Distributed Dynamic State Estimator: Extension to Distribution Feeders

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Workshop on
Challenges for Distribution Planning, Operational and Real-time Planning Analytics
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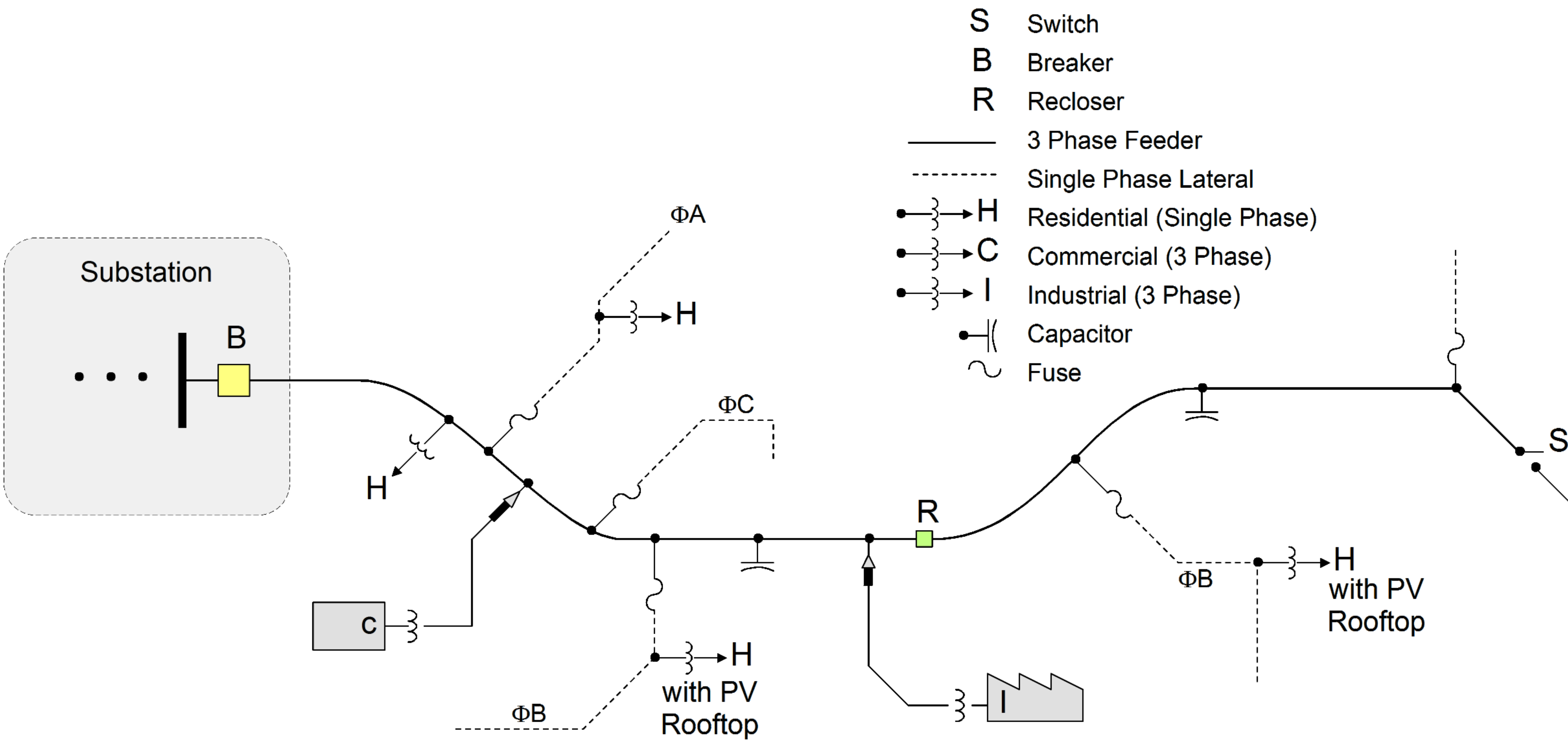
DS-SE Challenges



Issues, Challenges & Opportunities

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

Need to integrate existing measurements that may be at varying time scales

Typically not Enough for Full Observability

Feeder Sections May Be not Observable
Need to augment measurements set (virtual, derived, pseudo)

Implementation Approaches Become Important

Multiphase Modeling is a Necessity
Many More Power Devices than Transmission Systems
Measurement data at disparate time scales (very important obstacle)

Object Oriented DS-SE Formulation

Use Existing Measurements

Supplement with

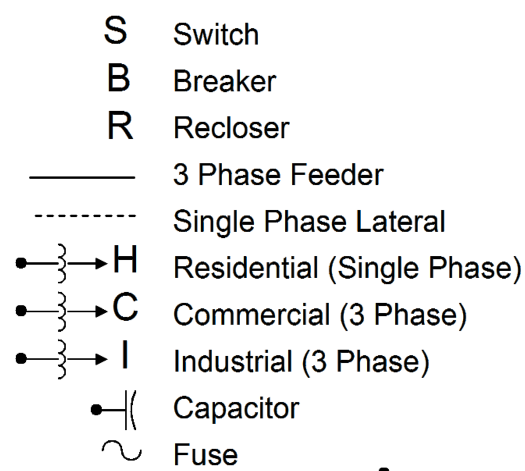
Virtual, Derived, and Pseudo-measurements

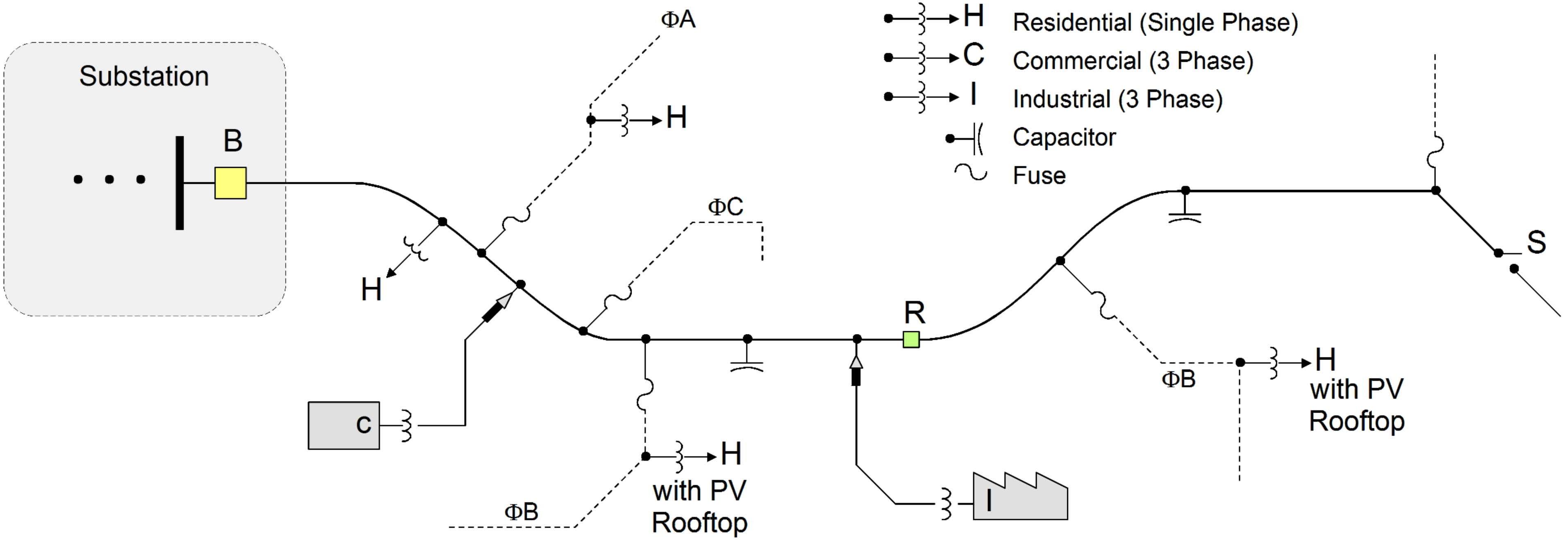
Distributed State Estimation:

Arbitrarily partition DS into Sections

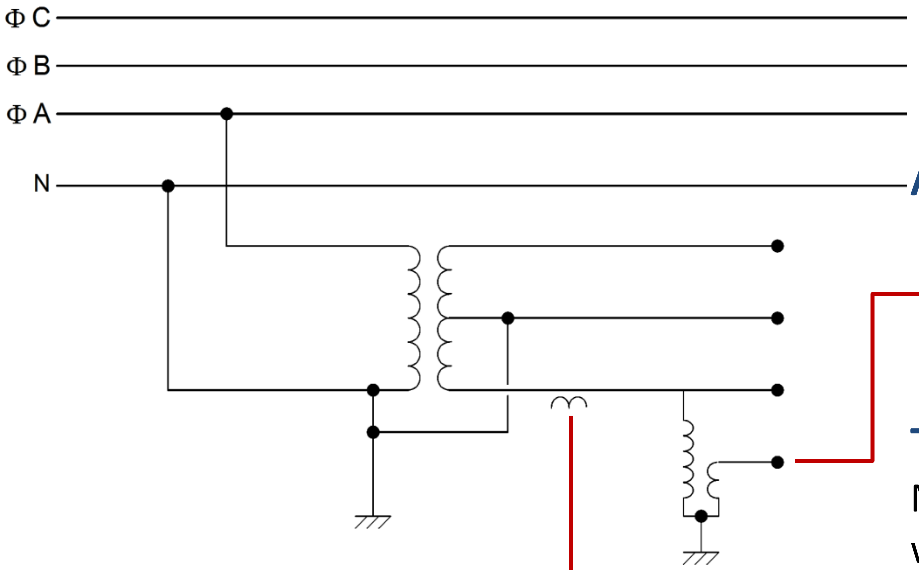
Need: At Least One GPS Sync Meas

At Each Section





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

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

Row k

Object Oriented Model

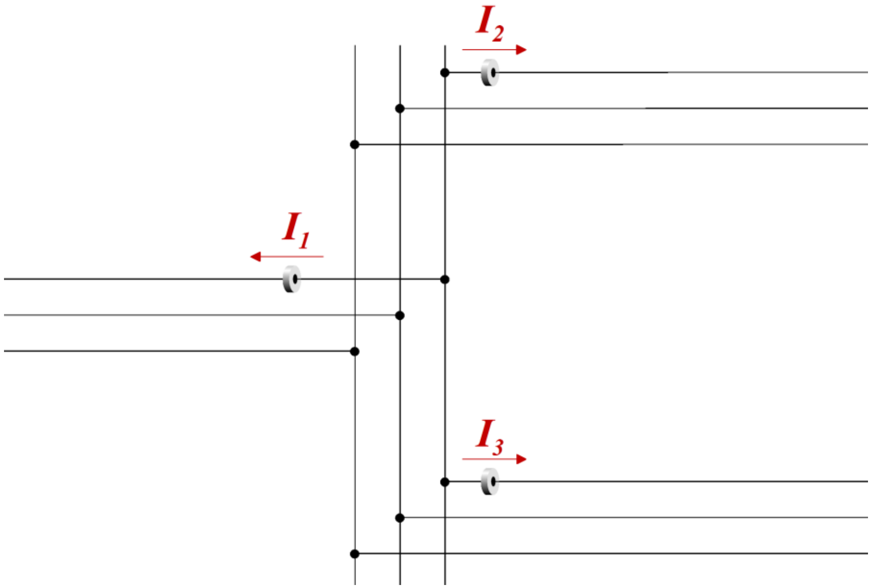
$$\begin{bmatrix} \tilde{I}(t) \\ 0 \\ \tilde{I}(t_m) \\ 0 \end{bmatrix} = Y_{eq} \begin{bmatrix} \tilde{V}(t) \\ \tilde{Y}(t) \\ \tilde{V}(t_m) \\ \tilde{Y}(t_m) \end{bmatrix} + \left[\left[\tilde{V}^T(t) \quad \tilde{Y}^T(t) \quad \tilde{V}^T(t_m) \quad \tilde{Y}^T(t_m) \right] \cdot F_{eq} \cdot \begin{bmatrix}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

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

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

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

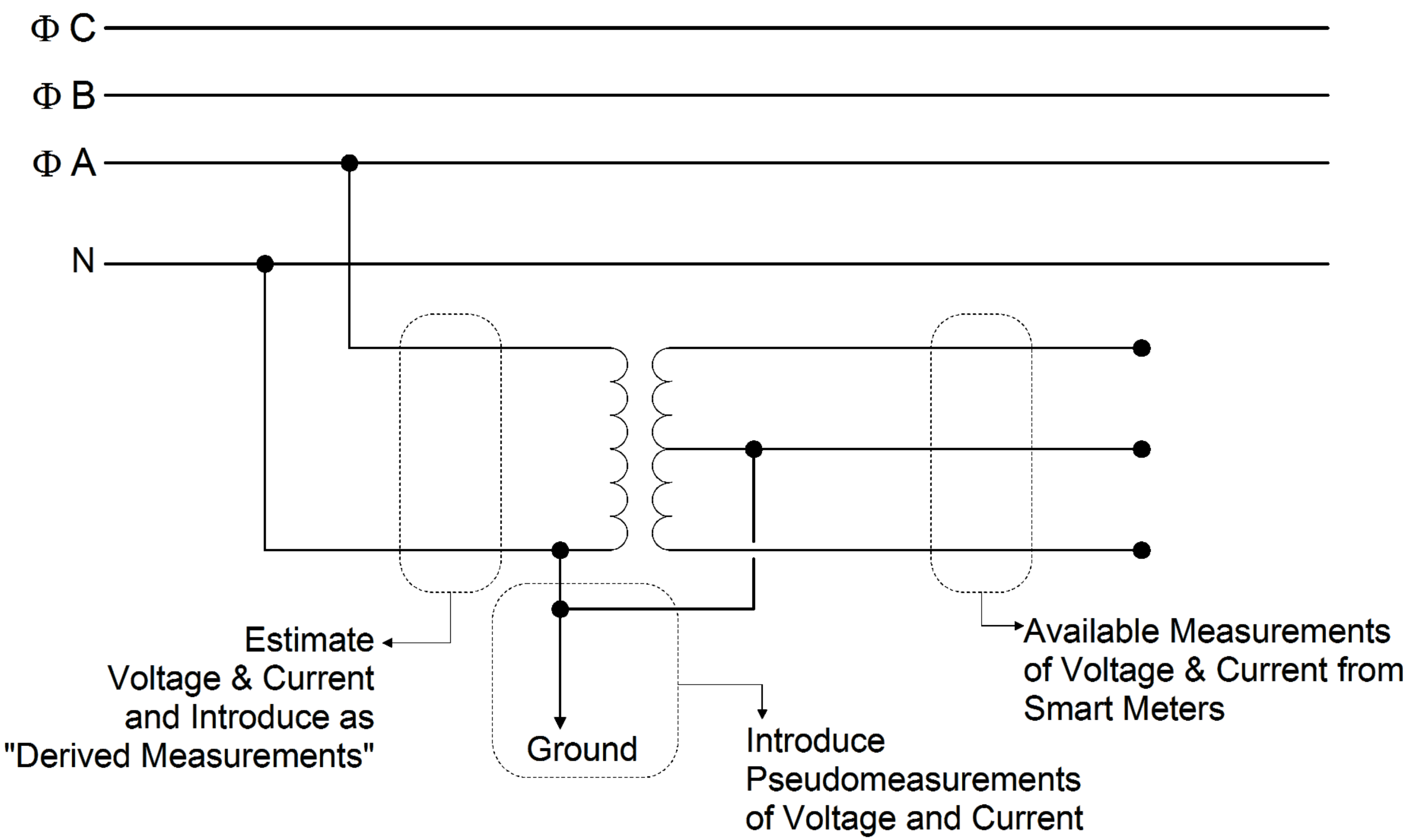
Virtual Measurement

$z_m = 0$ value

$\sigma_m = 0$ standard deviation

Distributed State Estimation

Derived and Pseudo-Measurements - Examples



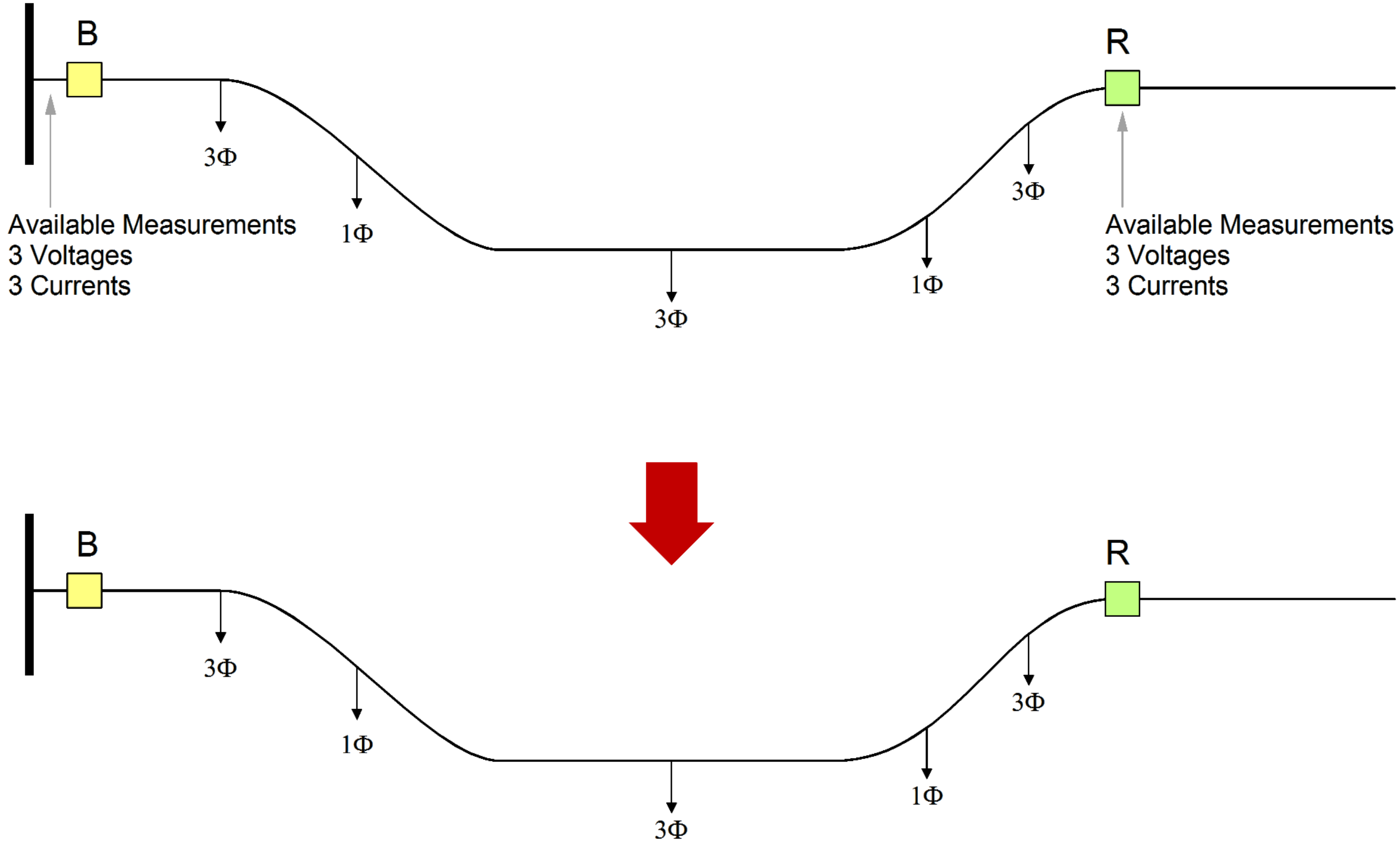
Distributed State Estimation

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



Define Current Pseudomeasurements as 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

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

Solution

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

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 Projects

Application to PV Farms (1.16 MW Array)

What is Monitoring via State Estimation?

Implementation: Inclusion of Both AC and DC sides

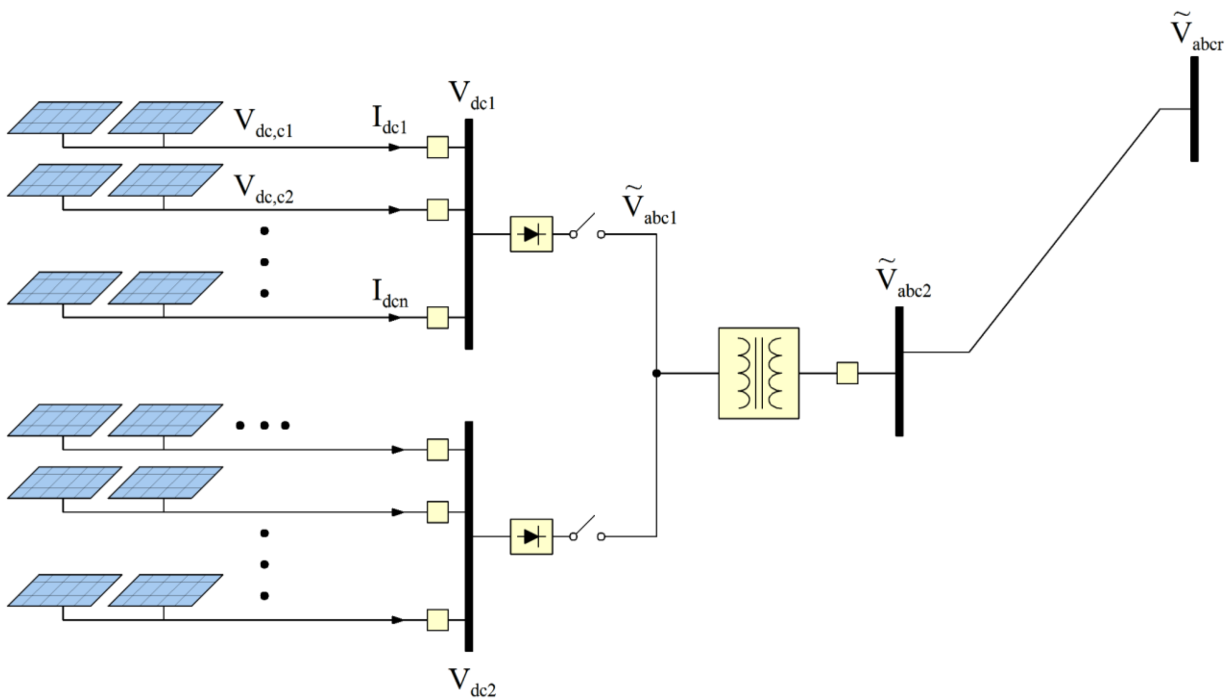
System is Represented with a Set of Differential Equations (DE) in terms of the system state
SYSTEM STATE: Voltages at each node of the system (see example system)
The State Estimator Fits the Streaming Data to the Model of the System via a least square approach.
END RESULT: Best estimate of system state,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

The Estimator is Defined in Terms of:

- Model
- State
- Measurement Set
- Estimation Method

Observability

Redundancy

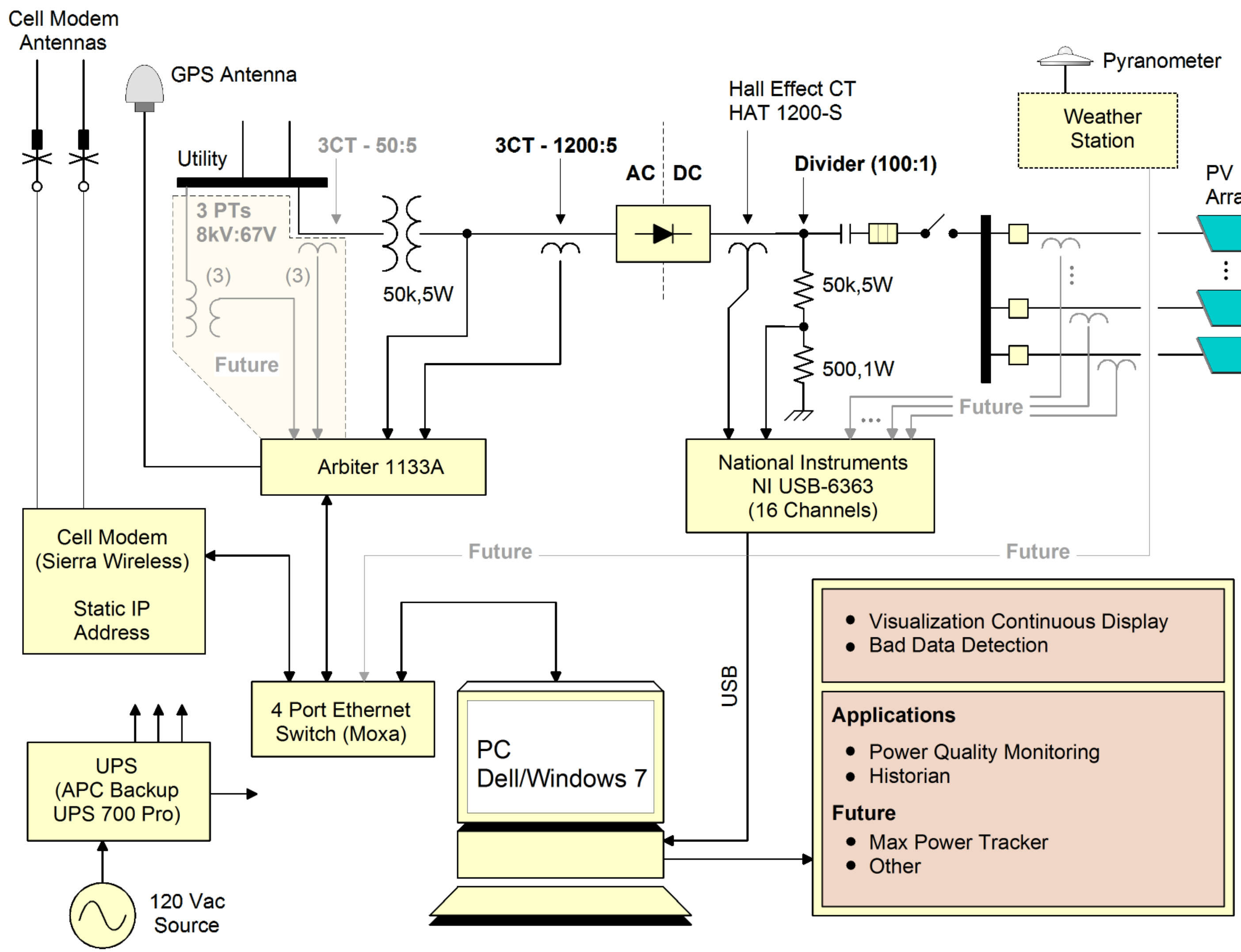


1.16 MW PV Array

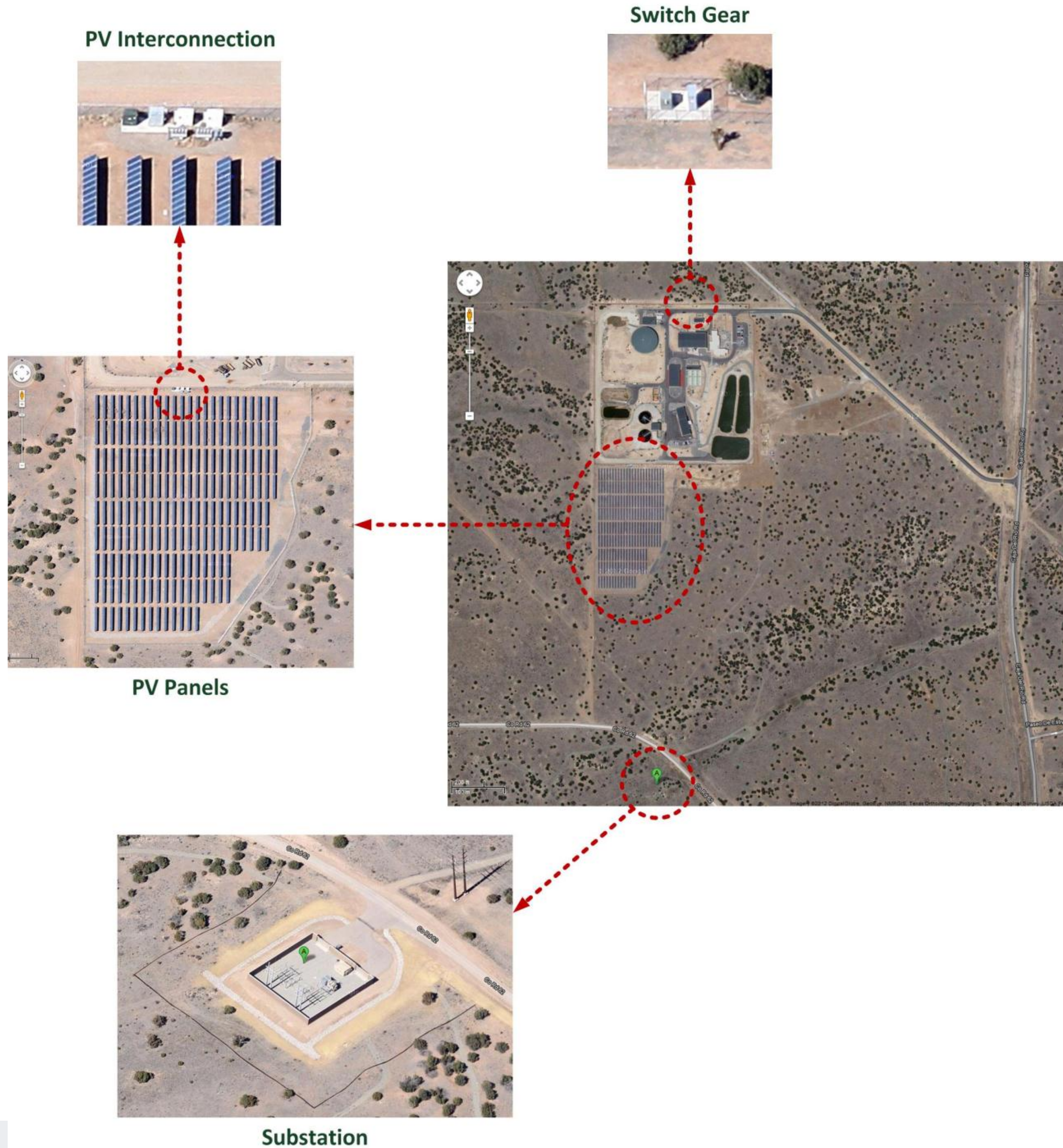
4224 Panels (270-280W)
2 Solarex Inverters (500kW each)
10 Combiners per Inverter

Field Demonstration

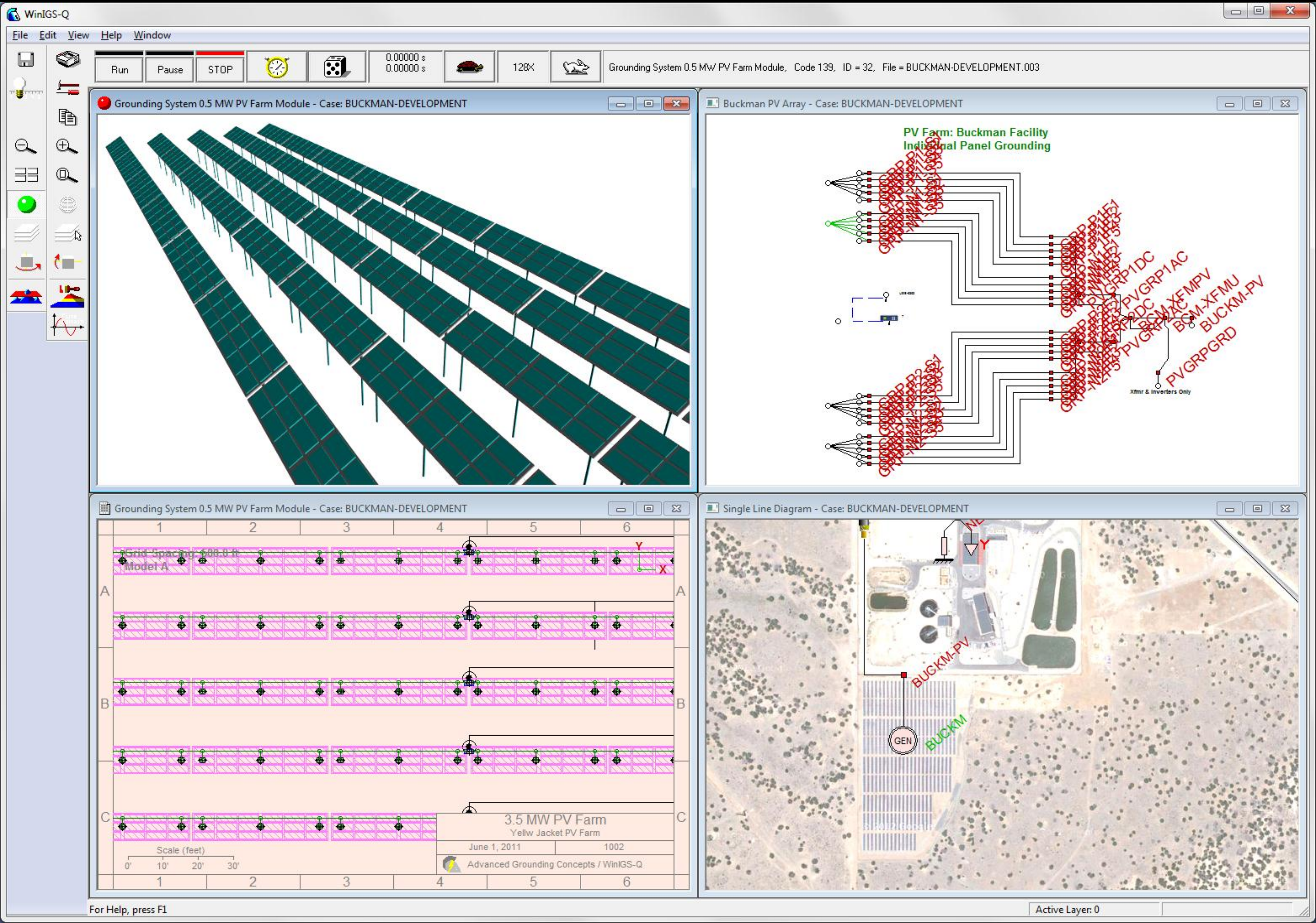
1.16 PV Array



Model Overview



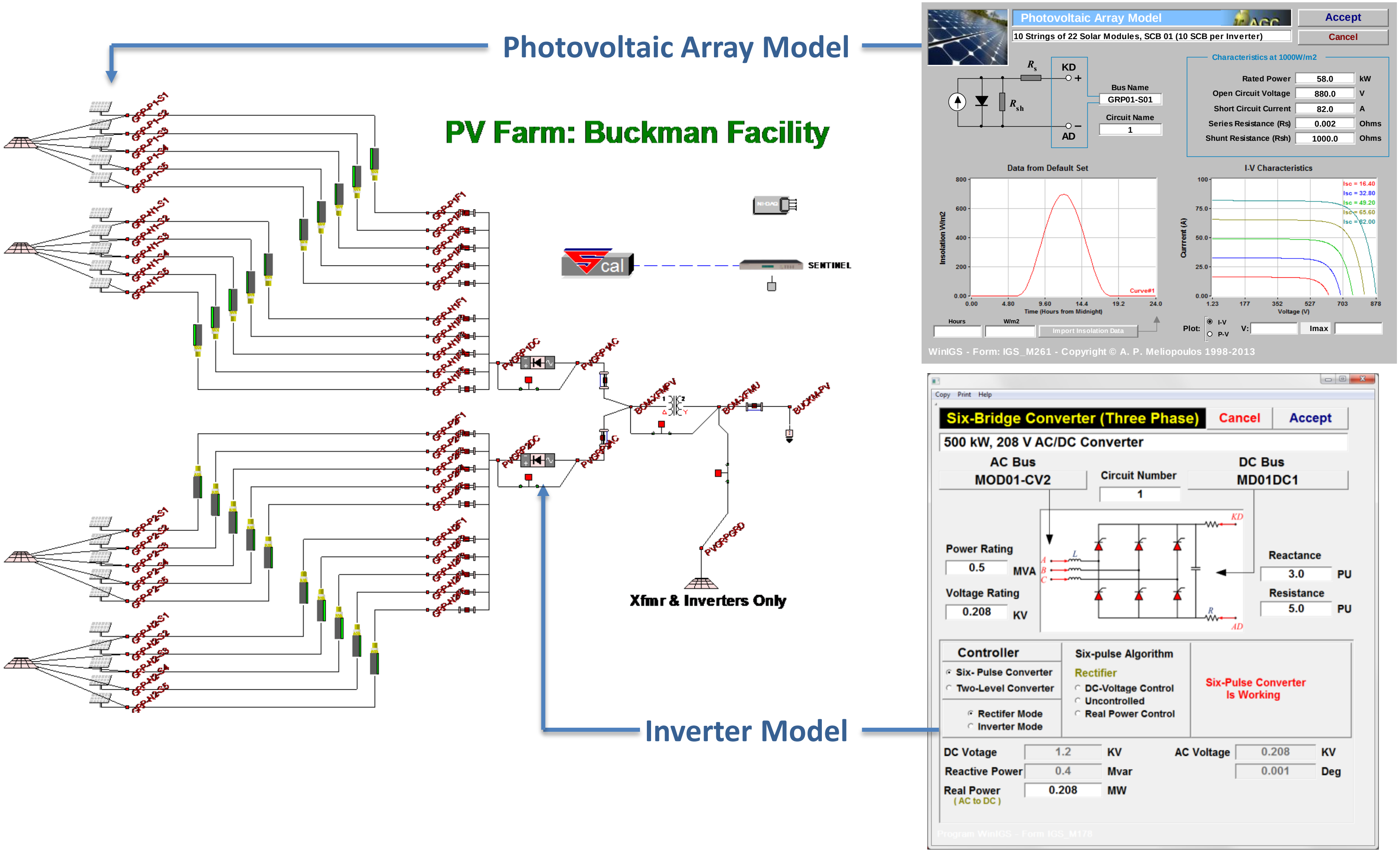
Buckman PV Array WinIGS Model



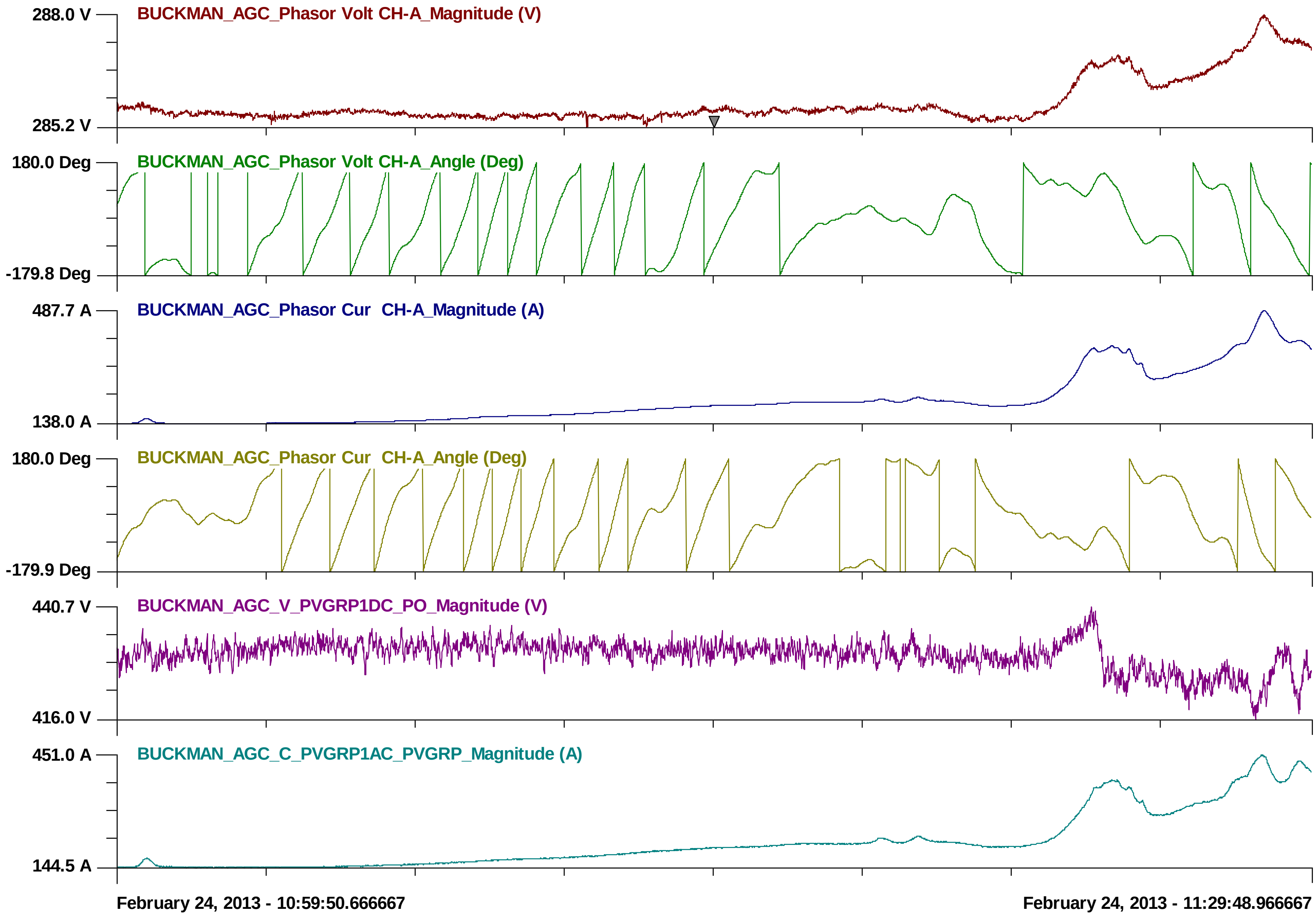
Buckman PV Array WinIGS Model

Buckman PV Array WinIGS Model

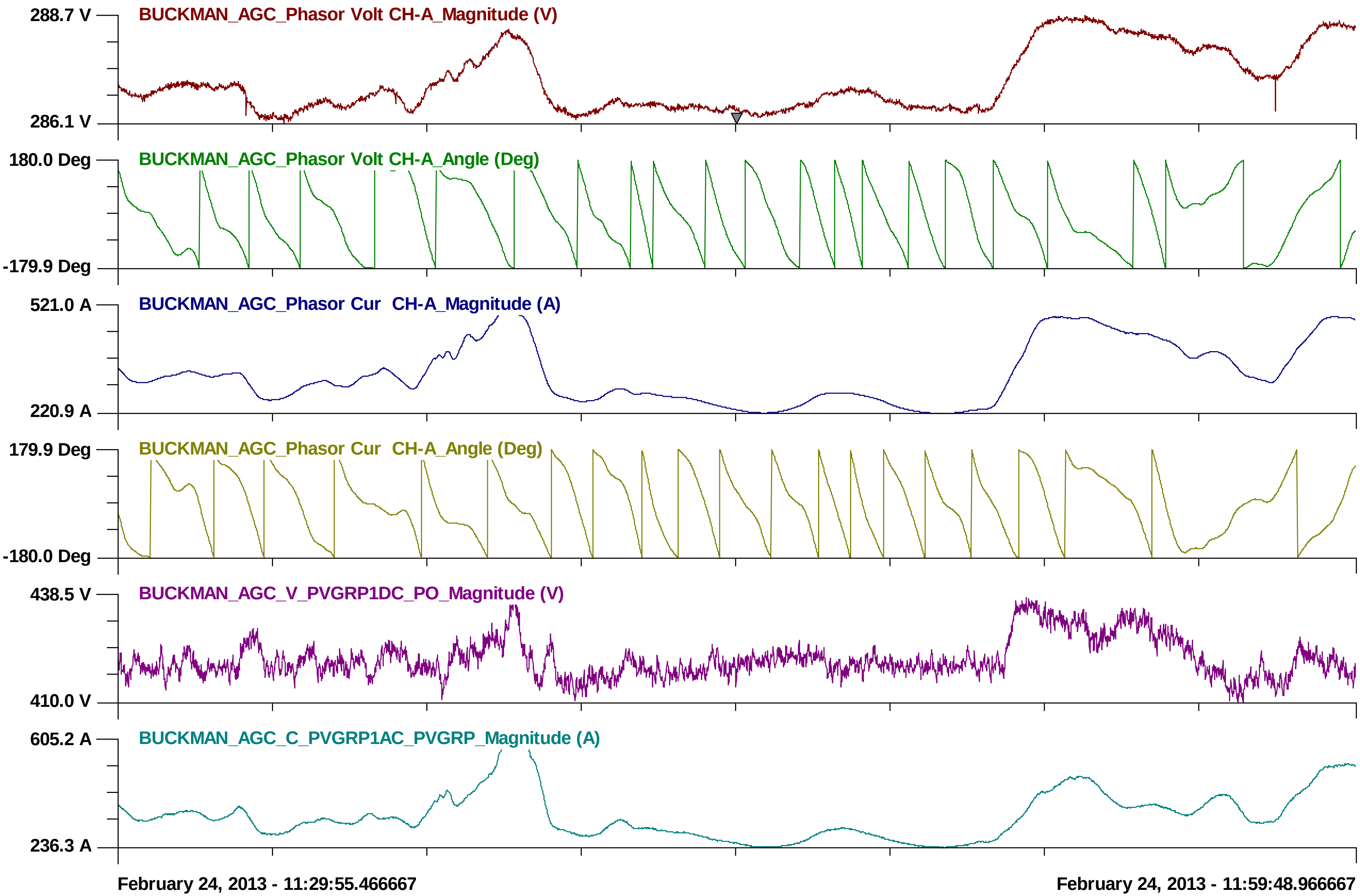
PV Module Model: PV Strings, PV String model, Converter Model



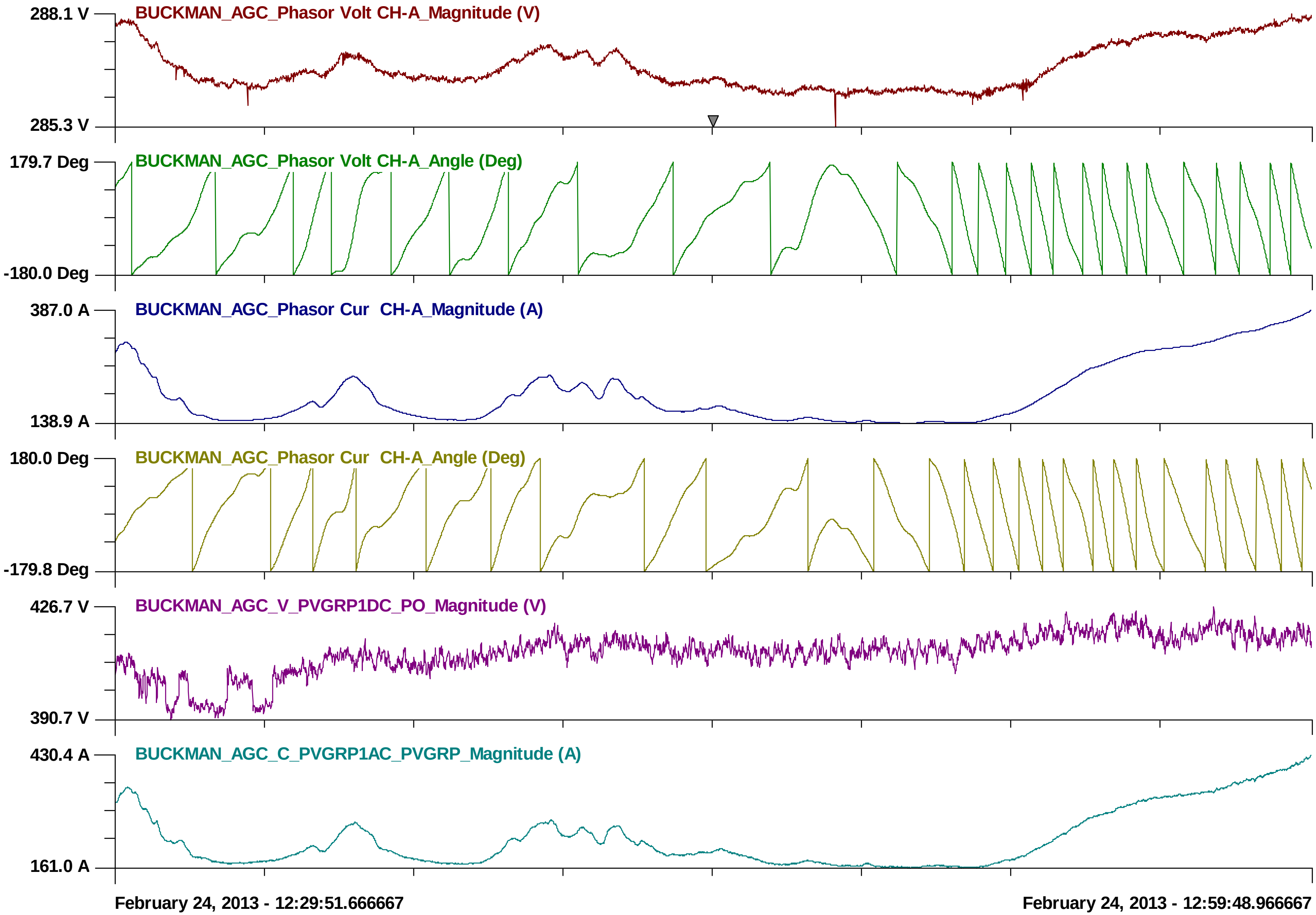
Field Data – 9:00 – 9:30 am (30 Samples / Sec)



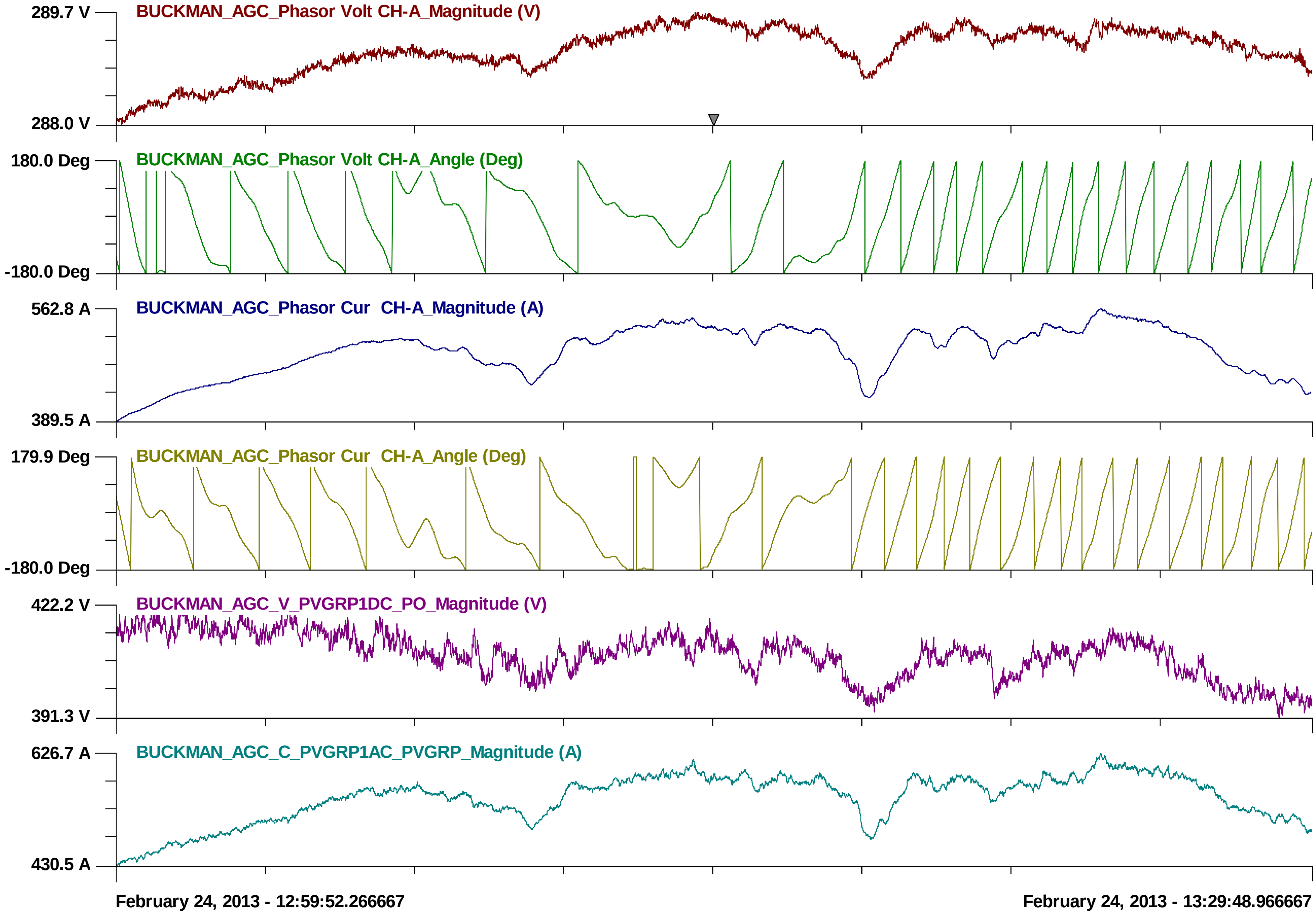
Field Data – 9:30 – 10:00 am (30 Samples / Sec)



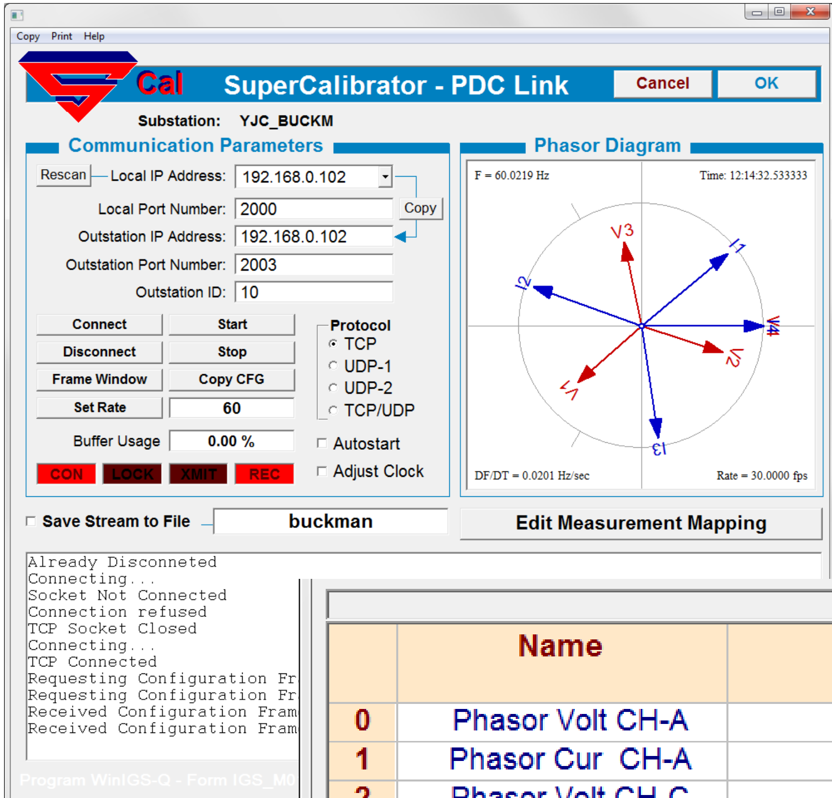
Field Data – 10:30 – 11:00 am (30 Samples / Sec)



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



Synchrophasor Field Data Snapshot



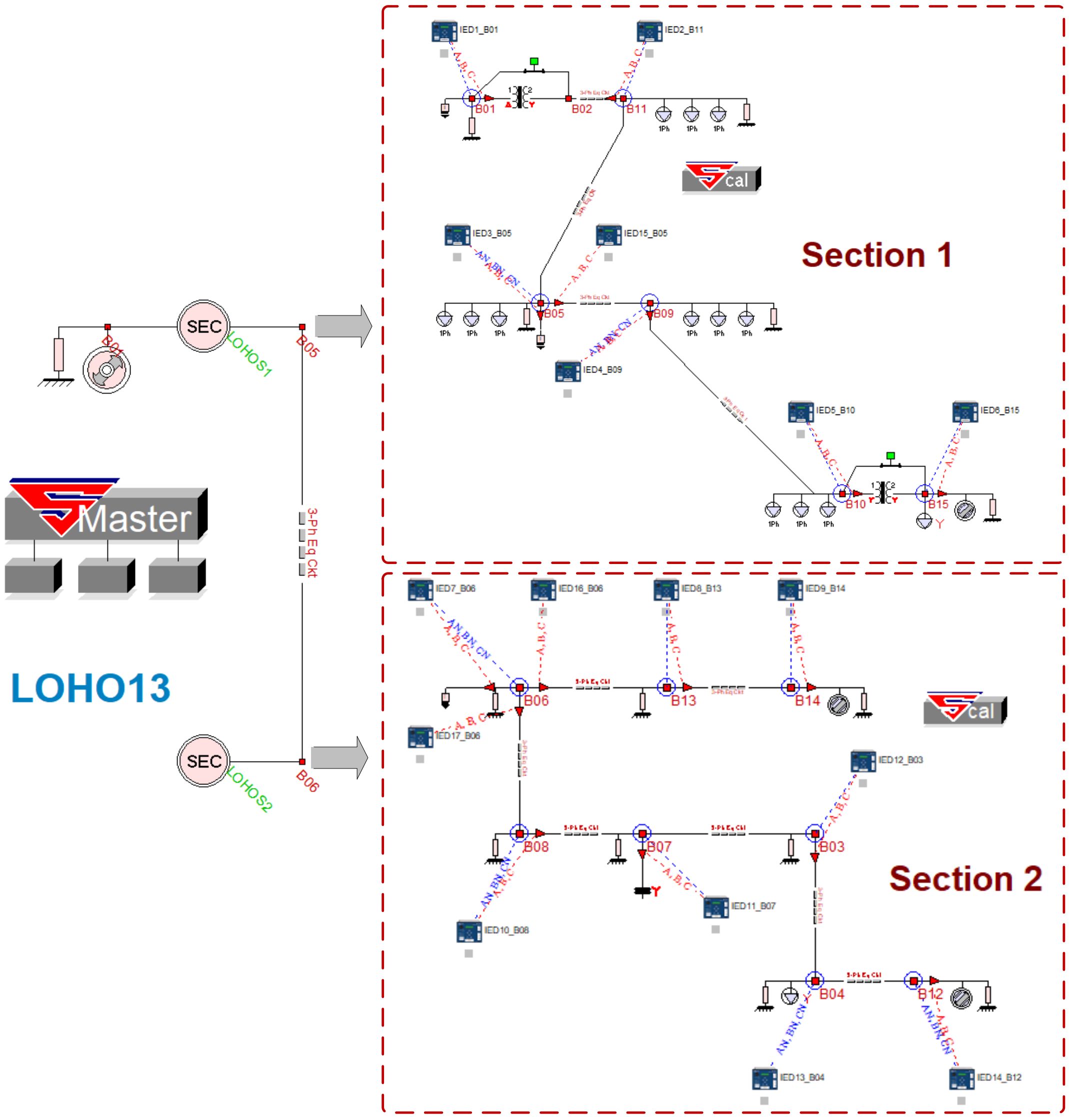
Phasors

	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

Demonstration Projects

ENERGIZE Project: Voltage Regulation and Protection Assurance using DER Advanced Grid Functions (lead: SNL)

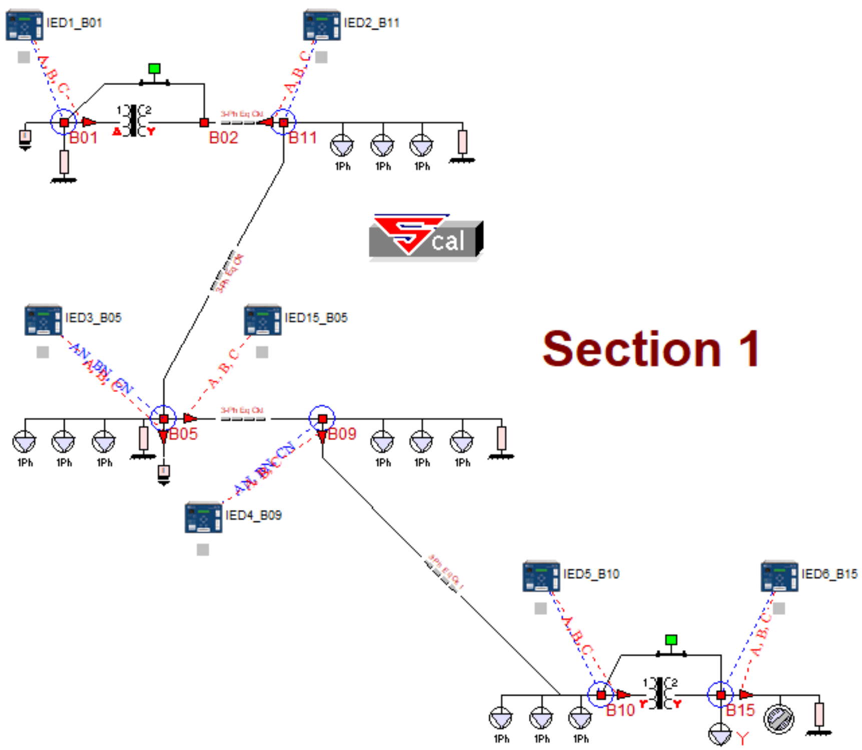
Demonstration Example – PNM LOHO13 Feeder



LOHO13 Reduced Feeder Model

- LOHO13 Reduced Feeder Model (15-three-Phase buses) provided by PNM.
- Rated Voltage: 12.47 kV/0.48 kV
- The feeder is separated into two sections, with each section containing a state estimator.
- Each state estimator runs quasi-dynamic state estimation in the local section and outputs the estimated states, estimated measurements, and validated model to the master state estimator.

LOHO13 Feeder – Section 1



Section 1

Measurements from Section 1 (7 IEDs)

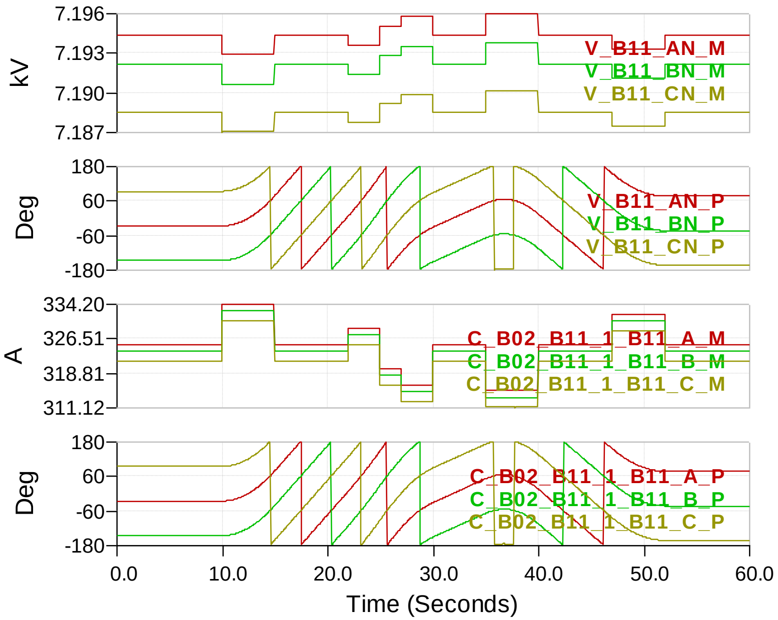
IED Name	Voltage Measurements	Current Measurements	# of Measurements
IED1_B01	AN, BN, CN at B01	A, B, C at B01, from B01 to B02 (Tran1)	6
IED2_B11	AN, BN, CN at B11	A, B, C at B11, from B11 to B02 (Line149)	6
IED3_B05	AN, BN, CN at B05	A, B, C at B05, from B05 to B06 (Line59)	6
IED4_B09	AN, BN, CN at B09	A, B, C at B09, from B09 to B10 (Line105)	6
IED5_B10	AN, BN, CN at B10	A, B, C at B10, from B10 to B15 (Tran20)	6
IED6_B15	AN, BN, CN at B15	A, B, C at B15, into the PV Source (PVSy3)	6
IED15_B05		A, B, C at B05, from B05 to B09 (Line135)	3

System Configuration:

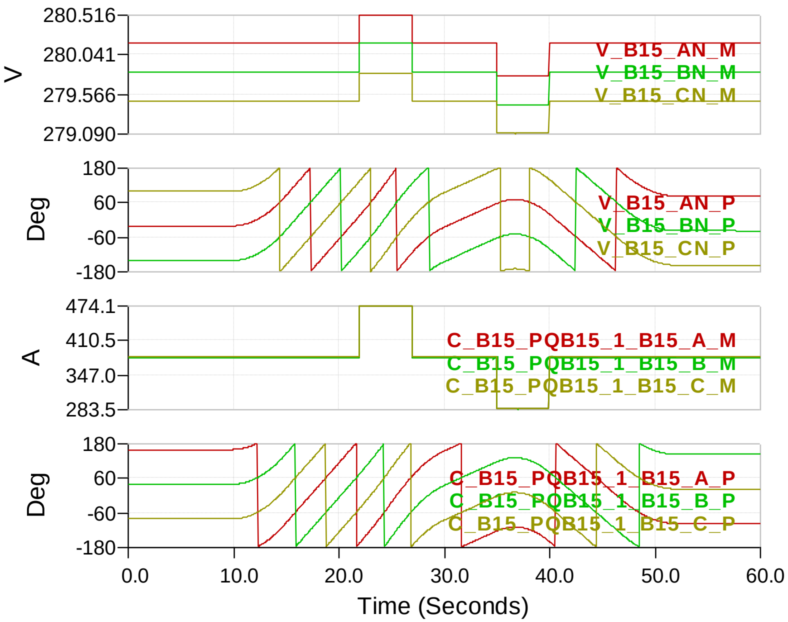
- 2 three-phase two-winding XFMRs (115/12.47 kV, 12.47/0.48 kV)
- 6 three-phase distribution line segments
- 1 three-phase load (0.48 kV)
- 12 single-phase loads (feed: 7.2 kV)
- Total load consumption: 683.6 kW, 126.71 kVar
- 1 PV source (0.48 kV, 258 kW)

LOHO13 Feeder – Section 1

- **Section 1 (7 IEDs installed)**
  - 18 voltage & 21 current phasor measurements, 78 actual measurements in total.
  - 120 type I derived measurements, 30 type II derived measurements, 42 virtual measurements, and 14 pseudo measurements.
  - States: 114, Measurements: 284, Redundancy: 249.12%.
  - 60-second event, sampling rate: 60 samples/second, PV output changes during the event.



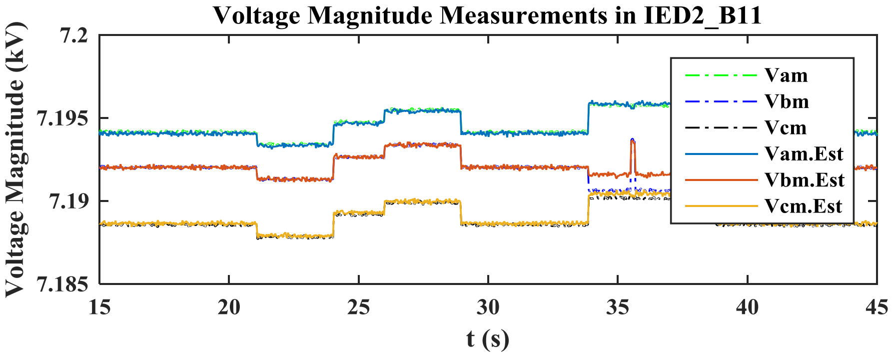
Measurements from IED2_B11 (located at bus B11)

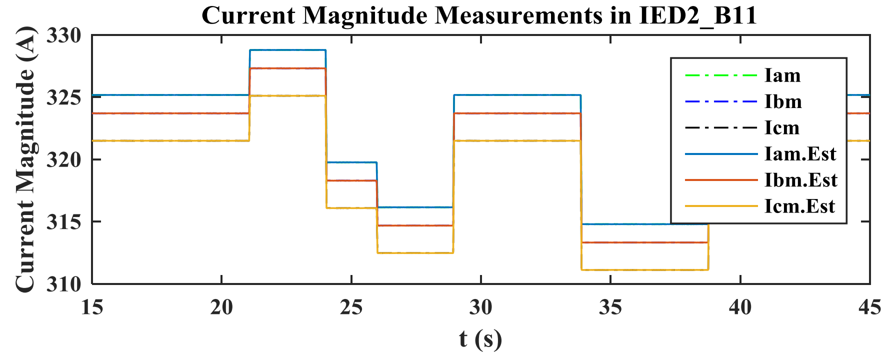


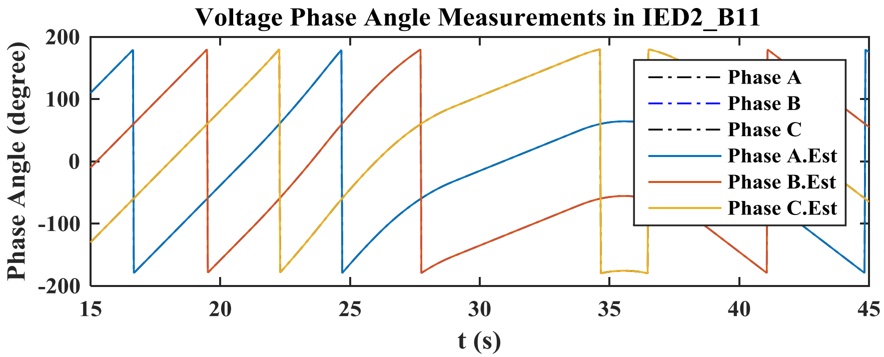
Measurements from IED6_B15 (located at bus B15)

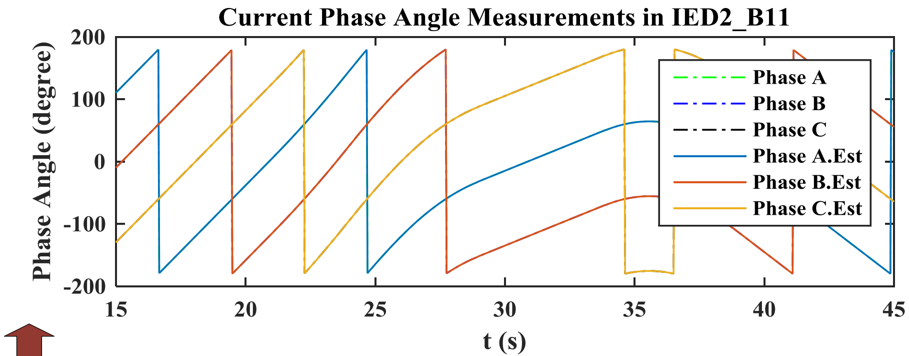
LOHO13 Feeder – Section 1

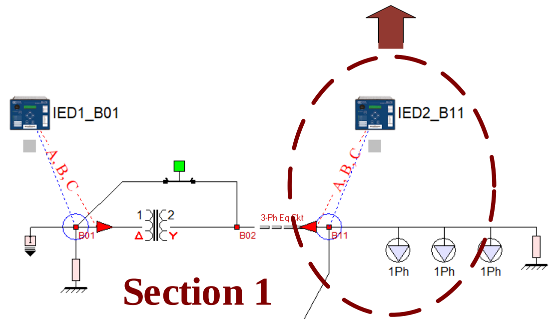
- **State Estimation Results – Measurements** & Estimated Measurements





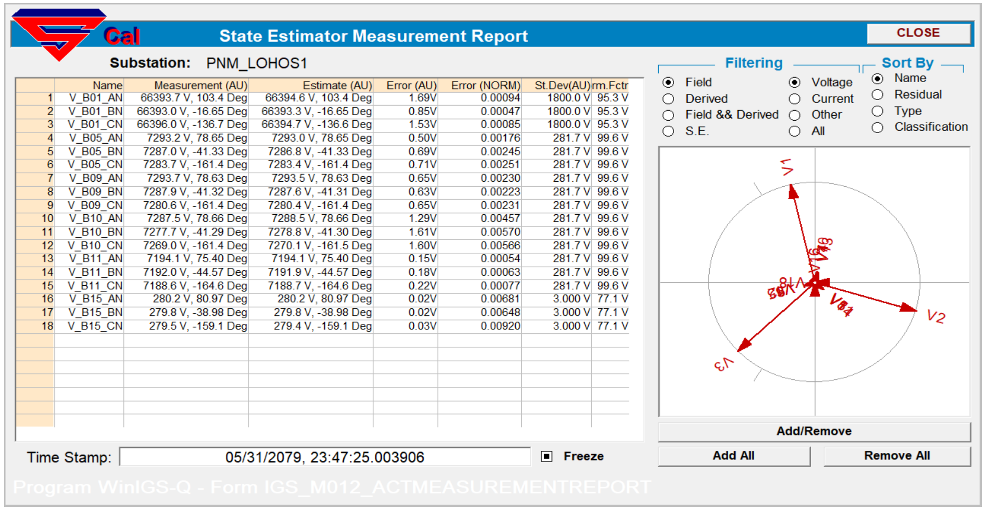






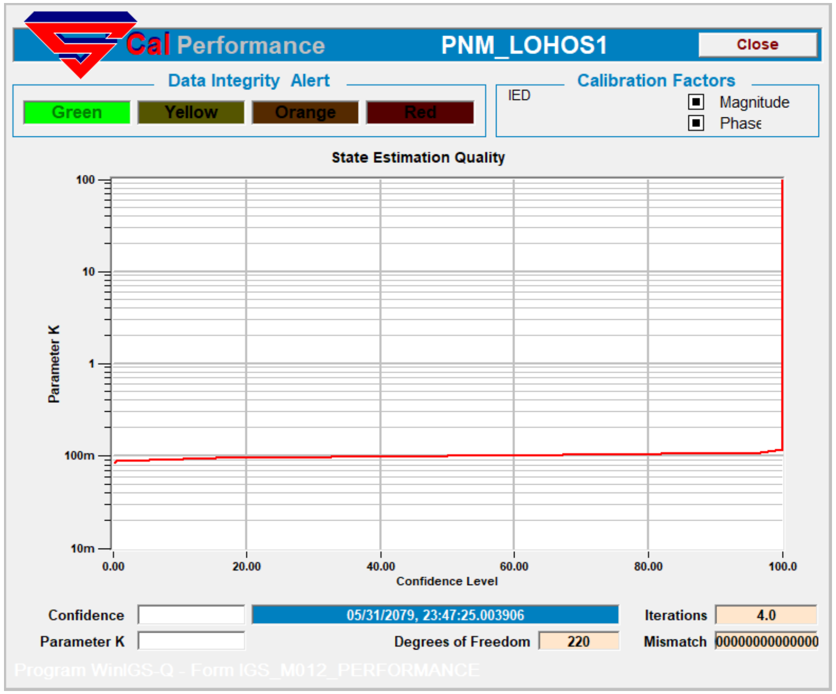
LOHO13 Feeder – Section 1

- State Estimation Results



	Name	Measurement (AU)	Estimate (AU)	Error (AU)	Error (NORM)	St.Dev(AU)	rm.Fctr
1	V_B01_AN	66393.7 V, 103.4 Deg	66394.6 V, 103.4 Deg	1.69V	0.00094	1800.0 V	95.3 V
2	V_B01_BN	66393.0 V, -16.65 Deg	66393.3 V, -16.65 Deg	0.85V	0.00047	1800.0 V	95.3 V
3	V_B01_CN	66396.0 V, -136.7 Deg	66394.7 V, -136.6 Deg	1.53V	0.00085	1800.0 V	95.3 V
4	V_B05_AN	7293.2 V, 78.65 Deg	7293.0 V, 78.65 Deg	0.50V	0.00176	281.7 V	99.6 V
5	V_B05_BN	7287.0 V, -41.33 Deg	7286.8 V, -41.33 Deg	0.69V	0.00245	281.7 V	99.6 V
6	V_B05_CN	7283.7 V, -161.4 Deg	7283.4 V, -161.4 Deg	0.71V	0.00251	281.7 V	99.6 V
7	V_B09_AN	7293.7 V, 78.63 Deg	7293.5 V, 78.63 Deg	0.65V	0.00230	281.7 V	99.6 V
8	V_B09_BN	7287.9 V, -41.32 Deg	7287.6 V, -41.31 Deg	0.63V	0.00223	281.7 V	99.6 V
9	V_B09_CN	7280.6 V, -161.4 Deg	7280.4 V, -161.4 Deg	0.65V	0.00231	281.7 V	99.6 V
10	V_B10_AN	7287.5 V, 78.66 Deg	7288.5 V, 78.66 Deg	1.29V	0.00457	281.7 V	99.6 V
11	V_B10_BN	7277.7 V, -41.29 Deg	7278.8 V, -41.30 Deg	1.61V	0.00570	281.7 V	99.6 V
12	V_B10_CN	7269.0 V, -161.4 Deg	7270.1 V, -161.5 Deg	1.60V	0.00566	281.7 V	99.6 V
13	V_B11_AN	7194.1 V, 75.40 Deg	7194.1 V, 75.40 Deg	0.15V	0.00054	281.7 V	99.6 V
14	V_B11_BN	7192.0 V, -44.57 Deg	7191.9 V, -44.57 Deg	0.18V	0.00063	281.7 V	99.6 V
15	V_B11_CN	7188.6 V, -164.6 Deg	7188.7 V, -164.6 Deg	0.22V	0.00077	281.7 V	99.6 V
16	V_B15_AN	280.2 V, 80.97 Deg	280.2 V, 80.97 Deg	0.02V	0.00681	3.000 V	77.1 V
17	V_B15_BN	279.8 V, -38.98 Deg	279.8 V, -38.98 Deg	0.02V	0.00648	3.000 V	77.1 V
18	V_B15_CN	279.5 V, -159.1 Deg	279.4 V, -159.1 Deg	0.03V	0.00920	3.000 V	77.1 V

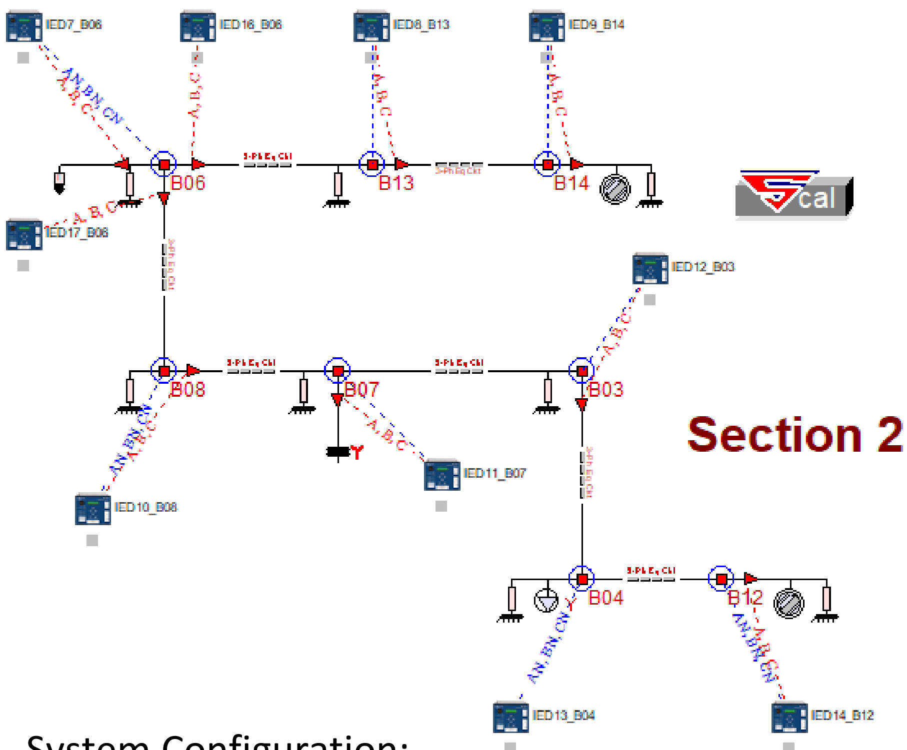
Snapshot of SE Voltage Measurement Report, Section 1



Confidence Level of Section 1

- Estimated measurements track the measurements accurately.
- All errors are small.
- Confidence level of section 1 remains at 100% → the estimated states of this section are trustworthy, the system model of this section is validated.

LOHO13 Feeder – Section 2



Measurement from Section 2 (10 IEDs)

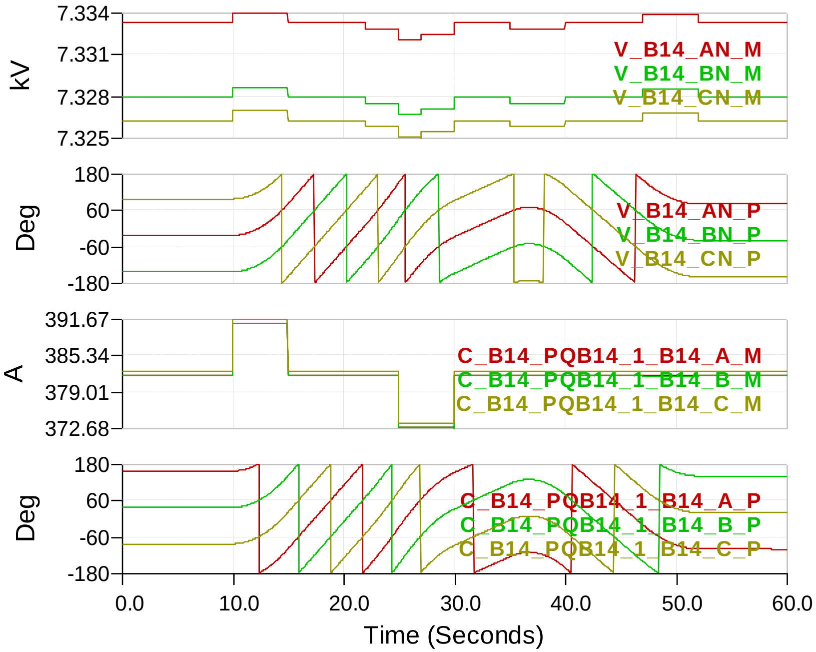
IED Name	Voltage Measurements	Current Measurements	# of Measurements
IED7_B06	AN, BN, CN at B06	A, B, C at B06, from B06 to B05 (Line59)	6
IED8_B13	AN, BN, CN at B13	A, B, C at B13, from B13 to B14 (Line196)	6
IED9_B14	AN, BN, CN at B14	A, B, C at B14, into the PV Source (PVSy2)	6
IED10_B08	AN, BN, CN at B08	A, B, C at B08, from B08 to B07 (Line97)	6
IED11_B07	AN, BN, CN at B07	A, B, C at B07, into the capacitor bank (Capa1)	6
IED12_B03	AN, BN, CN at B03	A, B, C at B03, from B03 to B04 (Line4)	6
IED13_B04	AN, BN, CN at B04		3
IED14_B12	AN, BN, CN at B12	A, B, C at B12, into the PV Source (PVSy1)	6
IED16_B06		A, B, C at B06, from B06 to B13 (Line167)	3
IED17_B06		A, B, C at B06, from B06 to B08 (Line188)	3

System Configuration:

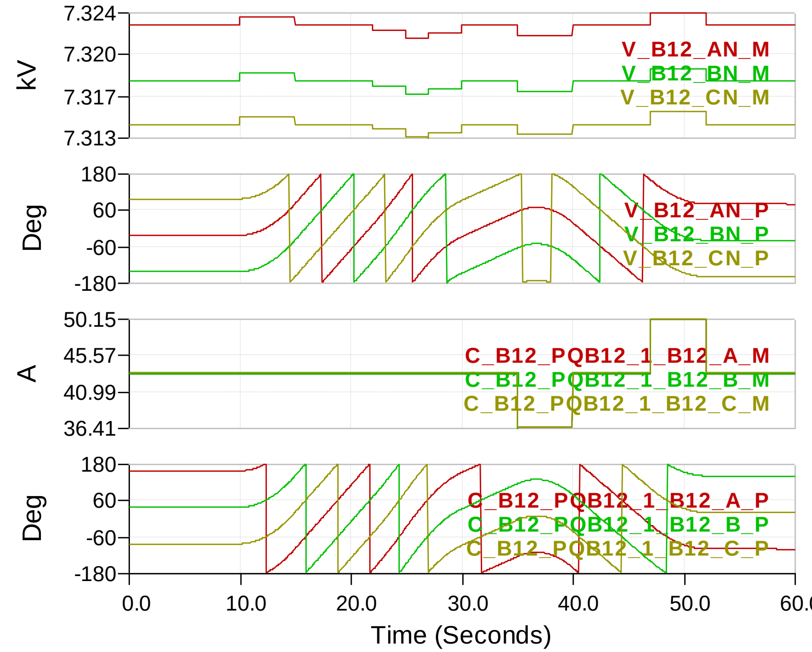
- 8 three-phase distribution line segments
- 1 three-phase load (12.47 kV, 1885 kW, 1292 kVar)
- 1 capacitor bank (12.47 kV, 1800 kVar)
- 2 PV source
  - PV at bus B14 (12.47 kV, 1 MW)
  - PV at Bus B12 (12.47 kV, 10 MW)

LOHO13 Feeder – Section 2

- **Section 2 (10 IEDs installed)**
  - 24 voltage & 27 current phasor measurements, 102 actual measurements in total.
  - 66 type I derived measurements, 14 type II derived measurements, 20 virtual measurements, and 16 pseudo measurements.
  - States: 88, Measurements: 218, Redundancy: 247.73%.
  - 60-second event, sampling rate: 60 samples/second , PV output changes during the event.



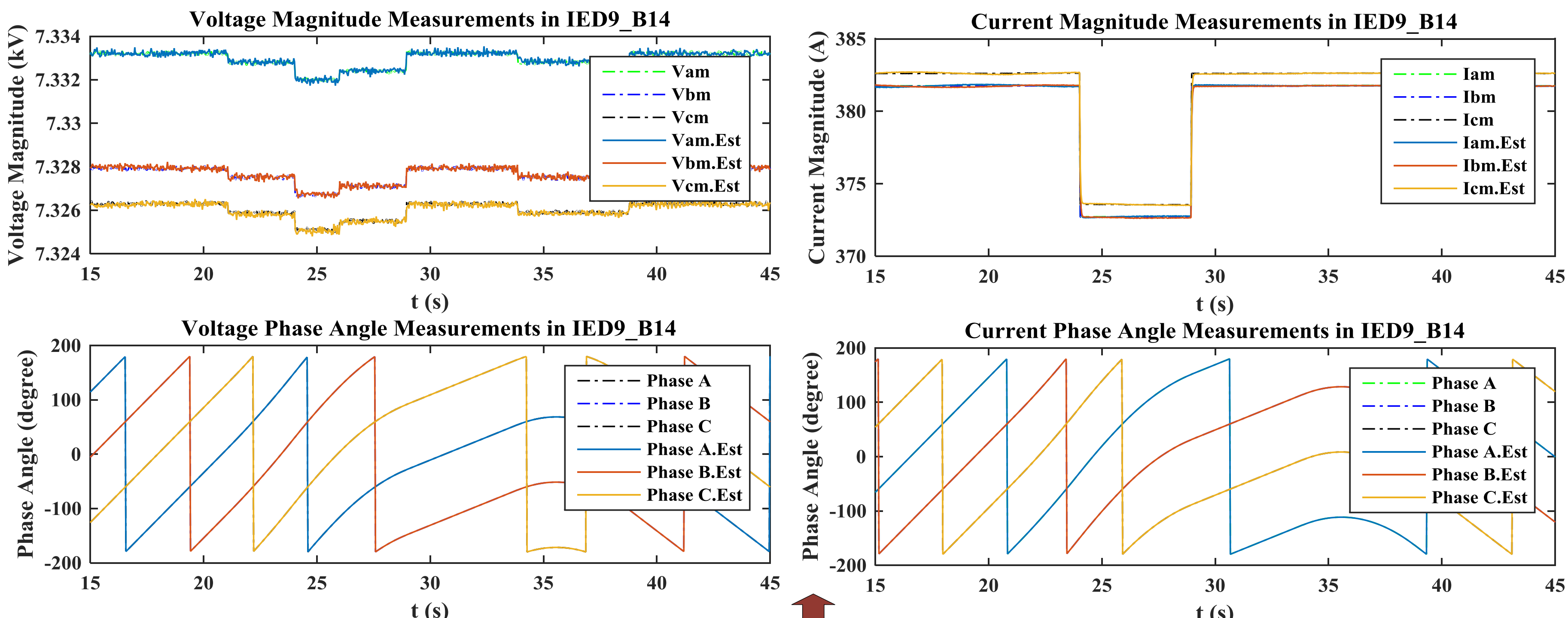
Measurements from IED9_B14 (located at bus B14)

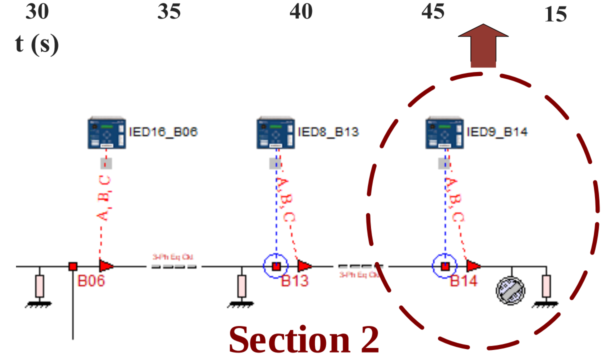


Measurements from IED14_B12 (located at bus B12)

LOHO13 Feeder – Section 2

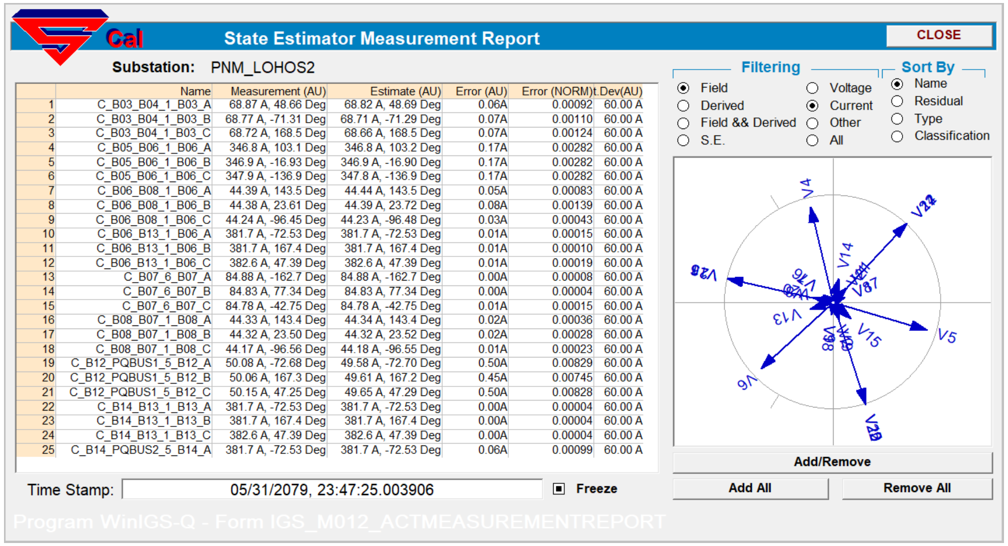
- State Estimation Results – – Measurements & Estimated Measurements





LOHO13 Feeder – Section 2

- State Estimation Results


State Estimator Measurement Report

CLOSE

Substation: PNM_LOHOS2

	Name	Measurement (AU)	Estimate (AU)	Error (AU)	Error (NORM)	t.Dev(AU)
1	C_B03_B04_1_B03_A	68.87 A, 48.66 Deg	68.82 A, 48.69 Deg	0.06A	0.00092	60.00 A
2	C_B03_B04_1_B03_B	68.77 A, -71.31 Deg	68.71 A, -71.29 Deg	0.07A	0.00110	60.00 A
3	C_B03_B04_1_B03_C	68.72 A, 168.5 Deg	68.66 A, 168.5 Deg	0.07A	0.00124	60.00 A
4	C_B05_B06_1_B06_A	346.8 A, 103.1 Deg	346.8 A, 103.2 Deg	0.17A	0.00282	60.00 A
5	C_B05_B06_1_B06_B	346.9 A, -16.93 Deg	346.9 A, -16.90 Deg	0.17A	0.00282	60.00 A
6	C_B05_B06_1_B06_C	347.9 A, -136.9 Deg	347.8 A, -136.9 Deg	0.17A	0.00282	60.00 A
7	C_B06_B08_1_B06_A	44.39 A, 143.5 Deg	44.44 A, 143.5 Deg	0.05A	0.00083	60.00 A
8	C_B06_B08_1_B06_B	44.38 A, 23.61 Deg	44.39 A, 23.72 Deg	0.08A	0.00139	60.00 A
9	C_B06_B08_1_B06_C	44.24 A, -96.45 Deg	44.23 A, -96.48 Deg	0.03A	0.00043	60.00 A
10	C_B06_B13_1_B06_A	381.7 A, -72.53 Deg	381.7 A, -72.53 Deg	0.01A	0.00015	60.00 A
11	C_B06_B13_1_B06_B	381.7 A, 167.4 Deg	381.7 A, 167.4 Deg	0.01A	0.00010	60.00 A
12	C_B06_B13_1_B06_C	382.6 A, 47.39 Deg	382.6 A, 47.39 Deg	0.01A	0.00019	60.00 A
13	C_B07_6_B07_A	84.88 A, -162.7 Deg	84.88 A, -162.7 Deg	0.00A	0.00008	60.00 A
14	C_B07_6_B07_B	84.83 A, 77.34 Deg	84.83 A, 77.34 Deg	0.00A	0.00004	60.00 A
15	C_B07_6_B07_C	84.78 A, -42.75 Deg	84.78 A, -42.75 Deg	0.01A	0.00015	60.00 A
16	C_B08_B07_1_B08_A	44.33 A, 143.4 Deg	44.34 A, 143.4 Deg	0.02A	0.00036	60.00 A
17	C_B08_B07_1_B08_B	44.32 A, 23.50 Deg	44.32 A, 23.52 Deg	0.02A	0.00028	60.00 A
18	C_B08_B07_1_B08_C	44.17 A, -96.56 Deg	44.18 A, -96.55 Deg	0.01A	0.00023	60.00 A
19	C_B12_PQBUS1_5_B12_A	50.08 A, -72.68 Deg	49.58 A, -72.70 Deg	0.50A	0.00829	60.00 A
20	C_B12_PQBUS1_5_B12_B	50.06 A, 167.3 Deg	49.61 A, 167.2 Deg	0.45A	0.00745	60.00 A
21	C_B12_PQBUS1_5_B12_C	50.15 A, 47.25 Deg	49.65 A, 47.29 Deg	0.50A	0.00828	60.00 A
22	C_B14_B13_1_B13_A	381.7 A, -72.53 Deg	381.7 A, -72.53 Deg	0.00A	0.00004	60.00 A
23	C_B14_B13_1_B13_B	381.7 A, 167.4 Deg	381.7 A, 167.4 Deg	0.00A	0.00004	60.00 A
24	C_B14_B13_1_B13_C	382.6 A, 47.39 Deg	382.6 A, 47.39 Deg	0.00A	0.00004	60.00 A
25	C_B14_PQBUS2_5_B14_A	381.7 A, -72.53 Deg	381.7 A, -72.53 Deg	0.06A	0.00099	60.00 A

Filtering: Field / Derived / Field && Derived / S.E. — Voltage / Current / Other / All

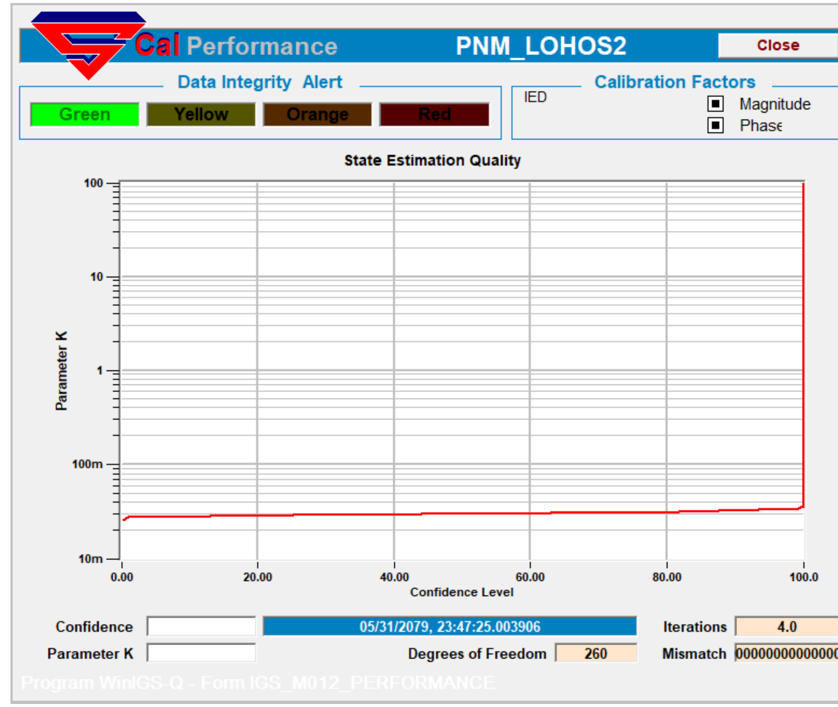
Sort By: Name / Residual / Type / Classification

Add/Remove — Add All — Remove All

Time Stamp: 05/31/2079, 23:47:25.003906 — Freeze

Program WinIGS-Q - Form IGS_M012_ACTMEASUREMENTREPORT

Snapshot of SE Current Measurement Report, Section 2



Confidence Level of Section 2

- Estimated measurements track the measurements accurately.
- All errors are small.
- Confidence level of section 2 remains at 100% → the estimated states of this section are trustworthy, the system model of this section is validated.

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

Questions?