Traceable Synchrophasors

The calibration of PMU calibration systems

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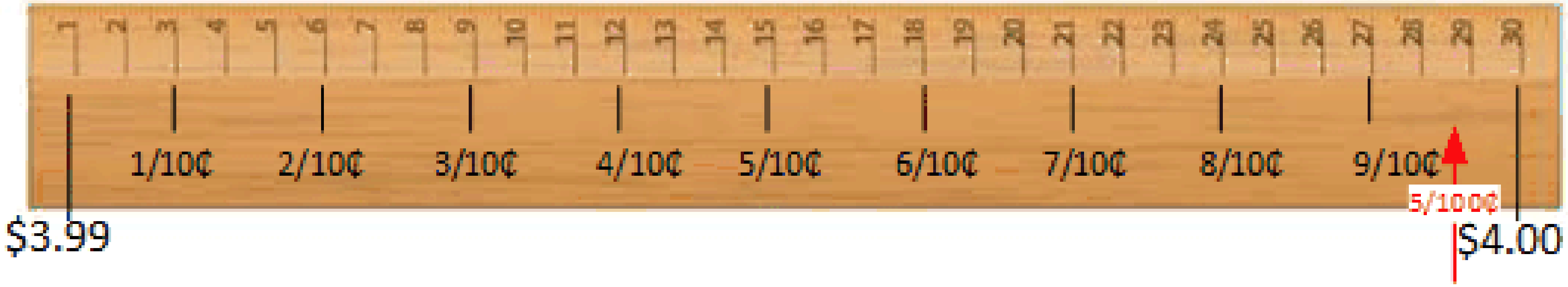
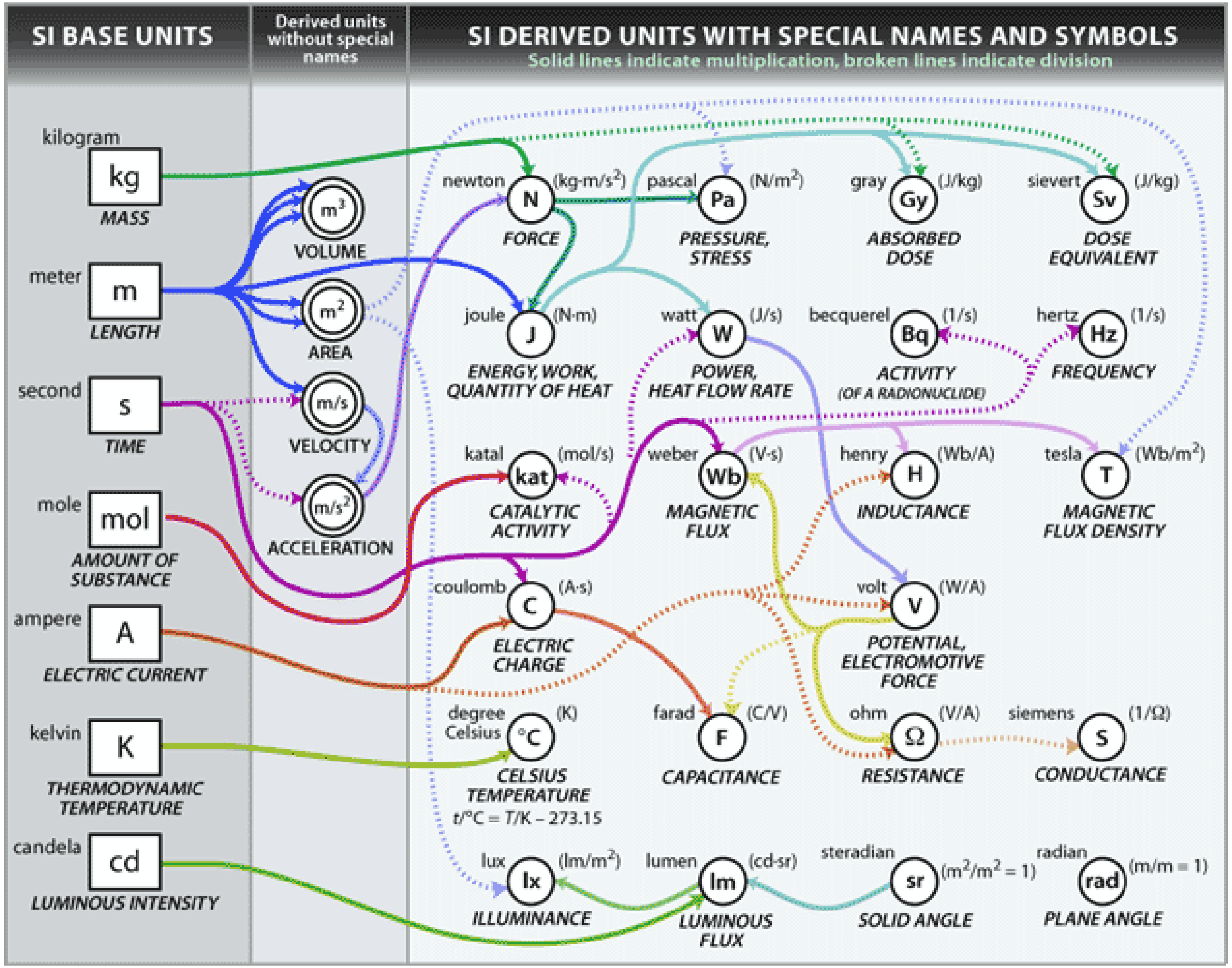
Disclaimer

Why Traceably Calibrate?

But how do you know???




SI BASE UNITS
Derived units without special names
SI DERIVED UNITS WITH SPECIAL NAMES AND SYMBOLS
Solid lines indicate multiplication, broken lines indicate division
kilogram
kg
MASS
meter
m
LENGTH
second
s
TIME
mole
mol
AMOUNT OF SUBSTANCE
ampere
A
ELECTRIC CURRENT
kelvin
K
THERMODYNAMIC TEMPERATURE
candela
cd
LUMINOUS INTENSITY
m³
VOLUME
m²
AREA
m/s
VELOCITY
m/s²
ACCELERATION
newton N (kg·m/s²) FORCE
pascal Pa (N/m²) PRESSURE, STRESS
gray Gy (J/kg) ABSORBED DOSE
sievert Sv (J/kg) DOSE EQUIVALENT
joule J (N·m) ENERGY, WORK, QUANTITY OF HEAT
watt W (J/s) POWER, HEAT FLOW RATE
becquerel Bq (1/s) ACTIVITY (OF A RADIONUCLIDE)
hertz Hz (1/s) FREQUENCY
katal kat (mol/s) CATALYTIC ACTIVITY
weber Wb (V·s) MAGNETIC FLUX
henry H (Wb/A) INDUCTANCE
tesla T (Wb/m²) MAGNETIC FLUX DENSITY
coulomb C (A·s) ELECTRIC CHARGE
volt V (W/A) POTENTIAL, ELECTROMOTIVE FORCE
degree Celsius °C (K) CELSIUS TEMPERATURE
t/°C = T/K – 273.15
farad F (C/V) CAPACITANCE
ohm Ω (V/A) RESISTANCE
siemens S (1/Ω) CONDUCTANCE
lux lx (lm/m²) ILLUMINANCE
lumen lm (cd·sr) LUMINOUS FLUX
steradian sr (m²/m² = 1) SOLID ANGLE
radian rad (m/m = 1) PLANE ANGLE

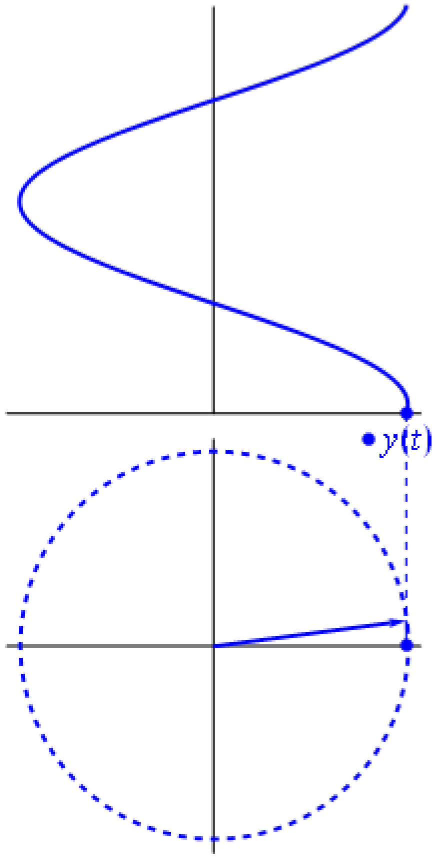
Motivation

- Between 2012 and 2014 NIST assessed the electrical performance of 15 PMUs
  - some “legacy” PMUs in use today
  - some prototype PMUs still in development.
  - none of the legacy PMUs met the 2011 standard
- 2013 North American Synchrophasor Initiative Report of Task Force on Testing and Certification Final Report
- 2014 IEEE Synchrophasor Measurement Test Suite Specification (TSS), now available on IEEE Xplore.
- 2015 IEEE Synchrophasor Conformance Assessment Program begins (ICAP)

Synchrophasors (y'all know this, right?)

- Synchronous measurements of power system voltage and current magnitude and absolute phase
- Measurements are made across the power system within 1 µs of one another
- Measurements are transmitted over the wide area to power system control centers

Many applications for synchrophasor measurements



But a synchrophasor is an ESTIMATE

Not a measurement

A filtered value coming from a window of from 2 to hundreds of cycles

It always has some amount of error and uncertainty

And the more the power system signal is changing inside the window, the larger the error will be

So IEEE has set limits to the allowable error under many different power system signal conditions

And PMU test reports have very detailed data on the PMU errors under these conditions

But synchrophasor *applications* are designed assuming the phasor “measurement” is perfect!

NASPI is forming a new task force to attempt to determine the PMU errors that applications can tolerate.

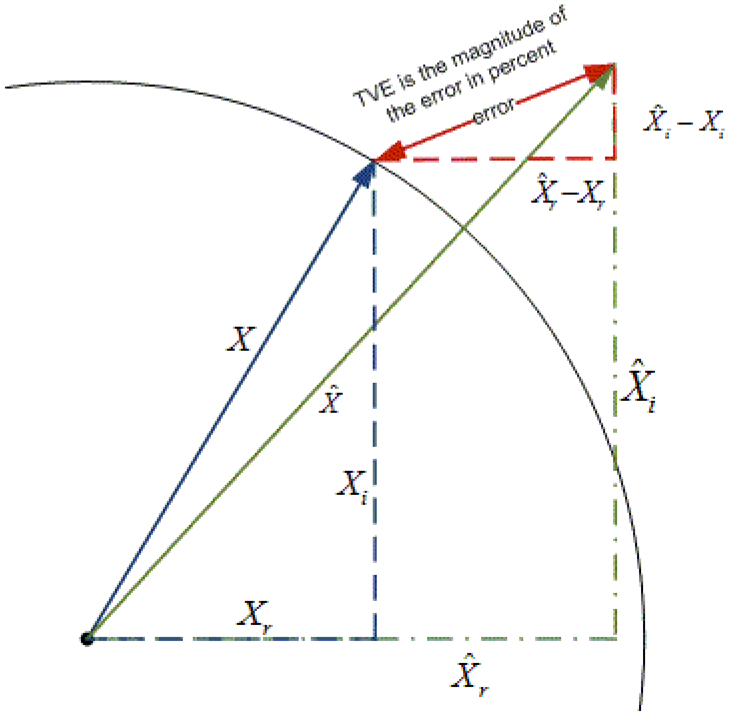
Total Vector Error

$$TVE(n) = \sqrt{\frac{\left(\hat{X}_r(n) - X_r(n)\right)^2 + \left(\hat{X}_i(n) - X_i(n)\right)^2}{\left(\left(X_r(n)\right)^2 + \left(Xi(n)\right)^2\right)}}$$

where:

$\hat{X}_r$ and $\hat{X}_i$ are sequences of estimates given by the PMU under test

X_r and X_r are sequences of the theoretical values of the input signal



- •TVE is a good method of determining if the synchrophasor error exceeds a specified limit.

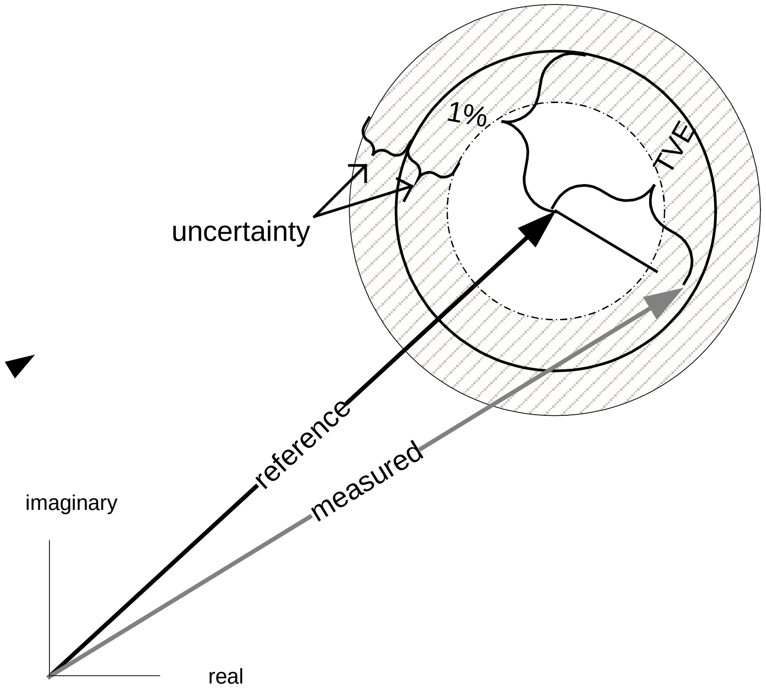
- •However when troubleshooting PMU algorithms or determining the uncertainty of a calibration system, the Magnitude error and Phase error components of the TVE are indispensable.

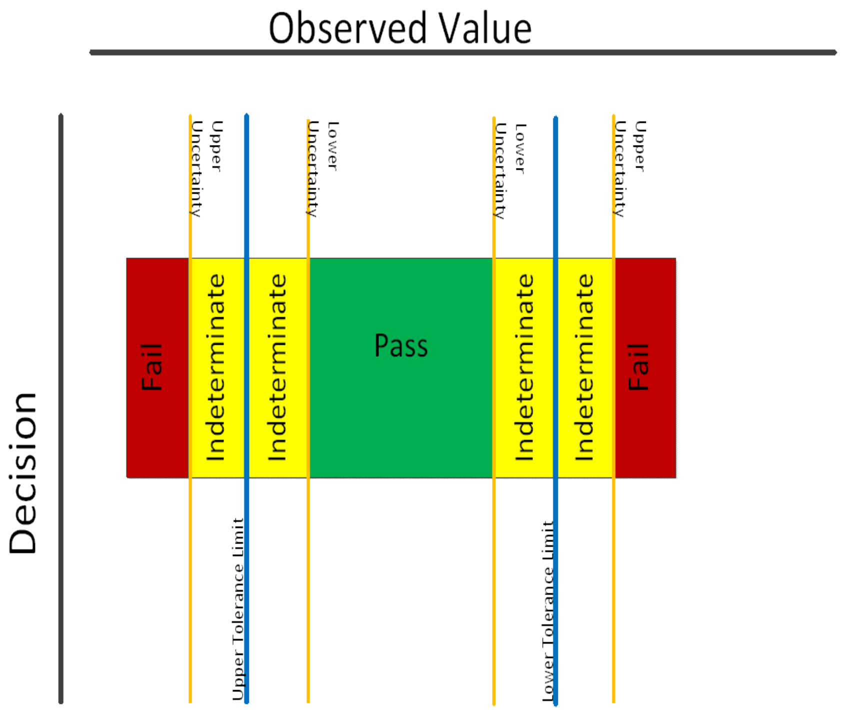
Calibration of calibrators

- In support of the IEEE Synchrophasor Conformance Assessment Program, NIST has developed a special calibration for PMU Calibration Systems
  - Traceable
  - Reports on the uncertainty of the Calibrator Under Test (CUT)
- The uncertainty will be used by the ICAP program to determine PMU pass / fail / indeterminate status
- Over the next 12 to 18 months, NIST will develop a Standard Calibration Service

What do we mean by "Pass / Fail / Indeterminate"?

- Calibrating the PMU will yield a set of PMU errors under specified input conditions.
- According to the IEEE standard, the maximum error under each condition shall not exceed a specified limit
- However, the PMU calibration system has a some uncertainty
- So if the calibrator measures a PMU error which is within the calibrator's uncertainty of the limit, ICAP can neither determine if the PMU passes nor fails the test
  - ICAP must say the status is indeterminate

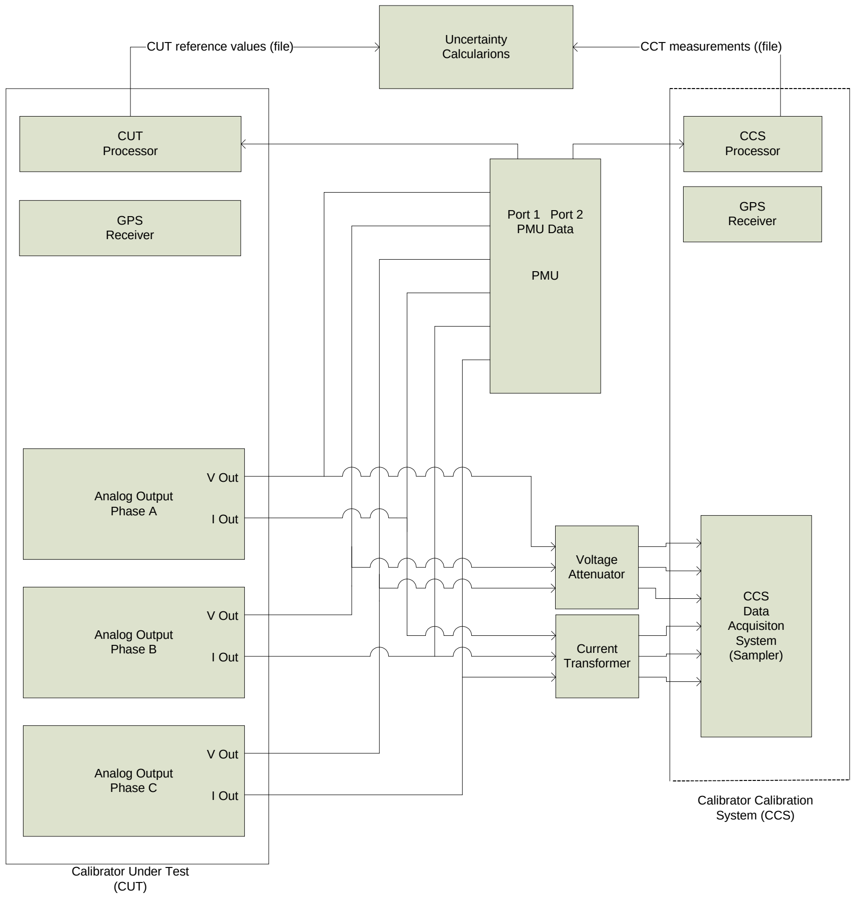




Requirements for a PMU calibration system

- Signal source magnitude and absolute phase shall be traceable to first principles as represented by national standards
  - “absolute” phase is phase relative to time.
- “True” (reference) value uncertainty shall be verified.
  - “True” values are the values of the signal source which are compared to the PMU Under Test’s output to determine TVE, Fe, and RFe.
- Result calculations shall be verified to be compliant with IEEE C37.118.1:2011.
  - Result calculations include TVE, Fe, RFe, Step Response Time, Step Delay Time, and Step Overshoot.

PMU Calibrator Calibration System Block Diagram



PMU Calibrator Under Test (CUT)

- Processor
  - receives PMU measurements
  - compares measurements to its reference signal (the phasor values of its output)
- Analog Outputs (3-phase) generate time-synchronized test signals in accordance with the PMU standard

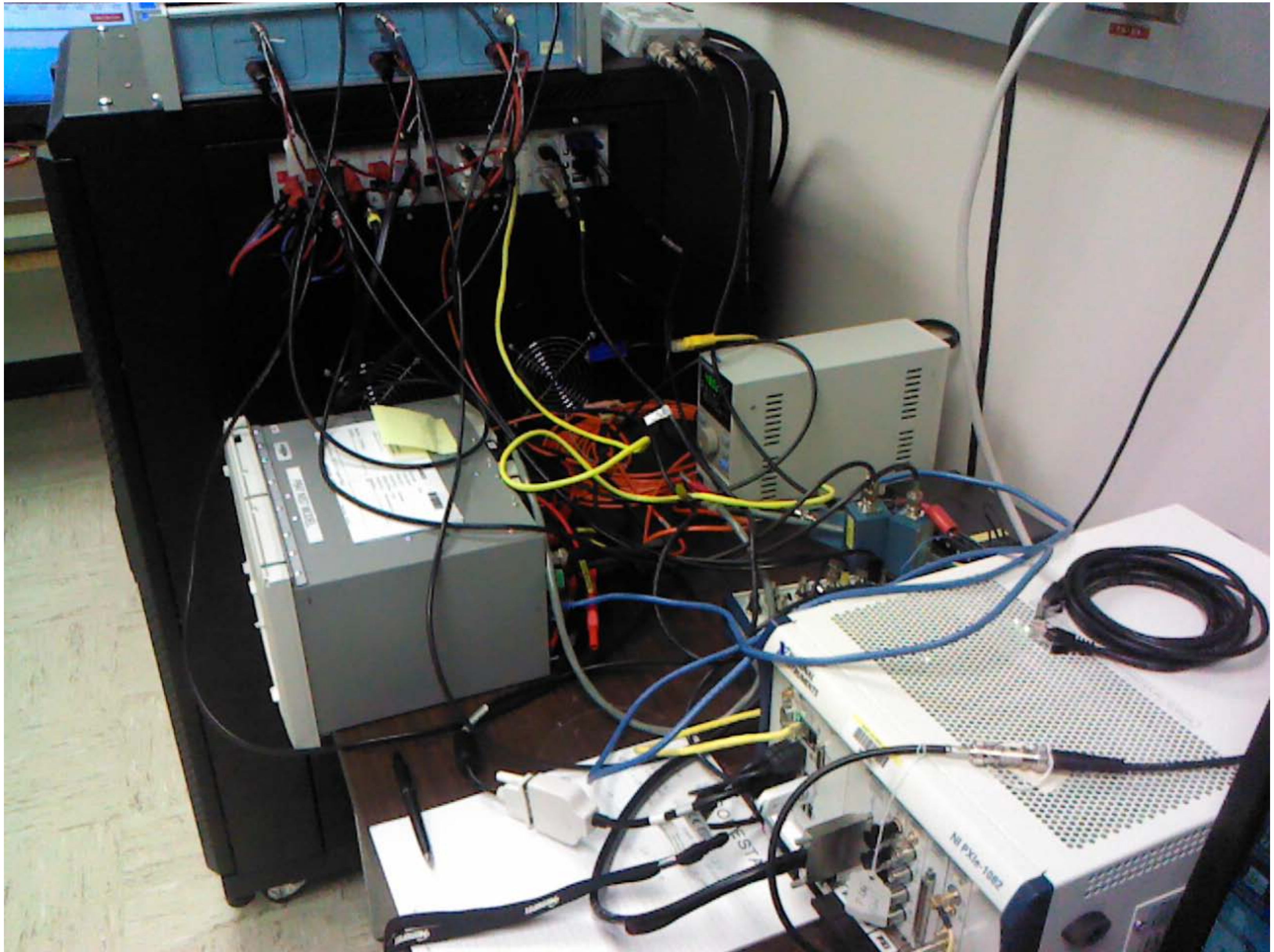
Calibrator Calibration System (CCS)

- Measures the analog output from the CUT and determines a measured synchrophasor value.

Uncertainty Calculations

- Off-line system compares CUT reference phasors to CCT measured phasors.
  - Determines offset, systematic errors, and random (noise) error
  - Calculates expanded (k=2) uncertainty of the CUT's reference values in units of TVE, FE, and RFE

NIST PMU Calibrator Calibration System in the field



Measuring PMU electrical conformance

IEEE Std. C37.118.1-2011 Section 5: Synchrophasor measurement requirements and compliance verification

- 5.5.5 Steady state compliance:
  - Signal frequency range tests (41 to 101 tests per configuration)
  - Signal magnitude tests (approx. 20 tests/configuration)
  - Harmonic distortion tests (50 tests /configuration)
  - Out of band interfering signals (50 to 100 tests/configuration)
- 5.5.6 Dynamic measurement bandwidth (modulation tests) (11 to 51 tests/configuration)
- 5.5.7 Dynamic ramp tests (2 tests/configuration)
- 5.5.8 Dynamic step tests (40 tests/configuration*)
  - * 4 tests of 10 iterations each
- 5.5.9 Measurement reporting latency (1 test)

Steady State Frequency and Magnitude Range Tests

Test input signals:

$X_a = X_m \cos(2pft)$

$X_b = X_m \cos(2pft-2p/3)$

$X_c = X_m \cos(2pft+2p/3)$

- Frequency range test:
  - A series of tests are run for 5 s duration with the signal frequency beginning at F_0 - 5 Hz.
  - For each test run, the signal frequency is incremented by 0.1 Hz until F_0 + 5 Hz is reached.
- Magnitude range test:
  - f is the nominal frequency but X_m is varied in a series of tests beginning at $0.1X_0$ (the nominal magnitude) to $1.2X_0$ for Voltage and $2.0X_0$ for current.

Steady State Harmonic Distortion and Out-of-Band Interfering Signals Tests

Harmonic distortion test:

$X_a = X_m \cos(2pf_0t) + X_m k_x \cos(2pnf_0t)$

$X_b = X_m \cos(2pf_0t-2p/3) + X_m k_x \cos(2pnf_0t-2p/3)$

$X_c = X_m \cos(2pf_0t+2p/3) + X_m k_x \cos(2pnf_0t+2p/3)$

note: the harmonics are NOT positive sequence but their positive 0 crossing occurs at the same time at the fundamental

A series of 5 s duration tests with n beginning at 2 and ending at 50 with n incremented by 1 each test.

Out-of-band interfering signals test:

$X_a = X_m \cos(2pf_{in}t) + X_m k_x \cos(2pf_it)$

$X_b = X_m \cos(2pf_{in}t-2p/3) + X_m k_x \cos(2pf_it-2p/3)$

$X_c = X_m \cos(2pf_{in}t+2p/3) + X_m k_x \cos(2pf_it+2p/3)$

note: the interharmonics ARE positive sequence

A series of 5 s duration tests are run where $f_{in} = F_0$ and begins at 10 Hz and ends at $2F_0$.
No tests are conducted within ½ the reporting rate of the nominal frequency.
F_i increments logarithmically with more tests closer to the reporting rate Nyquist frequency.

Dynamic Measurement Bandwidth (modulation) tests

$X_a = X_m\ [1+k_x\cos(\omega t)] * \cos\ [\omega_0 t+k_a\cos(\omega t\text{-}p)]$

$X_b = X_m\ [1+k_x\cos(\omega t)] * \cos\ [\omega_0 t\text{-}2p/3+k_a\cos(\omega t\text{-}p)]$

$X_c = X_m\ [1+k_x\cos(\omega t)] * \cos\ [\omega_0 t+2p/3+k_a\cos(\omega t\text{-}p)]$

Amplitude modulation ($k_x \neq 0$) and phase modulation ($k_a \neq 0$) are conducted separately (there are no longer any combined modulation tests required).

A series of 5 s duration tests are run with $2\pi\omega$ beginning at 0.1 Hz and ending at 5 Hz with 0.2 Hz increments.

Dynamic Ramp of System Frequency test

A linear ramp of the system frequency applied as balanced three phase input signals:

$X_a = X_m \cos [\omega_0 t+pR_f t^2]$
$X_b = X_m \cos [\omega_0 t-2p/3+pR_f t^2]$

$X_c = X_m \cos [\omega_0 t+2p/3+pR_f t^2]$

Two tests are run at each nominal frequency F_0 where R = 1 (positive ramp) for one test then R = -1 (negative ramp) for the other test

Dynamic Step in Magnitude or Phase Tests

Balanced step changes to balanced three phase input signals

$X_a = X_m [1+k_x f_1(t)]$
$x \cos [w_0 t+k_a f_1(t)]$

$X_b = X_m [1+ k_x f_1(t)]$
$x \cos [w_0 t-2p/3+ k_a f_1(t)]$

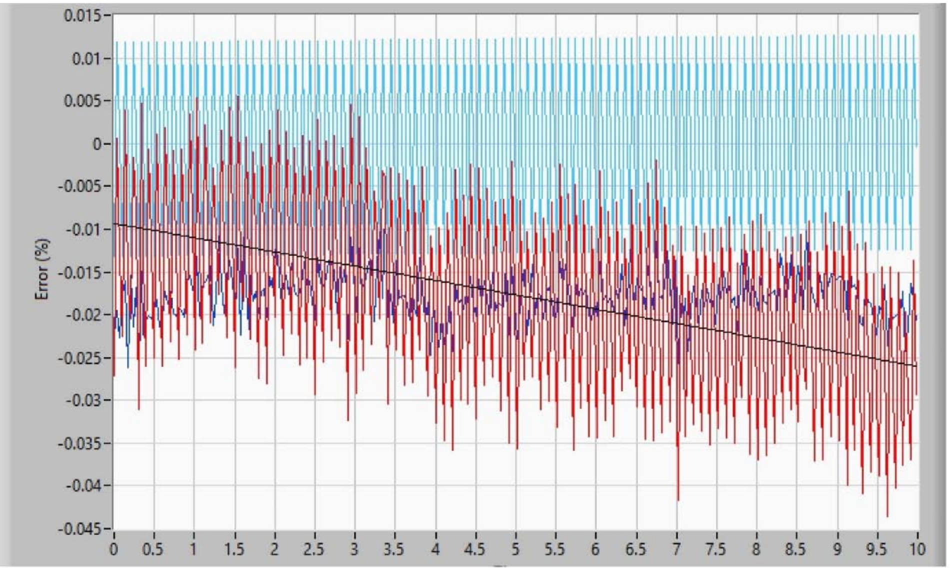
$X_c = X_m [1+ k_x f_1(t)]$
$x \cos [w_0 t+2p/3+ k_a f_1(t)]$

Equivalent time sampling technique:

- each test run is made of 10 step iterations
- 1st step occurs on the UTC second in the first iteration of the test,
- step occurs 1/10th of a reporting period later than the previous iteration
- data from all iterations are interlaced to form continuous waveforms
- timestamps adjusted to form a continuous time stream.
- resulting waveform is the equivalent of a waveform where the reporting rate is 10 times that of the reporting rate of the test.

Four tests are run for each nominal frequency F_0. Two magnitude step tests with step amplitudes of $\pm 0.1X_0$, and two phase steps with step amplitudes of ±10°.

Elements of PMU Calibrator Error

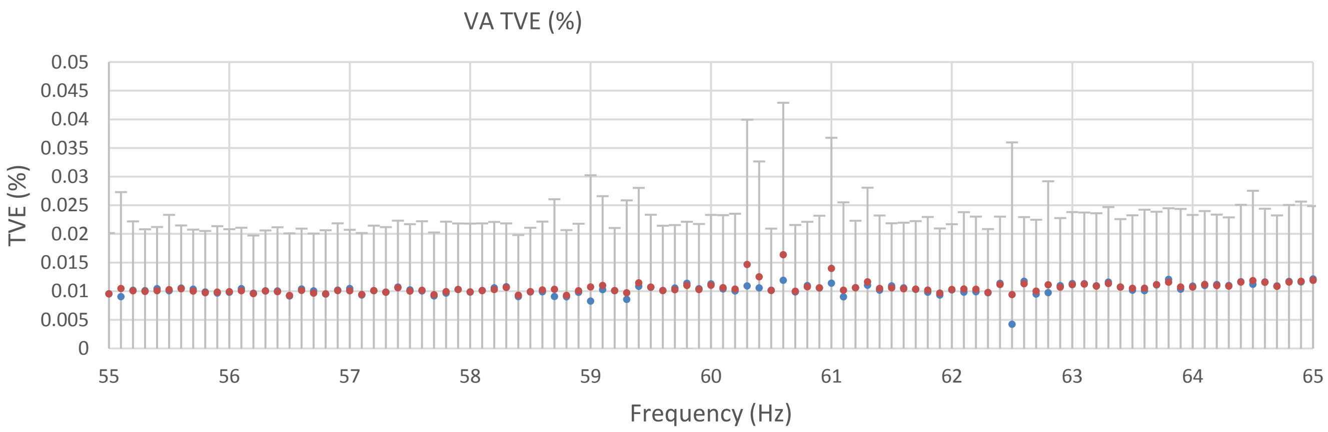


Phase Uncertainty:
Approx 0.04%
(about 0.022 degrees)

Above is an example of calibrator phase error during a 10-second test.

- Error shown in % (0.57 degrees of phase error per percent)
- Red curve is the reference phase minus the measured phase (error)
- Black line is the best fit linear curve showing phase drift
- Powder blue is best fit sinusoid of normalized (flattened) error
- Dark blue is the residual error after subtracting the phase drift and the sine error, offset to the midpoint of the drift.
- Uncertainty is the mean of the residual error (offset), half the drift, half the sine amplitude, and twice the standard deviation of the residual.

Calibrator uncertainty for the test type

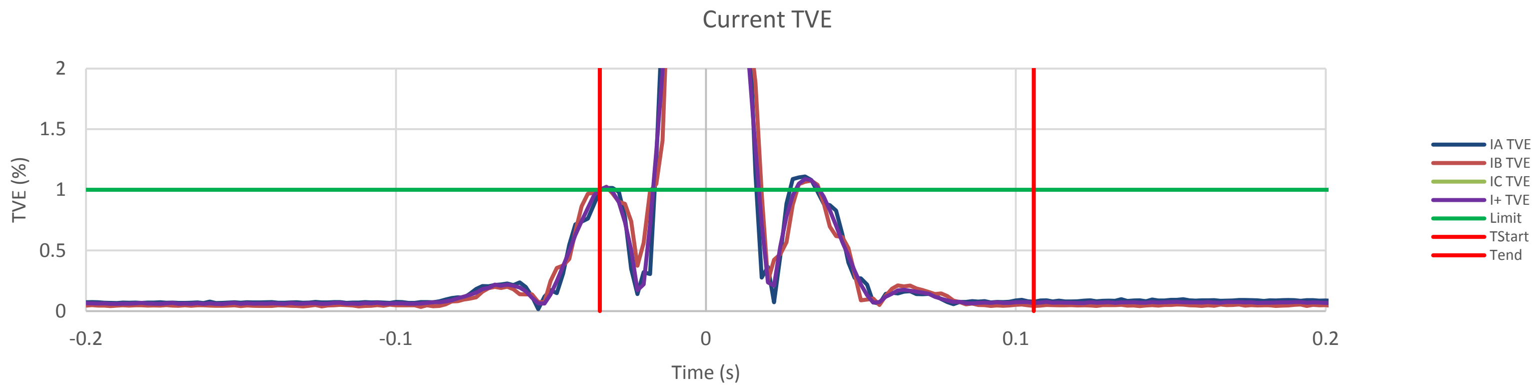


Above example is from a set of steady state tests from 55 Hz to 65 Hz

- Red dots show the normalized mean offset to ½ of the drift
- Blue dots show normalized mean not offset by the slope
  - Note that some tests did not drift much
- Grey error bars show the sum: ½ the drift, the sine peak amplitude and 2 times the standard deviation.

From the above data, we can take a single figure of merit for the test type uncertainty: Median of the red dots plus the mean of the error bars.

Uncertainty in the step test response time



Step response time is the period of time between the TVE, FE, or RFE rising above the limit, to the time it returns and remains below the limit:

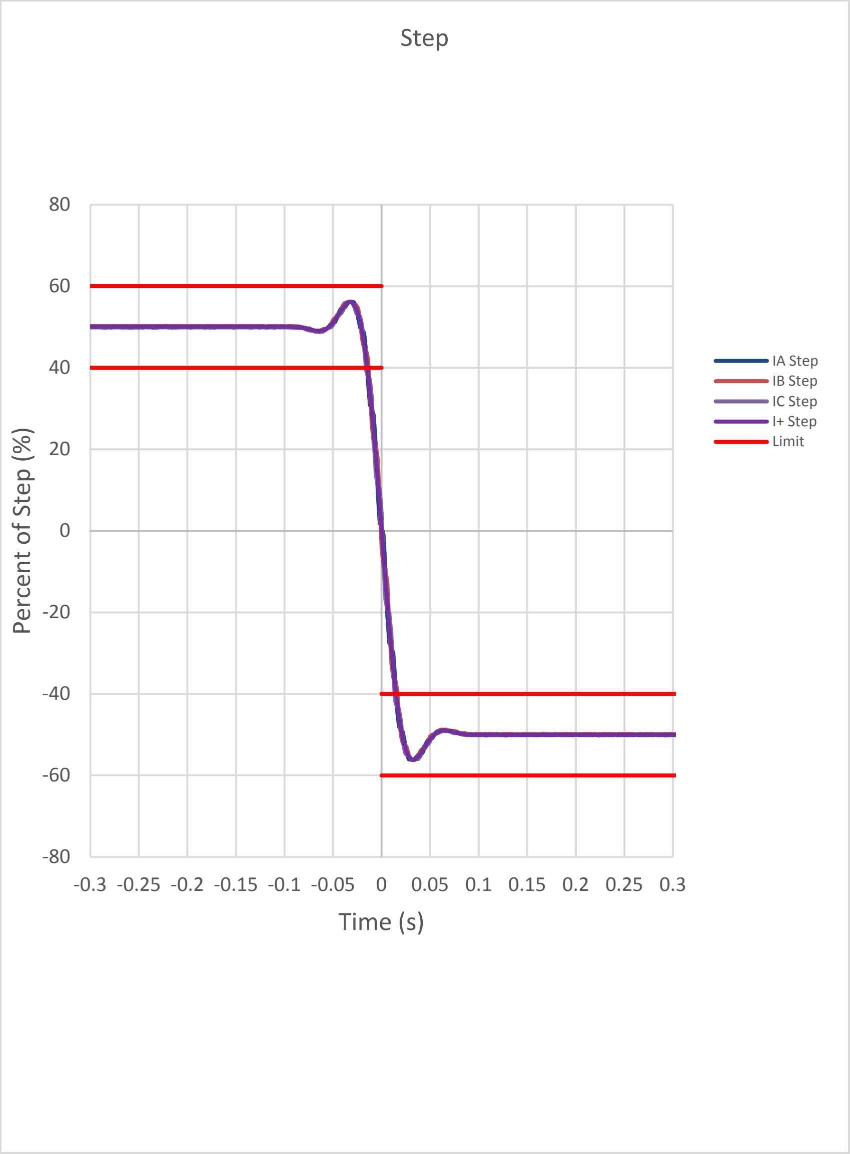
- Green horizontal line above shows the TVE limit of 1%
- Red vertical lines show the maximum allowable response time

Notice that the first crossing of the limit approaches very near the limit then goes back down.

- But the uncertainty of the TVE has the effect of shifting the entire curve up or down
  - So did the TVE cross the limit here or not?

The uncertainty of the step response time depends on the PMU being measured and not only on the Calibration System itself!

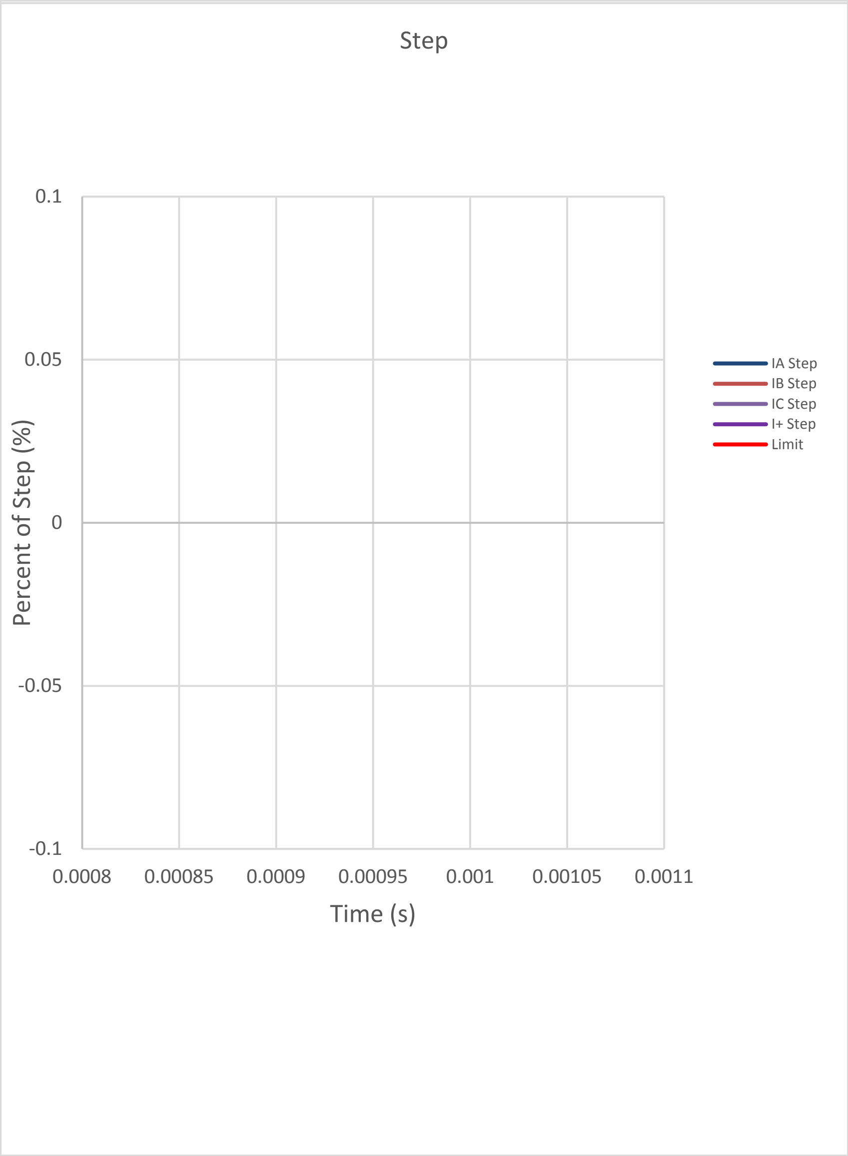
Uncertainty in step test overshoot and undershoot



Overshoot and undershoot of steps in phase and magnitude are the deviation from the initial and final values of phase and magnitude in terms of the percent of the step amplitude.

- In the plot to the right, the Y-axis is % of step from -50% to 50%.
- Red horizontal lines show the maximum and minimum allowable overshoot or undershoot
- Uncertainty in phase and magnitude has the effect of shifting the measurements up or down.

Uncertainty in step test delay time



Zoom into the where the step response plots cross zero an you see the delay time:

- The difference in time between the zero crossing of the reference and the zero crossing of the step response.
- Uncertainty in phase and magnitude has the effect of shifting the measurements up or down, thus moving the delay time depending on the slope of the response at the zero crossing.
- Like response time, delay time uncertainty is a function of the PMU as well as the PMU calibration system.

If your PMU is not traceably calibrated, you do not know what the error performance is going to be

AND…

Warmans Law:

Anything that can be configured, must be configured

Corollary to Warman’s Law:

Defaults aren’t

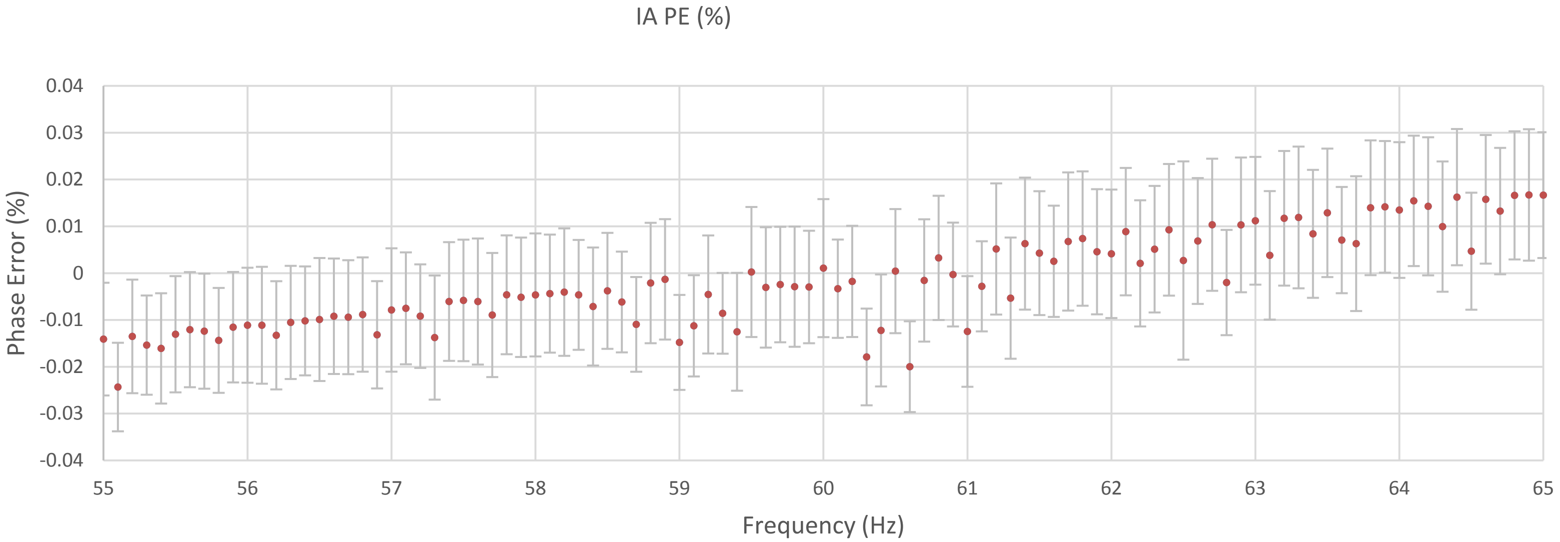
Your PMU can be calibrated with the configuration that you use

An idea:

We should be able to determine the power system signal conditions for any set of PMU data.

Given the amount of PMU error information in a calibration report for many different input signals, we should be able to “correct” the PMU estimate…

I call this process “unmodeling” the PMU data.



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