# Applicability of Synchrophasor Based Frequency Data for Protection and Control Applications

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TEXAS A&M

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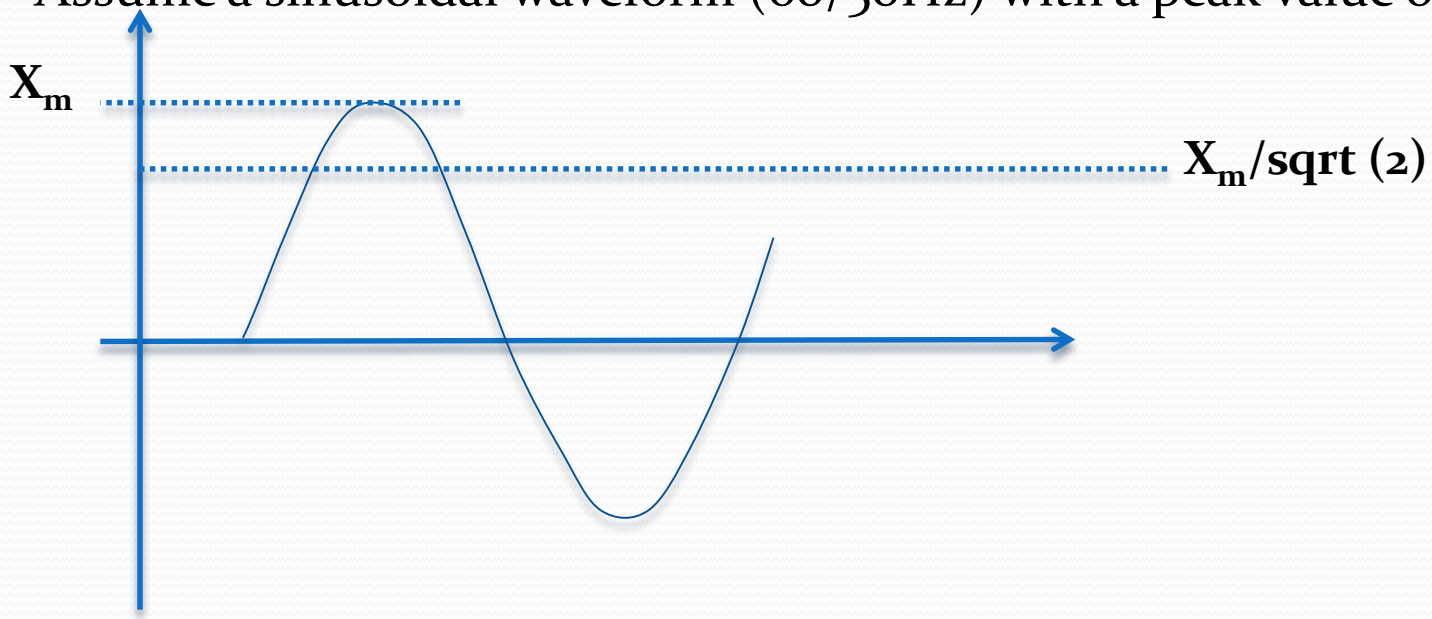
- Introduction to PMU
- Frequency Measurement
  - Standard definition
  - P/M filters
- Simulation Based Analysis
  - Standard steady state requirements
  - Standard dynamic requirements
  - NERC example
  - Abnormal frequency variations
- Considerations for IEC 61850 9-2 LE applications
- Conclusions

# Definition of RMS

- *RMS Magnitude* and *Phase Angle* are calculated using DFT
- Assume a sinusoidal waveform (60/50Hz) with a peak value of $\mathbf{X_m}$



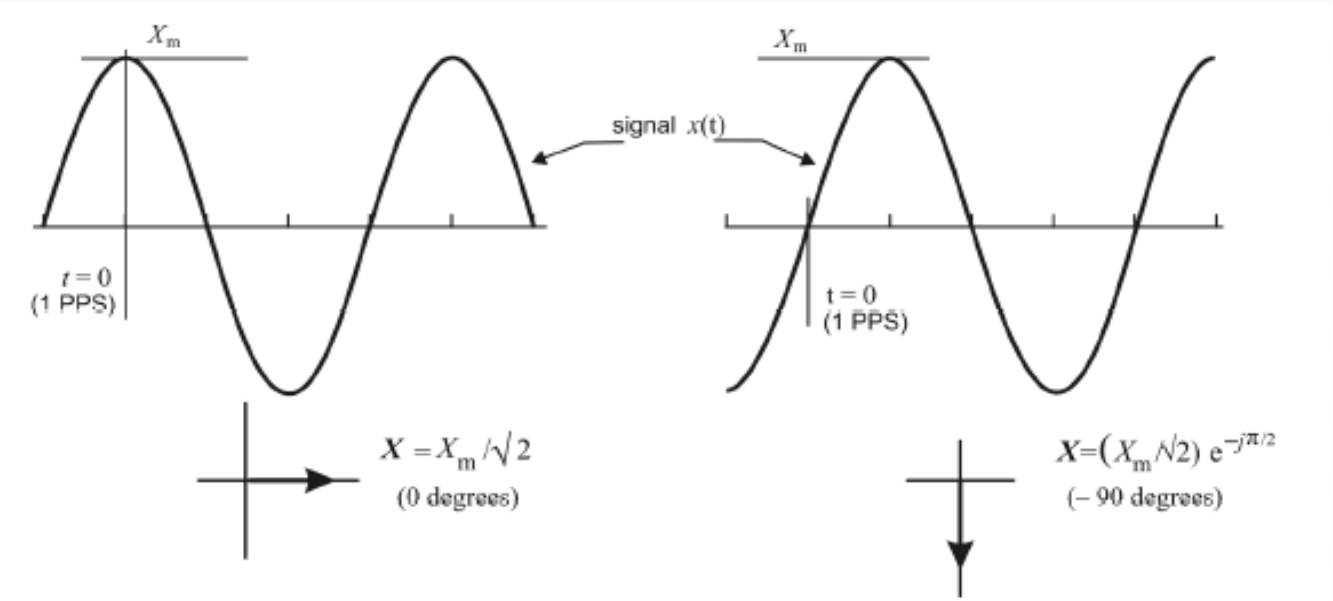

- Root Mean Square (RMS) = $X_m$/sqrt (2)
- Phase angle is calculated with respect to the DFT reference (i.e. sampling point on the waveform)

# Definition of Phasor

- Phasor: **magnitude** and **phase angle** representation of a sinusoidal signal.
  - 69.1 kV, 25.1 deg.
- <u>Limitations in phase angle calculations</u>
  - Phase angle calculations are affected by:
    - Starting point of the sampling
    - Drift in internal clock
  - This results in non-comparable/unusable calculations even for the same input signal measured using two devices.
- <u>Solution</u>
  - Sampling is done in a synchronized manor (1-PPS)

# Definition of Synchrophasor (C37.118.1)

- ϕ is the offset from a cosine function at the nominal system frequency synchronized to UTC (1 PPS)
- A cosine has a maximum at t = 0, so the synchrophasor angle is 0 degrees when the maximum of x(t) occurs at the UTC second rollover (1 PPS time signal), and –90 degrees when the positive zero crossing occurs at the UTC second rollover (sin waveform).



## Global Time Reference

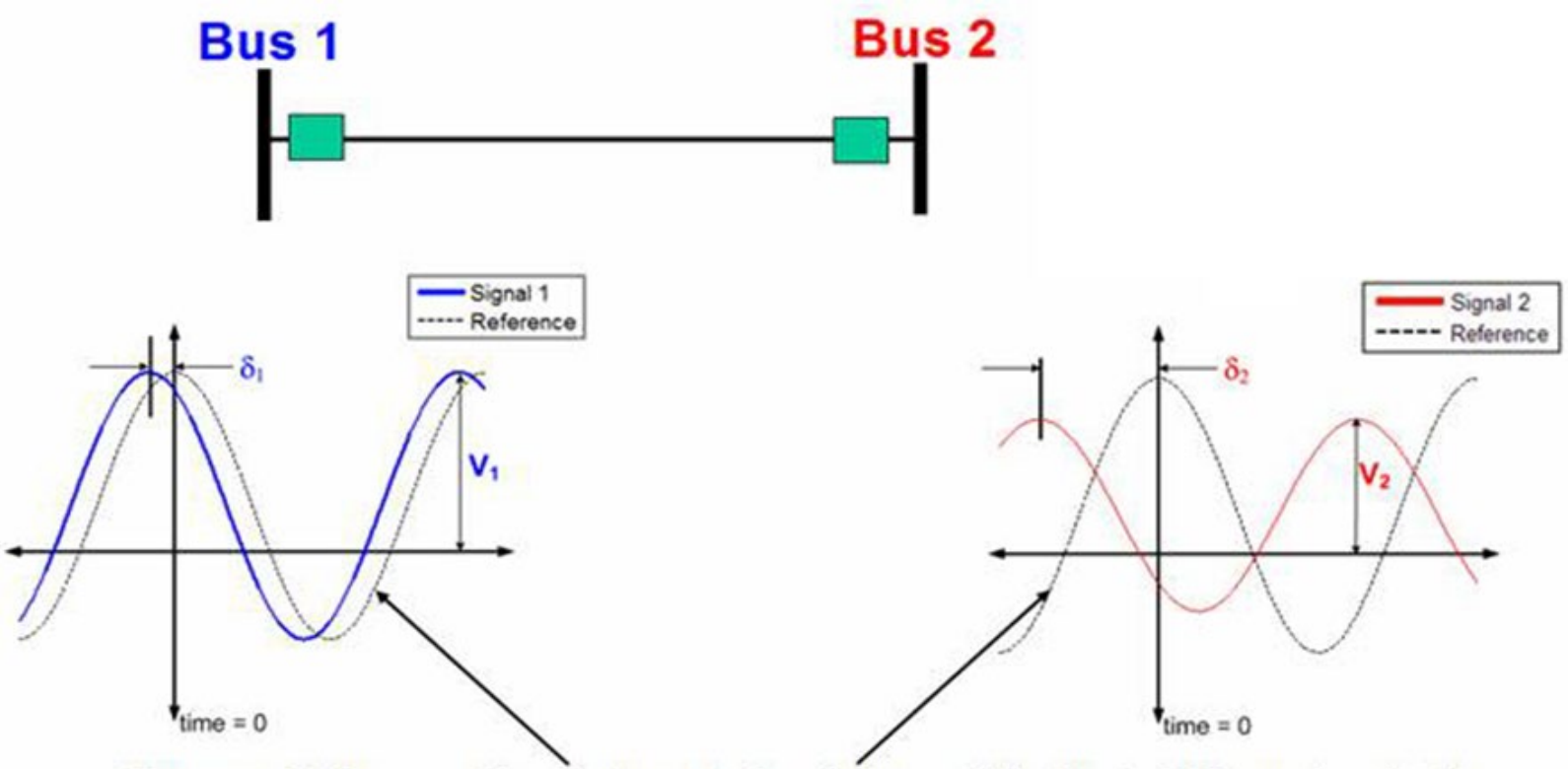
- GPS (Global Positioning System) synchronized with UTC (< 1 uS)
  - error of 1 μs corresponds to a synchrophasor phase error of **0.022 degrees for a 60 Hz** system and **0.018 degrees for a 50 Hz** system

- Most widely used is IRIG-B (Inter Range Instrumentation Group)

# Importance of Global Reference

- Estimation of Power Transfer

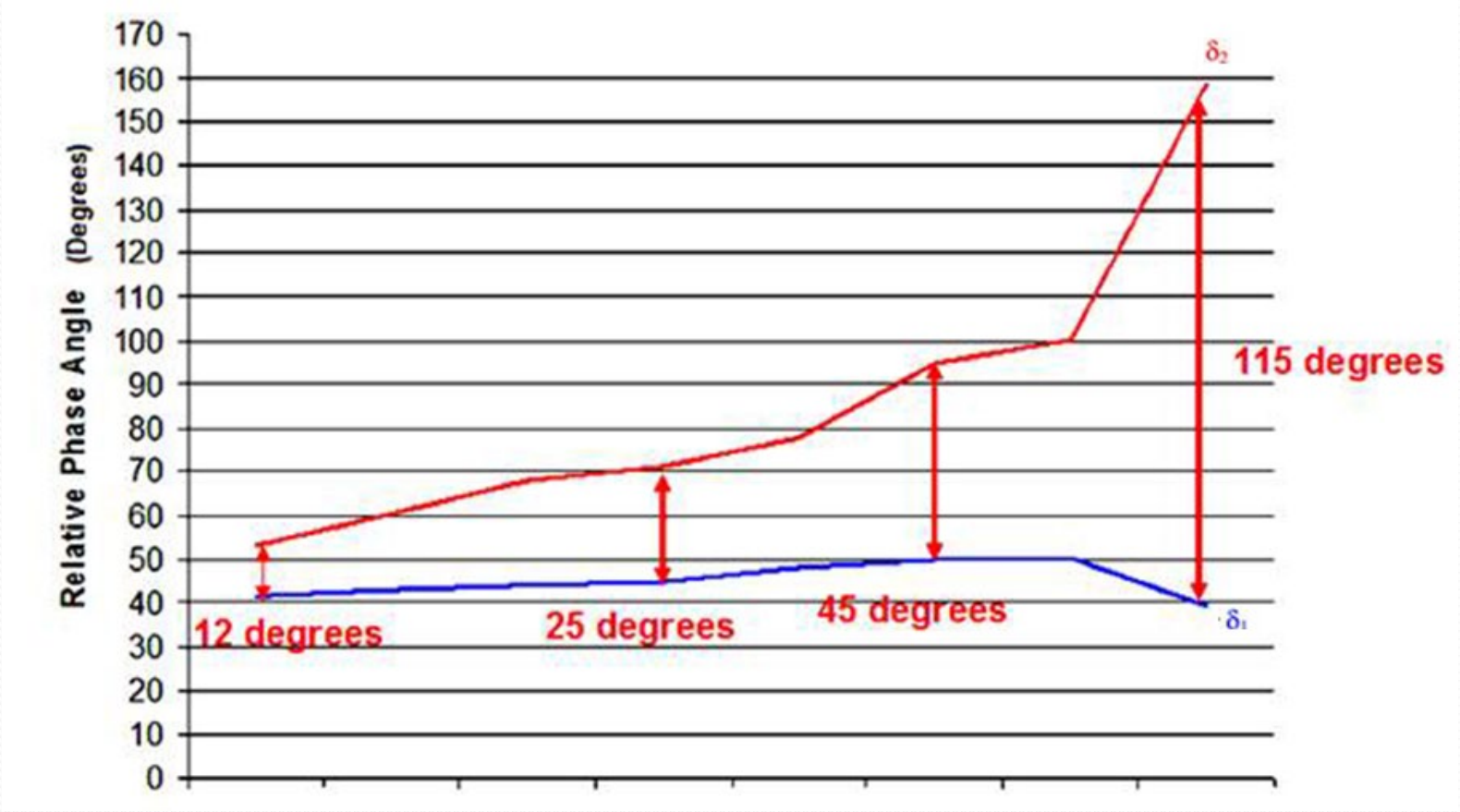
$$P = \frac{V_s V_r}{X} \sin \delta \qquad Q = \frac{V_r}{X}(V_s \cos \delta - V_r)$$




**Common Reference Signal** at remote locations possible due to GPS synchronization

# Importance of Global Reference…….

- Power system dynamic condition



# Off-nominal Frequency Response

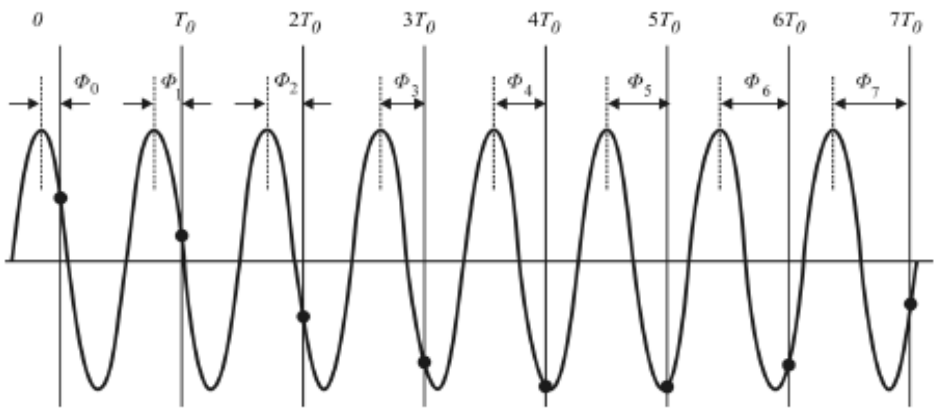



**Figure 2—A sinusoid with a frequency $f > f_0$ is observed at instants that are $T_0$ seconds apart—the phase angle $\Phi$ increases uniformly in relation to the frequency difference, $f - f_0$**

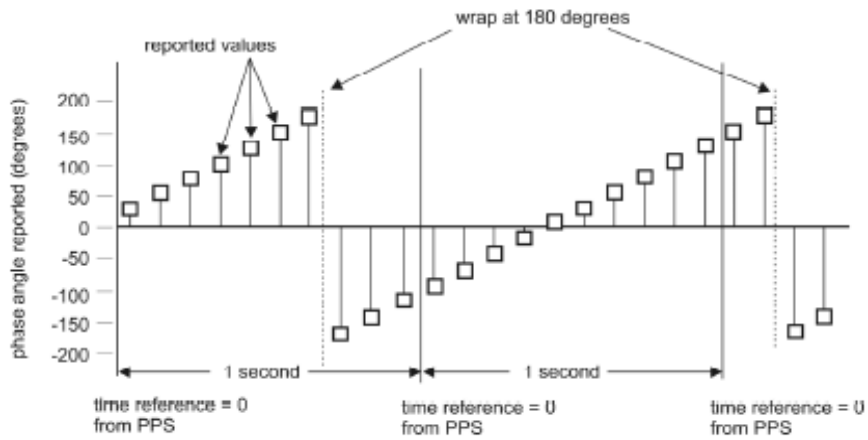
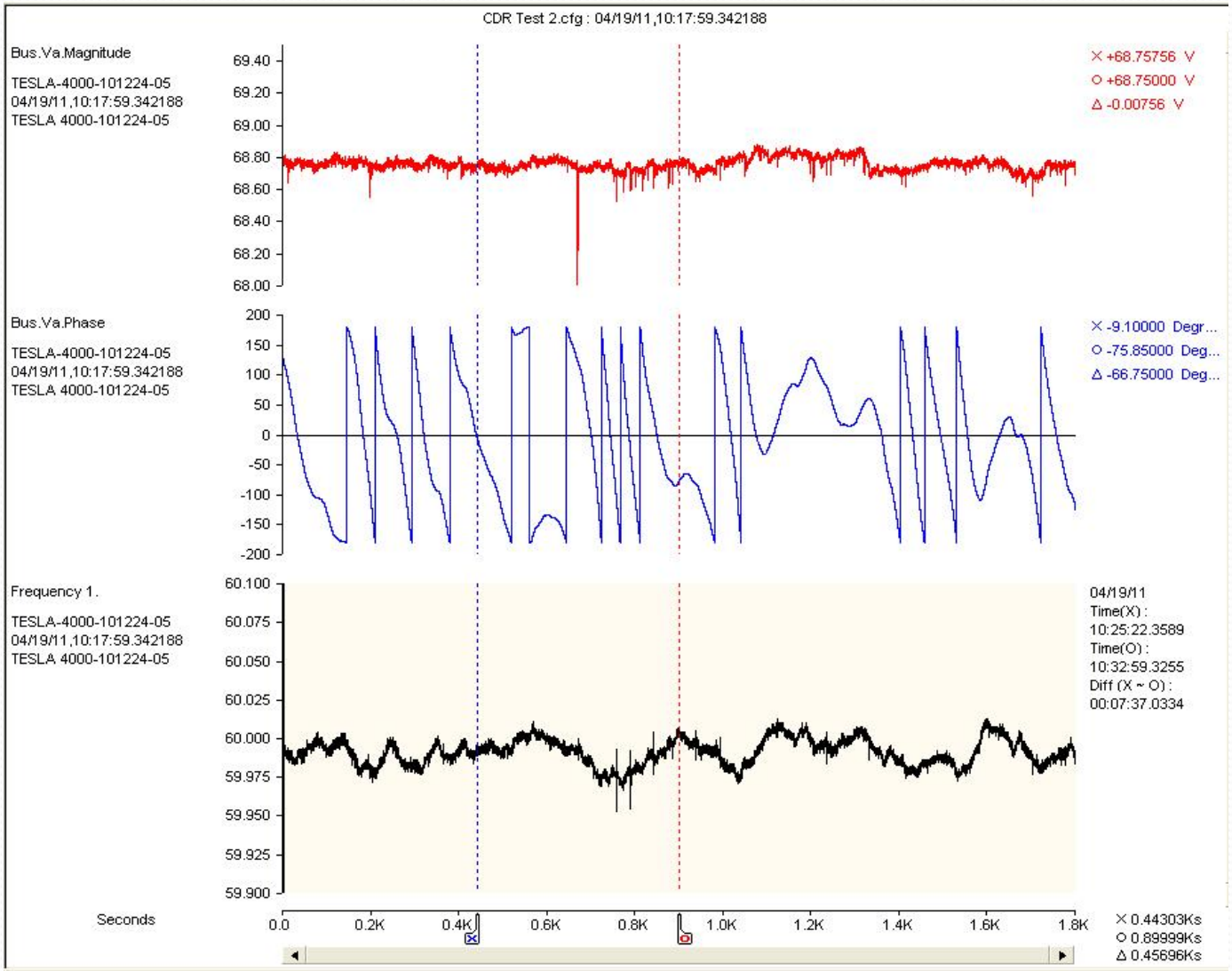



**Figure 3—Sampling a power frequency sinusoid at off-nominal frequency**

# Example


CDR Test 2.cfg : 04/19/11,10:17:59.342188
Bus.Va.Magnitude
TESLA-4000-101224-05
04/19/11,10:17:59.342188
TESLA 4000-101224-05
69.40
69.20
69.00
68.80
68.60
68.40
68.20
68.00
X +68.75756 V
O +68.75000 V
Δ -0.00756 V
Bus.Va.Phase
TESLA-4000-101224-05
04/19/11,10:17:59.342188
TESLA 4000-101224-05
200
150
100
50
0
-50
-100
-150
-200
X -9.10000 Degr...
O -75.85000 Deg...
Δ -66.75000 Deg...
Frequency 1.
TESLA-4000-101224-05
04/19/11,10:17:59.342188
TESLA 4000-101224-05
60.100
60.075
60.050
60.025
60.000
59.975
59.950
59.925
59.900
04/19/11
Time(X) :
10:25:22.3589
Time(O) :
10:32:59.3255
Diff (X ~ O) :
00:07:37.0334
Seconds
0.0
0.2K
0.4K
0.6K
0.8K
1.0K
1.2K
1.4K
1.6K
1.8K
X 0.44303Ks
O 0.89999Ks
Δ 0.45696Ks

# Frequency Calculations

- Signal

$$x(t) = X_m \cos[\psi(t)]$$

- Frequency

$$f(t) = \frac{1}{2\pi}\frac{d\psi(t)}{dt}$$

- Calculated based on phase angles estimated from DFT
  - ~ 1 cycle (assuming one cycle DFT)

# Impact of P/M Class filters

- P- Class: 16 s/c sampling: ~ 2 cycle filter

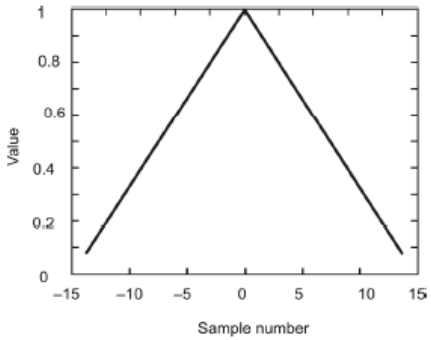



Figure C.3—P class filter coefficient example [$N$ = 2 x (15 – 1) = 28]

- M- Class: 16 s/cy sampling: ~6 cycle filter

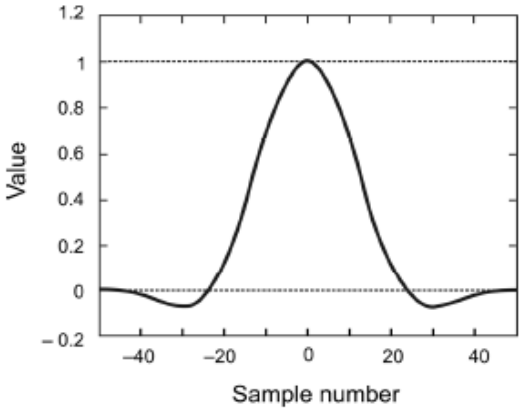


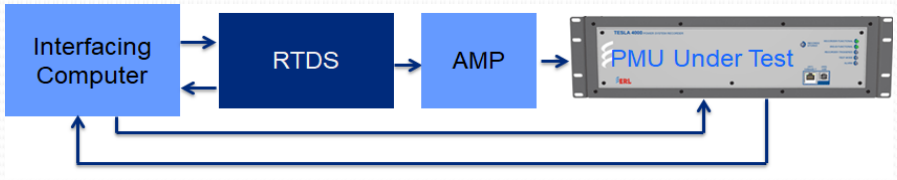

Figure C.6—M class filter coefficient example ($F_s$ = 60 fps, $F_{sampling}$ = 960 Hz, $N$ = 96)

# Impact of P/M filters

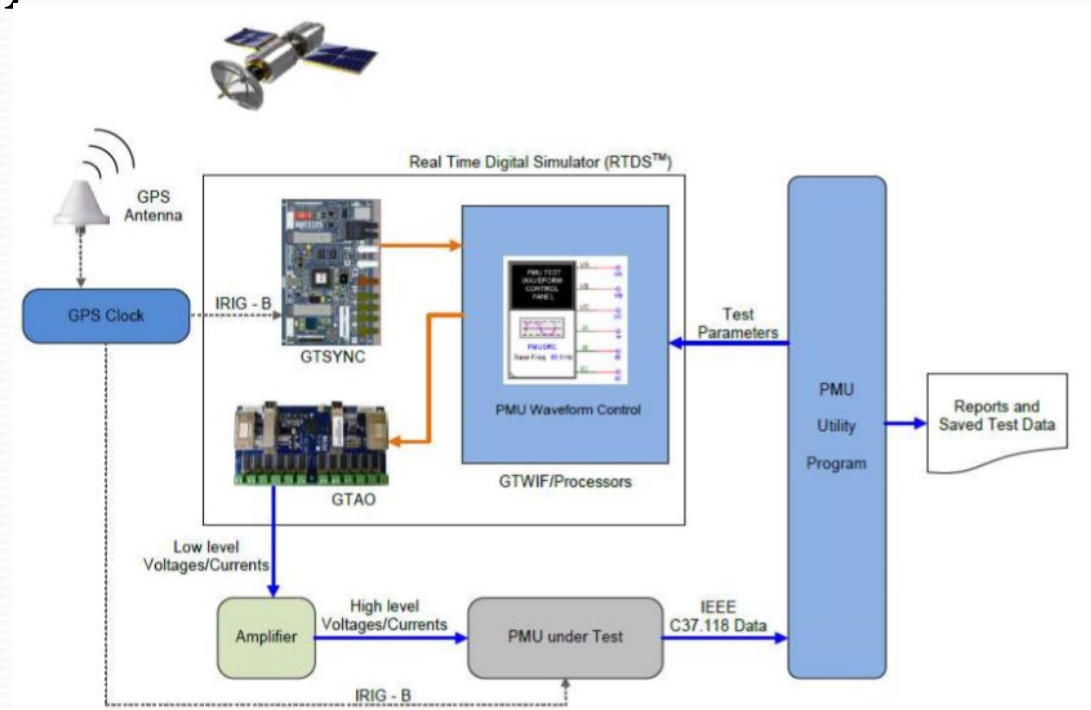
- Factors affecting the frequency
  - Sampling rate
  - Reporting rate
  - Type of filter (P/M)
  - Manufacture specific filters

# Performance Evaluation

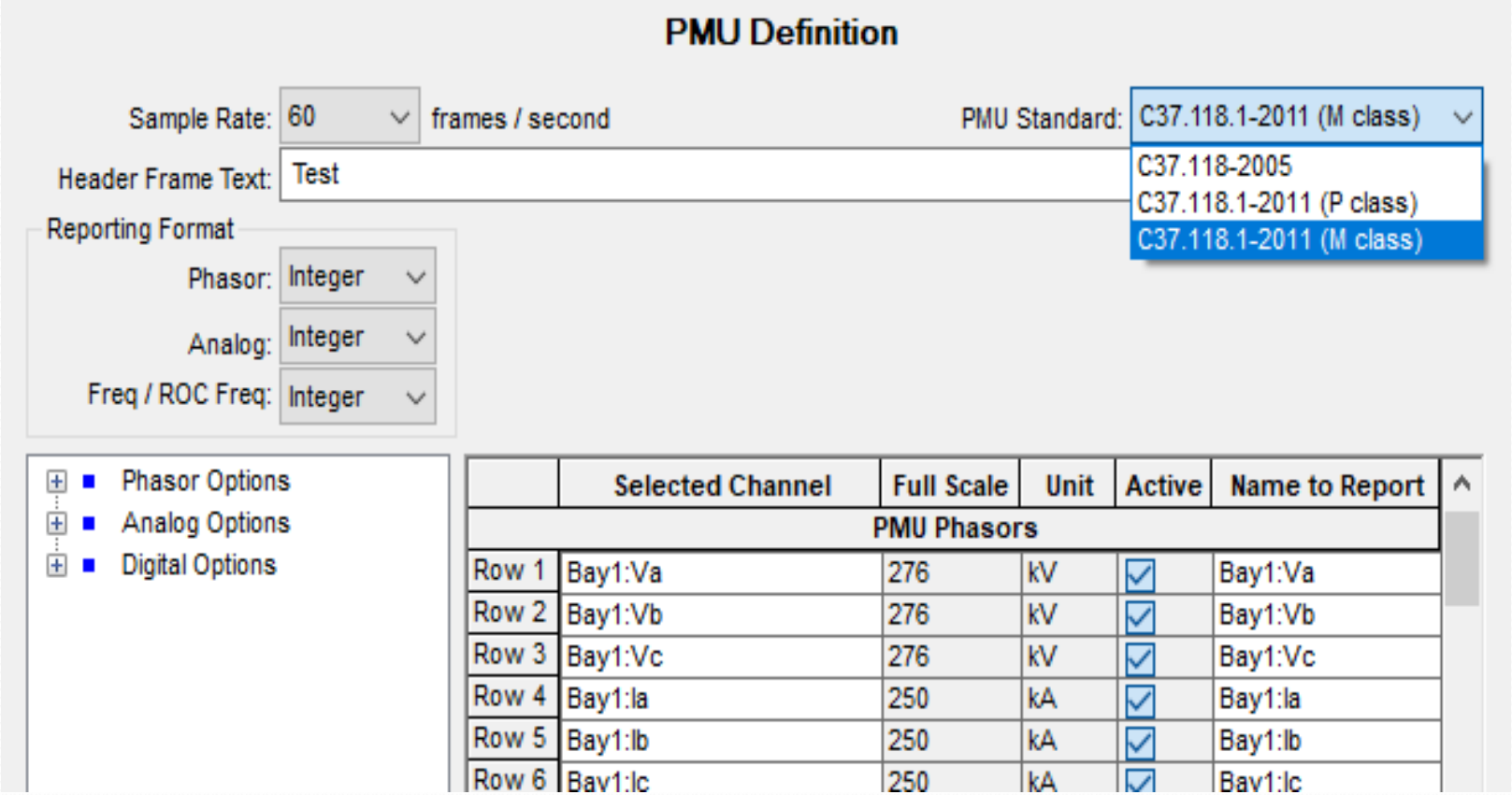
- RTDS Test Setup




- PMU Utility Software



# PMU Configurations



# Standard Test Results

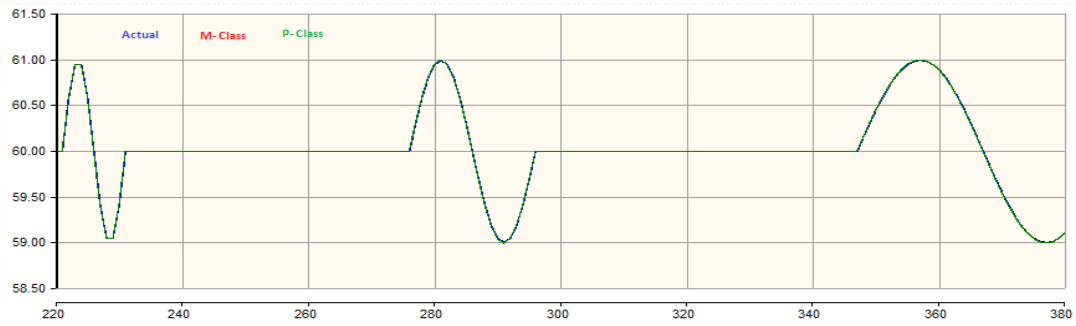
- Steady State Testing

| Influence quantity | Reference condition | Error requirements for compliance | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | P class | | | | M class | | | |
| Signal frequency | Frequency = $f_0$ ($f_{nominal}$) Phase angle constant | Range: $f_0 \pm 2.0$ Hz | | | | Range: $f_0 \pm 2.0$ Hz for $F_s \leq 10$ $\pm F_s/5$ for $10 \leq F_s < 25$ $\pm 5.0$ Hz for $F_s \geq 25$ | | | |
| | | **Max. \|FE\|** | | **Max. \|RFE\|** | | **Max. \|FE\|** | | **Max. \|RFE\|** | |
| | | Standard requirements | Results 50/60Hz | Standard requirements | Results 50/60Hz | Standard requirements | Results 50/60Hz | Standard requirements | Results 50/60Hz |
| | | **0.005 Hz** | **0.003/ 0.002** | **0.4 Hz/s** | **0.12/ 0.04** | **0.005 Hz** | **0.034/ 0.003** | **0.1 Hz/s** | **0.07/ 0.02** |
| Harmonic distortion (single harmonic) | < 0.2% THD | Range: 1%. each harmonic up to 50th | | | | Range: 10%. each harmonic up to 50th | | | |
| | $F_s > 20$ | **0.005 Hz** | **0.0008/ 0.001** | **0.4 Hz/s** | **0.102/ 0.02** | **0.025 Hz** | **0.0005/ 0.007** | **None** | **None** |
| | $F_s \leq 20$ | **0.005 Hz** | - | **0.4 Hz/s** | - | **0.005 Hz** | - | **None** | **None** |
| Out-of-band interference | < 0.2% of input signal magnitude | Range: No requirements | | | | Range: Interfering signal 10% of signal magnitude | | | |
| | | **None** | **None** | **None** | **None** | **0.01 Hz** | **0.003** | **None** | **None** |

# Standard Test Results

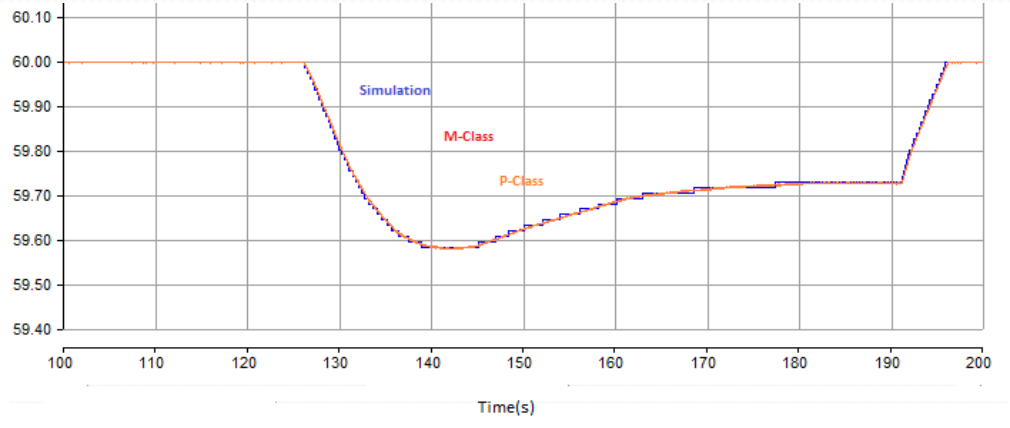
- Dynamic Testing

| F and ROCOF performance limits | Error requirements for compliance | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | P class | | | | | M class | | | | |
| Reporting rate $F_s$ Hz | $F_r$ Hz | Max. \|FE\| | | Max. \|RFE\| | | $F_r$ Hz | Max. \|FE\| | | Max. \|RFE\| | |
| | | Standard req. | Results 50/60Hz | Standard req. | Results 50/60Hz | | Standard req. | Results 50/60Hz | Standard req. | Results 50/60Hz |
| 50 | 2 | **0.06** | **0.002** | **2.3** | **0.061** | 5 | **0.30** | **0.192** | **14** | **10.41** |
| 60 | 2 | **0.06** | **0.011** | **2.3** | **1.45** | 5 | **0.30** | **0.015** | **14** | **1.56** |
| Formulas | min ($F_s$/10.2) | $0.03 \times F_r$ | | $0.18 \times \pi \times F_r^2$ | | min ($F_s$/ 5.5) | $0.06 \times F_r$ | | $0.18 \times \pi \times F_r^2$ | |



# Example Event

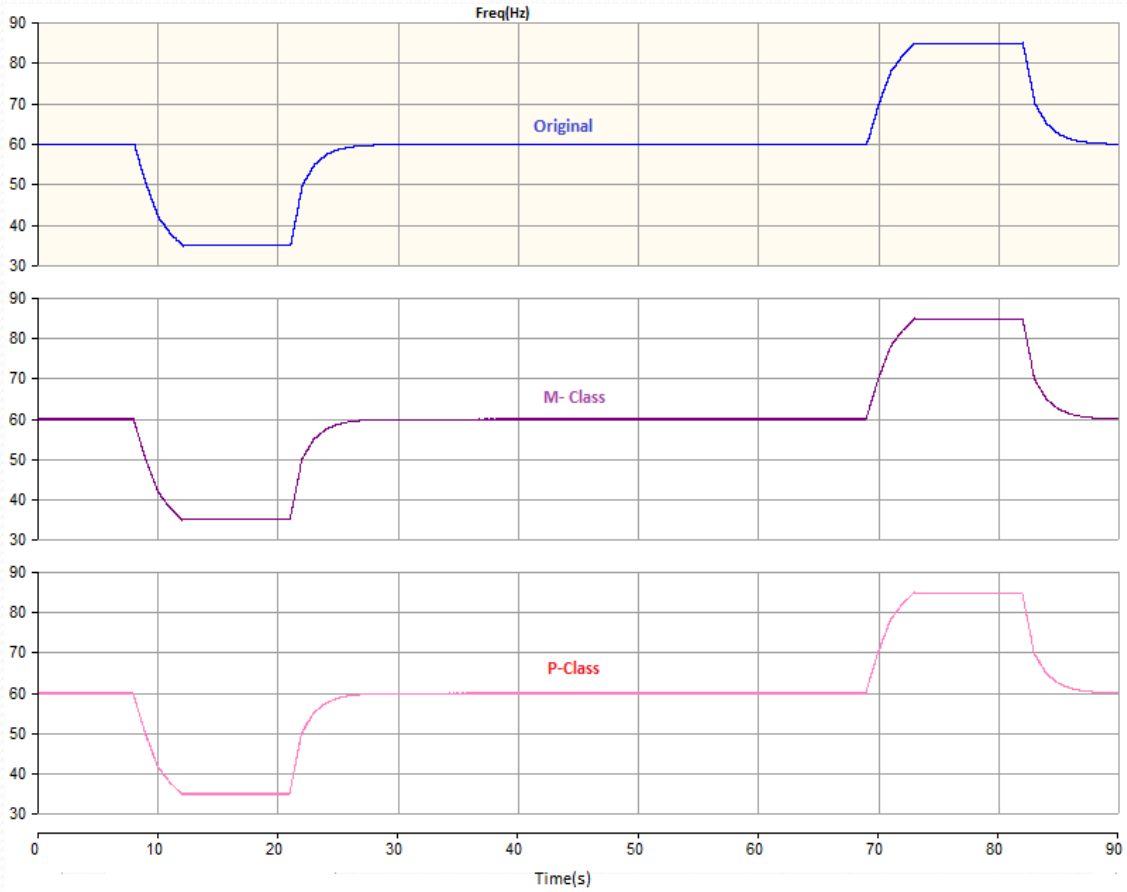
- NERC Example




- This covers under dynamic test cases

# Abnormal Frequency Variations

- 35 Hz to 85 Hz



## Sources of Errors

- Primary Sensor bandwidth
  - CTs, PTs, CVTs
- Secondary sensor bandwidth
- PMU Time Synchronization
- Aging affects
- Temperature affects
- Digital resolution
  - ADC

# Summary

- Applicability of a synchrophasor based frequency measurements is investigated using an industrial PMU.
  - IEEE C37.118 (2011)
- Testing was carried out using the IEEE standard test conditions including some conditions well beyond the standard frequency limits.
- Results obtained from this analysis showed the impact of the P and M class filtering methods.
- It is recommended to select the type of the filters (P/M) based on the application needs and adjust the application settings accordingly.

**Thank you!**