

IEEE PES DLP

“Managing Uncertainties of the Future Grid”

PMU Synchrophasor Solutions at EMS Control Centers

Part 2 of 2

Athens, July 8th 2016

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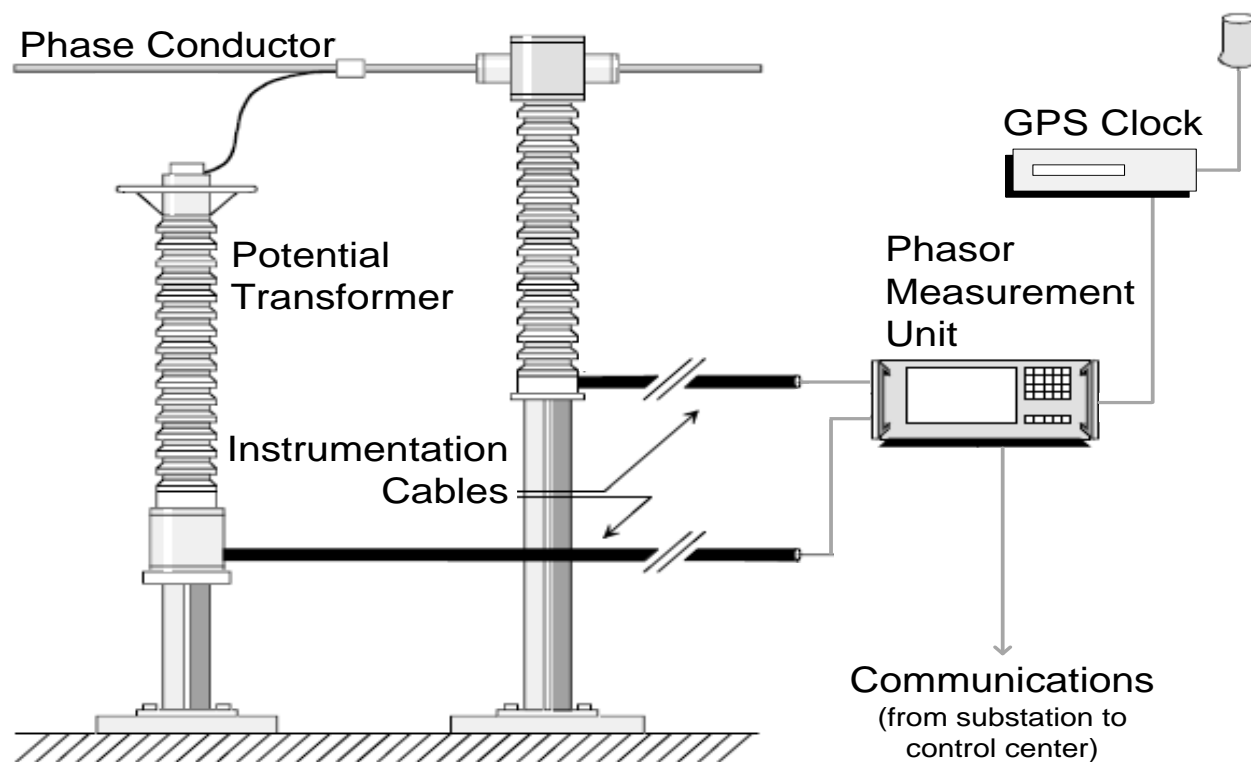
Agenda

1. Overview of the Power Grid
2. EMS – Genesis & Evolution
3. EMS Trends Today
- 4. Synchrophasor Benefits for EMS Grid Operations**
5. Practical Deployments of Synchrophasors
6. The India Synchrophasor project
7. Evolution Towards a Smarter Grid

Phasor Measurement Unit (PMU)

Invented in '80s

Sudden rapid deployment since 2009

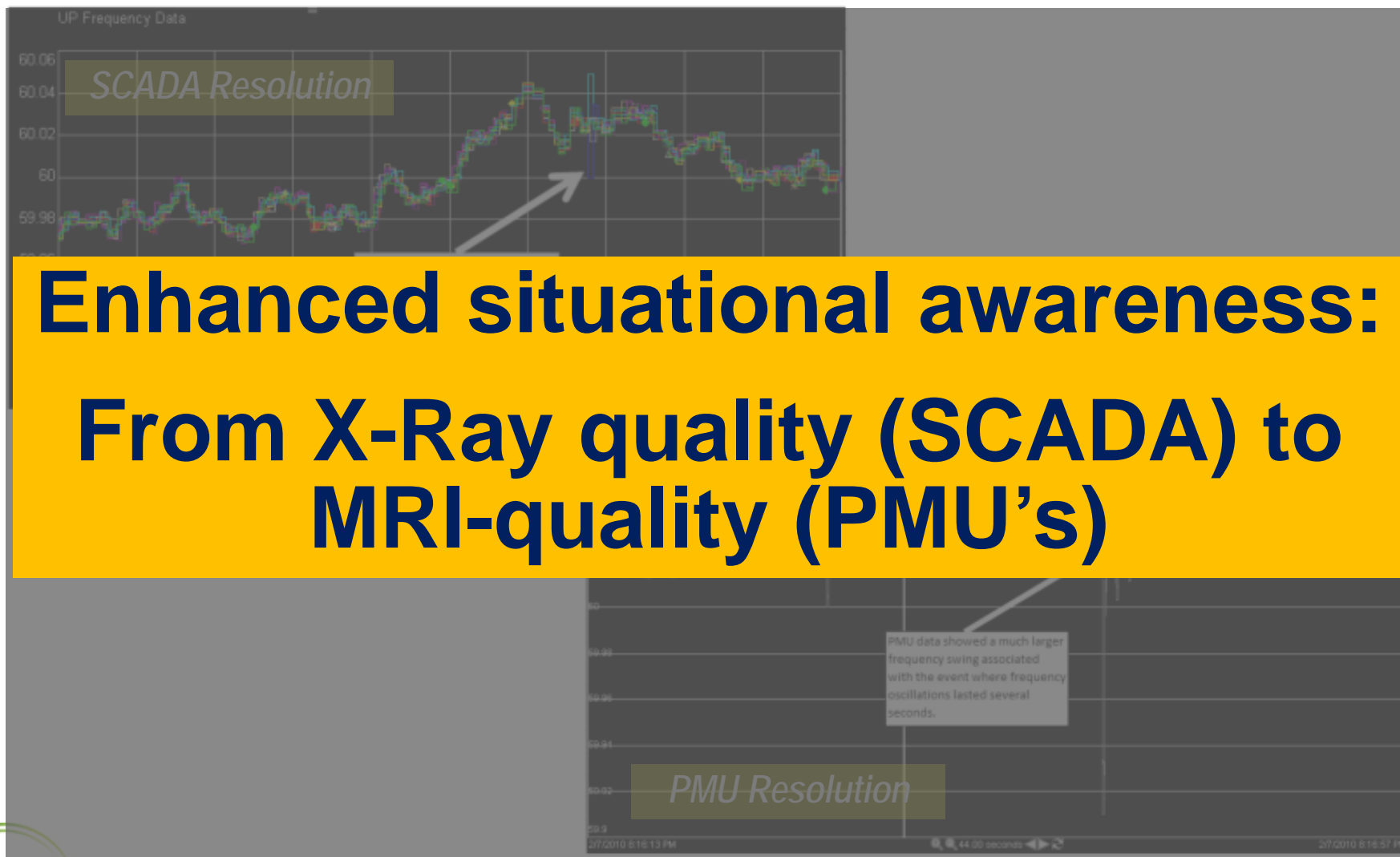




What is SynchroPhasor Technology?

- Synchronous measurements:
 - Voltages, currents:
 - a,b,c phases
 - Positive, negative and zero sequences
 - Frequency, frequency rate-of-change,
 - Status
- Higher resolution sub-second scans
- Precise GPS time-stamping

What is SynchroPhasor Technology?



The New SCADA Frontier

SCADA Data - Today	Phasor Data (PMU) - Tomorrow
Refresh rate 2-5 seconds	Refresh rate 30-60 samples/sec
Latency and skew	Time tagged data, minimal latency
'Older' legacy communication	Compatible with modern communication technology
Responds to quasi-static behavior	Responds to system dynamic behavior
Frequency change means: Sudden Gen-Load MW imbalance <u>somewhere in the grid</u>	Angle-pair change means: Sudden MW change in a <u>specific location of the grid</u>
X-ray	MRI

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**Earlier
Information
for Better
Decisions**

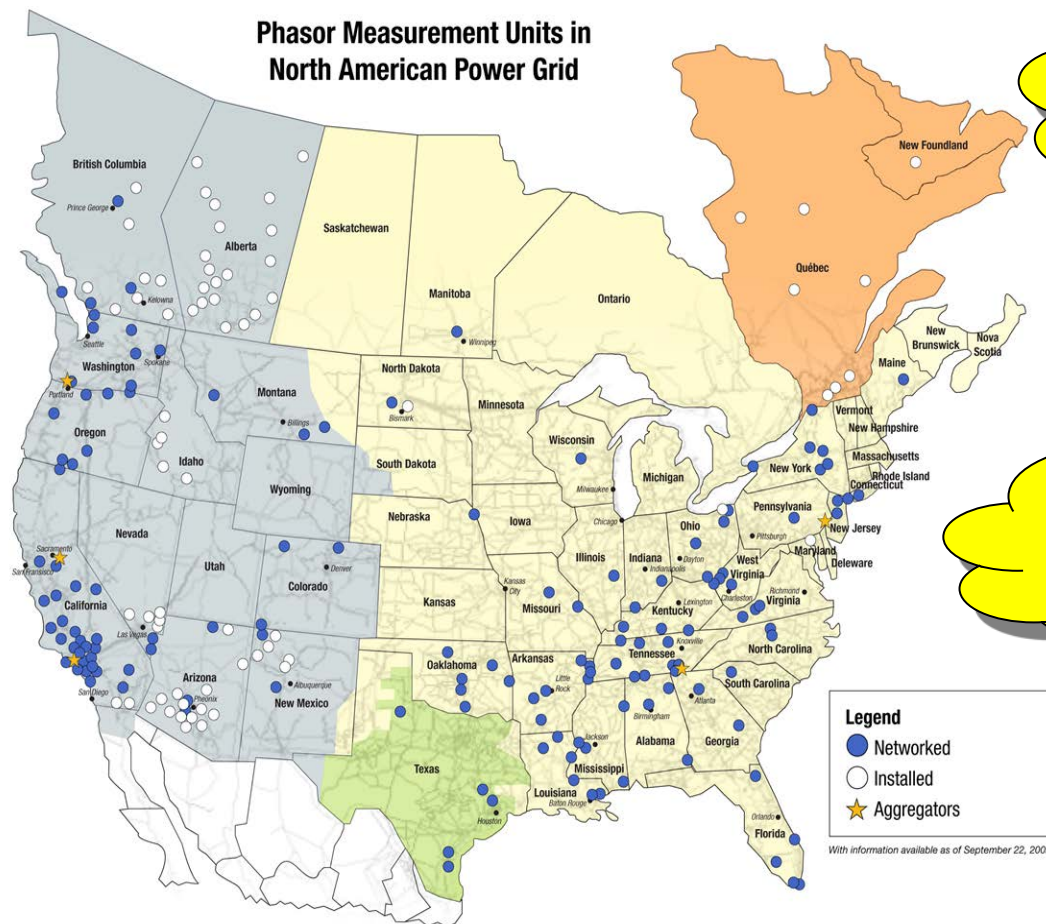
Today's Grid Monitoring landscape is Changing

- Real-time grid measurements will be 50-60 to 100-120 times faster!

“An Unprecedented Transformational Change to help operate the grid more efficiently & reliably - and to facilitate integration of green energy resources”.

DoE Smart Grid Investment Grants Synchronphasor Projects

courtesy DoE, NASPI



\$300M in grants for Synchronphasor projects in 2009!

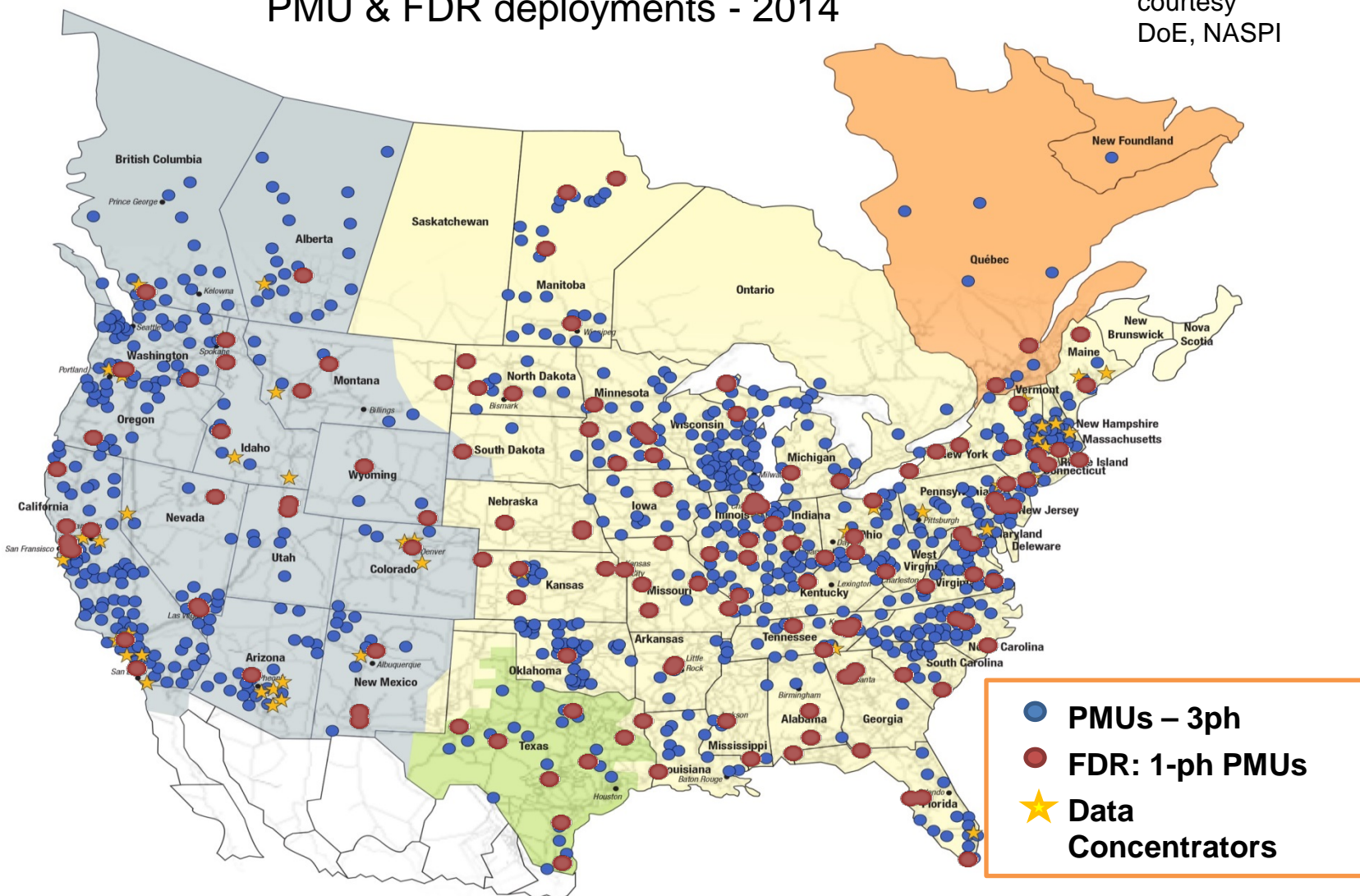
Another \$10M in 2014.

200 PMUs in 2009...

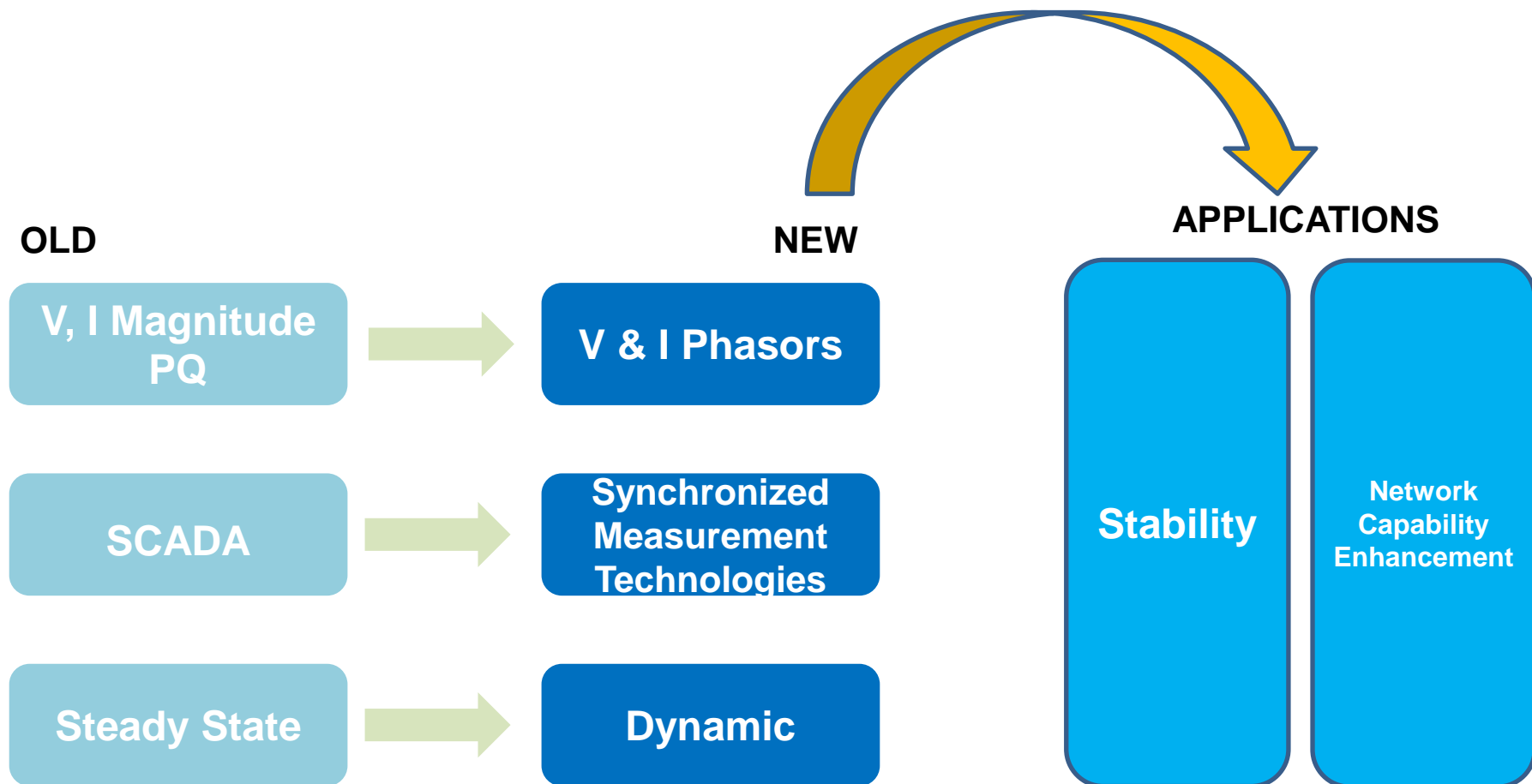
1800+ PMUs by 2015

PMU & FDR deployments - 2014

courtesy
DoE, NASPI

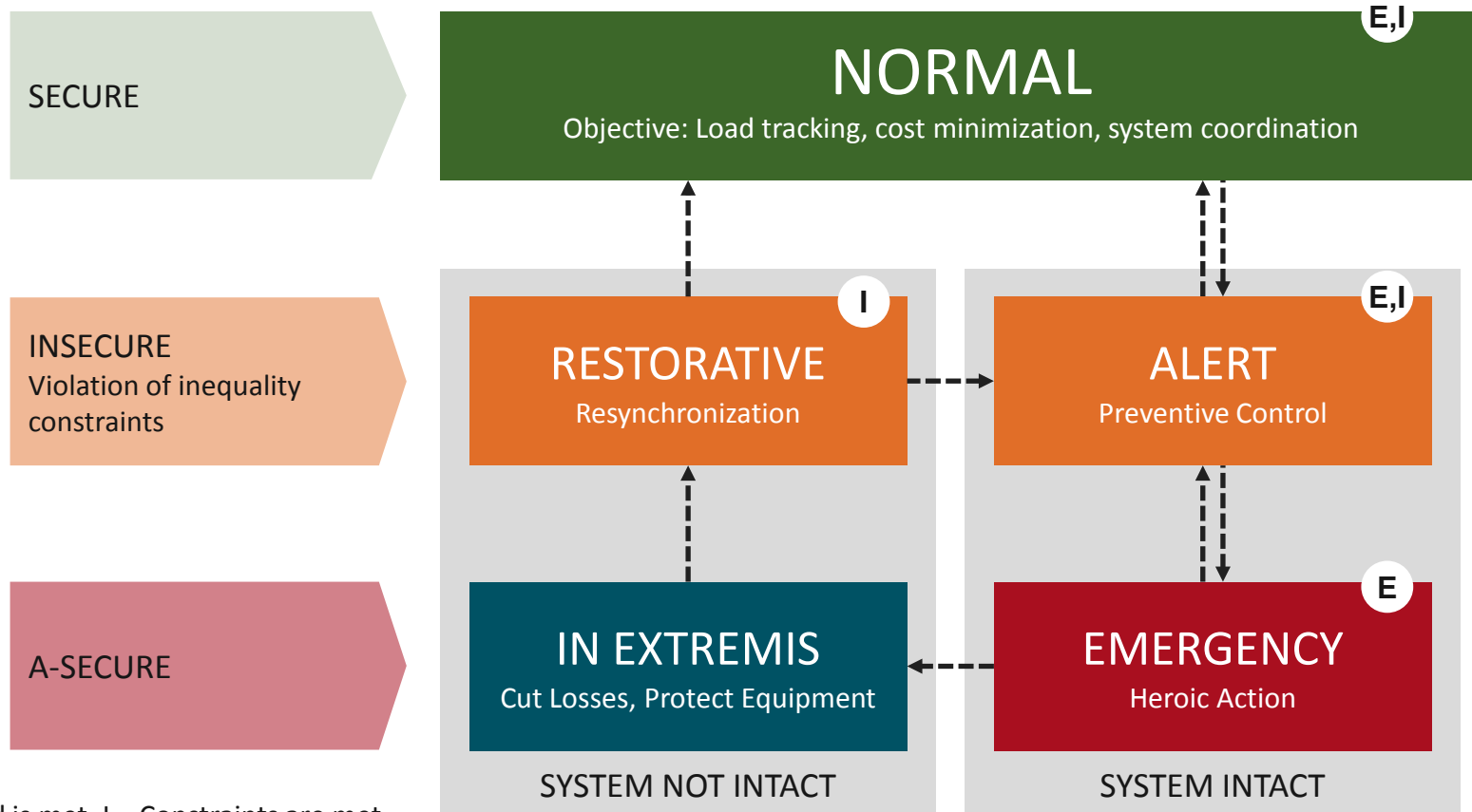


Measurement Evolution



Power System Grid Operating States

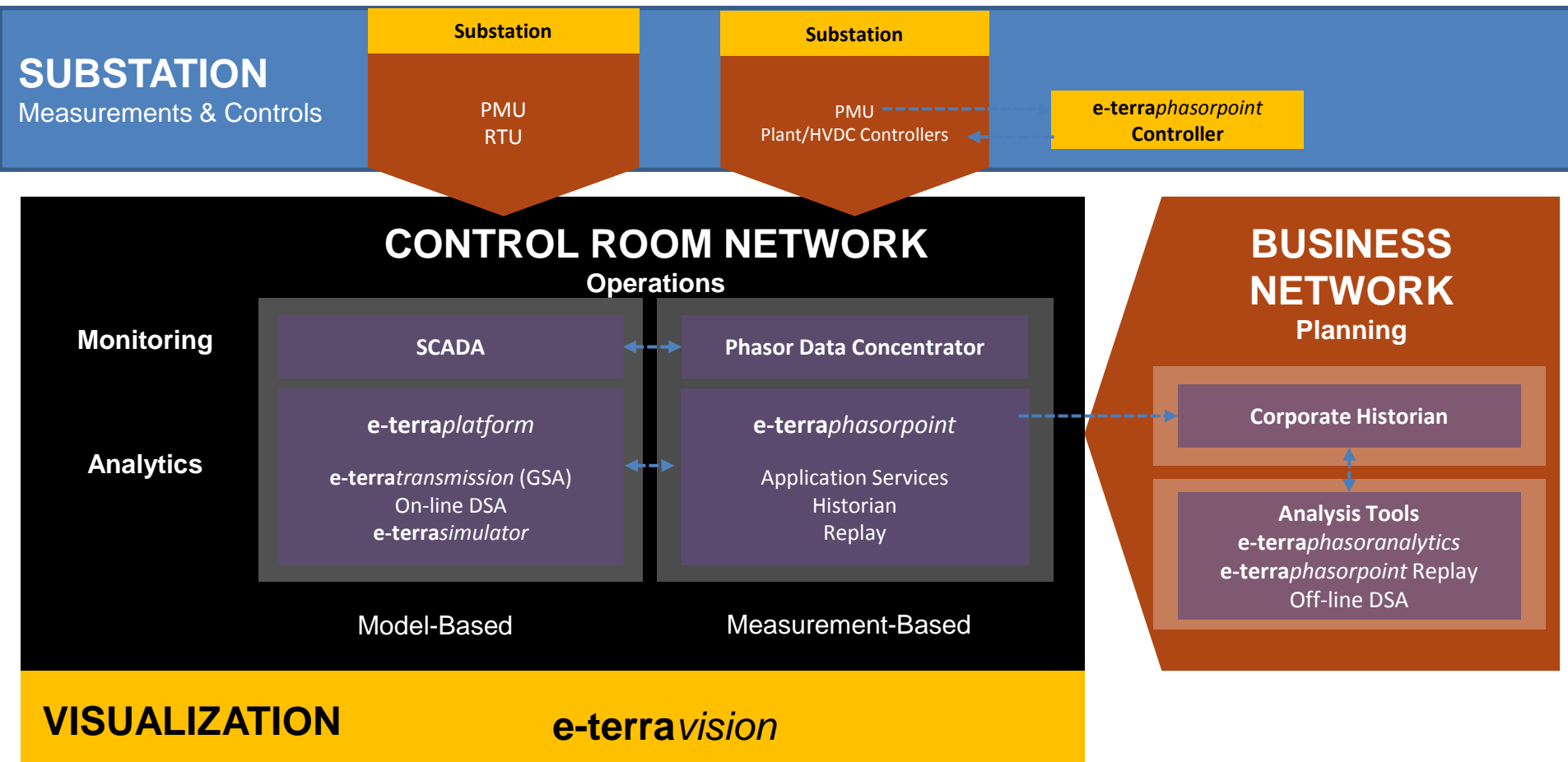
Focus now includes Dynamic Security too!



E = Demand is met, I = Constraints are met

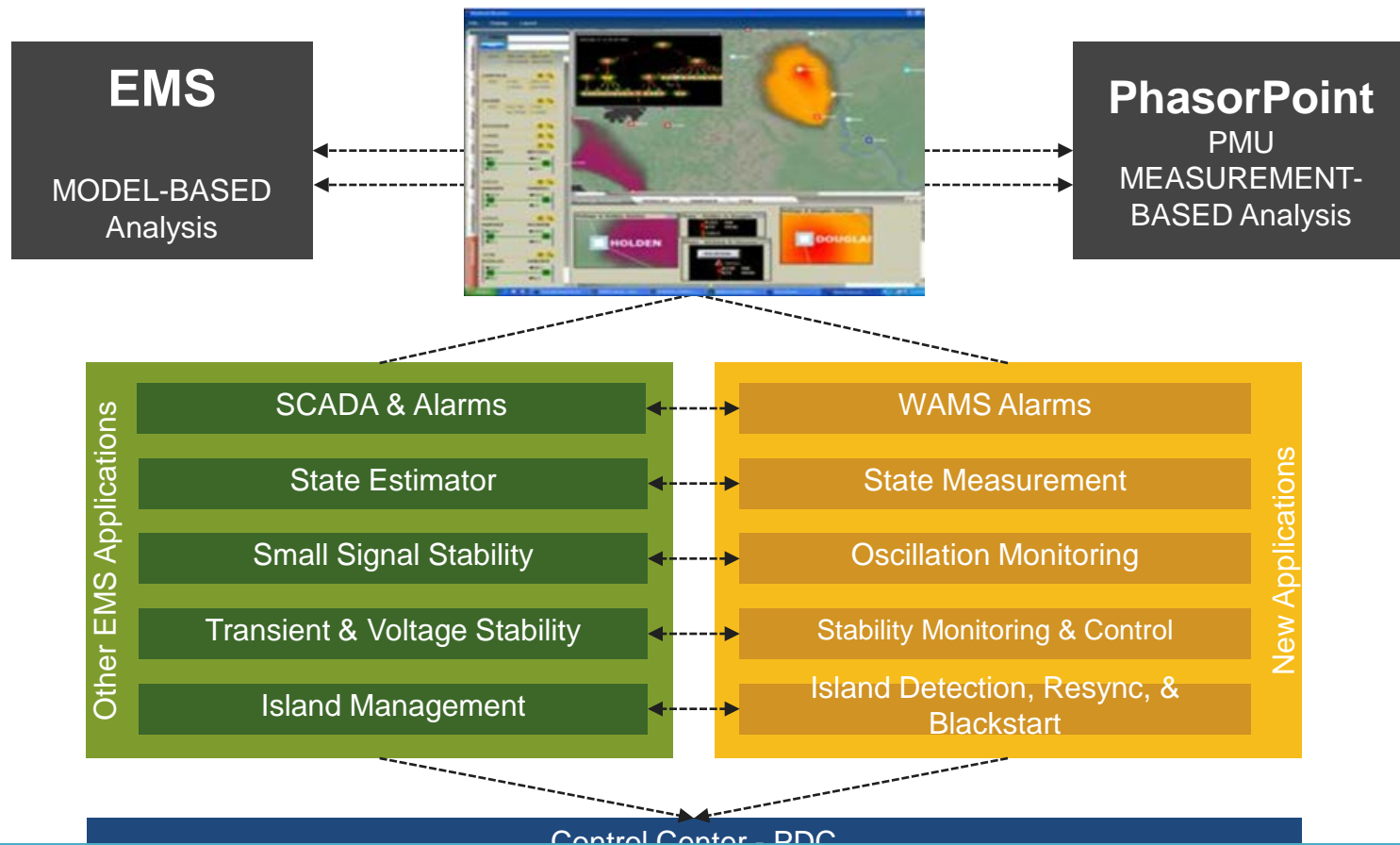
L. Fink, K. Carlsen, IEEE Spectrum, March 1978

Wide Area Monitoring System (WAMS)

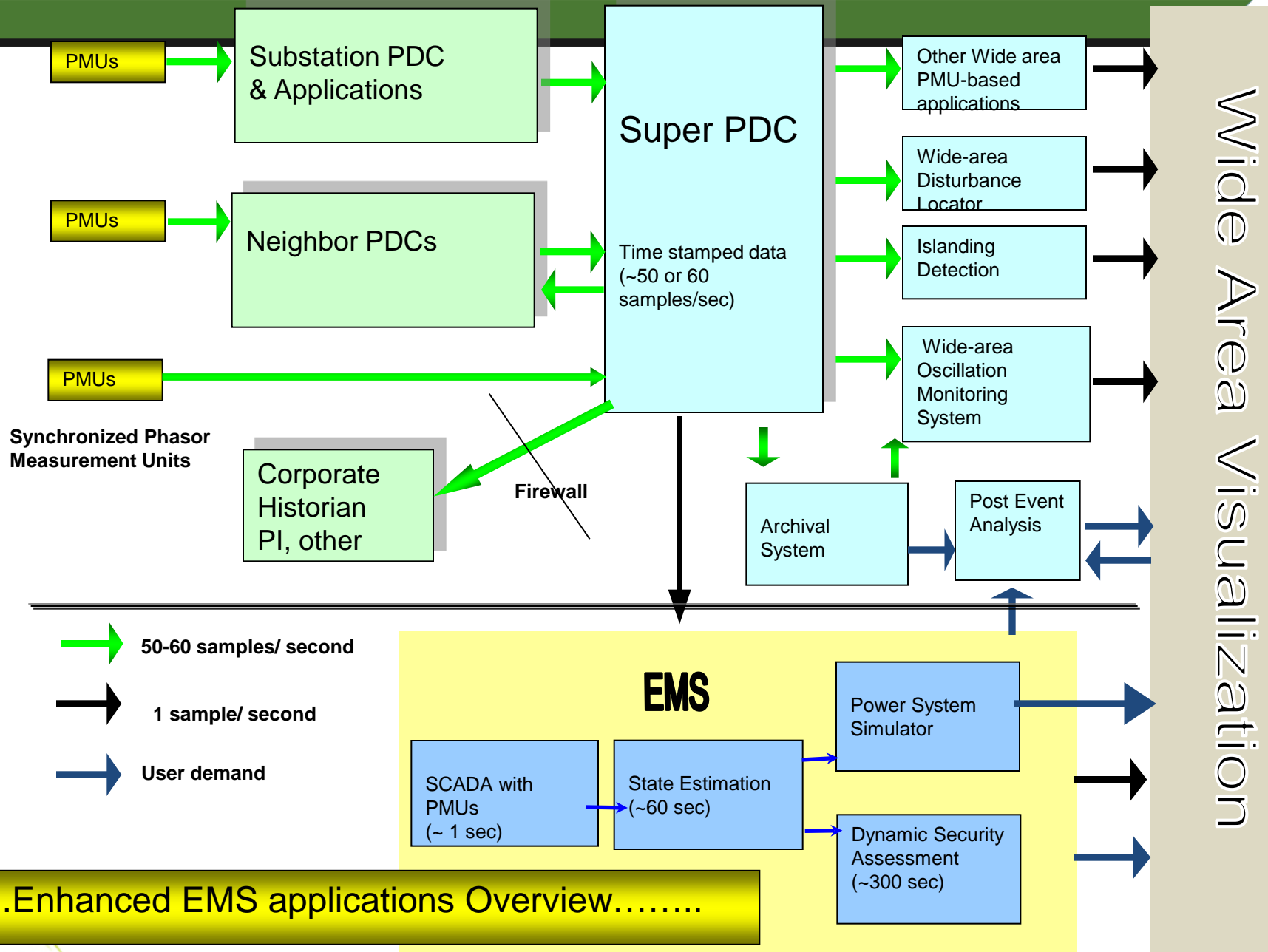


Control Room Operations

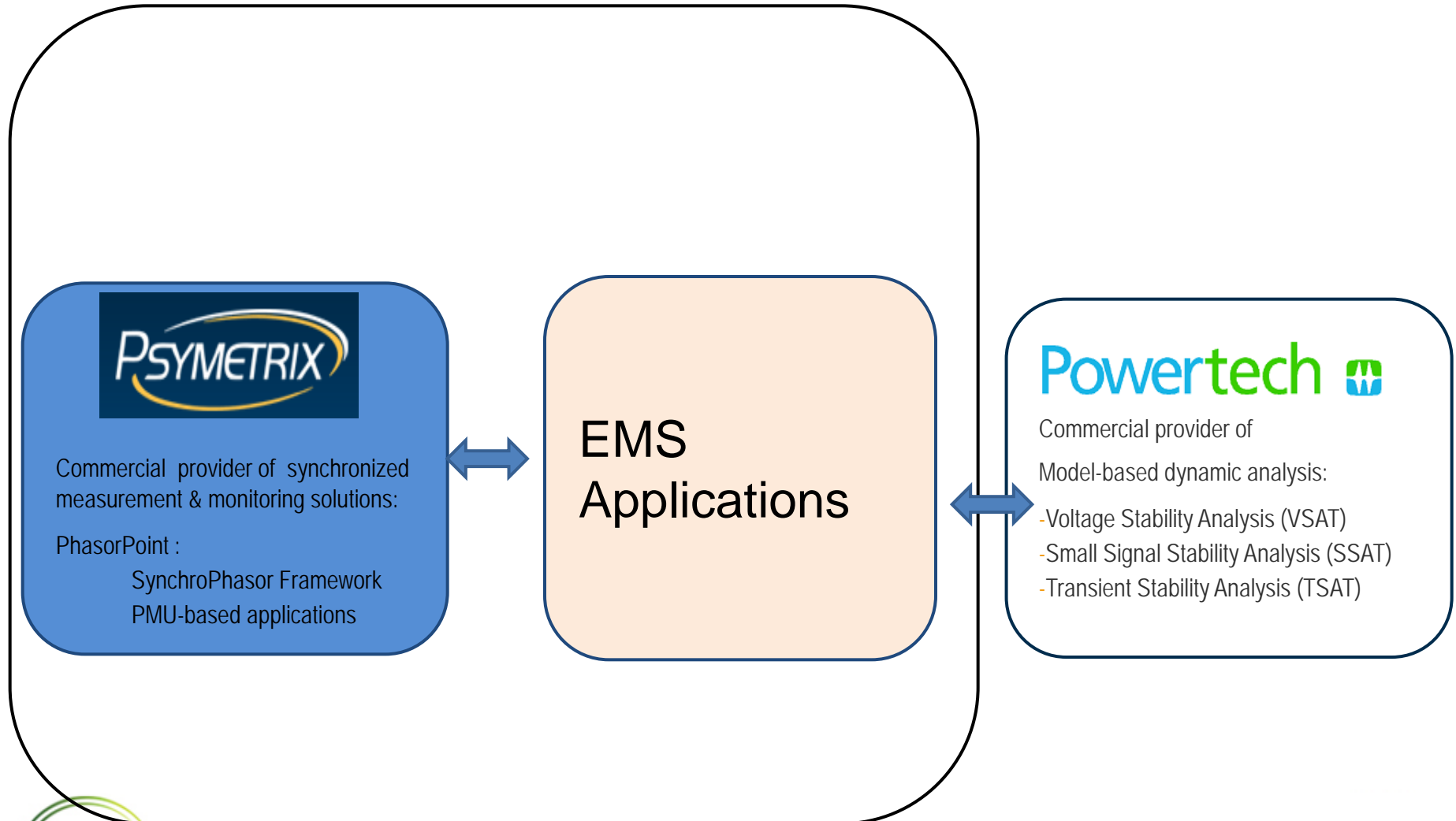
The Next Generation Energy Management System!



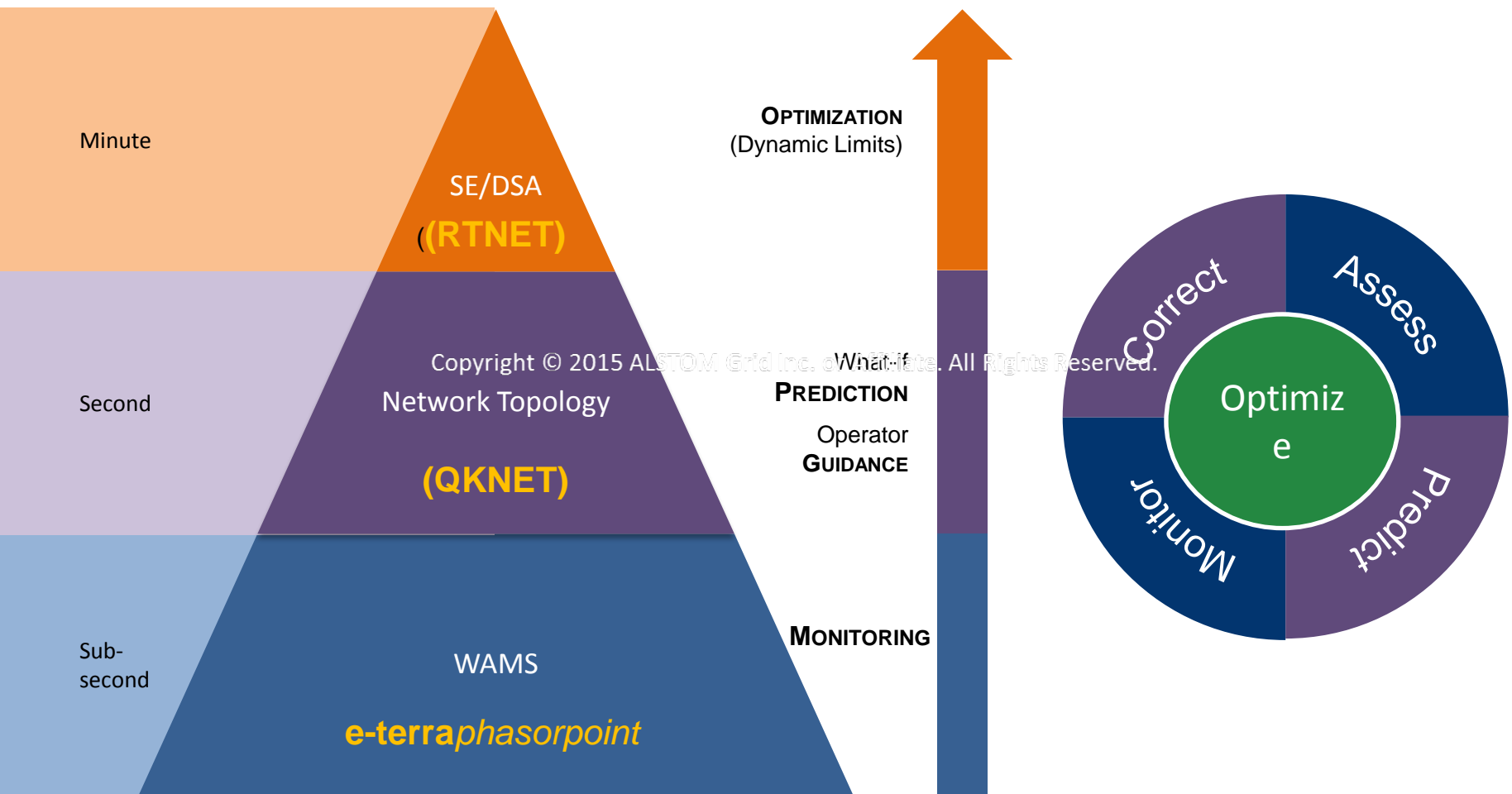
Transitioning from traditional “steady-state” view to enhanced “dynamic” situational awareness.



Integrated Solutions – An Example



Integrated WAMS-EMS Benefits



Where do we deploy these new PMUs?

PMU Siting criteria

- To improve SE solution
 - Observability, critical measurement locations
- Critical Paths
 - Tie-lines, Congested corridors, Angular separation potential
- Major generation or loads
- Special substation locations:
 - Renewable generation
 - Islanding separation & restoration regions
 - RAS & SPS importance
 - FACTS, SVC and HVDC
- Other locational aspects:
 - Upgradeable relays already exist
 - Communication network already exists
 - Helps neighboring systems' situation awareness

PMU Visualization

Monitor 'angular separation' as an indicator of increased grid stress due to:

- increased transmission path loading between 'Sources' and 'Sinks' of power
- sudden events such as line outages (i.e. weakening of the grid)

Monitor 'Angle Separation' between source & sink

1

Phase angular spread across power system

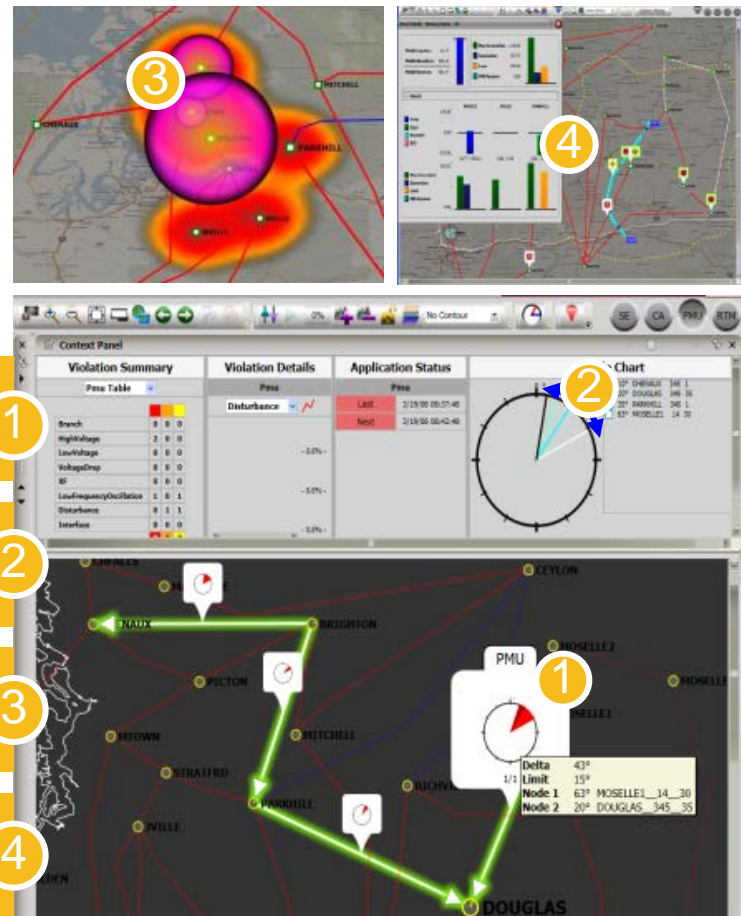
2

Identify low voltage areas

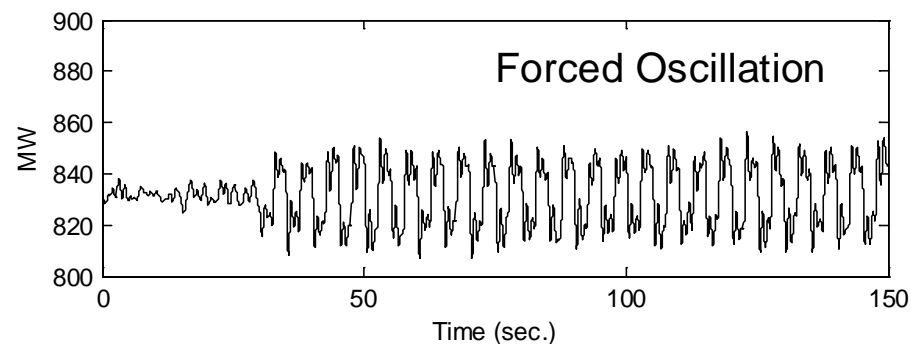
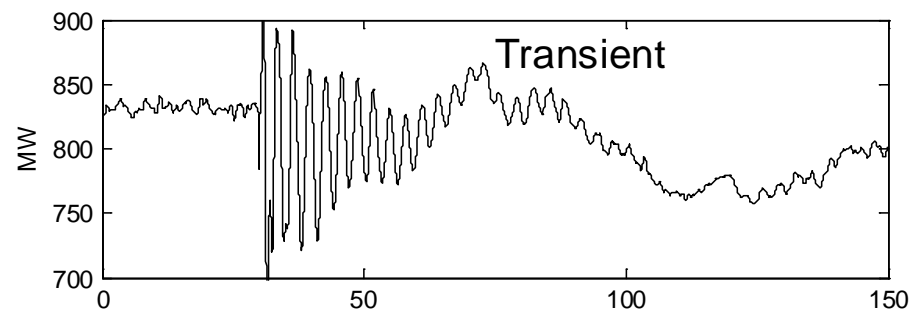
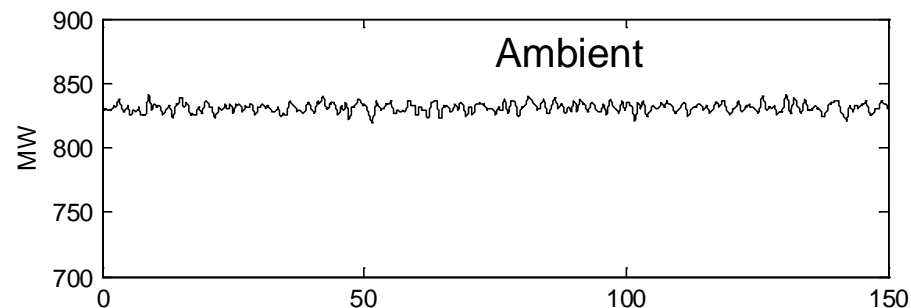
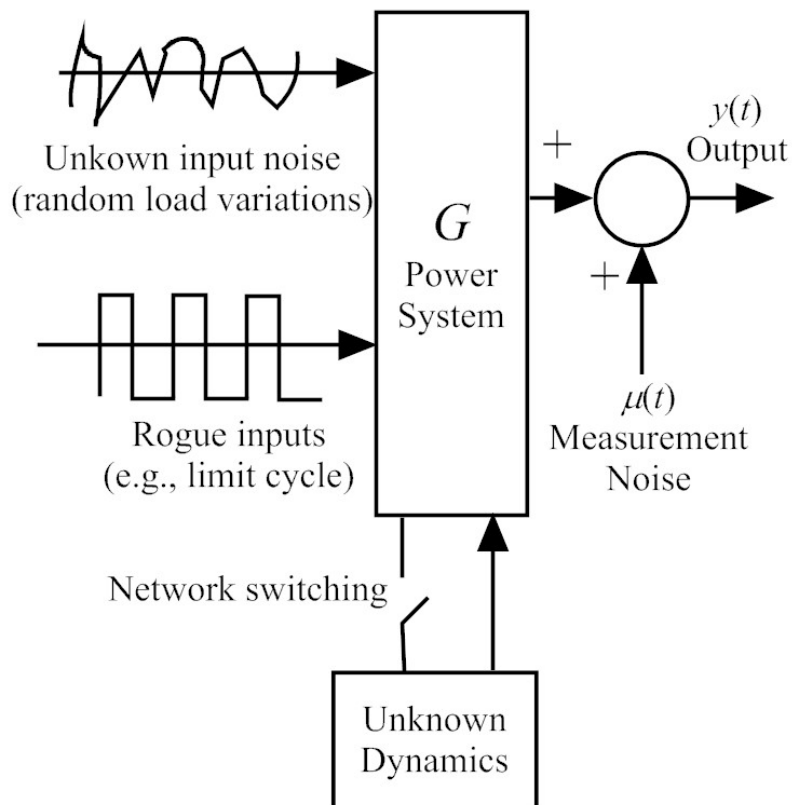
3

Detailed summary of existing resources within chosen region

4



Oscillations are always occurring in the grid...

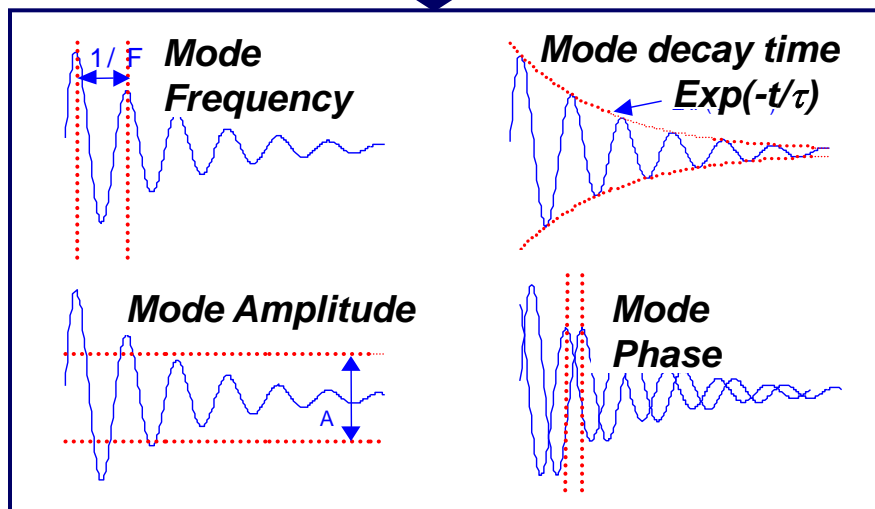
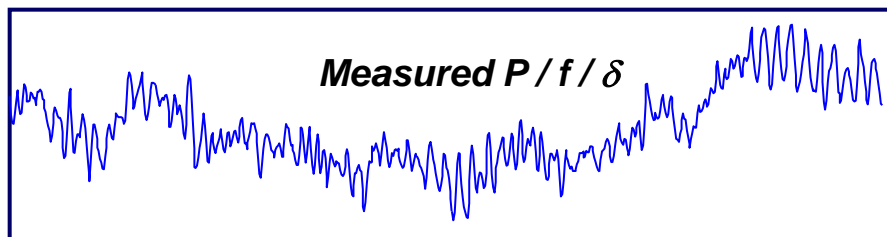


Types of oscillation modes in the grid

- Plant 0.01 - 0.1Hz
- Local area 0.15 - 1Hz
- Electro-mechanical, Inter-area 0.1 - 4Hz
- Voltage control 1.5 - 6Hz
- Power Electronics, HVDC 5 - 14Hz
- Sub-synchronous resonance 4 - 46Hz
 - generator torsional, series capacitors
- Others:
 - Hydro forbidden zones

Oscillatory Stability Management

Simultaneous multi-oscillation detection and characterisation
direct from measurements



Fast Modal Analysis: Alarms

Trend Modal Analysis: Analysis

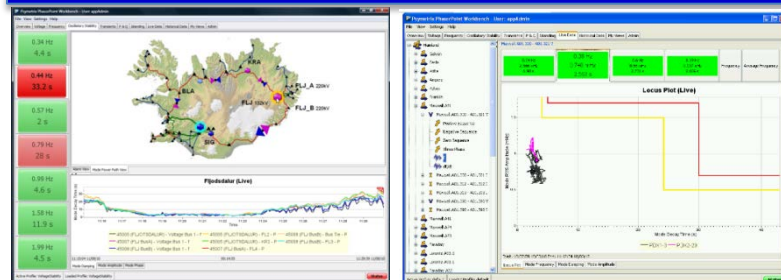
Operations

Unlimited oscillation frequency sub-bands

Early warning of poor damping (two level alarms)

Individual alarm profiles for each sub-band

For each oscillation detected, alarm on:
mode damping and/or
mode amplitude for



Planning & Analysis, Plant Performance

Post-event analysis

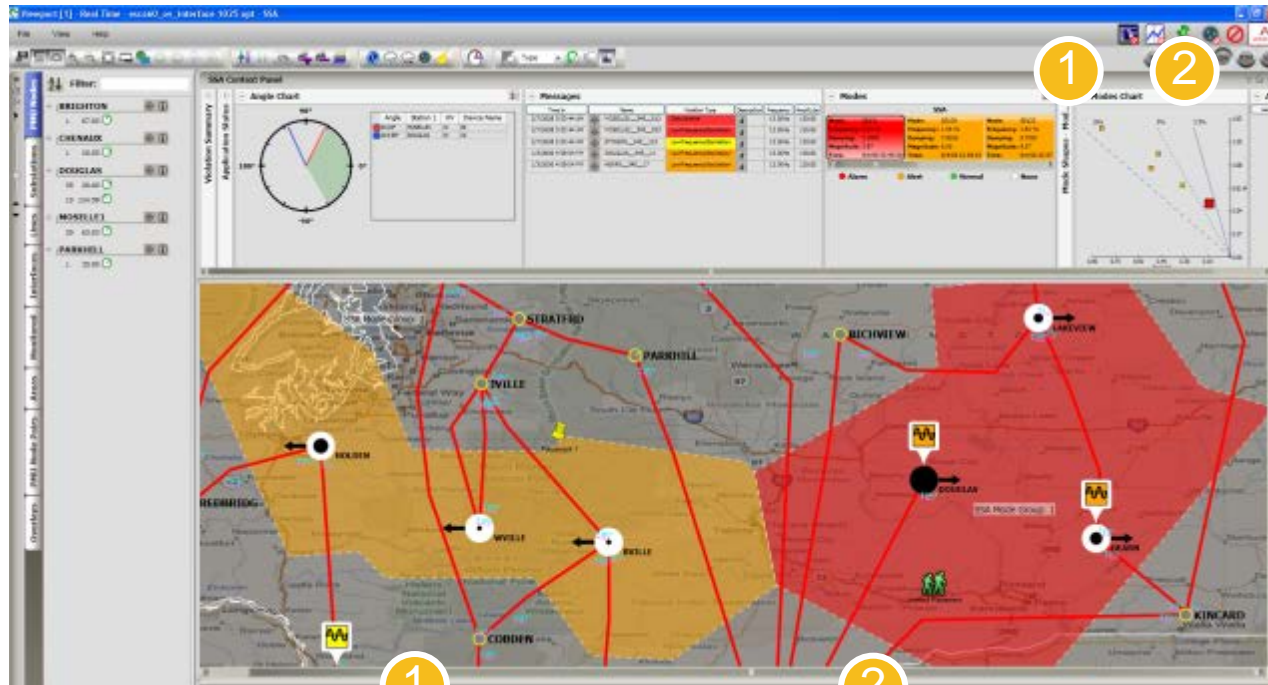
Dynamic performance baselining

Dynamic model validation

Damping controller performance assessment

Small Signal Oscillation Visualization

Modes shapes, amplitudes, damping, frequency, etc



Real-time alerts on poorly damped oscillations

Track oscillatory stability in real-time.

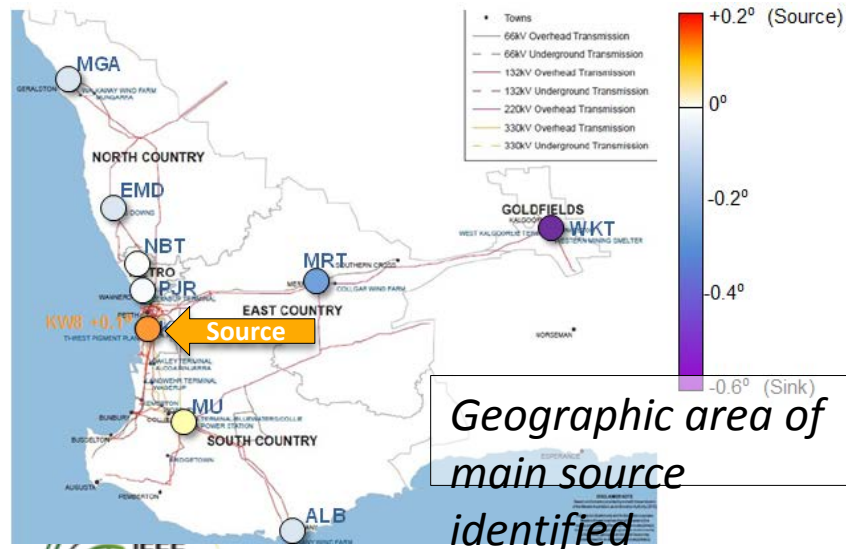
Identify regions where inter-area oscillations are observable

Oscillation Source Location

Concept

Uses mode phase changes to identify relative damping contributions, thus identifying sources

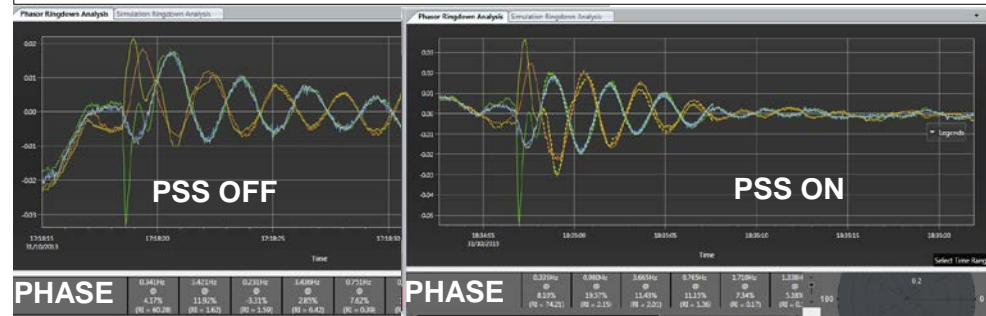
Source/Sink Location Map, 0.045Hz



Benefits

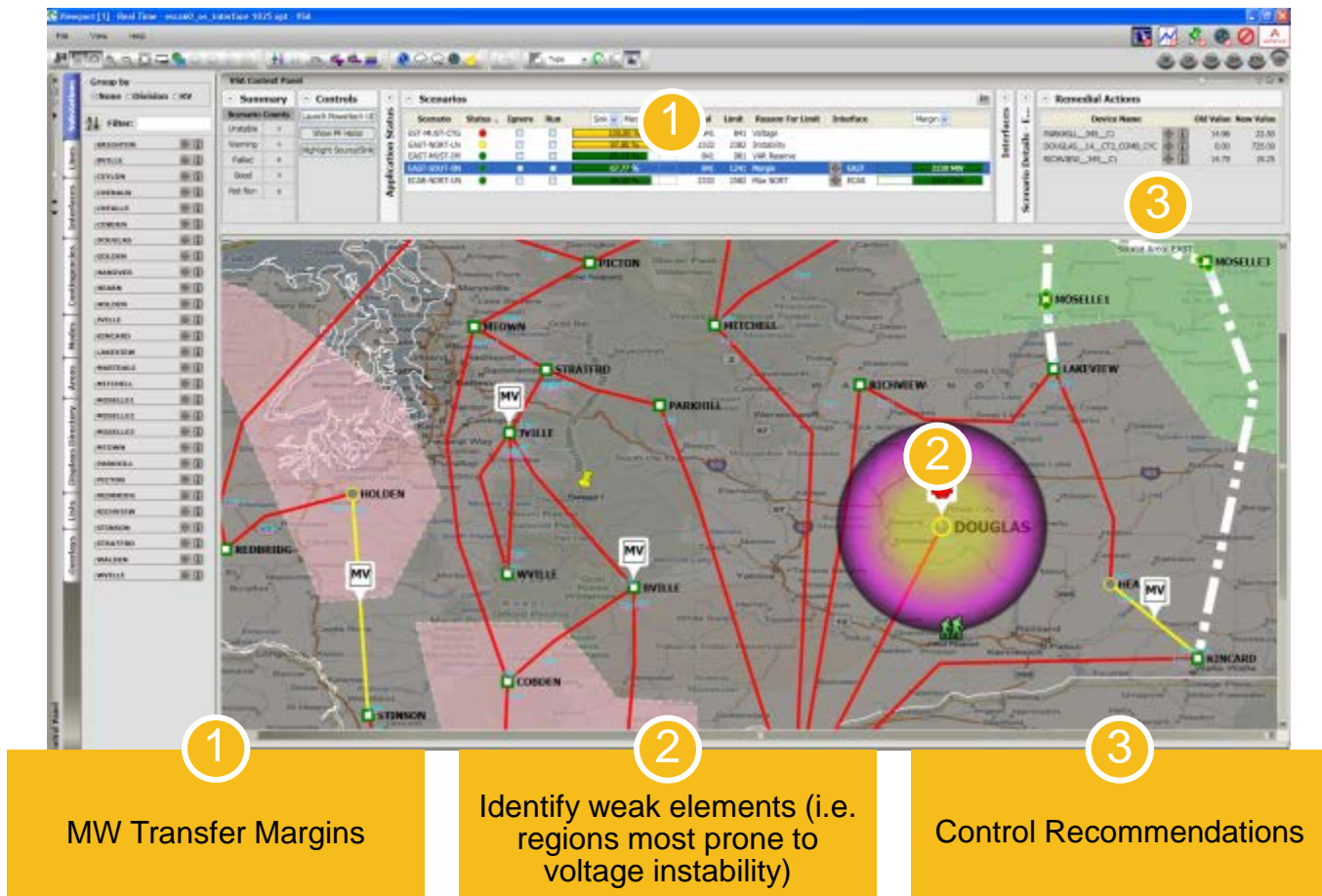
- Determine location of sources in large system with summary data
 - Real-time response procedure
 - Direct analysis effort for model validation & tuning
- Assess system tests of control tuning and control tuning effect
- Identify & correct plant malfunction or misconfiguration quickly

Mode Damping & Phase Tests for PSS Tuning



Voltage Stability Assessment

Voltage Contours, MW Margins, Weak Elements, Remedial Actions



MW Transfer Margins

Identify weak elements (i.e. regions most prone to voltage instability)

Control Recommendations

Phasor Analytics – Offline Analysis

Post Event Analysis

- Quicker post-mortem analysis.
- Sequence of events & root cause analysis.

Dynamic Model Validation

- Dynamic model verification.
- Generator model calibration.
- Load characterization.

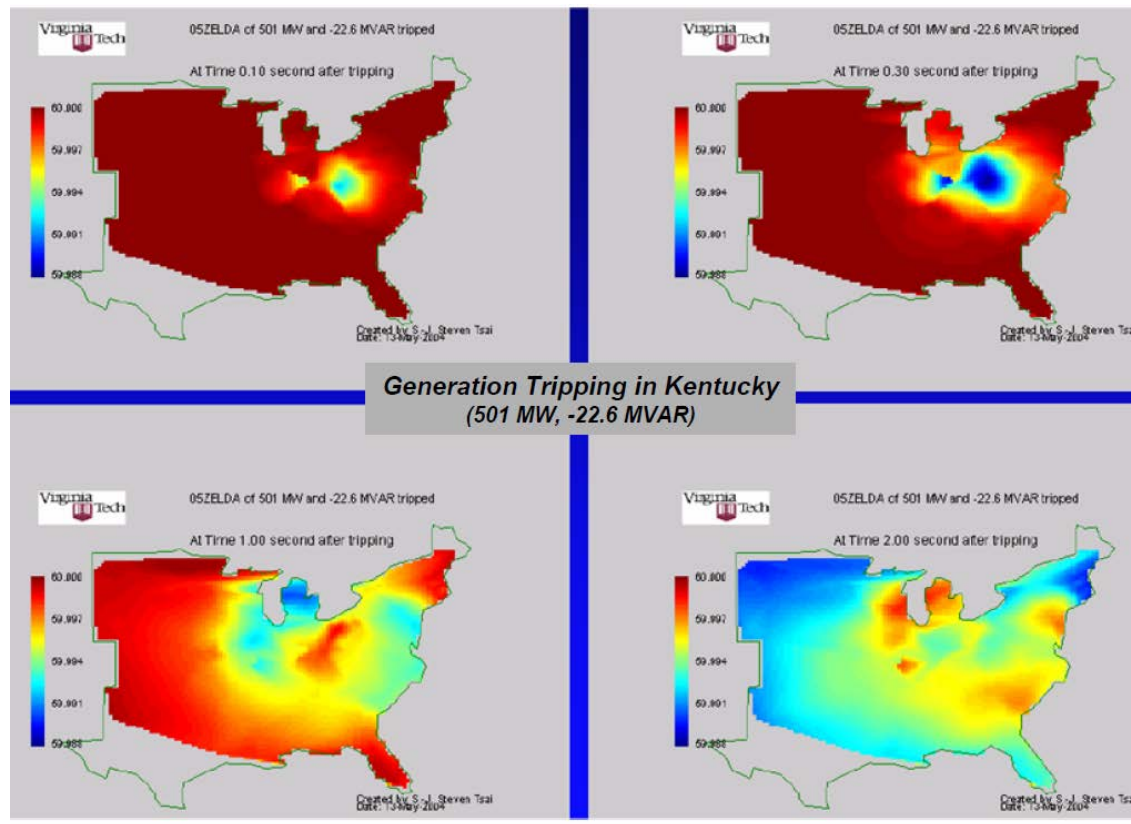
Baselining

- Assess dynamic performance of the grid.
- Steady-state angular separation.
- System disturbance impact measures.

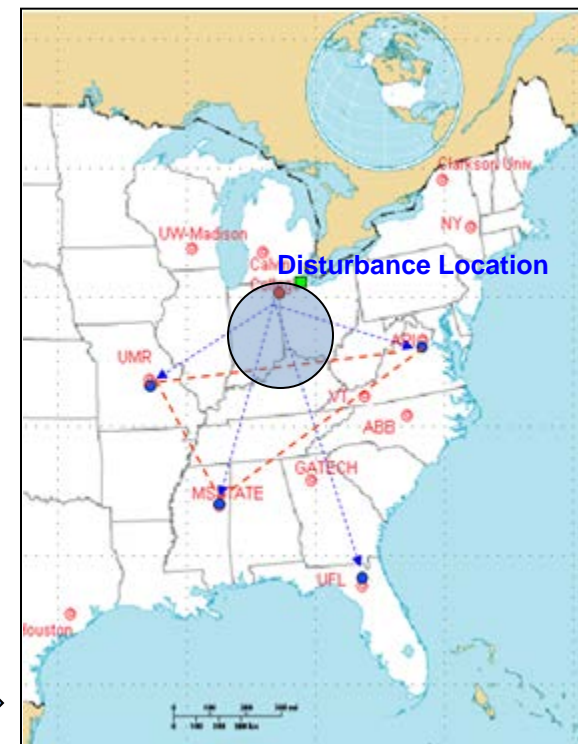
Compliance Monitoring

- Primary frequency (governing) response.
- Power System Stabilizer (PSS) tuning

A sudden disturbance causes a propagating traveling wave that can be detected by PMU data across the grid



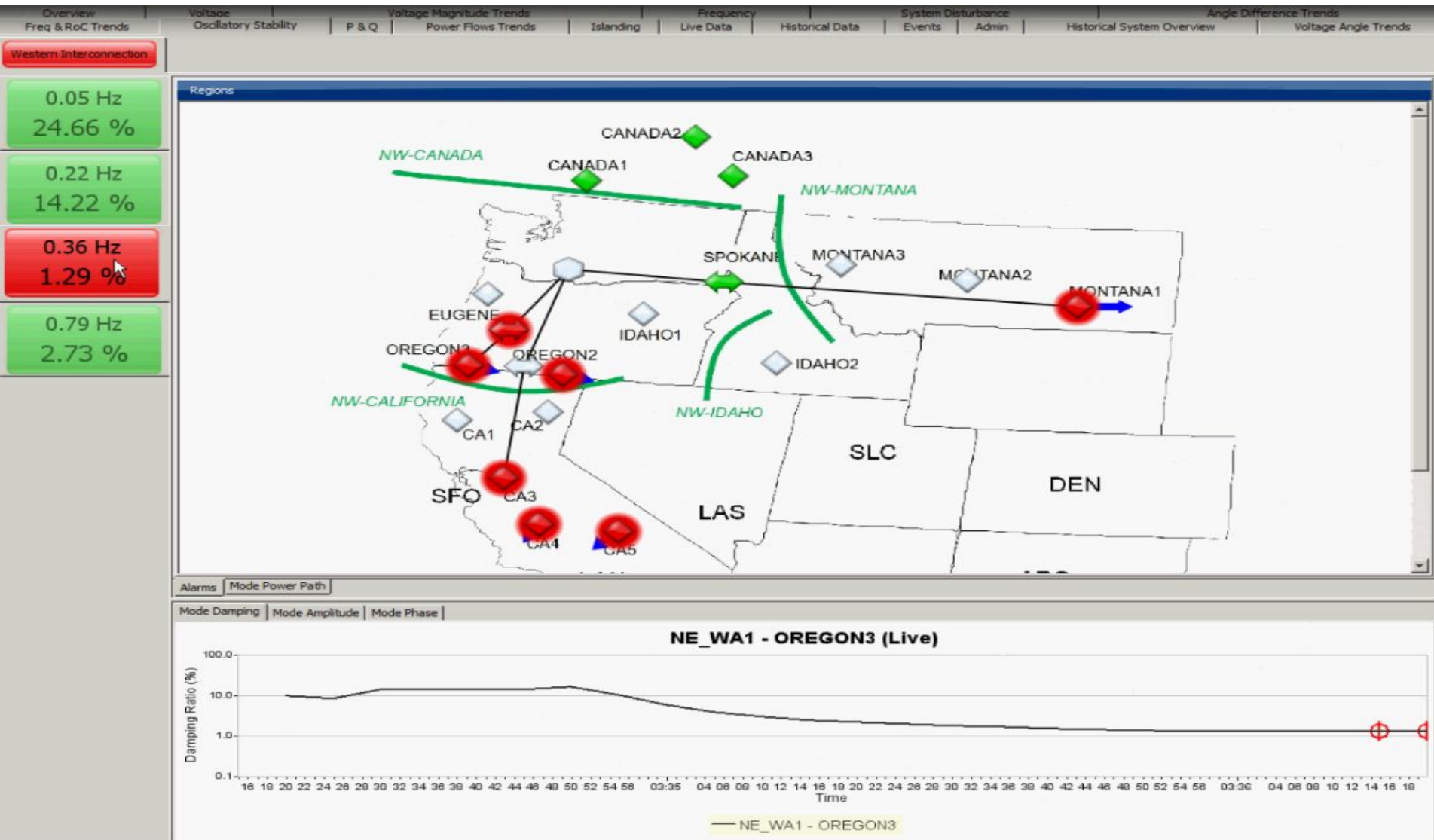
Source: VirginiaTech FNET



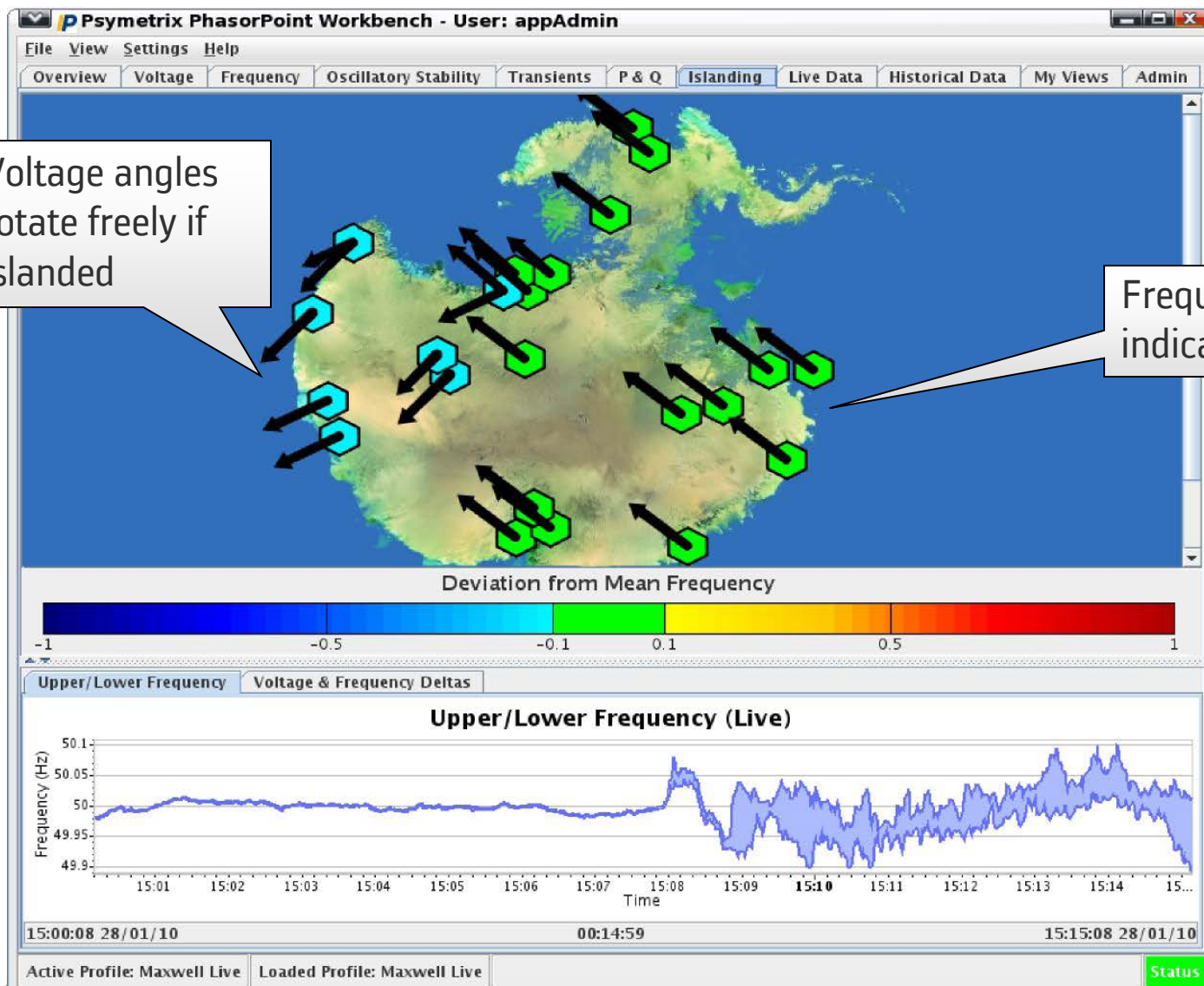
Use PMU and to triangulate & precisely locate the origin of the disturbance



WECC PMU data – Oscillation detection



Islanding, Resynchronisation & Blackstart



ISR Map

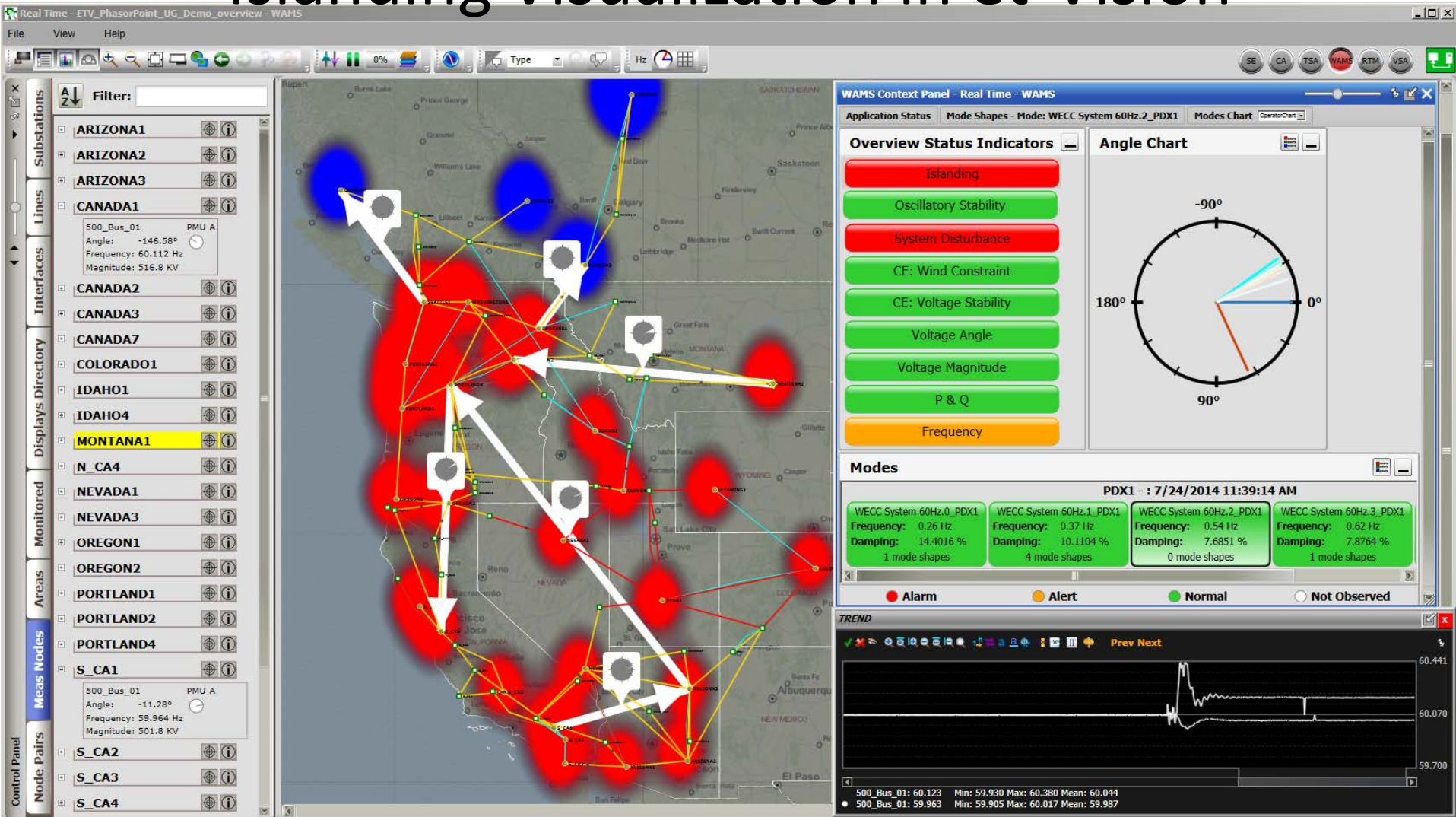
Frequency deviation indicated by colour

Frequency Deviation Colour key

Chart Selector tabs

Live Max/Min Frequency Deviation Chart

Islanding Visualization in et-Vision



Planning Benefits

Dynamic Model Validation

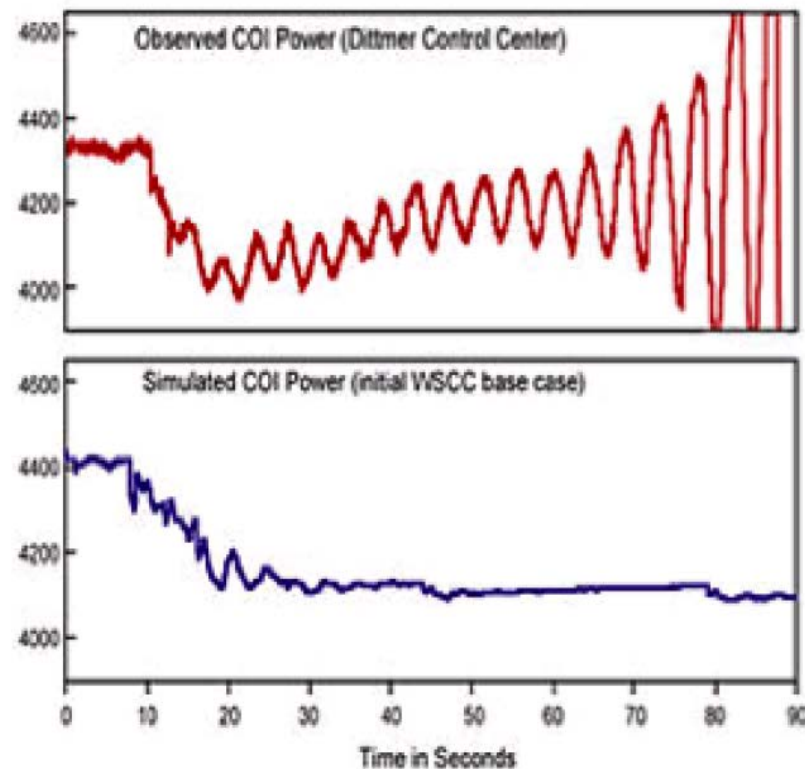
Western Interconnection
August 10th, 1996 Blackout

Dynamic models predicted stable system when the system was in fact unstable.

PMU provide necessary dynamic data to calibrate dynamic power system models.

Actual System Performance

- unstable system behavior observed.



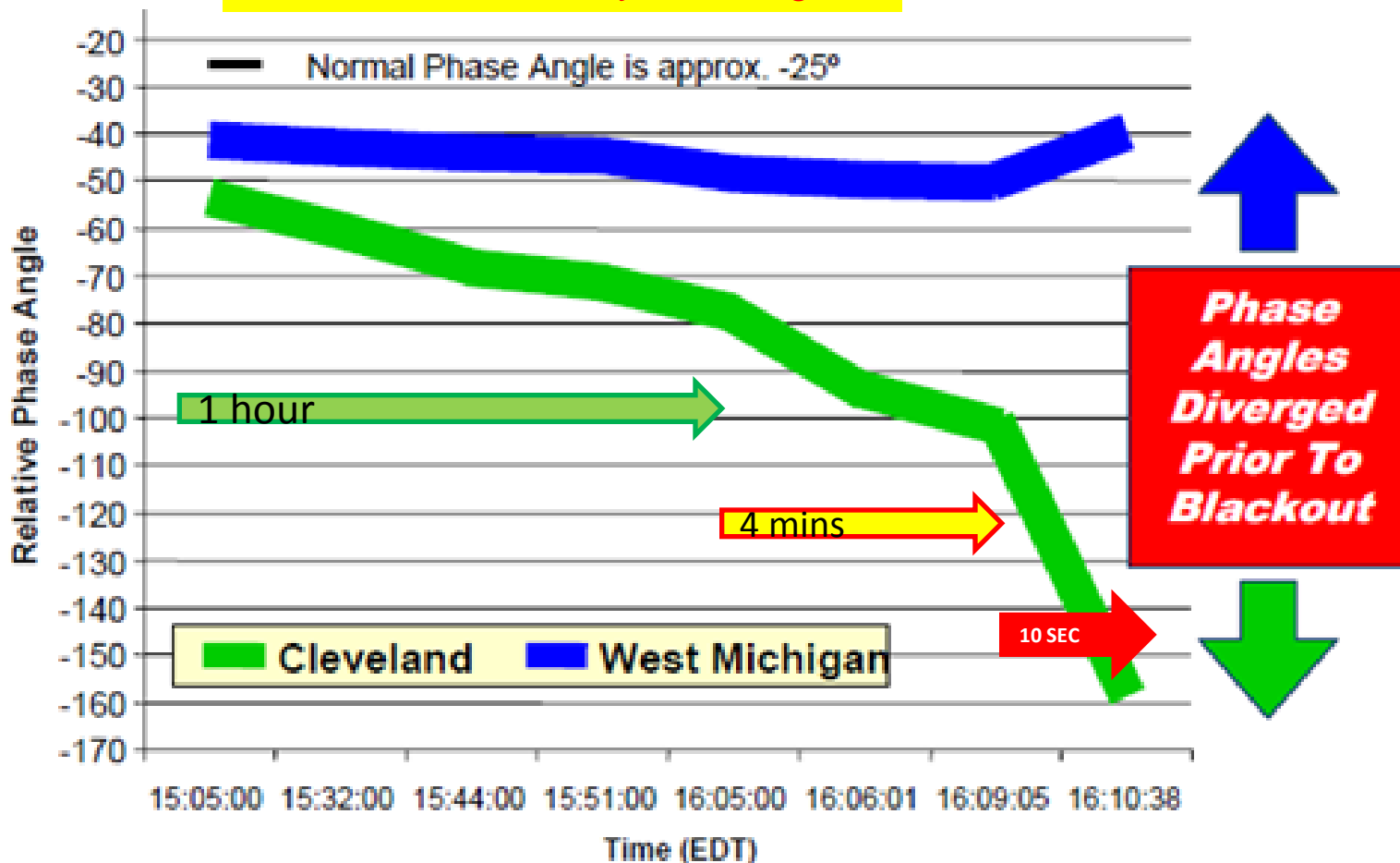
Model Simulation

- predicted stable system performance.

August 14th, 2003 Blackout Timeline

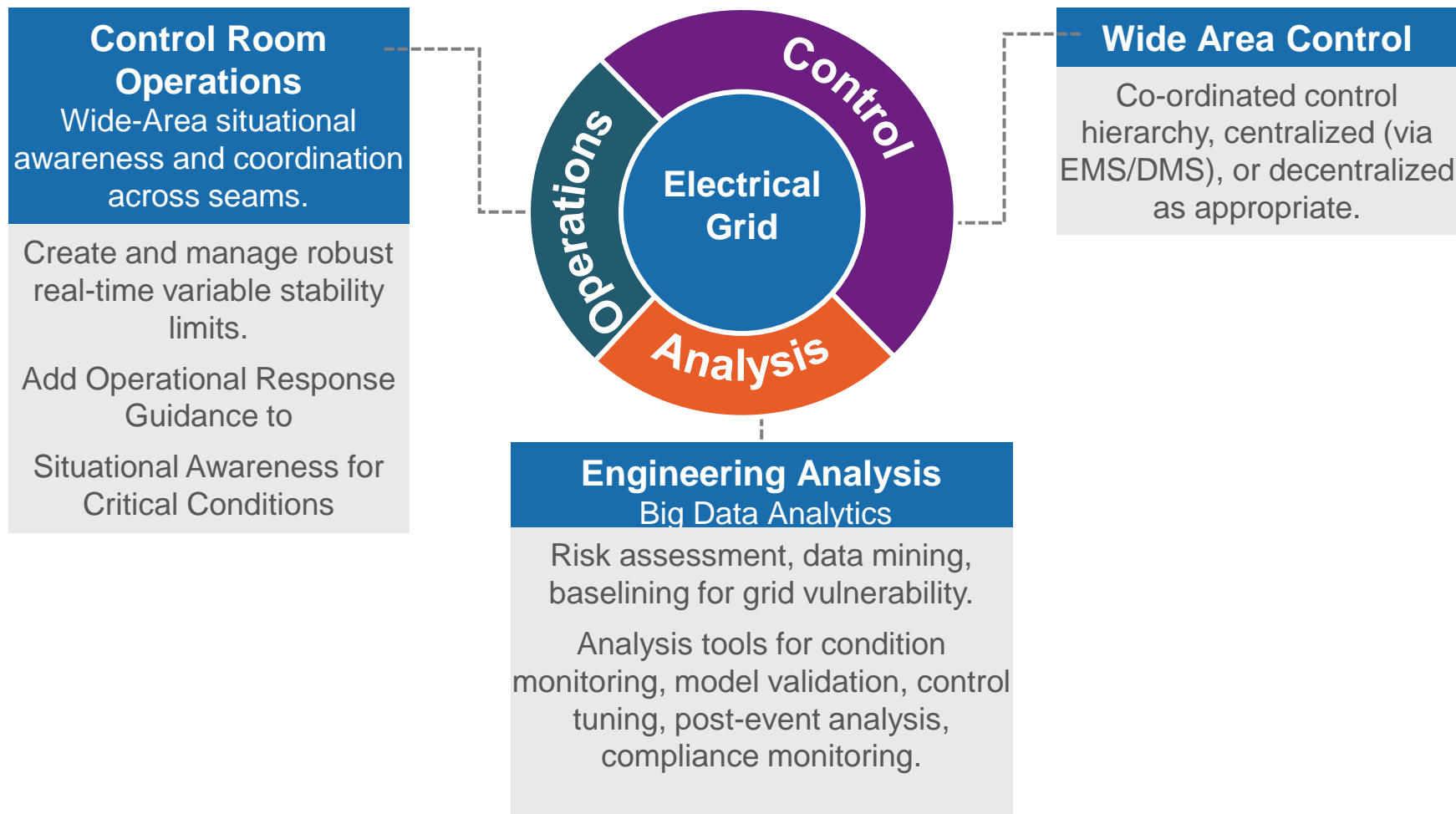
Monitor wide area grid stress

An hour to react, analyze & mitigate!

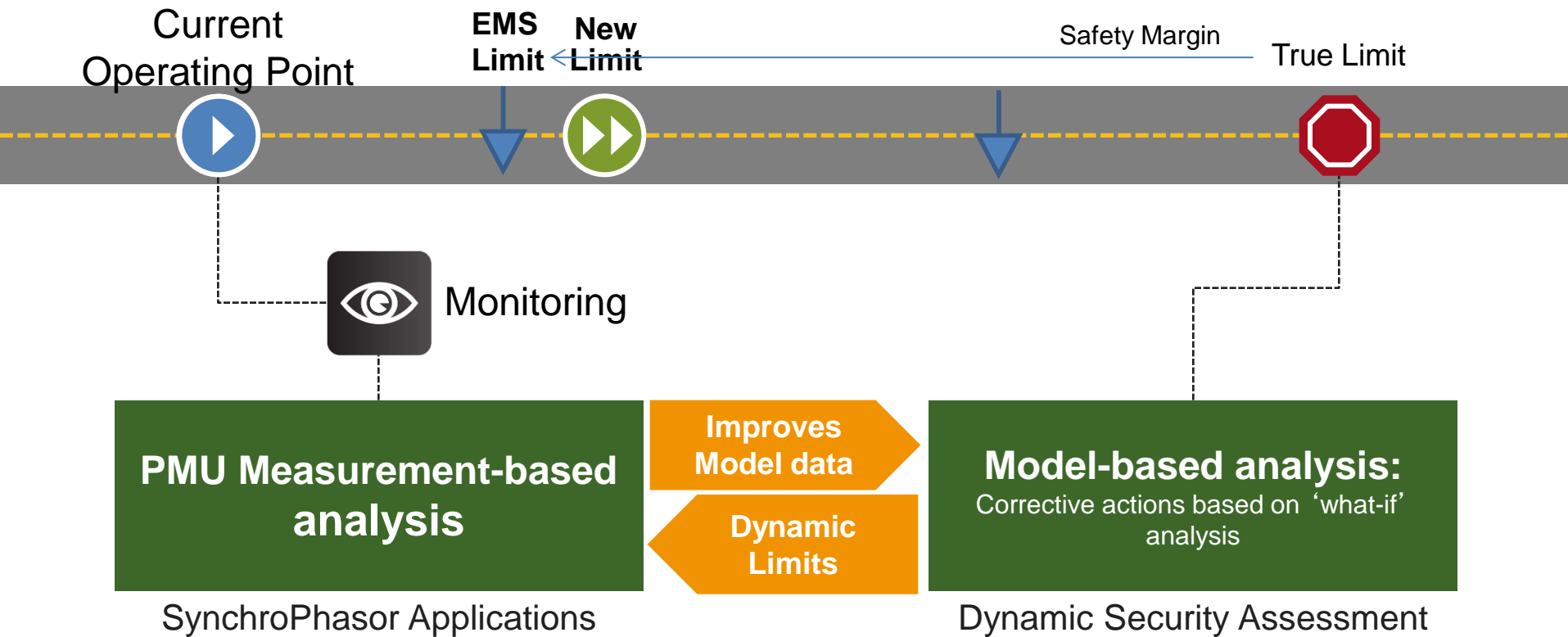


Benefits of WAMS

“Model, Measure, Monitor, Mitigate!”



Integrated “Measurement-Based” and “Model-Based” Stability Analysis



PMU Benefits to Grid Operations.....

- Situational awareness tools
- More Robust, Improved State Estimation
- Fast online stability solutions
- Maximize utilization of congested corridors
- Disturbance Locator
- Identification of coherent groups of generators
- Improved forensic analysis

I have a fully functional EMS..

Tell me, why do I need Synchrophasor WAMS?

- Observability of the grid - **beyond your SCADA system**
 - Disturbances, oscillations, islanding, angles diverging, overloads, etc
- Detect **undamped grid oscillations** that may lead to a blackout
- **Calculate line impedances** online with a PMU at each end of the line
- Monitor **diverging voltage angles** that may lead to a blackout
- Monitor **low voltage regions & reactive margins** to prevent instability
- **Maximize MW capacity** across existing congestion corridors
- **Immediate online replay of a recent disturbance**
- **Faster forensic, post-event analysis** and detailed event re-creation
- **Detection of islanding** in the grid; assist in **re-synchronization**
 - “Synchrocheck relay for the grid”

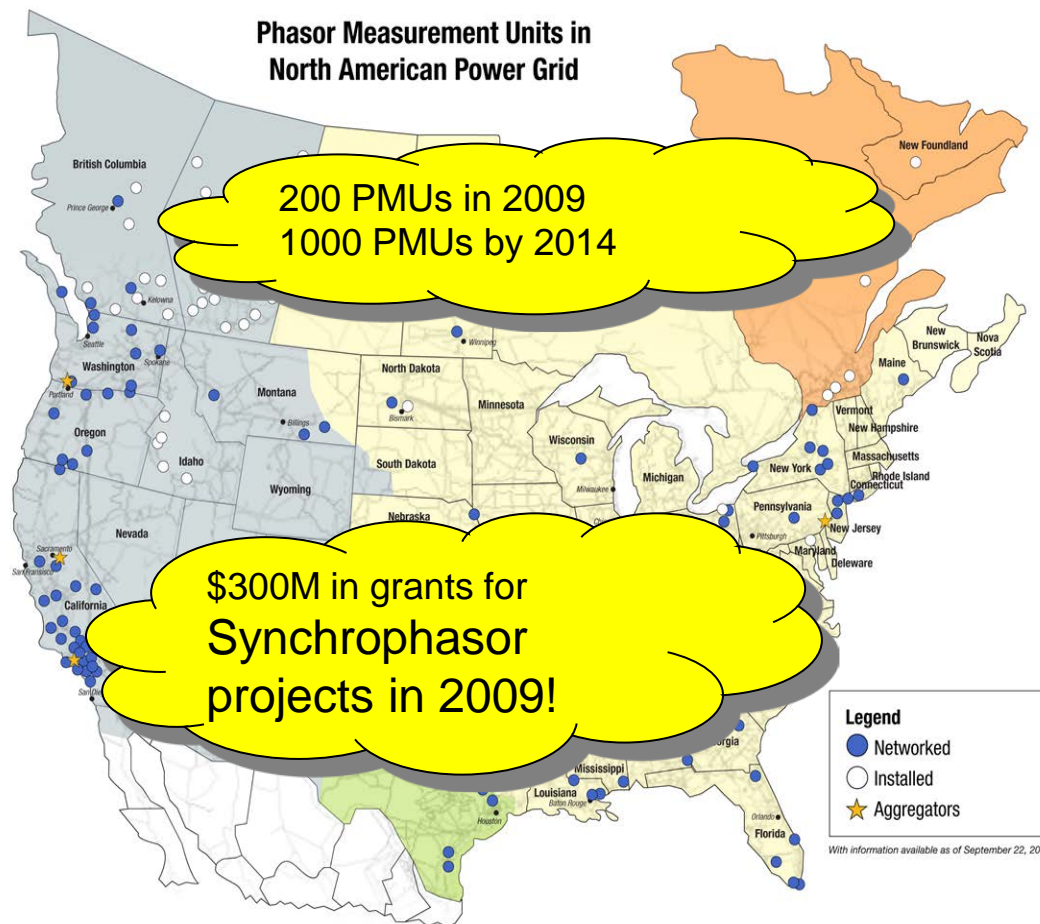
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6. Evolution Towards a Smarter Grid

DoE Smart Grid Investment Grants Synchrophasor Projects 2009-2013

courtesy DoE, NASPI

- **WECC**, 250 PMUs, \$108M
- **PG&E** (\$50M), BPA, SCE, SRP
- **ISO New England**, 30 PMUs, \$9M
- **MISO**, 150 PMUs, \$35M
- **Duke Energy**, 45 PMUs \$8M
- **Entergy**, 18 PMUs, \$10M
- **PJM**, 90 PMUs, \$28M
- **NY ISO**, 35 PMUs, \$74M
- **ATC**, 5 PMUs, \$28M
- ... a few others



Scope Specification of a DOE SGIG Project

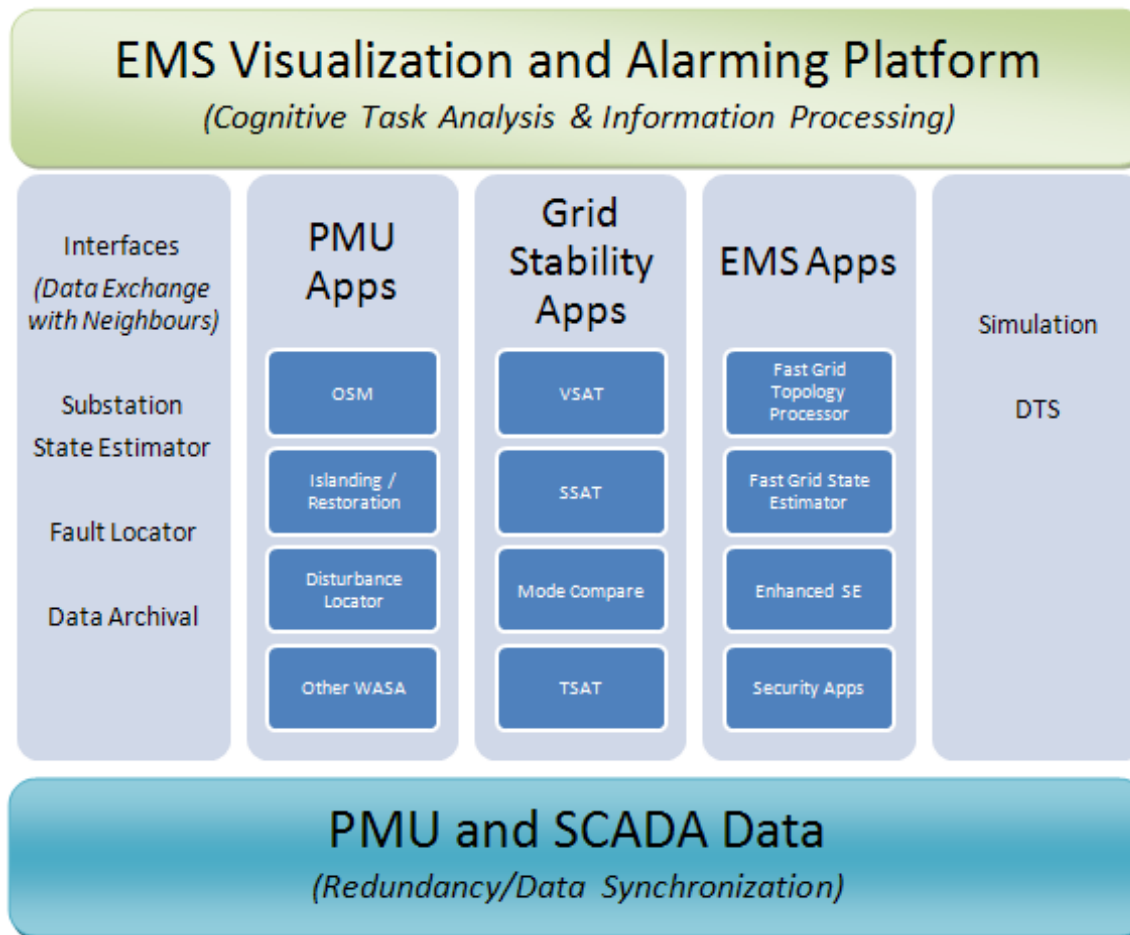
an example

Source – DOE

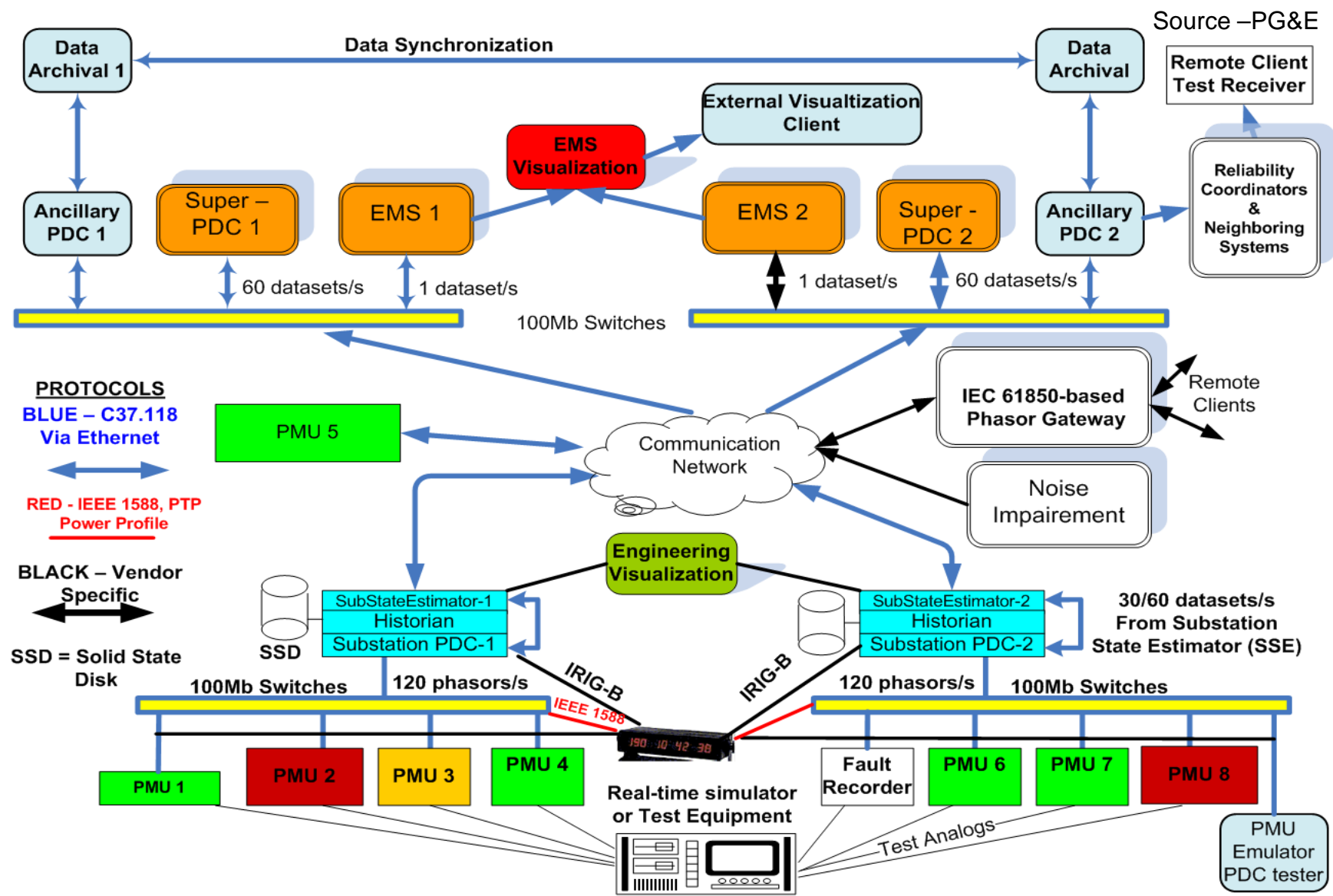
- 1. Real-time data display for wide area visualization**
 1. Frequency and frequency rate of change
 2. RMS voltage
 3. RMS current (line)
 4. Phase angle
 5. Positive sequence voltage
 6. Positive sequence current
- 2. Calculation and real-time display for wide area visualization**
 1. Path flow
 2. Reactive capacity/reserves
 3. Voltage stability
 4. Oscillation energy
 5. Mode meter
 6. Percent damping
- 3. Monitor real-time PMU and calculated data for alarms**
 1. Frequency
 2. RMS voltage
 3. RMS current
 4. Phase angle
 5. Path flow
 6. Reactive capacity/reserves
 7. Voltage stability
 8. Oscillation energy
 9. Mode meter
 10. Percent damping
- 4. Display options of all PMU and calculated values**
 1. X/Y 2-dimensional
 2. Polar chart of phase angle
 3. X/Y/Z 3-dimensional
 4. State values of alarms
 5. Grid text in rows and columns
- 5. Alarm management**
 1. Set warning and alarm thresholds or limits
 2. Playback and archive of alarm
 3. Set alarm prioritization / levels
 4. Capture of events based on alarms
 5. Visualization of alarm status in real-time
- 6. Power system performance and post event analysis**
 1. Post event analysis
 2. Power system performance baseline
 3. Power system performance analysis
- 7. System wide model validation**
 1. Generation model validation
 2. High voltage DC intertie
 3. Load model validation
 4. System model verification
- 8. Export of data in common formats**

EMS Application Enhancements at PG&E

Source –PG&E



Example of Synchrophasor Project – Proof of Concept Architecture



Enhanced EMS State Estimator with PMUs

Uses PMU data at the 1 sample/sec rate

Utilization of PMU data (voltage & Current Phasors) in SE to improve round-the-clock reliability & robustness.

- Increase the number of 'Valid Solutions' \Rightarrow improved reliability
- Reduce dependency on 'Critical Measurements' \Rightarrow better observability

- Improved SE solution quality to minimize 'Variance of State'

\Rightarrow higher accuracy

- Fewer SE iterations

\Rightarrow faster performance

TELE_PMU_BUS_PDEG_DATA, RTNET [ONLINE] DNB.CCN.BPA.GOV(C) - DNB

File Navigate PCPrint HAB Application EMP Application Related Displays Analyst Displays Help

now

Telemetered PMU BUS Data All PKV PDEG

Time: 04-Jun-2007 15:01:48 RTNET REALTIME LOSSES CALC ED

Station	Device Type	Device	Analog	Quality	SCADA / Estimated	Value SCADA / Estimated	Weighted Residual	Standard Deviation	Bias	
ASHE	BUS	PMU	PDEG	Good	/ Available	9.90 / 9.45	0.504	0.044	0.400	Row
BELL	BUS	500_PMU	PDEG	Good	/ Available	25.80 / 24.01	1.992	0.318	1.606	Row
BELL	BUS	230_PMU	PDEG	Good	/ Available	28.20 / 26.18	2.248	0.307	1.875	Row
BIG_EDDY	BUS	500_PMU	PDEG	Good	/ Available	-2.90 / -2.89	-0.015	0.104	-0.028	Row
BIG_EDDY	BUS	230_PMU	PDEG	Good	/ Available	-7.10 / -5.97	-1.254	0.065	-1.130	Row
CAPTJACK	BUS	PMU	PDEG	Good	/ Available	-17.00 / -16.02	-1.089	0.319	-1.098	Row
CHIEF_JO	BUS	500_PMU	PDEG	Good	/ Available	23.30 / 22.81	0.545	0.307	0.312	Row
CHIEF_JO	BUS	230_PMU	PDEG	Good	/ Available	26.10 / 25.42	0.754	0.302	0.500	Row
CUSTER	BUS	500_PMU	PDEG	Good	/ Available	7.70 / 8.98	-1.423	0.316	-1.369	Row
CUSTER	BUS	230_PMU	PDEG	Good	/ Available	6.00 / 7.41	-1.563	0.320	-1.521	Row
GARRISON	BUS	500_PMU	PDEG	Estimated	/ Unavailable	24.03 / 23.99				Row
GARRISON	BUS	230_PMU	PDEG	Estimated	/ Unavailable	21.83 / 21.79				Row
G_COULEE	BUS	500_PMU	PDEG	Good	/ Available	23.60 / 22.97	0.704	0.201	0.568	Row
JOHN_DAY	BUS	500_PMU	PDEG	Good	/ Available	-0.40 / -0.39	-0.172	0.010	0.002	Row
KEELER	BUS	500_PMU	PDEG	Good	/ Available	-5.50 / -5.30	-0.219	0.184	-0.254	Row
KEELER	BUS	230_PMU	PDEG	Good	/ Available	-8.00 / -7.61	-0.435	0.235	-0.473	Row
MALIN	BUS	PMU	PDEG	Good	/ Available	-16.90 / -16.03	-0.962	0.332	-1.084	Row
MAPLE_VL	BUS	230_PMU	PDEG	Good	/ Available	4.90 / 5.37	-0.522	0.227	-0.486	Row
MCNARY	BUS	500_PMU	PDEG	Good	/ Available	9.00 / 8.58	0.466	0.391	0.159	Row
MCNARY	BUS	230_PMU	PDEG	Good	/ Available	8.20 / 7.79	0.459	0.310	0.228	Row
SLATT	BUS	PMU	PDEG	Good	/ Available	3.20 / 3.09	0.125	0.244	-0.002	Row
SUMMERLK	BUS	PMU	PDEG	Good	/ Available	-13.90 / -13.21	-0.769	0.305	-0.874	Row
COLSTRIP	BUS	500_PMU	PDEG	Good	/ Available	38.20 / 34.66	3.936	0.258	3.306	Row
YELLOWTLP	BUS	PMU	PDEG	Estimated	/ Unavailable	16.84 / 16.90				Row
DIABLOPG	BUS	PMU	PDEG	Good	/ Available	-17.80 / -16.68	-1.247	0.361	-1.452	Row
MIDWAYPG	BUS	500_PMU	PDEG	Good	/ Available	-21.50 / -24.12	2.909	0.396	2.257	Row
MOSSLAND	BUS	500_PMU	PDEG	Good	/ Available	-29.70 / -28.70	-1.108	0.370	-1.240	Row
PITSBURG	BUS	PMU	PDEG	Estimated	/ Unavailable	-33.55 / -33.31				Row
TESLA	BUS	500_PMU	PDEG	Good	/ Available	-26.60 / -27.57	-1.147	0.383	-1.333	Row
DEVERS	BUS	PMU	PDEG	Good	/ Available	31.40 / 28.93	2.468	0.373	8.027	Row
SYLMARS	BUS	230_PMU	PDEG	Good	/ Available	1.00 / 0.99	0.006	0.240	0.000	Row
VINCENT	BUS	PMU	PDEG	Good	/ Available	1.00 / 0.99	0.006	0.240	0.000	Row
AULT	BUS	PMU	PDEG	Good	/ Available	23.70 / 19.19	5.011	0.742	4.026	Row
BEARS	BUS	PMU	PDEG	Good	/ Available	2.20 / 0.99	1.200	0.590	0.888	Row
SHIPROCK	BUS	PMU	PDEG	Good	/ Available	2.50 / 0.99	1.500	0.350	0.428	Row

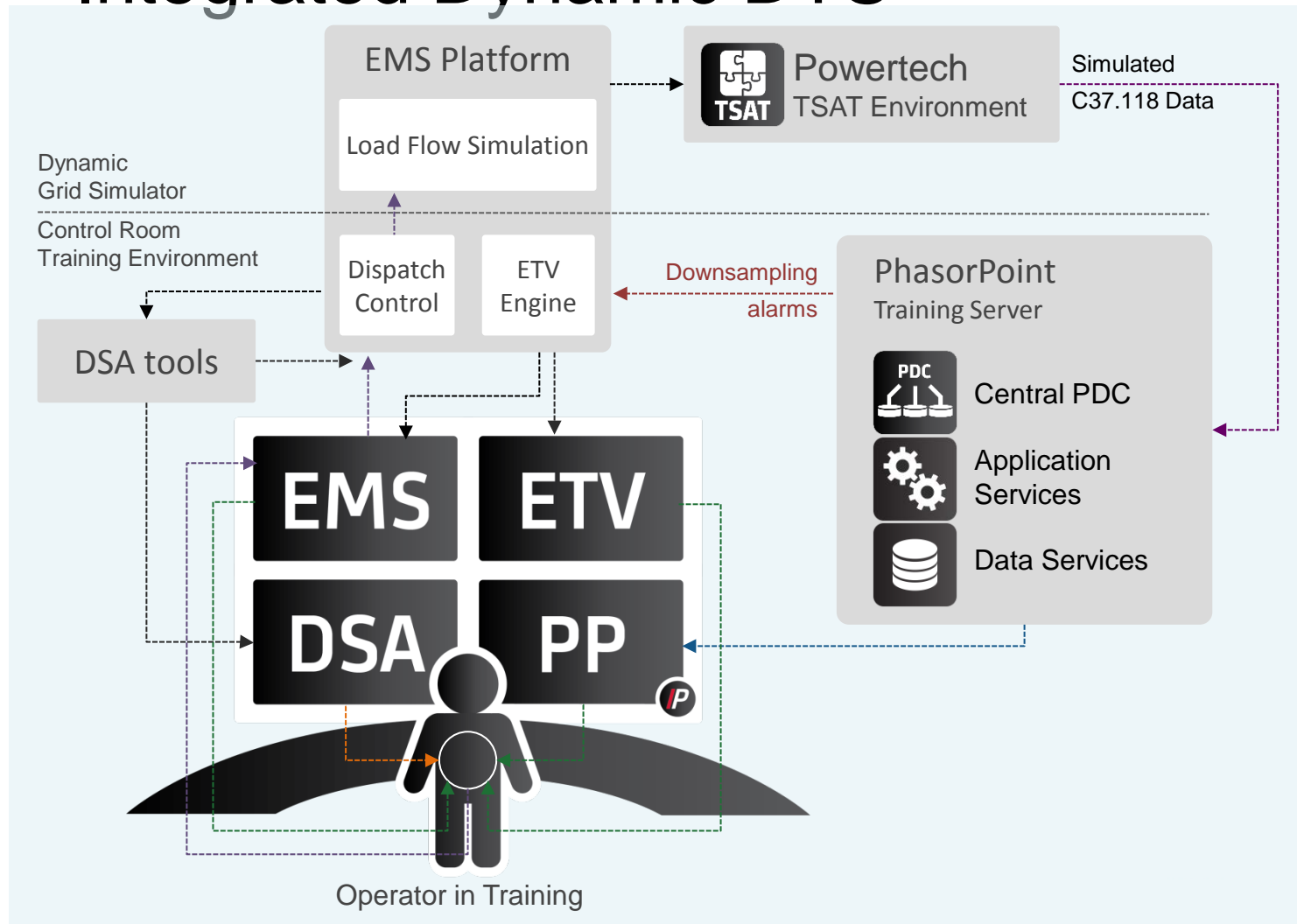
Compare PMU with SE Results

Operator Training Environment Integrated Dynamic DTS

Integrated Dispatcher Training System:

- Real-time simulator based on Powertech TSAT
- Simulated data is fed directly into PP as C37.118 streams
- Data is also downsampled and sent to the EMS & DSA Tools
- EMS integrated with PhasorPoint and DSA tools

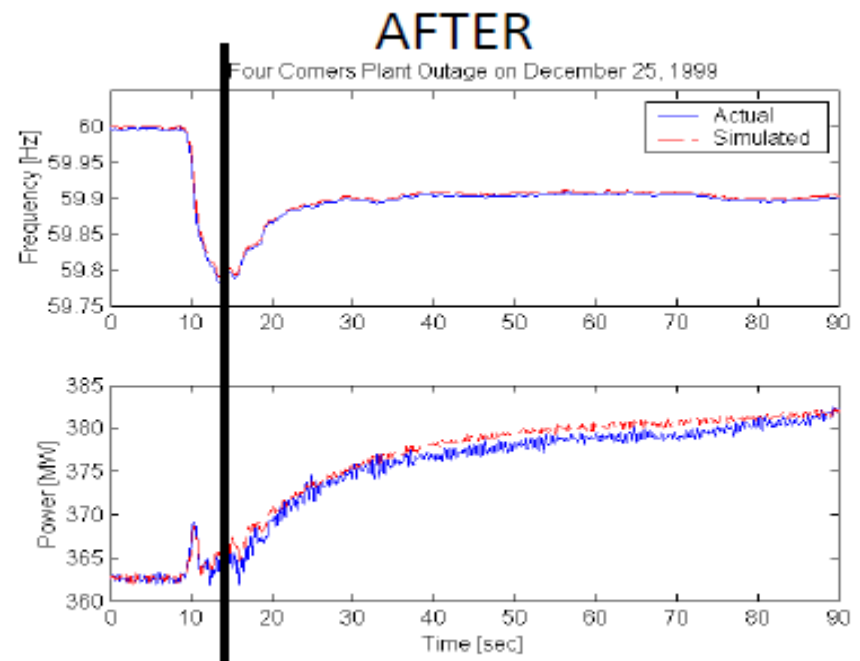
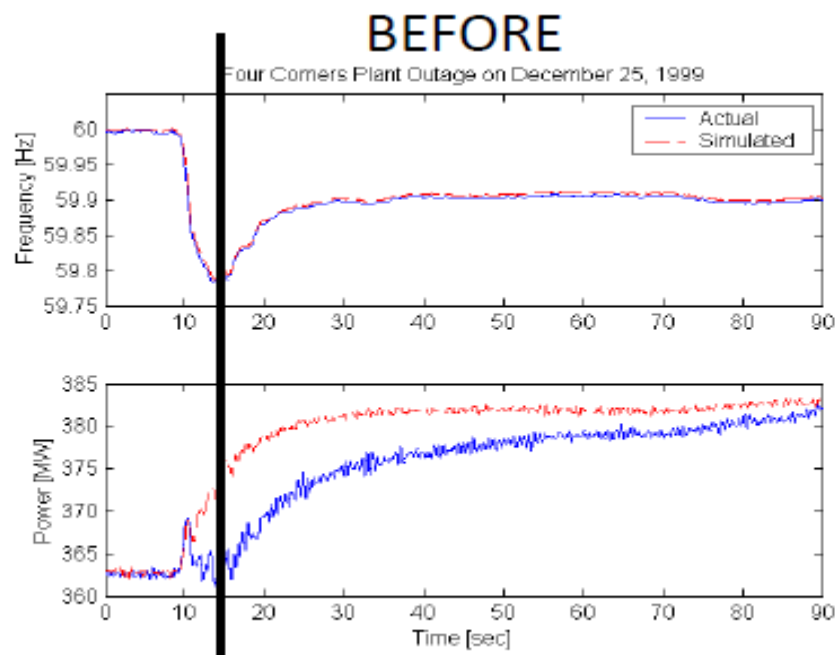
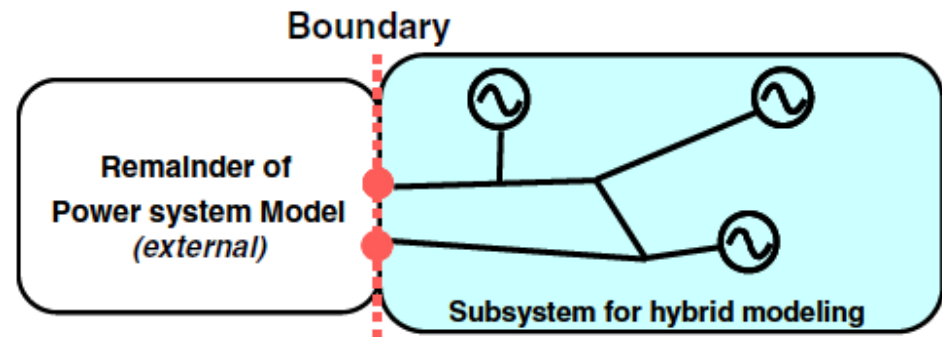
- IEEE C37.118
- IEC 60870-5-104
- PhasorPoint HMI Services
- e-terra services
- Control
- Observe



System Model Validation and Calibration

• MODEL VALIDATION

- Power Plant Model Validation
- Load Model Validation
- CT/PT Calibration



Blue = actual, Red = model

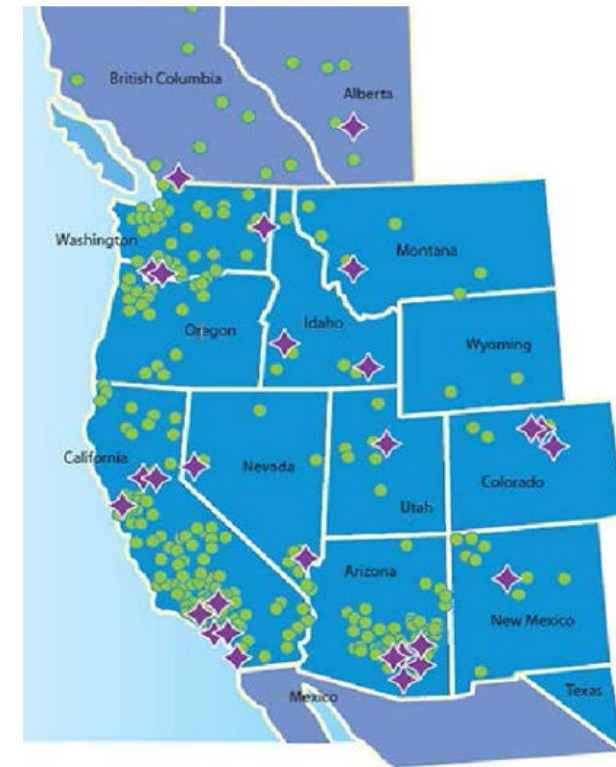
courtesy: BPA

Western Interconnect Synchrophasor Project (WISP)



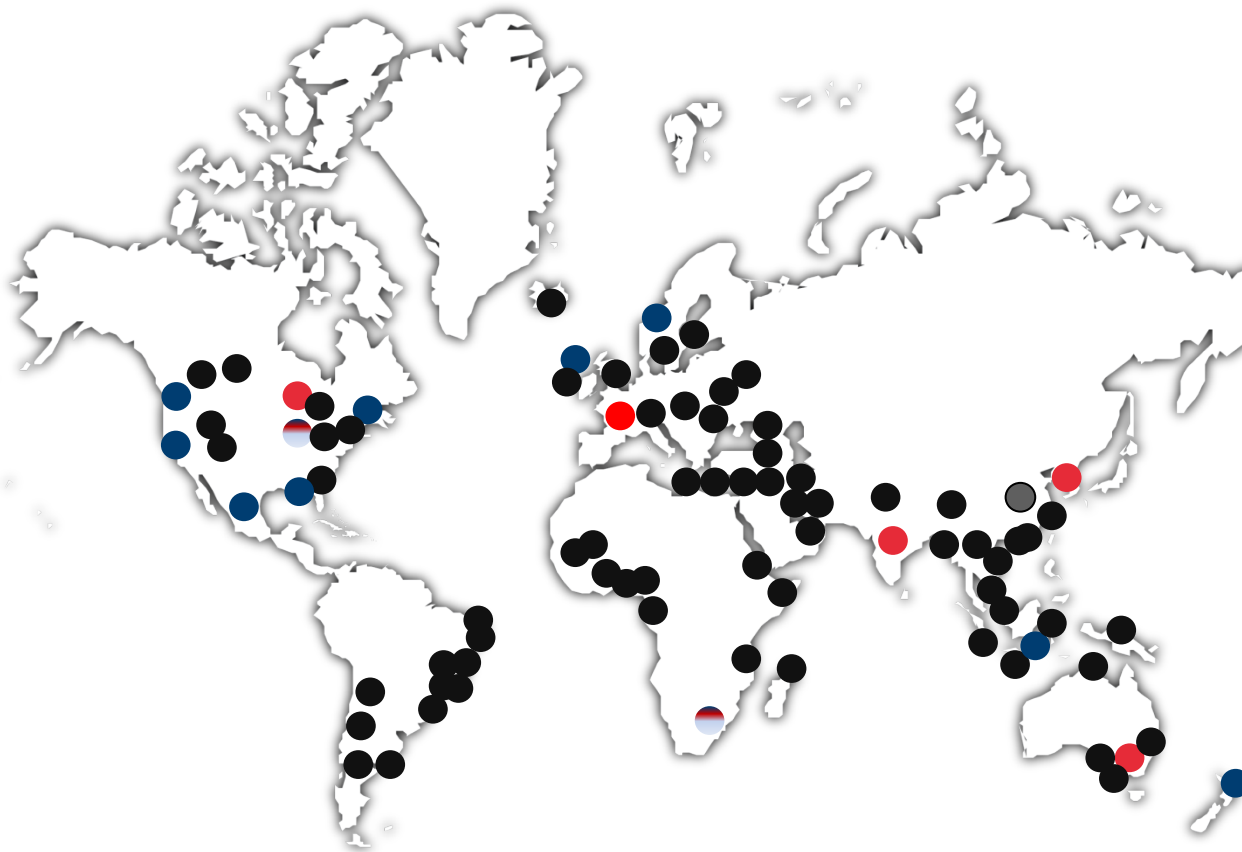
Wide Area Monitoring System (WAMS) Deployment:

- **Customer:**
 - WECC and the WECC Participants – Unilateral data sharing for the WISP project.
- **Scope:**
 - 19 organizations with over 300 PMUs and 60 PDCs.
 - Phasor data sharing and visibility amongst the participants.
 - Enhanced situational awareness for control room decisions.
- **Schedule:**
 - Awarded as part of ARRA in 2009
 - General visualization, alarming, archiving, December 2012
 - NASPInet Phasor Gateway demo: March 2013
- **Project Highlight:**
 - Large PMU penetration and 100% participant involvement
 - Dedicated communications infrastructure (fiber) private network
 - Assisting the Western region in Control Room decision making today.



WAMS Solutions

Deployments Worldwide



- AEP (USA)
- **MISO (USA)**
- AESO (Canada)
- BC Hydro (Canada)
- BPA (USA)
- Duke Energy (USA)
- **Entergy (USA)**
- **PG&E (USA)**
- **WECC (USA)**
- **ISONE (USA)**
- TVA (USA)
- **ERCOT (USA)**
- SPP (USA)
- FPL (USA)
- Selpac (Central America)
- SING (Chile)
- Canutillar (Chile)
- Codelco (Chile)
- ICSA (Argentina)
- Light Rio SESA (Brazil)
- Light Energia (Brazil)
- Furnas (Brazil)
- Electronorte (Brazil)
- CHESF (Brazil)
- AES Sul (Brazil)
- AES Eletropaulo (Brazil)
- Landsnet (Iceland)
- Scottish Power (UK)
- **EIRGRID (Ireland)**
- SONI (UK)
- **RTE (France)**
- ADMIE (Greece)
- **STATNETT (Norway)**
- Energinet (Denmark)
- Serbia (Serbia)
- Ukrenenergo (Ukraine)
- Transelectrica (Romania)
- FSK (Russia)
- Libanon
- Syria
- Senegal
- Ivory Coast
- Libya
- STEG (Tunisia)
- EETC and West Delta (Egypt)
- Saudi SEC (Saudi Arabia)
- GCCIA (Saudi Arabia)
- Kuwait
- Qatar
- UAE
- Bahrain
- Yemen
- Ethiopia
- Manantali (Mali)
- Djibouti TSO (Djibouti)
- TANESCO (Tanzania)
- SONABEL (Burkina Faso)
- CEB (Togo/Benin)
- SEEG (Gabon)
- **ESKOM (South Africa)**
- CEB (Mauritius)
- Pakistan
- **PGCIL (India)**
- Bangladesh
- Thailand EGAT (Thailand)
- MEA Bangkok (Thailand)
- **Malaysia TNB (Malaysia)**
- EVN (Vietnam)
 - Central (Danang)
 - South (HCMC)
- Indonesia PLN (Indonesia)
 - Sumatera
 - Pontianak
 - Manado
 - Makassar
- NCG China (China)
- CPL Hong Kong (China)
- **Korea Kepco (Korea)**
- PNG Power (Papua New Guinea)
- **AEMO (Australia)**
- Power Water (Australia)
- Electranet (Australia)
- SP Ausnet (Australia)
- Power Water Corp (Australia)
- **Transpower (New Zealand)**

India's grid evolution

“Today, the Indian power system is one of the largest synchronous grids in the world”

1. Initially, State grids were inter-connected to form regional grid and India was demarcated into 5 regions namely Northern, Eastern, Western, North Eastern and Southern region.
2. In October 1991 North Eastern and Eastern grids were connected.
3. In March 2003 WR and ER-NER were interconnected .
4. August 2006 North and East grids were interconnected thereby 4 regional grids Northern, Eastern, Western and North Eastern grids are synchronously connected forming central grid operating at one frequency.
5. On 31st December 2013, Southern Region was connected to Central Grid in Synchronous mode with the commissioning of 765kV Raichur-Solapur Transmission line thereby achieving **'ONE NATION'-'ONE GRID'-'ONE FREQUENCY'**.

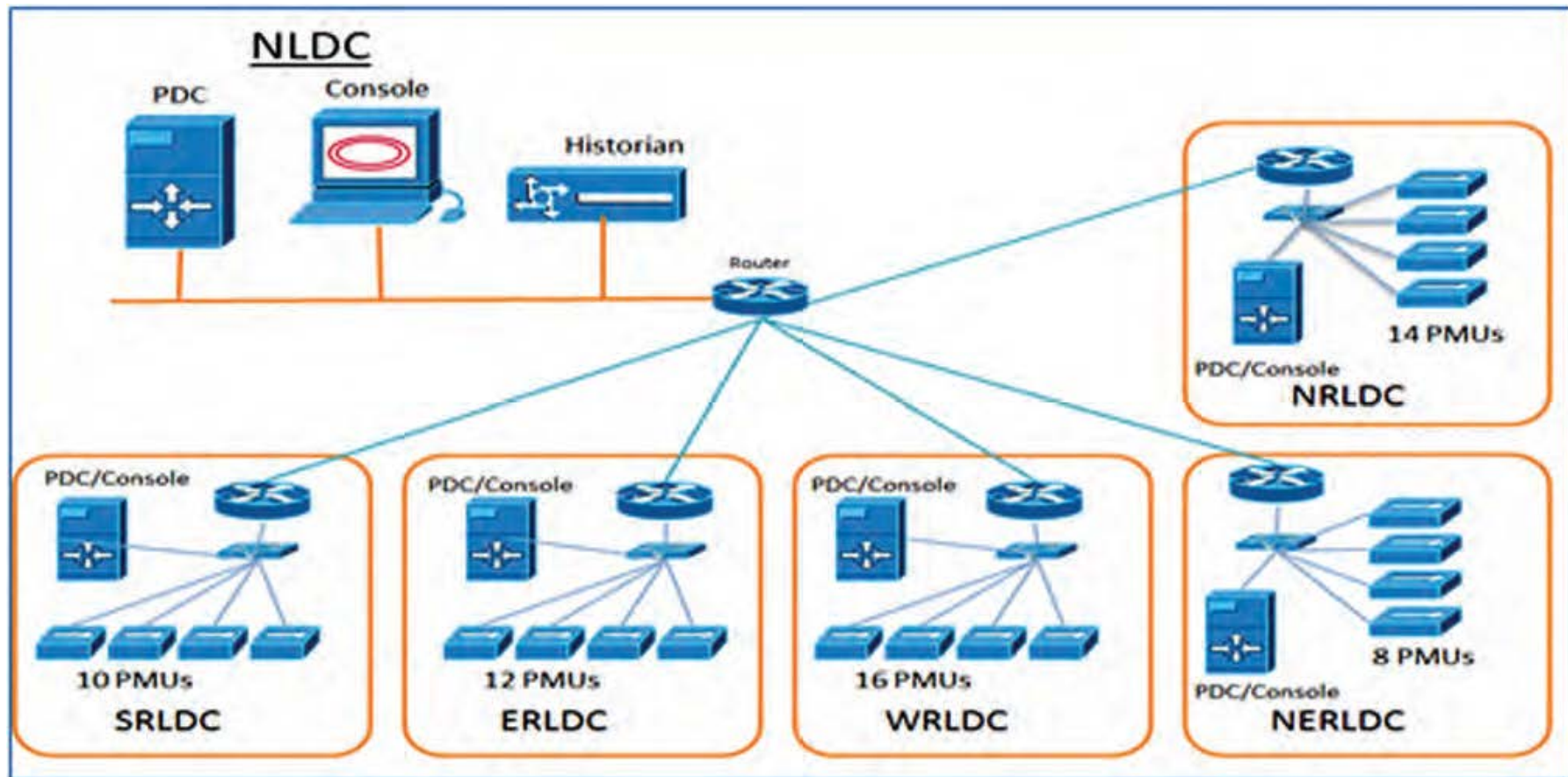
PMU Deployments in India Today

source: POSOCO – “Synchrophasors in India” Dec 2013



India WAMS Architecture

source: POSOCO – “Synchrophasors in India” Dec 2013



India URTDSM

Unified Real-Time Dynamic State Measurement

*The World's Largest WAMS Project,
on one of the World's largest Grids!*

- **Customer:**
 - Power Grid Corporation of India Limited, INDIA
- **Scope:**
 - Two Packages covering all 5 Regions of India
 - Phasor Data Concentrator for 34 Control Centers
 - > 1000 Phasor Measurement Units for 351 Substations



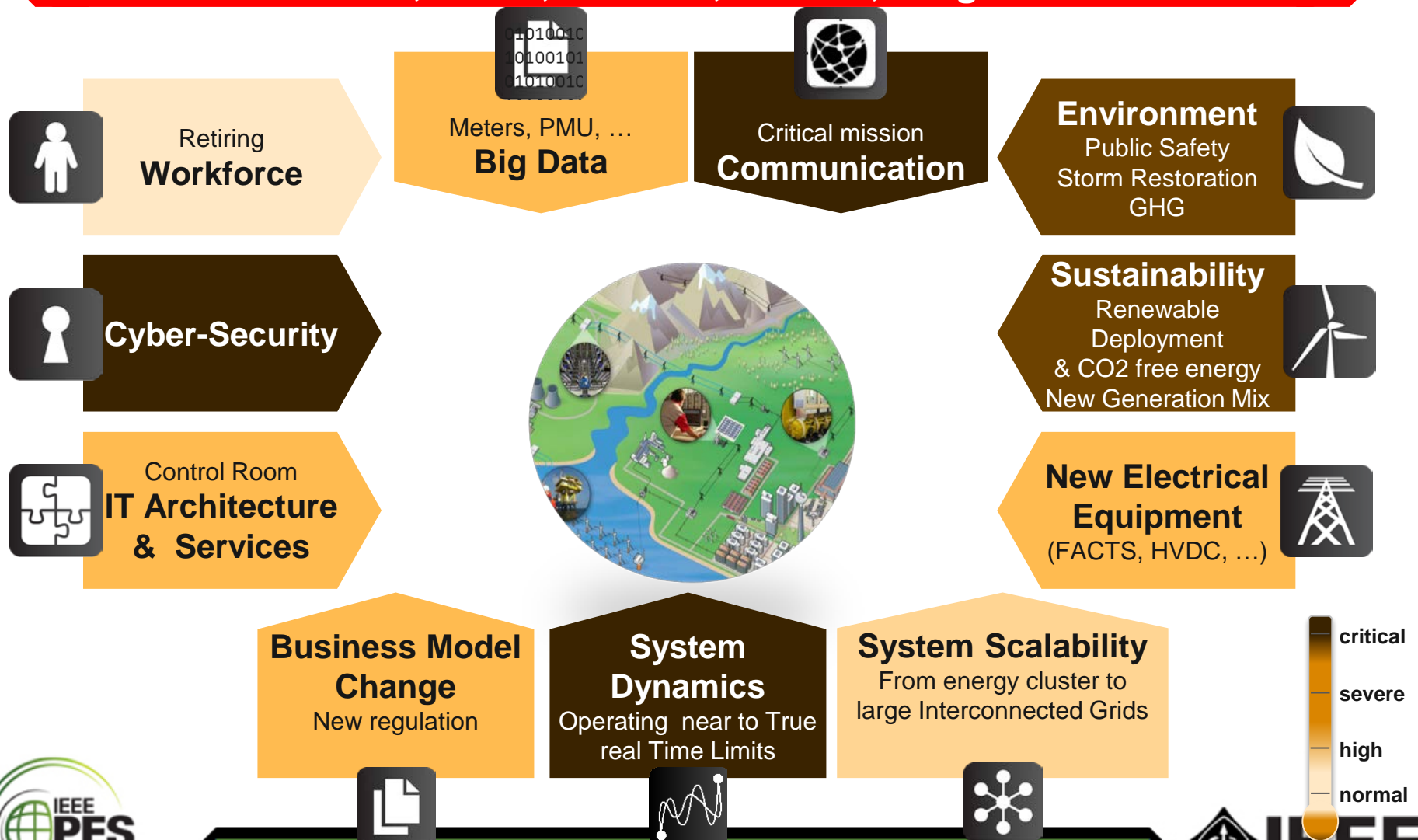
source: www.powergridindia.com

Agenda

1. Overview of the Power Grid
2. EMS – Genesis & Evolution
3. EMS Trends Today
4. Synchrophasor Benefits for EMS Grid Operations
5. Practical Deployments of Synchrophasors
6. India Synchrophasor project
- 7. Evolution Towards a Smarter Grid**

Today's and tomorrow's grid challenges

Plan, Model, Measure, Monitor, Mitigate



What is a Smarter Grid (SG)?

“A precise definition of the Smart Grid remains elusive as organizations invest in the idea that the development and application of technology to the electrical grid has value today and in the future”

IEEE:

“The term ‘Smart Grid’ represents a vision for a digital upgrade of distribution & transmission grids both to optimize current operations and to open up new markets for alternative energy production.”

FERC:

“Grid advancements will apply digital technologies to the grid and enable real-time coordination of information from both generating plants and demand-side resources.”

Wikipedia:

“A Smart Grid delivers electricity from suppliers to consumers using digital technology to save energy, reduce cost, and increase reliability.”

DOE:

“A smarter grid applies technologies, tools, and techniques available now to bring knowledge to power – knowledge capable of making the grid work far more efficiently...”

GE:

“The Smart Grid is in essence the marriage of information technology and process-automation technology with our existing electrical networks.”

Common themes of a smarter grid

- **Efficiency**
 - *Demand response*
 - *Consumer savings*
 - *Reduced emissions*
- **Technology**
 - *Two-way communication*
 - *Advanced sensors*
 - *Distributed computing*
- **Reliability**
 - *Interconnectivity*
 - *Renewable integration*
 - *Distributed generation*

US statistics

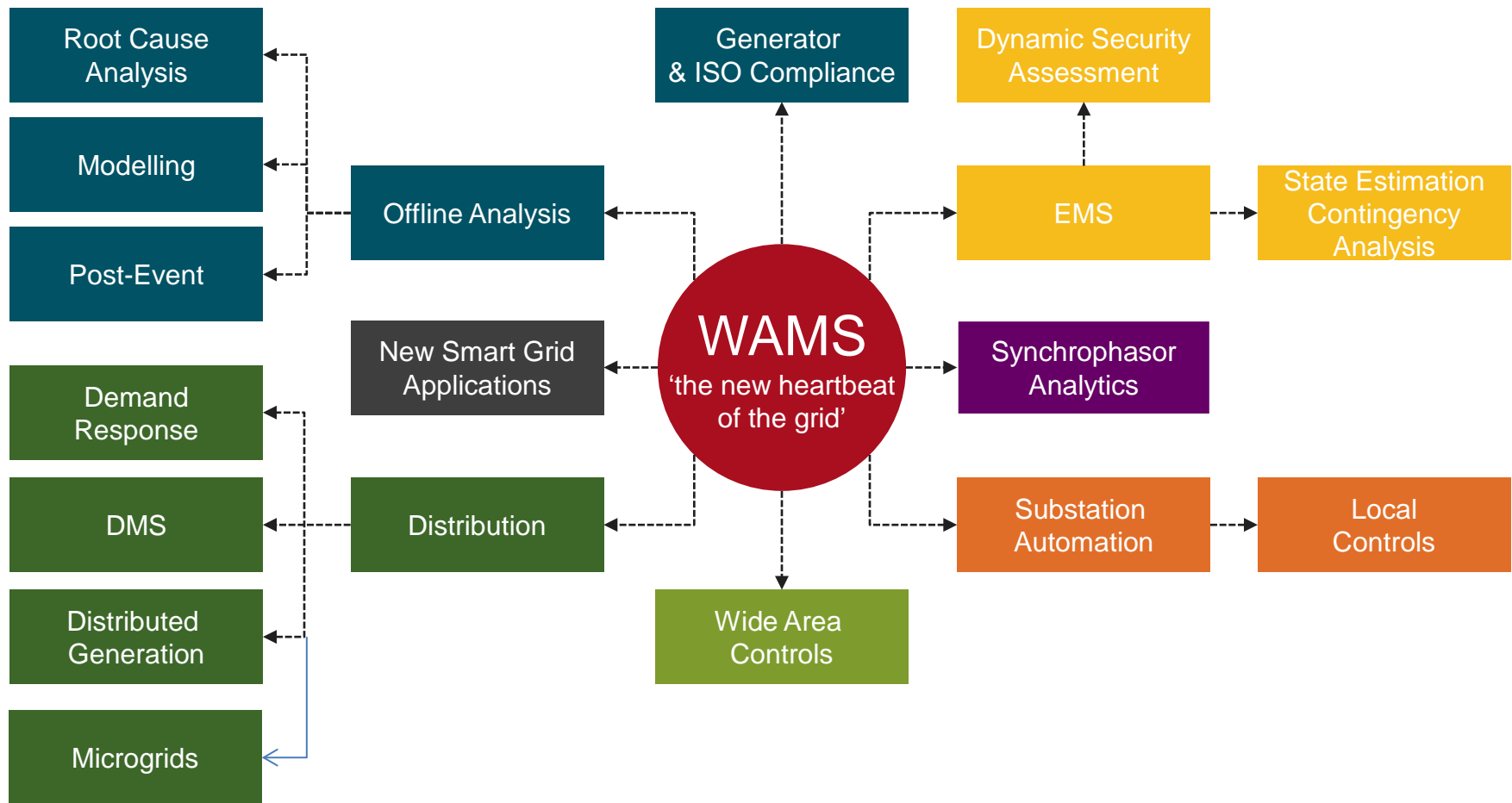
source: IEEE P&E, jan/feb 2014 p 112, – Massoud Amin, ‘in my view’ article

- Cost US Outages from all sources:
 - \$80-188B annually
- A smarter grid means:
 - Reduce low-end \$80B estimate to \$31B – savings of \$49B annually
 - Increase system efficiency by 4.5% - \$20B savings annually
 - Reduce CO2 emissions by 12-18%
- Costs of making the grid smarter:
 - \$338B to \$476B for SG infrastructure
 - \$82B in SG hardening costs
- Costs for a 20 year deployment:
 - \$25-30B per year.
 - ROI also includes job creation and economic stimulus
 - Estimate \$1 invested returns \$2.80 -6 to the broader economy.

How do you Measure whether the Grid is Smarter?

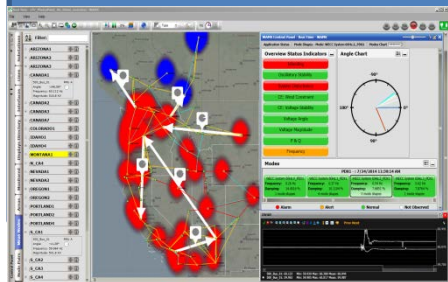
- Improve Power Delivery System Efficiency
 - 4 to 6 % in distribution systems
- Improve Reliability of supply to customers
 - SAIFI, SAIDI and CAIDI
- Improve Voltage Regulation
 - ± 5 % (114-V to 126-V on 120-V basis)
- Improve Frequency Regulation
 - ± 0.05 Hz (59.95- to 60.05-Hz on 60-Hz basis)
- Reduce Unbalance in 3-phase networks
 - ± 5 % (both negative- and zero-sequence unbalance)
- Minimize cost of operation to reduce electric bill to consumers
- Improve Security (system and cyber)

Managing the Future Grid

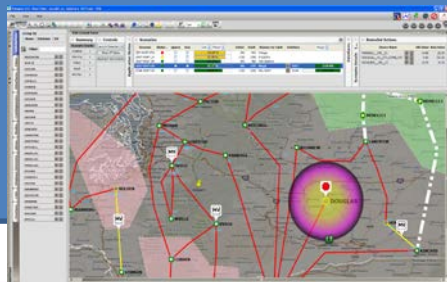


Enhanced Situational Awareness in the Control Room

Frequency Stability



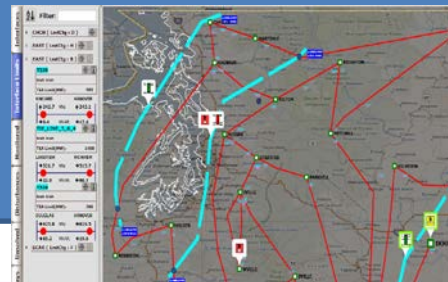
Voltage Stability



Oscillatory Stability



Transient Stability



Real-Time Situational Awareness



Grid Reliability and Security

Wide Area
Security

Steady State
Security

Dynamic
Security

Look-Ahead
Studies

Asset Health
Management

Cyber
Contingency

PMU &
Oscillation
Monitoring

EMS/DMS
OMS

DSA

Gen, Load,
DER
Forecast

Non-
Operational
Data

Cyber
Security
Engine

Measurement
Based Apps

Network
Model Based
Apps

Network
Model Based
Apps

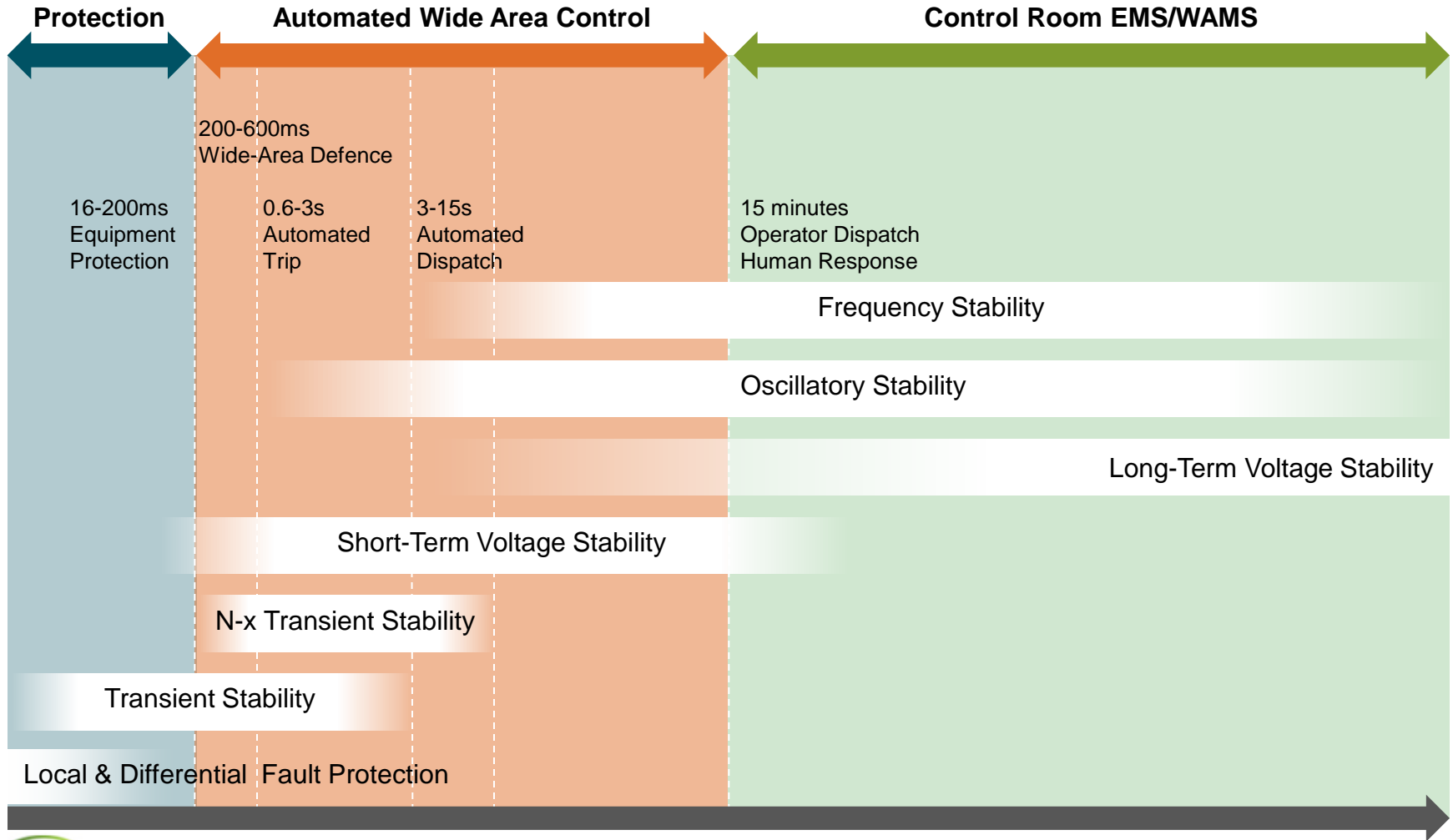
Weather
Conditions

Condition
Monitoring
DLR

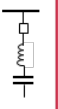
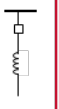



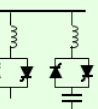
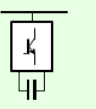
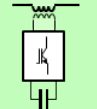
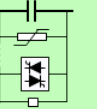
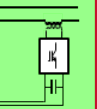
Cyber
Security
Services

Wide Area Control

Bridging the grid control gap!



Grid Control Devices

						FACTS Devices					
						<i>Shunt</i>		<i>Series</i>		<i>Combined</i>	
Solution Problem		M S C	M S R	SC	SR	P S T	SVC (TSR/ TCR/ TSC)	STAT -COM D-STAT -COM	SSSC (DVR)	TCSC TSSC TPSC	IPFC UPFC
Not appropriate	Voltage Control – Steady State	☹	☹	☹	☹	☹	😊	😊	😊	☹	☹
	Voltage Control – Dynamic	☹	☹	☹	☹	☹	😊	😊	😊	☹	☹
	Phase Balancing – Steady State	☹	☹	☹	☹	☹	😊	😊	☹	☹	☹
Adequate	Phase Balancing – Dynamic	☹	☹	☹	☹	☹	😊	😊	☹	☹	☹
	Power Oscillation Damping	☹	☹	☹	☹	☹	😊	😊	😊	😊	😊
Best	Transient Stability	☹	☹	😊	☹	☹	😊	😊	☹	😊	😊
	Power Flow – Steady State	☹	☹	😊	😊	😊	😊	😊	😊	😊	😊
	Fault Current Limitation	☹	☹	☹	😊	☹	☹	☹	☹	☹	☹
Circuit											

MSC = Switched Capacitor
MSR = Switched Reactor
SC = Series Capacitor
SR = Series Reactor
PST = Phase Shifting Transformer

SVC = Static Var Compensator
TSC = Thyristor Switched Capacitor
TSR = Thyristor Switched Reactor
TCR = Thyristor Controlled Reactor
DVR = Dynamic Voltage Restorer

STATCOM = Static Synchronous Compensator
D-STATCOM = Distribution STATCOM
TSSC = Thyristor Switched Series Capacitor
TCSC = Thyristor Controlled Series Capacitor
TPSC = Thyristor Protected Series Capacitor

IPFC = Interline Power Flow Controller
UPFC = Unified Power Flow Controller
SSSC = Static Synchronous Series Compensator

“Dispatching AC Power” in the grid with FACTS

Adding ‘muscle’ to the grid!

$$P = \frac{V_1 \cdot V_2 \cdot \sin(\delta)}{X_{line}} + P \text{ (HVDC/FACTS)}$$

Voltage Control, SVCs
TCR, STATCOM, etc

Phase angle regulators,
IPC, SSSC, UPFC

Series Capacitors/Reactors, TCSC,
TSSC, TCSR, TSSR, IPC etc

HVDC/FACTS
Emergency Injections

Storage Technology Opportunities

Technology	Advantage	Disadvantage	Power	Energy
Pumped Storage	High Capacity / Low Cost	Site Requirement		●
CAES	High Capacity / Low Cost	Site Requirement		●
Flow Battery	High Capacity / Independent Power and energy	Low Density (Large footprint)	○	●
Metal – Air	Very High Density	Charging is difficult / Lifetime		●
NaS	High Power and energy densities / High Efficiency	High in cost / Safety concerns	●	●
Li-Ion	High power and energy densities and efficiency	Cost	●	○
Lead – Acid	Low cost	Limited Lifecycle	●	○
Flywheels	High Power	Low Energy Density	●	
Capacitors	Very long cycle life / Efficiency	Low Energy Density	●	

Future Grid Management

- Shifting from a Reactive paradigm to a Proactive paradigm!
- Facilitate smooth integration of:
 - Microgrids,
 - Renewables,
 - Distributed Generation,
 - Demand Response,
 - etc

Today's Smart Automation for Protecting the integrity of the grid

- Local, Device protection predominantly:
 - Transformers, lines, bus structures, generating units, etc
- System-wide protection:
 - AGC: Automatic Generation Control
 - A pioneering Smart-Grid application since the '70s!
 - Automatically maintains system's frequency and tie-flows
 - Remedial action schemes (RAS), special protection schemes (SPS or SIPS), etc.
 - Drawbacks are:
 - Logic is fixed and does not adapt to current conditions
 - Are conservative by design;
have to work for a wide range of 7/24 operating conditions
 - Under/over-voltage and under/over-frequency load shedding

Tomorrow's Smarter Automation will include: Fast local and wide-area automated control!

- Develop protective control schemes that dynamically adapt to current power system conditions,
to preserve the integrity of the “grid” as an entity.
- Tightly integrate fast sub-second measurements with fast sub-second controls (FACTS, HVDC, etc)
- Dispatch the transmission system with FACTS, HVDC, etc

Transition to Wide Area Grid Control

Think Globally
&
Act Locally!

“The Future A’int what it used to be!”

- [illegible]

Italy takes the next step towards the European Supergrid

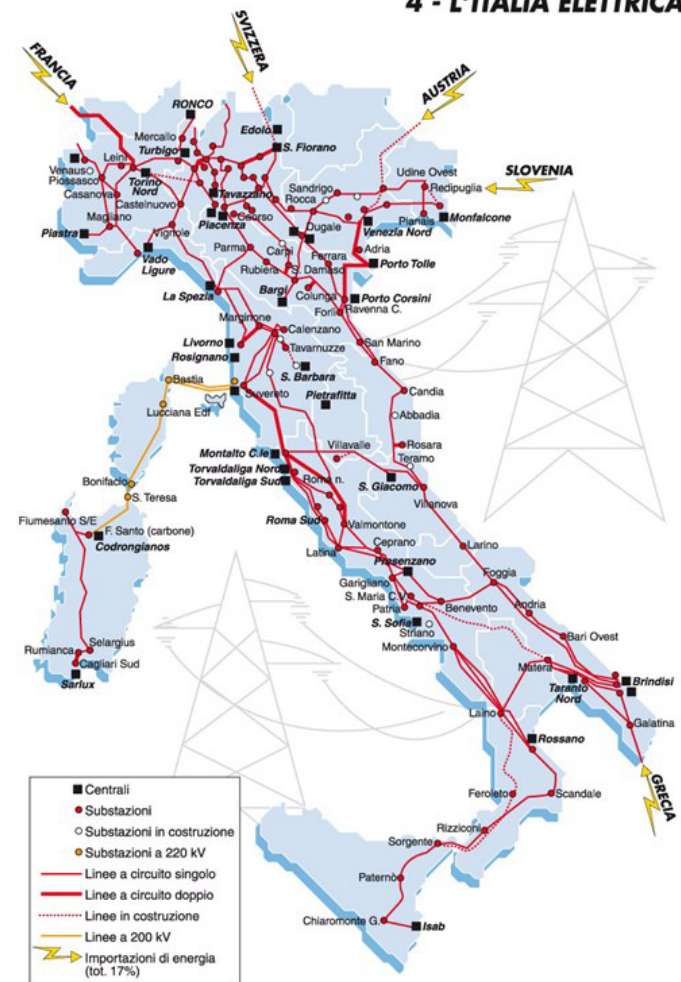
PARIS, May 2, 2016 – The European Supergrid takes another step towards smarter, more sustainable electricity transmission. Last year, Transmission System Operator, Terna Rete Italia, SpA, took delivery of e-terraphasorpoint: the world-leading Wide Area Monitoring (WAMS) software system from GE GE (NYSE: GE). This is GE's first deployment of its synchrophasor-based measurement and monitoring software in Italy. Now live, e-terraphasorpoint has improved both grid visibility and electricity availability across the Italian utility's entire network. And thanks to WAMS agreements, they are expanding their visibility to include neighboring countries.

Terna has been a leader in adopting WAMS technology. In this first phase, they are using the e-terraphasorpoint software to collect data from approximately half of their installed Phasor Measurement Units (PMUs). GE's e-terraphasorpoint software is fully scalable. It will allow Terna to quickly move into the next phase in the near future and expand their system to double the number of PMUs connected, as well as collect data from partner countries. This is the basis of the European Supergrid: improving network intelligence to optimize availability and enable cross-border energy trading.

GE's complete e-terraphasorpoint base package includes visualization, notification, alarm management and historical data services, including additional configuration, training, testing and warranty support. E-terraphasorpoint works to optimize capacity, while detecting potential disturbances to the grid. It provides actionable information so that system operators can make fast, informed decisions. With its "big picture" capabilities it is able to provide an overview of available renewable and distributed energy sources, making integration easier to anticipate and manage. This is essential, as Terna has fixed CO2 emission reduction goals at 15 million tons per year. Finally, by better understanding system constraints and localized pain points, network analysts will be in a better position to plan future improvements cost effectively.

"The European Supergrid is fast becoming a reality," said Karim El Naggat, Software Solutions General Manager, GE's Grid Solutions and Chief Digital Officer, GE Energy Connections. "Italy's deployment of GE's e-terraphasorpoint technology makes this transition much more viable. It increases visualization and optimization across borders. This solution helps each interconnected country benefit from the highest possible availability of sustainable electricity, using the smartest GE digital solutions to make these connections."

4 - L'ITALIA ELETTRICA



Further reading..

- 2016 IEEE Smart Grid newsletter:
- <http://smartgrid.ieee.org/newsletters/april-2016/transitioning-from-wide-area-monitoring-to-wide-area-management>
- 2015 IEEE PETS open access article:
“Proactive Management of the Future Grid,” IEEE Power & Energy Technology Systems Journal, Open Access article:
<http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7080837>

Videos of PMU Solutions

www.naspi.org

www.youtube.com

search for ‘psymetrixsolutions’

