Frontiers in Smart Grid Data Availability

IEEE Smart Grid Comm (Singapore, October 26, 2022)

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Data-Driven Smart Grid Research

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Which Data?

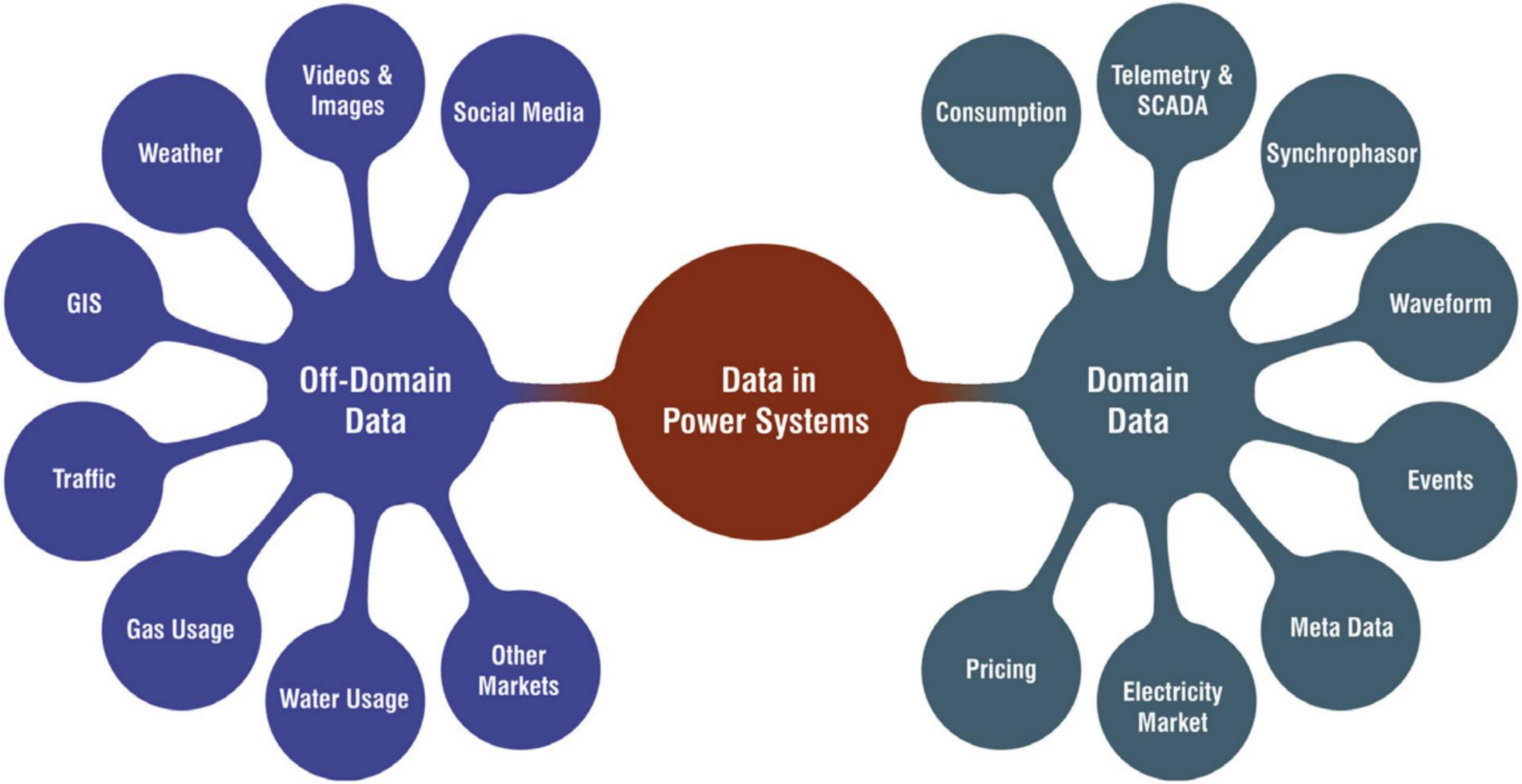
Data-Driven Smart Grid Research

Which (Real) Data?

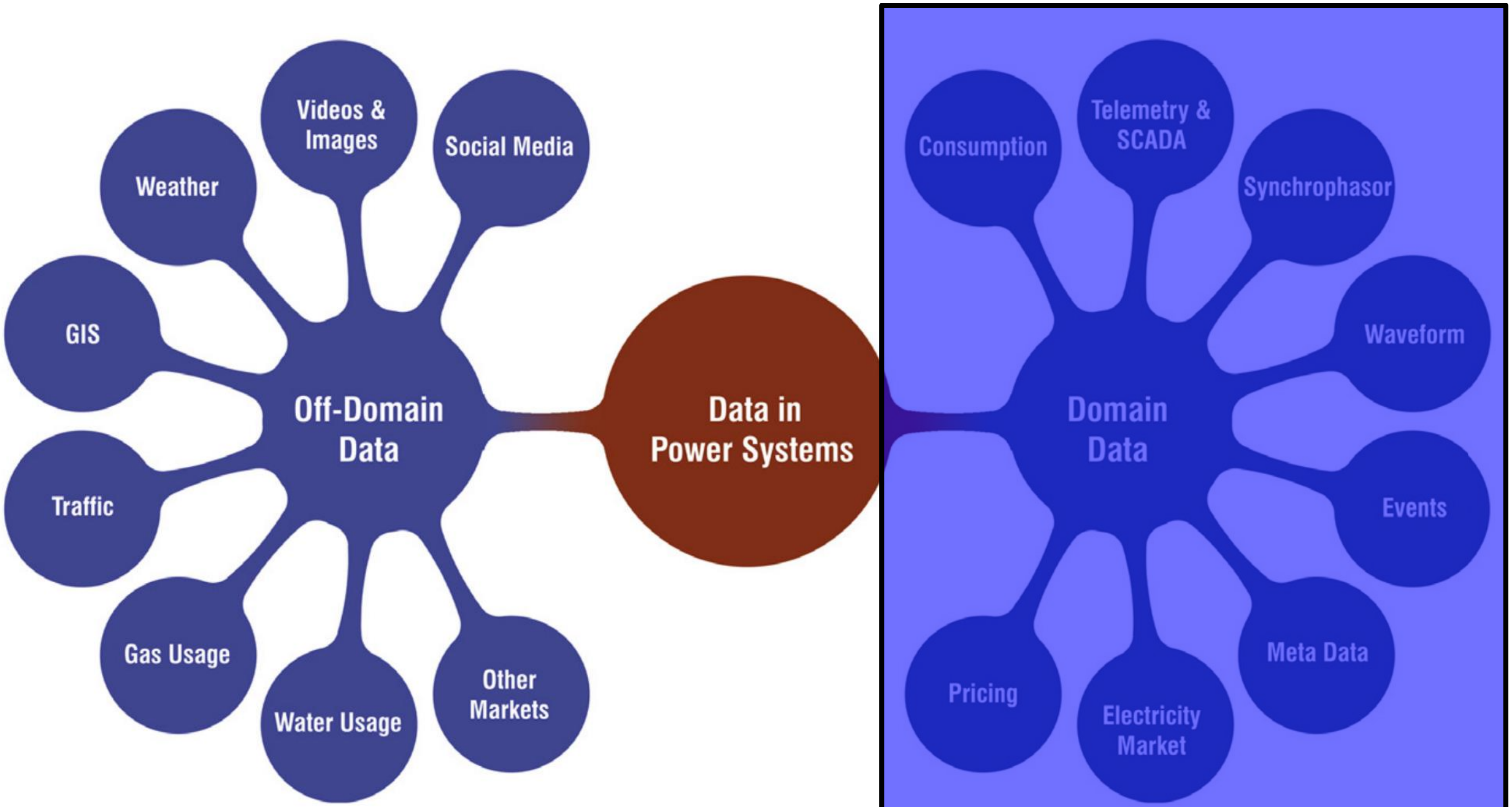
Data-Driven Smart Grid Research

Our Focus: Some Recent Updates!

Data-Driven Smart Grid Research



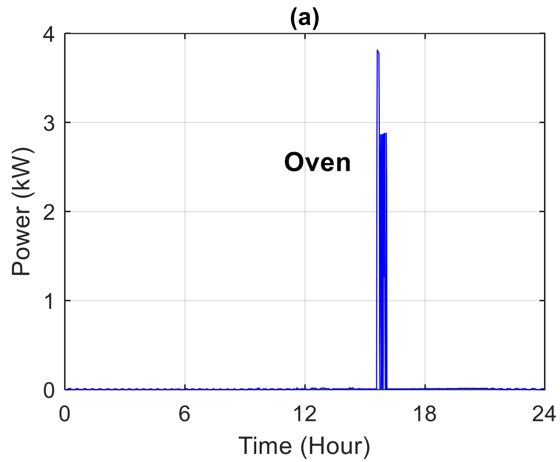
Data-Driven Smart Grid Research



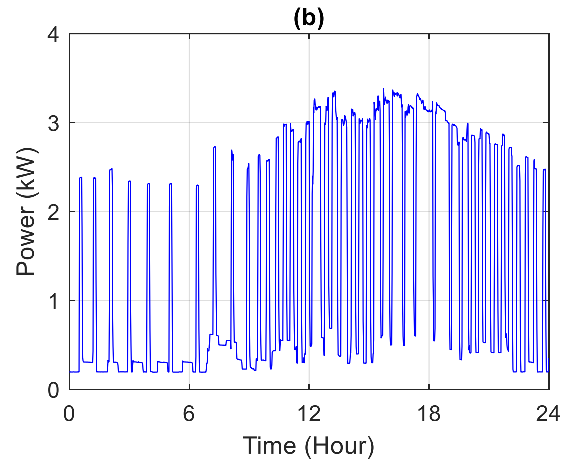
Our Focus

Common Domain Data: Power

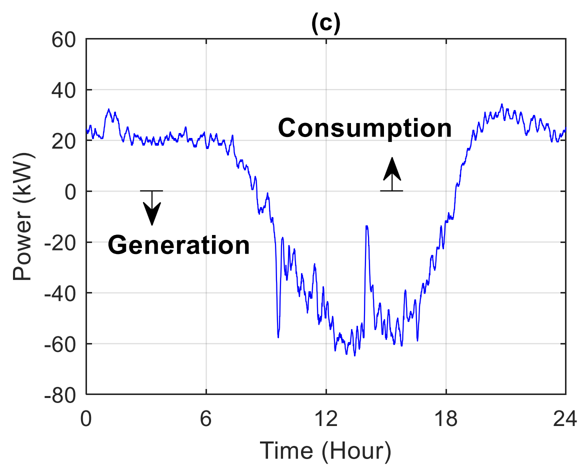
Appliance



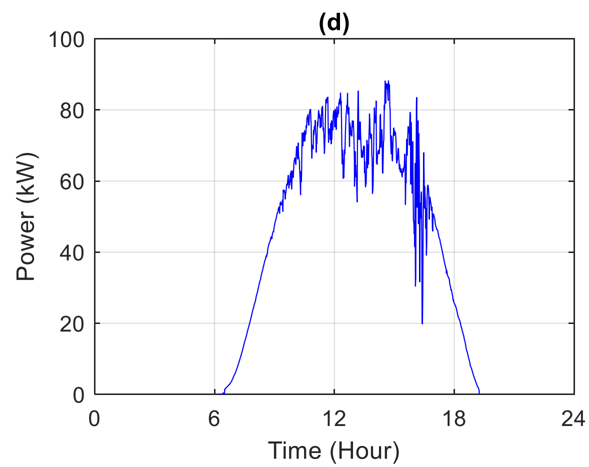
House



Building with DERs



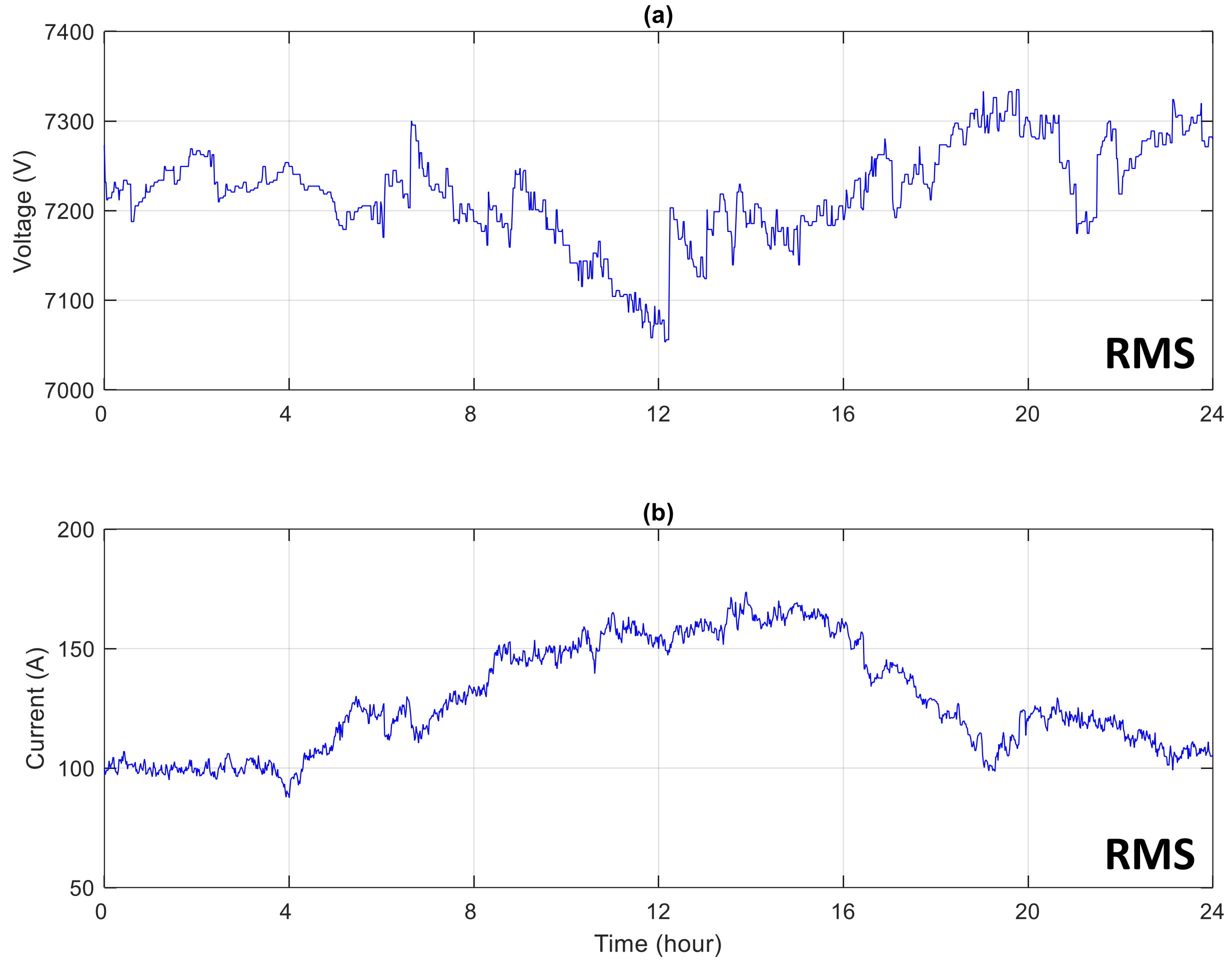
Solar



Common Domain Data: Voltage and [Maybe] Current

Substation

(69 kV / 12.47 kV)



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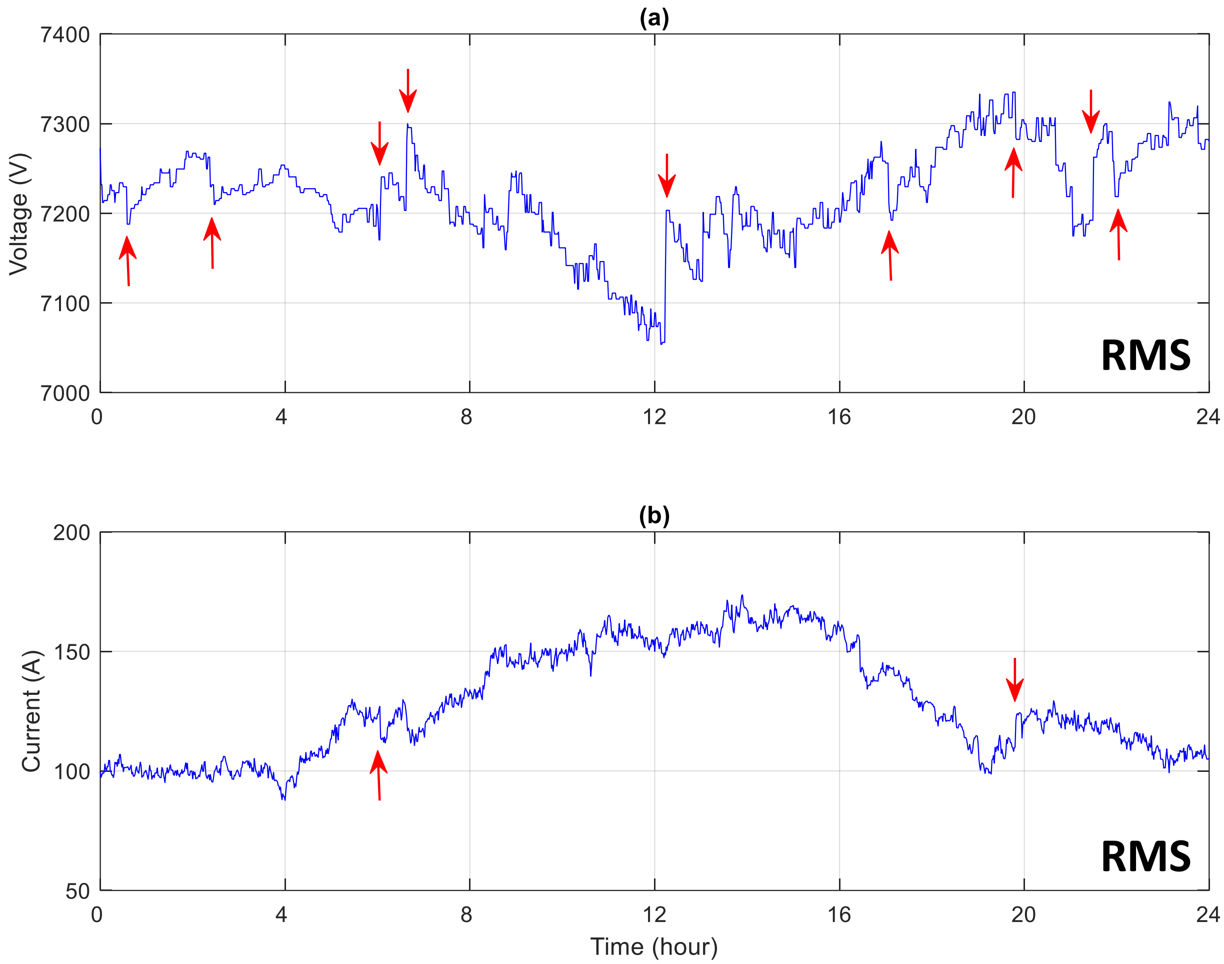
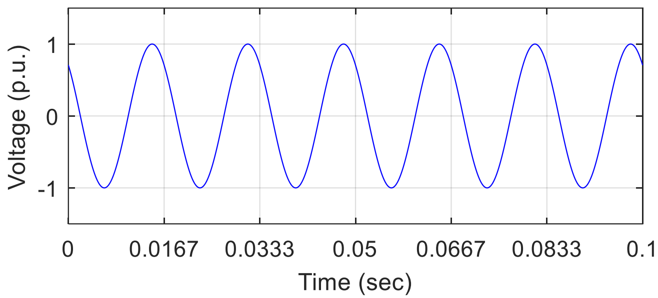
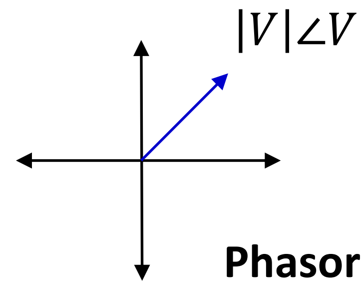


Phasor Measurements - PMUs

$$v(t) = |V|\cos(\omega t + \angle V)$$





Phasor Representation

Sensor: Phasor Measurement Unit (**PMU**)

FFT $\mapsto$ Fundamental Component

Phasor Measurements - PMUs

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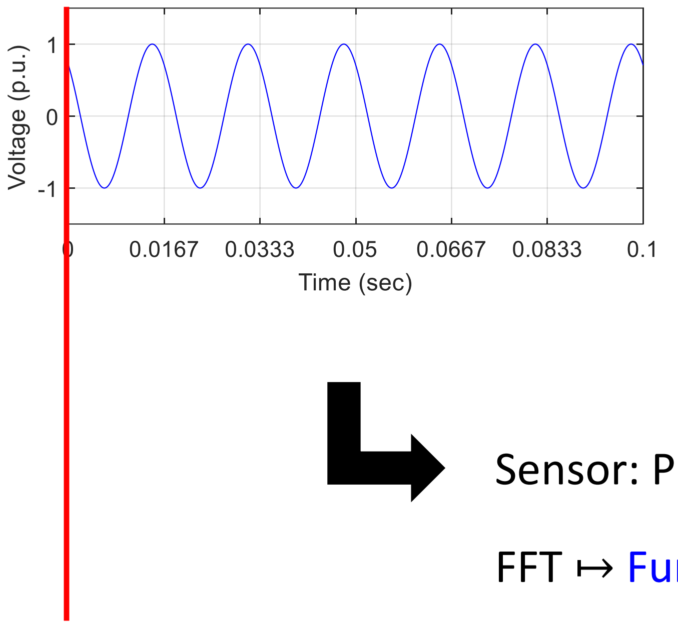
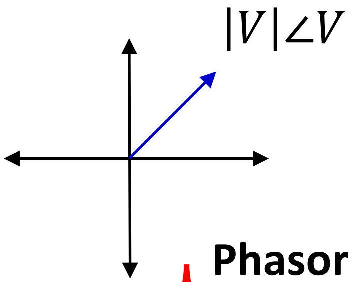




Phasor Representation

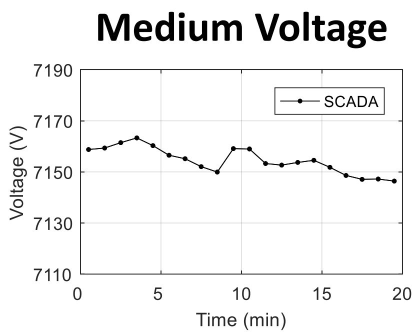
Synchro

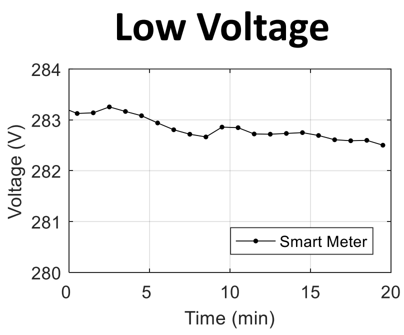
Sensor: Phasor Measurement Unit (**PMU**)

FFT ↦ Fundamental Component

Time Reference

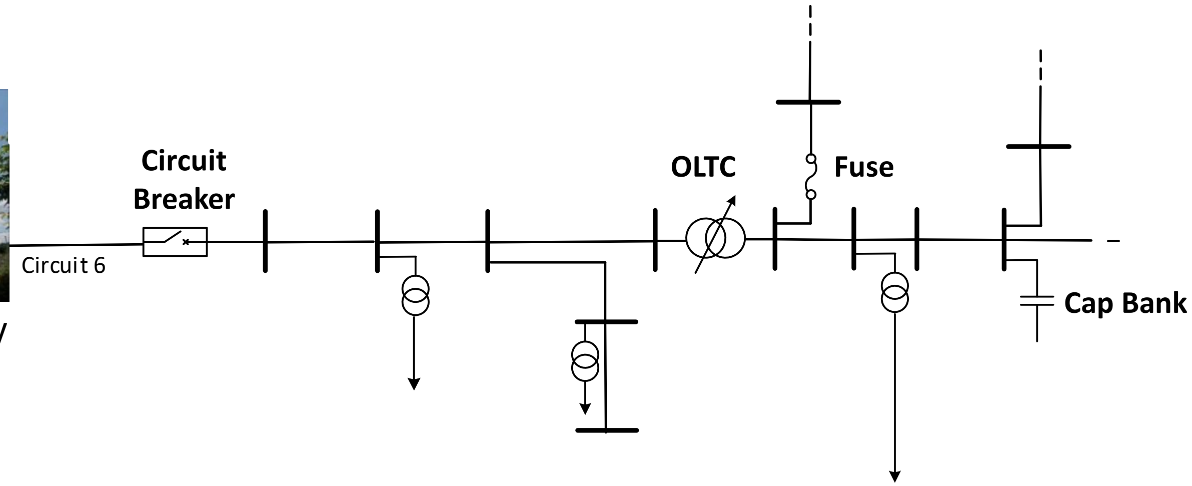
GPS Satellites





Substation: 69 kV / 12 kV

Riverside, CA



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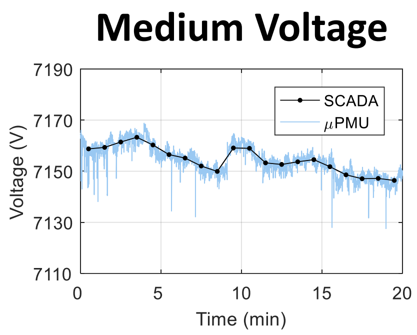

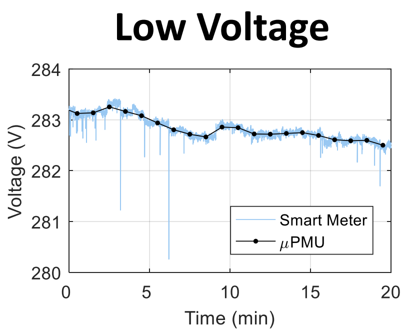

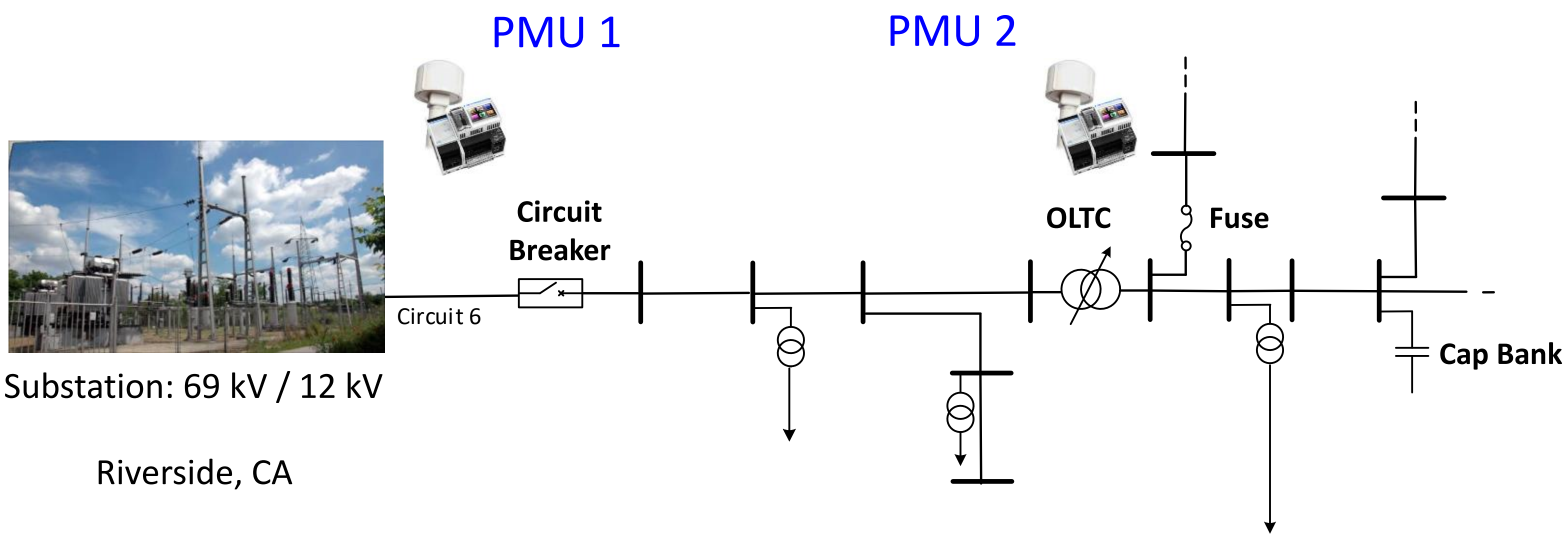

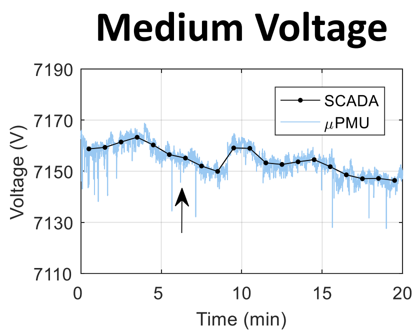

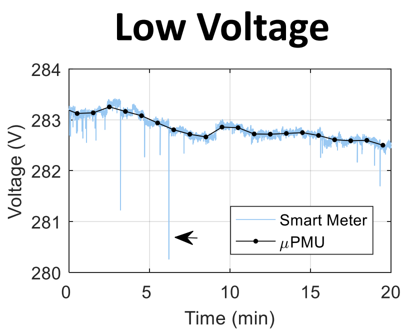

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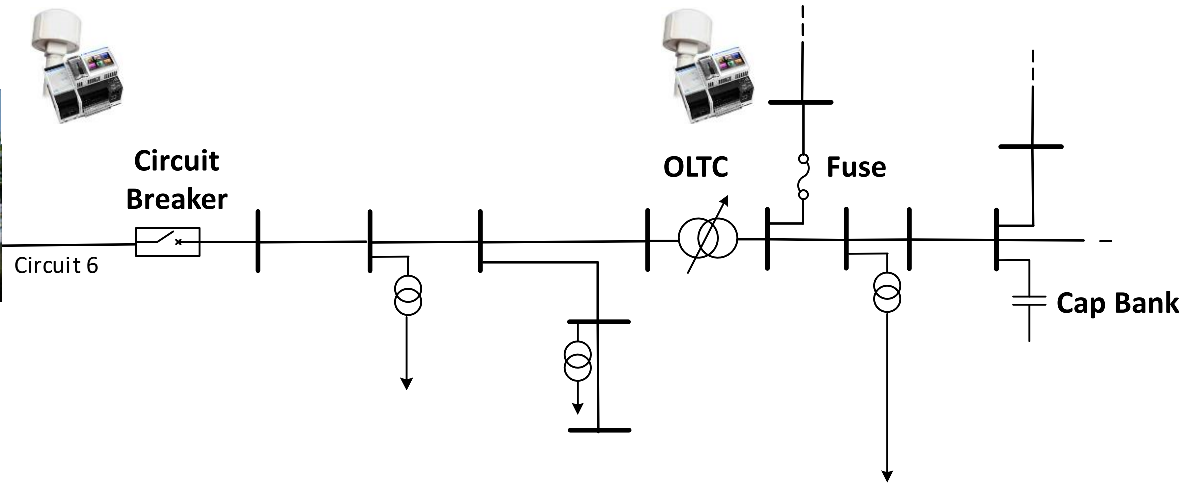
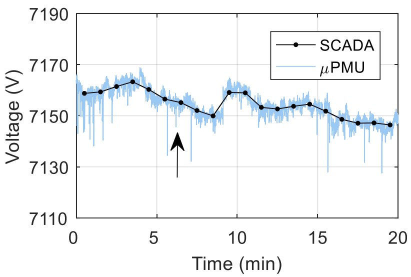
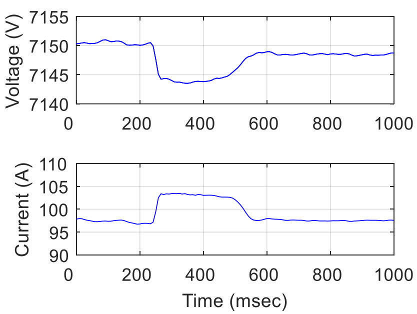


Phasor Measurements - PMUs

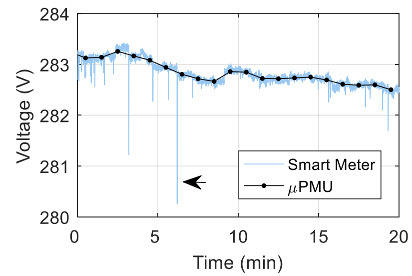
Medium Voltage

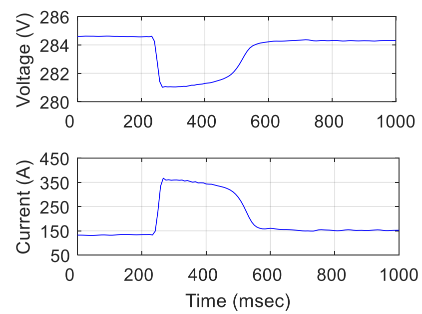




Magnitude

Low Voltage





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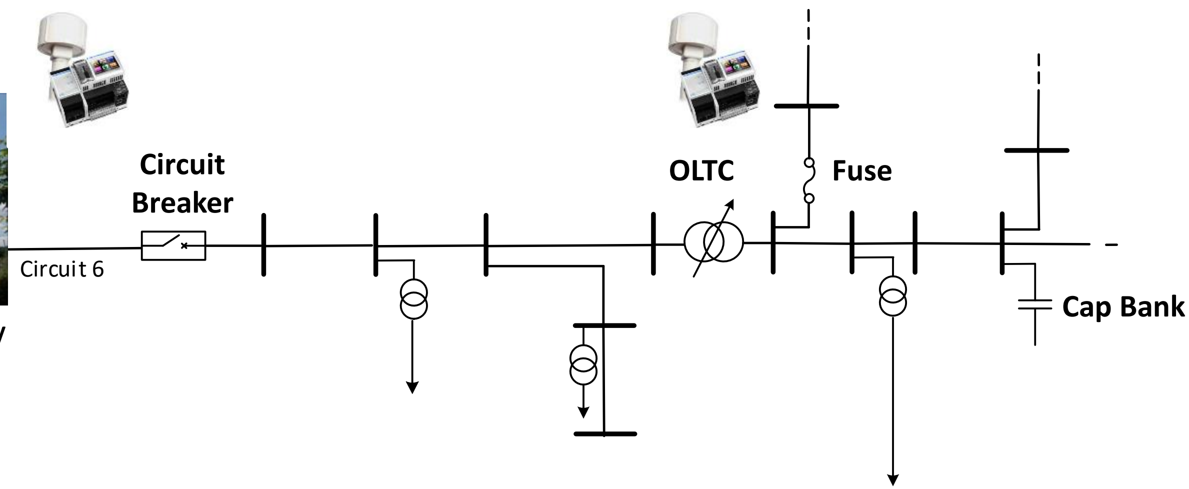

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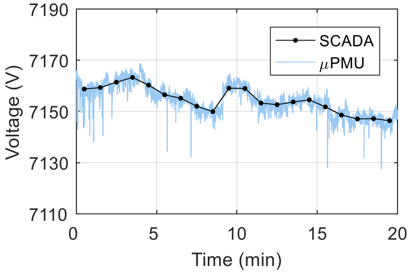
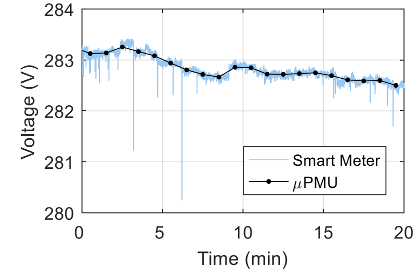
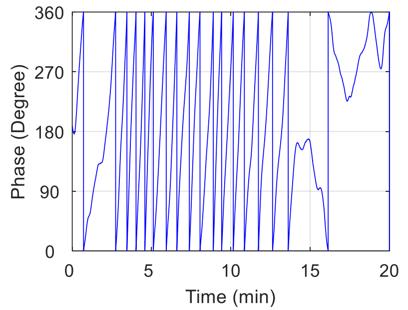
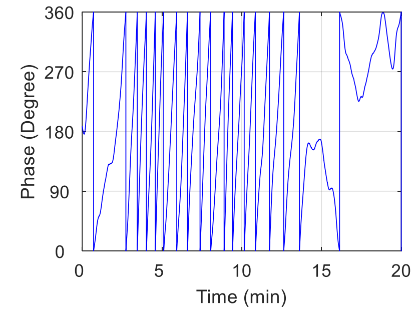


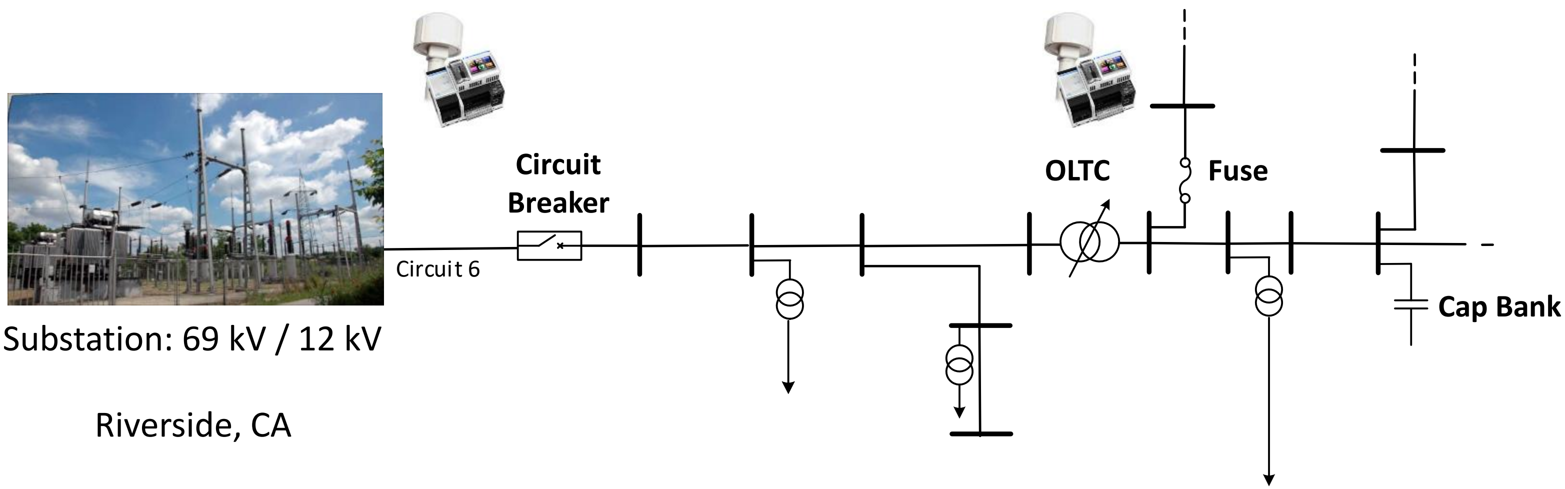
Low Voltage





Phase Angle





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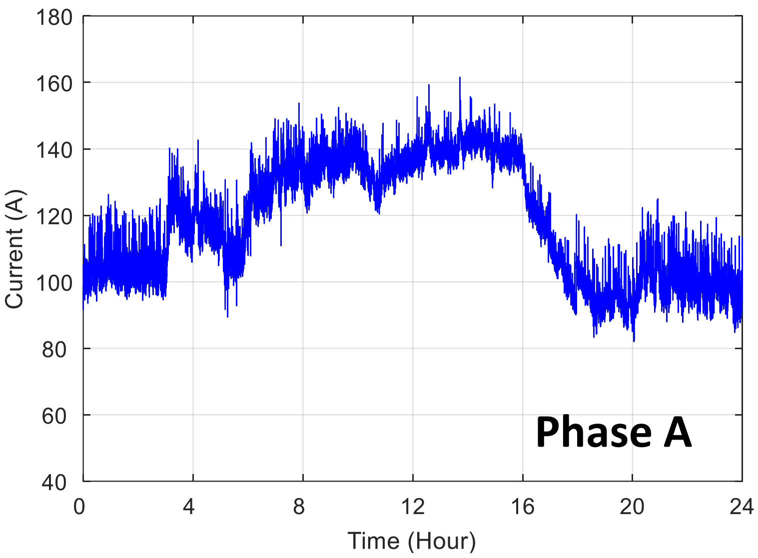
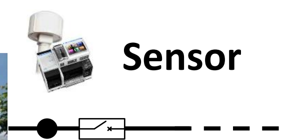


Event Signature

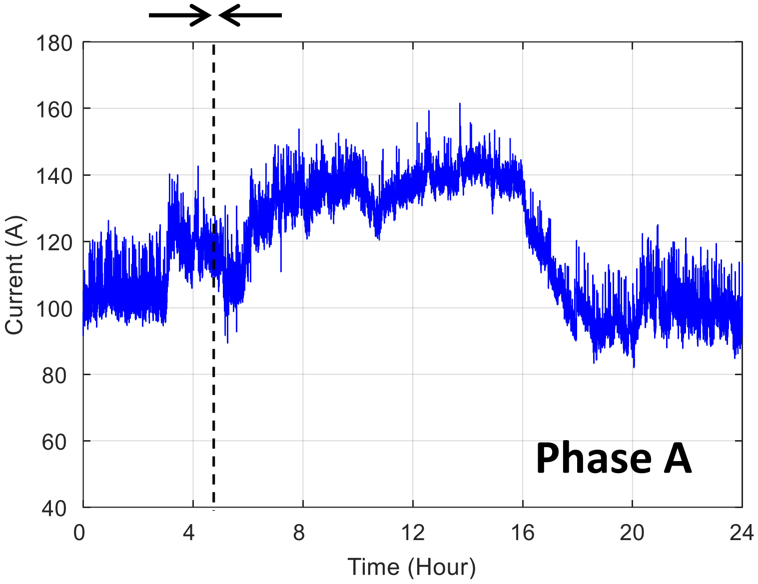
- Current (I)
- Voltage (V)



Micro-PMU

(Riverside, CA)

Phasor Measurements - PMUs



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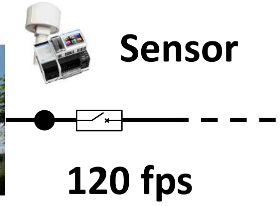

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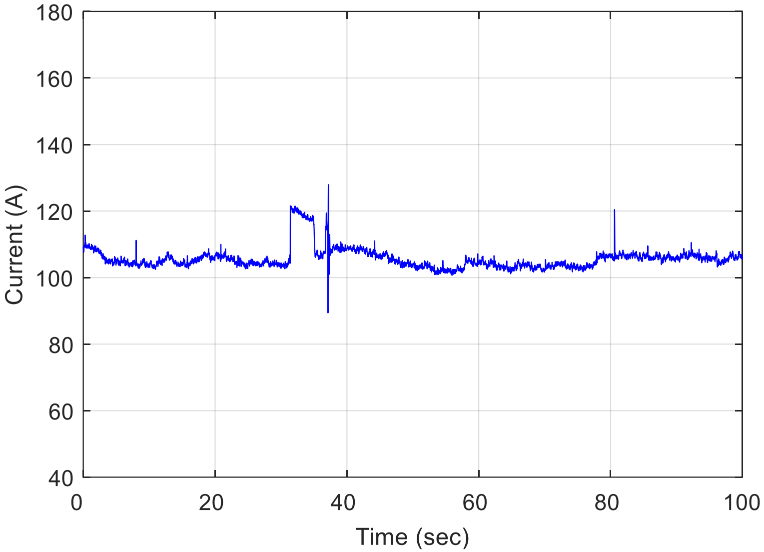
Phasor Measurements - PMUs



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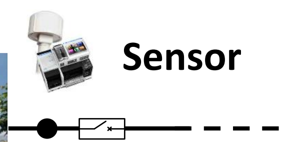
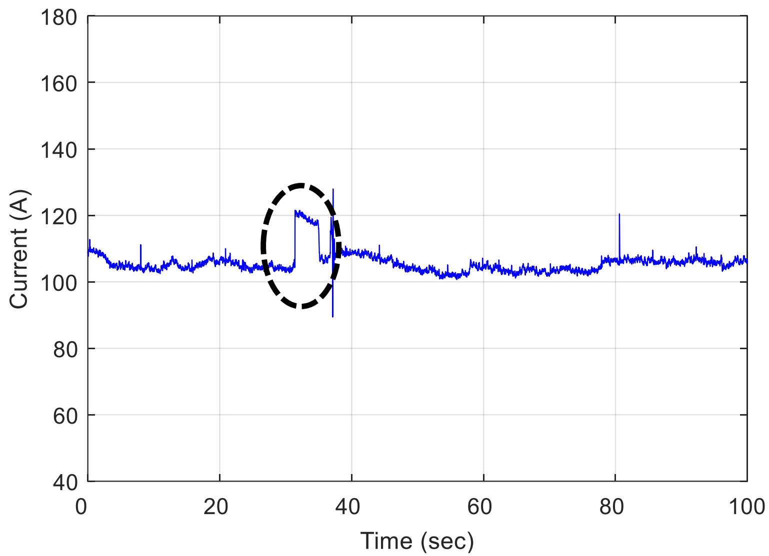


Sensor

120 fps

Micro-PMU

(Riverside, CA)



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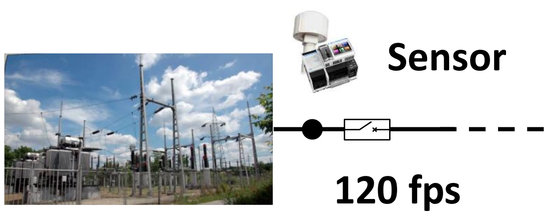

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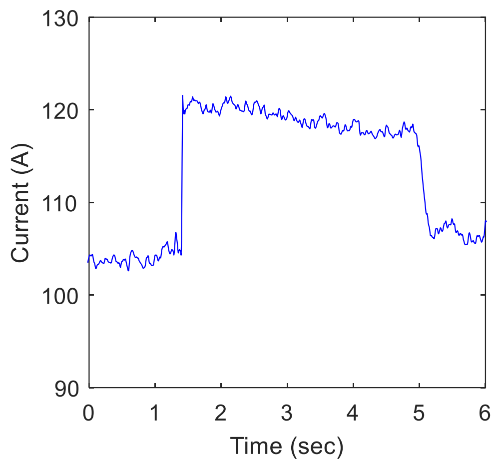
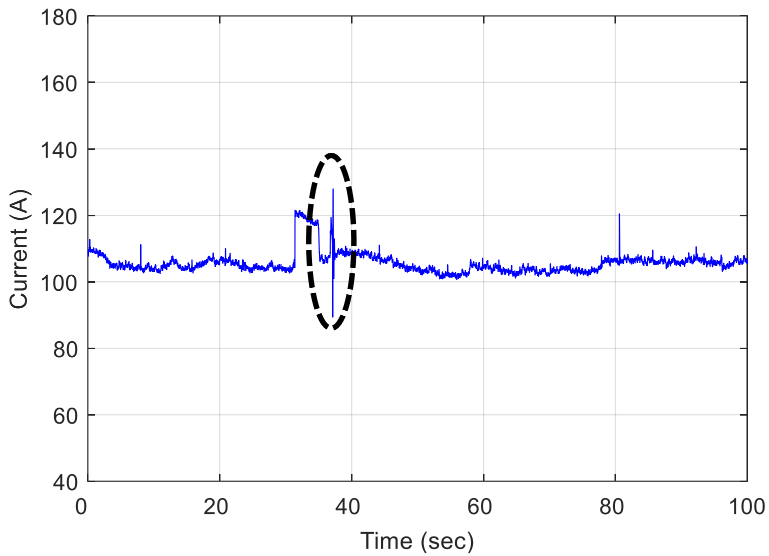


Phasor Measurements - PMUs



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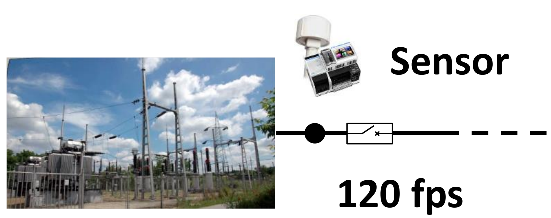

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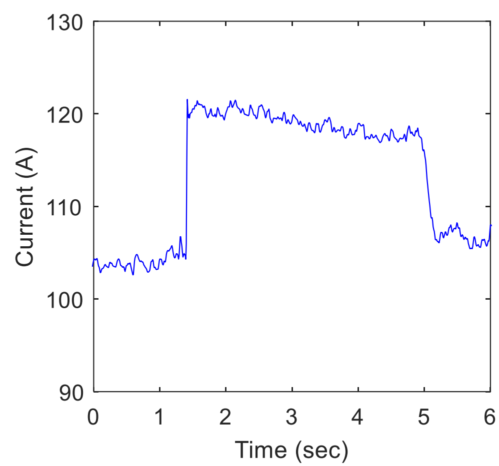
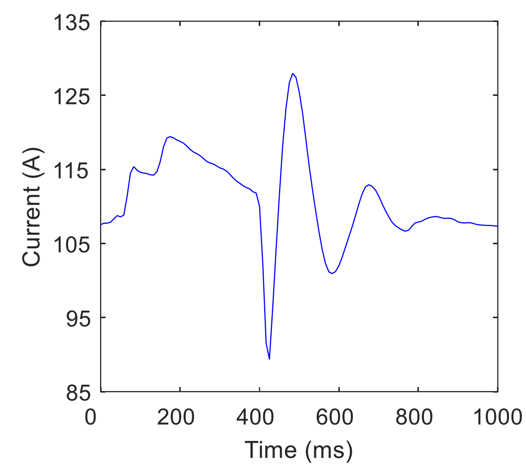
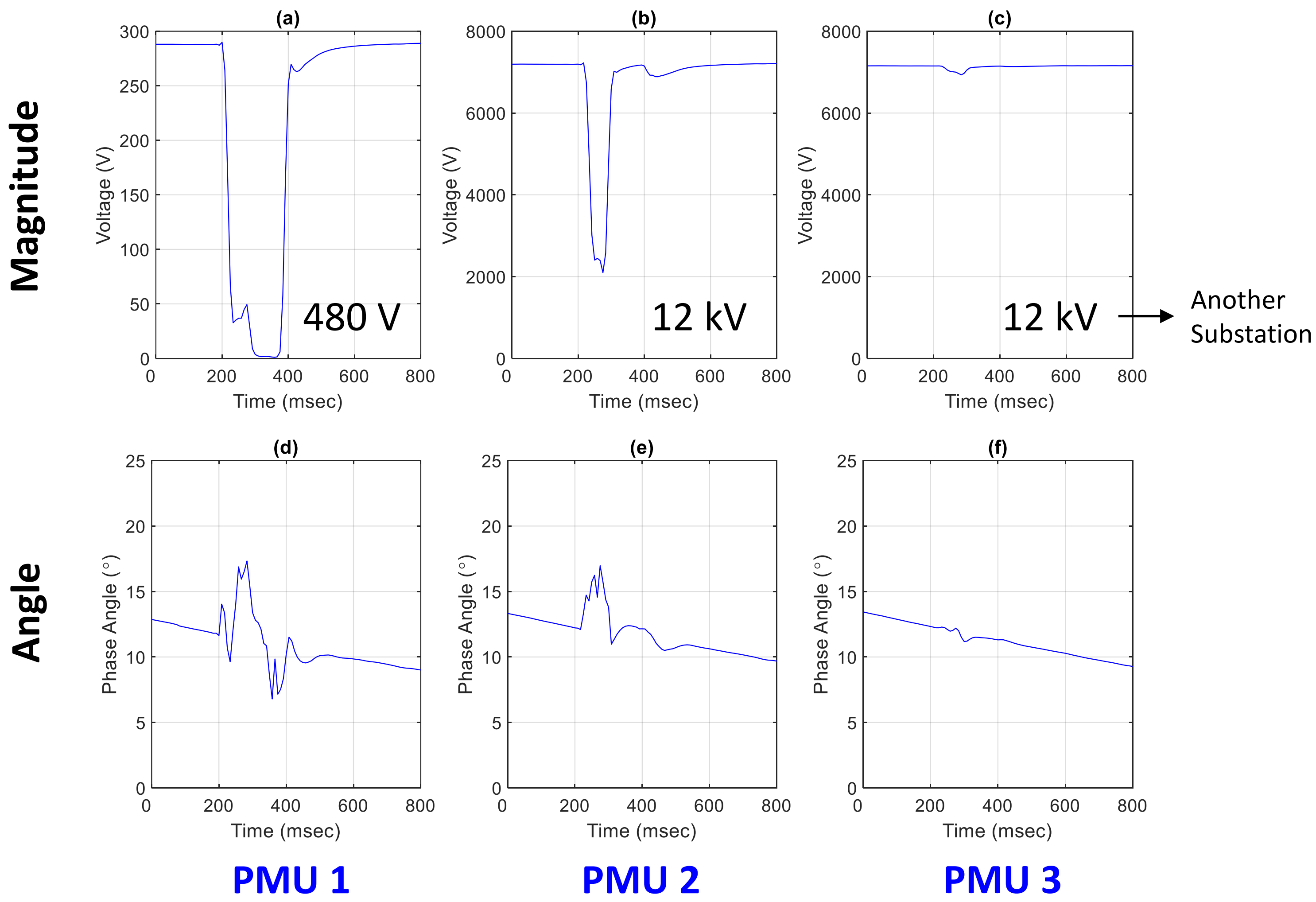




Phasor Measurements - PMUs

- **Example**: “Synchro-Phasor” Data from 3 PMUs During a Fault



- **Example Application**: Event *Classification*

  - **Class 1**: Transmission-Level — **Class 2**: Distribution-Level

  ---

  - **Class A**: Sustained Change — **Class B**: Momentary Oscillation

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  - **Class I**: Grid Equipment
    - **Class I-a**: Transformer
    - **Class I-b**: Capacitor Bank
    - …

    Class II: Customer Devices
    - **Class II-a**: HVAC Load
    - **Class II-b**: DER / PV
    - …

  - **Class X**: Benign — **Class Y**: Fault or Incipient Failure

Phasor Measurements - PMUs

- **PMU Data Analytics Package**
  - **Event Detection**
  - **Event Classification**
  - **Event Location Identification**
  - **Event-based State Estimation**
  - **Event-based Asset Monitoring**
  - **Event-based Model Validation**
  - …

Supervised Learning

Unsupervised Learning

Graph Learning

Hybrid Model-Based

⋮

- [31][32][4][88][10][21][26][94] [13][98][6][100][102][103][104] [115][106][107][108][112][90][34]

https://www.ece.ucr.edu/~hamed

Beyond PMUs

- Q: What is the next technology, beyond PMUs and synchro-phasors?
- Q: Why should we limit ourselves to fundamental phasors?

Beyond PMUs

- Q: What is the next technology, beyond PMUs and synchro-phasors?

- Q: Why should we limit ourselves to fundamental phasors?

- **New Frontier / New Concepts**:
  - **H-PMUs**
  - **WMUs**
  - **Probing Devices**

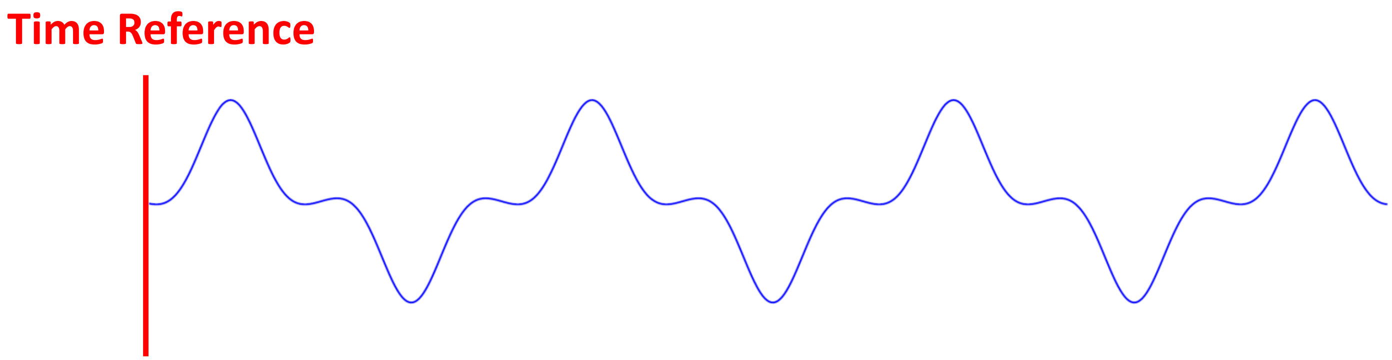
H-PMUs

- Q: Why should we limit ourselves to fundamental phasors?

H-PMU: Harmonic Phasor Measurement Unit

It is a New Concept (*Harmonic Synchro-Phasors*)

It can report *harmonic* phasor measurements



Fundamental *Phasor* + 3th Harmonic *Phasor* + 5th Harmonic *Phasor*

H-PMUs

- Note: We cannot report *all* harmonic orders!

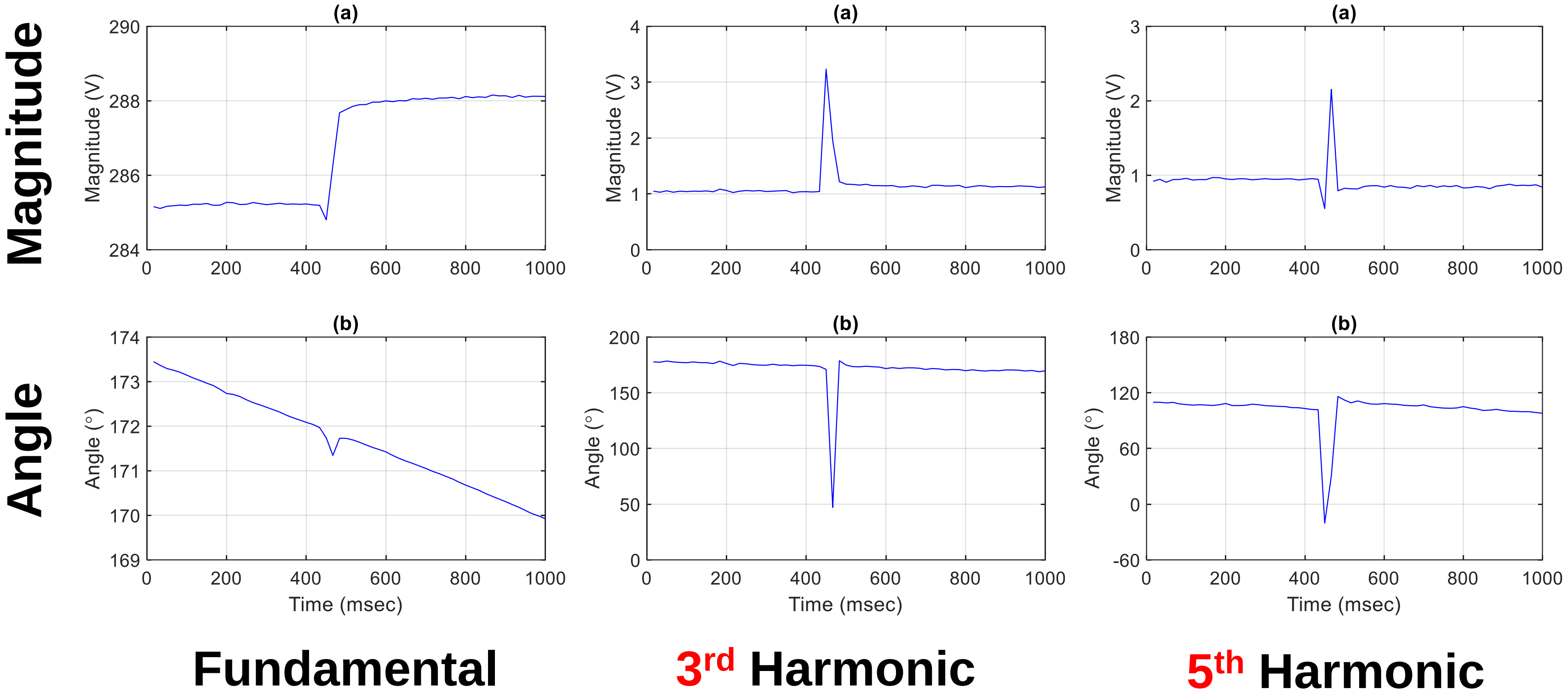
- Typical Settings:

  - The 3rd harmonic; the 5th harmonic; and the 7th harmonic.

  - The most dominant harmonic; the second most dominant harmonic; and the third most dominant harmonic.

- They are the same in many cases.

- **Example**: Phasor Measurements During an Event



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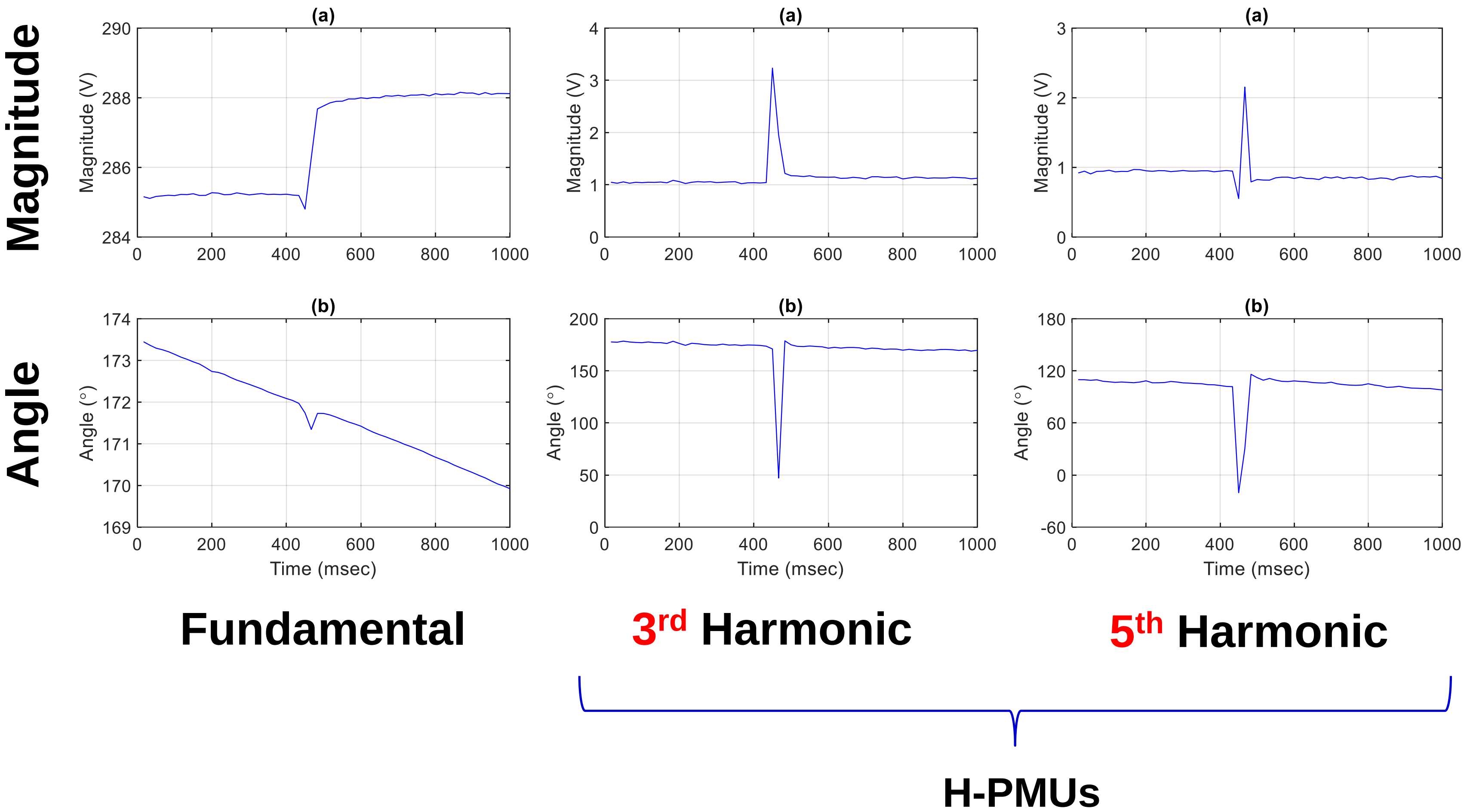
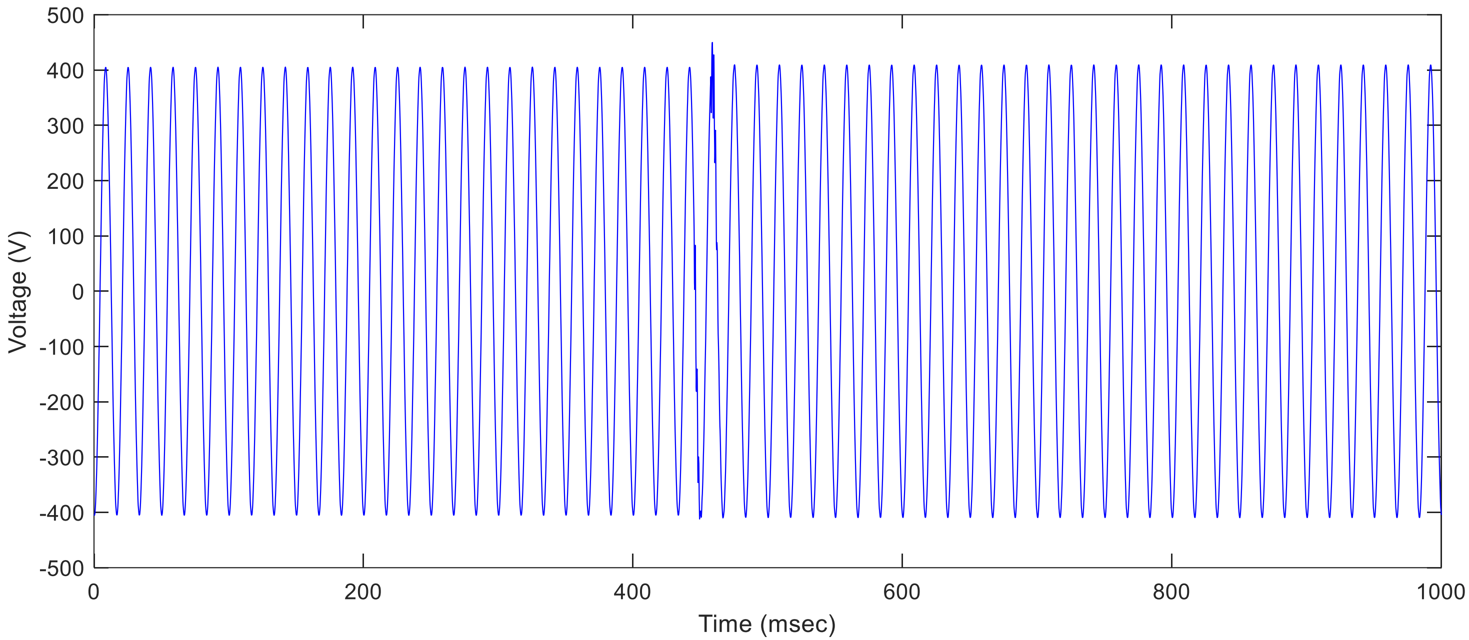


H-PMUs

- Q: What was the waveform of the event in the last example?



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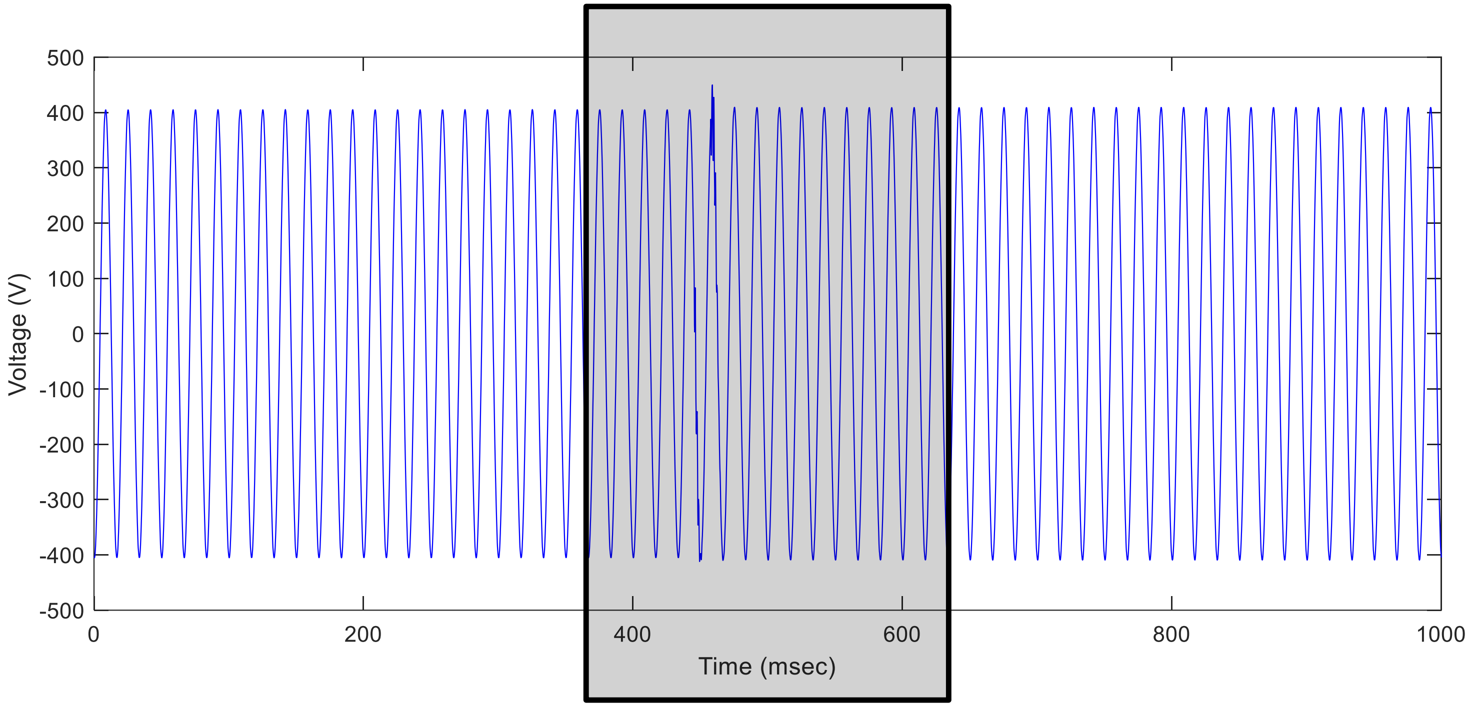

Let’s Zoom In

H-PMUs

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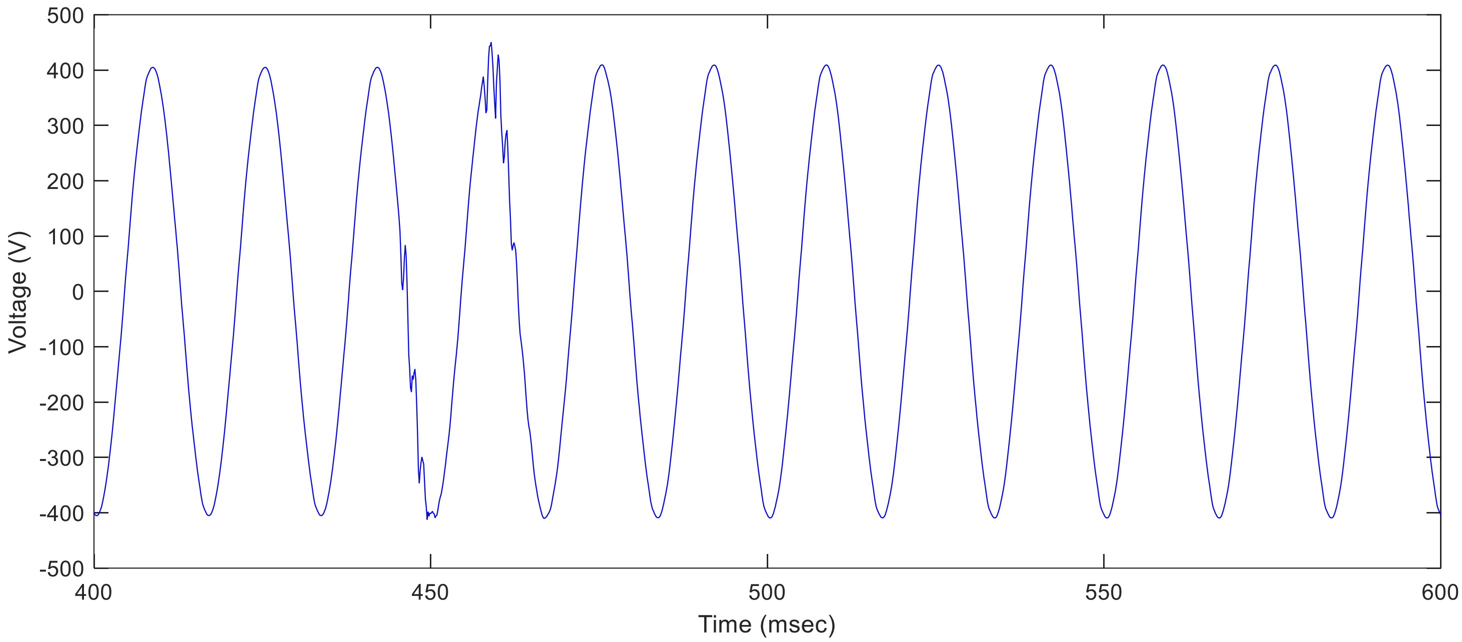

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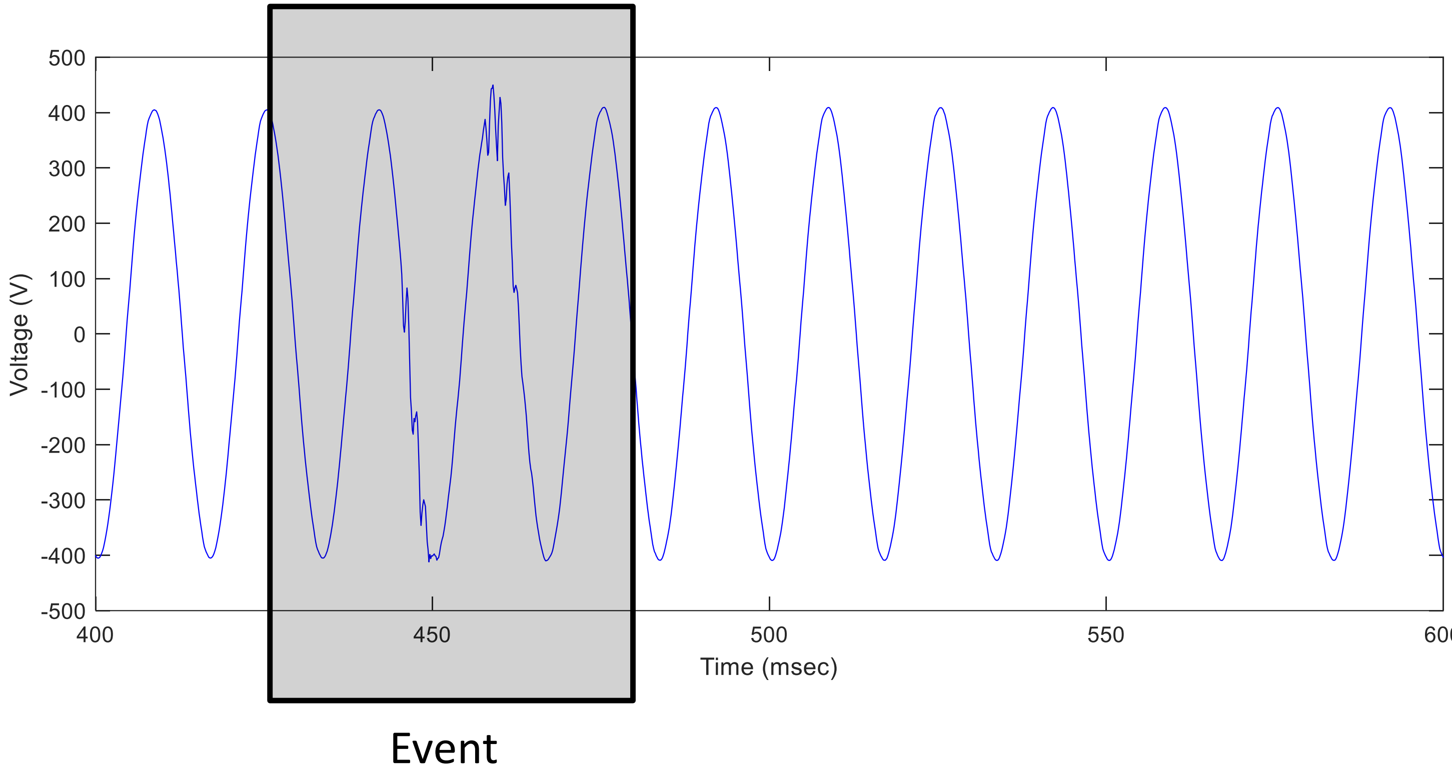

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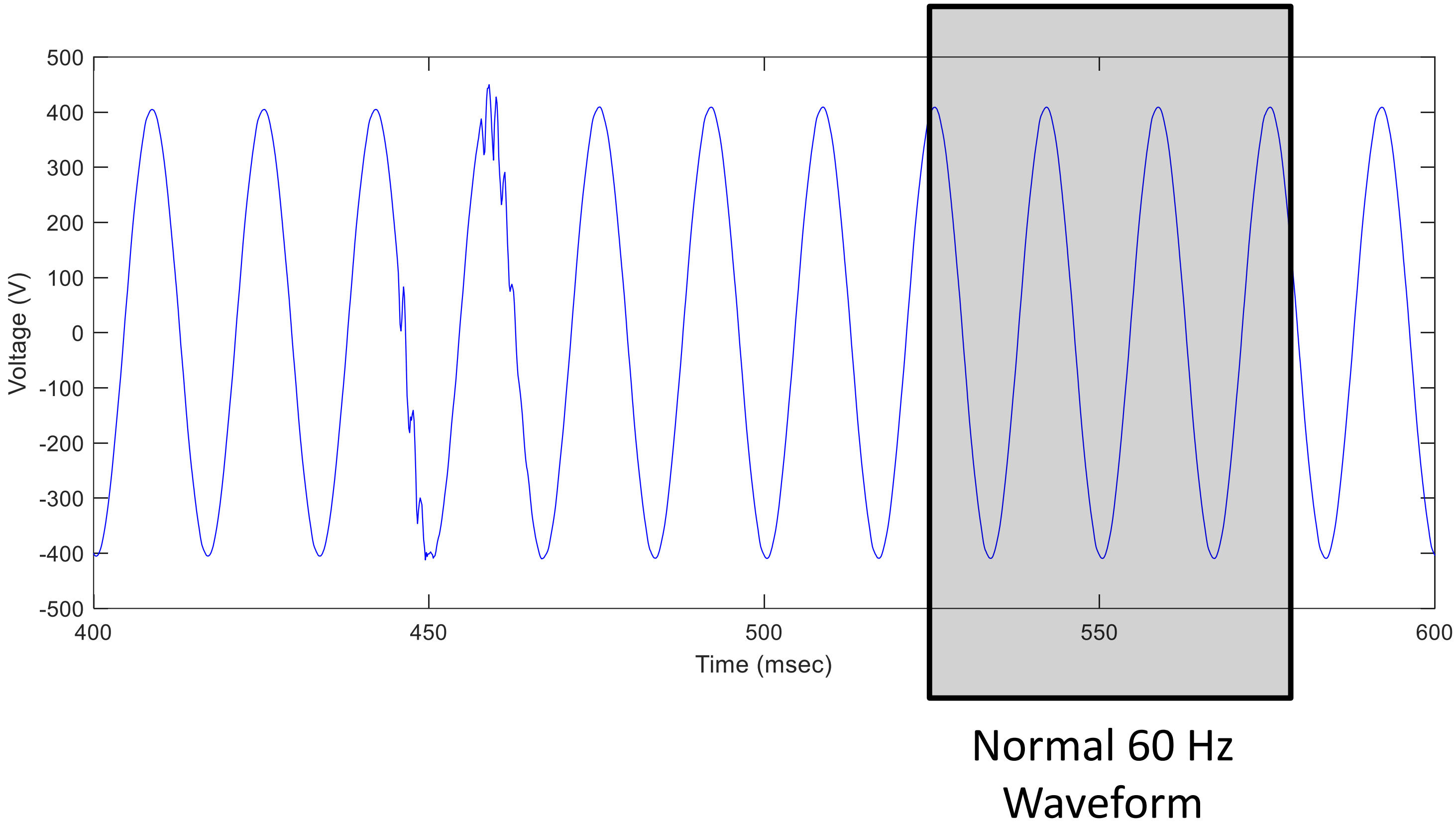

WMUs

- Q: Why don't we measure the waveform itself?

  - **WMU: Waveform Measurement Unit**
  - **It is a New Concept (*Synchro-Waveforms*)**
  - **It can report the raw waveform measurement samples**

WMUs

- Q: Why don't we measure the waveform itself?

  - **WMU: Waveform Measurement Unit**
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  - **It can report the raw waveform measurement samples**

- WMU is a generic term. The actual sensor might be called:
  - Power Quality Meter
  - Point-on-Wave (POW) Sensor (As long as they are time-synchronized)
  - Digital Fault Recorder (DFR)

WMUs

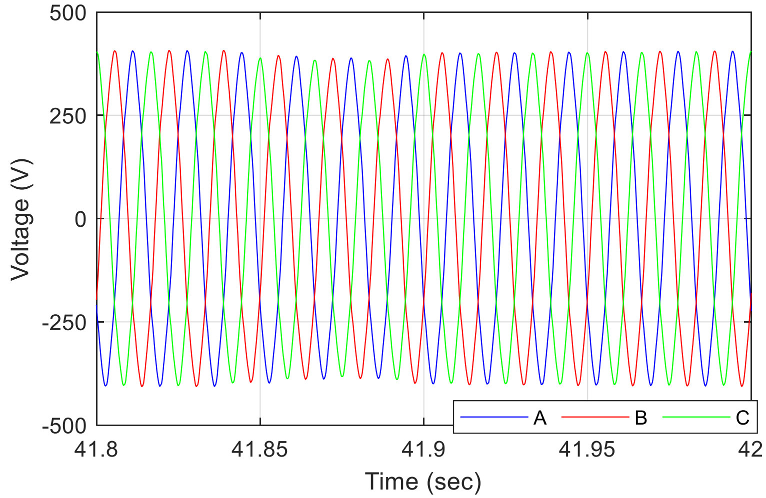
- Two Concepts:

Synchro-Phasors = Phasors + Time Synchronization

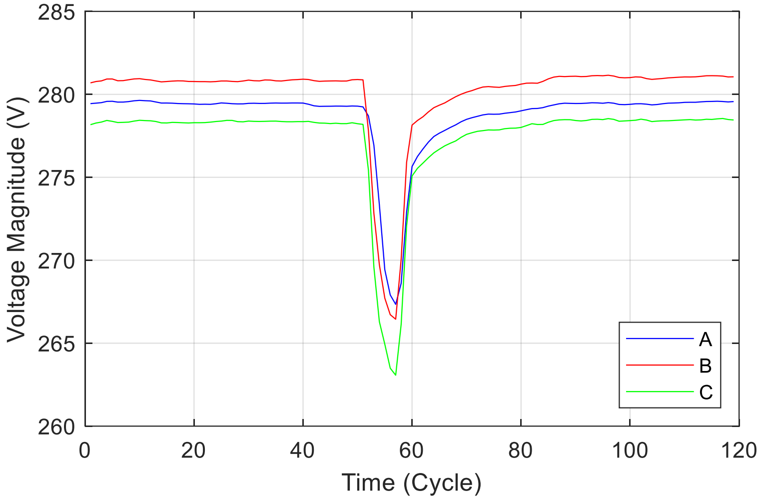
Synchro-Waveforms = Waveforms + Time Synchronization

PMU GPS Antenna →  ← WMU GPS Antenna

- **Example**: Voltage Sag



Waveform

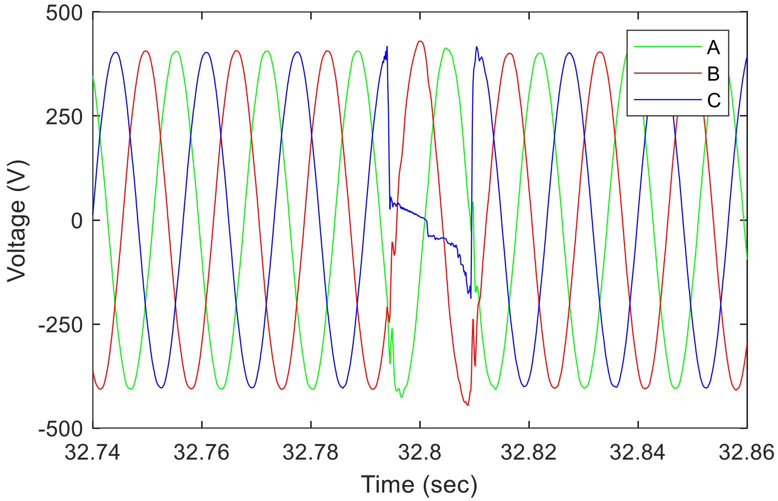


Phasor

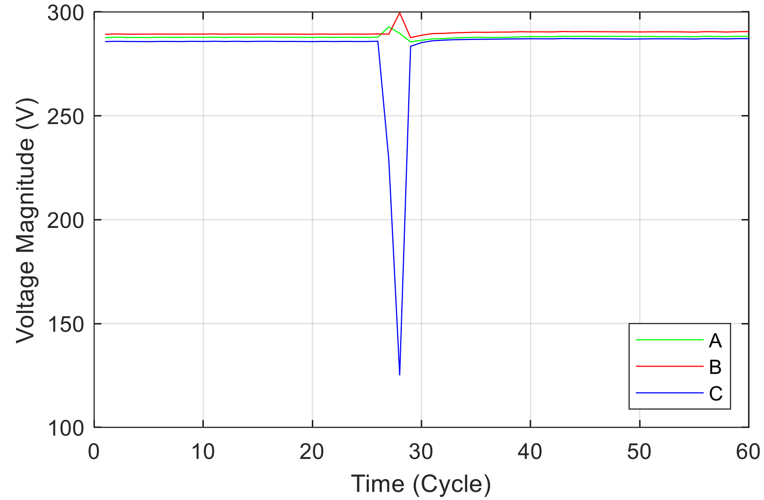
- Looking at voltage waveform is *not* necessary in this example.

- **Example**: Fault

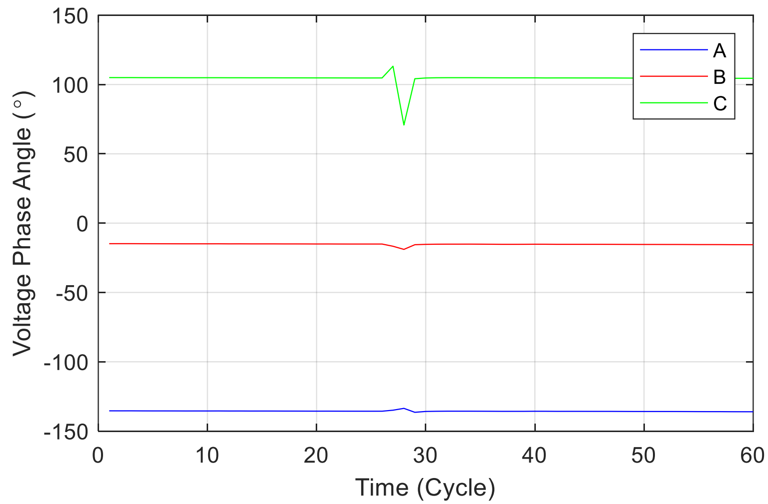
Phasor



Waveform



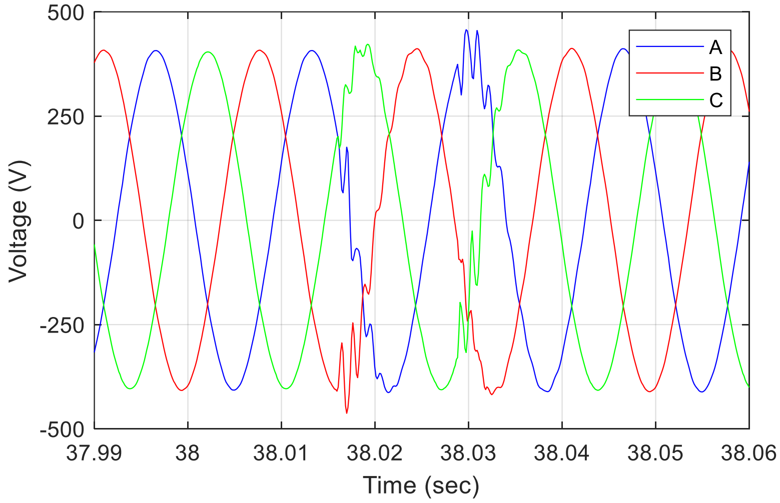
Magnitude



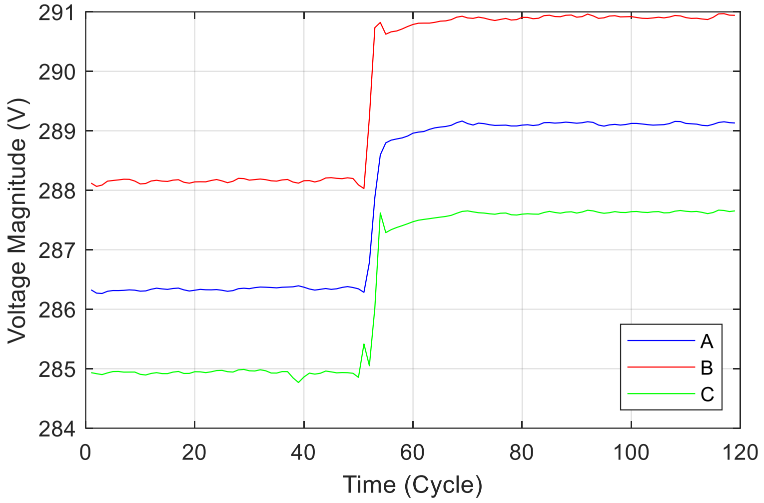
Angle

- Waveform shows much more details about the event.

- **Example**: Resonance



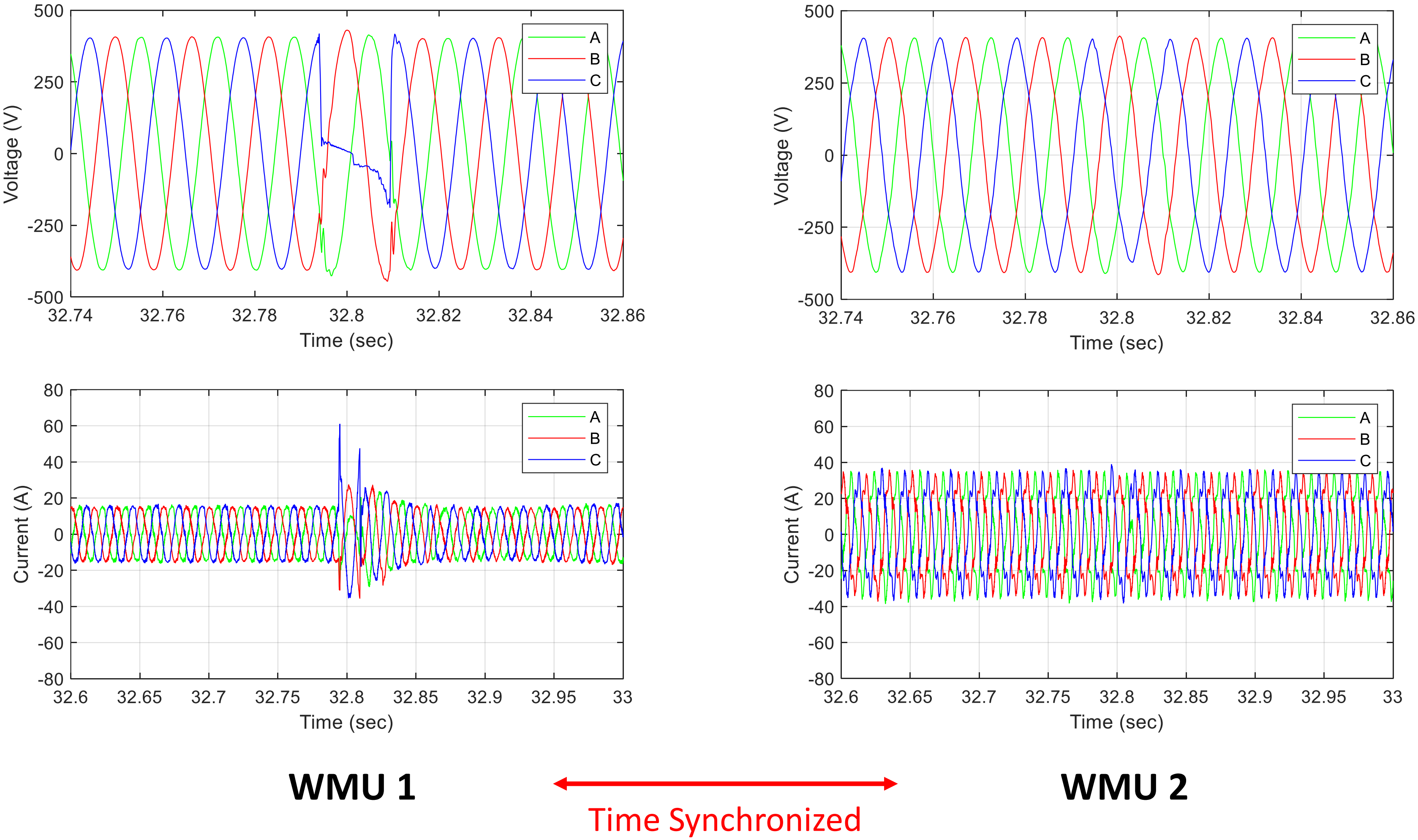
Waveform



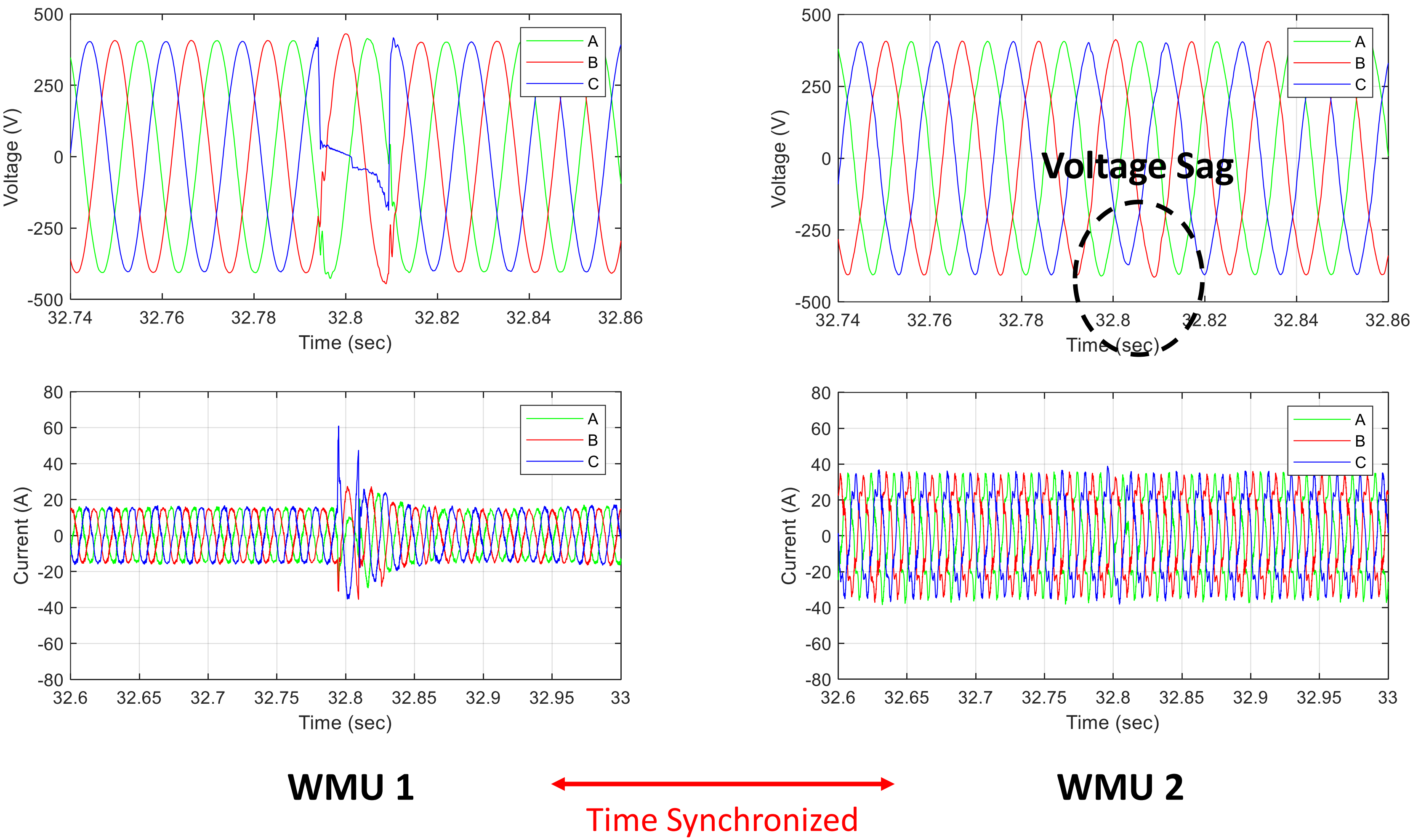
Phasor

- We do *not notice* the resonance in the phasors.

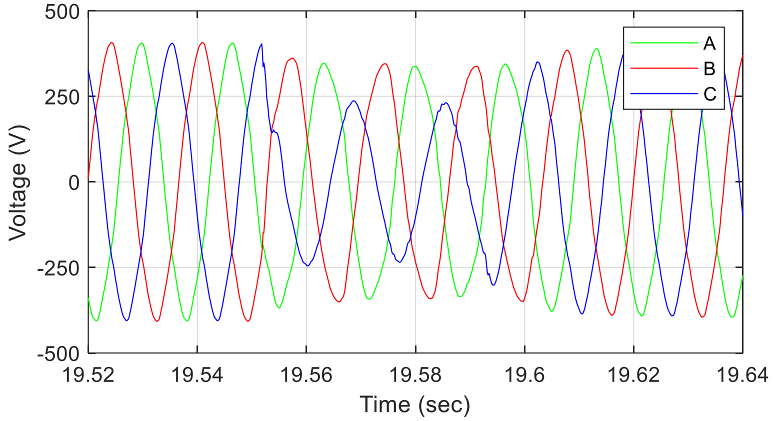
- **Example**: Synchro-Waveforms (Fault):

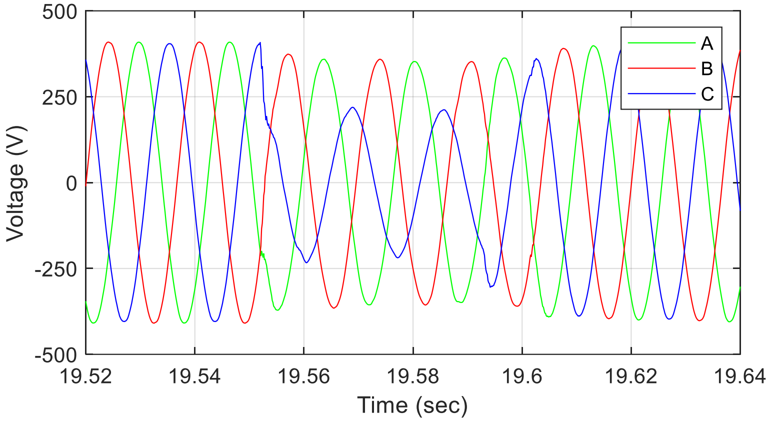


- **Example**: Synchro-Waveforms (Fault):



- **Example**: Synchro-Waveforms (Another Fault):





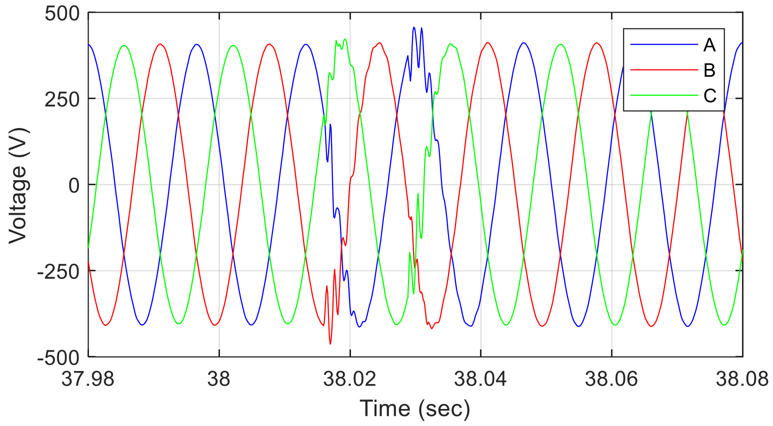
WMU 1 ⟷ **WMU 2**

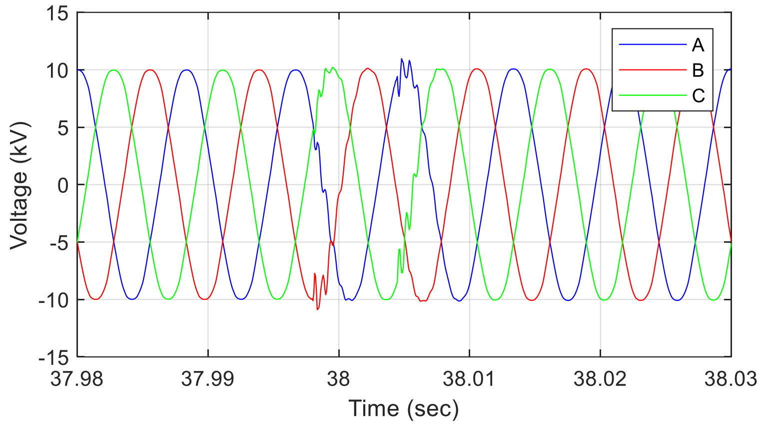
Time Synchronized

- The two locations experienced *similar* signatures.

WMUs

- **Example**: Synchro-Waveforms (Resonance):





WMU 1

Time Synchronized

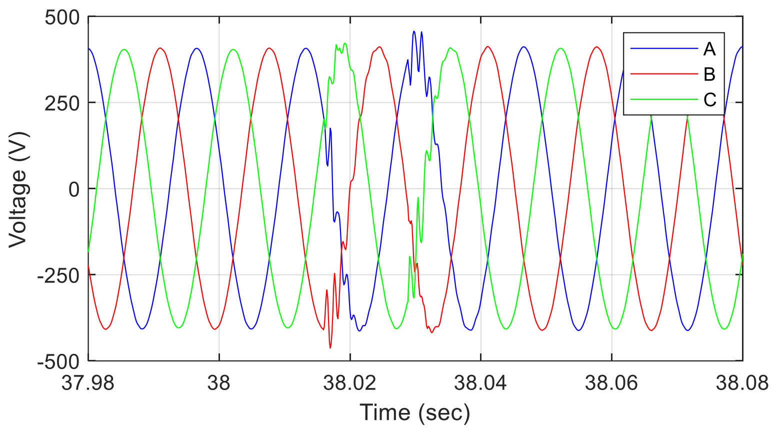
WMU 3

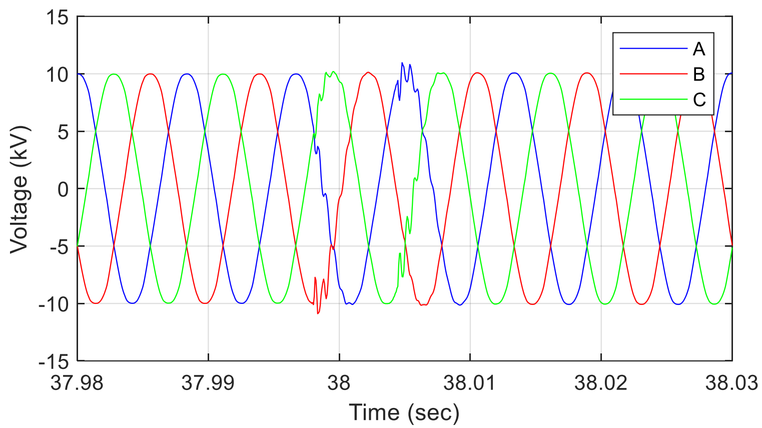
Another Location

(Also, Different Voltage Level)

WMUs

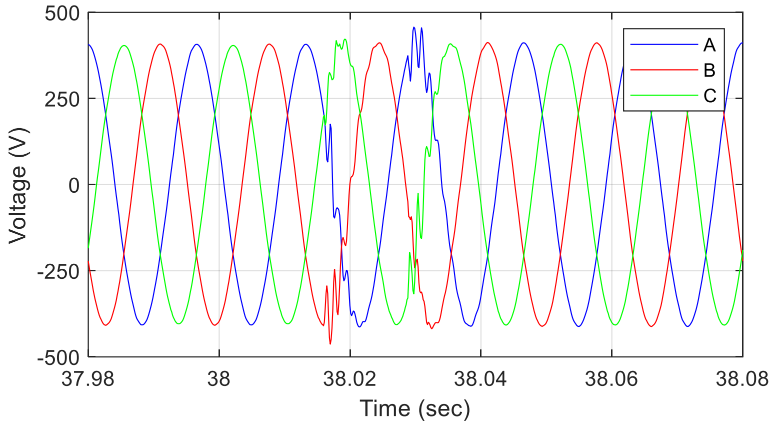
- **Example**: Synchro-Waveforms (Resonance):

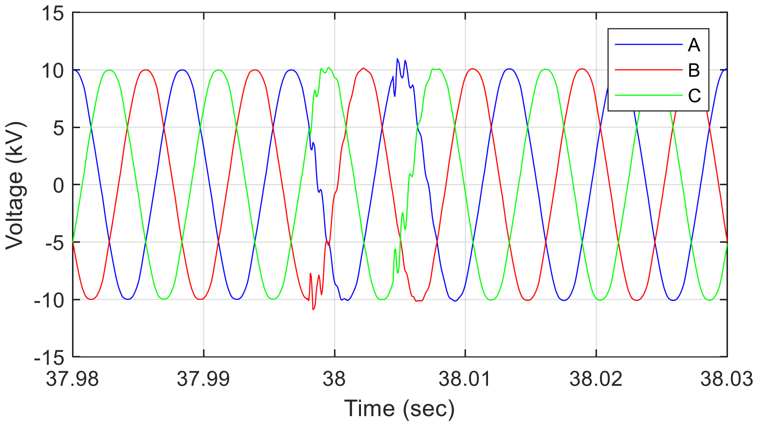




WMU 1 ← Time Synchronized → **WMU 3**

- **Example**: Synchro-Waveforms (Resonance):





WMU 1 ⟷ Time Synchronized **WMU 3**

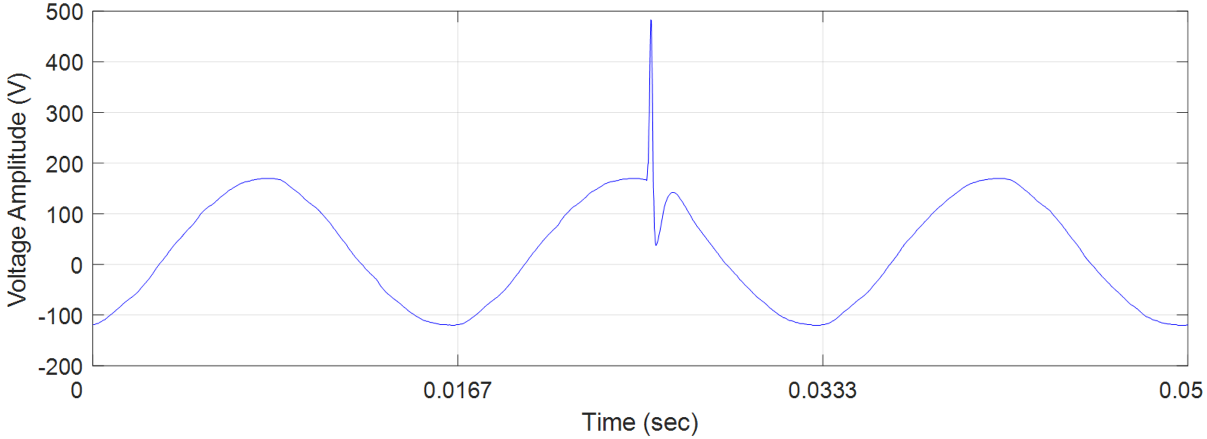
- WMUs observe the same physical phenomena at different locations.

→ **Synchro-Waveform Situational Awareness**

→ Covering Various Event Signatures (Sub-Cycle, Few-Cycle, etc.)

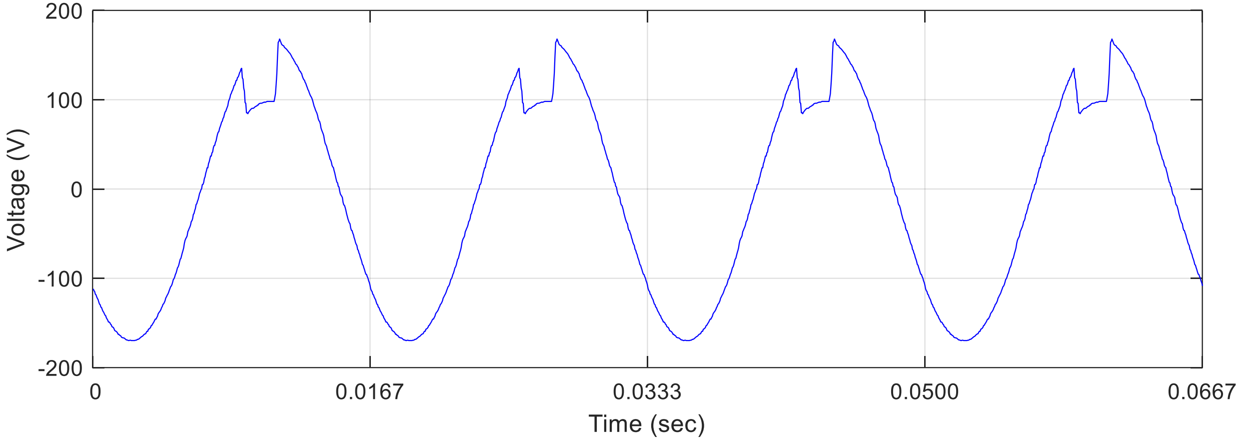
- Example Waveform Signature:

Lightning



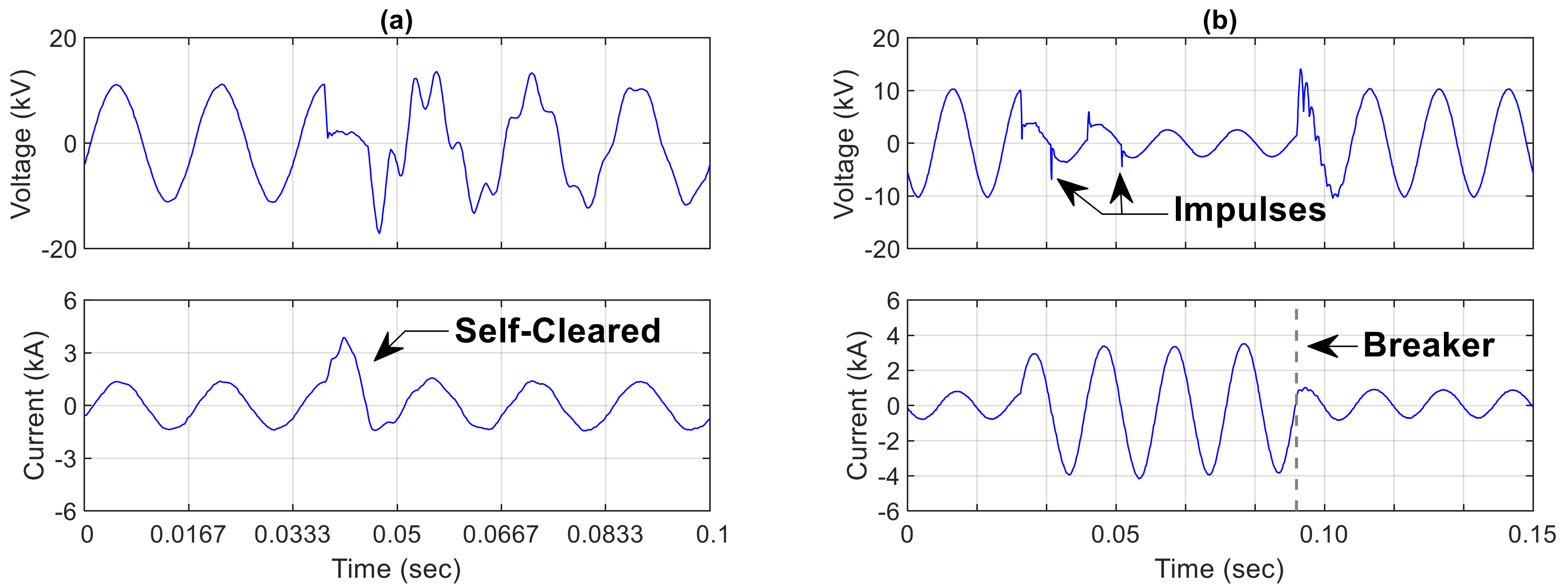
[211] in Book

Notching



[209] in Book

- Example Waveform Signatures (Equipment Issues):

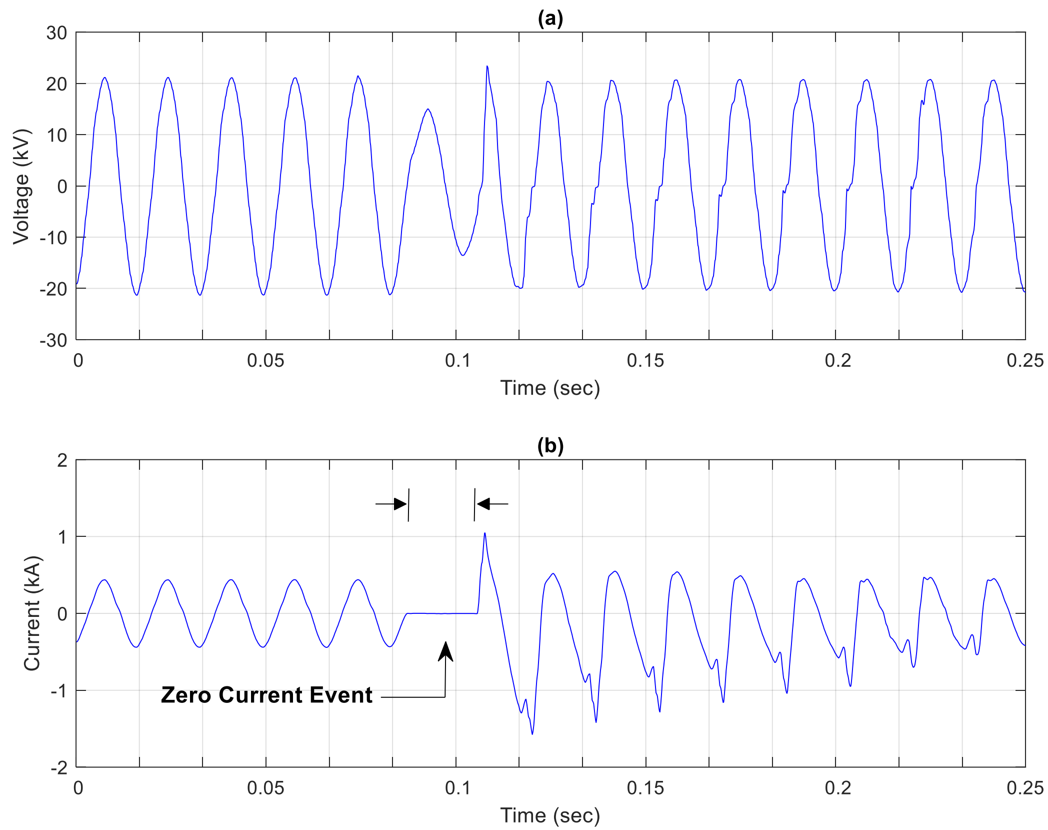


[214][217] in Book

Self-Clearing **and** ***Breaker-Clearing*** **Faults in Cables**

- Example Waveform Signatures (Equipment Issues):

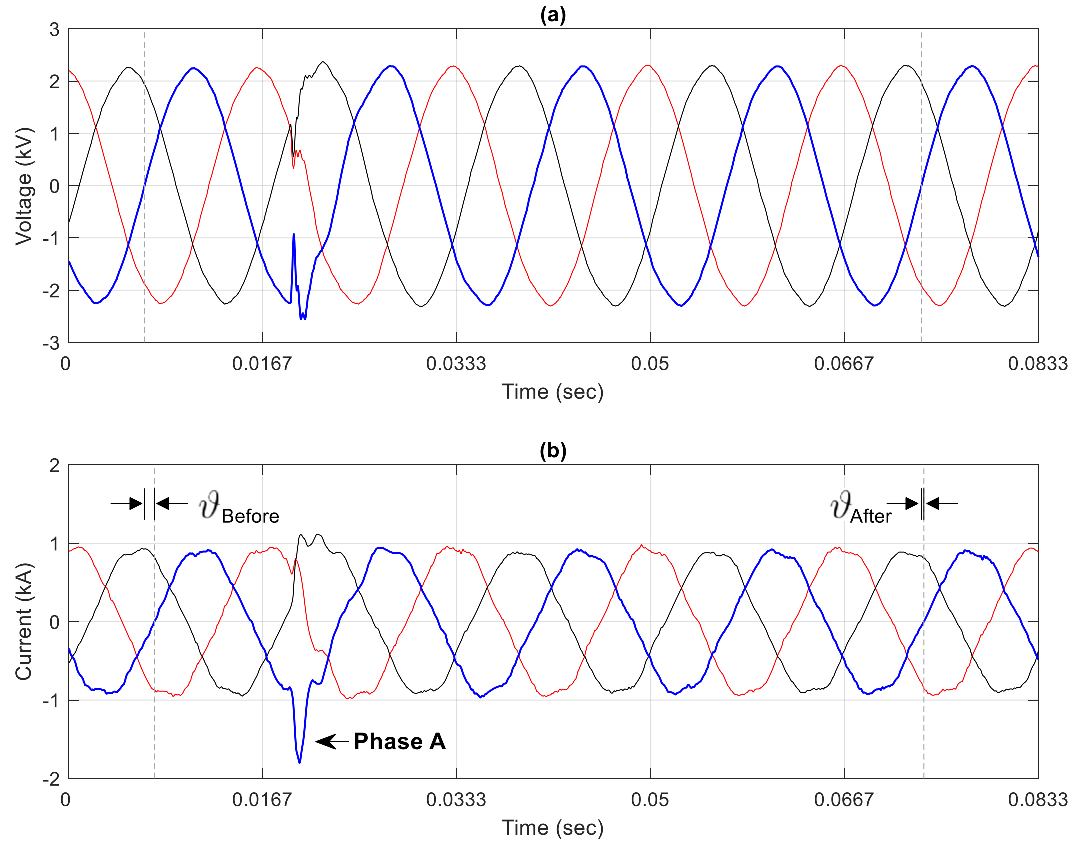
Self-Clearing Fault in Transformer



[220] in Book

- Example Waveform Signatures (Equipment Issues):

Capacitor Bank Switching



[221] in Book

- Synchronized Lissajous Graphs:

Location 1 / WMU 1

$v_1(t), i_1(t)$

Location 2 / WMU 2

$v_2(t), i_2(t)$

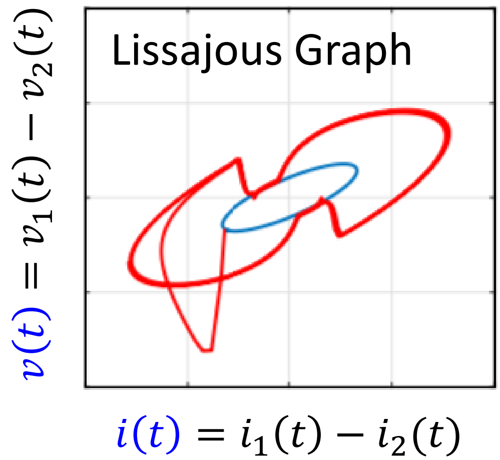
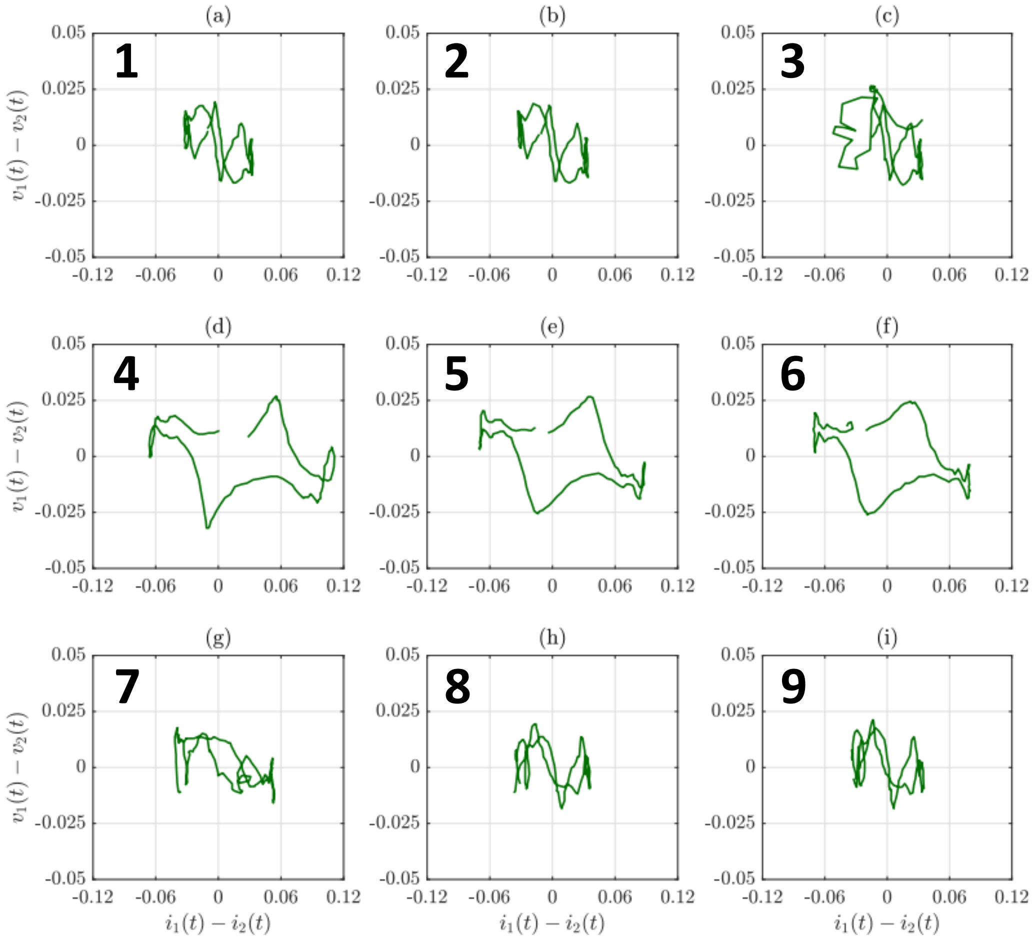


Image Processing

Credit: Milad Izadi

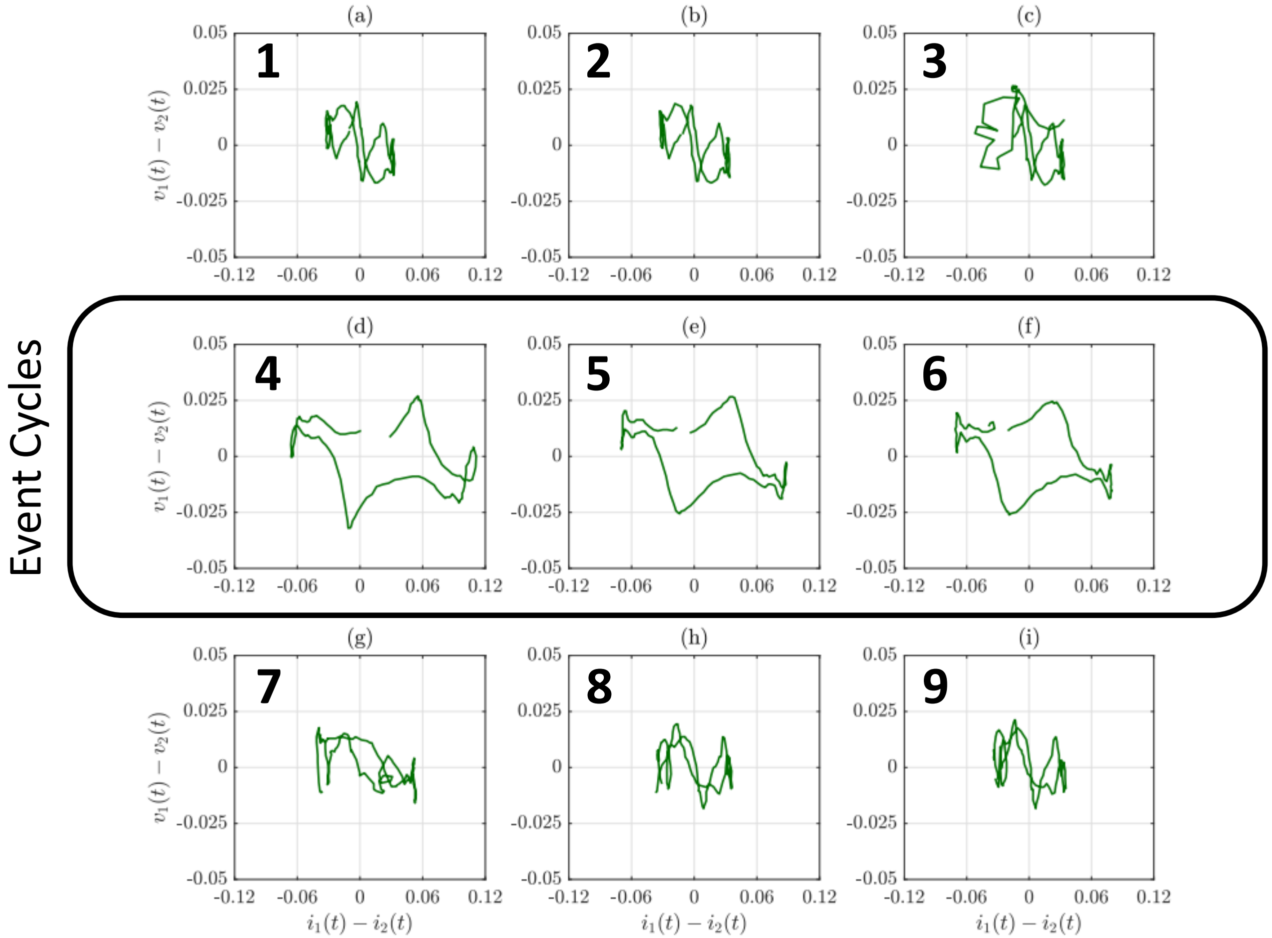
- Synchronized Lissajous Graphs:



Credit: Milad Izadi

WMUs

- Synchronized Lissajous Graphs:



Credit: Milad Izadi

- Field Installation:

Single-Phase (120 V)

Three-Phase (12.47 kV)

Three-Phase (480 V)

WMUs

- Comparison with SCADA:

High-Resolution SCADA: 3x60x60x24 = **86,400** Reading / Day

Continuous WMU: 3x256x60x60x60x24 = **3,981,312,000** Reading / Day

- Comparison with SCADA:

High-Resolution SCADA: 3x60x60x24 = **86,400** Reading / Day

Continuous WMU: 3x256x60x60x60x24 = **3,981,312,000** Reading / Day

H-PMUs and WMUs

- **H-PMU and WMU Data Analytics Packages**
  - **Even Detection**
  - **Event Classification**
  - **Event Location Identification**
  - **Incipient (*Early-Stage*) Faults** → **Asset Health, Wildfire Detection, …**
  - **Harmonic & Transient State Estimation**
  - **Harmonic & Transient Model Validation**
  - **Topology Identification**
  - …

- [2][3][8][9][12][27][89][86][93][96][113]   https://www.ece.ucr.edu/~hamed

Probing

- Q: Can we *actively* create opportunities to learn about the system?
  - **Probing: Perturbing the System to Learn about it**
  - **It is *NOT* New Concept but Gaining Attention Recently**
  - **It can be done by a wide range of probing devices**

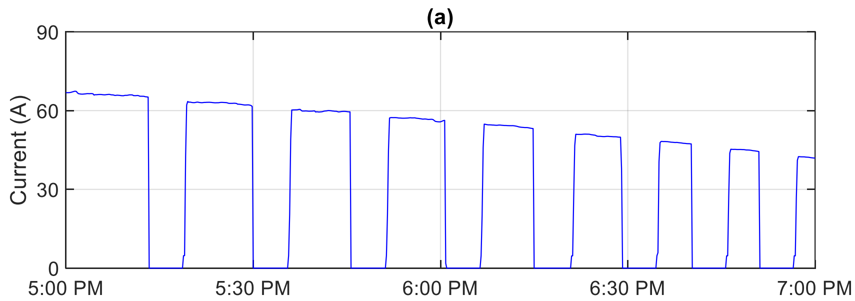
Sensing → ***Passive*** Monitoring

Probing + Sensing → ***Active*** Monitoring

Probing

- **Example**: Creating "Events" by switching PV Inverter:

Current:

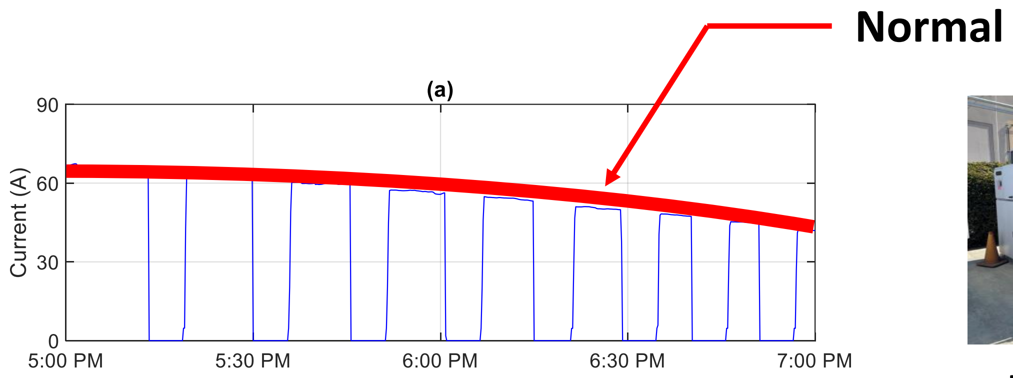


Inverter

Probing

- **Example**: Creating "Events" by switching PV Inverter:

Current:



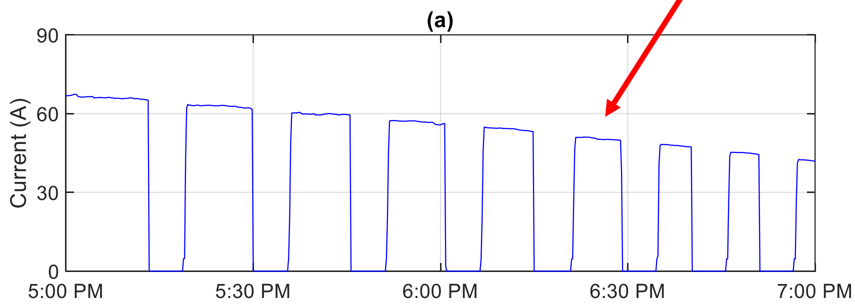
Inverter

Probing

- **Example**: Creating “Events” by switching PV Inverter:

Not **Normal (Probing)**

Current:

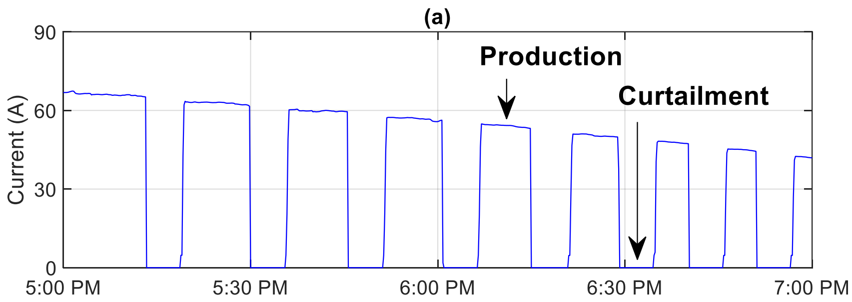


Inverter

Probing

- **Example**: Creating “Events” by switching PV Inverter:

Current:



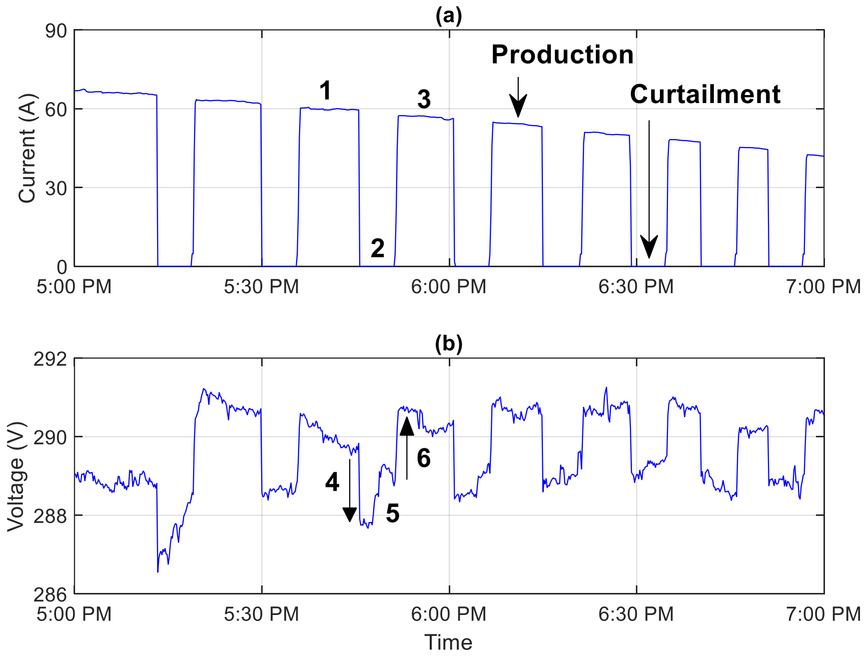
Inverter

Probing

- **Example**: Creating “Events” by switching PV Inverter:

Current:

Voltage:



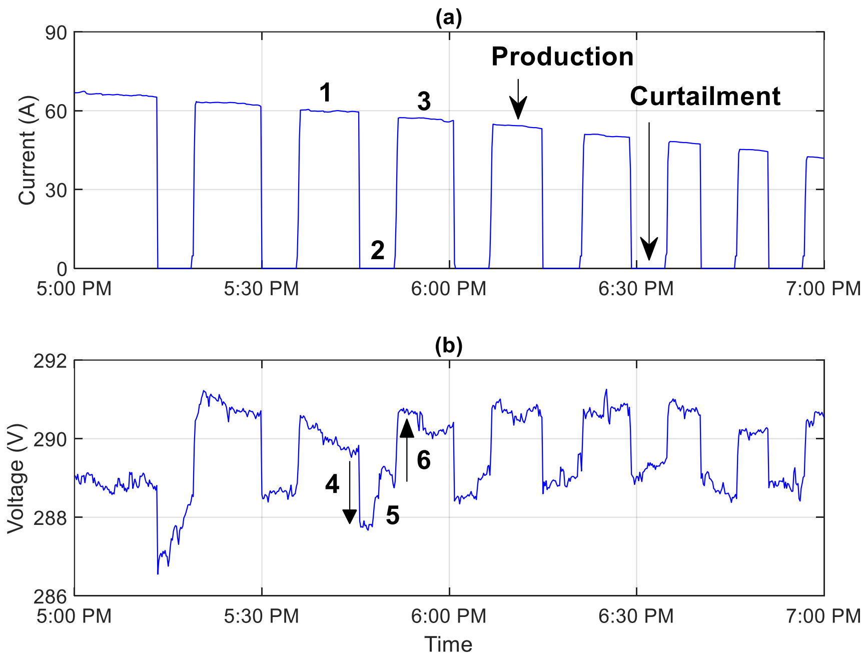
Inverter

Probing

- **Example**: Creating “Events” by switching PV Inverter:

Current:

Voltage:

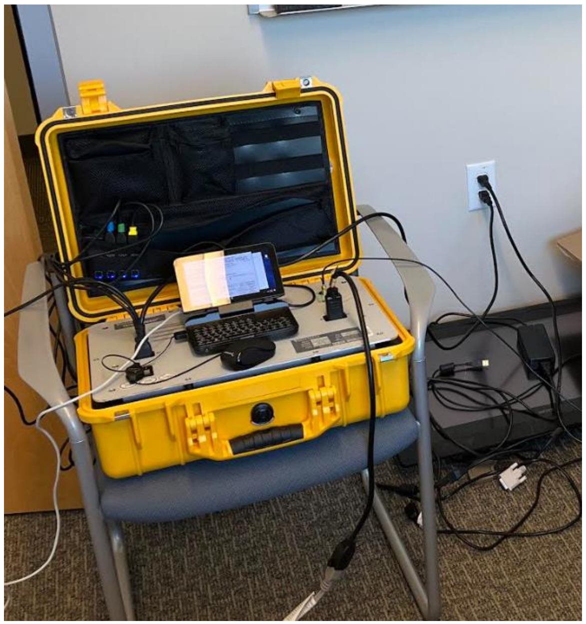


Inverter

Outcome → **Model-Free Assessment of *Inverter’s Impact* on Voltage**

- **Example**: One can also create a "*probing signal*":

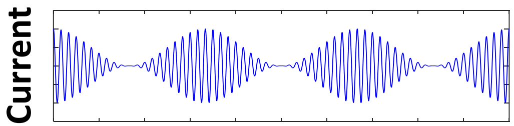
Credit: Zong-Jhen Ye



Single-Phase
Sensor Device

Single-Phase
Probing Device

Controllable Load
(Heater)

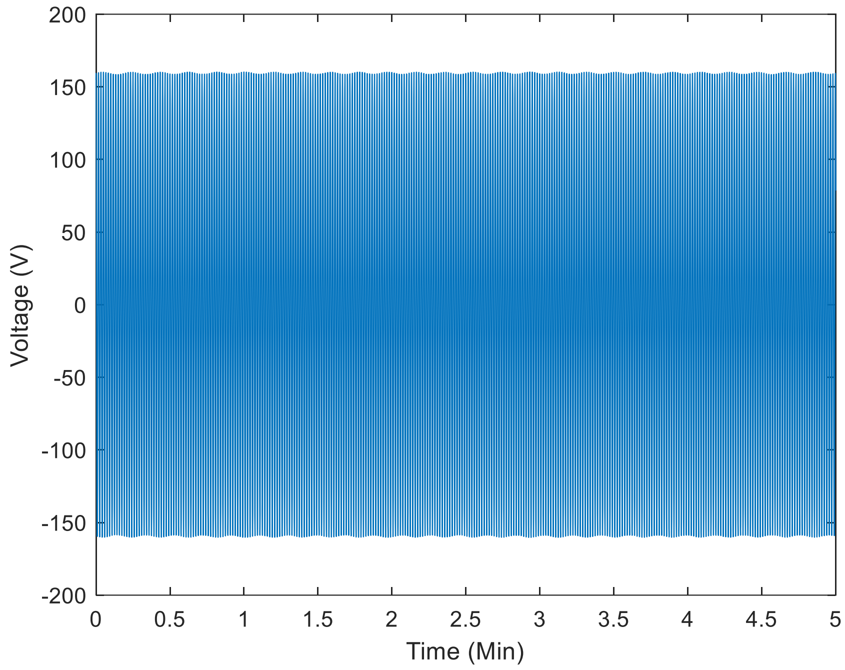


Measuring Voltage

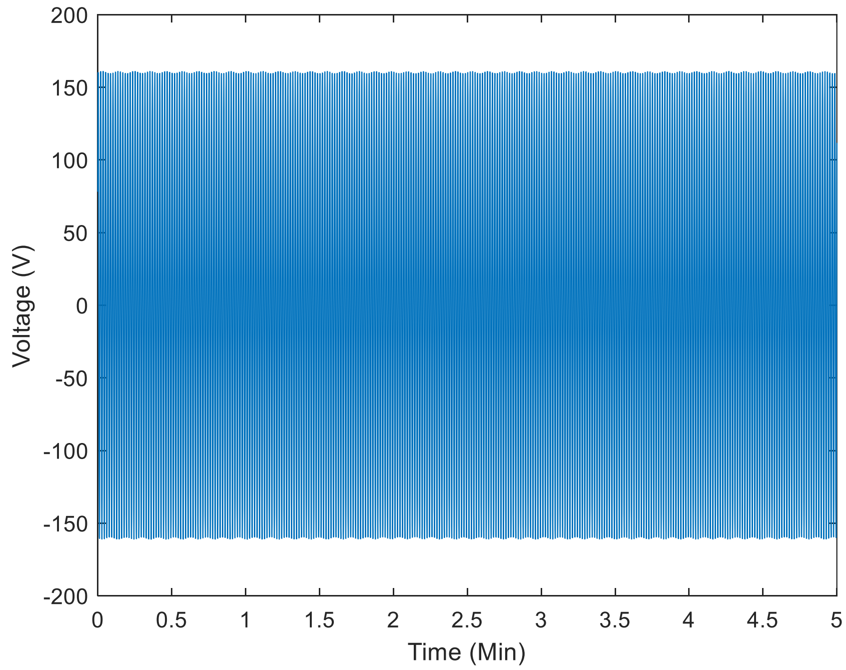
GridSweep
Probing Device
(McEachern Lab)
(DoE Funded Project)

Probing

- **Example**: One can also create a modulated *probing signal*:



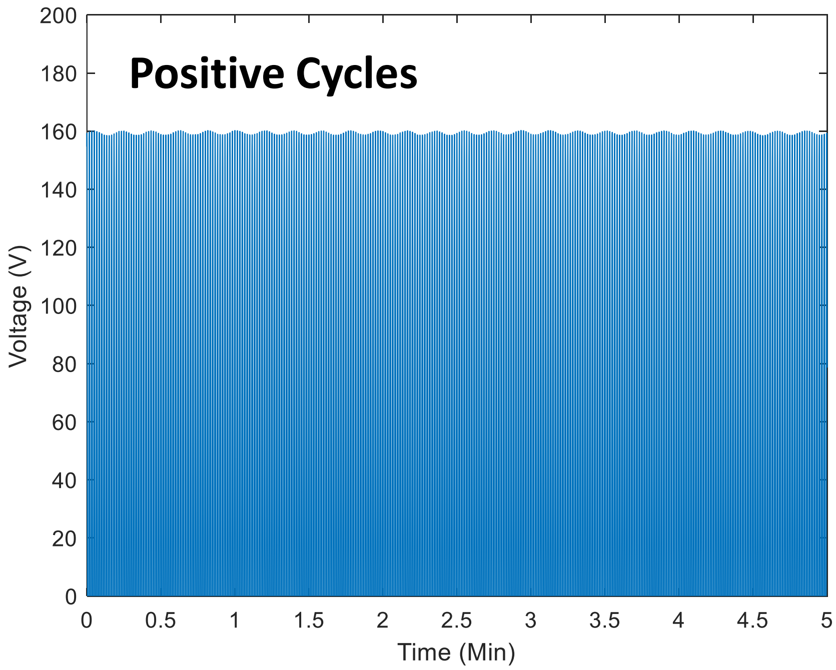
Probing Frequency: 5.2 Hz



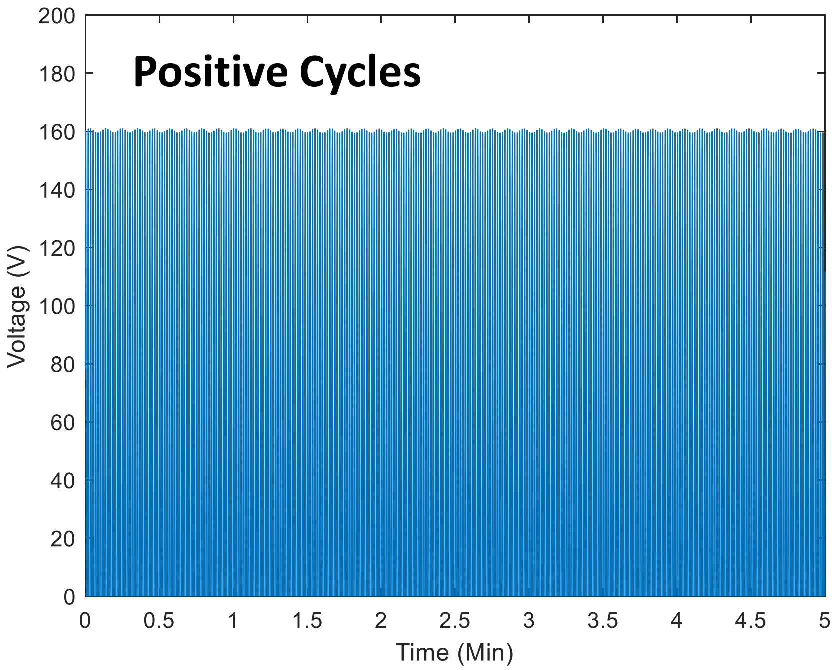
Probing Frequency: 9.2 Hz

Probing

- **Example**: One can also create a modulated *probing signal*:



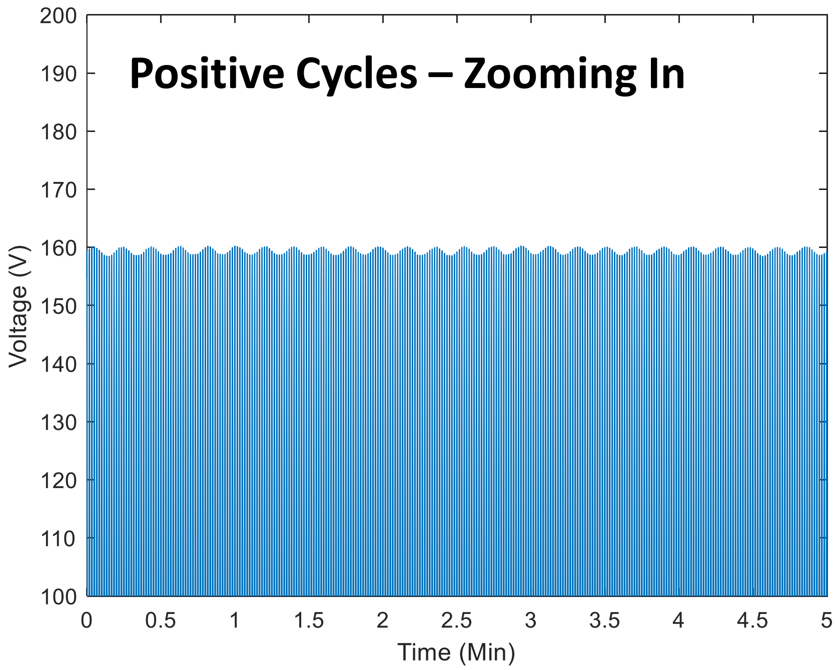
Probing Frequency: 5.2 Hz

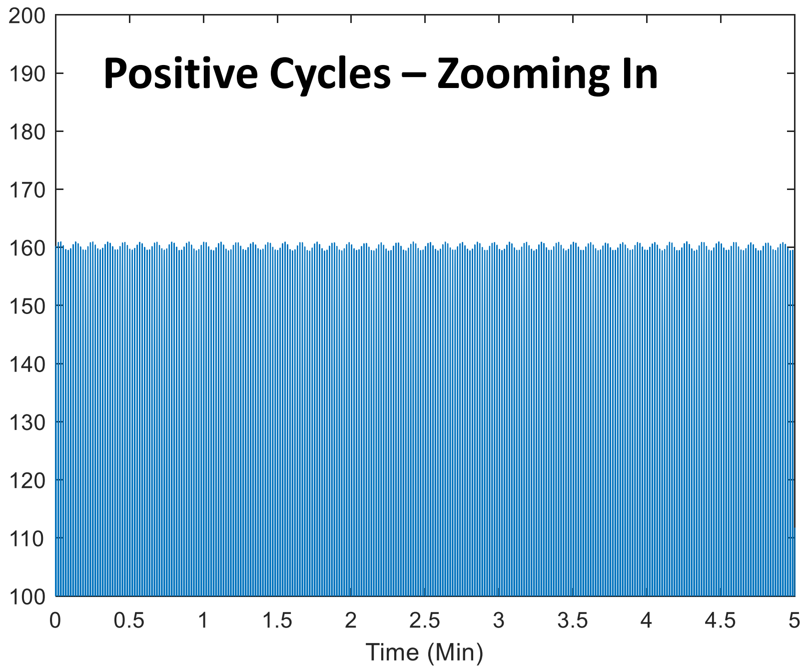


Probing Frequency: 9.2 Hz

Probing

- **Example**: One can also create a modulated *probing signal*:

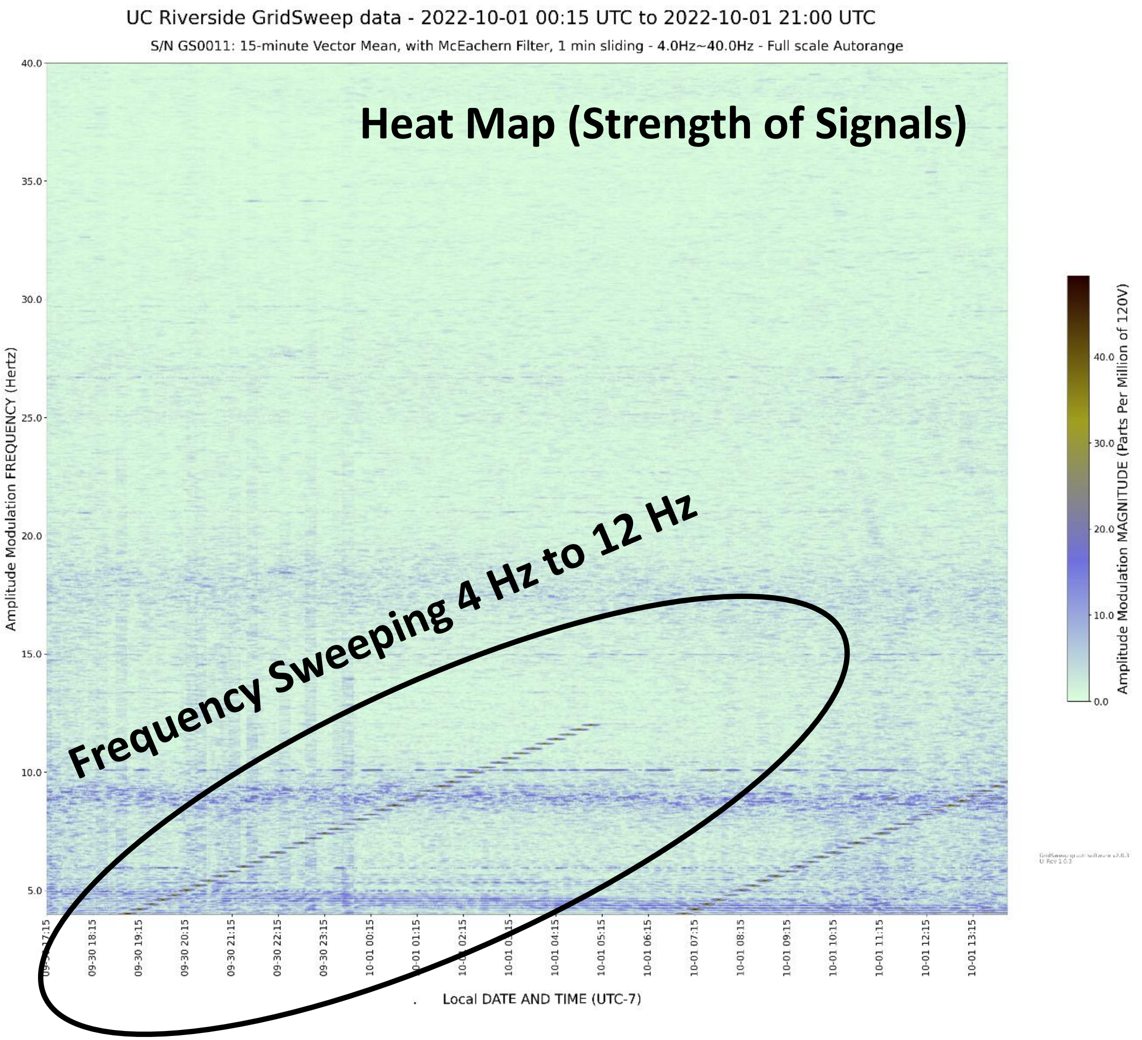




Probing Frequency: 5.2 Hz

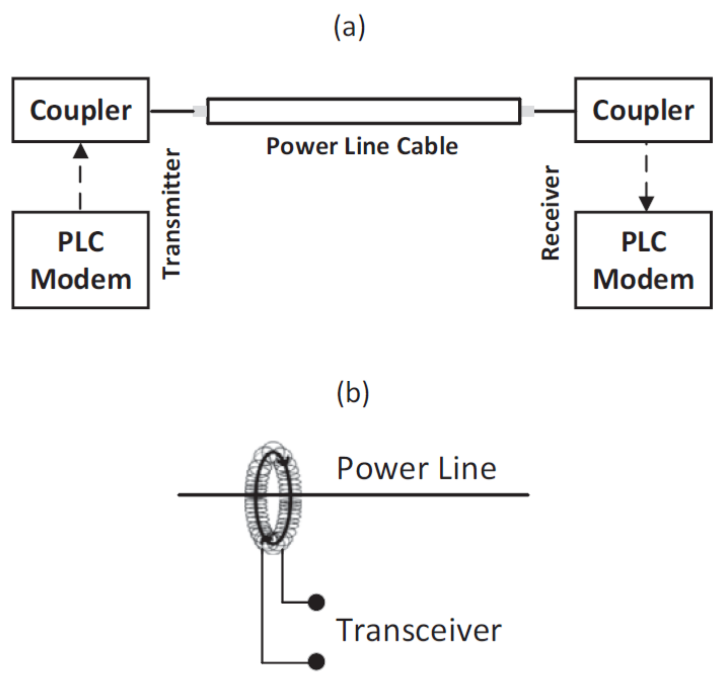
Probing Frequency: 9.2 Hz

- **Example**: One can also create a modulated *probing signal*:

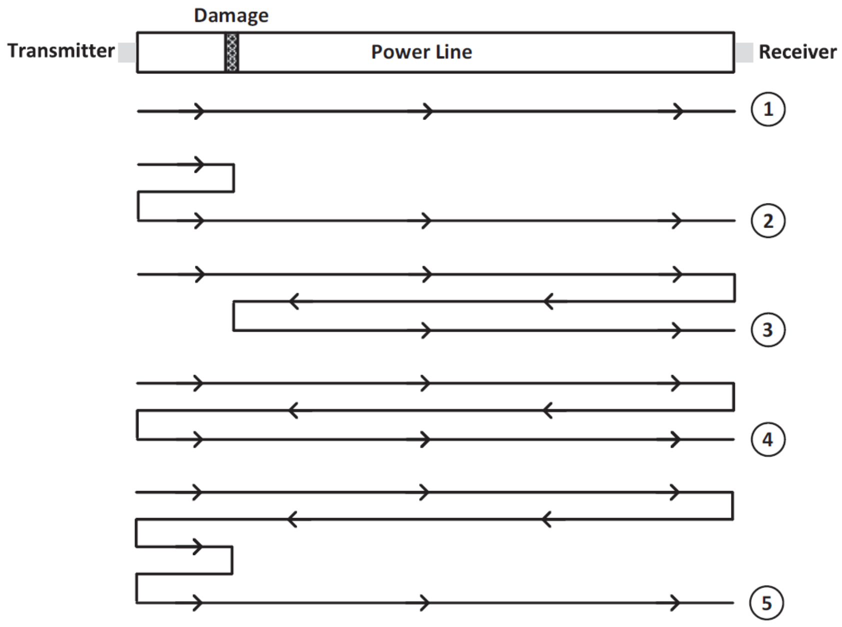


***Credit*: Alex McEachern**
(GridSweep, McEachern Lab)

- Power Line Communications (PLC) is also a "probing tool":



Power Line Communication



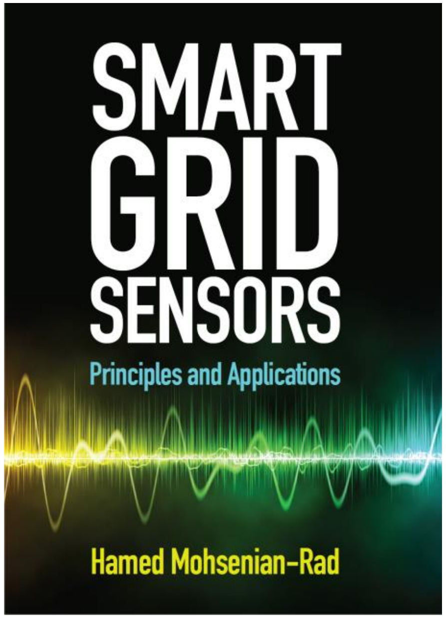
[427] in Book

Application: Power Cable Monitoring

Credit: Lehmann, *et al.* 2016

Further Reading

- *New Textbook*



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April 2022
348 Pages
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- *Ch 2: Voltage and Current Measurements and Their Applications*
- *Ch 3: Phasor and Synchrophasor Measurements and Their Applications*
- *Ch 4: Waveform and Power Quality Measurements and Their Applications*
- *Ch 5: Power and Energy Measurements and Their Applications*
- *Ch 6: Probing and Its Applications*
- *Ch 7: Other Sensors and Off-Domain Measurements and Their Applications*

Thank You!

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