Micro-synchrophasors for distribution grids: *instrumentation* lessons learned (so far!)

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Additional thank-you: ARPA-E projects assign Intellectual Property to the developers, so we have many patents at various stages. I will try to identify during my talk.
ARPA-E (Power Standards Lab) Micro-PMU
Lesson Learned:
Expect moderately harsh environments, even at national labs in California.

ARPA-E (Power Standards Lab) Micro-PMU
Lesson Learned:
Mounting location in the field may be... er... unexpected.
Micro-PMU requirements (1)

- 100V-690V applications: ±1,000V rating, ±6,000V measurement range, ±15,000V insulation test
- Ultra-precise CT’s: 5-amp, individually calibrated to 50th harmonic, ±0.01%, ±0.001° (fundamental)
- Minimum 2-week data buffer, or 16 gigabytes. Drop-anywhere communications via cell phone Ethernet
- Harsh environments...

http://PQube3.com/tough
Micro-PMU requirements (2)

- **Lesson Learned:** Accuracy is not as important as resolution, and short-term stability.

- Micro-PMU resolution and short-term stability:
  - Magnitude measurements: ±0.01% (±0.00001% for some applications – 100 PPB)
  - Angle measurements: ±0.010° (±0.002° for some applications)
  - Roughly 2 or 3 orders of magnitude better TVE than transmission PMU specs...
Initial micro-PMU Field Installations

• Lesson Learned: Line-to-ground or Line-to-Neutral voltage measurements?
  • Standardized on phase-to-earth voltage measurements

• Lesson Learned: Cyber probes almost immediately.
  • Full Linux firewall built inside micro-PMU, and more coming

• Lesson Learned: GPS orbital “surprises” -- to me, anyway
  • No issues throughout the project, due to special GPS receiver(?)

• Lesson Learned: always surprises!
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Technical instrumentation lessons learned (1)

• **Example Lesson Learned:** an anti-alias filter can use up your entire timing error budget.
  • At ±0.001° your total time error budget is 50 nanoseconds. (Remember, short-term stability!)
  • With 64 samples per cycle, your anti-alias filter has a cut-off frequency of 2 kHz ~ 500,000 nanoseconds.
  • So if the capacitors in your anti-alias filters can be are ±0.01% unstable in value... there goes your entire timing-error budget.
  • (Patent still in process on this one.)
Technical instrumentation lessons learned (2)

• Example Lesson Learned: A simple GPS cable shield can use up your entire magnitude error budget.
  • At ±10PPM, with a 3.0000V reference, your entire error budget is 30 microvolts.
  • With a 24-bit A-to-D converter, each tick is 0.13 microvolts.
  • With a 1 microamp cell-phone-RF-current flowing through your GPS antenna shield, then across your instrument ground through a 50-ohm path at 3 GHz, you’ve got a 50 microvolt problem.
  • (Patent issued this week! Only 4 years in process at USPTO... sigh.)
Technical instrumentation lessons learned (3)

- Example Lesson Learned: Higher samples-per-cycle can be a challenge too.
  - Eases anti-alias filter design, transferring it to digital domain.
  - Micro-PMU uses 512 samples-per-cycle at 50.000 Hz or 60.000 Hz.
  - But downsampling to synchrophasor calculation input must be done carefully.
- Lesson Learned: simple decimation works in the lab, but sensitive to specific real-world harmonics.
Technical **communication** lessons learned  

- **Example Lesson Learned:** every time the distribution grid does something interesting, communication fails.
  - Streaming protocols, like C37, are not the best choice for distribution grid applications.
    - In most C37 implementations, all data is lost when comms is down.
  - Micro-PMU stores everything in an ordinary file structure, 2 weeks of backup.
  - UC Berkeley software (1) gathers, (2) confirms, then (3) remotely deletes.
  - Optimal for research, but not optimal for control.
Technical communication lessons learned (2)

• Example Lesson Learned: C37 streaming is pretty good for adding micro-PMU measurements to control loops.
  • Local network, and unlikely to go down.
  • OK if network fails when power fails.
  • In control loops, the meaning of time-stamps becomes important, and confusing.
  • Kirkham’s goodness-of-fit could become important.
Technical communication lessons learned (3)

• Example Lesson Learned: Some C37 receivers struggle with 120 samples per second.
  • 120 samples per second is the slowest a micro-PMU can go.
  • Roughly 500 megabytes per day from each micro-PMU, or for a smallish set of 60 micro-PMU’s:
    • 1 terabyte of raw data per month
    • 4 terabytes of “interesting” calculated data per month.
Distribution grid lessons learned (1)

• Example Lesson Learned: PT’s and CT’s are **not** accurate, but they are **stable**.
  • Can be calibrated to some extent – an order of magnitude better.
  • Important to choose algorithms that are sensitive to stability, not accuracy.
  • Distribution grid sensors exist that should not be used for uPMU measurements.
    • Poor stability of capacitive-coupled voltage sensors, lay-in current sensors
Distribution grid lessons learned (2)

• Example Lesson Learned: Distribution grid models can be quite wrong.
  • Example: assumed lengths of conductors, assumed configuration
  • Example: the impedance of a 3-phase run is NOT the same on all three phases.
  • Example: simplifying assumptions may not match the real world measurements.
  • Good news: use micro-PMU measurements to update grid models.
Distribution grid lessons learned (3)

- **Example Lesson Learned:** For distribution, costs matter.
  - **ARRA:** $340 million, 1100 transmission PMU’s installed: $40k(?) per point
    - Includes instrument development, software dev, installation, coms
  - **ARPA-E:** $4 million, 100 distribution microPMU’s installed: $10k(?) per point
    - Includes instrument development, software dev, installation, coms
    - Factor of 10, but two more factors of 10 would be useful…
Lessons learned: synchrophasor domain vs. time domain or frequency domain

Harold Kirkham – I’m paraphrasing – pointed out to me that synchrophasor measurements answer the question “if – IF! – the underlying signal were a cosine wave, what would its amplitude be, and what would its phase angle be relative to a timing pulse?”

THIS IS IMPORTANT.

1. On distribution grids, the underlying signal is NOT a cosine wave.
   a. In steady state, both voltages and currents have significant harmonics.
   b. During any interesting event, the voltages and currents are rapidly changing.
2. For harmonics, you’re often better off measuring in the frequency domain, not the synchrophasor domain.
3. For rapidly changing voltages and currents, you’re often better off measuring in the time domain, not the synchrophasor domain.
4. Maybe we should reserve the synchrophasor domain for quasi-steady-state fundamental analysis: grid control-loop stability, grid impedances, and the like?
Good news: we can flip the micro-PMU back and forth between synchrophasor recording, or frequency domain and triggered-time-domain recording

Internally, it’s all the same commercially-available instrument: micro-PMU, or PQube 3 (http://PQube3.com).

- Slightly different calibration procedure, but merging now
- Not even a firmware change – but it runs one function, or the other
- ARPA-E project requirements:
  - Ultra-precise microPMU measurements, and
  - IEC 61000-4-30 Class A power quality triggered measurements, and
  - IEC /ANSI Class 0.2 Certified revenue measurements, and
  - UL-recognition
- Some projects putting in both instruments, side-by-side (DARPA, NSA, etc.)
PQube 3: time domain and freq domain

Lesson Learned:
Time domain data and Frequency domain data nicely supplement Synchrophasor data.
Example PQube 3 / microPMU triggered-time-domain recording

512-samples-per-cycle, “Waveshape change” trigger:

No software required – Instrument emails this GIF, plus Microsoft Excel files...
Example PQube 3 / microPMU triggered-time-domain recording

4-million-samples-per-second, “Impulse” trigger:

No software required – Instrument emails this GIF, plus Microsoft Excel files...

High Frequency Impulse

- Peak: 194Vpk
- Rate of Rise: 56V/µs
- Total Volt-Seconds: 0.00V-s
- Peak Volt-Seconds: 0.01V-s
- Joules (50 Ohm, 150 V Threshold): 0.000J
- Trigger Threshold: 150V

L-E Voltage

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Example PQube 3 / microPMU frequency-domain recording

1-million-samples-per-second, 2kHz-150kHz voltage

No software required – Instrument emails this GIF, plus Microsoft Excel files...

L-E 2kHz-150kHz Conducted Emissions

Max Values

Coverage: 100.0%
**ARPA-E lesson learned: MicroPMU Quick Start Kit**

*Fast and easy way to get started on Micro Synchrophasors*

**Description**

PSL's Complete Quick Start package includes everything you need to get started!

1. **Four pre-configured ARPA-E micro-synchrophasor instruments:**
   - a. 1-phase or 3-phase 10-volt - 1000-volt voltage input channels, 50/60 Hz
   - b. 5-amp snap-on current transformers for current input channels
   - c. Calibrated, certified, isolated GPS receiver for each instrument
2. **Cables** - every cable you need to connect-and-go, with both ends of each cable carefully labeled
3. **Powerful Dell Blade server**
   - a. pre-loaded with research-grade support software, including the amazing BIT/DB uPMU package
   - b. Configured to support up to 15 micro-PMU instruments
   - c. 64 gigabytes of RAM, y terabytes of disk storage
   - d. 16-port switch

**Wireless router (optional)**

**Highlights**

- The Quick Start Kit comes with a private, physically-isolated, lab-bench LAN (local area network)
- No need for IT Department approval or support – does NOT connect to your institution's internet
- No need for internet connections
- Later, you can easily expand to internet-based connections to your uPMUs... but get started quickly with local connections

**Setup Instructions**

Here are the complete, step-by-step instructions for getting a 4-uPMU Quick Start Kit up and running on your lab bench:

1. Unpack your uPMU Starter Kit boxes.
2. Plug in your pre-labeled cables - just read the labels on each end of every cable, and pop them in!
   - 1. plug into a 100V-240V mains socket.
   - 2. position the GPS receivers near a window, so they can see the sky.
   - 3. Connect your laptop to the Quick Start Kit Wi-Fi router.
   - 4. Type the router's Gateway IP (usually 192.168.1.1 or 10.0.0.1) into your browser.
   - 5. Start plotting, reviewing, studying the measurements from your uPMUs!
Thank you.

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