Synchrophasors at Dominion Energy

Yesterday – Today – Tomorrow

Presented by

David Roop &
Kevin D. Jones, Ph.D.

September 30, 2020

Dominion Energy

Oct. '09 – Oct. '20

Looking Back Over 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
  - Towards total transmission system coverage
- **2018** – Analytics Journey Begins
  - High performance sandbox for use case development
- **2019** – Go-Live of Cloud-Hosted PingThings' Platform
- **2020** – Leaning into Data Analytics

The Value of Collaboration

Recognizing Industry and University Partnerships

2009-2020

The Value of Industry Collaboration

Pacific Northwest NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

FPL

Rensselaer

VirginiaTech

NASPI

CURENT CENTER FOR ULTRA-WIDE-AREA RESILIENT ELECTRIC ENERGY TRANSMISSION NETWORKS

SEL SCHWEITZER ENGINEERING LABORATORIES

pjm

QUANTA TECHNOLOGY Smart Solutions, Practical Results

OAK RIDGE National Laboratory

PingThings

GRID PROTECTION ALLIANCE

THE UNIVERSITY OF TENNESSEE KNOXVILLE

AMERICAN ELECTRIC POWER BOUNDLESS ENERGY™

TVA

SPP Southwest Power Pool

OG+E

BERKELEY LAB Lawrence Berkeley National Laboratory

NERC NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Bonneville POWER ADMINISTRATION

DUKE ENERGY®

Southern Company

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Graduate Student Internship Program

- Dominion hires graduate student interns each summer to work on exciting and challenging 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 per summer.
- Applications for next summer will be posted soon on the Dominion Careers website.

2009-2017

The Story Begins

2009-2013

SGIG Demonstration Project

Three Phase Linear State Estimator & Its Applications

- Overview
  - Installation of PMUS
  - Development of WAMS
  - Application Development & Testing
  - Linear State Estimation
  - CTPT Calibration
  - Islanding Detection
  - Imbalance Monitoring
  - Real-Time Visualization

U.S. DEPARTMENT OF ENERGY

Dominion

VirginiaTech

QUANTA TECHNOLOGY Smart Solutions, Practical Results

SGIG Demonstration Project

Three Phase Linear State Estimator & Its Applications

- Deployment of 80 PMUS to the Dominion Energy 500kV Network
  - 21 Substations 70%
  - 35 Transmission Lines 75%
  - 28 Transformers 20%
  - 110 Circuit Breakers 85%
  - 12 230kV Transmission Lines 5%

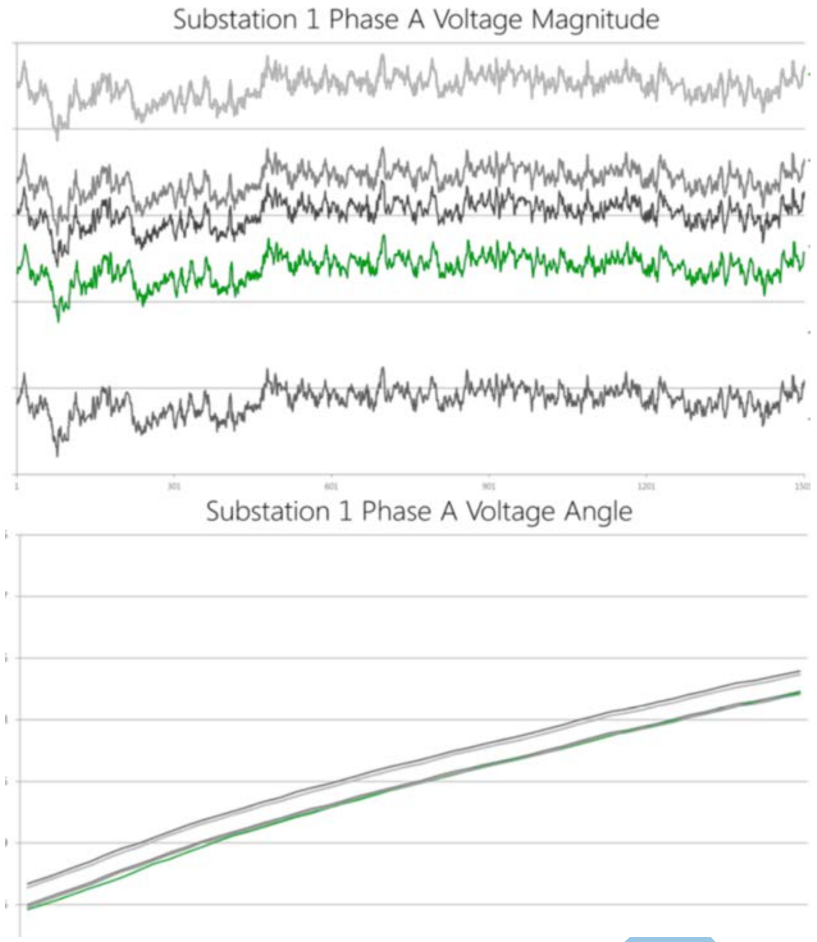
2009-2013

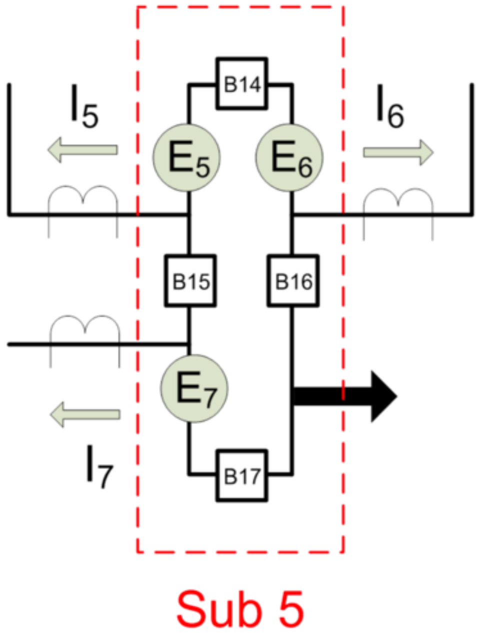
SGIG Demonstration Project

Three Phase Linear State Estimator & Its 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 contained:
    - 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

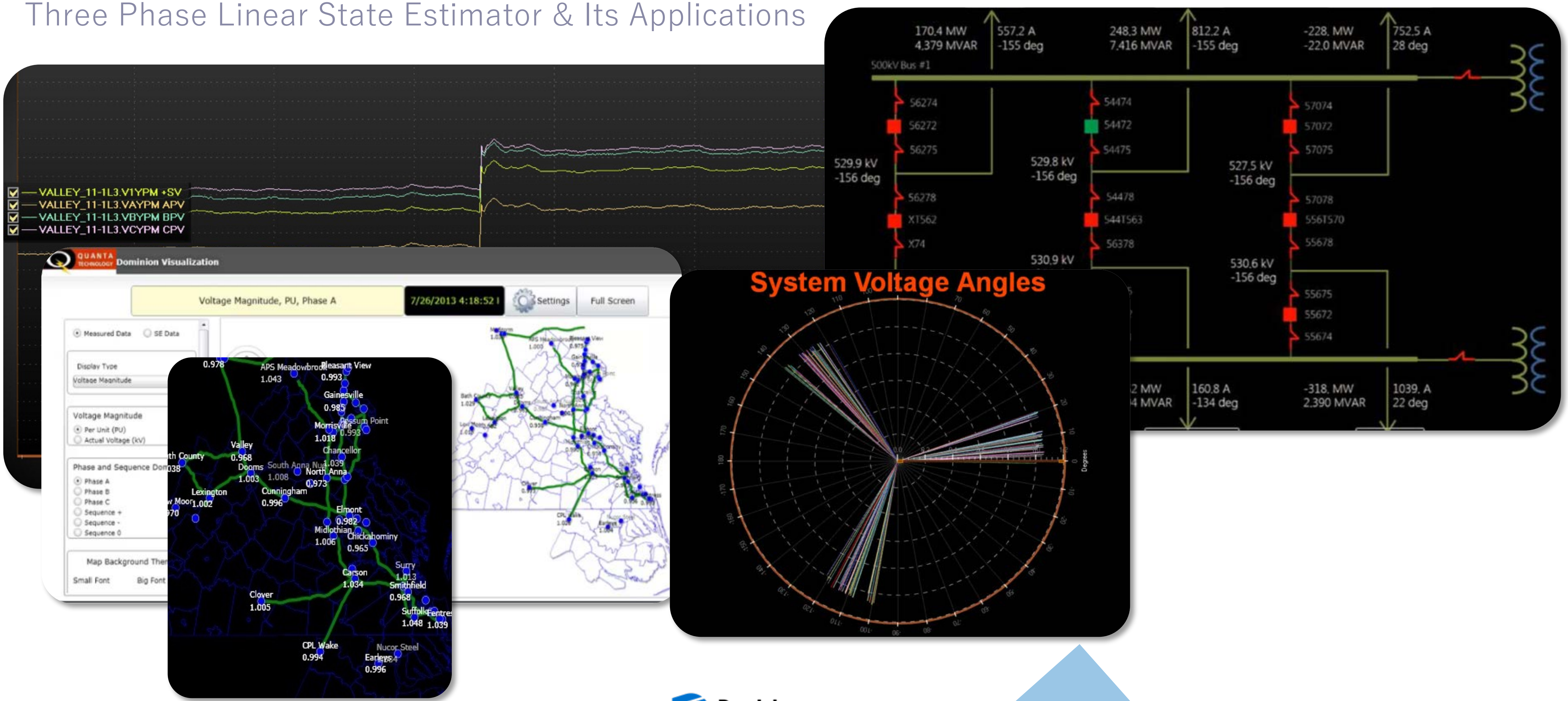




2009-2013

SGIG Demonstration Project

Three Phase Linear State Estimator & Its Applications

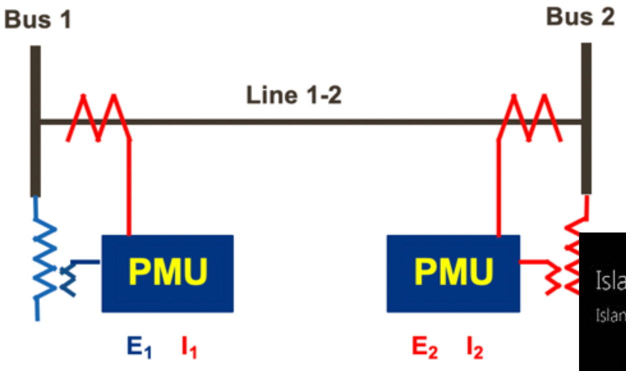


2009-2013

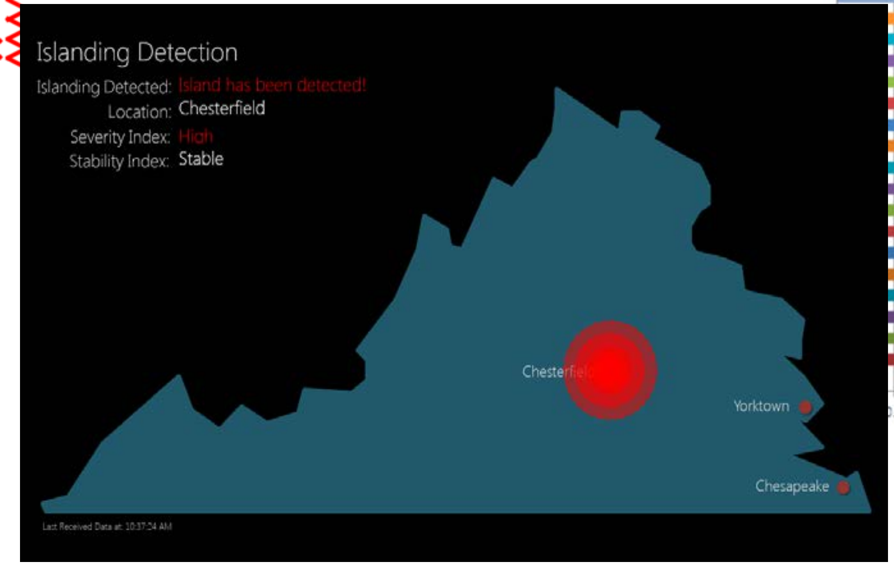
SGIG Demonstration Project

Three Phase Linear State Estimator & Its Applications

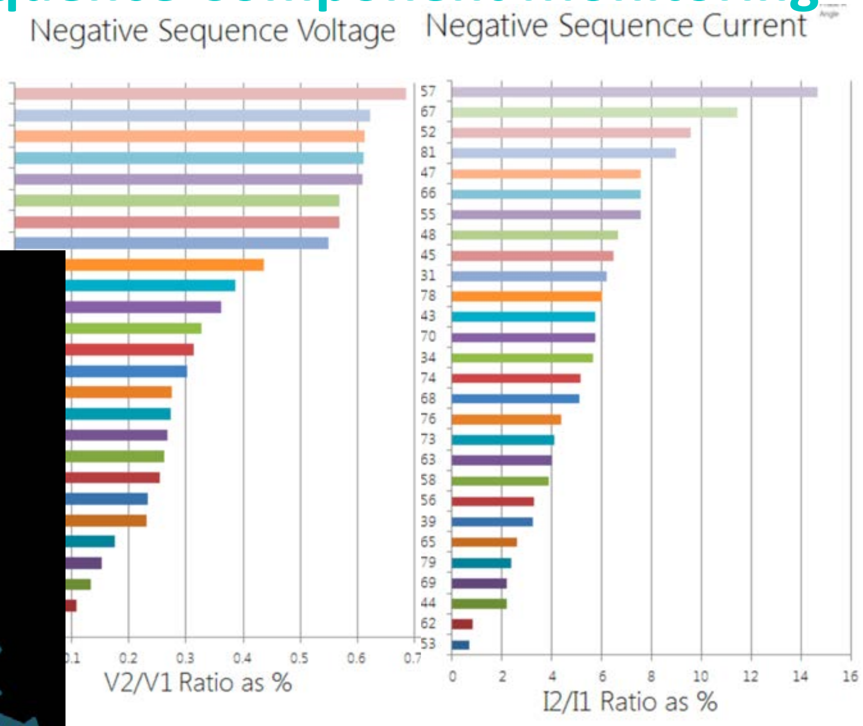
Instrument Transformer Calibration



Islanding Detection



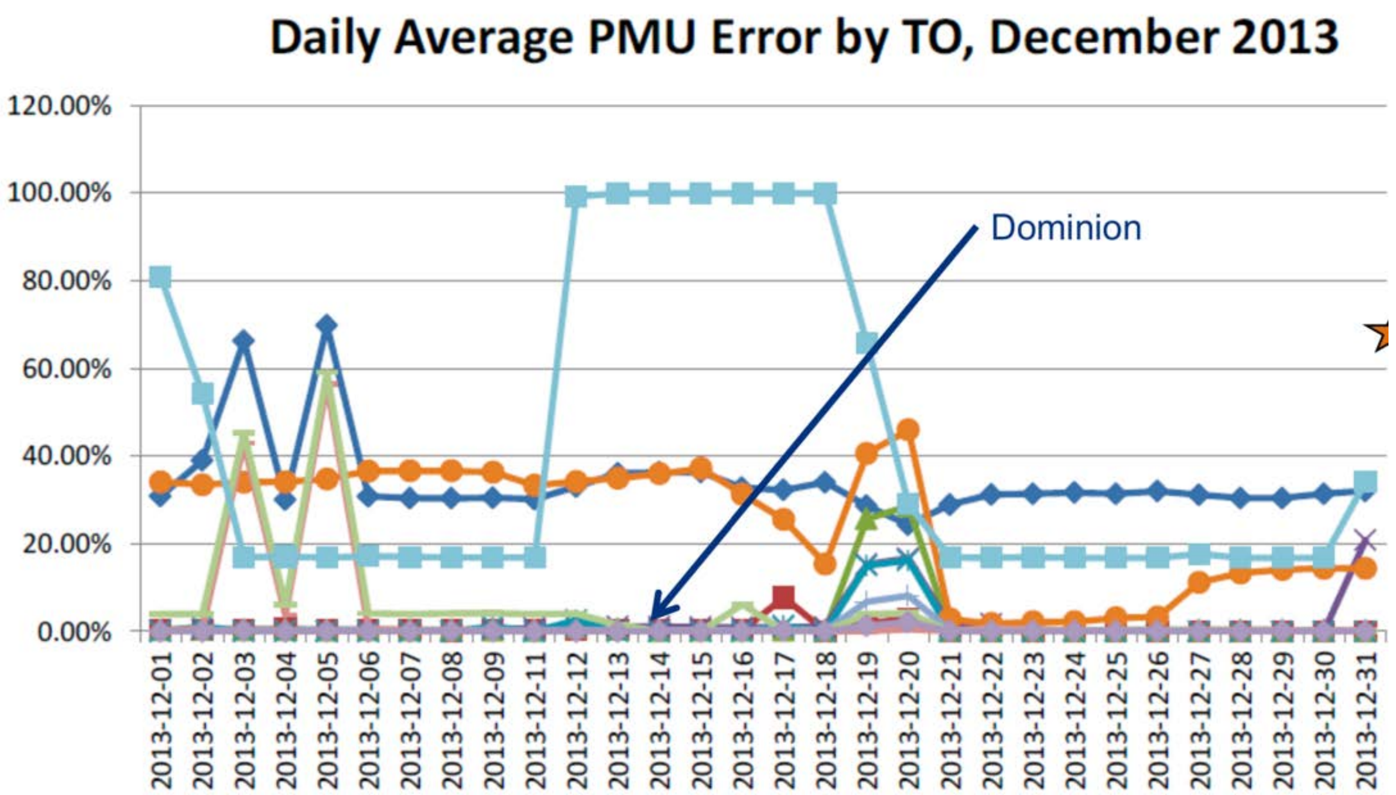
Sequence Component Monitoring



2013

Streaming Synchrophasor Data to PJM

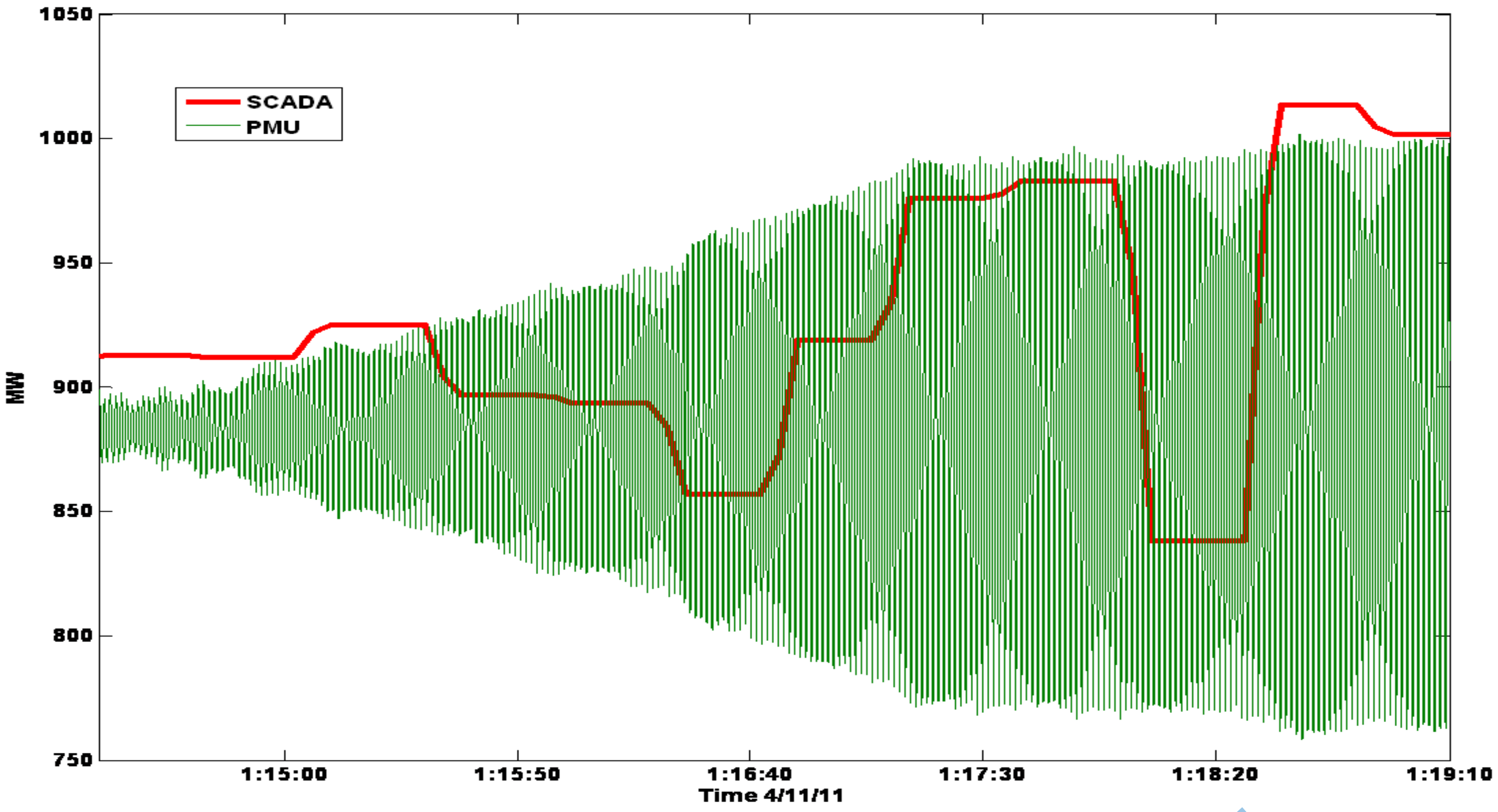
- Sharing data with PJM
- Top performing data quality in 2013
- Developed custom automation for naming translation and phase angle rotation – released open source



2011

Some Early Wins

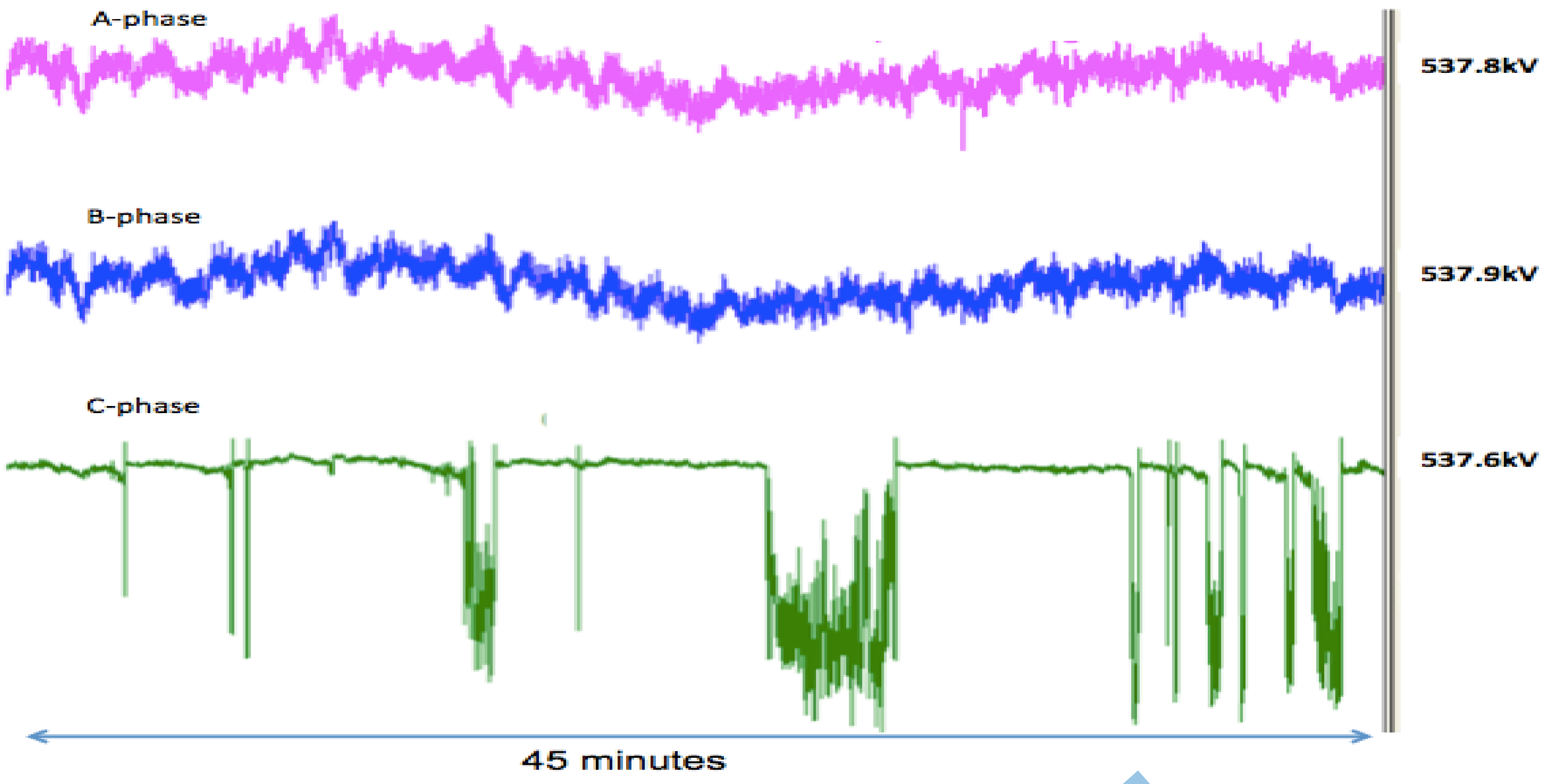
Oscillations



2012

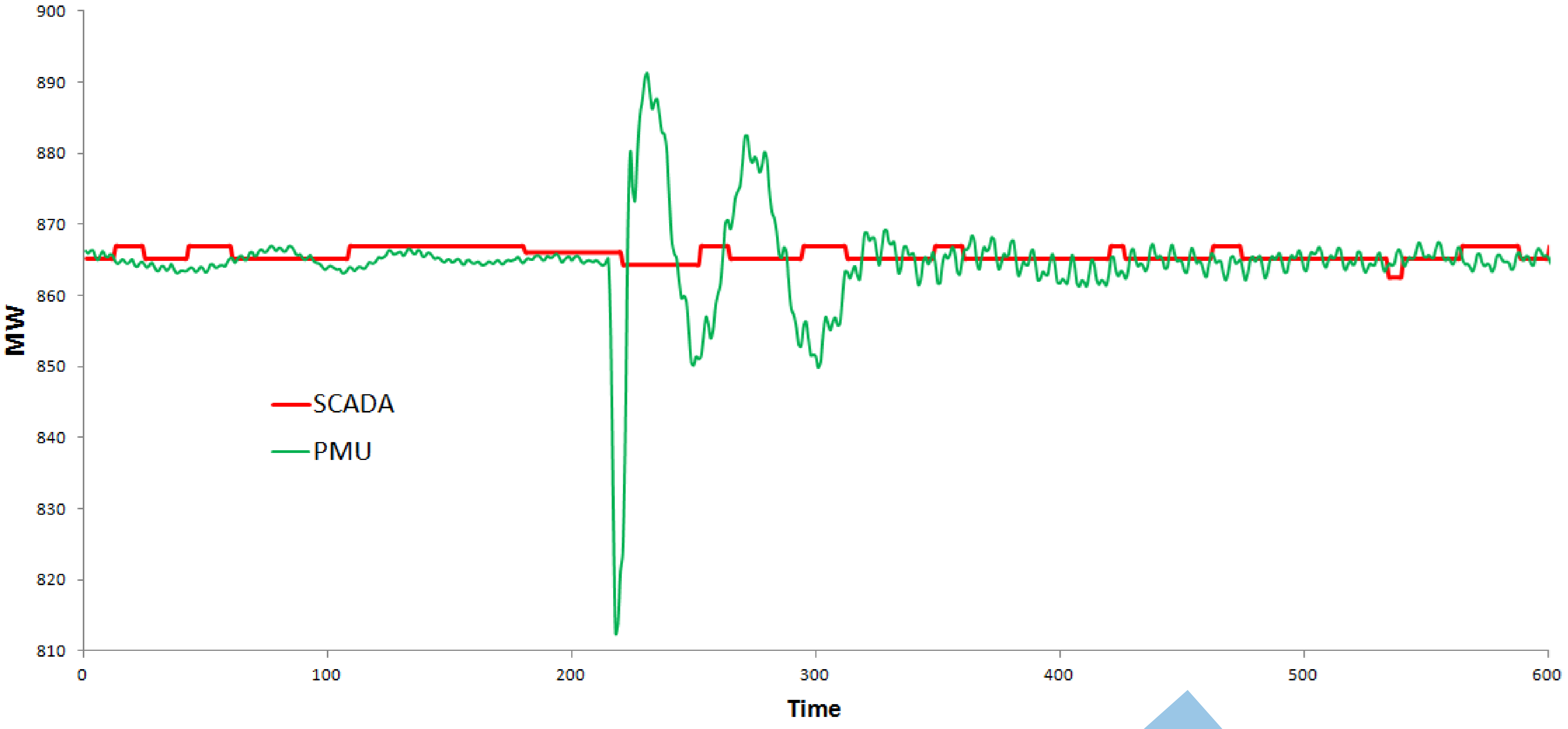
Some Early Wins

Instrument Transformer Failure Detection



Some Early Wins

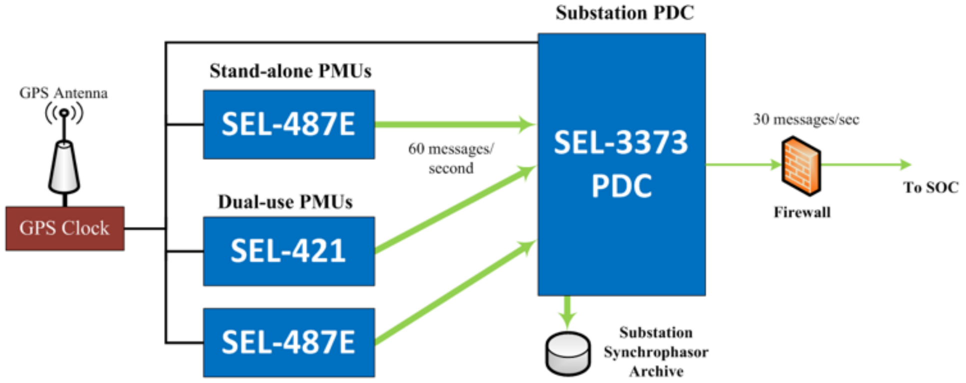
Looking at Faults



2012

Standardized PMU & PDC Deployment

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



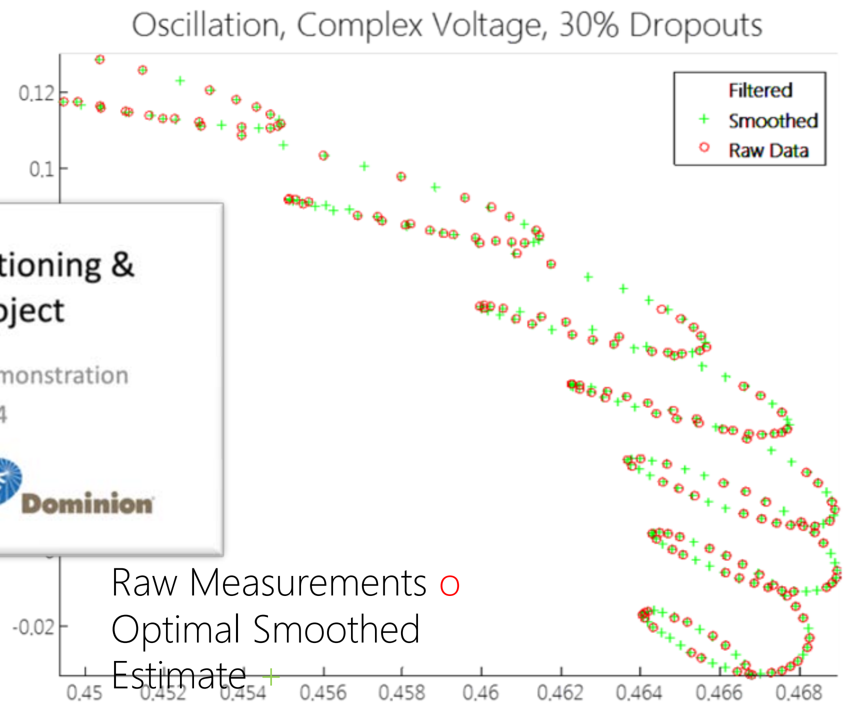
- This created an automatic mechanism for growing the number of PMU measurements.

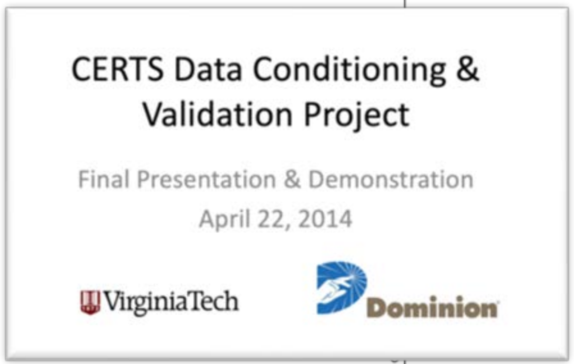
2019 Totals	Average Per Relay-PMU	Relay-PMU EOY 2019 Total
Frequency	1	600
DFDT	1	600
Status	1	600
Voltage Magnitude	5	3,000
Voltage Angle	5	3,000
Current Magnitude	6	3,600
Current Angle	6	3,600
Digital	1	600
Analog	0	0
Totals	26	15,600

CERTS Data Conditioning & Validation

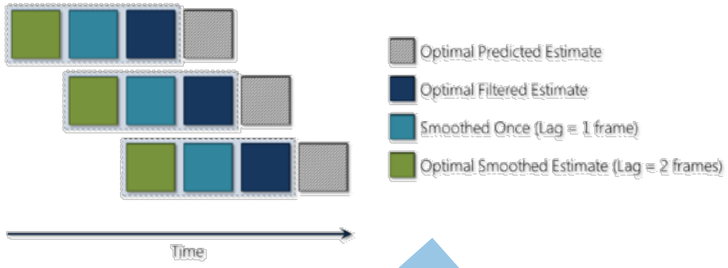
2012-2014

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



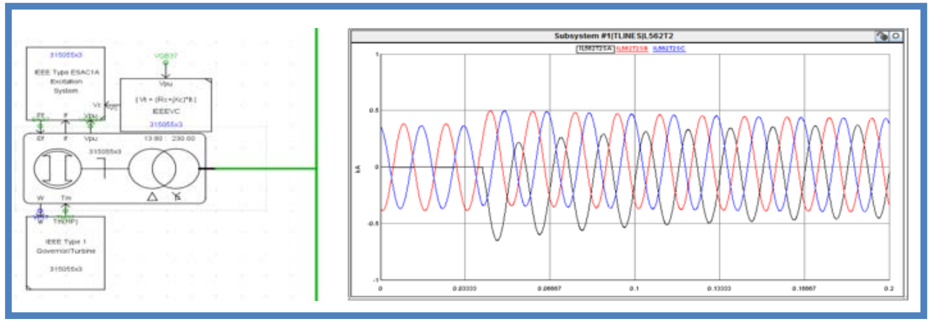


Raw Measurements o
Optimal Smoothed Estimate +

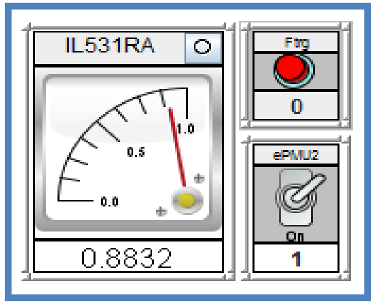


2014

Operator Training Simulator

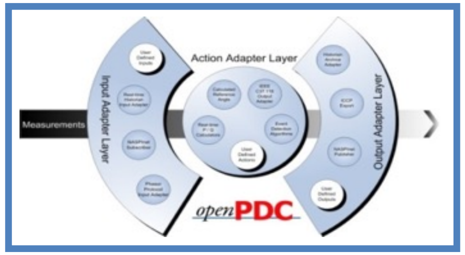


Electromechanical & Electromagnetic Dynamics

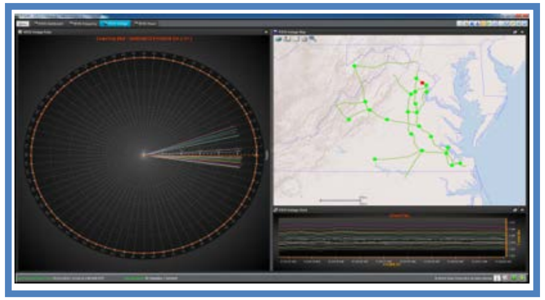


Operator-In-Loop Runtime Controls

Closed-Loop Relay/PMU Interface



Virtual PMUs Streaming Data

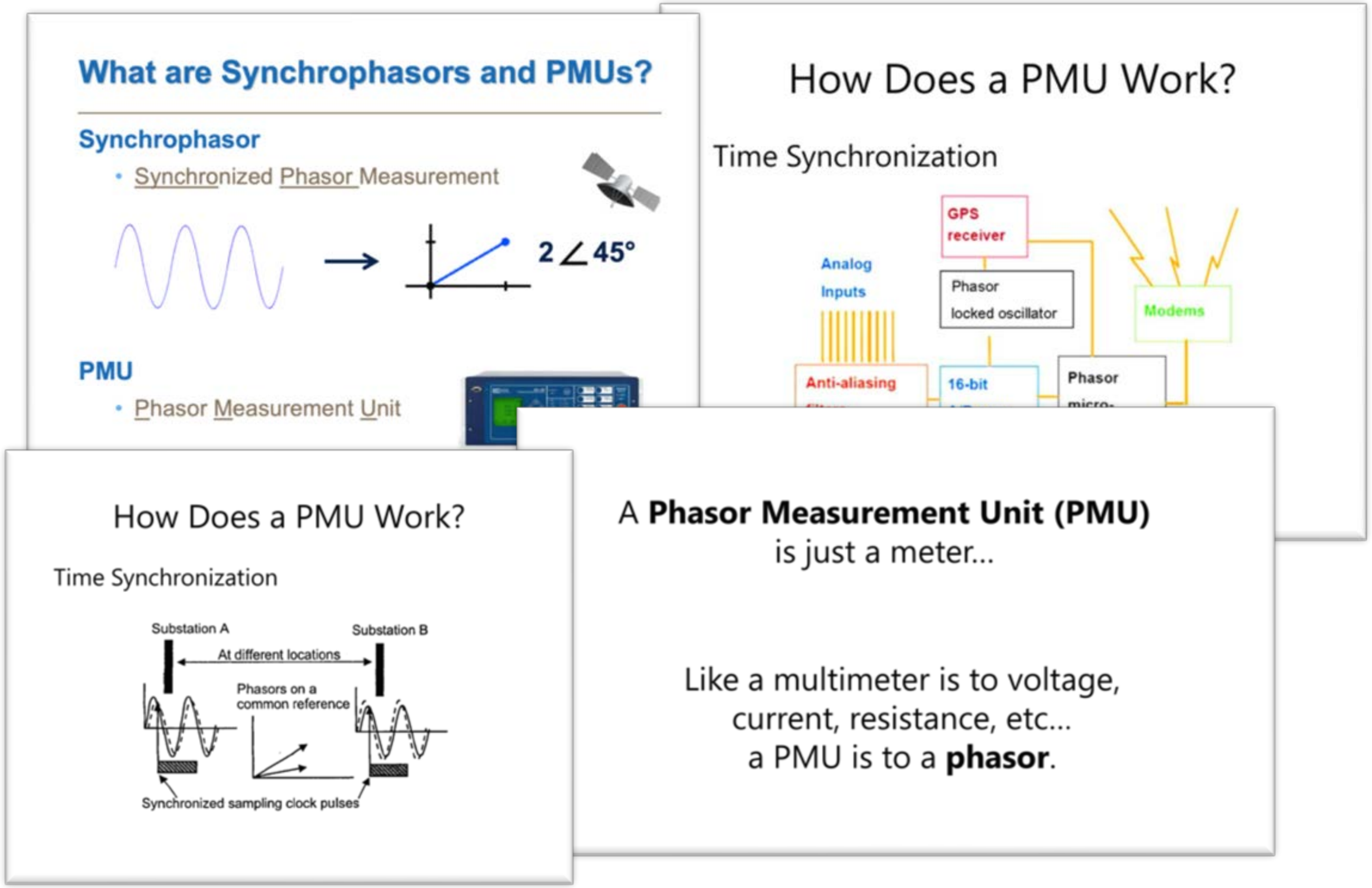


Visualization Software

2014-2019

Relay Technician Training Course

- Dominion has a world class Relay Tech Program.
- Relay Techs commission all Dominion PMUs
- Step 6 course teaches:
  - PMU Fundamentals
  - Why PMUs matter to Dominion



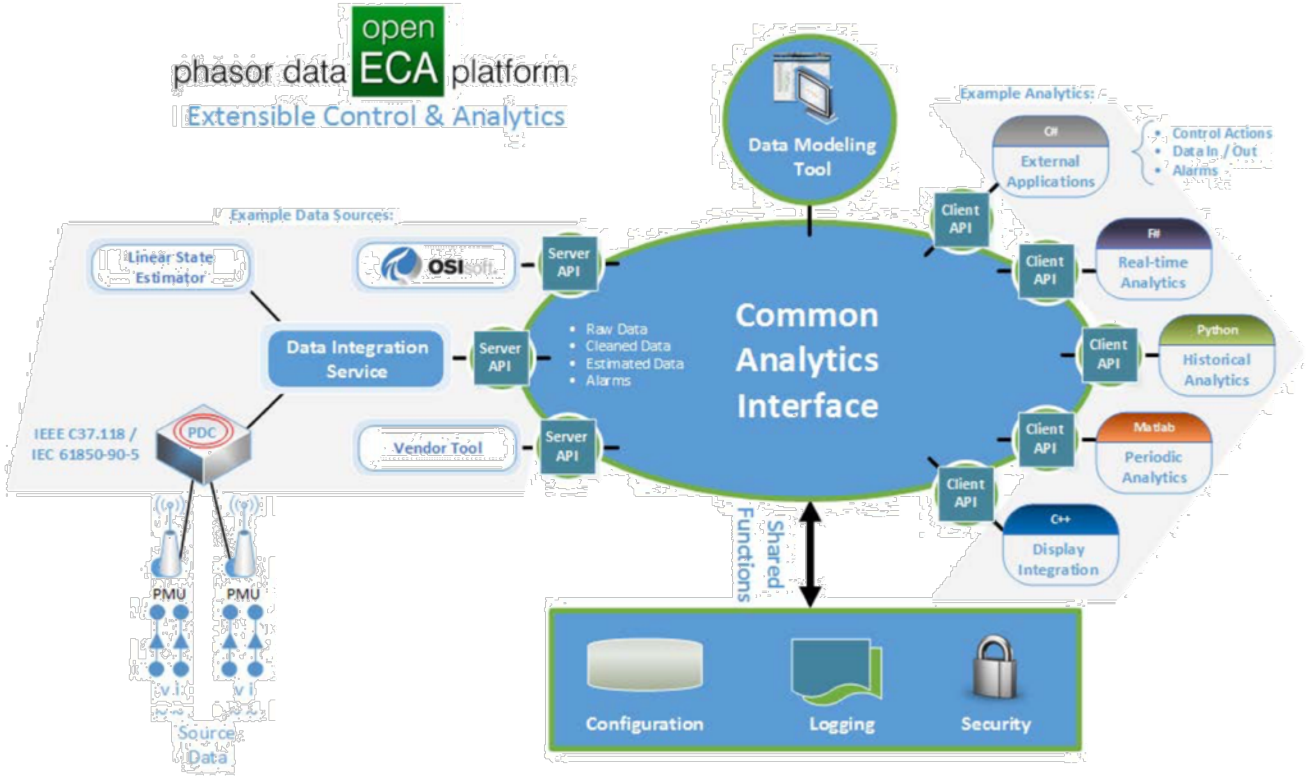
2015-2017

DOE FOA970

openECA

T&D Consulting Engineers

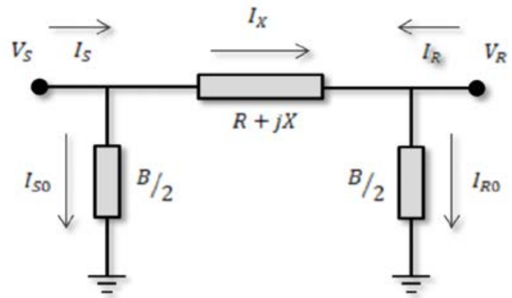
- Develop an open source real-time control and analytics platform based on Grid Solutions Framework
- Develop and test 10 applications with project partners
- Technology improvements to LSE

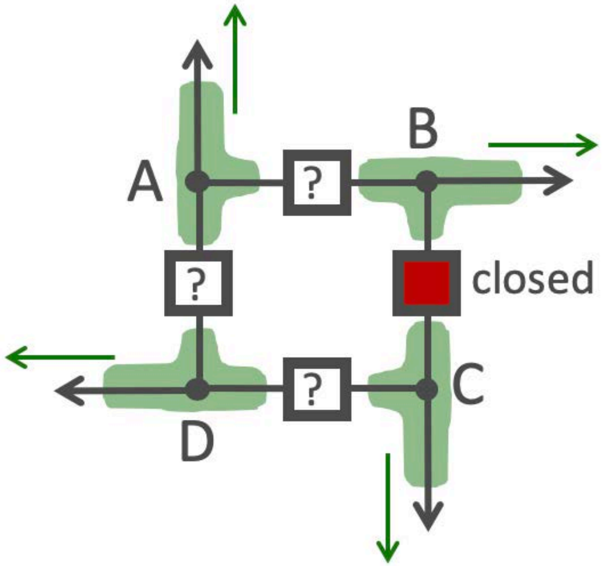


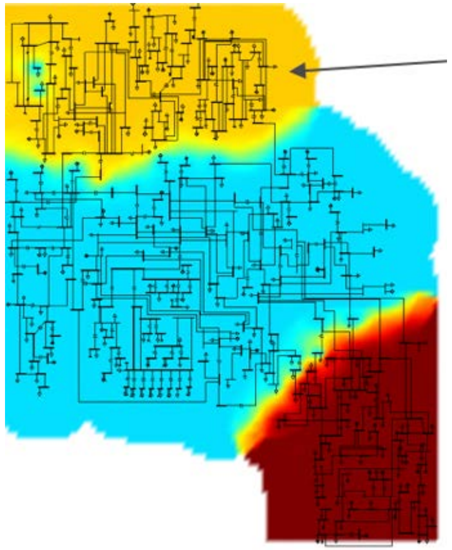
openECA

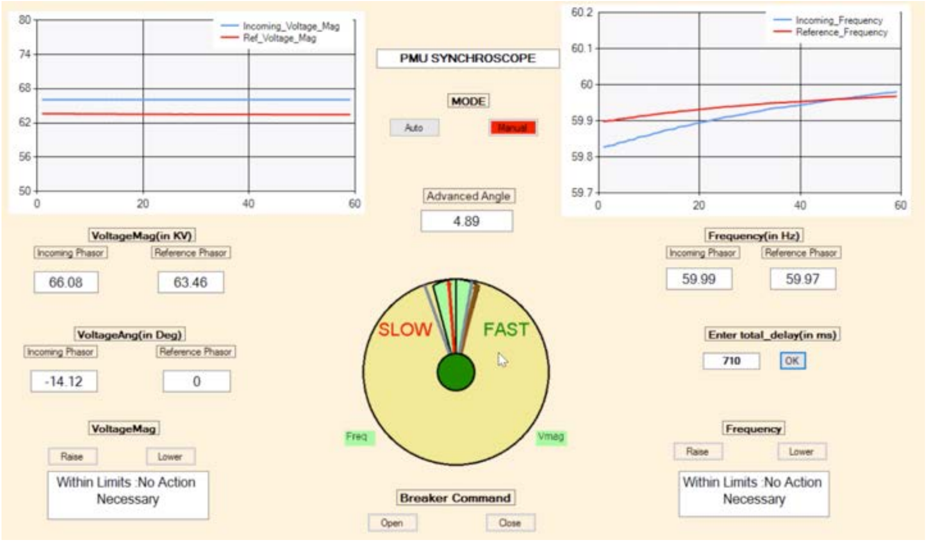
7 Network Apps from Dominion + Virginia Tech

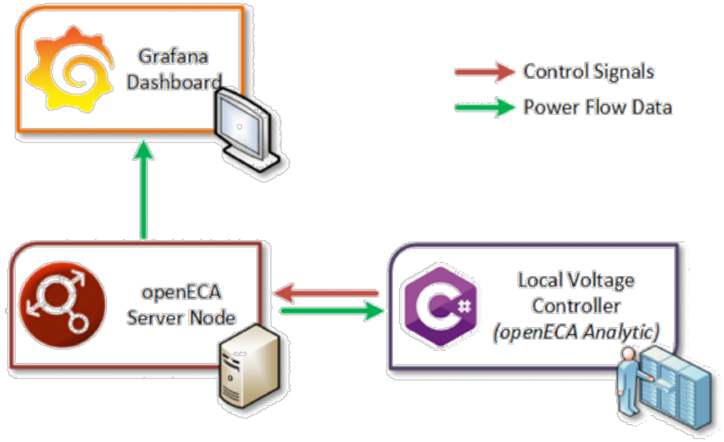
- Topology Estimator
- Local Voltage Controller
- Regional Voltage Controller
- PMU Synchroscope
- Instrument Transformer Calibration
- Transmission Line Impedance Calibration
- Real-Time Impedance Calculator







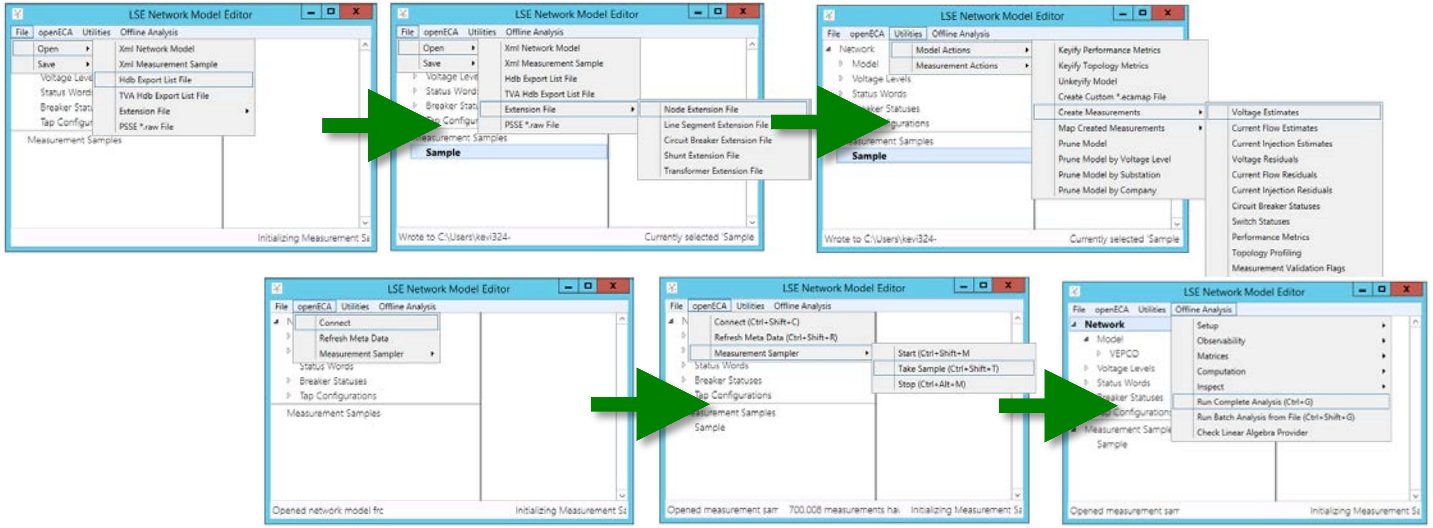


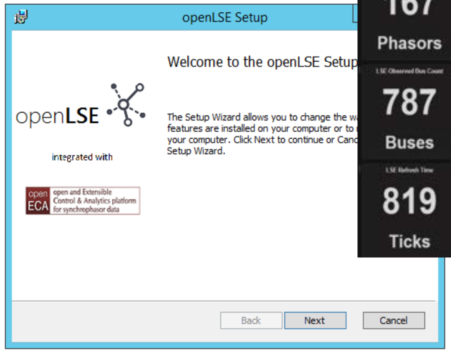


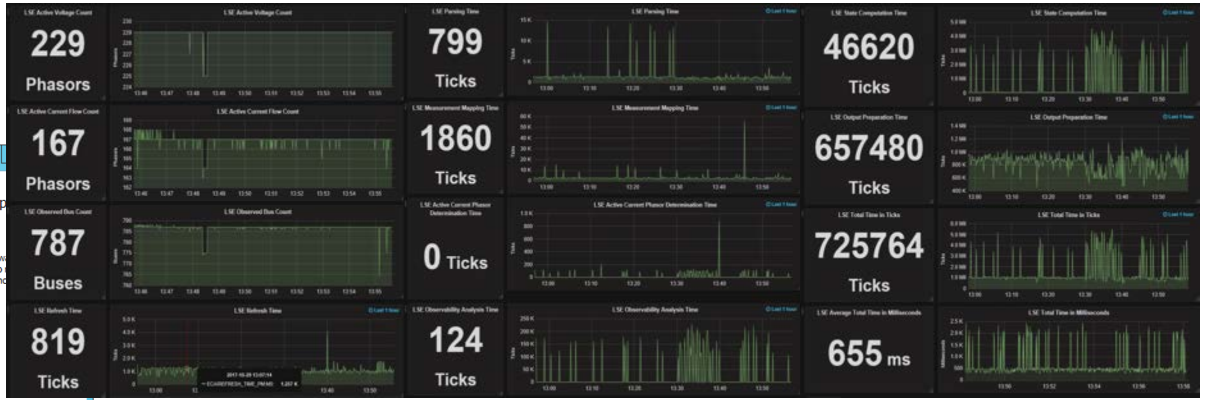
openECA

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 as open source
- Demonstrated at
  - SPP
  - TVA
  - Dominion Energy







https://github.com/kdjones/openlse
https://github.com/kdjones/lse

Dominion Energy

2016-2019

DFRs Get PMU Functionality

- 2013 – DFR manufacturers 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 recorder PMU feature on in the field *500kV 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

2018-2020

What Happened Next?

A Home for Synchrophasors • PingThings at Dominion • Data Analytics

Hitting the Wall

A Path Forward for Synchrophasors

We must drive down the cost of working with data!

THE RIGHT TOOL FOR THE JOB

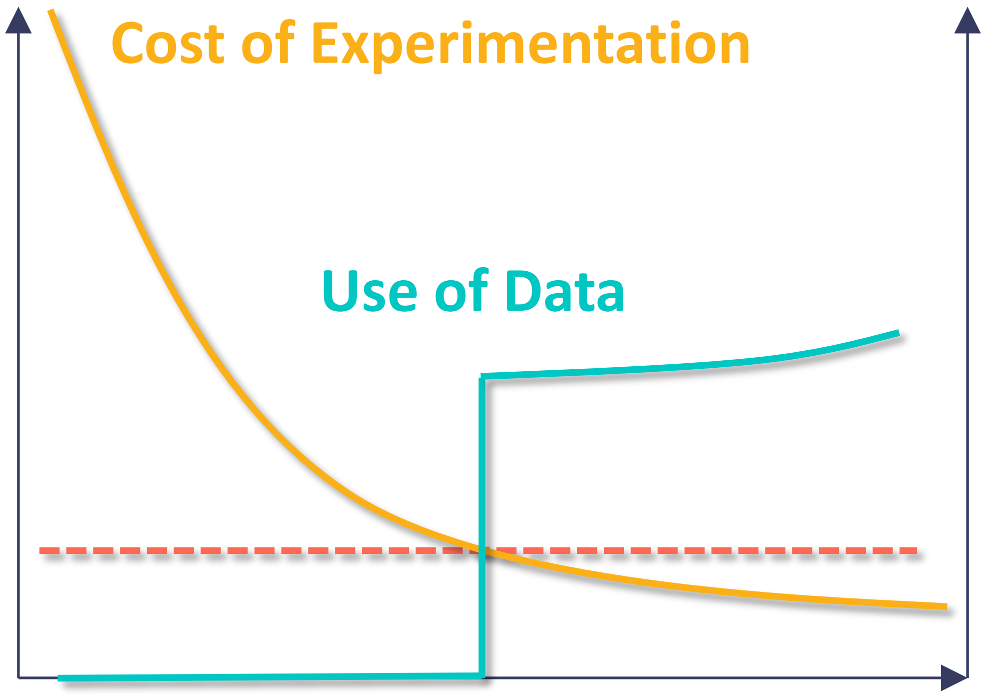
High resolution time series (e.g. synchrophasors) is a special comp. sci problem • Big Data technologies evolved towards specialization • Not all time-series DBs are equal • Historians make data history • Data at rest stays at rest

NO SINGULAR "KILLER APP"; ENSEMBLE INSTEAD

The literature is full (10^3s) of proposed applications • Each utility may have niche use cases • Value prop. of individual use cases is myopic

ANALYTIC EXPERIMENTATION >> A PRIORI "GUESSES"

We need to use lean methodologies, not guesses that play out over years, to arrive at our highest valued use cases



A Fork in the Road. . .

Technology

- First-Principles Approach
- Platform vs Siloed Applications
- Cloud vs On-Prem

Engineering vs Real-time Operations

- Rapid prototyping & integration
- Quicker ROI for synchrophasors

Capital vs O&M

- Larger company/societal impact

2018-2020

The Solution

PingThings Platform • Engineering Analytics & Modeling Team • Rapid, Cost-Effective Experimentation

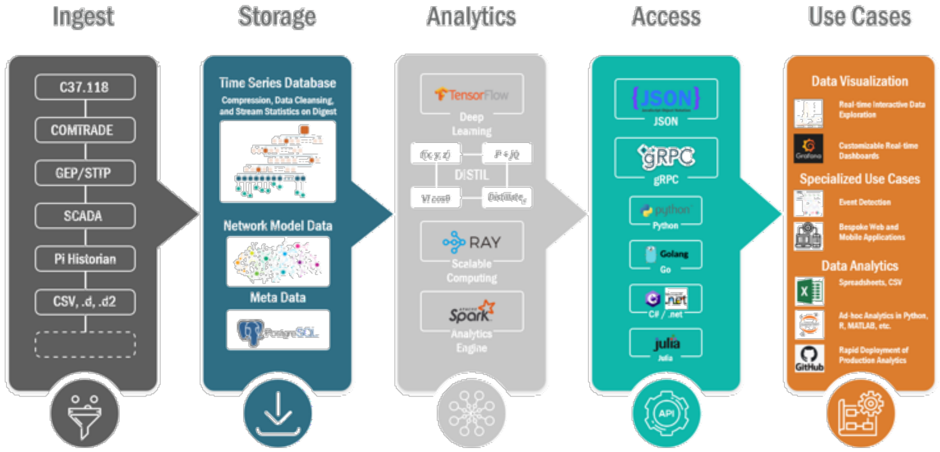
PingThings` PredictiveGrid Platform

PREDICTIVEGRID IS A PLATFORM-AS-A-SERVICE

This means we pay an annual subscription as an *all-in-cost* for:

- All Platform Features
- Infrastructure
- Maintenance
- Scheduled Upgrades
- Security
- Services

The combination of best-in-class tech, hosted in the cloud, and supported by a world-class team allows us to achieve at a scale and pace that would be otherwise impossible.



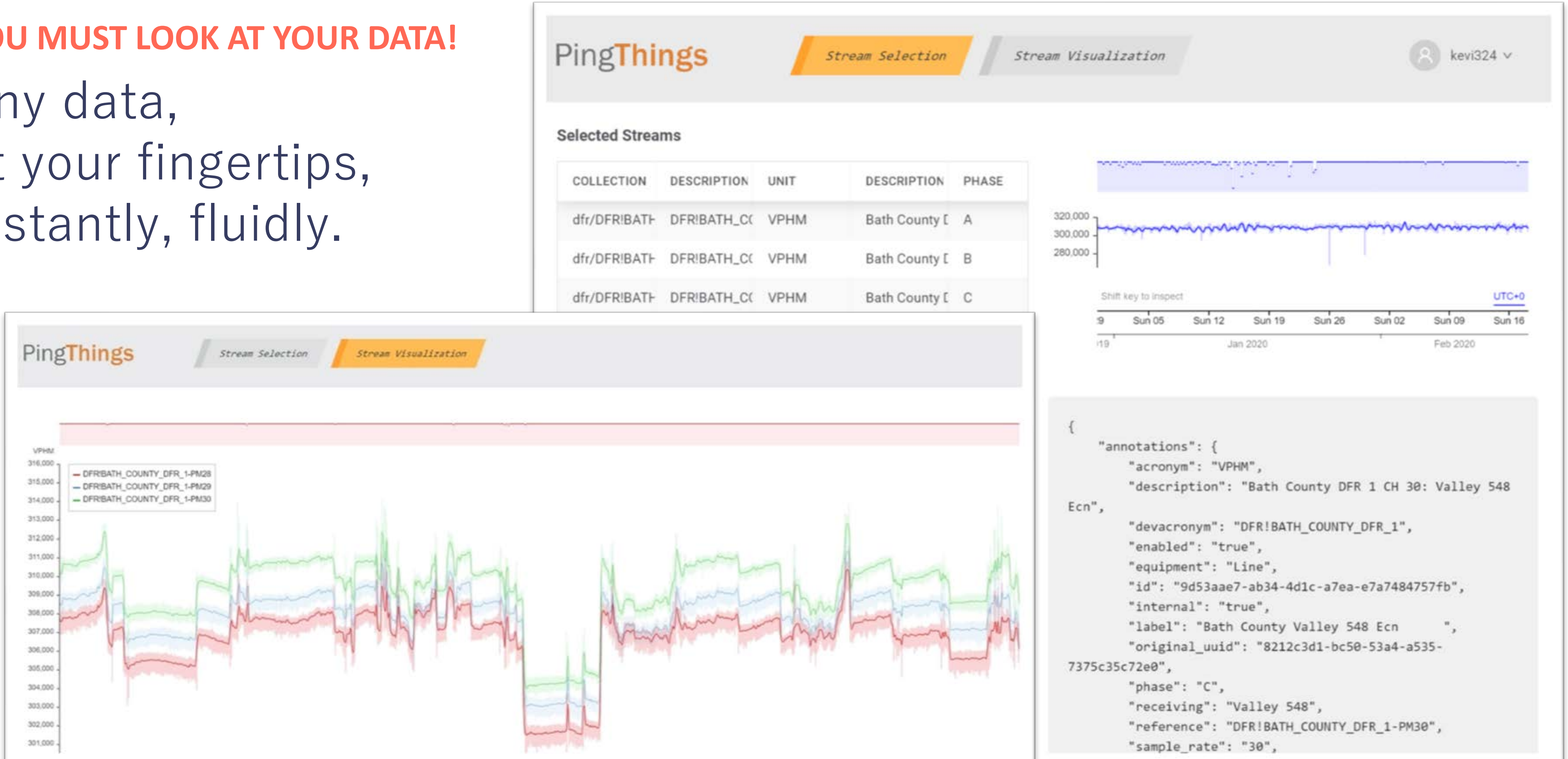
Zero to streaming data in under 4 months.

We can do more with less [people, time, and resources] with PingThings & PredictiveGrid.

Human-Scale Data Exploration

YOU MUST LOOK AT YOUR DATA!

Any data,
at your fingertips,
instantly, fluidly.



Data Exploration: A Case Study

Fault Analysis is a heavy user of Mr. Plotter.

RAPID EVENT ANALYSIS

Problem: Event analysis is tedious and time consuming – delaying restoration time. 45-60 minutes per event to visualize and analyze the data.

Solution: Mr. Plotter makes this instantaneous and flexible (multiple locations at once) saving critical time and answer key questions during critical restoration activities.

Opportunity: 87 events in the last 365 days

EVENT DATA REQUESTS

Problem: Generation often waits 45+ days to ask for event data but DFRs only store data for 30 days.

Solution: PredictiveGrid saves data forever and Mr. Plotter makes event data exports trivial.

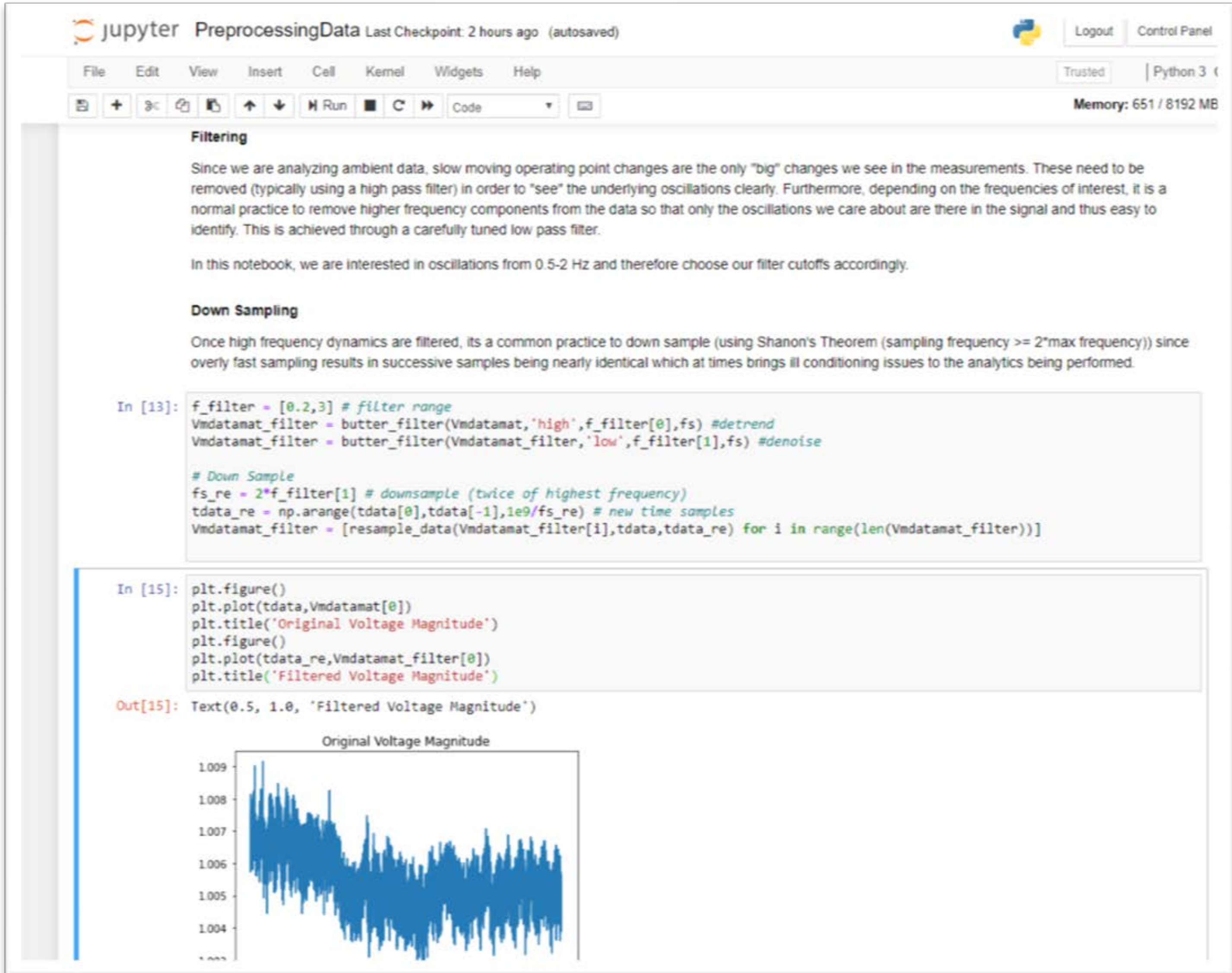
Opportunity: ~20 events each year – mostly storm season for critical locations like Surry, North Anna, Greensville.

"The plotter was worth the cost of admission … because it makes the data real." - Brian Starling

Rich, Programmatic Access

PREDICTIVEGRID DRIVES DOWN THE COST OF ANALYTIC DEVELOPMENT

- Ad-hoc Analytics & Experimentation
  - *Exploration*
- Rapid & Targeted Use Case Development
  - *Exploitation*
- Great for Exploration and Exploitation.
- Great for beginner, intermediate, and advanced users.



Our Team

Chetan Mishra, Ph.D.
Data Analytics Lead

Chen Wang, Ph.D.
Data Analytics, Data Eng.

Hesen Liu, Ph.D.
Data Analytics, Data Eng.

Duotong Yang, Ph.D.
Modeling

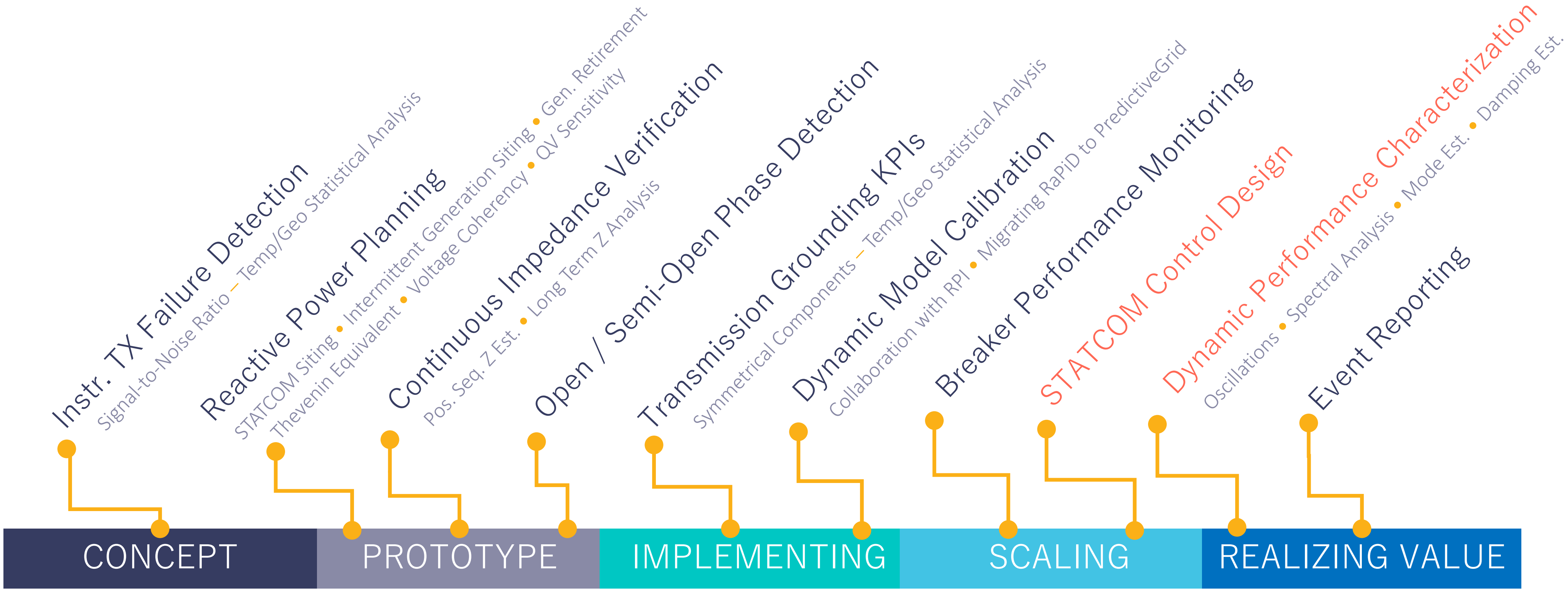
Benjamin Diller
Technology, Data Eng. (Joining Soon)

Xin Xu
Data Analytics (Joining Soon)

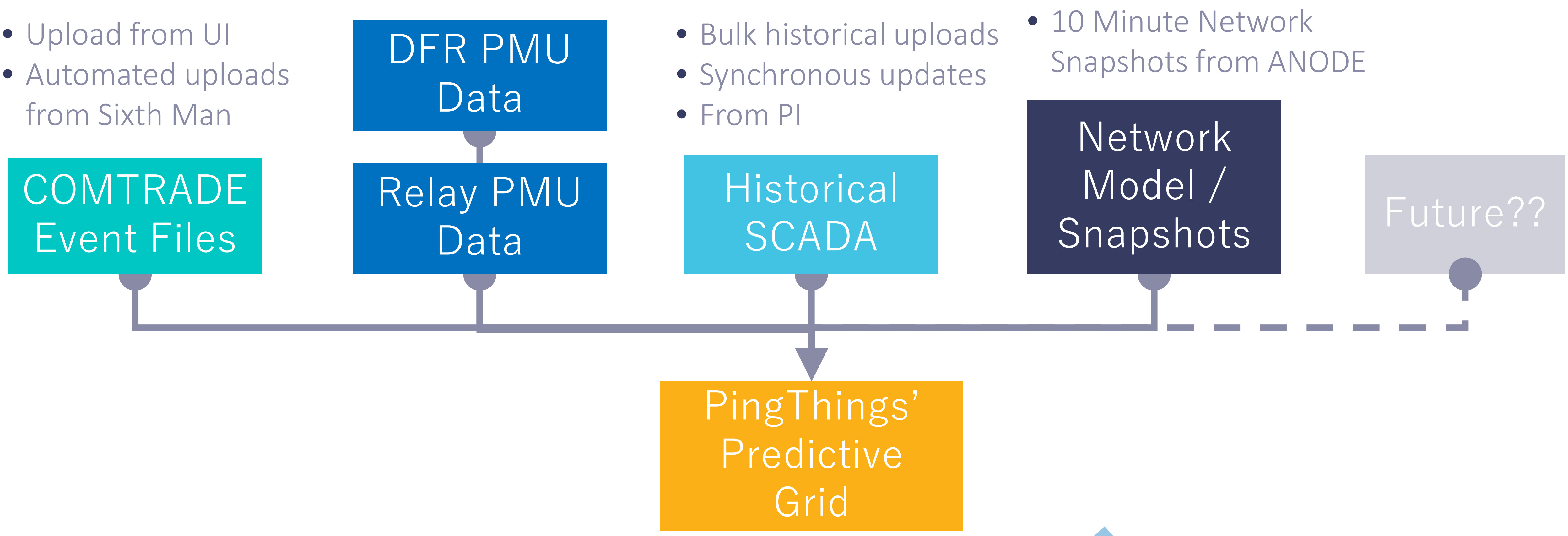
Marcelo de Castro Fernandes
Data Analytics Intern, Summer 2020

Xianda Deng
Data Analytics Intern, Summer 2020

Promising Use Cases

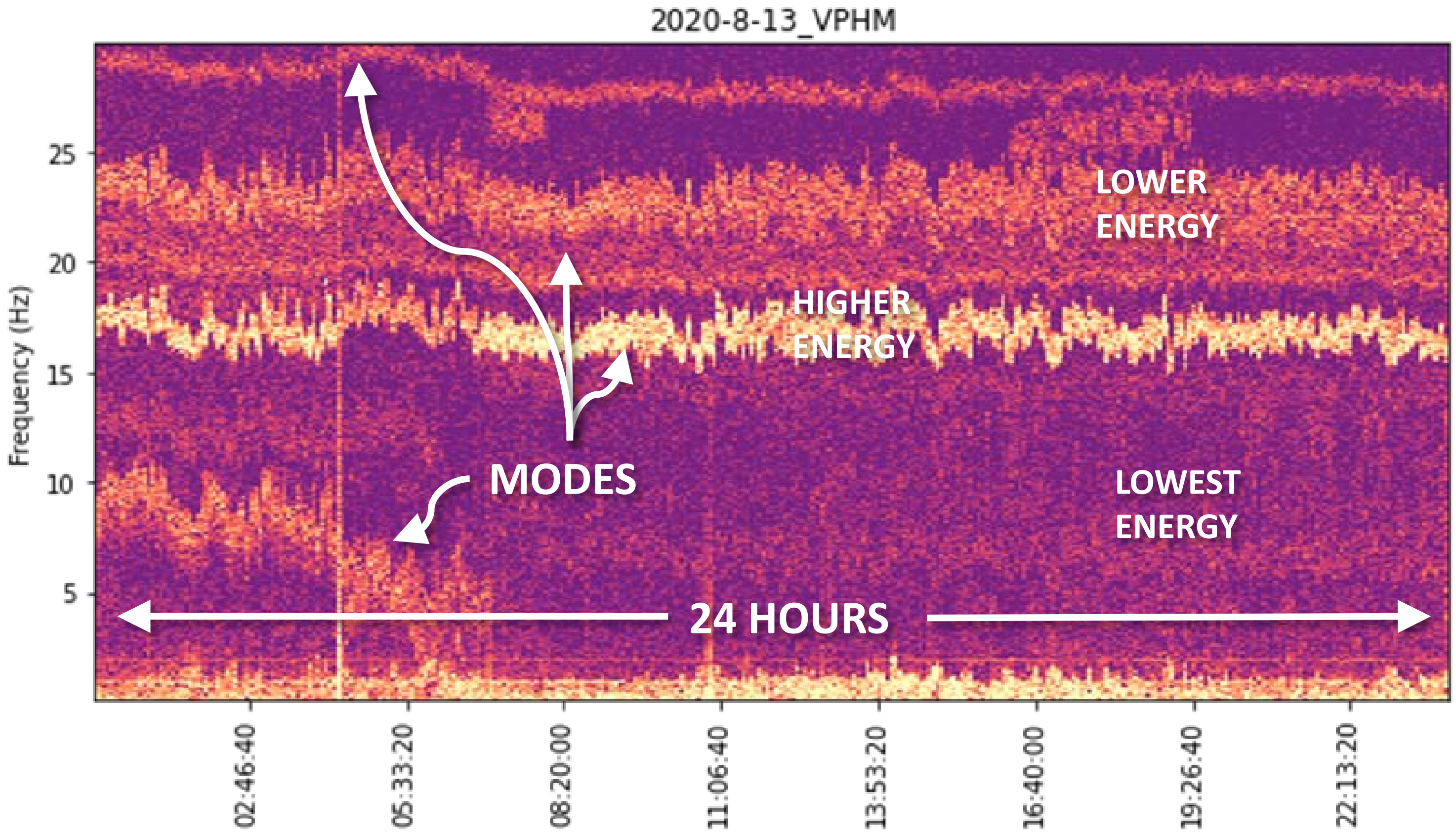


Beyond Synchrophasors



Today: Small Signal Analysis Case Studies

- Richness of ambient data
- Our homegrown toolbox is growing; dozens of techniques
- Must consider system level behaviors under all operating conditions across months of history
- This analysis requires working at a scale only made possible by PingThings` PredictiveGrid

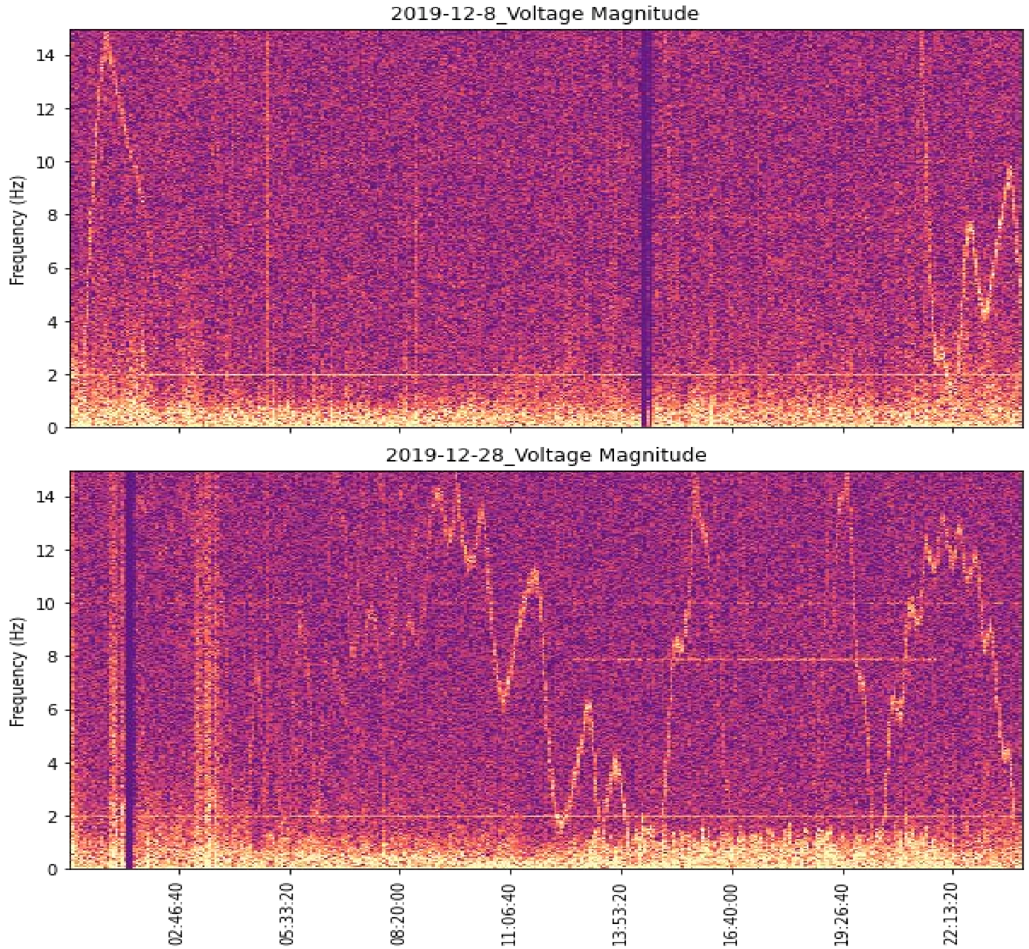


Recent Case Studies

And what they mean to Dominion and the industry…

1: Regional Industrial Dynamics

Case Study: The Need to Improve Grid Models



MOTIVATION

Distribution no longer passive • Regional dynamics influence integration of new devices • Avoid unwanted interactions • Solar and industrial use power electronics • Existing modeling practices overlook such dynamics

OBSERVATIONS

"Stumbled" onto interesting dynamics in voltage magnitude • Found poorly damped modes varying rapidly between 0-15 Hz • Nearby polymer plant and pet food plant have frequent customer complaints

TAKEAWAYS

Dynamics not reflected in models • Stumbling onto this implies many other locations with unaccounted dynamics • Matters when connecting other power electronic devices like solar

2: Regional Solar Dynamics

Case Study: The Need to Improve Grid Models & Analyses

MOTIVATION

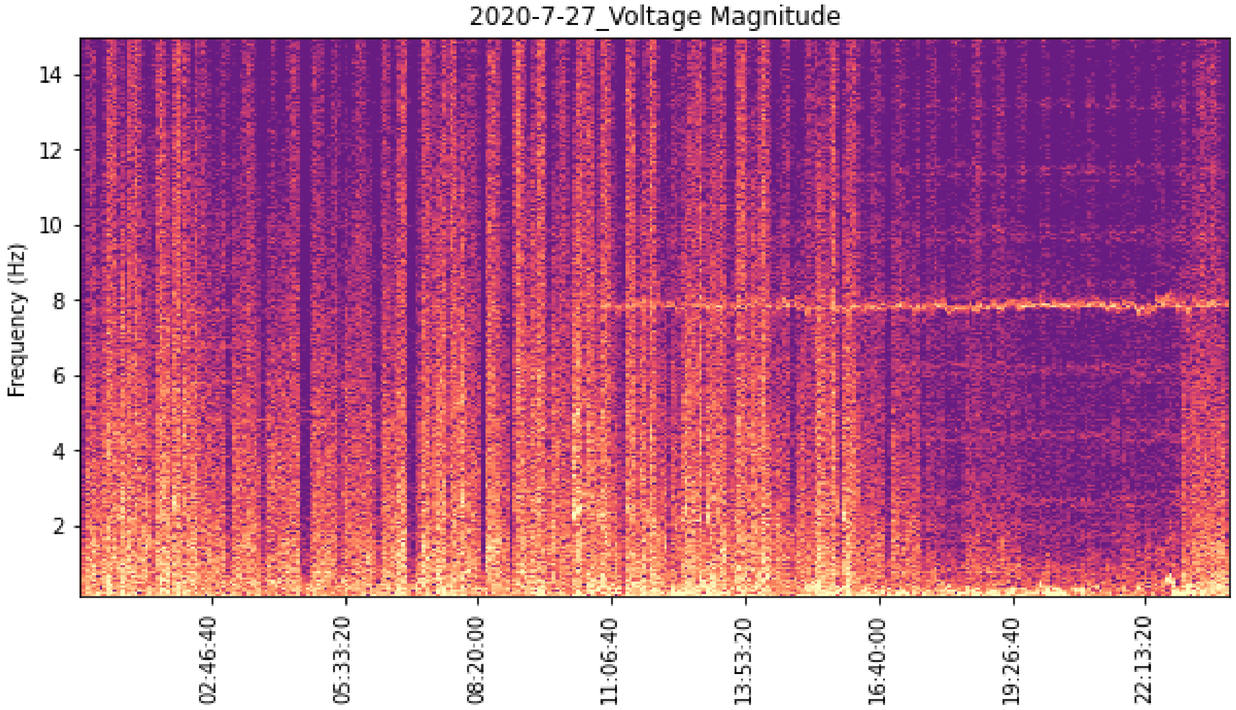
Distribution no longer passive • Regional dynamics influence integration of new devices • Avoid unwanted interactions • Solar and industrial use power electronics • Existing modeling practices overlook such dynamics

OBSERVATIONS

Sustained 8Hz oscillations observed at multiple locations • Invariant with operating conditions • From sunrise to sunset…solar! • Source identification through mode shape analysis of multiple locations • Confirmed solar plant

TAKEAWAYS

Dynamics not reflected in models • Solar interconnections will grow, exponentially increasing the likelihood of interactions • Needs to be accounted for during interconnection process



3: STATCOM Controller Dynamics Pt. 1

Case Study: Performance Assessment of FACTS

MOTIVATION

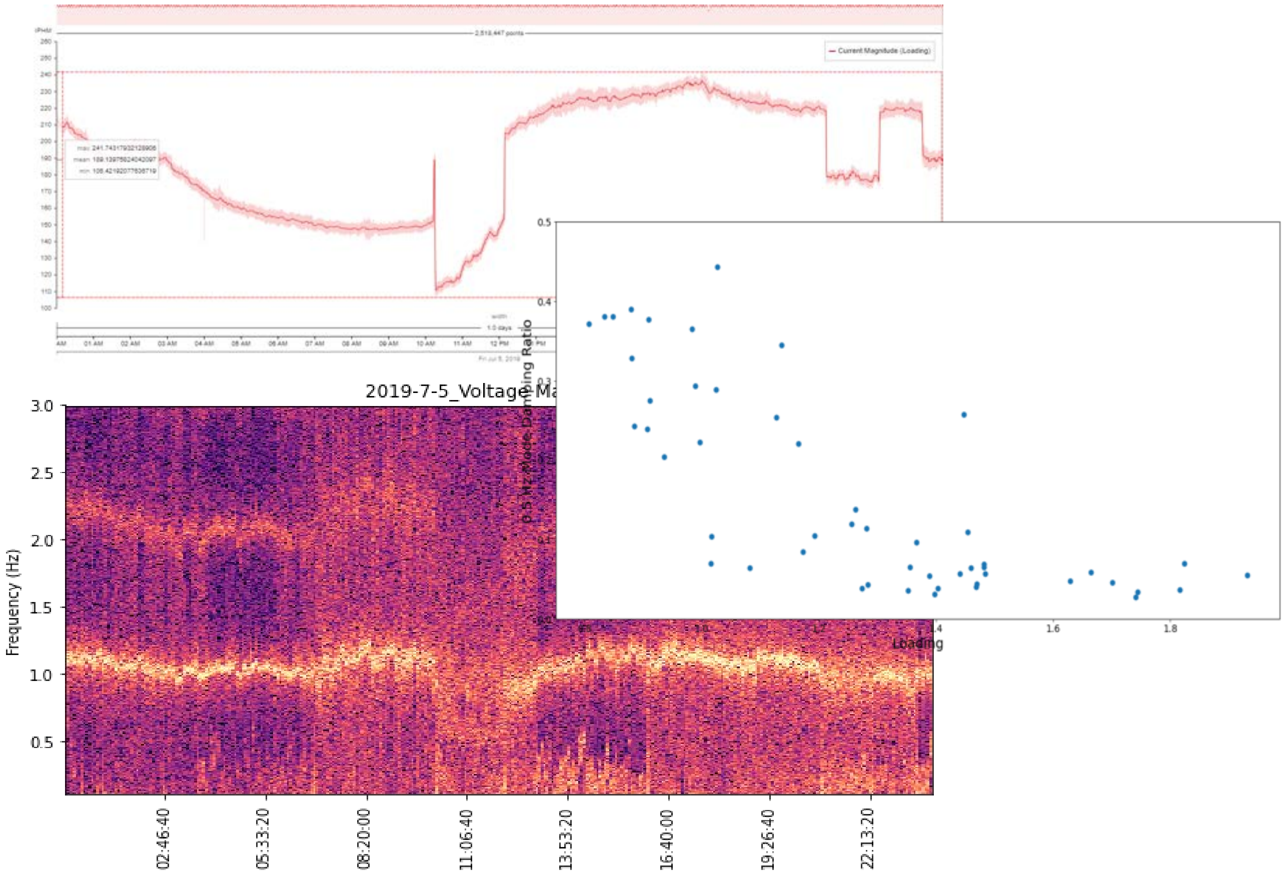
Investment in FACTS • Our duty to validate performance, suggest fixes, and influence future design • Feb 2019: topology change led to sustained oscillation • Found to be due to NSC • Deenergize control during low system strength.

OBSERVATIONS

Spectral analysis shows 2-3 modes from 0-3Hz • Modes become poorly damped under certain conditions • Damping estimated over many days showing negative correlation with system loading

TAKEAWAYS

Controller design didn't account for these system conditions • Need for adaptive gain adjustment hypothesized • Desire to validate hypothesis in the field

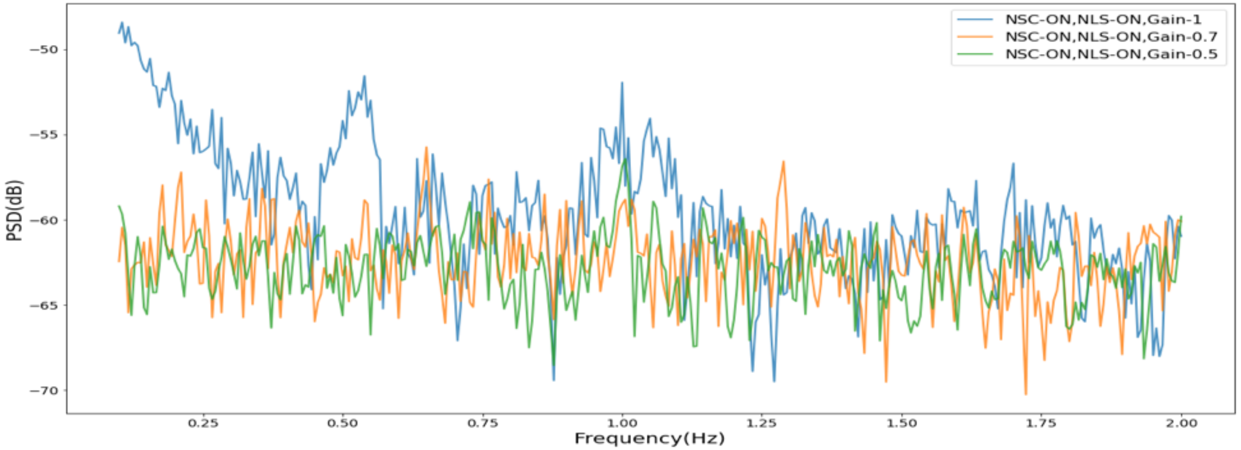


4: STATCOM Controller Dynamics Pt. 2

Case Study: Performance Assessment of FACTS

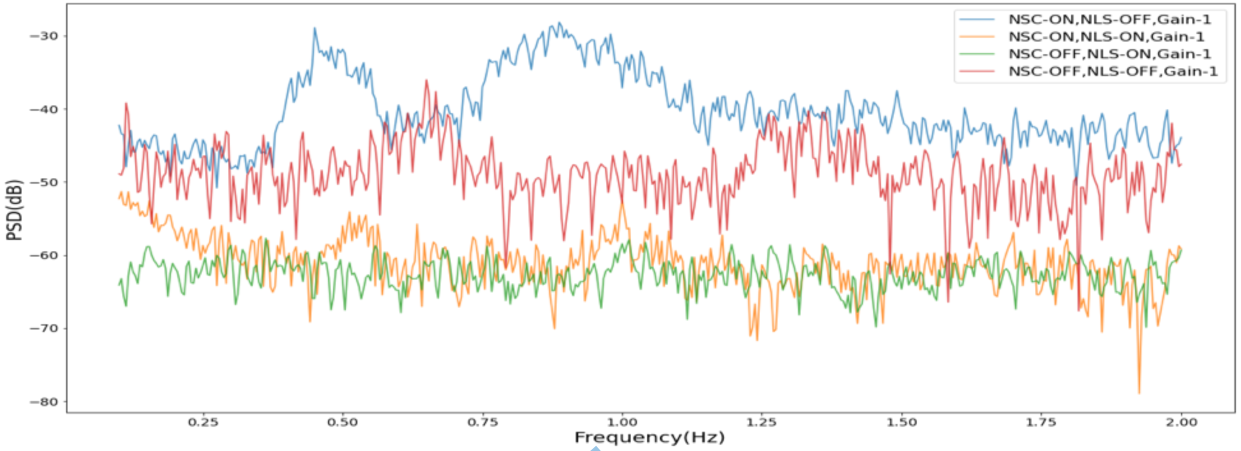
MOTIVATION

Investment in FACTS • Our duty to validate performance, suggest fixes, and influence future design • Sep 2020: STATCOM tested for NSC and NLS and multiple gain settings (100-70-50%) • Perfect *in-vivo* experiment to validate our observations.



OBSERVATIONS

Poorly damped modes at 100% gain virtually gone at lower gains • NLS can be observed as a limiting factor for effective regulation during ambient conditions



TAKEAWAYS

Confirms the need for adaptive gain • Confirms the need to validate performance of FACTS assets

5: STATCOM Controller Interactions

Case Study: Performance Assessment of FACTS

MOTIVATION

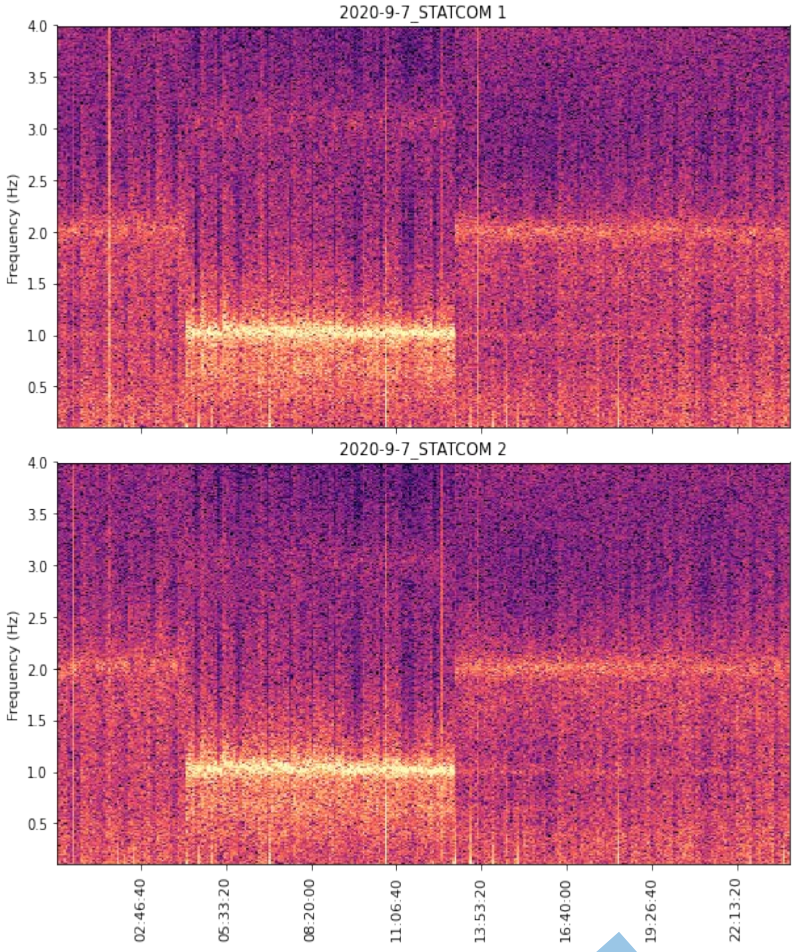
Investment in FACTS • Our duty to validate performance, suggest fixes, and influence future design • Neighboring STATCOMs may interact

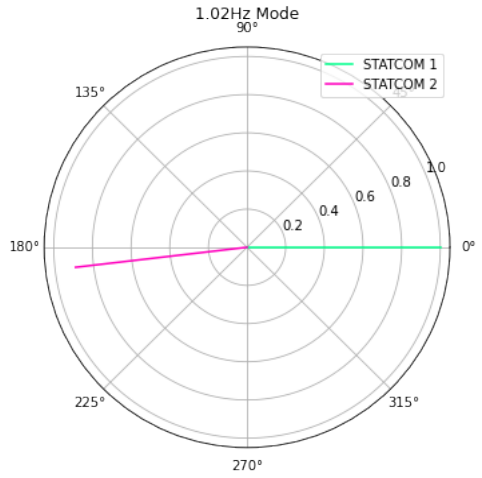
OBSERVATIONS

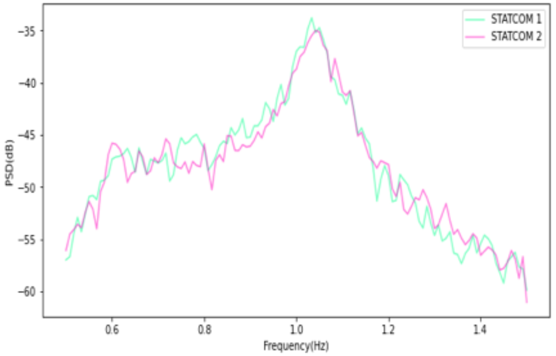
"Stumbled" onto poorly damped 1Hz V&I mode while baselining a region preparing for wind integration • Mode shape shows two STATCOMs participating 150deg+ out of phase

TAKEAWAYS

STATCOMs can interact • Need for coordinated control • There are 4 STATCOMs, not 2 so need to expand study • Study still ongoing







6: SVC Dynamics

Case Study: Performance Assessment of FACTS

MOTIVATION

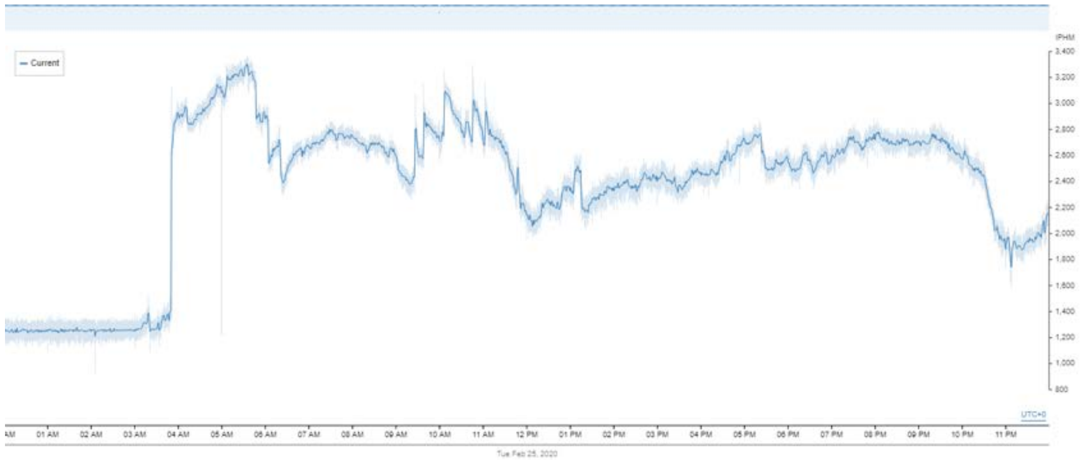
Investment in FACTS • Our duty to validate performance, suggest fixes, and influence future design

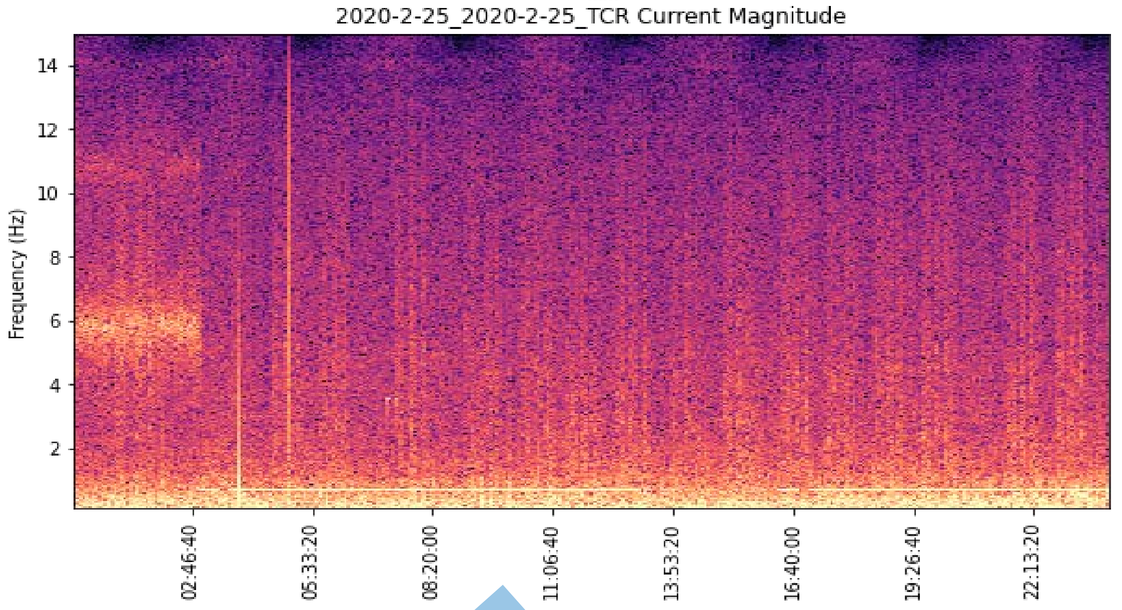
OBSERVATIONS

6Hz poorly damped modes observed • Randomly vanish throughout the day • Showed to be characteristic of Q control mode of SVC • Local generation setpoint change pushed voltage out of bounds of SVC, activating V control mode and eliminating oscillation

TAKEAWAYS

Interactions with other diverse, local assets can create unexpected interactions





7: Hydro Plant Dynamics

Case Study: Data + Models for Diagnostic Analyses

MOTIVATION

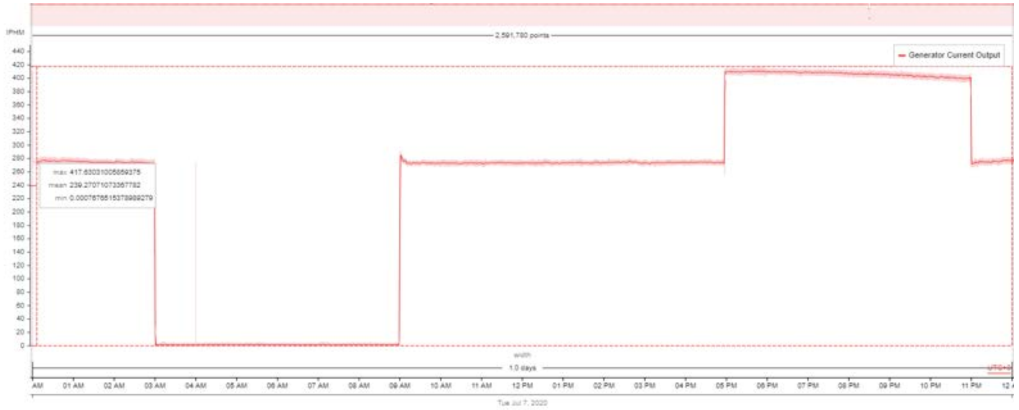
How to mitigate oscillator behavior observed in data? • For local issues, usually a controller design issue • Data alone insufficient to create new control • Recreate phenomena in simulation • Use data to improve models • Use models to identify mitigation

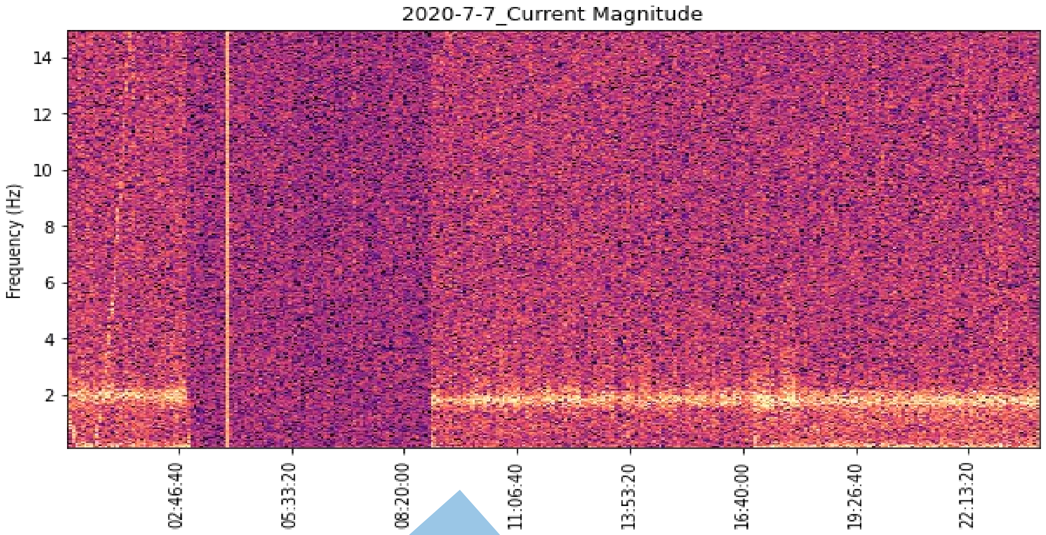
OBSERVATIONS

During plant operation, a poorly damped 2Hz mode is present • A modified model reproduces the oscillation in simulation • Sensitivity analysis then yields the appropriate control parameters to change

TAKEAWAYS

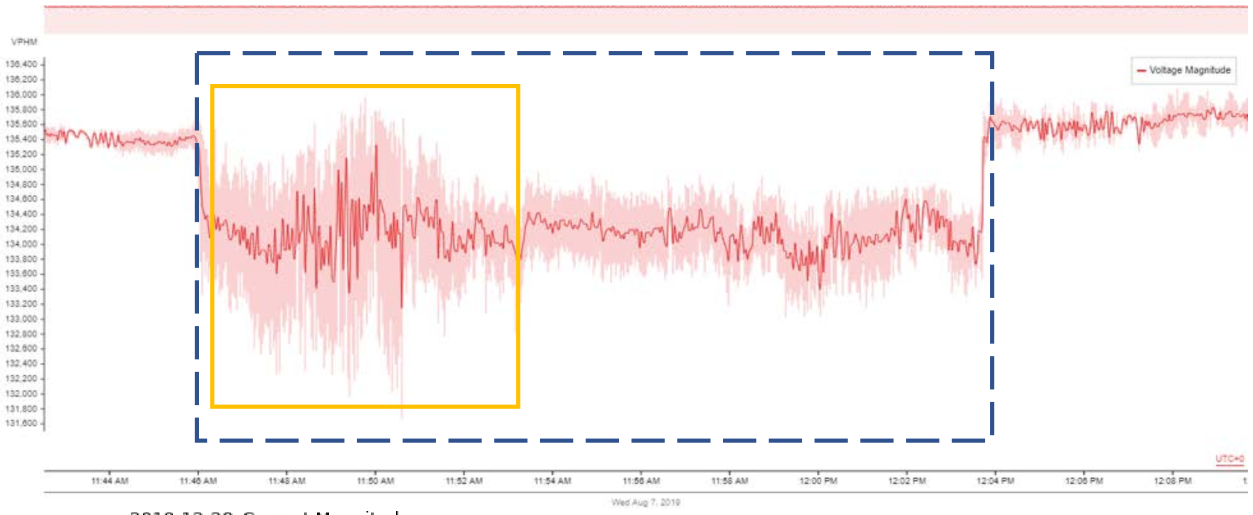
Gain of derivative block found to be most effective • Models can be manipulated to reproduce, diagnose, and identify suggested changes to mitigate observations from data • Implies a deeper synergy between data + models





8: Impacts of Arc Furnace

Case Study: Working with Real Data

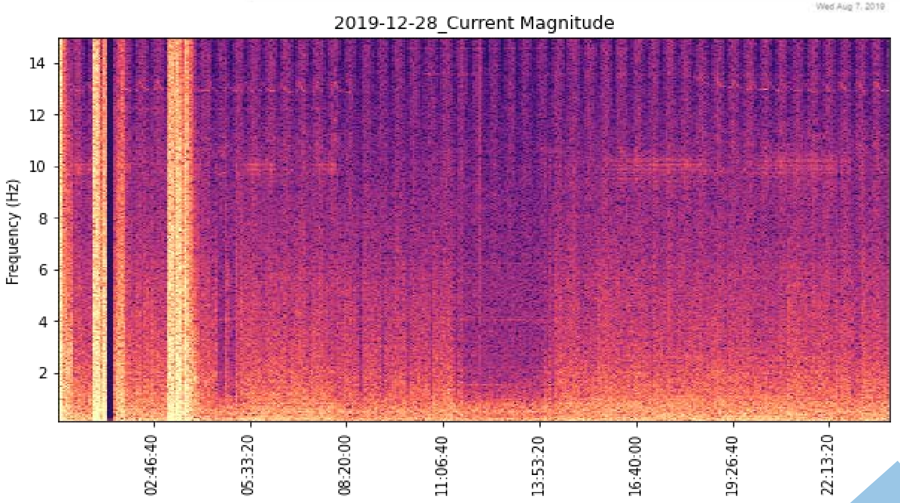


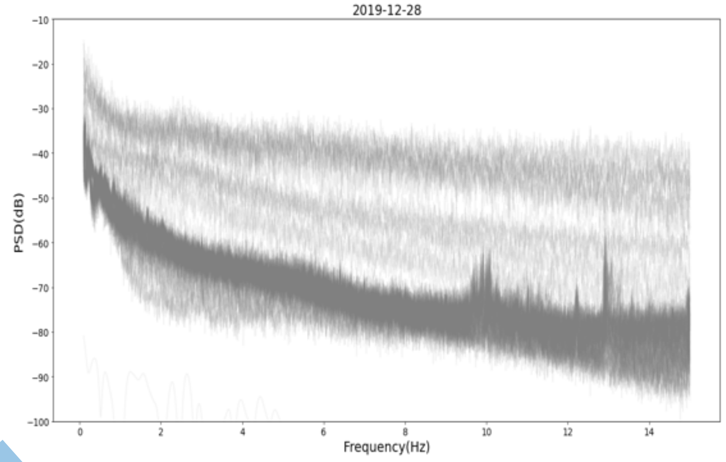
ABOUT

Arc Furnace (1) melts (orange box – higher variance, non-homogenous metal, varying Z), and (2) refines (blue box outside of orange box - less variance, constant Z

OBSERVATIONS + TAKEAWAYS

Impacts of Arc Furnace can be observed daily across the system • Aggravates FACTS devices • Cannot assume linearity • Must be compensated for in analysis of other dynamics





9: Nuclear Gen & Gas Gen Dynamics

Case Study: Going Beyond Synchrophasor Data

MOTIVATION

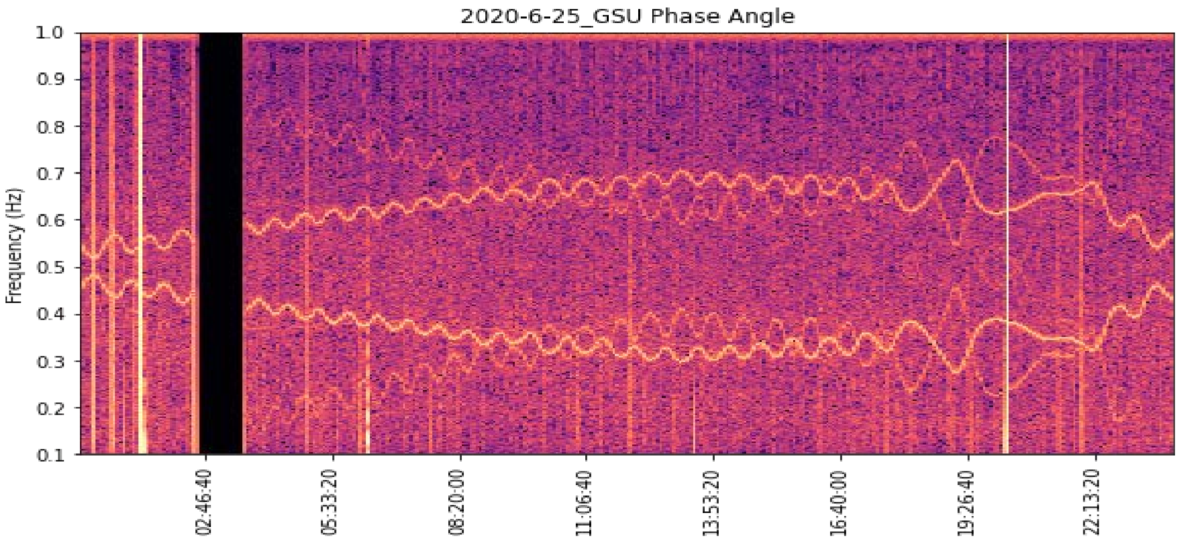
Observations in synchrophasor data are sometimes insufficient for diagnosis • How to leverage increased phasor reporting rates and waveform data to dive deeper?

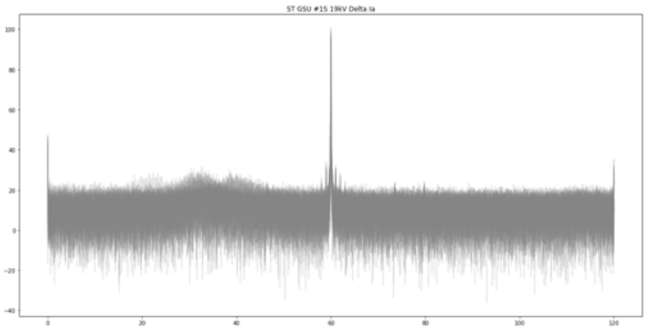
OBSERVATIONS

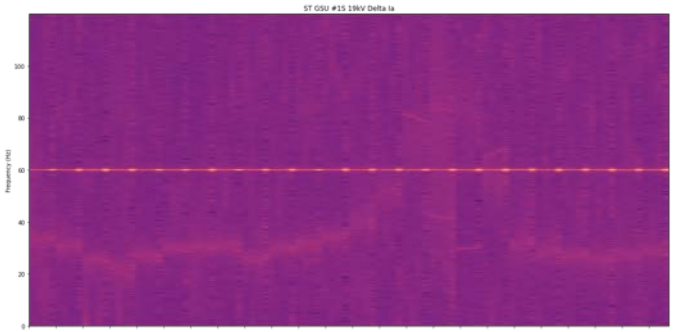
Original observation as <1Hz modes at nuclear plant GSU in phase angle w/r/t system • More prominent during summer • Hypothesized subsynchronous resonance/shaft dynamics • Triggered by combination of plant setpoint + grid condition • Strange symmetry • Similar observations at gas plant • 60Hz phasor data and waveform data imply hypothesis is correct because of higher frequency oscillations

TAKEAWAYS

Sampling minutes of waveform data over days can help dive deeper when lower res data suggests the need • Study still ongoing to learn vs modes and grid state + plant setpoints • Will resume once we have mechanical measurements







Metabolizing the Results

- Yes – it still takes time to turn these observations into business outcomes

- Yes – We're just getting started. Lots of left to explore/exploit.
  This will keep my team employed for 10+ years ;)

- But – there is now be no question of the value of synchrophasors, the right data analytics tools, and investing in these competencies.

Why Does This Matter?

Why Does This Matter?

Consider a future where. . .

INCREASED RENEWABLES

Exponentially increases the likelihood of undesirable device interactions.

INCREASED DYNAMIC COMPENSATION DEVICES

As a key enabler of renewable integration, design must consider actual small signal characteristics.

LIMITATIONS ON TRADITIONAL SOLUTIONS

New technologies will be required, data analytics can compensate for uncertainty.

NEED FOR MULTI-MODAL INVESTMENT JUSTIFICATION

Data will become a necessary part of the simulation/model-based investment proposal process.

GROWING WORKFORCE OF TECH-SAVVY ENGINEERS

Talent will be available to build data teams

More Specifically. . .

MODELING

Data and models are deeply synergistic. Data can be used to improve models and models can be used in a diagnostic fashion when field observations are made.

DESIGN

Design of our assets will need to take into consideration actual system conditions observed at their planned installation location.

PLANNING

Data greatly augments our ability to identify and refine proposals for improving the grid.

INTERCONNECTIONS

Data driven small-signal analysis will need to become part of the interconnection analysis process.

A New Competitive Advantage

GROWTH OPPORTUNITIES

Competencies in grid data analytics such as those at Dominion Energy will become a competitive advantage for utility companies: improving regulatory approval and access to affordable capital.

PANDORA'S BOX

Pandora's box is now open – now that it is known what is possible, it won't be long until it becomes a de-facto standard, perhaps even a requirement.

A New Utility

- Unification of Physics + Data
  - Data Flows • Power Flows
- More Capital Efficient
  - Financial Capital • Human Capital
- Greater Adaptability

A Fork in Your Road. . .

- The path is clear – start today.
- Questions?
  - droop9495@gmail.com
  - kevin.d.jones@dominionenergy.com
- NASPI: naspi.org
  - Virtual Conference Nov 3-5
- NI4AI: ni4ai.org