Dominion's Synchrophasor Deployment and Applications

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Dominion Profile Overview

Dominion (NYSE:D), headquartered in Richmond, VA, is one of the nation's largest producers and transporters of energy, with a portfolio of approximately:

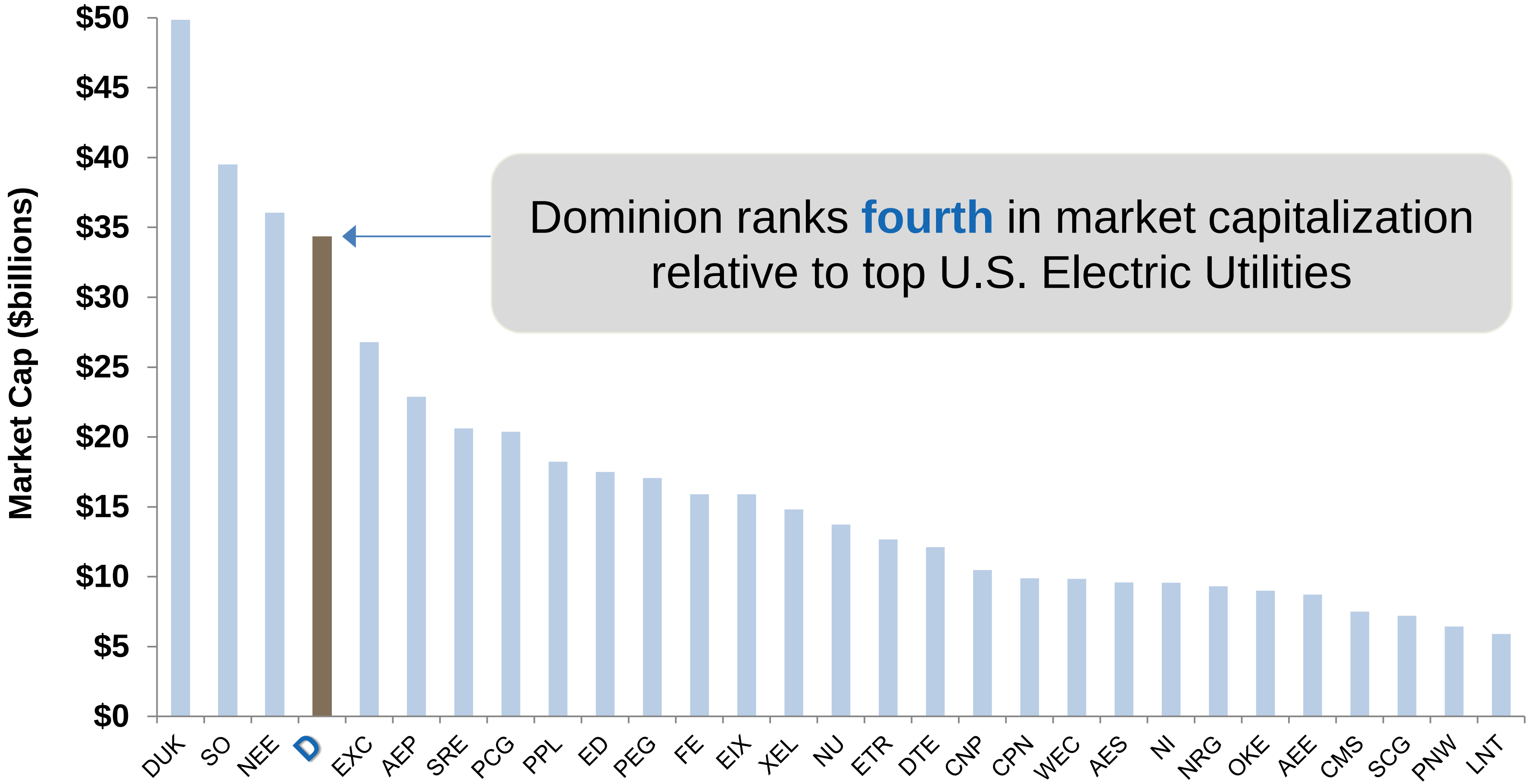
- ~23,500* megawatts of electricity generation
- 11,000 miles of natural gas transmission, gathering and storage pipeline and
- 6,400 miles of electric transmission lines.

Dominion operates the nation's largest natural gas storage system with 947 billion cubic feet of storage capacity and serves retail energy customers in 15 states.

*Excludes ~4,000 MW of announced planned facility divestitures and decommissionings.
Please refer to page 2 for risks and uncertainties related to projections and forward looking statements.

Dominion Profile

Market Capitalization – Electric Utilities



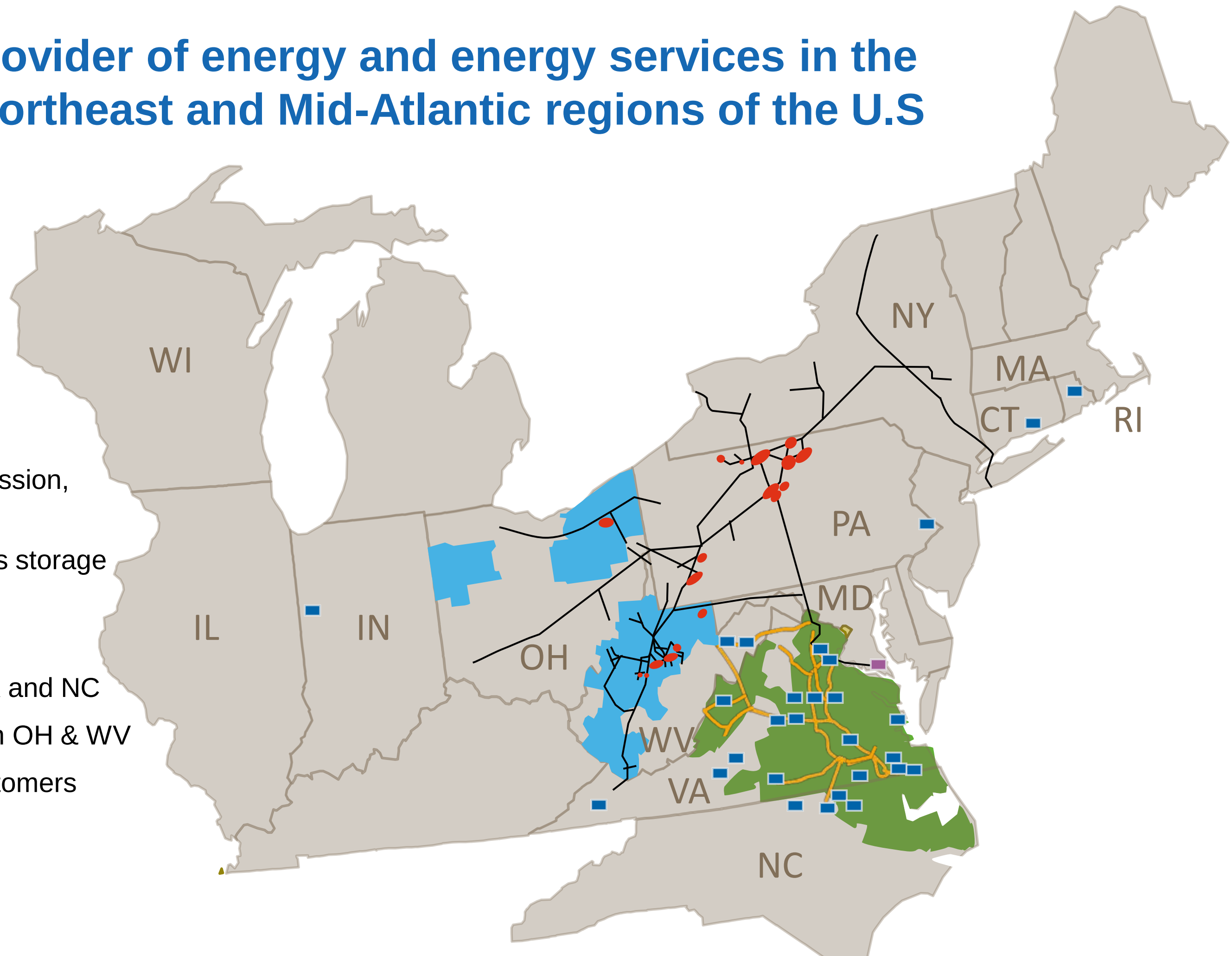
Source: Bloomberg as of 7/17/13

Please refer to page 2 for risks and uncertainties related to projections and forward looking statements.

Dominion Profile
Power and Natural Gas Infrastructure

Leading provider of energy and energy services in the Midwest, Northeast and Mid-Atlantic regions of the U.S

- **~23,500* MW** of electric generation
- **6,400 miles** of electric transmission
- **11,000 miles** of natural gas transmission, gathering and storage pipeline
- **947 billion cubic feet** of natural gas storage operated
- Cove Point LNG Facility
- **2.5 million** electric customers in VA and NC
- **1.3 million** natural gas customers in OH & WV
- **2.1 million** non-regulated retail customers in **15** states (not shown)



Dominion

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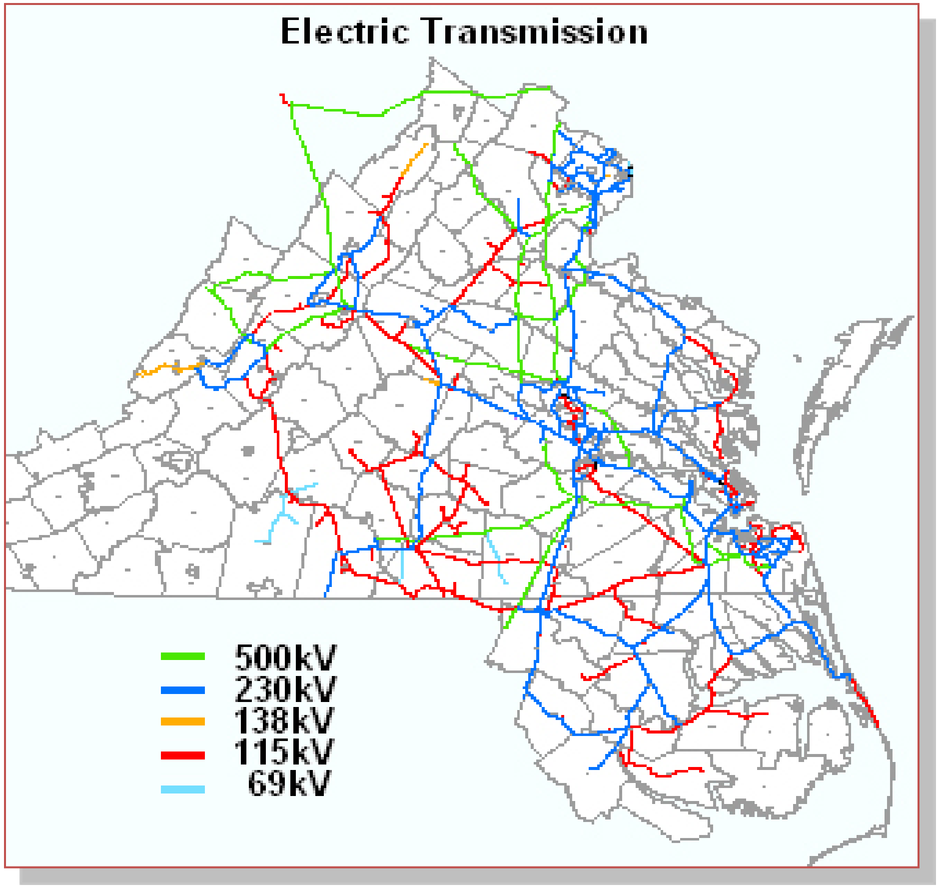
The Dominion Electric Transmission System at a Glance

$2.1B of assets in service
- 6400+ miles of transmission lines
  - 500kV – 1250 mi.
  - 230kV – 2600 mi.
  - 115kV – 2300 mi.
- 400+ substations
- 885 FTEs

Keys to Success:
- Safety
- Reliability
- Compliance
- Project Execution



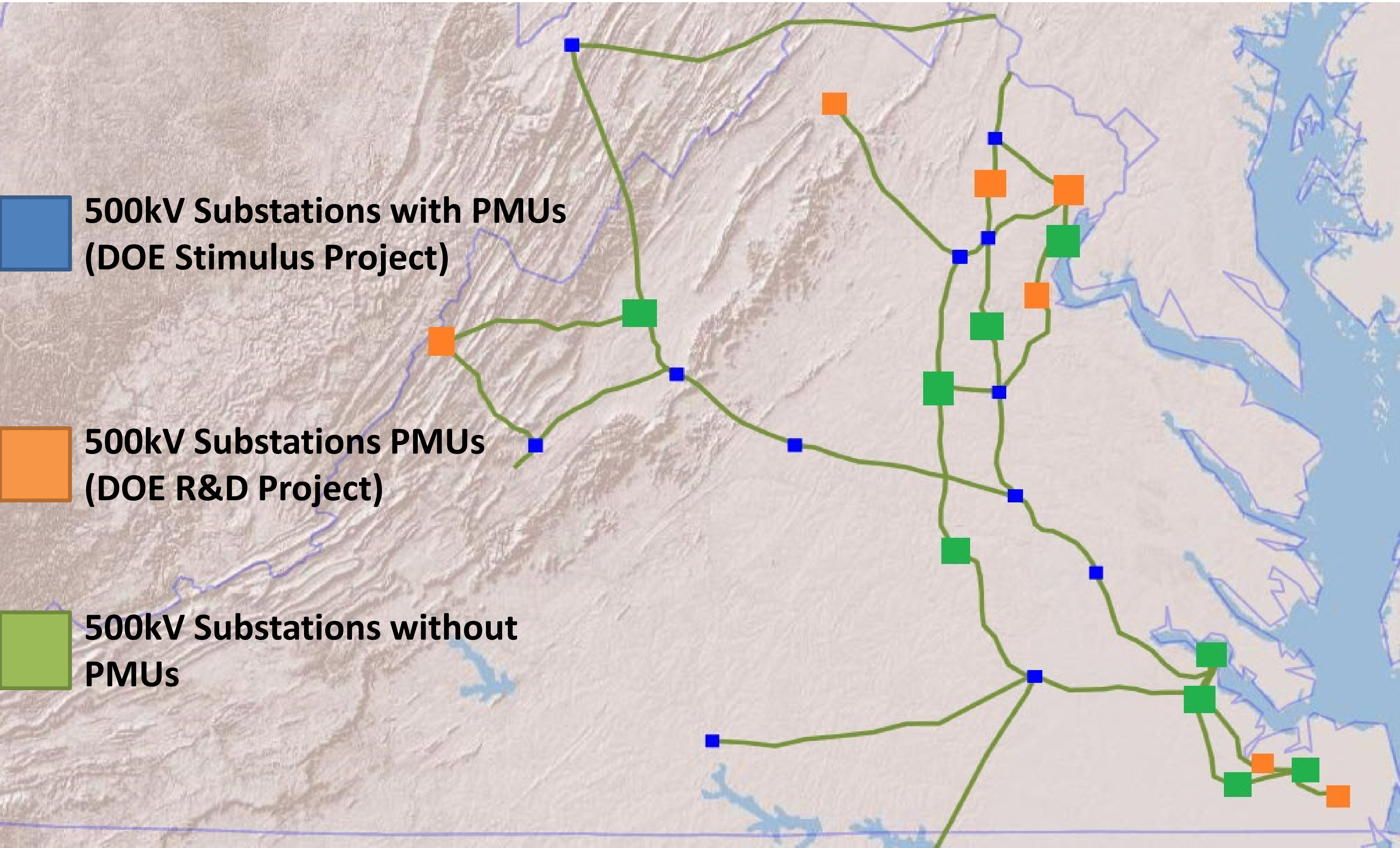
Dominion

New Challenges; More Opportunities

- Demand for reliability and the need for situational awareness
- Generation retirements
- Generation remote from load centers
- Stability concerns
- Voltage swings
- Distributed Generation
- Alternative energy sources

Dominion

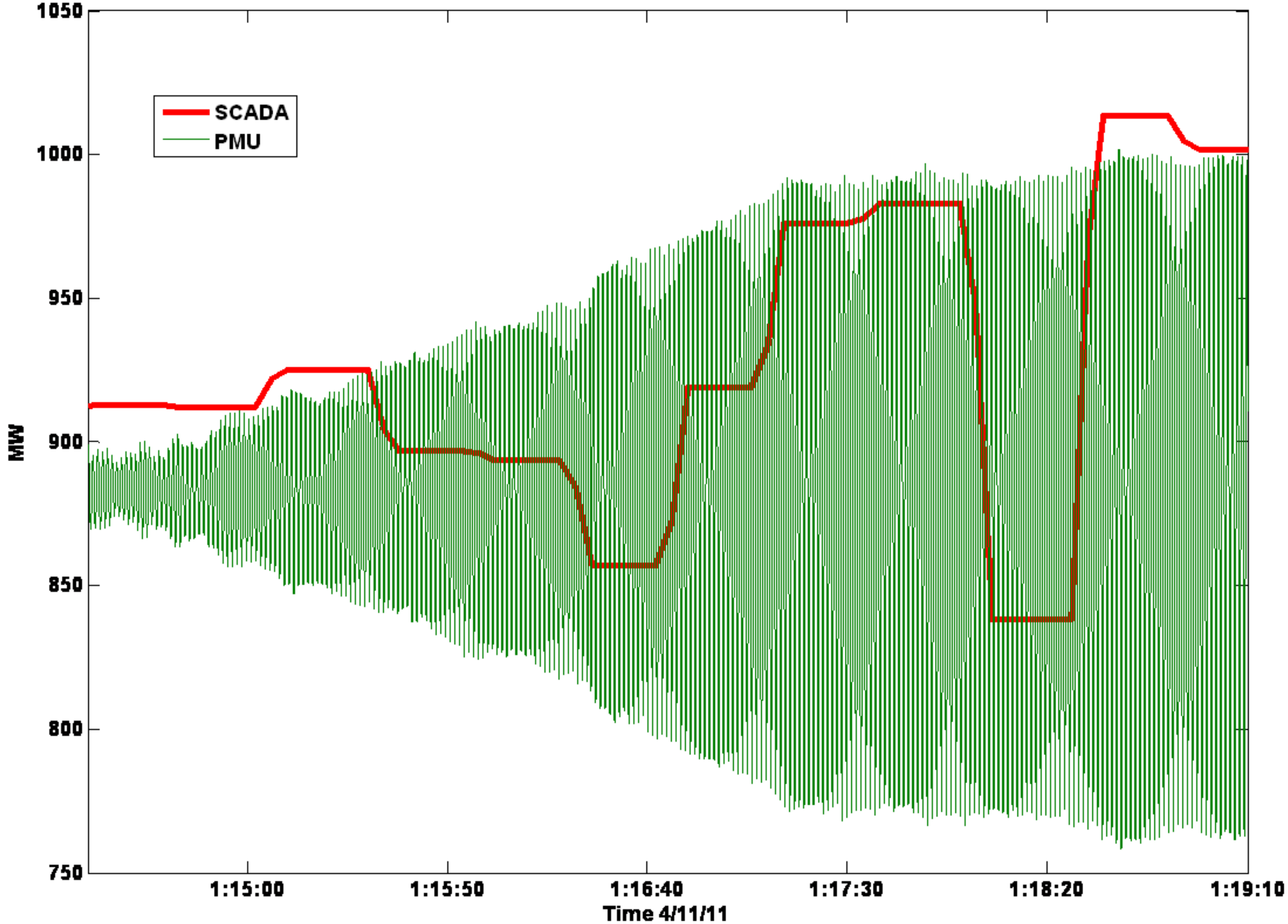
DVP PMU Deployment (EOY 2012)



DVP Assets directly monitored by PMUs

– 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)

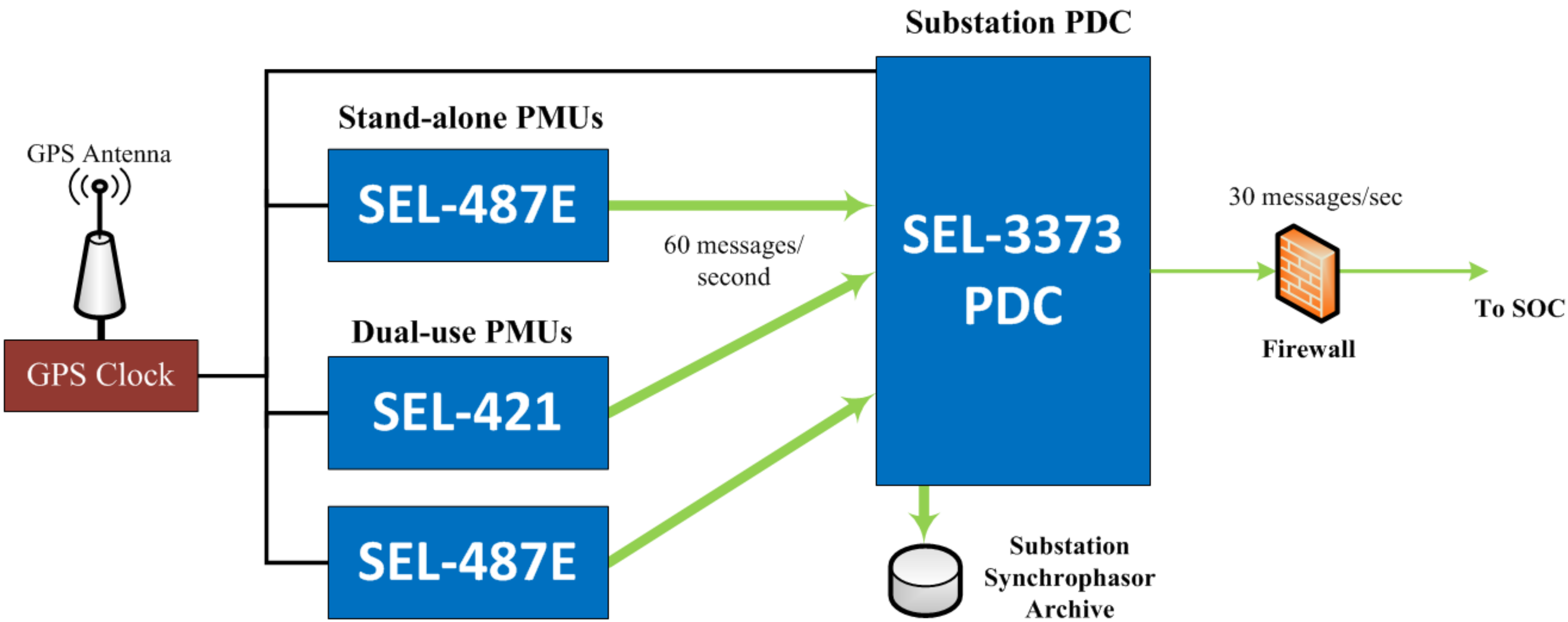
A trip down memory lane…



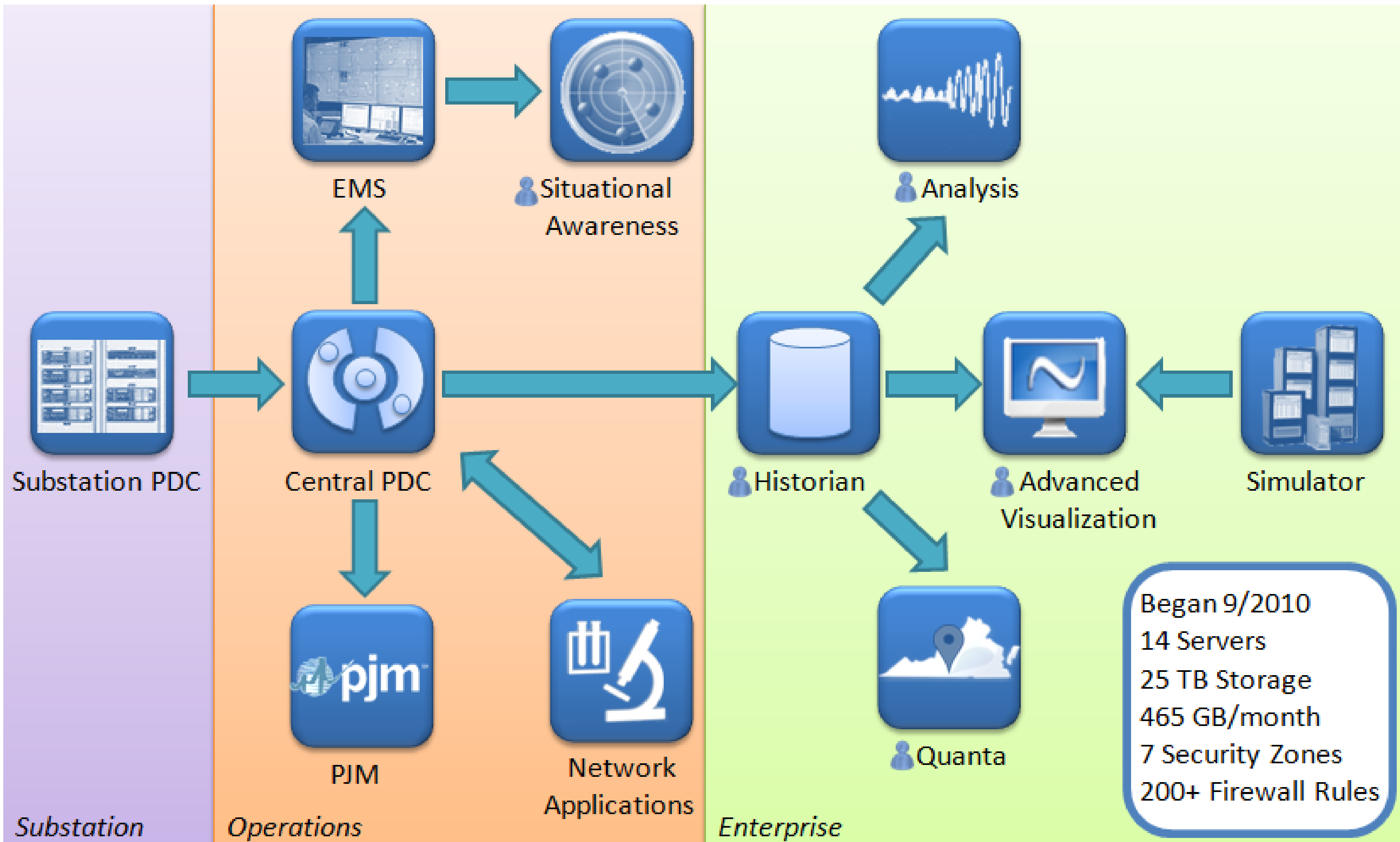
New Substation Architecture for PMUs

- Independent from SCADA Systems
- **Capture all three phases**

- PMUs made CIP CCAs
- Back-up Archive (30 days)



Central Synchrophasor Architecture



Virginia Tech Thesis Topics in Network Applications

- State Estimation: A New Paradigm
- Measurement Calibration
- Monitoring System Unbalances
- Using Synchrophasors for System Islanding Detection

Students:
Kevin Jones
Zhongyu Wu
Rui Sun

Motivation & Objective

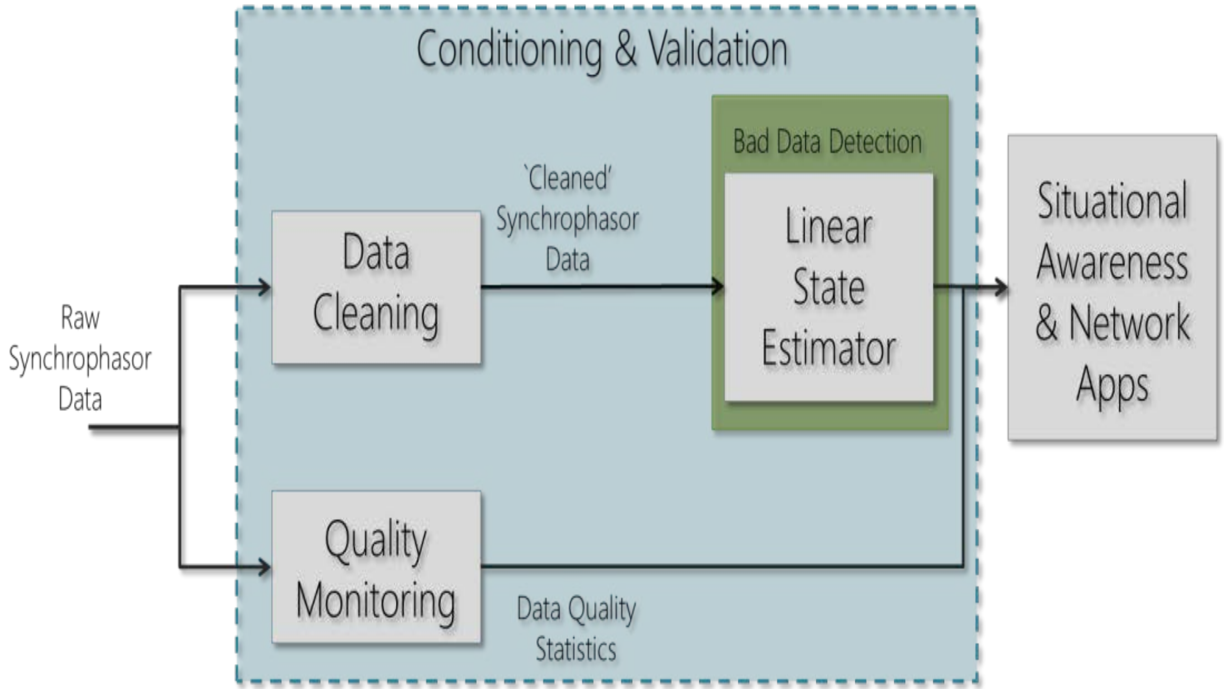
– Obtain wide-area monitoring of Dominion's EHV system with large scale deployment of PMUs

– Develop and implement novel synchrophasor applications including a **Synchrophasor-Only Three-Phase Linear State Estimator**

– Why state estimation?
  - Improve data quality
  - Extend observability

Synchrophasor-Only State Estimation

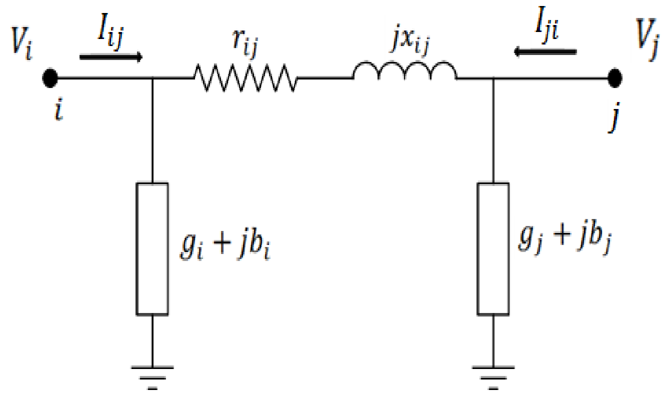
The linear state estimator should serve as the data conditioning front end for any network application or consumer of synchrophasor data



Synchrophasor-Only State Estimation

LSE appeared early in PMU literature (1980)

- Directly measuring the system state
- No scan times!
- No divergence!
  - **State estimator availability is critical during stressed conditions**
- Three-Phase LSE is the **only way to get true sequence (+, -, 0) components**
- Value proposition for three phase is growing



Synchrophasor-Only State Estimation

- PMUs measure complex voltages and currents
- Optimal estimate derived from redundant measurements
- Observability expanded through transmission lines with current phasor measurements

$$z = \begin{bmatrix} II \\ YA + Y_s \end{bmatrix} E + \varepsilon = HE + \varepsilon$$

- An over-determined system; a linear transformation from measurements to state estimate

Handling Bad or Missing Data

- Need for commissioning process
  - Scripts for finding data quality problems before connected to SOC
- Filtering & Smoothing
  - Predictive capability to mitigate bad or missing data
  - Useful for LSE pre-processing

$$\hat{y}_t = \alpha_1 y_{t-1} + \alpha_2 y_{t-1} + \cdots \alpha_m y_{t-m} + \omega_t \quad t = m+1, \cdots n$$

$$\hat{x}(n) = 3x(n-1) - 3x(n-2) + x(n-3)$$

Utility Perspective

State estimation is inherently a real-time network application

- How does this fit into today’s strategy?
- How does this fit into the long term strategy?
- Maintaining parallel systems?

LSE as EHV Backup Observability

Fully paralleled infrastructure from substation

- If EHV observability lost through EMS, operations must dispatch resources to all EHV substations and monitor by phone
- EHV network fully/redundantly observed using the linear state estimator
- **Solves in real-time**, omnipresent, high availability
- **Comfortable, familiar visualization** reminiscent of EMS

Augmenting the Production EMS

Improved state estimator performance through:

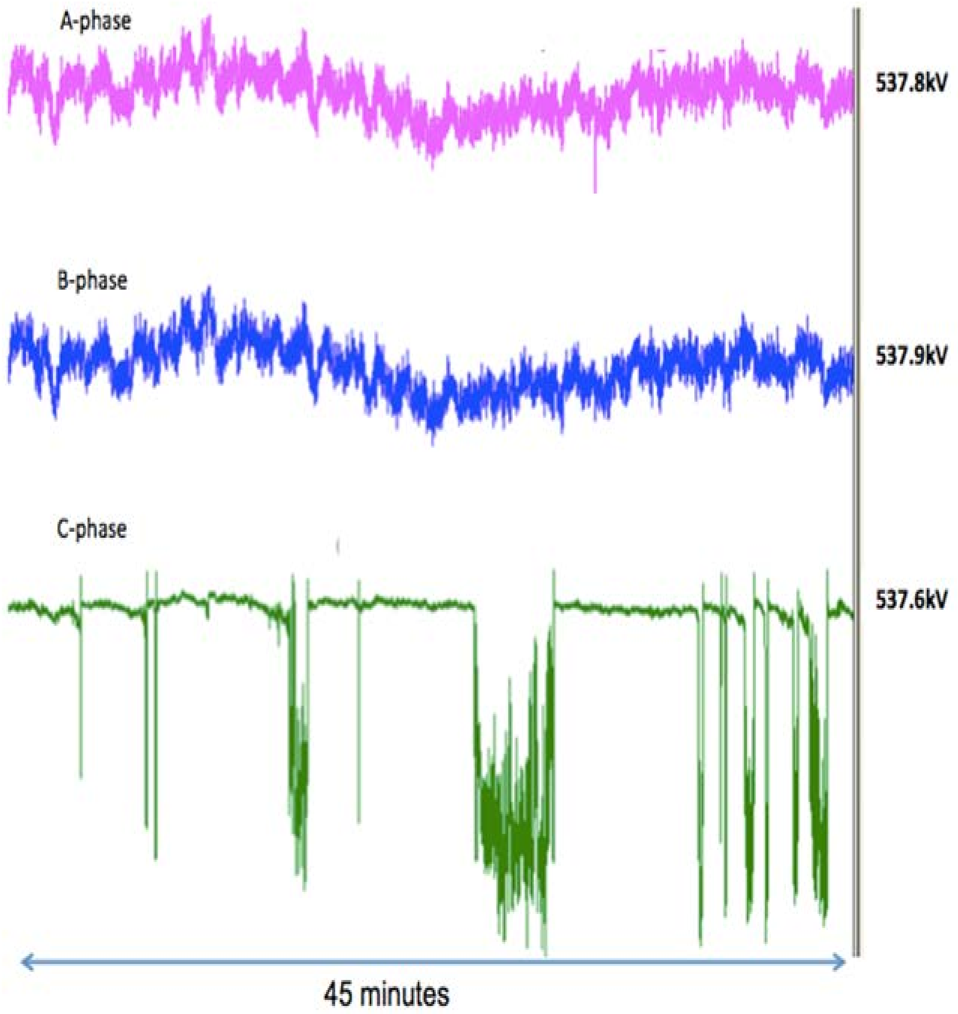
- ISD Adapter in PDC Architecture for PMU Data to EMS
    - **Use output of LSE as high accuracy pseudo-measurements**
    - Voltage magnitude, P-Q flow
- CT/PT calibrations to improve raw SCADA measurements
- Empirically determined/tracked impedance values
- Real-time observation of sequence components

Calibrating Instrument Transformers

Voltage and Current Transformers

- These devices are installed on all high voltage transmission lines and transformers.
- They are in the path of all measurements made in power systems, whether for SCADA monitoring, PMUs, or protection systems.
- These devices are subject to errors in their performance, usually expressed as Ratio Correction Factors (RCFs).
- The present application of Wide Area Measurement Systems (WAMS) is to obtain accurate estimates of these RCFs, and thereby improve measurement quality.
- By trending the calibrations, early warning of imminent failures of the transformers can obtained.

A field example of PMU records indicating imminent failure of the voltage transformer in phase-C four days before the failure alarm on the line relays were triggered.



Calibrating Instrument Transformers

The technique developed for instrument transformer calibration has a very interesting extension which will be undertaken in the following work.

It is known that network parameter data – such as line impedances, transformer impedances etc. are often incorrect in system data base.

Correct values of these parameters are essential for determining network performance during normal and abnormal conditions. Thus the fate of accurate security assessment depends upon having correct values for these quantities.

By adding a precision current transformer in addition to the precision voltage transformer to the network, it seems possible to obtain automatic estimation of these parameters.

This will be investigated by our team as a follow-up to this work.

Calibrating Instrument Transformers

The technique:

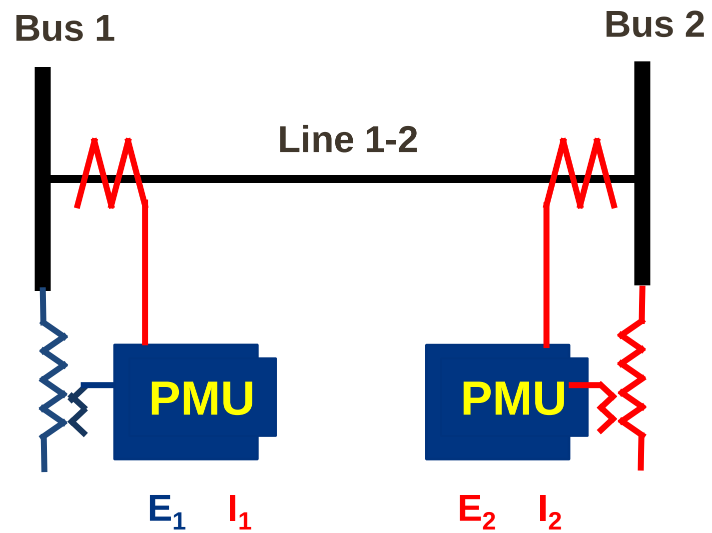
- The calibration technique is based on using measurements made from a high accuracy voltage transformer in conjunction with measurements made with imprecise current and voltage transformers.
- Using a sufficient number of measurement sets over a period of several hours as the system load changes, the developed technique is able to obtain RCFs of all imprecise instrument transformers with very high accuracy.
- The technique was perfected through simulations of the DVP system over its daily load variations, and is now working with real time data being obtained from PMUs.

Calibrating Instrument Transformers

Voltage transformer at Bus 1 is assumed to be perfect.

Voltage transformer at Bus 2 and current transformers at Bus 1 and Bus 2 are imperfect and have RCFs which need to be determined.

The unknown quantities are
- **RCF-E2**
- **RCF-I1**
- **RCF-I2**



PMUs at two ends of the line provide 4 sets of measurements: E_1, E_2, I_1, and I_2 . Using multiple sets of these measurements obtained over several hours of system load variations the unknown RCFs can be determined.

CT and CCVT Calibration (use 60 Hz data only)

CT and CCVT ratio errors can be calibrated in a batch calculation with one set of measurements each hour over a 12 hour period (so load variation takes place from minimum to maximum) if:

There is path through the measured network that connects a known good voltage measurement (a metering PT or a fiber optic voltage measurement) to each measurement. That is, the measurements form a tree. One good voltage per island is needed if no tree

The assumption is that the ratio errors are constant over periods like weeks. The resulting ratio errors are as good as the good measurement. High accuracy PTs are +/- 0.15%,0.104 degrees

Monitoring system current unbalance

Nature of current unbalance

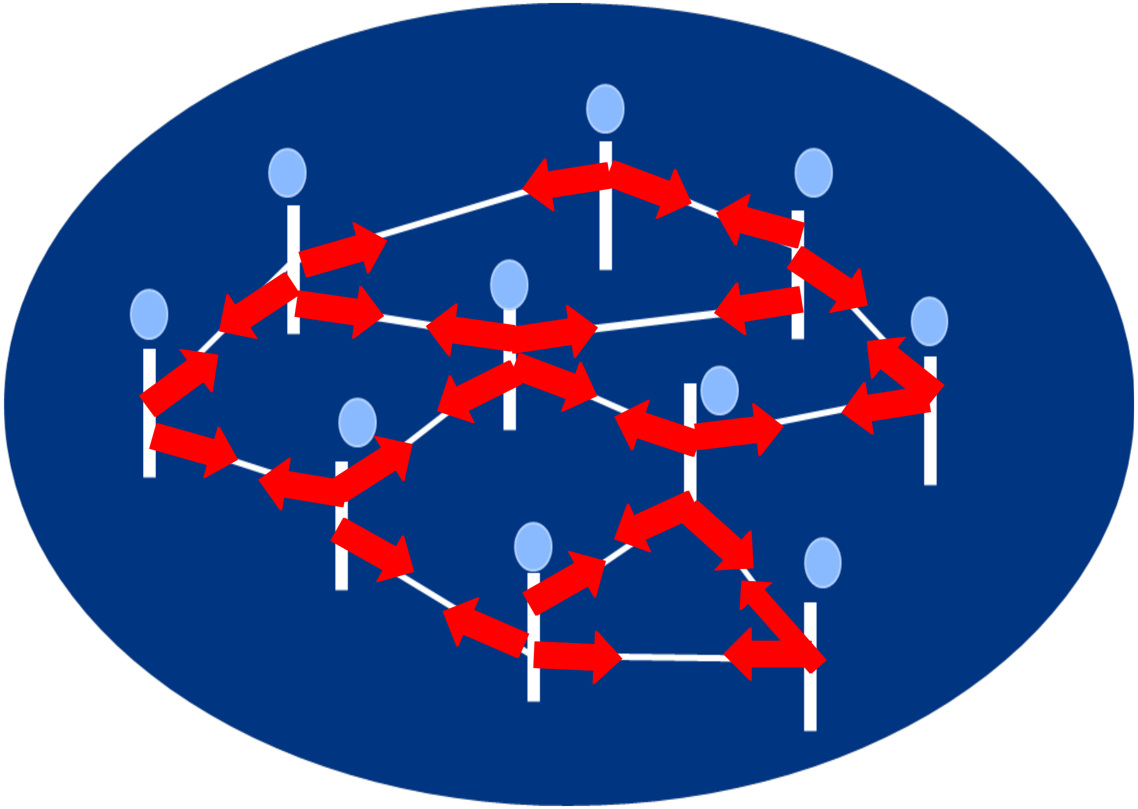
Voltages and currents in a three phase network are rarely balanced , i.e. magnitudes of quantities in the three phases are not equal, and the phase angles of quantities in the three phases are not 120° apart.

Unbalances are due to network unbalances existing within the networks of interconnected systems as well as unequal loads in the three phases.

Unbalanced currents are particularly harmful to the rotors of large power generators, as they may be overheated if the unbalance exceeds a threshold.

Monitoring system current unbalance

PMUs measure three phase currents in all the lines:



Monitoring system current unbalance

The phase currents at each location are converted to their Symmetrical components by the traditional transformation:

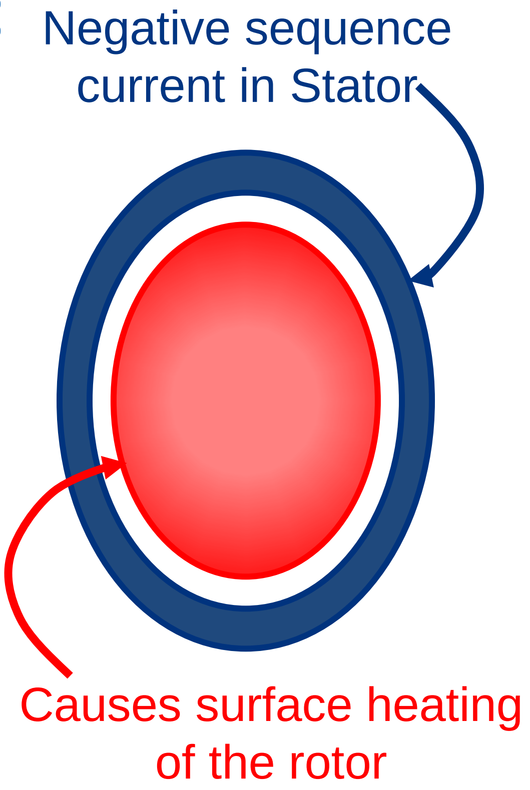
I_2 is the negative sequence current, which is most harmful to generators.

Monitoring system current unbalance

Negative Sequence current

Symmetrical components of three phase quantities are termed positive, negative, and zero sequence quantities.

Of these three, the negative sequence component of currents is most harmful to generator rotors.



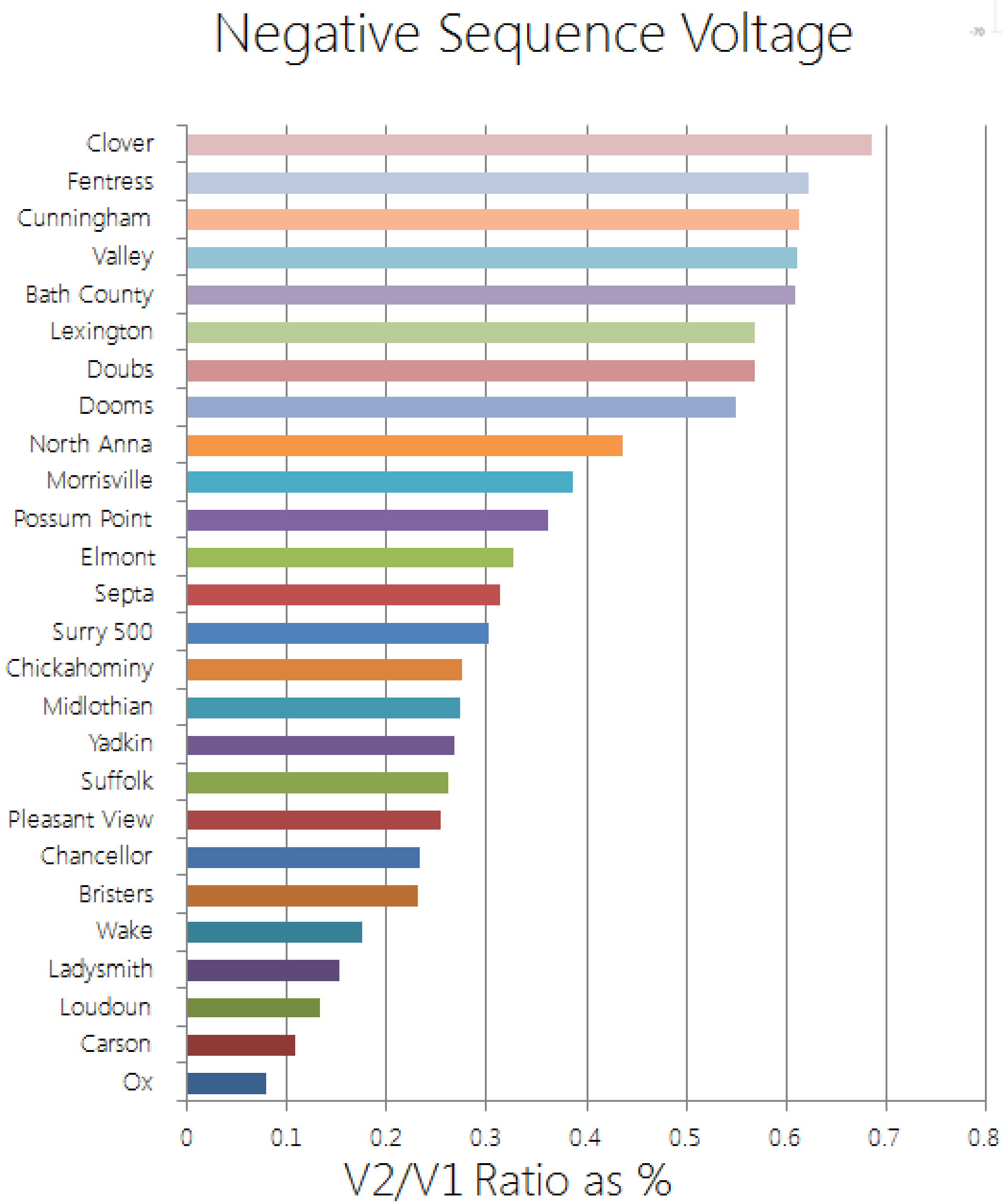
Monitoring system current unbalance

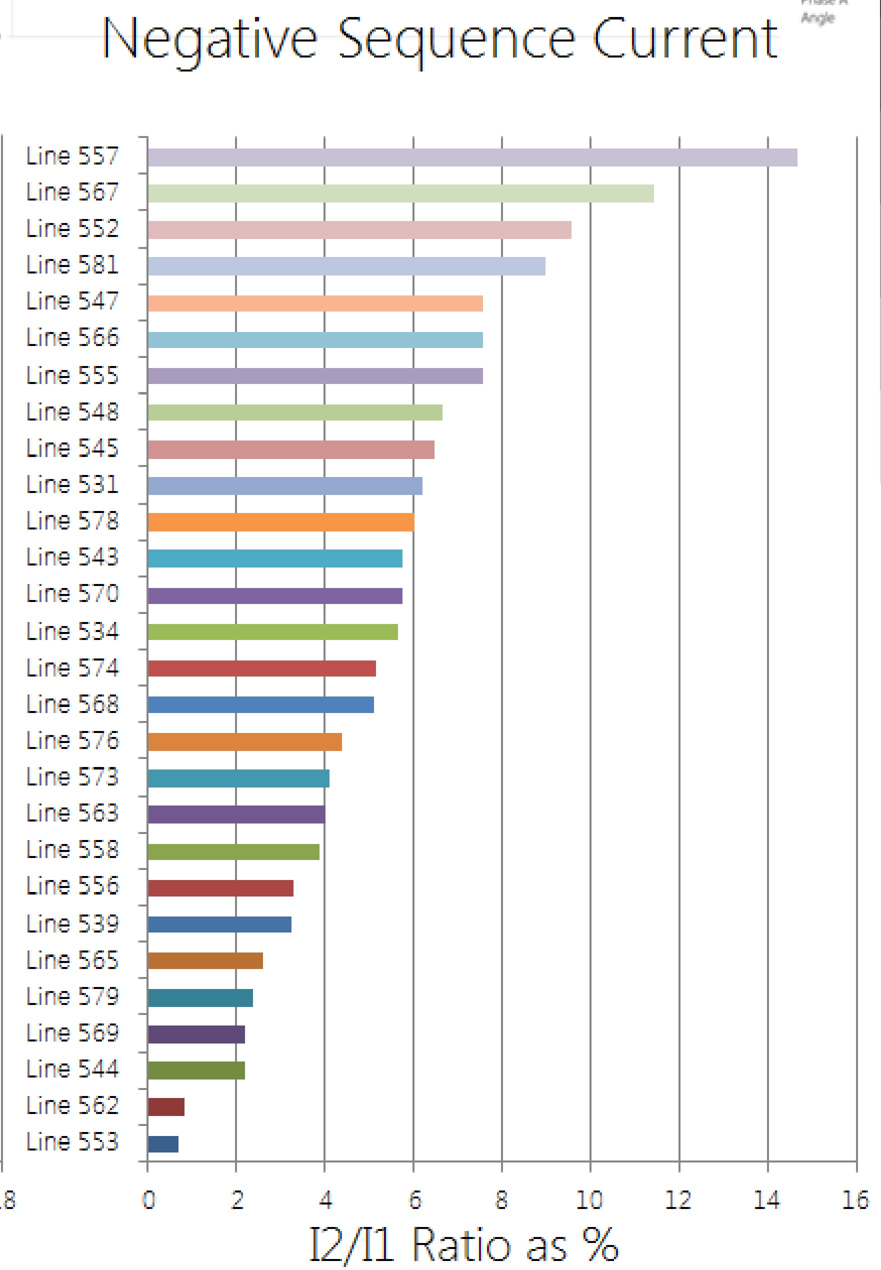
Negative sequence currents are continuously monitored on the network. Summing up all negative sequence currents in lines connected to generators, the generator negative sequence currents can be monitored.

Typically, generators have limits set by the manufacturer for the amount of negative sequence current heating that can be tolerated.

$$\boxed{\int I_2^{\,2}\,dt < K}$$

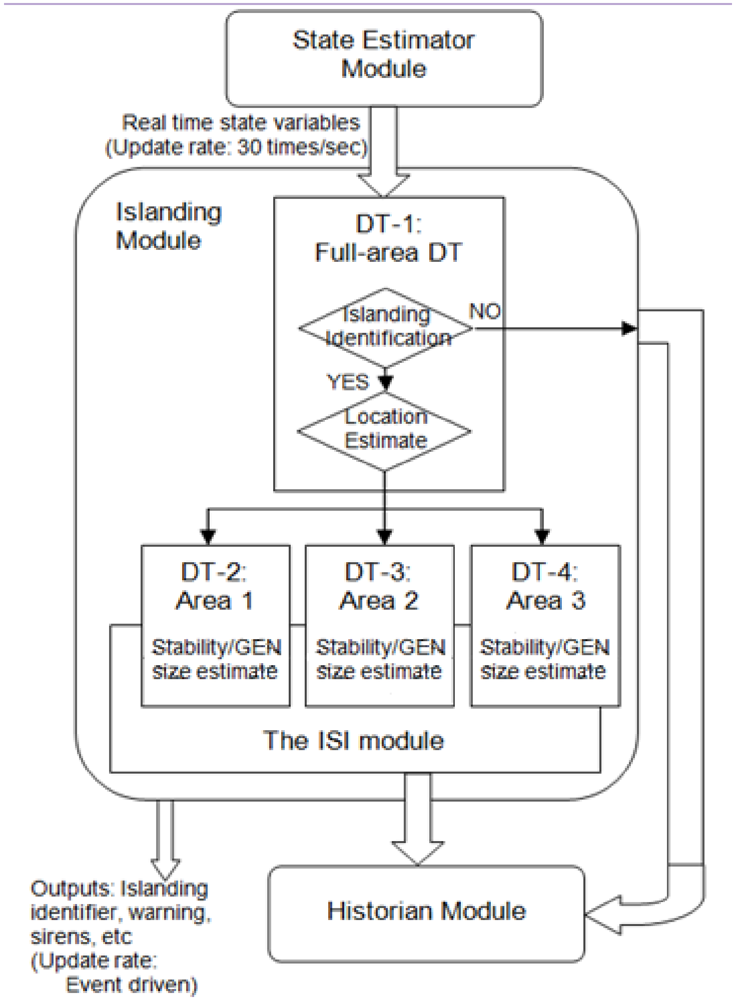
Alarms can be created when the limits are exceeded.


Negative Sequence Voltage
Clover
Fentress
Cunningham
Valley
Bath County
Lexington
Doubs
Dooms
North Anna
Morrisville
Possum Point
Elmont
Septa
Surry 500
Chickahominy
Midlothian
Yadkin
Suffolk
Pleasant View
Chancellor
Bristers
Wake
Ladysmith
Loudoun
Carson
Ox
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
V2/V1 Ratio as %


Negative Sequence Current
Line 557
Line 567
Line 552
Line 581
Line 547
Line 566
Line 555
Line 548
Line 545
Line 531
Line 578
Line 543
Line 570
Line 534
Line 574
Line 568
Line 576
Line 573
Line 563
Line 558
Line 556
Line 539
Line 565
Line 579
Line 569
Line 544
Line 562
Line 553
0 2 4 6 8 10 12 14 16
I2/I1 Ratio as %

Island Detection using Synchrophasors

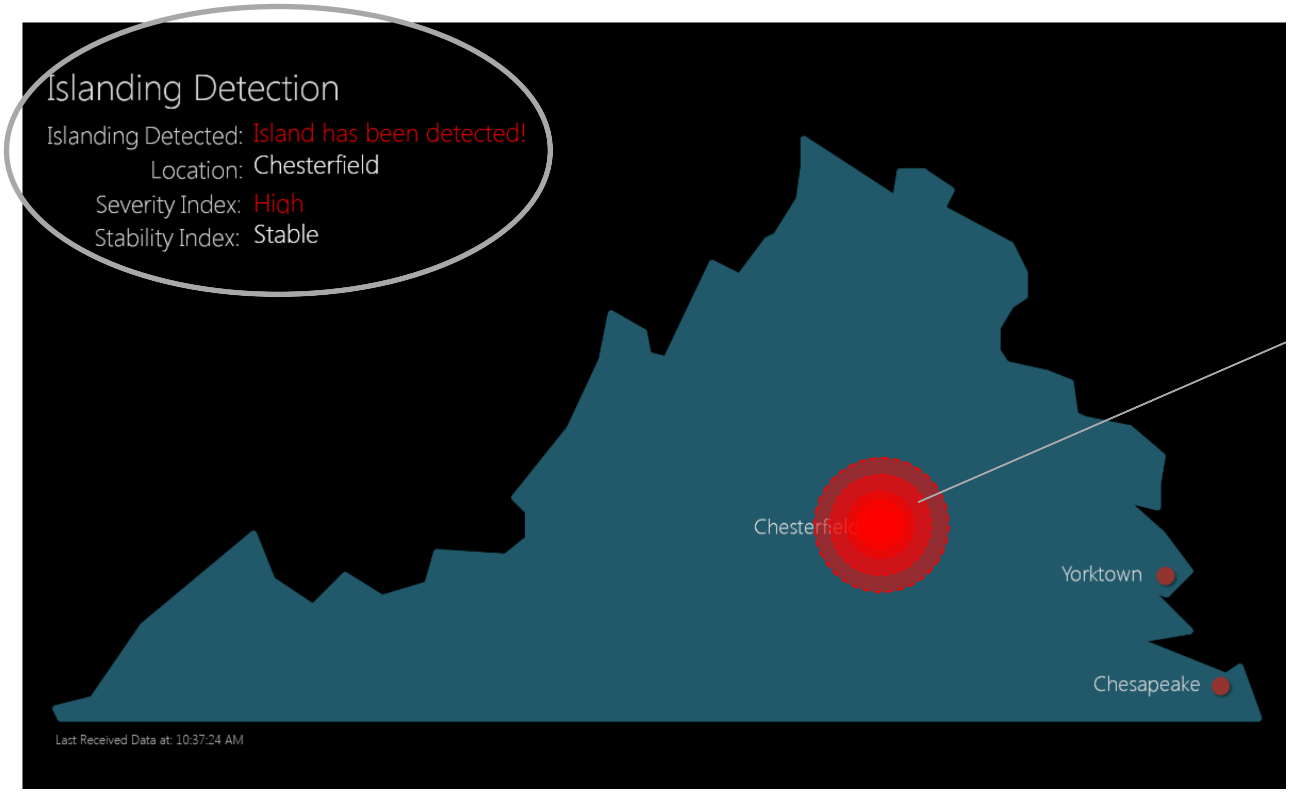
- Module inputs
  - Voltage / current phasors
  - Raw PMU & State estimator data streams
  - EHV (500kV) measurements
- Module outputs
  - Islanding occurrence indicator
  - Island location estimator
  - Island stability estimator
  - Island severity (gen. & load size) estimator
- DT judgment component
  - Full-area tree: identification & location
  - Sub-system trees: stability & severity estimation
- Potential island regions determination



Island Detection using Synchrophasors

- Module tests & results (prediction success)
  - Islanding detection: 95.67%
  - Island location estimation: 97.71%
  - Island stability estimation: 90.44% (averaged)
  - Island severity estimation: 86.36% (averaged)

Real-time
Event driven
outputs



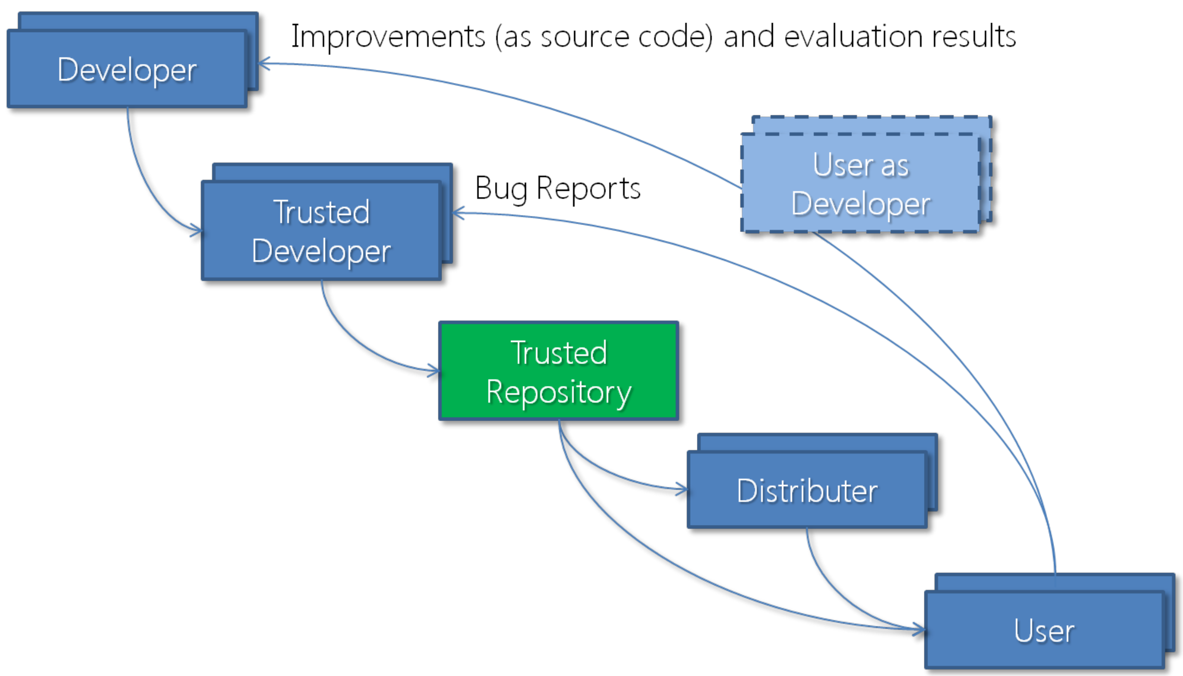
Locations flash and
change circle size
when islanding

Technology Transfer through Open Source

- Homegrown solutions have intrinsic downfall
- DOE funded work is already public domain
- As a hedge against the future…
  - Use the open source model!
  - All source code and documentation available at: http://phasoranalytics.codeplex.com
  - Phasor Analytics contains base code libraries and apps such as LSE and other forms of PMU data conditioning
  - Integrated with a host openPDC
  - Fully extensible library and applications
  - Fully generic implementation - *anyone with any size synchrophasor deployment can deploy and find value in this implementation.*

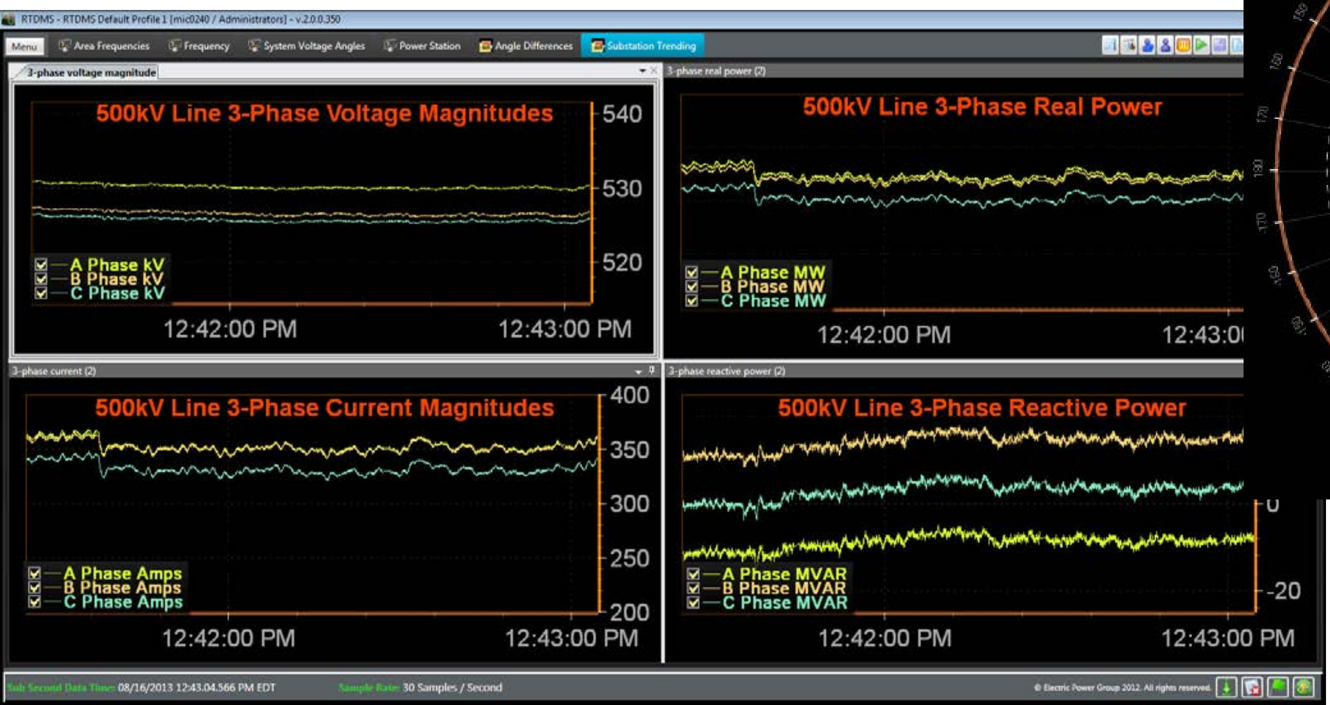
Why Open Source?

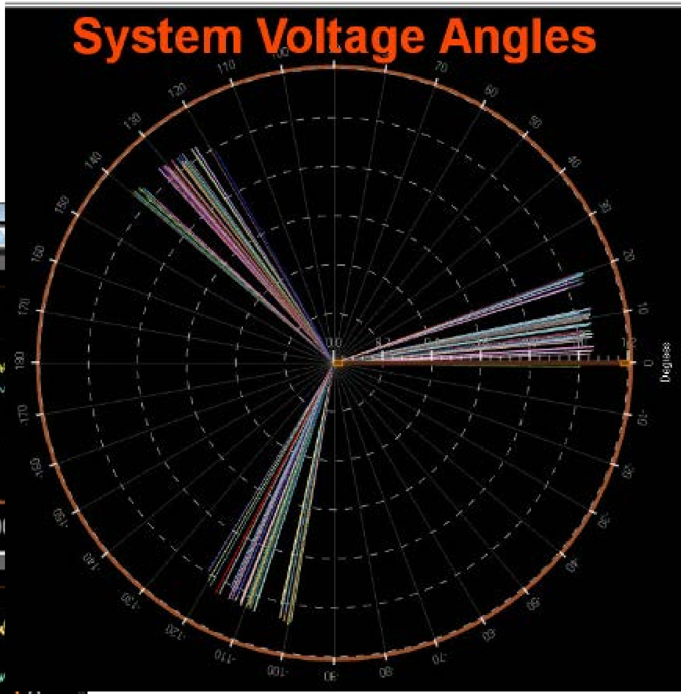
- Generating user base provides mechanisms for growth/support
  - It's all about the numbers!
  - Utility industry is very specialized – small numbers
- University use dramatically increases user base and trains engineers of tomorrow
  - Bridges technology transfer gap; decreases cost of innovation



RTDMS Visualizations

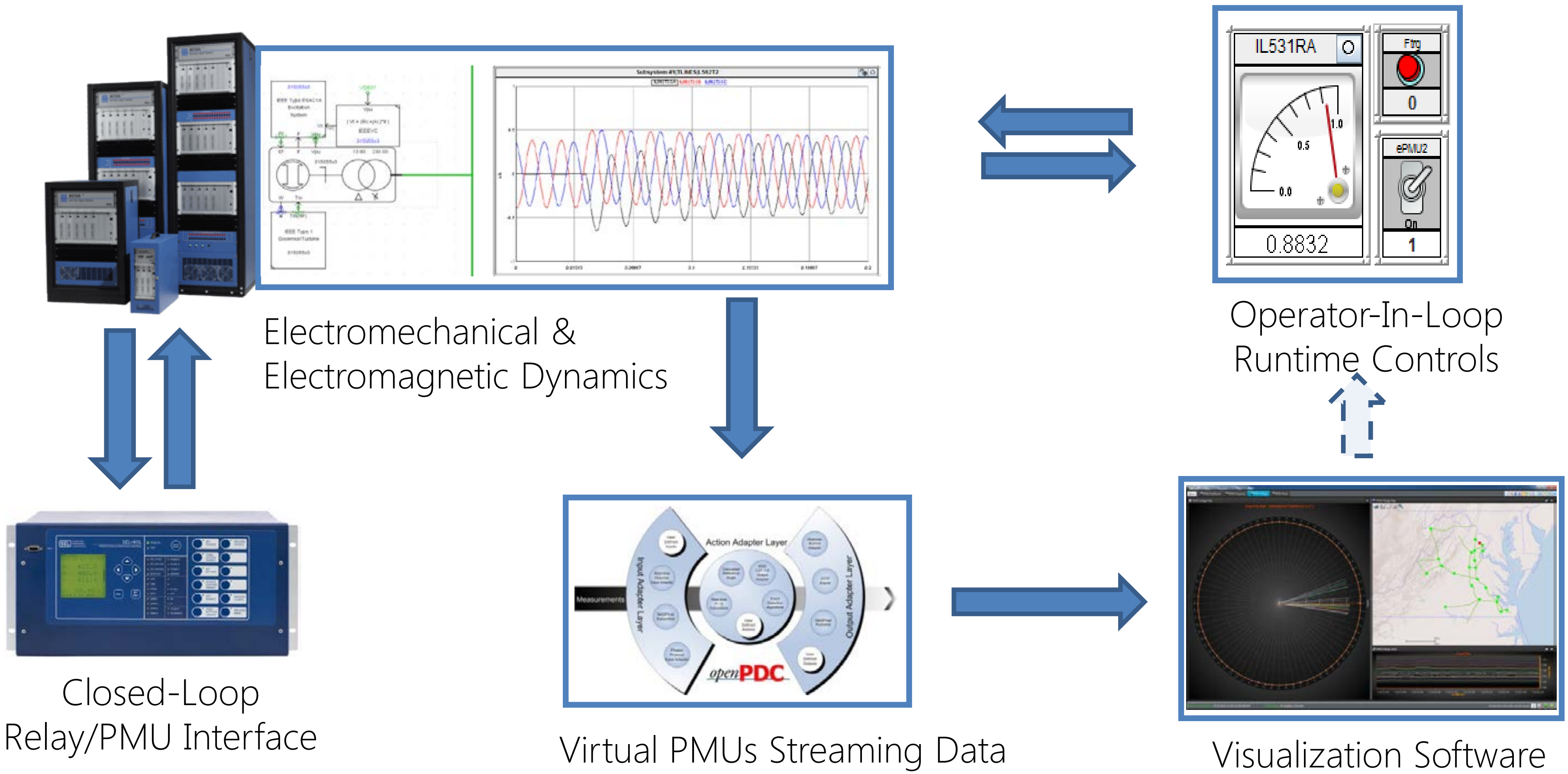
- PJM deployed RTDMS
- Adapter made for connection to openPDC system
- Addressed all other needs, including custom display possibilities for all end-user groups





Synchrophasor Training

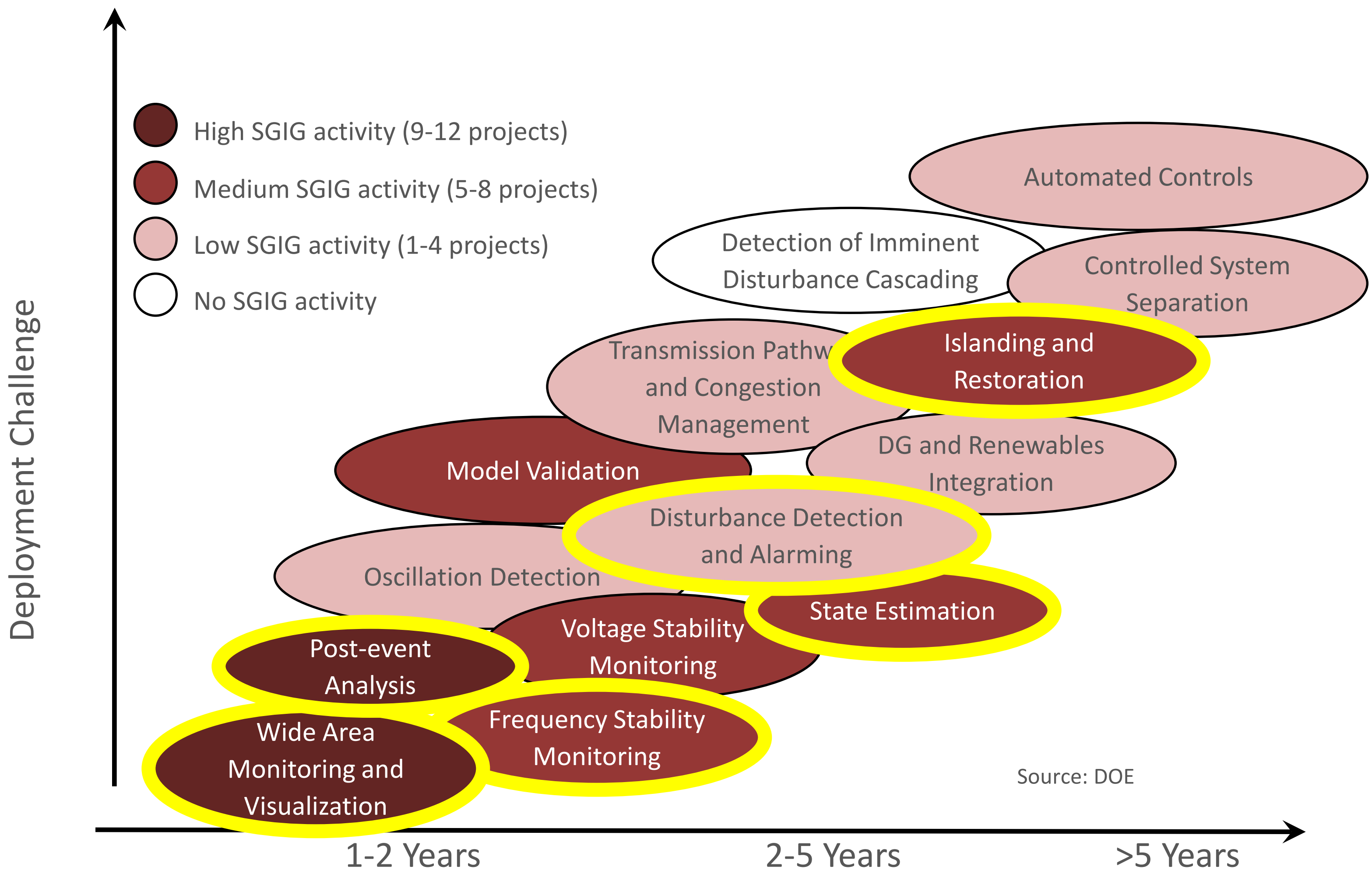
- Created an Operator Training Simulator for training end-users on real-time synchrophasor data, WITH all the applications available to them



Dominion's RTDS Lab

Dominion's RTDS Lab

Where does Dominion's deployment stand?



Organic Growth Through Standardized Deployment

- Scalability of Dual-Use Relay PMUs & Substation PDCs
  - As digital relays continue to replace EM relays, take advantage of scheduled replacements by using relays with PMU capabilities
  - We have changed our substation protection and control standards for to reflect this. When new PMU-capable protection relays are installed for capital or O&M projects:
    - Satellite clock coaxial cables are connected to the PMU-capable relays
    - PMU-capable relays have PMU settings enabled/configured
    - A PDC is installed in the control house(s)
- Expectations for First Year ‘Post-Stimulus’
  - More than 35 locations (transmission lines, transformers) will have PMUs installed
  - 3 Phase voltages, 3 phase currents, and breaker statuses for each relay/PMU deployed
  - All transmission voltage levels: 500, 230, 115

Project Priorities From Here + Future

- Complete deployment of all visualization applications to end-user groups
- Continue deploying PMUs across Dominion's grid
- New applications
  - System model validation
  - Generator model validation
  - Transmission line parameter estimation
  - Equipment monitoring
  - Fault Location/Analysis
  - Load modeling with distribution level PMUs

Project Priorities From Here + Future

- **Synchrophasors are not really R&D anymore** (now we have to operationalize – need trustworthy data source, visualization, and training/process integration)
- Use RTDS/RTDMS to train operators on synchrophasor technology (part of operationalizing)
- Continued growth through standardized deployment of synchrophasors
- Continue to develop applications in house to leverage the investment
- Technology transfer through open source

Helpful Hints & Lessons Learned

– PMUs/PDCs are not plug and play! Take the settings seriously!
– Managing memory/CPU resources on clusters/servers
– There is a critical mass for the ROI of synchrophasors to become sustainable.
– Synchrophasors make it possible to begin to question established assumptions (positive sequence, impedance values, etc)
– Make larger ‘pie-in-the-sky’ goals achievable by asking how can we extract value not just in the future but presently (today, tomorrow)

Our Thanks!

U.S. DEPARTMENT OF ENERGY

VirginiaTech

CURENT

pjm

QUANTA TECHNOLOGY

Smart Solutions, Practical Results

Dominion