

Phasor Measurement (Estimation) Units

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WASHINGTON STATE
UNIVERSITY



World Class. Face to Face.

Hand-On Relay School

Outline

- Motivation for Synchronized Measurements
 - Power System Operational Paradigm
 - Synchronized Measurements
- Synchrophasor Fundamentals
 - Synchrophasor Definition
 - Introduction to PMU
 - Phasor Estimation
 - PMU standards
- Application of Synchrphasors
 - Examples of Synchrophasor Applications

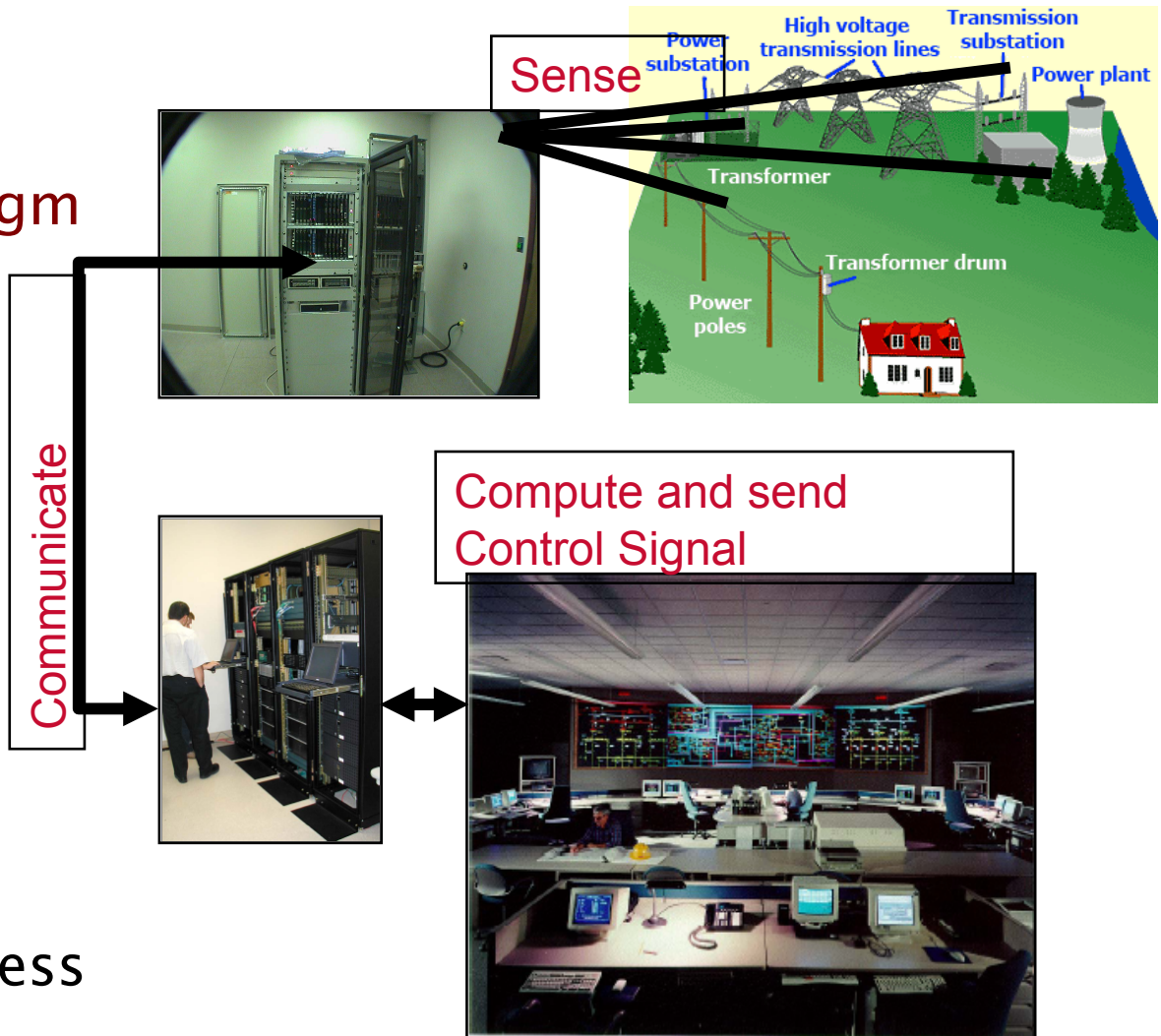
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Motivation for Synchronized Measurements

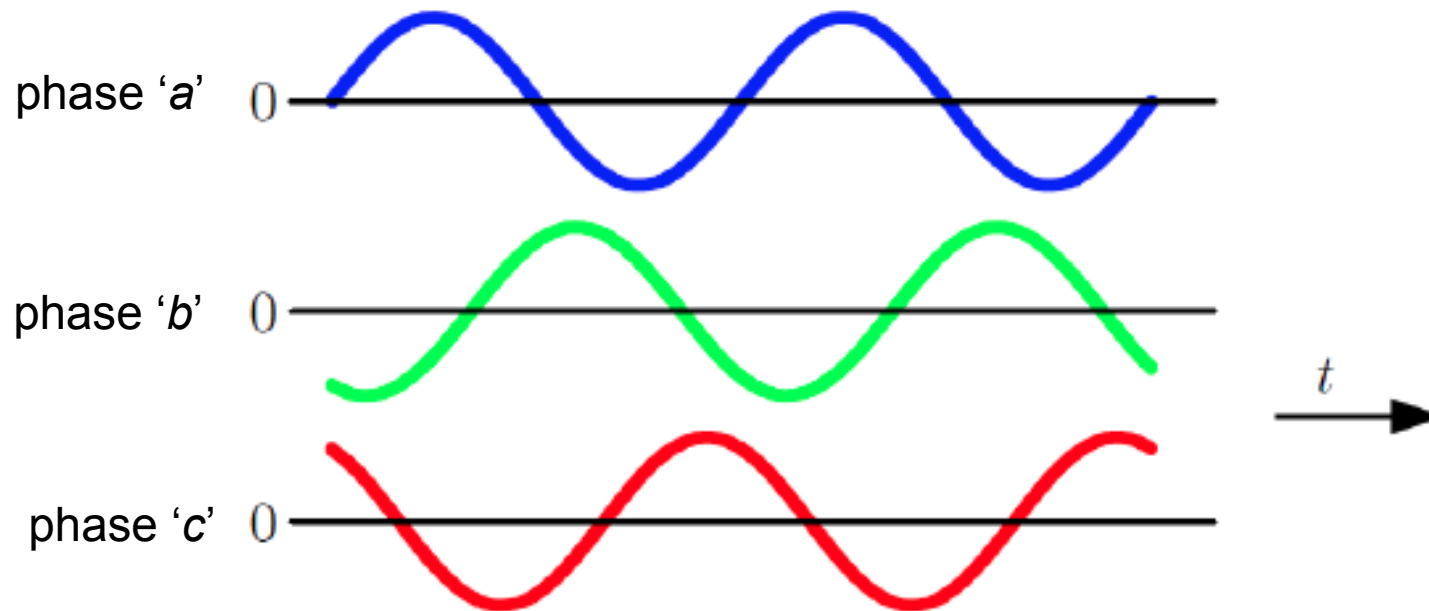
- Power System Operational Paradigm
 - Sense
 - Communicate
 - Compute
 - Visualize
 - Control

- Situational Awareness and Decision Support



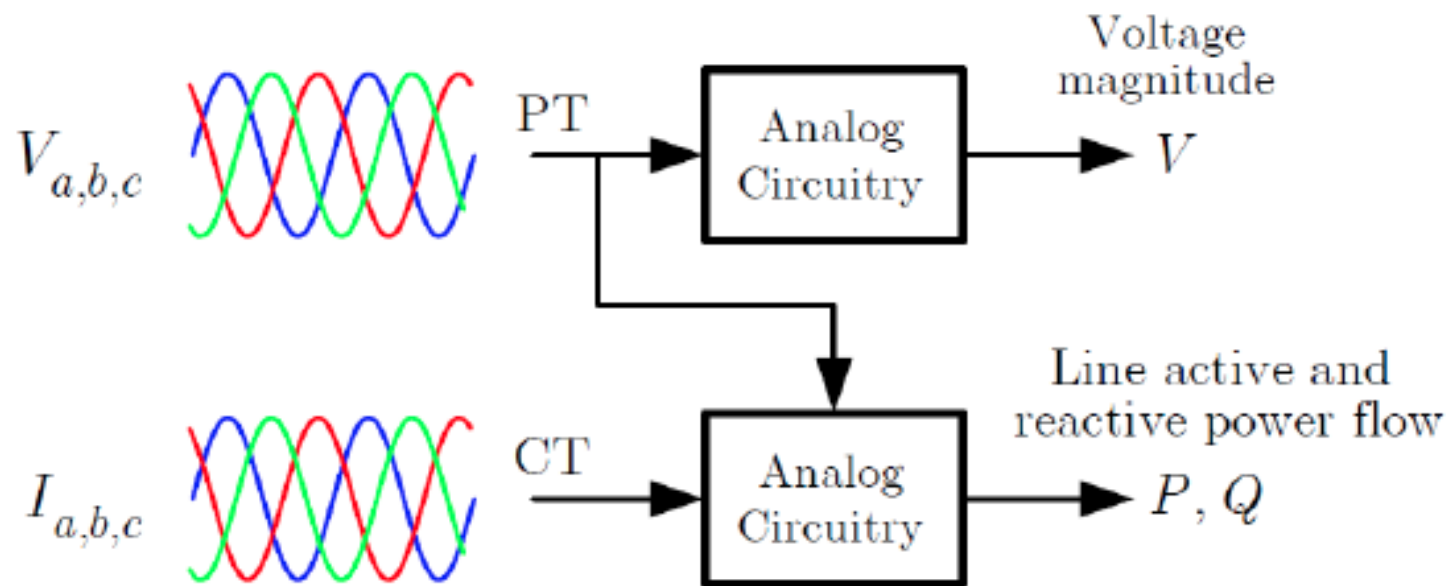
Motivation for Synchronized Measurements: Current/ Voltage Measurements

- Measurements from CT/ PT: 3 phase sinusoidal AC voltages and currents at a frequency of 60 Hz
- Phase 'a' quantities (*voltages and currents*) lead phase 'b' quantities by 120 degrees, which leads phase 'c' by 120 degrees (depending on phasor rotation practice)



Motivation for Synchronized Measurements: Current and Voltage Measurements

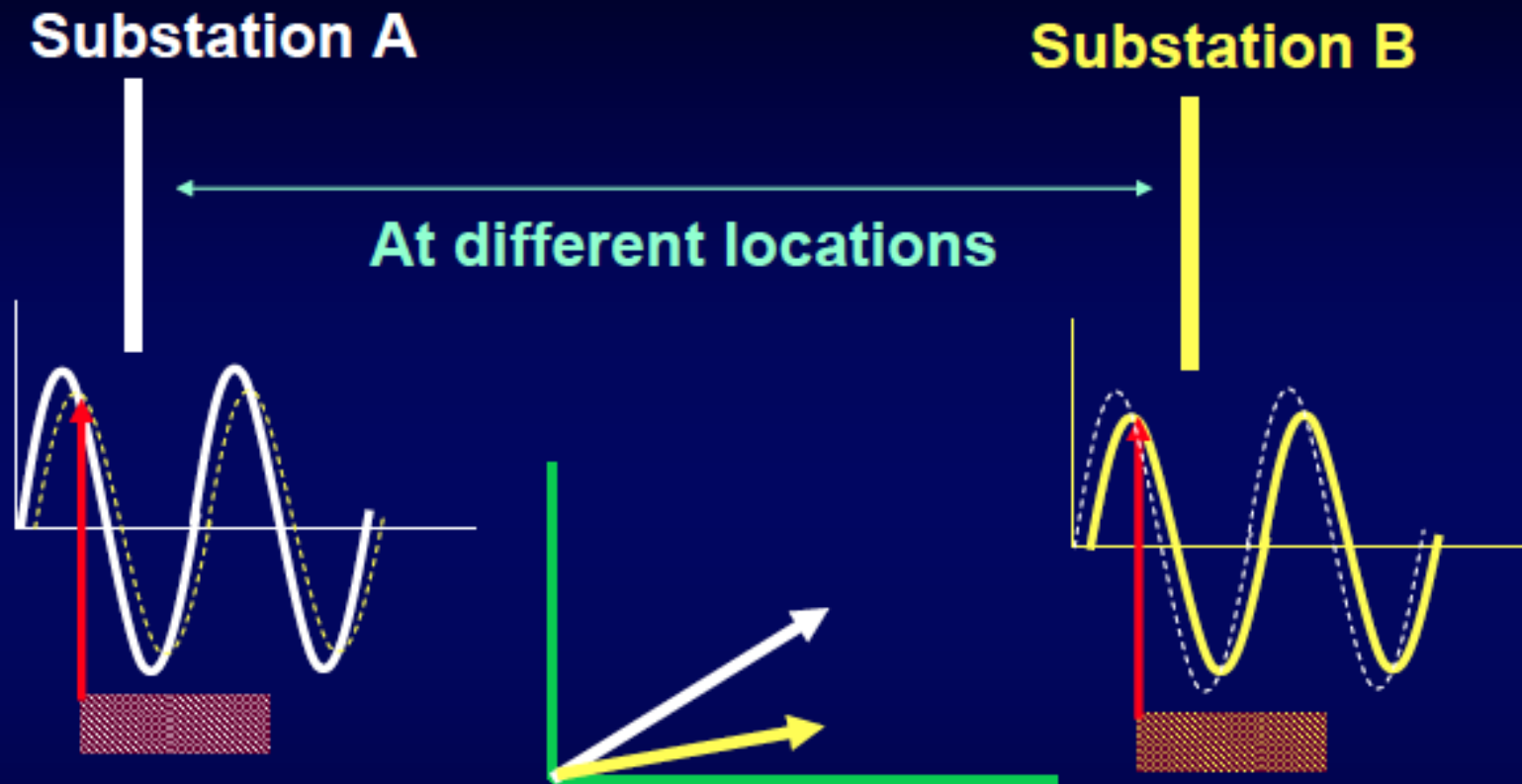
- Measured values sampled generally every 4 seconds are displayed on the Energy Management System (EMS) screens
- *V and P, Q are generally transmitted via modems, microwave, or internet directly to control rooms.*



Motivation for Synchronized Measurements: Need for High Resolution Synchronized Data

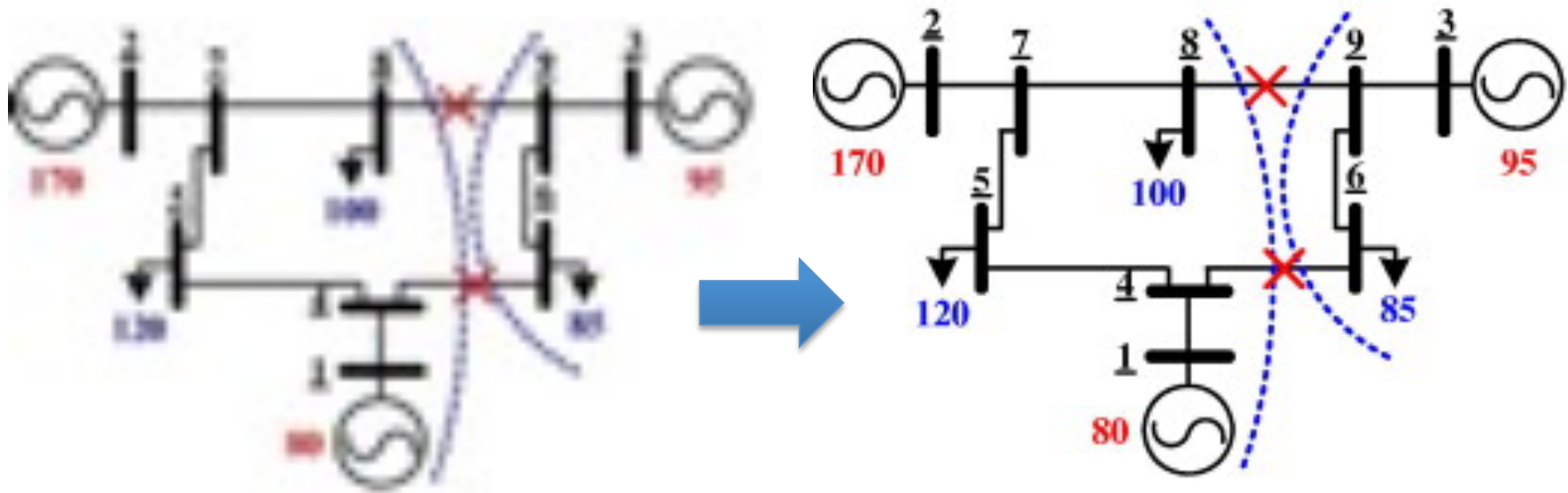
- The data from different locations are not captured at precisely the same time.
- However, V, P, and Q normally do not change abruptly, unless there is a large disturbance nearby.
- System monitoring is more critical during disturbance and transients
- Faster synchronized data is needed to capture the dynamics
- Fast real time control is possible only with real time situational awareness

- Motivation for synchronization



By synchronizing the sampling processes for different signals - which may be hundreds of miles apart, it is possible to put their phasors on the same phasor diagram.

Motivation for Synchronized Measurements: High Resolution Situational Awareness



“It’s like going from an X-ray to a MRI of the grid.”
Terry Boston, CEO PJM Interconnection

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Synchrophasor Fundamentals: Historical Prospective

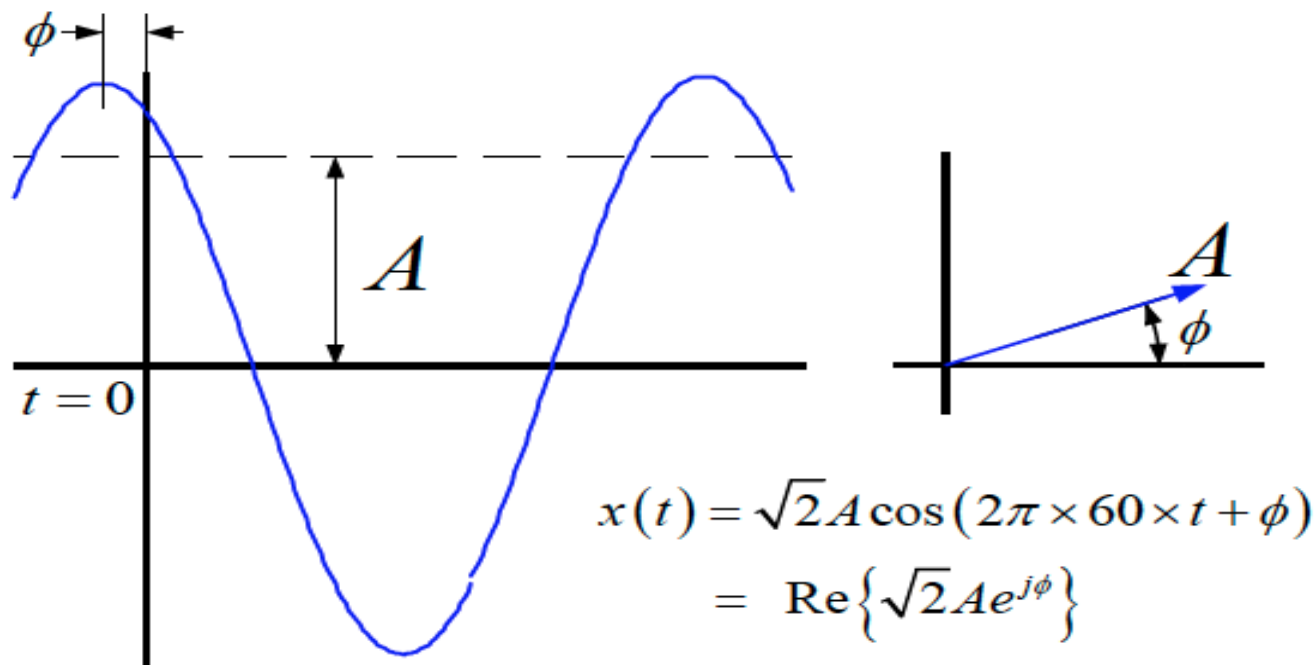
- The concept of using phasors to describe power system operating quantities dates back to 1893 and Charles Proteus Steinmetz's paper on mathematical techniques for analyzing AC networks.
- More recently, Steinmetz's technique of phasor calculation has evolved into the calculation of real-time phasor measurements synchronized to an absolute time reference.
- Although phasors have been clearly understood for over 100 years, the detailed definition of a time-synchronized phasor has only recently been codified in the IEEE 1344 and the soon-to-be voted IEEE C37.118

Synchrophasor Fundamentals: Historical Prospective

- Emergence of computer relaying: digital relays
- Development of symmetrical component distance relays and positive sequence measurements
- Synchronized measurements made possible by Global Positioning System (GPS) satellites
- Development of the first PMUs at Virginia Tech ~ 1982-1992 by Professor Arun Phadke, funded by AEP, DOE, BPA, and NYPA; prototype units assembled at Va Tech and installed on BPA, AEP, and NYPA systems.
- First commercially available PMUs made by Macrodyne (Model 1690, 16/32 channels) in the early 1990s, and installed at Western System, AEP, and NYPA.

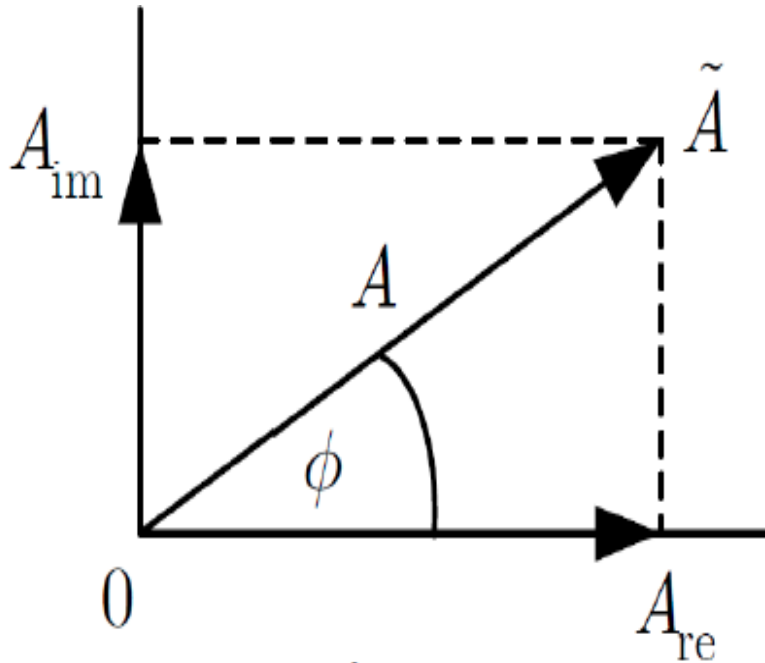
Synchrophasor Fundamentals: Phasor Definition

- Phasor: A sinusoidal signal can be represented by a cosine function with a magnitude A , frequency ω , and phase ϕ .
- A is the rms value of the voltage/current signal



Phasor representation of a sinusoidal wave form

Synchrophasor Fundamentals: Phasor Definition



- Two phasor representations

- Polar coordinates:

$$\tilde{A} = A\varepsilon^{j\phi} = (A, \phi)$$

- Rectangular coordinates:

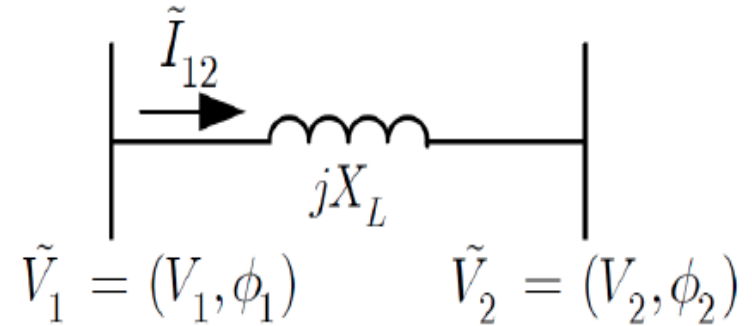
$$\tilde{A} = A_{\text{re}} + jA_{\text{im}} = (A_{\text{re}}, A_{\text{im}})$$

Phasor is a rotating vector: Animation

- Both formats acceptable for phasor data streaming

Synchrophasor Fundamentals: Synchrophasor Need

- From the synchronized measurement of the adjacent bus voltage phasors at the same time instants, the P, Q flow can be computed
- Note: The two voltage phasors have to be measured at exactly the same time



$$\tilde{I}_{12} = \frac{\tilde{V}_1 - \tilde{V}_2}{jX_L}, \quad S_{12} = \tilde{V}_1 \bullet \tilde{I}_{12}^* = P_{12} + jQ_{12}, \quad P_{12} = \frac{V_1 V_2 \sin(\phi_1 - \phi_2)}{X_L}$$

- Looking at angle separation between generator and load buses provide a reliable way to assess system stress conditions

Synchrophasor Fundamentals: Synchrophasor Definition

- Synchrophasor: Precision Time-tagged Positive Sequence Phasor measured at different locations
- A **Phasor Measurement Unit (PMU)** has been defined by the IEEE as “a device that produces Synchronized Phasor, Frequency, and Rate of Change of Frequency (ROCOF) estimates from voltage and/or current signals and a time synchronizing signal”.
- Phasor Measurement Unit (PMU) – A transducer that converts three-phase analog signal of voltage or current into Synchrophasors



Synchrophasor Fundamentals: Synchrophasor Definition

- The synchrophasor and frequency values must meet the general definition and minimum accuracy required in the IEEE Synchrophasor Standard, C37.118-2011.
- The device must provide a real-time data output which conforms to C37.118.1 requirements.
- The IEEE definition clarifies that “the same device may perform other functions and include another functional name”.



Synchrophasor Fundamentals

- In the real world, the power system seldom operates at exactly the nominal frequency.
- As such, the calculation of the phase angle, needs to take into account the actual frequency of the system at the time of measurement.
- For example, if the nominal frequency is 59.5Hz on a 60Hz system, the period of the waveform is 16.694ms instead of 16.666ms – a difference of 0.167%.
- The captured phasors are to be time-tagged based on the time of the UTC Time Reference and accuracy is important.

Synchrophasor Fundamentals: PMU Measurements

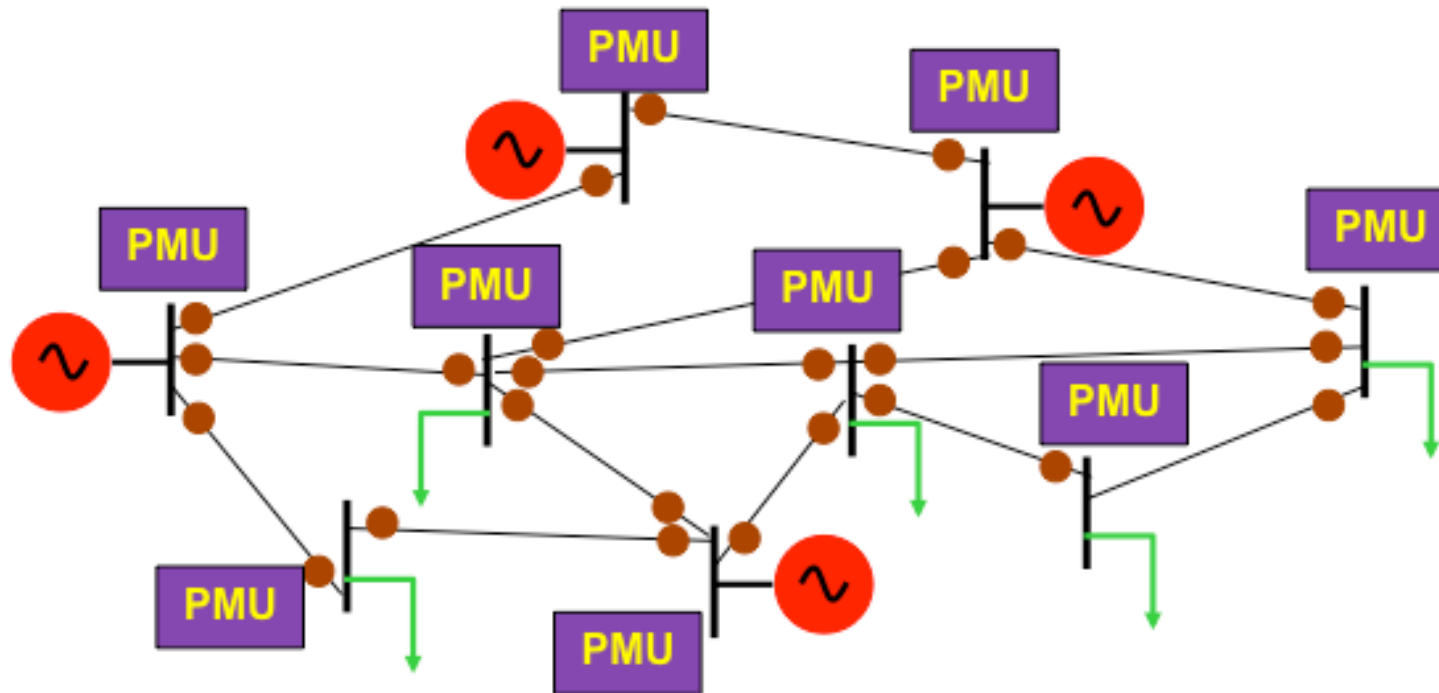
PMUs measure (synchronously):

- Positive sequence voltages and currents
- Phase voltages and currents
- Local frequency
- Local rate of change of frequency
- Circuit breaker and switch status

Synchrophasor Fundamentals: Basic PMU applications

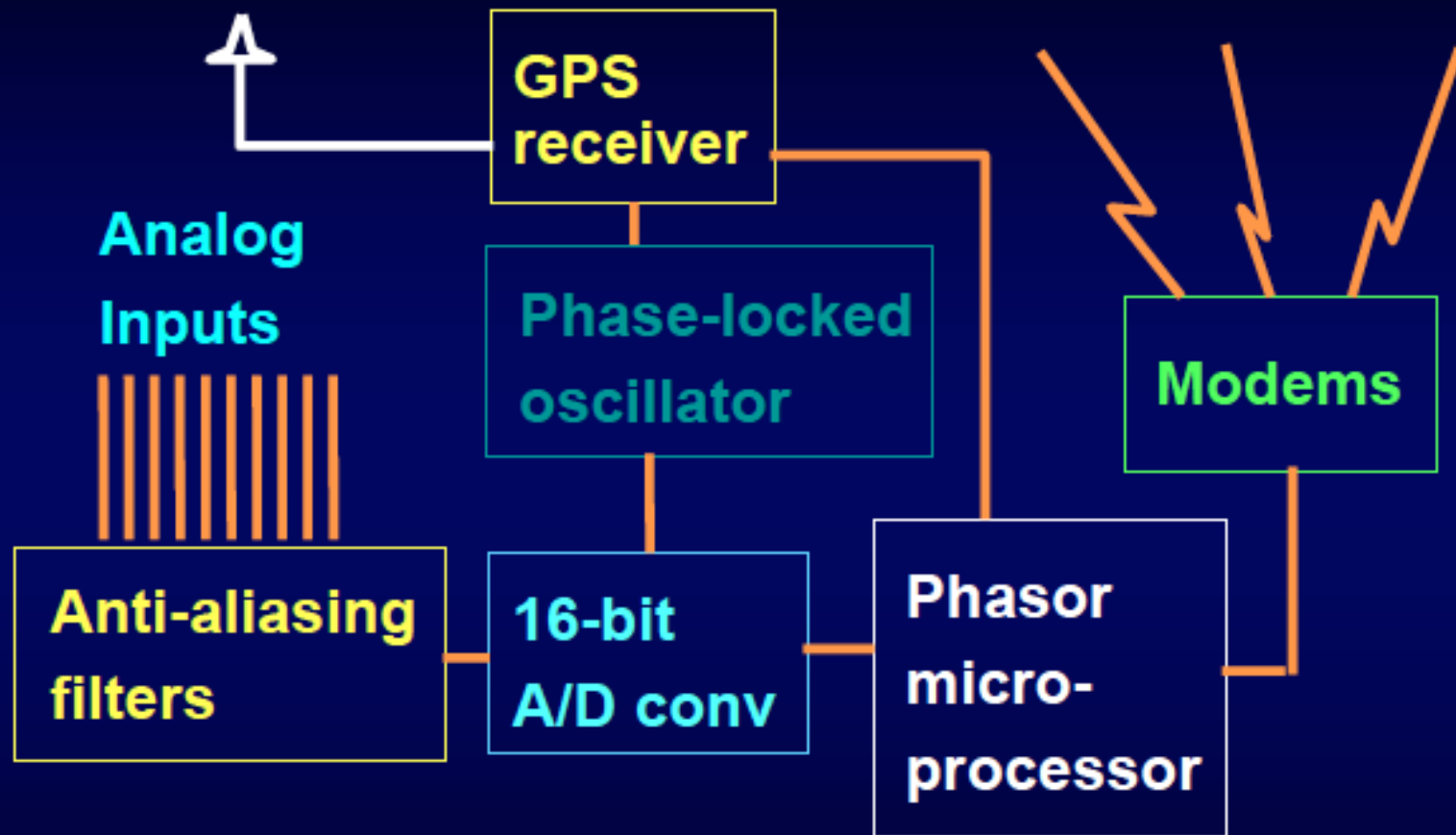
- Global behavior may be understood from local measurement
 - Phasor measurement data can be used to supplement/enhance existing control center functions and provide new functionalities.
 - Phasor measurement data with GPS signal can provide synchronized voltage and current phasor measurements across a wide region
 - By measuring the phase directly, the power transfer between buses can be computed directly
 - High sampling rate (30 samples per second) Extended visibility: beyond one's own operating region
 - Disturbance monitoring –transient and steady-state responses

Synchrophasor Fundamentals: Basic Applications



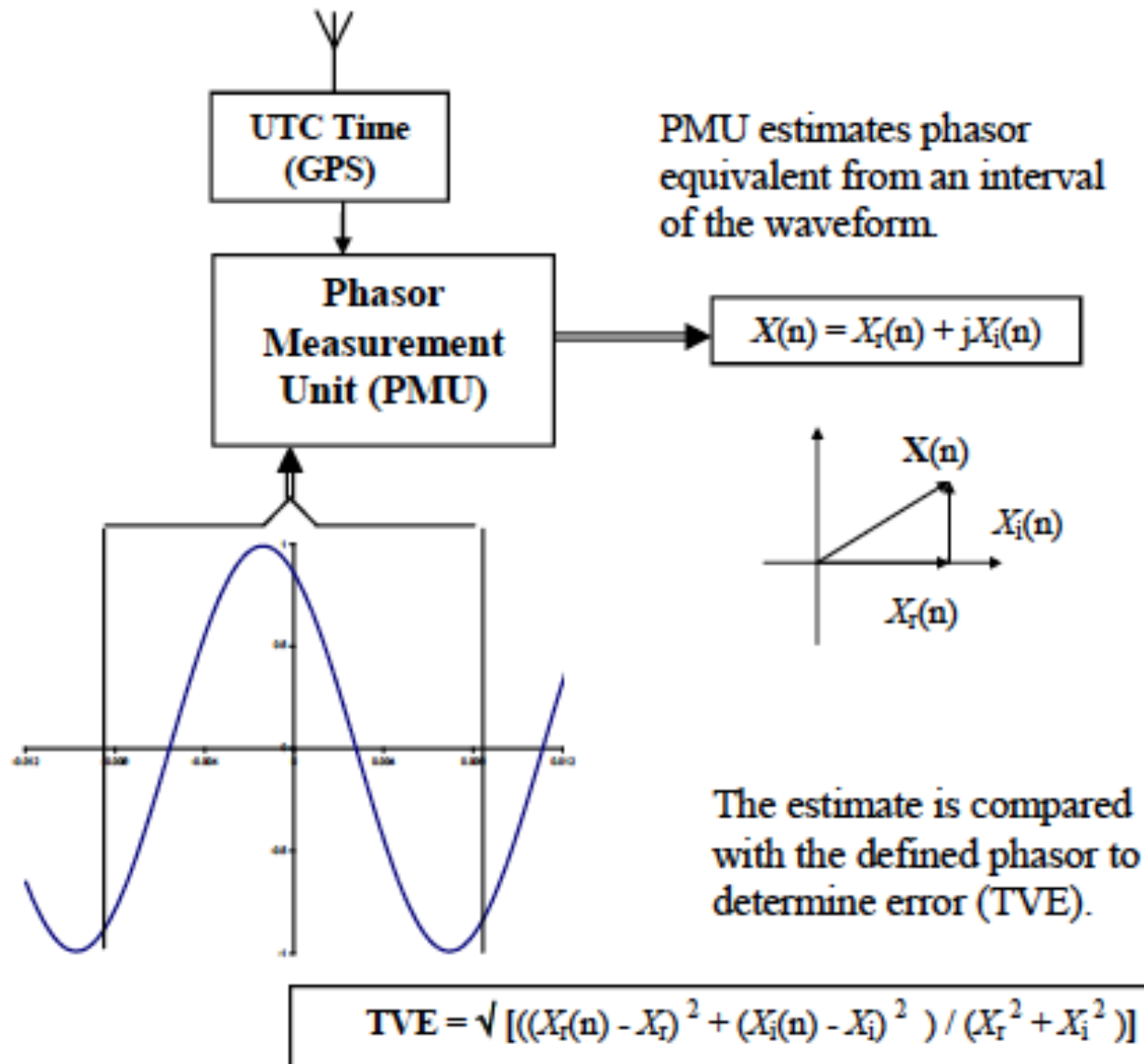
- Exposes system (local and interarea mode) oscillations
- Can be used to validate system performance, model parameters, and control equipment settings
- Set up more reliable protection systems
- System restoration

- **A phasor measurement unit**

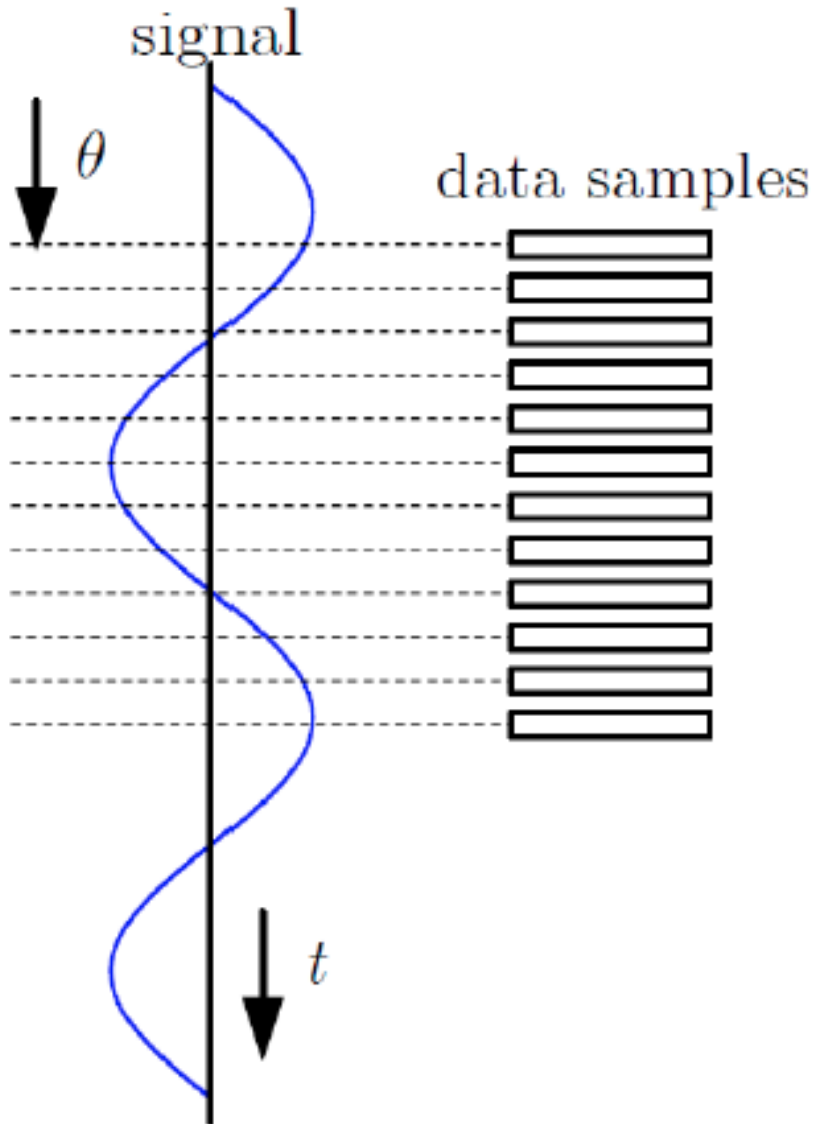


Except for synchronization, the hardware is the same as that of a digital fault recorder or a digital relay.

Synchrophasor Fundamentals: Sampling



Synchrophasor Fundamentals: Estimation



Sample the continuous voltage or current signal. The figure shows 12 points per cycle (the sampling rate is $12 \times 60 = 720$ Hz).

Use Discrete Fourier Series (DFS/DFT) method to compute the magnitude and phase of the signal (i.e., applying DFS formula).

Calculate magnitude and phase for each phase of the 3-phase quantity

Using one period of data reduces the effect of measurement noise

Synchrophasor Fundamentals: Estimation

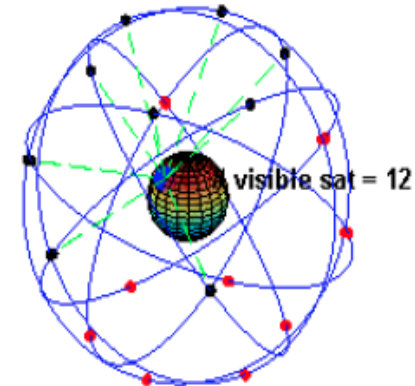
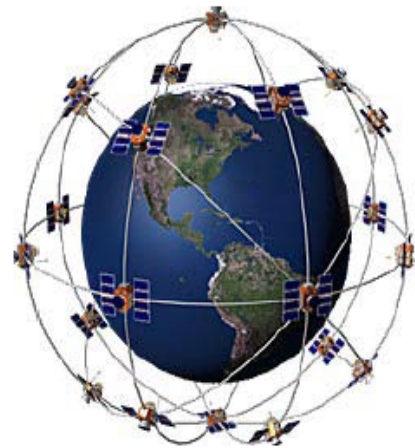
- Although theoretically one can get a data point on phase a , another data point on phase b , and a third data point on phase c to compute the positive sequence quantity, the approach is prone to measurement noise.
- There is no standard phasor algorithm used by different PMU manufacturers
- Most phasor calculation in commercial PMUs uses a 1-cycle window, likely centering in the window
- To reduce noise, some manufacturers use the average value over an even number of windows (2 or maybe 4)
- There is latency in the PMU itself –number of cycles and processing time
- Using the PMU from the same supplier at least provides consistency of the phasor algorithm.

Synchrophasor Fundamentals: Time Signal

- Correct operation of a PMU requires a common and accurate timing reference. The timing reference is described in IEEE Std. C37.118.1-2011.
- To achieve a common timing reference for the PMU acquisition process, it is essential to have a source of accurate timing signals (i.e., synchronizing source) that may be internal or external to the PMU.
- For internal, the synchronization source is integrated (built-in) into the PMU (external GPS antenna still required). In the latter case, the timing signal is provided to the PMU by means of an external source, which may be local or global, and a distribution infrastructure (based on broadcast or direct connections).

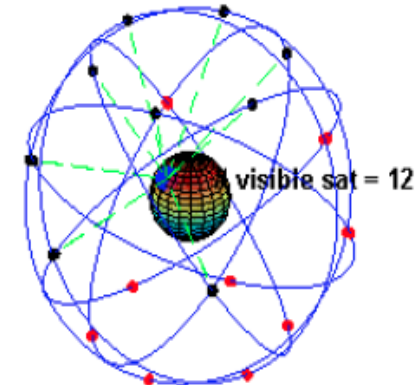
Synchrophasor Fundamentals: Time Signal

- GPS (Global Positioning System, 1973, originally 24 satellites) – 32 satellites in medium Earth orbit: 2 micro-second accuracy
- IRIG-B pulses
- IEEE 1588: distributed by Ethernet
- The GPS clock signal is received once every second on the second.



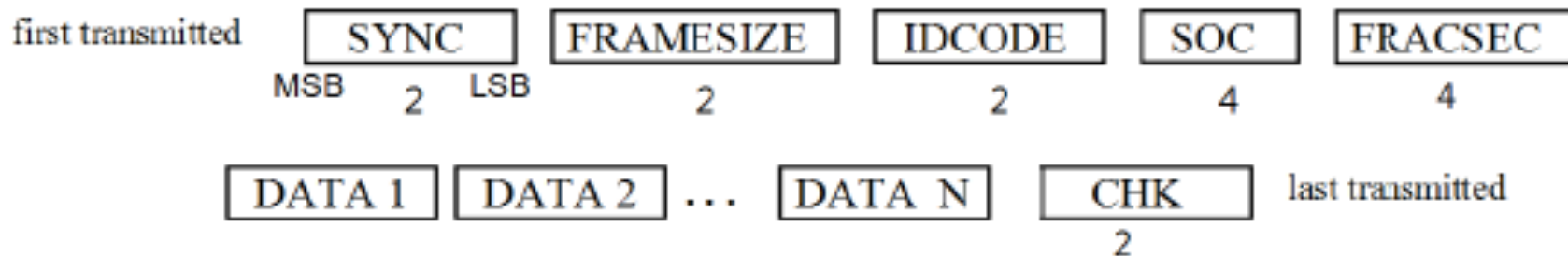
Synchrophasor Fundamentals: Time Signal

- Within a PMU, a phase-locked oscillator is used to generate the time tags within the second.
- The time tag is sent out with the phasors. Thus if a phasor information packet arrives out of order to a PDC (phasor data concentrator), the phasor time response can still be assembled correctly.
- If the GPS pulse is not received for a while, the time tagging error may result in significant phase error.



Synchrophasor Fundamentals: Data Packets

- SOC count starting at midnight 01 Jan-1970



Synchrophasor Fundamentals: Setting PMU

=ACC

Password: ?*****

Relay 2
Station A
Level 1

Date: 06/09/2011 Time: 21:04:12.964
Serial Number: 1110670278

=>2AC

Password: ?****

Relay 2
Station A
Level 2

Date: 06/09/2011 Time: 21:04:18.916
Serial Number: 1110670278

=>>SET G EPMU

Global

Global Enables

Synchronized Phasor Measurement (Y,N)

EPMU := Y ?

Synchrophasor Fundamentals: Setting PMU

Current and Voltage Source Selection (Y,N,1,2) ESS := Y ?

Line Current Source (IW,COMB) LINEI := IW ?

Alternate Line Current Source (IX,NA) ALINEI := NA ?

Breaker 1 Current Source (IW,IX,NA) BK1I := IW ?

Polar. Current (IAX,IBX,ICX,NA) IPOL := NA ?

Alternate Line Voltage Source (VZ,NA) ALINEV := NA ?

Synchronized Phasor Measurement Settings

Message Format (C37.118,FM) MFRMT := C37.118?

Messages per Second (1,2,4,5,10,12,15,20,30,60) MRATE := 60 ?

PMU Application (F = Fast Response, N = Narrow BW) PMAPP := N ?

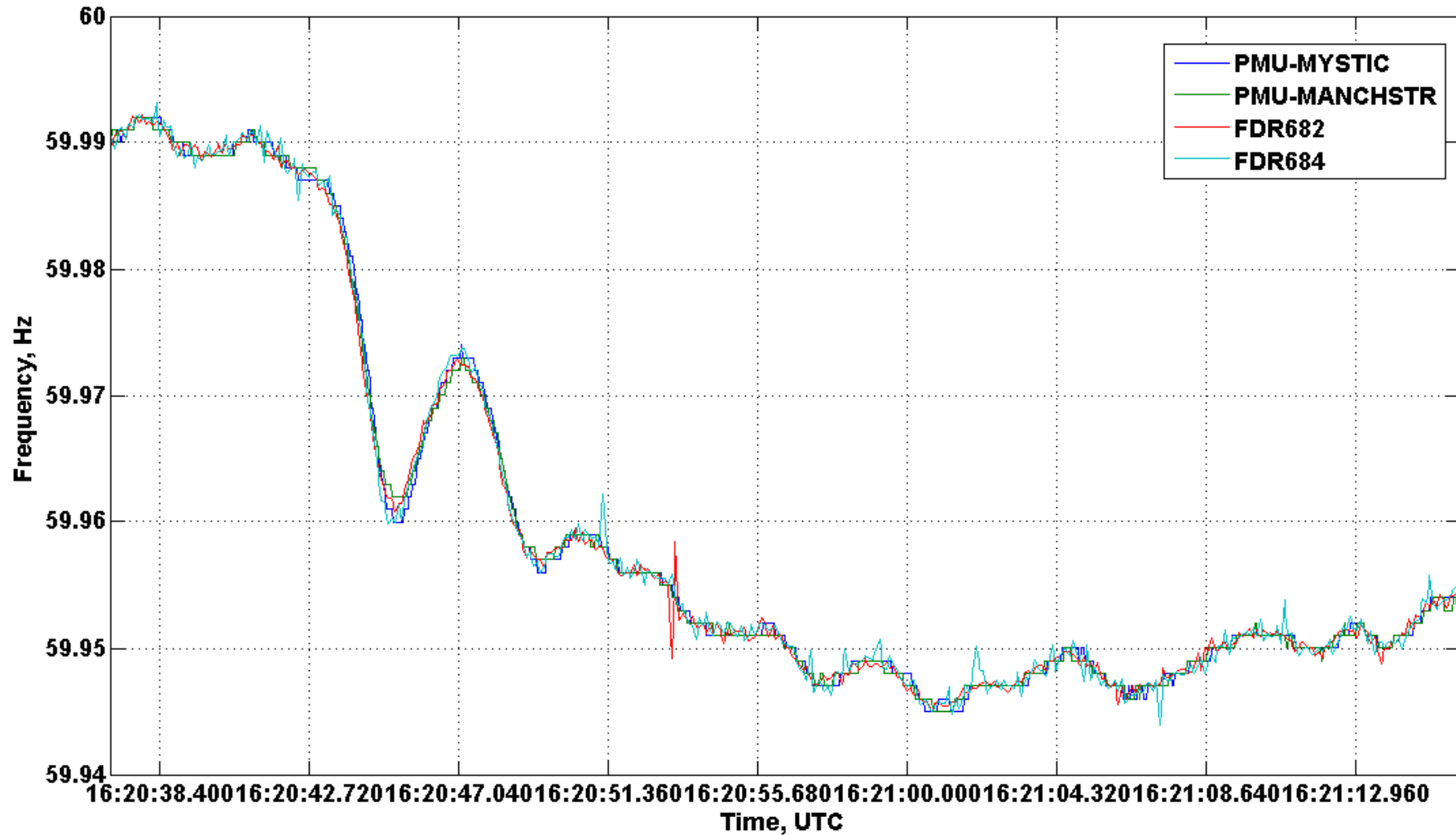
Freq. Based Phasor Compensation (Y,N) PHCOMP := Y ?

Station Name (16 characters)

PMSTN := "SEL421_1"

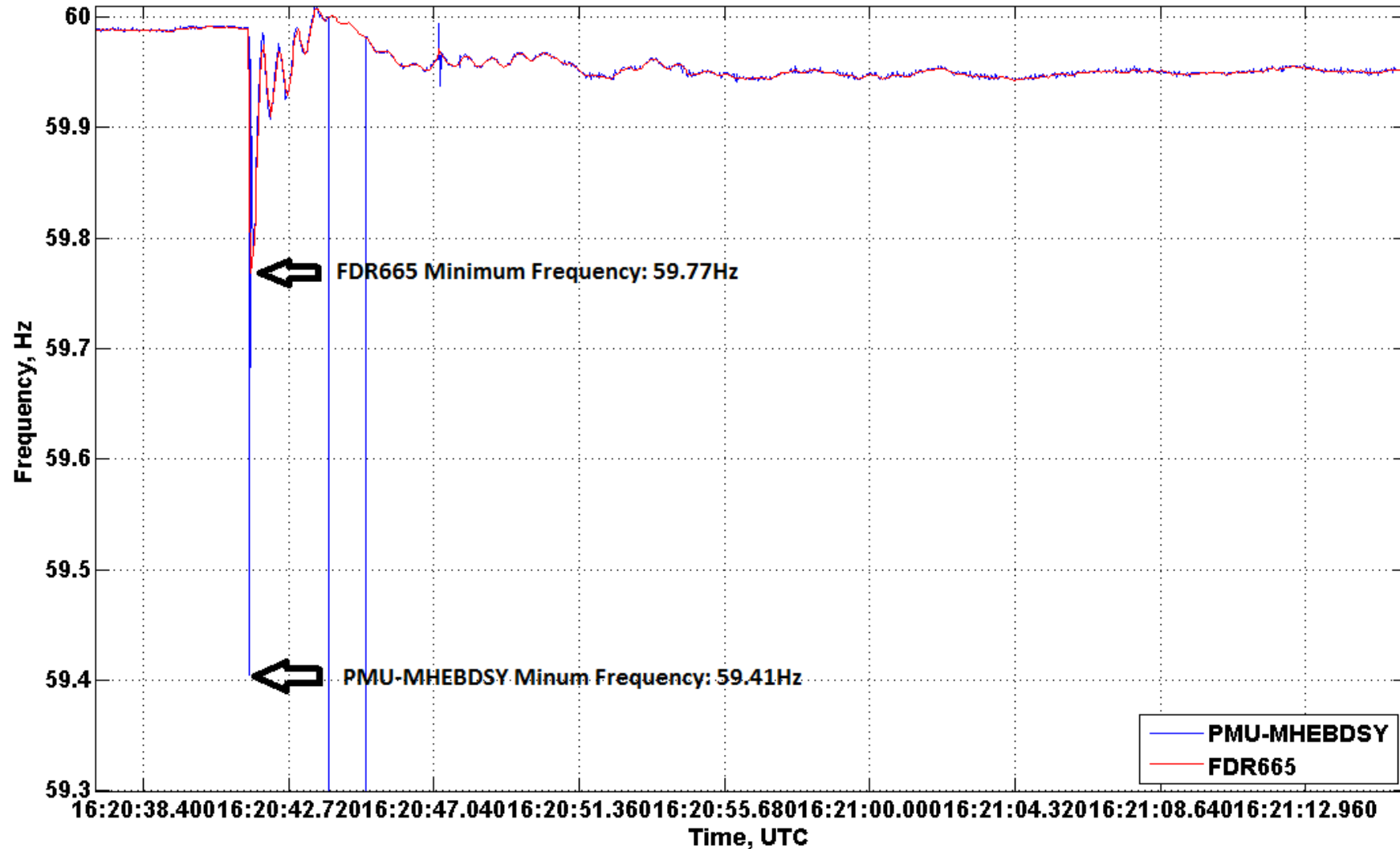
Synchrophasor Fundamentals: Data Quality

Frequency - New England PMU & FDR



Synchrophasor Fundamentals: Data Quality

Frequency - Manitoba PMU and FDR



Synchrophasor Fundamentals: Data Quality

- According to the Standard C37.118.1, PMUs can be broadly classified into two classes of performance – P Type (Protection applications requiring fast response) and M-Type (Measurement applications requiring high precision). The class of performance needs to be provided by the Vendor.
- The Standard C37.118.1 specifies the Steady State & Dynamic Performance Compliance Criteria for each performance class of PMUs.

Steady State Performance: Magnitude & Phase Angle (Clause: 5.5.5)

Influence quantity	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit			
		P class		M class	
		Range	Max TVE (%)	Range	Max TVE (%)
Signal frequency range— f_{dev} (test applied nominal + deviation: $f_0 \pm f_{dev}$)	$F_{nominal}$ (f_0)	± 2.0 Hz	1	± 2.0 Hz for $F_s < 10$ $\pm F_s/5$ for $10 \leq F_s < 25$ ± 5.0 Hz for $F_s \geq 25$	1
The signal frequency range tests above are to be performed over the given ranges and meet the given requirements at three temperatures: T = nominal (~ 23 °C), T = 0 °C, and T = 50 °C					
Signal magnitude— Voltage	100% rated	80% to 120% rated	1	10% to 120% rated	1
Signal magnitude— Current	100% rated	10% to 200% rated	1	10% to 200% rated	1
Phase angle with $ f_m - f_0 < 0.25$ Hz	Constant or slowly varying angle	$\pm \pi$ radians	1	$\pm \pi$ radians	1
Harmonic distortion (single harmonic)	<0.2% (THD)	1%, each harmonic up to 50th	1	10%, each harmonic up to 50th	1
Out-of-band interference	<0.2% of input signal magnitude		None	10% of input signal magnitude for $F_s \geq 10$. No requirement for $F_s < 10$.	1.3

Steady State Performance: Frequency & ROCOF (Clause: 5.5.5)

Influence quantity	Reference condition	Error requirements for compliance			
		P class		M class	
Signal frequency	Frequency = f_0 (f_{nominal}) Phase angle constant	Range: $f_0 \pm 2.0$		Range: $f_0 \pm 2.0$ Hz for $F_s \leq 10$ $\pm F_s/5$ for $10 \leq F_s < 25$ ± 5.0 Hz for $F_s \geq 25$	
		Max FE	Max RFE	Max FE	Max RFE
		0.005 Hz	0.01 Hz/s	0.005 Hz	0.01 Hz/s
Harmonic distortion (single harmonic)	<0.2% THD	1% each harmonic up to 50th		10% each harmonic up to 50th	
		Max FE	Max RFE	Max FE	Max RFE
	$F_s > 20$	0.005 Hz	0.01 Hz/s	0.025 Hz	6 Hz/s
	$F_s \leq 20$	0.005 Hz	0.01 Hz/s	0.005 Hz	2 Hz/s
Out-of-band interference	<0.2% of input signal magnitude	No requirements		Interfering signal 10% of signal magnitude	
				Max FE	Max RFE
		None	None	0.01 Hz	0.1 Hz/s

Dynamic Performance: Magnitude & Phase Angle for Step Change Tests (Clause: 5.5.8)

Step change specification	Reference condition	Maximum response time, delay time, and overshoot					
		P class			M class		
		Response time (s)	Delay time (s)	Max overshoot/undershoot	Response time (s)	Delay time (s)	Max Overshoot/undershoot
Magnitude = $\pm 10\%$, $k_x = \pm 0.1$, $k_a = 0$	All test conditions nominal at start or end of step	$1.7/f_0$	$1/(4 \times F_s)$	5% of step magnitude	See Table 11	$1/(4 \times F_s)$	10% of step magnitude
Angle $\pm 10^\circ$, $k_x = 0$, $k_a = \pm \pi/18$	All test conditions nominal at start or end of step	$1.7/f_0$	$1/(4 \times F_s)$	5% of step magnitude	See Table 11	$1/(4 \times F_s)$	10% of step magnitude

k_x = Amplitude Modulation Factor
 k_a = Phase Angle Modulation Factor

Dynamic Performance: Magnitude & Phase Angle for Step Change Tests (Clause: 5.5.8)

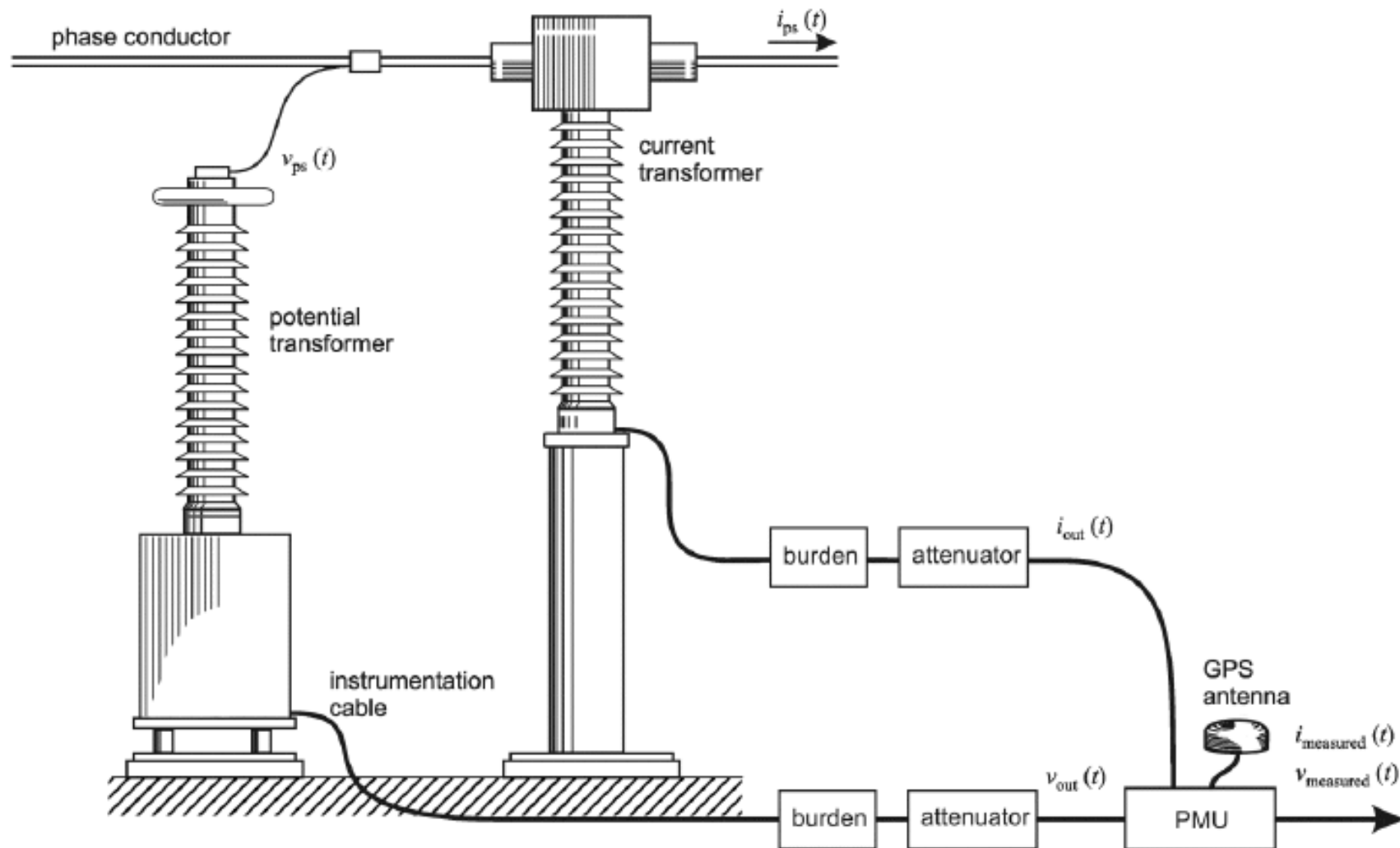
Signal specification	Reference condition	Maximum response time			
		P class		M class	
		Frequency response time (s)	ROCOF response time (s)	Frequency response time (s)	ROCOF response time (s)
Magnitude test	Same	$3.5/f_0$	$4/f_0$	See Table 11	See Table 11
Phase test	Same	$3.5/f_0$	$4/f_0$	See Table 11	See Table 11

Table 11 —Response time for M class phasor, frequency, and ROCOF for input step change

Maximum response time in step change test for M class, in seconds										
Reporting rate (F_s)	10	12	15	20	25	30	50	60	100 ^a	120 ^a
Phasor (TVE)	0.595	0.493	0.394	0.282	0.231	0.182	0.199	0.079	0.050	0.035
Frequency (FE)	0.869	0.737	0.629	0.478	0.328	0.305	0.130	0.120	0.059	0.053
ROCOF (RFE)	1.038	0.863	0.691	0.520	0.369	0.314	0.134	0.129	0.061	0.056

^a Rates higher than 60 are not required, so this listing is advisory only. Rates even higher will be limited by the measurement window. Rates lower than 10/s are not expected to be used for dynamic measurement and are not included in this table.

Synchrophasor Fundamentals: Instrumentation



Synchrophasor Fundamentals: Data Quality

- GPS-synchronized equipment has the capability to provide a data acquisition system with the following accuracy:
 - a) Time tagging with accuracy better than 1 microsecond (or equivalently 0.02 degrees of phase at 60 Hz).
 - b) Magnitude accuracy of 0.1% or better.
- VT/CT error
- Instrumentation Channel error (500 ft=0.54 degree)
- Can be modeled to correction

Synchrophasor Fundamentals: Data Quality

- Generally Voltage and current magnitude data are quite accurate ($\sim 1\%$ error).
- Voltage and current phase angle errors occur in some PMUs. “Random” jumps of 7.5 degrees or integer multiples of it, followed by resets at a later time
- The errors are attributed to
 - Wrong phase connection to a PMU: a constant bias, trivial to correct
 - Signal processing algorithms used in the PMU: off-nominal frequency values and phase-lock oscillator implementation
 - Error with time synchronization: GPS clock signal overload or temporary loss of GPS signal
 - Delays due to instrumentation cables and filter time constants

Synchrophasor Fundamentals: Standards

- IEEE 1344-1995
- IEEE C37.118 – 2005
 - Measurement requirements
 - Specified in terms of the result
 - Error limits specified
 - Data transmission
 - Messaging requirements only
 - Adapted to TCP/IP & UDP/IP
- Measurements - IEEE C37.118.1-2011
- Communications - IEEE C37.118.2-2011 & IEC 61850-90-5

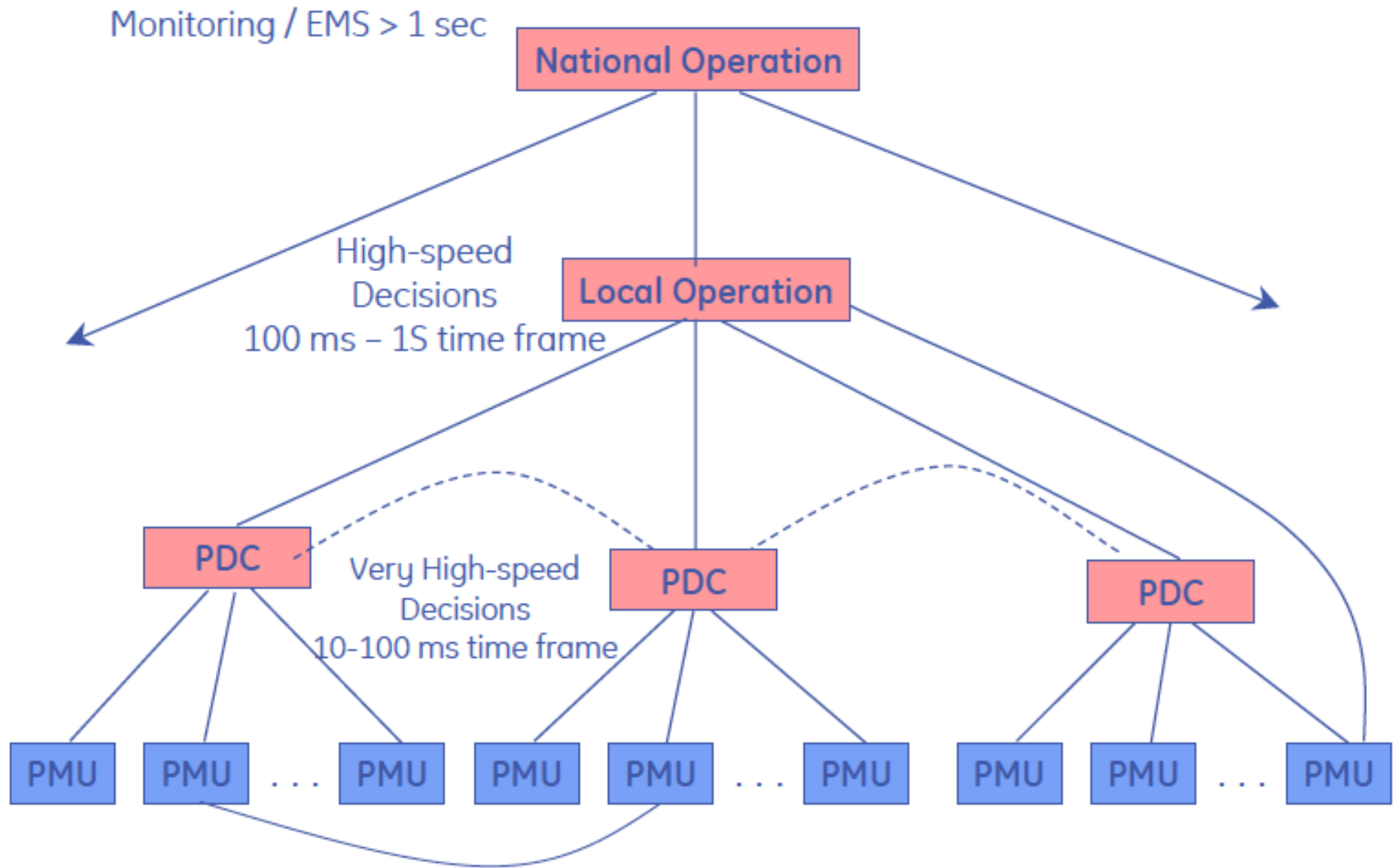
Synchrophasor Fundamentals: Standards

- Existing C37.118-2005 split into two standards
- PC37.118.1
 - Covers measurements only
 - Adds frequency & ROCOF, and dynamic operation
- PC37.118.2
 - Preserves existing data exchange
 - Adds needed current improvements (flags & configuration)
- IEC 61850-90-5
 - Joint IEEE-IEC project for synchrophasor data communication
 - Uses standard 61850 models & processes
 - Adds communication methods where needed

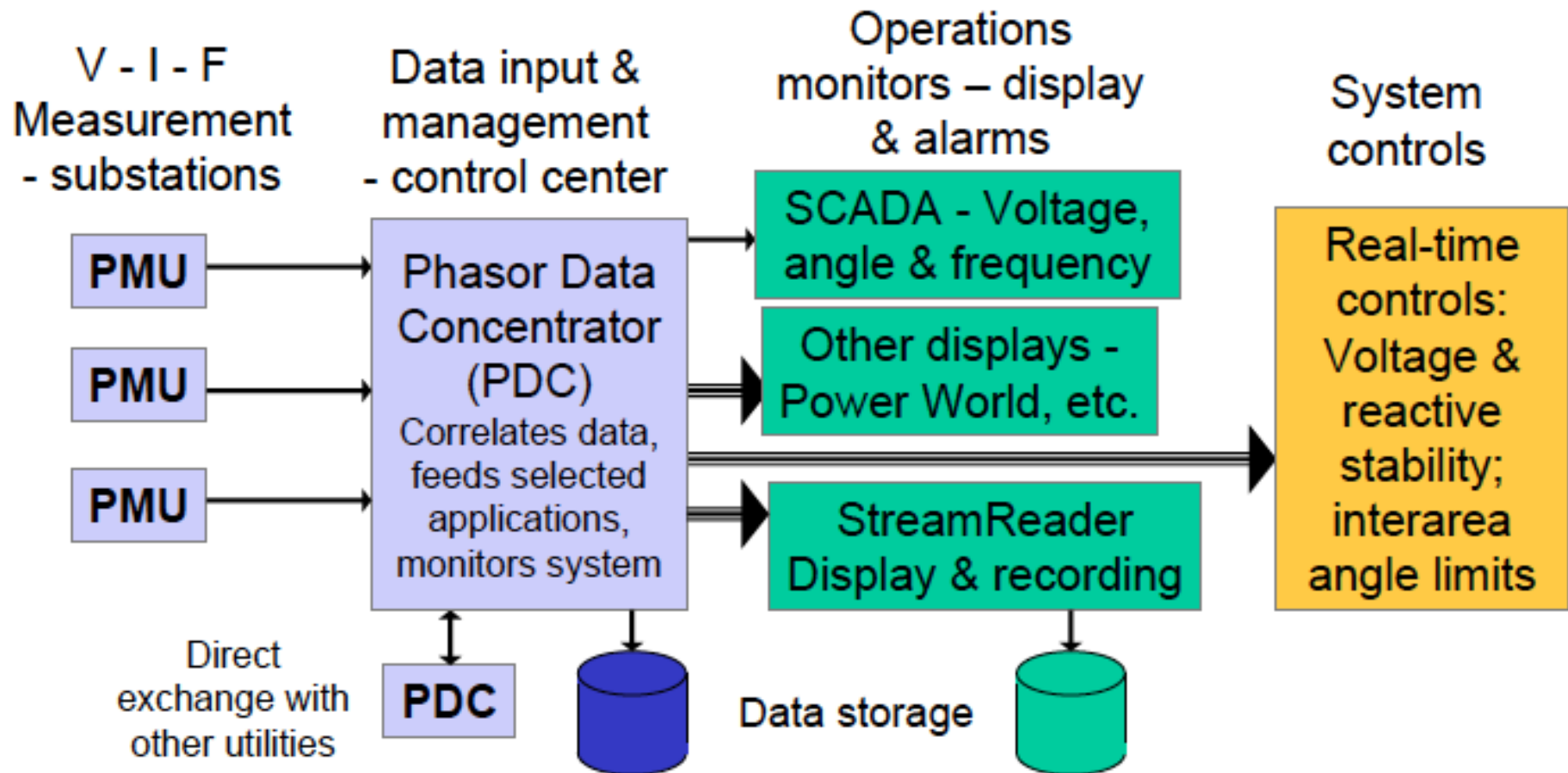
Synchrophasor Fundamentals: Standards

- C37.242-2013
- Guidelines for installation Testing
- C37.244-2013
- PDC Communication and requirements

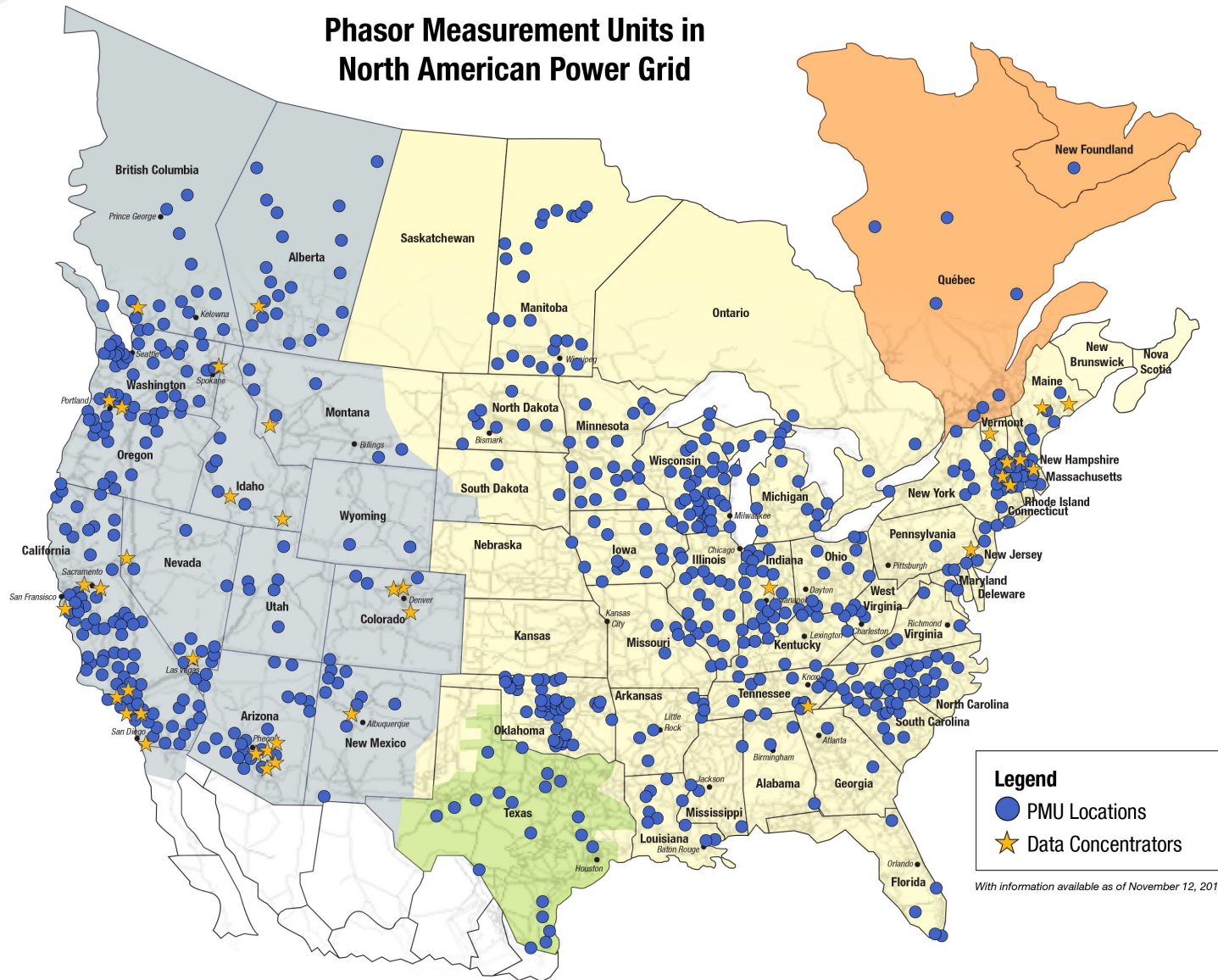
Phasor Measurement Unit: Architecture



Phasor Measurement Example



Phasor Measurement Units in North American Power Grid



Legend

- PMU Locations
- ★ Data Concentrators

With information available as of November 12, 2012

Synchrophasor Fundamentals: Installation

- Primary source of current and voltages? (contingencies, burden)
- Does PMU require direct GPS antenna input? (IRIG-B?)
- Does the PMU output match the communications system interface? (data throughput with available bandwidth)
- What types of communications are established within the substation? (Fiber or metallic?)
- Does the application have particular filtering needs (P and M classes as defined in IEEE Std. C37.118.1-2011)? (SE, Oscillation Monitor?)

PMU Installation

The number of PMUs deployed will depend on several factors:

- Whether the tools and data are recognized to provide value
- Learning how to do effective physical and cyber-security at reasonable cost
- Ease of implementation and integration into the communications and data systems; they should be plug & play and remotely configurable, under detailed interoperability specifications and protocols
- Deployment cost should be a minor issue for new facilities
- To assure that PMUs once deployed will receive consistent support with O&M, communications links, and consistent data quality,
- The technology has to be integrated with utility processes.

PMU Installation (Source: NASPI)

Phasors will be deployed at the following locations by 2014:

- Major transmission interconnections and interfaces
- All 500kV and above substations and most 200 kV and above substations
- Key generating plants (all > 500 MW) in generator switchyards, even on some individual generators
- Major load centers
- Large wind generators, solar and storage locations
- Other locations to assure observability in areas with sparse PMU coverage

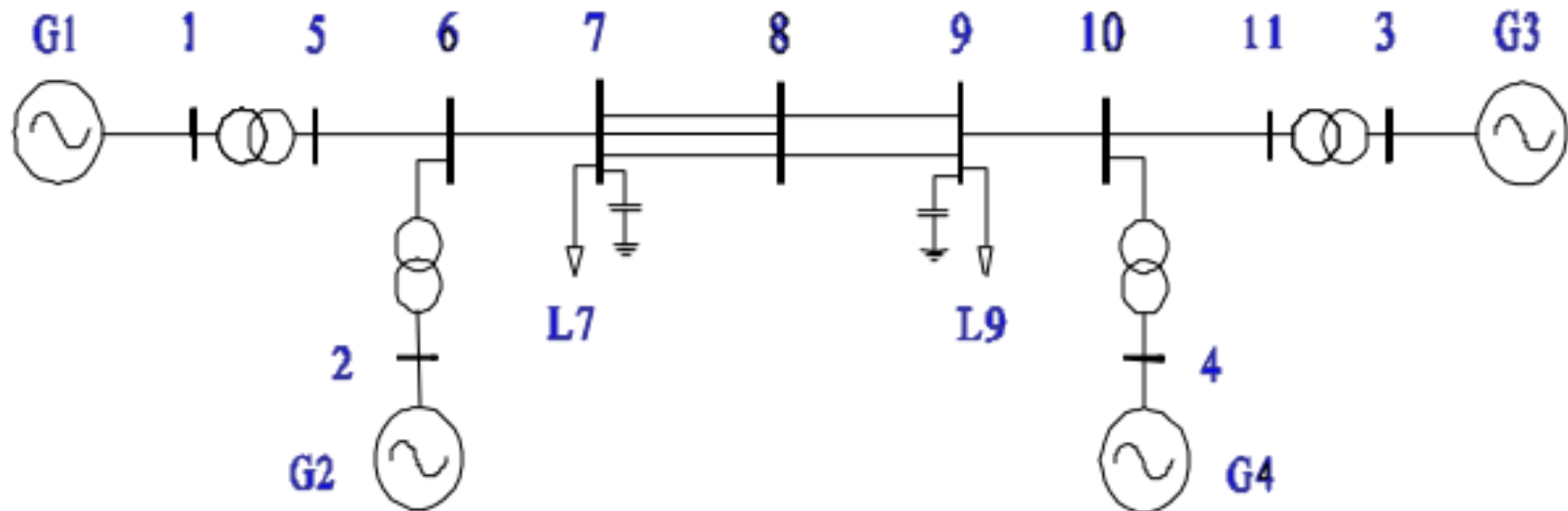
By 2019, remaining 200kV and above substations, in locations needed for local control actions, and even on the distribution network.

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PMU Applications

Kundur's Two-Area System



PMU Applications

table 1. PMU deployment in different parts of the world.

PMU Applications	North America	Europe	China	India	Brazil	Russia
Post-disturbance analysis	✓	✓	✓	P	T	✓
Stability monitoring	✓	✓	✓	P	P	✓
Thermal overload monitoring	✓	✓	✓	P	P	✓
Power system restoration	✓	✓	✓	P	P	P
Model validation	✓	✓	✓	P	T	✓
State estimation	P	P	P	P	P	P
Real-time control	T	T	T	P	P	P
Adaptive protection	P	P	P	P	P	P
Wide area stabilizer	T	T	T	P	P	P

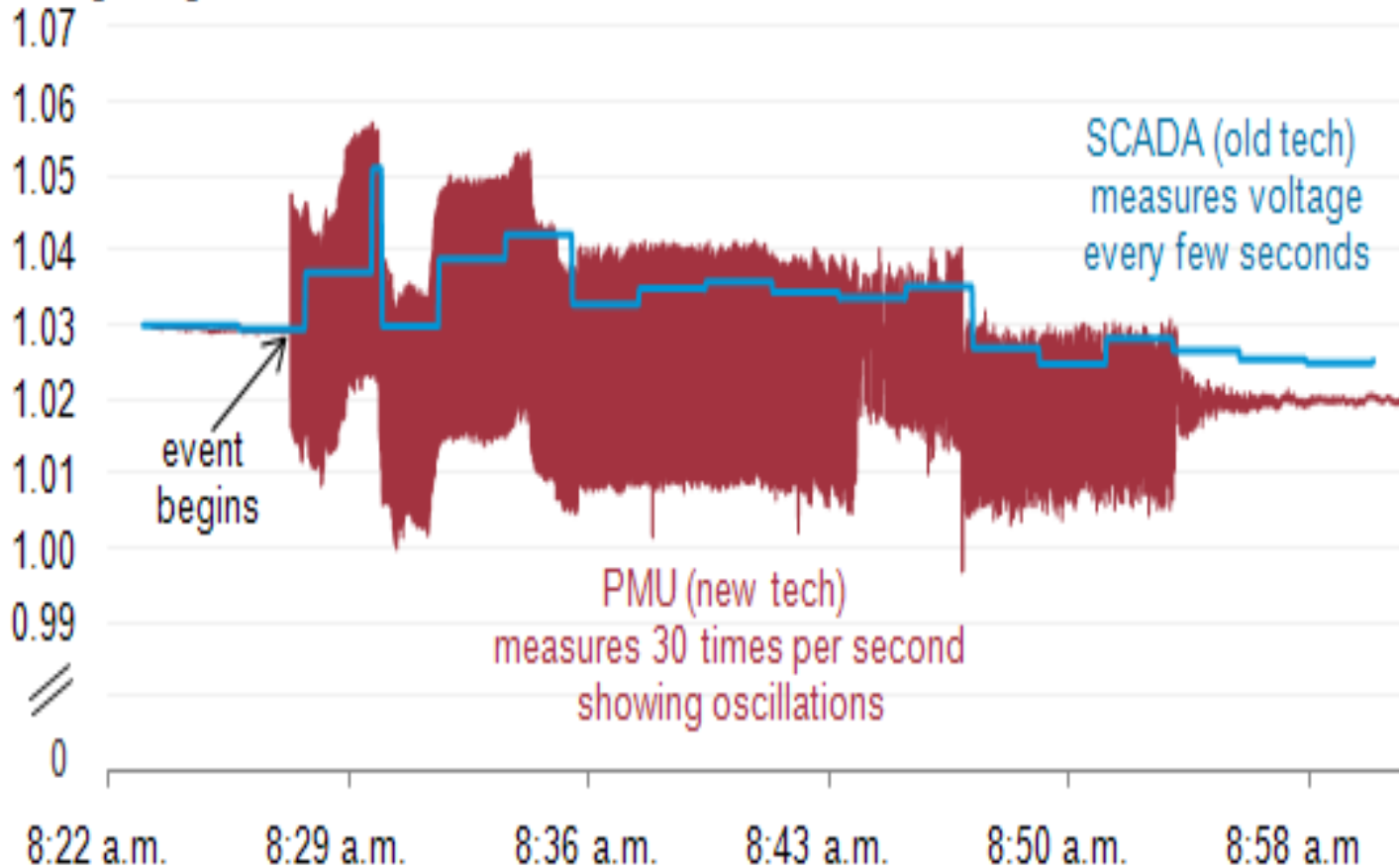
T = Testing phase; P = Planning stage

Source – Chakrabarti, Kyriakides, Bi, Cai and Terzija, "Measurements Get Together," IEEE Power & Energy, January-February 2009, at http://www.ieee.org/portal/cms_docs_pes/pes/subpages/publications-folder/07mpe01-chakrabarti-mo.pdf

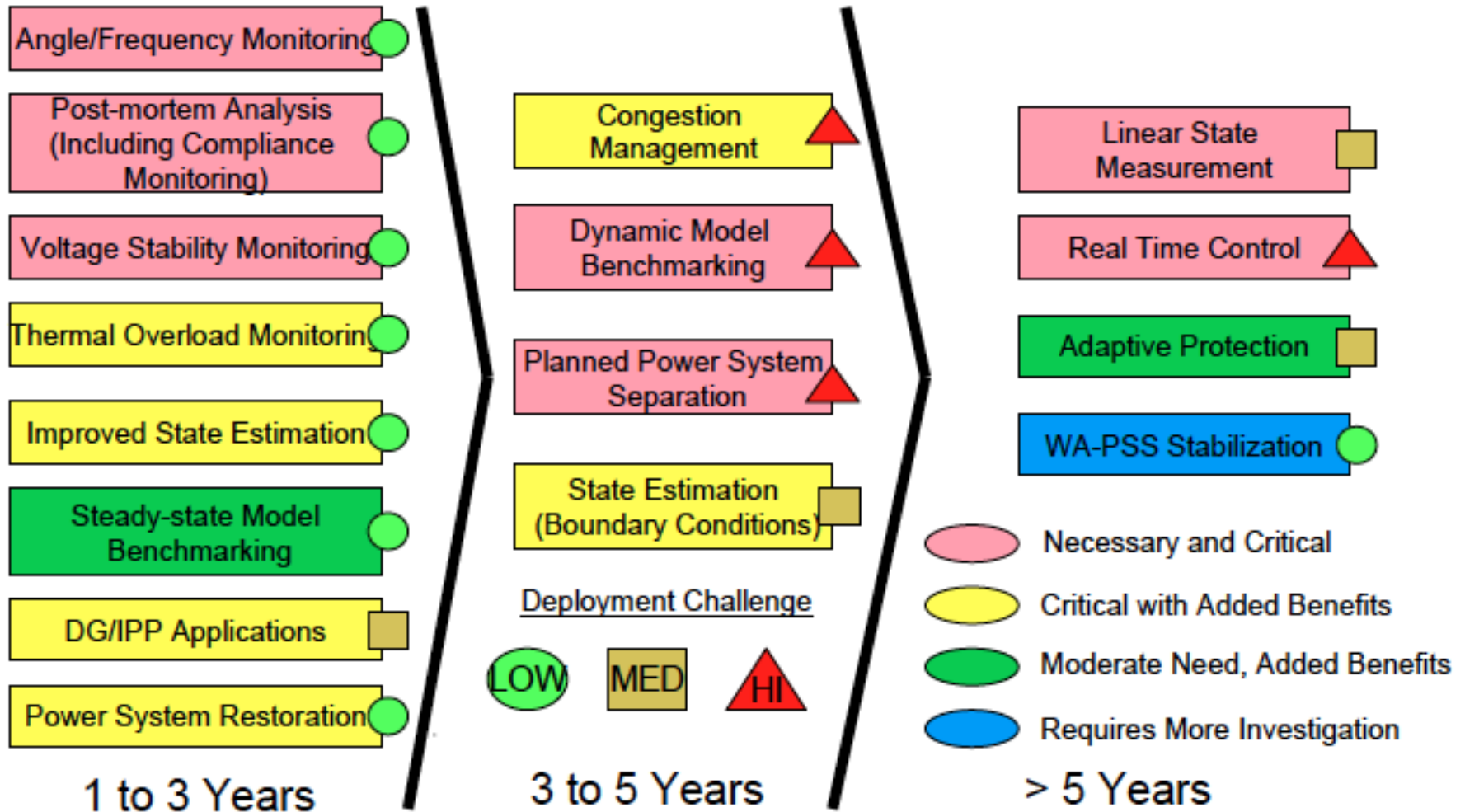
PMU data reveal dynamic behavior as the system responds to a disturbance

Data comparison example, voltage disturbance on April 5, 2011

voltage magnitude, indexed



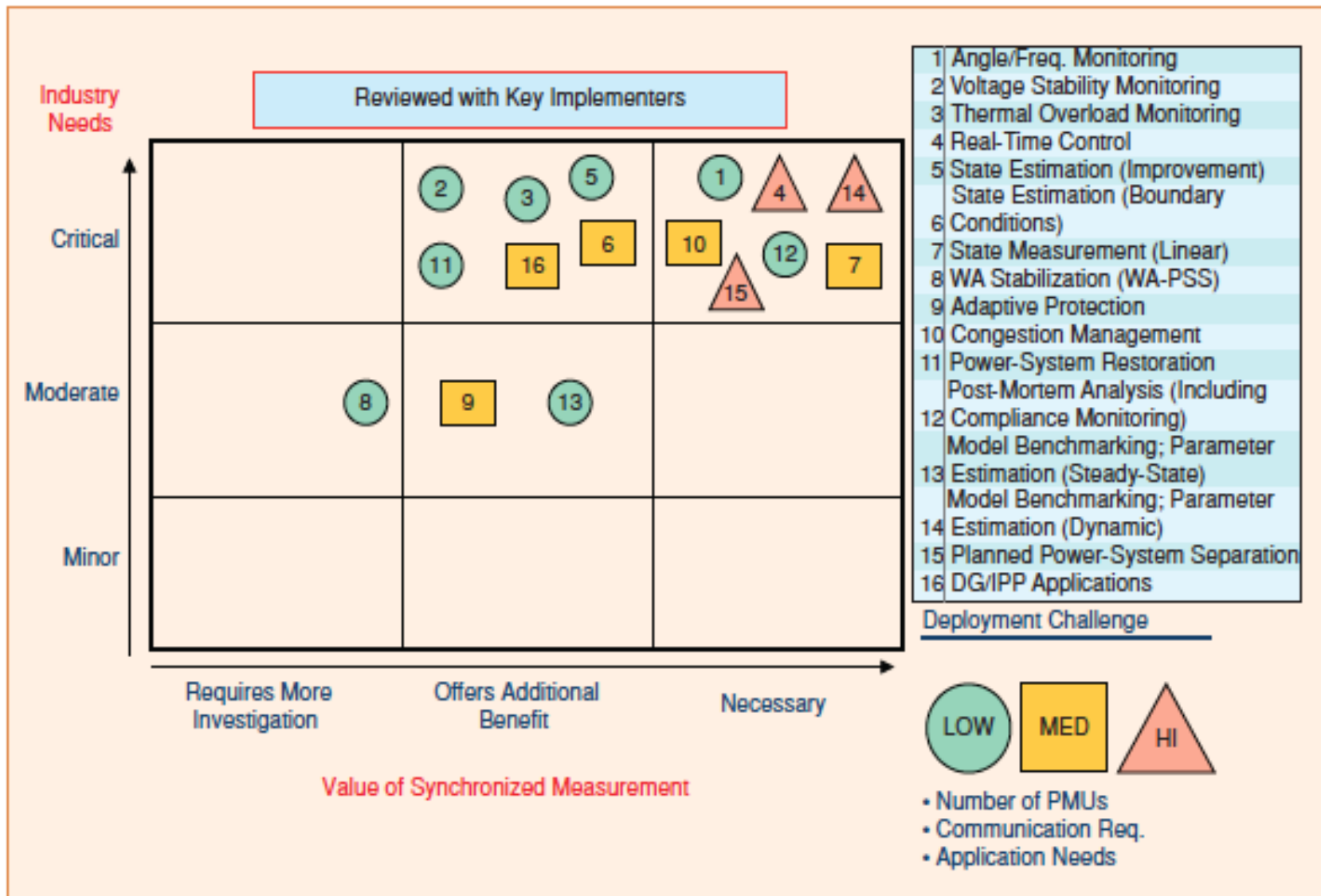
Sense: PMU Applications (2009)



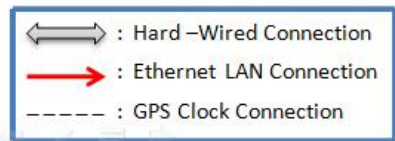
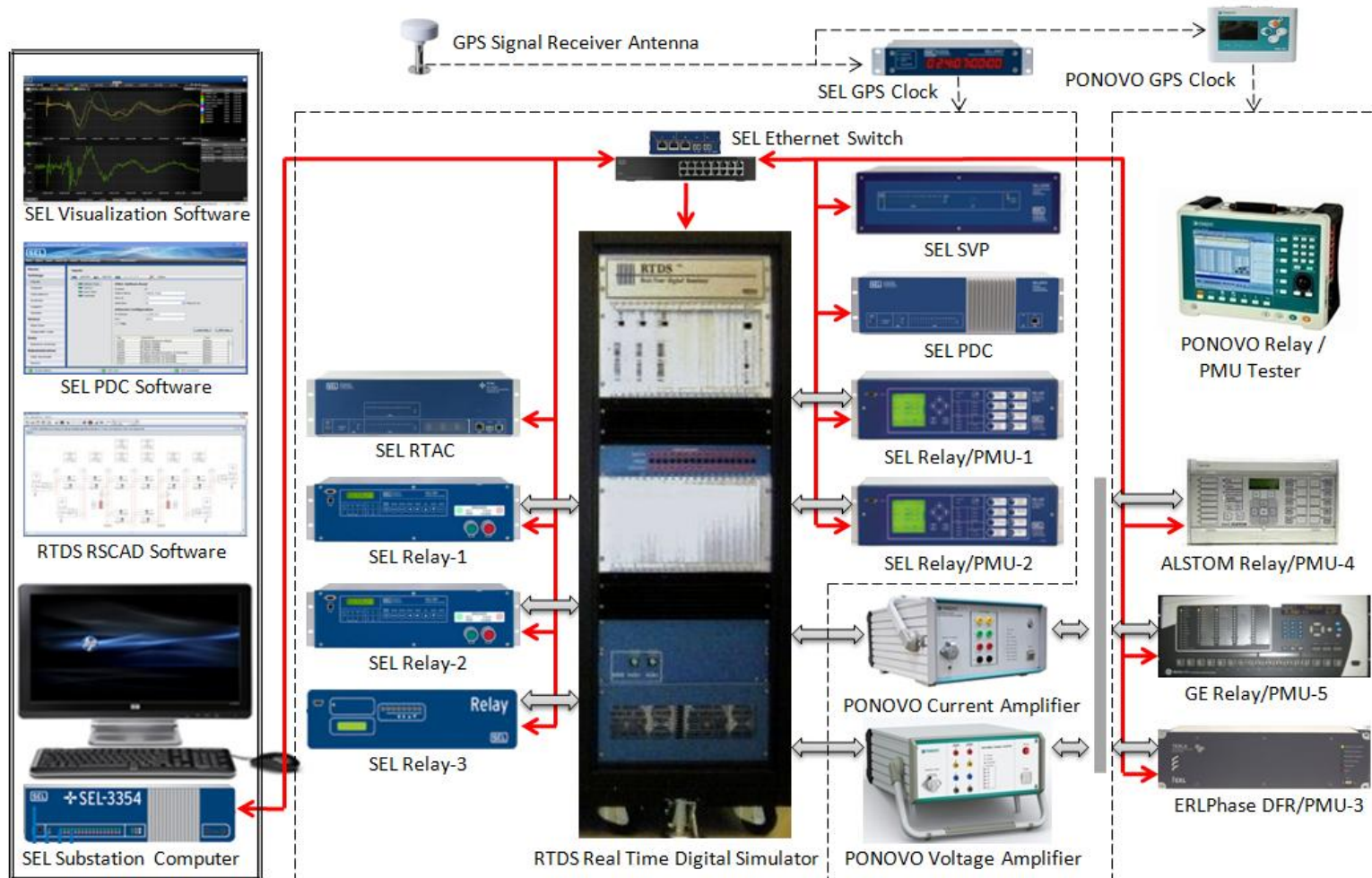
Credit to NASPI Research Initiatives Task Team

Sense: PMU Applications

<i>Class</i>	<i>Basic Description</i>	<i>Sampling/ Data Rate</i>	<i>Required Latency</i>
A	Feedback Control	Fast	Fast
B	Open Loop Control	Medium	Medium
C	Visualization	Medium	Medium
D	Event Analysis	Fast	Slow
E	Research/Experimental	N/A	N/A



Source: Novosel, 2008



Smart Grid Test Bed @ SGDRIL, WSU

Questions

