Virginia Tech
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

PMU Implementation Issues

Experiences in Incorporating PMUs in Power System State Estimation

July 29, 2015
Denver, CO

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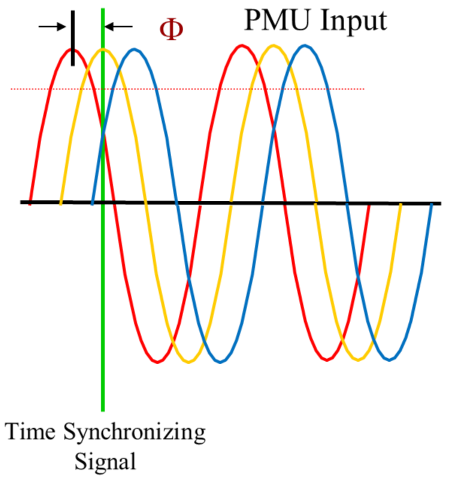
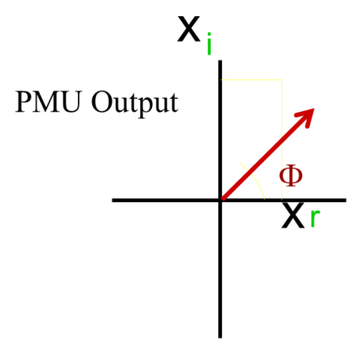
Historical Overview of PMU Implementation

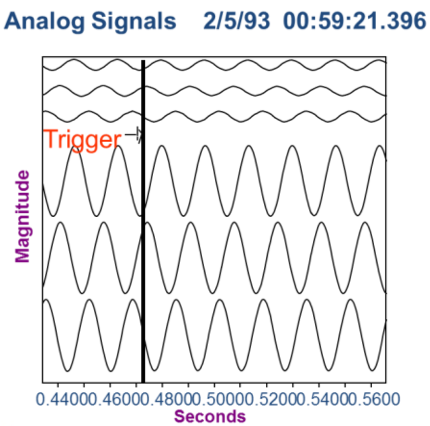
1988 First Academic PMU installed at substation
1990 First Commercial Phasor Measurement Unit
1992 First staged Wide Area Measurement event
1992 National Energy Policy Act approved by congress
1995 First Synchrophasor Standard IEEE 1344 Standard for Synchrophasor
1996 Two summer Blackouts in the Western USA
2003 First Comparative Testing of PMUs
2003 Large Northeast Blackout / EIPP is Formed
2005 IEEE C37.118 Synchrophasor Standard replaces the 1344 standard
2007 EIPP evolves into **N**ational **S**ynchro**p**hasor **I**nitiative (NASPI)
2005 IEEE C37.118 Synchrophasor Standard replaces the 1344 standard
2009 Federal recovery act budgets 400M for Transmission system smart grid
2011 Revised IEEE C37.118 divided into C37.118.1 and C37.118.2
2013 First PMU only Linear Three Phase Estimator becomes operational
2014 IEEE C37.118.1a-2014 - Amendment 1
2015 First PMU passes most Challenging Requirements of Latest Standard

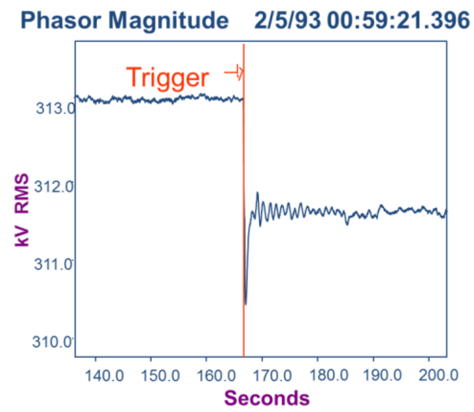
1988 First Practical Implementation





Phasor 60 Hz Component
Magnitude: RMS value
Angle: Referenced to time signal





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First PMU Implementation Issues

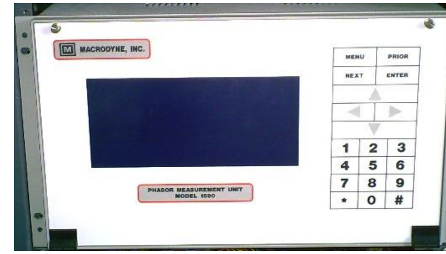
Time synchronization:
- Achieve best possible time synchronization

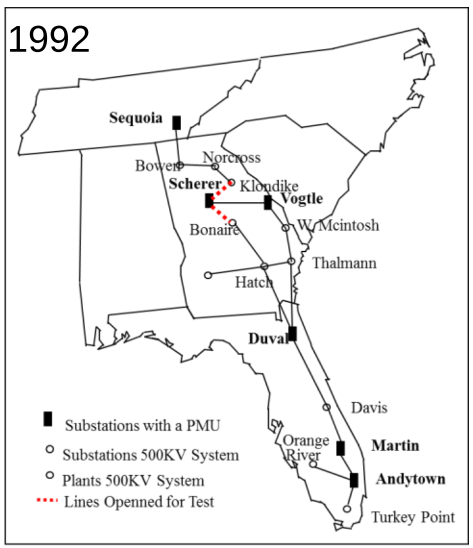
Computational Limitations:
- Compute 3 Phasors, Frequency and df/dt

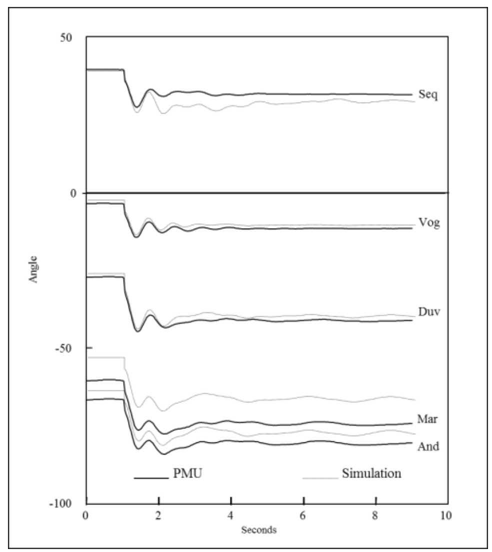
Communications:
- Limited by modems 4800 baud maximum

1990 First Commercial PMU

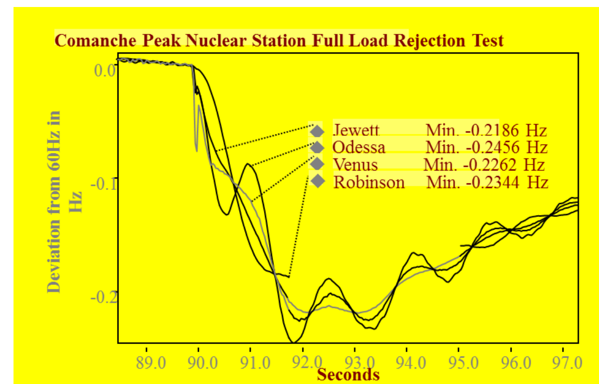
Up to 30 Channel per Chassis
Internal GPS Clock
Individual Channels Clock Synchronized







1994



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IEEE standard 1344-**1995** “IEEE Standard for Synchrophasors for Power Systems”

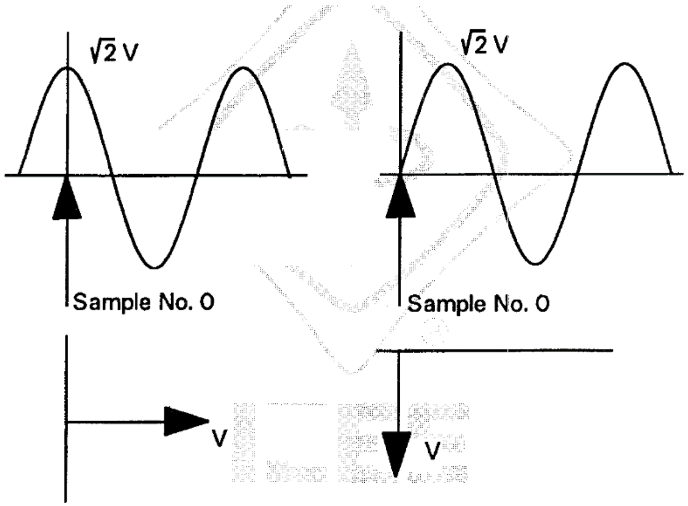
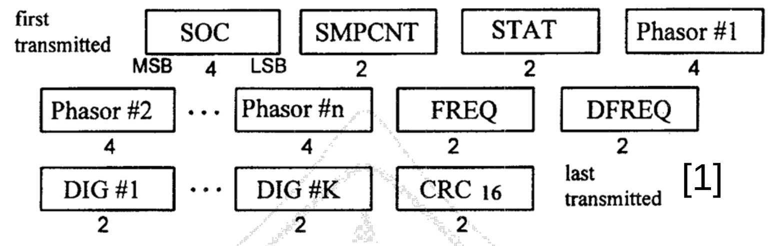


Figure 1—Convention for phasor representation [1]



[1]

STAT bits	Definitions
bit 15	synchronization status (0: valid, 1: invalid)
bit 14	Data integrity (0: valid data, 1: invalid data)
bits 13–11	Trigger status: 111: Frequency trigger 110: df/dt trigger 101: Angle trigger 100: Overcurrent trigger 011: Undervoltage trigger 010: Rate trigger 000–001: Unused, user defined
bits 10–0	Number of bytes in frame including SOC, SMPCNT, STAT, and CRC_{16}, 10–2047

“For a steady-state signals at off-nominal frequency ω_1, the measured phasor with time-tag corresponding to 1 PPS instant to is $Ve^{j(\omega_1 t_0+\varphi)}$.”

[1] IEEE 1344-1995 IEEE Standard for Synchrophasors for Power systems

First Commercial PMU Implementation Issues

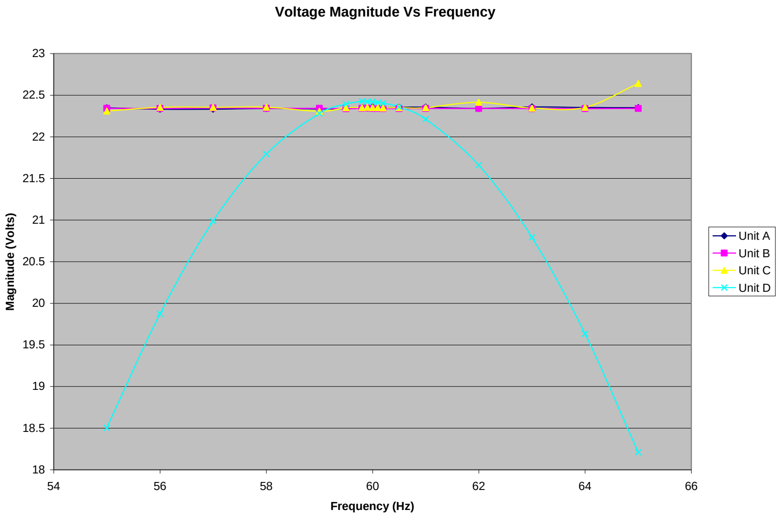
Time synchronization:
Uncertainty on GPS availability

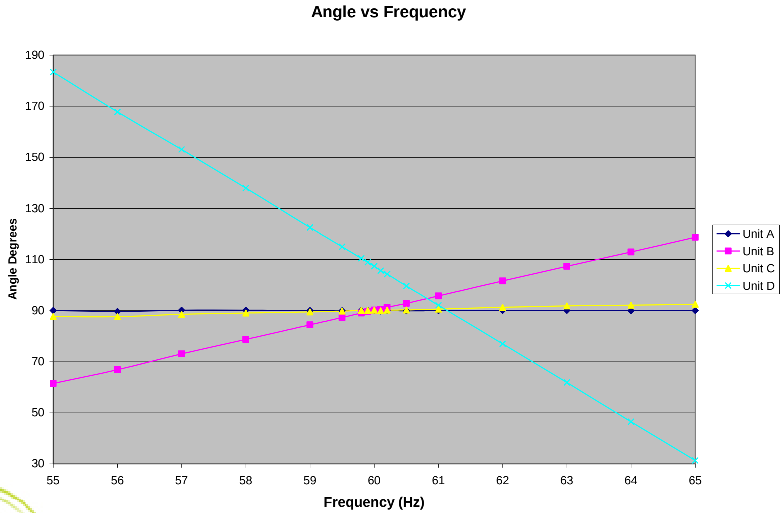
Non-Compliant to a limited Standard:
Did not track frequency

Communications:
Send as much information as 9800 baud allows

National Energy Policy Act approved 1992:
Low sales in the USA

PMU Testing Comparative Testing (May 2003)





Test Compliance Results

	Unit A	Unit B	Unit C	Unit D
Data Format	No	Yes	No	No
Time Synchronization	Yes*	Partial	Yes	No

2003 North East Blackout

Few PMUs key to investigation

"A valuable lesson from the August 14 blackout is the importance of having time-synchronized system data recorders. The Task Force's investigators labored over thousands of data items to determine the sequence of events, much like putting together small pieces of a very large puzzle. That process would have been significantly faster and easier if there had been wider use of synchronized data recording devices."

2011 Southeast Blackout Report

"…the data available through the PMUs, as well as their wide distribution throughout the power system, proved especially valuable to the inquiry in forming an accurate picture of the SOE and state of the system at particular points in time throughout the disturbance."

[2] NERC Final Report on the August 14, 2003 Blackout in the United States and Canada
[3] FERC, NERC Report on Arizona Southern California Outages September 8, 2011

PMU Implementation Issues 2003

Very Limited Standard and changes anticipated:
- Not Enough Guidance for Manufacturers

Evolving Communications:
- Shift from Serial to Network Communications

Application Specific Needs:
- Metering
- Protection/Control

IEEE C37.118-2005 Standard for Synchrophasor

Steady State only

- Recommendations for dynamics

Define 2 classes of PMU

- Class 0: Relaxed compliance level
- Class 1: “standard” compliance level

Better timing Requirements

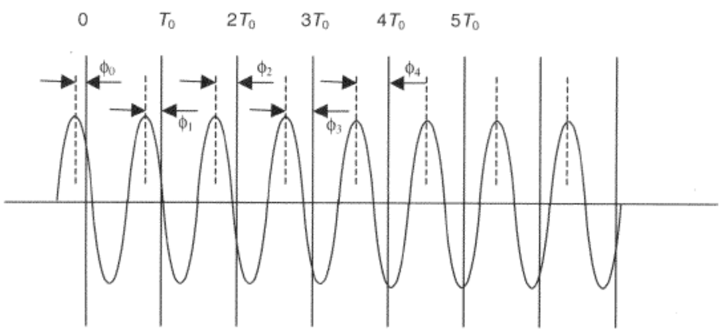
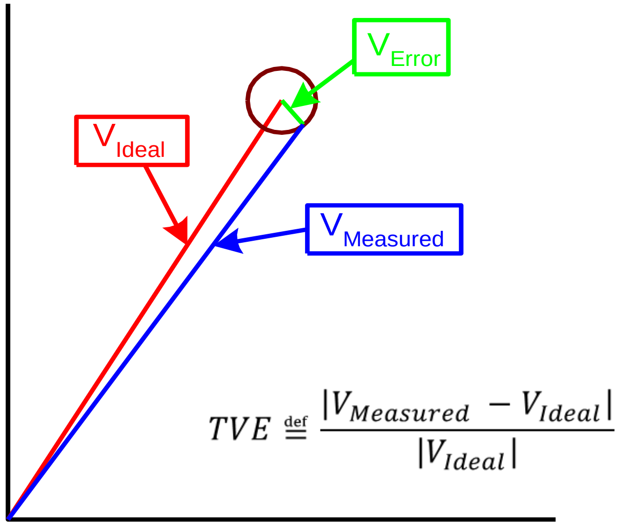


Figure 1—A sinusoid with a period of *T* observed at instants that are multiples of T_0 apart. T_0 is not an integer multiple of *T*. [4]



$$TVE \stackrel{\text{def}}{=} \frac{|V_{Measured} - V_{Ideal}|}{|V_{Ideal}|}$$

Errors defined in terms of TVE

[4] IEEE C37.118-2005 IEEE Standard for Synchrophasors

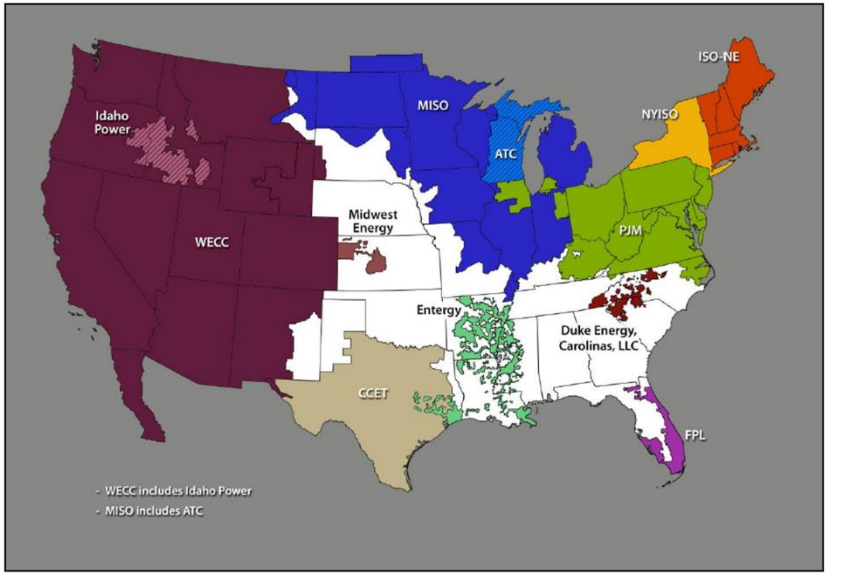
2009 American Recovery and Reinvestment Act

$4.5 billion for the Smart Grid Investment Grant, Smart Grid Demonstration Program, and other DOE Energy smart grid programs.

- 12 recipients awarded $400 million (50% cost Share) to deploy Synchrophasor Technologies

SGIG and SGDP Synchrophasor Project	PMUs Installed*		PDCs Installed*	
	Recovery Act Project^	System Total	Recovery Act Project^	System Total
American Transmission Company	45	92	0	2
Center for Commercialization of Electric Technologies	15	18	4	4
Duke Energy Carolinas	98	98	2	2
Entergy Services Inc.	49	49	9	10
Florida Power & Light Company	45	45	13	13
Idaho Power Company	8	15	0	1
ISO-New England	77	77	8	8
Midwest Energy	7	7	1	1
Midwest Independent Transmission System Operator	148	148	21	21
New York Independent System Operator, Inc.	40	40	8	8
PJM Interconnection	56	56	15	15
Western Electricity Coordinating Council	336	481	49	69
TOTAL	924	1126	130	154

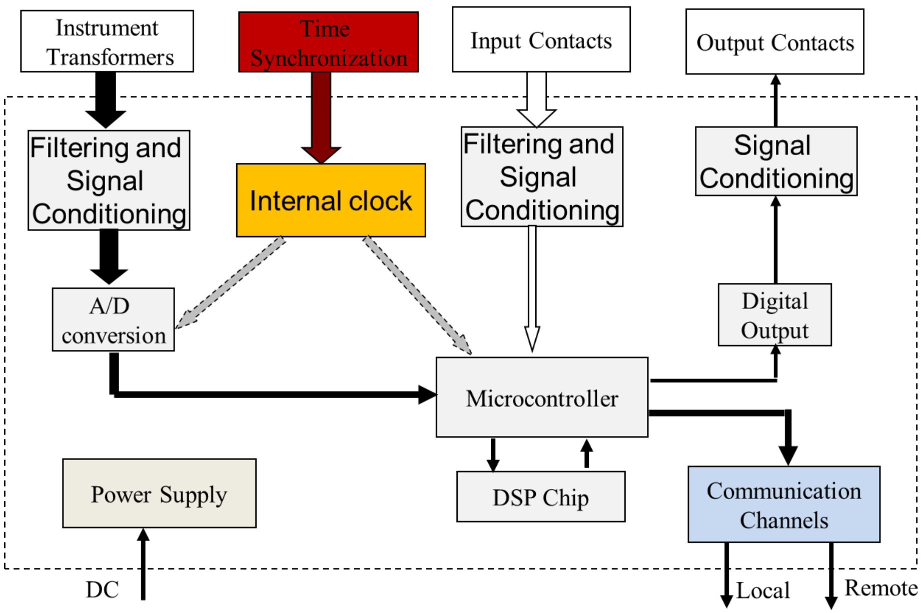
** As of 03/31/2013* [5]

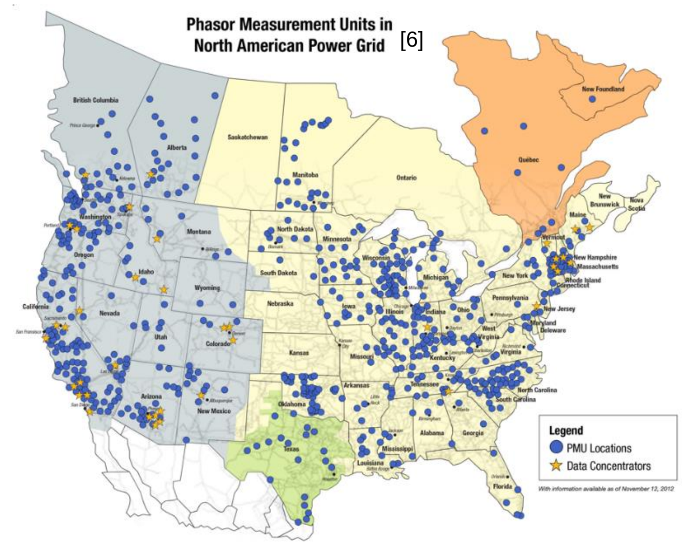


[5] DOE Synchrophasor Report 08 09 2013

2011 PMU Status

PMU Functionality is added to most advanced IEDs with minor changes





[6] NASPI 2012 PMU Installation Map

2011 PMU Implementation Issues

Standard Limited to steady state
    Recommended dynamic response?

Cyber Security a new problem
    Not included in standard

No Homologating Labs
    NIST performs first PMU tests

Push for IEC 61850 Compliance
    Not Compatible with C37.118

Legacy Limits on some PMUs

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IEEE C37.118-2011 Standard for Synchrophasor

Adds [7]:

- Frequency Error (FE) tests
- Rate of Change of Frequency Error (ROCOFE)
- Defines Dynamic Requirements

Redefines Two classes [7]:

- Class M or metering type PMU, and
- Class P for a protection type PMU

Separates standard [7]:

- IEEE C37.118.1-2011 for Signals
- IEEE C37.118.2-2011 for Data Communications

[7] IEEE C37.118-2011 IEEE Standard for Synchrophasors

Steady state Requirement:

Similar to C37.118-2005

Test Requirements [7]:

Frequency Test:	55 - 65 Hz Class M 58 – 62 Hz Class P	TVE < 1%
Magnitude Test:	10% - 120% Current 10% - 120% Class M Voltage 80% - 120% Class P Voltage	TVE < 1%
Angle Test:	±180º both classes	TVE < 1%
Harmonic Distortion:	10% Harmonic Class M 1% Harmonic Class P	TVE < 1% (1- 50th)
Out-of-band Interference:	N/A for P Class 10% interference input	TVE < 3%

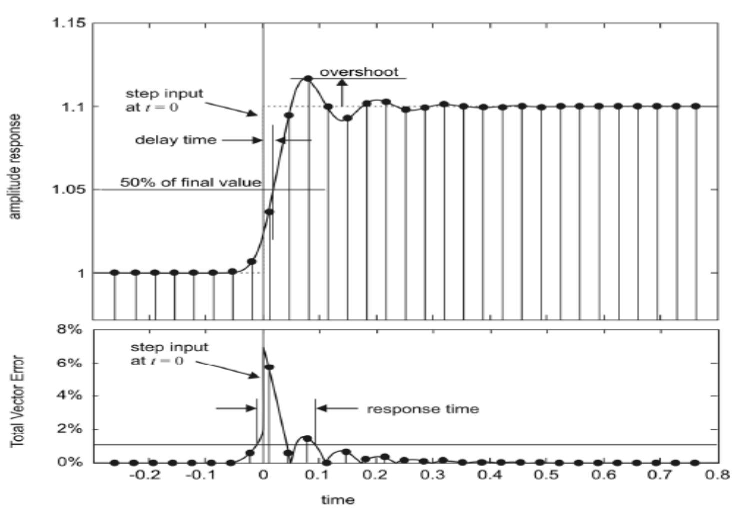
[7] IEEE C37.118-2011 Standard for Synchrophasors

Dynamic Requirements[7]:

Modulation Tests: 0.1 to 2 Hz P Class; 0.1 to 5 Hz M Class — TVE < 3%

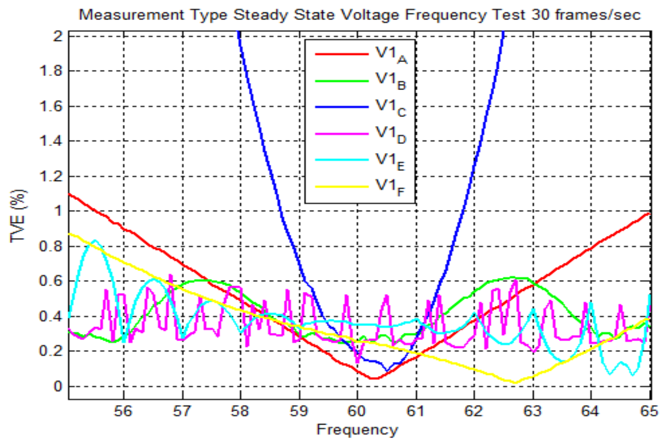
Frequency Ramp: (1 Hz/sec) 58 to 62 Hz P Class; 55 to 65 Hz M Class — TVE < 1%

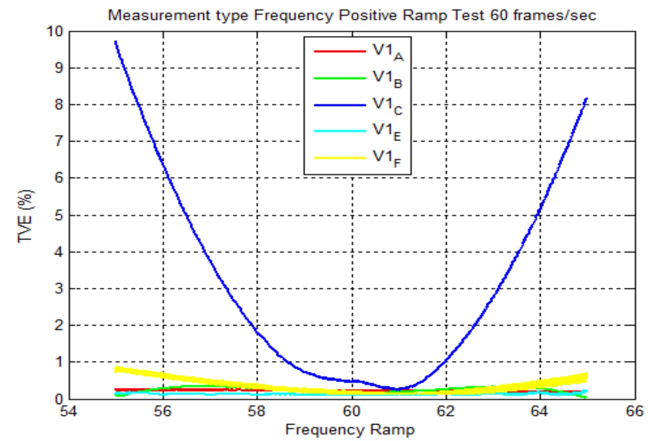
Magnitude and angle Step: (TVE < 1%)
- Response time < $1.7/f_0$ — Class
- Delay time < $|1/(4 \times F_s)|$ — P & M class
- Max. Overshoot < 5%/10% P/M Class

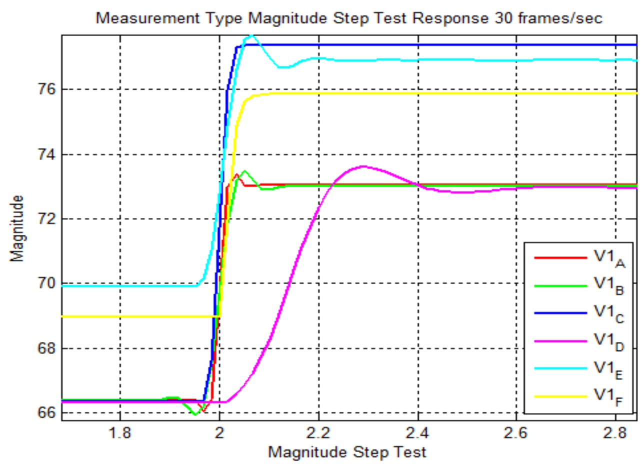


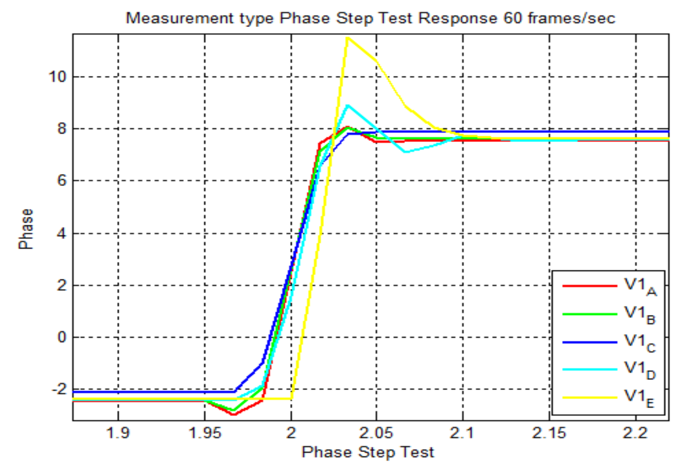
Maximum response time in step change test for M class, in seconds										
Reporting rate (F_s)	10	12	15	20	25	30	50	60	100[a]	120[a]
Phasor (TVE)	0.595	0.493	0.394	0.282	0.231	0.182	0.199	0.079	0.050	0.035
Frequency (FE)	0.869	0.737	0.629	0.478	0.328	0.305	0.130	0.120	0.059	0.053
ROCOF (RFE)	1.038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

[7] IEEE C37.118-2011 Standard for Synchrophasors









Manufactures Struggle to comply with small portion of the Standard

[8] PJM PMUs Accumulative Tests Report, Virginia Tech 2011

2014 IEEE PC37.118.1a - Amendment 1

Changes are minimal but address important points[9]:

Relaxes or suspends ROCOF (so it does not drive designs)

Fixes Ramp test & further defines procedure for better consistency

Simplifies & clarifies Latency tests

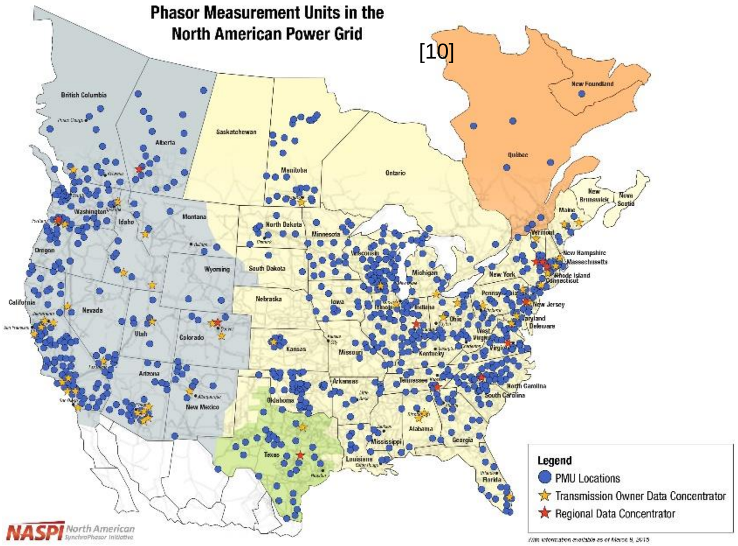
Small changes in a few performance requirements

February 2015 First PMU passes all tests of IEEE C37.118.1a

[9] IEEE C37.118.1a-2014 Amendment to IEEE Standard for Synchrophasors

PMU Status 2015:

- More mature standard
- Several PMU Testing Labs
- Commercial PMU Testing devices
- > 1700 PMUs Installed
- > 20 Manufacturers



Current Implementation Issues shift to:

PDC
  Data Processing
  Missing Data
Instrument Transformer
  Periodic Calibration

Future Implementation Issues?:

Enhanced Accuracy PMUs
  Better than 1% TVE
Instrument Transformers
  Optical/Digital devices

Questions?

[10] NASPI 2015 PMU Installation Map