Digital Voltage and Current Sensors

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NASPI Webinar
May 26, 2021

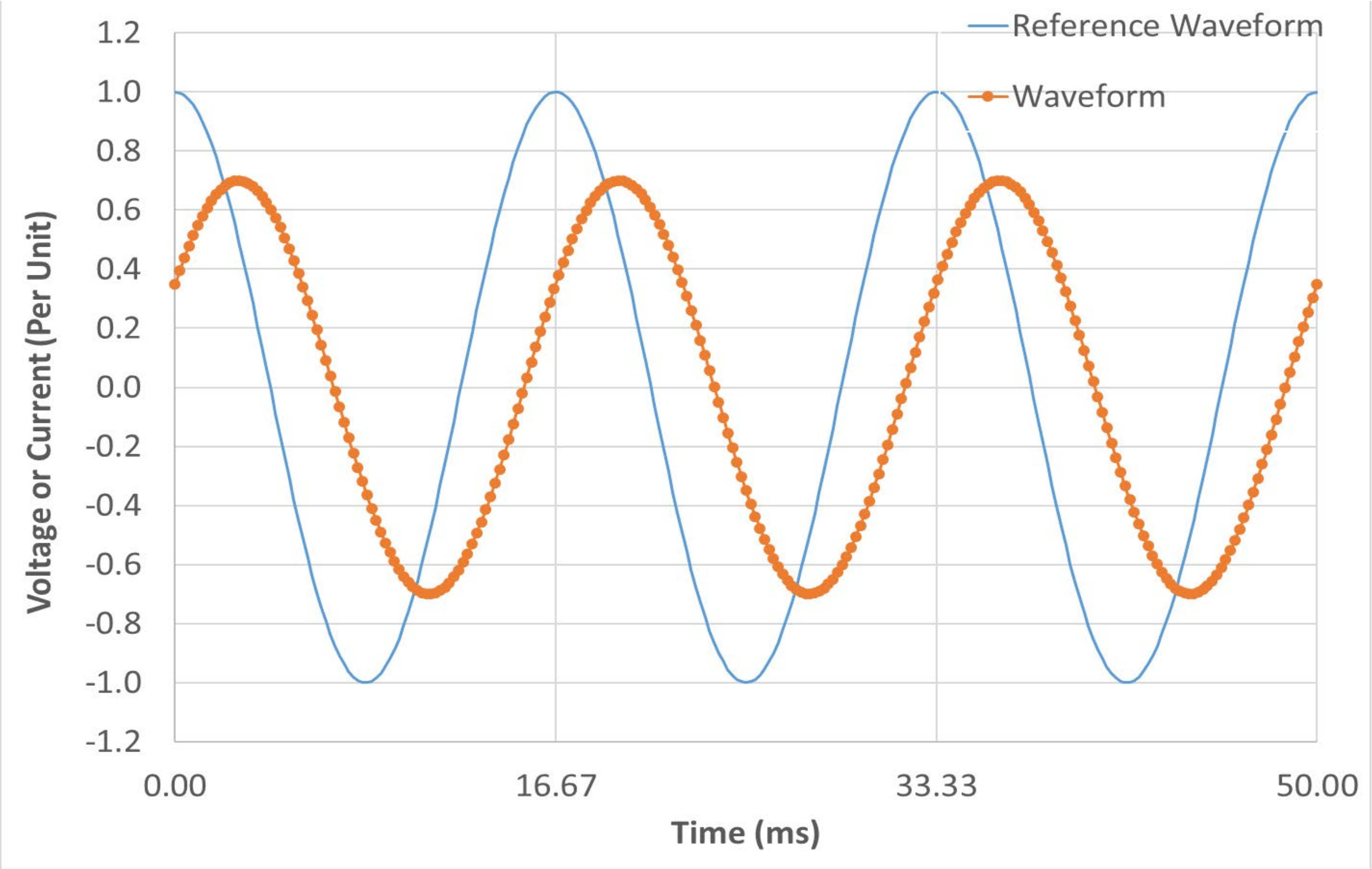
Outline

- Voltage and current on the grid
- What is a digital voltage or current sensor
- V & I sensing technologies
- Serving multiple applications
  - Multiple requirements
  - Layered architecture
- Measurement speed, sampling rate and bandwidth
  - Faster phenomena
- Waveform vs. calculated quantities
  - Lossy compression?

Voltage and Current Waveforms – Ideal

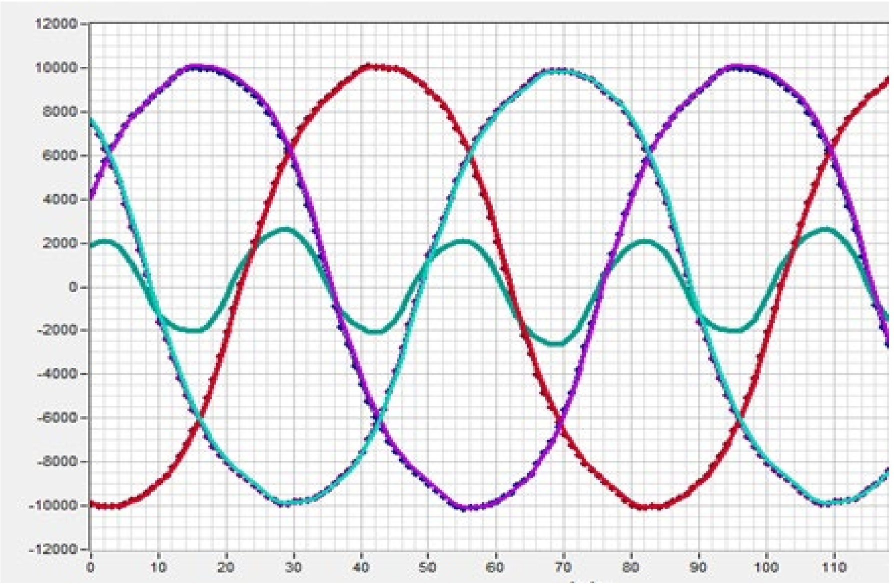
$$v\ (t) = V\cos(\omega t + \varphi)$$

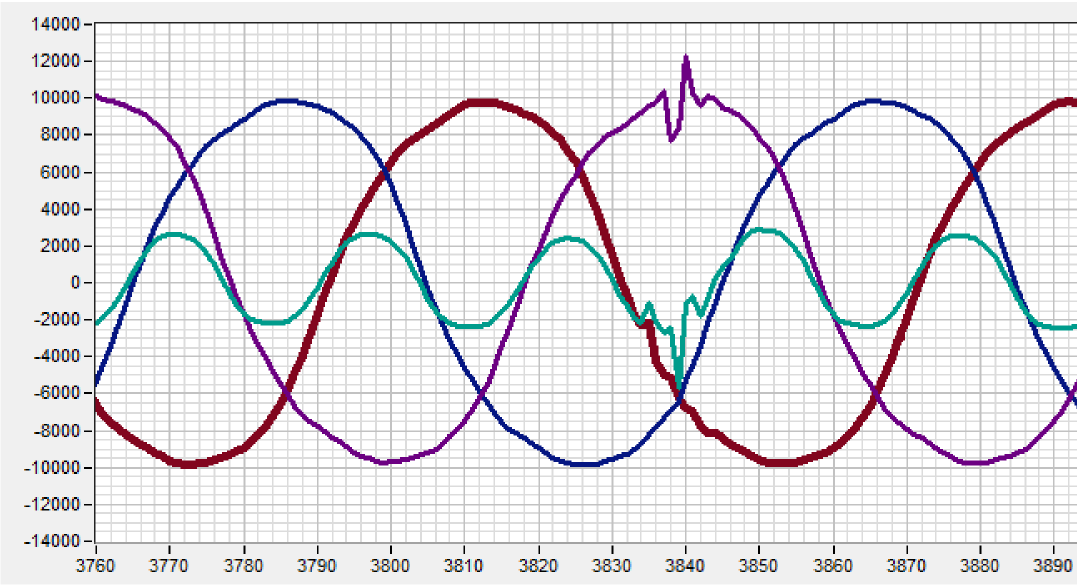
$$i\ (t) = I\cos(\omega t + \theta)$$



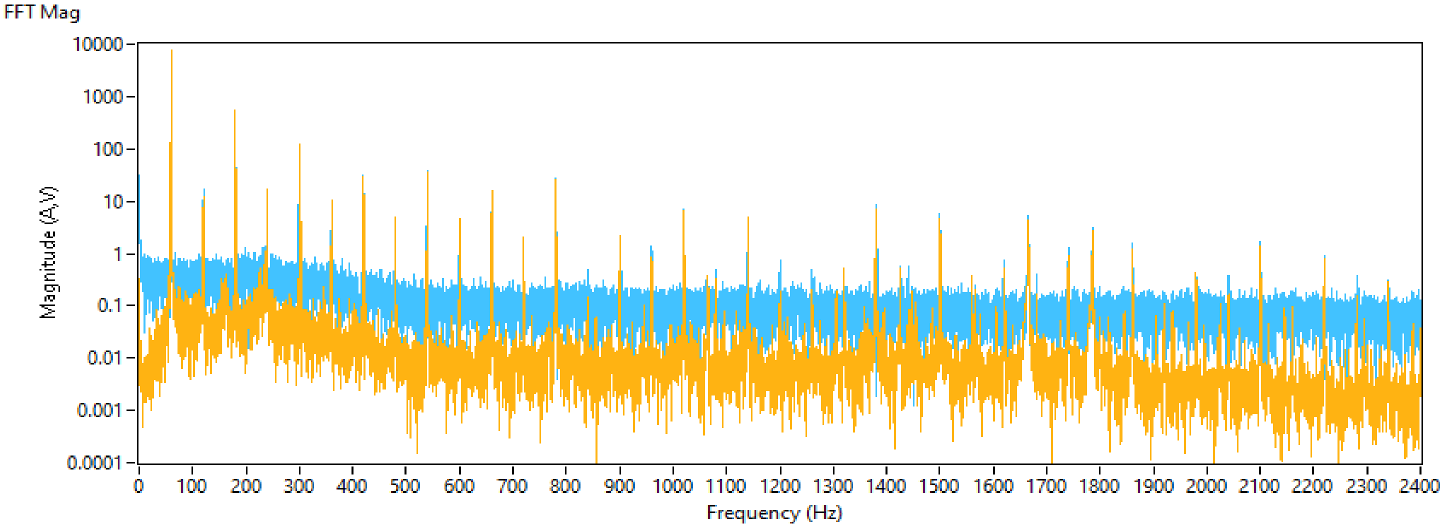
Voltage and Current on the Grid – Regular Days

Time Domain

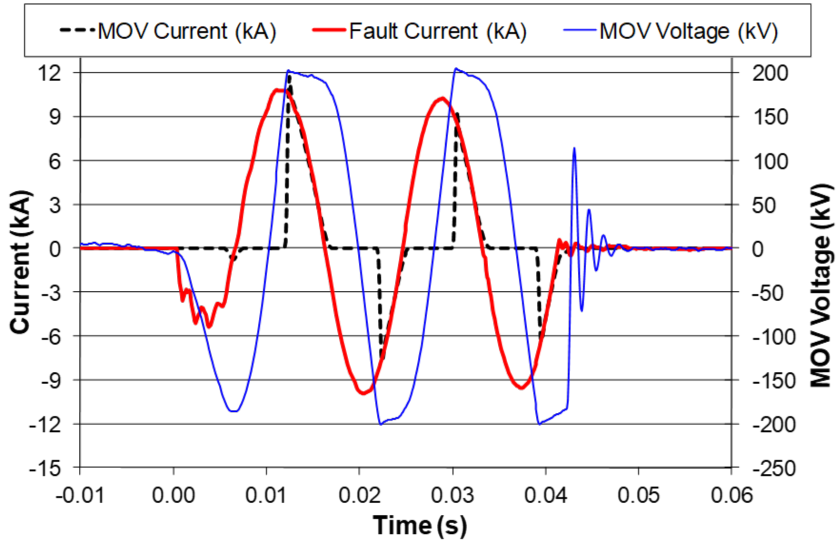


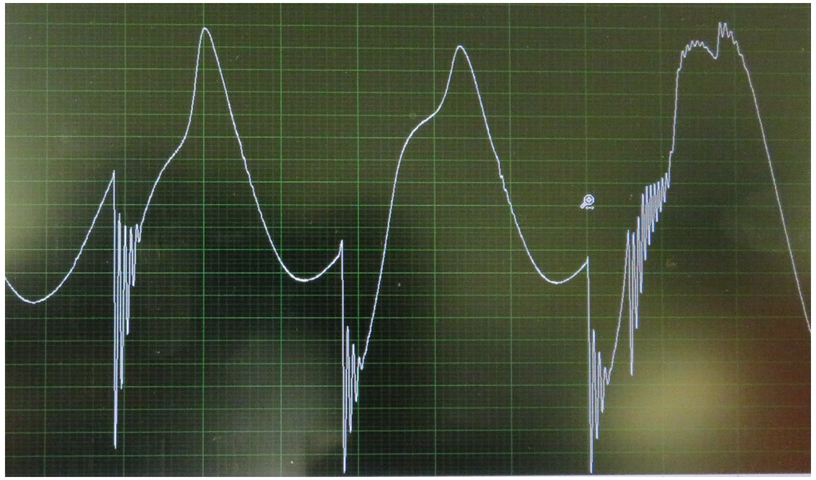


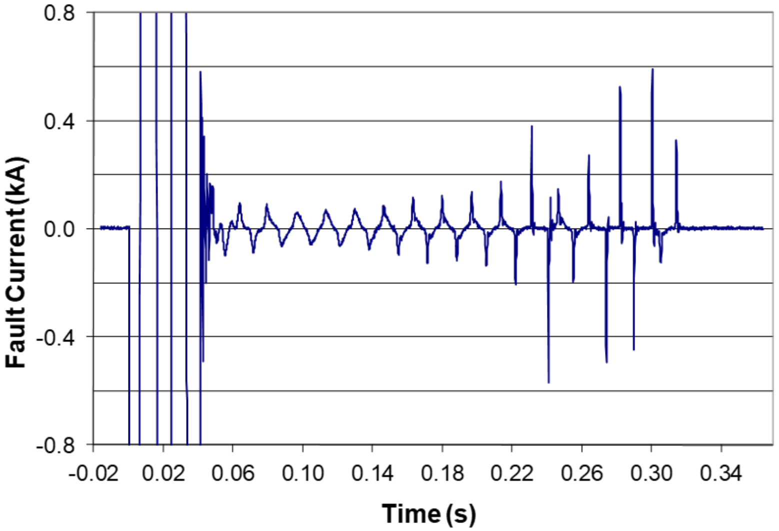
Frequency Spectrum

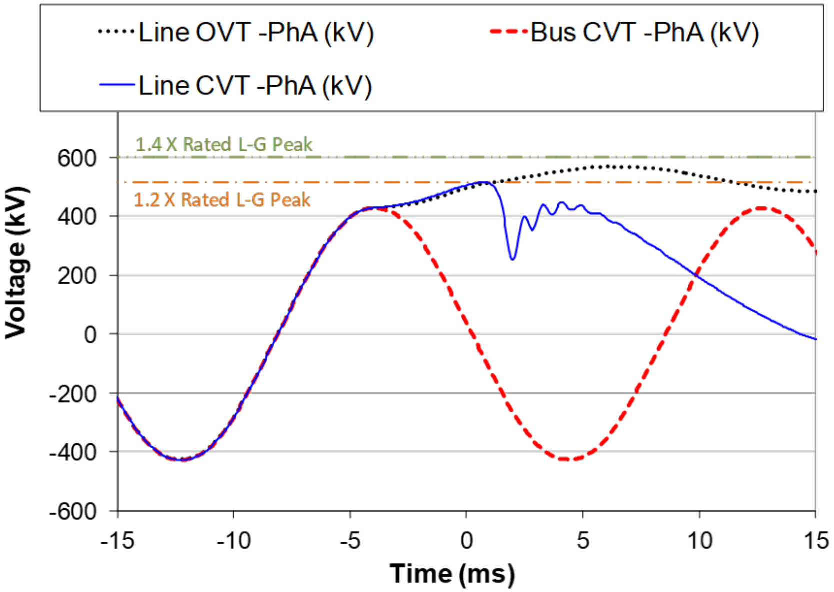


Voltage and Current on the Grid – Exciting Days

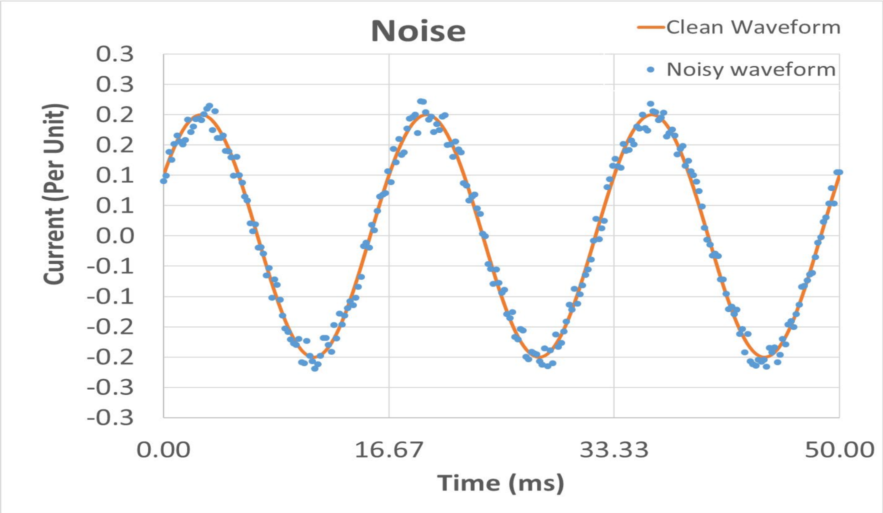


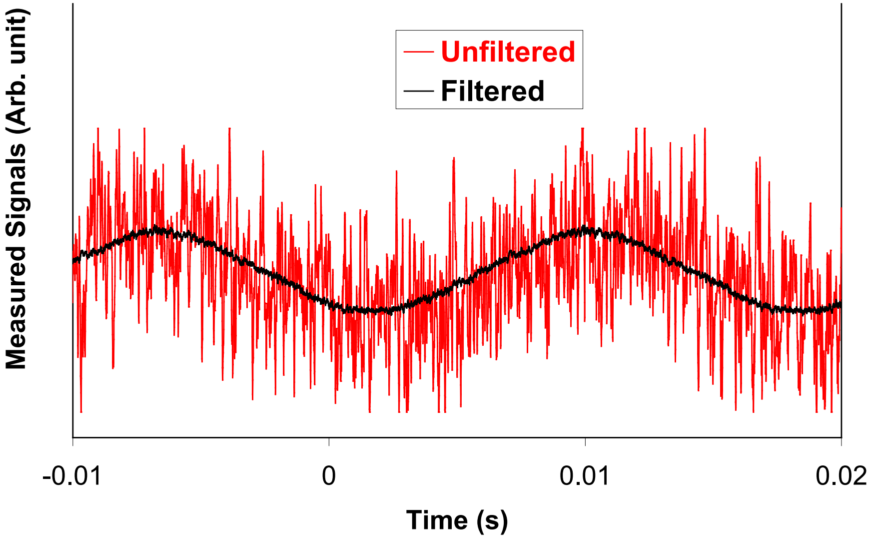


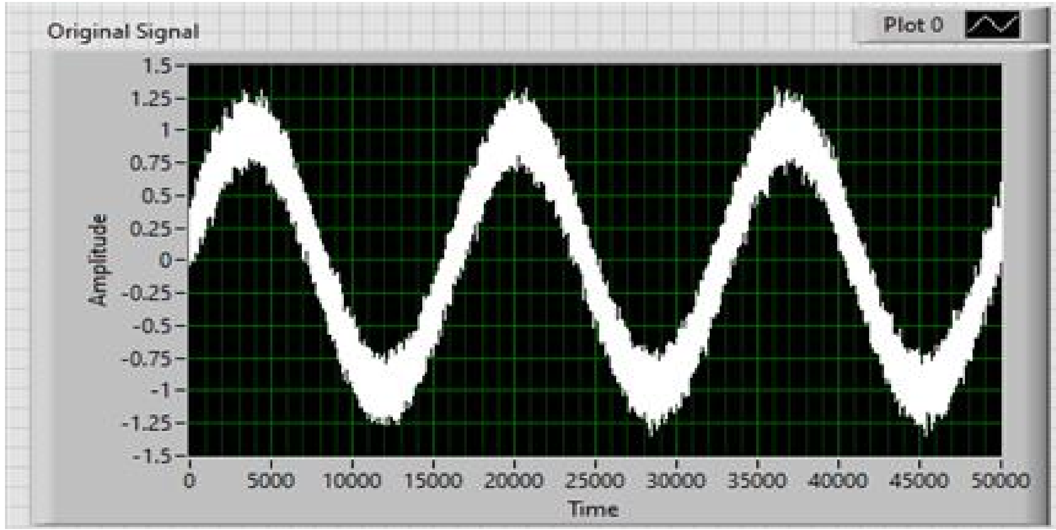


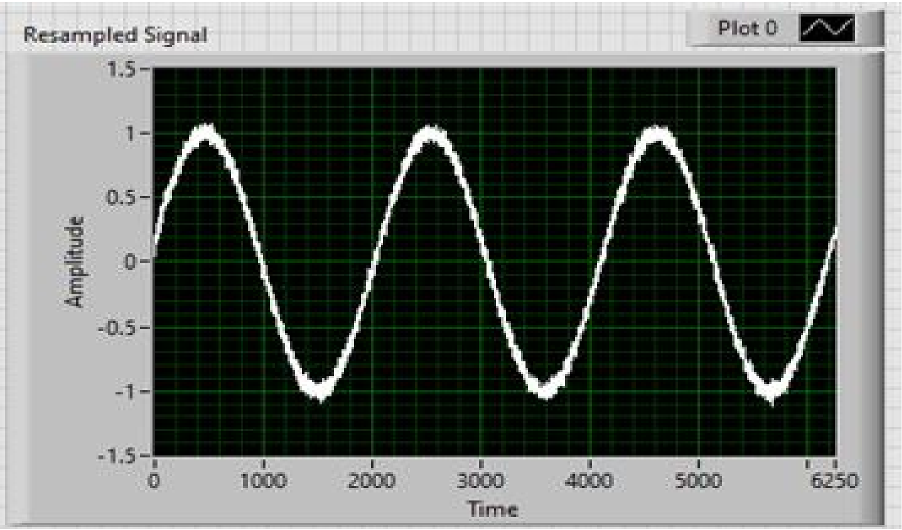


Noise









Sample rate of 1 MHz
Std. Dev. of Gaussian noise ~ 0.1 p.u.

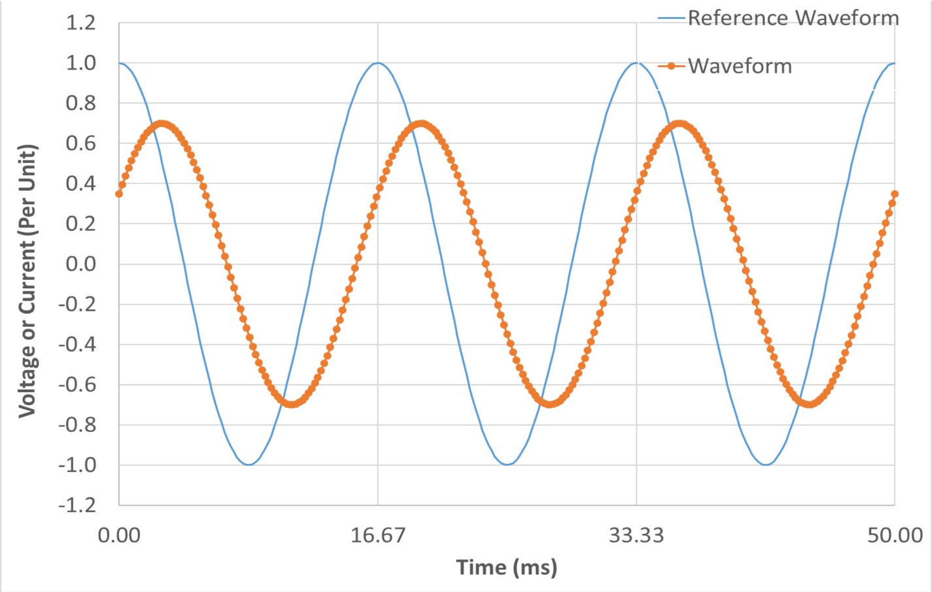
Sample rate of 125 kHz
8-to-1 re-sampling
(& anti-alias filtering @ ~ 40 kHz)

What is a Digital Voltage or Current Sensor?

A voltage or current sensor that provides digital/numerical output.

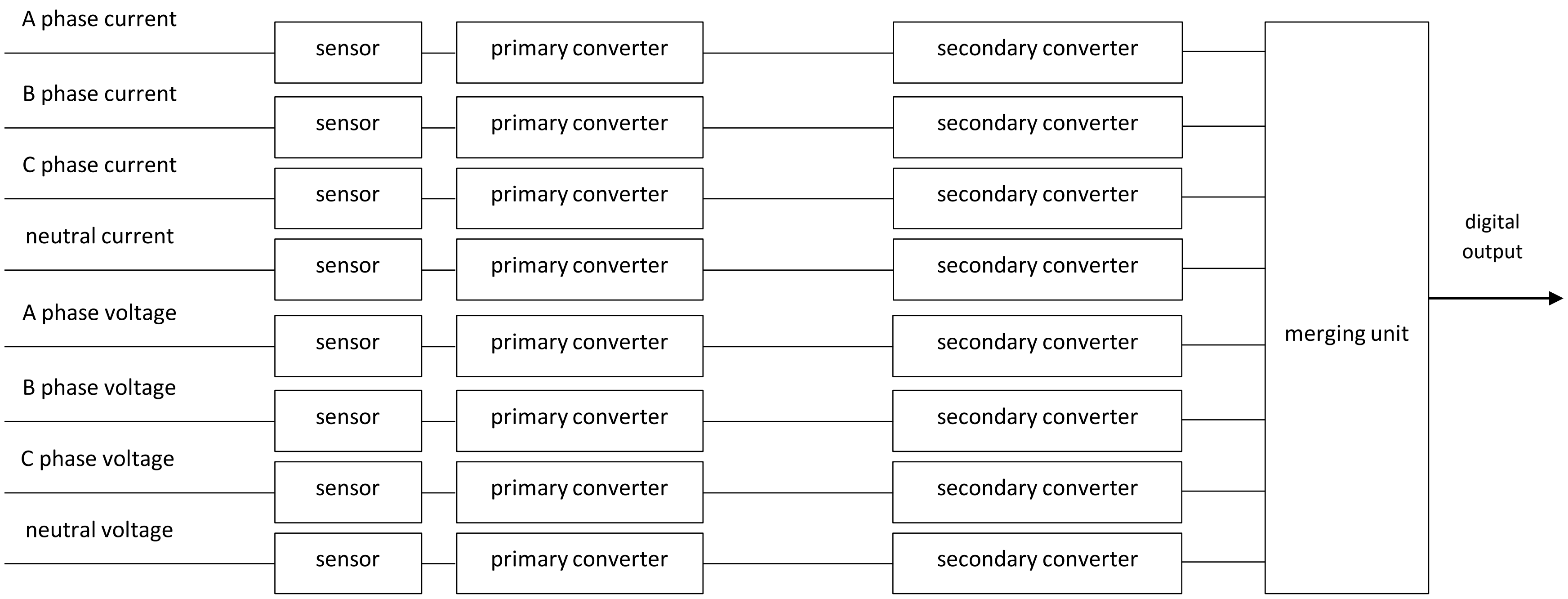
Basic attributes:

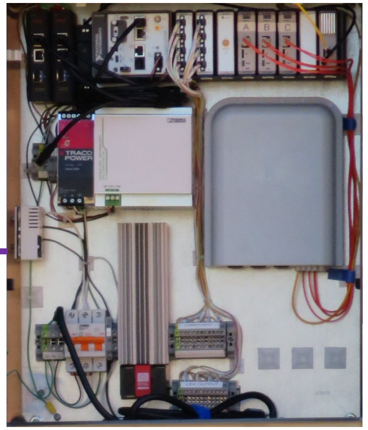
- Sampling frequency (or sampling time resolution), e.g., 4800 Samples/s
- Measurement resolution, e.g., 32 bits
- Time synchronization / uncertainty, e.g., 1 µs
- Filtering – good and bad
  - Anti-aliasing
- Datagram format / Communications



Digital Voltage or Current Sensor System

IEC 61869

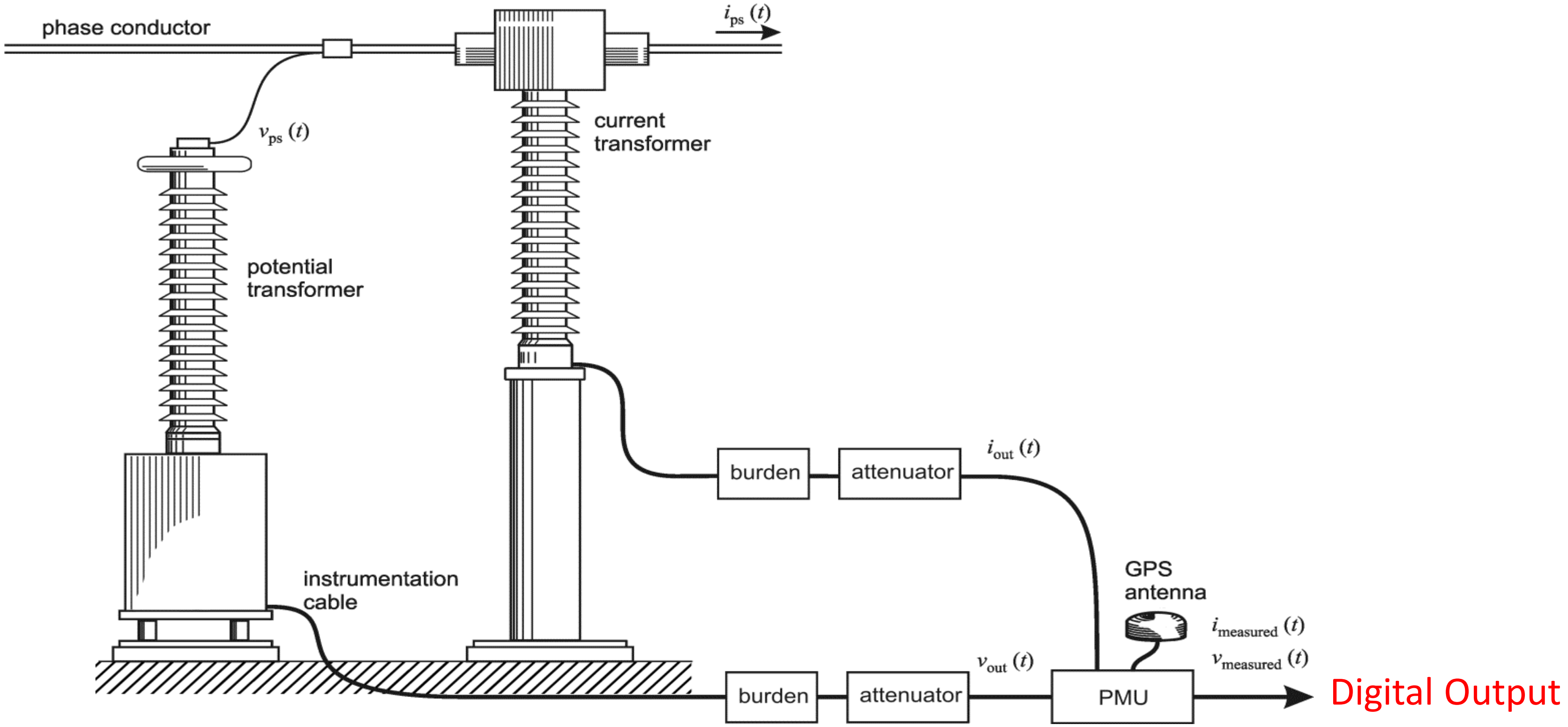




digital output

Digital Voltage or Current Sensor System - Example

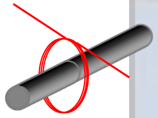
IEEE C37.242



Voltage or Current Measurement Technologies

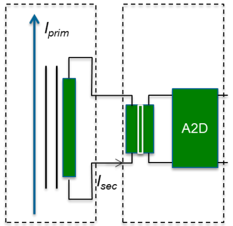
Current Measurement

- Iron-core current transformer (CT)
    - A.K.A. Conventional CT
- Rogowski coils (air-coil CTs)
- Fixed-burden CTs (low-power CTs)
- Hall effect sensors
- Magneto-optic effect (Faraday Effect)
- Hybrid solutions

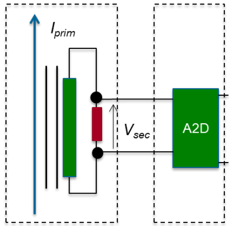


Voltage Measurement

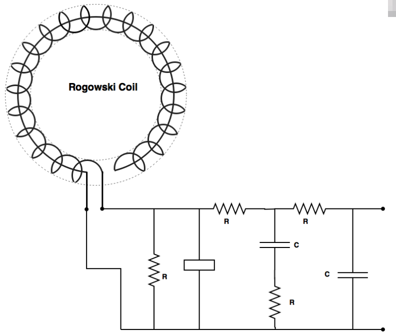
- Iron-core voltage transformer (VT or PT)
- Capacitively Voltage Transformer (CVT)
- Electro-optic effect
- Piezo-electric Effect
- Resistive and/or Capacitive dividers
- Hybrid solutions



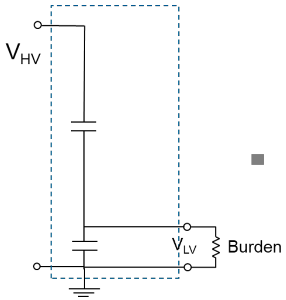
Conventional CT



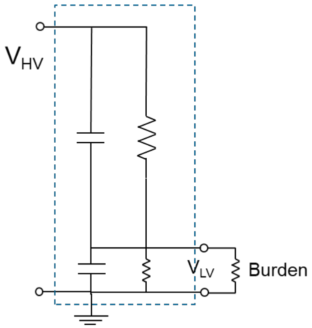
Low-power CT



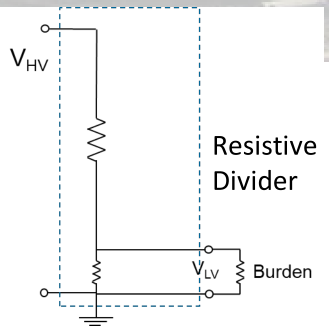
Air-coil (Rogowski coil) with passive integrator



Capacitive Divider



RC Divider



Preferred Voltage and Current Sensor Features

- Performance Features
  - **Linearity** – Accuracy over a very wide dynamic range
  - **Bandwidth** – DC and harmonic
  - Seismic performance
  - User-adjustable sensitivity
  - No iron-core Saturation
- Safety & Environmental
  - No oil or SF6 (depending on design)
  - No open secondaries
  - No ferro-resonance
  - Galvanic isolation from HV line
- Digital Communications & Enabling Intelligence

- Installation Features
  - Small size and weight
  - Voltage & current in one device
  - Zero footprint devices
  - **Multifunction** – e.g., Metering & protection relaying capability in one device
- Smart
  - Self-monitoring
  - Self-calibrating
- Simple and Scalable Architecture
  - Linear sensors can simplify design by allowing a simple template design for multiple applications

Why to Measure?

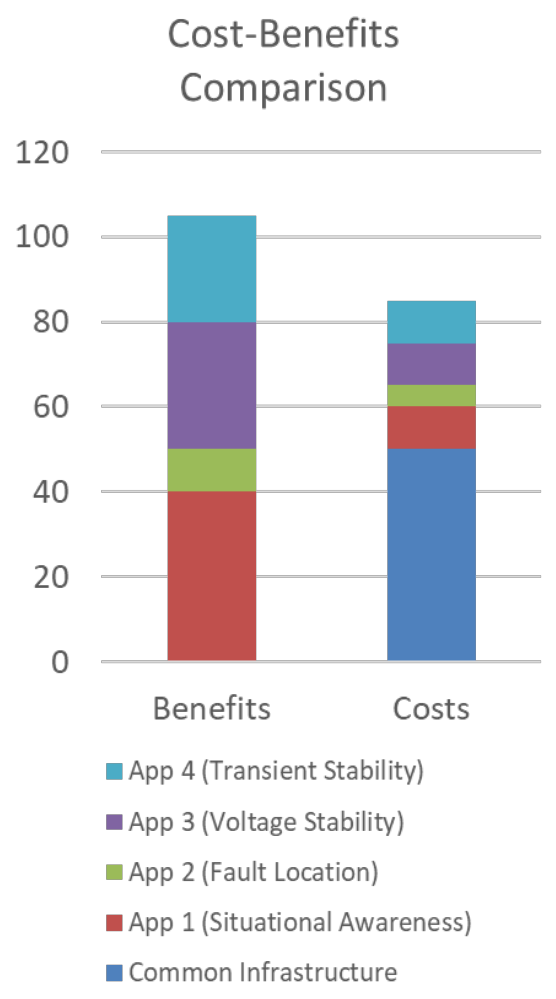
- What do we want to do with the measurements?
- What is the application?
- The application dictates the measurement requirements
  - Accuracy
  - Resolution
  - Dynamic range
  - Bandwidth
  - Synchronization
  - Latency

Sensors and Applications – Dedicated Sensors

- Traditionally, different functions are served by their dedicated sensors
- Examples
  - Protection CTs with various burden ratings and dynamic ranges (e.g., 10% to 2000% of rated current) for mainstream relaying
  - Matching CTs for high-impedance bus protection
  - Revenue metering CTs with IEC 0.2S or IEEE 0.3 accuracy (5% to 400% dynamic range)
- Why?
  - Limited linearity, dynamic range, and bandwidth of traditional sensors
  - Analog interface complicates sharing (burden issues, safety issues, …)
  - Reliability and redundancy

Value Optimization

- Importance of stacking up values/benefits with shared cost
    - Serving multiple applications with one measurement system
- Importance of suitable architecture
    - Expandable and modular
    - Maintainable (design for maintainability)
- Value of using "**deep-data**" sensors
    - Wide Dynamic range
    - Wide frequency response
    - Accuracy and linearity

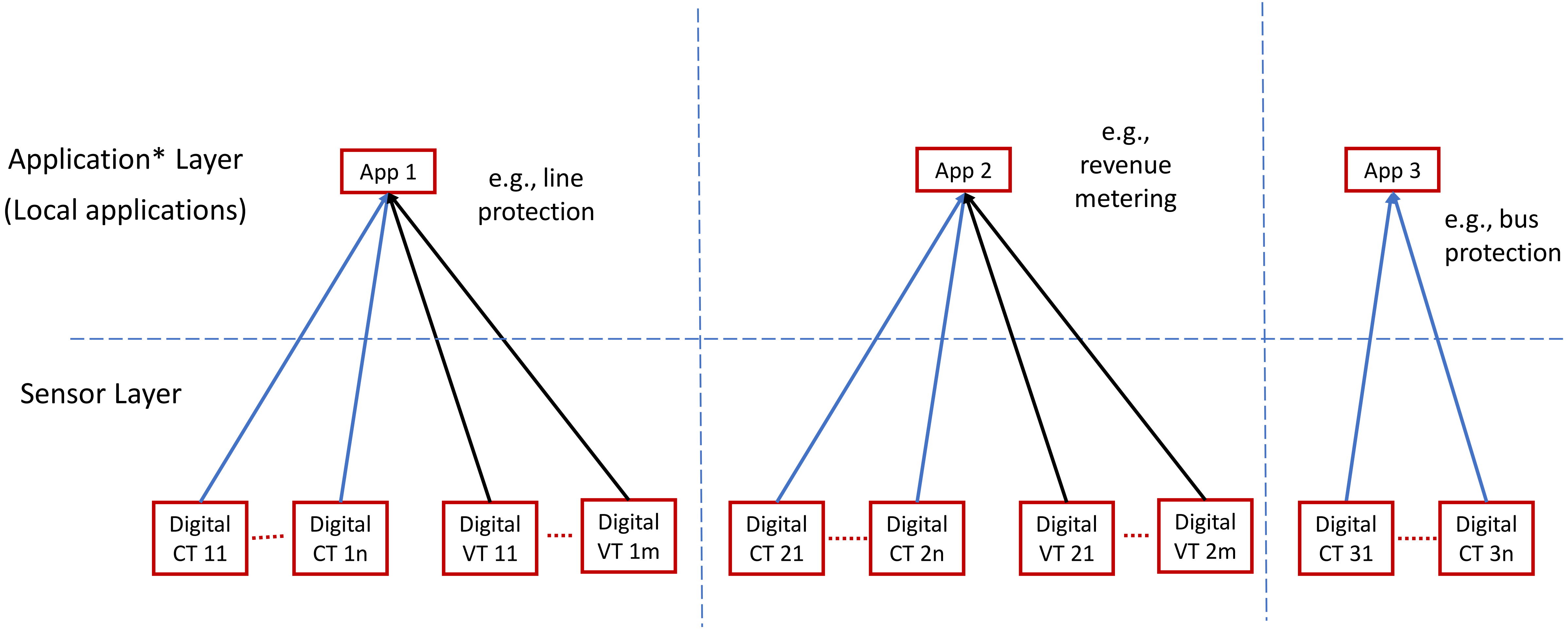


Panel on **Innovative monitoring issues of smart grid**
- IEEE PES GM – July 2017 – Chicago, IL

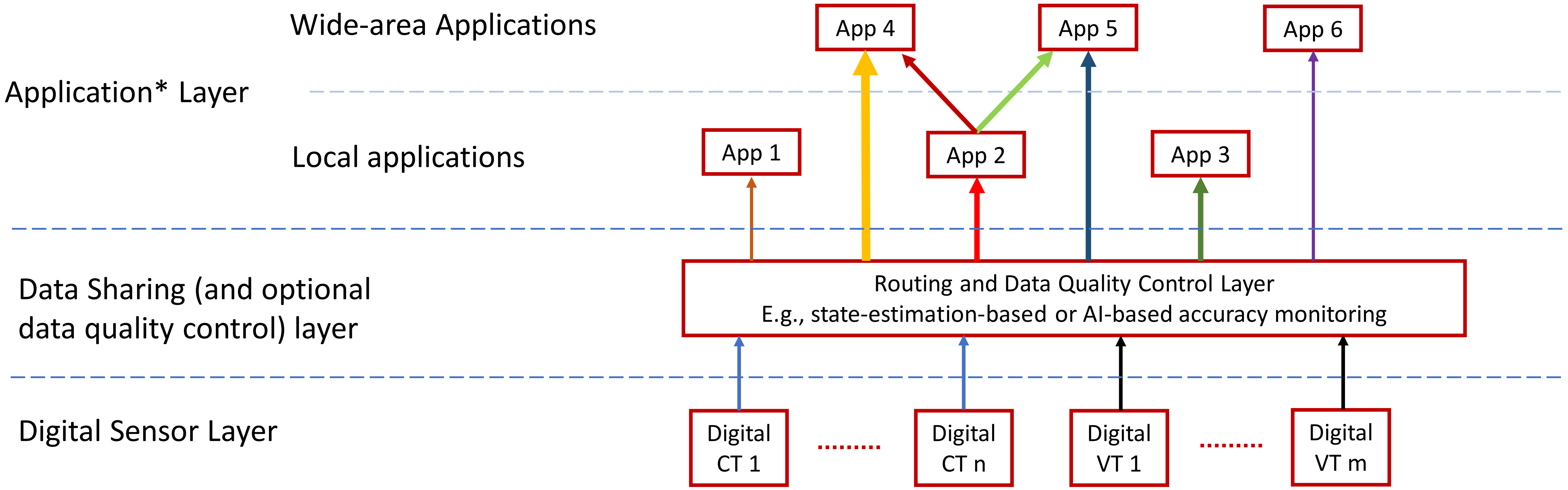
Sensors and Applications – Sharing Sensors

- A sensor with linearity over a wide dynamic range and wide bandwidth can serve as a “deep data” sensor
  - Allows accurate measurements at low currents/voltages and high currents/voltages
  - Allows observation of low frequency and high frequency phenomena
  - Applications can filter “deep data” to obtain what they need
- Digital interface can di-risk sharing
  - Digital (and ideally optical digital) interface can allow data sharing without analog interaction/complications (burden issues, voltage level safety issues, …)
- Reliability and redundancy available at system level

Sensors and Applications – Traditional Architecture with App Silos (redundancy not shown)



Sensors and Applications – Layered Architecture (redundancy not shown)

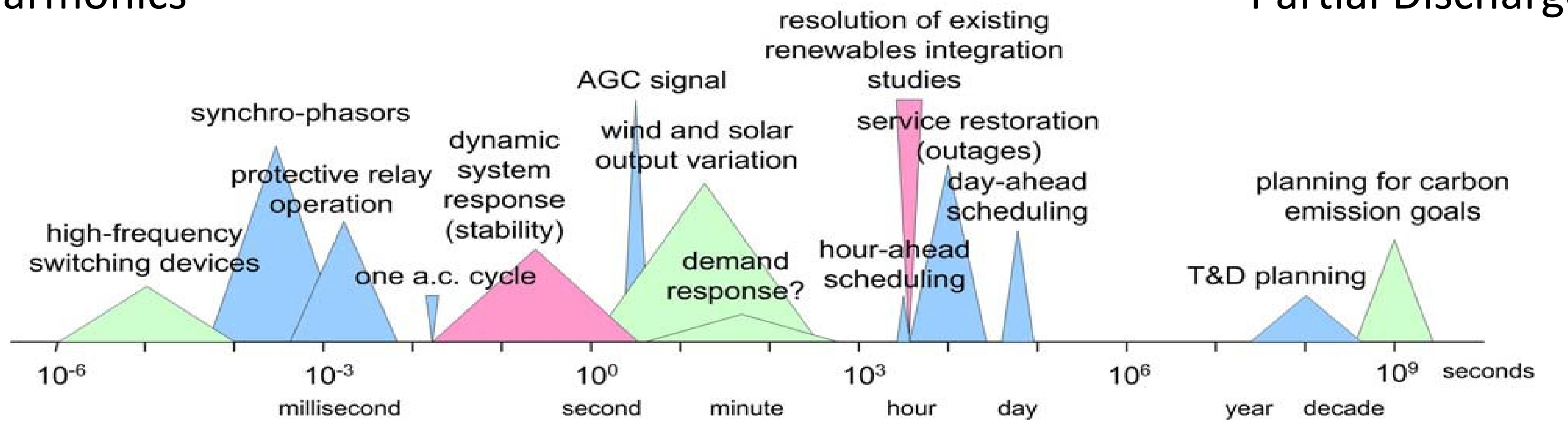


*Local or remote storage can be one of the Apps

Time Scale of Measurements

- Load profiles
- SCADA
- Synchrophasors / RMS
- Harmonics

- Slow transients
- Travelling Wave
- Fast Transients
- Partial Discharge



Time Scales for Power System Planning and Operation*

*A. von Meier, "Challenges to the Integration of Renewable Resources at High System Penetration," California Energy Commission, May 2014

Electrical Measurement in the Utilities

	Travelling Wave & Fast Transients	Meters & PQ & Recorders	Relays	Merging Units (61850 SV)	PMUs	RTUs and SCADA
Signals sampled	I from CTs (and V some VTs)	V and I from VTs and CTs	V and I from VTs and CTs	V and I from VTs and CTs	V and I from VTs and CTs	Phase-to-phase Voltage
Typical sampling rates	1 MS/s	960 to 50,000 S/s	960 to 8,000 S/s	4,800 to 14,400 S/s	960 to 8,000 S/s	Typically under 1,000 S/s
Output data intervals	By exception	0.2s (PQ) to 5 minutes	By exception	0.4 ms	8 ms to 33 ms	2s to 10s
Output data rate	Irregular	12 per hour (0.003 per second)	Irregular	2400 per second	30 to 120 per second	0.1 to 0.5 per second
Approx. Number of input channels	6 (3I and 3V)	6 (3V and 3I)	6 (3V and 3I)	6 (3V and 3I)	6 (3V and 3I+)	1 (V_{AB})
Number of parameters measured per device	1 to 6 +	1 to 20	1 to 6 +	3 to 8	5 to 20 (Vs, Is, f, etc.)	1 (V_{AB}) +
Number of devices acting	1 or 2 local or 2 to 3 across a line	1 local	1 to 2 local	1 to 5 per relay 1-200 in substation	100s to 1000s Wide Area	1000s Wide Area

Faster Phenomena

- Traditional grid switching events such as TRV (Transient Recovery Voltage) measurements* (up to a few 10’s of kHz)
- Fast switching and lightning phenomena detection (up to a few MHz)
  - Including travelling-wave protection function support
- Basic harmonics up to 3 kHz (up to 50^{th} harmonic, IEC 61000-4-7)
- Inverter and power electronics measurements up to 10 kHz
- Advanced inverter and EV charging systems, signals up to 100 kHz
- Supra-harmonic measurement 2-150 kHz (IEC 61000-4-30)
- Grid event signature analysis

* For example see IEEE PES Tutorial on TRV and its measurement https://resourcecenter.ieee-pes.org/education/tutorials/PES_Ed_TUT_TRV4_100620.html

Waveform vs. Calculated Quantities

- Phasors are calculated quantities – based on assumptions about the signal being measured
- A “Fitting Challenge” can be graded using a Goodness of Fit (GoF) metric

$$\text{GoF} = 20\,log\frac{A}{\sqrt{\frac{1}{(N-m)}\sum_{k=1}^{N}(u_k - v_k)^2}}$$

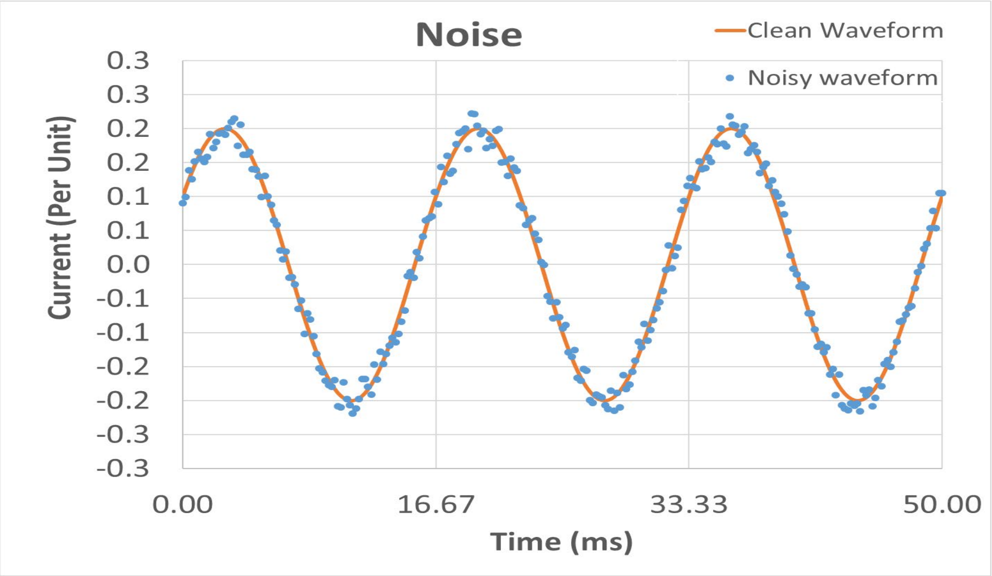
$m = 3$

Actual Sampled Data

Obtained from the Synchrophasor Estimated

$$v_k = V\cos(\omega t_k + \varphi)$$

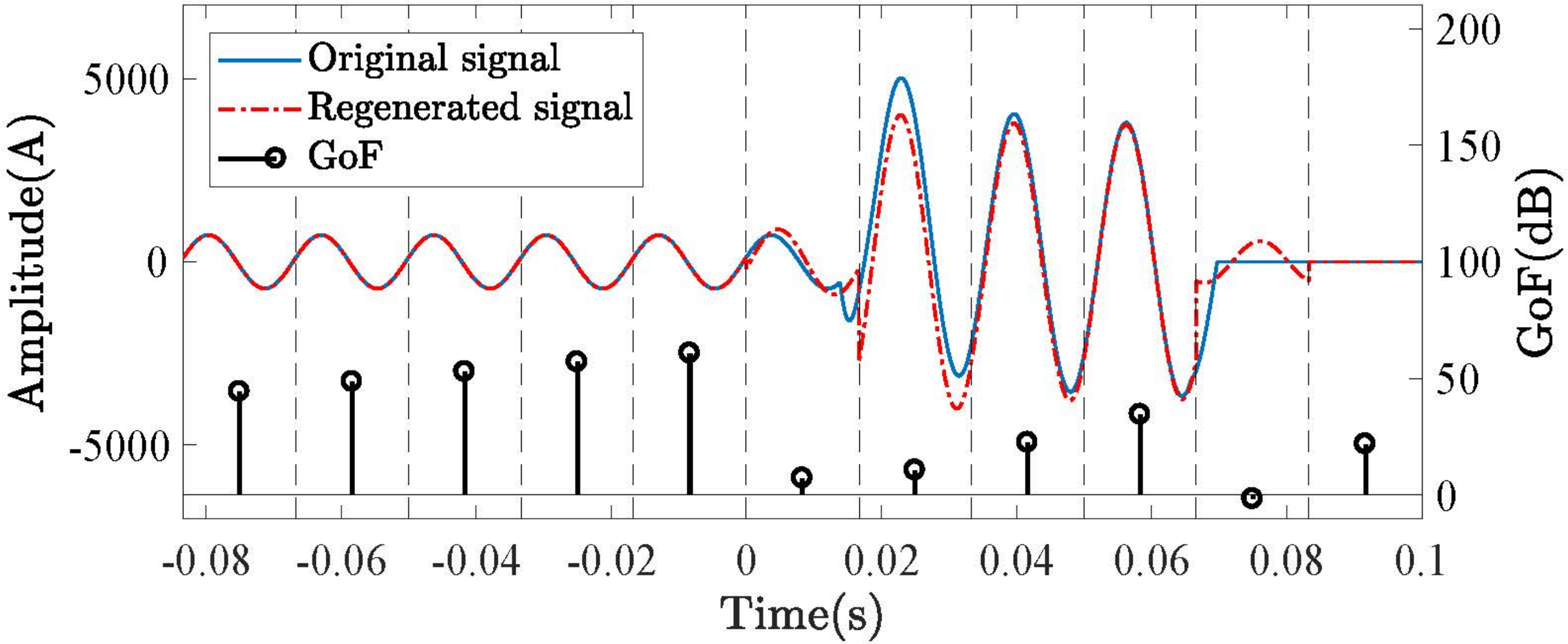
$$\text{SNR} = 20\,log\frac{A}{\sqrt{\frac{1}{N}\sum_{k=1}^{N}(u_k - v_k)^2}}$$



A. Riepnieks and H. Kirkham, “An introduction to goodness of fit for PMU parameter estimation,” *IEEE Transactions on Power Delivery*, vol. PP, no. 99, pp. 1–1, 2016.

Lossy Compression?

$$\mathrm{GoF} = 20\,log \frac{A}{\sqrt{\frac{1}{(N-m)}\sum_{k=1}^{N}(u_k - v_k)^2}}$$

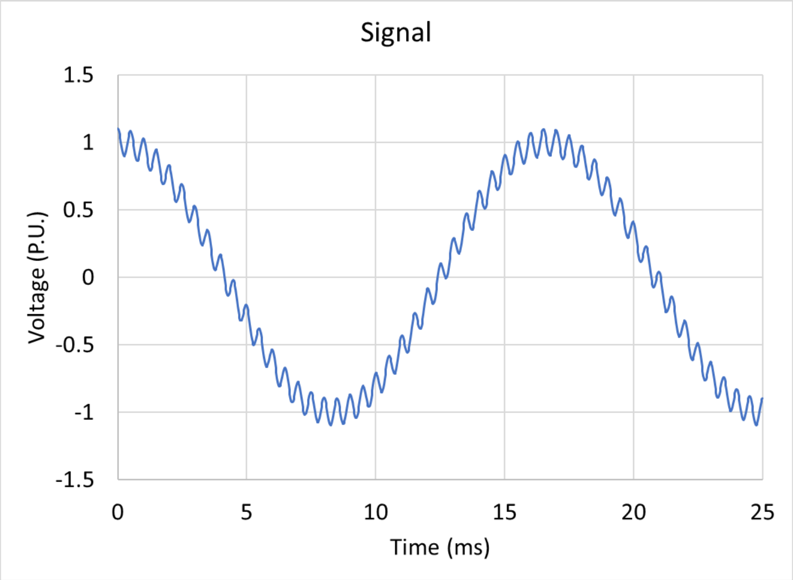


GoF can be low for various reasons:

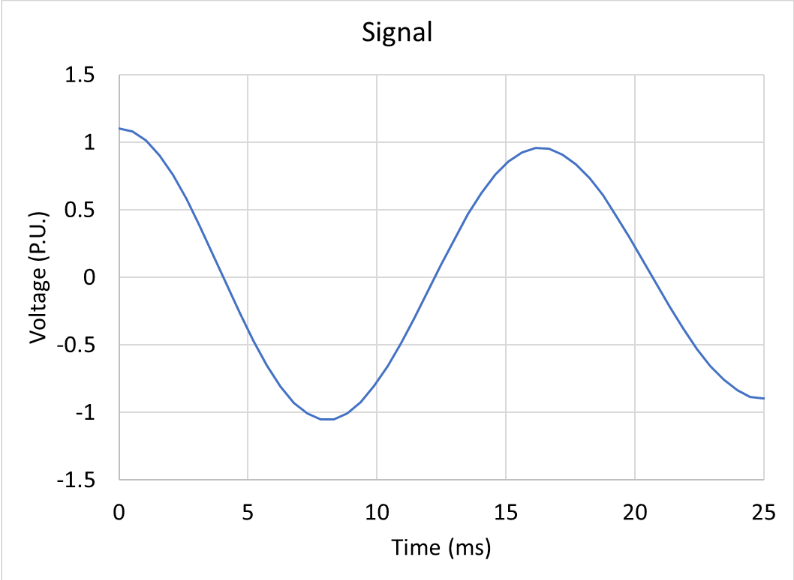
- Noise in the measured signal, especially at low currents (low SNR)
- Distorted waveforms, particularly during the first or last cycle of faults
- DC offsets (decaying DC) during the early cycles of faults with long time constants
- Distortions due to CT saturation
- Distorted waveforms during high-impedance faults

Bandwidth and Sampling Rate

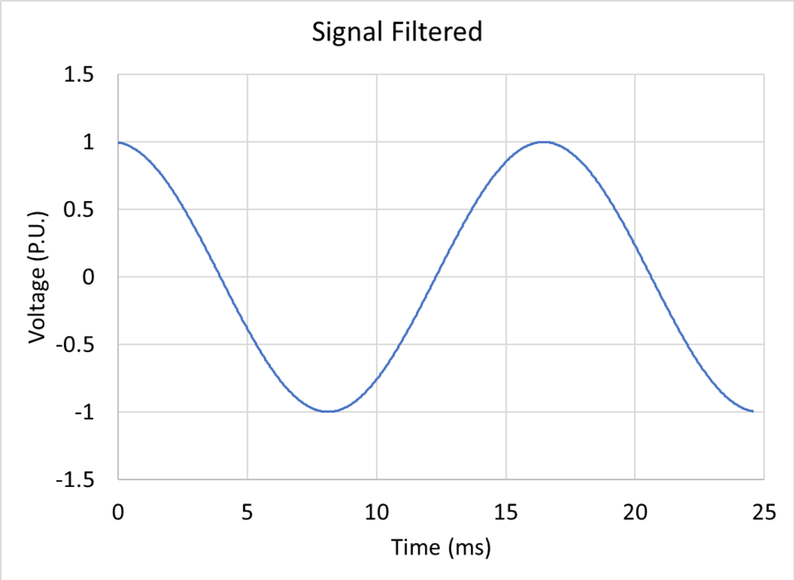
- Low sampling rate and filters can result in loss of information too



60Hz signal + 0.1 p.u. 2 kHz signal,
Sampled at 40,000 S/s

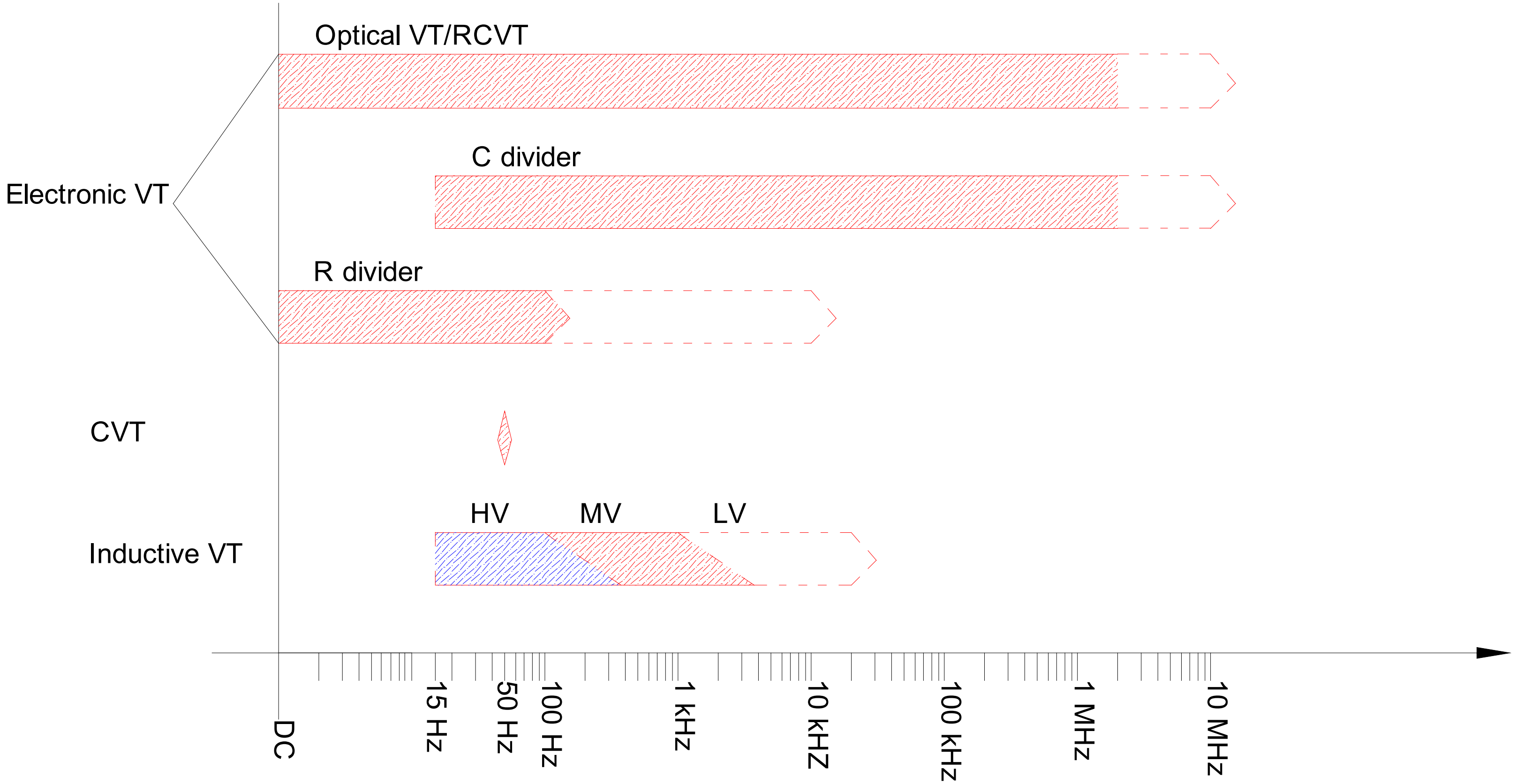


60Hz signal + 0.1 p.u. 2 kHz signal,
Sampled at 1920 S/s
(without anti-alias filtering)



60Hz signal + 0.1 p.u. 2 kHz signal,
Filtered

Sensor Bandwidth



- IEC 61869-103:2012, Figure 9 – Voltage Transformer technologies' frequency range according to present experience*

* There are multiple exceptions and custom devices

Some Relevant Recent Presentations

NASPI meeting, April 2021

- Using High-Resolution Time-Stamped Data to Improve System Operations – Richard Kirby,
  - ✓ 1 MHz sampling for Travelling Wave
- Design, Development and Field Validation of Sensors with Intelligent Measurement Platform - Niroj Gurung
  - ✓ Showing some compensation for limited sensor bandwidth
- Identifying Oscillations Injected by Inverter-Based Solar Energy Sources in Dominion Energy's Service Territory - Chen Wang
  - ✓ Showing how 22 Hz oscillation looks like 8 Hz due to aliasing
- Facilitating Inverter-based Generation Integration with High-resolution Data - Gefei "Derek" Kou
  - ✓ Megahertz measurement for cap bank switching oscillography

Two Great References

Two very useful recent references on NASPI website

- High-Resolution, Time-Synchronized Grid Monitoring Devices
  - https://www.naspi.org/node/819
- Phasors or Waveforms: Considerations for Choosing Measurements to Match Your Application
  - https://www.naspi.org/node/899

Some Pointers

- It is more cost-effective to share
  - And linear wideband sensors are easier to share
- Always remember the entire measurement chain – both the analog and the digital portions
  - It helps to learn about digital signal processing and filters
- Time synchronization matters
  - But your system architecture and application design can help too
- Do not under-appreciate the value of the traditional analog sensors already installed
  - Can transition to digital by adding standalone merging units (e.g., IEC 61869-13)
- Paying attention to the faster phenomena is critical for improving the reliability and resiliency of the grid
  - Better eyes and ears don't make us smarter immediately, but they allow our brain to develop better understating of our world

Standards – IEC

Current

- 60044-1 Current Transformers (obsolete, replaced by 61869-2)
- 61869-2 Current Transformers (CT)
- 60044-8 Electronics Current Transformers
- 61869-4 Combined CT/VT
- 61869-6: General Requirements for Low Power Instrument Transformers (LPIT)
- 61869-8: Electronic Current Transformers
- 61869-9: Digital Interface for Instrument Transformers
- 61869-10: Passive Current Sensors
- 61869-12: Combined LPIT
- 61869-13: Stand Alone Merging Unit (SAMU)
- 61869-14: DC CT

Voltage

- 60044-2 Voltage Transformers (obsolete, replaced by 61869-3)
- 61869-3 Inductive Voltage Transformers (VT)
- 61869-5 Capacitor Voltage Transformers
- 60044-7 Electronic Voltage Transformers
- 61869-4 Combined CT/VT
- 61869-6: General Requirements for Low Power Instrument Transformers (LPIT)
- 61869-7: Electronic Voltage Transformers
- 61869-9: Digital Interface for Instrument Transformers
- 61869-11: Passive Voltage Sensors
- 61869-12: Combined LPIT
- 61869-13: Stand Alone Merging Unit (SAMU)
- 61869-15: DC VT

Standards and Guides – IEEE

- IEEE C57.13: Instrument Transformers (conventional)
- IEEE Std. 1601-2010: Trial-Use Standard for Optical AC Current and Voltage Sensing Systems
- IEEE Std. C37.92-2005, Standard for Analog Inputs to Protective Relaying from Electronic Voltage and Current Transformers [Low Energy Analog or LEA] --- being revised (PSRC WG I-38)
- IEEE C37.241:2017, Guide for Application of Optical Instrument Transformers for Protective Relaying
- PSRC, WG I-24, Report on the Use of Hall Effect Sensors for Protection and Monitoring Applications
- IEEE C37.235, Guide for the Application of Rogowski Coils Used for Protective Relaying Purposes

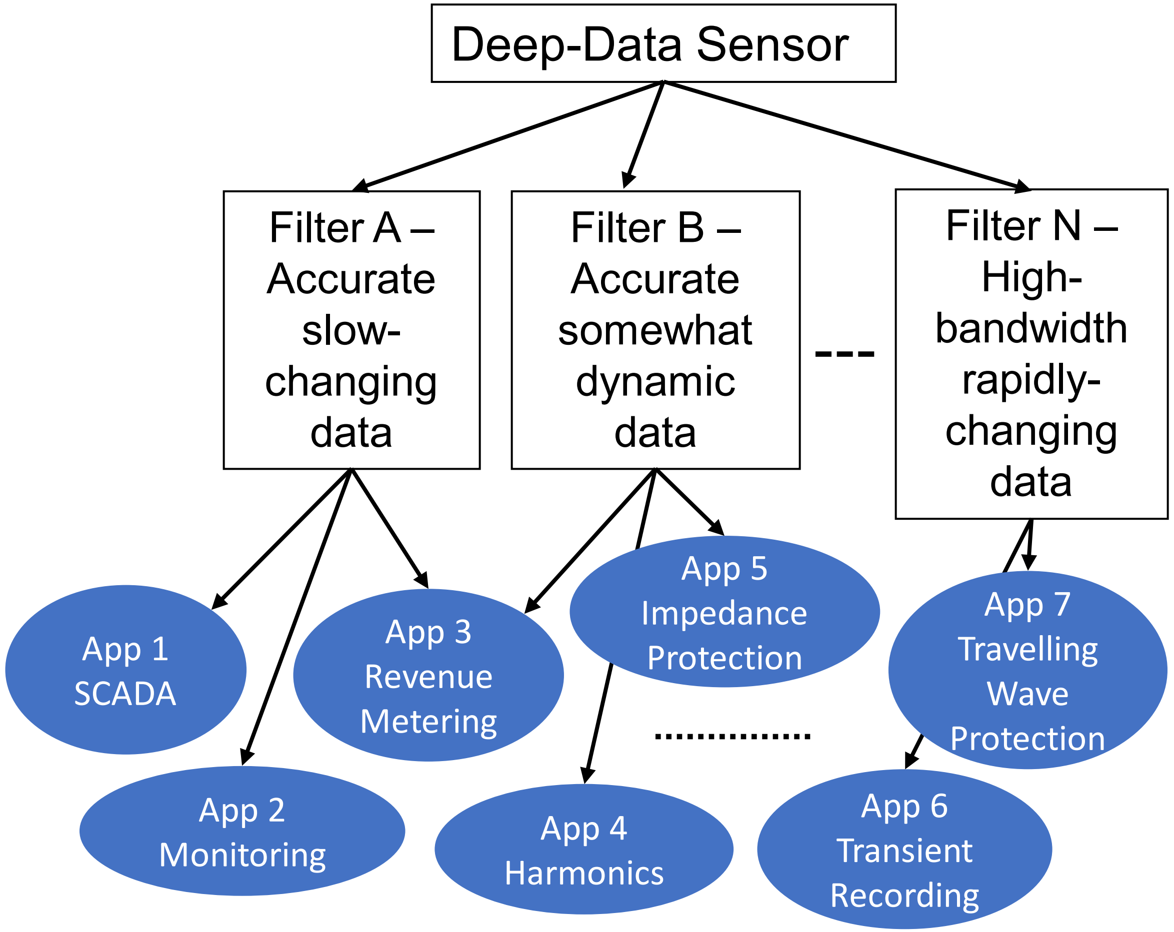
Questions?

Data Optimization – Deep Data Sensor

Definition:

"DEEP-DATA Sensor"

A sensor that has the linearity, accuracy, and bandwidth to provide source data for various filtering/optimization to serve a wide variety of applications with different data requirements.



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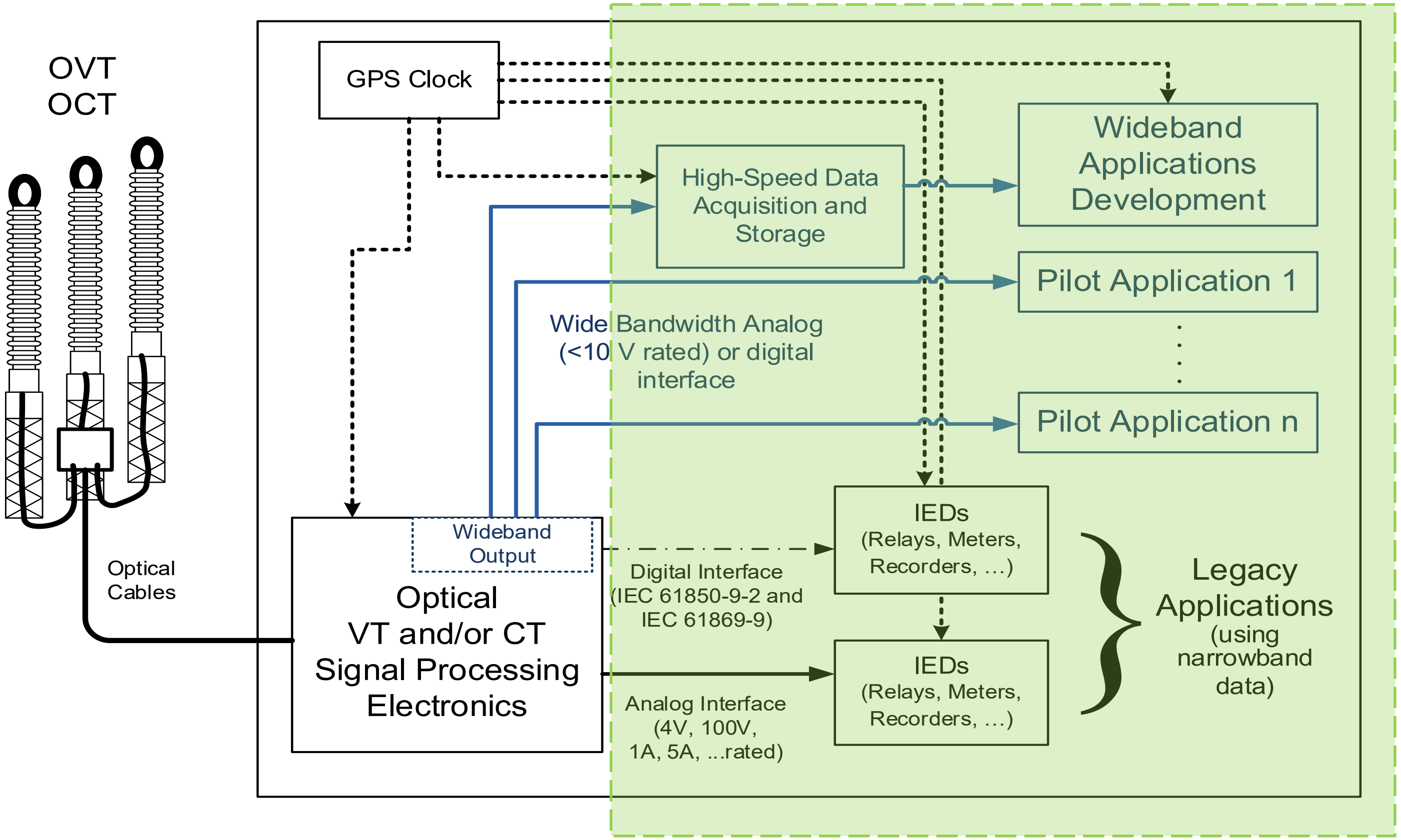
Data Optimization – Example of Deep Data Sensor

Example* of a "DEEP-DATA Sensor" design:

Optical Voltage and Current Measurement System (Redundancy Not Shown)

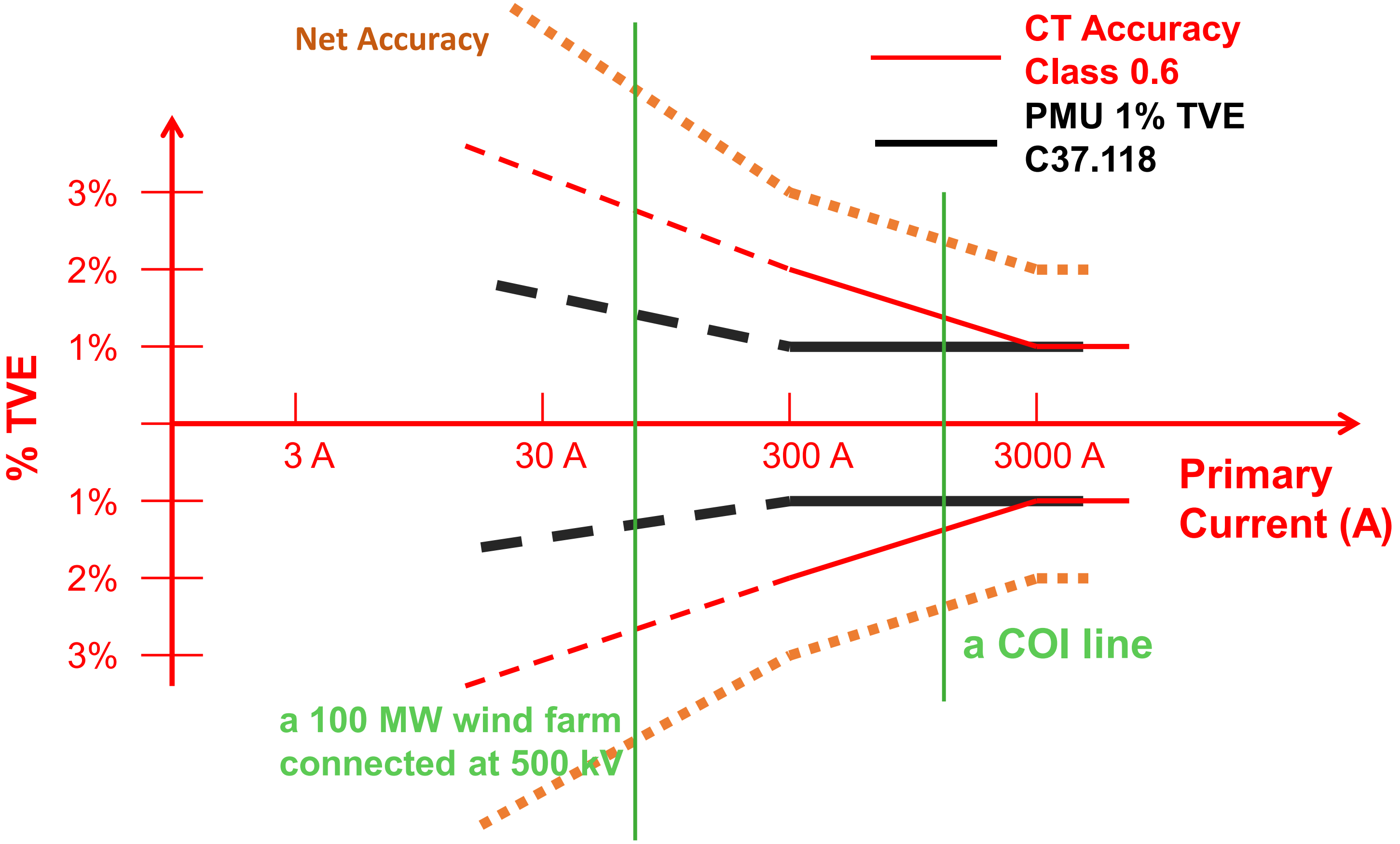


* D. F. Peelo, F. Rahmatian, M. Nagpal, and D. Sydor, "Real-time Monitoring and Capture of Power System Transients," *CIGRE General Session 44*, Aug. 26 - 31, 2012, paper B3-101.

Measurement Chain Alignment

Example:

- PMU Accuracy – 1% TVE
- Instrument Transformer accuracy class 0.6, rated for protection application with rated primary current of 3000 A



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