Precision Frequency Measurements in the Power System

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History
Early History

• Mostly analog measurements
• Panel meters, resonant-reed meters
• Local use only
• Accumulated frequency error (system time deviation) monitored with synchronous-motor master clocks at several locations
• These devices are narrow band, and largely insensitive to harmonics and most inter-harmonics
Analog frequency meters ca. 1960-1970

- Meters like this can still be found in use...
1970s

- Electronic counters become common
- Gated cycle count (cycles per gate period)
- Limited resolution at power line frequency is not very useful (1% in 2 sec.)
- Later, reciprocal method developed
- Allows much finer resolution (e.g., 1 ppm in one power-line cycle)
- Both are wide-band, dependent on zero crossings (and therefore noise sensitive)
Nixie tube counter
1980s

• First automated frequency measurements in the electric power system
• Using GOES satellite time reference
• To monitor system time deviation, i.e. accumulated time error due to frequency error
• Could keep time to better than 1 ms
• Could also measure frequency, but not the primary emphasis
1990s

- First deployment of SynchroPhasor Measurement Units (PMUs)
- GPS replaces GOES for time reference
- PMUs can measure frequency with adequate resolution for power system (<0.01 Hz)
- Anti-alias and out-of-band rejection of early PMUs limited by available technology
- Early PMU networks show the value of frequency data for system analysis
- IEEE 1344-1995 standard for PMUs
2000s

- IEEE C37.118-2005 introduces more stringent PMU requirements
- PMUs begin to be more widely deployed, still mostly pilot projects
- EIPP, now NASPI, promotes widespread use
- PMUs generally recognized as the best devices to measure frequency in the power system
- Some other frequency-only measurement devices also deployed
2010s

- IEEE C37.118.1-2011 introduces dynamic PMU requirements
- PMUs more widely deployed, connected to ISOs and other master control centers
- C37.118.1-2011 includes requirements for frequency measurement accuracy for the first time
- Vendors and independent labs (NIST) discover problems with these requirements
Now and Into the Future

- Frequency measurement is now accepted as the best tool to understand many aspects of system performance and operation
- The performance of frequency measurement technology continues to evolve
- The requirements of frequency measurement in the power system are very different from ‘conventional’ frequency counters, due to the presence of signals in addition to the system frequency
Accuracy Requirements for Measurements in the Power System
Voltage and Current

• Most devices make measurements ~1% of measured value, more or less

• Magnitude accuracy limited by several factors:
  • Measuring device
  • Instrument transformers
  • Calibration cycle

• This is generally adequate for most requirements, except some differential measurements
Phase Angle

• Most devices make measurements ~1 degree (1% TVE is equivalent to 0.57 degrees)
• Phase accuracy also limited by several factors:
  • Measuring device
  • Instrument transformers
  • Reference accuracy (absolute or relative)
• This is generally adequate for most requirements
• Absolute time accuracy requirements are not as stringent as commonly believed; 100 us is good enough for usable data in most applications
Power and Energy Metering

- Depending on class of measurement, typically a few tenths of a percent (0.1-0.6% class)
- Used for revenue metering ($$$)
- Requires ~10x lower errors than provided by a standard PMU
- Normally uses measurement-class instrument transformers, which are much more accurate than protection transformers, especially at nominal operating current levels
Frequency

- Measurements of 1% (0.5 or 0.6 Hz) not very useful - where 0.1 to 1% is adequate for most other measurements
- Must be approximately 100x better (0.001 - 0.01 Hz)
- Fortunately, frequency is a ‘relative’ measurement (phase variation vs. time), so many fixed errors cancel out
- Timebase error affects frequency measurements, but is not a significant factor: 1 ppm = 0.00006 Hz
Actual frequency measurement data
Frequency: the most demanding measurement we make

- Requirements for V, I, phase: 1% TVE
- Requirement for power and energy: 0.1-0.6%
- Requirement for frequency: 0.001-0.01%

So, to measure frequency, some PMU requirements, for instance out-of-band rejection, must be tighter than required to meet the TVE specs alone

- Zero crossing method is very wideband, essentially rejects nothing - so not useful for accurate frequency measurement in power system
State of the Art Measurement Performance

- Voltage: 0.02%
- Current: 0.03%
- Power/Energy: 0.025%
- Phase Angle: 0.01 degree (relative), 0.03 degree (absolute)
- Frequency: 0.001 Hz typical noise
  - Source: Arbiter Model 1133A Data Sheet
- ABB PMU in 0.1% class; most others worse
  - (Both of these PMUs are >10 years old designs)
What Limits Performance?

- Instrument Transformers do.
  - Measurement grade ITs: 0.3 to 2% max.
    ~2-3x rated ‘class’ actual performance including influence quantities.
  - Protection grade ITs: 5-10% at nominal levels
  - This error affects both magnitude and phase angle (can be considered as Total Vector Error or TVE)

- But these errors cancel for frequency measurements
What Really Is ‘Frequency’ in the Power System?
IED Terminals vs. Rotating Machines

- IEDs can only measure the signal applied to their terminals
- Often, what is desired is the ‘synchronous frequency’ of the rotating machines in the system
- Phase steps are caused by switchgear operation, VAR compensators, customer load switching etc.
- These phase steps cause spikes in the frequency measured in an IED
- Time constant of machines much longer than IED
Calculating Frequency in an IED

- Frequency typically calculated as rate of change of phase angle
- But, of what signal?
  - A-phase voltage
  - Positive-sequence voltage
  - Weighted average of A, B, C phase frequency
  - ?
- Should the IED attempt to ‘smooth out’ frequency measurements to mimic rotating machines?
Things Which Degrade Frequency Measurement Performance
Impact of Out-of-Band Signals

• Any single added signal frequency has two equal, simultaneous effects on the total signal:
  • Frequency (or phase) modulation
  • Amplitude modulation (flicker)
• This is from communications theory
• If these signals are not harmonics, they are often called inter-harmonics
• PMUs are required to reject these signals, or they fail to meet the TVE, Frequency, or ROCOF limits
Out-of-Band Signals - Example

• Assume a 10% signal, +20 Hz relative to system

• This causes a simultaneous 10% AM and 0.1 radian PM modulation of the system frequency (both of these have a ‘modulation index’ = 0.1)

• AM is rejected by any decent frequency estimator

• 0.1 radian PM causes a 2 Hz peak frequency modulation of the system signal (58 to 62 Hz in a 60 Hz system), because FM deviation = modulation index multiplied by the rate (20 Hz) - again from communications theory
Out-of-Band Signals - Example cont’d

• For reporting rate of 30/s or less, this signal must be attenuated by 68 dB to meet the standard for ROCOF

• Whereas for TVE, only 20 dB of attenuation is needed

• The test conditions in C37.118.1-2011 (10% interfering signal level) are worse than typical operating conditions, but they are used to make sure that under more realistic conditions, the PMU measurements are not degraded
Effect of Harmonics

• Harmonics will alias close to the system frequency, with an offset equal to the system frequency error multiplied by the harmonic number (in a PMU with UTC-synchronous sampling)

• Therefore they can resemble low-frequency system modes

• So they must be attenuated enough (before decimation to the reporting rate) that this effect is not objectionable
Harmonic Attenuation

- P-class filter does well (deep nulls at harmonics)
- M-class requirements presently under review
Noise

- Noise comes from many sources:
  - Switchgear operation on the system
  - IED front-end noise (thermal noise, shot noise)
  - ADC noise (quantization noise, differential non-linearity, aperture jitter)
  - Timebase noise (oscillator phase noise, divider noise, spurious coupling onto ADC sampling clock)
- Noise in the IED is normally not the limiting factor in frequency measurement, if the IED is well-designed
Latency of Frequency Measurements

• Frequency estimation is done by finding the difference in phase angle from successive phasor estimates

• The group delay of the resulting estimate is increased by half the time between the phase angle measurements

• If PMU data is to align properly to the time tag, this must be allowed for
Effect of Timebase Errors is Inconsequential

- 1 ppm error = 0.00006 Hz frequency error (at 60 Hz)

- What is typical timebase error?
  - Free running processor oscillator: 100 ppm
  - TCXO: 1 ppm
  - OCXO: 0.01 ppm
  - Inexpensive oscillator locked to GPS: 0.001 ppm
  - OCXO locked to GPS: <0.001 ppm
  - Cesium beam or GPS, averaged over one day: 0.000001 ppm
Conclusions
Conclusions

- Frequency measurements have become an essential tool to understand power system performance and operation

- Measurement technology is useful right now, and is continuing to evolve

- Measuring frequency in the power system is much more complex than measuring frequency in a lab, because of the effects of interfering signals
Thank you. Questions?