Synchrophasors: Overview & Applications

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Multilin

The Need for Wide-Area Measurements

- Following the east coast blackout, a federal commission was appointed
- Fault found with utility companies: no real-time knowledge of the state of the power system was available
- Recommendation made: establish a real-time measurement system and develop computer based operational and management tools

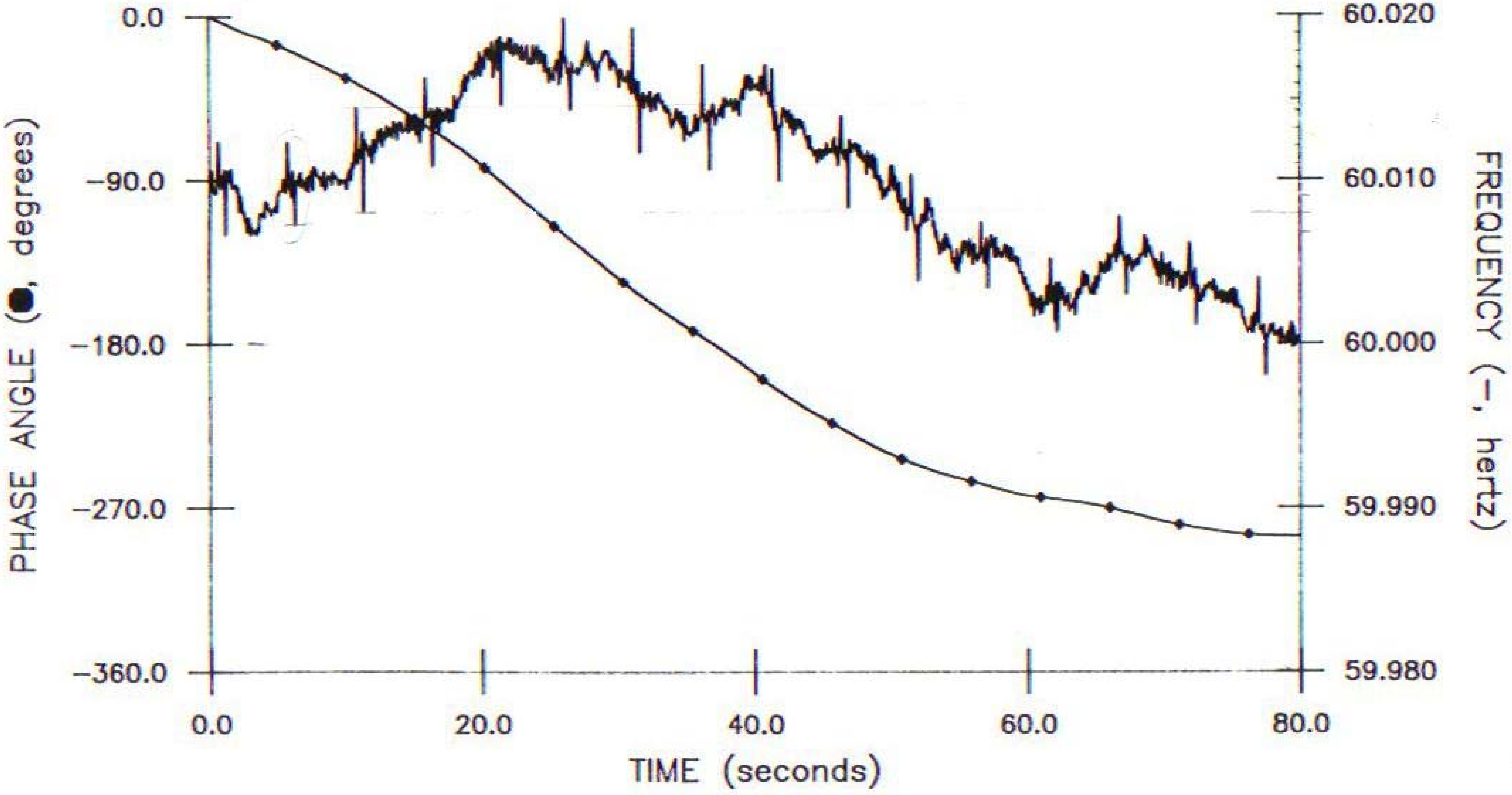
This Was after the 1965 blackout!

DOE/FERC Feb 2006 Report to Congress:

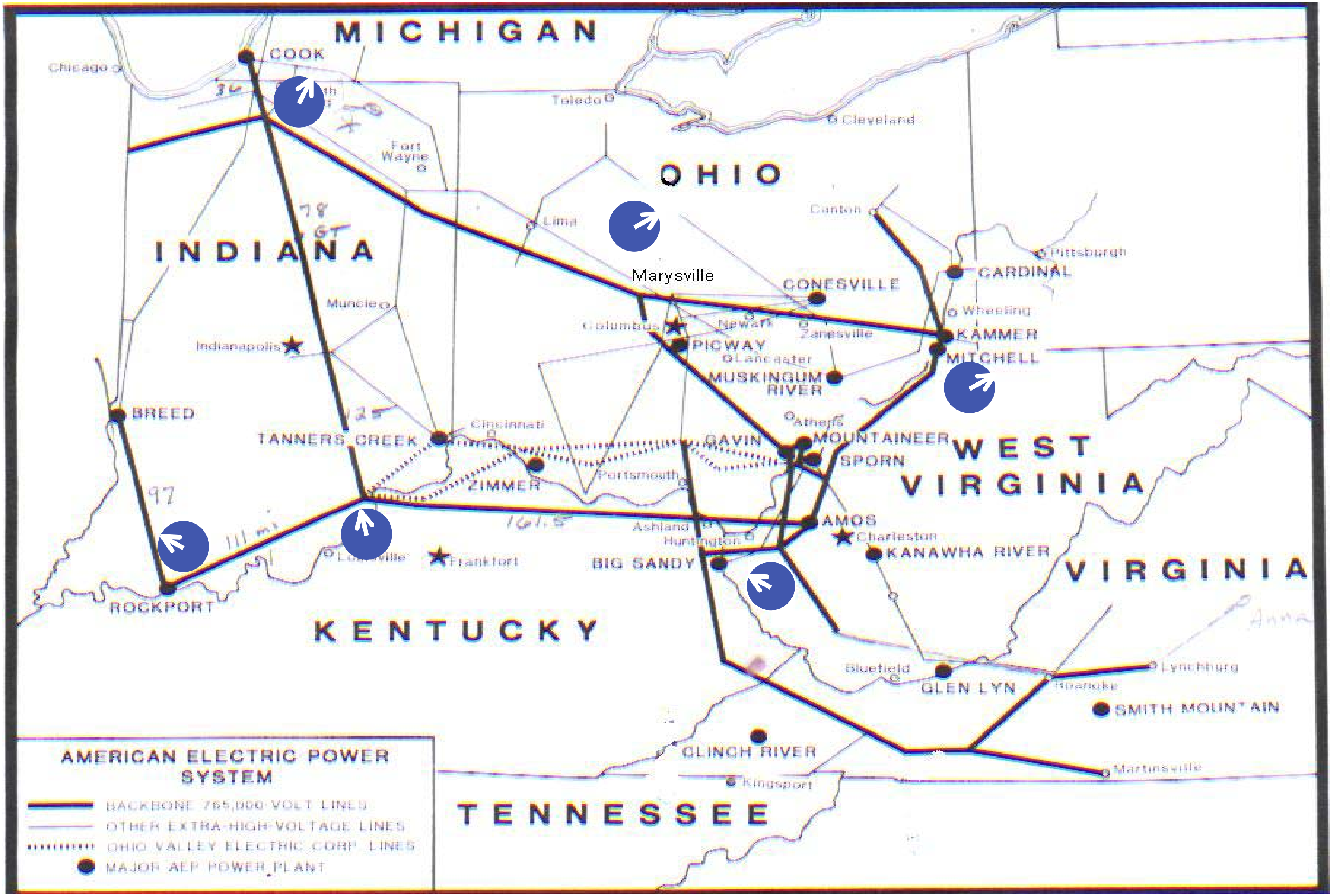
- 2003 Blackout due, in part, to “lack of awareness of deteriorating conditions”
- “Technology now exists that could be used to establish a real-time transmission monitoring system…”
- Additionally: NERC identified the need for “Situational Awareness” of the power grid

Ye Olde PAM Data

Marysville – 14:35 EST June 14, 1989

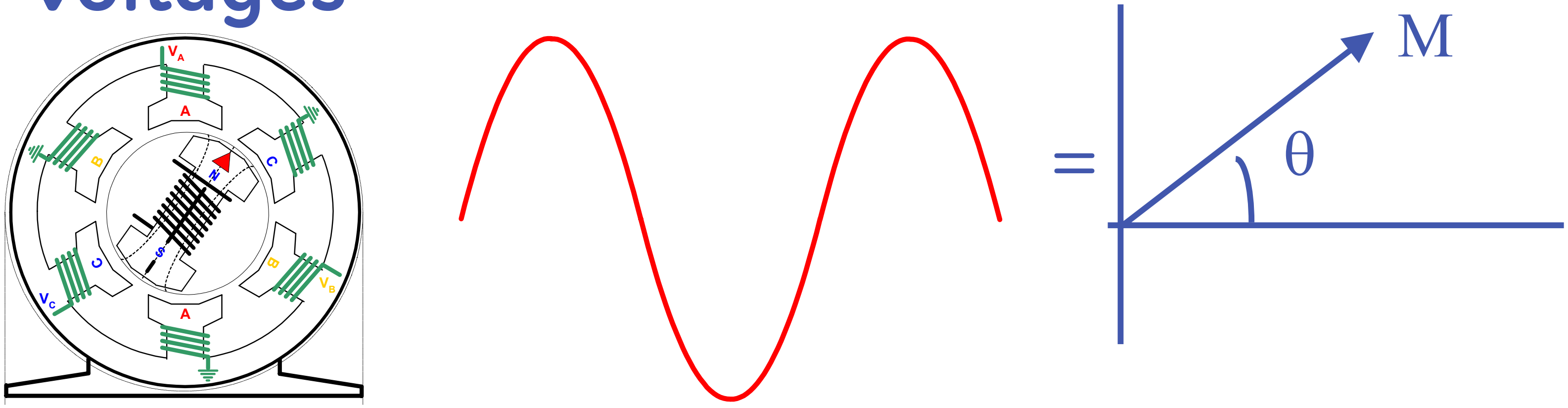


Synchrophasor View of the Power System



Origin of Phasors

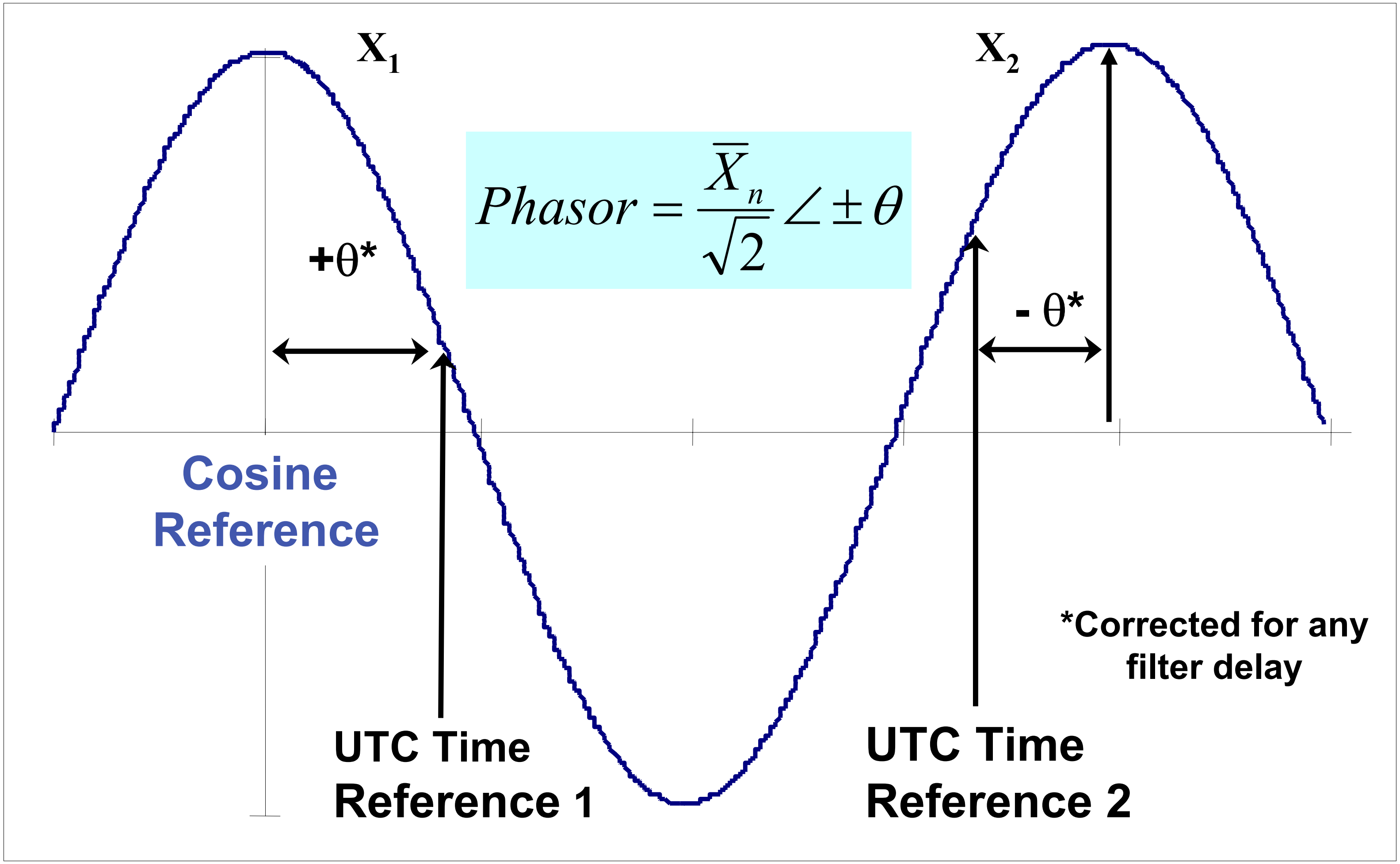
- Rotating rotors = alternating currents & voltages



- Phasors are well established means of representing ac circuits

Charles Proteus Steinmetz (1865-1923)
Complex Quantities and their use in Electrical Engineering; Charles Proteus Steinmetz; Proceedings of the International Electrical Congress, Chicago, IL; AIEE Proceedings, 1893; pp.33-74.

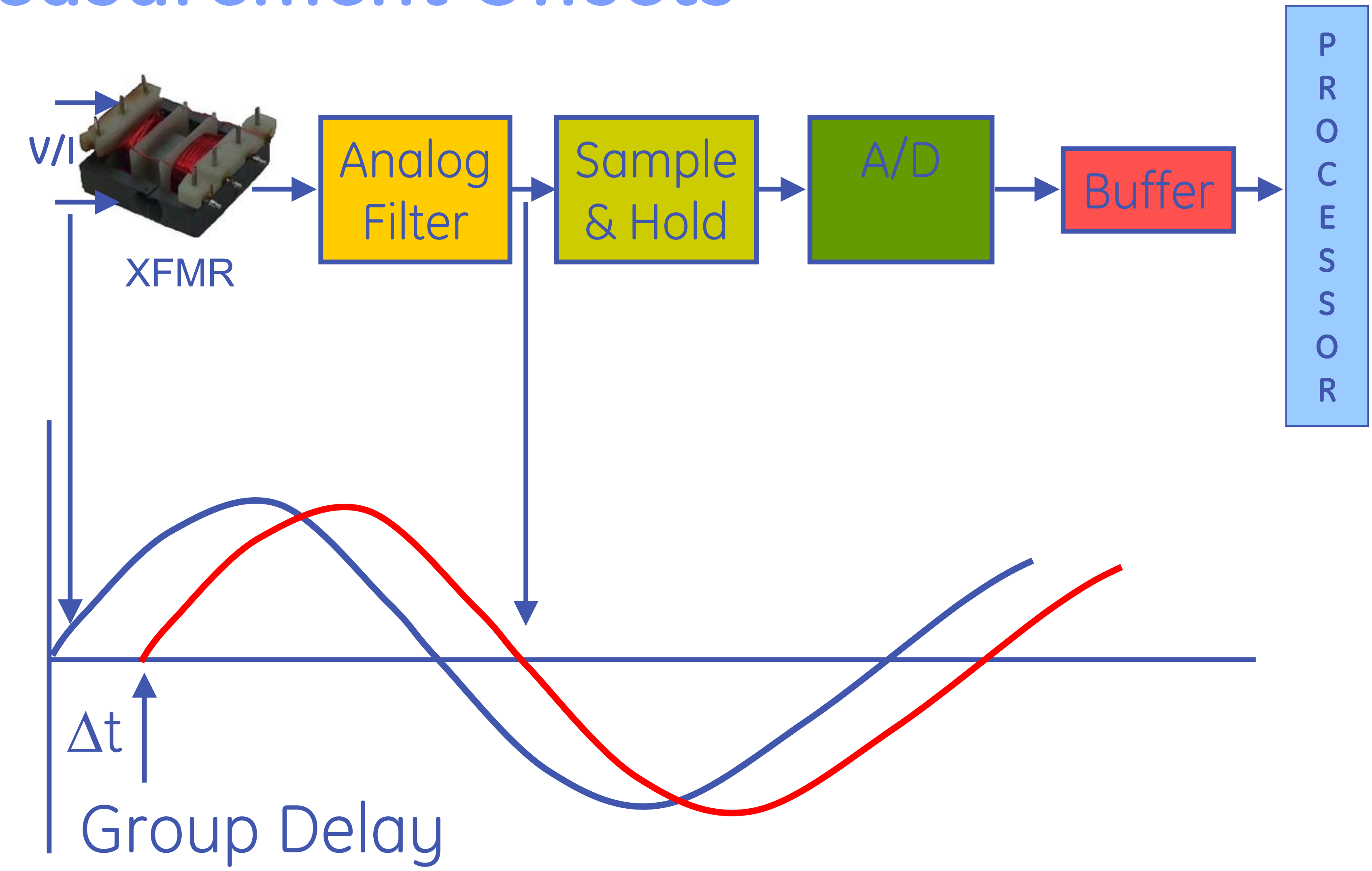
IEEE C37.118 Synchrophasor Definition



$$Phasor = \frac{\overline{X}_n}{\sqrt{2}} \angle \pm \theta$$

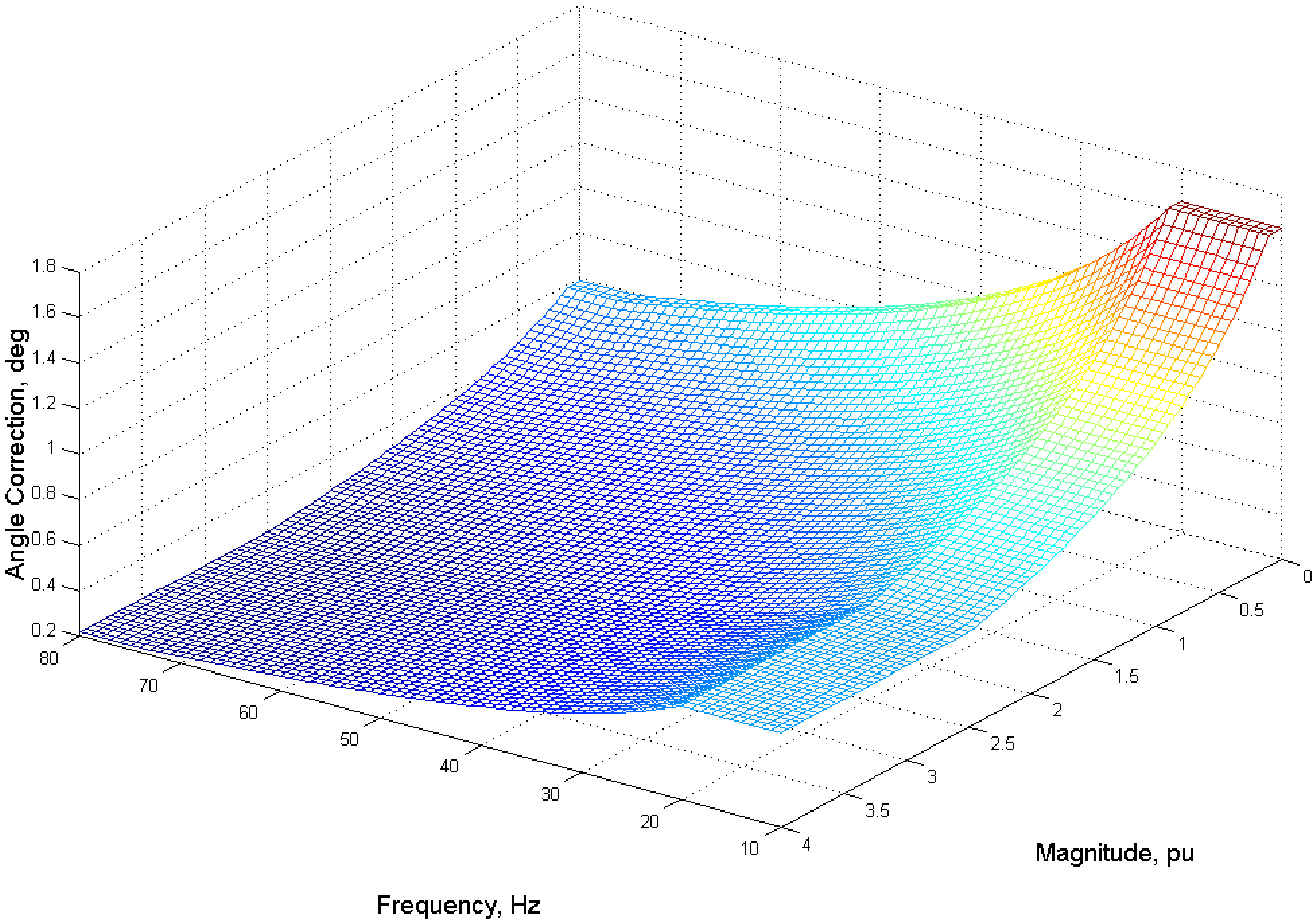
*Corrected for any filter delay

Measurement Offsets



PMU Must Compensate for Phase & Magnitude Errors!

Real-Time Correction - Currents



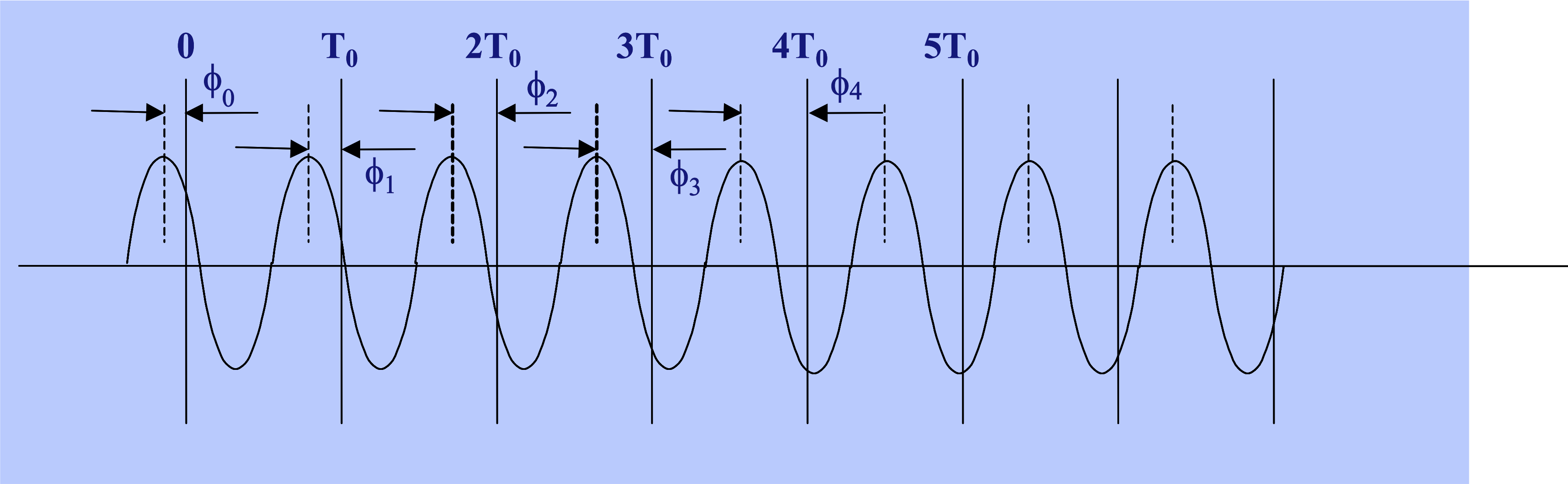
C37.118 Synchronous Reporting Rates

System Frequency	50 Hz		60 Hz				
Report rates (phasors/sec)	10	25	10	12	15	20	30

Optional Phasor Reporting Rates:
50/100 phasors/sec on 50 Hz systems
60/120 phasors/sec on 60 Hz systems

Synchronized Reporting

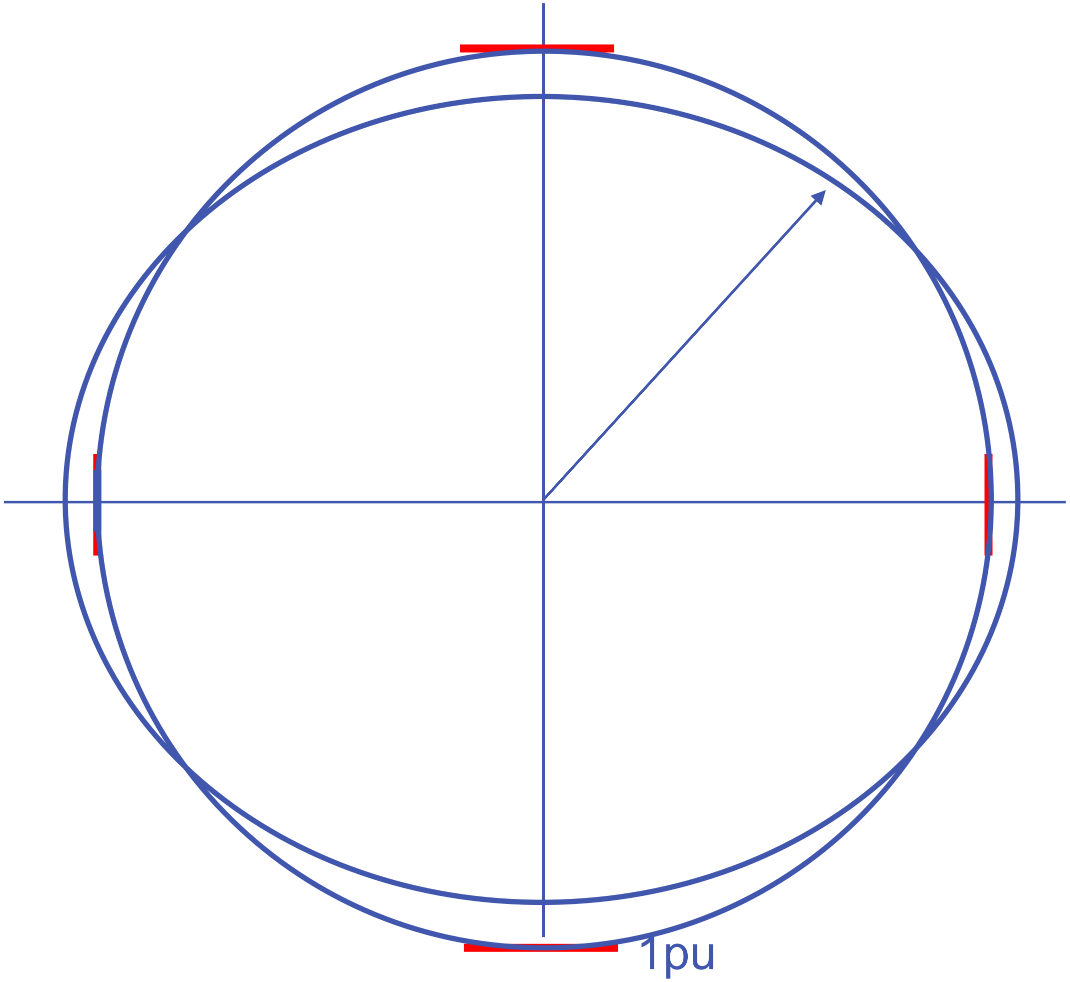
Report Rate = 60 Phasors/second



Where: 0 = Top of Second

$T_n = n*(1/60)$

Classic Fourier Response to off-nominal Frequency



Mathematical Foundation

Phasor Model and Taylor Series Expansion of Model

$$x(t) \approx \sqrt{2}\,\mathrm{Re}\,al(\overline{X}(t) \bullet e^{j2\pi \bullet f \bullet t}) \approx \sqrt{2} \bullet \mathrm{Re}\,al((\overline{X} + \dot{\overline{X}} \bullet t) \bullet e^{j2\pi \bullet f \bullet t})$$

Traditional “Boxcar” Phasor Calculation

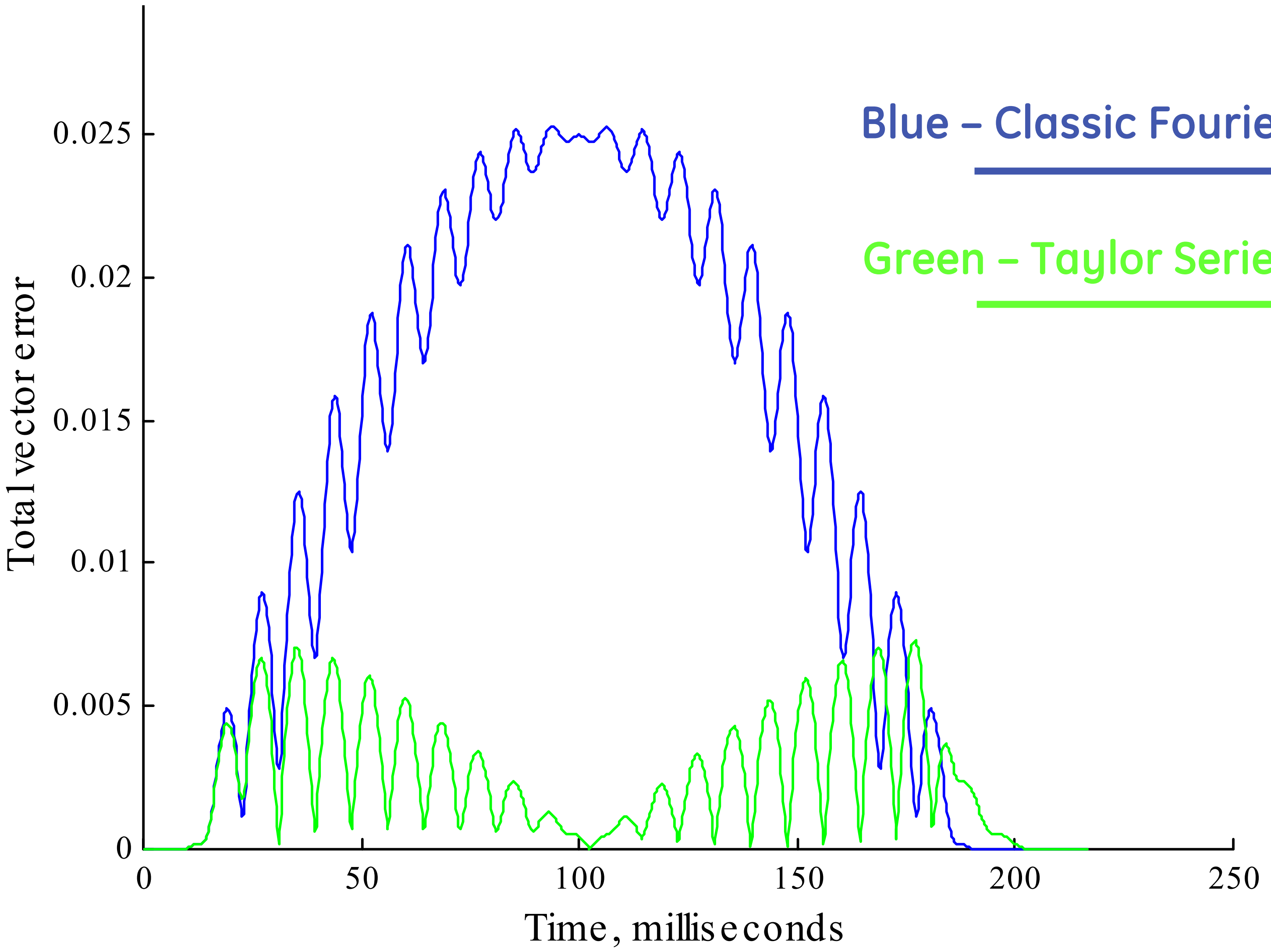
$$\overline{Y} = \frac{\sqrt{2}}{N} \sum_{n=-\frac{N}{2}}^{\frac{N}{2}-1} x(n) \bullet e^{-j(n+1/2)\frac{2\pi}{N}}$$

Compensated Synchronized Phasor$_1$

$$\overline{X}_M \approx \overline{Y}_M - j \bullet \frac{(\overline{Y}_M - \overline{Y}_{M-1})}{2N \bullet \sin(\frac{2\pi}{N})}$$

$_1$ Patent Pending

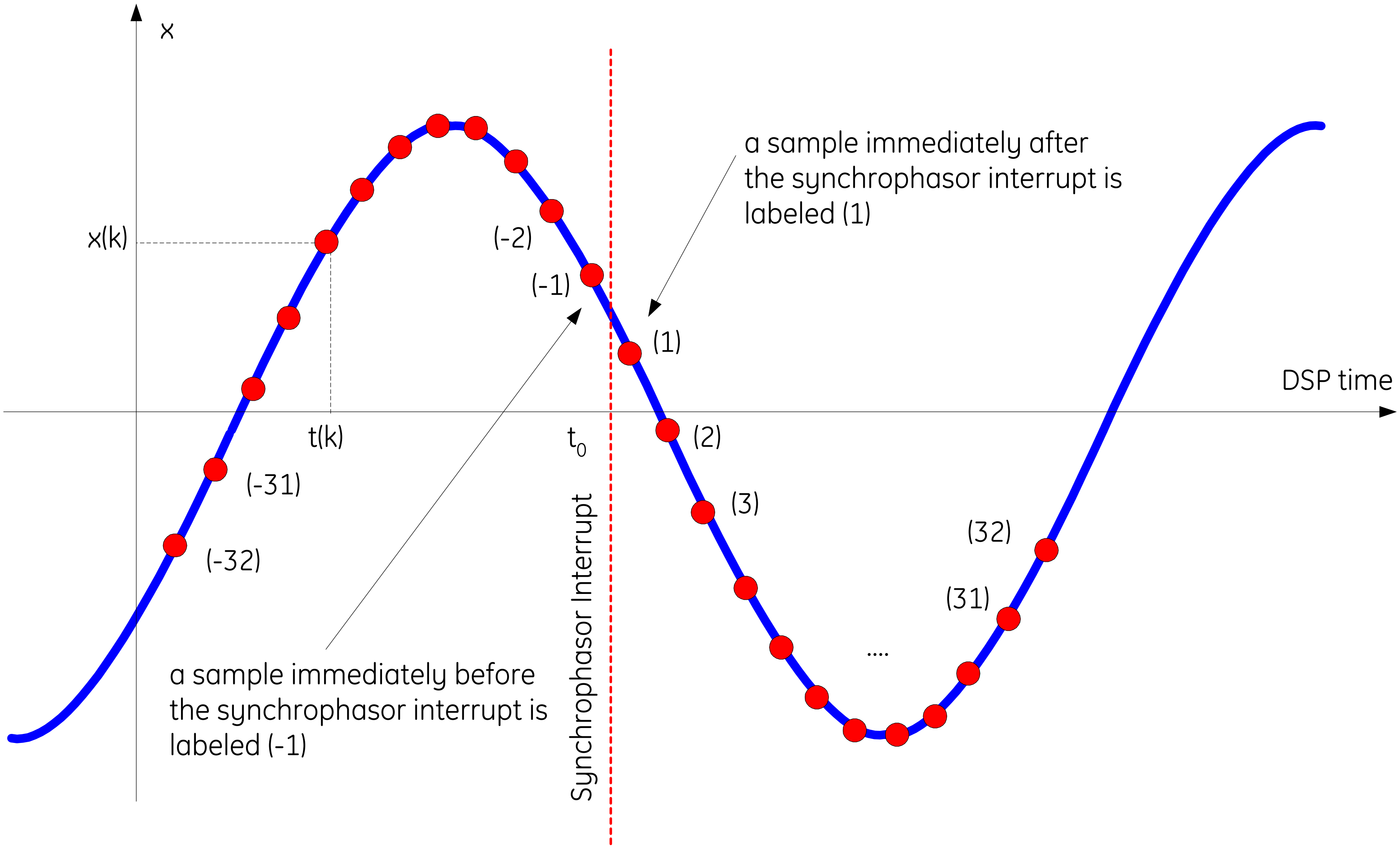
Vector Error to a Cosine Ramp



Blue – Classic Fourier Response

Green – Taylor Series Enhanced

Asynchronous Sampling & Timing



a sample immediately after the synchrophasor interrupt is labeled (1)

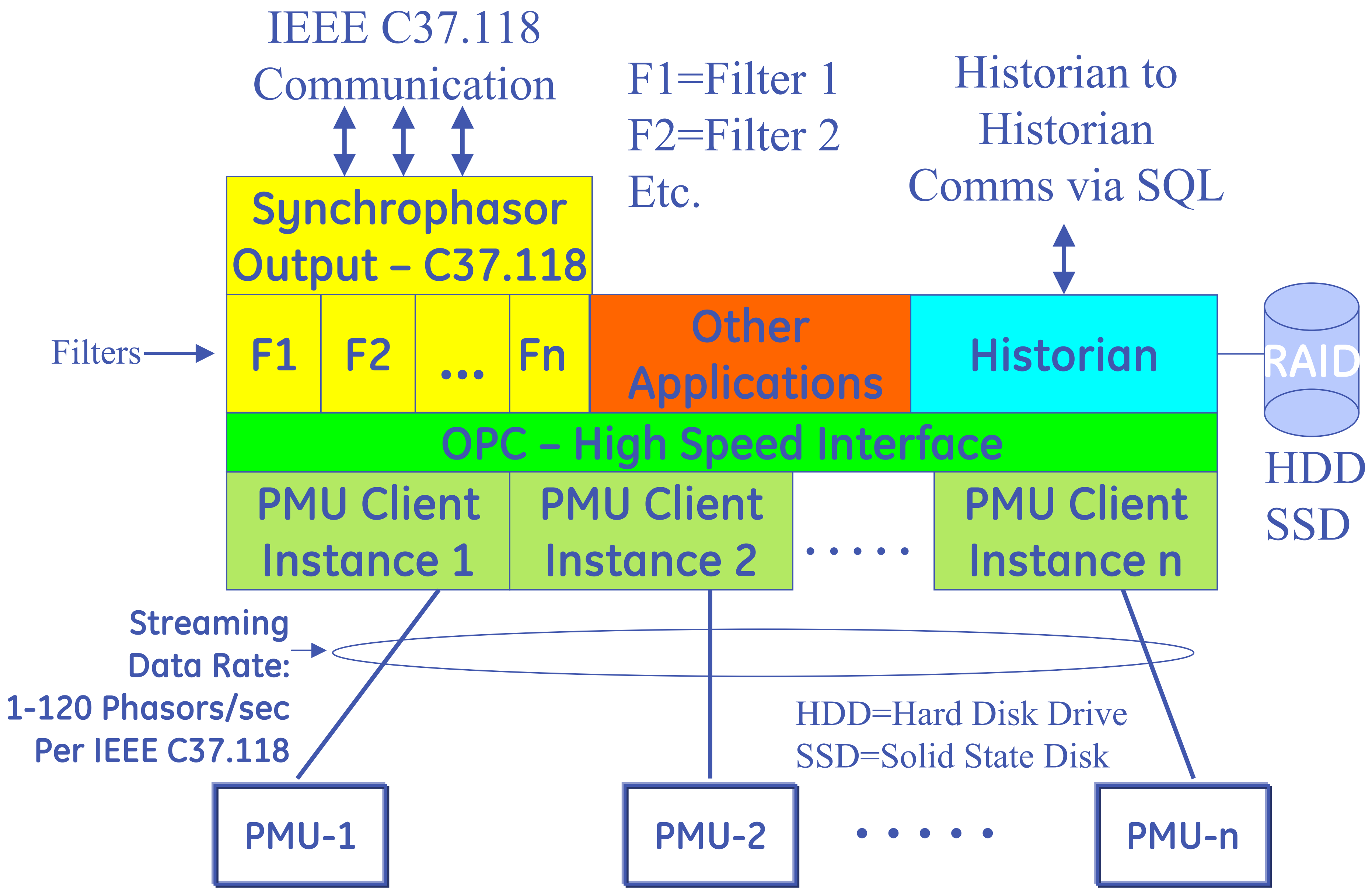
a sample immediately before the synchrophasor interrupt is labeled (-1)

Test Results of the 4-Parameter Model:

Over the frequency range of 45-70Hz:

- TVE for voltages < 0.30%
- TVE for currents < 0.40%
- TVE at 10% of THD < 0.45%

Phasor Data Concentrator Architecture



IEEE C37.118 Communication

F1=Filter 1
F2=Filter 2
Etc.

Historian to Historian Comms via SQL

Synchrophasor Output – C37.118

Filters

F1 | F2 | … | Fn

Other Applications

Historian

RAID

HDD
SSD

OPC – High Speed Interface

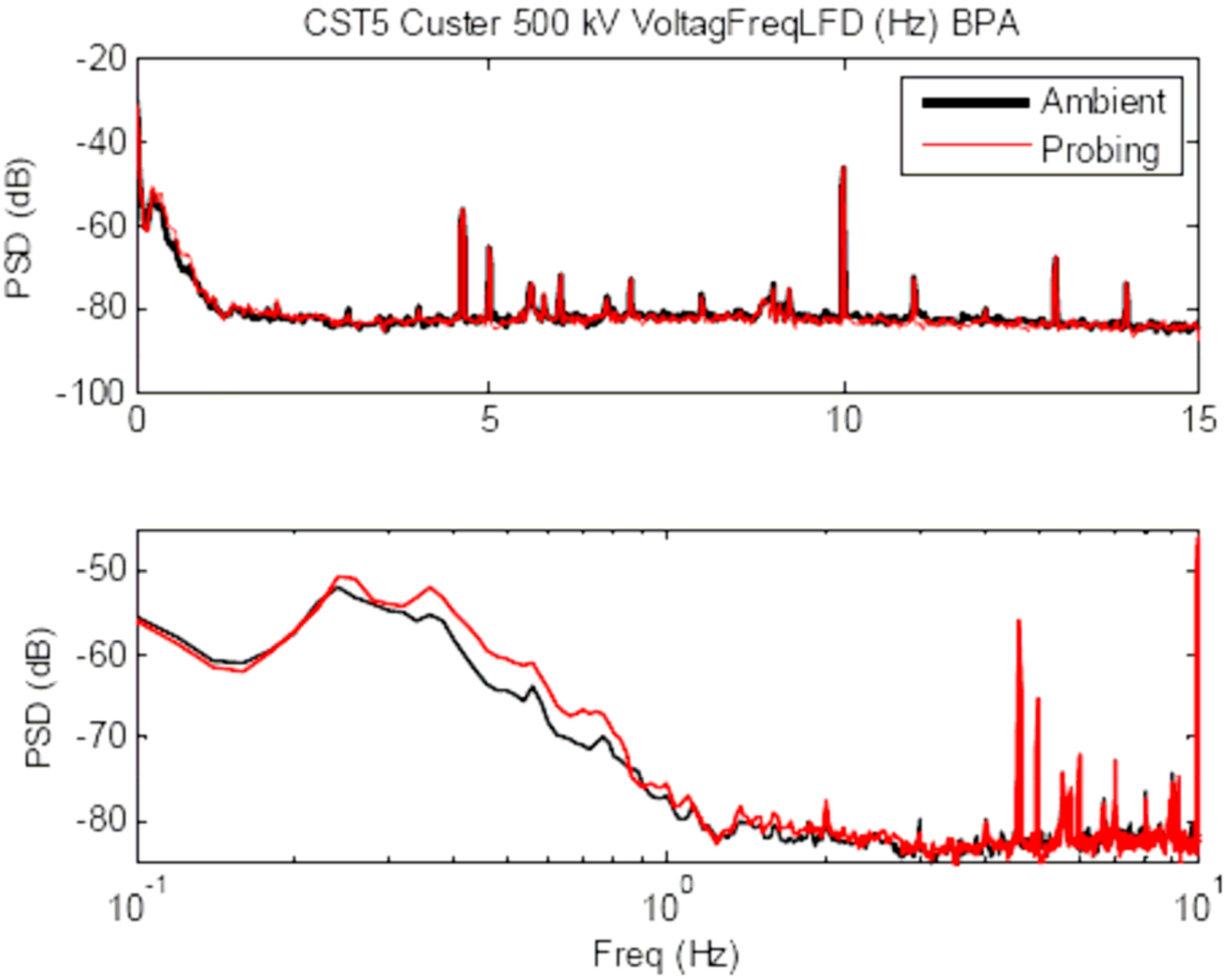
PMU Client Instance 1 | PMU Client Instance 2 | …… | PMU Client Instance n

Streaming Data Rate:
1-120 Phasors/sec
Per IEEE C37.118

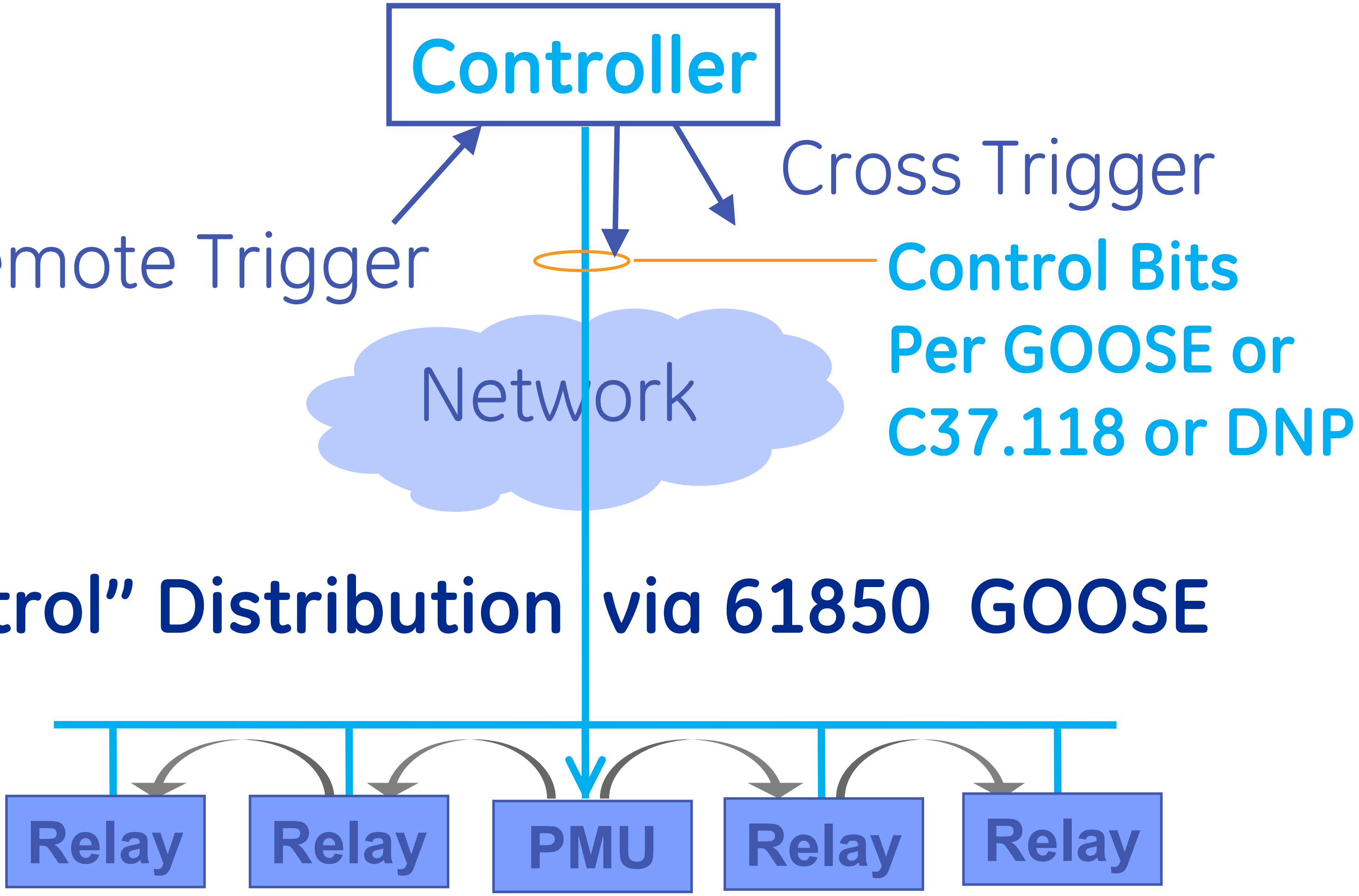
HDD=Hard Disk Drive
SSD=Solid State Disk

PMU-1 | PMU-2 | ….. | PMU-n

Power Density Spectrum – West Coast



PDC Remote Control



Controller

Cross Trigger

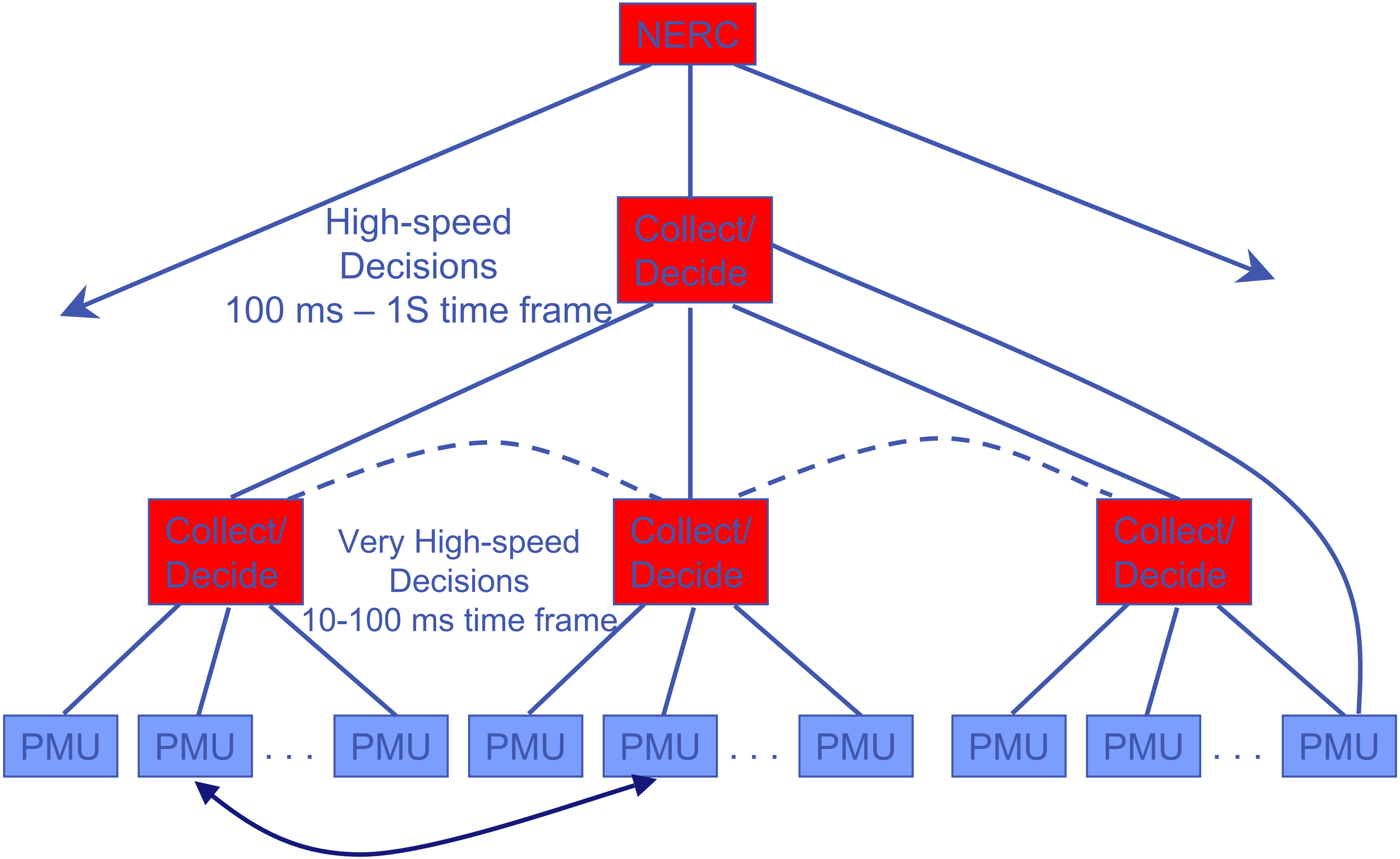
Remote Trigger

Control Bits
Per GOOSE or
C37.118 or DNP

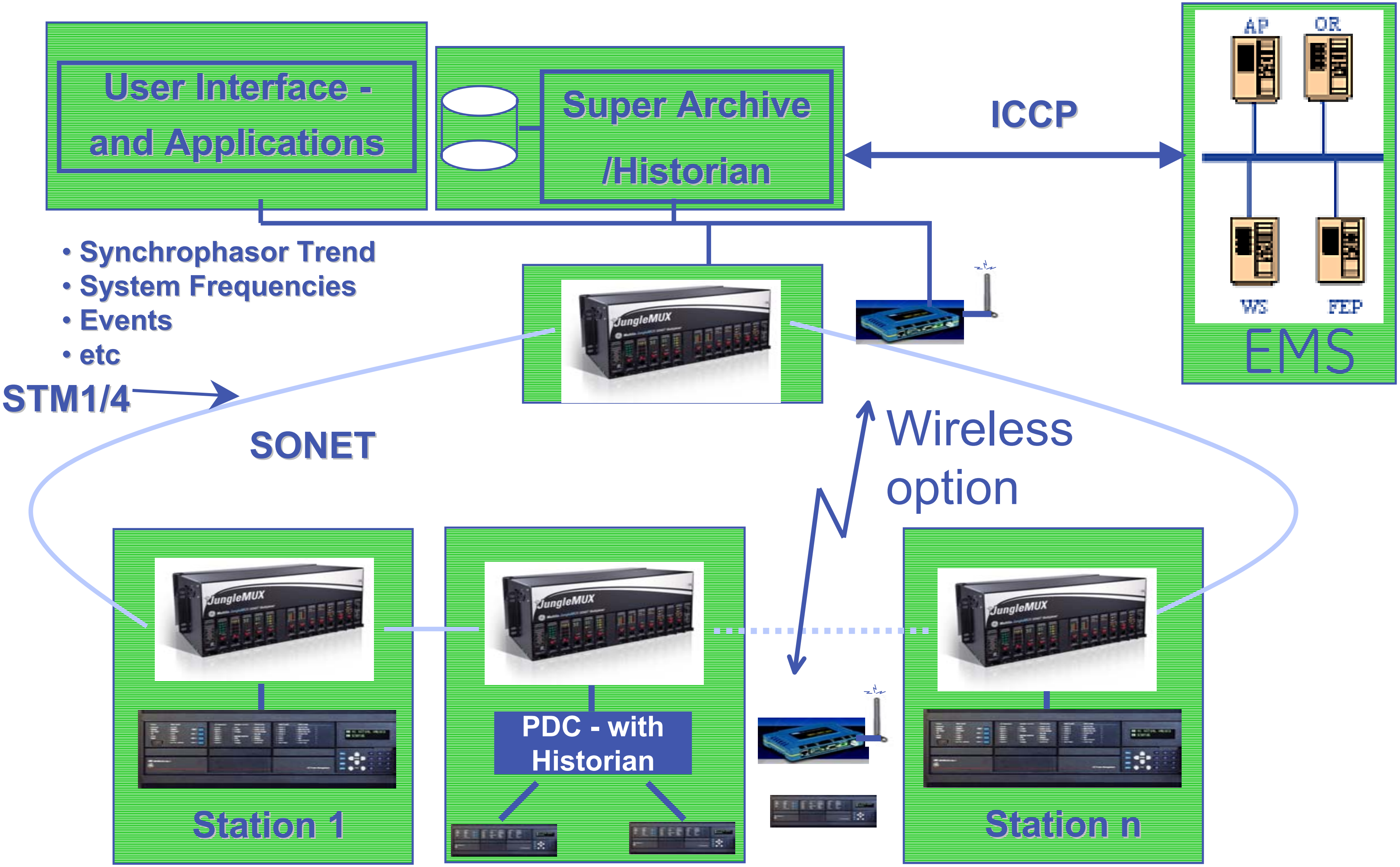
Network

"Control" Distribution via 61850 GOOSE

Reporting Hierarchy Options



Synchrophasor System Architecture



User Interface - and Applications

Super Archive /Historian

ICCP

EMS

AP

OR

WS

FEP

- **Synchrophasor Trend**
- **System Frequencies**
- **Events**
- **etc**

STM1/4

SONET

Wireless option

PDC - with Historian

Station 1

Station n

Decision: Stand Alone vs. Integrated PMU

Client/Server Functionality

- Client:
  - Request for Configuration
  - Request to Start/Stop Stream
  - File Request (not addressed in Standard)
  - Command Issuance
- Server:
  - Streams data / Sends configuration / files when requested
  - Provides operational status
    - Clock Synched
    - Triggered
    - Configuration Changed
- Responds to Commands

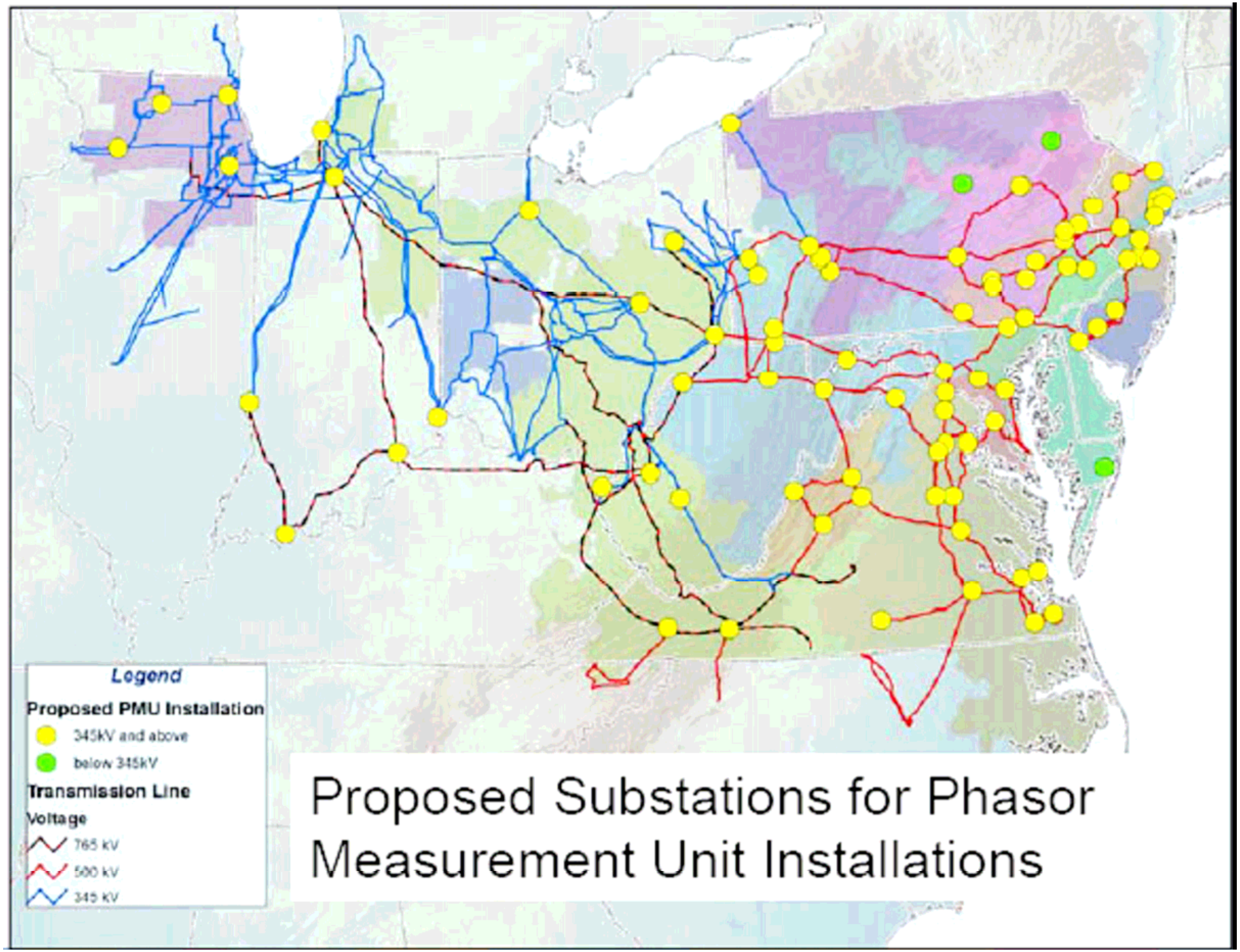
Streaming Data Rates – Single PMU

- Packet Model #1:
  - 14 Phasors
  - 8 Analogs
  - Frequency
  - ROCOF
  - 1 Digital Words
  - > All *Real* Numbers
  - > 60 Packets/sec
- Communication Bandwidth Requirement:
  - 106,560 Bits/sec

System Storage Requirements

- 100 PMU Model @ 60 Packets/sec:
  - 250 Bytes/packet/PMU
  - 25,000 Bytes/packet for 100 PMUs
  - 1.5 MB/sec
  - 90 MB/min
  - 5.4 GB/hour
  - 129.6 GB/day
  - 3.9 TB/month
  - 46.6 TB/year

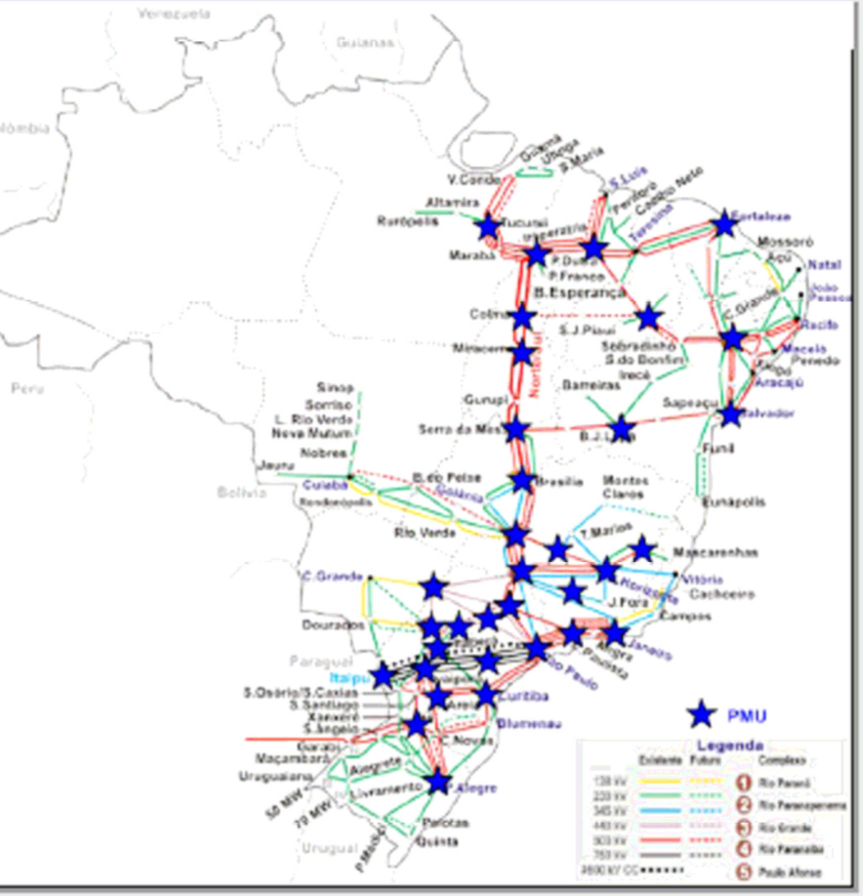
Proposed PJM PMU Locations



Proposed Substations for Phasor Measurement Unit Installations

ONS - Brazil

PMU Placemen



Current placement calls for:

- 12 Agents
- 58 substations
- 38 transformers
- 345 transmission lines

SUBSTATION	AGENT
ADRIANOPOLIS	FURNAS
AGUA VERMELHA	AES TIETÊ
ANGELIM II	CHESF
ANGRA FUR	FURNAS
ARARAQUARA	CTEEP
ARARAQUARA FUR	FURNAS
AREIA	ELETROSUL
ASSIS	CTEEP
B. ESPERANCA	CHESF
B.DESPACHO 3	CEMIG
B.J.LAPA II	TSN
BATEIAS	COPEL-TRA
BAURU	CTEEP
C. PAULISTA	FURNAS
CAMACARI II	CHESF
COLINAS	ELETRONORTE
EMBORCACAO	CEMIG
F.IGUACU 60HZ	FURNAS
FORTALEZA II	CHESF
FURNAS	FURNAS
GRAVATAI	ELETROSUL
IBIUNA	FURNAS
ILHA SOLTEIRA	CESP
IMPERATRIZ	ELETRONORTE
ITA	ELETROSUL
ITABERA	FURNAS
ITUMBIARA	FURNAS
IVAIPORA	FURNAS
IVAIPORA ESUL	ELETROSUL

SUBSTATION	AGENT
JAGUARA-SE	CEMIG
JAGUARA-US	CEMIG
JARDIM SE	CHESF
JUPIA	CESP
L.C.BARRETO	FURNAS
LUZIANIA	SMTE
MARIMBONDO	FURNAS
MILAGRES	CHESF
MIRACEMA	ELETRONORT
NEVES 1	CEMIG
NOVA PONTE	CEMIG
OLINDINA	CHESF
OURO PRETO 2	CEMIG
P. AFONSO IV	CHESF
P.DUTRA	ELETRONORT
RECIFE II	CHESF
S.DA MESA	FURNAS
S.JOAO PIAUI	CHESF
SAMAMBAIA	FURNAS
SAO SIMAO-SE	CEMIG
SAO SIMAO-US	CEMIG
SERRA MESA 2	INTESA
SOBRAL III	CHESF
TERESINA II	CHESF
TIJUCO PRETO	FURNAS
TUCURUI	ELETRONORT
U.SOBRADINHO	CHESF
US. L.GONZAGA	CHESF
USINA XINGO	CHESF

Applications

Computer Apps

- State Estimator (SE) integration
- Advanced Contingency Analysis

Operations

- **Black Start exercise visibility**
- **General operational visibility**

Planning

- **Island phase angle studies**
- Voltage collapse proximity indicator

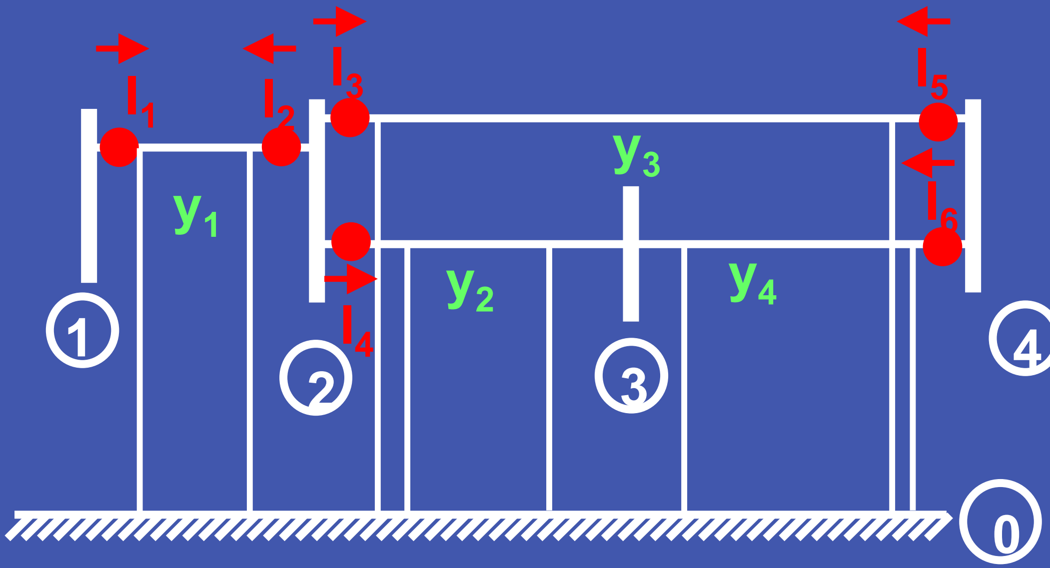
System Protection

- System-wide disturbance post-analysis
- **Line impedance verification**
- **Wide Area Out-of-Step**

State estimation with phasor measurements:

$$\begin{bmatrix} E_1 \\ E_2 \\ E_4 \\ I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ y_1+y_{10} & -y_1 & 0 & 0 \\ -y_1 & y_1+y_{10} & 0 & 0 \\ 0 & y_3+y_{30} & 0 & -y_3 \\ 0 & y_2+y_{20} & -y_2 & 0 \\ 0 & -y_3 & 0 & y_3+y_{30} \\ 0 & 0 & -y_4 & y_4+y_{40} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix}$$

which corresponds to the measurements on the network.



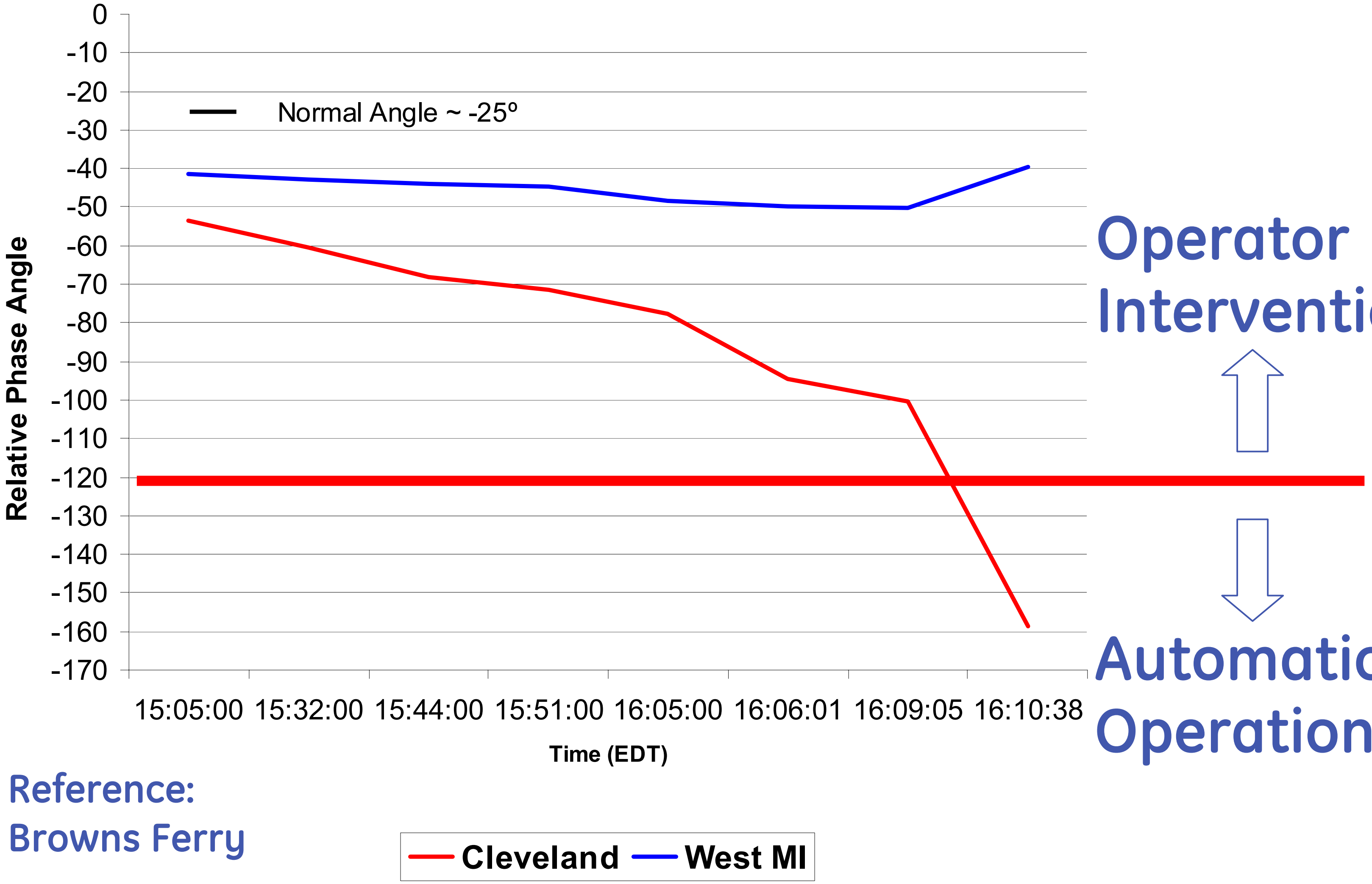
Synchrophasor Display

Reference PMU: Grand Coulee

Date: 01/09/1999

Time: 03:00:11

Cleveland Separation – Aug 14, 2003

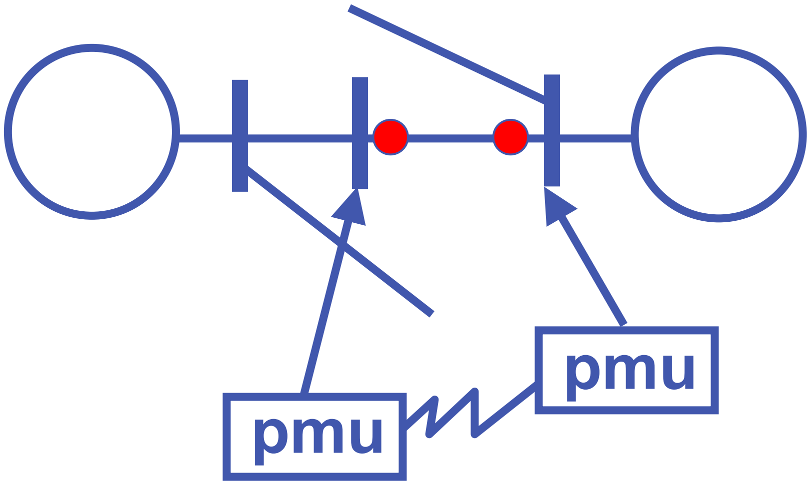


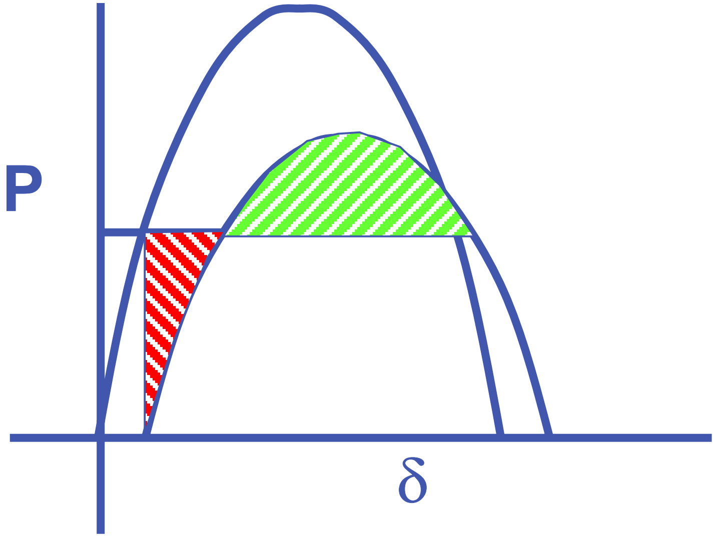
Operator Intervention

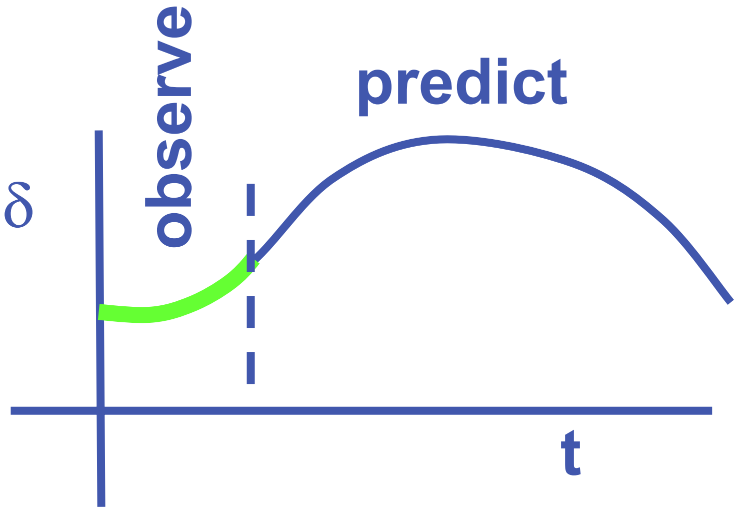
Automatic Operation

Reference:
Browns Ferry

Adaptive out-of-step relaying

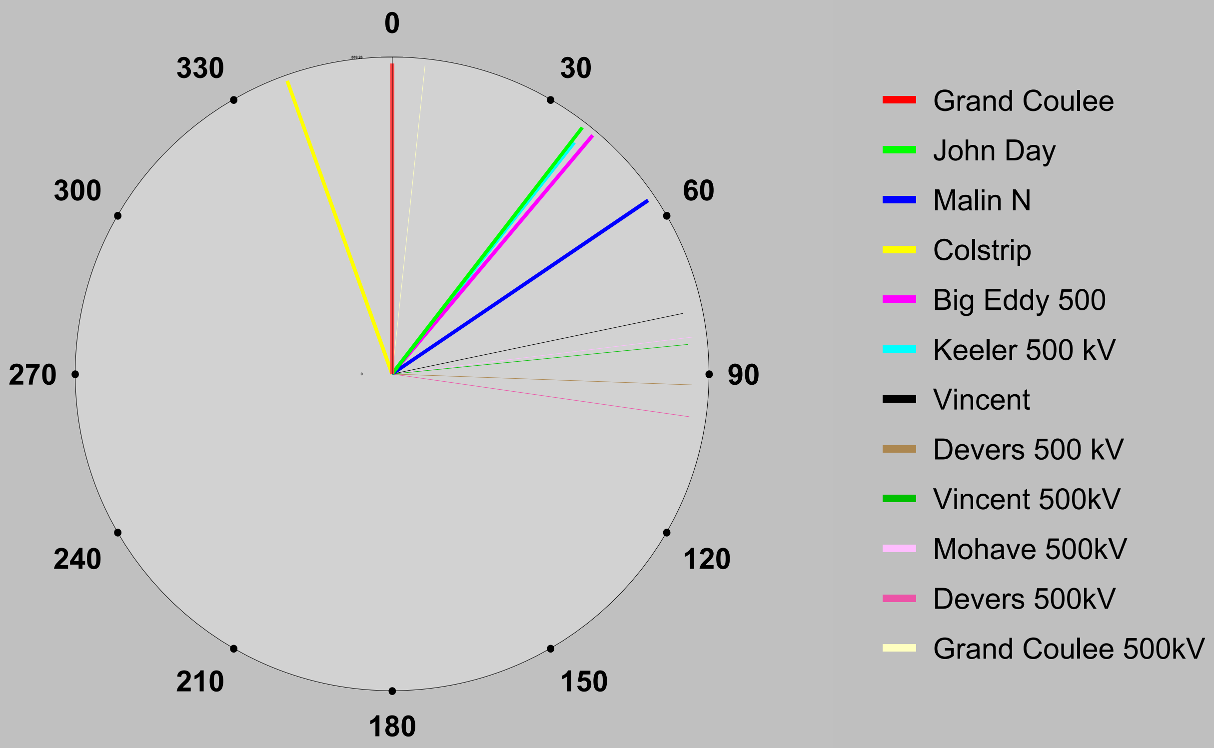






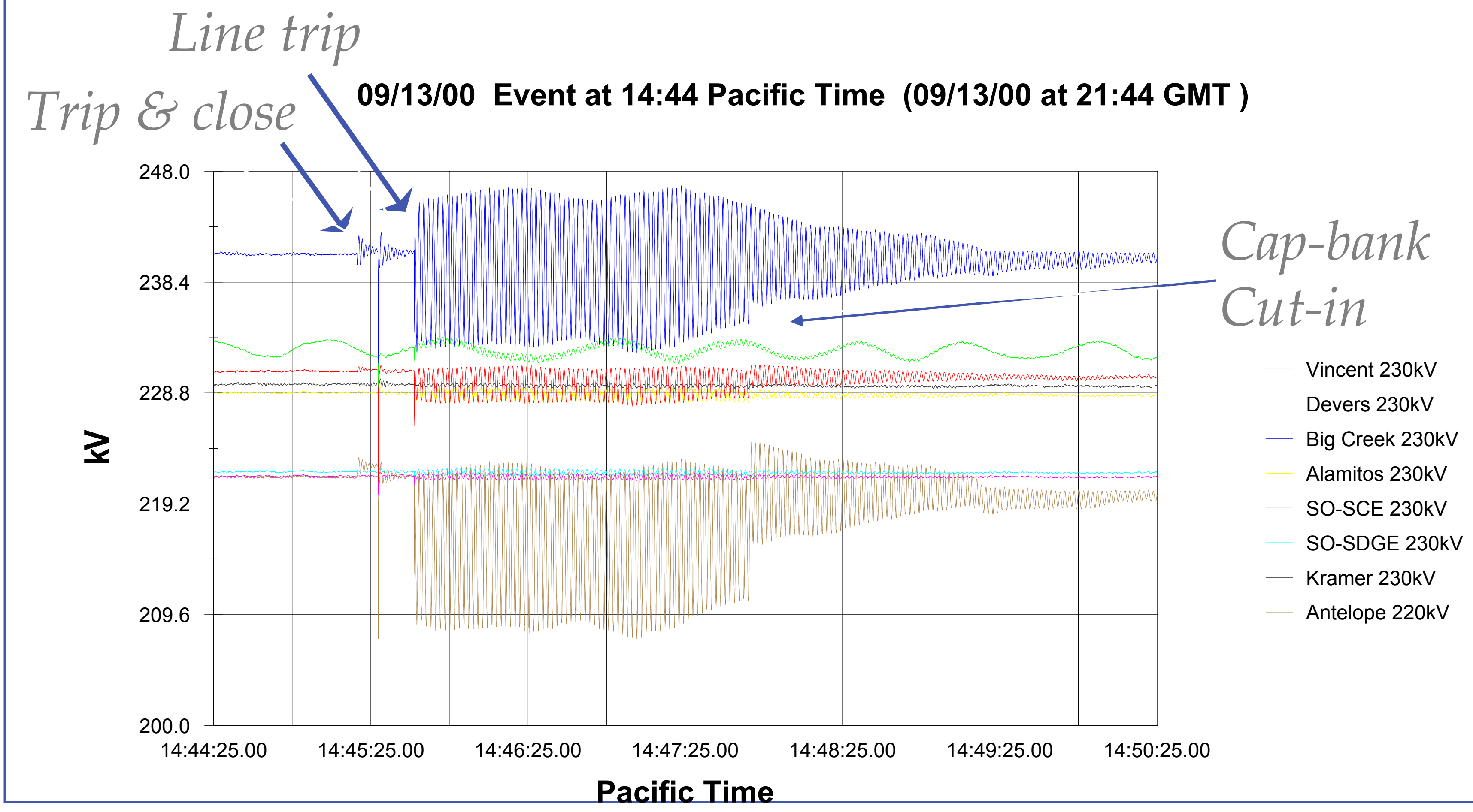
Wide Area Phasor Viewing

08/04/00 Event at 12:55 Pacific Time (08/04/00 at 19:55 GMT)



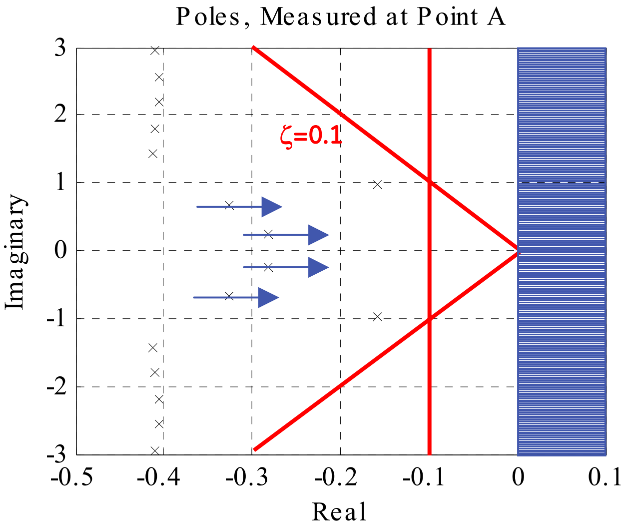
Angle Reference is Grand Coulee

Real Time Trending / Historical Playback

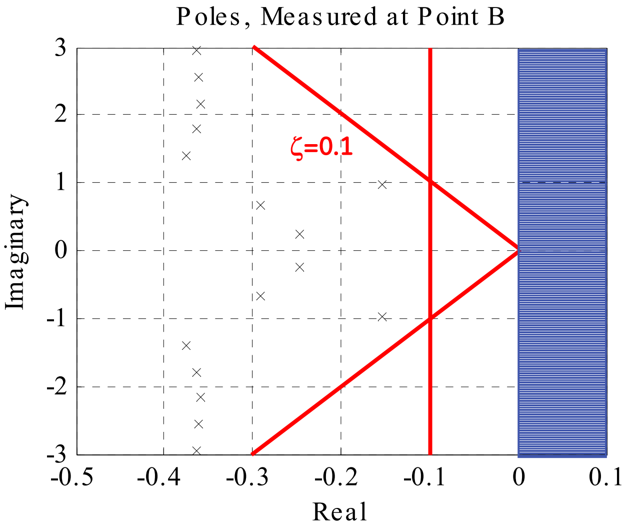


Wide-Area Analytics – Results To Date

Real-time measurement of system stability

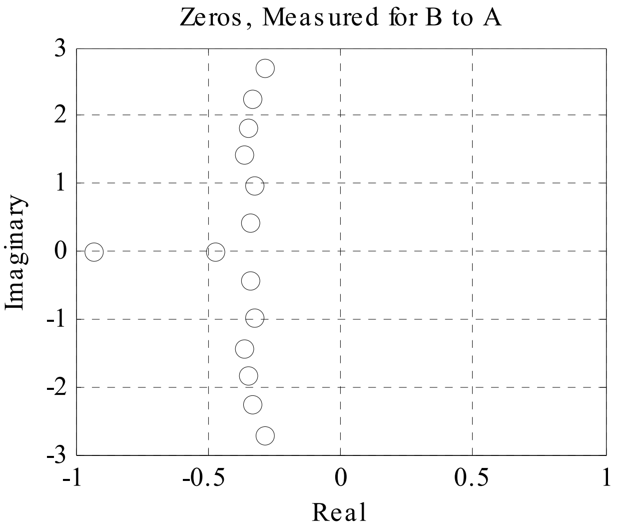


Poles, Measured at Point A

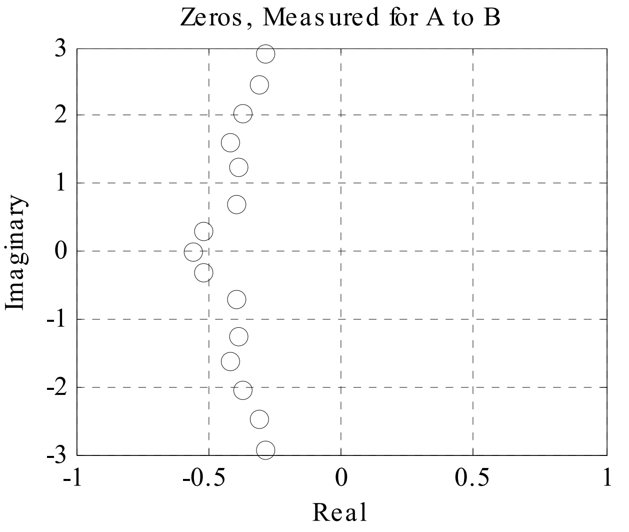


Poles, Measured at Point B

Real-time measurement of system dynamics



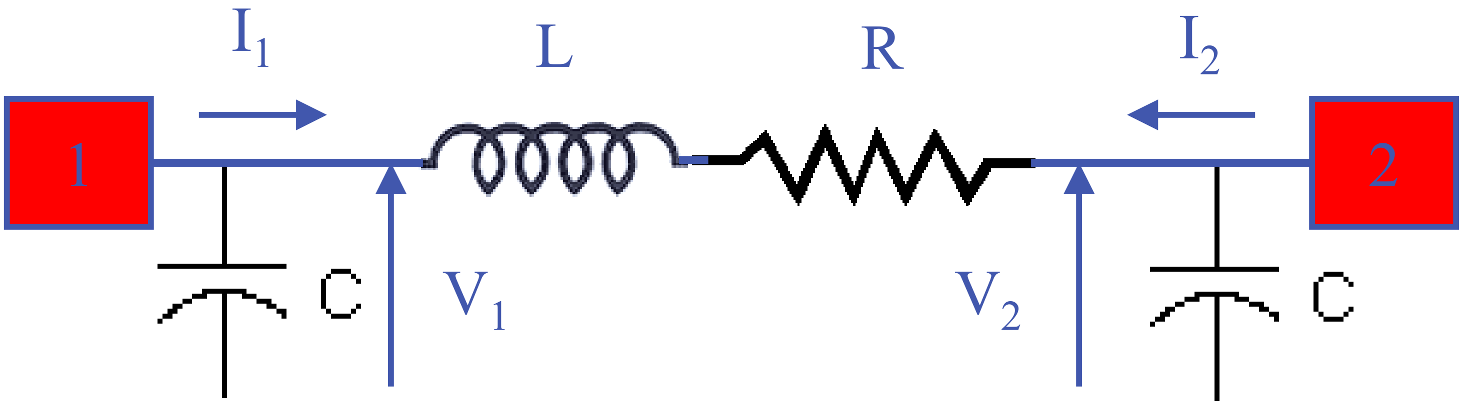
Zeros, Measured for B to A



Zeros, Measured for A to B

Power system model with 2 PMUs

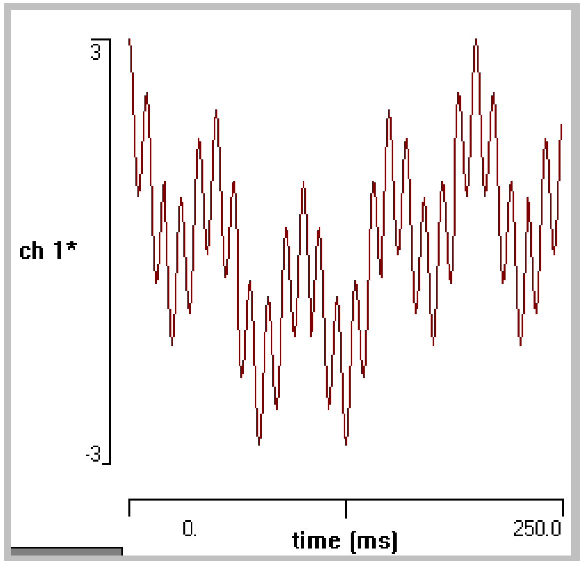
Line Parameter Calculation / Dynamic Line Loading



Measure: V_1, I_1, V_2, I_2, T_a
Compute: R, L, C, ΔC, T_c

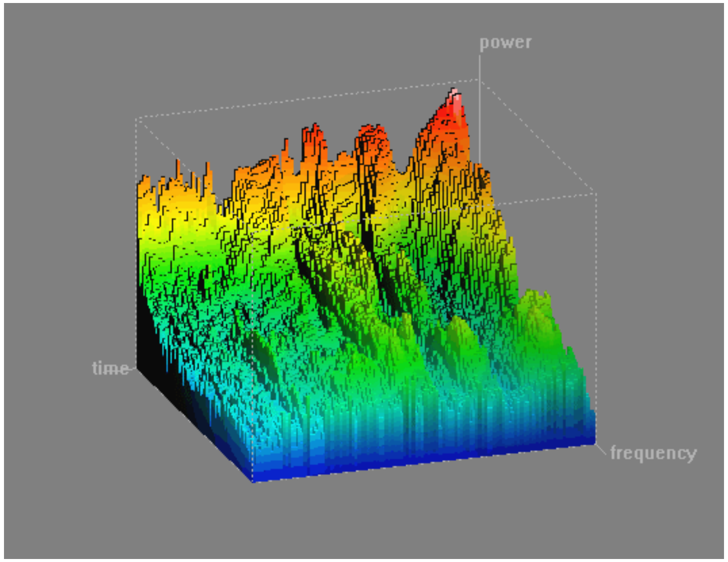
Simple Calculation…High Impact
T_c, ΔC may be an indication of sag…potential patent

Synchrophasor Spectral Analysis



Input: Synchrophasors

Data Transform

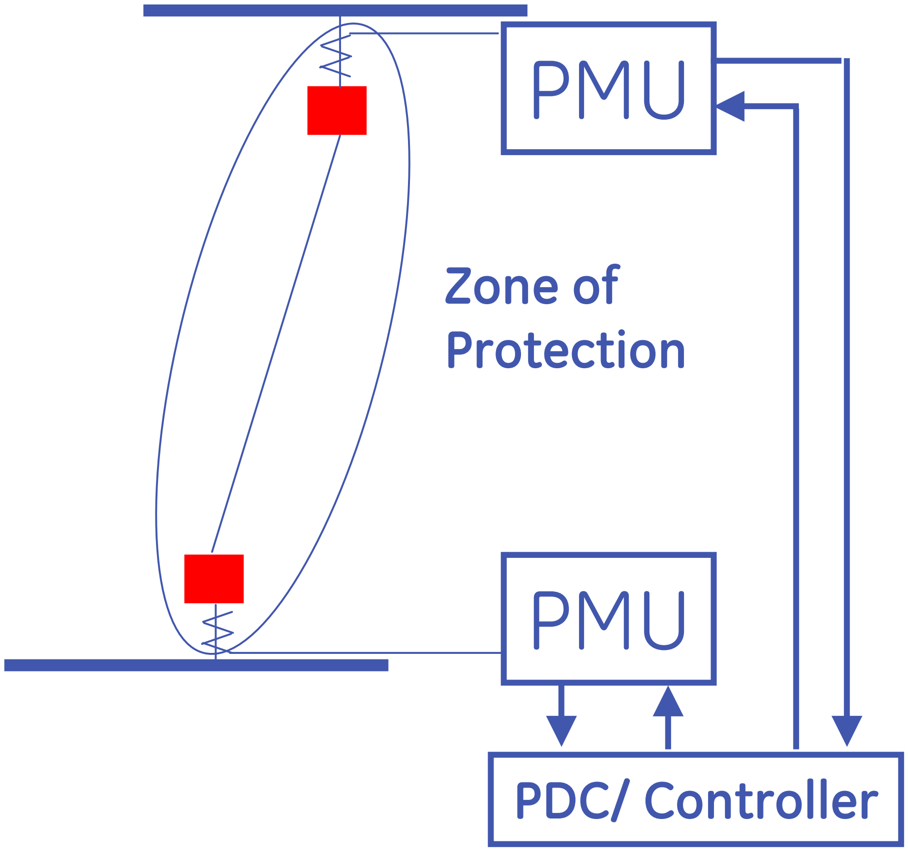


Output: Sub-synchronous Modal Analysis

Provide Tools (Fourier Transform) to Aid Analysis

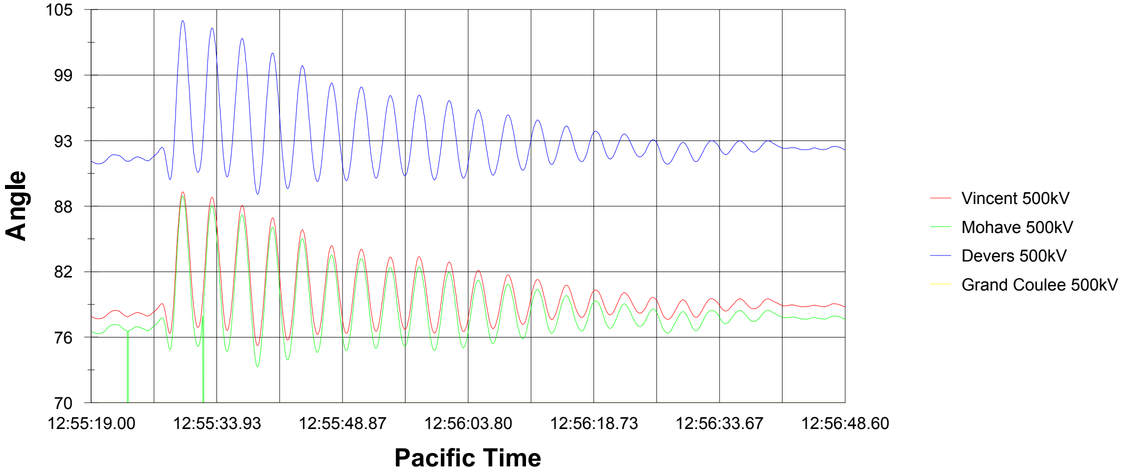
Synchrophasor Based Backup Current Differential

- Hi-Speed data streaming standardized (30 phasors/sec per standard)
- Low Communication latency available (7ms as seen previously)
- Precise Zone isolation through current differential protection
- Bonus: Double ended fault location



Power System Model Validation

08/04/00 Event at 12:55 Pacific Time (08/04/00 at 19:55 GMT)



Angle Reference is Grand Coulee 500kV

Input

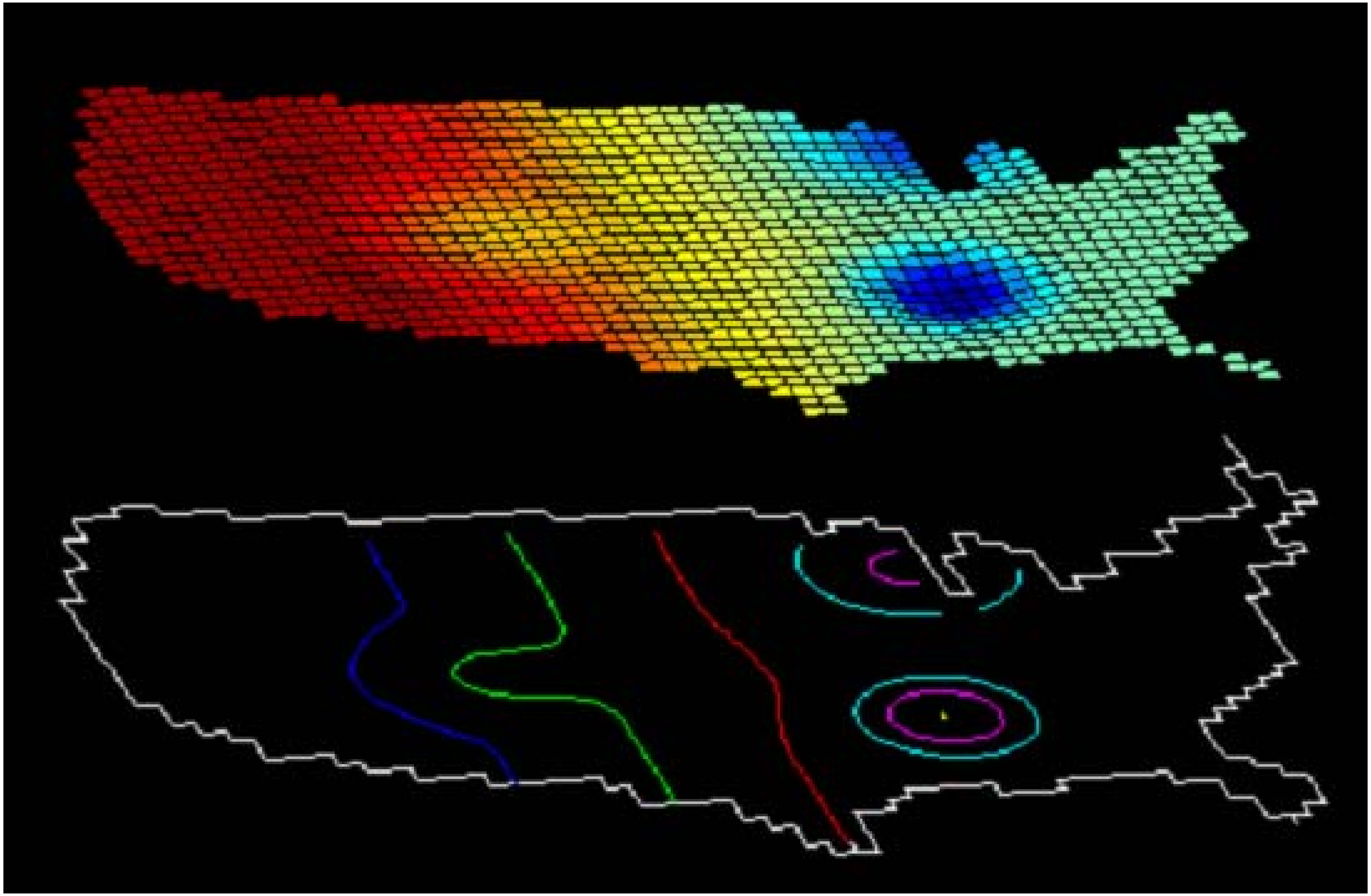
Response

Use System Disturbances to Create/Validate/Correction F(s)

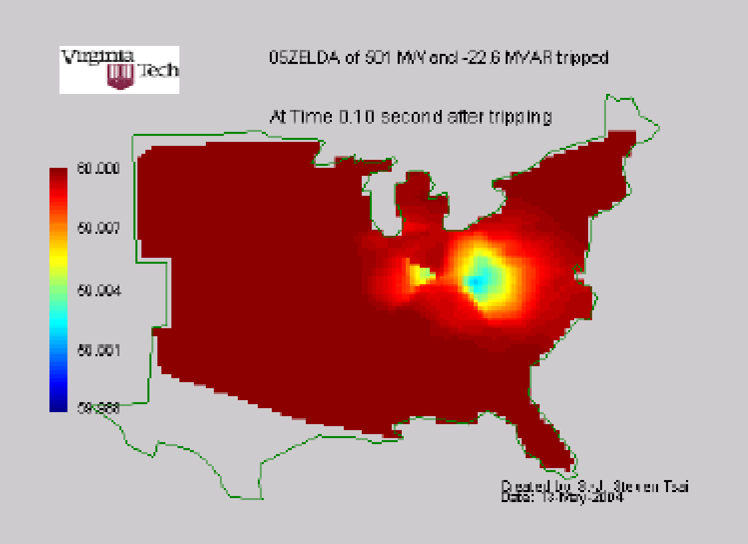
System Contour View

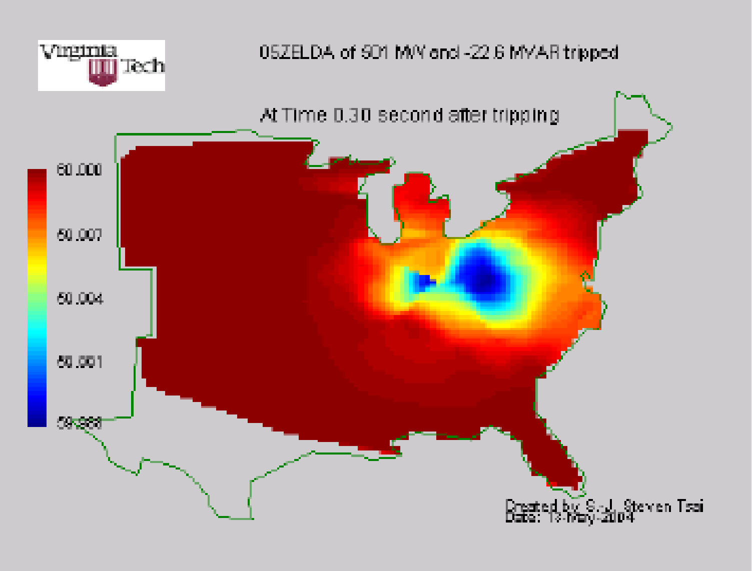
Phase Angle

- +30
- +20
- +10
- +00
- -10
- -20
- -30



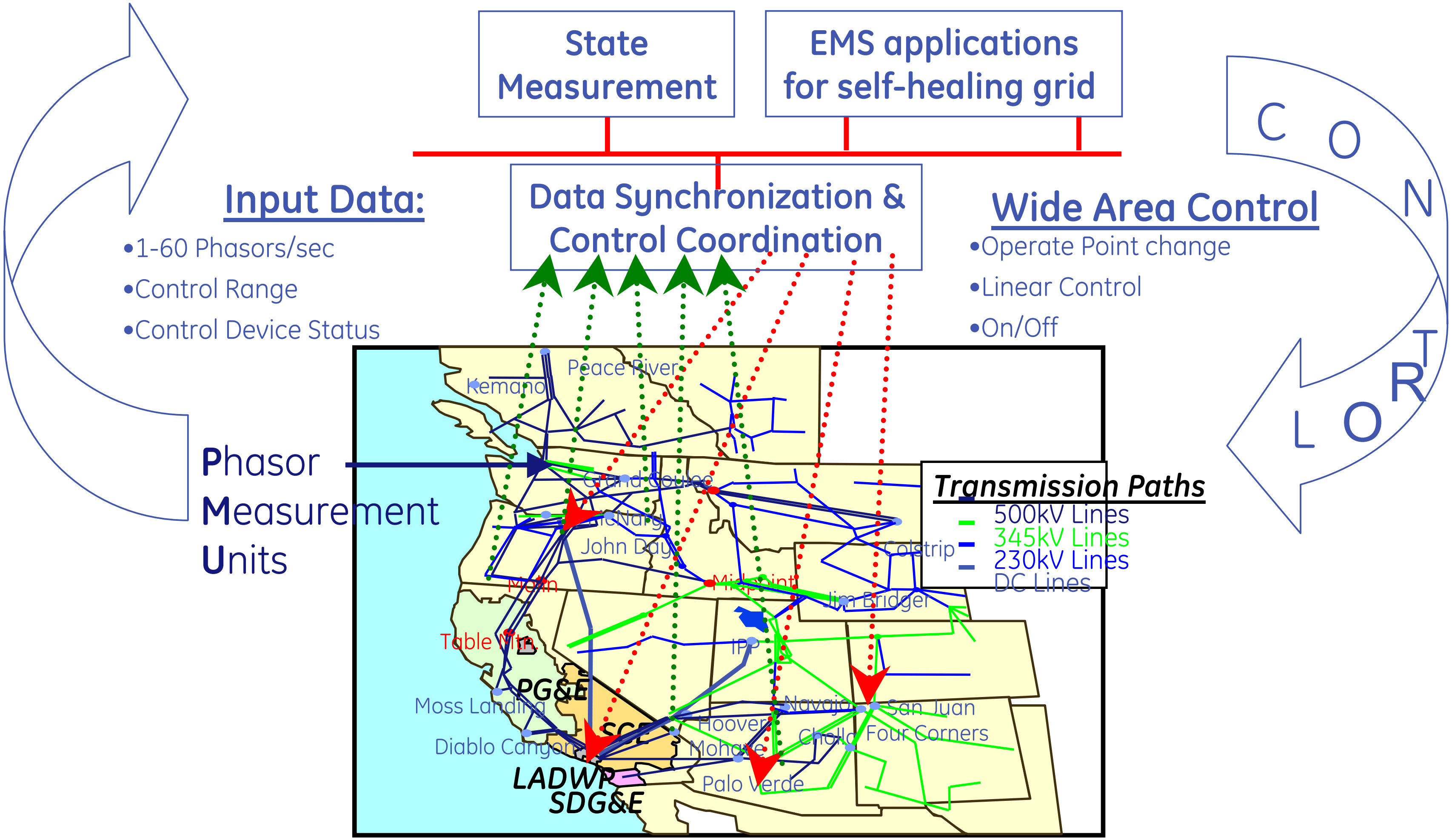
System Frequency View





- Frequency – critical parameter for understanding system behavior
- FNET project at VaTech tracks frequency after an event
- Speed of Frequency Wave:
  - 350 Mi/Sec – East
  - 1100 Mi/Sec – WECC
- MW Lost ≈ Δf * 31464

Development Needs: Wide Area Control



State Measurement

EMS applications for self-healing grid

Data Synchronization & Control Coordination

Input Data:

- 1-60 Phasors/sec
- Control Range
- Control Device Status

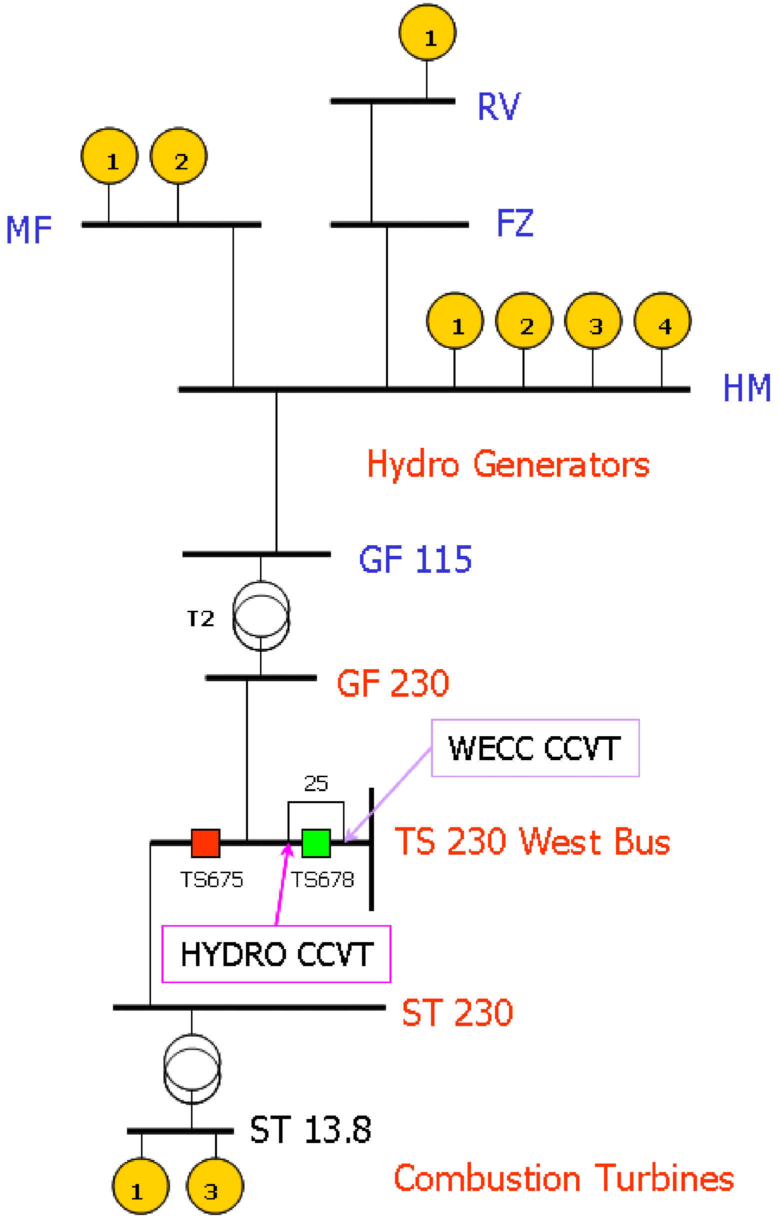
Wide Area Control

- Operate Point change
- Linear Control
- On/Off

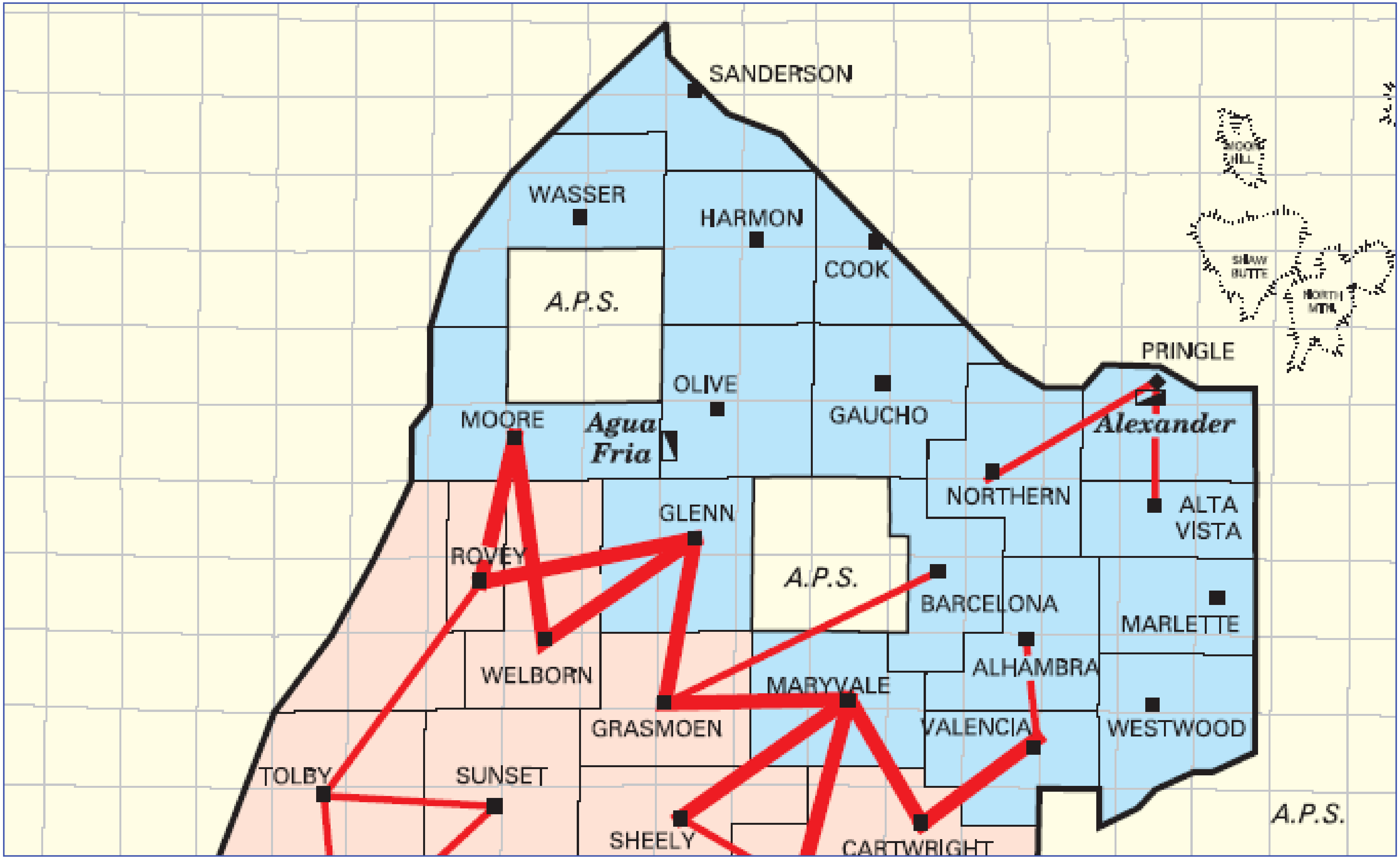
Phasor Measurement Units

Focus: Dynamic Stability (advanced Weiner-Hopf) & Closed Loop Control

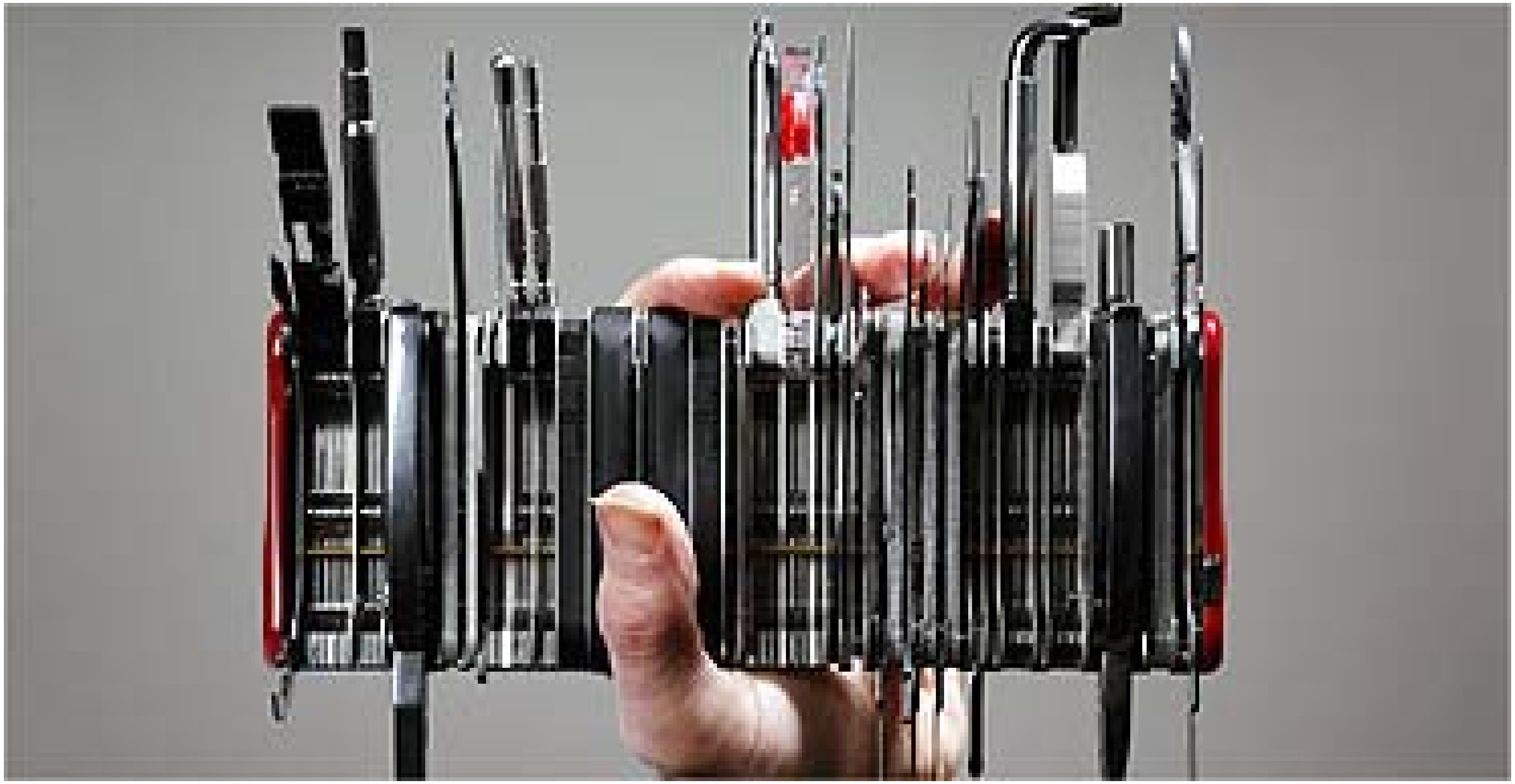
SRP Black Start System Configuration



69kV Islands –
Excessive Angle Detection



Synchrophasors: The “Swiss Army Knife” of the Electric Utility Industry



Smart Grid Technologies

imagination at work

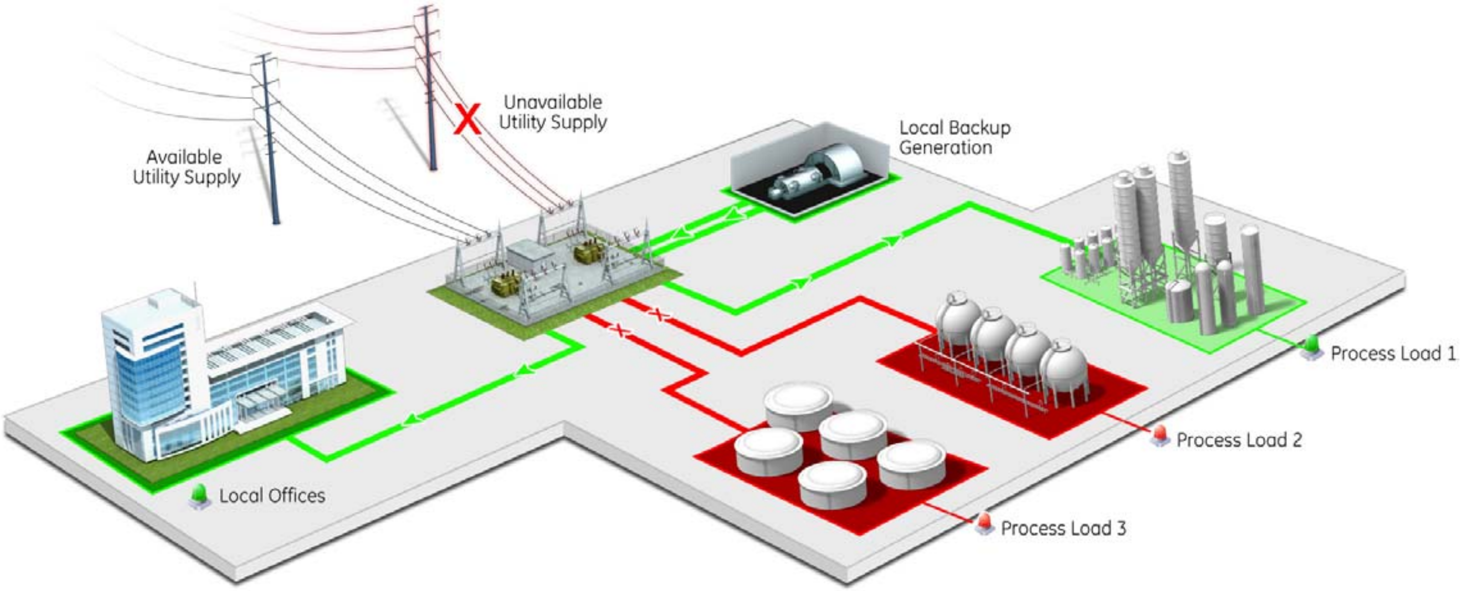
Mark's Definition of the Smart Grid:

- Finally implementing what was proposed more than 25 years ago…
  - "Homeostatic Utility Control", F.C. Schweppe et al, **IEEE Transactions on Power Apparatus and Systems**, Vol. PAS-99, Number 3, May 1980 - (Schweppe mentions five minute updates of prices)
  - A New Measurement Technique for Tracking Voltage Phasors, Local System Frequency, and Rate of Change of Frequency – IEEE 1982 Summer Meeting
  - Development and Pilot Demonstration of Hardware for an AEP System Test Program Relative to the Variable Spot Pricing of Electricity – American Power Conference – 1990.
  - EPRI Distribution Automation Project – 1990.
  - EPRI Electric Vehicle Program - 1978

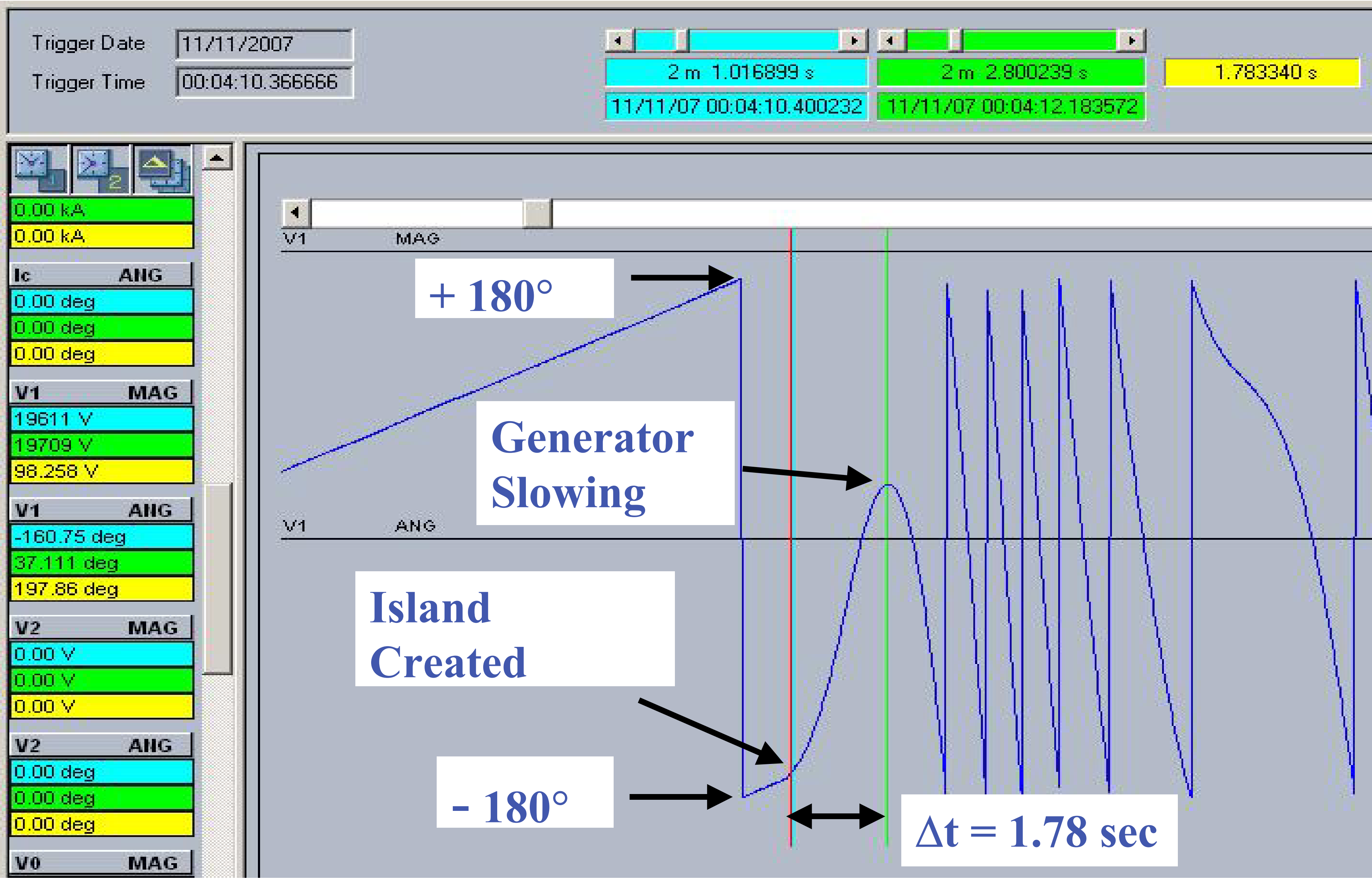
Example: Industrial Load Shedding

Load Shedding solutions to keeps critical processes running

- Identifies when there is a lack of power to supply required load
- Dynamically sheds least critical loads to keep processes essential to the business running



V1 Angle Response to Overpower Island



Trigger Date 11/11/2007
Trigger Time 00:04:10.366666

2 m 1.016899 s
11/11/07 00:04:10.400232

2 m 2.800239 s
11/11/07 00:04:12.183572

1.783340 s

0.00 kA
0.00 kA

Ic ANG
0.00 deg
0.00 deg
0.00 deg

V1 MAG
19611 V
19709 V
98.258 V

V1 ANG
-160.75 deg
37.111 deg
197.86 deg

V2 MAG
0.00 V
0.00 V
0.00 V

V2 ANG
0.00 deg
0.00 deg
0.00 deg

V0 MAG

+ 180°

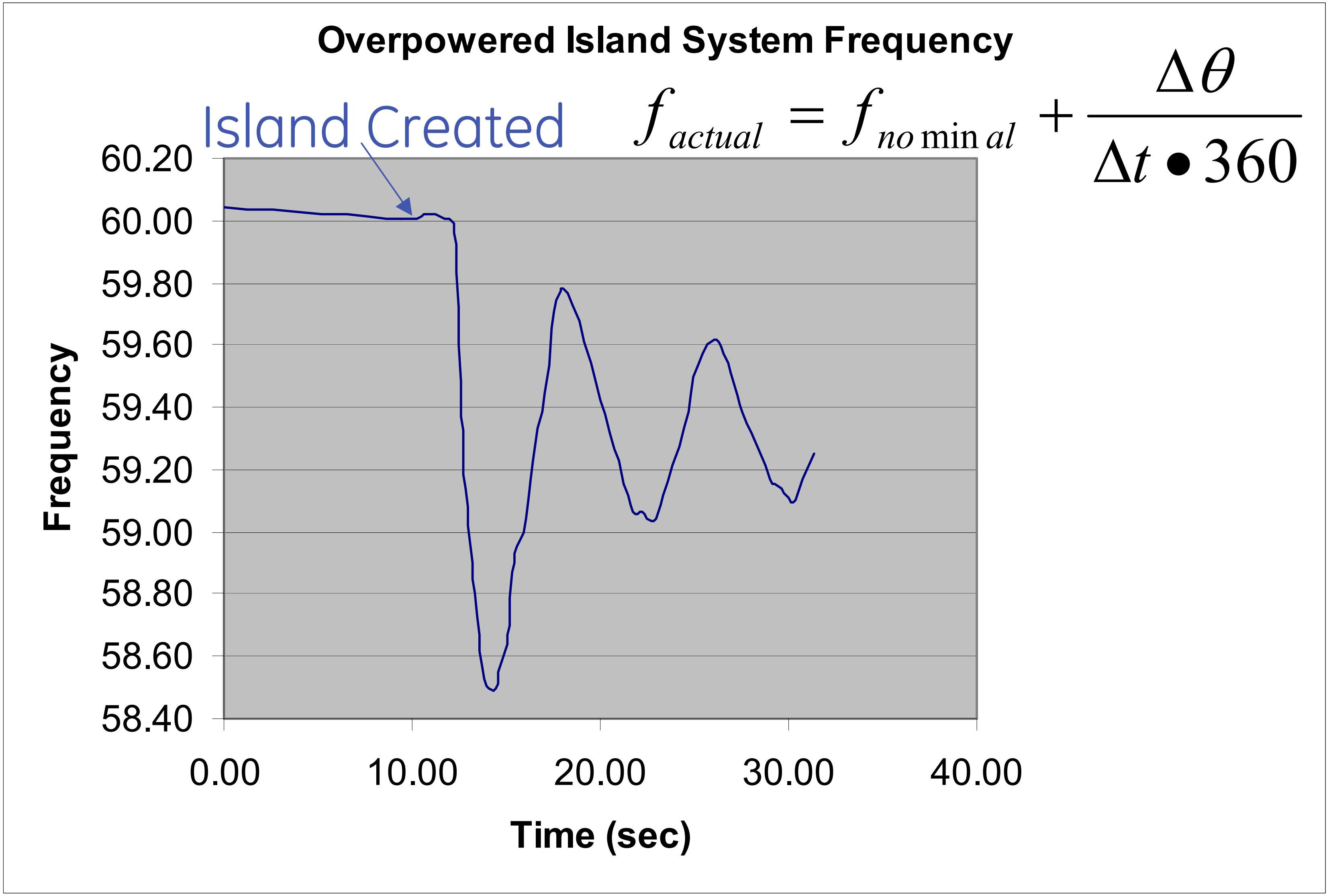
Generator Slowing

Island Created

- 180°

Δt = 1.78 sec

Calculated System Frequency



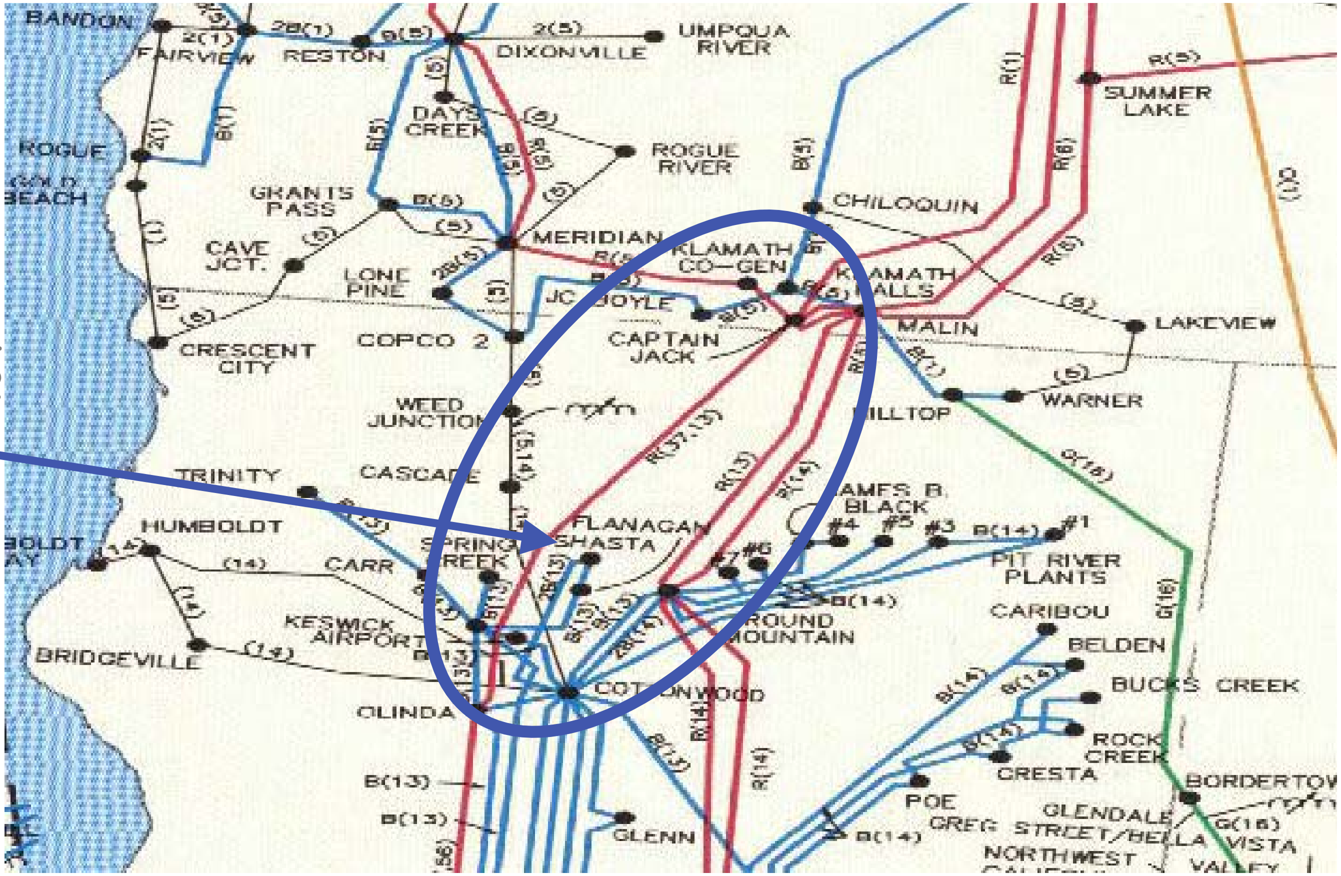
Island Created

$$f_{actual} = f_{nominal} + \frac{\Delta\theta}{\Delta t \bullet 360}$$

Utility Load Shed:
Palo Verde Nuclear Power Plant SIPS

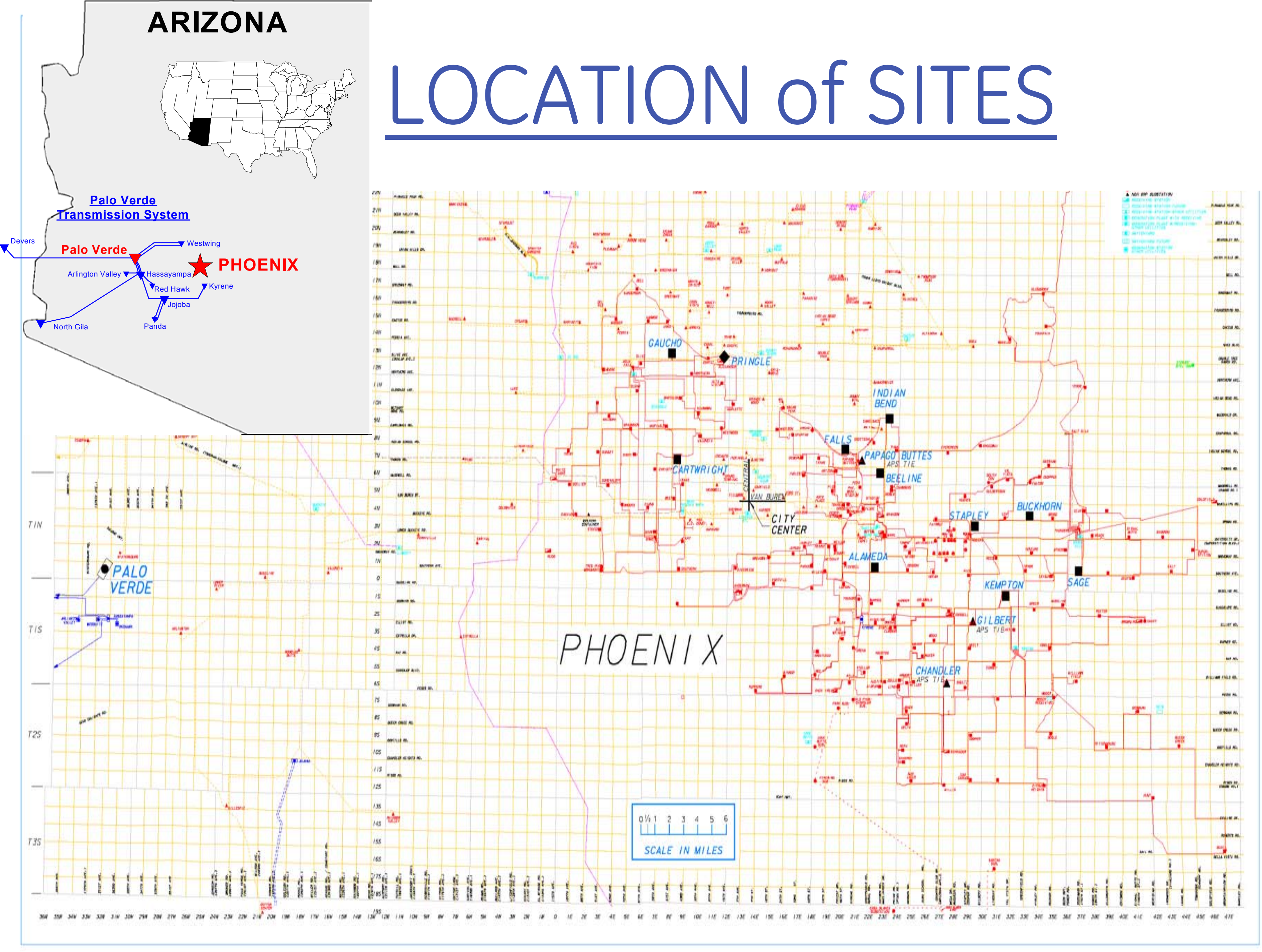
The Need For Mitigation?

- ➢ Palo Verde Unit 2 Was Up-Rated by 121MW.
- ➢ This Impacted the safe Operation of COI. (COI is 3 500KV lines, WECC Path 66)

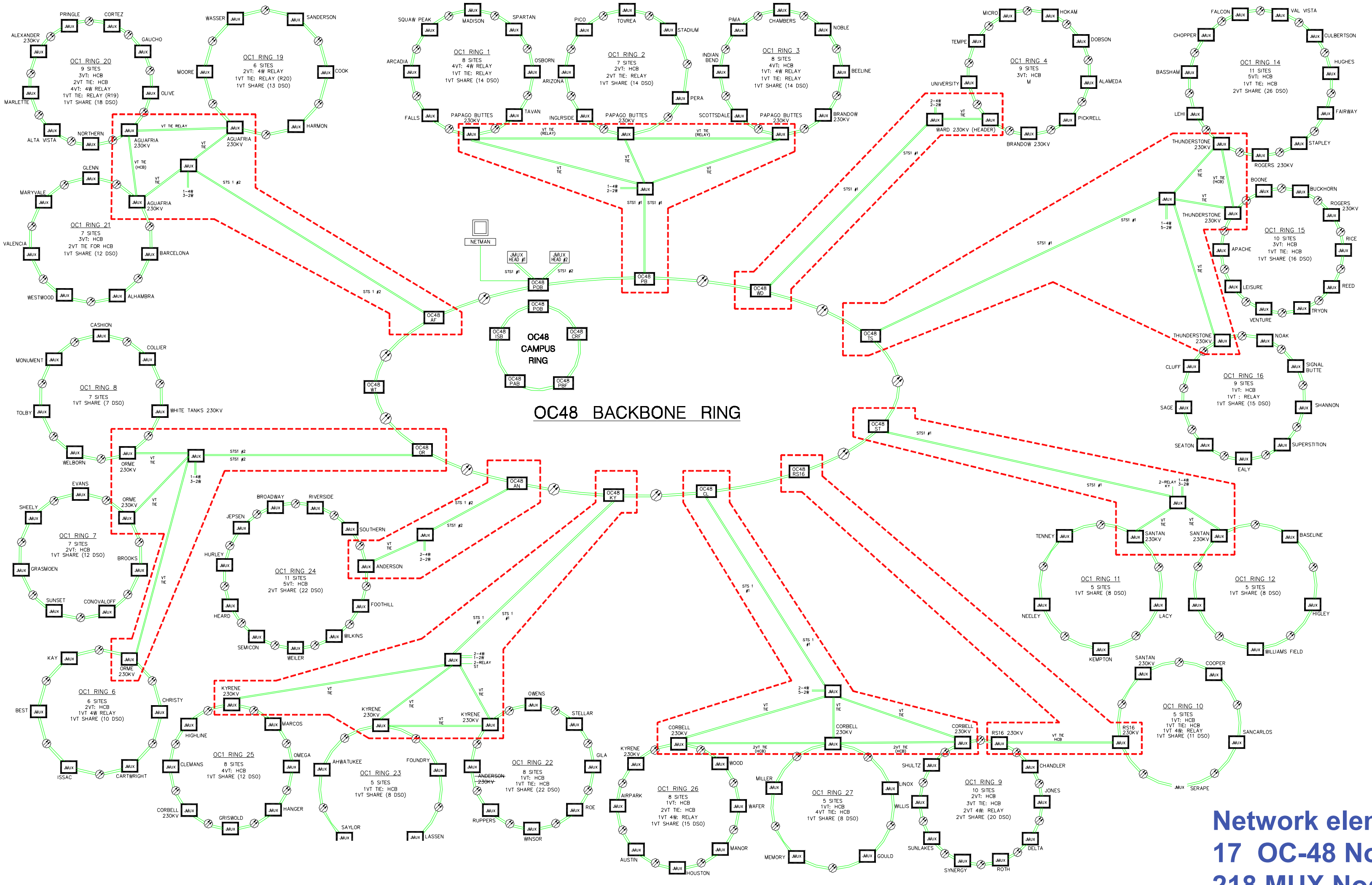


Malin / Round Mountain #1
Malin / Round Mountain #2
Captain Jack / Olinda

LOCATION of SITES



SRP SONET System

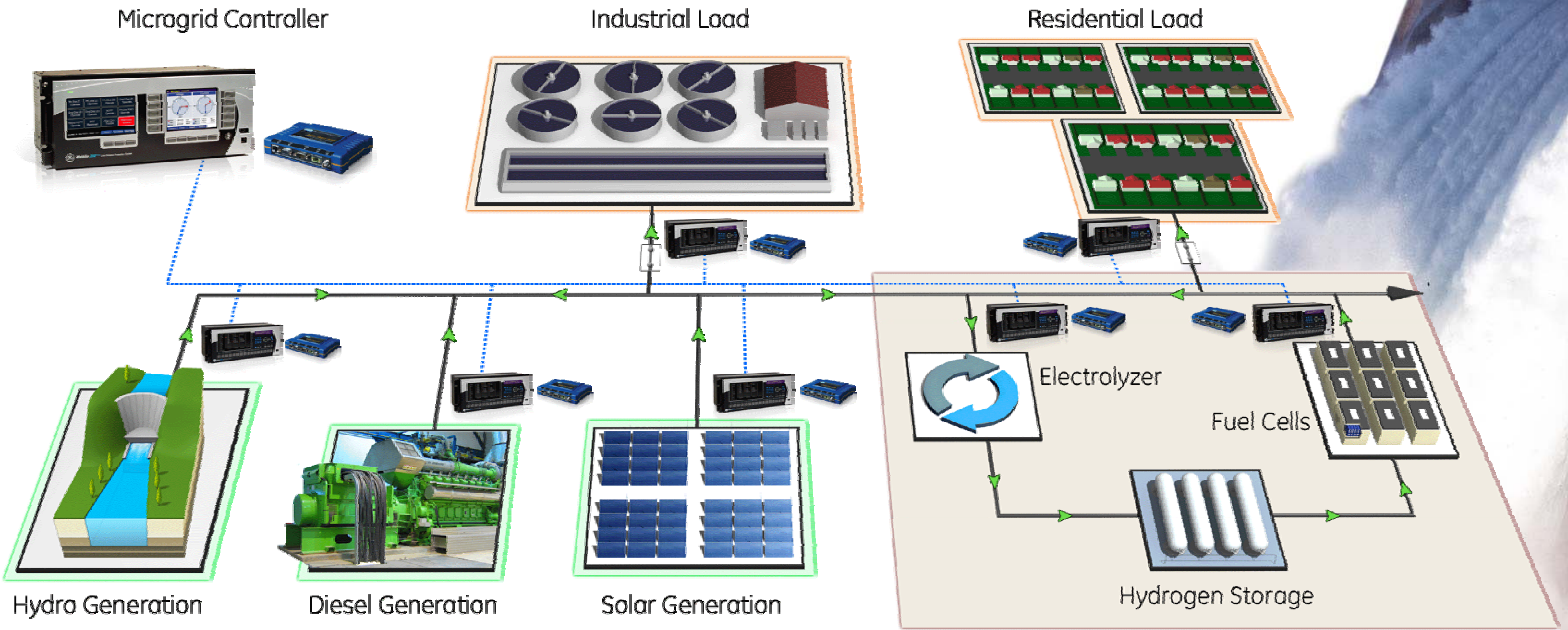


Network elements:
17 OC-48 Nodes
218 MUX Nodes

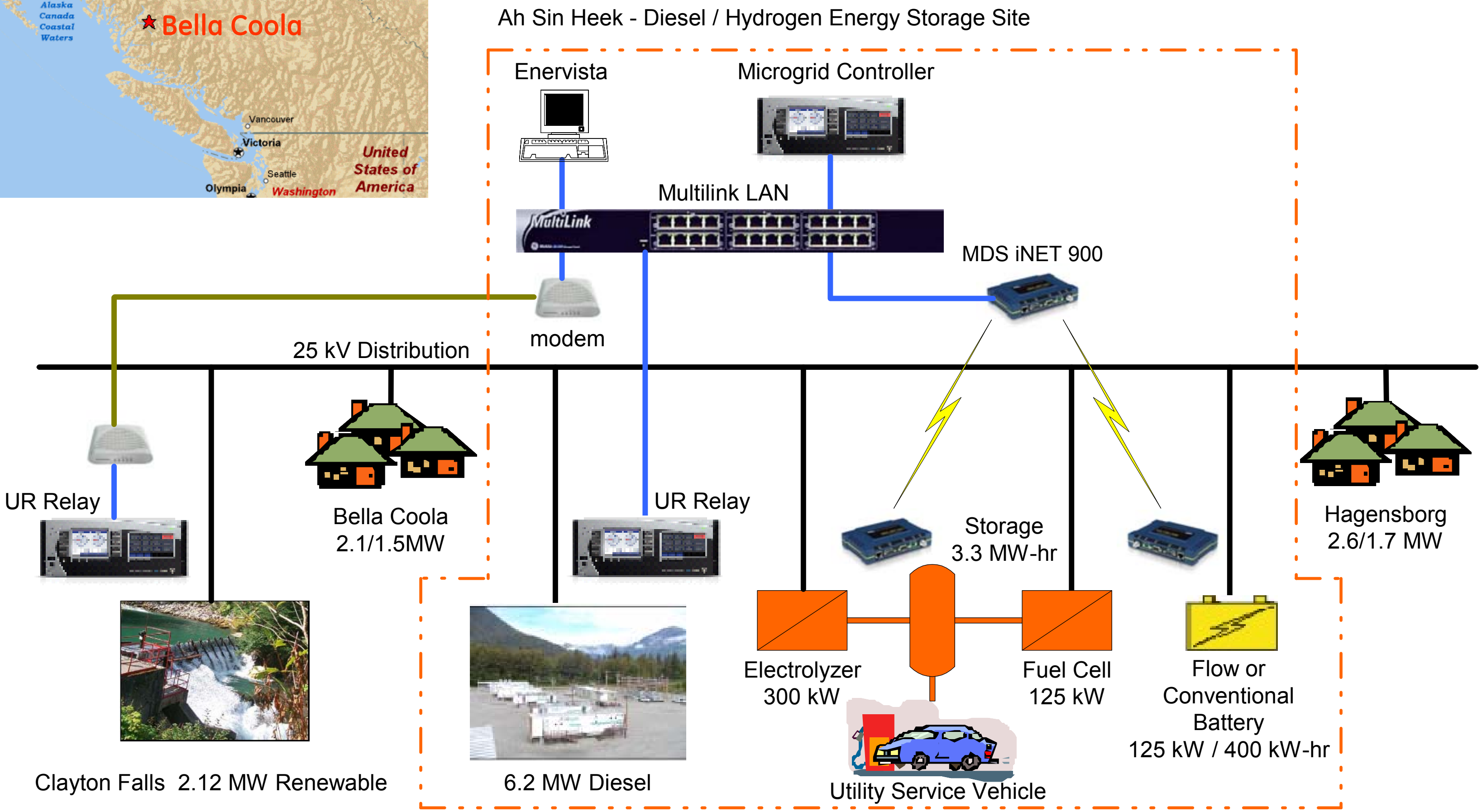
Example: Microgrid Control

Microgrid Controllers optimizes site generation

- Selects the most cost effective generation available to support the load
- Optimizes green power by dispatching power storage when excess generation is available
- Indicates amount of energy in storage (Fuel Cell and Diesel)



Example Microgrid: Bella



Ah Sin Heek - Diesel / Hydrogen Energy Storage Site

Enervista

Microgrid Controller

Multilink LAN

MDS iNET 900

modem

25 kV Distribution

UR Relay

Bella Coola
2.1/1.5MW

UR Relay

Storage
3.3 MW-hr

Hagensborg
2.6/1.7 MW

Electrolyzer
300 kW

Fuel Cell
125 kW

Flow or
Conventional
Battery
125 kW / 400 kW-hr

Clayton Falls 2.12 MW Renewable

6.2 MW Diesel

Utility Service Vehicle

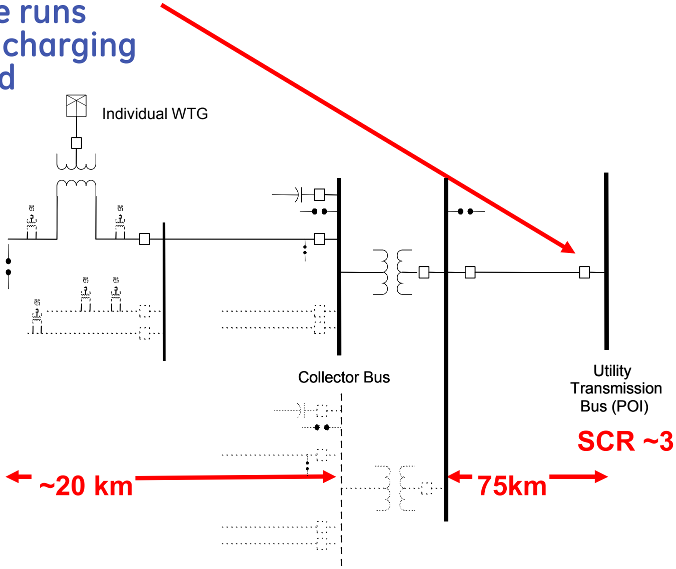
Microgrid Control System Features

3. Tie Line Control – *Distributed Energy Resource Aggregation*

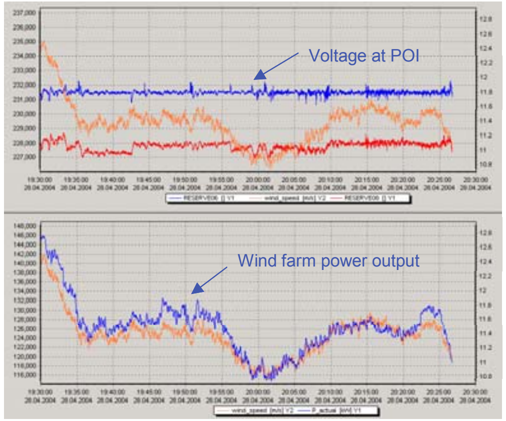
- Energy aggregation: To the grid, the aggregated distribution system looks like one well-behaved dispatchable energy resource
    - Active and reactive power
    - Power ramp rate limits
    - Ancillary services (voltage/VAR regulation, frequency droop…)

Example: Windfarm tieline Control

POI 75 KM away!
Compensation for long cable runs including charging is required



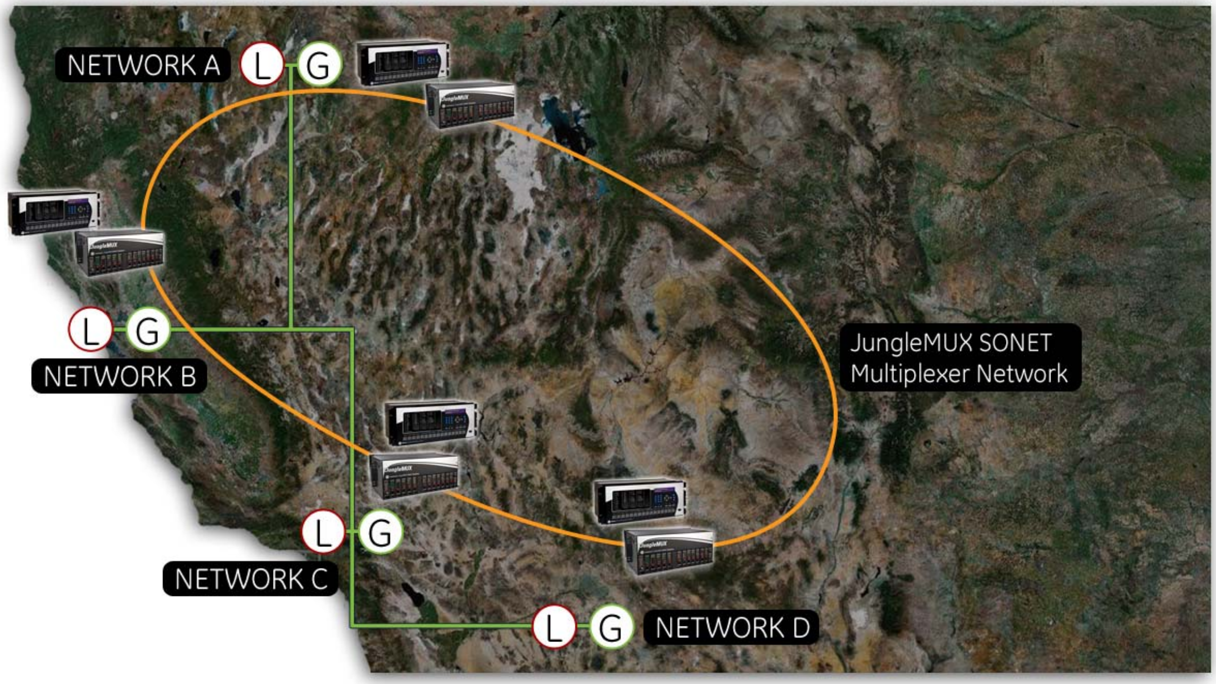
SCR ~3.5 (weak interconnection)



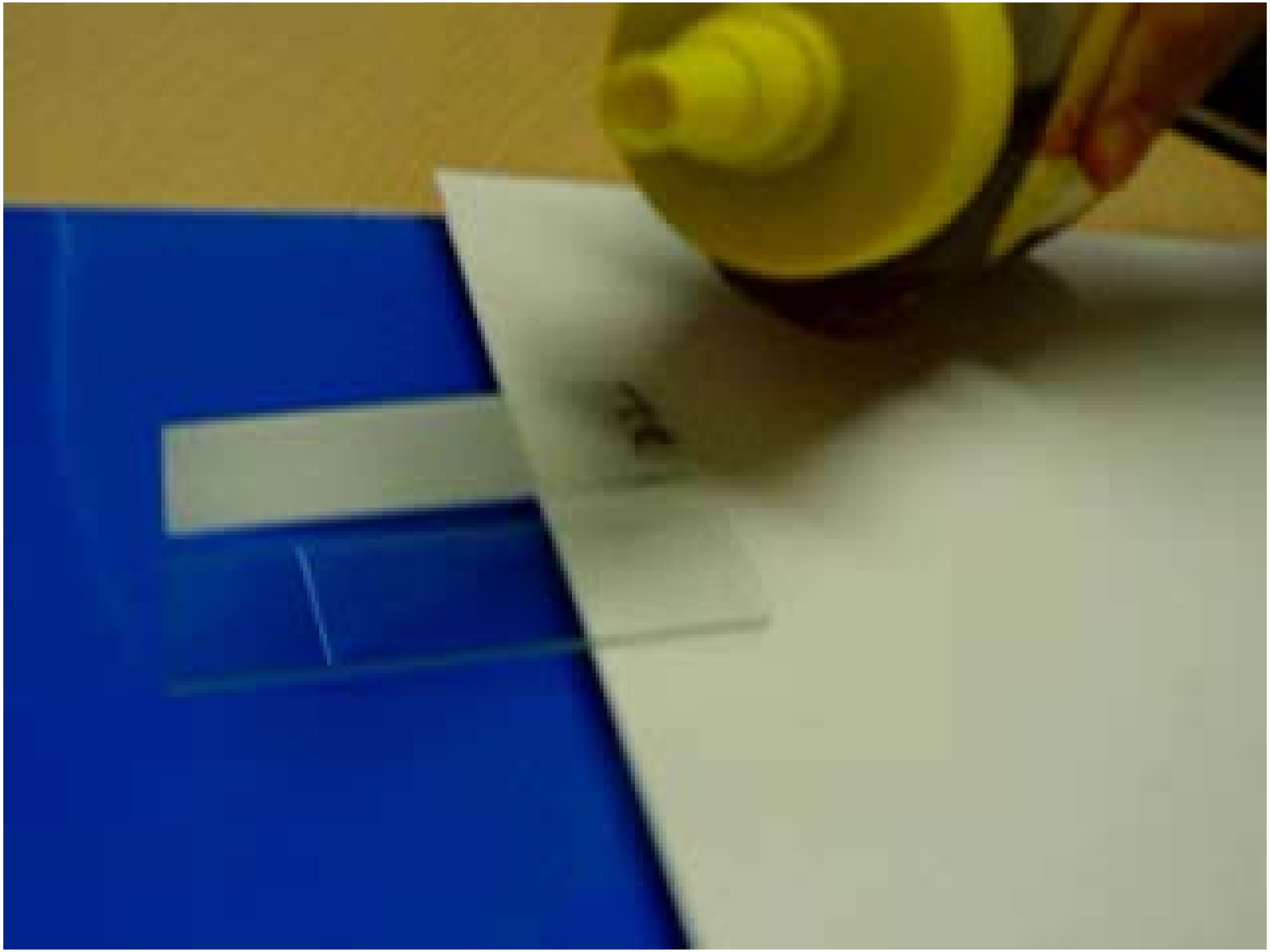
Example: Wide Area Protection

Enabling outage detection and allows emergency reconfiguration of the network

- Multiplexers provide the communications backbone to intelligent control devices
- Intelligent controllers shed load to match available generation
- Intelligent controllers switch to alternate generation sources and manage re-routing of power



NanoCoating Technology



Improving grid reliability

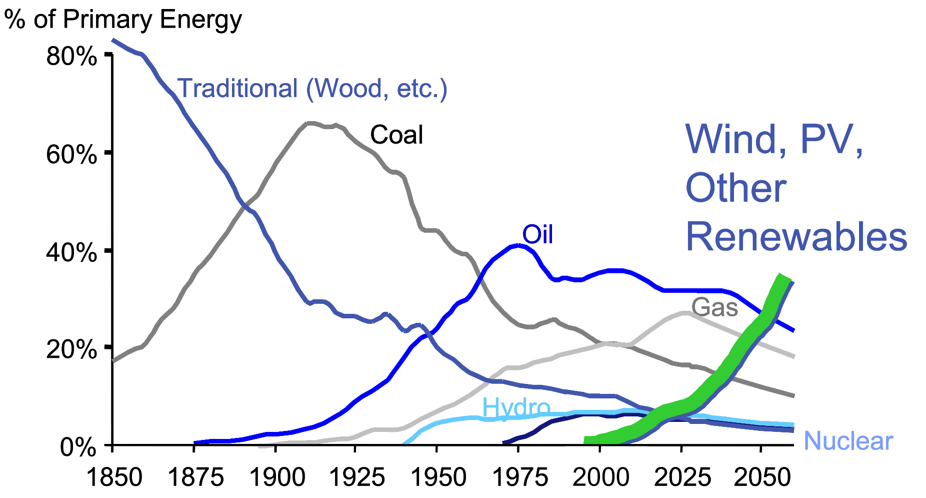
Super-Hydrophobic coatings so repellant that:

- Honey slides off it like mercury
- Water bounces and beads off

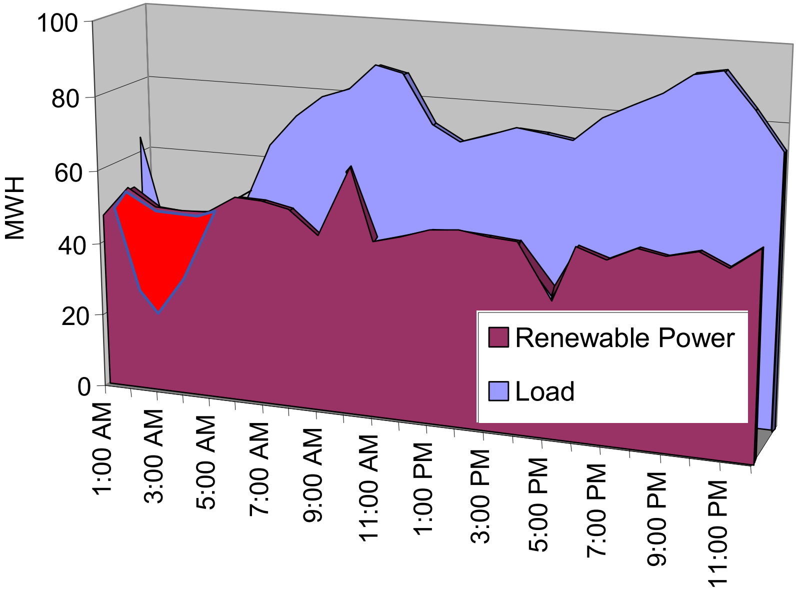
The Energy Sector Application

- New transmission & distribution line coating resists ice build-up
- New coatings protect coastal assets from salt damage
- New transformer winding material fights insulation breakdown

Looming Problems: Intermittent Renewables



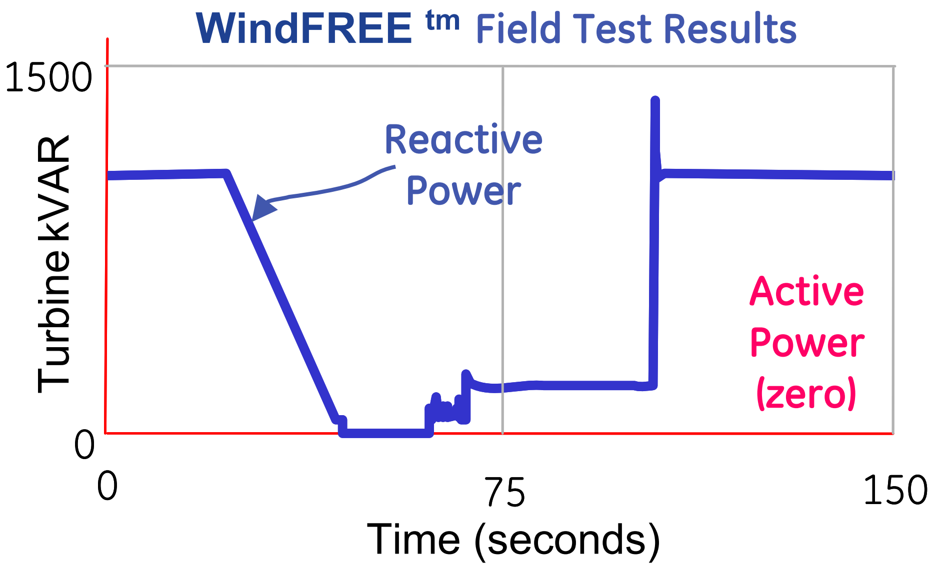
Source: Shell Global Scenarios

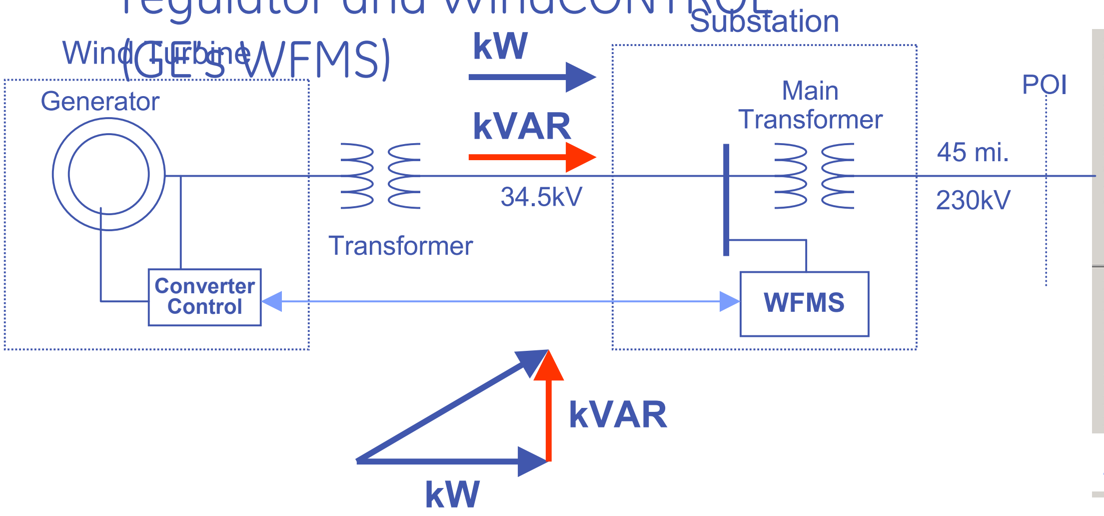


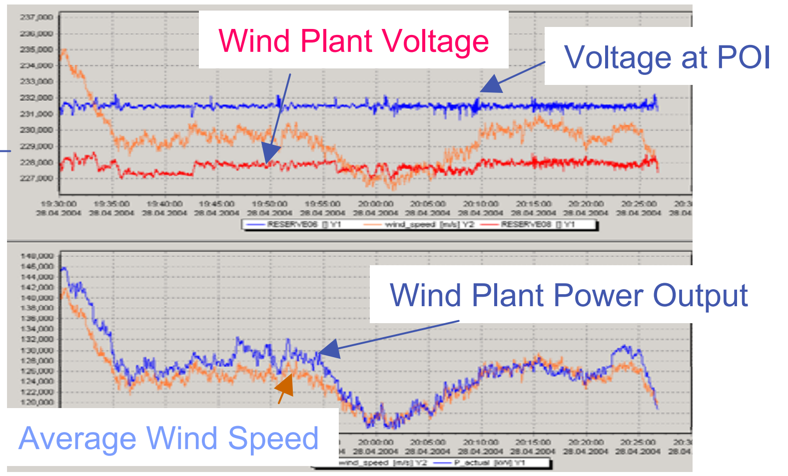
Voltage Regulation

Typical Grid Requirements

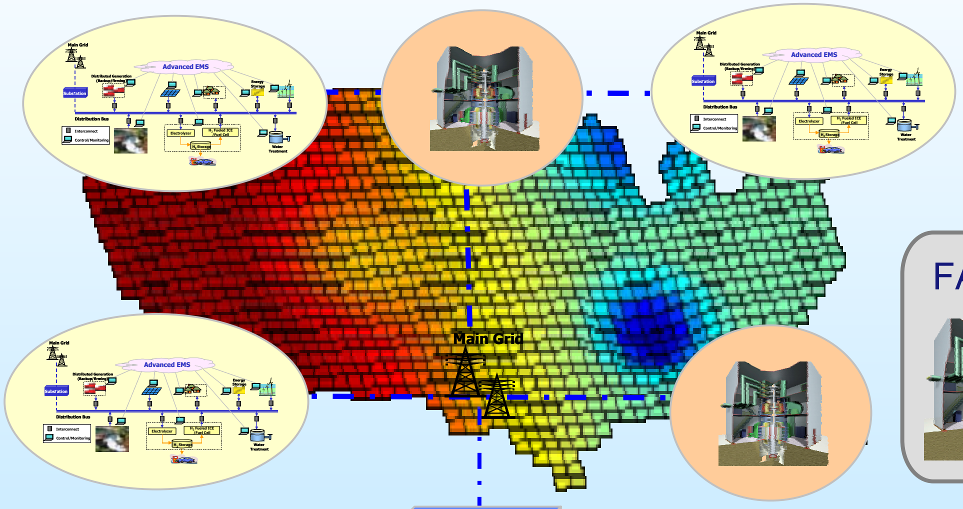
- +/- 0.95 pf req'd at POI, +/-0.9 at the turbine
- WindFREE tm voltage regulation
- GE patented turbine voltage regulator and WindCONTROL tm (GE's WFMS)



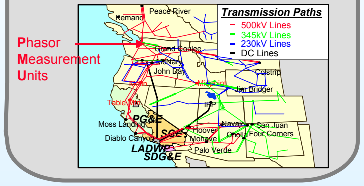




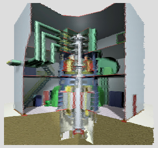
Capability Gaps – What's Missing Today



WAMACS

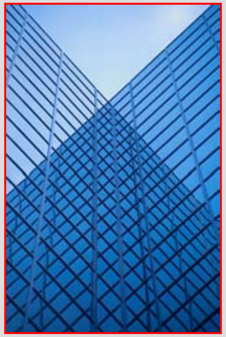


FACTS



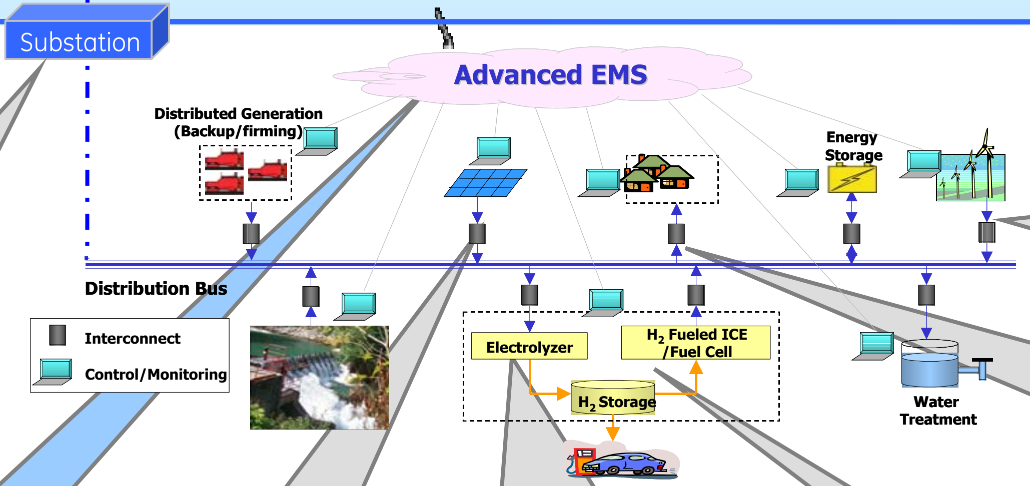
Market Functions and Settlement

Load Aggregation



Integration Technologies

Building Block Technologies



Substation

Advanced EMS

Distributed Generation (Backup/firming)

Energy Storage

Distribution Bus

Interconnect

Control/Monitoring

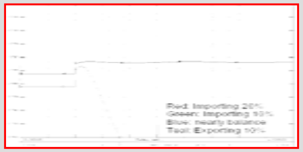
Electrolyzer

H_2 Fueled ICE /Fuel Cell

H_2 Storage

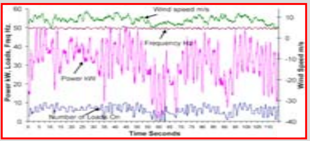
Water Treatment

Grid Interconnection & Integration



Red: Importing 20%
Green: Importing 10%
Blue: nearly balance
Teal: Exporting 10%

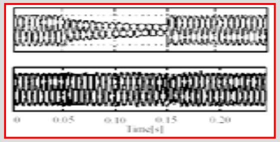
Intermittency Mgmt



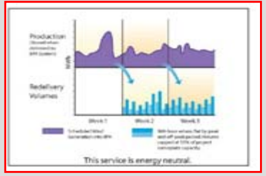
EMS+DMS Combined Functionality for Energy Management and Automation

Advanced Metering Infrastructure

Protection For Low Inertia Systems



Energy Storage for Power Firming and Regulation



This service is energy neutral.

Frequency/Voltage Control