Lessons learned from the NIST assessment of PMUs

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Allen Goldstein
National Institute of Standards and Technology
Synchrometrology Lab
U.S. Department of Commerce

allen.goldstein@nist.gov
(301) 975-2101

National Institute of Standards and Technology
U.S. Department of Commerce

NIST Assessment of PMUs

- IEEE C37.118.1-2011 as amended by IEEE C37.118.1a-2014
- 15 participating vendors
  - 9 PMUs fully assessed
  - 3 PMUs in assessment now
  - 3 PMUs awaiting assessment
- Estimated: over 100,000 individual tests have been run so far.

Success stories

- At the beginning of the assessment, none of the PMUs passed IEEE C37.118.1 requirements.
  - After results provided to the vendors and the vendors provided us with firmware or hardware changes, 3 PMUs of 9 now pass all requirements and 2 others are close to passing.
- Assessment results were provided to the authors of IEEE Std. C37.118.1-2011 and amendment C37.118.1a-2014 *during the drafting* of these standards. These results were discussed in-depth while the drafters determined the test methods and the limits.
- Assessment is still in progress and draft results are now being shared with the joint IEC/IEEE working group for the creation of a new PMU joint standard.
- Estimated completion: September 2014

Lessons learned

- Definition of frequency error as an absolute value is good for determining compliance to limits but signed error is needed to troubleshoot PMU.
- Some PMUs have delay in the frequency estimate
  - exhibited during ramp of system frequency test.
- Some PMUs have delay in the ROCOF estimate
  - exhibited in the modulation bandwidth (phase modulation) test.
- Many PMUs have insufficient out-of-band signal rejection
  - exhibited in the out-of-band interfering signals test.
- C37.118.1-2011 had insufficient M-class step test response time to provide the desired rejection of out-of-band interfering signals. The revised standard added more response time.
- Some PMUs have many choices in their settings: Filter type and length, frequency tracking on or off, etc. Some configurations meet the 2005 requirements but have issues with the 2011 requirements.

Frequency testing

C37.118.1 defines frequency error:

$$FE = |f_{true} - f_{measured}| = \ldots \qquad (13)$$

C37.118.1-2011 equation 13

This definition is good to determine if the frequency estimate complies with the limits of the error, however, when analyzing frequency estimate issues with PMUs, there are two problems:

Frequency testing

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C37.118.1-2011 equation 13

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1) Absolute value does not allow for determination of the mean frequency error.

a) for a frequency ramp test, a constant mean frequency error is directly proportional to the time offset between the frequency estimate and the PMU's reporting time.

2) By subtracting the measured value from the "true" value, the sign of a delay derived from a ramp test would be negative.

a) normally in metrology, the reference ("true") value is subtracted from the measured value

Determine the time delay from frequency ramp test mean frequency error:

$$Delay\ (seconds) = \frac{mean\ frequency\ error\ (Hz)}{rate\ of\ change\ of\ frequency\ (\frac{Hz}{sec})}$$

For the C37.118.1 required frequency ramp test, the required rate of change of frequency is one Hertz.

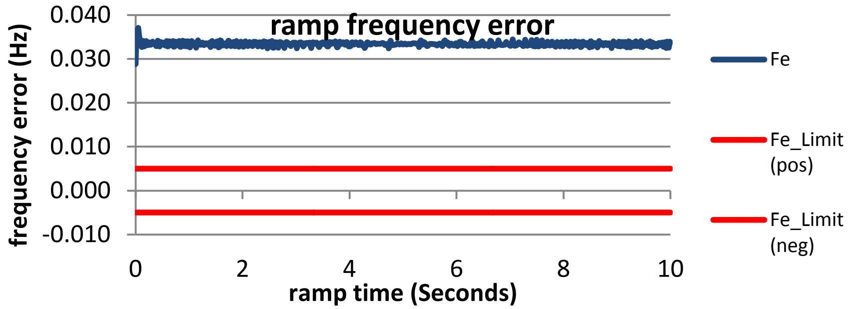


Figure 417: Fs = 60 FPS, ramp from 55 Hz to 60 Hz at 1 Hz/Second

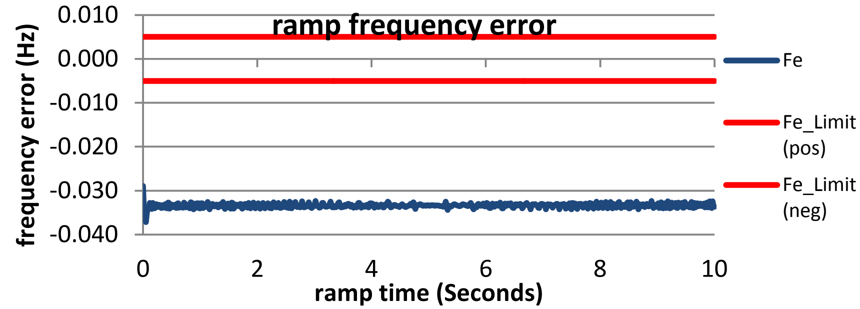


Figure 418: Fs = 60 FPS, ramp from 65 Hz to 55 Hz at -1 Hz/second

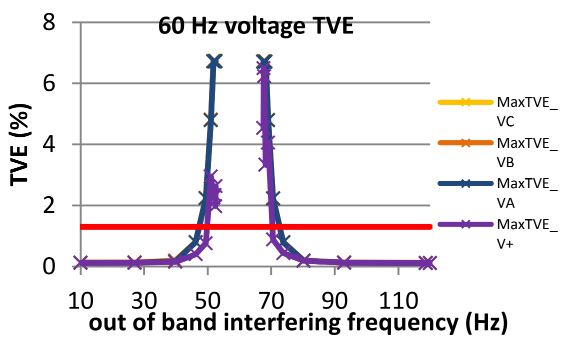
Actual measurements from PMU “B”, indicates about 34 ms of delay

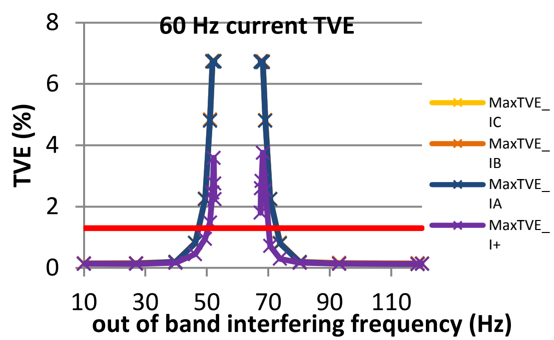
These test results were provided to the vendor and the vendor submitted a firmware revision which resolved the issue.

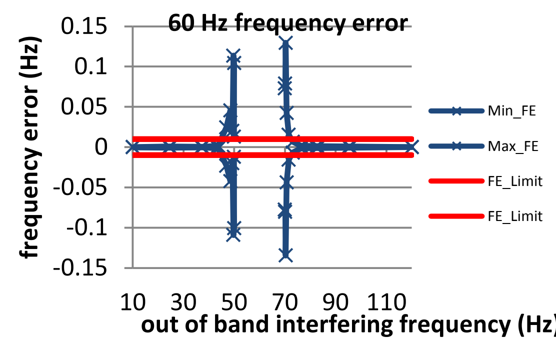
4 of 12 vendors tested had this issue, 3 of them have resolved the issue with new firmware.

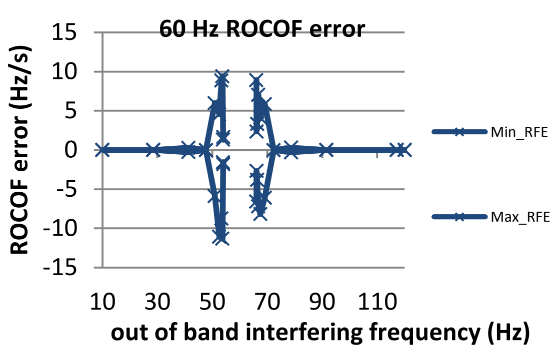
PMU Issues with PMU immunity to out-of-band interfering signals

- C37.118.1 steady state out-of-band interfering signals tests subject M-class PMU configurations to “interharmonic frequencies”
  - from 10 Hz up to the 2nd harmonic of the nominal frequency,
  - excluding frequencies between the nominal frequency plus and minus the nyquist frequency of the reporting rate.
  - interfering signal amplitude is 1/10 of the nominal amplitude.









Actual results from PMU OOB tests. Failures are at interfering signals near the nominal frequency ± reporting rate nyquist. All 12 PMUs failed this test, 3 vendors have provided updates which now pass the OOB test.

Note that there is no ROCOF error limit. Errors can be large so utilities may want to look out for these frequencies.

PMU issues with phase modulation tests

Some PMUs have issues tracking phase modulation as the modulation frequency increases.

Delays in the ROCOF estimate can only be seen in phase modulation test results.

Before describing the issues, it helps to understand what the phase modulation test is and why we test phase and amplitude modulation.

Phase modulation is one of the specific implementations of the "Measurement Bandwidth" test.

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Phase modulation is one of the specific implementations of the “Measurement Bandwidth” test.

The original purpose of the measurement bandwidth test was to stimulate the PMU with incrementally higher phase, magnitude, or combined phase and amplitude modulation frequencies until the Total Vector Error surpassed 3%.

The modulation frequency at which the TVE equals 3% is the 3 dB rolloff frequency of the PMU, which indicates the PMU bandwidth.

The test no longer requires modulation frequencies up to the PMU bandwidth but only up to the maximum of Fs/5 Hz or 5 Hz for M class or Fs/10 Hz or 2 Hz for P class.

The TVE limit for the test is still 3%

Phase Modulation tests

Phase is the derivative of frequency so phase modulation is modulating the frequency around the nominal frequency.

A series of modulation test frequencies begins at 0.10 Hz and increments at 0.2 Hz per test iteration until the modulation frequency reaches the limit.

The index (magnitude) of phase modulation is 10%, meaning for every 1 Hz of modulation frequency, the maximum frequency reached will be 0.1 Hz above and below nominal.

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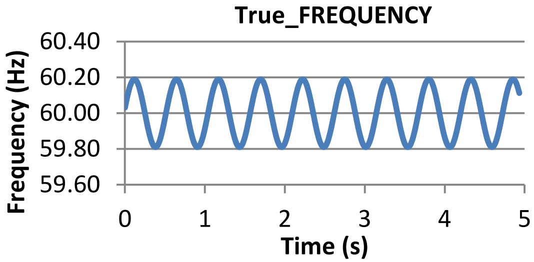
So for a maximum 5 Hz of phase modulation, the maximum frequency reached will be 0.5 Hz.

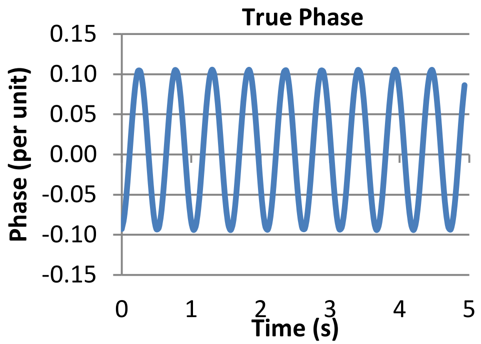


plot of frequency during a 1.9 Hz phase modulation

Note that while the max modulation frequencies are generally not seen at substations, greater modulation frequencies and indices have been measured at generator inter-ties under oscillation.

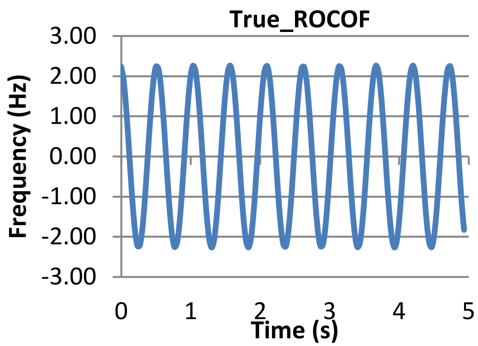
Phase modulation

$$phase = 0.1\ \cos\omega_m t$$



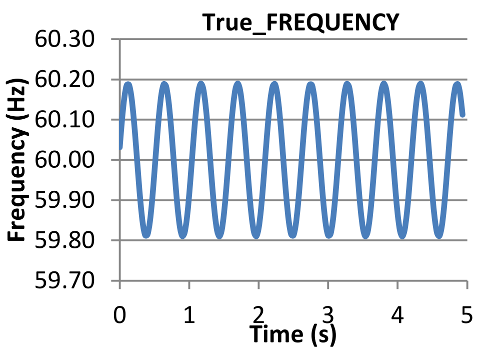
Phase modulation frequency 1.9 Hz, 10% index

$$ROCOF = -0.1\ \omega_m^2 \cos\omega_m t$$



ROCOF plot of 1.9 Hz phase modulation frequency, 10% index

$$frequency = 0.1\ \omega_m\ \sin\omega_m t$$



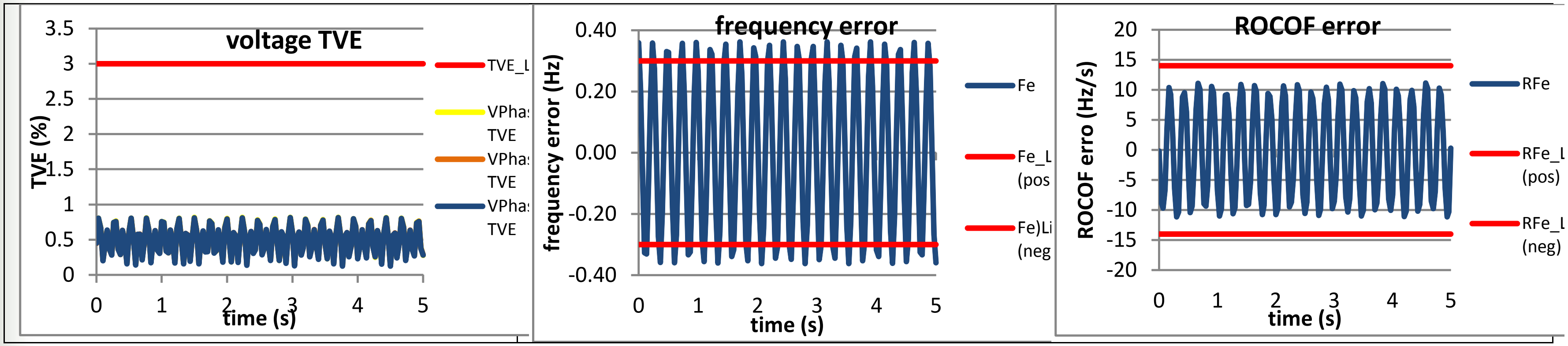
Frequency plot of 1.9 Hz phase modulation frequency, 10% index

Note on the next slide that the revised maximum error limits for frequency and ROCOF are quite high. A PMU that outputs 0 ROCOF all the time, only fails the phase modulation tests at the highest modulation frequencies.

Phase modulation results:

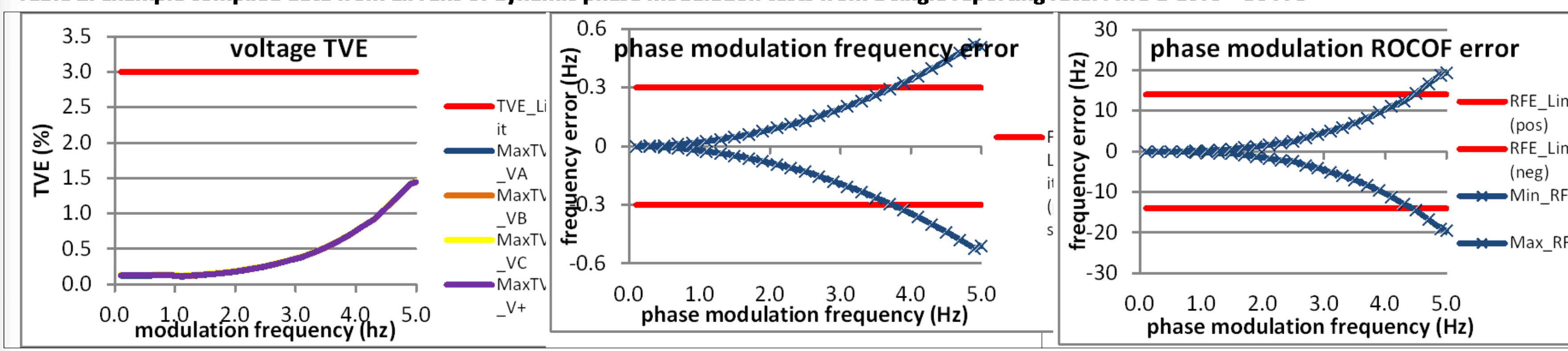
To illustrate an example of one PMU's response to one test, the below plots of TVE, Fe and RFe are made from the test run on PMU B at Fs = 30 FPS and a phase modulation frequency of 4.1 Hz:

Table 1: example data from one run of dynamic phase modulation test: PMU B at Fs = 30 FPS, 4.1 Hz modulation frequency



The plots below illustrate how the modulation test results are reported. The plots show a compilation of the MAXIMUM TVE, FE and RFE (Y-axis) for each of the different phase modulation frequencies (X – axis)

Table 1: example compiled data from all runs of dynamic phase modulation tests from a single reporting rate: PMU B at Fs = 30 FPS



PMU "B" phase modulation frequency and ROCOF errors

6.3.3 PMU B dynamic bandwidth measurement: phase modulation frequency error: F0 = 60 Hz, M class

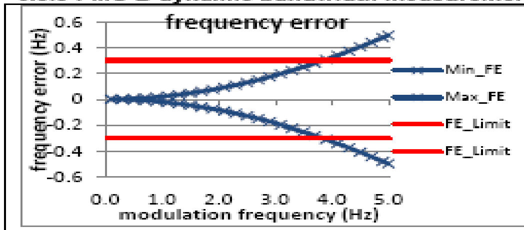


Figure 1310: Fs = 60 FPS

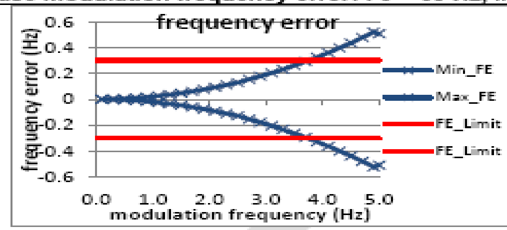


Figure 1311: Fs = 30 FPS

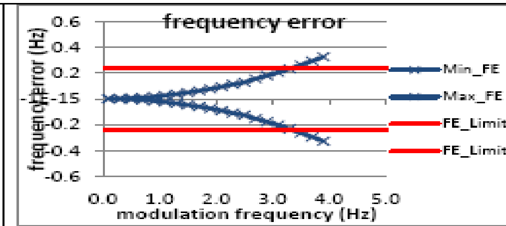


Figure 1312: Fs = 20 FPS

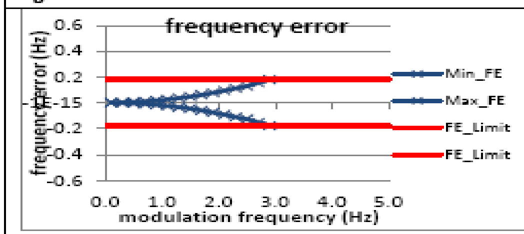


Figure 1313: Fs = 15 FPS

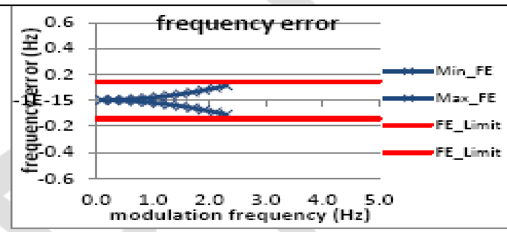


Figure 1314: Fs = 12 FPS

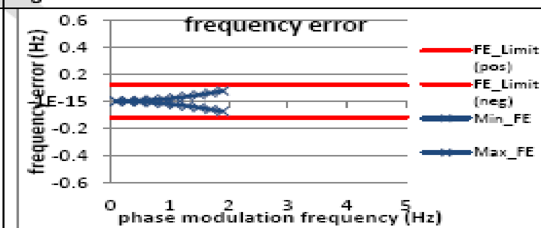


Figure 1315: Fs = 10 FPS

6.4.3 PMU B dynamic bandwidth measurement: phase modulation ROCOF error: F0 = 60 Hz, M class

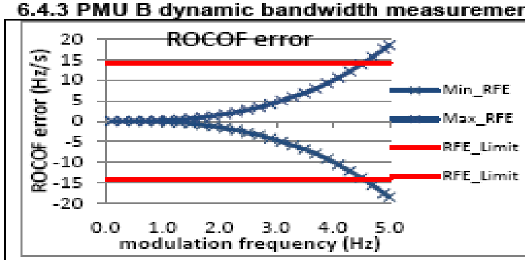


Figure 1356: Fs = 60 FPS

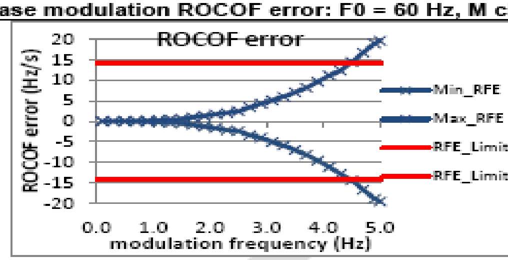


Figure 1357: Fs = 30 FPS

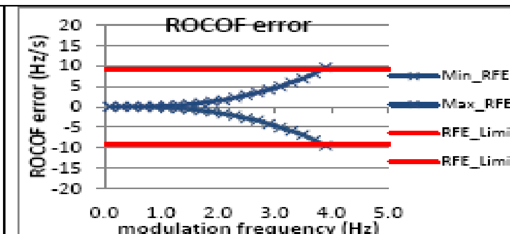


Figure 1358: Fs = 20 FPS

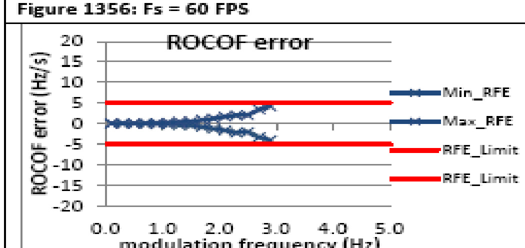


Figure 1359: Fs = 15 FPS

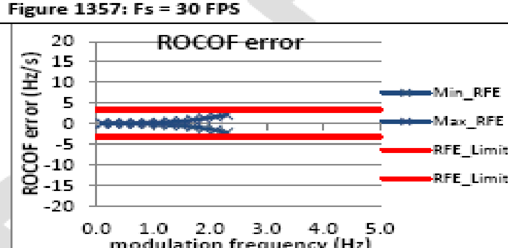


Figure 1360: Fs = 12 FPS

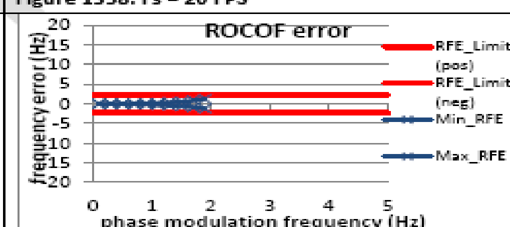


Figure 1361: Fs = 10 FPS

Lesson Learned: Combined (phase and amplitude) modulation test was replaced by amplitude mod test.

12 PMUs were tested for combined AM and PM.

Results were very different, some PMUs had PM issues, some had AM issues and some had both.

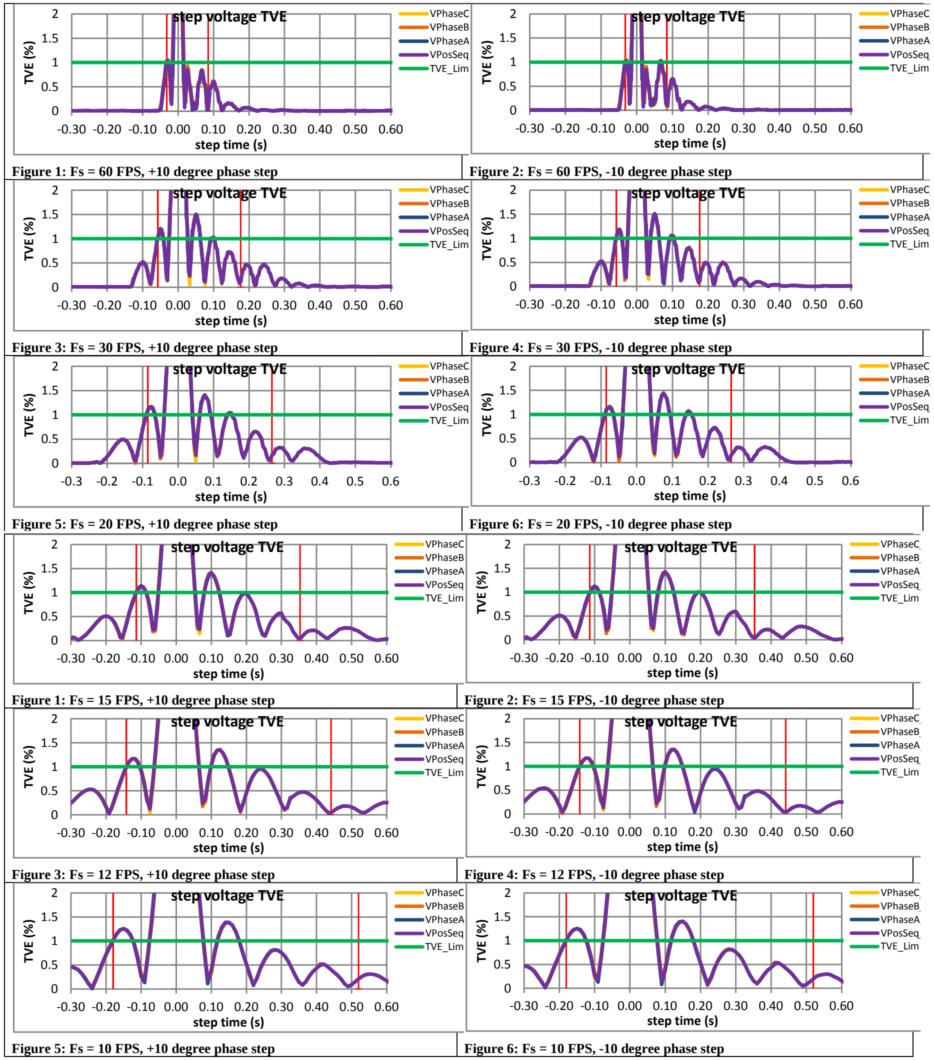
Since we also test for PM we saw that the combined issues were difficult to determine contribution of each error type.

It was difficult to determine realistic combined modulation limits due to the effects of combined modulation: In some cases the effects constructively or destructively interfere with each other.

The working group drafting the C37.118.1a revision determined it was better to replace combined modulation from the -2011 standard with amplitude only modulation in the .1a-2014 revision.

Lesson Learned: Revised standard adds more response time to step tests for M class PMUs

- PMU assessment includes the C37.118.1 Annex C Signal Processing Model.
- Results from the model and from some PMUs showed that in order to achieve the desired out of band interfering signal rejection, a longer filter was needed.
- The longer filter requires more step response time.
- The plots on the right show a PMU that passes both OOB limits and the revised response time limits.



Some -2005 compliant PMU configurations have dynamic test issues

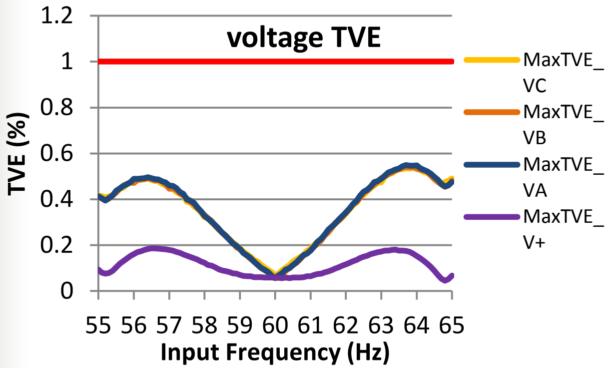
Some of the assessed PMUs have configuration options such as frequency tracking (on or off), configurable filter lengths, and a choice of filter types (Butterworth, Blackman-Harris, Flat Top, etc.)

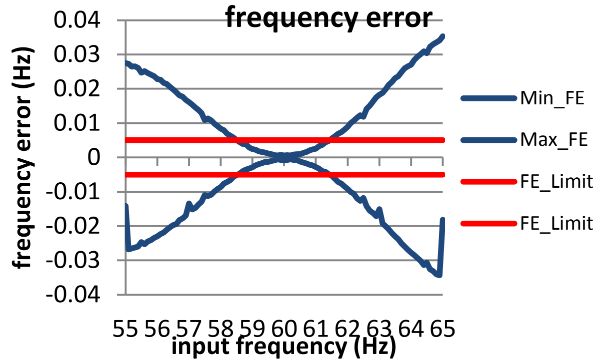
Frequency tracking can provide very good steady state TVE performance .

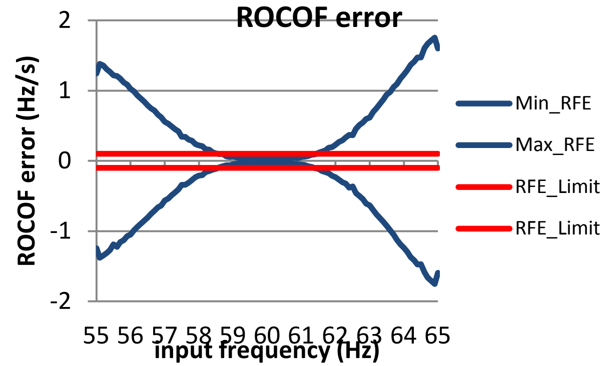
May meet the -2005 requirement, (which have no dynamic tests or frequency or ROCOF error limits).

Dynamic performance may suffer:

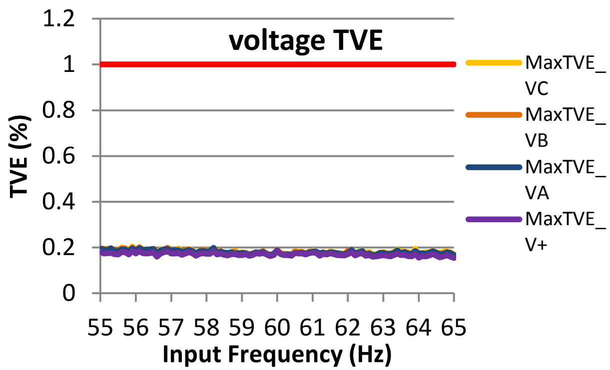
Frequency tracking PMU Steady State comparison

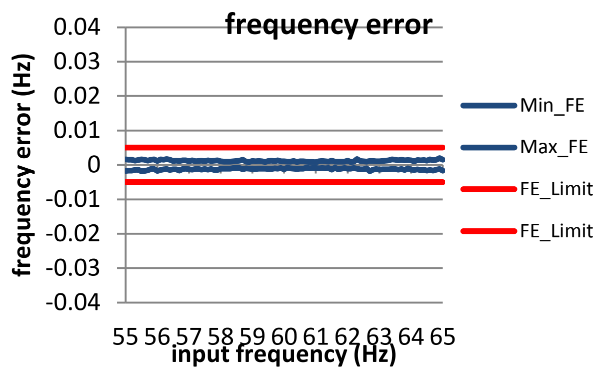


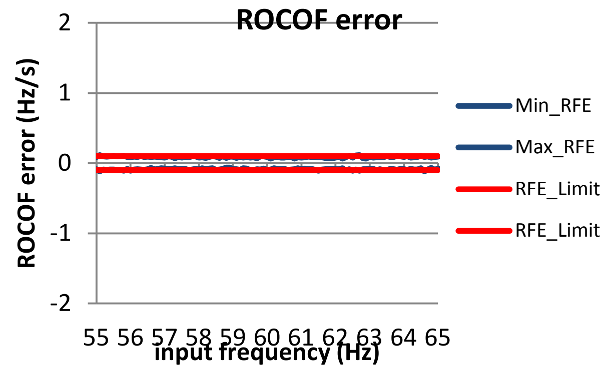




PMU C, Fs = 60 FPS with frequency tracking off. Steady State Frequency from 55 to 65 Hz

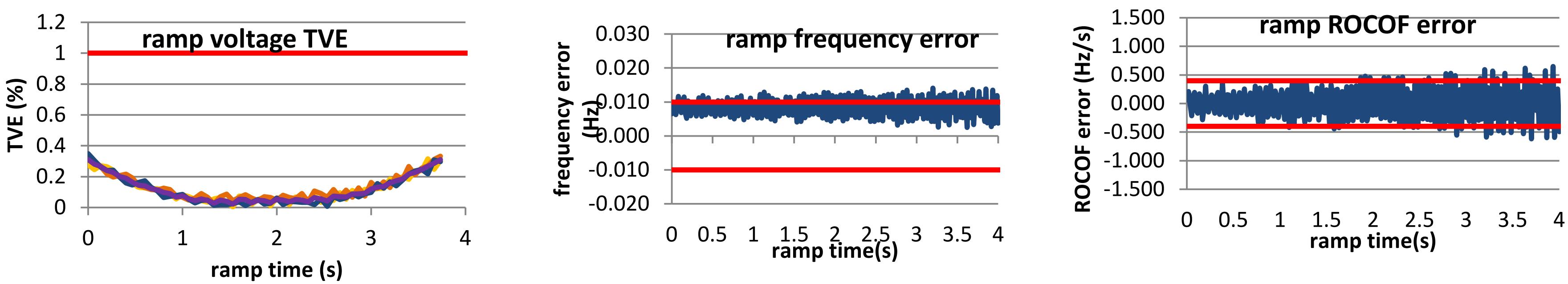




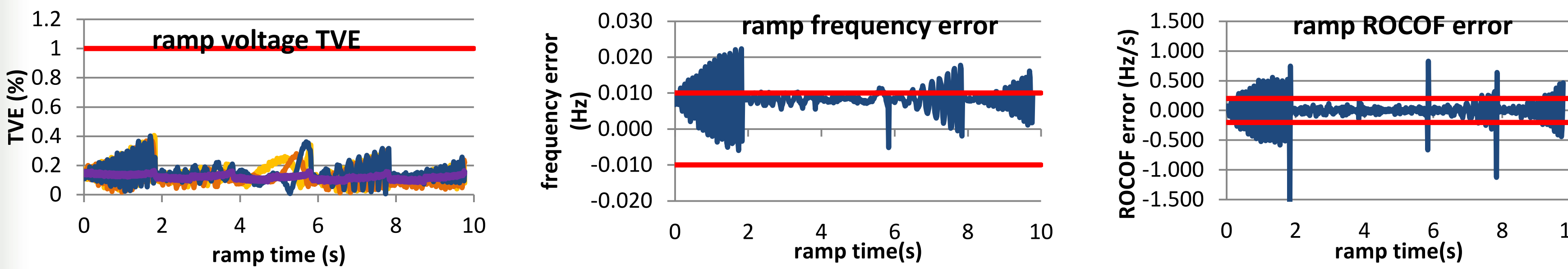


PMU C, Fs = 60 FPS with frequency tracking on. Steady State Frequency from 55 to 65 Hz

Frequency tracking PMU frequency ramp comparison



PMU C, Fs = 60 FPS with frequency tracking off. +1 Hz/s frequency ramp from 55 to 65 Hz



PMU C, Fs = 60 FPS with frequency tracking on. +1 Hz/s frequency ramp from 55 to 65 Hz

The takeaway: Know your PMU settings and the performance using those settings

Off Topic: Some questions for you:

- Are U.S. PMU manufacturers and utilities concerned about having PMUs tested for certification by a non-US entity?
  - Testing often exposes PMU design details.
  - Also test traceability would go outside the U.S.
- We have heard concerns that IEC 17025 certified labs may not feel there is a big enough market to cover their initial investment in PMU testing. We would like to hear from anyone who has any thoughts on this.
- How would U.S. government stakeholders (DOE, national labs, utilities, RTO's ISO's, etc) feel if PMU traceability went outside the United States?
- I am available during breaks and after the sessions to discuss

Thank you. Any questions?

Allen Goldstein
National Institute of Standards and Technology
Synchrometrology Lab
U.S. Department of Commerce

allen.goldstein@nist.gov
(301) 975-2101