Phasor Measurement: A Short History of the Technology and the Standards

Harold Kirkham
Pacific Northwest National Laboratory
harold.kirkham@pnnl.gov

Purpose of this talk

- Distribution PMUs exist
- It would be well to have standards

- Problems with existing standards can be avoided
- *If we are prepared to learn from history*

Overview

Part 1: Technology Review

Part 2: Standards Review

Part 3: Suggestions

Part 1

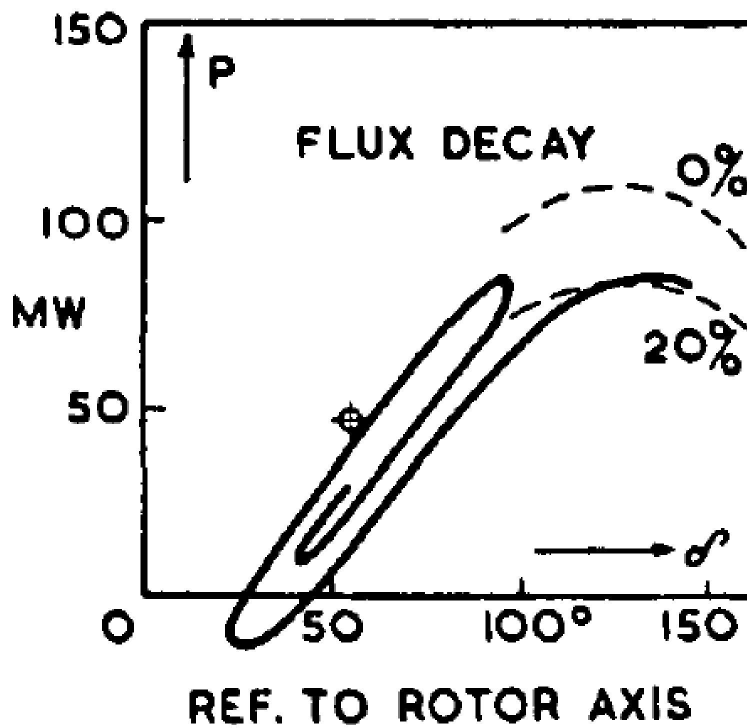
Technology Review

Early work

- Brownlee (1954) showed losses could be estimated if angle was known
  - Later got a patent for some of this
- British Central Electric Authority (1956) observed generator with faulted system
  - First ever real power system phase-plane plot?
- IREQ (1981) got interested

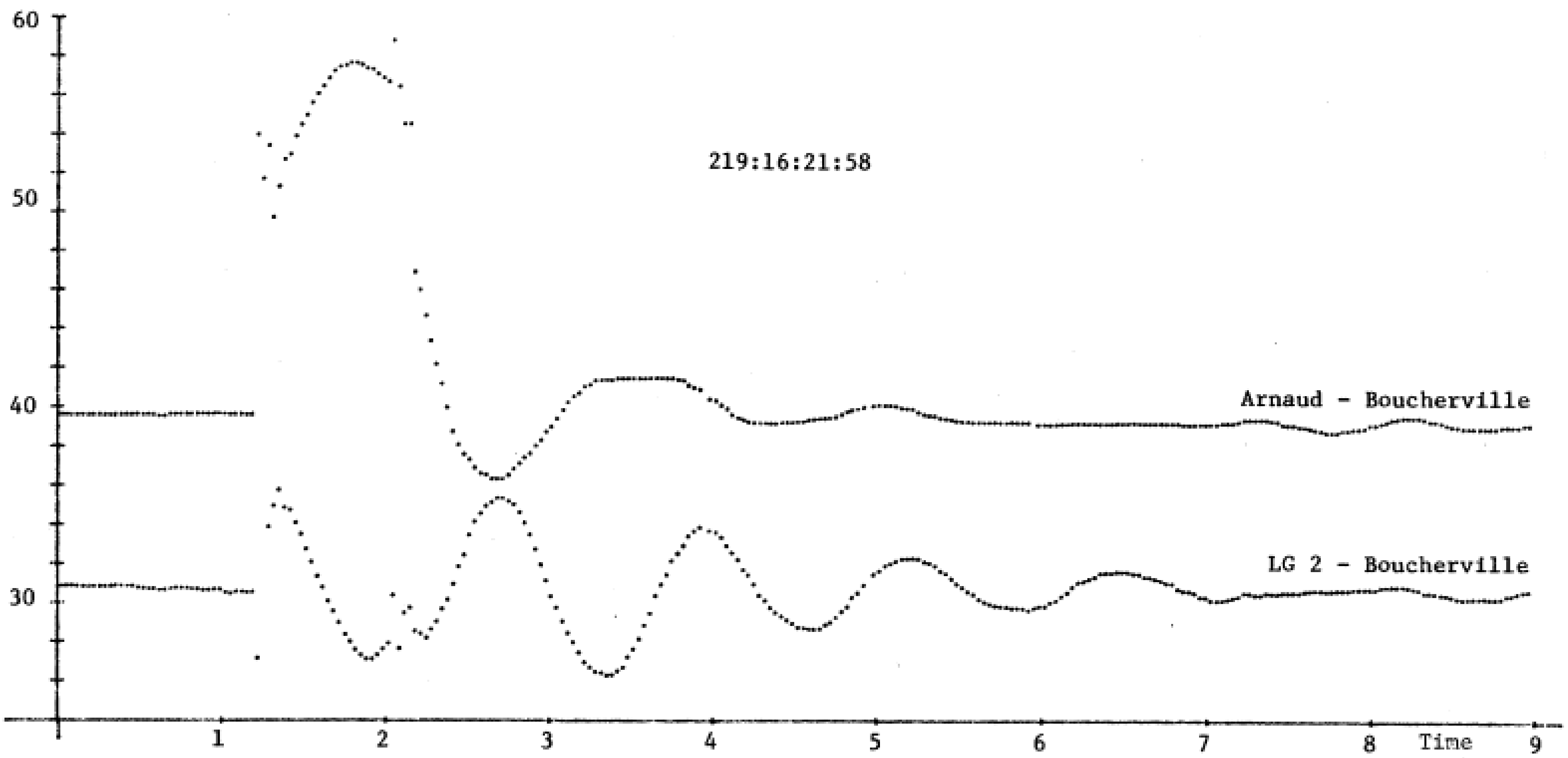
From Busemann and Casson, 1958: a phase-plane plot

RESULTS OF FULL-SCALE STABILITY TESTS ON THE BRITISH 132 kV GRID SYSTEM



From Missout *et al,* 1981: digital angle measurement

DYNAMIC MEASUREMENT OF THE ABSOLUTE VOLTAGE ANGLE ON LONG TRANSMISSION LINES



Voltage Angle Between Points

Figure 16

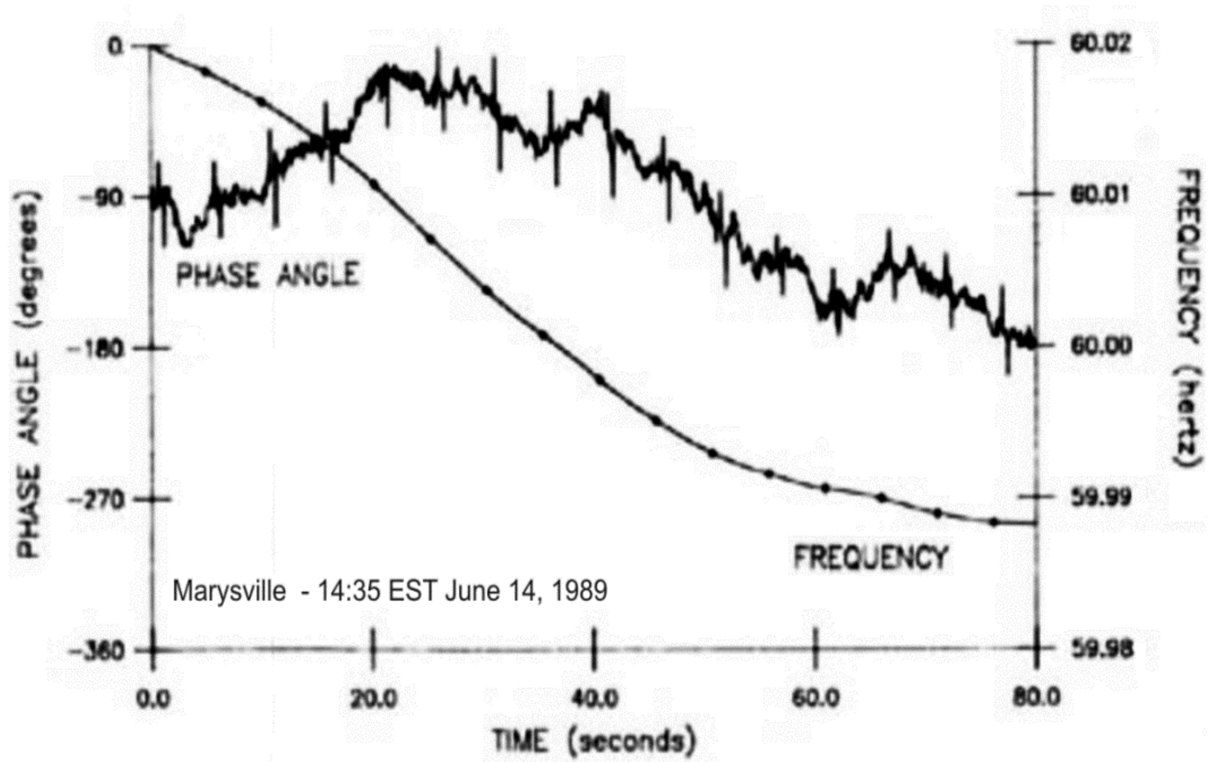
The PMU as we know it begins . . .

Phadke’s team (1972) was capturing voltage samples off a 138-line, and calculating phasors off-line.

Phadke, Thorp and Adamiak (1979) use a RISC computer that approached real-time performance but “freezes” the observations

There is the light-bulb moment. They are seeing angle change from moment to moment!

The PMU begins . . .



Disclosure

Phadke, Thorp and Adamiak (1983) disclosed their system, showing how to measure frequency, phase and rate of change of frequency in a way that required relatively short samples of the waveforms

GPS was launched, so as to make it workable

Macrodyne made a commercial version

Part 2

Standards Review

The first IEEE standard

IEEE Std 1344-1995

Working group included

- **Arun Phadke**
- **Ken Martin**
- Jim Thorp
- Mark Adamiak
- Jay Murphy
- Stan Horowitz
- Gabriel Benmouyal
- Jack Kusters

IEEE Std 1344-1995

- Mixture of requirements and tutorial
- Set 1 µs timing accuracy—achievable
- Specified 1 PPS
  - But later allowed alternatives
- Allowed for losing time ref, set speed limit for return
- "Recommended" certain scanning rates
  - Allowed for phase lock to signal
  - Showed how to calculate report time
- Called A and φ the *phasor,* added *frequency, ROCOF*

IEEE Std 1344-1995

- Used time of last sample to indicate window width
- Tried to help with words like:

If the 1 PPS signal occurs at time to, the measured phasor corresponding to a sinusoidal signal $v(t) = \sqrt{2}V \cos(\omega_o t + \varphi)$ with a frequency ω_o is $V e^j(\omega_o t_o + \varphi)$. For steady-state signals at off-nominal frequency ω_1, the measured phasor with time-tag corresponding to the 1 PPS instant to is $V e^j(\omega_1 t_o + \varphi)$.

- Set no requirements on performance

The second IEEE standard IEEE Std C37.118-2005

Working group included

- ~~**Arun Phadke**~~
- **Ken Martin**
- ~~Jim Thorp~~
- Mark Adamiak
- Jay Murphy
- ~~Stan Horowitz~~
- ~~Jack Kusters~~
- Gabriel Benmouyal
- Gustavo Brunello
- Bill Dickerson
- Vasudev Gharpure
- Arun Phadke
- Veselin Skendzic

IEEE Std C37.118-2005

- Still mixture of requirements and tutorial
- Set 1 μs timing accuracy—achievable
- ~~Specified 1 PPS~~
    - ~~But later allowed alternatives~~
- ~~Allowed for losing time ref, set speed limit for return~~
- ~~“Recommended” certain scanning rates~~
    - ~~Allowed for phase lock to signal~~
    - ~~Showed how to calculate report time~~
- Called *A* and φ the *phasor,* added *frequency, ROCOF*

IEEE Std C37.118-2005

- ~~Used time of last sample to indicate window width~~
- ~~Tried to help with words like:~~

~~If the 1 PPS signal occurs at time to, the measured phasor corresponding to a sinusoidal signal v(t) = √2*V* cos ($\omega_o t_o + \varphi$) with a frequency ω_o is *V* $e^j(\omega_o t_o + \varphi)$. For steady-state signals at off-nominal frequency ω_1, the measured phasor with time-tag corresponding to the 1 PPS instant to is *V* $e^j(\omega_1 t_o + \varphi)$.~~

- Set requirements on performance

IEEE Std C37.118-2005

- Set requirements on performance
  - Two “levels” of compliance
  - 1% TVE, but different dynamic range, distortion

- Ruled out response time issues
- Ruled out transient conditions

This standard does not specify limits to measurement response time, accuracy under transient conditions . . .

IEEE Std C37.118-2005

- Wrote:
  Harmonizing a common set of dynamic performance requirements *should be undertaken* once the range of implementations and measurement applications has been more fully explored.

- Wrote:
  At this time, dynamic performance under transient conditions *should be specified* and verified by the users to meet their application needs.

The third IEEE standard IEEE Std C37.118.1-2011

Working group similar to last one, larger

Now included

- Jerry Stenbakken
- Allen Goldstein
- Harold Kirkham

IEEE Std C37.118.1-2011

- Set requirements on performance
  - Two ~~“levels”~~ classes of compliance
  - 1% TVE, but different dynamic range ~~distortion~~
- Much space devoted to *testing*

IEEE Std C37.118.1-2011

Much entertainment on subject of latency:

Latency in measurement reporting is the time delay from when an event occurs on the power system to the time that it is reported in data. This latency includes . . . where the event occurs within the reporting interval.

For purposes of this standard, *PMU reporting latency* is defined as the maximum time interval between the data report time as indicated by the data time stamp, and the time when the data becomes available at the PMU output

- Got that?

IEEE Std C37.118.1-2011

The standard writes this:

PMU real-time output reporting latency shall be determined to an accuracy of at least 0.0001 s. See Table 12.

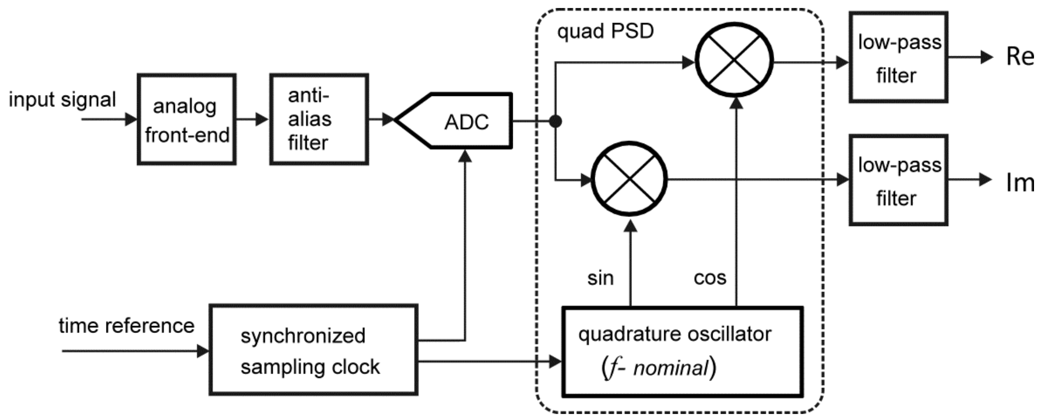
Table 12—Measurement reporting latency

Performance class	Maximum measurement reporting latency (s)
P class	$2/ F_s$
M class	$5/ F_s$

- Is that supposed to be *Latency in measurement reporting* or *PMU reporting latency*?

IEEE Std C37.118.1-2011

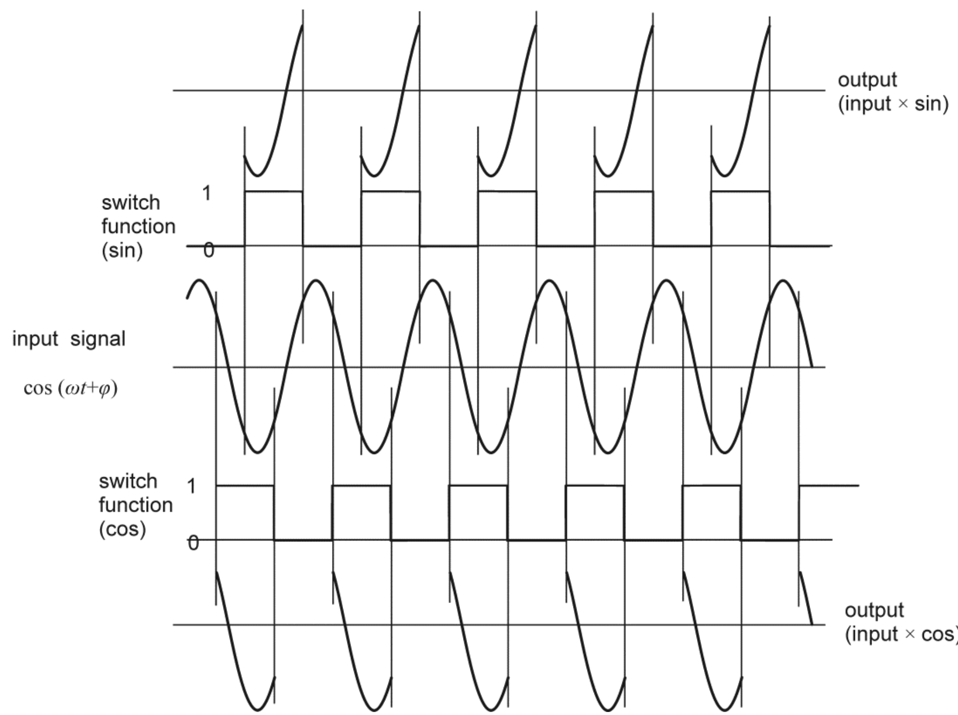
Standard introduces a (non-normative) "Reference Model"



- Note the PSD

IEEE Std C37.118.1-2011

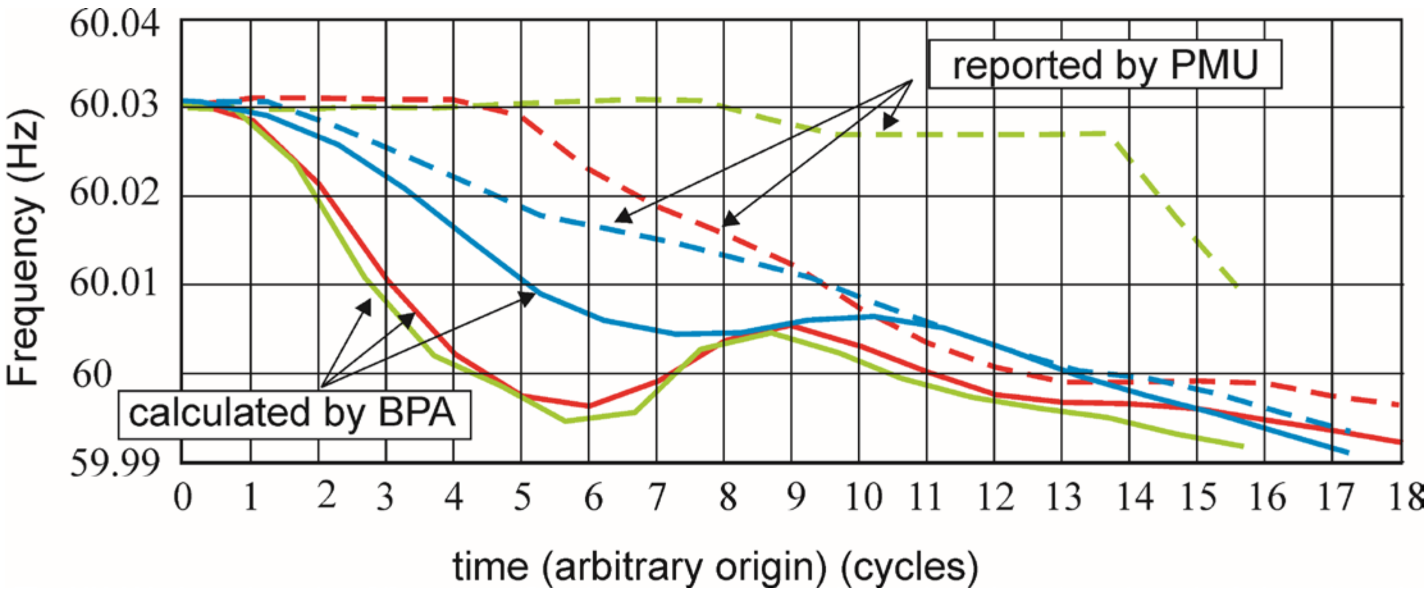
PSD



- Could be full-wave, but still needs a filter

IEEE Std C37.118.1-2011

Results from BPA:



Filter lag??

IEEE Std C37.118.1-2011

Standard writes:

Note that the allowed TVE, FE, and RFE may be exceeded during a "transition time" before and after a sudden change in ROCOF is made. The error calculation shall exclude measurements during the first two sample periods before and after a change in the test ROCOF. Sample periods are the reporting interval, 1/Fs, of the given test. For example, if the reporting rate Fs = 30 fps, then *measurements reported during a period of 67 ms before and after a transition shall be discarded.*

Comforting to the user??

The third IEEE standard is amended IEEE Std C37.118.1a-2014

Reference Model could not meet ROCOF requirements:

Requirements “relaxed” almost out of existence

IEEE Std C37.118.1a-2014

Table 4—Steady-state frequency and ROCOF measurement requirements

Influence quantity	Reference condition	Error requirements for compliance			
		P class		M class	
Signal frequency	Frequency = f_0 ($f_{nominal}$) Phase angle constant	Range: $f_0 \pm 2.0$		Range: $f_0 \pm 2.0$ Hz for $F_s \leq 10$ $\pm F_s/5$ for $10 \leq F_s < 25$ ± 5.0 Hz for $F_s \geq 25$	
		Max FE	Max RFE	Max FE	Max RFE
		0.005 Hz	~~0.01 Hz/s~~ 0.4 ~~1~~ Hz/s	0.005 Hz	~~0.01 Hz/s~~ 0.1 Hz/s
Harmonic distortion (same as Table 3 - single harmonic)	<0.2% THD	1% each harmonic up to 50th		10% each harmonic up to 50th	
		Max FE	Max RFE	Max FE	Max RFE
	$F_s > 20$	0.005 Hz	~~0.01 Hz/s~~ 0.4 ~~1~~ Hz/s	0.025 Hz	~~6 Hz/s~~ Limit suspended
	$F_s \leq 20$	0.005 Hz	~~0.01 Hz/s~~ 0.4 ~~1~~ Hz/s	0.005 Hz	~~2 Hz/s~~ Limit suspended
Out-of-band interference (same as Table 3)	<0.2% of input signal magnitude	No requirements		Interfering signal 10% of signal magnitude	
				Max FE	Max RFE
		None	None	0.01 Hz	~~0.1 Hz/s~~ Limit suspended

Part 3

Suggestions

avoid this:

The IEEE standard schedule steamroller

Some things just take longer to settle, and working on the early ones can back you up against the wall for resolving later ones.

Try to figure some of this out BEFORE you start!

Conclusions

- The technology has moved on
- The standard has been updated to keep up
- We (distribution) should try to do even better