Applicability of Synchrophasor Based Frequency Data for Protection and Control Applications

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TEXAS A&M
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  - Standard definition
  - P/M filters
- Simulation Based Analysis
  - Standard steady state requirements
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  - 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 $X_m$

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.

**Limitations in phase angle calculations**

- 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.

**Solution**

- Sampling is done in a synchronized manor (1-PPS)
Definition of Synchrophasor (C37.118.1)

- $\phi$ 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 μS)
  - 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

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

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

PMU Definition

- Sample Rate: 60 frames/second
- Header Frame Text: Test
- PMU Standard: C37.118.1-2011 (M class)

Reporting Format:
- Phasor: Integer
- Analog: Integer
- Freq / ROC Freq: Integer

Phasor Options
- Analog Options
- Digital Options

Selected Channel | Full Scale | Unit | Active | Name to Report
--- | --- | --- | --- | ---
Row 1 | Bay1:Va | 276 | kV | ✔ |
Row 2 | Bay1:Vb | 276 | kV | ✔ |
Row 3 | Bay1:Vc | 276 | kV | ✔ |
Row 4 | Bay1:ia | 250 | kA | ✔ |
Row 5 | Bay1:ib | 250 | kA | ✔ |
Row 6 | Bay1:lc | 250 | kA | ✔ |
## Standard Test Results

### Steady State Testing

<table>
<thead>
<tr>
<th>Influence quantity</th>
<th>Reference condition</th>
<th>Error requirements for compliance</th>
<th>P class</th>
<th>M class</th>
</tr>
</thead>
</table>
| Signal frequency             | Frequency = \( f_0 \) (\( f_{\text{nominal}} \))  
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 \( 10 < F_s < 25 \)  
\( \pm 5.0 \) Hz for \( F_s \geq 25 \) | | |

<table>
<thead>
<tr>
<th>Max.</th>
<th>Max.</th>
<th>Max.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Harmonic distortion (single harmonic)</th>
<th>Range: 1%. each harmonic up to 50th</th>
<th>Range: 10%. each harmonic up to 50th</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_s &gt; 20 )</td>
<td>( 0.005 ) Hz 0.0008/0.001 0.4 Hz/s 0.1/0.002</td>
<td>( 0.025 ) Hz 0.0005/0.007 None None</td>
</tr>
<tr>
<td>( F_s \leq 20 )</td>
<td>( 0.005 ) Hz - 0.4 Hz/s 0.005 Hz -</td>
<td>None None</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Out-of-band interference</th>
<th>Range: No requirements</th>
<th>Range: Interfering signal 10% of signal magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>0.01 Hz</td>
<td>0.003</td>
<td>None</td>
</tr>
<tr>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>
# Standard Test Results

## Dynamic Testing

<table>
<thead>
<tr>
<th>Reporting rate $F_s$ Hz</th>
<th>$F_r$ Hz</th>
<th>P class</th>
<th>M class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max.</td>
<td>Max.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FE</td>
<td>RFE</td>
</tr>
<tr>
<td></td>
<td>Standard</td>
<td>Results</td>
<td>Standard</td>
</tr>
<tr>
<td></td>
<td>req. 50/60Hz</td>
<td>50/60Hz</td>
<td>req. 50/60Hz</td>
</tr>
<tr>
<td>50</td>
<td>0.06</td>
<td>0.002</td>
<td>2.3</td>
</tr>
<tr>
<td>60</td>
<td>0.06</td>
<td>0.011</td>
<td>2.3</td>
</tr>
</tbody>
</table>

### Formulas

- $\min\left(\frac{F_s}{10.2}\right)$
- $0.03 \times F_r$
- $0.18 \times \pi \times F_r^2$
- $\min\left(\frac{F_s}{5.5}\right)$
- $0.06 \times F_r$
- $0.18 \times \pi \times F_r^2$
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!