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Precision Frequency Measurements in the Power System

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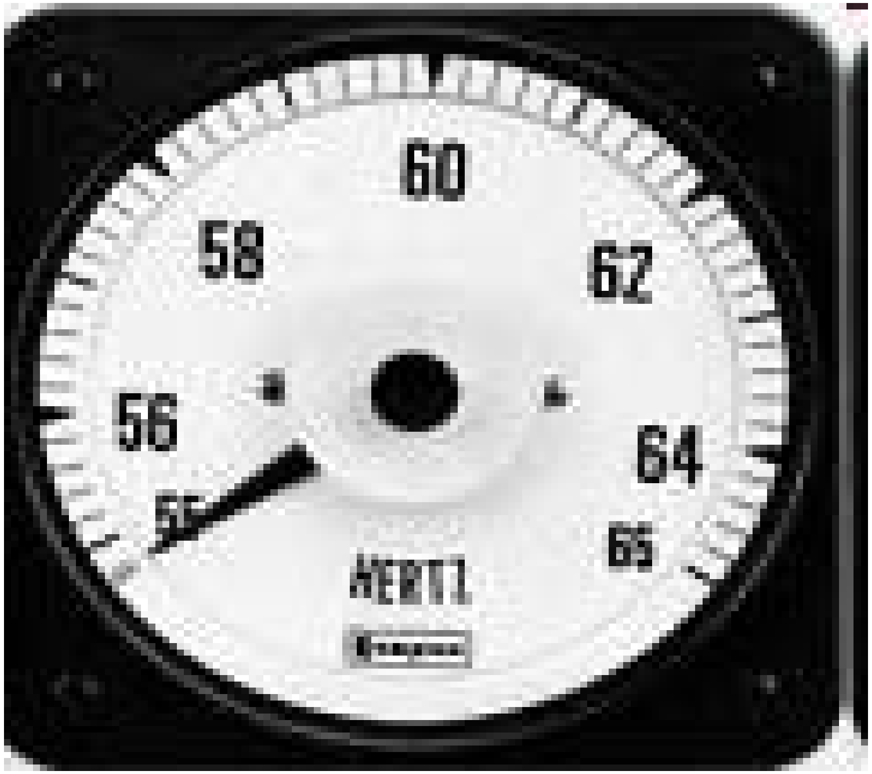
History

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**

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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

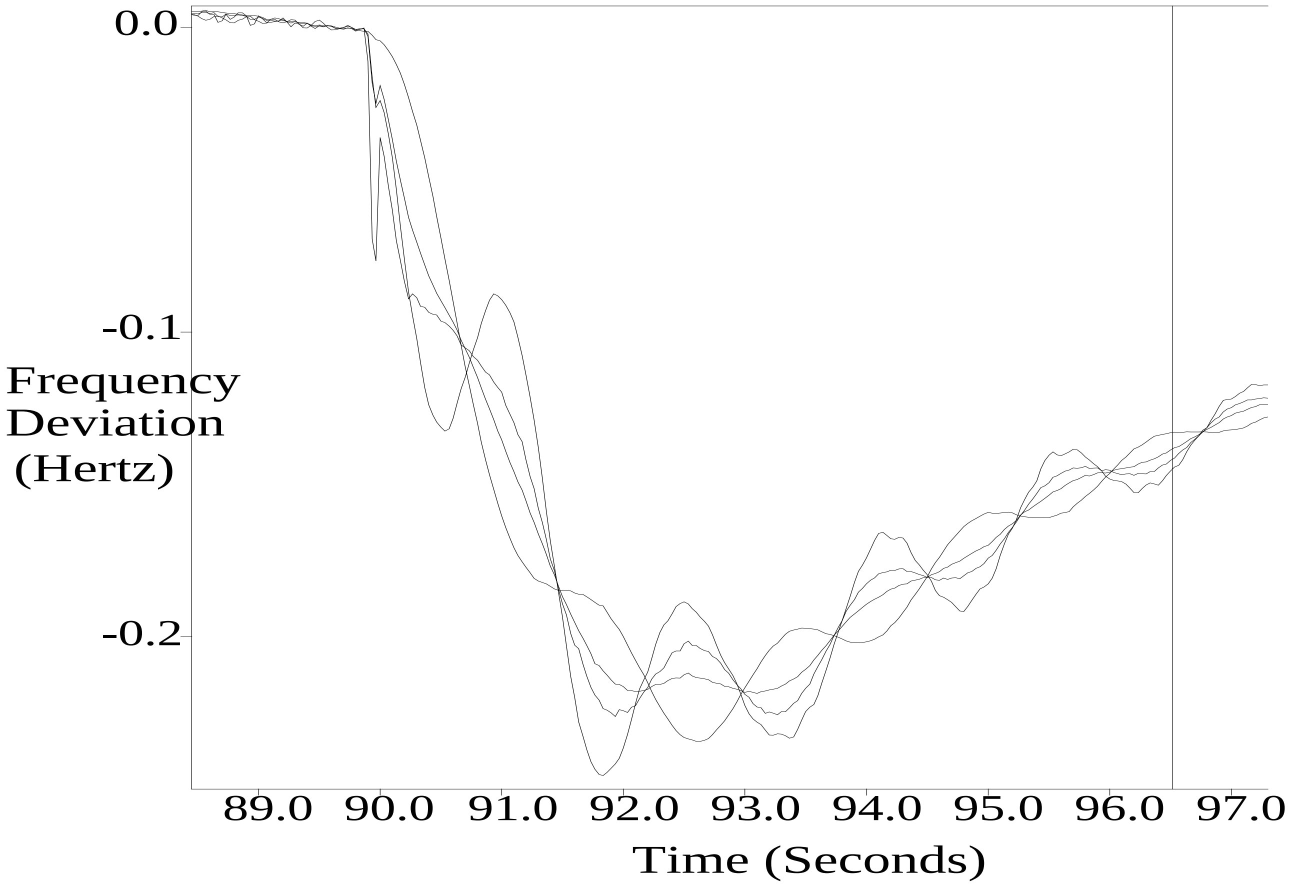
Power and Energy Metering

- 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**

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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

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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

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Thank you. Questions?