A Synchronized Self-Contained Line-Powered Continuous Point-on-Wave Recorder

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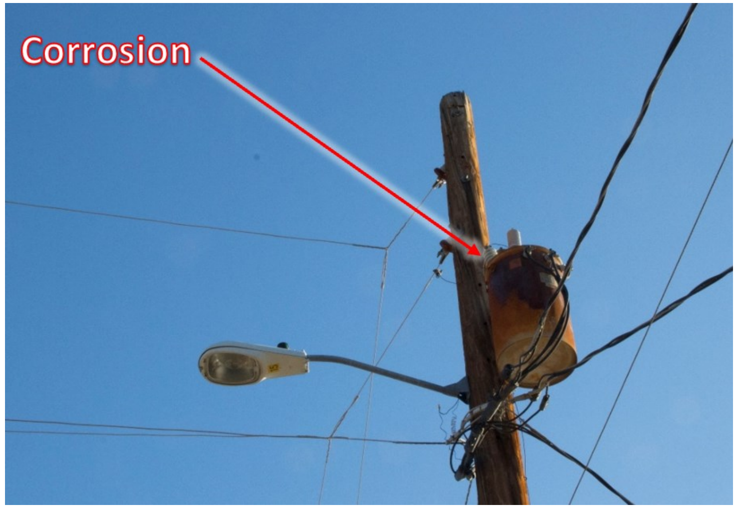
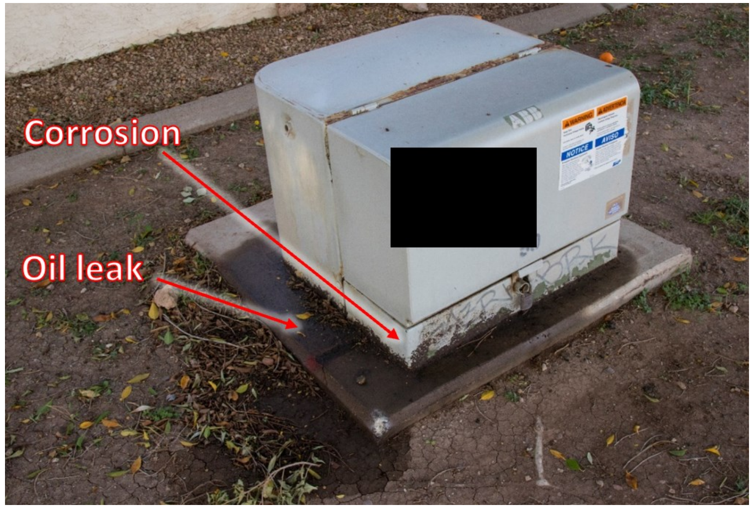
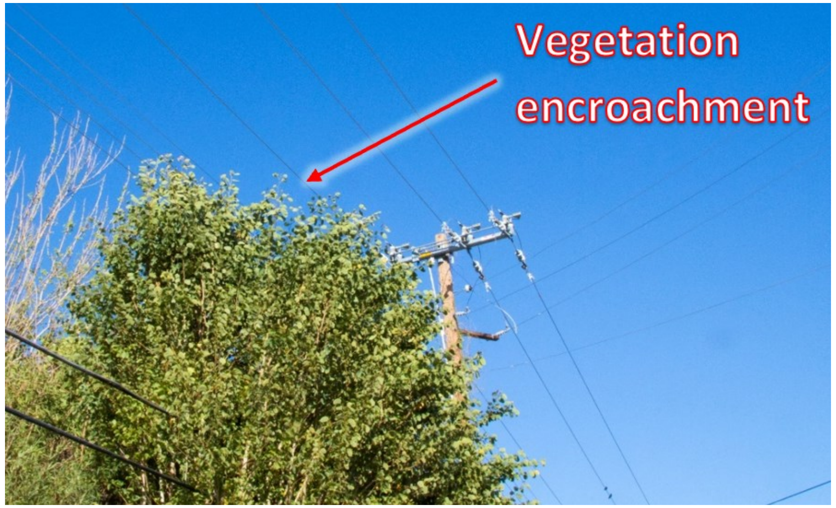
Observing the Distribution System



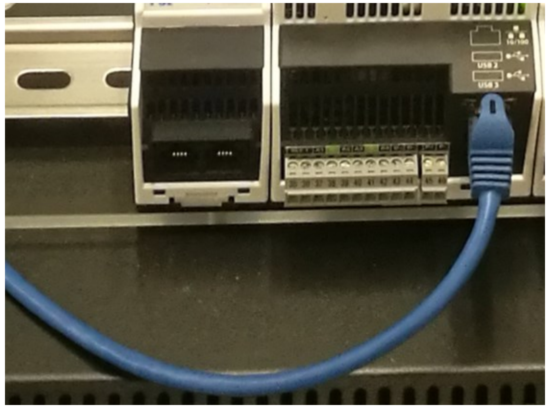




- Many areas of the **distribution system** are not monitored in real-time
- Distribution **asset degradation** is prevalent
- Distribution system asset degradation contributes to:
  - Wildfire danger from **vegetation strikes** and **insulator failure**
  - **Public safety power shutoffs** (PSPS)
  - **Reliability problems**; unplanned **power outages**

Observing the Distribution System

- Existing real-time measurement equipment typically requires:
  - Dedicated **low-voltage power supply**
  - Dedicated **communication network connection**
  - Equipment **installation footprint** for:
    - Instrument transformers
    - Measurement equipment
    - Network hardware
    - On-site power conversion
- Closely monitoring the **distribution network edge** is challenging with current tech!

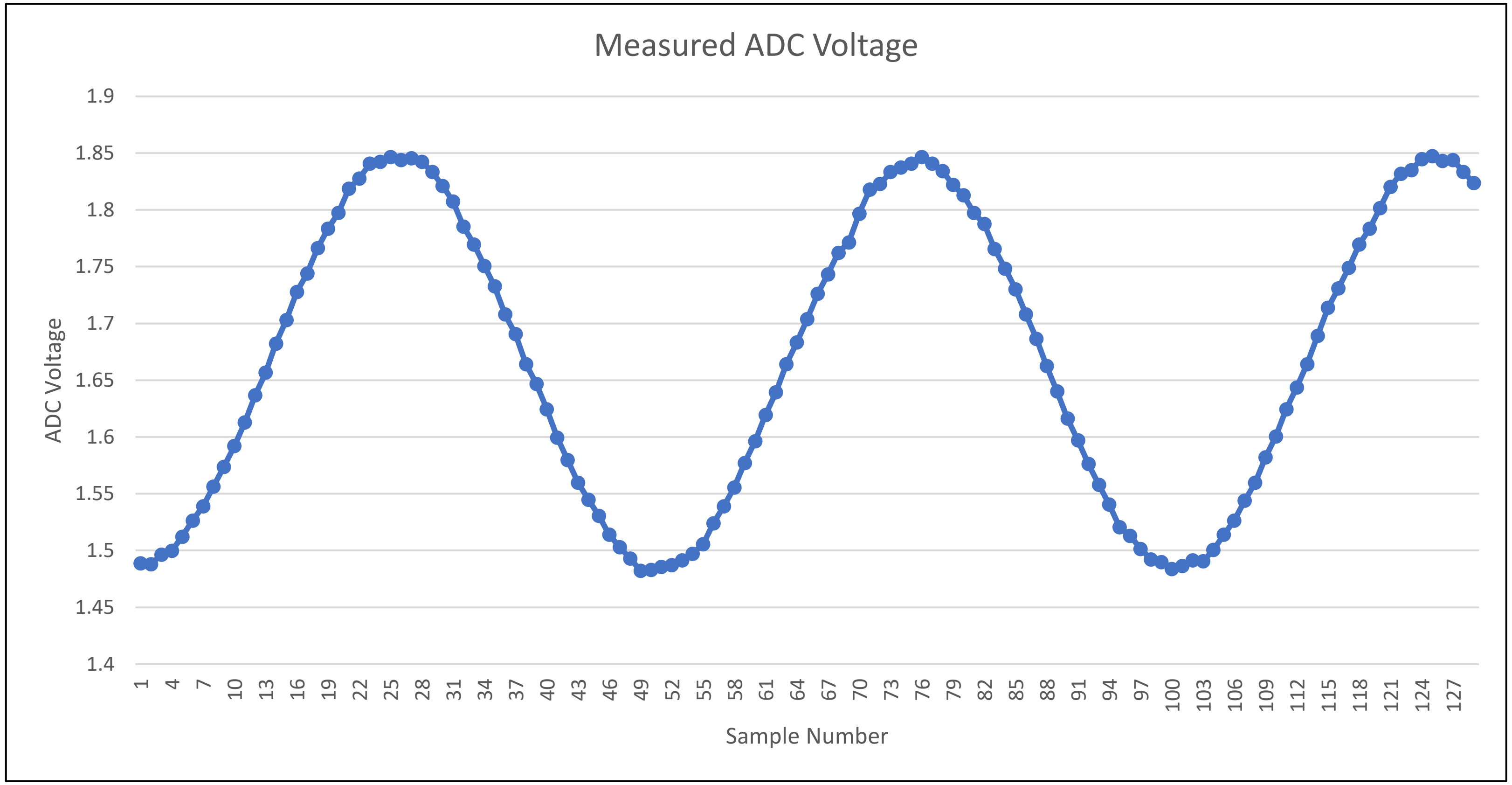





[1]

[1]: https://commons.wikimedia.org/wiki/Category:Voltage_transformers#/media/File:Spannings_meettransformator_TP_150kV.jpg

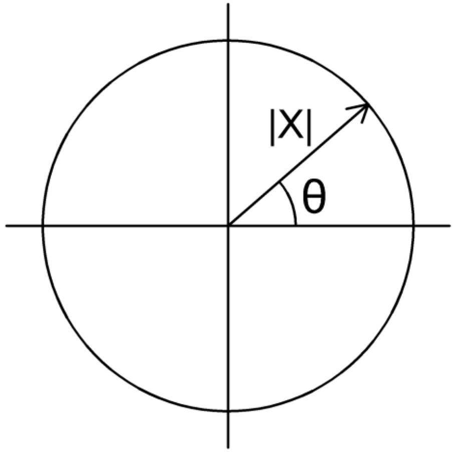
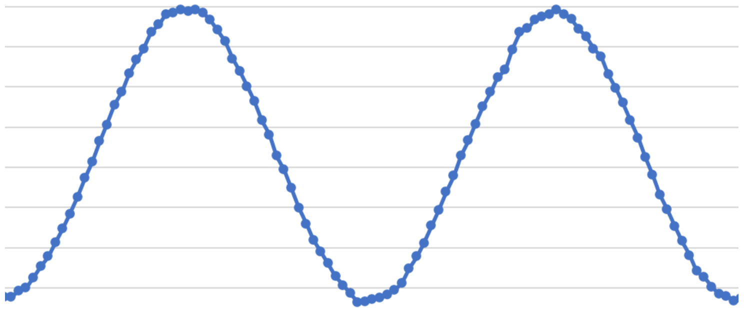
Review: What are Continuous Point-on-Wave (CPoW) measurements?



- PoW measurements record **instantaneous** values of electrical signals (voltage, current, etc.)
- PoW measurements are typically **much faster** than the fundamental frequency of the signals being measured (typically thousands of samples per second)
- **Continuous** PoW measurements are **taken at all times**, and are typically streamed in real-time to a storage database

Point-on-Wave (PoW) vs. PMU Measurements

Traditional PMU Measurements	Point-on-Wave Measurements

• Rate: **30-120 Samples/second**
• Available measurements:
    o **Magnitude** (voltage and current)
    o **Angle** (voltage and current)
• Derived measurements:
    o **Frequency** (fundamental)
    o **Rate of change of frequency** (RoCoF)
    o **Positive sequence**
    o **Power flow**
• **Time-synchronized**

 	
	• Rate: **512-10,000+ Samples/second**
	• Available measurements:
	    o **Instantaneous** values (voltage and/or current)
	    o Sub-cycle **transients**
	    o **Wave shape**
	    o **Derived measurements:**
	        ▪ Fundamental frequency
	        ▪ Higher-order harmonic content
	        ▪ Magnitude, angle
	        ▪ RoCoF
	• **Time-synchronization** is optional (required for synchrophasor conversion)
	

Event-Triggered PoW vs. CPoW

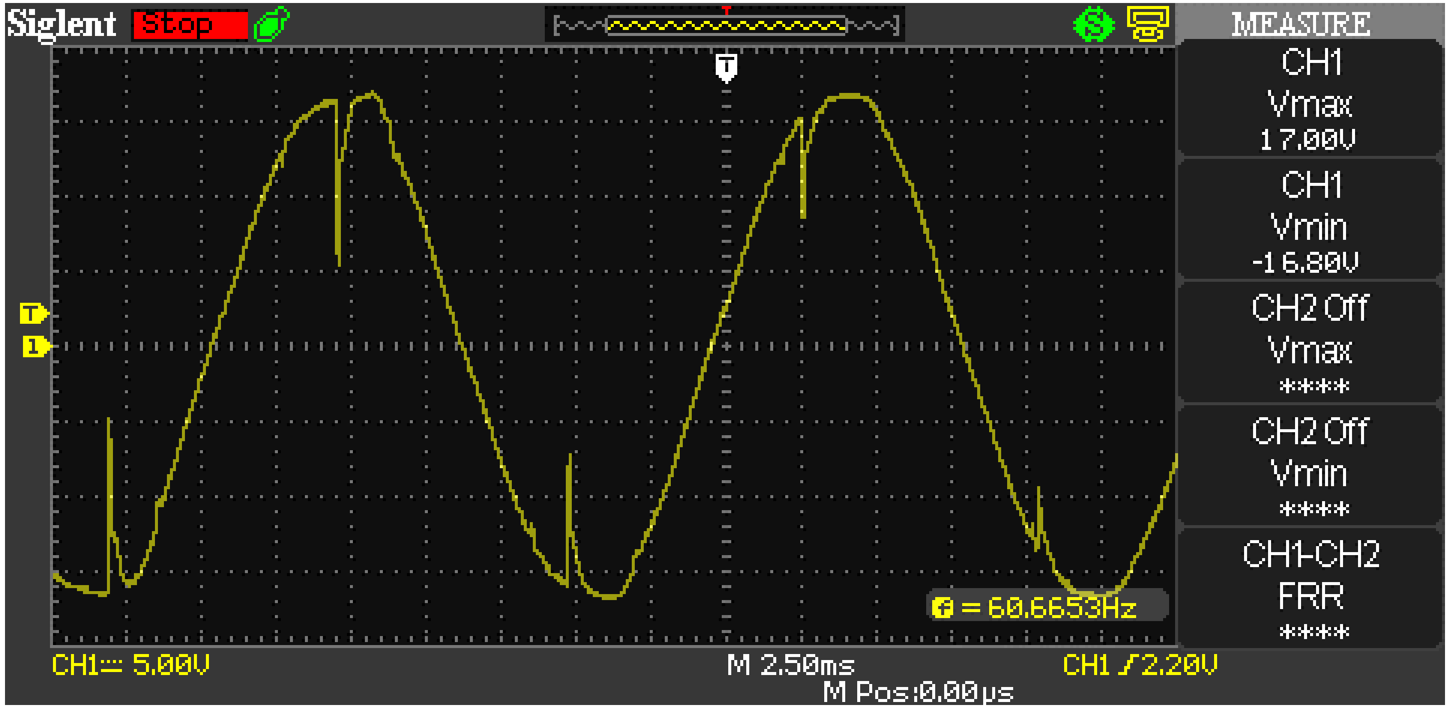
Event-Triggered PoW	Continuous PoW
• **Requires event to be detected** in order to save recorded data • Stores **seconds – minutes** of data for a given event • Data is typically stored on **local archive** (not live-streamed) • Data may require **manual retrieval** • This is the existing **dominant PoW technology in use today**	• Captures high sample-rate data **at all times** • Offloads data to **remote server**; no need for large onboard data cache • Data is available **as soon as it is transmitted** • Archive may be **polled when necessary** • Polling **may be event-triggered** • This is the technology recommended in **NASPI PNNL-29770** in 2020 [2].

[2]: A. Silverstein, "High-resolution, time-synchronized grid monitoring devices," in *North American Synchrophasor Initiative (NASPI)*. Rep. PNNL-29770, 2020. [Online]. Available: https://www.naspi.org/sites/default/files/reference_documents/pnnl_29770_naspi_hires_synch_grid_devices_20200320.pdf.

Why do we need CPoW measurements?

Fast events:

- Certain power system events may occur in **less than 1 AC cycle**
- Actual sub-cycle disturbance observed on June 9, 2020 ("spur of the moment" oscilloscope capture)



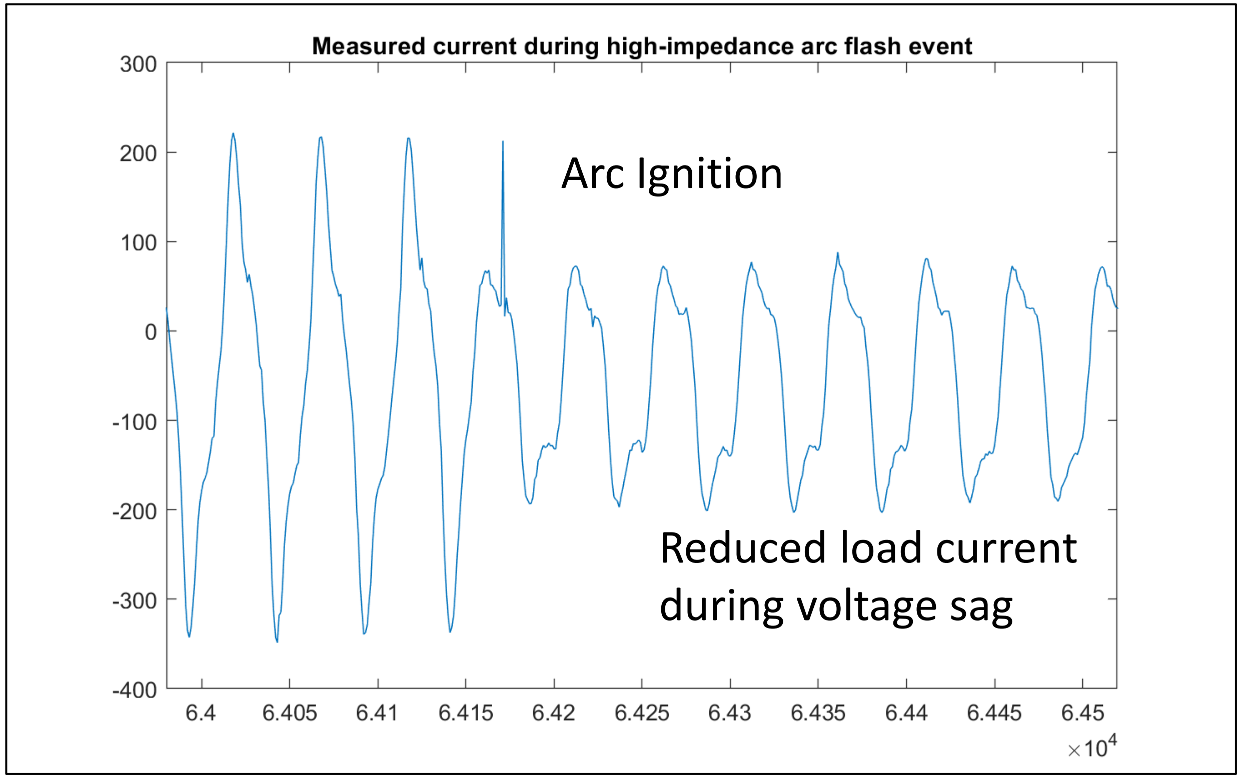
- Event **persisted for 6 hours** before problem was resolved (unknown cause)

30 Sa/sec PMU would not have been able to accurately characterize this disturbance!

Why do we need CPoW measurements?

<u>Fast events:</u>

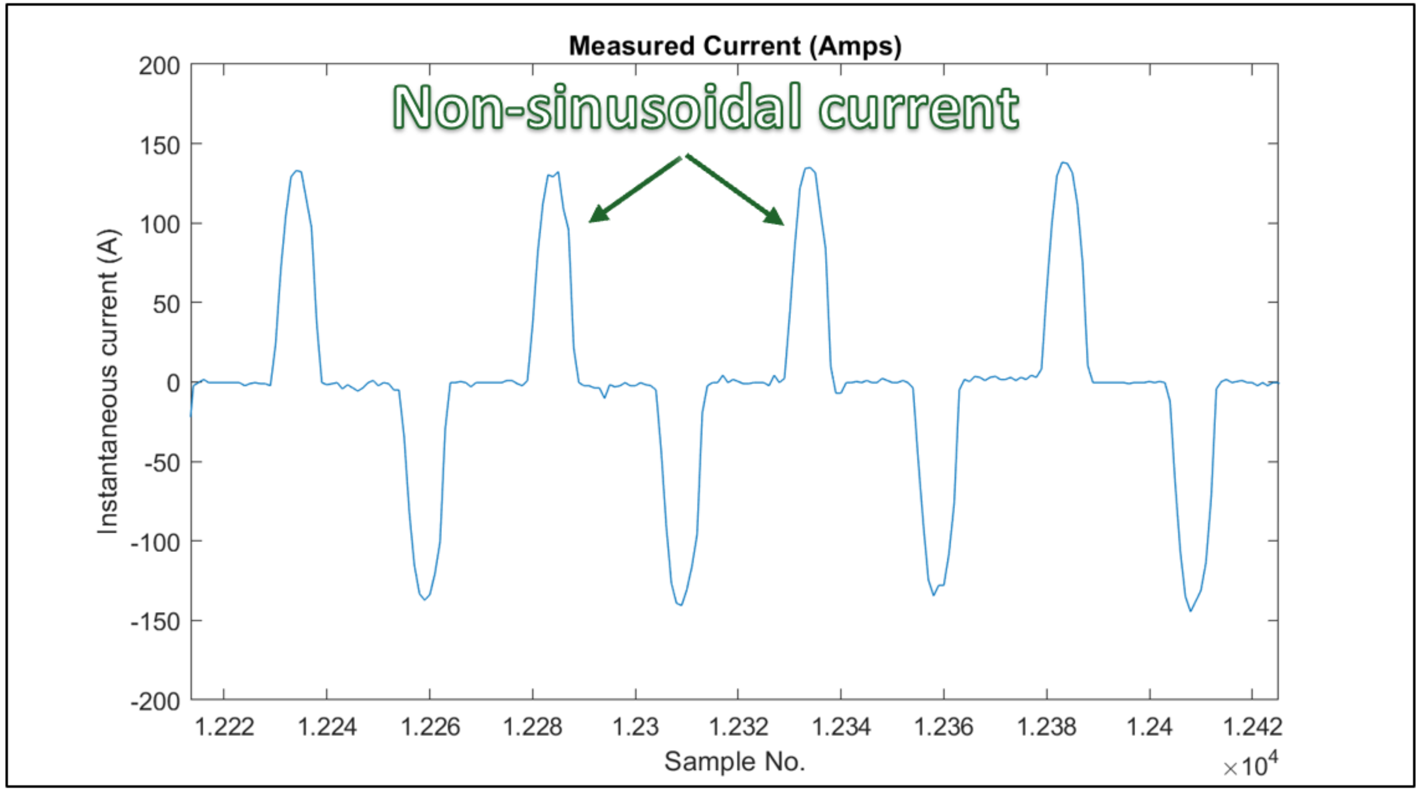
- Characteristics of **certain serious events** may also be fast (sub-cycle)
- For example, bench test of **arc-flash event** shows initial current spike during arc ignition:



Why do we need CPoW measurements?

Harmonic content:

- **Photovoltaic inverters** may introduce harmonic content into the distribution system
- **Power electronics loads** may also introduce harmonic content
- Characterization of this harmonic content requires **high-frequency measurement**



Why should CPoW measurements be time-synchronized?

Event location analysis:

- Time-synchronized measurements can be **compared to other distant measurements** even if packets do not arrive at the same time
  - **Magnitude** of simultaneous event signatures can be compared in order to locate event cause
  - **Response effort** to events can be more quickly coordinated

Post-mortem analysis:

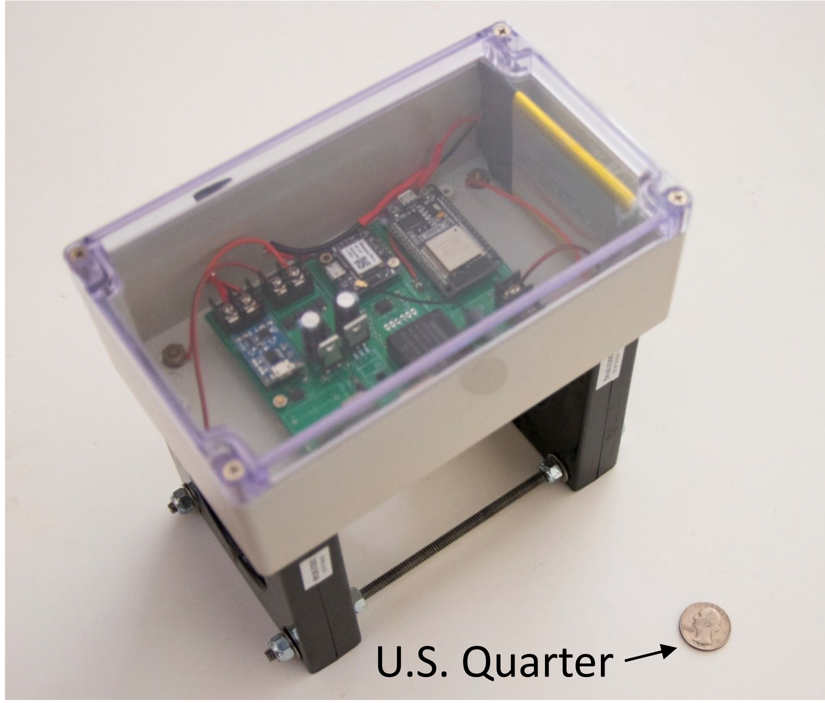
- Time-synchronized measurements indicate **exactly when an event happened**
- Time-synchronized measurements indicate **what was happening before the event**

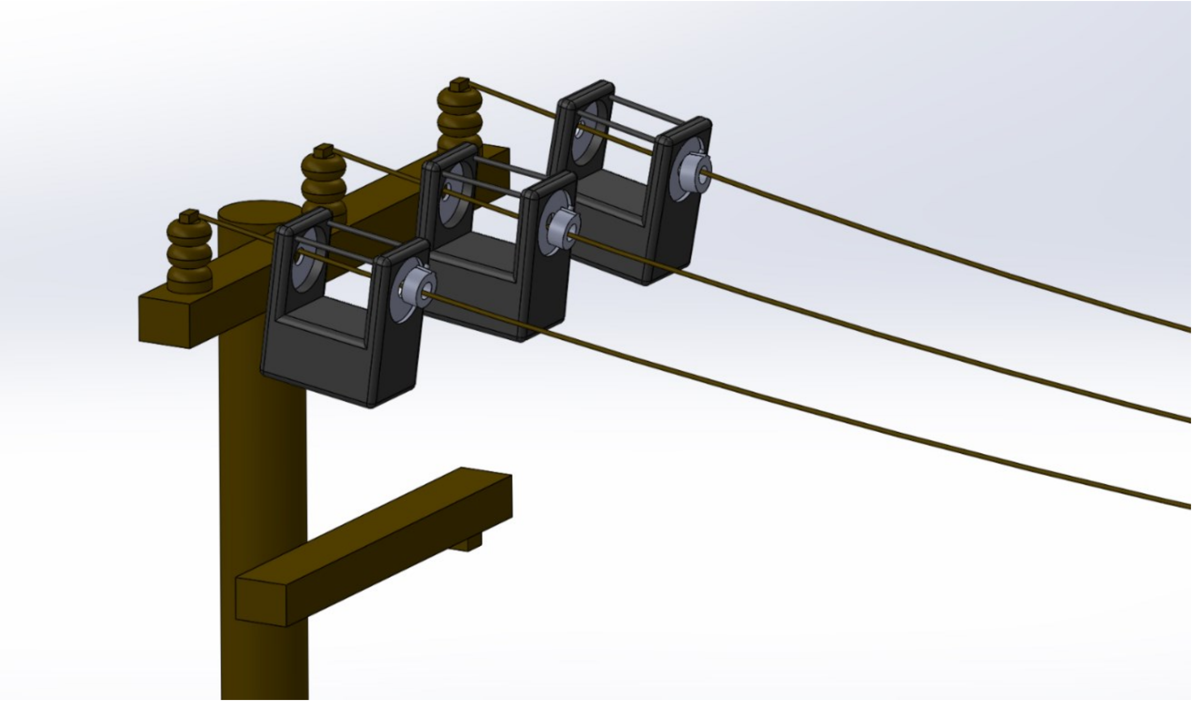
Conversion to synchrophasor:

- Time-synchronized point-on-wave measurements can be converted to **phasors**
  - Timestamp of phasors is known, so **synchrophasors** can be obtained
  - Synchrophasors from multiple event sites can be used in **power flow analysis and state estimation**
  - Synchrophasor format is an **efficient archiving method** for high-resolution CPoW data

Solution: A Synchronized Self-Contained Line-Powered CPoW Recorder

- A CPoW recorder module has now been developed with:
  - **Fully wireless communication**
  - **Internal energy harvesting from power line current**
  - **Internal instrument transformer for accurate measurement**

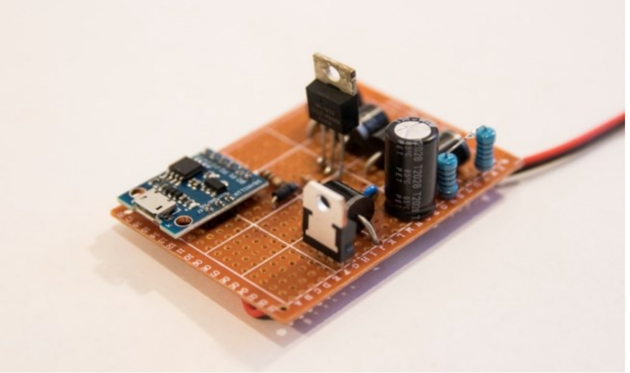


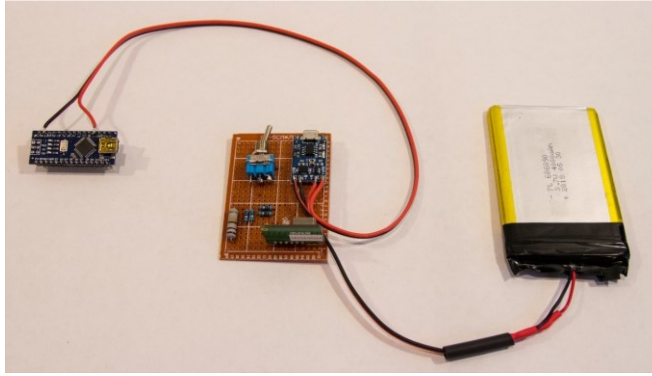


Functional Components Required

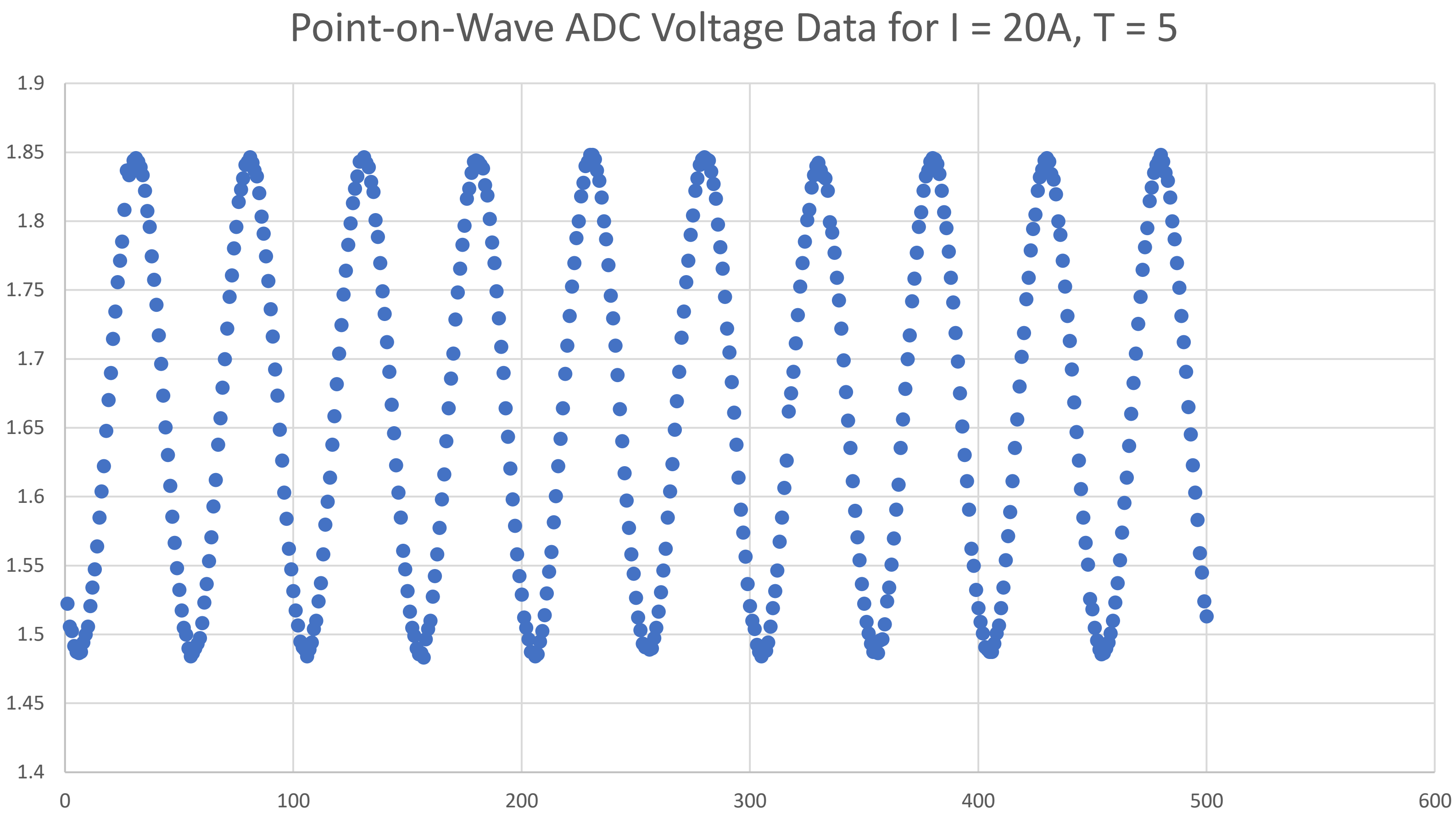
The following components were individually developed or selected to achieve design goals:

- An **energy-harvesting circuit** compatible with a commercially available current transformer (CT)
- A **signal conditioning circuit** to interface a commercially-available CT to an analog-to-digital converter (ADC)
- A **battery energy storage** block to ensure continued module operation during low-current conditions or power outage conditions
- A **GPS receiver unit** capable of providing high-resolution timestamp data
- A **microcontroller unit** with ADC and wireless communication system



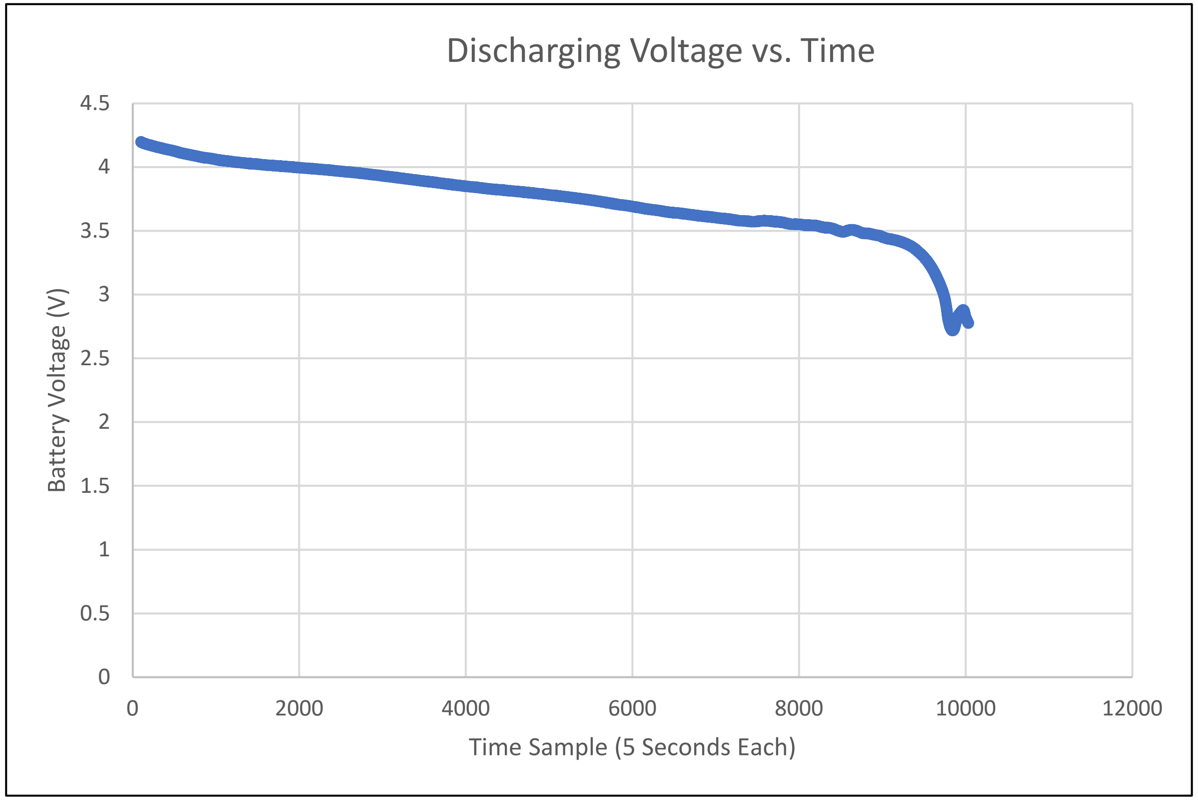


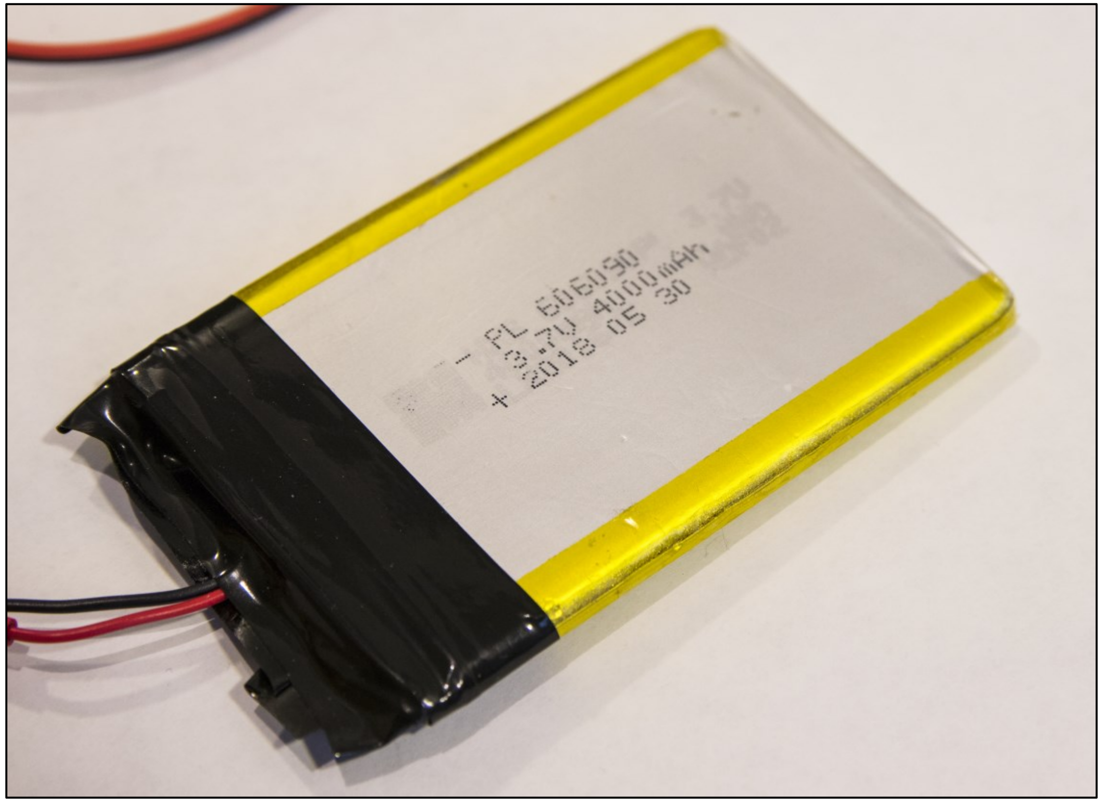
Validation Testing: THD with Ideal Sinusoidal Current



I_{RMS} = 101.07 A THD = 0.8969%

Validation Testing: Battery Discharge Runtime





- Total battery discharge runtime (4000 mAh cell): **~13.6 hours**
- Can easily achieve higher runtimes using **larger battery sizes**
  - 8,000 mAh, 16,000 mAh, 24,000 mAh are all practical

Validation Testing: Minimum Operating Current

With Battery Connected/Charging:

	Run 1:	Run 2:	Run 3:
Minimum start current (A):	41.3	41.1	40
Minimum hold current (A):	40.7	39.7	39.3

*Minimum currents defined as current levels required for continuous recording and transmission of data.

*Boost converter disabled for battery testing to prevent batery from powering the device

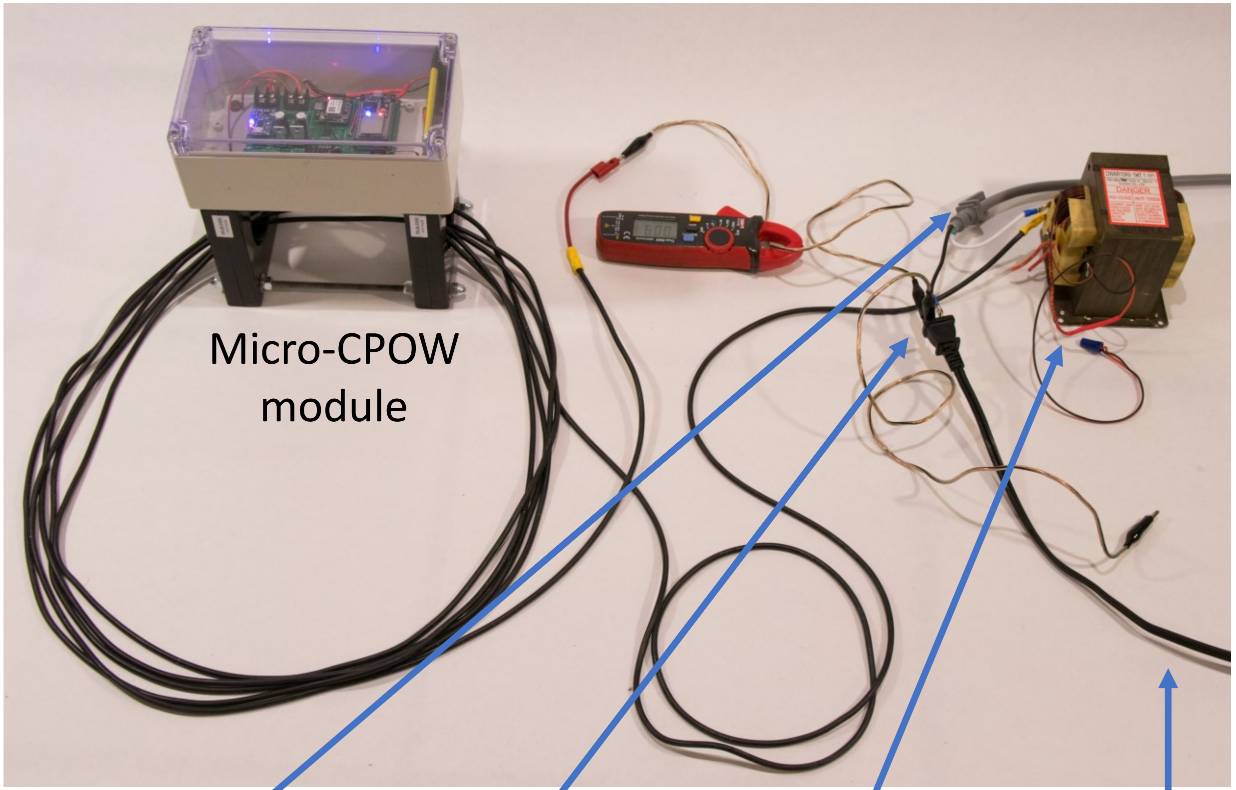
Without Battery:

	Run 1:	Run 2:	Run 3:
Minimum start current (A):	33.1	32.3	31.9
Minimum hold current (A):	29.9	30.1	29.8

- Utilization of MPPT tracking will enable **even lower operating line currents**

Practical CPoW Applications: Short-Circuit Detection

Simulated downstream short-circuit testing (9.5 A load, 40 A line fault capability):

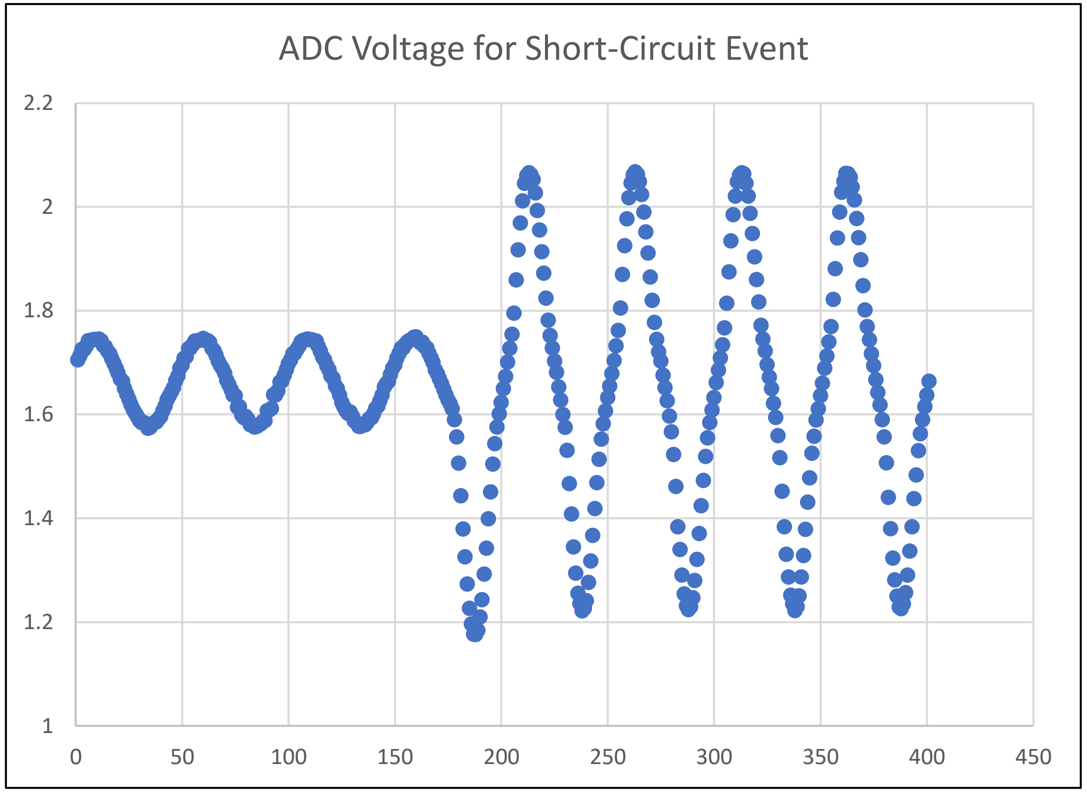


120 V AC supply

Short-circuit location

Transformer with secondary shorted out

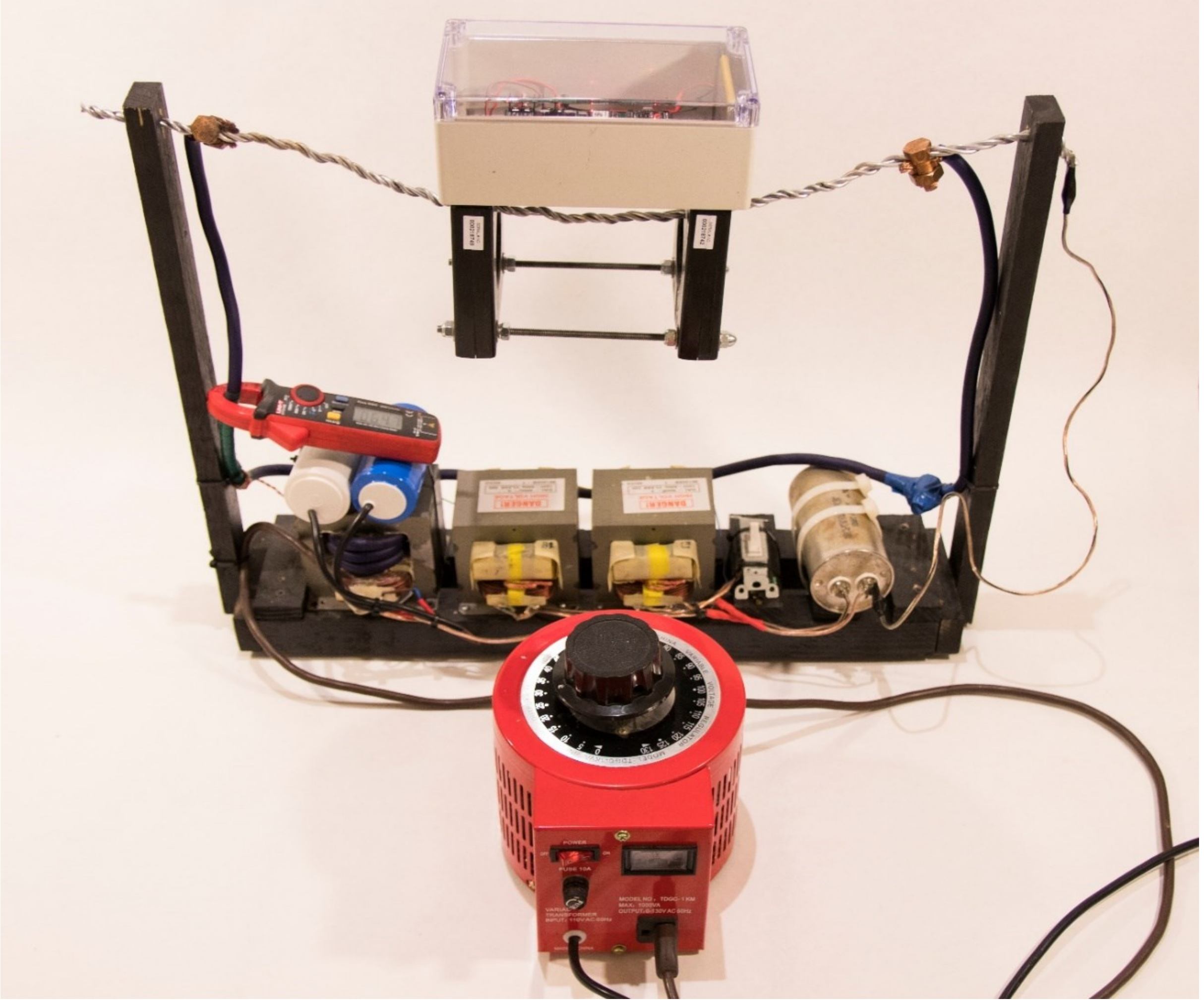
9.5 A resistive load



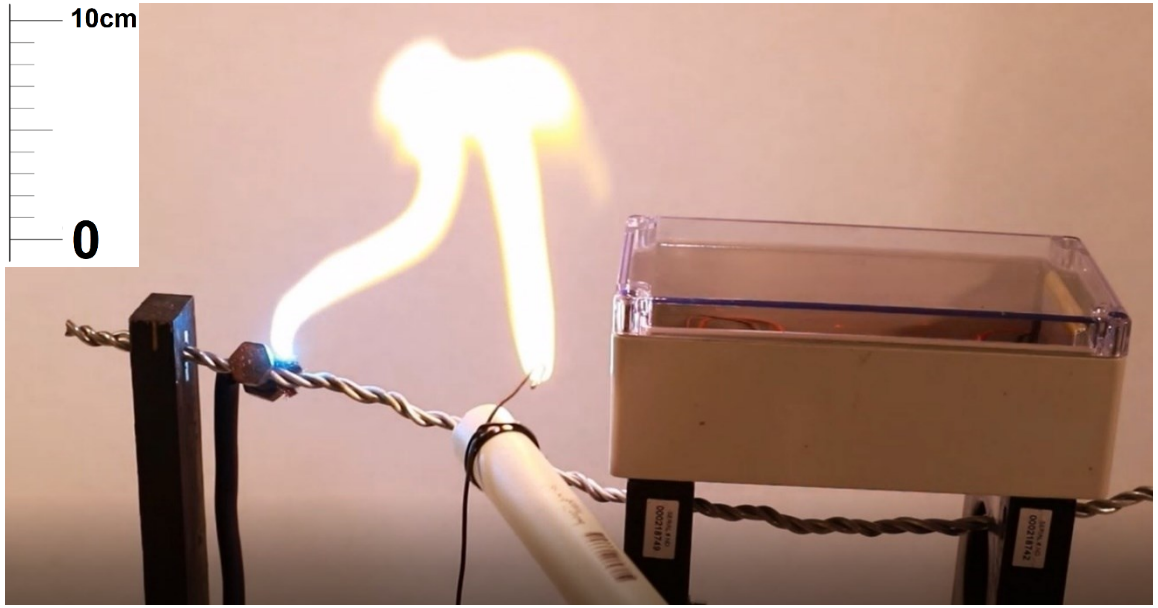
Abnormal current detectable (with timestamp) in
<3 samples (1 millisecond)!

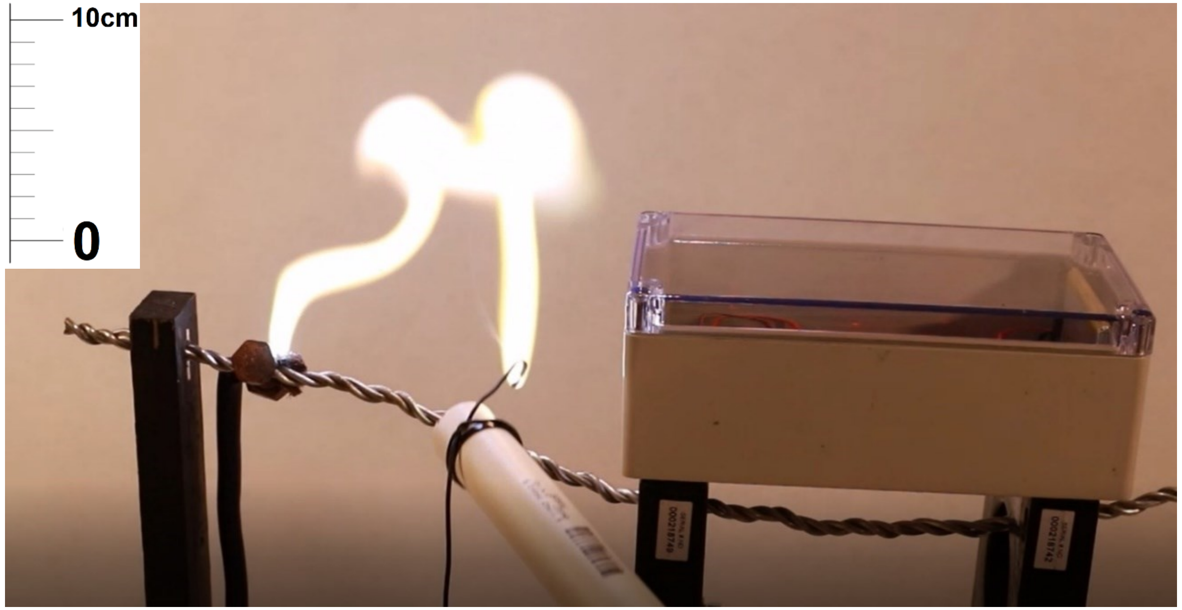
Practical CPoW Applications: Arc Fault Tolerance and Detection

- Constructed a simulated distribution line
- **100 A line current from, 4400 V line-to-ground potential** from HV source
- **1.0 A fault capability** from the HV source



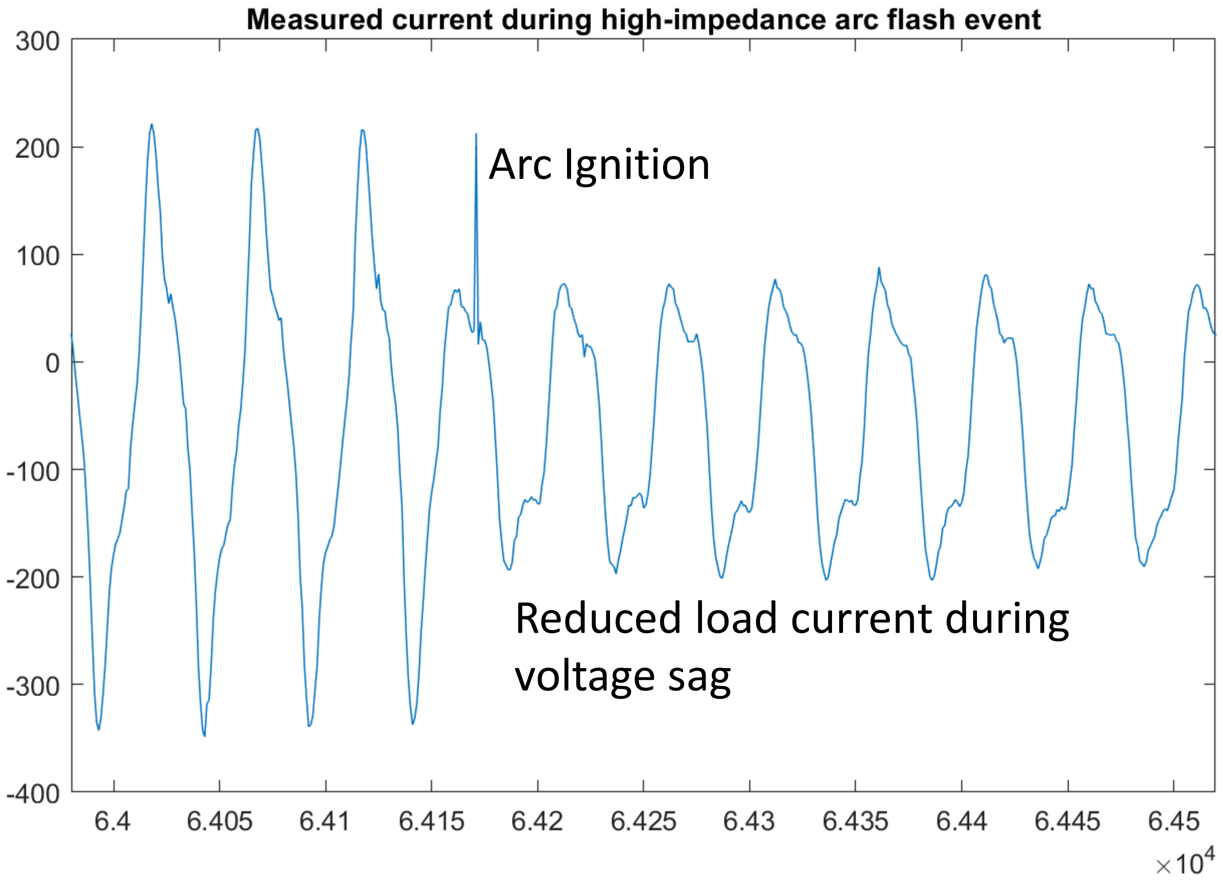
Practical CPoW Applications: Arc Fault Tolerance and Detection





- Arc flash from a 4400 V AC, 1.0 A source **did not adversely affect performance**
- **Signs of arcing** were detectable in the current measurements

Practical CPoW Applications: Arc Fault Tolerance and Detection



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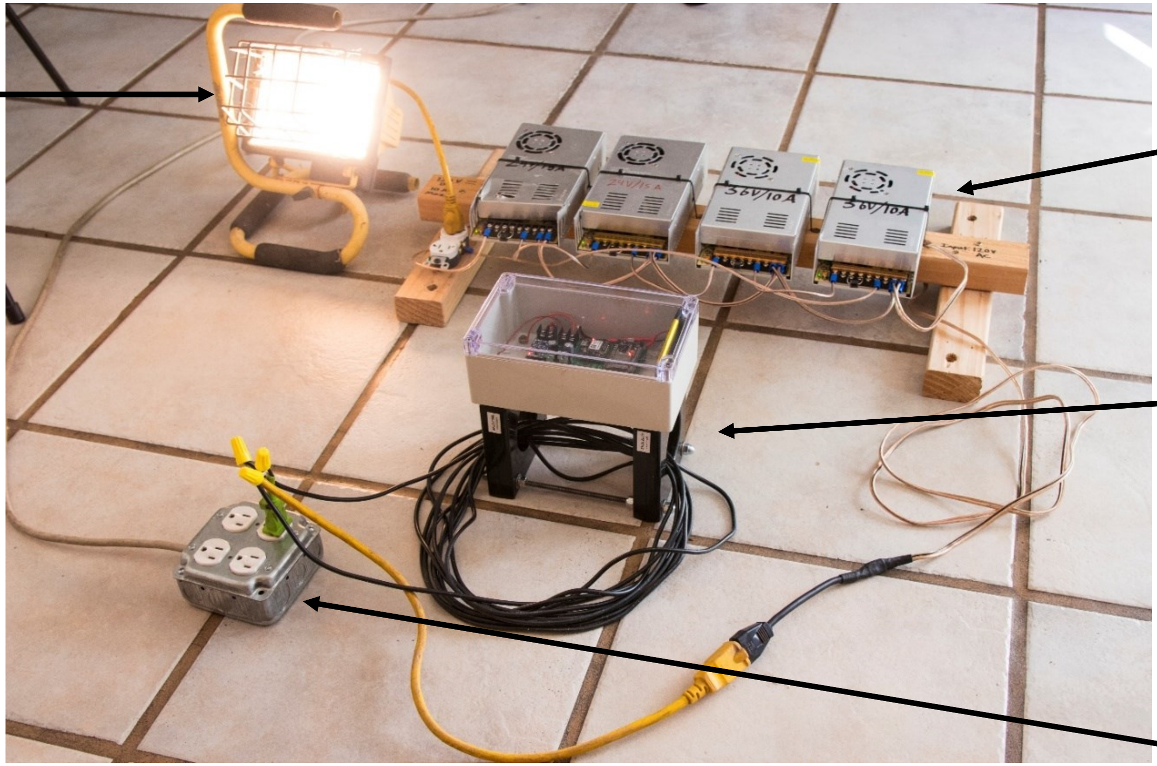
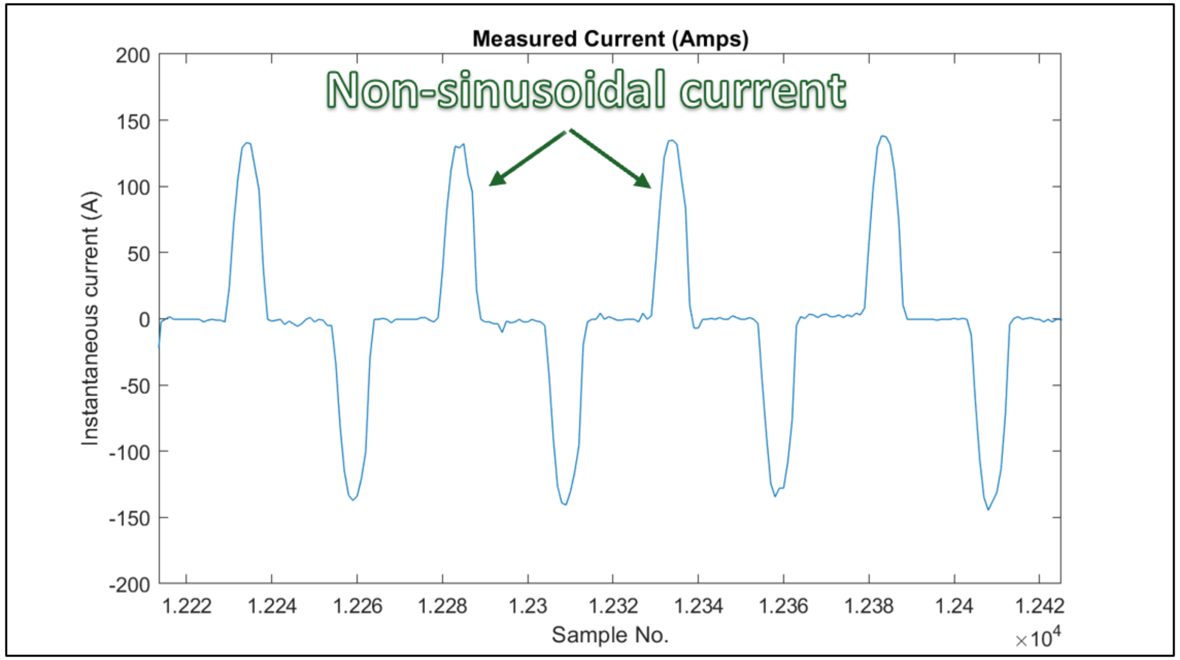
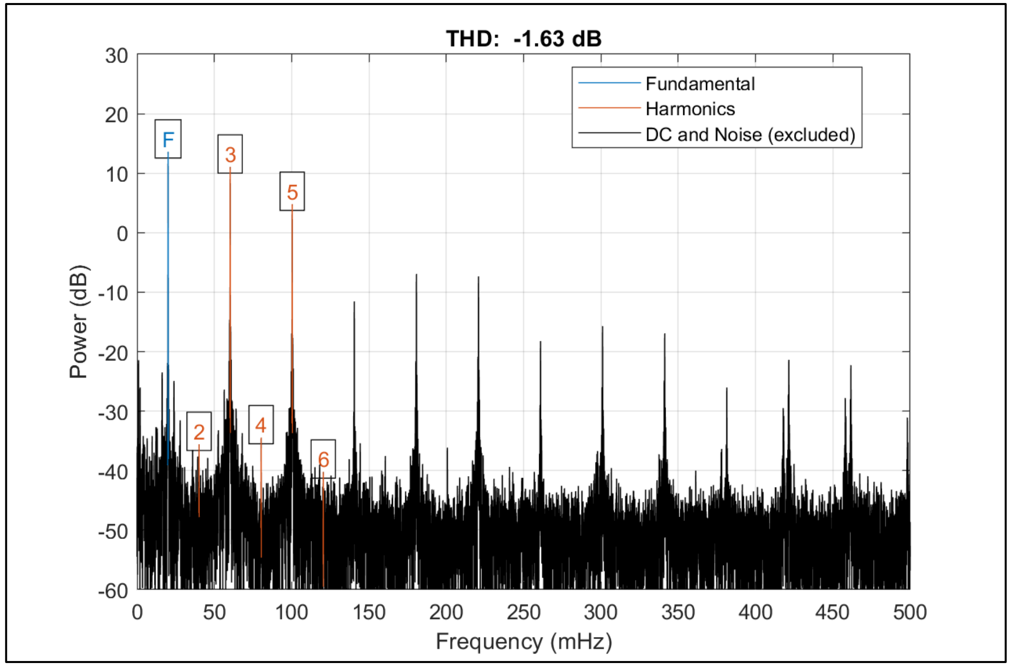
Practical CPoW Applications: Load Harmonics Characterization



- Connected a bank of low-voltage power supplies with **no power factor correction** to the CPoW device for monitoring

Practical CPoW Applications: Load Harmonics Characterization

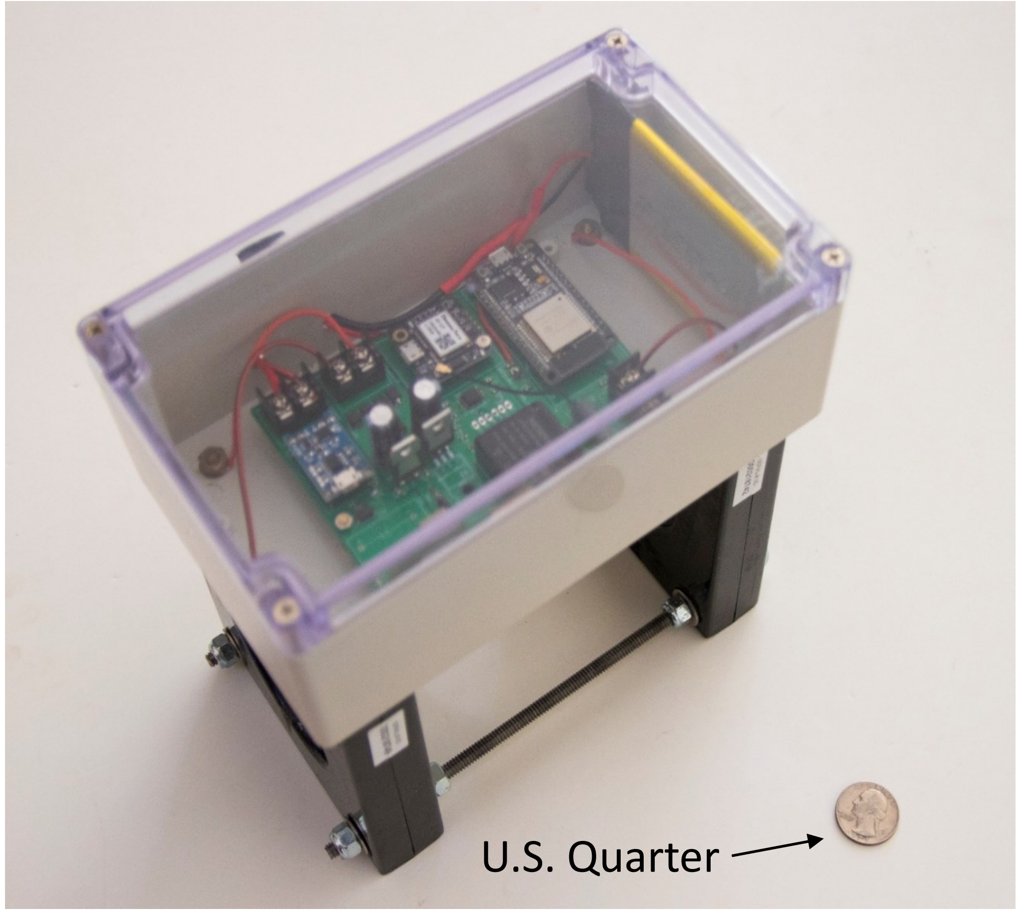


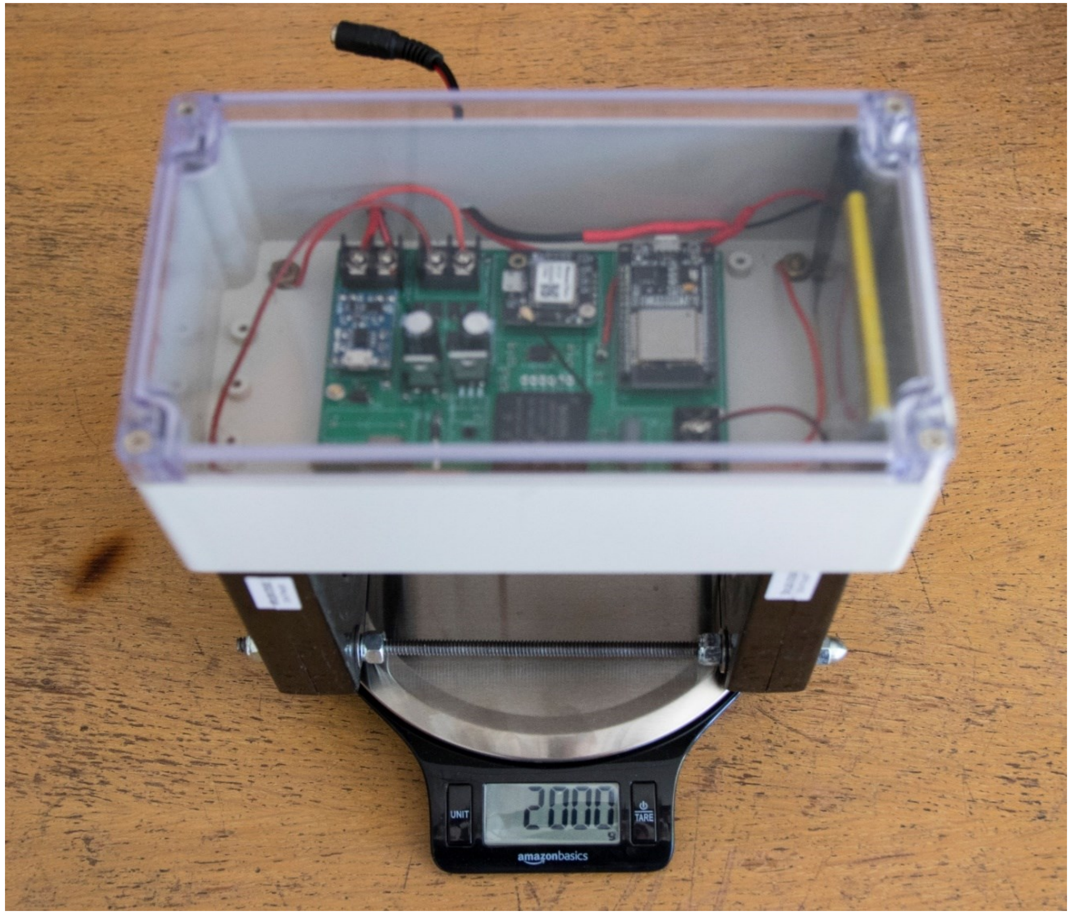


RMS Current (A):	6.35 A
Average Current (A):	3.65 A
Peak Current (A):	15.78 A
THD (%)	82%

- Resulting measured current shows **high odd-order harmonic content**
- **Fourier decomposition of output signal** confirms 3rd and 5th harmonics dominate

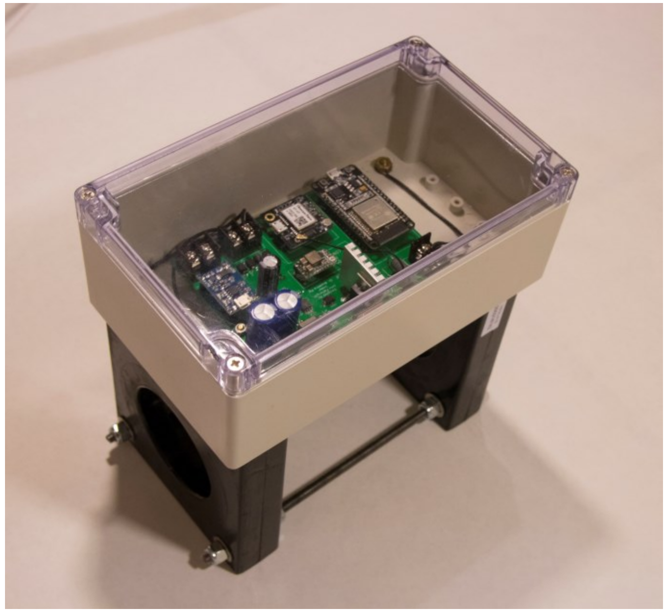
Physical Dimensions

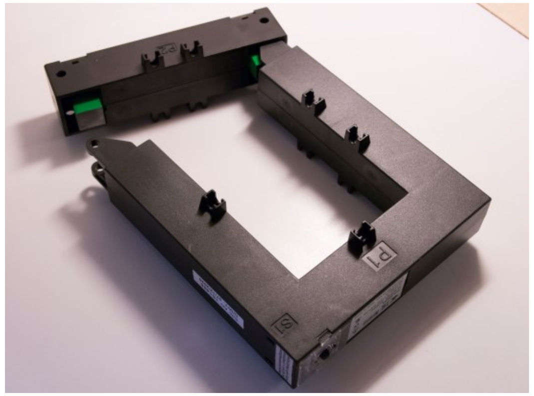




- Total device mass is **2.000 kg**, equivalent to less than 2.1 m of additional 4/0 conductor
- Overall dimensions are **200 mm by 200 mm by 120 mm**

Future Research Topics





- Optimize **manufacturability**
  - Custom-build weatherproof cases
  - Utilize **split-core CTs**
- Better characterize **real-world events**
  - **Full-current** vegetation strike events
  - **Full-current** short-circuit events
- Implement **voltage measurement**
  - Line-to-ground capacitor method
  - E-field sensing method
- Optimize **battery life** (including **MPPT**)
  - Leverage **FPGAs or other embedded solutions** for better power use efficiency
- Implement **compression algorithms** for better data efficiency
- Implement **end-to-end encryption** for improved data security

Conclusion

- A **Synchronized Self-Contained Line-Powered Continuous Point-on-Wave Recorder** was designed, constructed, and characterized
- The micro-CPoW module **performs well in laboratory conditions**
- CPoW measurement technology is expected to **play an increasing role** in the real-time monitoring of the distribution system in the future
  - It is hoped that through the deployment of this technology, **wildfire impact can be reduced,** and **system reliability can be improved**
  - Everyone will benefit from a **better understanding of the high-speed behavior of the distribution system edge**

Thank you!

Any questions?