Looking Back:
A 10 Year Retrospective on Synchrophasor Technology at Dominion Energy

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Thanks for Choosing Richmond!

Looking Back over the Last 10 Years

2009 – Kicked off synchrophasor initiative; DOE SGIG kickoff;

2012 – Began standardized relay/PMU sensor deployment

2013 – DOE SGIG Demonstration

Linear State Estimator v1.0 released as OSS

2014 – CERTS Synchrophasor Data Conditioning and Validation Project

2015 – DOE FOA970 Kickoff

2017 – DOE FOA970 Demonstration

Linear State Estimator v2.0

2017 – DFR PMU Conversion begins

Total transmission system coverage

2019 – Scaling towards Sustainability

High Performance Analytics Sandbox for Use Case Development

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2009-2013

SGIG Demonstration Project

Three Phase Linear State Estimator & It's Applications

Overview

- Installation of PMUs
- Development of WAMS
- Application Development & Testing
- Linear State Estimation
- CTPT Calibration
- Islanding Detection
- Imbalance Monitoring
- Real-time Visualization Applications

U.S. DEPARTMENT OF ENERGY

Dominion

VirginiaTech

QUANTA TECHNOLOGY
Smart Solutions, Practical Results

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SGIG Demonstration Project

Three Phase Linear State Estimator & It's Applications

Deployment of 80 PMUs to the Dominion Energy 500kV Network

- 500kV Substations = **21** (70% of total)
- 500kV Transmission Lines = **35** (75% of total)
- 500kV Transformers = **28** (20% of total)
- 500kV Circuit Breakers = **110** (85% of total)
- 230kV Transmission Lines = **12** (5% of total)

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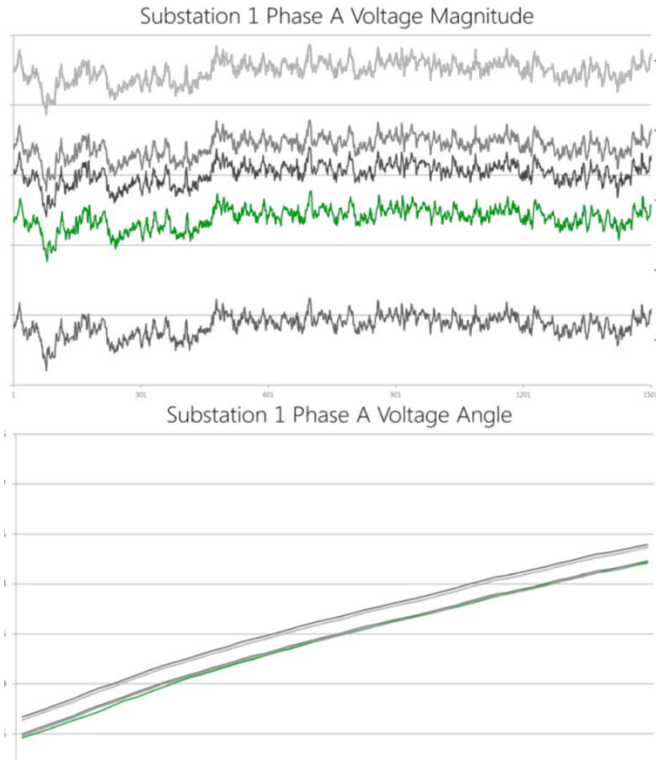
2009-2013

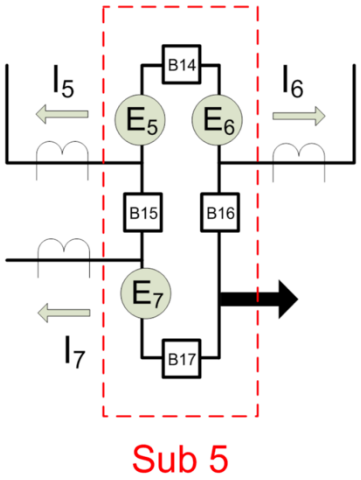
SGIG Demonstration Project

Three Phase Linear State Estimator & It's Applications

Created the first three phase linear state estimator

- Demonstrated at Dominion Energy in 2012 and 2013
  - 80 PMUs w/ over 600 phasor quantities
  - Network Model contains:
    - 107 Circuit Breakers
    - 216 Switches
    - 329 Nodes
    - 28 Substations
    - 30 Transmission Lines
- Fully integrated topology processor
- LSE v1 released open source
- LSE v1 commercialized by vendors





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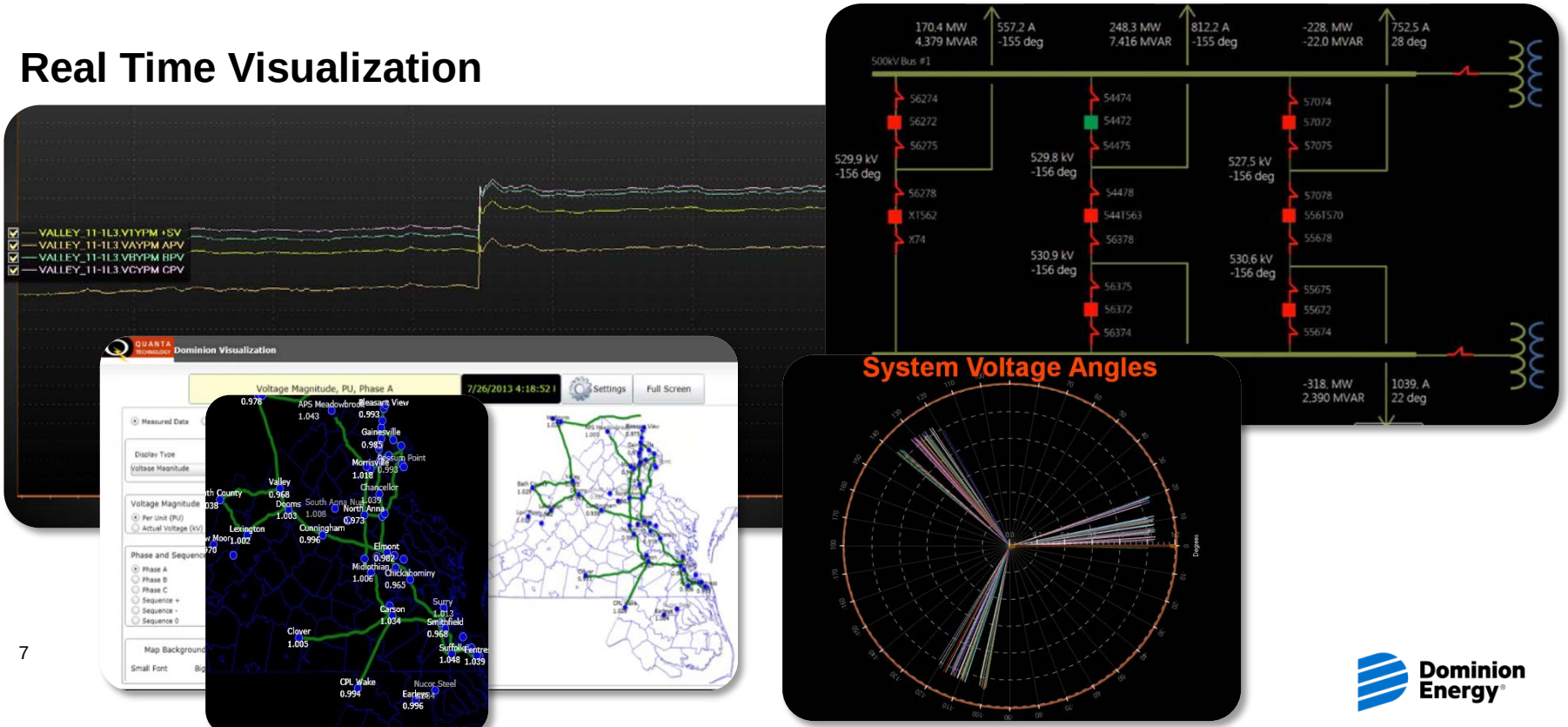
SGIG Demonstration Project

Three Phase Linear State Estimator & It's Applications

Real Time Visualization



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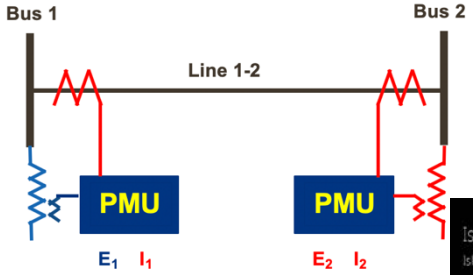
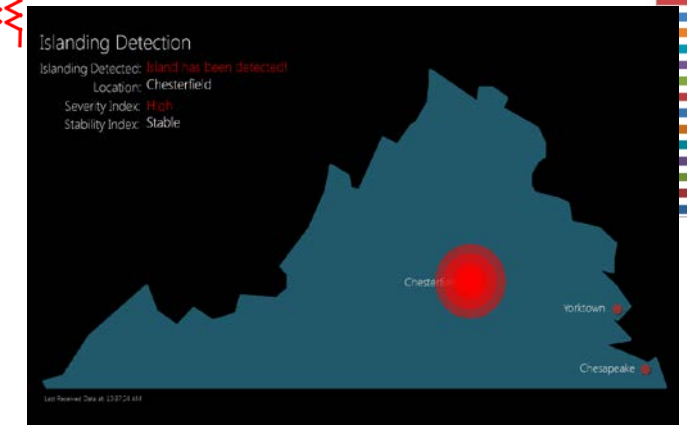
SGIG Demonstration Project
Three Phase Linear State Estimator & It's Applications

Network Applications

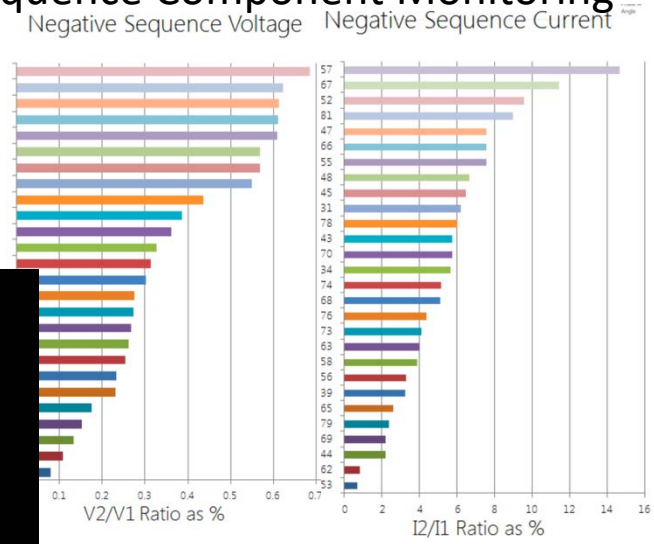
Instrument Transformer Calibration



Islanding Detection



Sequence Component Monitoring



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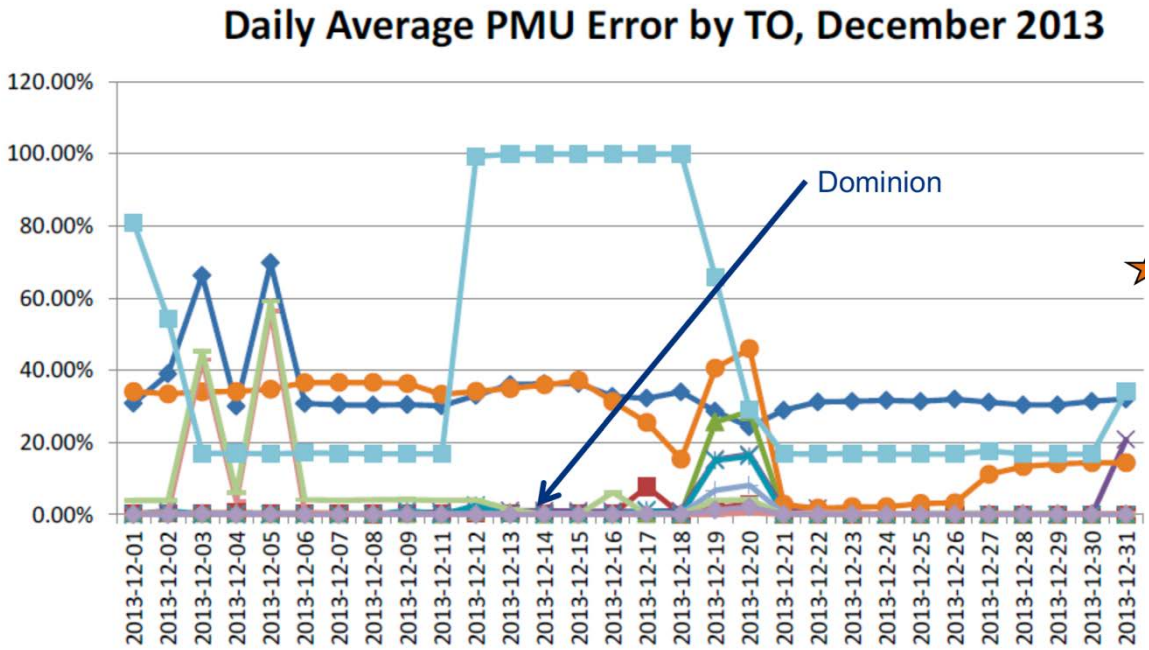
Streaming Synchrophasor Data to PJM

- Sharing data with PJM
- Top performing data quality in 2013
- Developed custom automation for naming translation & phase angle rotation - released open source



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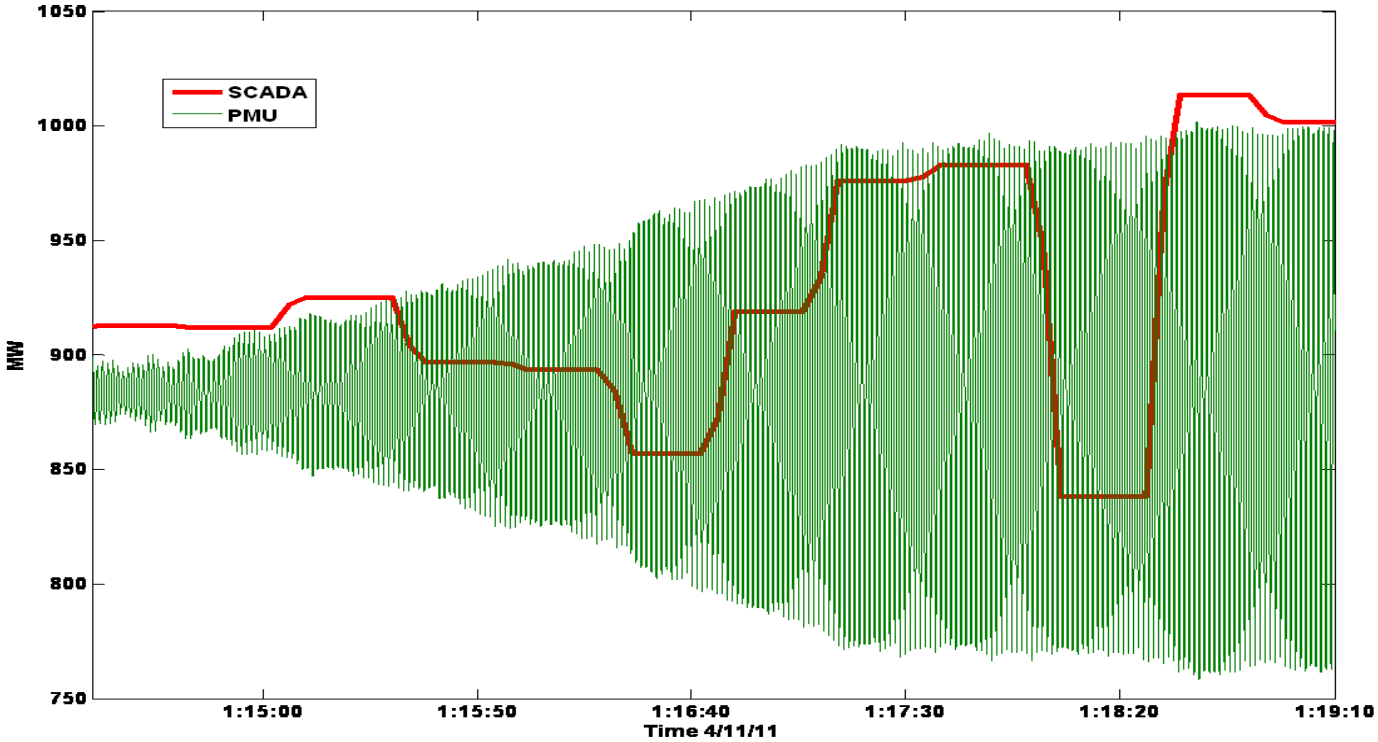
Some Early Wins
Oscillations



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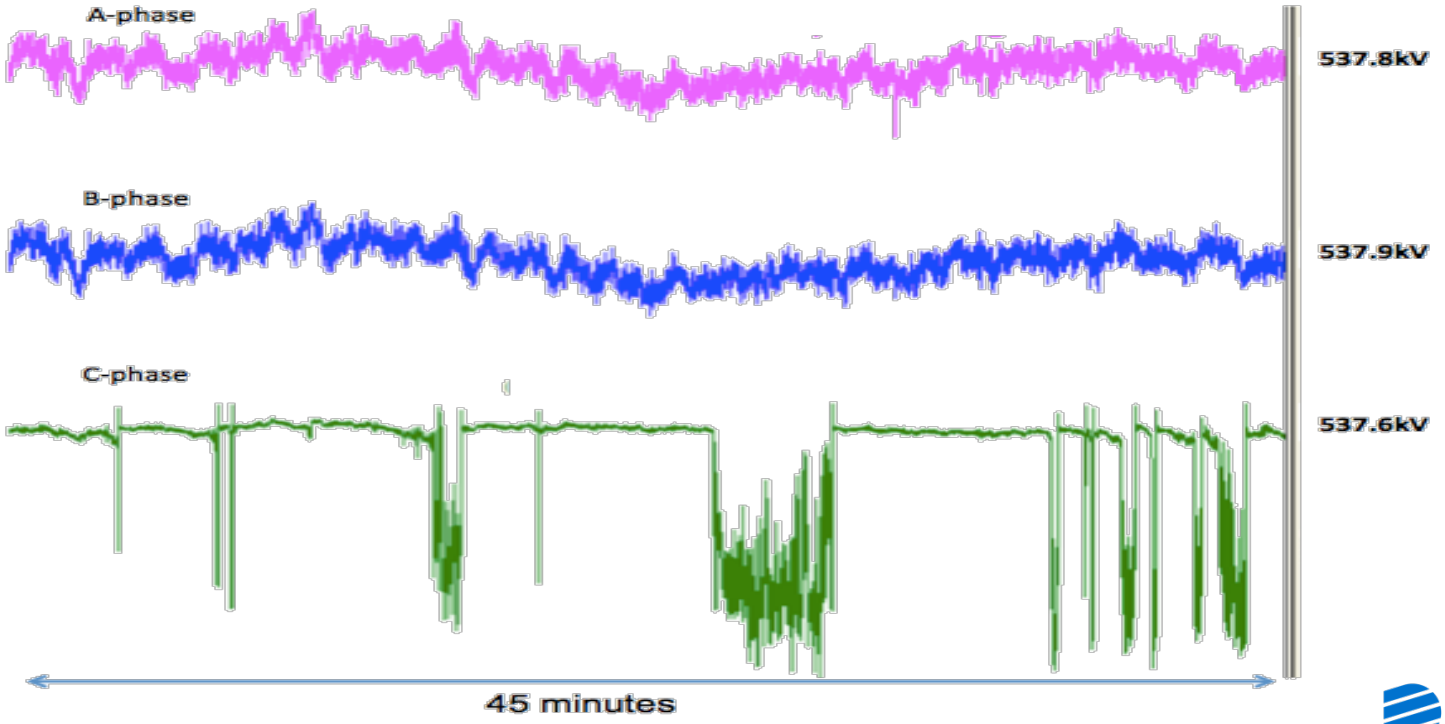
Some Early Wins
Instrument Transformer Failure



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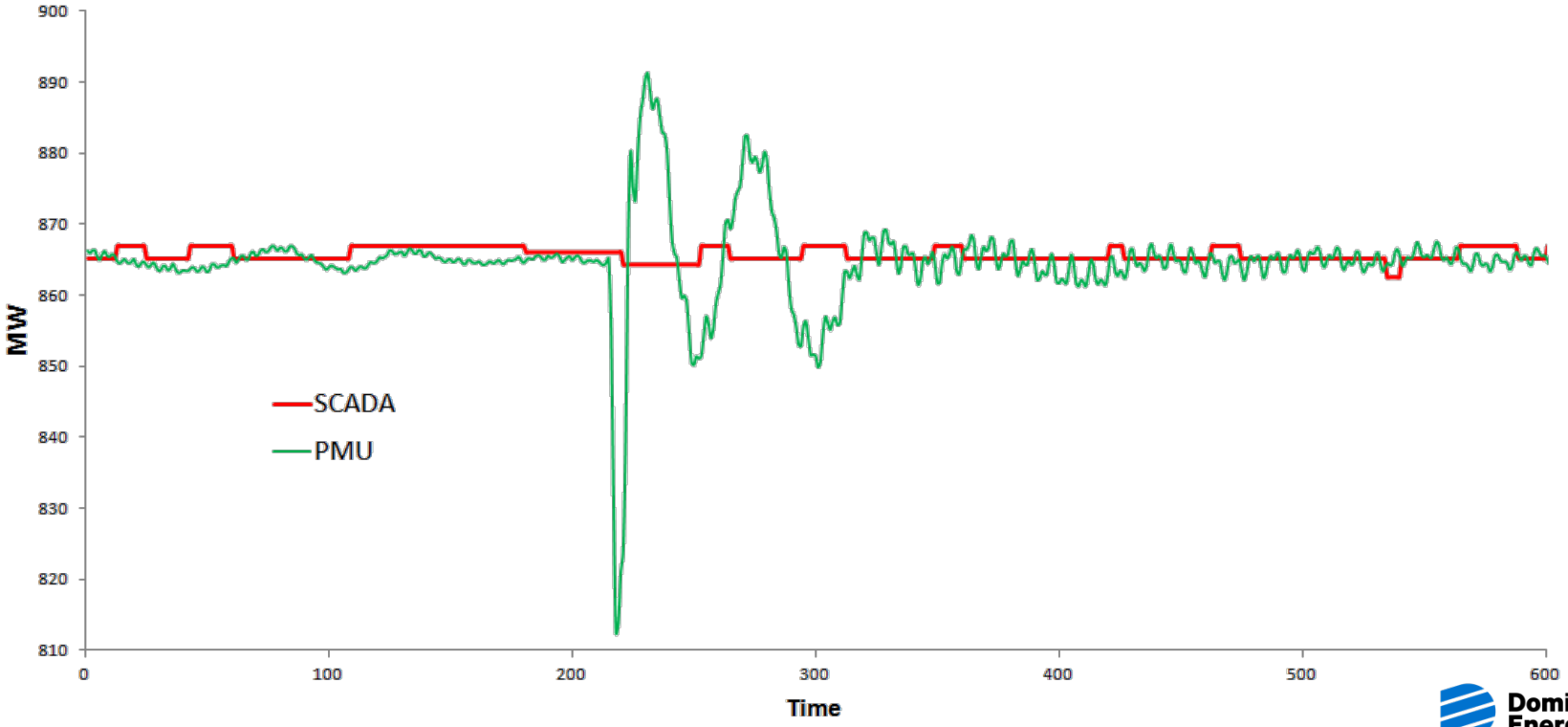
Some Early Wins
Looking at Faults



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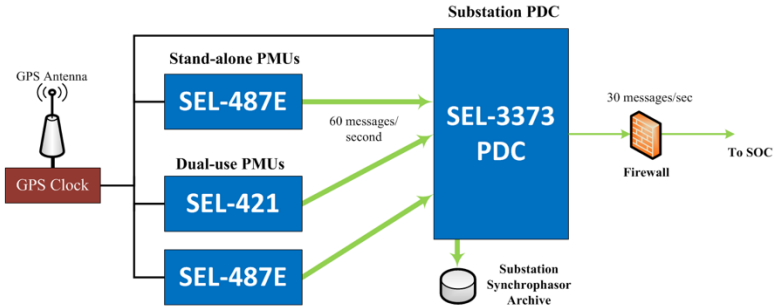
Standardization of PMU & PDC Deployment

- PMU & PDC deployment was standardized in substations where new construction took place.



- This created an automatic mechanism for growing the number of PMU measurements

2019 Totals	Average Per Relay-PMU	Relay-PMU EOY 2019 Total
Frequency	1	600
DFDT	1	600
Status	1	600
Voltage Magnitude	5	3,000
Voltage Angle	5	3,000
Current Magnitude	6	3,600
Current Angle	6	3,600
Digital	1	600
Analog	0	0
Totals	**26**	**15,600**

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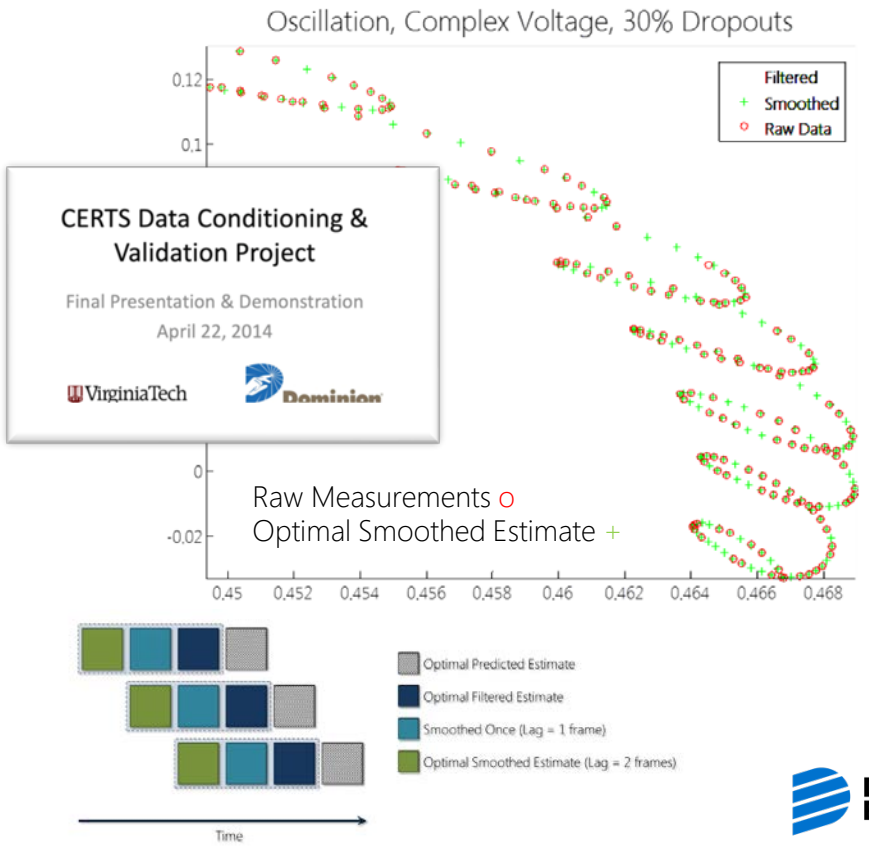
2012-2014

CERTS Data Conditioning & Validation Project

- Collaboration with Dominion, Virginia Tech, and LBNL
- Improved LSE Technology
- Created real-time active data conditioning
- Released open source



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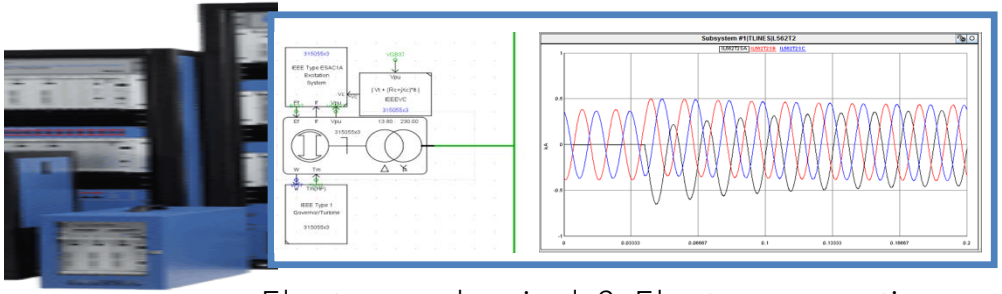
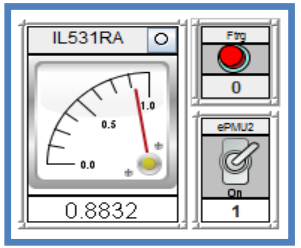
Operator Training Simulator for PMU Visualization

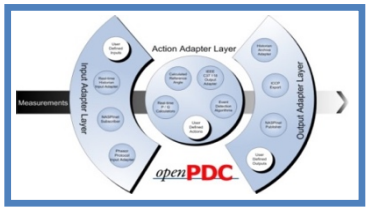


Electromechanical & Electromagnetic Dynamics

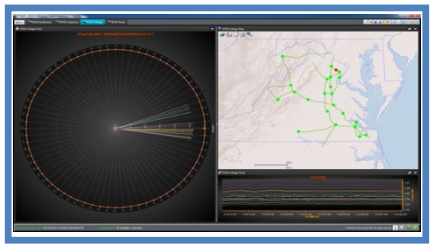


Operator-In-Loop Runtime Controls

Closed-Loop Relay/PMU Interface



Virtual PMUs Streaming Data



Visualization Software

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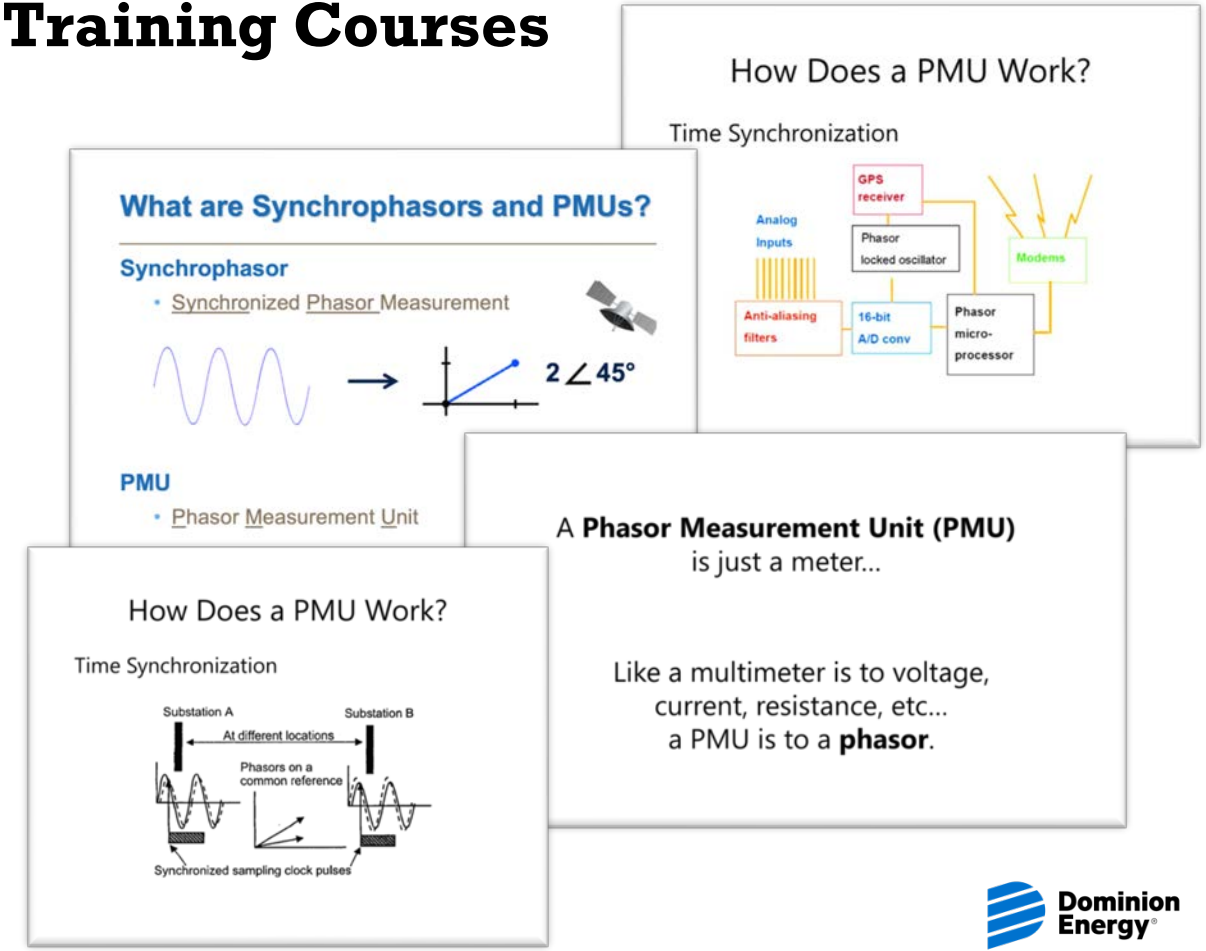
2014-2019

Relay Technician Training Courses

- Dominion has a world class Relay Tech Program
- Relay Tech's commission all Dominion PMUs
- Step 6 course teaches:
  - *PMU fundamentals*
  - *Why PMUs matter to Dominion*



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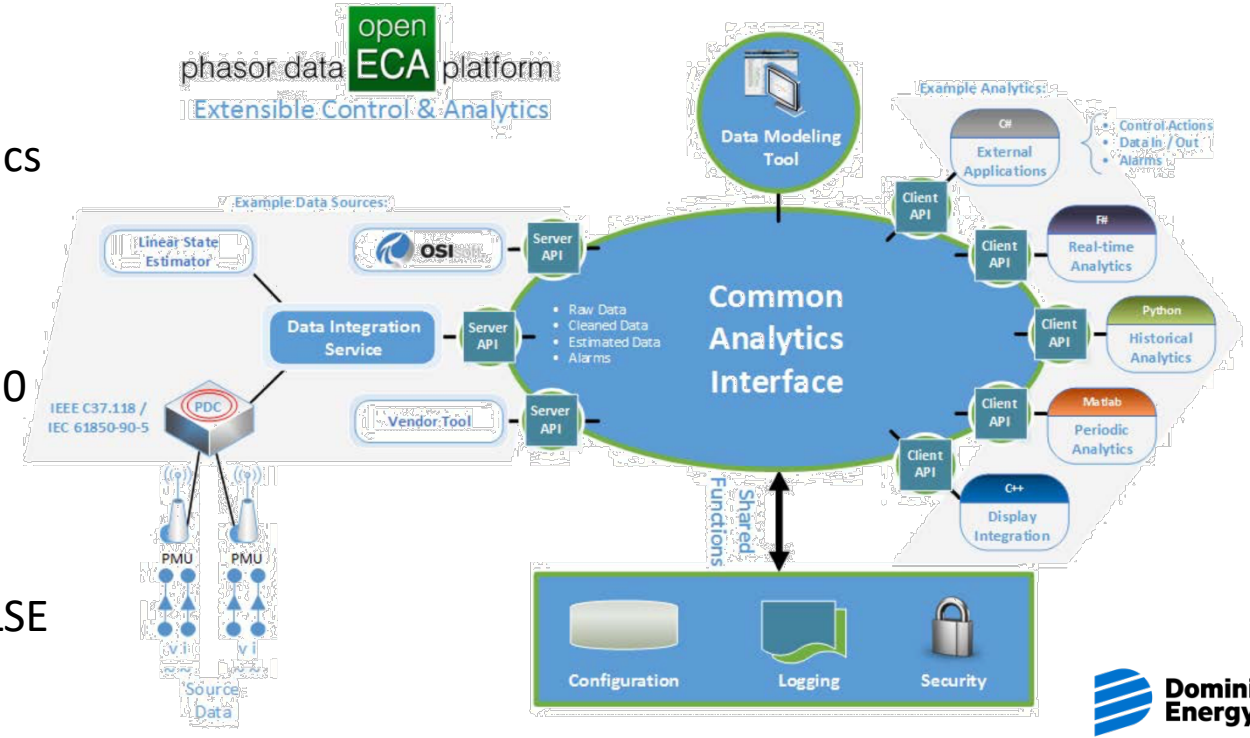
DOE FOA970
openECA

DOE FOA 970
DE-OE0000778

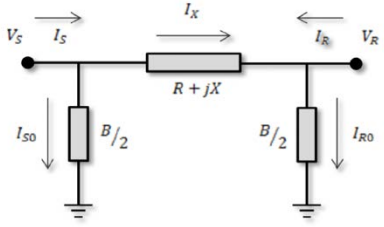
- Develop an open source real-time control and analytics platform based on Grid Solutions Framework
- Develop and test 10 applications with project partners
- Technology improvements to LSE

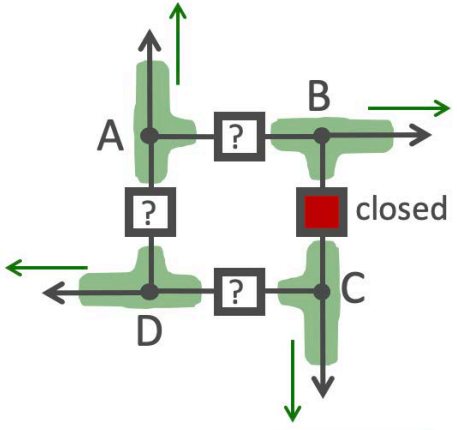


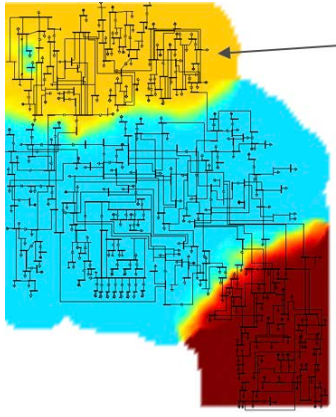
openECA

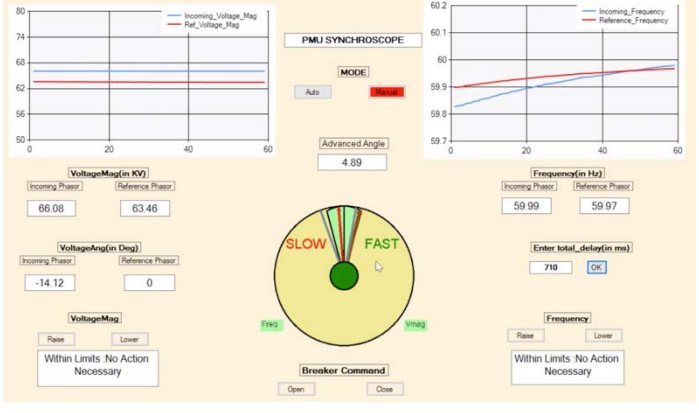
7 Network Applications from Dominion + Virginia Tech

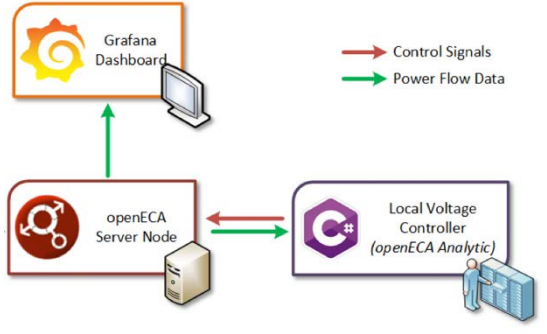
- Topology Estimator
- Local Voltage Control
- Regional Voltage Control
- PMU Synchroscope
- Instrument Transformer Calibration
- Transmission Line Impedance Calibration
- Real-Time Impedance Calculator



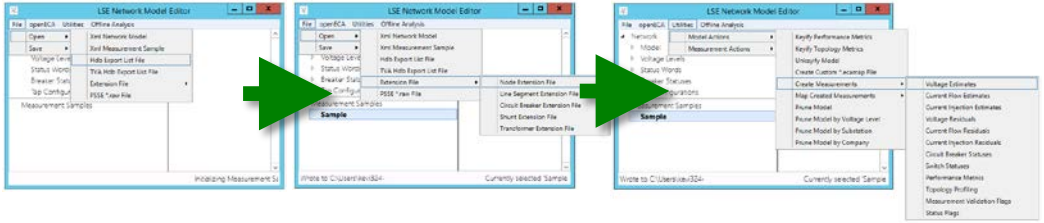


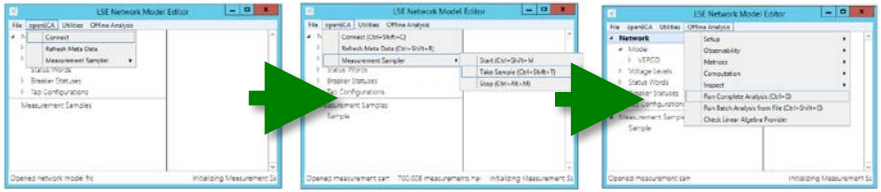






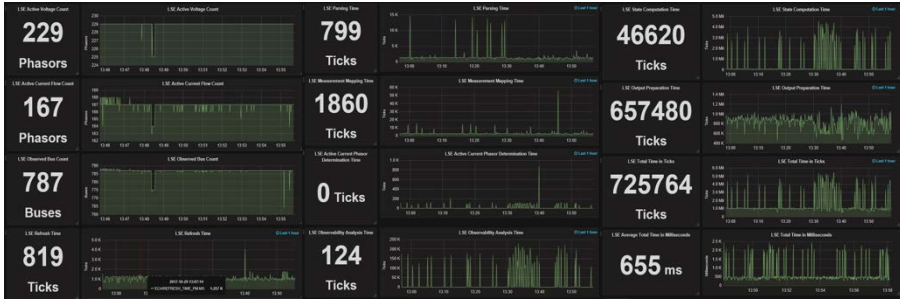
openECA
LSE v2 & the openLSE





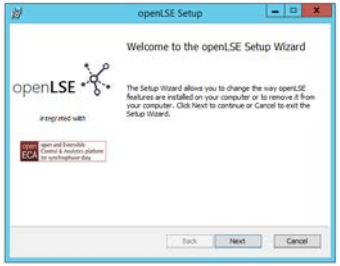
New Features

- Built-in topology estimator
- Built-in-performance metrics
- Performance improvements for large systems
- Modeling automation
- Packaged and installable
- Improved offline analysis
- Integrated with openECA
- LSE Core v2 and openLSE available open source



Demonstrated at:

- SPP
- TVA
- Dominion Energy



https://github.com/kdjones/openlse

https://github.com/kdjones/lse

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DFRs Get PMU Functionality

2013 – DFR manufactures added PMU functionality as a selling point.

2014 – Dominion purchases 3 portable DFRs for synchrophasor deployment

2015 – Lab Testing with many vendors

2016 – Turning APP recorders on the feature in the field

- 500kV and Power Stations

2017 – All APP Recorders turned on

2018 – Upgraded and turned on Emax DFRs

2019 – USI upgrades

2020 – Complete Emax and USI upgrades

	Average Per DFR PMU	DFR-PMU EOY 2019 Total
Frequency	1	280
DFDT	1	280
Status	1	280
Voltage Magnitude	16	4,480
Voltage Angle	16	4,480
Current Magnitude	23	6,440
Current Angle	23	6,440
Digital	4	1,120
Analog	0	0
Totals	85	23,800

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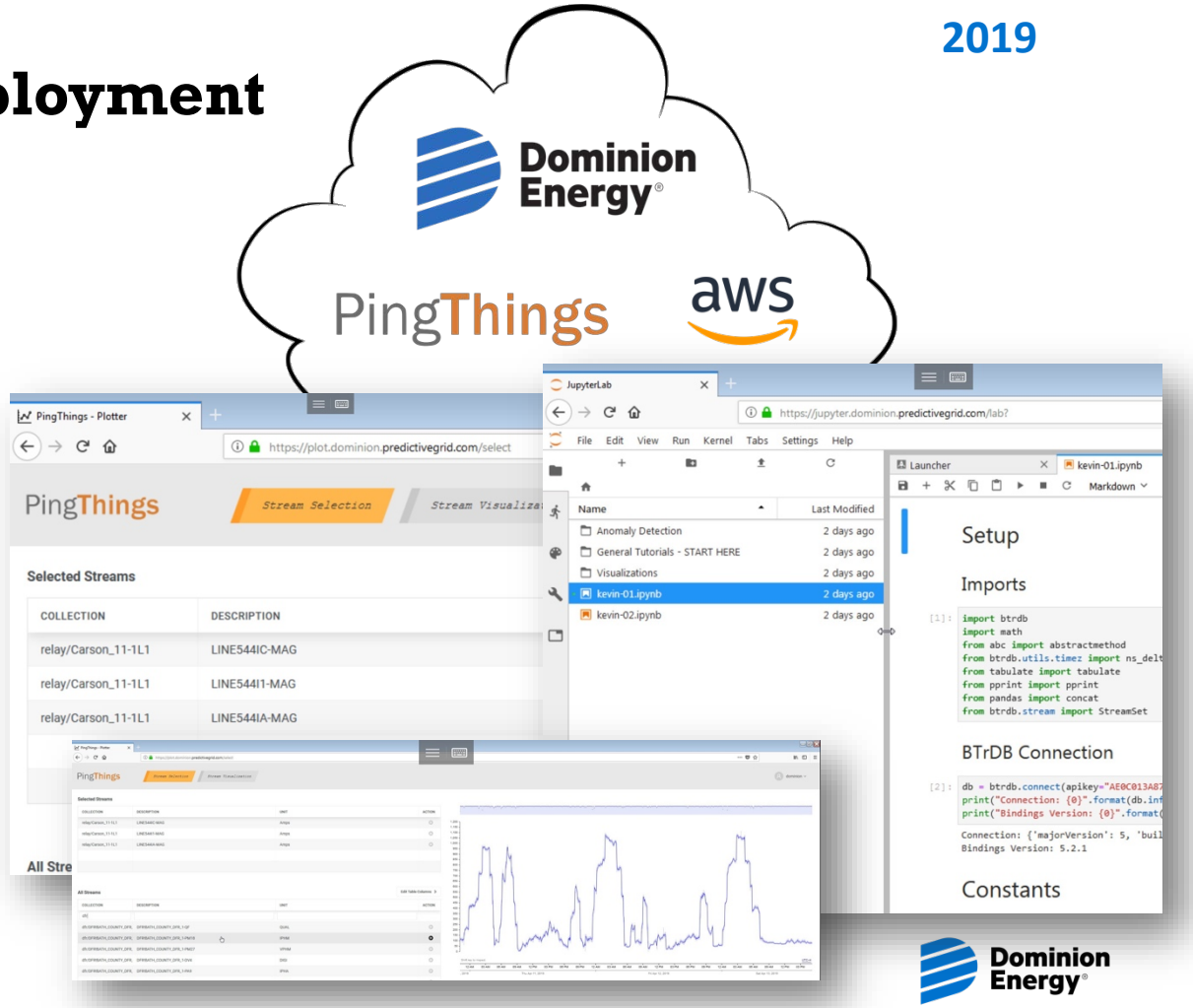
2019

PredictiveGrid Deployment

- For storage, visualization, and engineering analysis of bulk historical synchrophasor data
- Proof-of-concept in 2017-2018
- Deployment in AWSGovCloud in 2019
- From contract to live data and platform ready in 3 months
- Super users spread across ET



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2019

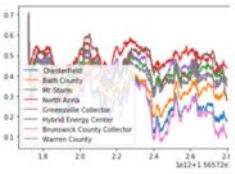
PredictiveGrid & Synchrophasor Use Cases

Currently exploring a wide variety of use cases for parameterizing the performance of the transmission grid.

Detecting Critical Operating Point

- Approaching critical operating condition (Hopf or saddle node bifurcation), oscillation damping decreases
- Autocorrelation coefficient increases rapidly near critical point, used as a metric

$$\rho(t) = \frac{\sum_{\tau=t-2\,mins:\,t} \hat{x}(\tau-1)\times\hat{x}(\tau)}{\sigma^2}$$

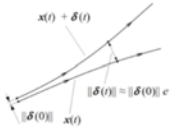


Transient Stability Detection

- The Lyapunov exponent (LE) is the principal criteria of chaos and represents the growth or decline rate of small perturbation along each main axis of the phase space system.
- Positive value gives loss of synchronism

$$\lim_{t\to\infty}\frac{1}{t}\log\frac{\|\delta x(t)\|}{\|\delta x(0)\|}$$

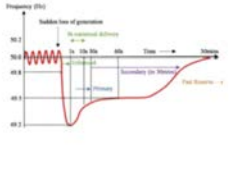
- Done on voltage phase angle at generator bus



Estimation of Inertial Response

$$M\times\dot{f} = P_{in} - P_{out}$$

- Challenges
  - P_{in} (changes with governor response) is not measured
    - Can give negative inertia values (P_{out} positively correlated with f since P_{in} changes)
  - For monitoring we need to estimate from ambient data and not only event data (using a model fit on small variations to estimate response during large disturbances)
- Some approaches –
  - Event based – Assume $P_{in} = constant$, linear regression
    $M\times\delta\dot{f} = -\delta P_{out}$
  - Ambient data
    - Large a large signal type dynamic model between f and P_{out}
    - Only large changes present are slow variations in equilibrium point



ZIP Load Model Tuning

- ZIP load model is widely used for load flow/steady state studies

$$P, Q = a_0 + a_1 V + a_2 V^2$$

- Aim is to tune the model parameters online with PMU data
- Linear regression,

$$\begin{bmatrix} P(t_1),\ldots,P(t_n) \\ Q(t_1),\ldots,Q(t_n) \end{bmatrix} = \begin{bmatrix} a_0^P, a_1^P, a_2^P \\ a_0^Q, a_1^Q, a_2^Q \end{bmatrix} \times \begin{bmatrix} 1,\ldots,1 \\ V(t_1),\ldots,V(t_n) \\ V^2(t_1),\ldots,V^2(t_n) \end{bmatrix}$$

- Challenge is that load is of the form,

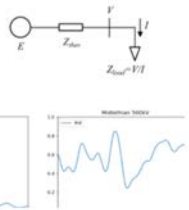
$$(P, Q)_{scale}\times(a_0 + a_1 V + a_2 V^2)$$

Where we don't have access to $(P, Q)_{scale}$ data

Data-driven Voltage Stability Assessment via Thevenin Equivalent

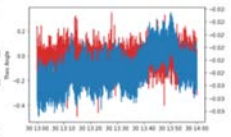
- Find load margin of each bus
- Equate external system by Thevenin circuit
- Voltage stability index based on maximum power transfer on equivalent system

$$Ind = \frac{|Z_{load}| - |Z_{thev}|}{|Z_{load}|}$$



Angular Stability Monitoring

- To monitor steady state angular stability (saddle node bifurcation) using local line measurements
- Voltage phase angle difference across line has limited information
- Thevenin voltage phase angle difference has been shown to be a good observer
  - Monitoring it and comparing it to normal limits found through historical data or heuristic limits e.g. $\pm\frac{\pi}{2}$



Investing in Collaboration

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2009-2019

Value of Industry Collaboration

Investing in Student Internships & Recruitment

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2009-2019

Graduate Student Internship Program

- Dominion hires graduate student interns each summer to work on challenging and exciting projects.
- Dozens have come in through the program, many are now full time engineers at Dominion
- The program has been active for over 10 years
- Currently we take ~10 students across all of T&D
- Applications for next summer are still up and available on the Dominion Careers website

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WHERE DO WE GO FROM HERE?

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Next Steps for Synchrophasors in the SOC

- Experiment with contemporary vendor tools and technologies for
  - Real-time visualization
  - Situational awareness
  - Resiliency
- Develop compliant data systems to support operator decisions
- Reliability Engineering Operator training

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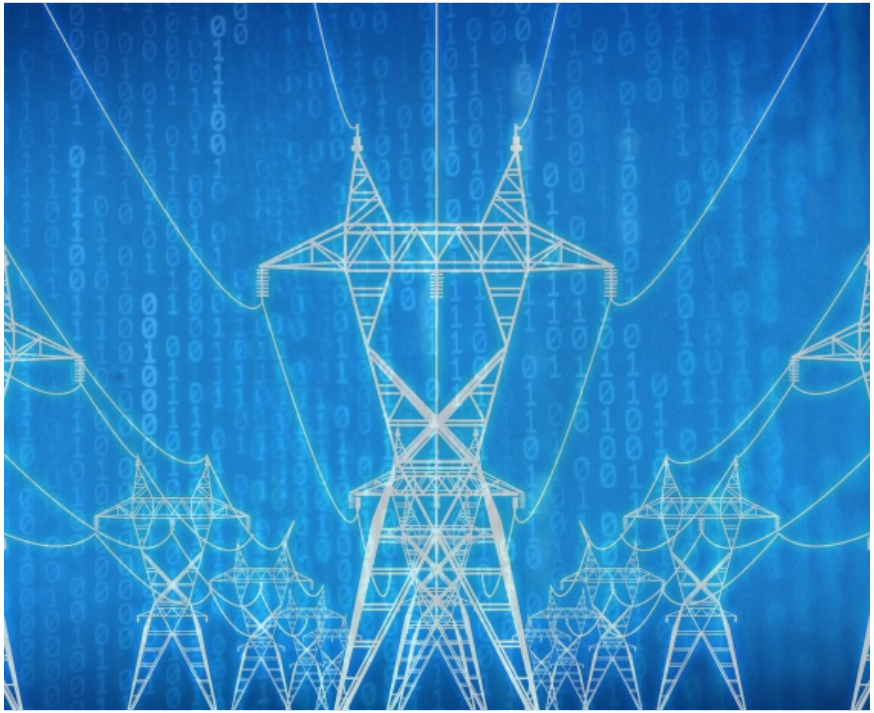
Next Steps for Synchrophasors in Big Data Analytics

- Explore various ways to parameterize the performance of the grid
- Develop robust engineering KPIs
- Scale engineering metrics geographically and historically
- Create feedback loops into the business



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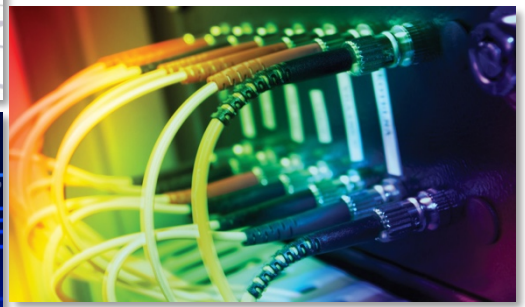
Next Steps for Synchrophasors in Closed-Loop Control

- Wide-Area Closed Loop Control?
- Cyber security
- Communication
- Exploring IEC 61850



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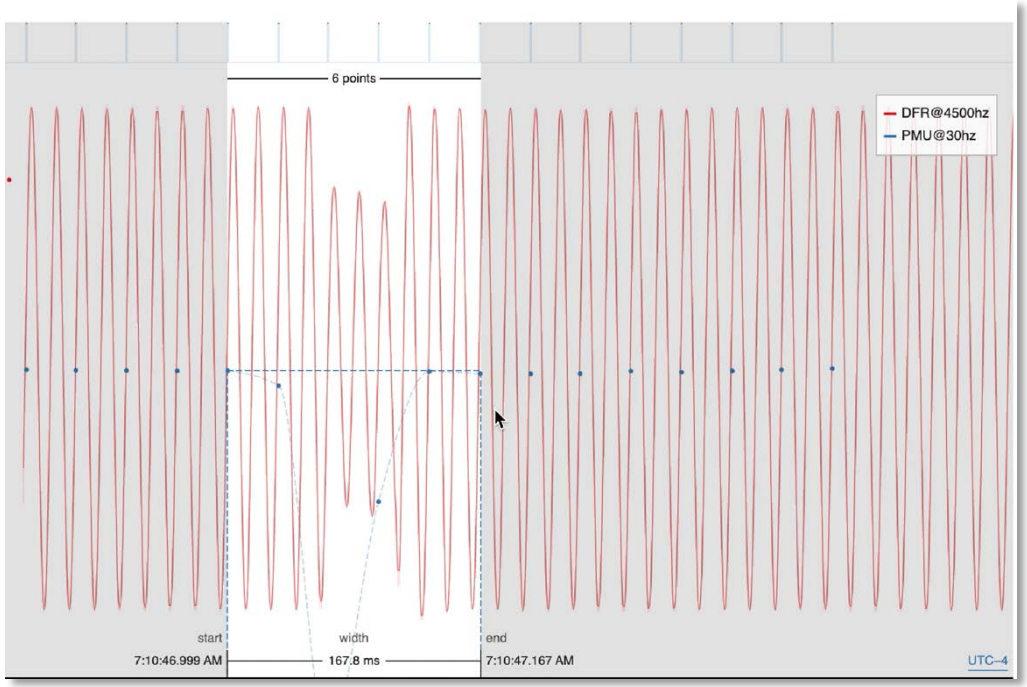
Next Steps for PMU & POW Sensor Deployment

More data to come…

- Distribution PMU Deployment?
- 5G communication networks?
- Waveform Monitoring?
- Other sensor types?
- Bringing it all together with data fusion



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What Does the Future Hold for the Industry?

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Thank you!

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