A Generic and Robust Model Validation & Calibration Software

NASPI Work Group Meeting, April 15-17 - San Diego, CA

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WAMS-based Dynamic Model Validation & Calibration

Value Proposition

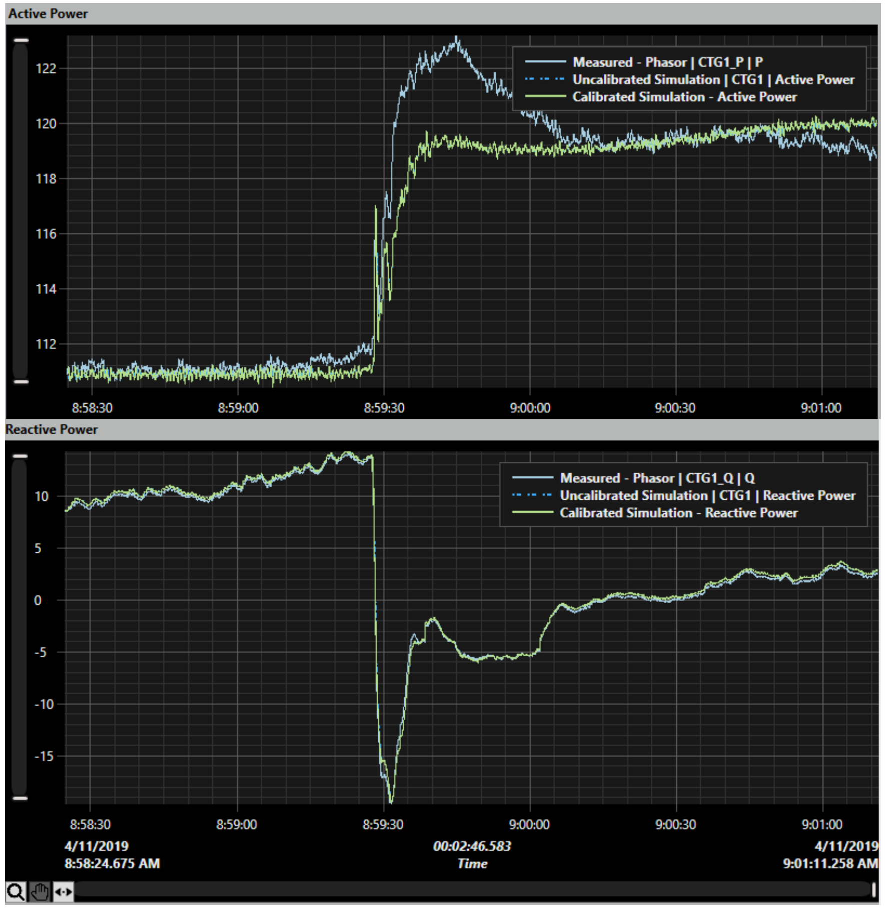
Drivers:

- **Inaccurate Dynamic models:** Inability to predict grid conditions
  - PG&E case (see figure)
  - BPA experience suggests 60-70% of power plant models did not match disturbance recordings even after the baseline test was performed.
- **Mandated Reliability Standards:**
  - **PRC-012-2 Remedial Action Schemes** requiring PCs to evaluate existing RAS within its planning area.
  - **NERC MOD-026 and MOD-027** requiring transmission planners and operators to verify generator models (turbine and excitation controls) on a periodic basis.
  - **MOD-033-1 Steady-State and Dynamic System Model Validation** requiring PCs to validate system planning models against real-time system data.
  - Validate Dynamic model for Real time operational studies

Benefits:

- **Cost-effective** method for TOs and GOs to **satisfy NERC Reliability Standards**.
- **Non-invasive online approach** that allows asset owners to continue operating the plant (and realizing revenue) without stopping operations.
- More accurate models for stability analysis => **Improved Reliability**
- More accurate calculation of system operating limits => **Better Asset Utilization**

PG&E Colusa case



Conceptual Approach

Disturbance Data

V, f, P, Q PMU data at POI

Model Validation

Forced Simulation

Run Simulation Engine using Forced Simulation

Simulation Validation

Compare measurements to initial model response

Sensitivity Analysis

Stage I

Event Analysis

Determine events qualitatively different from previous events

Parameter Identifiability

Determine most identifiable set of parameters across all events

Model Calibration

Stage II

Optimization

Optimization based parameter estimation

Calibration Validation

Compare measurements to calibrated model response

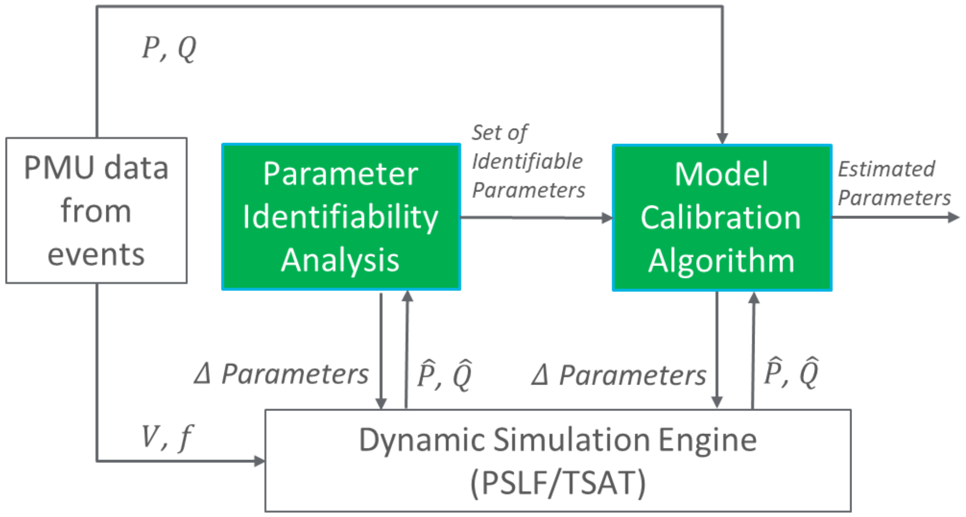
Calibration Report

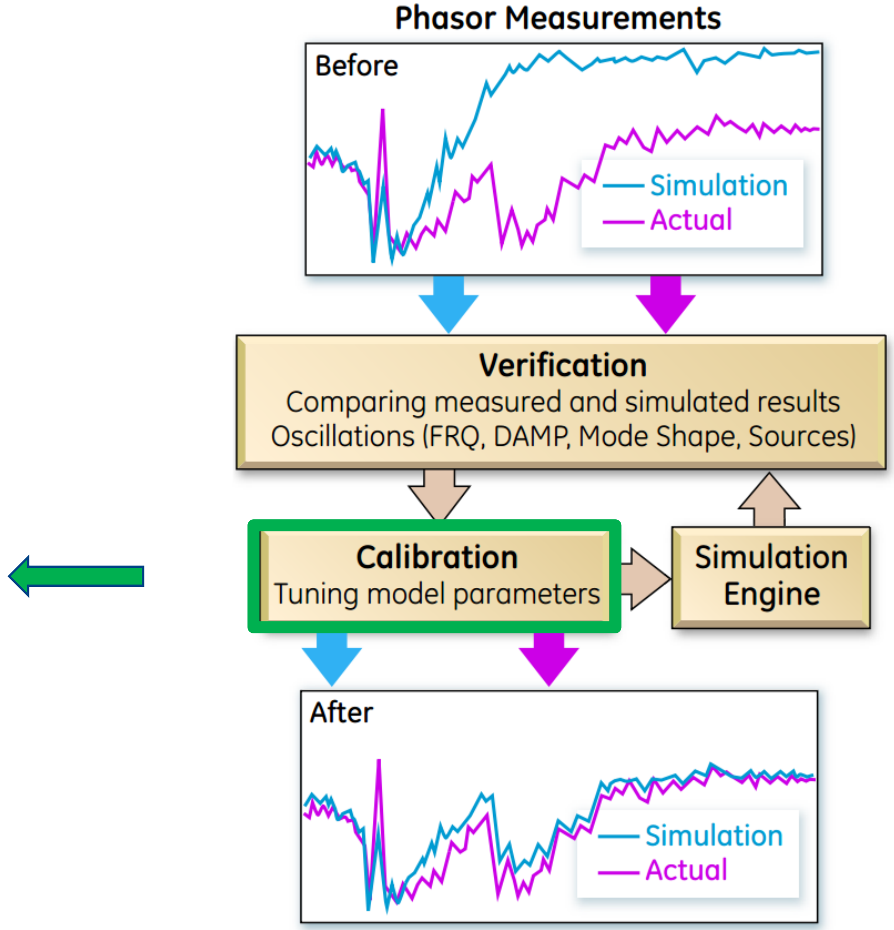
Report estimated parameter values, confidence metrics

Two Stage Approach for Model Calibration

Design Considerations

- **Production-grade** software tool
- **Generic** for wide variety of models (PSLF, TSAT and PTI PSS/E)
- **Minimal data flow change** on existing tools
- Account for **non-linearity** in models
- Quality of solution with **reasonable speed**
- Account for **multiple different events**
- Avoid tuning parameters that may already be at their true values



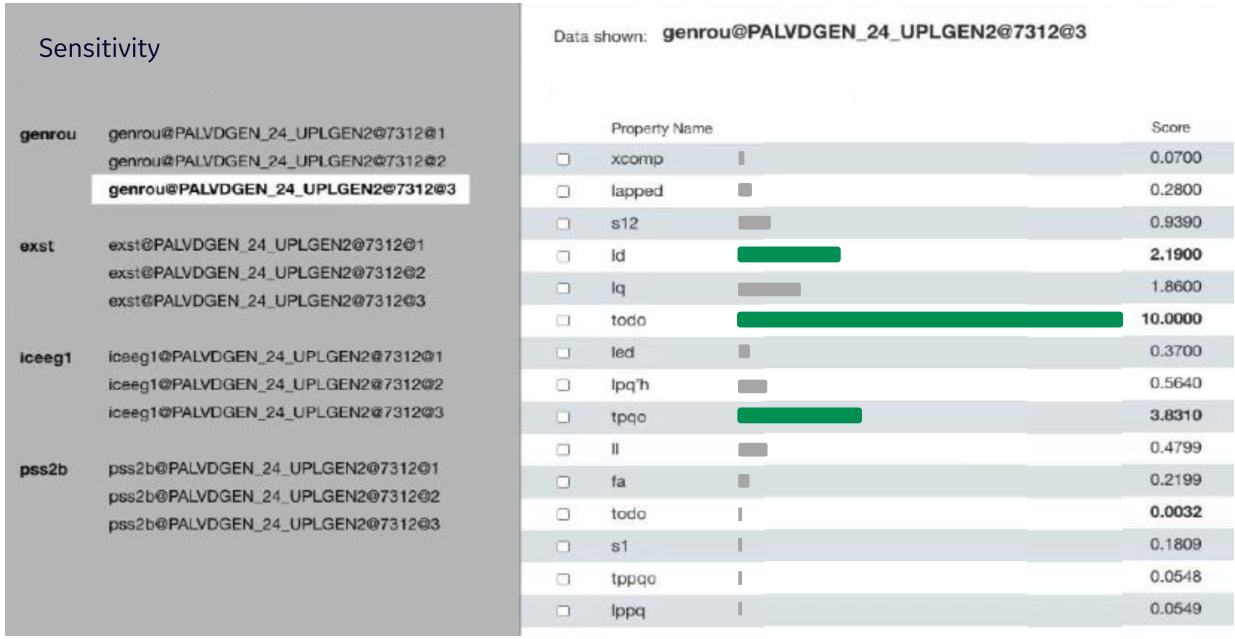


Stage I: Sensitivity Analysis

Determine most identifiable set of parameters across all events

- Jacobian matrix, $A =$

$$\begin{bmatrix} \frac{\partial P(t_1)}{\partial \theta_1} & \frac{\partial P(t_1)}{\partial \theta_2} & \cdots & \frac{\partial P(t_1)}{\partial \theta_k} \\ \frac{\partial P(t_2)}{\partial \theta_1} & \frac{\partial P(t_2)}{\partial \theta_2} & \cdots & \frac{\partial P(t_2)}{\partial \theta_k} \\ & \vdots & & \\ \frac{\partial P(t_N)}{\partial \theta_1} & \frac{\partial P(t_N)}{\partial \theta_2} & \cdots & \frac{\partial P(t_N)}{\partial \theta_k} \\ \frac{\partial Q(t_1)}{\partial \theta_1} & \frac{\partial Q(t_1)}{\partial \theta_2} & \cdots & \frac{\partial Q(t_1)}{\partial \theta_k} \\ \frac{\partial Q(t_2)}{\partial \theta_1} & \frac{\partial Q(t_2)}{\partial \theta_2} & \cdots & \frac{\partial Q(t_2)}{\partial \theta_k} \\ & \vdots & & \\ \frac{\partial Q(t_N)}{\partial \theta_1} & \frac{\partial Q(t_N)}{\partial \theta_2} & \cdots & \frac{\partial Q(t_N)}{\partial \theta_k} \end{bmatrix}$$



- Rank deficiency of A can result from:
  - (1) very small entries in columns of A
  - (2) columns of A being nearly linearly dependent

Stage II -Multi-Event Calibration

Performance (in r.m.s. terms) of events calibrated for only one event (in corresponding column) evaluated against all other events (listed in the rows). It shows the generator parameters tuned by single event could not explain other event very well.

Models and data sets obtained via NASPI-NERC model verification workshop, 2016*

2 orders of magnitude reduction from initial error
1 order of magnitude reduction from initial error
reduction from initial error
Increase from initial error

Event no.		True set	Def	Tuned for event 1	Tuned for event 2	Tuned for event 3	Tuned for event 4	Tuned for event 5	Tuned for event 6	Tuned for event 7	Tuned for event 8	Tuned for event 9	Tuned for event 10	Tuned for event 11	Tuned for event 12
1	Perr rms	0.19	2.80	2.33	3.06	1.83	3.36	49.35	52.00	49.04	47.79	49.51	5.78	49.93	2.00
2		0.28	1.34	2.14	0.28	0.98	2.81	2.09	0.50	0.31	0.68	2.37	0.64	5.15	1.03
3		0.03	1.23	1.07	2.31	1.00	1.55	27.93	28.24	27.76	12.05	28.08	3.23	28.07	1.12
4		0.35	2.64	2.73	2.13	1.90	3.16	35.59	41.91	33.80	34.07	35.23	2.03	36.46	2.34
5		4.15	3.10	4.44	3.07	4.20	5.21	0.76	8.07	1.38	5.03	0.62	6.48	1.02	4.00
6		0.29	1.56	2.27	0.29	1.10	2.92	3.40	0.55	0.38	0.46	2.59	0.62	6.54	1.15
7		20.49	14.68	24.23	16.28	23.15	30.12	4.06	3.17	2.73	26.27	7.14	37.09	14.11	20.27
8		0.03	0.99	1.02	1.62	0.88	1.45	18.19	18.39	18.07	1.08	18.37	2.58	18.42	0.91
9		1.14	4.82	5.56	0.75	2.69	6.60	20.02	18.78	15.99	16.52	19.47	1.65	21.76	3.30
10		0.24	1.12	1.45	0.22	0.65	1.74	1.95	5.69	0.99	0.45	1.51	0.49	2.15	0.86
11		0.01	0.27	0.29	0.32	0.23	0.88	1.85	5.63	2.25	0.39	0.36	0.49	2.09	0.35
12		0.02	0.62	0.54	0.85	0.51	0.80	12.39	12.43	12.23	0.88	0.84	2.01	12.41	0.51

*Courtesy: Dr. Ryan Quint, NERC

Multi-event Calibration-Preliminary Results

2 orders of magnitude reduction from initial error
1 order of magnitude reduction from initial error
reduction from initial error
Increase from initial error

Obvious solution: run calibration simultaneously on all events of interest strung together but this comes at the cost of computational expense and engineering involved in enabling running a batch of events simultaneously.

Our solution: carry some essential information from the earlier calibrations runs and guide the subsequent calibration run that helps explain the new disturbance without losing earlier calibration matches.

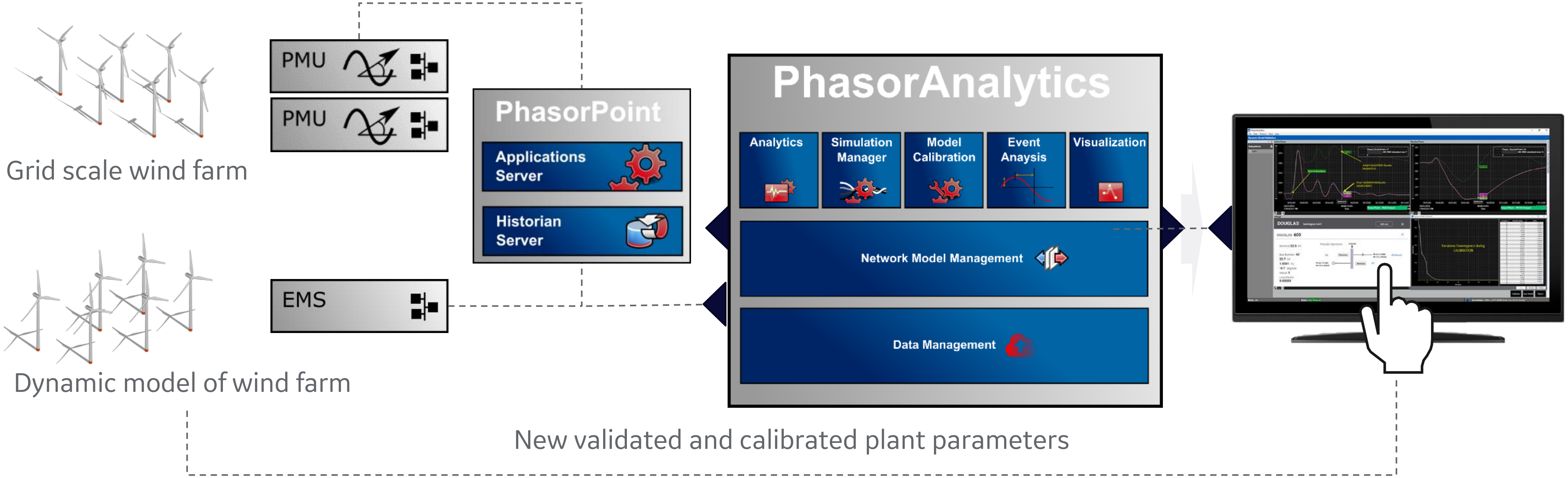
Performance of estimates from the sequential estimation approach for the gas plant case shows the proposed approach effectively reduce the overall error across all events.

Event no.		True set	Def	Sequential, forgetting factor = 1e-2	Sequential without prior weight
1	Perr rms	0.19	2.80	1.02	0.38
2		0.28	1.34	0.32	0.25
3		0.03	1.23	0.58	0.37
4		0.35	2.64	1.00	0.35
5		4.15	3.10	3.81	3.72
6		0.29	1.56	0.35	0.30
7		20.49	14.68	19.39	19.25
8		0.03	0.99	0.47	0.18
9		1.14	4.82	1.17	0.83
10		0.24	1.12	0.27	0.29
11		0.01	0.27	0.10	0.04
12		0.02	0.62	0.29	0.08
1	Qerr rms	0.21	1197.90	2.71	0.91
2		0.04	60.99	0.29	0.03
3		0.22	995.61	3.25	0.69
4		0.46	1370.90	27.41	10.48
5		0.13	215.22	1.24	0.38
6		0.03	41.74	0.54	0.10
7		0.92	1856.30	9.45	0.69
8		0.26	668.64	3.18	0.38
9		0.43	2613.00	304.42	6.79
10		0.07	57.92	5.16	0.81
11		0.05	63.22	0.93	0.15
12		0.12	474.97	0.18	0.08
	delta p 2-norm			12.2178	15.9934
	delta p inf-norm			9.2333	14.402

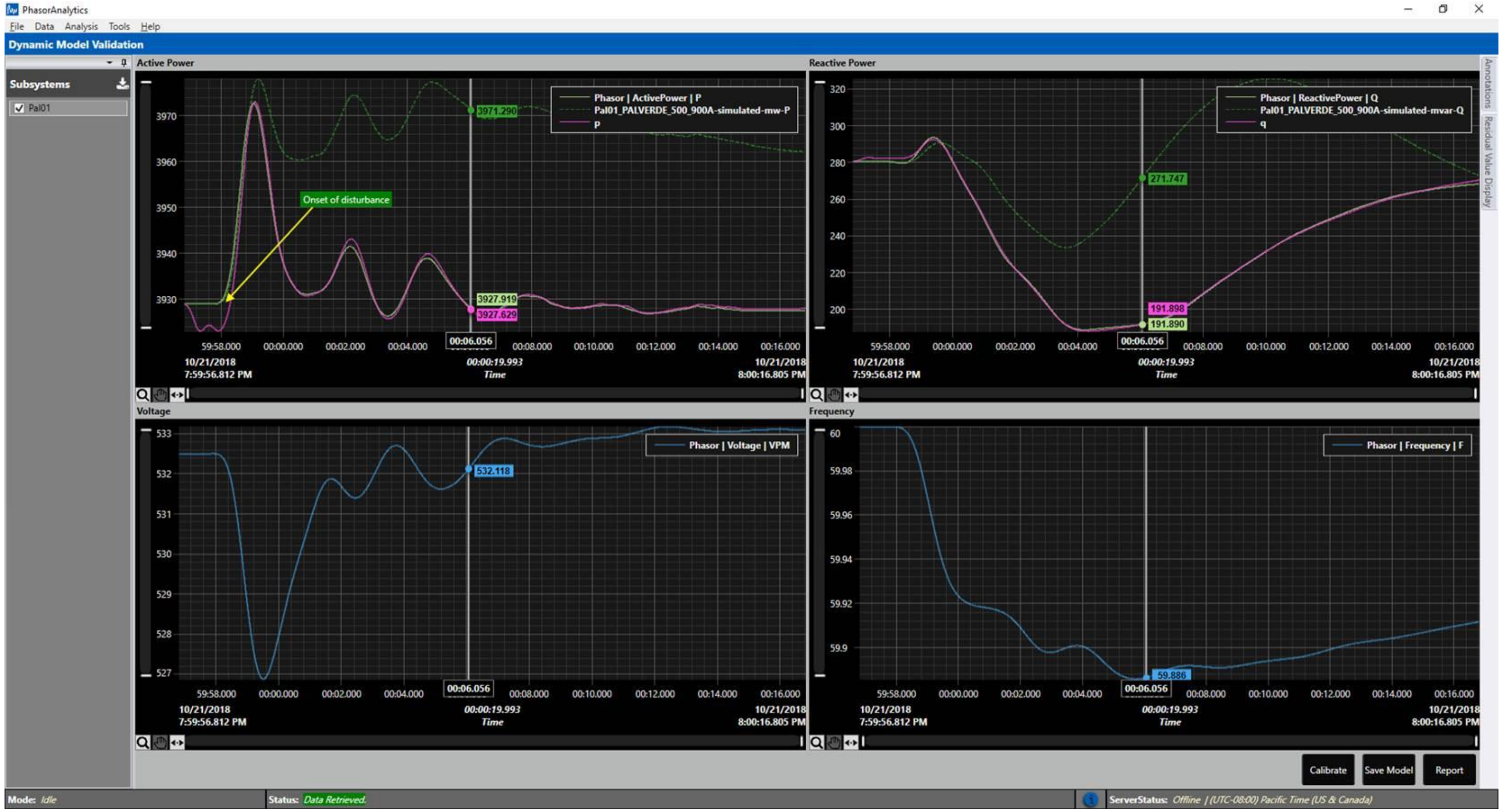
Implementation & Demonstration

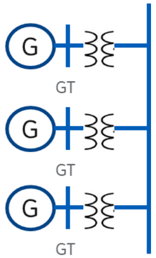
Software Implementation-Generality & Robustness

- **Dynamic simulation engine**
  - ✓ GE's PSLF
  - ✓ PowerTech's TSAT
- **System Configuration**
  - ✓ PMU at POI
  - ✓ PMU at Generator Terminal
- **Steady state & Dynamic model**
  - ✓ EMS-operational model
  - ✓ System planning model
- **Phasor Data**
  - ✓ e-terraphasorpoint/openPDC/openHistorian
  - ✓ JSIS CSV files/COMTRADE files/PI historian

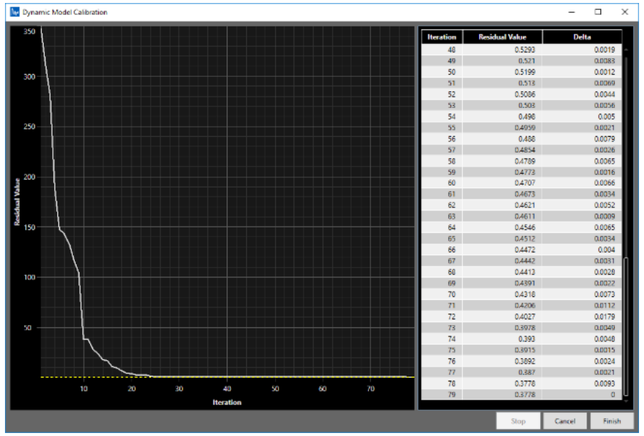


Demonstration Using US WECC Model





Units operational	1 × 1311 MW
	1 × 1314 MW
	1 × 1312 MW
Units cancelled	2 × 1270 MW
Thermal capacity	3 × 3990 MW_{th}



* Note: Synthesized PMU data using Dynamic Model

Courtesy WECC


PhasorAnalytics
File Data Analysis Tools Help
Dynamic Model Validation
Subsystems
PALOV1
Active Power
Measured - P
Init Sim - P
Initial VALIDATION Results
(MISMATCH)
Onset of disturbance
3967.869
3930.648
Reactive Power
Measured - Q
Init Sim - Q
234.477
189.610
Voltage
Measured - Phasor | Voltage | VPM
532.678
Frequency
Measured - Phasor | Frequency | F
59.901
00:12.034
3/12/2019
4:00:04.975 PM
00:00:19.993
Time
3/12/2019
4:00:24.968 PM
Calibrate
Save Model
Report
Mode: Idle
Status: Data Retrieved.
ServerStatus: Offline | (UTC-08:00) Pacific Time (US & Canada)

Parameter Selection

Select Tunable Parameters

Calibration

Select parameters to calibrate

PALVDGEN_24_UPLGEN3	genrou	(10)
	wsccst	(7)
	exst3a	(7)
	ieeeg1	(3)
PALVDGEN_24_UPLGEN2	pss2b	(12)
	genrou	(6)
	ieeeg1	(3)
	exst4b	(2)
PALVDGEN_24_UPLGEN1	pss2b	(13)
	genrou	(6)
	ieeeg1	(3)
	exst4b	(2)

Parameters for : **genrou@PALVDGEN_24_UPLGEN3@7313@3**

User sensitivity score to identify most sensitive parameters. Use min, max values to specify limits

	Property Name	Score	Actual Value	Min Value	Max Value
☑	xcomp	0.6297	0.0700	-9999.0000	9999.0000
☑	lppd	0.3308	0.2800	-9999.0000	9999.0000
☑	tpdo	0.3040	10.0000	-9999.0000	9999.0000
☑	lq	0.2679	1.8600	-9999.0000	9999.0000
☑	ld	0.1787	2.1900	-9999.0000	9999.0000
☑	s12	0.1725	0.9390	-9999.0000	9999.0000
☑	s1	0.1717	0.1810	-9999.0000	9999.0000
☑	ll	0.1205	0.2200	-9999.0000	9999.0000
☑	lpd	0.0967	0.3700	-9999.0000	9999.0000
☑	h	0.0648	3.8310	-9999.0000	9999.0000
☐	lpq	0.0283	0.5640		
☐	tppdo	0.0277	0.0330		
☐	tpqo	0.0276	0.4800		
☐	tppqo	0.0095	0.0550		
☐	ra	0.0042	0.0036		
☐	lppq	0.0000	0.2800		

Cancel | Proceed

Calibration - Progress

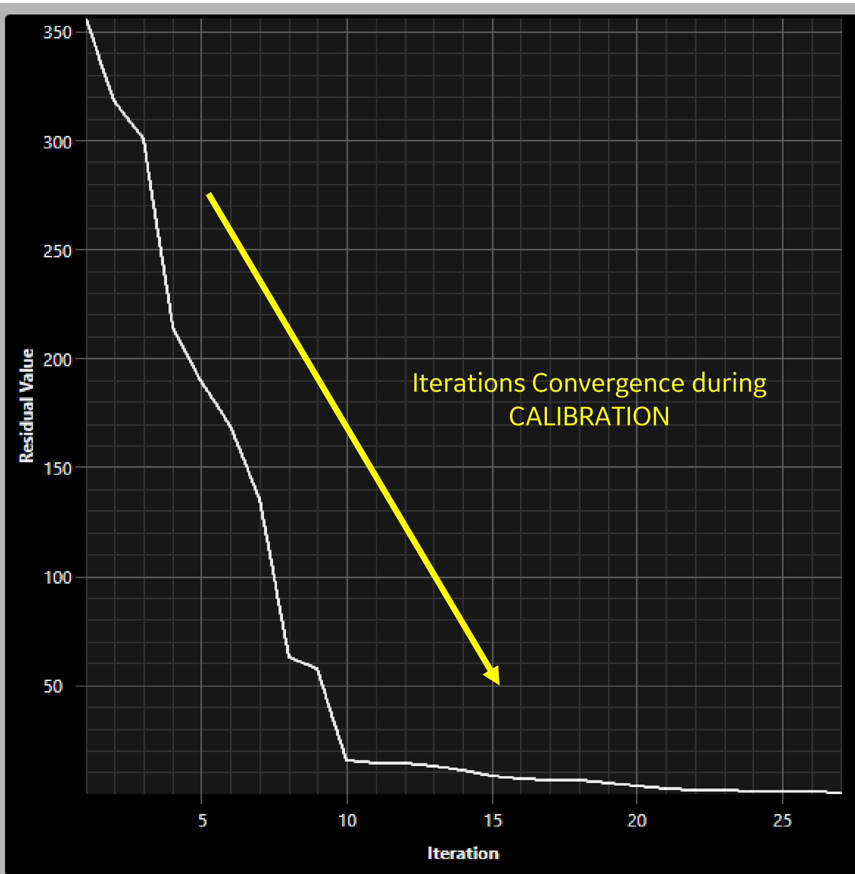
Parameter Optimization Dialog

Calibration

Results can take a few minutes to display.

PALVDGEN_24_UPLGEN3

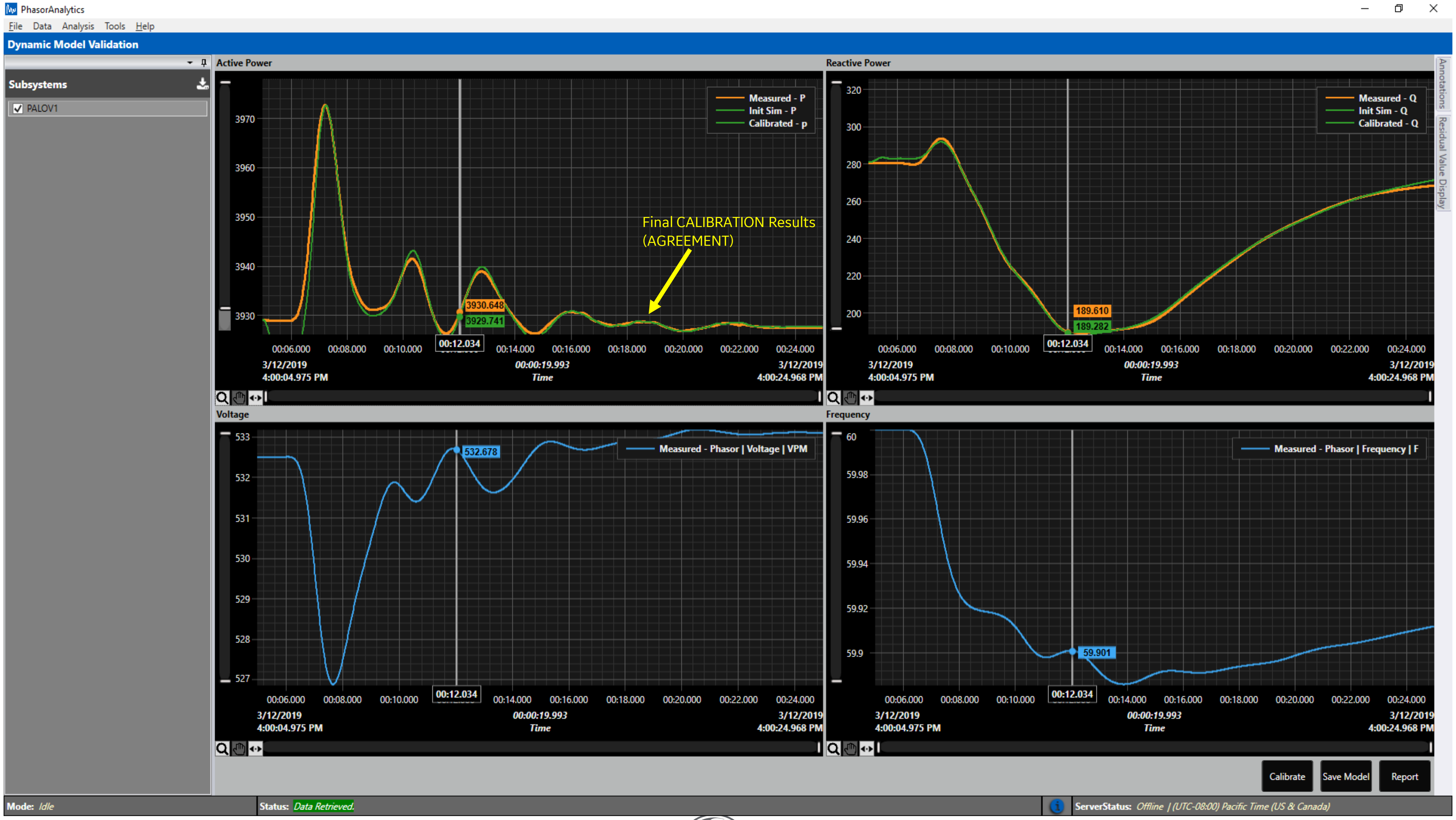
	Score	Actual	Min	Max	Calibrated
xcomp	0.630	0.0700	-9999.0000	9999.0000	0.1097
lppd	0.331	0.2800	-9999.0000	9999.0000	0.1952
tpdo	0.304	10.0000	-9999.0000	9999.0000	12.0469
lq	0.268	1.8600	-9999.0000	9999.0000	2.2621
ld	0.179	2.1900	-9999.0000	9999.0000	2.7063
s12	0.172	0.9390	-9999.0000	9999.0000	0.6928
s1	0.172	0.1810	-9999.0000	9999.0000	0.1808
ll	0.120	0.2200	-9999.0000	9999.0000	0.2167
lpd	0.097	0.3700	-9999.0000	9999.0000	0.3815
h	0.065	3.8310	-9999.0000	9999.0000	5.5396
tq	0.546	2.0000	-9999.0000	9999.0000	2.7332



Iteration	Residuals	Delta
1	356.109	-
2	318.464	37.6449
3	300.656	17.8077
4	214.187	86.4693
5	190.081	24.1055
6	169.072	21.0091
7	135.121	33.9513
8	62.484	72.6368
9	57.281	5.2038
10	15.702	41.5787
11	13.976	1.7255
12	13.974	0.0026
13	12.783	1.1905
14	11.173	1.6103
15	8.045	3.1276
16	7.073	0.9727
17	6.461	0.6120
18	6.168	0.2930
19	4.940	1.2279
20	4.066	0.8736

Cancel Stop Finish

Calibration - Results



Calibrated Parameters

Parameter Optimization Dialog

Calibration

Results can take a few minutes to display.

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lq	0.268	1.8600	-9999.0000	9999.0000	2.2621
ld	0.179	2.1900	-9999.0000	9999.0000	2.7063
s12	0.172	0.9390	-9999.0000	9999.0000	0.6928
s1	0.172	0.1810	-9999.0000	9999.0000	0.1808
ll	0.120	0.2200	-9999.0000	9999.0000	0.2167
lpd	0.097	0.3700	-9999.0000	9999.0000	0.3815
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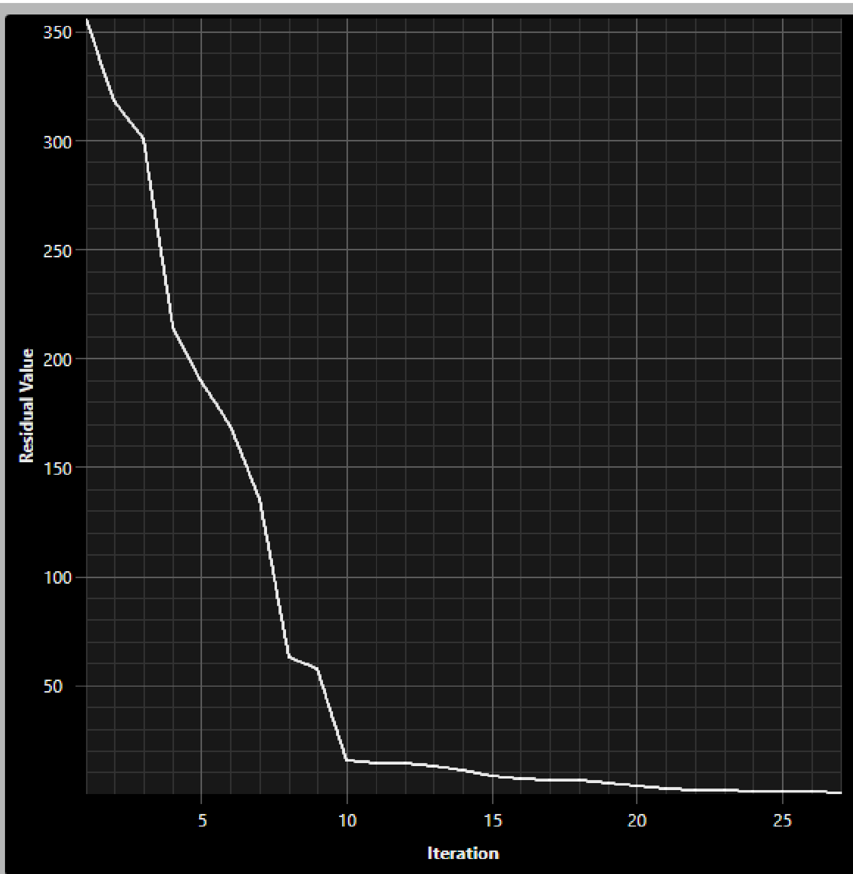
tq	0.546	2.0000	-9999.0000	9999.0000	2.7332



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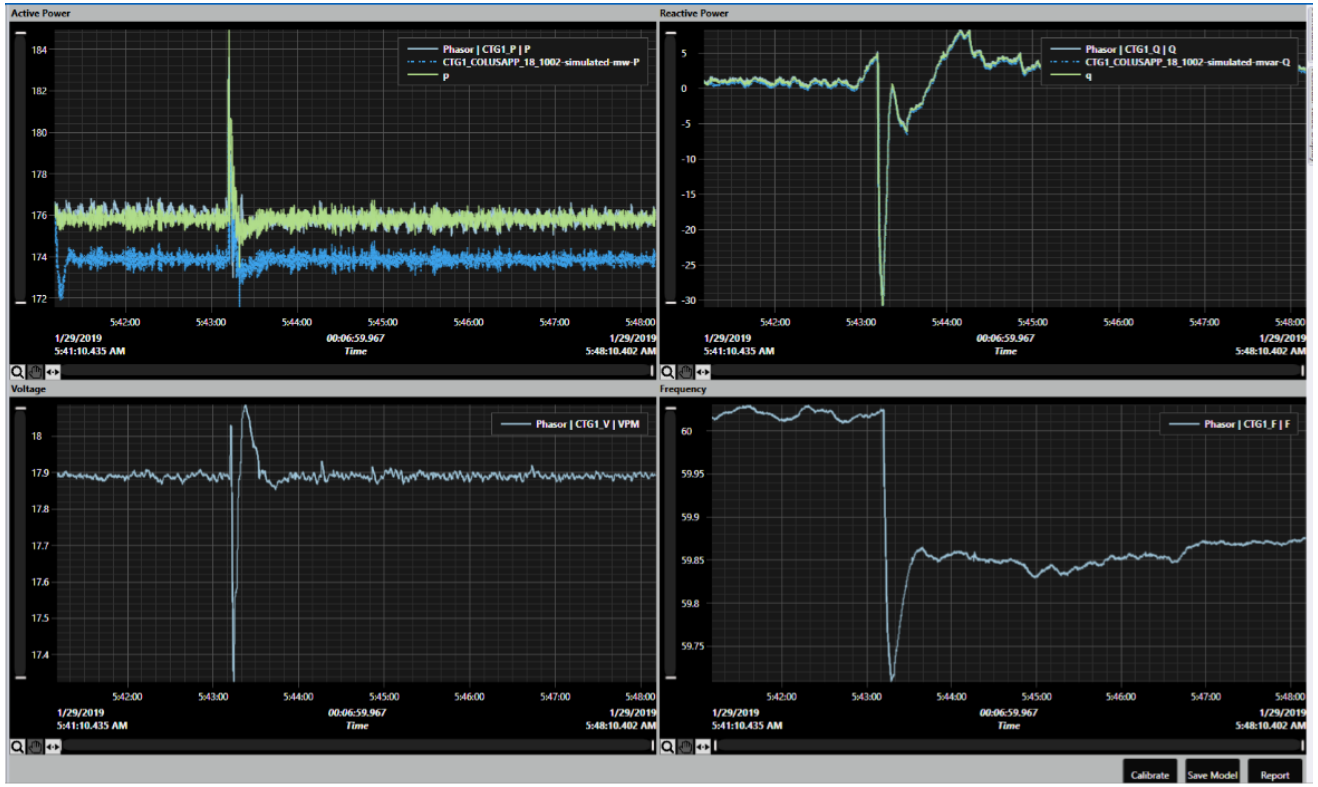
Cancel Stop Finish

Original **Actual** Parameters

Final **Calibrated** Parameters

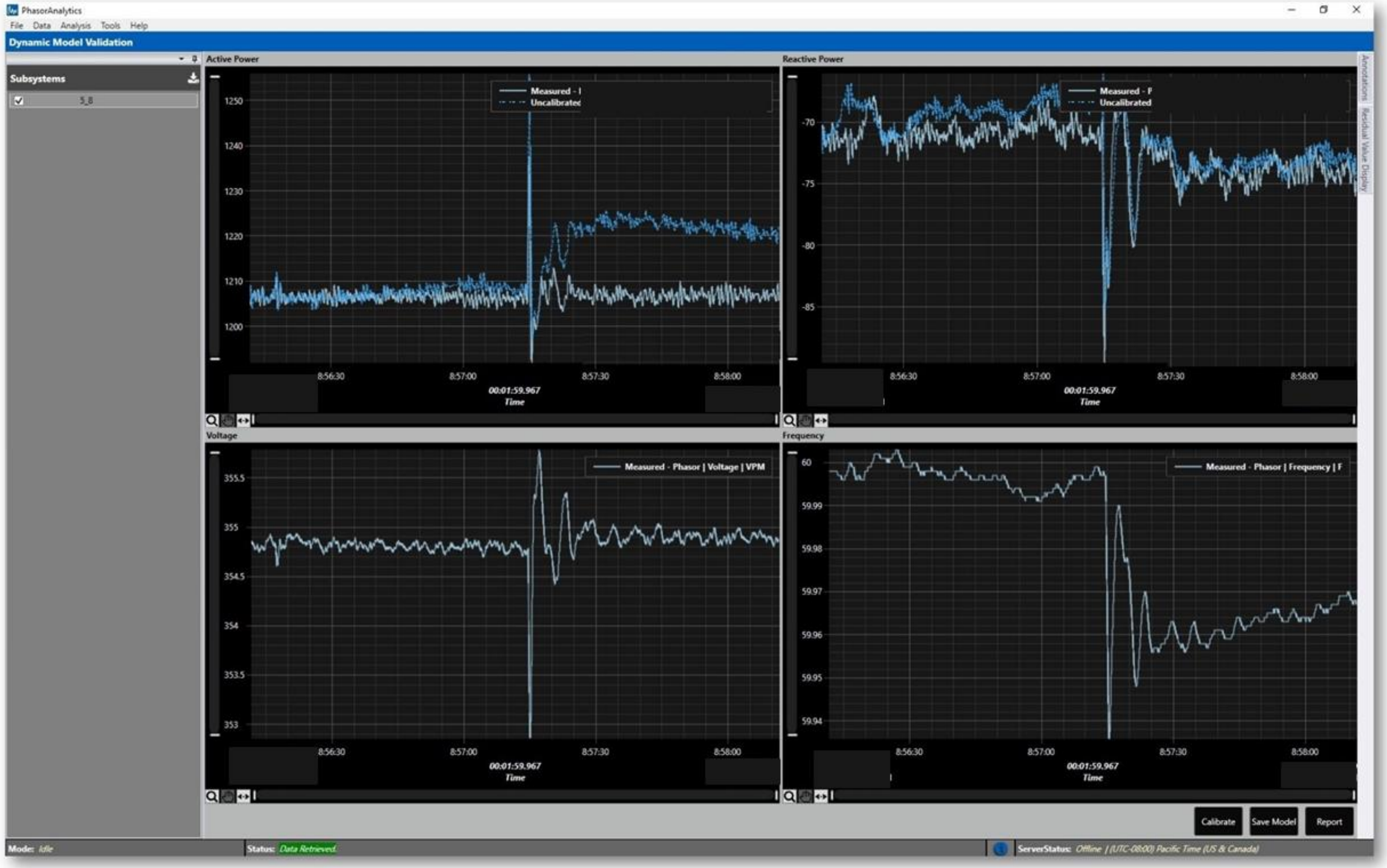
PG&E test case

PSLF



- 1040 Pacific DC Intertie rate of change activated . Plant info: GE's 2 GT and 1 ST, GE's Generators and GE's Excitation system EX2100. Siemens' three step-up Xfmrs.
- Both PSLF and TSAT has to add an impedance to handle PMU located at generator terminal.
- Identified need to define the high/low bounds of parameter before calibration.

ISO-NE test case



- MV&C using TSAT engine is being verified using a Power plant under ISO-NE foot print
- Dynamics observed is because of another generator trip nearby
- Mismatch observed is mainly in the active power
- Makes a case for tuning governor control

Conclusion

- **Lesson learned and new feature for production grade MVC software**
- **A sequential estimation approach designed and verified using multiple event data**
- **Model Validation and Calibration software tested using field data from PG&E and ISO-NE**

Next Step

- Validate multi-event calibration approach against real test data
- Model Calibration field tests at PG&E and ISO-NE, June
- DOE Peer Review, June 12-13, Washington DC

Presentations/Publications

1. IEEE PES Innovative Smart Grid Technologies (ISGT) Conference, February 2018 – ***Presented paper*** on model parameter identifiability analysis titled, “Synchrophasor based dynamic model validation leveraging multiple events”
2. i-PCGRID Workshop, March 2018 – ***Presentation*** on synchrophasor applications being developed on this project
3. NASPI Work Group Meeting, April 2018 – ***Presentation*** on Fast Voltage Stability Assessment algorithm
4. GE Grid Solutions User Group Meeting, June 2018 – ***Presentation*** on synchrophasor applications being developed on this project
5. IEEE PES General Meeting, August 2018 – ***Presented paper*** on the developed model validation/calibration algorithm titled, “Towards a commercial-grade tool for disturbance-based model validation and calibration.”
6. NASPI Work Group Meeting, October 2018 – ***Presentation*** on model validation/calibration algorithm integration into the PhasorAnalytics with a live demonstration.

Thanks the team!

U.S. DEPARTMENT OF ENERGY

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Alex Santos: Contract manager
Na Jing: Financial Analyst

Developers

GE Grid Software Solutions

Lead FAT and field demos, Develop model cal., AGM and operator guidance software tools; Model val./cal. platform integration of PSLF & TSAT with WAMS product

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Krish Srinivasan
Russ Frizzell-Carlton
Vijay Sukhavasi

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Jovan Bebic
Chaitanya Baone
Anup Menon
Naresh Acharya
Yan Pan

GE Energy Consulting

Model validation/ calibration platform integration of PSLF with WAMS product

Haris Ribic
Juan Sanchez-Gasca
Brian Thomas
Develop APIs to enable Communication between WAMS product and PSLF

Powertech
The Power of Trust. The Future of Energy.

Model validation/ calibration platform integration of TSAT with WAMS product, assist with AGM

George Zhang
Develop APIs to enable Communication between WAMS product and PSLF

Utility Partners

MISO Midcontinent ISO

*Provide cost share, test data and models, assist/host applications in QA environment, **Field tests***

Keith Mitchell
Field demo for AGM and operator guidance.

PG&E Pacific Gas & Electric

*Provide cost share, test data and models, assist/host applications in QA environment, **Field tests***

Sherman Chen
Field demo for Model Validation/ Calibration tool.

ISO new england

Provide feedback on developed Applications

Xiaochuan Luo
Frankie Zhang
Field demo for Model Validation/ Calibration tool.

Peak Reliability

Provide feedback on developed Applications

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Alex Ning
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