Cigré Synchrophasor Tutorial

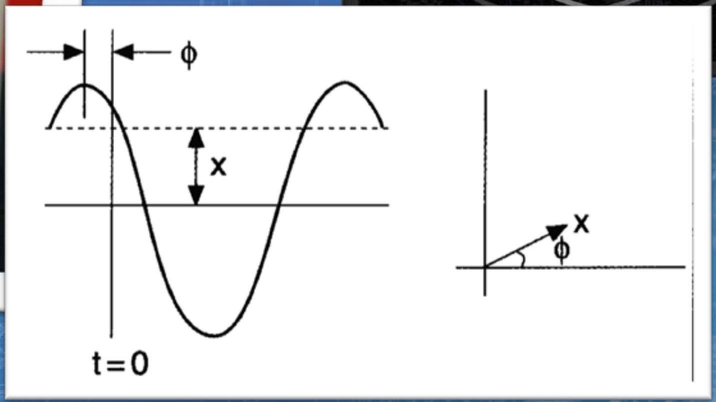
Houston, Texas

Sunday, October 19, 2014

Kevin Jones, Ph.D.

Kyle Thomas, MSEE

R. Matthew Gardner, Ph.D., P.E.



Myth #1 → The synonym myth

"A synchrophasor is a PMU"

The synonym myth

- A synchrophasor is a PMU 

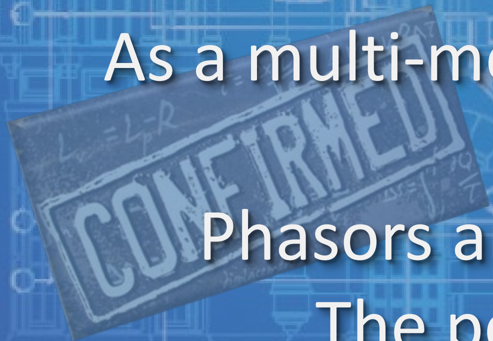
- PMUs are just a fast SCADA 

- It's spelled 'phaser' 

- Raw PMU angles are stationary 

A Phasor Measurement Unit (PMU) is just a meter…

As a multi-meter is to voltage, current, resistance, etc…
a PMU is to a synchrophasor.
Phasors are a basic tool of AC circuit analysis and
The power system is one giant AC circuit!



s ARE the holy grail of power system metering!

Why are we just now talking about synchrophasors?

They are a brand new technology?

Enter the PMU…

OK, maybe "Enter" isn't the right word here

- The first PMU was invented at Virginia Tech back in 1988.
- To put this into context:
  - Northeast Blackout of 1965 –Advent of SCADA
  - Data Processing Problems – State Estimation by Fred Schweppe in 1970
  - Invention of Digital Relaying in late 1970s, early 1980s
  - Proliferation of Digital Relaying in late 1990s
  - **PMU Technology was clearly way ahead of its time!**

Summary Findings – Widespread Outages

- Widespread electric outages are not merely a disease but a symptom of strategies for grid management
- What is the prescription for reliable power?
- Before we study prevention, we need to
  - Understand the symptoms and learn of the root causes
    - Multiple examples of blackouts in recent decades
    - Opportunity to gain expert knowledge from each incident
      - Validations of system models
  - Learn of proven methods to mitigate
    - Comprehensive reports of findings and recommendations - By Investigative teams
    - There are over 150 recommendations since 1994 Cascading Outage
      - 38 conclusions, 28 recommendations - December 1994
      - 130 conclusions, 54 recommendations combined list – July & August 1996
      - 60 recommendations - August 2003 (14 by NERC, and 46 by the US / Canadian Task Force)
      - 14 recommendations - September 2003, The Union for the Coordination of Electricity Transmission (UCTE)

Vahid Madani

Bottom Line Findings: Similarities

- Between the 1994 – 1996, UTCE report in continental Europe, and August 2003 North America
  - If 1994 -1996 recommendations had been applied in other parts of the world, the impacts of the 2003 outages immensely reduced
- Problem categories
  - Systems operating outside of safe limits
  - System expansions and upgrades are inevitable to sustain reliability and meet the energy demand
- Contributing factors
  - Poor Monitoring Systems
  - Protection Performance – Not Designed or Set for Grid Problems
  - Influential, powerful, and Strategically located tree
    - What do we do if this was lightning, dense fog, or other natural events?
    - We cannot fully control, “trim” natural calamity events

Vahid Madani

Similar Chain of Events: Learn From the Past

Western US, 1996: 7.5M people	NE US-Canada, 2003: 50M people	Italy, 2003: 57 M people
• An hour before the disturbance, three 500 kV lines disconnect • Heavy power flow in region • Two lines disconnect due to a fault and a protection trip	• Two hours before the disturbance, 500kV line disconnect • Heavy power flow in region • One 500 kV line sags into a tree and disconnects	• Heavy import to Italy • One 380 kV line sags into a tree and disconnects
• Heavy load through 230kV and 115kV lines • 230kV/115 kV lines disconnect due to overload	• Heavy load through 230kV and 115kV lines • 230kV/115 kV lines disconnect due to overload • More 345kV lines trip	• Heavy load through parallel line that sags into a tree • 220kV/110kV trip due to overload resulting in isolating Italy
• Voltage declines and power units trip • Power oscillations and voltage instability cause cascading separations • Blackout occurred in 3 min. System restored in ~ 6 - 9 h	• Voltage declines and power units trip • Power oscillations and voltage instability cause cascading separations • Blackout occurred in 3 min. System restored in ~1-2 days	• Voltage declines and power units trip • Power oscillations and voltage instability cause cascading separations • Blackout occurred in 2.5min. System was restored in ~5 h

Vahid Madani

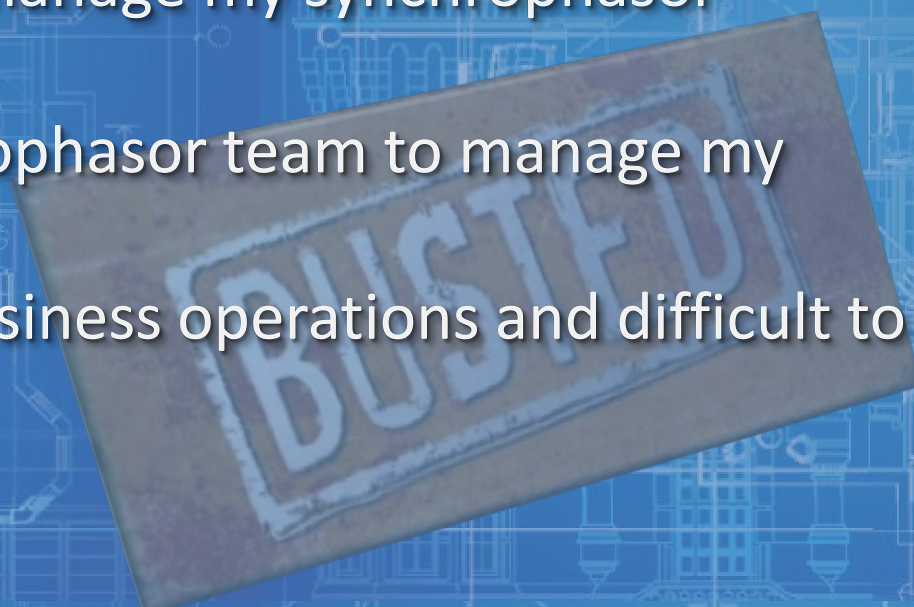
Myth #2 → Not in my house!

...and other misconceptions about PMU deployment

Deployment Myths & Misconceptions

Funding & Project Management

- I need a dedicated synchrophasor project to deploy PMUs
- I need a Government grant to deploy PMUs
- PMU installations are very expensive
- I only need a 50% FTE to manage my synchrophasor systems
- I need a dedicated synchrophasor team to manage my synchrophasor systems
- PMUs are disruptive to business operations and difficult to deploy

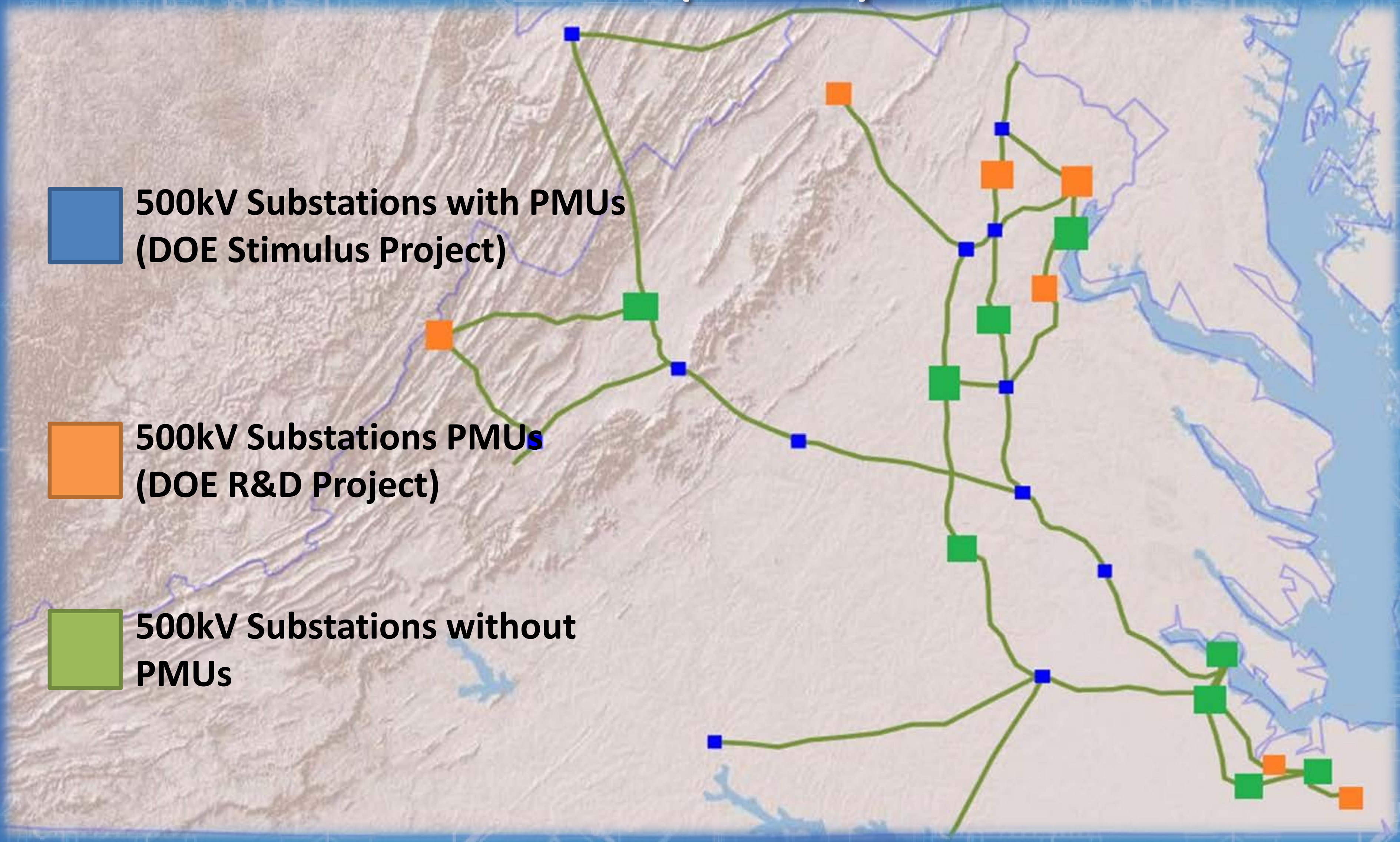


Deployment Myths & Misconceptions

- Substation Infrastructure
  - Synchrophasors can be transmitted over PLC
  - I cannot use my protective relays as PMUs
  - DFRs provide all the necessary data, we don't need PMUs
  - PMUs should only be installed in the transmission system, not generation or distribution
  - Synchrophasors can be processed in the same infrastructure as SCADA

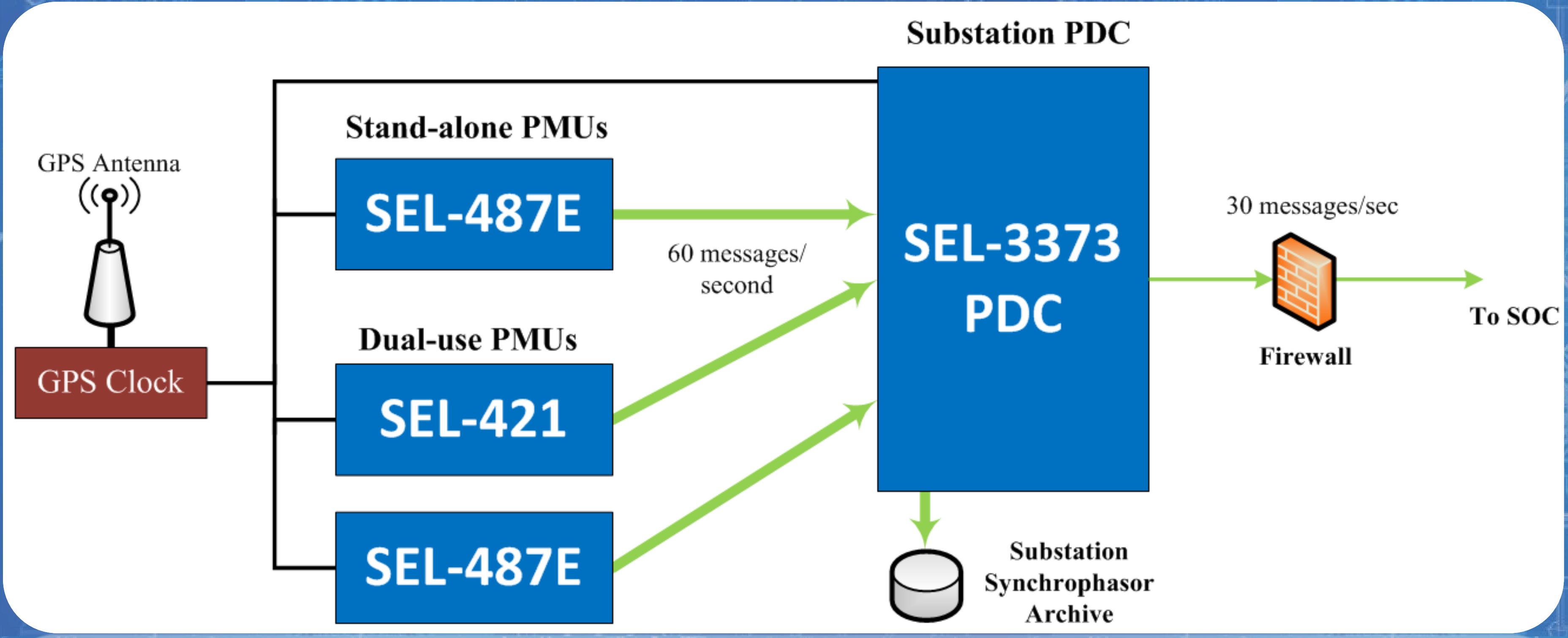
- Compliance
  - I cannot put PMUs into my CIP Environment
  - I cannot put PMUs into my NON-CIP environment

Dominion's Synchrophasor Deployment EOY (2012)



Substation Architecture for PMUs

- Independent from SCADA Systems
- Capture all three phases
- PMUs made CIP CCAs
- Back-up Archive (30 days)



Organic Growth Through Standardized Deployment

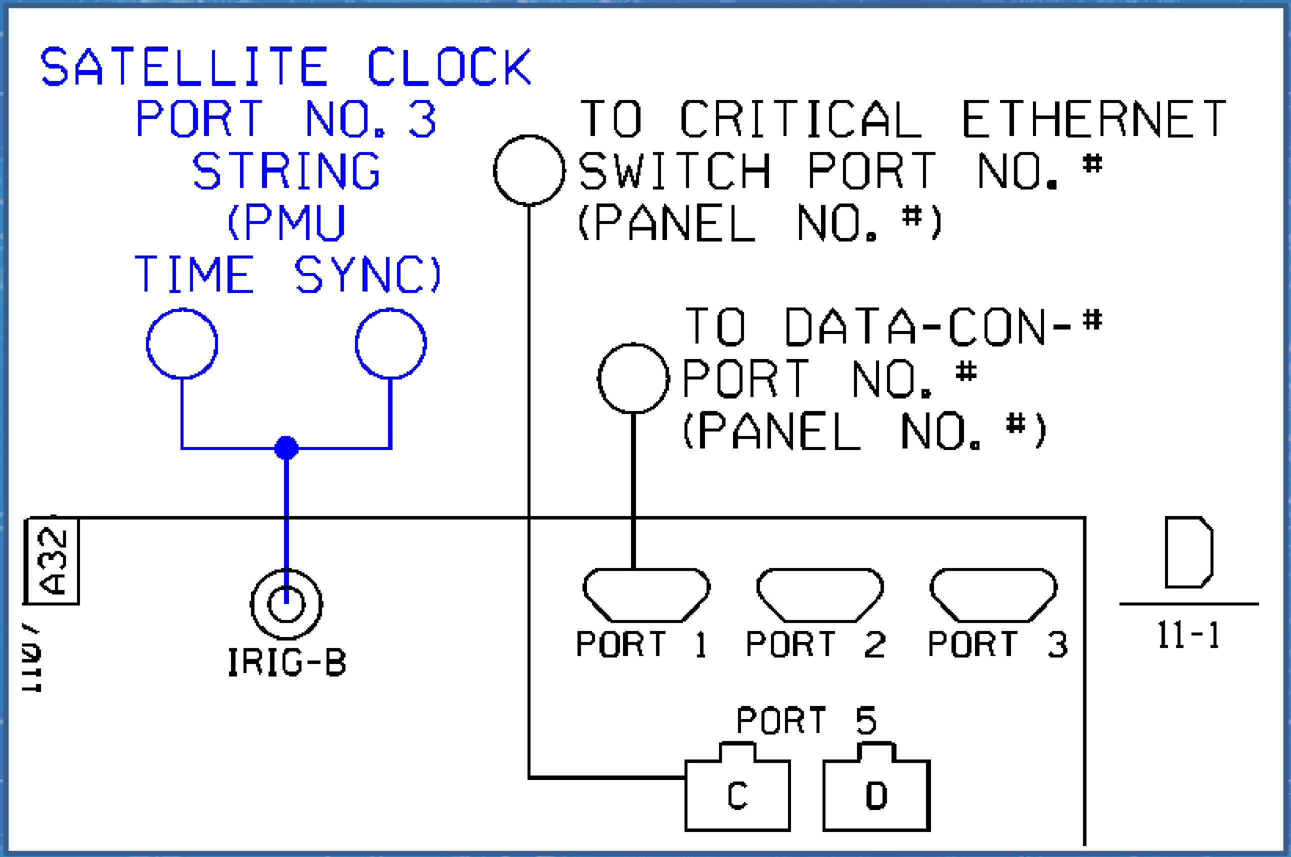
- Scalability of Dual-Use Relay PMUs & Substation PDCs
  - As digital relays continue to replace EM relays, take advantage of scheduled replacements by using relays with PMU capabilities
  - We have changed our substation protection and control standards for to reflect this. When new PMU-capable protection 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: 500kV, 230kV, 115kV

Substation Standards for Synchrophasors & PMUs

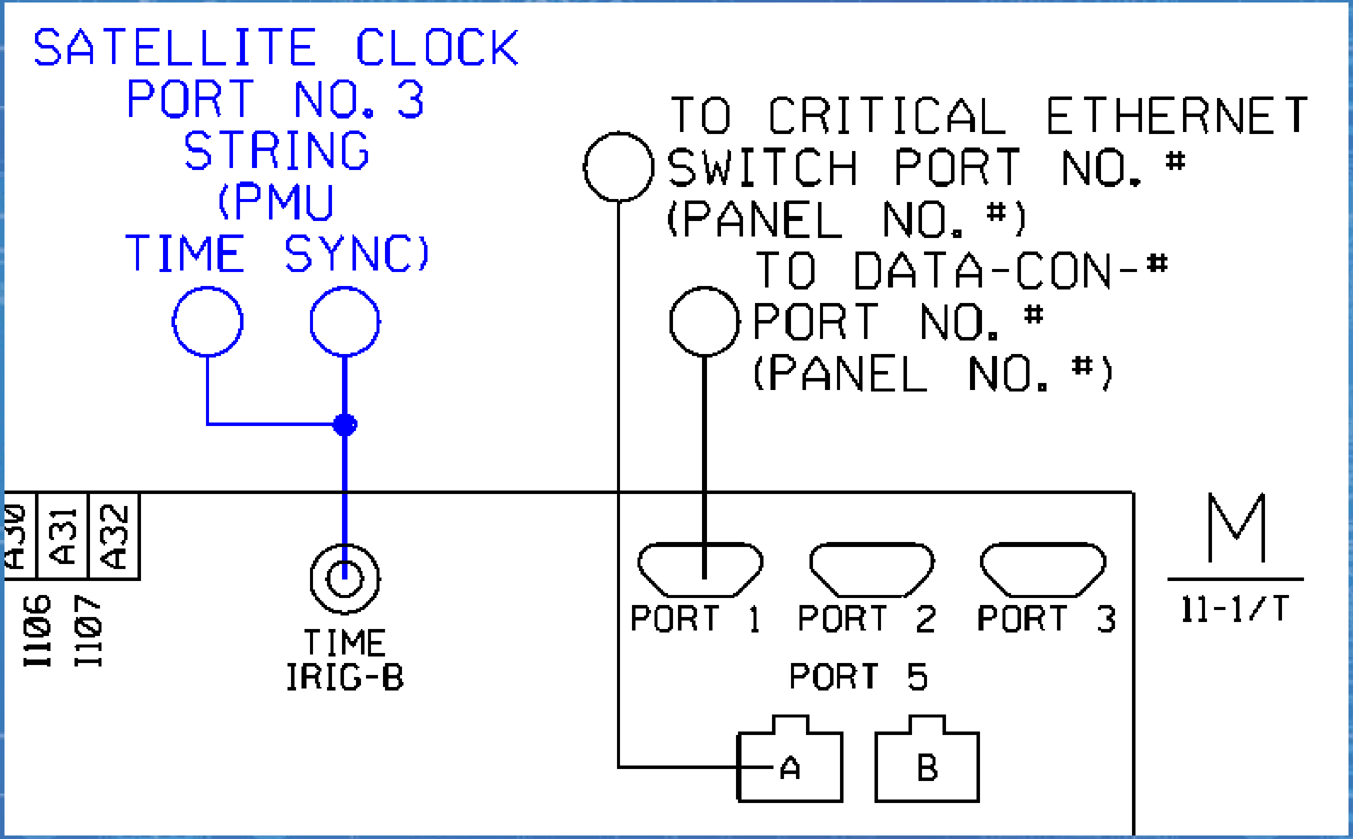
<u>Four Substation Standards for Synchrophasors & PMUs</u>

1. Transmission Line Relays
   - Add satellite coaxial cable, Ethernet connection, PMU Settings
2. Transmission Transformer Relays
   - Add satellite coaxial cable, Ethernet connection, PMU Settings
3. Stand-alone PMU Panel
   - Install if Lines/Transformer do not have PMU-capable relays (and are not being upgraded in near future)
   - Install if other voltages/currents/digitals in the station are needed (ex: cap banks, FACTs)
4. Substation PDC
   - Install one per control house (sufficient at this time, as one PDC can handle ~40 PMUs)
   - Install PDC on a Communication Panel or a
     Stand-alone PMU Panel

Standards for Transmission Line Relay (SEL-421)
Satellite Clock + Ethernet



Standards for Transmission TX Relay (SEL-487E) Satellite Clock + Ethernet



Standards for both SEL-421 and SEL-487E PMUs

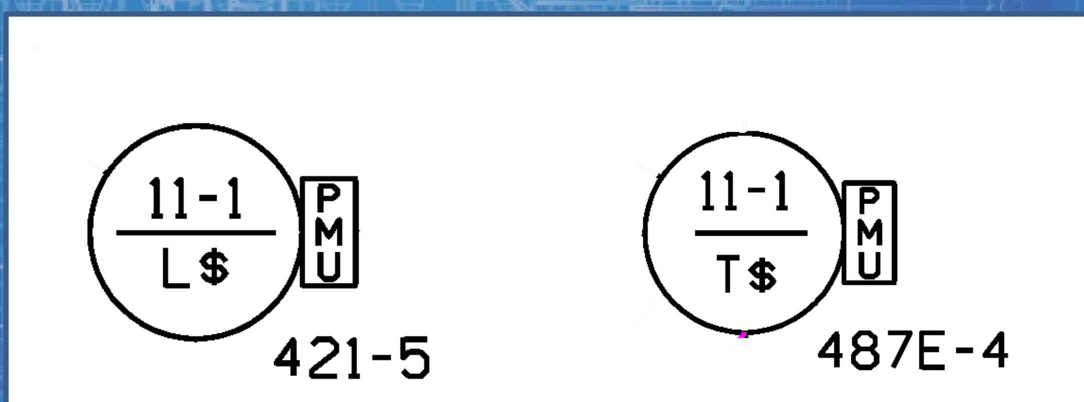
- PMU Logic for Breaker Status

PMU BREAKER STATUS

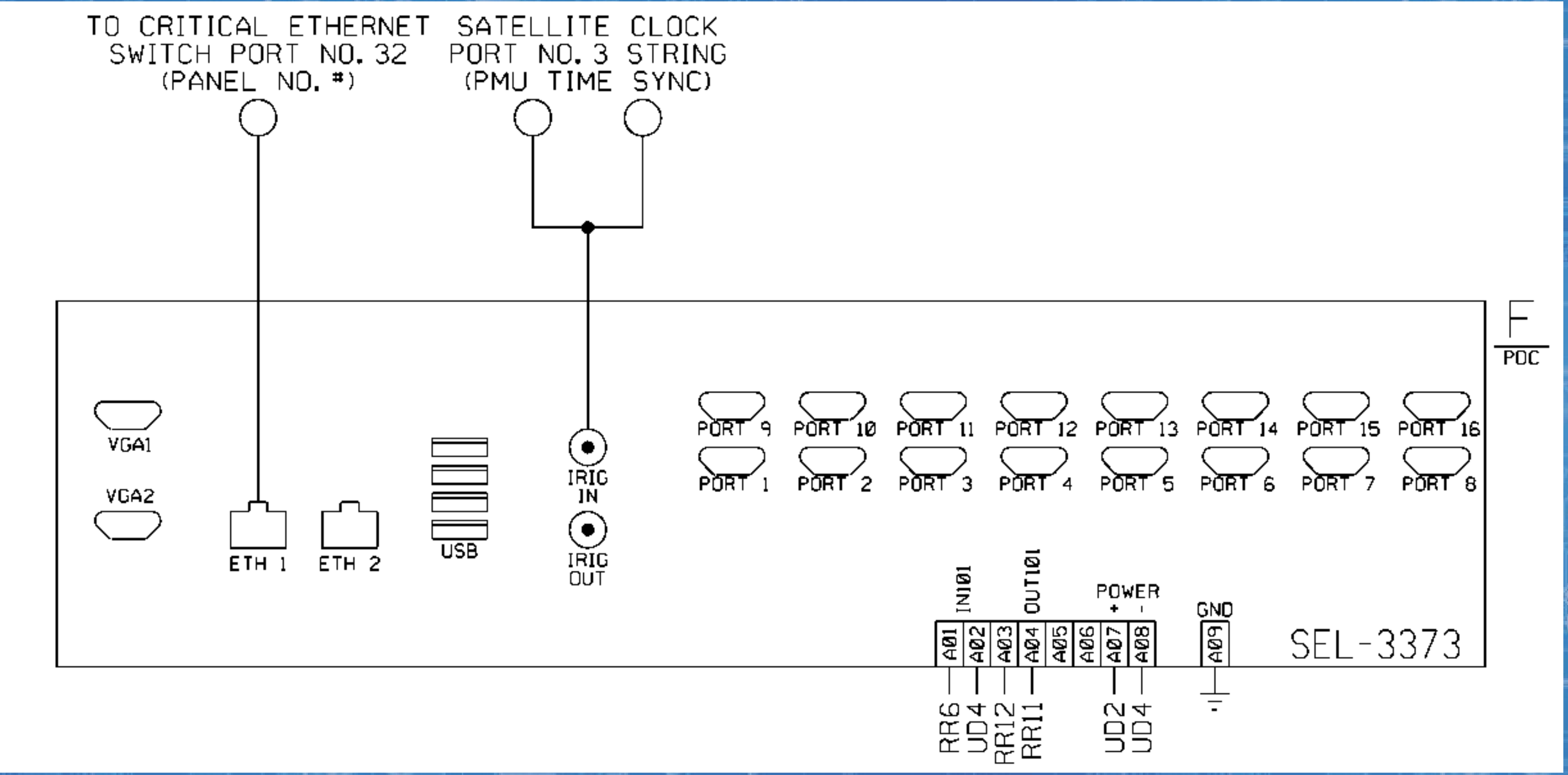
PSV64 := NOT 52AA1	C.B. NO. ??
PSV63 := NOT 52AA2	C.B. NO. $$

Breaker Status: often overlooked, but useful information and readily available.

- PMU Labels on Relay Functional Drawings



Standards for PDC (SEL-3373) Wiring Diagram



Standards for PDC (SEL-3373) Measurement Chart

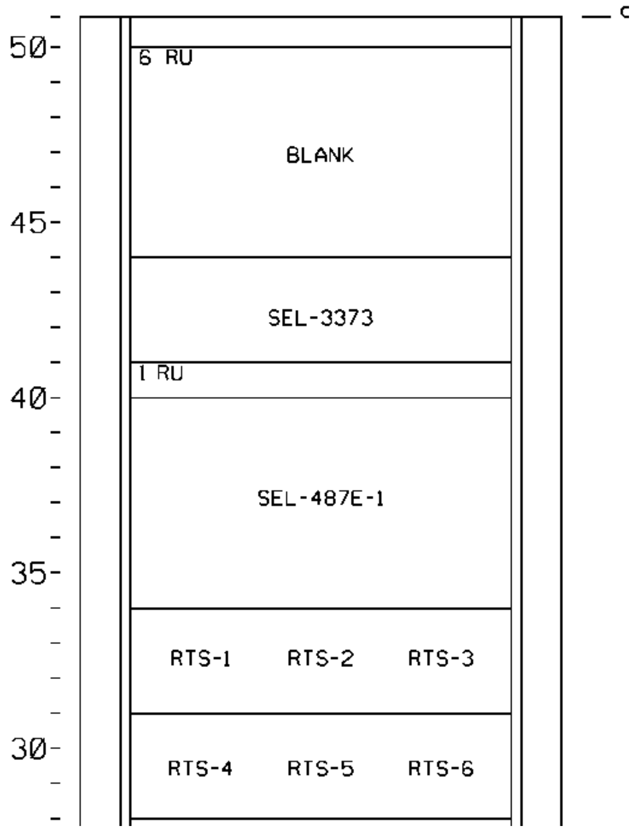
- Every PDC has a PMU Data chart with list of all synchrophasor measurements

PMU DATA			
DEVICE	TAG	DESCRIPTION	INPUT
11-1/L#	V1YPM	#### POSITIVE SEQUENCE VOLTAGE	VAY,VBY,VCY
	VAYPM	#### A PHASE VOLTAGE	VAY
	VBYPM	#### B PHASE VOLTAGE	VBY
	VCYPM	#### C PHASE VOLTAGE	VCY
	I1WPM	#### POSITIVE SEQUENCE CURRENT	IAW,IBW,ICW
	IAWPM	#### A PHASE CURRENT	IAW
	IBWPM	#### B PHASE CURRENT	IBW
	ICWPM	#### C PHASE CURRENT	ICW
	PSV64	######### (IN1Ø1)	NOT 52AA1
	PSV63	######### (IN1Ø2)	NOT 52AA2
	PSV62	######### (IN1Ø3)	NOT IN1Ø3
11-1/T#	V1VPM	#### POSITIVE SEQUENCE VOLTAGE	VAV,VBV,VCV
	VAVPM	#### A PHASE VOLTAGE	VAV
	VBVPM	#### B PHASE VOLTAGE	VBV
	VCVPM	#### C PHASE VOLTAGE	VCV
	V1ZPM	#### POSITIVE SEQUENCE VOLTAGE	VAZ,VBZ,VCZ
	VAZPM	#### A PHASE VOLTAGE	VAZ
	VBZPM	#### B PHASE VOLTAGE	VBZ
	VCZPM	#### C PHASE VOLTAGE	VCZ
	I1SPM	#### POSITIVE SEQUENCE CURRENT	IAS,IBS,ICS
	IASPM	#### A PHASE CURRENT	IAS

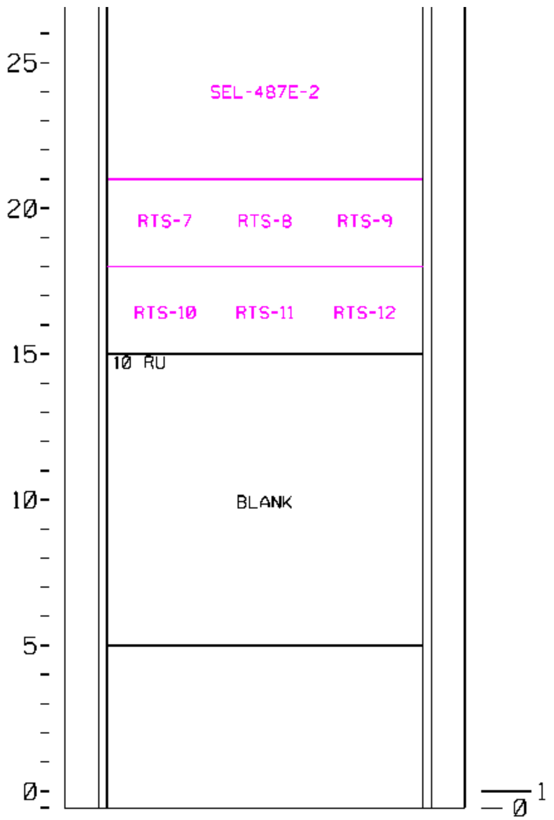
Standards for PMU Panel (Dual SEL-487E + PDC)

- Maximum of two SEL-487E on one panel
- PDC can be placed on this panel or a communications panel

Top half of panel



Bottom half of panel



PMU Settings

- Updated Relay Setting Documentation/Procedures so that PMU Settings are applied to Relays during project work

Synchronized Phasor Measurement

Enable Synchronized Phasor Measurements
EPMU: Y

Message Format
MFRMT: C37.118

Message per Second
MRATE: 60

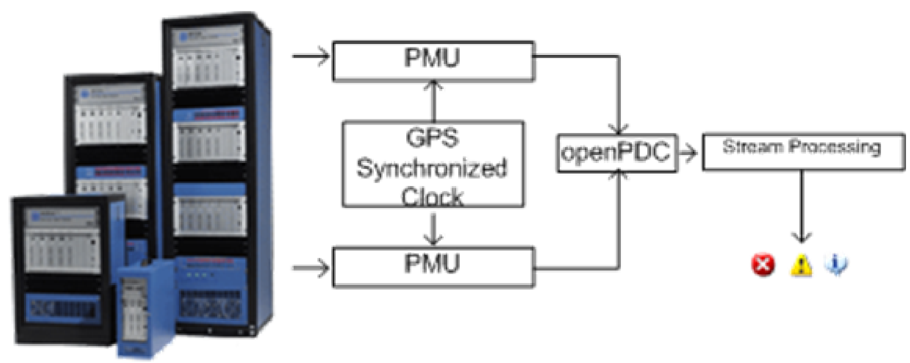
Type of PMU Application
PMAPP: N

Number of Data Configurations

PMU Global Variable Definitions		
	Primary 1	**Primary 2**
Station Name "PMSTN"	Station A_11-1L1	Station A_11-2L1
ID Number "PMID"	10100	20100

Data dimensionality – Typical Info.

- GE N60
  - 15 parameters
  - 15 dimensionality
- SEL 421
  - 10 parameters
  - 10 dimensionality



MSU RTDS setup.

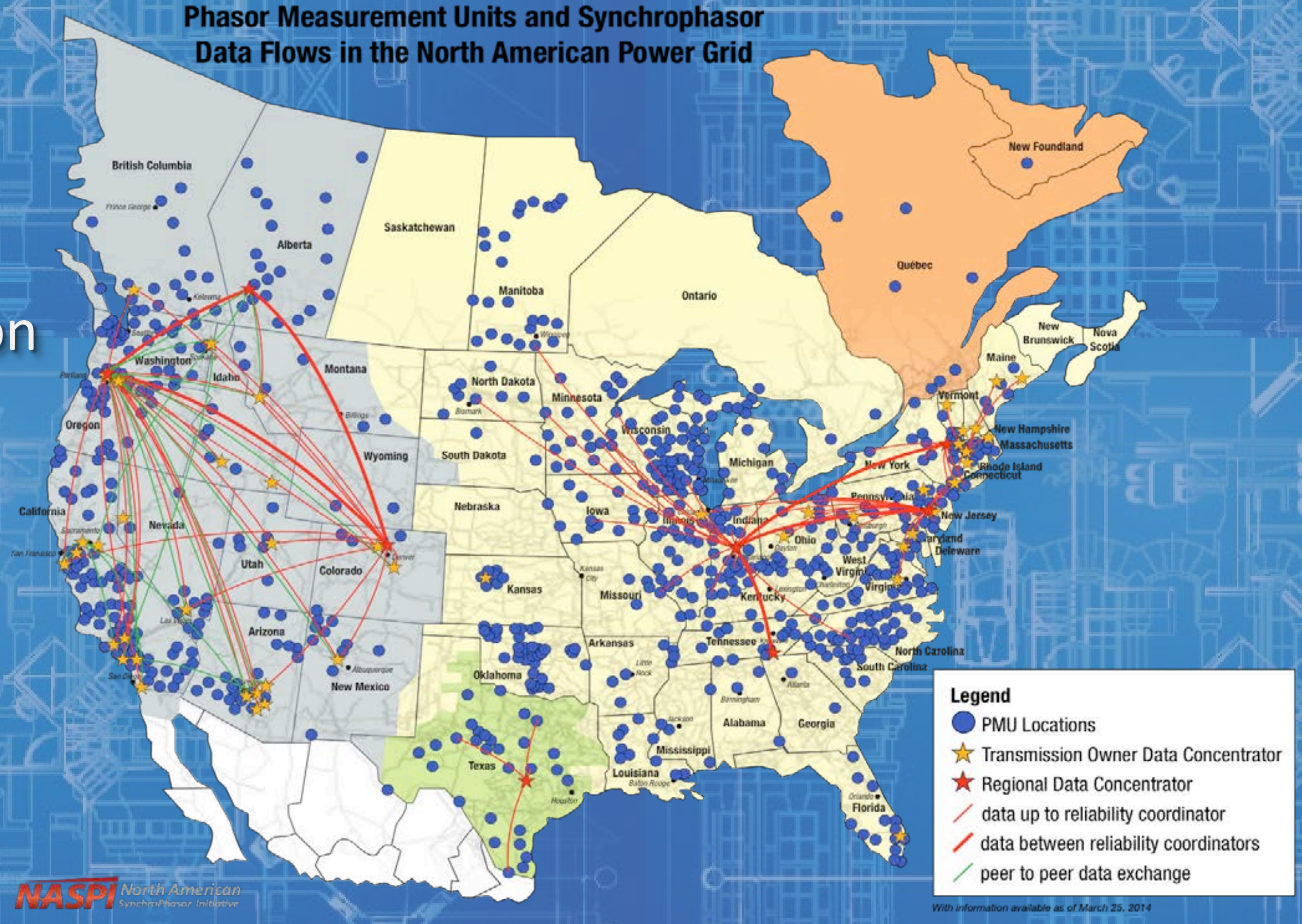
N60	Phase A Voltage
	Positive Sequence Current
	Negative Sequence Current
	Zero Sequence Current
	Ground Current
	Phase B Voltage
	Phase C Voltage
	Phase A Current
	Phase B Current
	Phase C Current
	Positive Sequence Voltage
	Negative Sequence Voltage
	Zero Sequence Voltage
	Rate of Change of Frequency (dF/dt)
	Frequency
SEL421	Phase A Voltage
	Positive Sequence Current
	Phase B Voltage
	Phase C Voltage
	Phase A Current
	Phase B Current
	Phase C Current
	Positive Sequence Voltage
	Rate of Change of Frequency (dF/dt)
	Frequency

Organic Growth Metrics

- 60+ new substations since January 1, 2013
  - Date standardization effective
  - End of DOE SGIG grant activity
  - Beginning of standard work
- Organic rollouts contribute to a 0.1% adder to annual capex over next 5 years
- Expect over 300 additional control houses with synchrophasors over next 5 years
  - 141 substation PDCs purchased to date
  - 55 to date in 2014 (expect 60 by EOY)
  - 47 in 2013
  - 39 from 2010-2012 (DOE stimulus and R&D grants)
- Actively pursuing similar standardization for distribution substations

PMU Deployment Over the Last Decade

Sparked by the Northeast Blackout of 2003 and early adoption by progressive organizations



Interoperability Considerations

- Standards
  - Standards required [but not sufficient] for interoperability.
  - Standard conformance is precursor for achieving interoperability
- Testing
  - Both standards and implementation agreements are subject to interpretation and may include options, choices, or configurations.
  - Consistent testing and conformance assessment can verify performance and potentially interoperability - key to consistent interpretation of test results
  - Identifies the need for improvements to devices/system, as well as feedback for improving standards and implementation agreements
- Life-cycle Management
  - Life-cycle management, asset utilization, and revision control are all considerations affected by interoperability
  - Architecture interoperability needs to support system life-cycle management and asset utilization (long-term system deployment roadmap)

Vahid Madani

Myth #3 → Set it and forget it!

"Synchrophasors are plug-and-play"

Data Quality is an Important Issue

- PMU Deployments have grown in size, shape, & number.
- Organizations now trying to extract value from their investments by “operationalizing” their data:
  - In the EMS
  - In special PMU data visualizations
  - In situational awareness and other special PMU applications
  - In engineering roles: planning and equipment engineering
- However, many are experiencing difficulties due to quality of the synchrophasor data.

Data Quality Myths & Misconceptions

- Synchrophasors are plug and play
- Data quality isn't important
- PMUs are the most accurate measurement device
- I just need to 'make it work'
- We are willing to sacrifice data integrity and/or quality to reduce data storage and/or network utilization
- Measurement-based methods using synchrophasors are equally as accurate as model-based or hybrid methods
- Existing applications are robust to bad data quality

Types of Phasor Data Quality Issues

Issues develop from many conditions:

- Dropouts/packet loss
- Latency
- Repeated values
- Measurement bias
- Bad/missing timestamps
- Loss of GPS synchronization
- Incorrect signal meta data
- Planned/Unplanned outage
- Poor server performance
- Improper device configs

Need for real-time, highly available data

Streaming data to PJM for system operations

- PJM data quality reports/checks

Real-time visualizations and applications in SOC and other Electric Transmission Departments

To support these areas:

- Need a robust synchrophasor architecture
- Need to know PMU is installed/configured correctly
  - **Commissioning Process**
- Need to provide clean data to these applications
  - **Data Filtering and Conditioning**

Pre-commissioning Requirements

PMU installed in substation

- All voltages/currents/digitals wired and energized
- PMU settings set to standard
- Ethernet communications active

PDC or Tool connected to PMU C37.118 stream

- Software or Hardware PDC
- PMU Connection Tester software or similar
  - Need to capture and store a timeframe of data from the PMU (1 minute to 5 minutes)

Commissioning Checkpoints

Timestamps and PMU Phasor Rate

- Per the C37.118 Standard, timestamps must start from .X00 second and evenly spaced samples per 0.1 second
  - Example: PMU set to 30 measurements per second
    - 0.000, 0.033, 0.066, 0.100, 0.133, etc.
- There should be no repeated timestamps or shifted timestamps
- The timestamp month/day/year is accurate

Good Timestamps	Bad Timestamps
04/22/2014 10:10:10.000	04/22/2014 12:12:12.000
04/22/2014 10:10:10.033	04/22/2014 12:12:12.050
04/22/2014 10:10:10.066	04/22/2014 12:12:12.077
04/22/2014 10:10:10.100	04/22/2014 12:12:12.123
04/22/2014 10:10:10.133	04/22/2014 12:12:12.143

Commissioning Checkpoints

PMU C37.118 Status Word

- A correctly installed PMU will report Status Words of **0**
- Any PMU measurements that have a Status Word equal to anything non-zero must be investigated
- While the C37.118 Standard defines all 16 bits in the Status word, we have found Status Words vary significantly across different PMU versions and different PMU vendors
  - Must speak with PMU vendor to get details on how the PMU sets the Status Word bits

Example: Status Word = A000 (HEX)

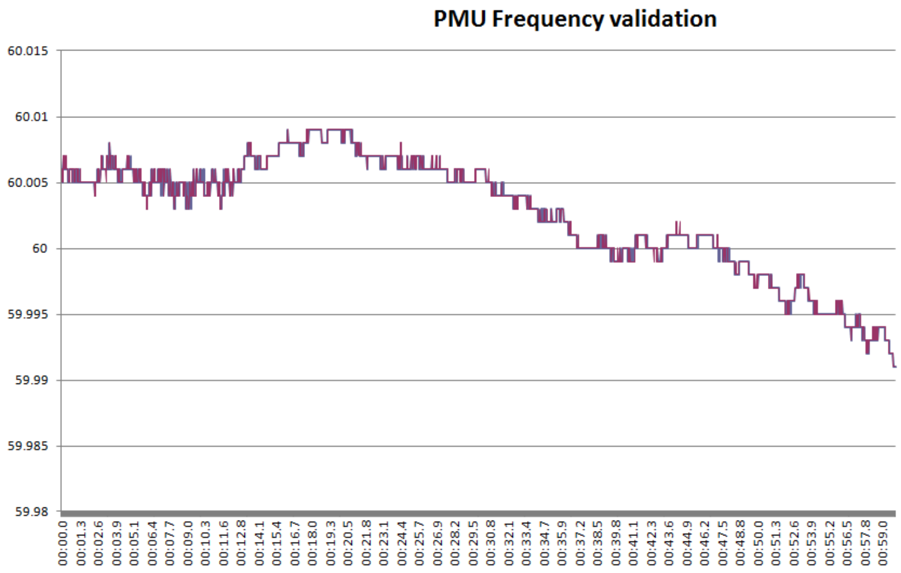
→ Data Invalid

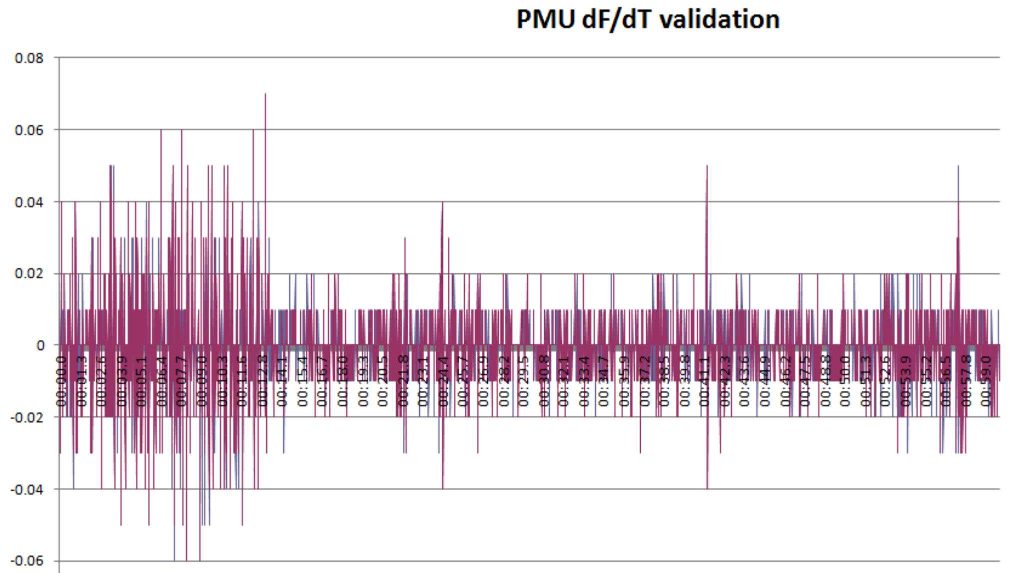
PMU not GPS synchronized

Commissioning Checkpoints

Frequency and DFDT

- Frequency should be around 60Hz, +/- 0.050 Hz
- DFDT values should be around 0 Hz/s, +/- 0.1 Hz/s
- Both should be constantly changing, not static numbers

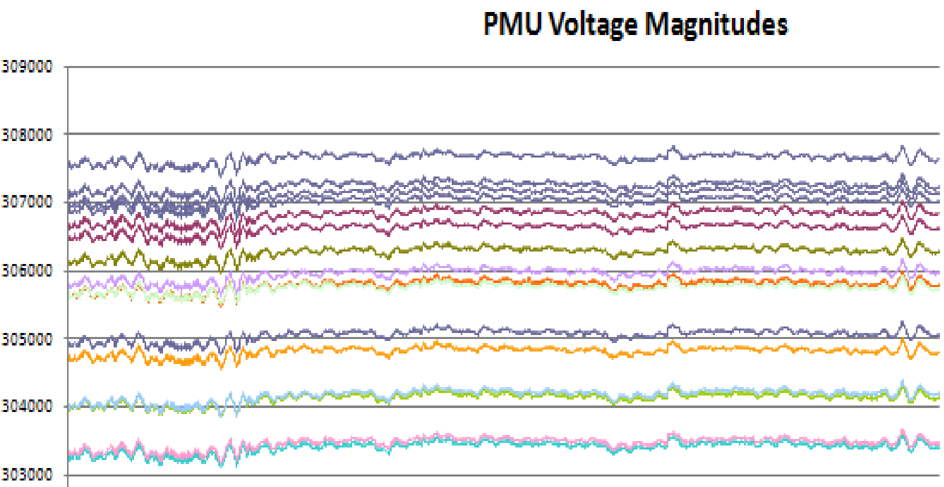


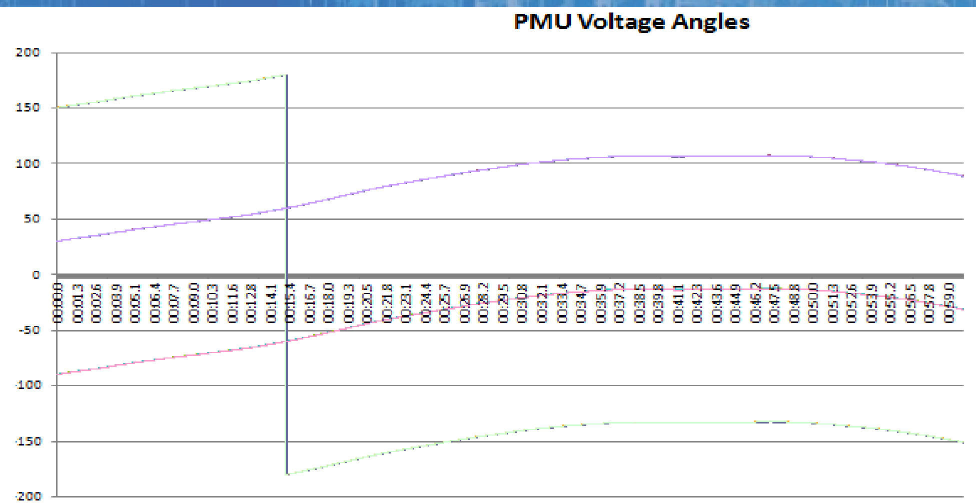


Commissioning Checkpoints

Voltage Phasors

- Voltage Magnitudes
  - Check all voltage magnitudes and compare to expected operating voltages (ex: 500kV nominal, 525kV operating)
  - Consider line-to-ground versus line-to-line voltages
  - Compare versus SCADA measurements for reasonability check
- Voltage Angles
  - Check angles for 120 phase rotation between each phase
  - Angle trends should be smooth, no sudden gaps or jumps, except for the jump to and from +/-180 degrees

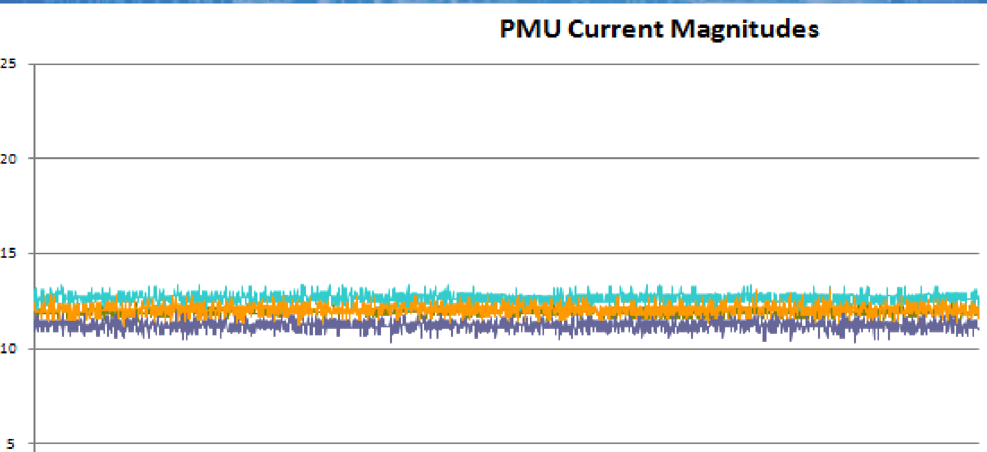


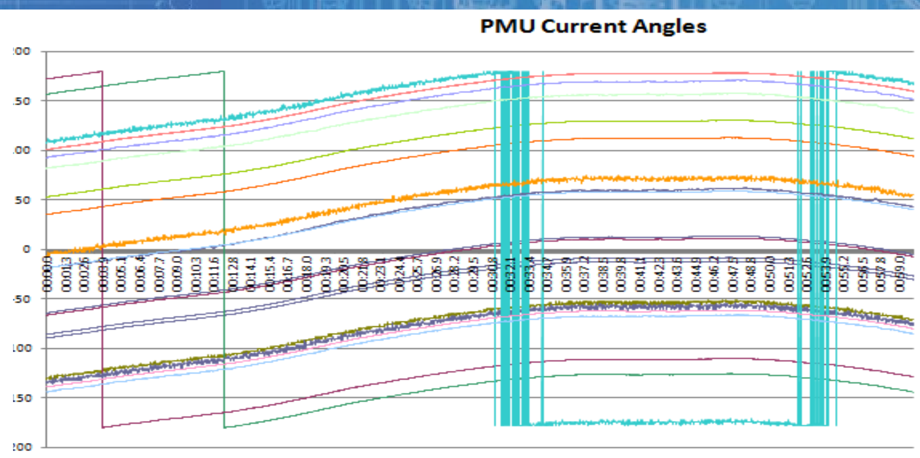


Commissioning Checkpoints

Current Phasors

- Current Magnitudes
  - Check all current magnitudes and compare with SCADA measurements for reasonability check
  - Check for zero currents, extra large/small values, and repeated values
- Current Angles
  - Check angles for 120 phase rotation between each phase
  - Angle trends should be smooth, no sudden gaps or jumps, except for the jump to and from +/-180 degrees





Commissioning Challenges

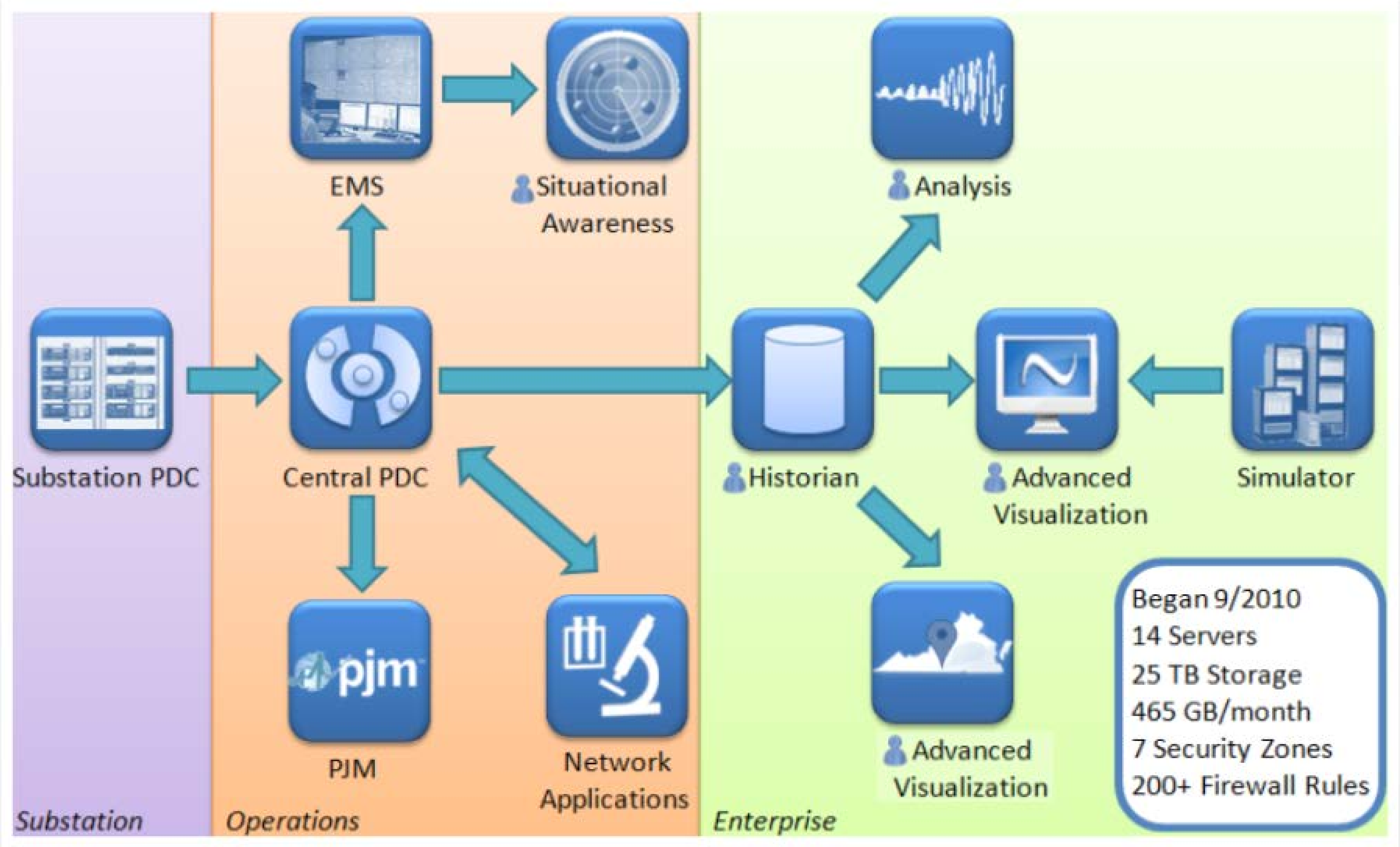
Must perform every checklist item for every PMU commissioned

- Immense volumes of data to analyze, very time consuming
  - 80 PMUs
  - 600+ voltage/current phasors
  - Report rate of 60 measurements per second
- Any issues must be investigated per PMU

Analysis of data can be automated

- Same checklist for all PMUs
- Same set of data (C37.118 Standard)
- Common/standard file types (CSV, Comtrade)

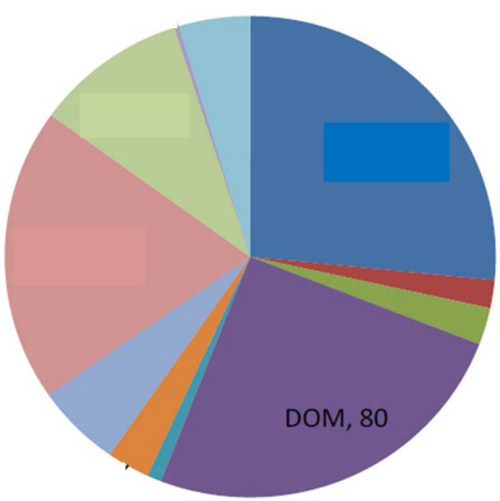
Dominion's Central Synchrophasor Data Systems Architecture



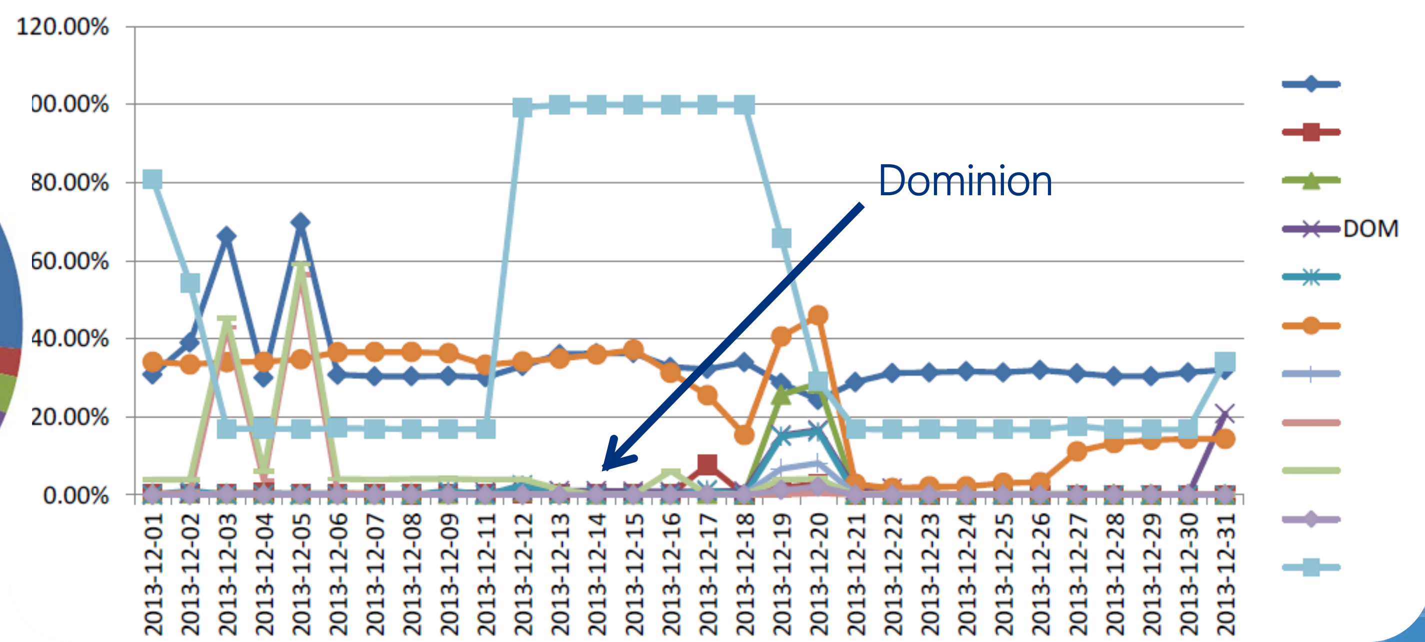
Data Forwarding to RTO

- "There is no utility benefit to synchrophasors aside from sending to RTO/ISO"
- Each TO is required to forward PMU data to PJM
  - Positive sequence voltage and current phasors
  - Breaker statuses, tap settings
  - Freq, df/dt, Status Words

PMU Count



Daily Average PMU Error by TO, December 2013



The Complete Package For Synchrophasors

- PMUs have been hailed as the holy grail of power systems metering technology but there is more than meets the eye:
  - Placement of devices for optimal “observability”
  - Proper configuration/tuning of the PMUs/PDCs
  - Substation architecture design and standards
  - Communications infrastructure
  - Central PDC design, architecture, modeling, and work processes
  - Data Conditioning & Linear State Estimation
- In short, you need the complete package to fully realize the potential of the technology.

Linear State Estimation
Myths & Misconceptions

- Full PMU coverage is required to do LSE
- I need more PMUs to do LSE
- I need a coherent network of measurements to do LSE
- I already have a state estimator so LSE serves no real purpose
- LSE is a steady state application
- The purpose of state estimation in general is to give me a base case.

Linear State Estimation

Appeared early in PMU literature (1980)

- Directly measuring the system state
- Fast, linear calculation… No divergence!
  - SE availability is critical during stressed conditions
- No scan times with synchronized measurements
- Handles computational and physical islands
  - State estimation during black start
  - Can process sparsely measured networks
- Puts phasor data in context of network model
- Provides trustworthy data for network apps
- Available open source at http://phasoranalytics.codeplex.com

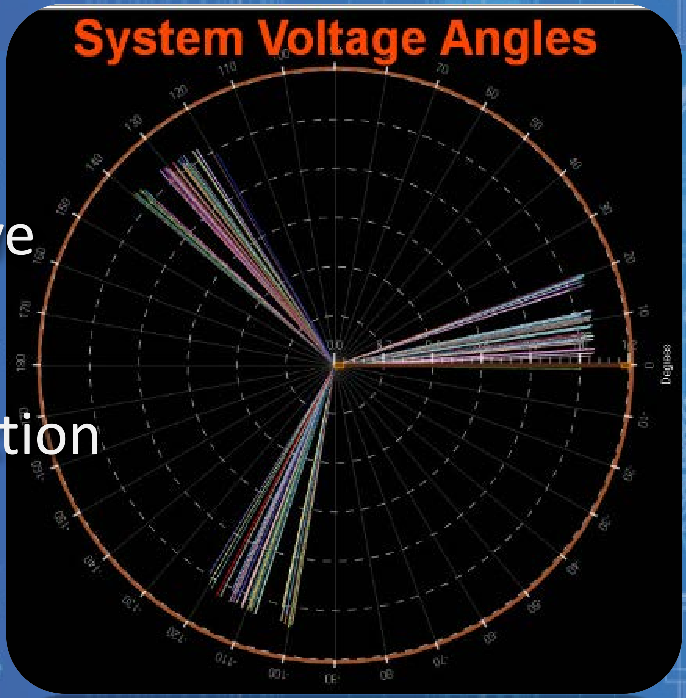
Myth #4 → if it looks like phasor data, and quacks like phasor data…

“Synchrophasor Visualization is Completely Mature”

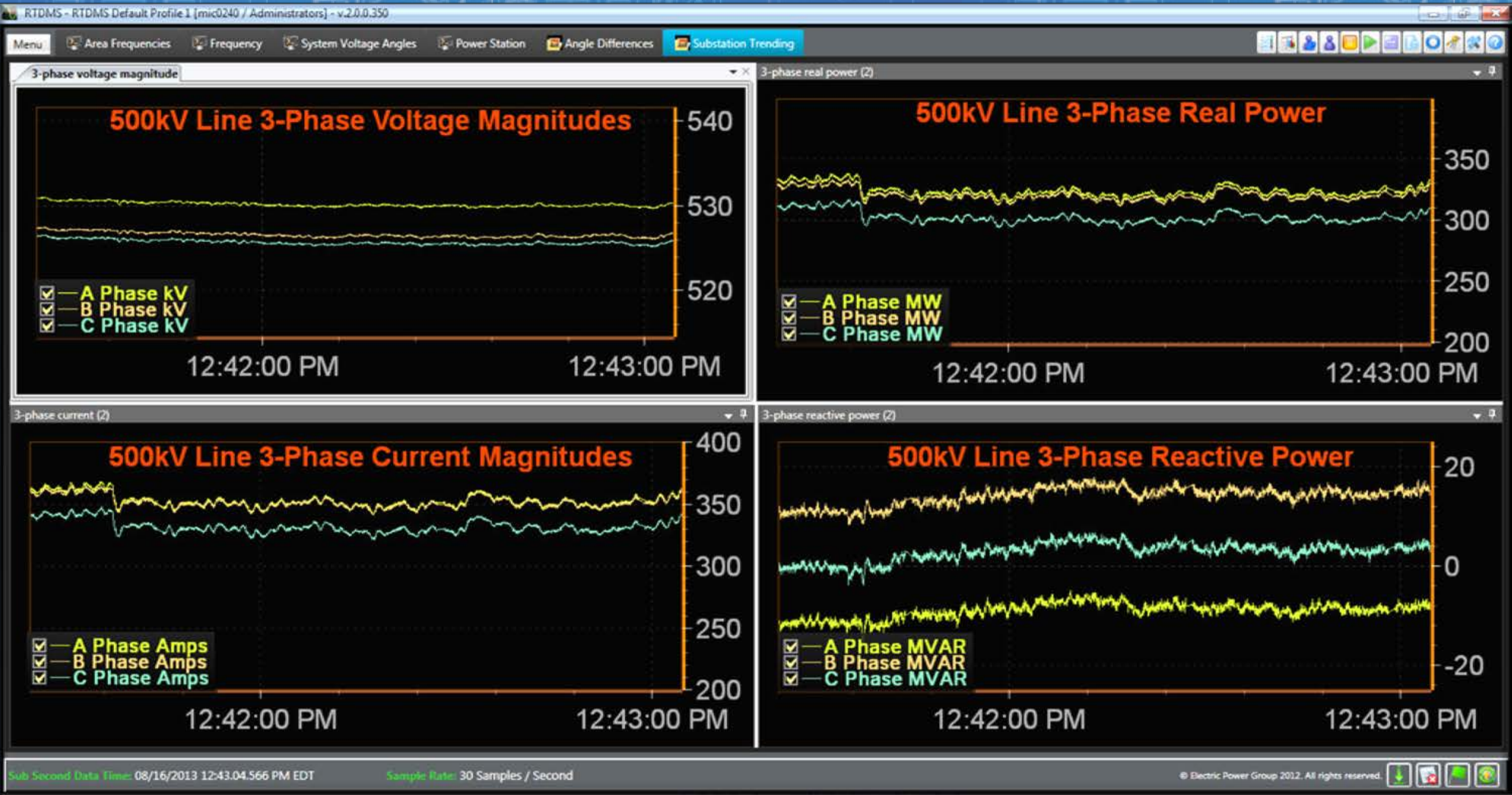
Visualization

Provide simple & intuitive ways to present new data

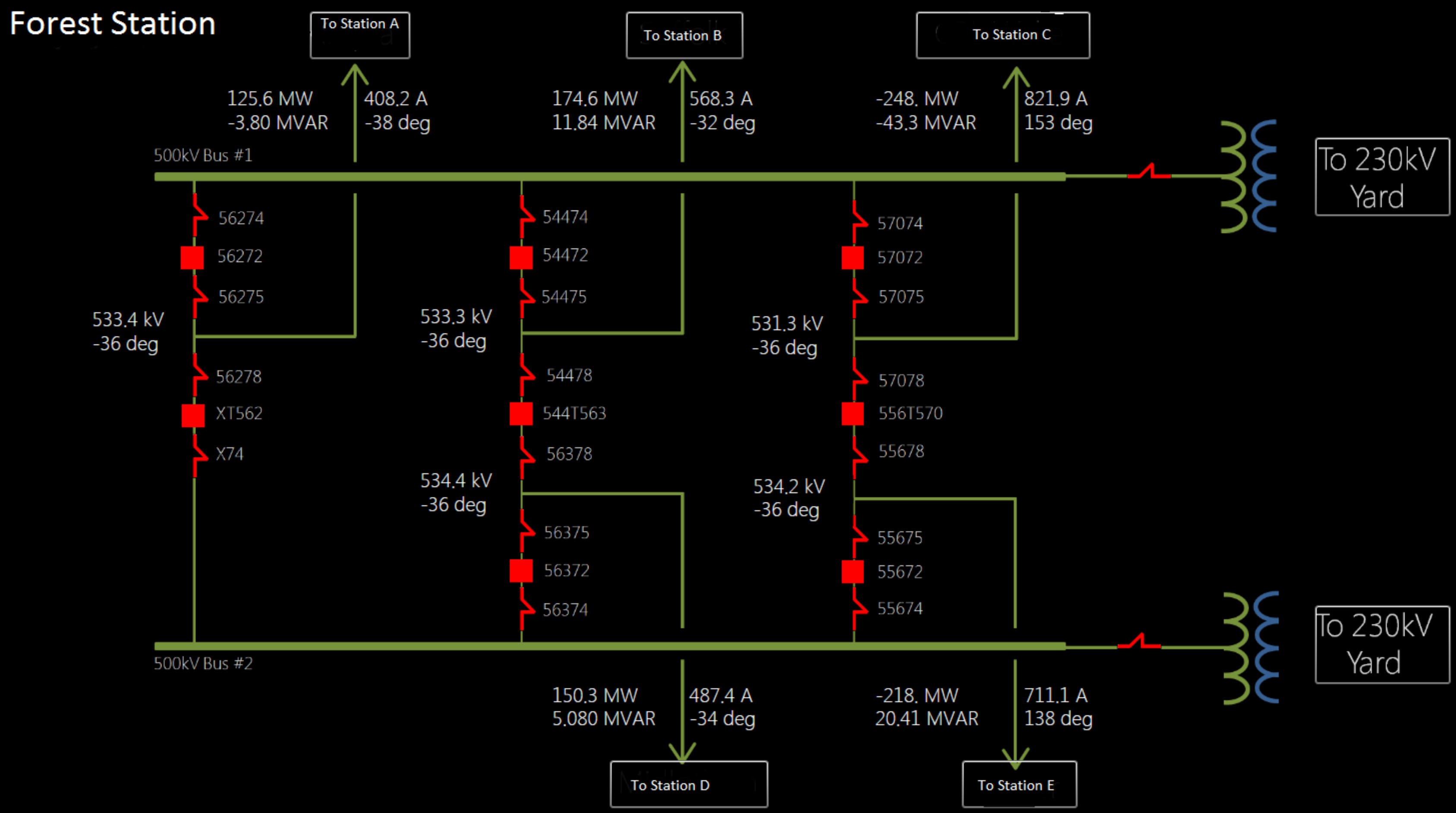
- Trending & stripcharts through RTDMS
  - Voltages, line flows, system frequency, angular separation
- One-line switching diagrams
  - Mirror EMS navigation
  - Human factors: zero learning curve
- Accessibility
  - Leverages Enterprise data connection
  - Flexibility during time of need



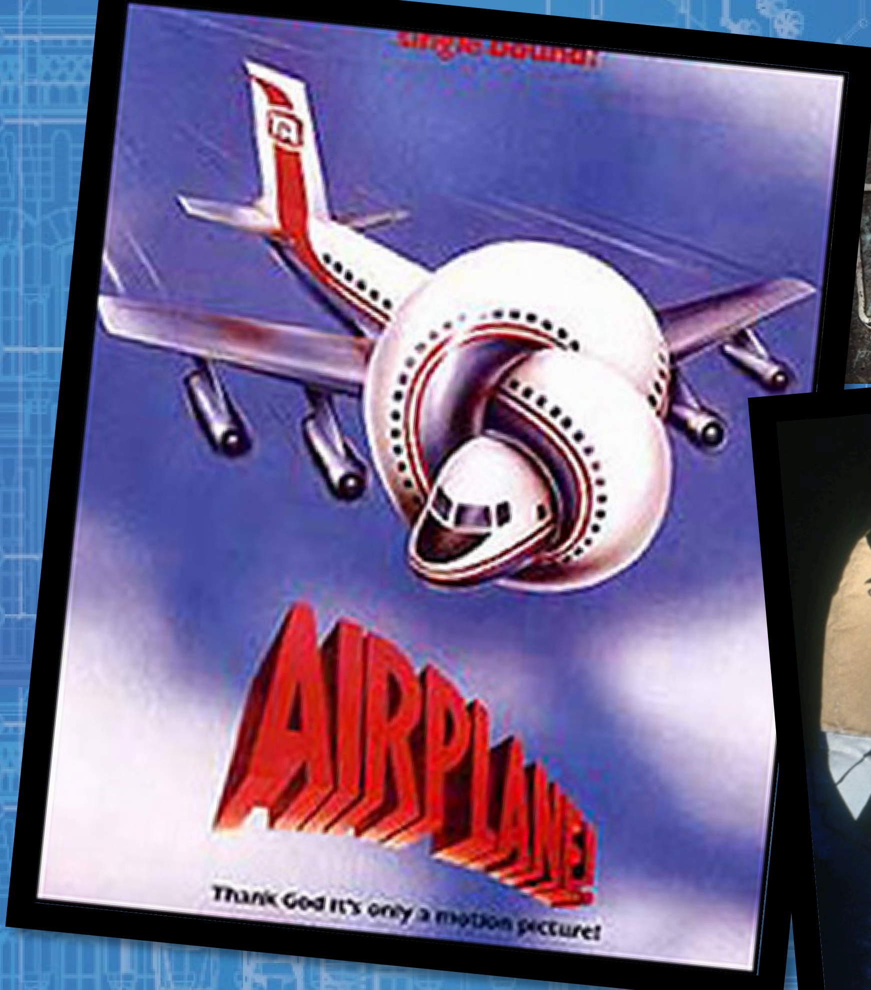
RTDMS Trending



SCHEMATIC ONE-LINES



Visualization: Not just for your control room

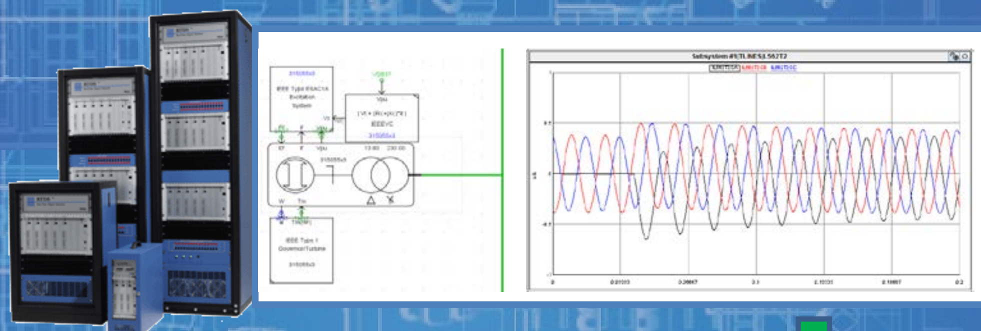


Myth #5 → I can’t fly this plane!

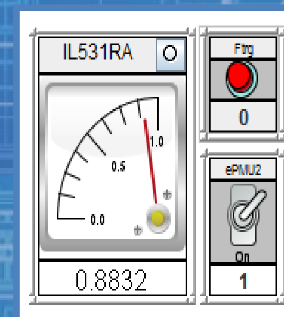
“My operators won’t know what to do with information provided from synchrophasors”

Synchrophasor Training

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



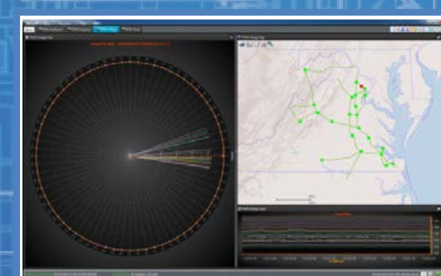
Electromechanical & Electromagnetic Dynamics



Operator-In-Loop Runtime Controls

Closed-Loop Relay/PMU Interface

Virtual PMUs Streaming Data



Visualization Software

Dominion's RTDS Lab & OTS

Dominion's RTDS Lab & OTS

Synchrophasor Proof of Concept (POC) Facility

Instrumental in gathering the knowledge to provide the industry with direction and a fast track process for maturing the standards such as the IEEE C37.118.2, C37.238, C37.242, C37.244, and IEC-61850-90-5

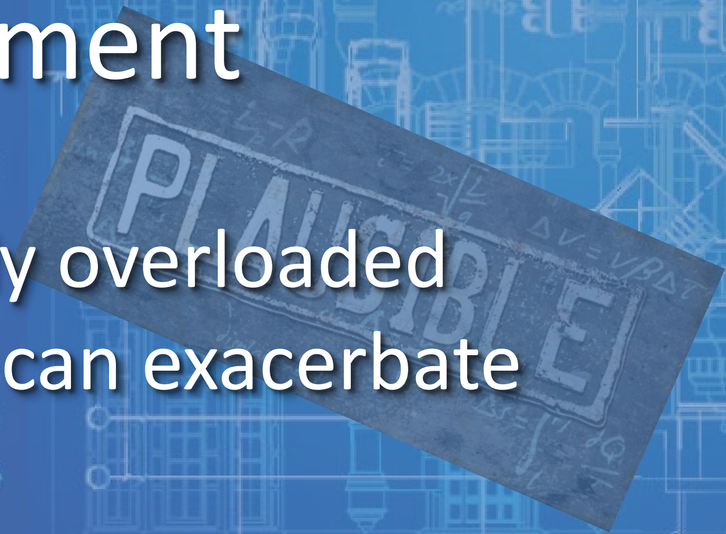
Partnership and Collaboration

- Risk management: Identifies and remedies product and system integration issues
- A conduit to the industry standards
- Tests have resulted in:
  - Identification of standards' gaps
  - Remedied integration issues with potential
    for serious delays during field installation
- Fine tuning applications for functionality and performance
- Transition from development to operation for training future users

Myth #6 → Alarming

"Synchrophasors will ALARM my operators 30 times a second!"

Alarm Management



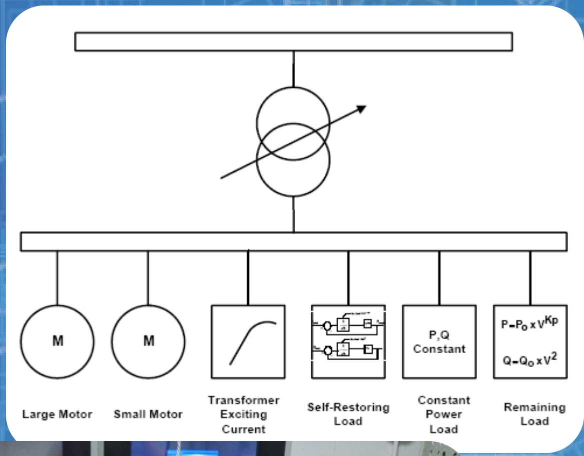
- "System operators are already overloaded with alarms, synchrophasors can exacerbate the problem."
- Alarm overload isn't a synchrophasor problem – it's an alarm problem.
- Same issue with SCADA alarms
- Intentional management of data needed during construction, maint., and testing
- Intelligent alarming

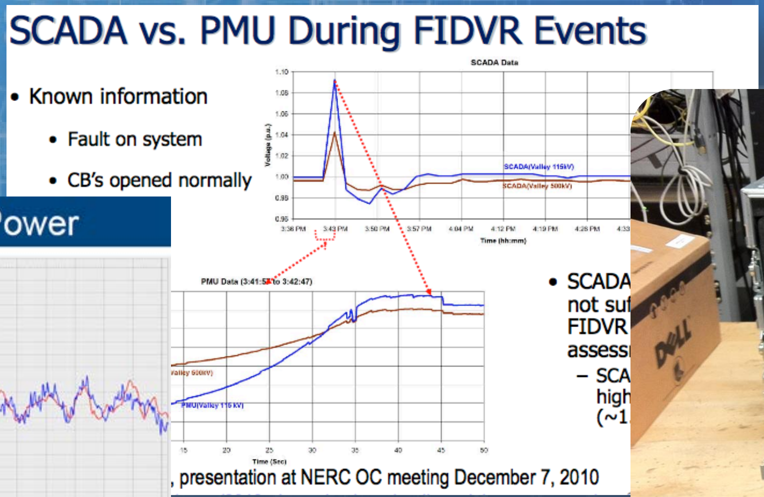
Myth #7 → The Grass is always Greener

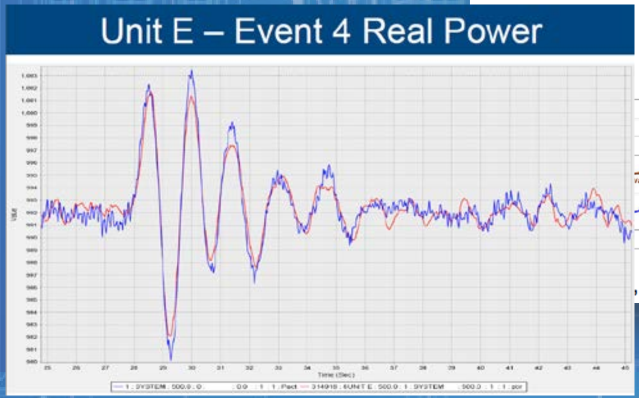
"Synchrophasors are only valuable to _____ And not for ME"

Model Validation (one of many)

- "Synchrophasors won't do anything for modelers"
- Empirically determined impedances
- Generator model validation
- Load composition modeling
- FIDVR

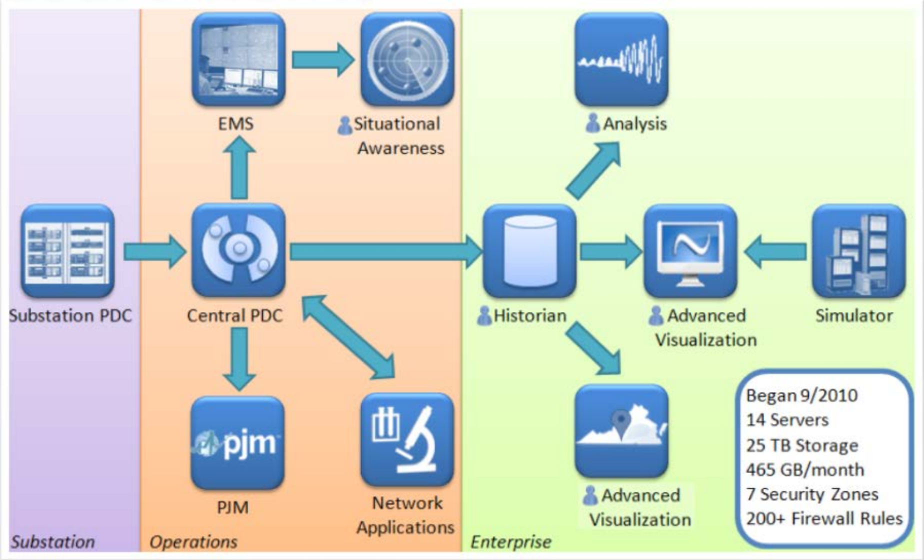






Enhanced EMS Functionality with PMUs

- Improved State Estimator Performance Through:
  - Link from Synchrophasor Data Systems to EMS
  - Estimated P&Q from LSE as SCADA psuedo-measurements
  - Empirically determined impedance values
- Additional frequency measurements
- Oscillation detection & monitoring

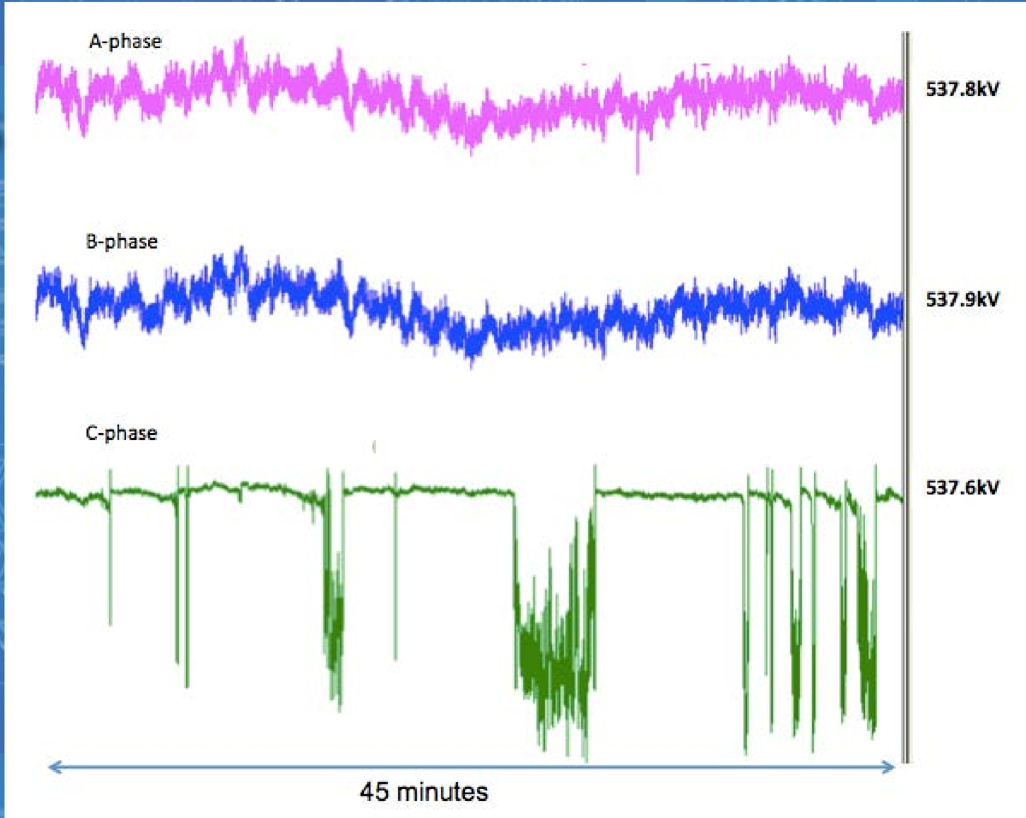


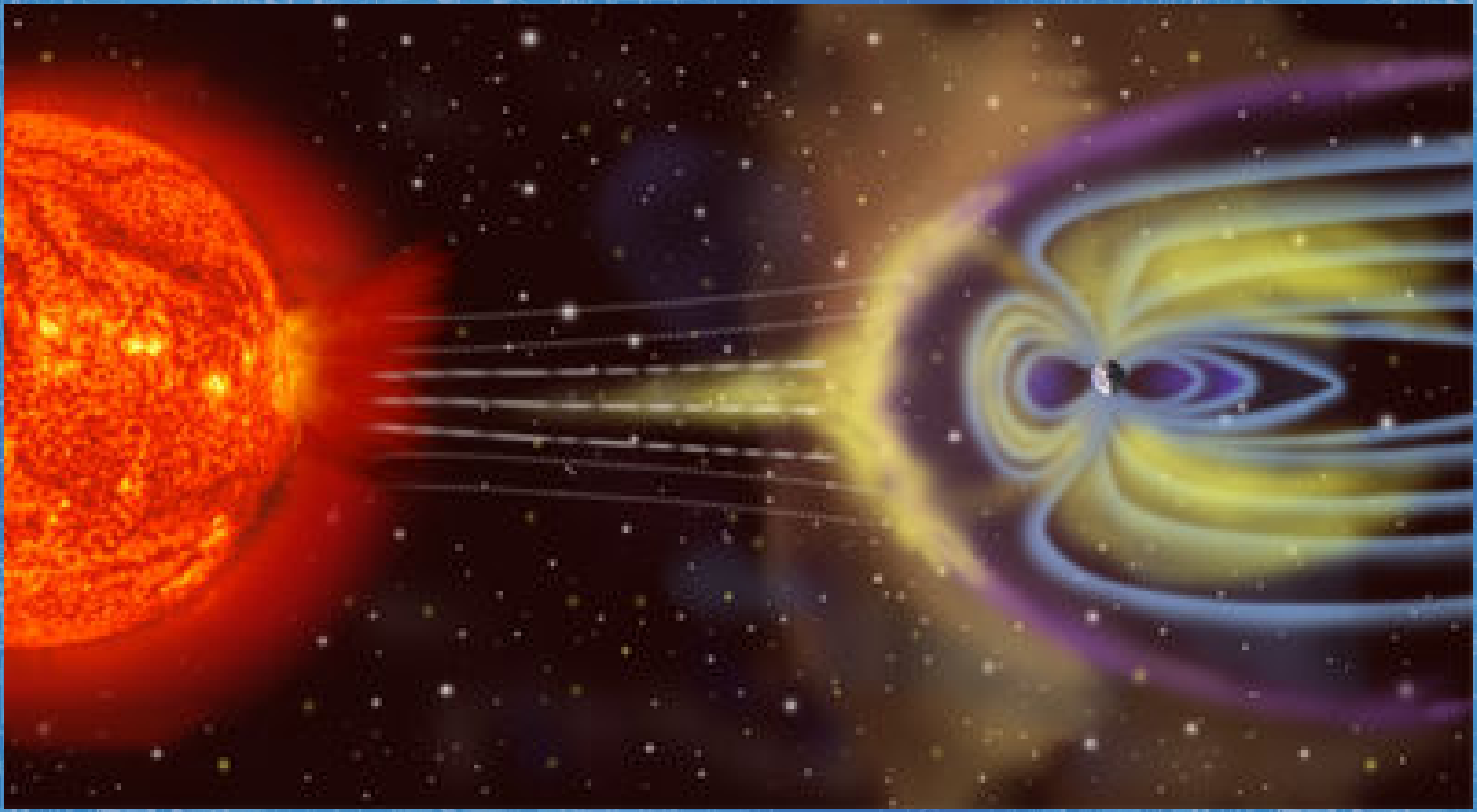
Myth #8 → No aid for assets

"Synchrophasors may be great for planning and operations but not for us equipment specialists and asset managers."

Abnormal Behavior Clearly Visible

- "I can't use synchrophasor data for asset health."
- High-resolution of synchrophasor data can be used to identify failing equipment.
- CCVT failure evident in synchrophasor data days before relay alarm.
- Signal-to-Noise ratio helpful for identifying abnormality



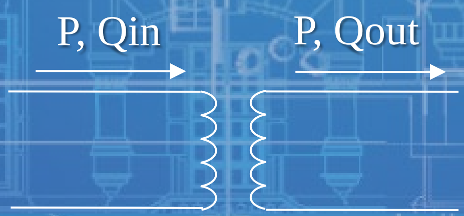


Myth #9 → Geomagnetic Disturbances

"Detecting geomagnetic disturbances and measuring geomagnetically-induced current requires special instrumentation."

GMD: Monitoring with PMU's

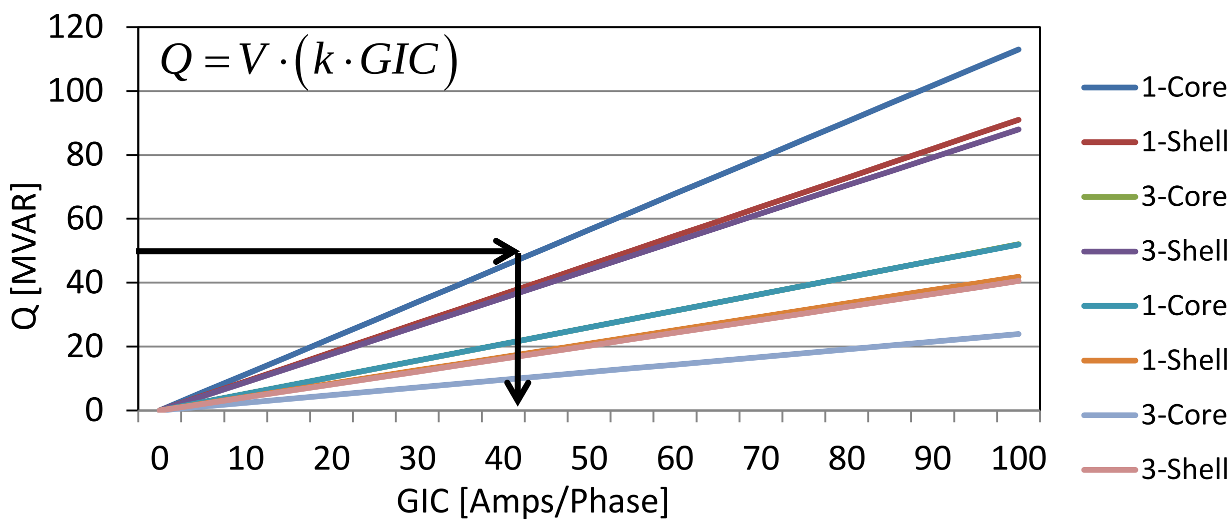
- "Synchrophasors are no help when it comes to the sun."
- Relationship: Q vs. GIC (effective)



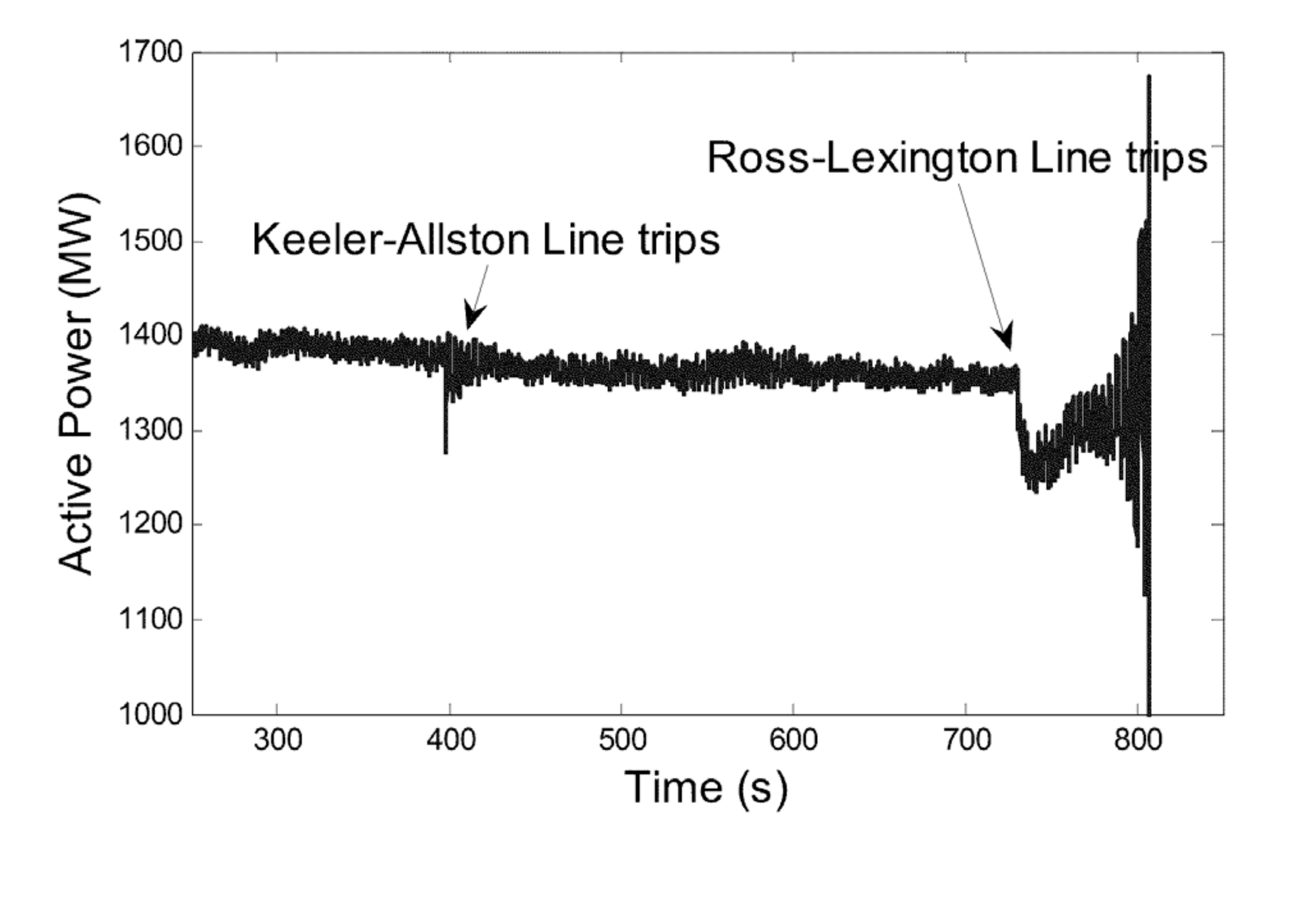
$$Q_{TX} = Q_{IN} - Q_{OUT}$$
$$Q_{TX}^{*} = I^{2} \cdot X$$

Normal State: $Q_{TX} = Q_{TX}^{*}$

GMD: $Q_{TX} \neq Q_{TX}^{*}$



Emanuel Bernabeu

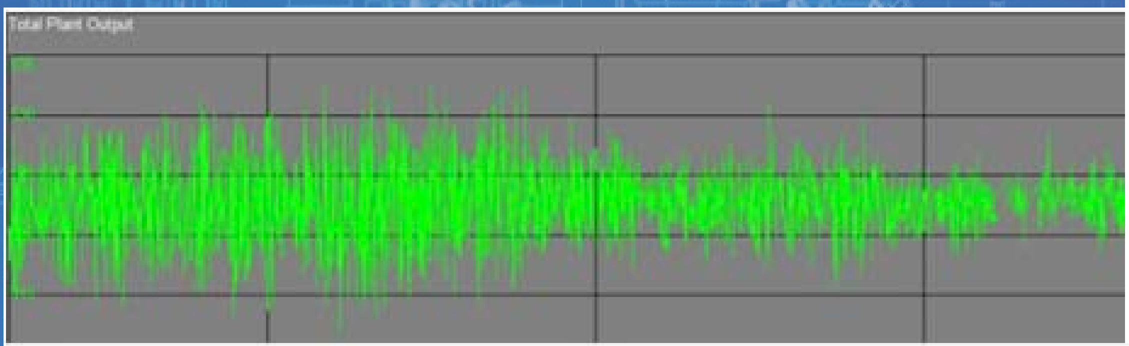


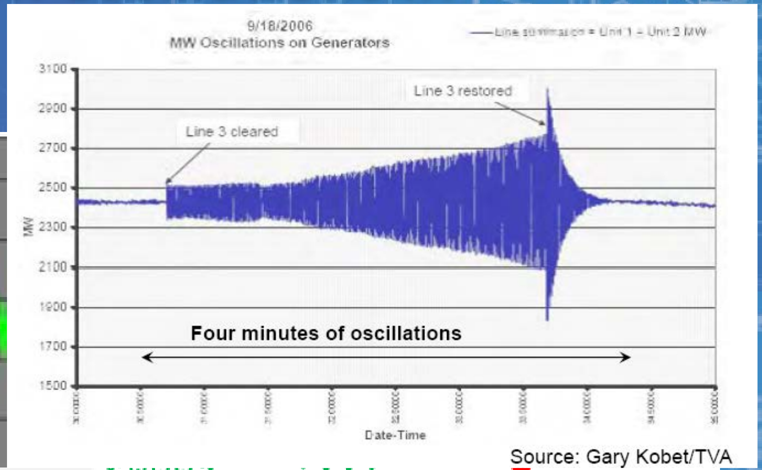
Myth #10 → Oscillations?

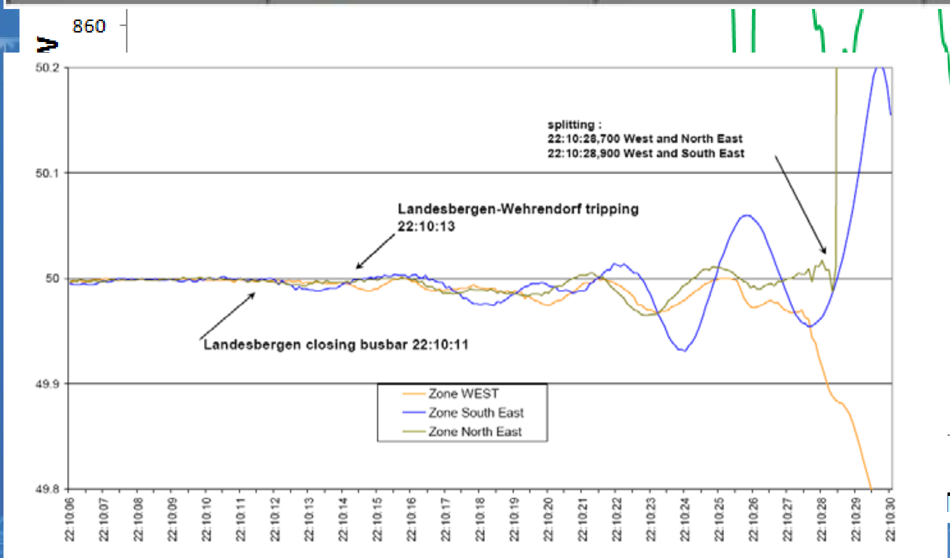
"Oscillations only occur in _____ and not in my interconnection"

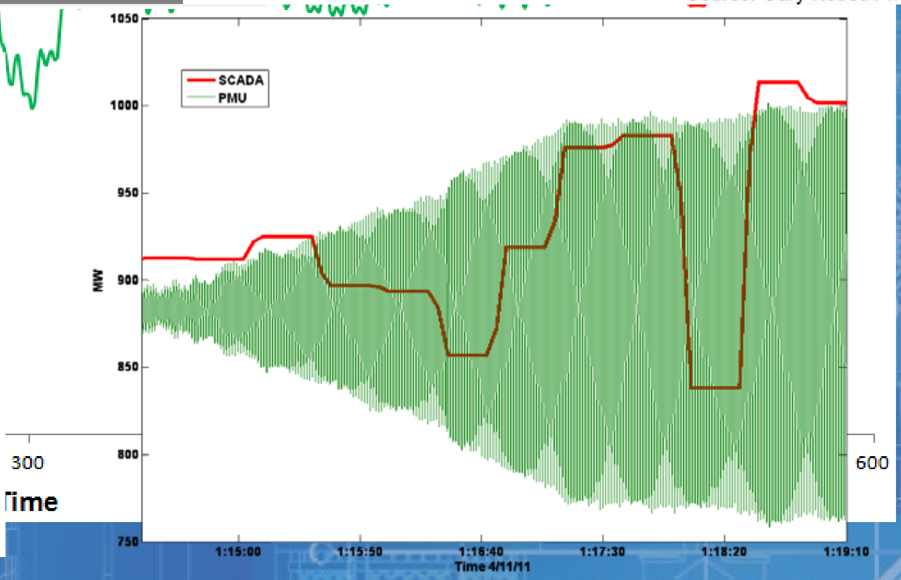
Oscillations

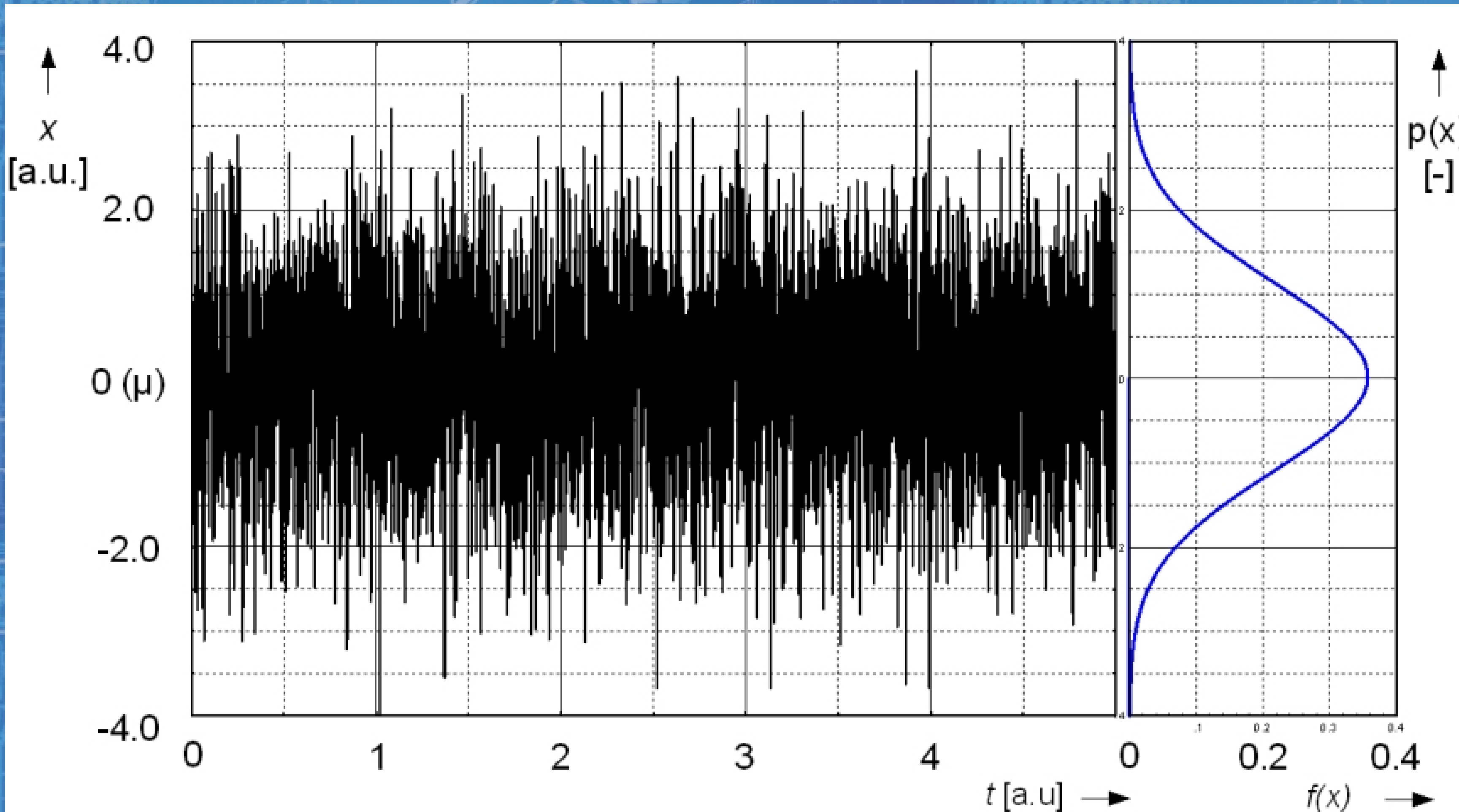
- "Oscillations are a WECC thing."
- Numerous examples of power system oscillations in interconnections around the world.









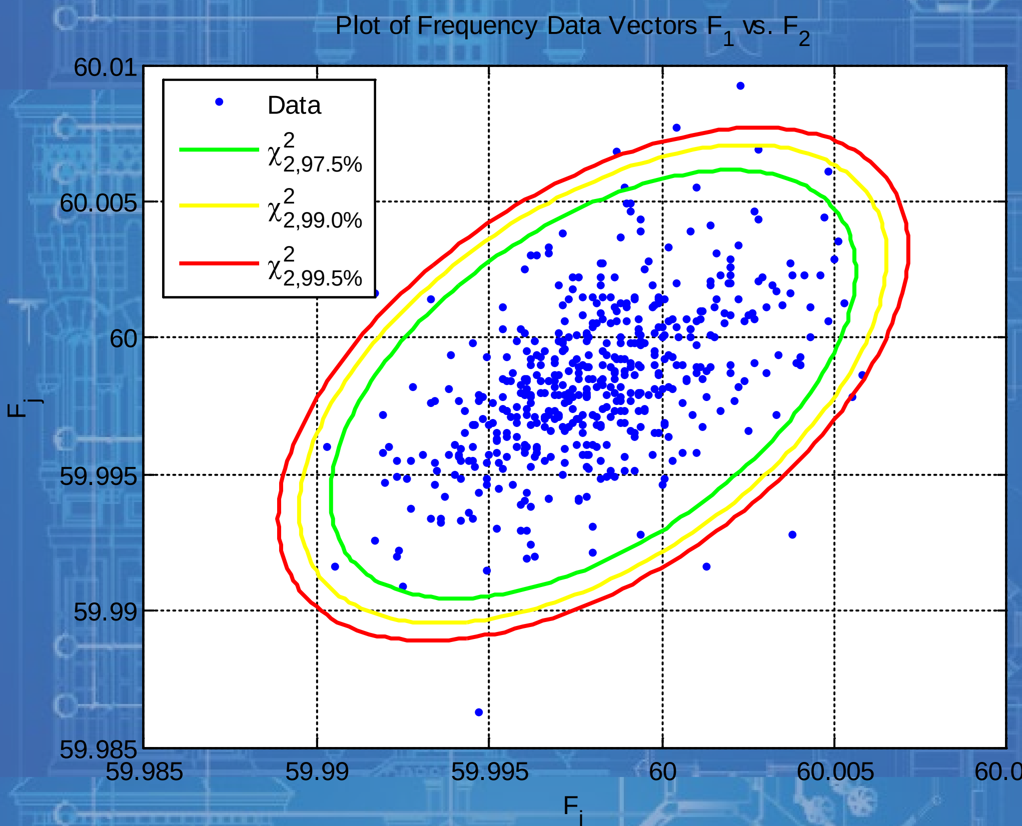


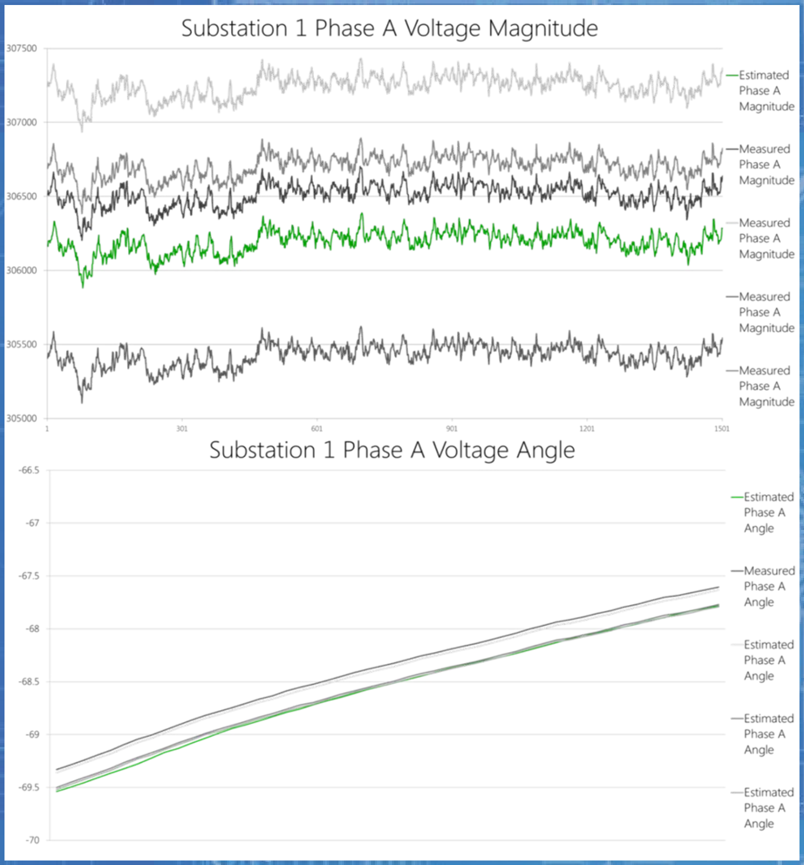
Myth #11 → All in the Noise…

"Synchrophasor data is just too noisy."

Noise vs. Need

- “The data is too noisy to use.”
- Higher resolution data appears “fuzzier” because the data contains more information. The issue becomes discriminating between important and unimportant information.

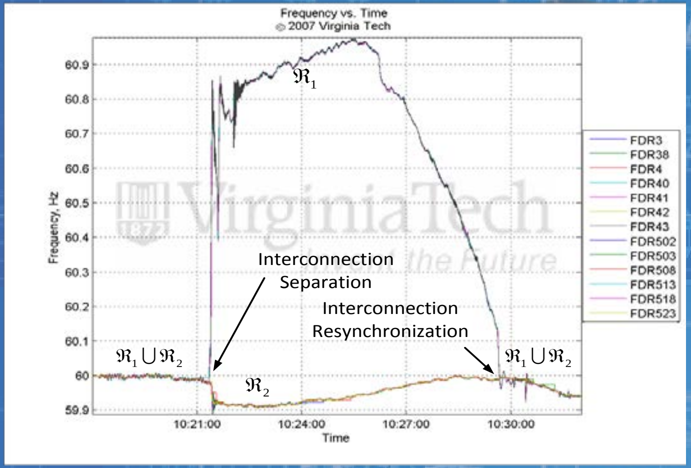


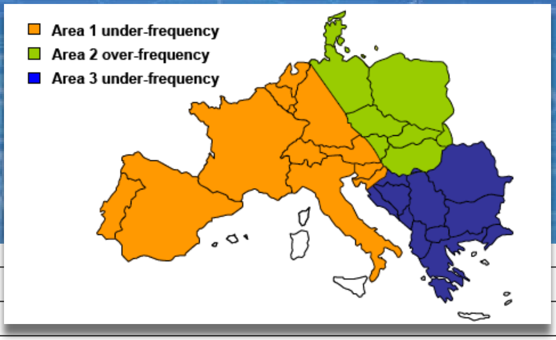


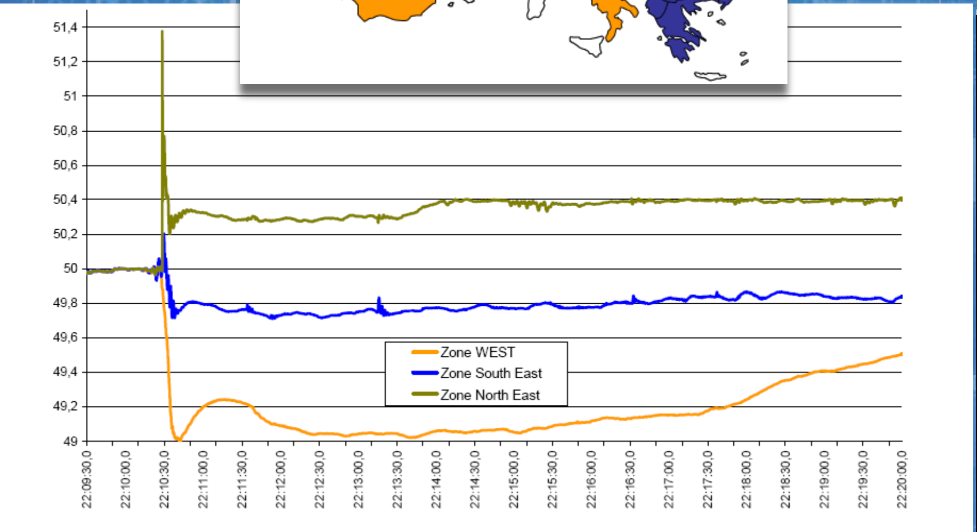

Myth #12 → Interconnection Islanding
“Islands are academic.”

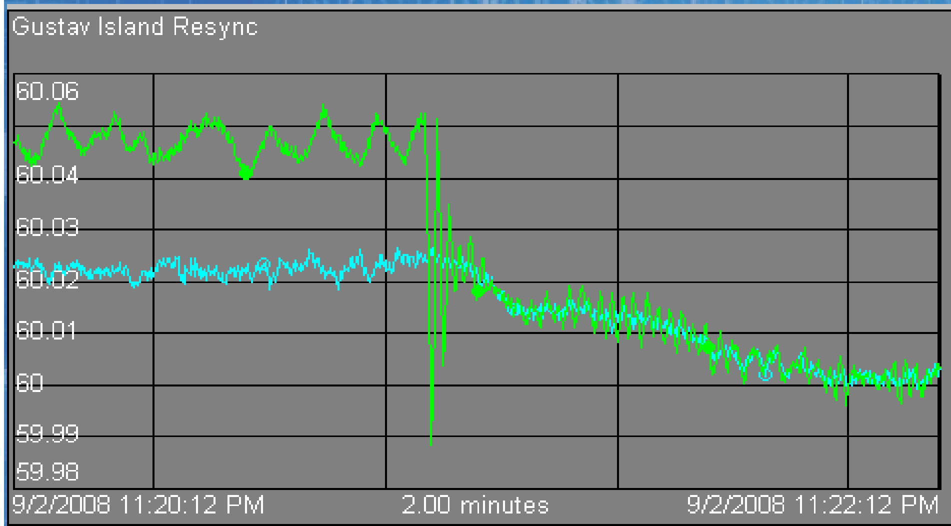
Islanding

- "Interconnections rarely break apart and when they do, they fall apart."
- Europe: 2006
- MRO/Eastern Interconnection 2007
- Entergy 2008







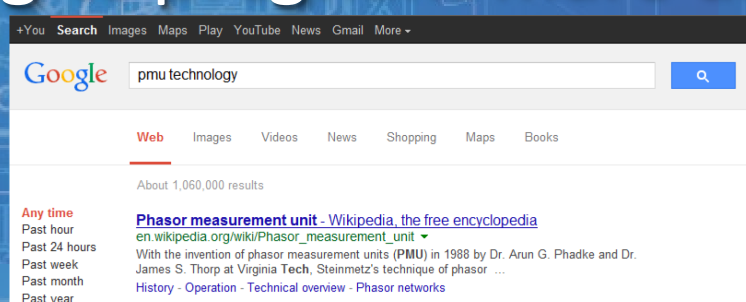


More Myths

- Synchrophasors are solutions looking for a problem

- NASPI stands for Not A Single Practical Application

- Synchrophasors are SCADA on steroids
- "Googling" PMU technology will return results pertaining to pregnant mare urine.



Benefits: Market Operations

- Congestion management: Accurate detection of Nominal Transfer Capability (NTC) based on thermal, voltage, or stability limitations
  - Improved reliability
  - Better use of transfer capability and avoidance of lost opportunity dispatch costs (CAISO congestion exceeded $250M USD in 2005)
- Locational Marginal Pricing (LMP)
  - Better accuracy through SE and modeling improvements
  - .5% LMP improvement may impact re-distribution of $70M of settlement costs
    - Thermal limit increase
    - Voltage / Damping inter-area stability limits

Benefits to Rate payers, Utilities, ISO, Power Producers

Key Takeaways

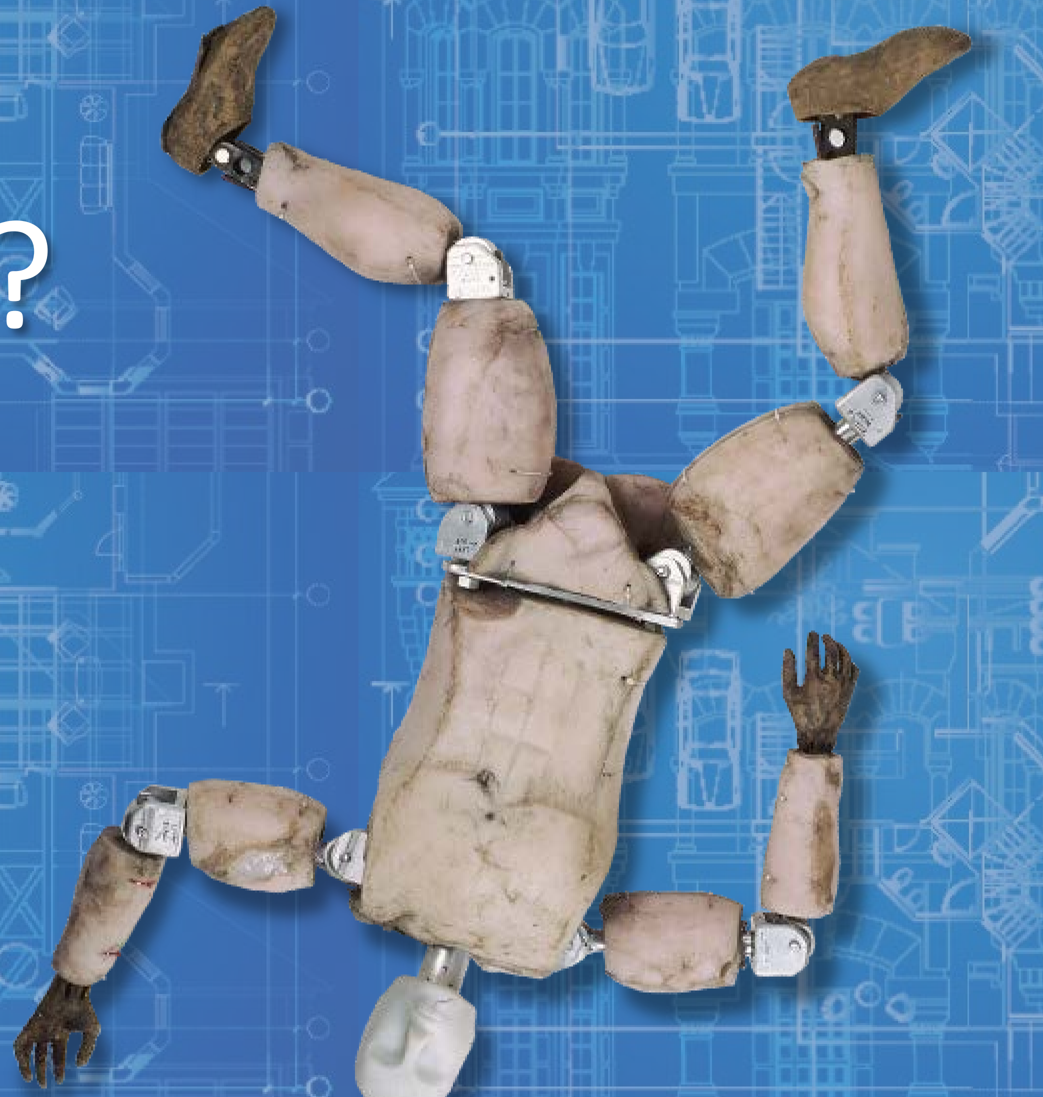
- Synchrophasors are still R&D/sci-fi

- Synchrophasors are only for niche applications

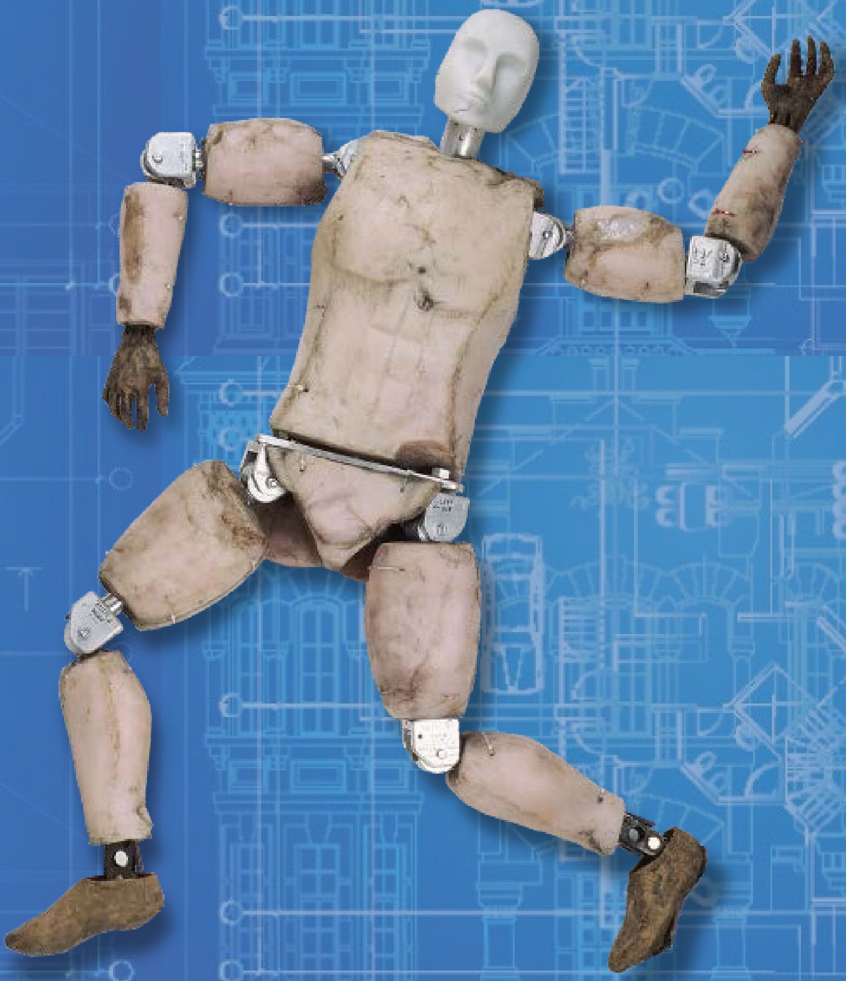
- Synchrophasors have a thin user space

- Wide-area control based on WAMS is only an academic exercise

QUESTIONS?



CONTACT INFO:
R. Matthew Gardner, Ph.D., P.E.
Dominion Virginia Power
Electric Transmission
Operations Engineering
Matthew.Gardner@dom.com



SPECIAL THANKS TO:
Dr. Kevin Jones
Mr. Kyle Thomas
Dr. Emanuel Bernabeu
Dr. Ryan Quint
Dr. Vahid Madani