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PMU (algorithm) Testing to C37.118.1(a) in software

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ENG52 SmartGrid II
SMART GRID METROLOGY

Rough Agenda

- C37.118.1 (2011) & C37.118.1a (2014)
  - Description of the six main tests in order
  - Making references to C37.118.1a and the new IEEE Synchrophasor Measurement Test Suite (TSS)
  - Problems with the tests
  - An introduction to some of the snags & ambiguities
  - Recent Synchrophasor Working Group debates
    - » E.g. Frequency ramp time-exclusion zone and limits
    - » Undershoot and Overshoot definitions
- Testing in software
  - Example of Strathclyde software environment
- Possible IEC extensions, including real-world effects

C37.118.1a-2014

IEC/IEEE 60255-118-1

References

IEEE, C37.118.1a-2014: 'IEEE Standard for Synchrophasor Measurements for Power Systems -- Amendment 1: Modification of Selected Performance Requirements ', 2014

IEEE, ISBN 978-0-7381-9360-1: 'IEEE Synchrophasor Measurement Test Suite Specification', 2014

IEEE, C37.118.1-2011: 'IEEE Standard for Synchrophasor Measurements for Power Systems', 2011

K. E. Martin, A. R. Goldstein, M. G. Adamiak, G. Antonova, M. Begovic, et al., "Synchrophasor Measurements under the IEEE Standard C37.118.1-2011 with amendment C37.118.1a," *IEEE Transactions on Power Delivery,* 2015

A. J. Roscoe, B. Dickerson, and K. E. Martin, "The amended standard C37.118.1a and its implications for frequency-tracking M-class Phasor Measurement Units (PMUs)," in IEEE Applied Measurements for Power Systems (AMPS), Aachen, Germany, 2014.

Recent Synchrophasor Working Group (WG) emails and meeting minutes.

Standard C37.118.1a Tests

1. Steady state - balanced sinusoids
   – Hardware, **ADC sampling quality/timing**, signal/noise ratio.
2. Steady state – single “balanced” harmonic at f_0
   – Very loose **stopband rejection** test.
3. Out of band (interharmonics <2 f_0) testing (close to f_0)
   – Very strict **stopband rejection** test.
4. Bandwidth (modulation)
   – Very strict **passband flatness** test
5. Frequency ramp test
   – Tests for **excessive uncompensated frequency and ROCOF post-filtering**, or timestamp calibration errors in them.
6. Step tests
   – Restrict the time window lengths of the total filter paths for phasors, frequency and ROCOF calculation. Limits on overshoot and undershoot.
7. Latency

Test 1 : Steady state - balanced sinusoids

- The test is the ONLY C37.118.1a test done across the PMU bandwidth (2 to 5 Hz)
- The waveforms are always balanced sinusoids
- For P class, the signal applied is as low as 0.8pu
- For M class, the signal applied is as low as 0.1pu

minimum of 5 s of test duration.

TVE compliance is "easy" so long as the PMU timing is working correctly.

Frequency (±0.005 Hz) and ROCOF (±0.4 Hz/s for P, (±0.1 Hz/s for M) are much harder.

The crux points are P class (~2 cycle window) at 0.8pu, and M class F_S=50 Hz (~10 cycle window) at 0.1pu.

Table 3—Steady-state synchrophasor measurement requirements

Influence quantity	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit			
		P class		M class	
		Range	Max TVE (%)	Range	Max TVE (%)
Signal frequency range—f_{dev} (test applied nominal + deviation: $f_0 \pm f_{dev}$)	$F_{nominal}$ (f_0)	± 2.0 Hz	1	± 2.0 Hz for F_s<10 ± F_s/5 for $10 \le F_s < 25$ ± 5.0 Hz for $F_s \ge 25$	1
The signal frequency range tests above are to be performed over the given ranges and meet the given requirements at three temperatures: T = nominal (~23 °C), T = 0 °C, and T = 50 °C					
Signal magnitude—Voltage	100% rated	80% to 120% rated	1	10% to 120% rated	1
Signal magnitude—Current	100% rated	10% to 200% rated	1	10% to 200% rated	1

Test 1 : Steady state - balanced sinusoids

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Table 4—Steady-state frequency and ROCOF measurement requirements

Influence quantity	Reference condition	Error requirements for compliance			
		P class		M class	
Signal frequency	Frequency = f_0 (f_{nominal}) Phase angle constant	Range: $f_0 \pm 2.0$		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 >25	
		Max FE	Max RFE	Max FE	Max RFE
		0.005 Hz	~~0.01 Hz/s~~ 0.4 ~~1~~ Hz/s	0.005 Hz	~~0.01 Hz/s~~ 0.1 Hz/s

NOT average, or RMS, the maximum single error observed!

The crux points are P class (~2 cycle window) at 0.8pu, and M class F_S=50 Hz (~10 cycle window) at 0.1pu.

In my experience (agreed with Bill Dickerson of Arbiter, you need about 12-13 bits of IDEAL ADC sampling across the ±pu signal input range to achieve compliance in those cases. Allowing for analogue circuit noise, and ADC non-linearity/noise, a 16-bit ADC is probably just enough.

$SNR(dB) = 1.76 + 6.02n = 74dB$ for n=12 bits, with a 1pu signal applied

In the M class test, at 0.1pu, 20dB is immediately lost so SNR in the PMU will only be 54dB.

In a software test environment, you should DEFINITELY model realistic noise and/or ADC quantisation, otherwise the algorithm may be too optimistically treated. It could pass in simulation, but be unsuitable for any realistic application.

Test 1 : Steady state - balanced sinusoids

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8.1.2 Test plan for signal frequency range

See IEEE Std C37.118.1-2011 Table 3 and Table 4 for the required TVE, FE, and RFE limits for the given reporting rate (F_s).

Oh! different frequencies not tested for off-nominal magnitudes!

a) Apply input signals at nominal magnitude at the frequency range limit: nominal frequency minus the lesser of F_s /5 or 5 Hz.

How long?

b) Wait for the system to settle.

c) Capture the PMU output for 5 s; allow for the settling period to elapse before changing the input signal.

d) Calculate the errors: ME, PE, FE, and RFE for each report.

e) Calculate the max TVE, FE, and RFE.

f) Increase the frequency by 0.1 Hz.

g) Repeat step b) through step f) until the upper frequency range limit is reached.

h) Compare the results to the class limits in the relevant standard.

i) Perform steps a) through h) at temperatures T = 23 °C, 0 °C, and T = 50.0 °C. Allow PMU to reach temperature equilibrium within 3 °C before running the test.

Test 1 : Steady state - balanced sinusoids

8.2.1 Test plan for signal magnitude—voltage and current

For both current and voltage input ranges, apply steady-state, nominal frequency (50 Hz or 60 Hz), balanced three-phase inputs. Compare the measurement with the input. Depending on the level or class, the PMU must operate over a range of voltages and currents, usually given as magnitudes relative to the nominal values. See Table 3 and Table 4 of IEEE Std C37.118.1-2011 for magnitude values and test limits.

Oh! different amplitudes not tested for off-nominal frequencies!

a) Begin at the low magnitude limits:

— P class: voltage = 80% of nominal, current = 10% of nominal.

— M class: voltage = 10% of nominal, current = 10% of nominal.

b) Wait for the system to settle.

c) Capture the PMU output for 5 s; allow for the settling period to elapse before changing the input signal.

d) Calculate the errors: ME, PE, FE, and RFE for each report.

e) Calculate the max TVE.

f) Increase the input magnitudes by 10% of the nominal value (not a percentage of the actual value).

g) Repeat step b) through step f) until the upper magnitude limits are reached: 120% of nominal voltage, 200% of nominal current (P and M class).

h) Compare the results to the class limits in the relevant standards.

Test 2 : Single “balanced” harmonic at f_0

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Influence quantity	Reference condition	Error requirements for compliance			
		P class		M class	
Harmonic distortion (same as Table 3 - single harmonic)	<0.2% THD	1% each harmonic up to 50th		10% each harmonic up to 50th	
		Max FE	Max RFE	Max FE	Max RFE
	$F_s > 20$	0.005 Hz	~~0.01 Hz/s~~ 0.4 ~~1~~ Hz/s	0.025 Hz	~~6 Hz/s~~ Limit suspended
	$F_s \leq 20$	0.005 Hz	~~0.01 Hz/s~~ 0.4 ~~1~~ Hz/s	0.005 Hz	~~2 Hz/s~~ Limit suspended

0.4 Hz/s uncertainty makes it a useless measurement from a network operators perspective!

The lack of ANY required uncertainty makes it a useless measurement from a network operators perspective!

NOTE. Some M-class PMUs can make very GOOD measurements in this particular test, and even across wide frequency ranges with simultaneous applied harmonics, if the algorithms are suitably adaptive to off-nominal frequency and use suitable filters/algorithms.

5.5.4 Reference and test conditions

All compliance tests are to be performed with all parameters set to standard reference conditions, except those being varied as specified for the test. The reference condition specified for each test is the value of the quantity being tested when not being varied. Only the parameters specified for each requirement shall be varied as the effects shall be considered independent. Reference conditions for all tests are as follows:

a) Voltage at nominal

b) Current at nominal

c) Frequency at nominal

So in this test, harmonics are being varied so frequency is left at nominal!

And, only one harmonic at a time is applied.

It is a very restrictive test!

Test 2 : Single “balanced” harmonic at f_0

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8.4.1 Test plan for harmonic distortion

Response to harmonic distortion is specified for 2nd harmonic to 50th harmonic individually.

a) Apply input signals at nominal magnitude with the addition of one harmonic, starting with the second harmonic, with the magnitude set to the level specified by IEEE Std C37.118.1-2011 for Class P or M PMUs:

— 1% of nominal magnitude for P class.

— 10% of nominal magnitude for M class.

b) Wait for the system to settle.

c) Capture the PMU output for 5 s; allow for the settling period to elapse before changing the input signal.

d) Calculate the errors: ME, PE, FE, and RFE for each report.

e) Calculate the max TVE, FE, and RFE.

f) Change to injecting the next harmonic.

g) Repeat step b) through step f) until all harmonics between 2nd harmonic and 50th harmonic have been tested.

h) Compare the results to the class limits in Table 3 and Table 4 of IEEE Std C37.118.1-2011.

Test 2 : Single "balanced" harmonic at f_0

8.4.2 Harmonic distortion test ambiguities

The phase sequence of the harmonics is not specified by IEEE Std C37.118.1-2011. For the purposes of this TSS, the harmonic sequence shall NOT be positive sequence for all harmonics but shall be in-phase with the fundamental frequency for all three phases. In other words, when the fundamental power signal of each phase crosses zero in the positive going direction, the injected harmonic signal shall also be crossing zero in the positive direction. In this case, the second harmonic will be negative sequence, the third harmonic will be zero sequence, and the forth harmonic will be positive sequence. The cycle repeats with the fifth harmonic being negative sequence and so on (see Table 4).

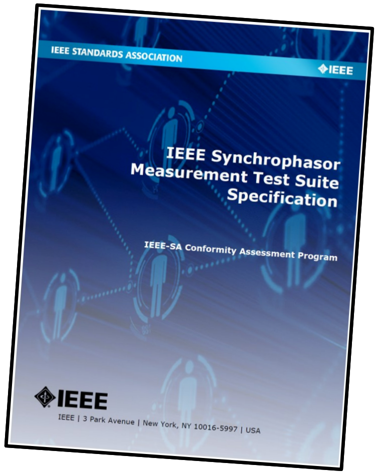
Table 4 —Harmonic phase sequence in a balanced three-phase system

Harmonic	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sequence	+	–	0	+	–	0	+	–	0	+	–	0	+	–	0
Harmonic	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Sequence	+	–	0	+	–	0	+	–	0	+	–	0	+	–	0
Harmonic	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Sequence	+	–	0	+	–	0	+	–	0	+	–	0	+	–	0
Harmonic	46	47	48	49	50										
Sequence	+	–	0	+	–										

This leads to the same waveshapes on all phases.

It is the most "usual" symptom in power systems.

Of course, there are many other permutations which are not explored by this approach.



The reason for specifying the phase sequence of harmonic signals is to provide a common reference for all PMU testing. PMUs have been shown to have different results when subjected to the same harmonics with different phase relations.

Test 2 : Single “balanced” harmonic at f_0

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The WGH11 discussed requiring this test to be done with multiple harmonics at one time, to more accurately simulate how harmonics appear in the power systems and to possibly reduce the testing time. Issues of signal crest factor and rise times and their impact on measurement were raised. Different power system operating scenarios produce different combinations of harmonics. The question of whether the test limits should apply to the total power of the harmonics or the individual amplitudes was raised. Without general agreement on these questions, the WGH11 decided the best approach is still to perform the test with one harmonic applied at a time. The 2014 amendment suspended the ROCOF error requirement for harmonic testing of M class PMUs, after testing of actual PMUs indicated that this requirement might be a driving factor in PMU design which could impair the phasor measurement capability. P class PMUs still have a ROCOF error limit for harmonic tests, though relaxed to 0.4 Hz/s.


Synchrophasor Measurements under the IEEE Standard C37.118.1-2011 with amendment C37.118.1a

Synchrophasor Measurements under the IEEE Standard C37.118.1-2011 with amendment C37.118.1a

Working Group H11 on the Synchrophasor Standard, C37.118.1 of the Relay Communications Subcommittee of the IEEE Power System Relaying Committee

K. E. Martin, A. R. Goldstein, M. G. Adamiak, G. Antonova, M. Begovic, et al., "Synchrophasor Measurements under the IEEE Standard C37.118.1-2011 with amendment C37.118.1a," *IEEE Transactions on Power Delivery*, 2015

Test 2 : Single "balanced" harmonic at f_0

The limits for RFE for class M have been suspended for the Harmonics and Out-of-Band tests. The interactions between the phasor, frequency and ROCOF computations are not well enough developed at the time of this standard's publication to assure that fixed limits for ROCOF in these tests will not constrain phasor or frequency measurement. This standard focuses on phasor and frequency measurement to best serve the user community. However, for sinusoidal interfering signals such as these, the limit on FE also implies a limit on RFE.

This implied limit can be calculated as:

$$RFE = FE \times 2 \times \pi \times | f_{int} - f_0 |$$

where:

f_{int} is the interfering signal frequency

f_0 is the nominal frequency

For example, for the 2nd harmonic of f_0 = 50 Hz (100 Hz), the difference (100 − 50) is 50 Hz, and the resulting implied limit is 7.85 Hz/s. In other words, a PMU which is at the FE limit with exactly 0.025 Hz frequency error due to the 100 Hz harmonic will produce a ROCOF error (RFE) of 7.85 Hz/s.

- Typical RFE results for the "Reference" algorithm are ! 0.02 Hz/s to 50 Hz/s ! depending on the additional post-processing (following the Hamming/Sinc window) applied to frequency and ROCOF.

Test 2 : Single "balanced" harmonic at f_0

- Personally, I run my own tests where I also sweep nominal frequency over the whole valid input range, as well as checking every harmonic.
- It is a long test – 49 harmonics times the number of frequency steps.
- But, it is often revealing.
- The standard test done only at f_0 is, in my opinion, too much of an "easy ride" for PMUs, and in no way certifies them for use in any real environments.

- I also like to run my own tests where multiple harmonics (e.g. to EN 50160) are applied at the same time, over non-linear frequency ramps!

Test 3 : Out of Band (OOB) (interharmonics between 10 Hz and 2*f_0 eg flicker)

- This test is “dressed up” as testing digital anti-aliasing filtering before the decimation to the reporting rate.
- The out of band test is really a test of the STOPBAND attenuation.
- It tests the ability of the algorith/filter/window to reject signals between $F_S/2$ and f_0 removed from the fundamental.
- The filter “stopband start frequency” is defined as $F_S/2$ which is the Nyquist frequency at the reporting rate.

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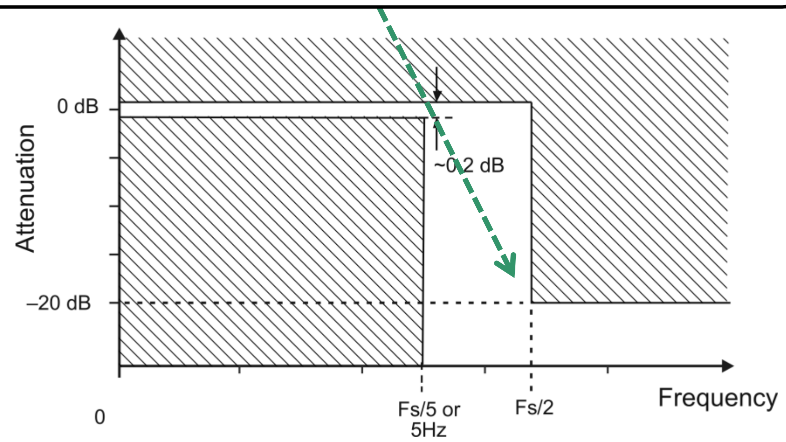
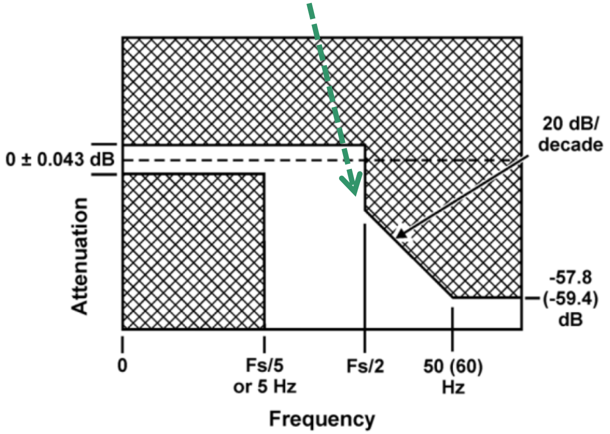
  - It tests the ability of the algorith/filter/window to reject signals with $(f_{IH}-f_0) \geq F_S/2$.
  - The filter "stopband start frequency" is defined as $F_S/2$ which is the Nyquist frequency at the reporting rate.

The required stopband attenuation in C37.118.1(2011) was just 20dB, but it was nowhere near enough to attain 0.01Hz accuracy with the applied interharmonics at 10% of fundamental.



The stopband attenuation at $F_S/2$ required to comply with C37.118.1a is closer to 54dB for a fixed-filter PMU



Test 3 : Out of Band (OOB) (interharmonics between 10 Hz and 2*f_0 eg flicker)

- The test exercises the PMU by testing the filtering with fundamental frequency varied over a reduced range.
  - This is somewhat of a “cheat”, and it acknowledges that the stopband rejection for a PMU which does not tune itself to the fundamental will be much poorer if frequency is at the edge of the actual quoted PMU range of operation.
- Achieving a TVE of 1.3% in this test is quite easy for the PMU filter if it has >20dB of attenuation in the stopband.

Influence quantity	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit			
		P class		M class	
		Range	Max TVE (%)	Range	Max TVE (%)
Out-of-band interference as described below (See NOTES 2 and 3)	<0.2% of input signal magnitude		None	10% of input signal magnitude for $F_s \geq 10$. No requirement for $F_s < 10$.	1.3

Out-of-band interference testing: The passband at each reporting rate is defined as $|f - f_0| < F_s/2$. An interfering signal outside the filter passband is a signal at frequency f where $|f - f_0| \geq F_s/2$

For test the input test signal frequency f_{in} is varied between f_0 and ± (10%) of the Nyquist frequency of the reporting rate.

That is $f_0 - 0.1\ (F_s/2) \leq f_{in} \leq f_0 + 0.1\ (F_s/2)$

where

F_s = phasor reporting rate
f_0 = nominal system frequency
f_{in} = fundamental frequency of the input test signal

Test 3 : Out of Band (OOB)
(interharmonics between 10 Hz and 2*f_0 eg flicker)

NOTE 3—Compliance with out-of-band rejection can be confirmed by using a single frequency sinusoid added to the fundamental power signal at the required magnitude level. The signal frequency is varied over a range from below the passband (at least down to 10 Hz) and from above the passband up to the second harmonic ($2 \times f_0$). If the positive sequence measurement is being tested, the interfering signal is a positive sequence.

The standard requires that when measuring the interference effects on a positive sequence phasor from the PMU, the interfering signal harmonics must be positive sequence. The need to make the interharmonics positive sequence arises from the fact that a PMU calculates symmetrical components from the phase components. Any non-positive sequence component of the interharmonics would be highly attenuated in the computation of the positive sequence phasor.

K. E. Martin, A. R. Goldstein, M. G. Adamiak, G. Antonova, M. Begovic, et al., "Synchrophasor Measurements under the IEEE Standard C37.118.1-2011 with amendment C37.118.1a," *IEEE Transactions on Power Delivery*, 2015

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Test 3 : Out of Band (OOB)
(interharmonics between 10 Hz and 2*f_0 eg flicker)

Out-of-band compliance shall be confirmed by adding a single frequency sinusoid to the fundamental power signal at the required amplitude level and measuring the TVE and FE for 5 s. A series of tests increments the frequency of this signal over the out-of-band range from below the in-band (at least down to 10 Hz) and above the in-band to the second harmonic ($2 \times f_0$) for each reporting rate. This test shall be repeated three times with input signal (f_{in}) frequency at nominal (f_0), at $f_{in} = f_0 \pm 0.10$ times the reporting rate Nyquist frequency. Table 5 shows the bandwidth and the in-band range for each reporting rate and nominal frequency. The in-band range is the range in which interfering signals will not be injected.

Table 5 —Out-of-band interference test with IEEE Std C37.118.1-2011

60 Hz nominal				In-band	Out-of-band
F_s	Bandwidth	$F_s/2$ (Nyquist)	10% Nyquist of F_s	$f_0 = 60$	$f_0 = 60$
10 or less	±2 Hz	5 Hz	±0.5 Hz	55–65 Hz	10–55, 65–120
12	±2.4 Hz	6 Hz	±0.6 Hz	54–66 Hz	10–54, 66–120
15	±3 Hz	7.5 Hz	±0.75 Hz	52.5–67.5 Hz	10–52.5,67.5–120
20	±4 Hz	10 Hz	±1 Hz	50-70 Hz	10–50, 70–120
30	±5 Hz	15 Hz	±1.5 Hz	45-75 Hz	10–45,75–120
60	±5 Hz	30 Hz	±3 Hz	30–90 Hz	10–30, 90–120
50 Hz nominal				In-band	Out-of-band
F_s	Bandwidth	$F_s/2$ (Nyquist)	10% Nyquist of F_s	$f_0 = 50$	$f_0 = 50$
10 or less	±2 Hz	5 Hz	±0.5 Hz	45–55 Hz	10–45, 55–100
25	±5 Hz	12.5 Hz	±1.25 Hz	37.5–62.5 Hz	10–37.5, 62.5–100
50	±5 Hz	25 Hz	±2.5 Hz	25–75 Hz	10–25, 75–100

Interfering signals are injected within the out-of-band frequencies above.

Test 3 : Out of Band (OOB) (interharmonics between 10 Hz and 2*f_0 eg flicker)

a) Add an interharmonic signal at $f_i = f_0 - F_s/2$ at 10% nominal magnitude.

b) Wait for the system to settle.

c) Capture the PMU output for 5 s; allow the settling period to elapse before changing the input signal.

d) Calculate the errors: ME, PE, FE, and RFE for each report.

e) Calculate the max TVE, and FE.

f) Run step b) through step e) repeatedly, decreasing the interharmonic frequency exponentially until it reaches 10 Hz:

— For each test run, the interharmonic frequency decrements exponentially, thus providing many tests near $f_i = f_0 - F_s/2$ and fewer tests further away from $f_i = f_0 - F_s/2$. For example, the first decrease should be 0.1 Hz ($f_0 - F_s/2 - 0.1$), the next decrease 0.2 Hz ($f_0 - F_s/2 - 0.2$), the third decrease 0.4 Hz ($f_0 - F_s/2 - 0.4$), then 0.8 Hz ($f_0 - F_s/2 - 0.8$) until an interharmonic frequency below 10 Hz is reached. For the last frequency, use 10 Hz rather than the frequency below 10 Hz.

g) Add an interharmonic signal at $f_i = f_0 + F_s/2$ at 10% nominal magnitude.

h) Run step b) through step e) repeatedly, increasing the interharmonic frequency exponentially until it reaches $2 \times f_0$:

— For each test run, the interharmonic frequency increments exponentially, thus providing many tests near $f_i = f_0 + F_s/2$ and fewer tests further away from $f_i = f_0 + F_s/2$. For example, the first increase should be 0.1 Hz ($f_0 + F_s/2 + 0.1$), the next increase 0.2 Hz ($f_0 + F_s/2 + 0.2$), the third increase 0.4 Hz ($f_0 + F_s/2 + 0.4$), then 0.8 Hz ($f_0 + F_s /2 + 0.8$), until an interharmonic frequency above $2 \times f_0$ is reached. For the last frequency use $2 \times f_0$ rather than the frequency above $2 \times f_0$.

i) Compare the results to the class limits in the amended IEEE Std C37.118.1-2011 and IEEE Std C37.118.1a-2014.

j) Run all steps a) through h) two more times with the input signal frequency at nominal frequency plus and minus 10% of $F_s/2$ (the Nyquist frequency of the reporting rate, F_s).

Test 3 : Out of Band (OOB)
(interharmonics between 10 Hz and 2*f_0 eg flicker)

NOTE—Out-of-band interfering signal testing requires many test runs. Increasing the increment of interharmonic frequency change exponentially rather than at small, constant increments reduces the total number of individual test runs while ensuring that many tests are run near the bandwidth limits.

For example:

$$f_i = \max\left[\left(f_0 - \frac{F_s}{2} - \left(0.1 \times 2^i\right)\right), 10\right] Hz$$

$$f_i = \min\left[\left(f_0 + \frac{F_s}{2} + \left(0.1 \times 2^i\right)\right), 2 \times f_0\right] Hz$$

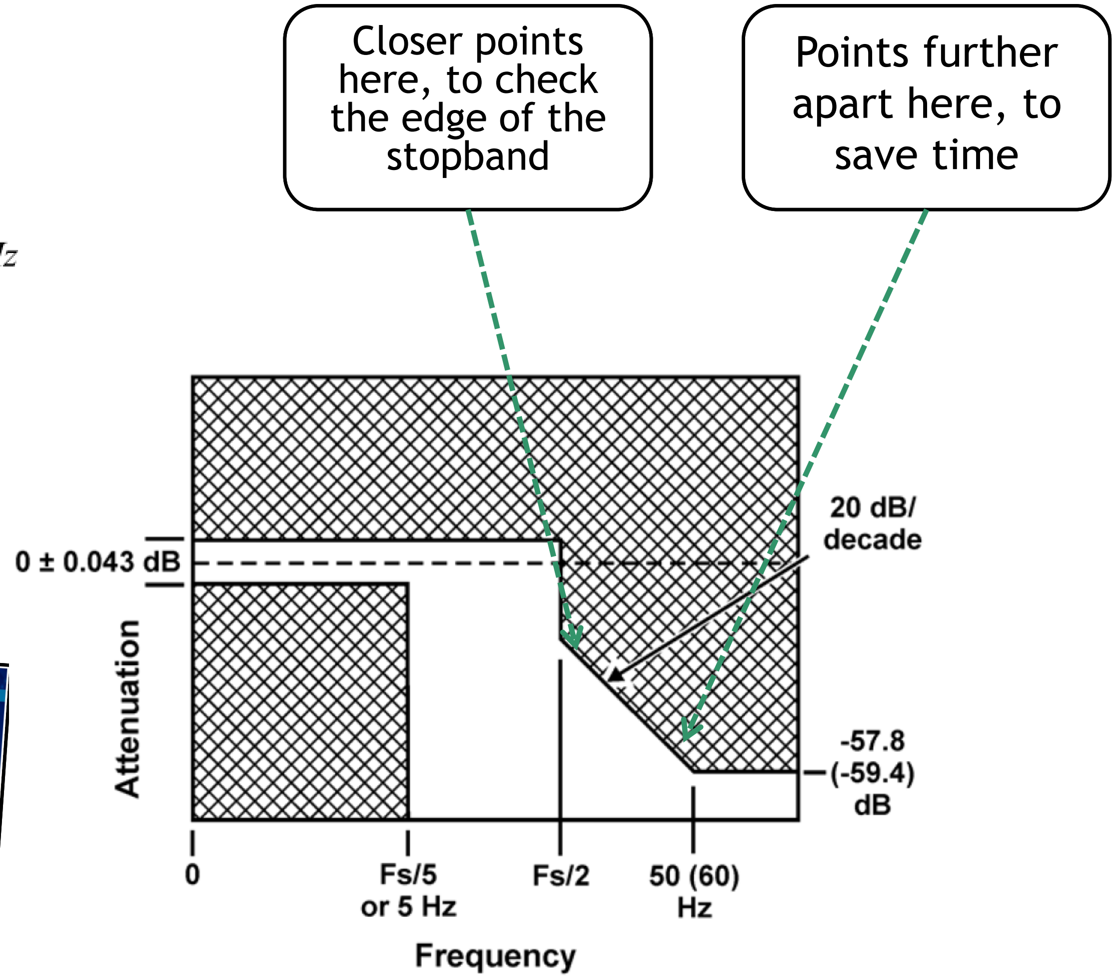
where

f_i is the frequency of the interfering signal

f_0 is the nominal frequency

F_s is the reporting rate

i is the index beginning at 0



Test 3 : Out of Band (OOB) (interharmonics between 10 Hz and 2*f_0 eg flicker)

- The passing or failing of this test will usually be determined by the FE limit, since the RFE limit is suspended. For a given filter, FE at 0.01Hz will fail long before TVE fails at 1.3%

Influence quantity	Reference condition	Error requirements for compliance			
		P class		M class	
Out-of-band interference (same as Table 3)	<0.2% of input signal magnitude	No requirements		Interfering signal 10% of signal magnitude	
				Max FE	Max RFE
		None	None	0.01 Hz	~~0.1 Hz/s~~ Limit suspended

- Typical RFE results for the “Reference” algorithm are up to 0.9 Hz/s.
- Achievable RFE results for “Better” algorithms are <0.15 Hz/s

Test 3 : Out of Band (OOB) (interharmonics between 10 Hz and 2*f_0 eg flicker)

- The way the test is applied is not "correct" for a PMU which adapts (tunes) itself so that its filter is centred on the ACTUAL frequency f, instead of being fixed at the the nominal f_0.
- For "adaptive PMUs", a better regime would be to test:
  - The ability of the algorith/filter/window to reject signals with($f_{IH} - f$) ≥ $F_S/2$.
  - Not the subtle difference between this and ($f_{IH} - f_0$) ≥ $F_S/2$.

$$\text{Fixed - filter stopband} \quad : \quad |f_{IH} - f_0| \geq \frac{F_S}{2} \qquad (30)$$

This matches exactly with the C37.118.1a OOB test, where the stopband is defined exactly as (30). C37.118.1a testing applies (30) but only varies fundamental frequency over a reduced range compared to the whole valid range ($f_0 \pm F_r$):

$$f \text{ range}: \quad \left(f_0 - \frac{F_S}{20}\right) \leq f \leq \left(f_0 + \frac{F_S}{20}\right) \qquad (31)$$

The actual C37.118.1a test applies the regime in (30) and (31).

C. Frequency-tracking algorithms

The effect and analysis of interharmonics within a frequency-tracking device is different. In such a device, $f_T = f$ if the algorithm is tracking correctly. Therefore, to define the required stopband from (28) and (29):

$$\text{Tracking stopband} \quad : \quad |f_{IH} - f| \geq \frac{F_S}{2} \qquad (33)$$

Notice that if the testing regime was changed to (33) for the frequency-tracking device, this 10% narrowing would no longer be required. Also, in that case, the full valid fundamental input frequency range ($f_0 \pm F_r$) (and potentially much wider) could be tested, using the same baseband filter design, and the same 0.01 Hz FE might still be attained, or nearly attained

A. J. Roscoe, B. Dickerson, and K. E. Martin, "The amended standard C37.118.1a and its implications for frequency-tracking M-class Phasor Measurement Units (PMUs)," in IEEE Applied Measurements for Power Systems (AMPS), Aachen, Germany, 2014.

Determining the required filter Mask for OOB testing

Frequency deviation

$$\frac{2\pi \cdot (f_{IH}-f) \cdot AF(f_{IH}-fT)}{2\pi \cdot (1-AF(f_{IH}-fT))}$$

Frequency deviation

$$\frac{\cancel{2\pi} \cdot (f_{IH}-f) \cdot AF(f_{IH}-fT)}{\cancel{2\pi} \cdot (\mathbf{1}\cancel{-AF(f_{IH}-fT)})}$$

$$F(f_{IH}-f_T) < \frac{FE_{max}}{A \cdot (f_{IH}-f)}$$

Minimum separation
of the interharmonic
from the tuned
(heterodyne) frequency.
Sets the width of the mask.

Maximum separation
of the interharmonic
from the
fundamental frequency, when
$(f_{IH}-f_T)$ is minimum,
sets the gain (attenuation)
Required at the “closest” mask point.

Out-of-Band testing, $f=f_0$
All algorithms

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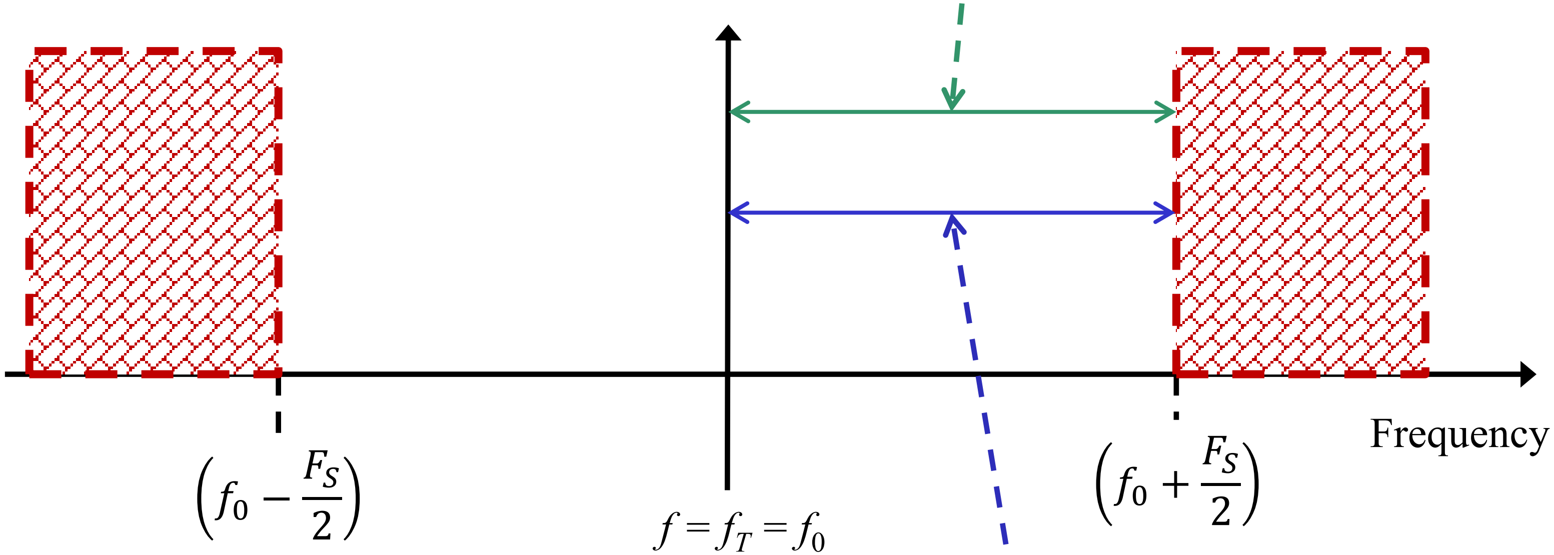
f_0 = Nominal frequency (Hz)
f = Actual fundamental frequency (Hz)
f_T = Tuned frequency (Hz)

Frequency in filter = $(f_{IH} - f_T)$

Minimum f_{IH} (upper) = $\left(f_0 + \frac{F_S}{2}\right)$

Minimum $(f_{IH} - f_T) = \left(f_0 + \frac{F_S}{2}\right) - f_0 = \left(\frac{F_S}{2}\right)$



Maximum $(f_{IH} - f) = \left(f_0 + \frac{F_S}{2}\right) - f_0 = \left(\frac{F_S}{2}\right)$

Mask width is "normal" $\left(\frac{F_S}{2}\right)$ and $(f_{IH} - f)$ tracks exactly with $(f_{IH} - f_T)$.

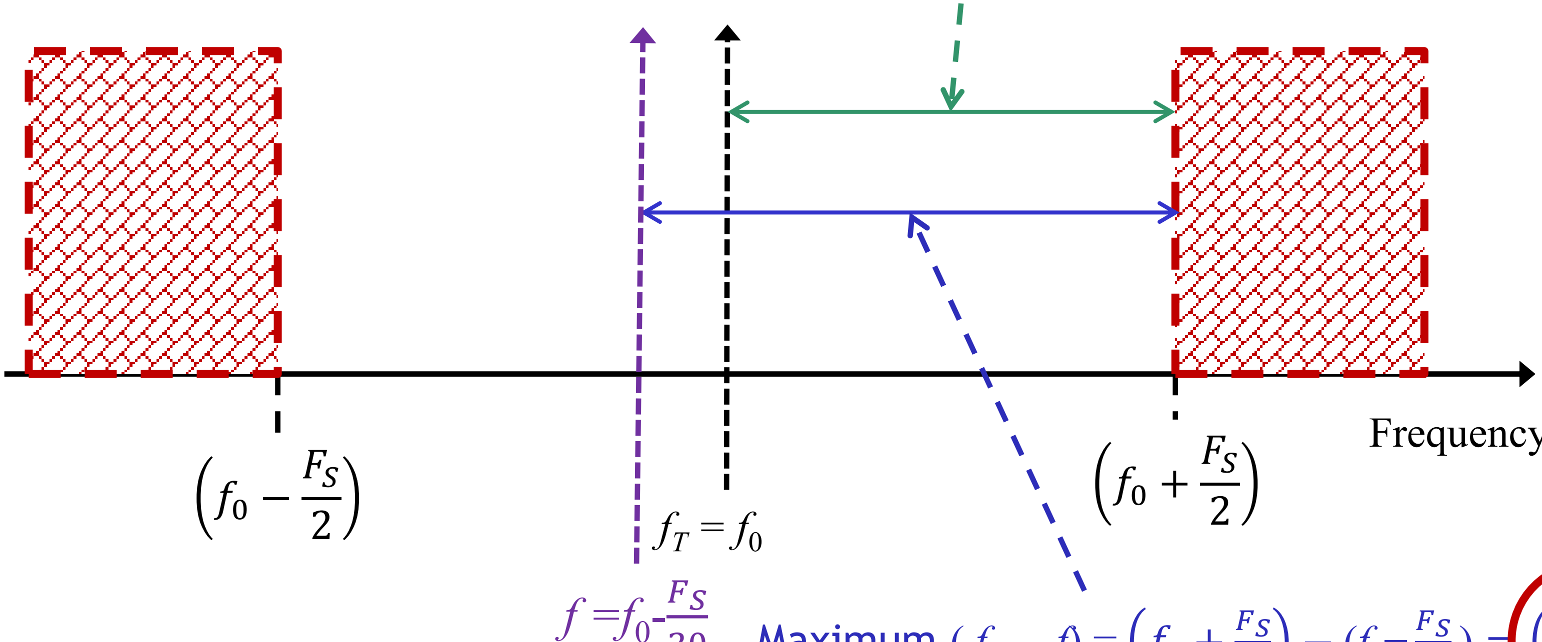
Out-of-Band testing, $f = f_0 - \frac{F_S}{20}$
Fixed-filter algorithm

f_0 = Nominal frequency (Hz)
f = Actual fundamental frequency (Hz)
f_T = Tuned frequency (Hz)

Frequency in filter = $(f_{IH} - f_T)$

Minimum f_{IH} (upper) = $\left(f_0 + \frac{F_S}{2}\right)$

Minimum $(f_{IH} - f_T) = \left(f_0 + \frac{F_S}{2}\right) - f_0 = \left(\frac{F_S}{2}\right)$



Maximum $(f_{IH} - f) = \left(f_0 + \frac{F_S}{2}\right) - \left(f_0 - \frac{F_S}{20}\right) = \left(1.1\frac{F_S}{2}\right)$

Mask width is "normal" $\left(\frac{F_S}{2}\right)$ but gain needs to be reduced by $20 \cdot \log\left(\frac{1}{1.1}\right)$ = 0.83 dB, at the closest frequency, from what you might expect.

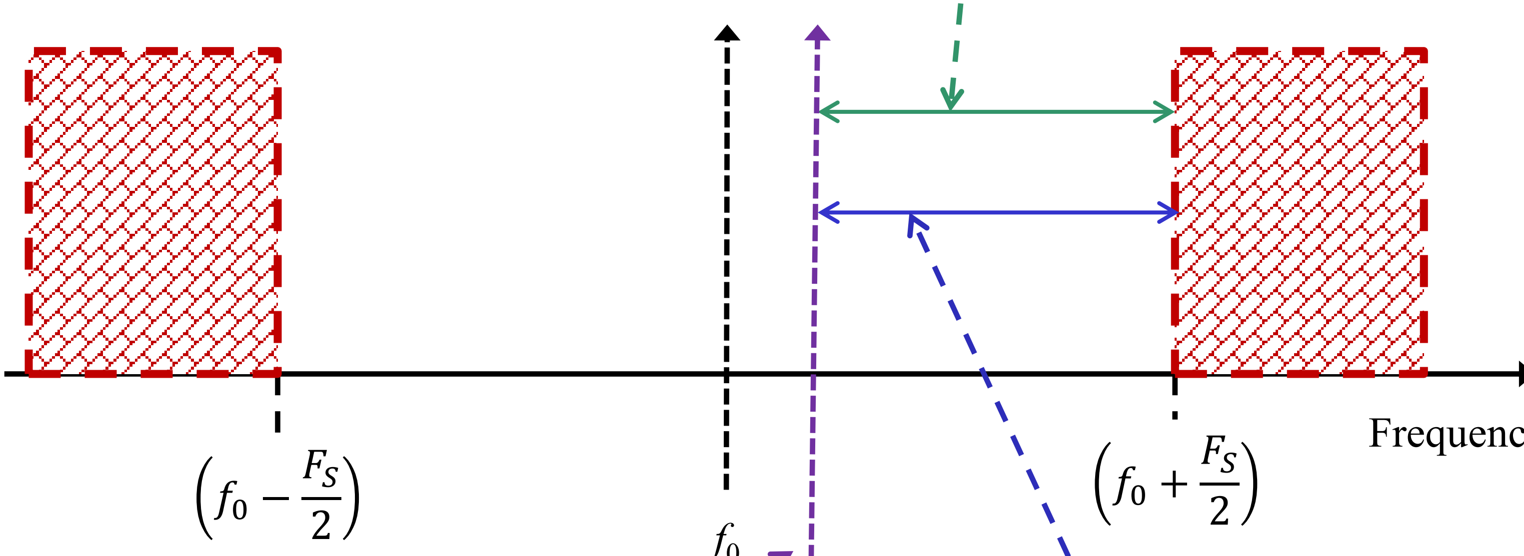
Out-of-Band testing, $f = f_0 + \frac{F_S}{20}$
Frequency-tracking algorithm

f_0 = Nominal frequency (Hz)
f = Actual fundamental frequency (Hz)
f_T = Tuned frequency (Hz)

Frequency in filter = $(f_{IH} - f_T)$

Minimum f_{IH} (upper) = $\left(f_0 + \frac{F_S}{2}\right)$

Minimum $(f_{IH} - f_T) = \left(f_0 + \frac{F_S}{2}\right) - \left(f_0 + \frac{F_S}{20}\right) = 0.9\left(\frac{F_S}{2}\right)$

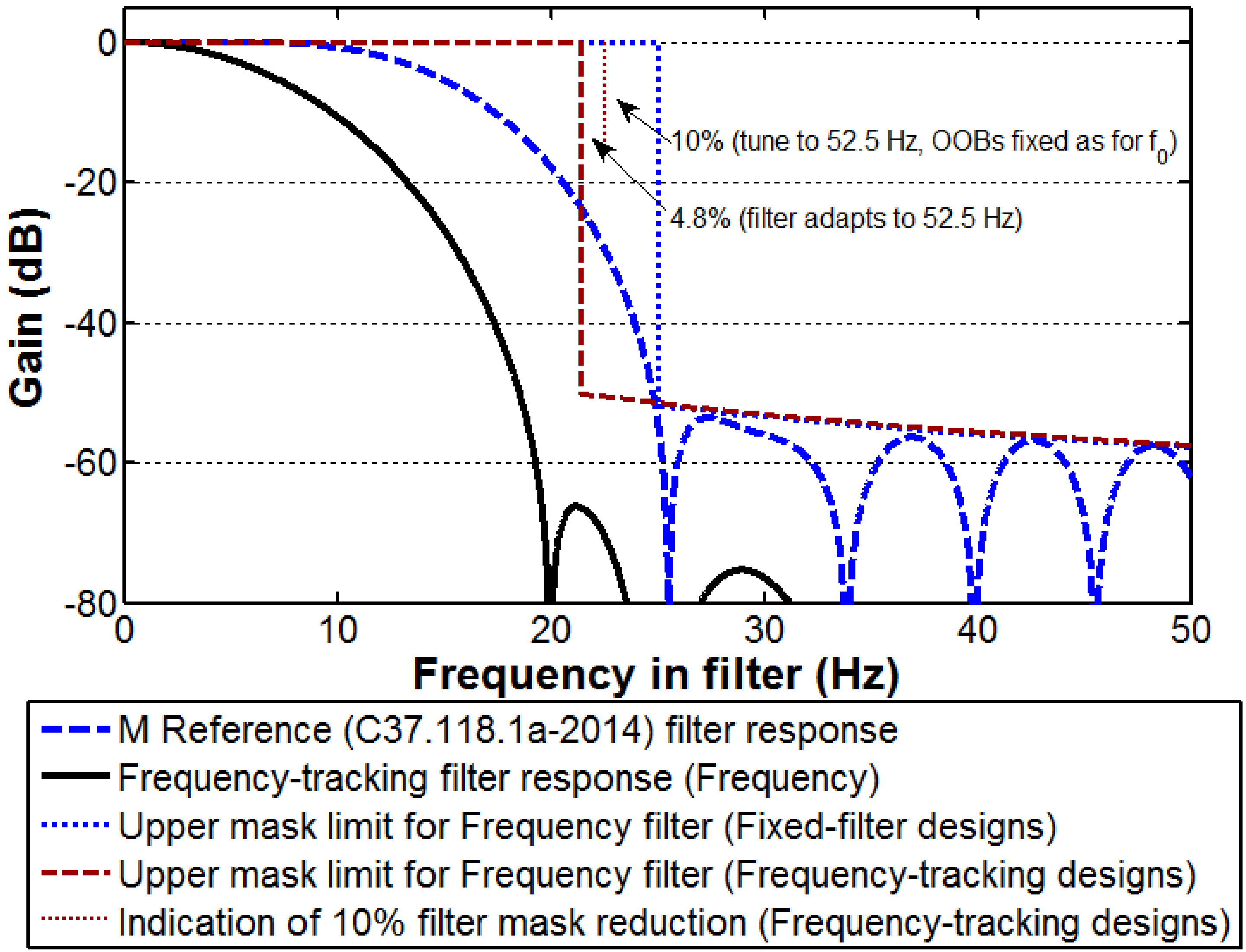


$f = f_T = f_0 + \frac{F_S}{20}$

Maximum $(f_{IH} - f) = \left(f_0 + \frac{F_S}{2}\right) - (f_0 + \frac{F_S}{20}) = \left(0.9\,\frac{F_S}{2}\right)$

Mask frequency width is reduced by 10% from $\left(\frac{F_S}{2}\right)$ but gain can be $20 \cdot log\left(\frac{1}{0.9}\right)$ = 0.92 dB higher, at the closest frequency, from what you might expect.

Simplified OOB requirements and examples, f_0=50 Hz, F_S=50 Hz



Simplified OOB requirements and examples, f_0=50 Hz, F_S=50 Hz

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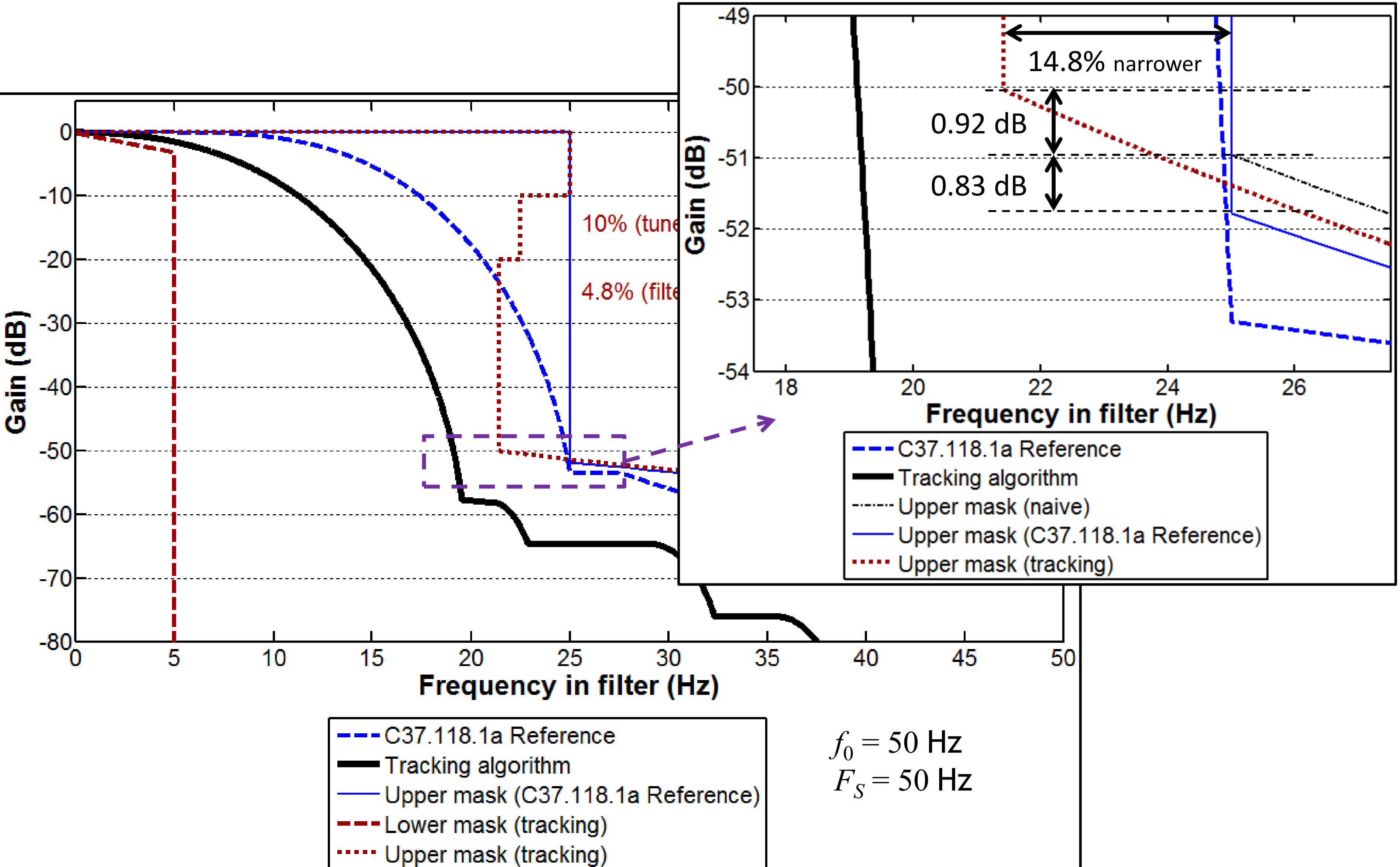
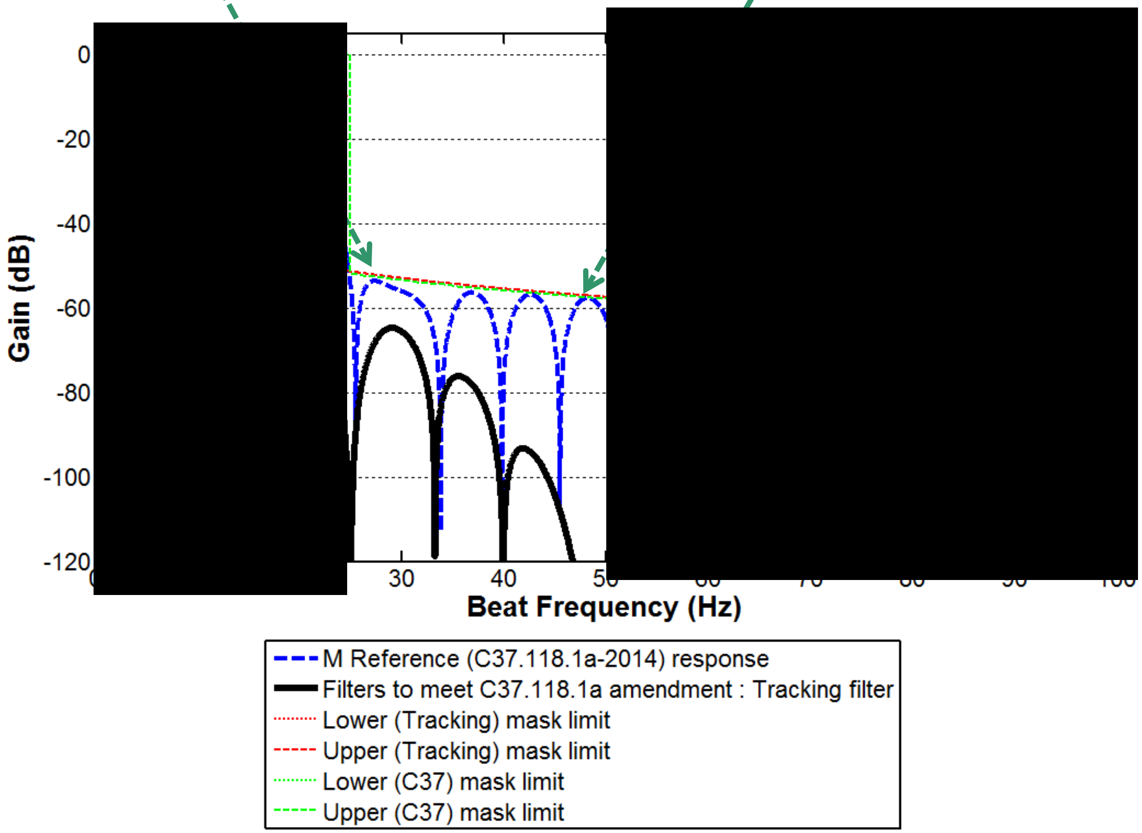


$f_0 = 50$ Hz
$F_S = 50$ Hz

Test 3 : Out of Band Examples with F_S=50 Hz

Closer points here, to check the edge of the stopband

Points further apart here, to save time



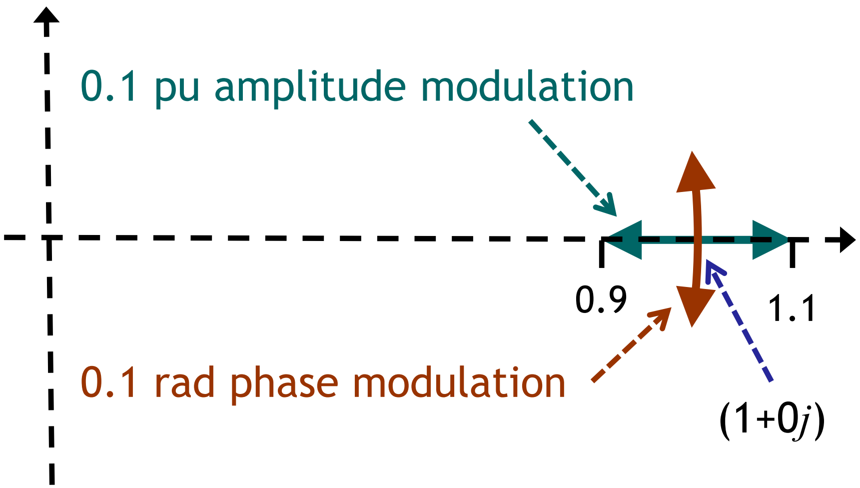
Test 4 : Modulation (bandwidth, passband flatness)

- The out of band test is really a test of the PASSBAND flatness.
- The PASSBAND for M class is defined as $F_{R=}F_S/5$ (F_S=reporting rate), but limited to a maximum value of 5 Hz.
- But, it is only 2 Hz for P class (this is not very useful – what happens at 47.5 Hz?!)

Table 5 —Synchrophasor measurement bandwidth requirements using modulated test signals

Modulation Level	Reference condition	Minimum range of influence quantity over which PMU must be within given TVE limit			
		Class P		Class M	
		Range	Max TVE	Range	Max TVE
$k_x = 0.1$, ~~$k_a = 0.1$~~ $k_a = 0$ radian	100% rated signal magnitude, $f_{nominal}$	Modulation frequency 0.1 to lesser of $F_s/10$ Hz or 2 Hz	3%	Modulation frequency 0.1 to lesser of $F_s/5$ Hz or 5 Hz	3%
$k_x = 0$ $k_a = 0.1$ radian	100% rated signal magnitude, $f_{nominal}$		3%		3%

The effect of modulation in the bandwidth test



$$V = \frac{M}{2}e^{j2\pi f_M t} + \frac{M}{2}e^{-j2\pi f_M t}$$

$$V_{Meas} = F(f_M)\frac{M}{2}e^{j2\pi f_M t} + F(-f_M)\frac{M}{2}e^{-j2\pi f_M t}$$

$$TVE = |V_{Meas} - V|$$

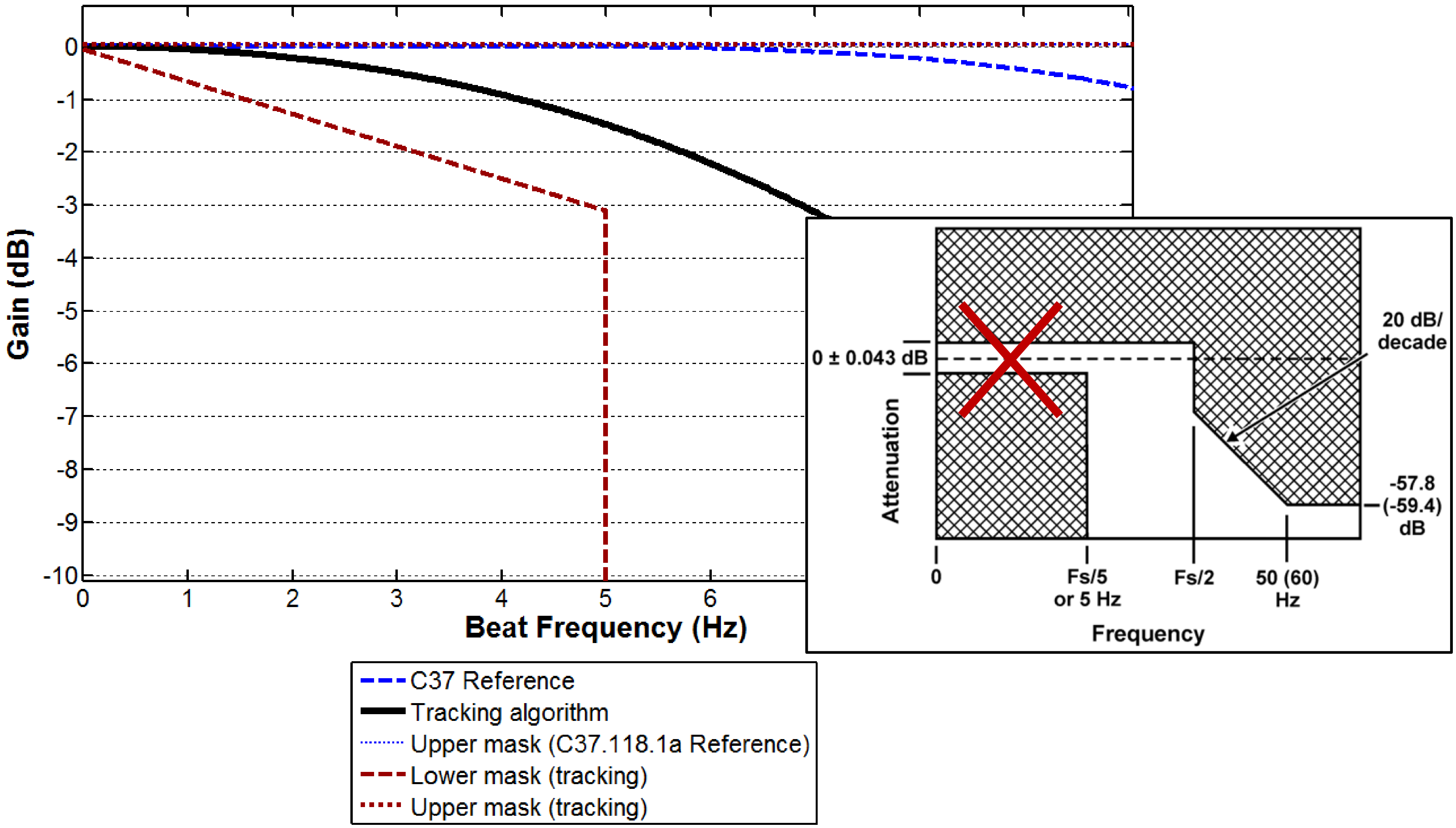
$$|F(f_M) - 1| < \frac{TVE_{Limit}}{M}$$

$$|F(f_M)| > 1 - \frac{0.03}{0.1}$$

$$|F(f_M)| > 0.7$$

$\boxed{F(f_M) > -3.098 \text{ dB}}$

Attenuation must be <3dB at passband edge
Example for M class 50 Hz reporting



Test 4 : Modulation (bandwidth, passband flatness)

- There are also limits for FE and RFE, but in general these will pass for most PMUs unless substantial post-filtering is applied to these (relative to the Phasor outputs).
- If the PMU applies post-filtering, or uses different filters/algorithms to determine FE and RFE, than were used to determine the phasors, then FE and RFE could still fail, even if TVE passes.

F & 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
10	1	0.03	0.6	2	0.12	2.3
12	1.2	0.04	0.8	2.4	0.14	3.3
15	1.5	0.05	1.3	3	0.18	5.1
20	2	0.06	2.3	4	0.24	9.0
25	2	0.06	2.3	5	0.30	14
30	2	0.06	2.3	5	0.30	14
50	2	0.06	2.3	5	0.30	14
60	2	0.06	2.3	5	0.30	14
Formulas	$\min(F_S/10,2)$	$0.03 * F_r$	$0.18*\pi*F_r$ 2	$\min(F_s/5,5)$	$0.06 * F_r$	$0.18*\pi*F_r^2$

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Test 4 : Modulation (bandwidth, passband flatness)

The test plan for measurement bandwidth is as follows:

a) Begin with amplitude modulated input at $\omega/2\pi = 0.1$ Hz, $k_x = 0.1$, $k_a = 0$.

b) Wait for the system to settle.

c) Capture the PMU output for at least 2 full cycles of modulation or 5 s, whichever is greater; allow for the settling period to elapse before changing the input signal.

d) Calculate the errors: ME, PE, FE, and RFE for each report.

e) Calculate the max TVE, FE, and RFE.

f) Increase the modulation frequency $\omega/2\pi$ by 0.2 Hz.

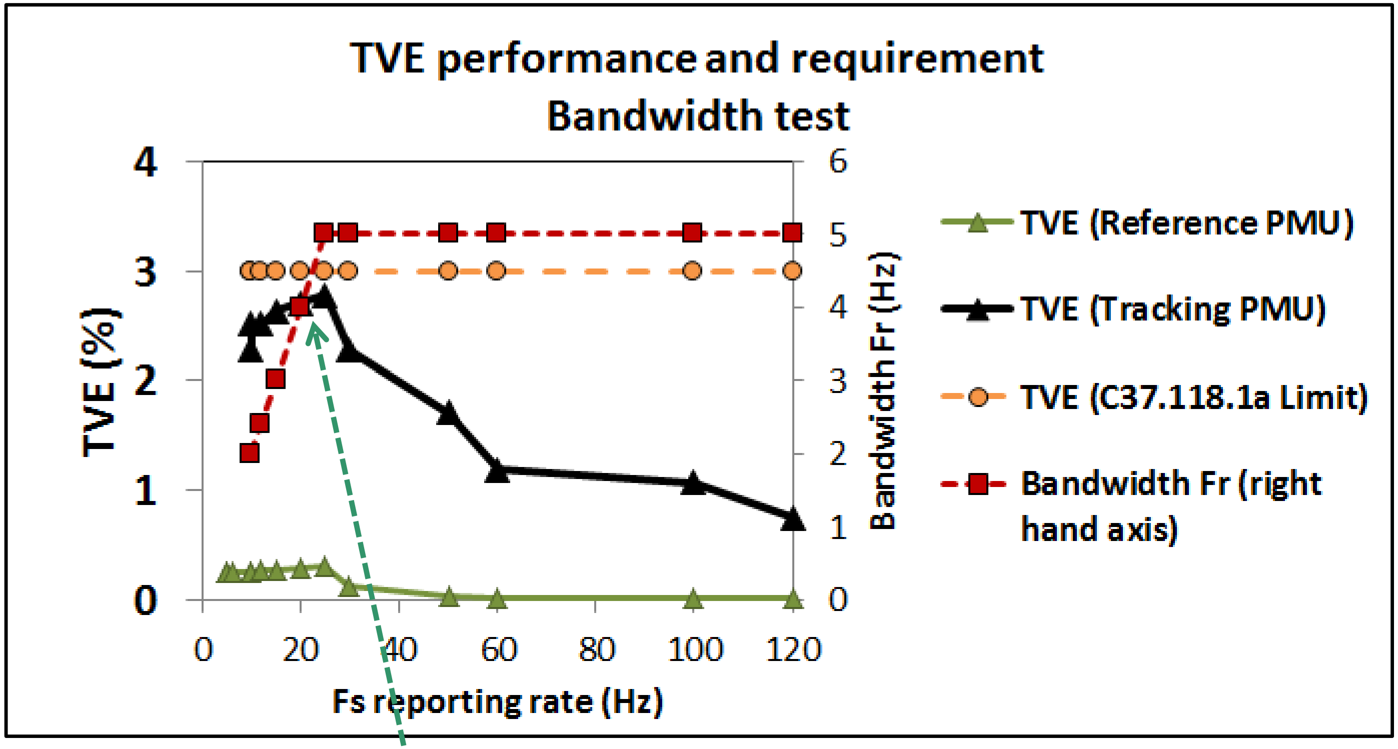
g) Repeat steps b) through f) until the upper frequency range limit is reached.

h) A test at the upper frequency range limit must be included despite the fact that the modulation frequency increment is 0.2 Hz.

i) Compare the results to the class limits in the amended Table 5 and Table 6 in IEEE Std C37.118.1a-2014.

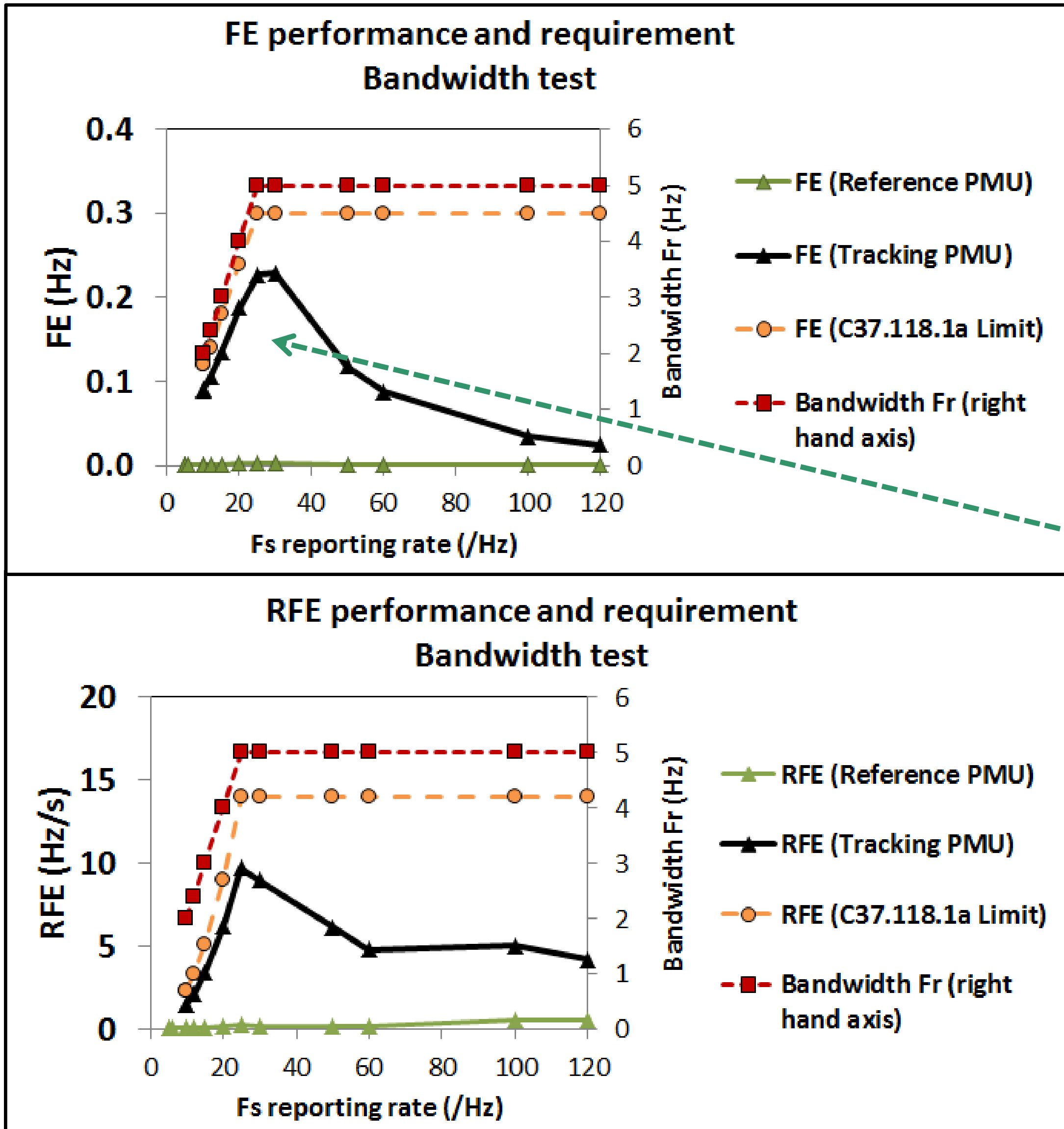
j) Repeat the entire test for phase modulation only: $k_x = 0$, $k_a = 0.1$.

Bandwidth test example – M class TVE



- If you have a PMU to test, the hardest PMU to make is:
  - For f_0=50 Hz, the M class device which reports at F_S=25 Hz
  - For f_0=60 Hz, the M class device which reports at F_S=60 Hz
- This is because the PMU bandwidth required is a full ±5 Hz, but the stopband (OOB test) will test the stopband starting at F_S/2=25/2=12.5 Hz
- This is only a 2.5:1 ratio.
  - For f_0=50 Hz, F_S=50 Hz, ratio = (50/2)/5 = 5:1
  - For f_0=50 Hz, F_S=25 Hz, ratio = (25/2)/5 = 2.5:1 But this is slightly harder than F_S=10 because the bandwidth is bigger.
  - For f_0=50 Hz, F_S=10 Hz, ratio = (10/2)/2 = 2.5:1

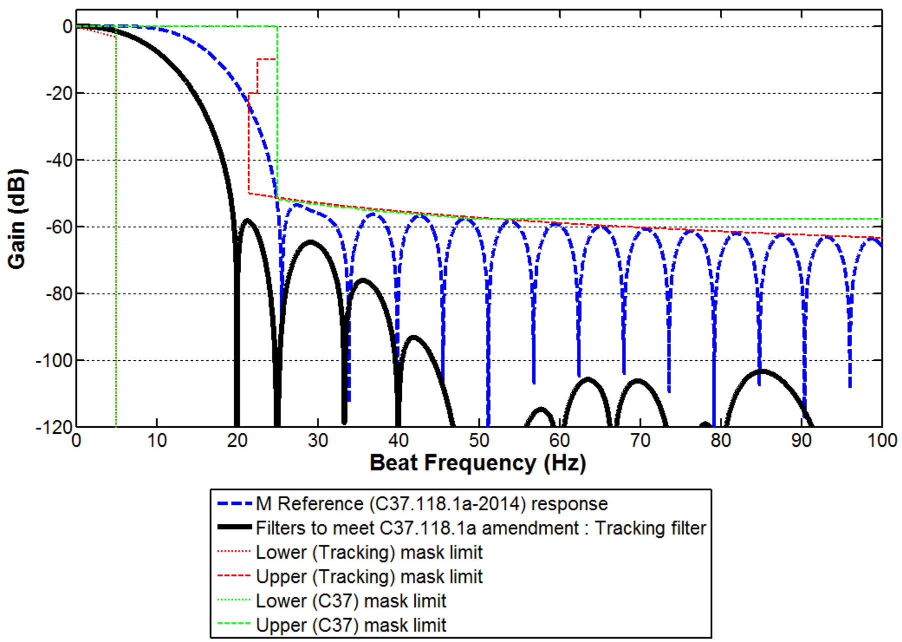
Bandwidth test example – M class
Frequency Error (FE) & ROCOF ERROR (RFE)



The low reporting rate devices are much harder to make compliant. Reporting rate 50 Hz is much easier.

OOB vs Bandwidth

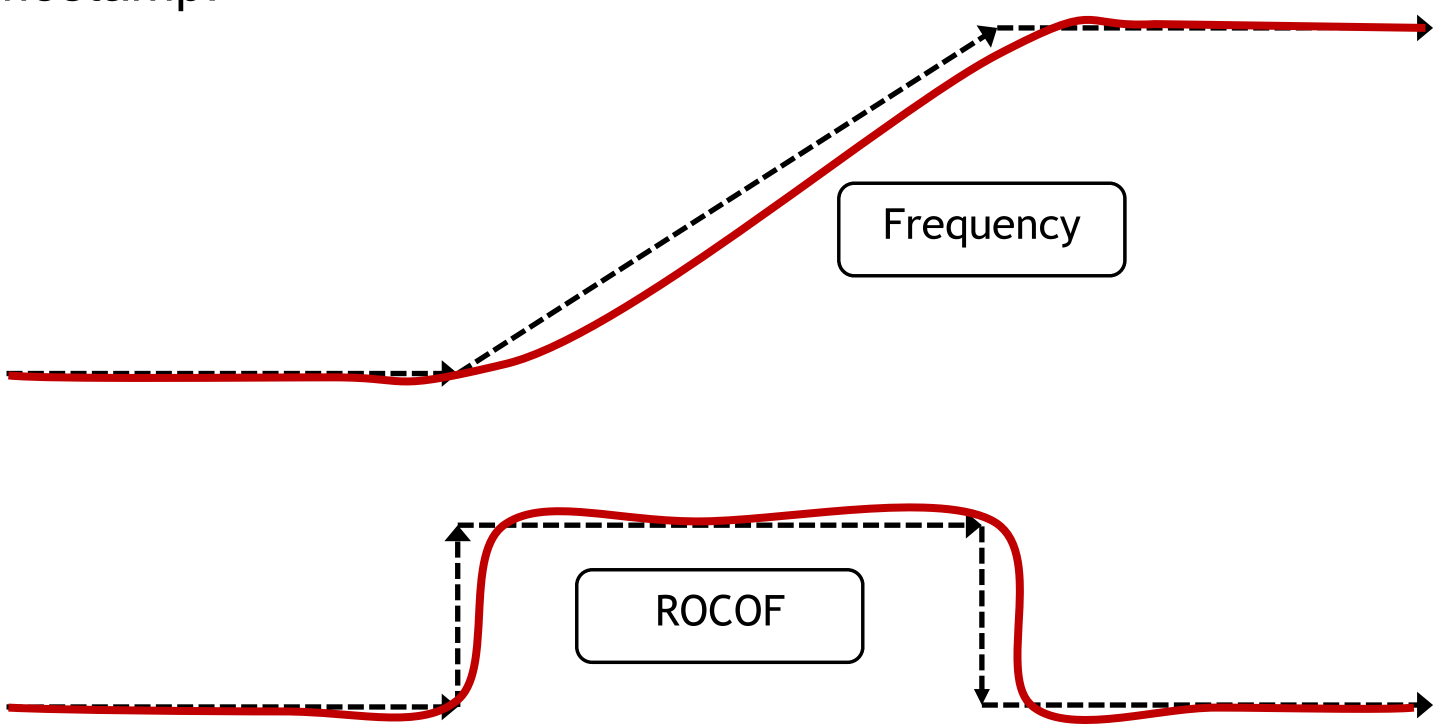
- The Bandwidth and OOB tests check passband flatness and stopband attenuation. The general frequency-domain shape of the filter response is tested against the “mask”.



- If these tests both pass, it is likely the PMU will also pass the response-time tests.

Test 5 : Frequency ramp

- In general, a PMU which passes the previous tests OUGHT to pass the Frequency ramp test.
- BUT, the frequency ramp test can catch out PMUs which apply excessive post-filtering to frequency or ROCOF outputs, especially if these are not carefully implemented with corrections for the timestamp.



Test 5 : Frequency ramp

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Table 7—Synchrophasor performance requirements under frequency ramp tests

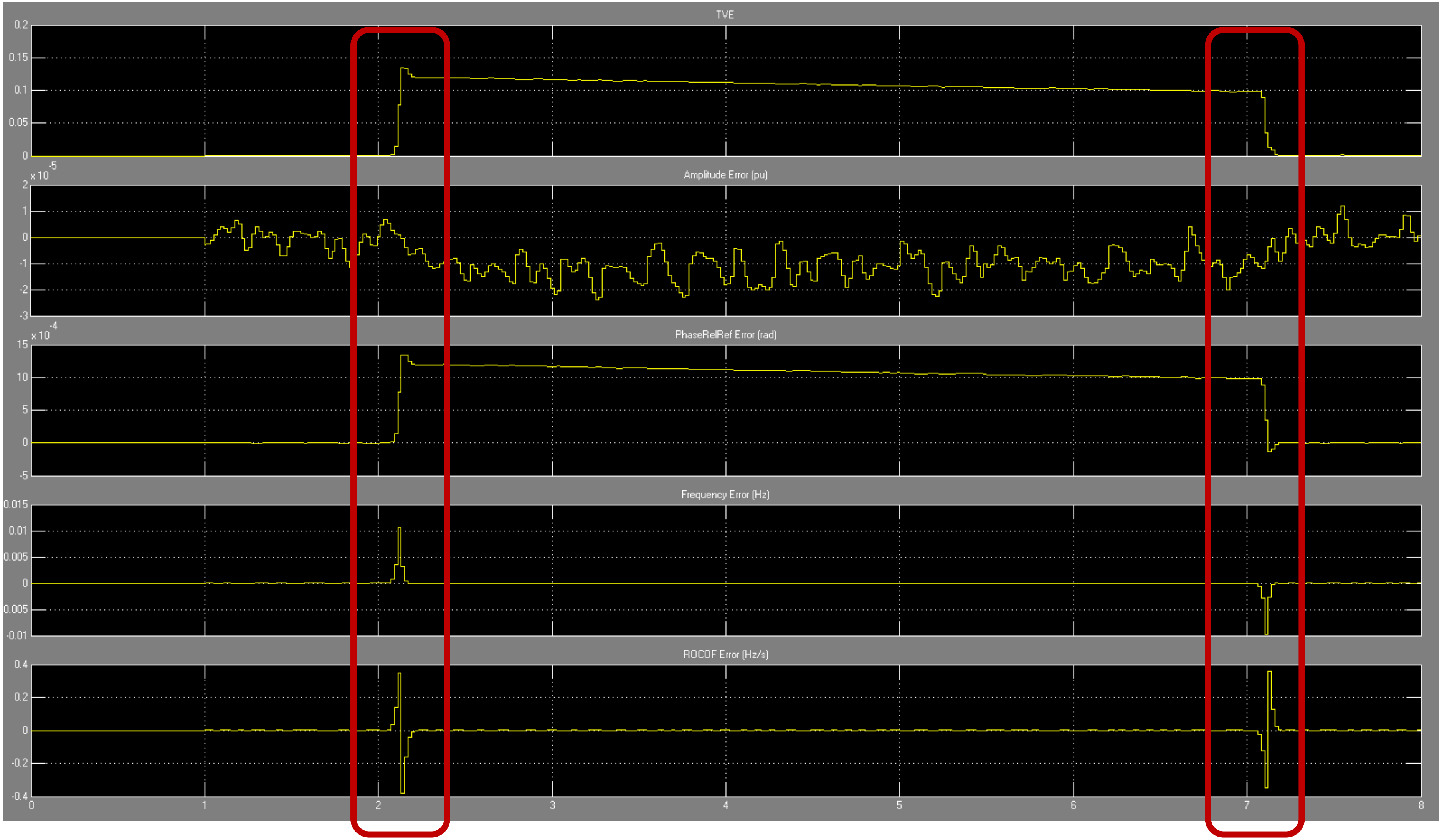
Test signal	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit does not include the exclusion interval multiplied by the ramp rate				
		Ramp rate (R_f) (positive and negative ramp)	Performance class	Exclusion interval	Ramp range	Max TVE
Linear frequency ramp	100% rated signal magnitude, and $f_{nominal}$ at a non-excluded point during the test	± 1.0 Hz/s	Class P	2/Fs	± 2 Hz	1%
			Class M	7/Fs	Lesser of ± (F_s /5) Hz or ± 5 Hz[a]	1%

[a]For F_s = 12 fps, ramp range shall be ±2 1/3 (two and one-third) Hz to allow for an integer number of samples in the result.

Table 8 —Frequency and ROCOF performance requirements under frequency ramp tests

Signal specification	Reference condition	~~Transition time~~ Exclusion interval	Error requirements for compliance			
			P class		M class	
			Max FE	Max RFE	Max FE	Max RFE
Ramp tests—same as specified in Table 7	100% rated signal magnitude and 0 radian base angle	~~± 2/F_s for the start and end of ramp~~ Same as specified in Table 7	0.01 Hz	~~0.1 Hz/s~~ 0.4 ~~2~~ Hz/s	~~0.005 Hz~~ 0.01 Hz	~~0.1 Hz/s~~ 0.2 Hz/s

Test 5 : Frequency ramp example
M Class 50 Hz reporting rate

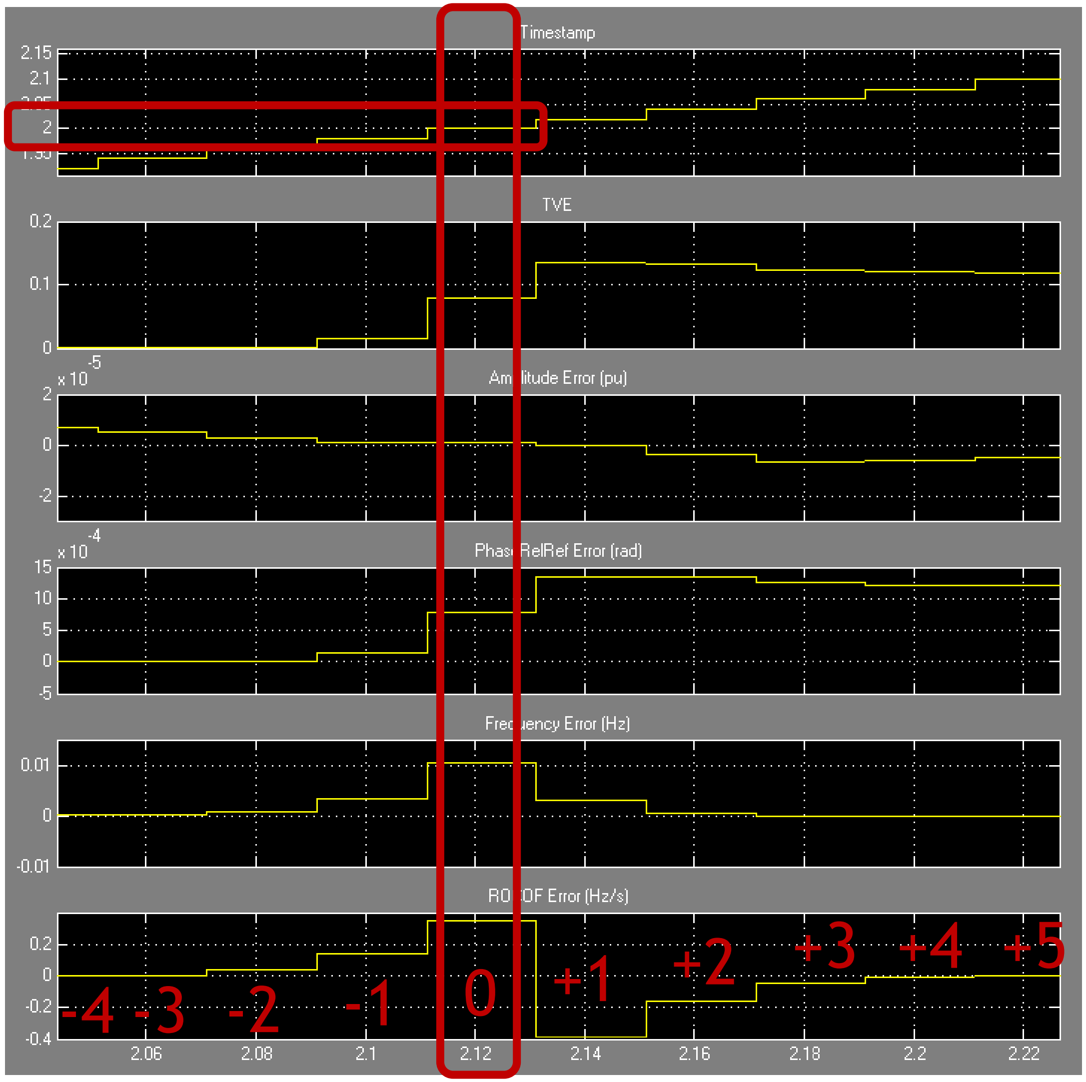


Test 5 : Frequency ramp example M Class 50 Hz reporting rate

In this example, the ramp starts at t=2.000s.

The reports with TIMESTAMPS around 2.000s are perturbed by the step in ROCOF.

In this example, 3-4 reports either side of the step time contain “non–ideal” data.



Test 5 : Frequency ramp example
M Class 50 Hz reporting rate

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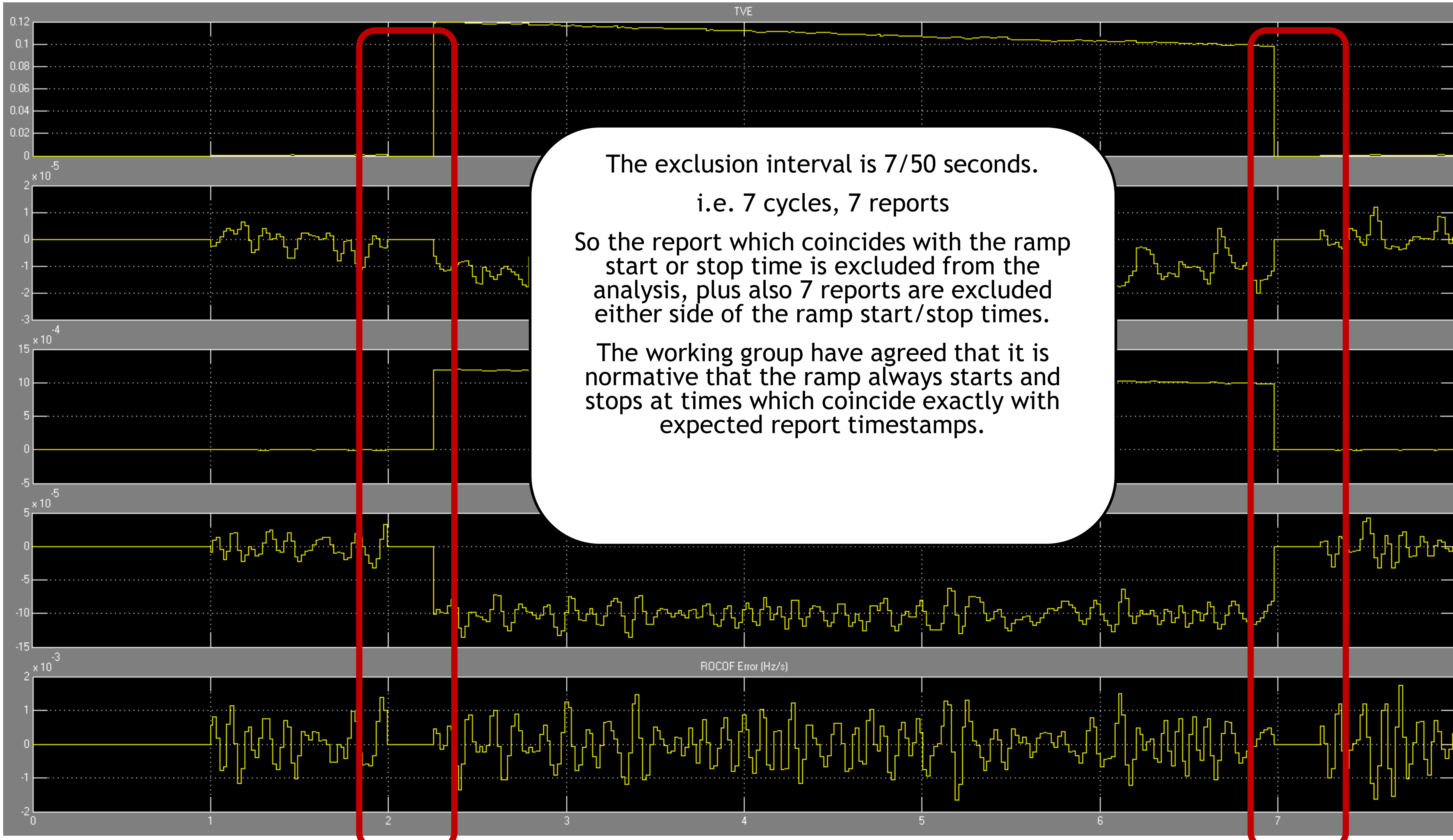

The exclusion interval is 7/50 seconds.

i.e. 7 cycles, 7 reports

So the report which coincides with the ramp start or stop time is excluded from the analysis, plus also 7 reports are excluded either side of the ramp start/stop times.

The working group have agreed that it is normative that the ramp always starts and stops at times which coincide exactly with expected report timestamps.

Test 5 : Frequency ramp - Exclusion interval

Last Month

Ken Martin	08/05/2015
Received: Fri 08/05/2015 08:02 Size: 2 MB Categories: ... time - URGENT	07/05/2015
Goldstein, Allen R. — Re: Ramp test issue: What do we all agree on?	07/05/2015
Ken Martin — RE: Ramp test issue: What do we all agree on?	07/05/2015
Brunello, Gustavo (GE Energy Management) — RE: Ramp test issue: Transition time - URGENT	07/05/20...
Goldstein, Allen R. — RE: Ramp test issue: What do we all agree on?	06/05/2015
Goldstein, Allen R. — RE: Ramp test issue: Transition time - URGENT	06/05/2015
Bill Dickerson — Re: Ramp test issue: What do we all agree on?	06/05/2015
Dan_Dwyer@selinc.com — RE: Ramp test issue: What do we all agree on?	06/05/2015
Ken Martin — RE: Ramp test issue: What do we all agree on?	06/05/2015
Dan_Dwyer@selinc.com — RE: Ramp test issue: What do we all agree on?	06/05/2015
Ken Martin — RE: Ramp test issue: What do we all agree on?	06/05/2015
Goldstein, Allen R. — RE: Ramp test issue: Transition time - URGENT	06/05/2015
Goldstein, Allen R. — RE: Ramp test issue: Transition time - URGENT	06/05/2015
Goldstein, Allen R. — RE: Ramp test issue: What do we all agree on?	06/05/2015
Ken Martin — RE: Ramp test issue: What do we all agree on?	06/05/2015
Ken Martin — RE: Ramp test issue: What do we all agree on?	06/05/2015
Bill Dickerson — Re: Ramp test issue: What do we all agree on?	06/05/2015
Dan_Dwyer@selinc.com — RE: Ramp test issue: What do we all agree on?	06/05/2015
Goldstein, Allen R. — RE: Ramp test issue: What do we all agree on?	06/05/2015
Goldstein, Allen R. — RE: Ramp test issue: What do we all agree on?	05/05/2015
Bill Dickerson — RE: Ramp test issue: What do we all agree on?	05/05/2015
Ken Martin — RE: Ramp test issue: What do we all agree on?	05/05/2015
Goldstein, Allen R.	05/05/2015

Fumio Kawano; Gabriel_Benmouyal@selinc.com; Galina Antonova; Geoff Ives; Stenbakken, Gerard N.;

Dear All:

The sub-group that agreed on the 7 key points from my email of May 6th, has now also agreed (with one abstention) that there is a set of normative requirements that define which reports are to be excluded when the ramp leaves and reaches the frequency range limits coincident to a report. In this case, N reports AFTER the report coincident with the signal leaving the range limit shall be excluded where N is 7 for M class and 2 for P class.

From c37.118.1a-2014 clause 5.5.7

The exclusion interval is the time interval after the ramp leaves or before the ramp reaches a frequency range limit or a point where ROCOF changes. (point 4)

Measurements made during an exclusion interval shall not be used when determining measurement compliance. (point 3)

We all agreed that the exclusion interval is a fixed period of time N/Fs (point 4). If the ramp begins coincident with a report, the exclusion interval begins AFTER that report and ends AFTER N reports later. If it the ramp ends coincident to a report, the exclusion interval ends BEFORE that report and begins BEFORE a report N reports earlier.

This should resolve the original issue with ICAP testing and testing and certification should now be able to proceed using the above interpretation.

The example from C37.118.1a-2014 (quoted in the email below with **) is agreed upon but the sub group to be ambiguous and may conflict with the above interpretation. However, the IEEE SA style manual states that examples cannot be normative and there may be no normative requirements stated in an example.

Cordially,
Allen Goldstein, NIST
(301) 975-2101 office/lab
(206) 276-7347 cell
allen.goldstein@nist.gov

From: Goldstein, Allen R.
Sent: Wednesday, May 6, 2015 9:24 AM
To: Bill Dickerson; Ravi Subramaniam
Cc: Veselin_Skendzic@selinc.com; Kirkham, Harold; Ashish Kulshrestha; Jose Eduardo Alves; Andrew Roscoe; Tianshu Bi (gml); Brian Kirby; Sunita Chohan; Chris Huntley; Dalibor

Allen Goldstein

Test 5 : Frequency ramp - Exclusion interval

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The ramp test frequency range, ramp rate, measurement exclusion interval, and measurement error limits for each class are shown in Table 7 and Table 8. The frequency range is the same as that specified in the steady-state frequency test, Table 3. Measurements made during an exclusion interval shall not be used when determining measurement compliance. The exclusion interval is the time interval after the ramp leaves or before the ramp reaches a frequency range limit or a point where ROCOF changes. This exclusion is provided to prevent measurement errors caused by signals where the frequency is outside of the filter pass band or which include the PMU's response to ROCOF changes. Both positive and negative ramps are required. The ramps shall start and end at the ramp range limits specified in Table 7.

The exclusion interval is based on the time window over which the phasor is estimated. Since the ramp is linear, the time exclusion interval corresponds directly to a frequency interval. The frequency interval $F_{exclusion}$ can be calculated:

$$F_{exclusion} = R_f \times n/F_s$$

where:

n	is 2 (P class) or 7 (M class)
R_f	is the ramp rate
F_s	is the reporting rate

For the given ramp rate R_f = 1 Hz/s, $F_{exclusion}$ = n/F_s (as shown in Table 7).

As an example, consider a case with a system frequency of 60 Hz, reporting rate F_s = 30 fps and the given 1 Hz/s ramp rate. For P class, the frequency range is ±2 Hz and the exclusion interval is $2/F_s$ = 0.067 s, so $F_{exclusion}$ = 0.067 Hz. The positive ramp test must start at 58 Hz and ramp up to 62 Hz. Measurements below 58.067 Hz and above 61.933 Hz will be excluded. The negative ramp test must start at 62 Hz and ramp down to 58 Hz, excluding the same frequencies from the evaluation. For M class, the principle is the same except the exclusion interval is 7/30 = 0.233 s, $F_{exclusion}$ = 0.233 Hz, and the test frequency limits are ±5 Hz. The positive ramp must start at 55 Hz and ramp up to 65 Hz. Measurements below 55.233 Hz, and above 64.777 Hz, will be excluded. The negative ramp test must start at 65 Hz and ramp to 55 Hz with the evaluation excluding measurements above 64.777 Hz and below 55.233 Hz.

~~The points at the exact EDGE of the exclusion interval should be assumed to be INCLUDED, NOT excluded.~~

The formulas for computing the phasor, frequency, and ROCOF values are based on an integer time step that only works when the ramp starts at nominal and with the count n=0 when the ramp starts … time must be t=0 when the ramp is at the nominal frequency. This is not stated. That further requires a report at that point since there is always a report at the second rollover which also means there will be a report at the limit since the limits are at integer frequencies (except 12 fps). I think that is your argument that the ramp has to start at a report time.

I think this is explicitly normative. Special consideration is even given in Table 7 for Fs=12 to satisfy this normative requirement.

Dan Dwyer, Ken Martin : 6th May 2015

i.e. the ramp should start and end **exactly** on a valid report time.

We all agreed that the exclusion interval is a fixed period of time N/Fs (point 4). If the ramp begins coincident with a report, the exclusion interval begins AFTER that report and ends AFTER N reports later. If it the ramp ends coincident to a report, the exclusion interval ends BEFORE that report and begins BEFORE a report N reports earlier.

This should resolve the original issue with ICAP testing and testing and certification should now be able to proceed using the above interpretation.

Allen Goldstein: 7th May 2015

Test 5 : Frequency ramp

The test plan for ramp of system frequency is as follows:

a) Begin with input at nominal magnitude and lower frequency range.

b) Wait for the system to settle.

c) Begin ramping the frequency with a positive ramp rate of 1 Hz/s, ramp until the upper frequency range is reached and hold at that frequency for at least the settling period.

d) Calculate the errors: ME, PE, FE, and RFE for each report.

e) Calculate the max TVE, FE, and RFE excluding data during the exclusion intervals as required by the standard.

f) Hold the frequency constant for at least the settling period, and then begin ramping the frequency at the negative ramp rate.

g) Calculate the max TVE, FE, and RFE excluding data during the exclusion intervals as required by the standard.

h) Compare the results to the class limits in IEEE Std C37.118.1-2011 and IEEE Std C37.118.1a-2014.

Note that the positive and negative ramps are not required to be contiguous as shown in step f). As long as the settling period is observed both before and after the frequency ramp, the signal may or may not be removed from the PMU between the frequency ramps.

Test 5 : Frequency ramp Limitations

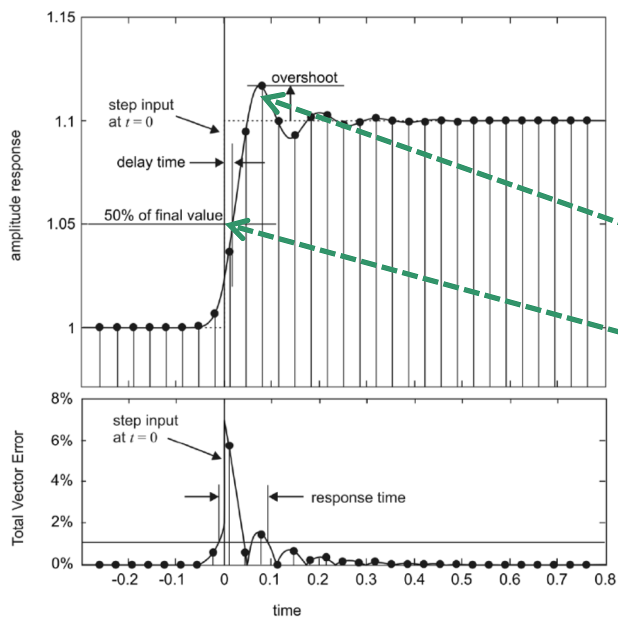
- It should ideally test for phasor phases not corrected for ROCOF (as the phase profile across the measurement window is parabolic, the waveform is a “chirp”), but the TVE limit is too large to detect this. For metrological units, a much tighter TVE limit could (and should?) be applied in this test.

- The C37.118.1a Reference PMU TVE is 0.05-0.5% during this test.
- It is possible to achieve significantly better results (<0.01%) if the PMU contains the appropriate corrections to apply during ROCOF events.

- There is no consideration of non-linear frequency ramps.

Test 6 : Dynamic step test

- The step test applies amplitude and phase steps.
  - The undershoot and overshoot tests evaluate the window shapes. Failures will occur if the windows contain a high proportion of negative weights.



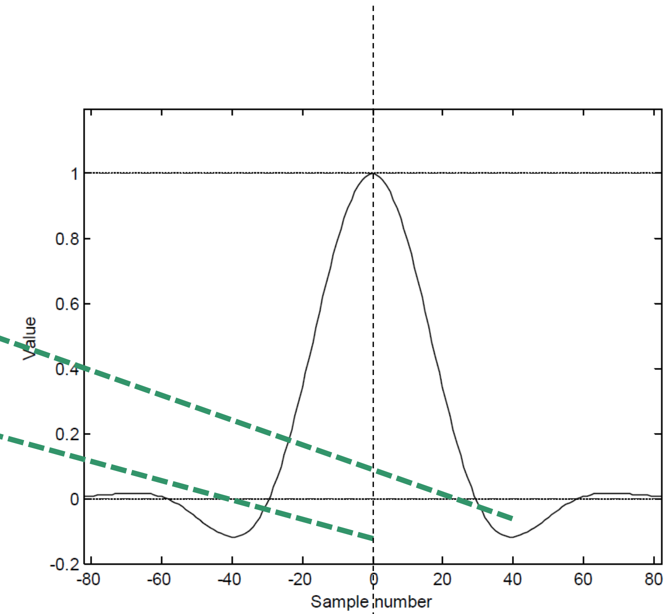
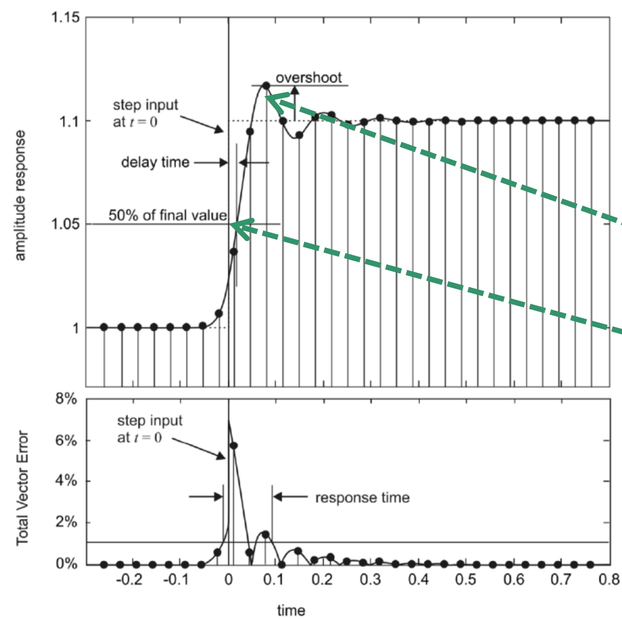


Figure C.6—M class filter coefficient example (F_s = 60 fps, $F_{sampling}$ = 960 Hz, N = 164

  - The delay parameter tests that the window is correctly centred and symmetric about the timestamp issued with the report
    - » Or it could be asymmetric but correctly calibrated/corrected

Test 6 : Dynamic step test - undershoot, overshoot, delay

- The step test applies amplitude and phase steps.
  - The undershoot and overshoot tests evaluate the window shapes. Failures will occur if the windows contain a high proportion of negative weights.



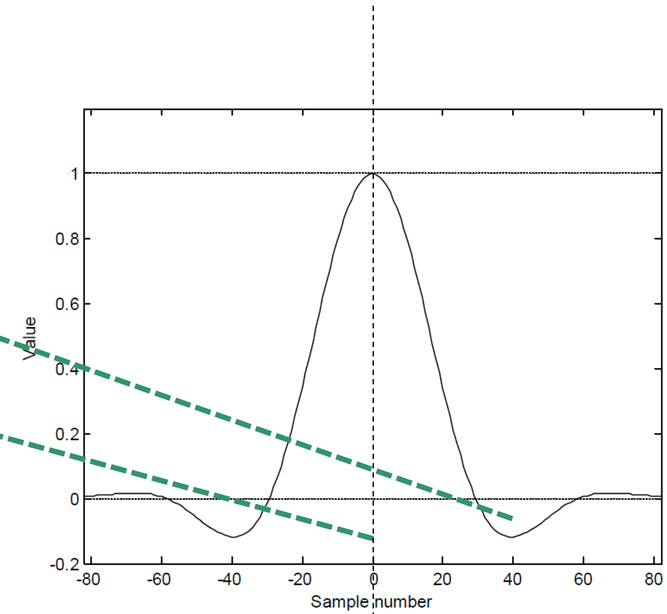


Figure C.6—M class filter coefficient example (F_s = 60 fps, $F_{sampling}$ = 960 Hz, N = 164

  - The delay parameter tests that the window is correctly centred and symmetric about the timestamp issued with the report
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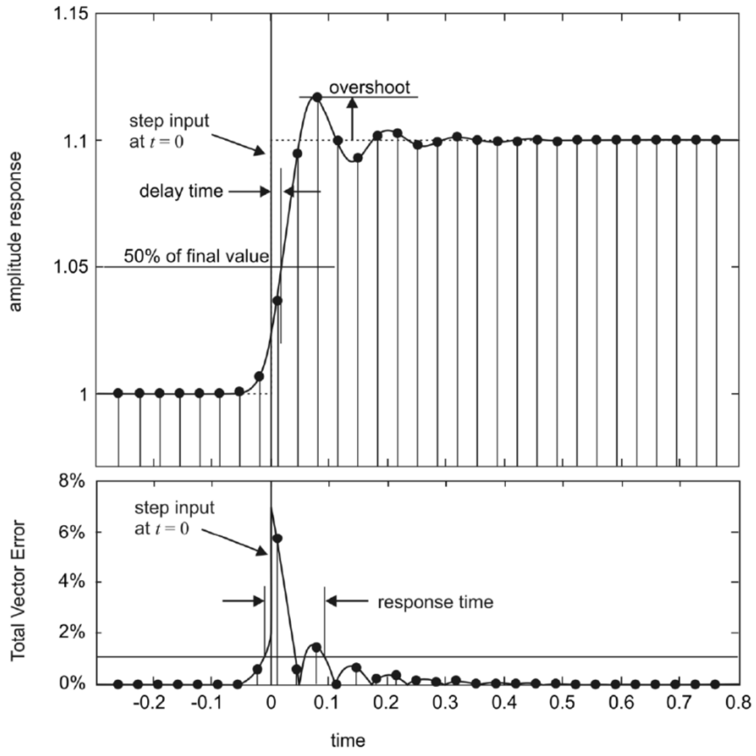
Test 6 : Dynamic step test – response



- Response can fail if:
  - The filter window is too long in the time domain
  - Too much post processing is applied to frequency and/or ROCOF outputs
  - The steady-state measurements are too close to the TVE, FE and RFE limits in the first place.

Test 6 : Dynamic step test – limits

Table 9—Phasor performance requirements for input step change

Step change specification	Reference condition	Maximum response time, delay time, and overshoot					
		Class P			Class M		
		Response time (s)	|Delay time (s)|	Max Overshoot /undershoot	Response time (s)	|Delay time (s)|	Max Overshoot /undershoot
Magnitude = ± 10%, $k_x = \pm 0.1$, $k_a = 0$	All test conditions nominal at start or end of step	2 ~~1.7~~/f_0	$1/(4 \bullet F_s)$	5% of step magnitude	~~See table 11~~ 7/F_s	$1/(4 \bullet F_s)$	10% of step magnitude
Angle ± 10°, $k_x = 0$, $k_a = \pm \pi/18$	All test conditions nominal at start or end of step	2 ~~1.7~~/f_0	$1/(4 \bullet F_s)$	5% of step magnitude	~~See table 11~~ 7/F_s	$1/(4 \bullet F_s)$	10% of step magnitude

Table 10—Frequency and ROCOF performance requirements for input step change

Signal specification	Reference condition	Maximum response time			
		Class P		Class M	
		Frequency	ROCOF	Frequency	ROCOF
		Response time (s)	Response time (s)	Response time (s)	Response time (s)
Magnitude test as in Table 9	Same as in Table 9	~~3~~4.5/f_0	4 6/f_0	~~See table 11~~ Greater of 14/F_s or 14/F_0	~~See table 11~~ Greater of 14/F_s or 14/F_0
Phase test as in Table 9	Same as in Table 9	~~3~~4.5/f_0	4 6/f_0	~~See table 11~~ Greater of 14/F_s or 14/F_0	~~See table 11~~ Greater of 14/F_s or 14/F_0

EDITOR's NOTE—Class P ROCOF changed from 4 to 6 in Table 10 (strike through not clear).

Test 6 : Dynamic step test – under/overshoot definitions

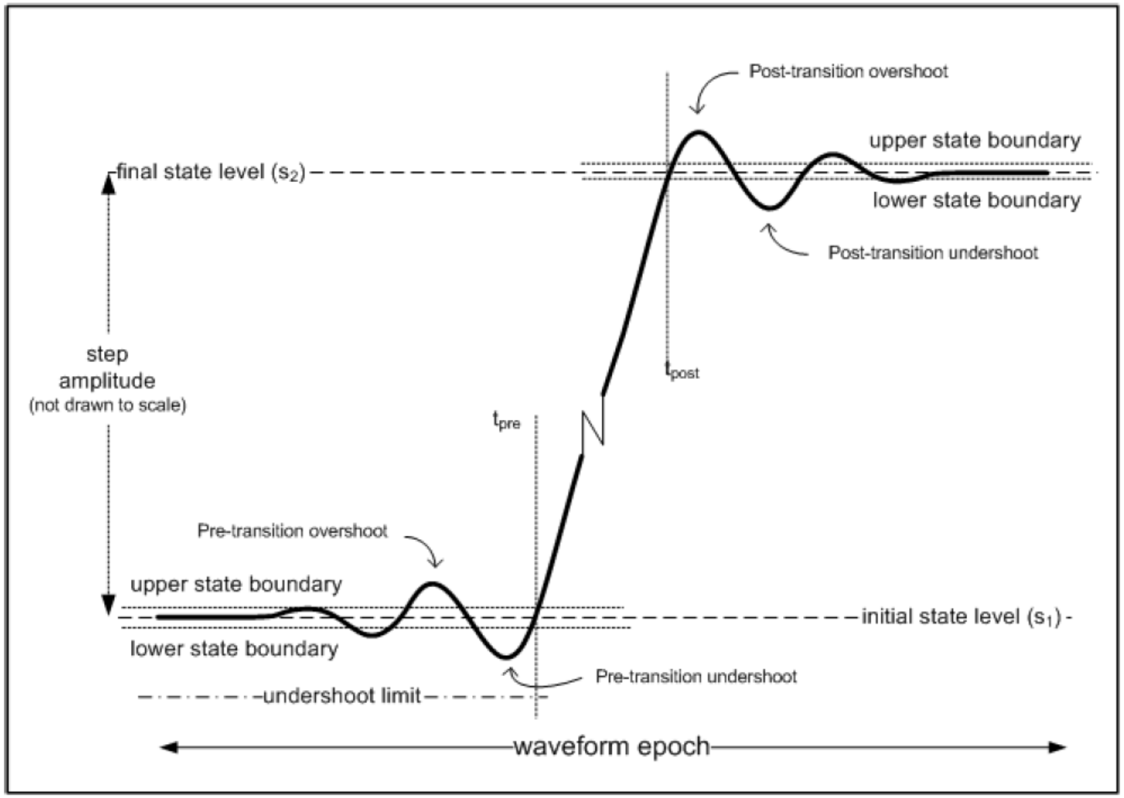


Figure 3 —Step transition example

Look in the Test Suite Specification!

Lots of information, specifying undershoot, overshoot, etc.

IEEE, ISBN 978-0-7381-9360-1: 'IEEE Synchrophasor Measurement Test Suite Specification', 2014

Test 6 : Dynamic step test – Test Plan – equivalent time sampling

The test plan for step change in phase and magnitude is as follows:

a) For the first test, let n = 0.

b) Begin with three-phase balanced input at nominal amplitude and frequency. Hold steady state for at least the greater of 1 s plus two response time periods or the settling period.

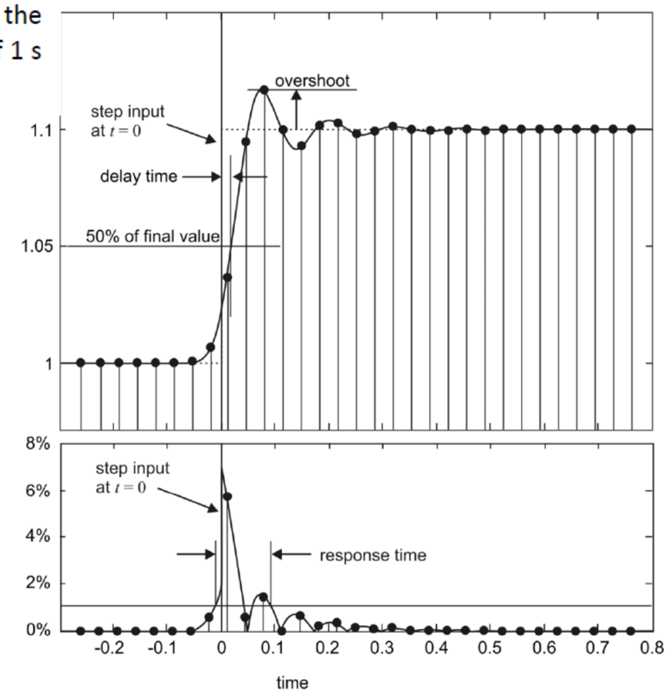
c) At the beginning of a reporting cycle plus $n/(10 \times F_s)$ (i.e., n × reporting period/10) step the magnitude by +10% of the nominal magnitude and hold steady state for at least the greater of 1 s plus two response time periods or the settling period.

d) Gather the PMU data, return the influence quantity to nominal, and wait for at least the greater of 1 s plus two response time periods or the settling period.

e) Increment n by one (n = n + 1), then repeat step c) through step d) until n = 10 – 1.

f) Index and overlay the PMU data to obtain a smooth response curve.

g) Repeat the tests for negative magnitude step, then for positive and negative 10° steps in phase.



The delay time is the time from the step in influence quantity until the point at which the linearly interpolated response curve exceeds 50% of the difference between the nominal value before the step and the value after the step. Note that delay time can be positive (after the step,) or negative (before the step) depending on the PMU algorithm.

The response times are the times between TVE, FE, and RFE exceeding the limits and the time where TVE, FE, and RFE reaches and remains within the limits as specified in IEEE Std C37.118.1-2011 and IEEE Std C37.118.1a-2014. Compare the measurement delay and response times to the limits in IEEE Std C37.118.1a-2014.

Look in the Test Suite Specification!

Lots of information, specifying undershoot, overshoot, etc.

Test 7 : Latency

IEEE Std C37.118.1a-2014 clarifies the latency test, changing the name from “measurement latency” to “PMU latency” and specifying the latency as the maximum time difference between the data report time (as indicated by the timestamp) and the time when the data becomes available at the PMU output.

Table 11—PMU reporting latency

Performance class	Maximum PMU reporting latency (s)
P class	$2/F_s$
M class	$\cancel{5/F_s}$ $7/F_s$
NOTE—For optional reporting rates F_s which are higher than nominal power system frequency $F_{nominal}$, maximum PMU reporting latency is equal to Table 11~~2~~ entry for $F_s = F_{nominal}$	

- Latency can fail if:
  - The filter window is too long in the time domain
  - The PMU processing takes too long
  - The report “packetisation” and/or LAN card takes too long to send it.
- Latency can be assessed during any of the previous tests, or during a dedicated test.
  - Many measurements are taken, because LAN cards change their latency over minutes or hours.
  - The latency for PMUs which adapt or tune to fundamental frequency may change with the fundamental frequency. Lower fundamentals may result on longer time windows.

What does the standard NOT test at all?

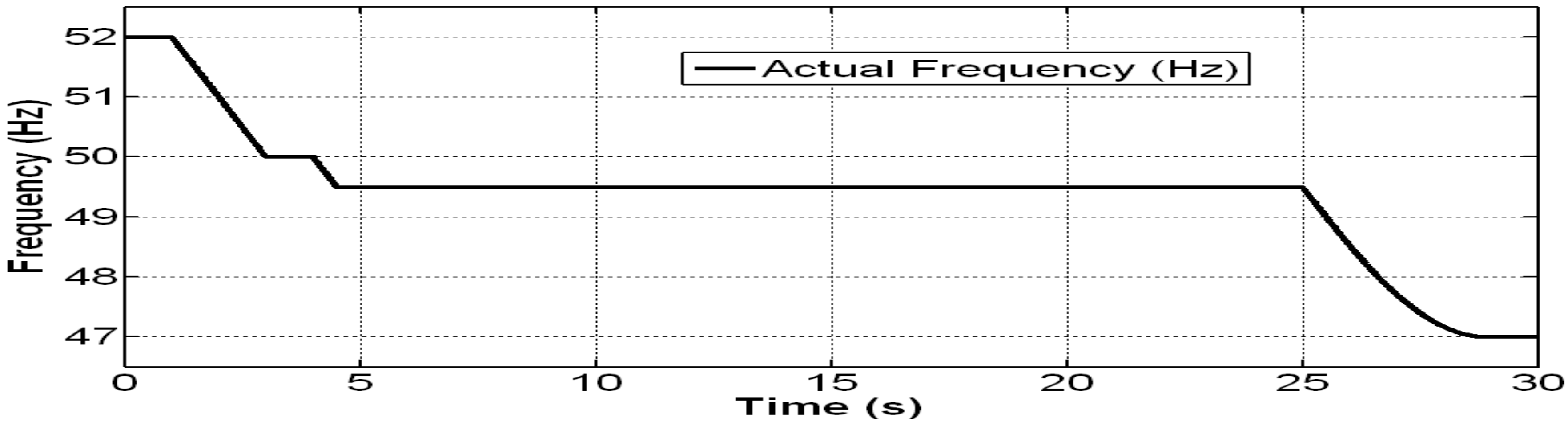
- It doesn't provide any overall "uncertainty" which can be applied **by a user**, in a particular network power quality condition.
- It does not test unbalance (at all).
- It is very limited in its treatment of harmonics, and the ROCOF errors can be very large in realistic power quality scenarios.
- It does not test at all for high frequency interharmonics from power electronics or HVDC.
- It does not test for any of the above, at off nominal frequencies, or during non-linear frequency ramps.
- The tested bandwidths of some PMUs (2 Hz) is not enough to cover cricitical network conditions (e.g. down to 47 Hz).
- The tested bandwidths of NONE of the PMUs is enough to gaurantee operational capability on islanded systems (42.5 Hz is not unknown).

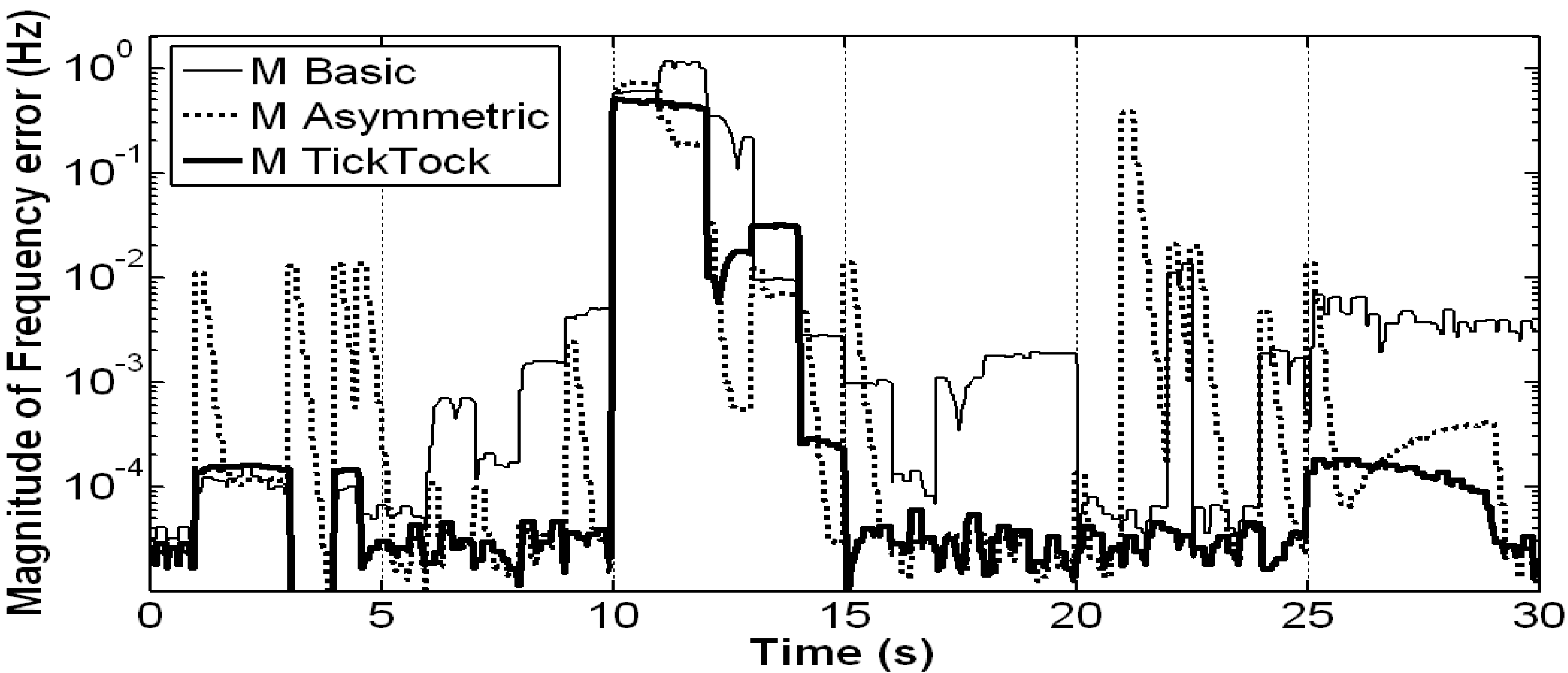
- A C37.118.1a-compliant PMU is not necessarily a reliable piece of equipment to be used in any power system. Each device should be independently tested to determine its suitability in a particular location with particular power quality conditions and requirements.

IEC/IEEE 60255-118-1 etc.

- Is there an opportunity to make subsequent standards (and testing) better?
- The Synchrohasor working group needs input from the PMU user community!
- E.g. minutes from last WG meeting:
  - *Updating the F and ROCOF limits: No real work has been done in this area. Allen did send out a report showing the performance of 10 PMUs and the reference model. What are the applications of ROCOF ? We need to know more.*
  - *Should we put something into the standard to test PMU handling of noise? What would such a test do? Where do we put in? What should the limits of error be? No current answers on this. A task force of Bill with anyone who wants to participate will investigate this and make a recommendation.*

Non-standard tests and real-world conditions





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Power outage in Glasgow after worker hits live cable

The worker was injured after making contact with a live cable on a building site in Allan Glen Place

A worker has been injured after making contact with a live cable at a building site in Glasgow city centre.

Police Scotland said there was a short power outage in the north of the city following the incident at Allen Glen Place at about 12:00 on Tuesday.

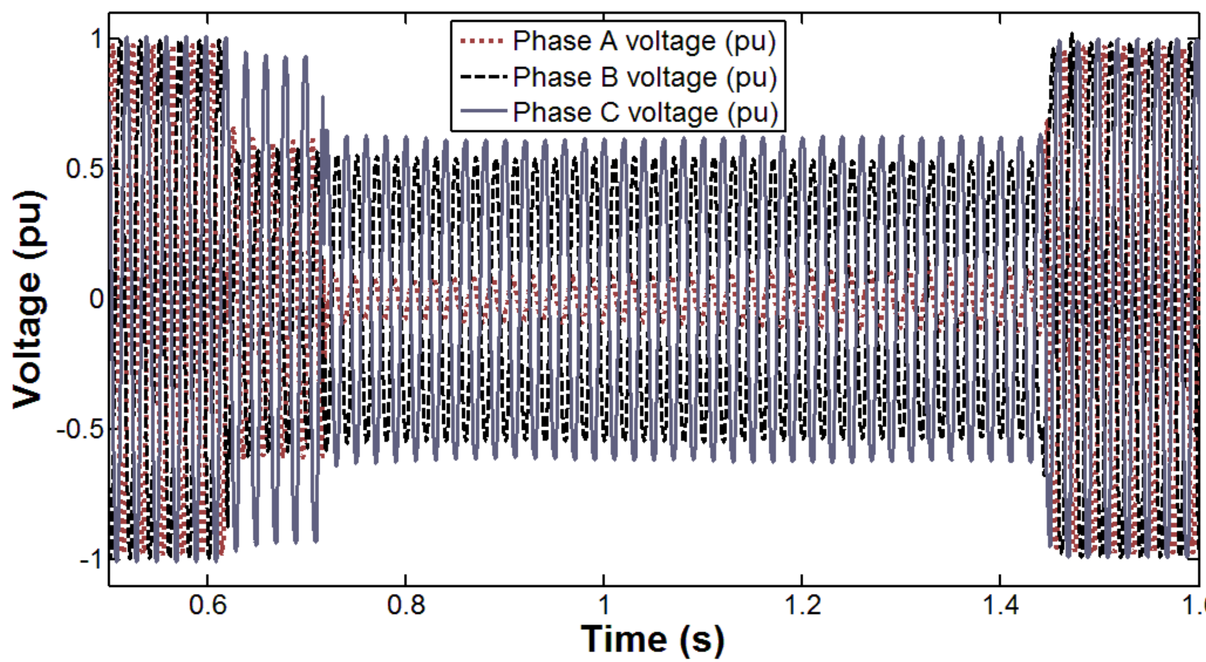
The injured man was taken to nearby Glasgow Royal Infirmary. Details of his condition are not yet known.

Emergency services remain at the scene. The incident has been reported to the Health and Safety Executive.

Scottish Power officials are also at the scene.

It is understood that people in the area reported hearing a "loud bang and explosion" when the incident occurred.

The power supply was restored a short time later.



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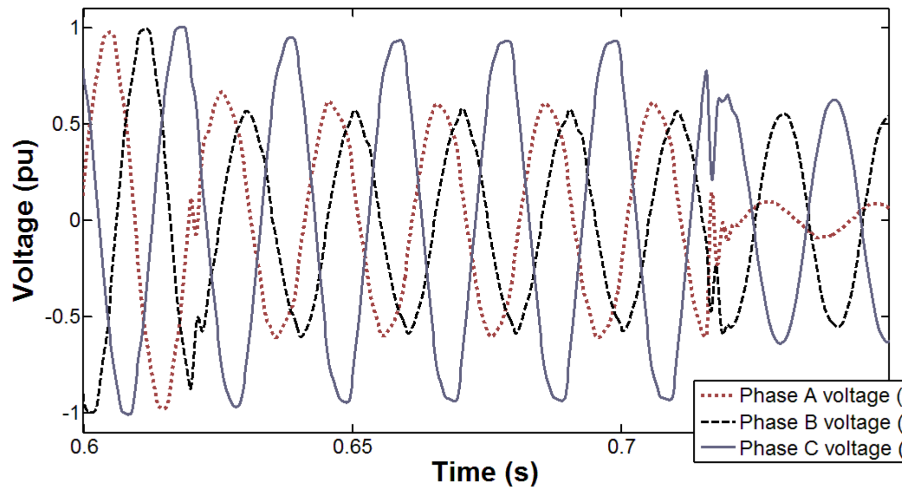

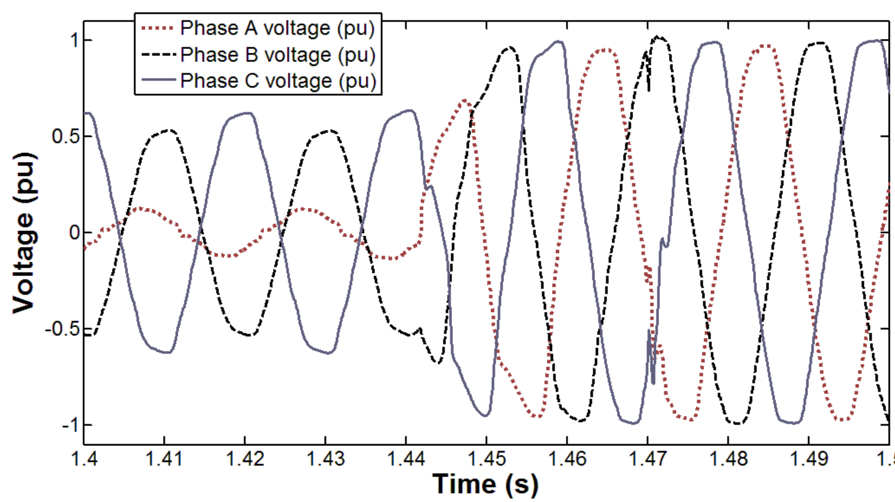

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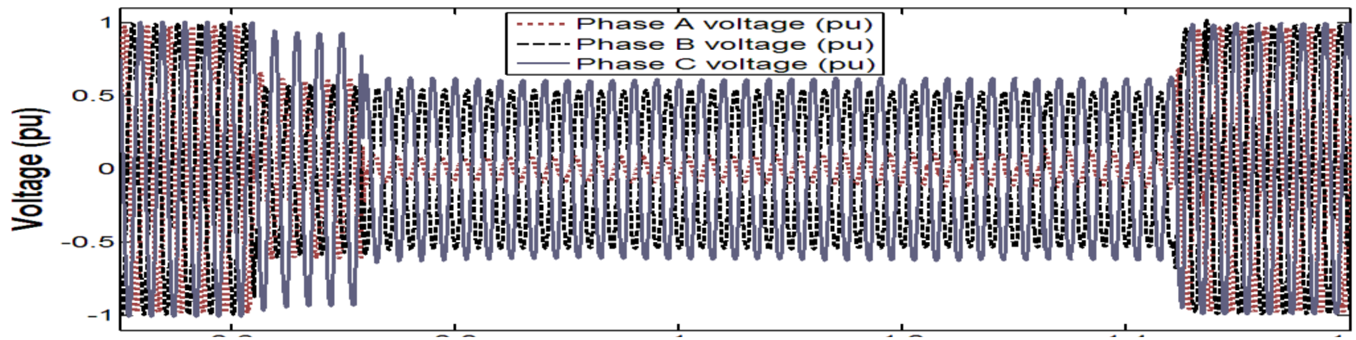
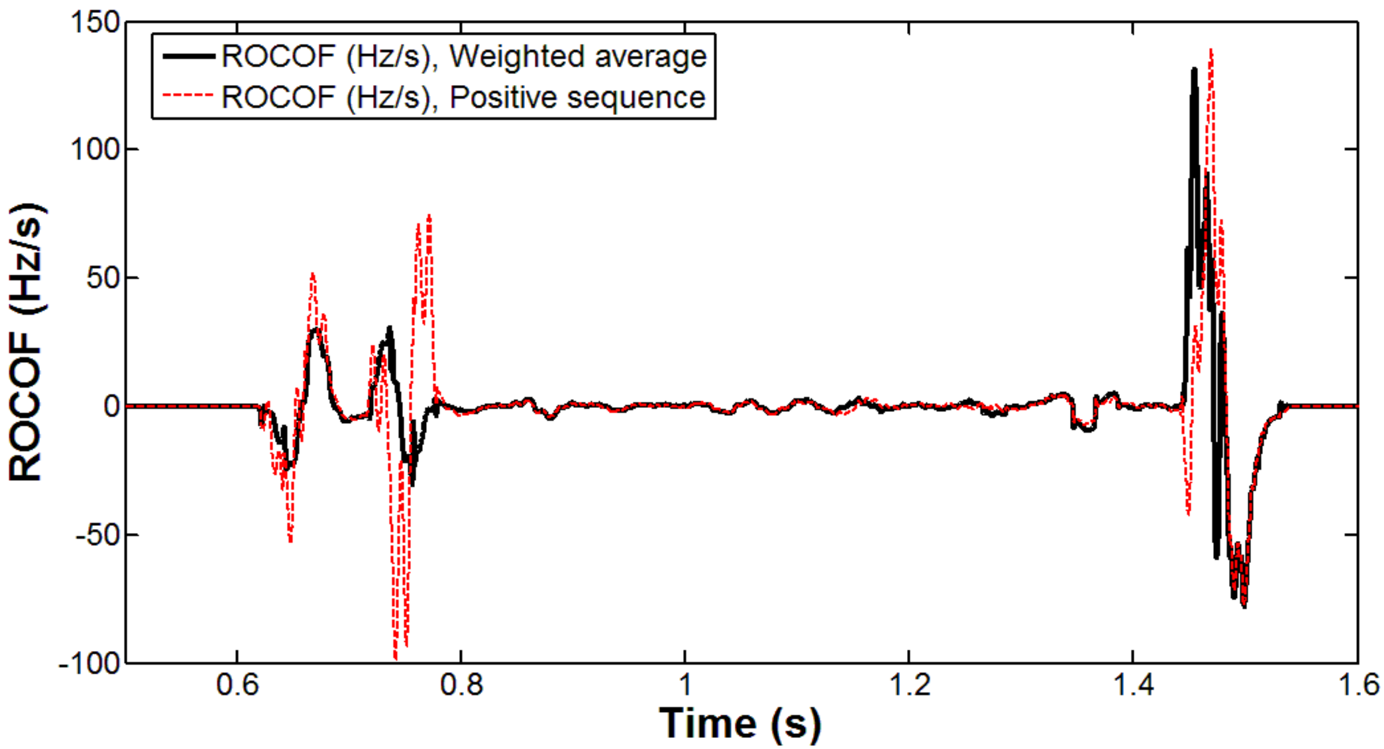
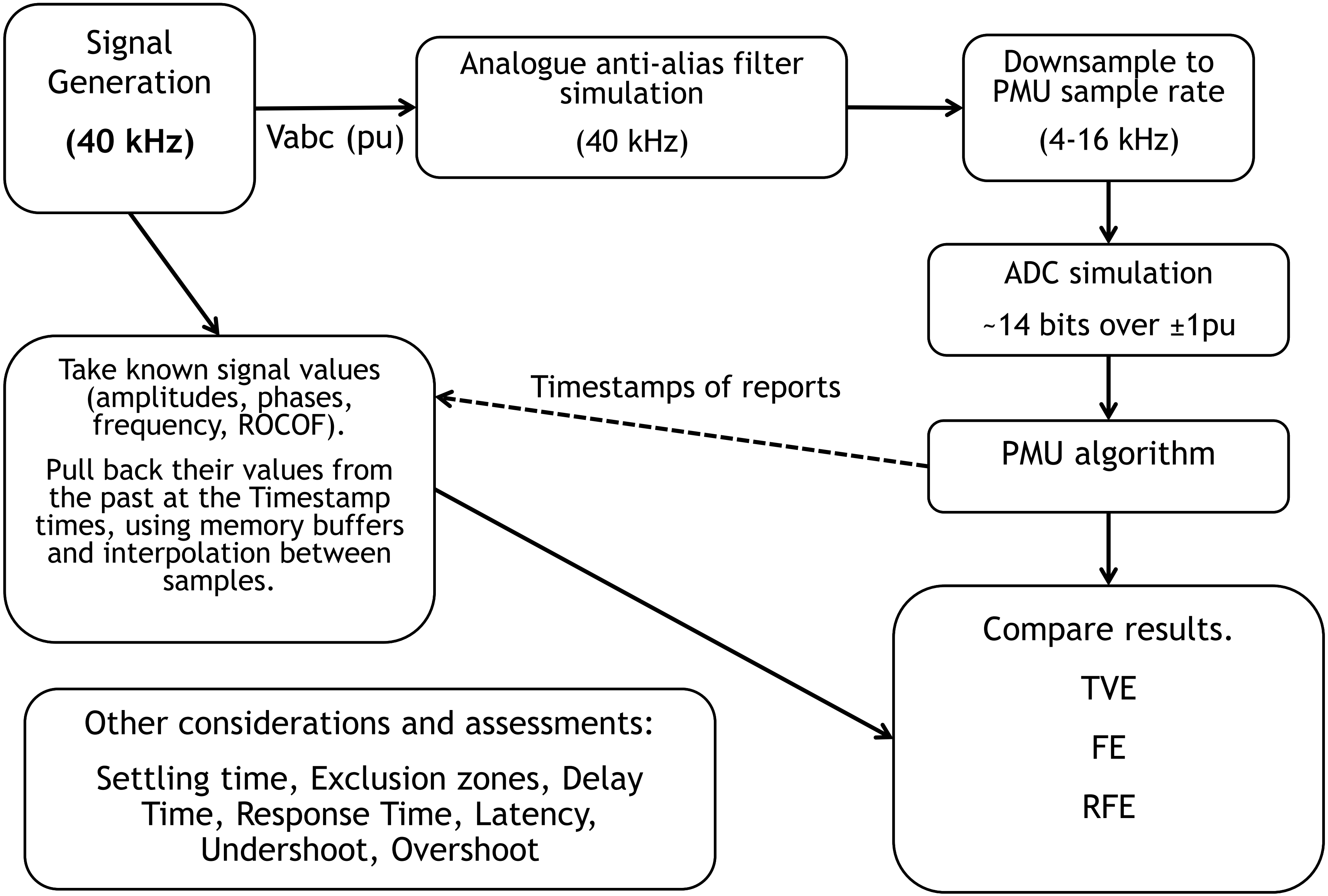




Testing in software – MATLAB environment

- MATLAB script configures and runs tests:
  - Choose PMU "brand"
  - Choose class (M or P)
  - Choose list of Reporting rates to test [F_{S1} , F_{S2} , F_{S3} .. F_{SN}]
  - Choose list of Tests to run [$Test\#_1$, $Test\#_2$ .. $Test\#_N$]
    - » [1-6 are standard tests, 6-10 are non-standard]
  - Choose options, e.g.
    - » Only test the hardest points (closest OOB points, highest modulation frequencies, etc).
    - » Test harmonics only at f_0 (standard) or across the frequency range (non-standard)
  - Loop round F_{Si}
    - » Start a summary log file for this PMU/Class/F_{Si} combination
    - » Loop round $Test_i$
      - Define require settling times for the PMU
      - Set signal generation parameters
      - Define exclusion zones (frequency ramp test)
      - Define pass/fail limits
      - Nested loops around frequency, amplitude, modulation freq, modulation type, step type, etc. as required (custom code required for each test)
        - Use sim() to call and run the Simulink model
        - Results are collected in the workspace
        - Next loop points
      - Store the detailed results to individual files
      - Analyse results against specifications
      - Write a summary to the log file
      - Next Test
    - » Close log file for that PMU/Class/F_{Si} combination
    - » Next reporting rate

Testing in software – Simulink environment



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