Synchrophasor Measurement Standard – IEC/IEEE 60255-118-1

Presented by

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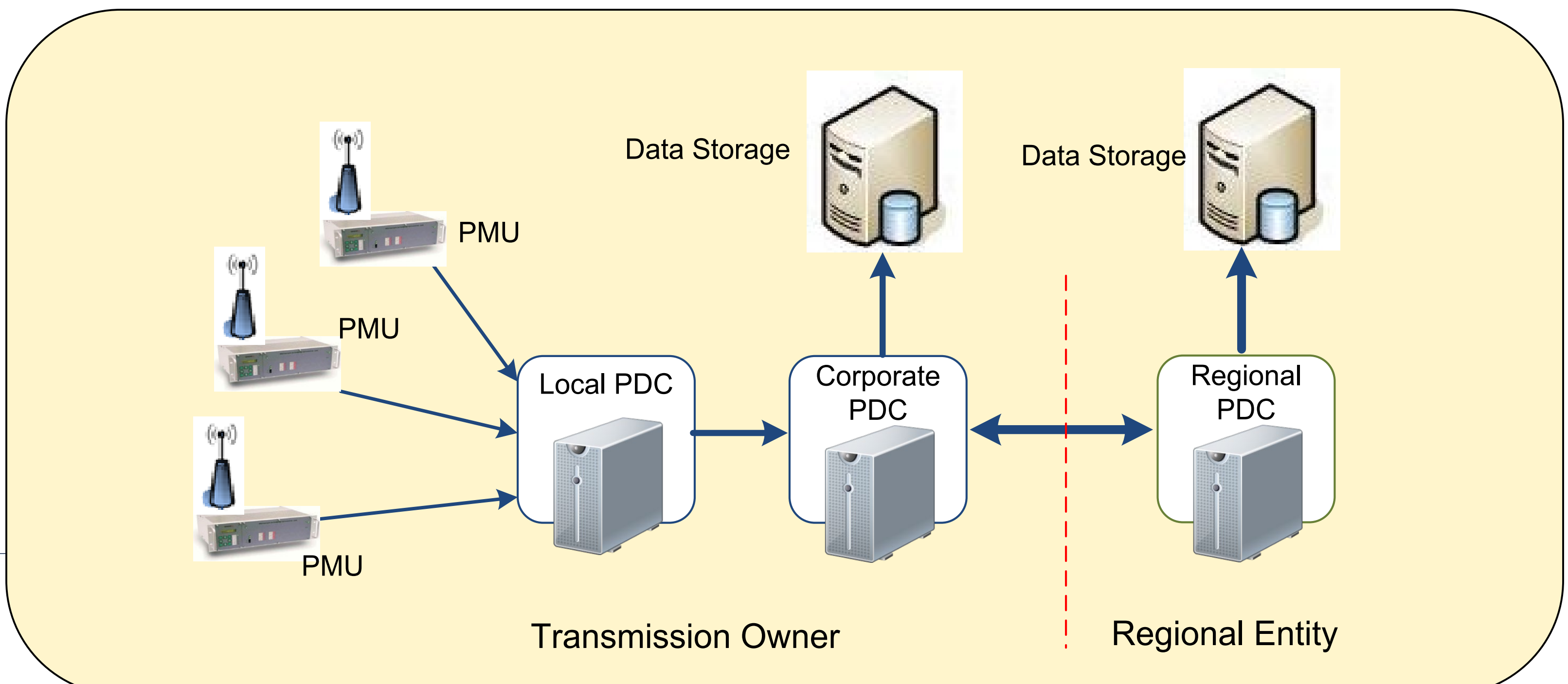
Outline

- Synchrophasor system overview
- Synchrophasor standards history
- Definitions & evaluation methods
- Requirement overview
- Annex review

Typical Synchrophasor Measurement System

- Measurements at substations, real-time data sent to control center
- Data collected & aligned, sent on to applications or higher level processing



First Synchrophasor Standard

- IEEE1344-1995
- Measurement requirements
  - Time synchronization specified
  - Data sampling requirements
  - No specification on resulting measurement
- Data transmission formats
  - Used COMTRADE syntax
  - Adapted for single PMU & serial data
- Unresolved issues & not widely implemented

Synchrophasor Standard C37.118-2005

- Measurement requirements
  - Test method & error limits specified
  - Steady-state phasor only
- Data transmission formats
  - Improved status and error indications
  - Includes single or multiple PMU data
  - Adaptable for network communication
- Widely used & very few problems

Synchrophasor Standards IEEE C37.118.x

- Existing C37.118-2005 split into two standards
  - For compatibility with IEC standards
- C37.118.1-2011 – Measurements only
  - Add frequency & rate of change of frequency (ROCOF)
  - Add Dynamic operation requirements
- C37.118.2-2011 – Communications only
  - Minimum changes, backward compatible
  - Added a few needed improvements
- C37.118.1a-2014 Amendment
  - Modified requirements for achievability

IEC – IEEE Joint Project

- IEC/IEEE 60255-118-1
  - Jointly developed by combined IEC & IEEE WG
    - IEC TC95 JWG1
    - IEEE PSRC H11
  - Started with IEEE C37.118.1 & C37.118.1a
  - Considered suggested changes & expansions
  - Added needed changes, updates, simplifications
- Completed in December 2018

IEC/IEEE 60255-118-1 – Summary

- Definitions for Synchrophasor, Frequency & ROCOF
- Measurement test & compliance requirements
- Steady-state includes accuracy and OOB rejection
- Dynamic tests include bandwidth, tracking, and response time
- Latency test for data output delay
- All tests include requirements for Phasor, Frequency & ROCOF

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Synchrophasor Definition Extended

- Generalized case where all parameters change:
  - Amplitude = $X_m(t)$
  - Phase = $\theta(t)$
  - Additive signals = $D(t)$
- The signal is defined: $x(t) = X_m(t)\cos[\theta(t)] + D(t)$
- Separate nominal signal from changes in phase:

  $$\theta(t) = 2\pi f_0\, t + \varphi(t)$$

- The phase value is: $\boldsymbol{X}(t) = (X_m(t)/\sqrt{2})e^{j(\varphi(t))}$
- Note that all phase variations including frequency differences are in the $\varphi(t)$ term

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Frequency & ROCOF Defined

- For the signal defined:
- $x(t) = X_m(t)\cos[\theta(t)]$
- Frequency: $f(t) = 1/(2\pi)\, d\theta(t)/dt$
- ROCOF: $ROCOF(t) = df(t)/dt$
- Same definitions at C37.118 series
  - Frequency & ROCOF are instantaneous values

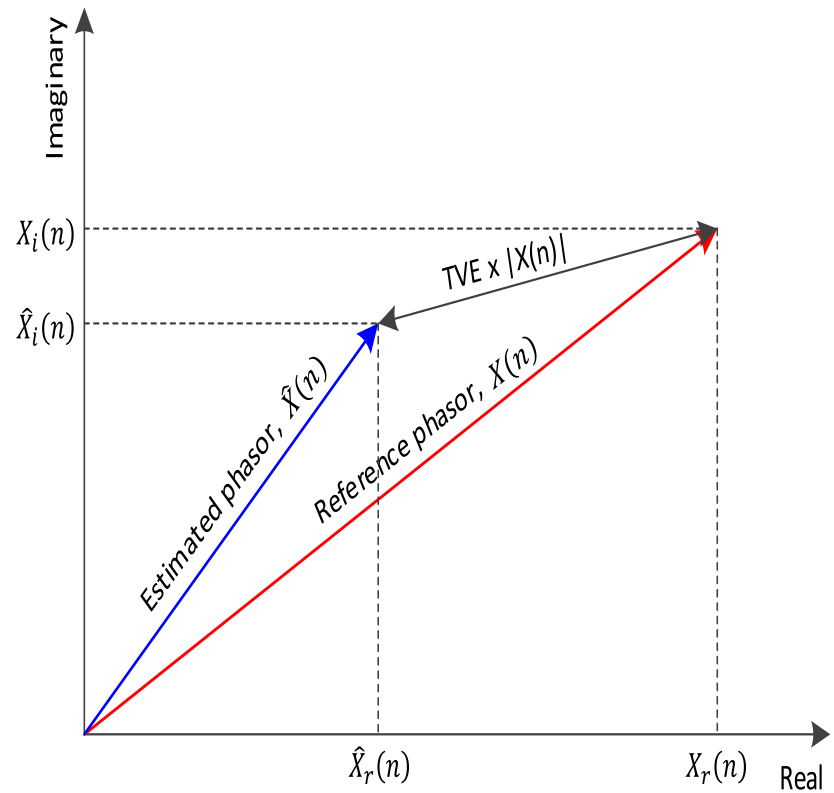
Measurement Compliance

- Evaluation of error

Reference (theoretical) phasor value	$\mathbf{X} = \frac{X_m}{\sqrt{2}} e^{j\phi} = X_r + jX_i$
Measured (estimated) phasor value	$\mathbf{X}(t_0) = X_r(t_0) + jX_i(t_0)$
Total Vector Error – the RMS difference)	$TVE = \sqrt{\frac{(X_r(t_0) - X_r)^2 + (X_i(t_0) - X_i)^2}{X_r^2 + X_i^2}}$
Frequency error (FE) – difference between measured & reference	$FE(n) = \hat{f}(n) - f_{ref}(n)$
ROCOF error (RFE) – difference between measured & reference	$RFE(n) = \frac{d\hat{f}}{dt}(n) - \frac{df_{ref}}{dt}(n)$

TVE Evaluation

- Compares the phasors as vector quantities (total vector error)
- Both magnitude and phase angle evaluated together
- Simplifies evaluation
- May mask individual phase angle and magnitude problems



Additional Standard Features

- Performance classes
  - Allow emphasizing certain uses
  - P class for minimal delay, no filtering (think Protection)
  - M class for more accurate reporting, may have delays (think Measurement)
  - Either class can be used according to needs
- Required data reporting rates extended
  - Reporting 10 to 50 (50 Hz) and 10 to 60 (60 Hz)
- Reporting latency defined & added to requirements

Key Steady-State Points

- Amplitude measurement
  - Over frequency ranges
  - Voltage 10-120% (80-120% P class), current 10-200 %
- Phase angle measurement checked at all angles in frequency tests
- Interference rejection
  - Harmonics
  - Anti-alias for M-class
- All tests laid out in series of tables (next slides)

Steady-State Synchrophasor Measurements

Influence quantity	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit			
		Performance – P class		Performance – M class	
		Range	Max. TVE %	Range	Max. TVE %
Signal frequency	Frequency = f_0 ($f_{nominal}$)	± 2,0 Hz Report rate independent	1	± 2,0 Hz for F_s < 10 ± F_s/5 for 10 ≤ F_s < 25 Corrected for report rate ± 5,0 Hz for F_s ≥ 25	1
Voltage signal magnitude	100 % rated	80 % to 120 % rated	1	10 % to 120 % rated	1
Current signal magnitude	100 % rated	10 % to 200 % rated	1	10 % to 200 % rated	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 as described below	< 0,2% of input signal magnitude		None	10 % of input signal magnitude for F_s ≥ 10. No requirement for F_s < 10.	1,3

Separate V & I tests

Steady-State Frequency & ROCOF

<table>
<tr><th rowspan="2">Influence quantity</th><th rowspan="2">Reference condition</th><th colspan="4">Error requirements for compliance</th></tr>
<tr><th colspan="2">P class</th><th colspan="2">M class</th></tr>
<tr><td rowspan="3">Signal frequency</td><td rowspan="3">Frequency = f_0 ($f_{nominal}$)
Phase angle constant</td><td colspan="2">Range: f_0 ± 2,0 Hz</td><td colspan="2">Range:
f_0 ± 2,0 Hz for $F_s \leq 10$
± $F_s/5$ for $10 \leq F_s < 25$
± 5,0 Hz for $F_s \geq 25$</td></tr>
<tr><td>Max. |FE|</td><td>Max. |RFE|</td><td>Max. |FE|</td><td>Max. |RFE|</td></tr>
<tr><td>0,005 Hz</td><td>0,4 Hz/s</td><td>0,005 Hz</td><td>0,1 Hz/s</td></tr>
<tr><td rowspan="4">Harmonic distortion

(single harmonic)</td><td rowspan="2">< 0,2 % THD</td><td colspan="2">1 % each harmonic up to 50th</td><td colspan="2">10 % each harmonic up to 50th</td></tr>
<tr><td>Max. |FE|</td><td>Max. |RFE|</td><td>Max. |FE|</td><td>Max. |RFE|</td></tr>
<tr><td>$F_s > 20$</td><td>0,005 Hz</td><td>0,4 Hz/s</td><td>0,025 Hz</td><td>No requirements</td></tr>
<tr><td>$F_s \leq 20$</td><td>0,005 Hz</td><td>0,4 Hz/s</td><td>0,005 Hz</td><td>No requirements</td></tr>
<tr><td rowspan="3">Out-of-band interference</td><td rowspan="3">< 0,2 % of input signal magnitude</td><td colspan="2">No requirements</td><td colspan="2">Interfering signal 10 % of signal magnitude</td></tr>
<tr><td></td><td></td><td>Max. |FE|</td><td>Max. |RFE|</td></tr>
<tr><td>None</td><td>None</td><td>0,01 Hz</td><td>No requirements</td></tr>
</table>

Dynamic Requirements

- Confirm measurement capability under dynamic system requirements
  - Swings, switching, power imbalance
  - Not intended for fault or catastrophic conditions
- Tests to confirm measurement compatibility
  - Characterize instrument
  - Emulate conditions of power system

Modulation Tests

- Sinusoidal modulation of amplitude and phase angle of the fundamental signal
  - Assures sufficient measurement bandwidth
  - Emulates a system oscillation
- Applied as amplitude or phase individually
  - $X_a = X_m\,[1+k_x\cos(\omega t)] \times \cos\,[\omega_0 t + k_a\cos(\omega t - \pi)]$
- Phasor, F, & ROCOF responses (points at t = nT)
  - $X(nT) = \{X_m/\sqrt{2}\}[1+k_x\cos(\omega nT)]\angle\{k_a\cos(\omega nT-\pi)\}$
  - $f(nT) = \omega_0/2\pi - k_a\,(\omega/2\pi)\sin\,(\omega nT-\pi)$
  - $ROCOF(nT) = -\,k_a\,(\omega^2/2\pi)\cos\,(\omega nT-\pi)$

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Frequency Ramp Tests

- Constant ramp in frequency
  - Determines measurement tracking system
  - $X_a = X_m \cos[w_0 t + \pi R_f t^2]$ where R_f is a constant ramp rate
  - Emulates a system separation causing power-load imbalance
- Ramp to frequency measurement limit
  - M class: ± F_s/5 Hz up to 5 Hz
  - P class: ± 2 Hz
  - Ramp rate ± 1 Hz /s

Step Tests

- Step change of amplitude or phase
  - Determines response time measurement
  - $X_a = X_m [1+k_x f_1(t)] \times \cos [\omega_0 t+k_a f_1(t)]$ where f_1 is a unit step
  - Emulates a switch action
  - Measurement values during the step are not evaluated (exclusion period)—only response time, overshoot, & delay
- 10% amplitude, 10° phase
- Requires oversampling to get entire response

Step Illustration

- Response between leaving initial & achieving final values
  - Applied to phasor, Frequency, ROCOF
- Delay indicates correct timetag
- Overshoot limited

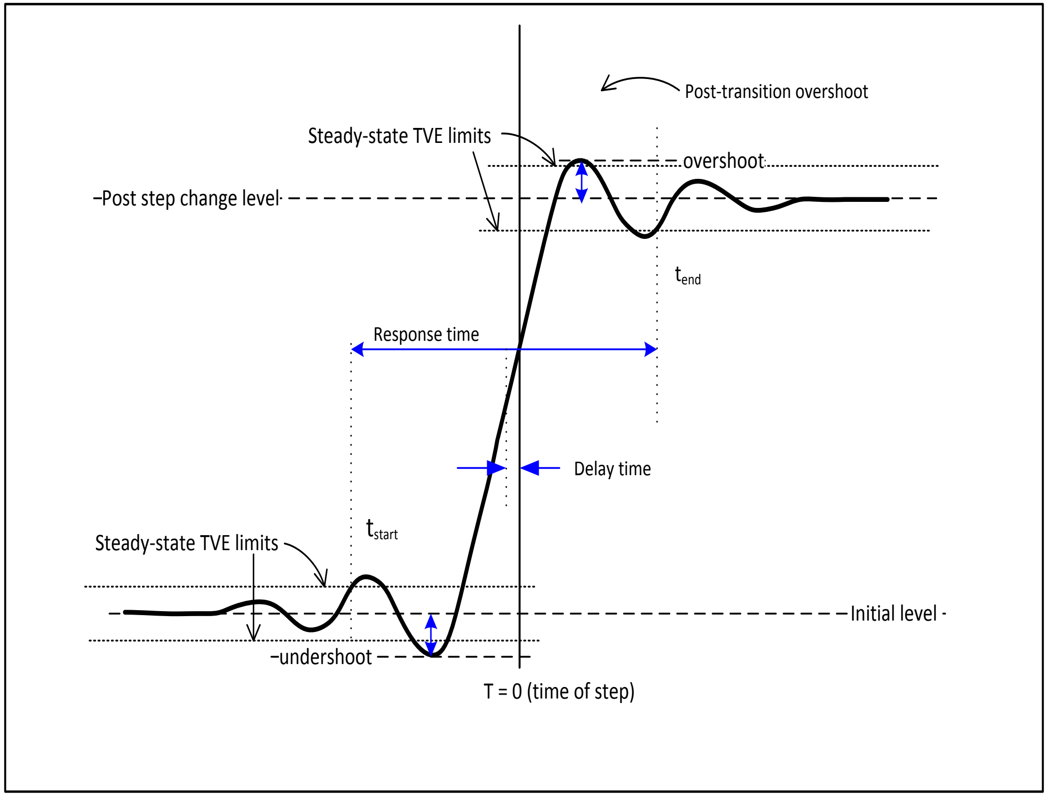
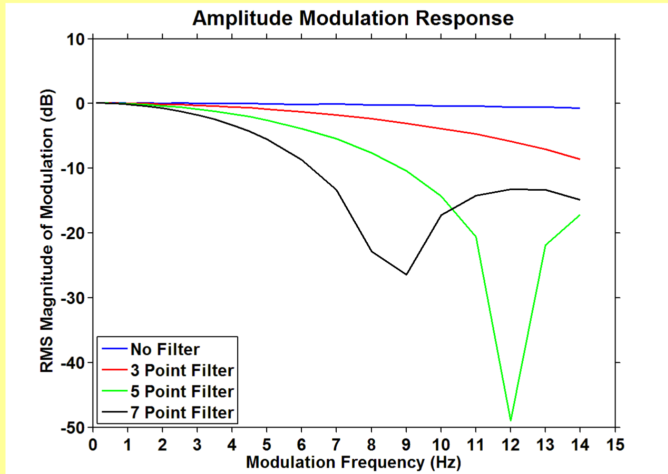
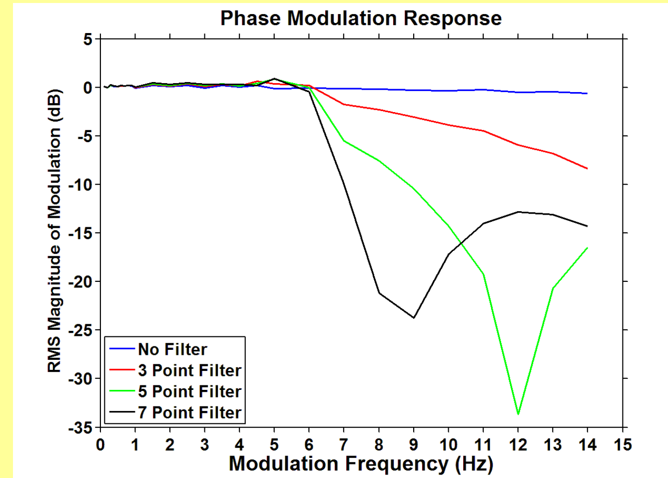


Illustration from IEEE C37.118.1

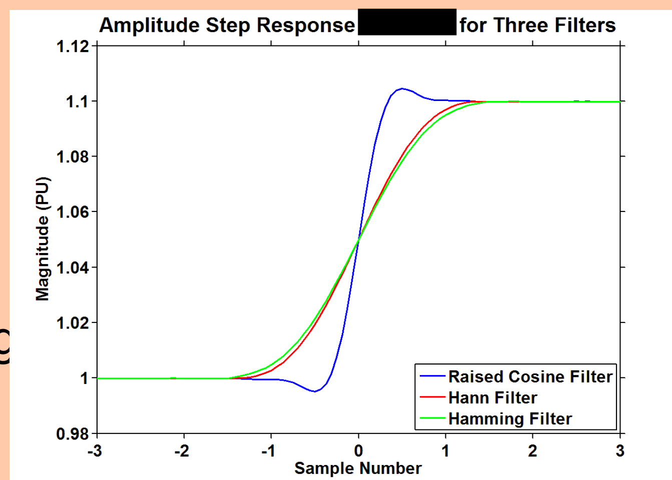
Modulation & Step Examples

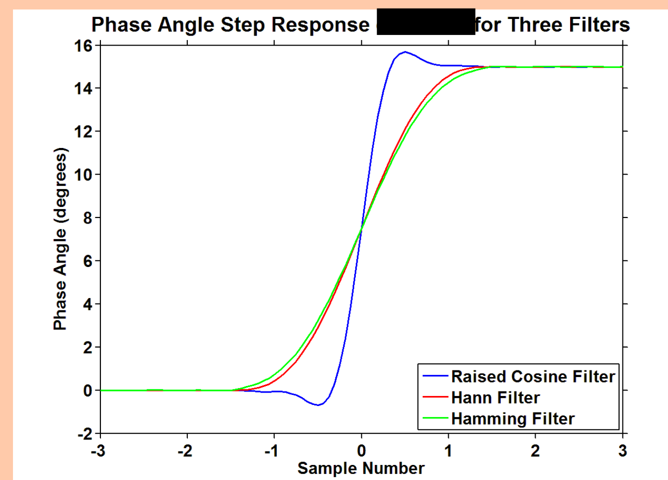
Amplitude & phase modulation – pass bands are similar for both.





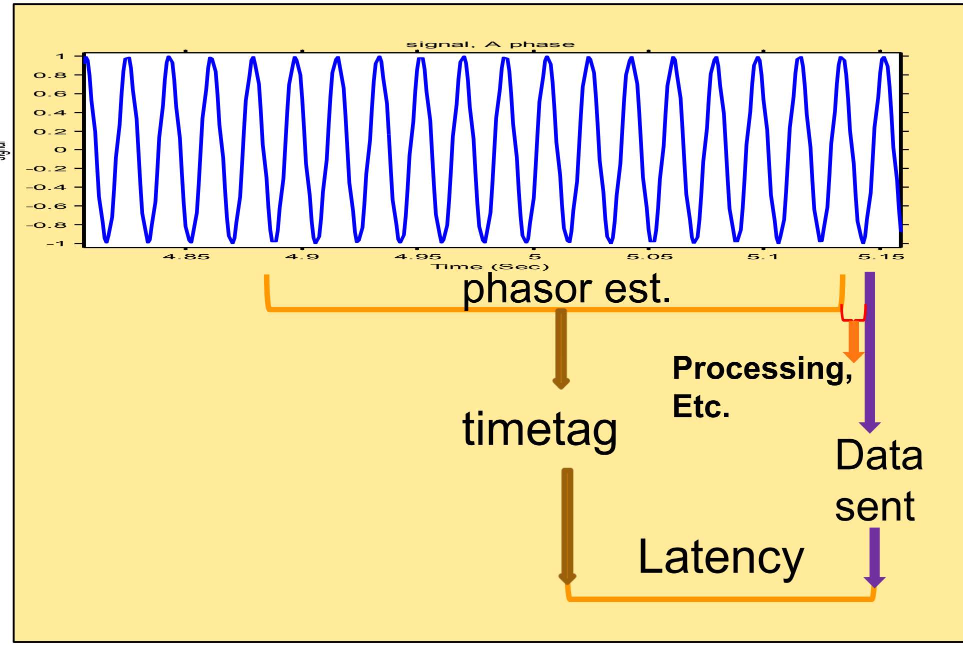
Amplitude & phase steps – differences in response clearly shown with delayed sampling (slip-sampling)





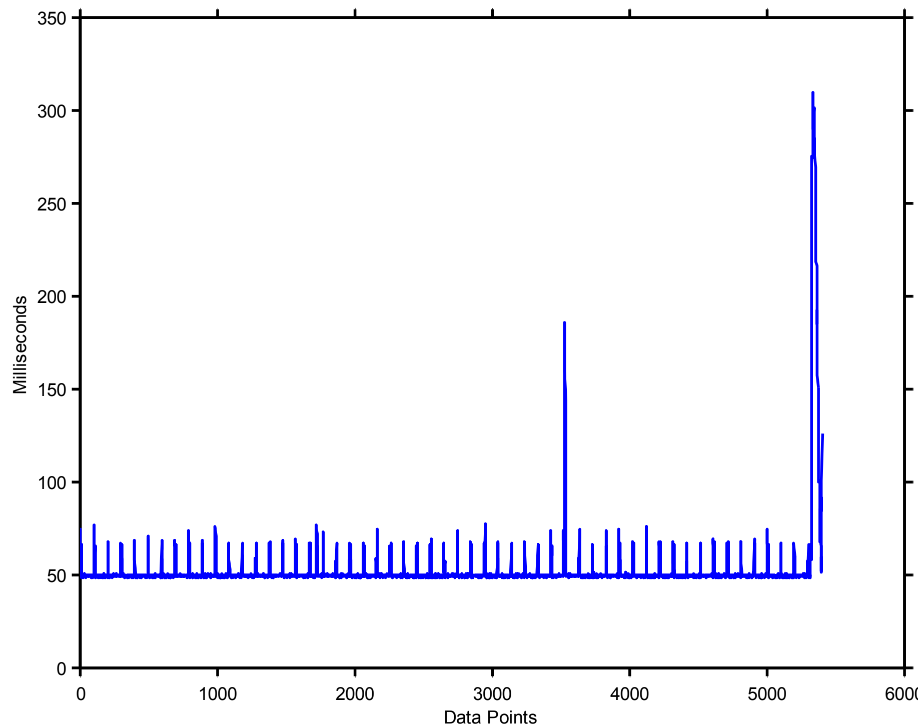
Latency Test

- Delay from time of measurement to data transmission
- Includes algorithm, processing & communication delays
- Important for applications sensitive to delays (eg. Controls)



Latency Test Example

- Baseline is windowing delay ~50 ms
- Additional ~20 ms delay spikes every second due to processor or communication delays



Annex Information

- Annexes include reference material on phasors, algorithms, testing, time tagging, environmental testing and rotor angle measurement
- Annex E – sample value systems
  - Analyzes the difference in measurement error sources
  - Suggests adjustment of requirements for performance
- Annex G – normative requirements for extended accuracy
  - A PMU may be certified for providing higher accuracy or extended measurement ranges
- Annex I – normative extended bandwidth determination
  - Basic certification only determines that the PMU has a minimum bandwidth
  - Provides procedures to determine the actual measurement bandwidth

Differences between IEEE 37.118.1-2011 and IEC/IEEE 60255-118-1

- Certification only requires testing at one reporting rate
  - Better meets user needs
  - Reduces testing cost and time
- Definitions changed but equivalent & compatible
- Testing at different temperatures not required
- Latency test clarified and simplified
  - Temperature testing left to user requirements along with other environmental requirements
- Numerous clarifications included
- Normative annexes for higher accuracy and bandwidth determination added

Summary

- Covers full PMU performance certification
  - Steady-state over full operating range
  - Realistic dynamic operating conditions
- Compatible with the IEEE C37.118
- International standard supported by both IEEE and IEC
- Published and available from both IEEE and IEC