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

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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
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
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:
  $$\theta(t) = 2\pi f_0 t + \phi(t)$$

- The phasor value is: $X(t) = (X_m(t)/\sqrt{2})e^{j\phi(t)}$

- Note that all phase variations including frequency differences are in the $\phi(t)$ term
Frequency & ROCOF Defined

- For the signal defined:
  \[ x(t) = X_m(t) \cos[\theta(t)] \]

- Frequency: \[ f(t) = \frac{1}{2\pi} \frac{d\theta(t)}{dt} \]

- ROCOF: \[ \text{ROCOF}(t) = \frac{df(t)}{dt} \]

- Same definitions at C37.118 series
  - Frequency & ROCOF are instantaneous values
Measurement Compliance

- **Evaluation of error**

Reference (theoretical) phasor value

\[ X = \frac{X_m}{\sqrt{2}} e^{i\phi} = X_r + jX_i \]

Measured (estimated) phasor value

\[ X(t_0) = X_r(t_0) + jX_i(t_0) \]

Total Vector Error – the RMS difference

\[ TVE = \sqrt{\left( X_r(t_0) - X_r \right)^2 + \left( X_i(t_0) - X_i \right)^2} \]

\[ \frac{X_r^2 + X_i^2}{X_r^2 + X_i^2} \]

Frequency error (FE) – difference between measured & reference

\[ FE(n) = \hat{f}(n) - f_{ref}(n) \]

ROCOF error (RFE) – difference between measured & reference

\[ RFE(n) = \frac{df}{dt}(n) - \frac{df_{ref}}{dt}(n) \]
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

<table>
<thead>
<tr>
<th>Influence quantity</th>
<th>Reference condition</th>
<th>Minimum range of influence quantity over which PMU shall be within given TVE limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Performance – P class</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range</td>
</tr>
<tr>
<td>Signal frequency</td>
<td>Frequency = ( f_0 ) (( f_{\text{nominal}} ))</td>
<td>± 2.0 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage signal magnitude</td>
<td>100 % rated</td>
<td>80 % to 120 % rated</td>
</tr>
<tr>
<td>Current signal magnitude</td>
<td>100 % rated</td>
<td>10 % to 200 % rated</td>
</tr>
<tr>
<td>Harmonic distortion (single harmonic)</td>
<td>&lt; 0.2% (THD)</td>
<td>1 %, each harmonic up to 50th</td>
</tr>
<tr>
<td>Out-of-band interference as described below</td>
<td>&lt; 0.2% of input signal magnitude</td>
<td>None</td>
</tr>
</tbody>
</table>
## Steady-State Frequency & ROCOF

<table>
<thead>
<tr>
<th>Influence quantity</th>
<th>Reference condition</th>
<th>Error requirements for compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal frequency</strong></td>
<td>Frequency = ( f_0 ) (( f_{\text{nominal}} ))&lt;br&gt;Phase angle constant</td>
<td>P class</td>
</tr>
<tr>
<td>( f_0 \pm 2,0 \text{ Hz} )</td>
<td>Range: ( f_0 \pm 2,0 \text{ Hz} ) for ( F_s \leq 10 )&lt;br&gt;( \pm F_s/5 ) for ( 10 \leq F_s &lt; 25 )&lt;br&gt;( \pm 5,0 \text{ Hz} ) for ( F_s \geq 25 )</td>
<td>Max.</td>
</tr>
<tr>
<td>( 0,005 \text{ Hz} )</td>
<td>( 0,4 \text{ Hz/s} )</td>
<td>0,005 Hz</td>
</tr>
<tr>
<td><strong>Harmonic distortion</strong></td>
<td>( &lt; 0,2 % \text{ THD} )</td>
<td>1 % each harmonic up to ( 50^{\text{th}} )</td>
</tr>
<tr>
<td>( F_s &gt; 20 )</td>
<td>Max.</td>
<td>Max.</td>
</tr>
<tr>
<td>( 0,005 \text{ Hz} )</td>
<td>( 0,4 \text{ Hz/s} )</td>
<td>( 0,025 \text{ Hz} )</td>
</tr>
<tr>
<td>( F_s \leq 20 )</td>
<td>( 0,005 \text{ Hz} )</td>
<td>( 0,4 \text{ Hz/s} )</td>
</tr>
<tr>
<td><strong>Out-of-band interference</strong></td>
<td>( &lt; 0,2 % \text{ of input signal magnitude} )</td>
<td>No requirements</td>
</tr>
<tr>
<td>( \text{None} )</td>
<td>( \text{None} )</td>
<td>( 0,01 \text{ Hz} )</td>
</tr>
</tbody>
</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)
  - \[ X(nT) = \{X_m/\sqrt{2}\}[1+k_x \cos(\omega nT)]\angle \{k_a \cos(\omega nT - \pi)\} \]
  - \[ f(nT) = \omega_0/2\pi - k_a (\omega/2\pi) \sin (\omega nT - \pi) \]
  - \[ \text{ROCOF}(nT) = - k_a (\omega^2/2\pi) \cos (\omega nT - \pi) \]
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
  - \( X_a = X_m \left[1+k_x f_1(t)\right] \times \cos \left[\omega_0 t+k_a f_1(t)\right] \) 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