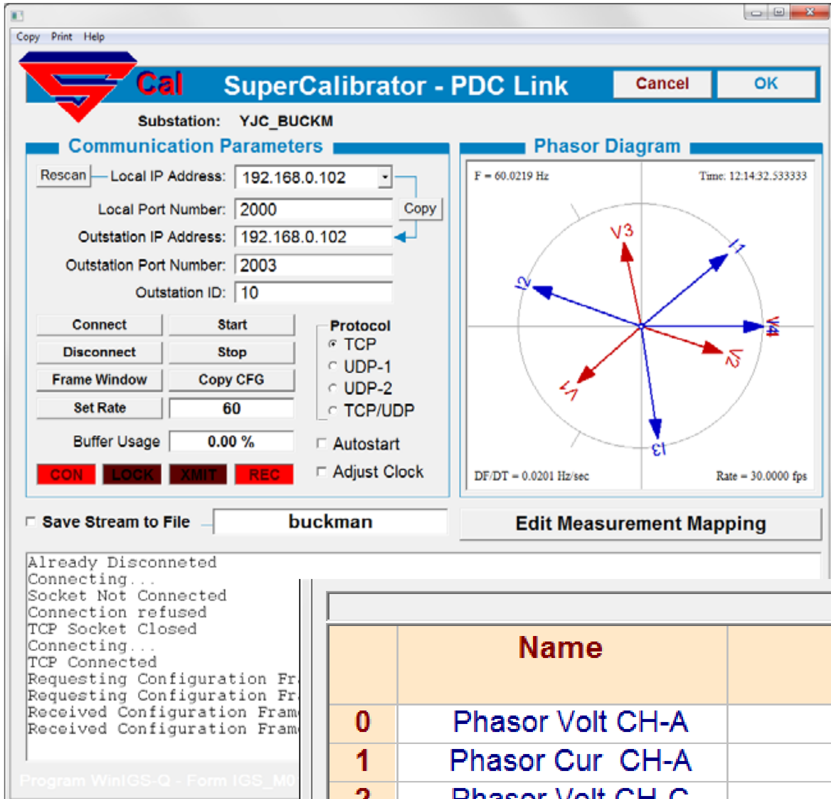
Synchrophasor Field Data Snapshot



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

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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