Tutorial: Synchro-waveform Data Analytics and Applications

IEEE PES Subcommittee on Big Data Analytics

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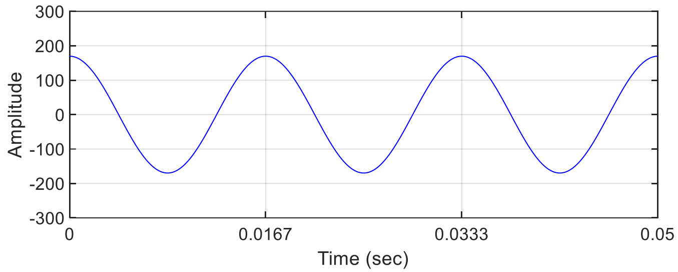
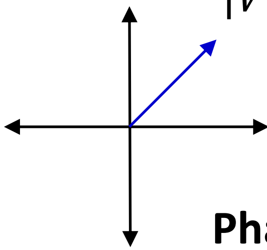
Motivation

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



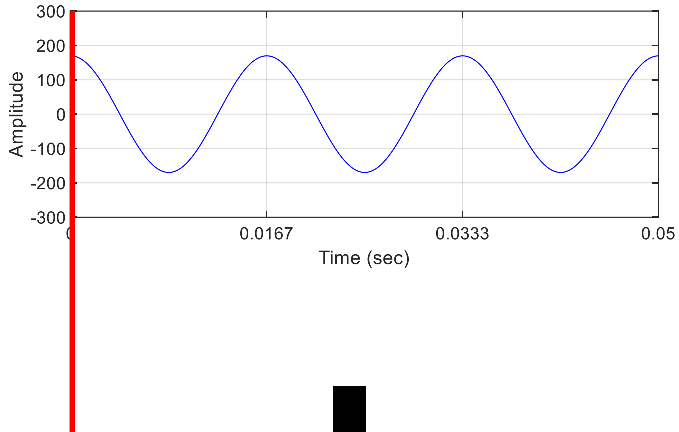


Phasor Representation

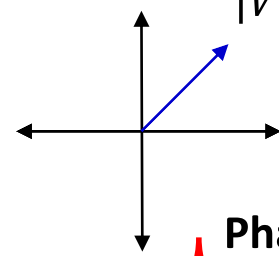
Sensor: Phasor Measurement Unit (**PMU**)

FFT $\mapsto$ Fundamental Component

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



Time Reference



$|V|\angle V$

Phasor Representation

Synchro

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

FFT ↦ Fundamental Component

GPS Satellites

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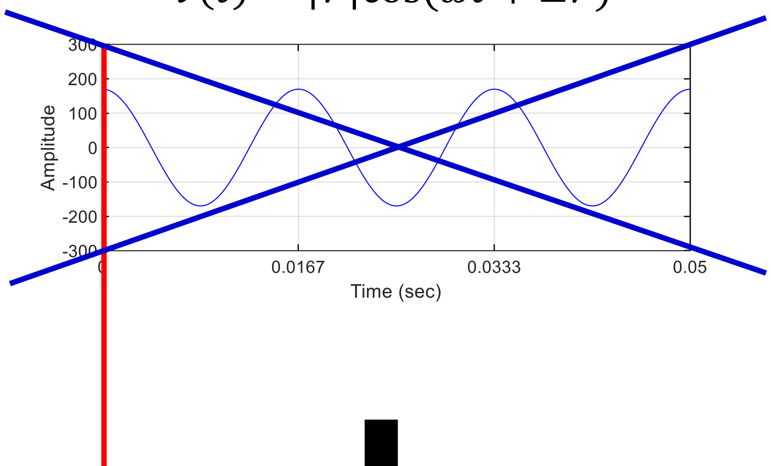

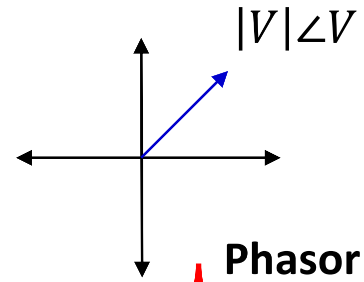

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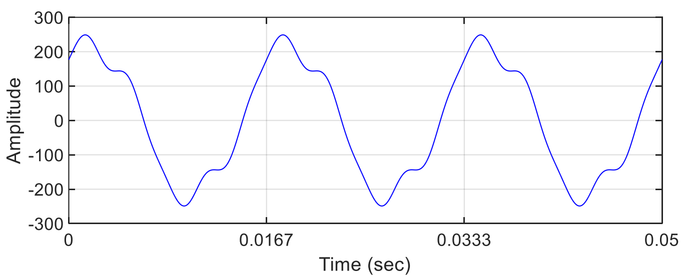

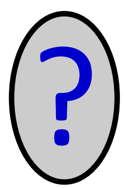

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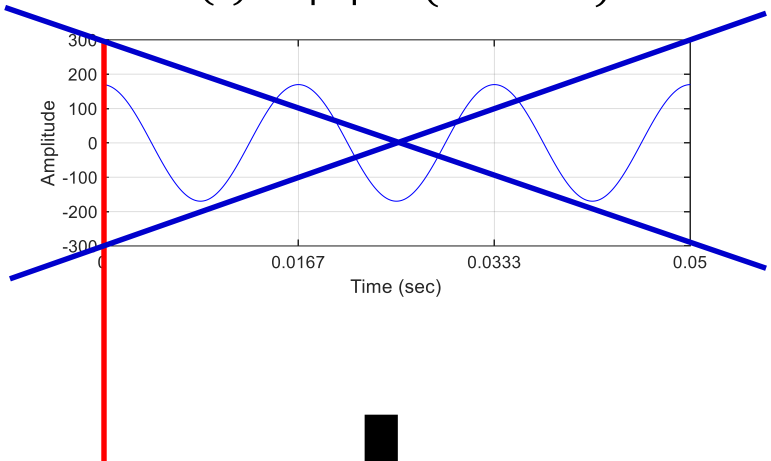

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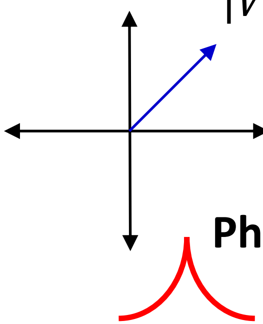

Phasor Representation

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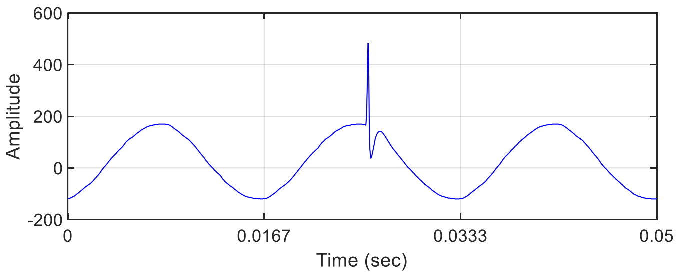
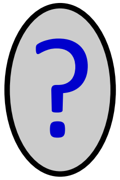




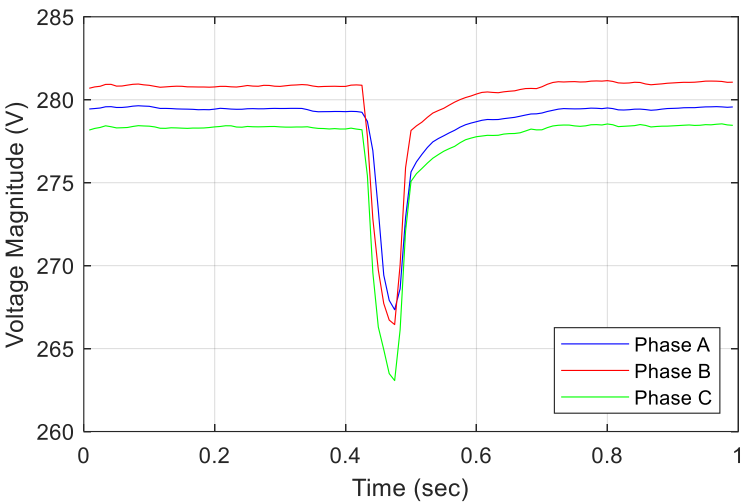
GPS Satellites

Agenda

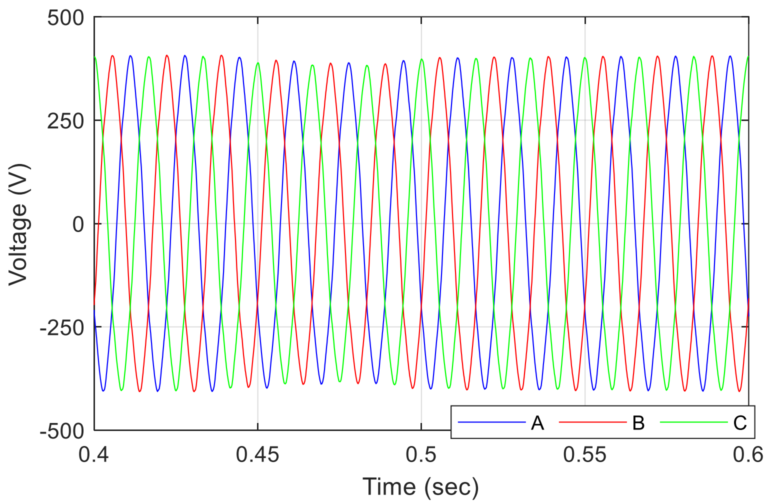
- **Fundamentals**
  - Waveform: Real-World Examples
  - Waveform Measurement Unit
  - Synchro-Waveforms
- **Data-Analytics Methodologies**
  - Detection
  - Location Identification
  - Characterization and Classification
- **Applications**
- **Further Reading**

Waveform: Real-World Examples

- Example 1 (Voltage Sag):



Phasor (Magnitude)

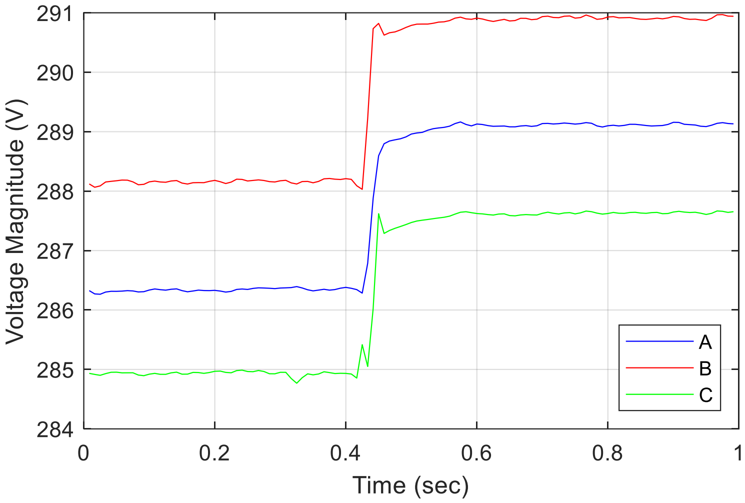


Waveform

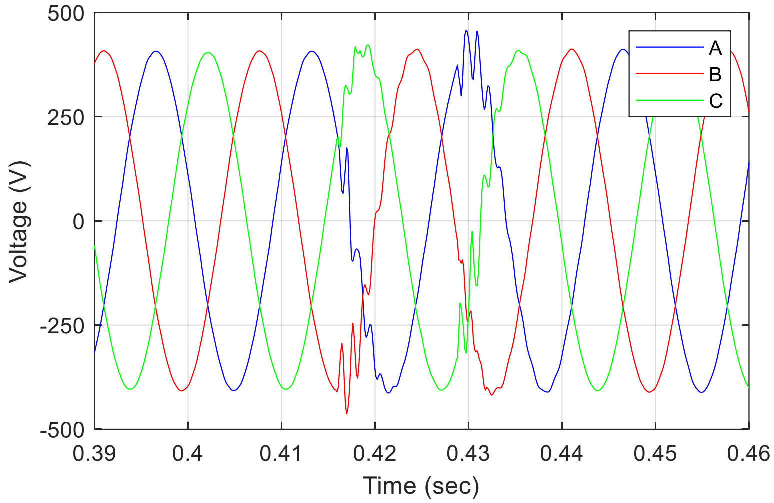
- Looking at voltage waveform is *not necessary* in this example.

Waveform: Real-World Examples

- Example 2 (Resonance):



Phasor (Magnitude)

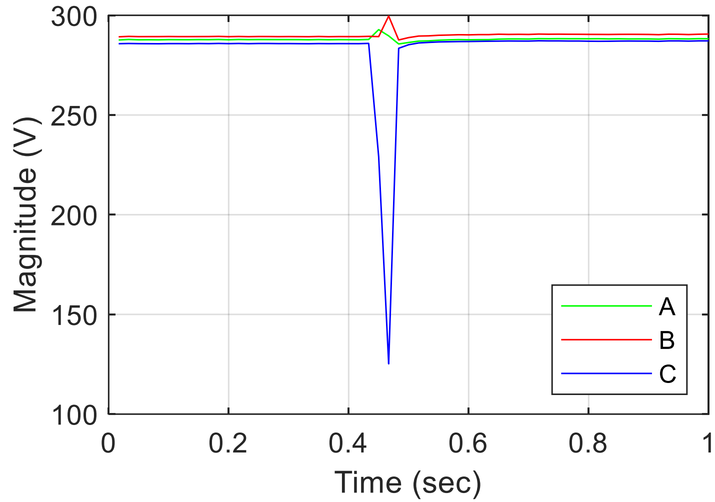


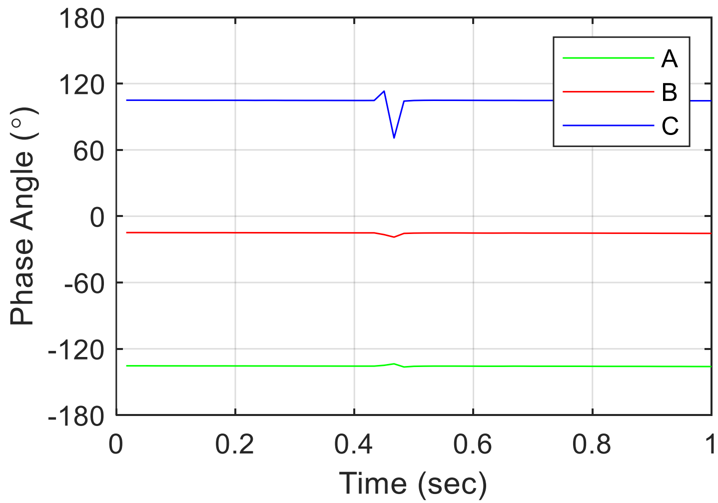
Waveform

- We *cannot see* the high-frequency resonance in the phasors.

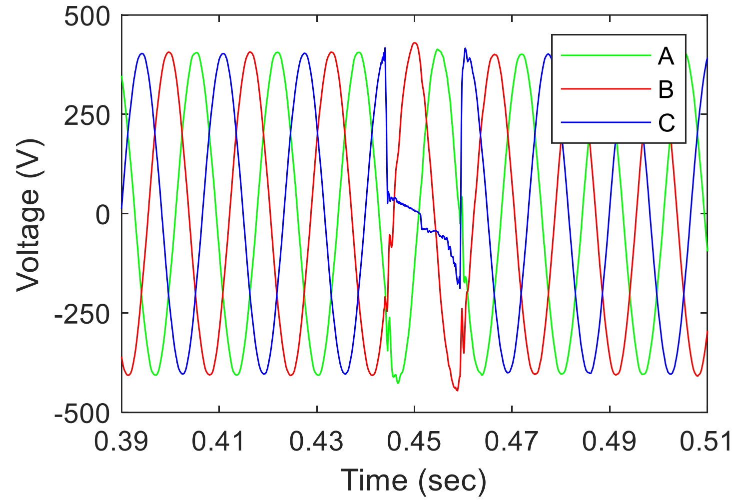
- Example 3 (Fault):

Phasor





Waveform



- Waveforms show much more details in this example.

Waveform Measurement Unit

- The device to measure voltage and current waveform:
  - **WMU**: Waveform Measurement Unit[1]

  (Compare it with **PMU**: Phasor Measurement Unit)

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

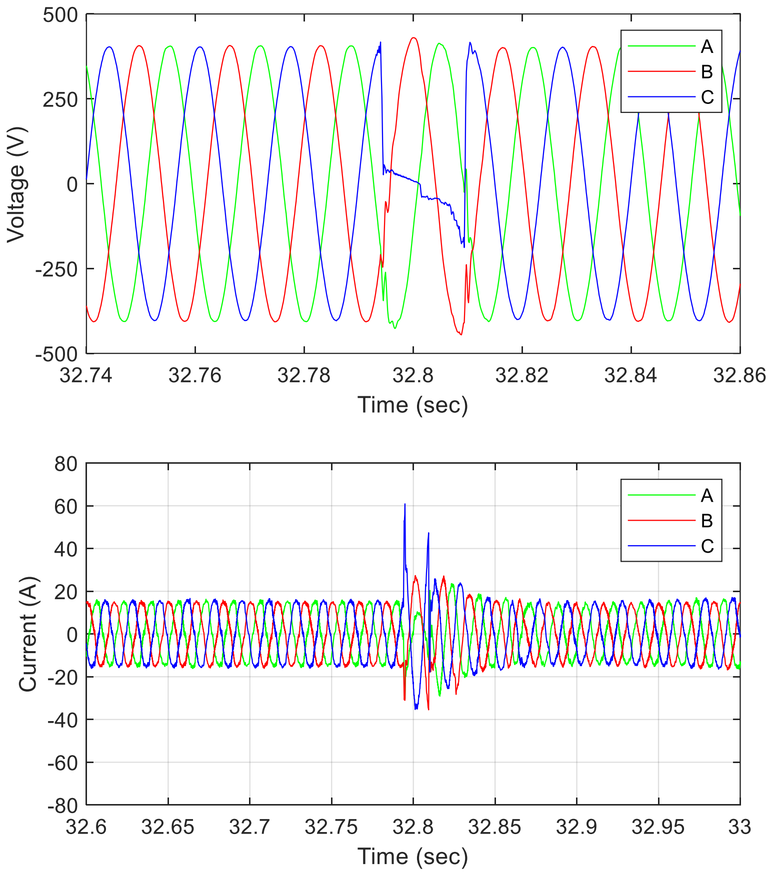
(They all measure waveform)

[1] H. Mohsenian-Rad, ***Smart Grid Sensors: Principles and Applications***, Cambridge University Press, April 2022.

Waveform Measurement Unit

- WMUs can measure both ***voltage*** and ***current*** waveforms:

- Measured by the same WMUs (over 12 terminals):



Synchro-Waveforms

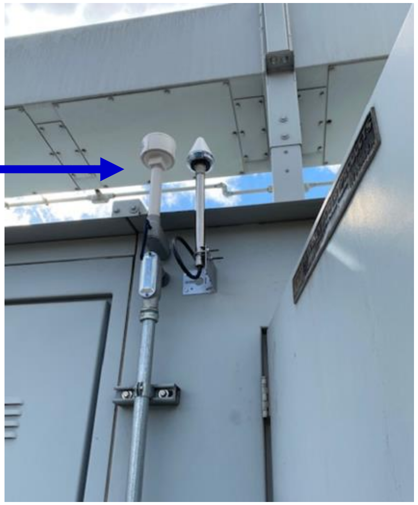
- Two Concepts:

Synchro-Phasors = Phasors + Time Synchronization

Synchro-Waveforms = Waveforms + Time Synchronization

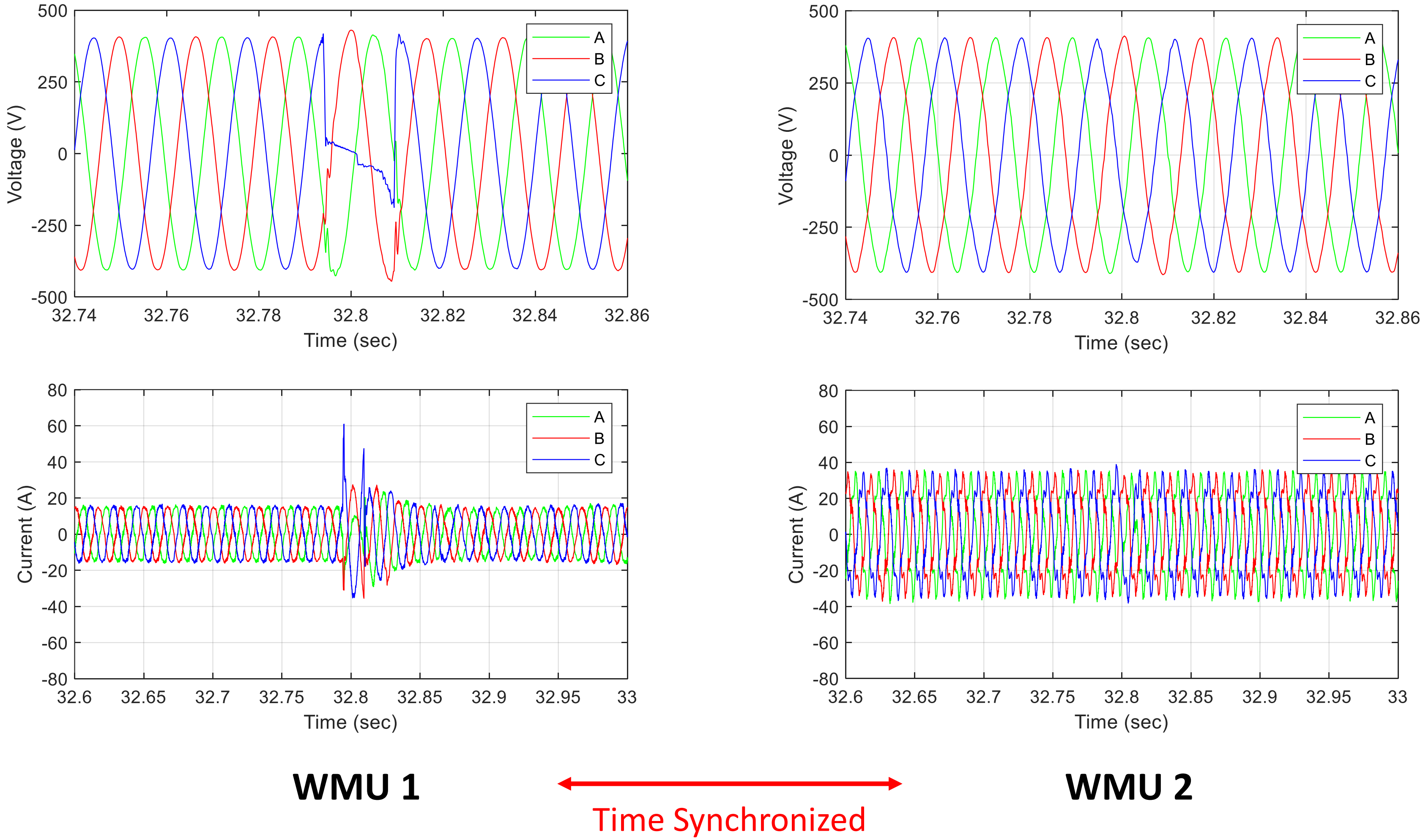
GPS Clock

GPS Antennas

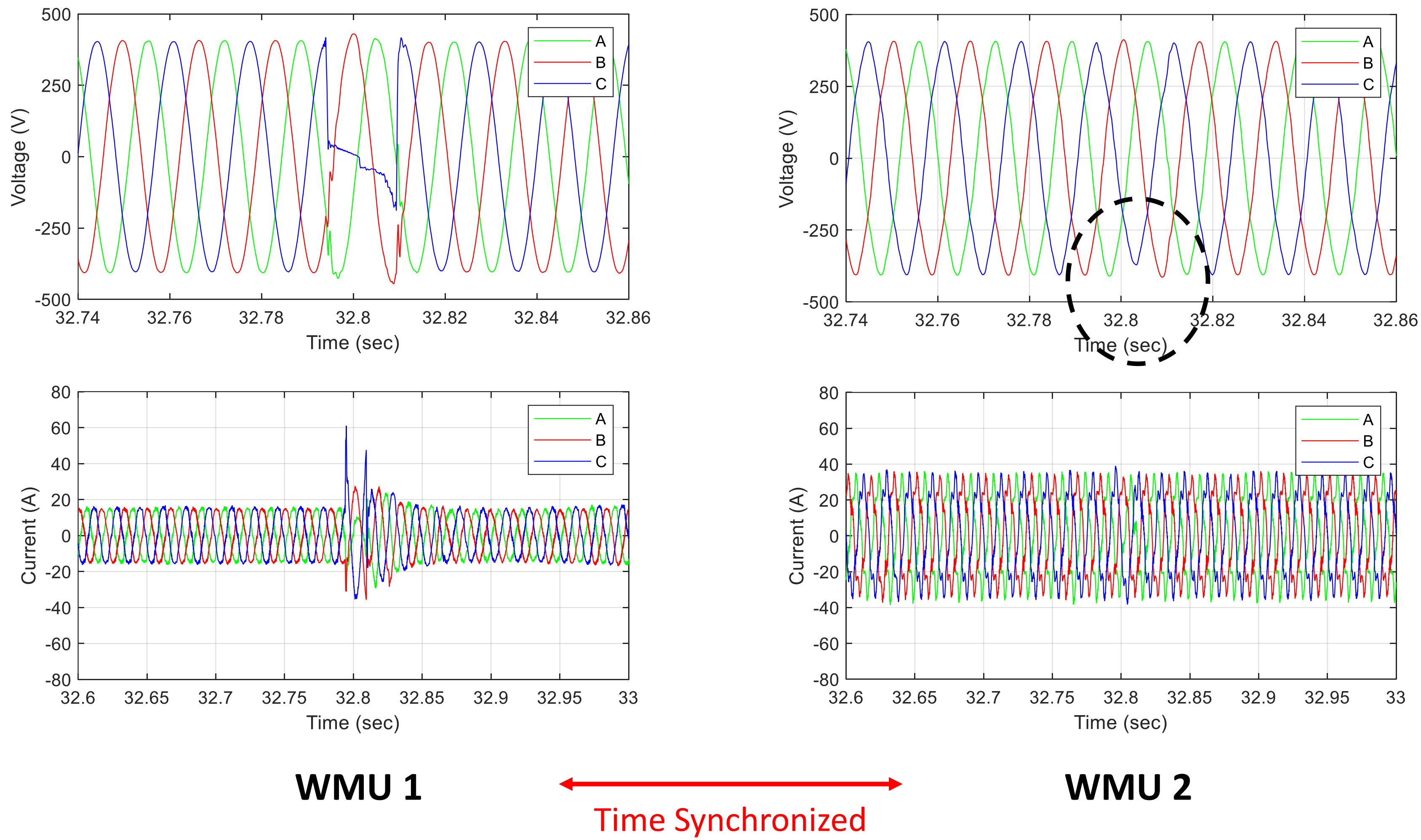


- Analysis of Synchro-Waveforms is the focus in this Tutorial.

- Synchro-Waveforms in Example 3:

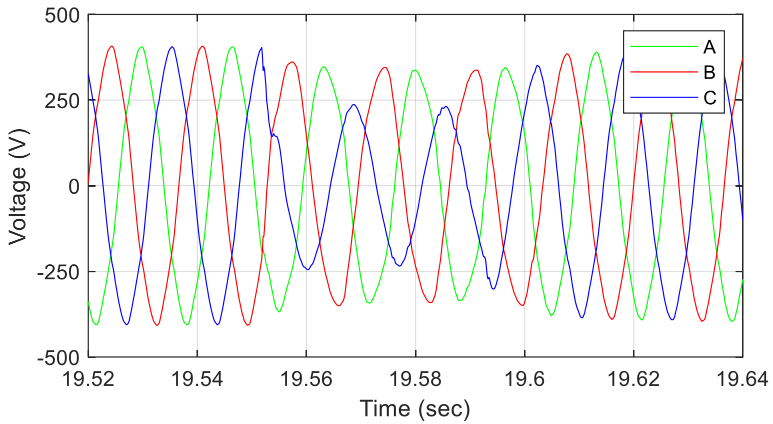


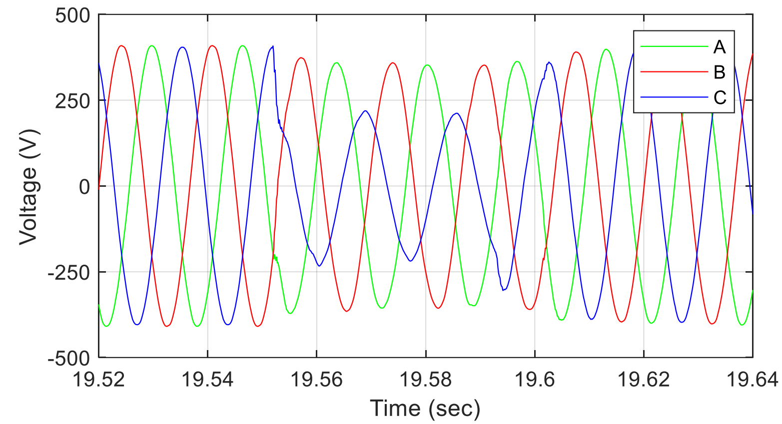
- Synchro-Waveforms in Example 3:



Synchro-Waveforms

- Another Example - Synchro-Waveforms:





WMU 1 ←→ **WMU 2**

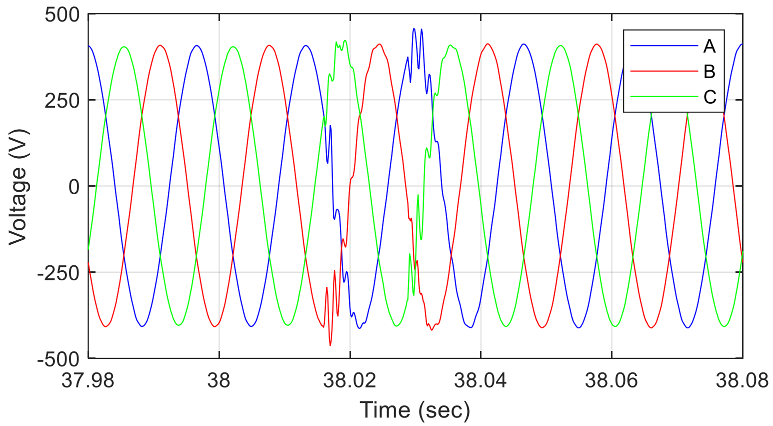
Time Synchronized

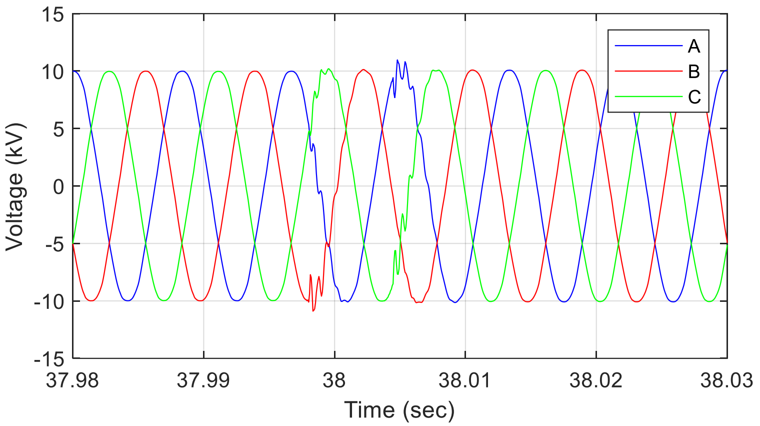
Minor Differences

(Event is Likely Far from both WMU 1 and WMU 2)

Synchro-Waveforms

- Synchro-Waveforms in the example with Resonance:





WMU 1 ⟷ **WMU 3**

Time Synchronized

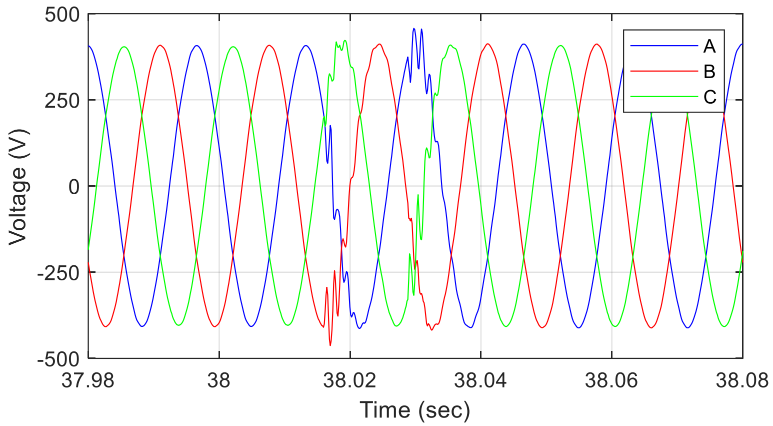
Another Location

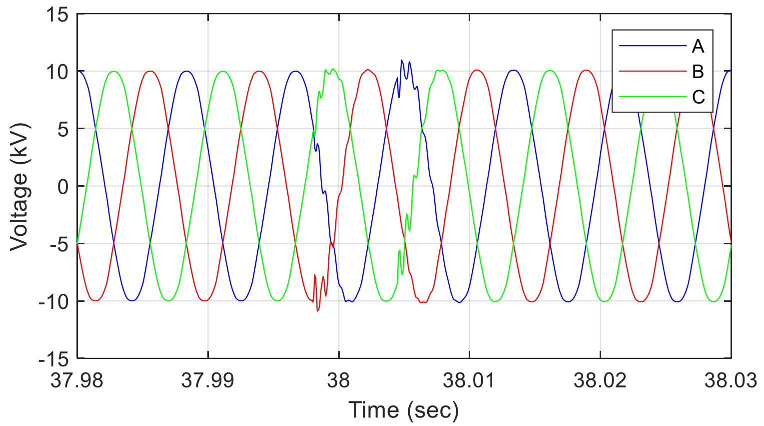
(Also, Different Voltage Level)

(System-Wide Sub-Cycle Resonance, Seen at Multiple Substations)

Synchro-Waveforms

- Synchro-Waveforms in the example with Resonance:





WMU 1 ⟷ **WMU 3**

Time Synchronized

- WMUs observe the same physical phenomena at different locations.

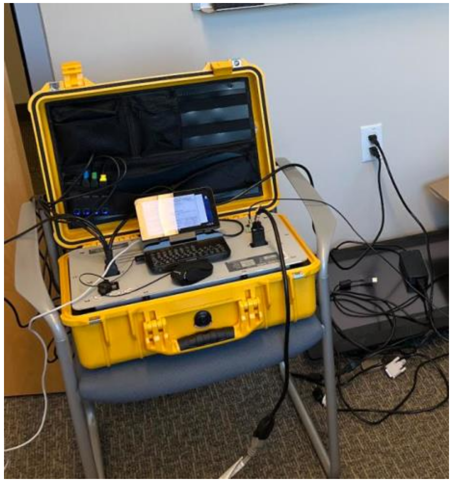
→ **Synchro-Waveform Situational Awareness**

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

- Field Measurements:

Three-Phase (12.47 kV)

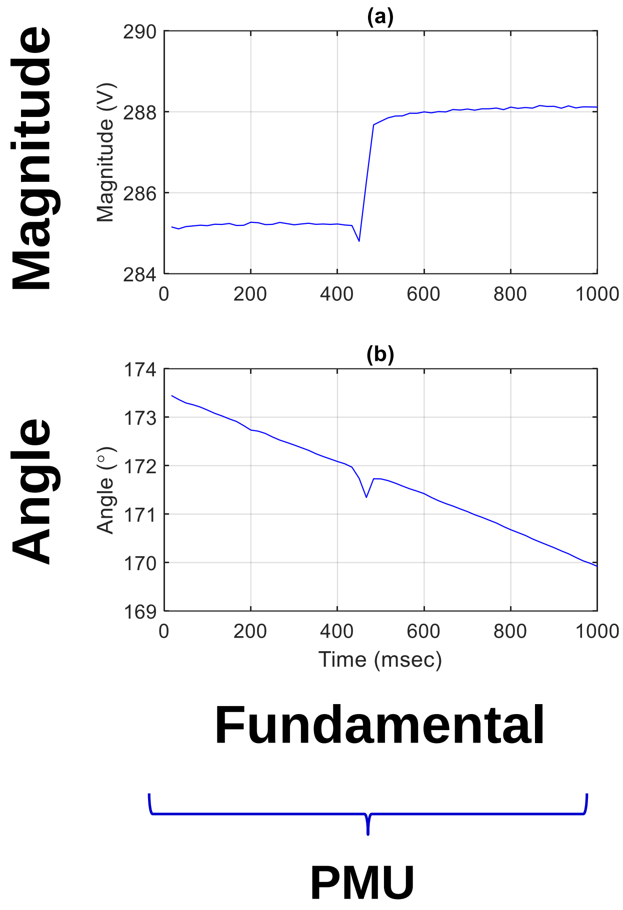
Three-Phase (480 V)



Single-Phase (120 V)

WMUs versus PMUs versus H-PMUs

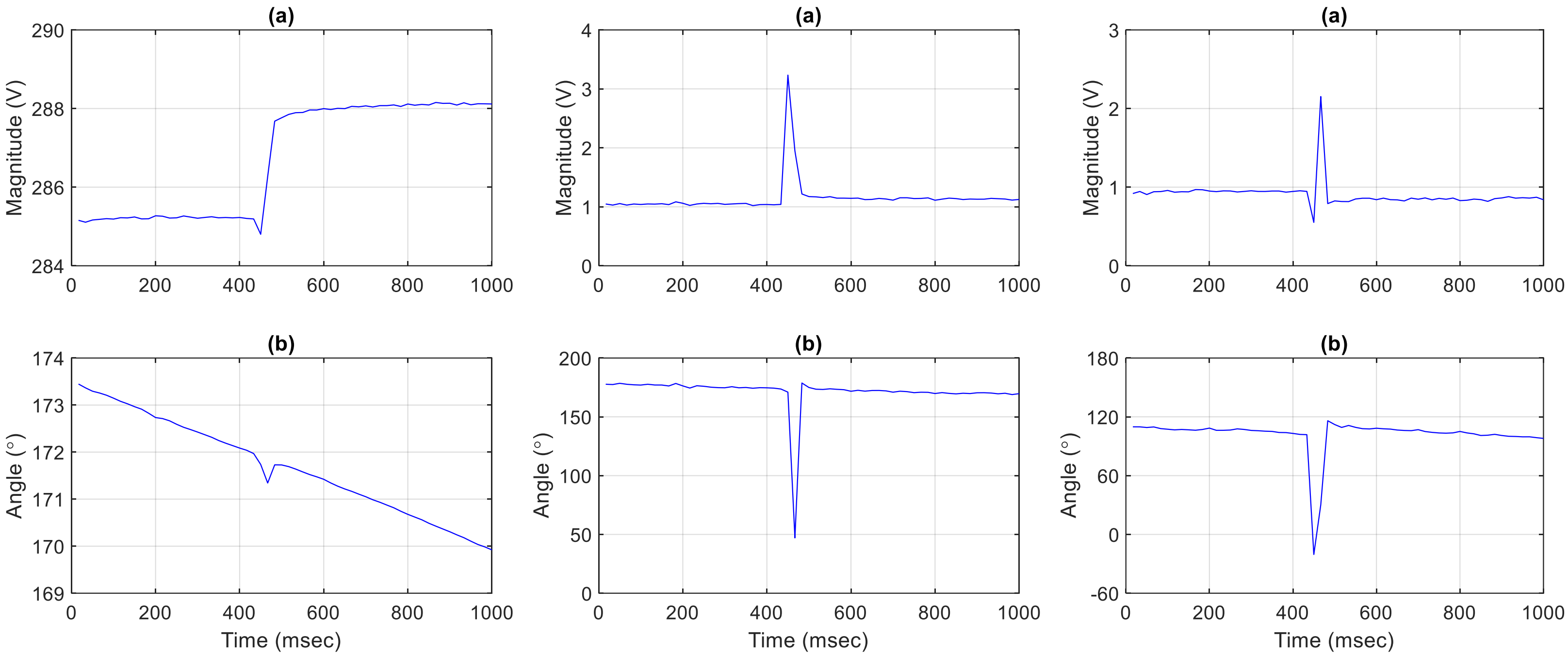
- **Example**: Phasor Measurements During an Event:



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

Magnitude

Angle



Fundamental | **3rd Harmonic** | **5th Harmonic**

PMU | **H-PMU**

WMUs versus PMUs versus H-PMUs

- **Note**: Adding *harmonic phasor data* is helpful:
  - Example: Improvement in Event Clustering[2] → 13% Improvement

[2] A. Aligholian and H. Mohsenian-Rad, "GraphPMU: Event Clustering via Graph Representation Learning Using Locationally-Scarce Distribution-Level Fundamental and Harmonic PMU Data," in ***IEEE Trans. on Smart Grid***, 2022.

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- **Question**: Why limit ourselves to "phasor" representation?

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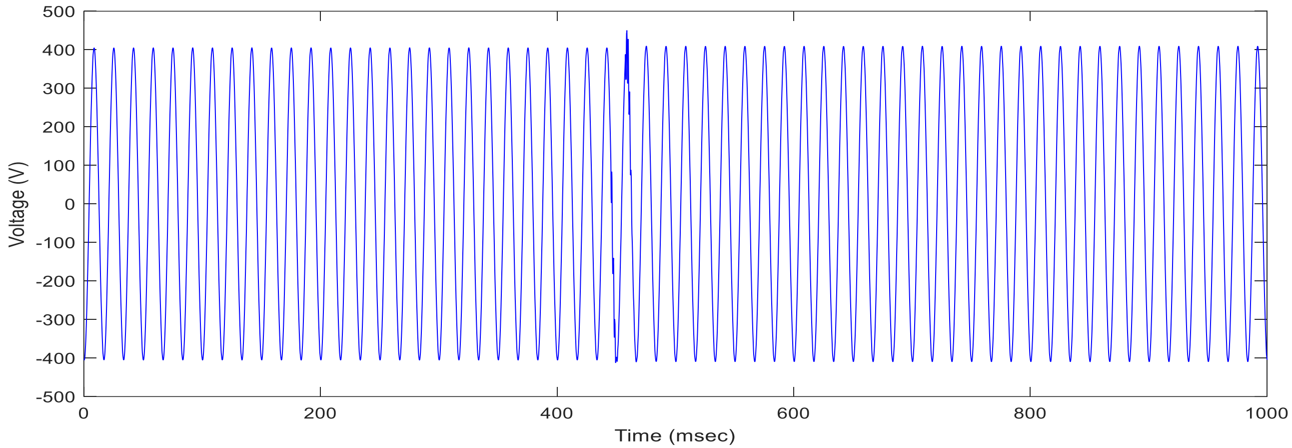
Waveform Data (Same Period)



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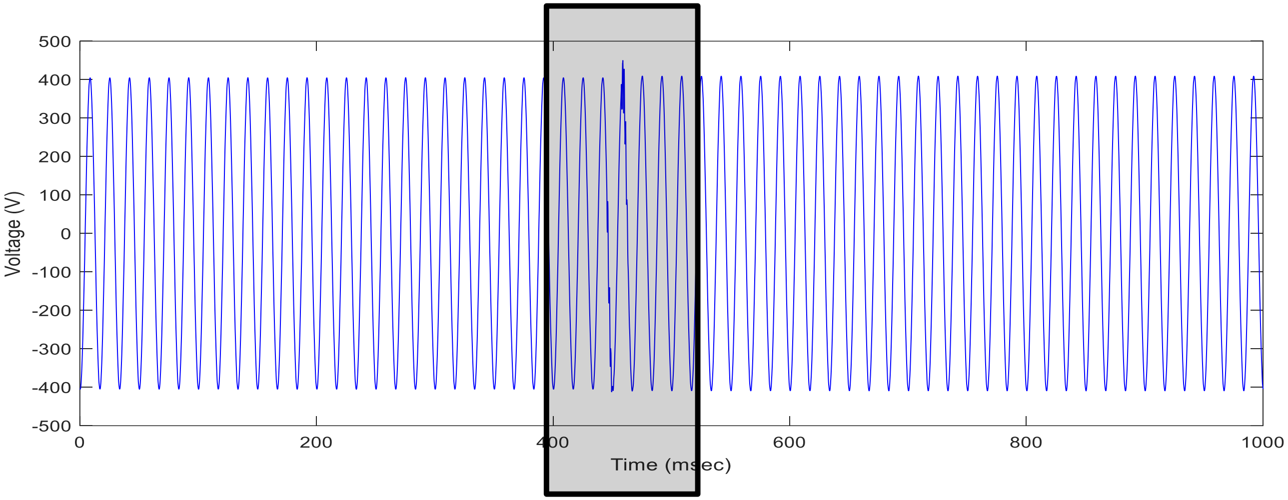

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Synchro-Waveform Data Analysis

- **Situational awareness** with synchro-waveform data:
  - Data Size Per WMU: **3,981,312,000 Readings Per Day**
  - One Pair of WMUs: 8 Billion Data Points Per Day
  - Event-Driven Data Analytics:
    - **Event Detection**
    - **Event Location Identification**
    - **Event Characterization / Classification**

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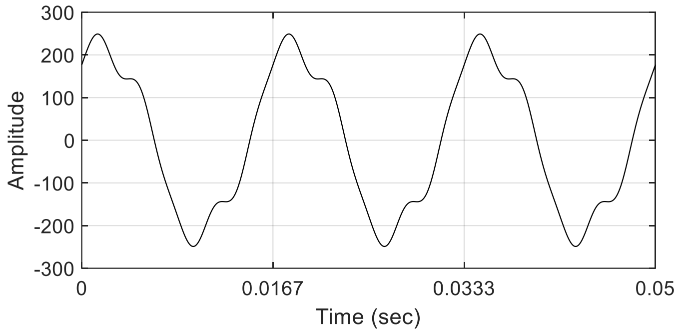
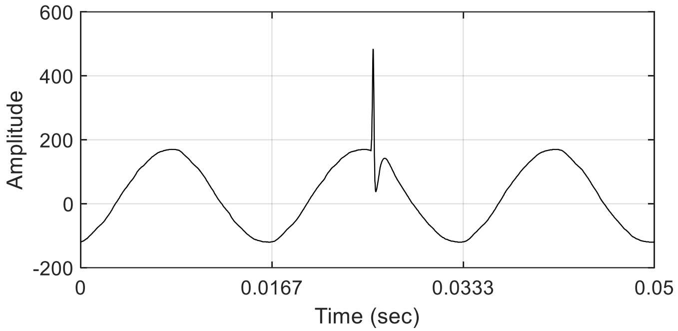
Event Detection

- Let's distinguish two cases:



Harmonic Distortions



Event

Event Detection

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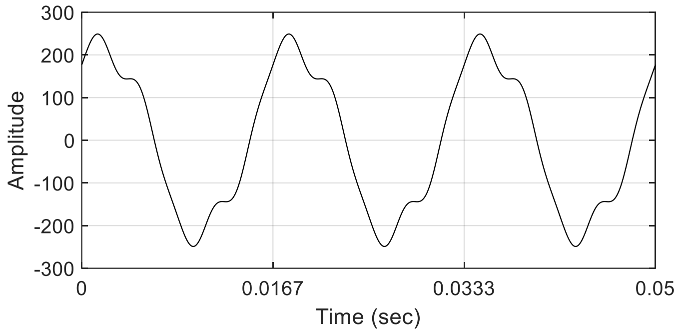

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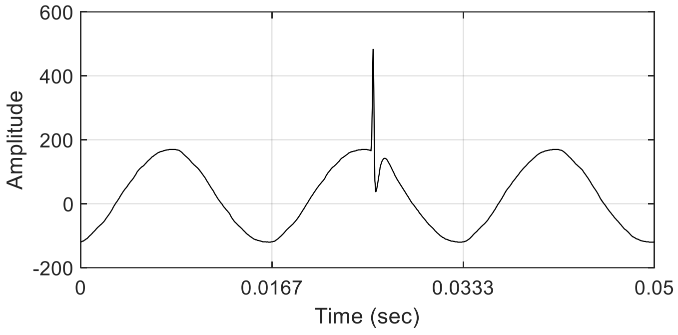

Event

(Steady-State Analysis[3] ⟼ H-PMUs)

[3] F. Ahmadi and H. Mohsenian-Rad, "A Physics-Aware MIQP Approach to Harmonic State Estimation in Low-Observable Power Distribution Systems Using Harmonic Phasor Measurement Units," in ***IEEE Trans. on Smart Grid***, Sept, 2022.

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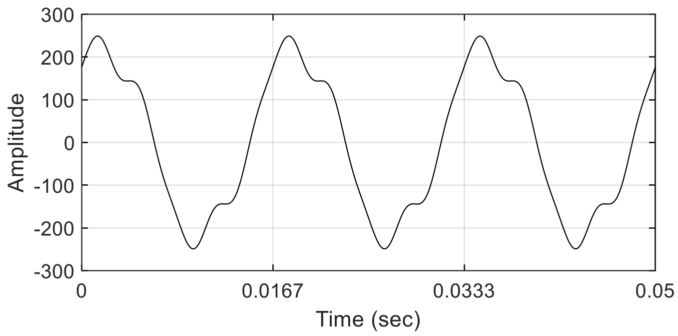

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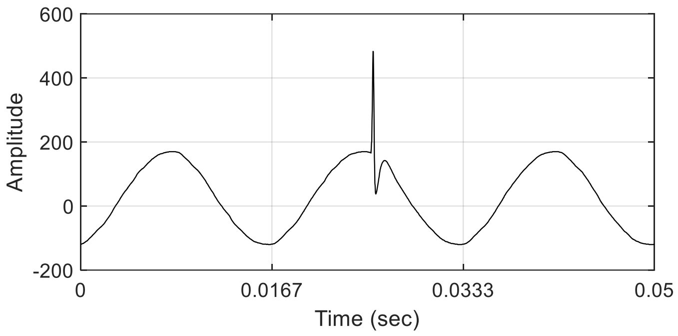

Event

Our Focus in This Section

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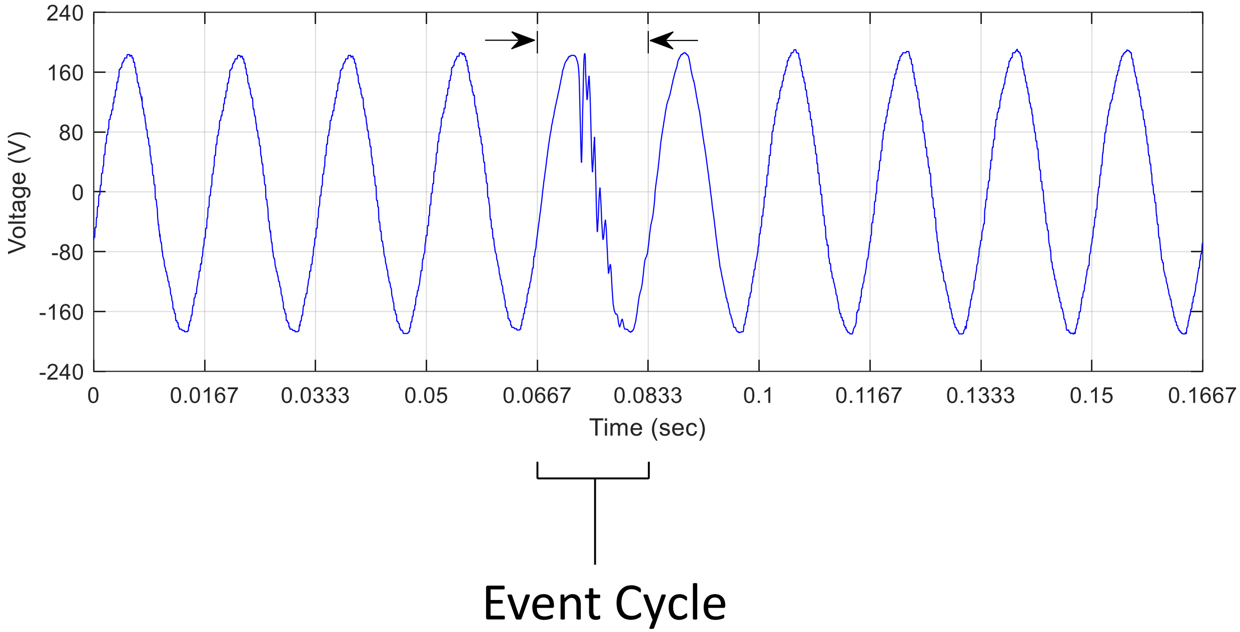
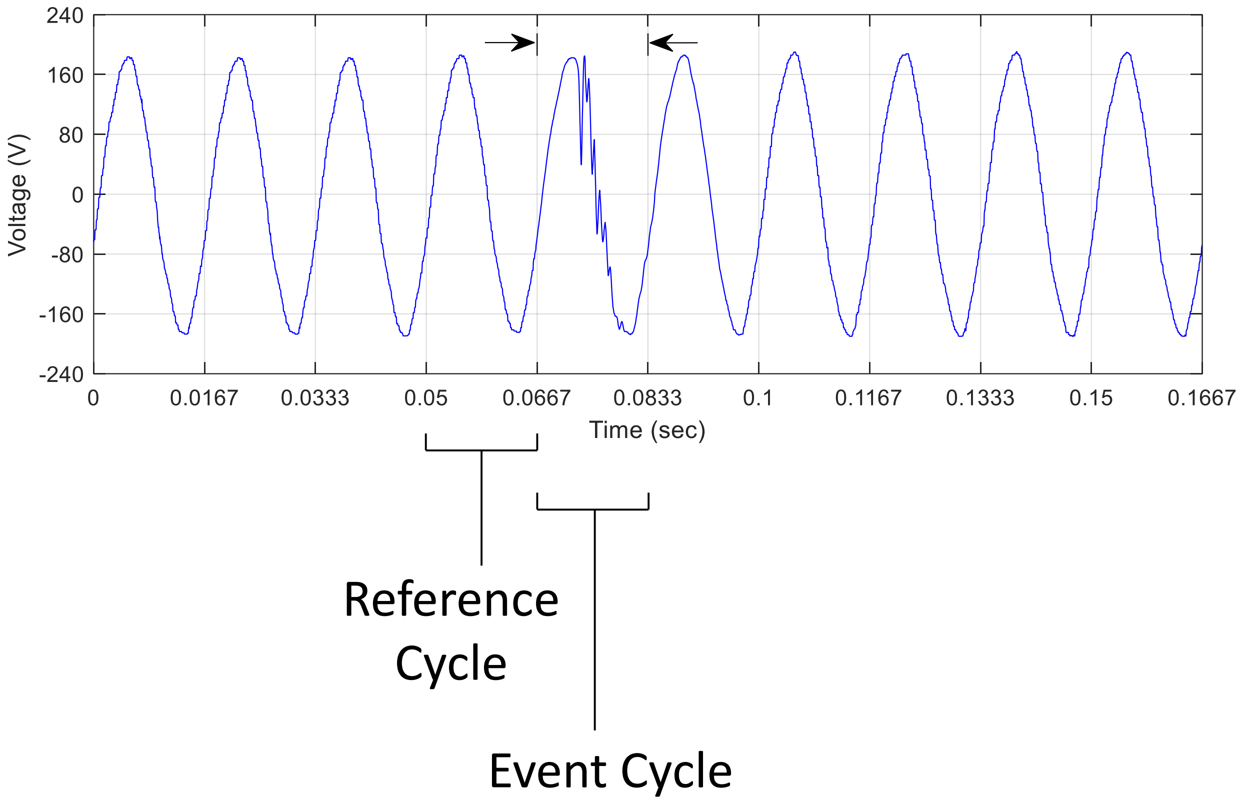
Event Detection

- Event-triggered waveform capture:



Event Detection

- In practice, it is common to simply *compare two consecutive cycles*:



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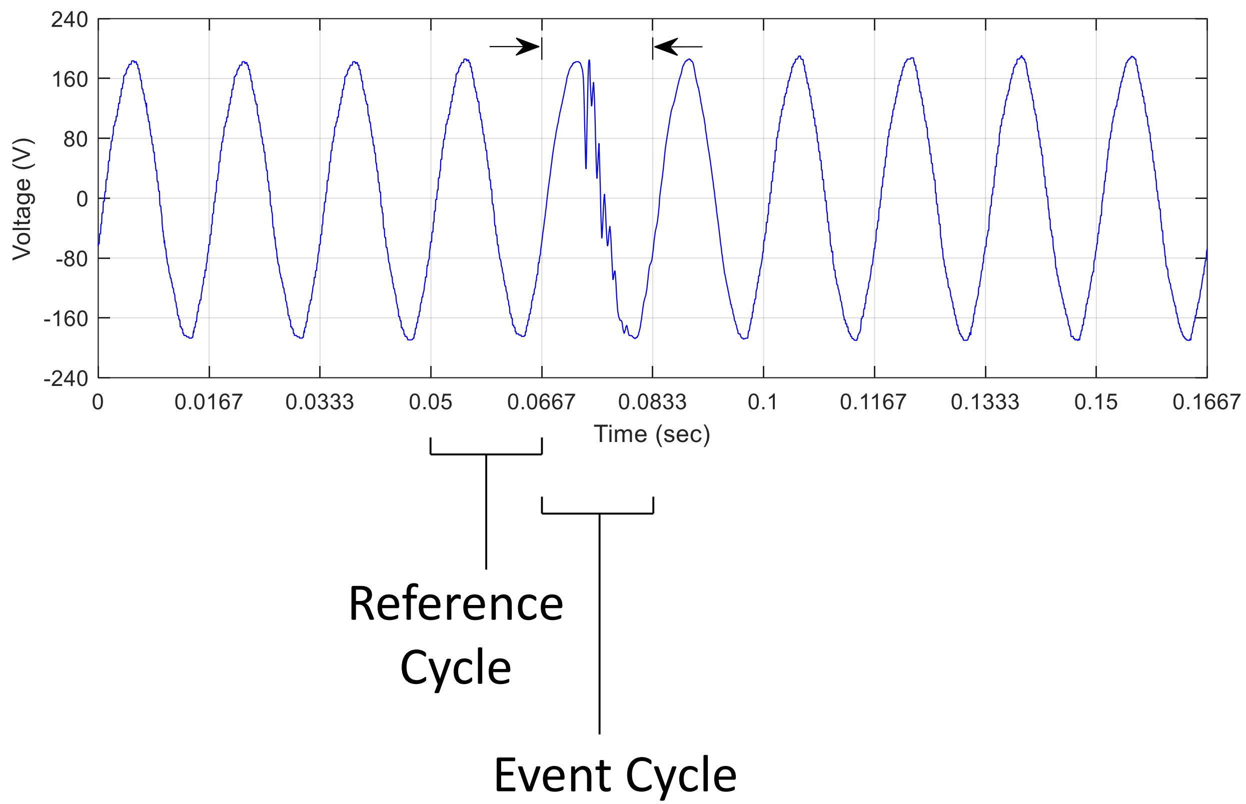
What Metric?



Event Detection

- Different ways to compare two cycles of waveforms[1]:
  - Comparing THD
  - Comparing RMS
  - Point-to-Point Comparison
  - Comparing Sub-Cycle RMS
  - Differential Waveform
  - Neutral Current Waveform
  - Other Factors and Methods

Event Detection

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  - Comparing RMS
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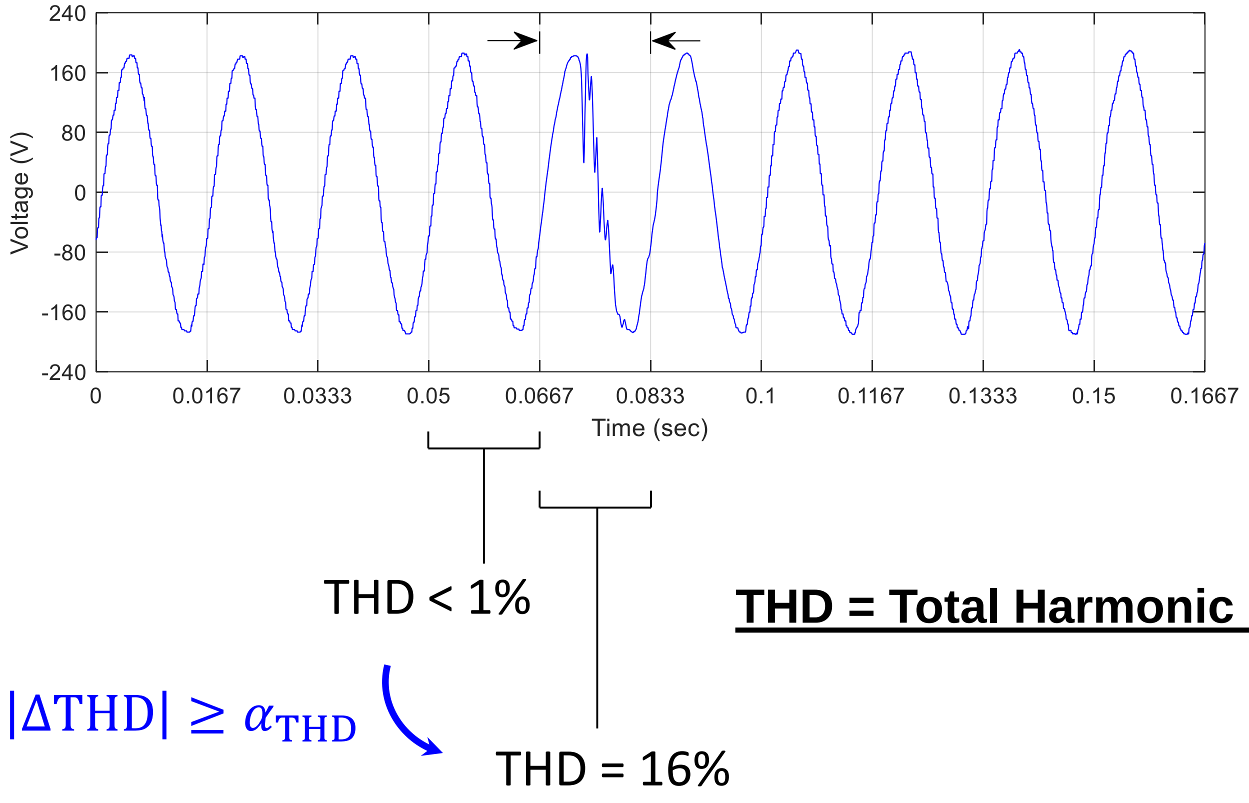
  - Neutral Current Waveform ⟵
  - Other Factors and Methods

Comparing THD

- Compare two consecutive waveform cycles based on their THD values.



THD = Total Harmonic Distortion

Differential Waveform

- It works based on obtaining the following *differential waveform*:

$$\Delta x(t) = x(t) - x(t - NT).$$

where

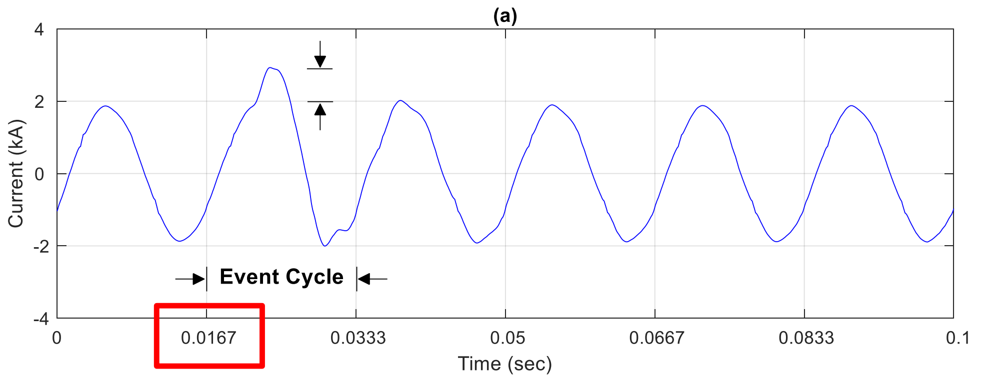
$x(t)$ is the measured current waveform or voltage waveform;
T is the waveform interval; and
N is a small integer number, e.g., 1, 2, 3, 4, or 5.

- We can detect an event based on the characteristics of $\Delta x(t)$.

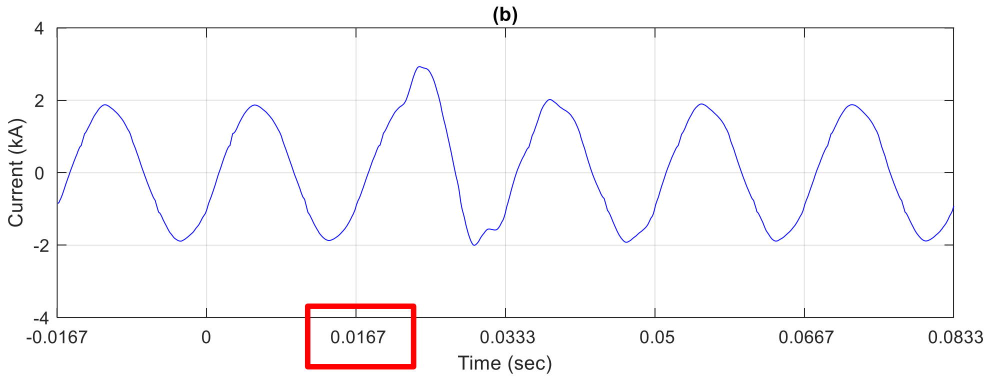
Differential Waveform

- Consider the current waveform measurements below:

$x(t)$

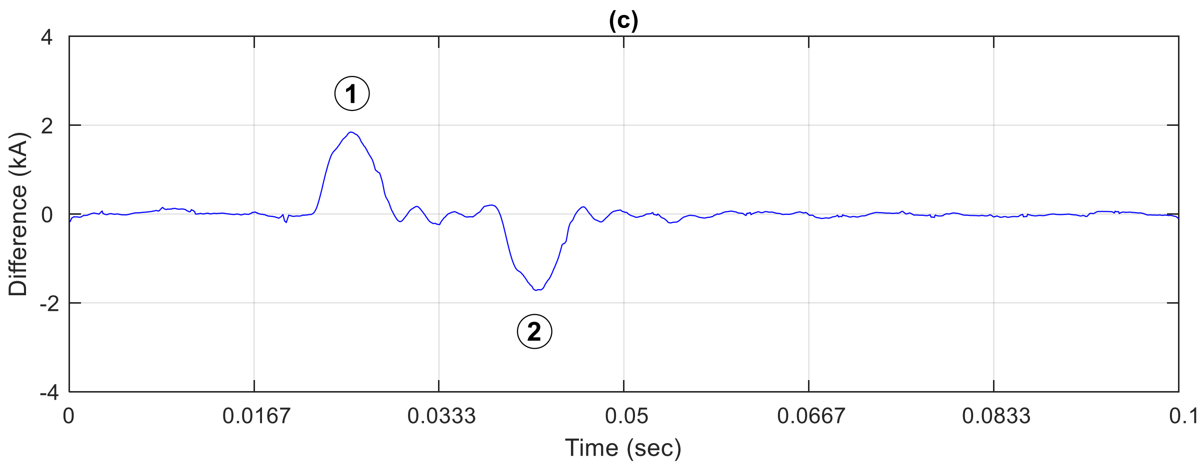


$x(t-T)$



Differential Waveform

• The differential waveform is obtained as:



• We can see that the event has created two distinct blips in the differential waveform, which are denoted by ① and ② .

• Note that *both* of them are associated with the *same* event.

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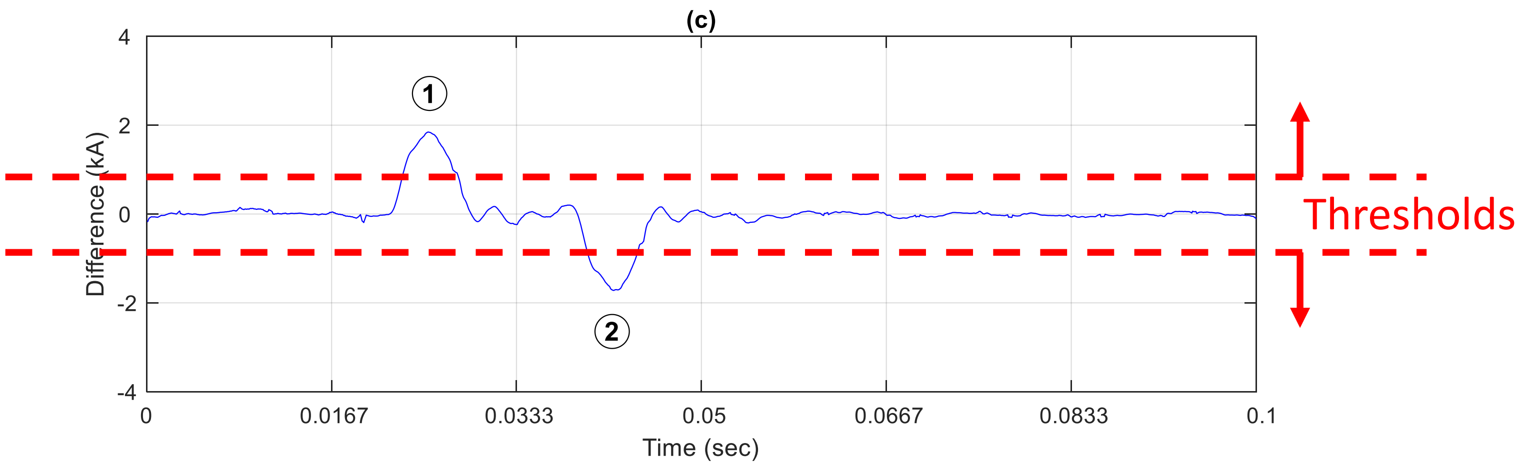

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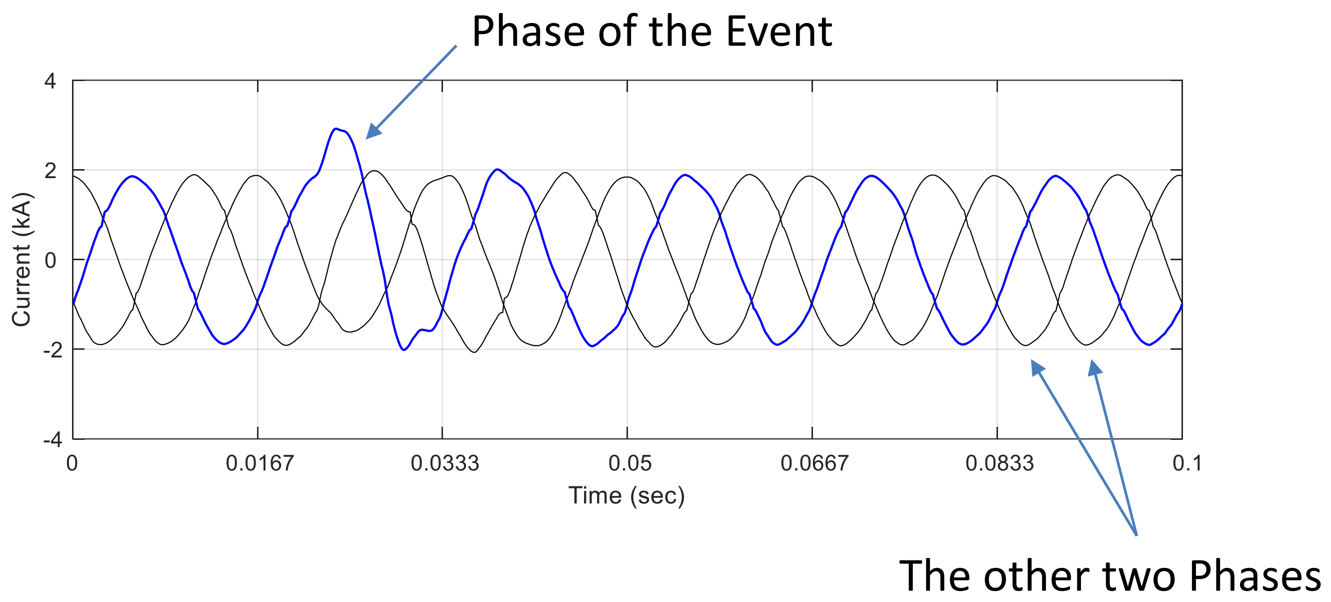
Neutral Current Waveform

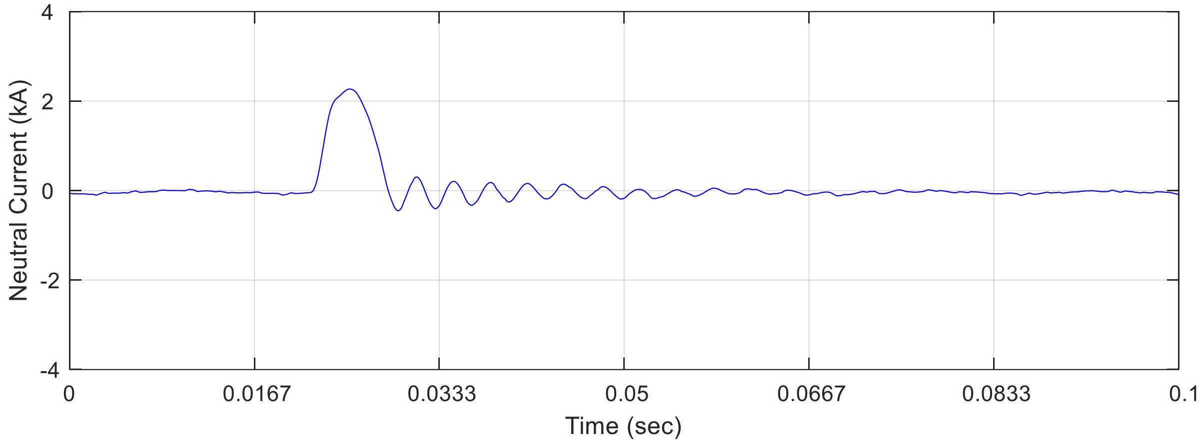
- Consider the following three-phase current waveform measurements:



Neutral Current Waveform

- The neutral current is obtained as:

$$i_{\mathrm{N}}(t) = i_{\mathrm{A}}(t) + i_{\mathrm{B}}(t) + i_{\mathrm{C}}(t).$$



- **Note**: No second blip, unlike in the differential waveforms.

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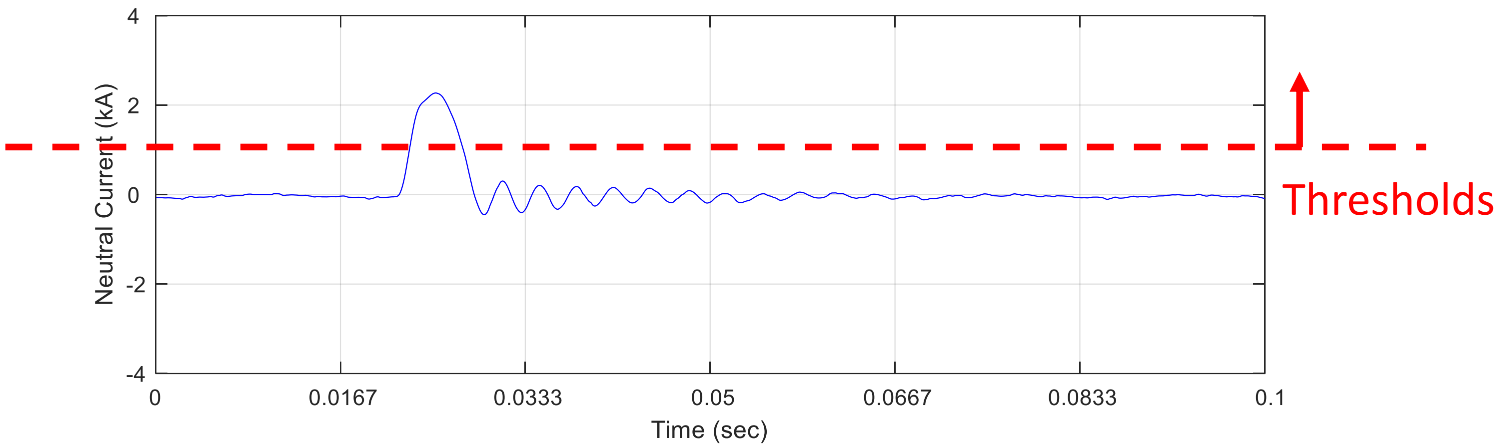

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Event Detection – Multiple Waveforms

- We may also try to *simultaneously* check multiple waveforms.

- For example, suppose two WMUs collect the following waveforms:

  - Voltage at WMU 1: $v_1(t)$

  - Current at WMU 1: $i_1(t)$

  - Voltage at WMU 2: $v_2(t)$

  - Current at WMU 2: $i_2(t)$

Event Detection – Multiple Waveforms

- We may also try to *simultaneously* check multiple waveforms.

- For example, suppose two WMUs collect the following waveforms:

  - Voltage at WMU 1: $v_1(t)$ → Detect
  - Current at WMU 1: $i_1(t)$ → Detect
  - Voltage at WMU 2: $v_2(t)$ → Detect
  - Current at WMU 2: $i_2(t)$ → Detect

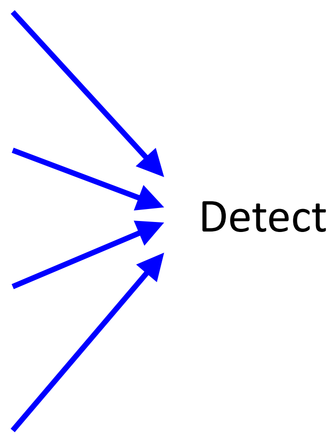
We can look for
event in *each* waveform.

Event Detection – Multiple Waveforms

- We may also try to *simultaneously* check multiple waveforms.

- For example, suppose two WMUs collect the following waveforms:

  - Voltage at WMU 1: $v_1(t)$
  - Current at WMU 1: $i_1(t)$
  - Voltage at WMU 2: $v_2(t)$
  - Current at WMU 2: $i_2(t)$



We can look for event in *all* waveforms.

Event Detection – Multiple Waveforms

- Graphical Metrics[4]:

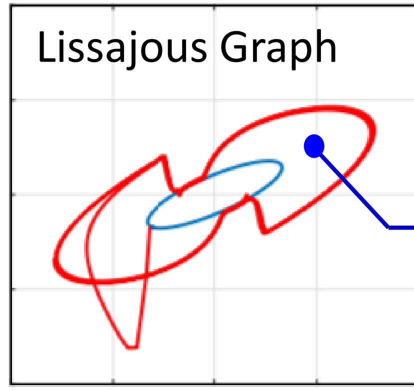
Location 1 / WMU 1

$v_1(t), i_1(t)$

Location 2 / WMU 2

$v_2(t), i_2(t)$

$v(t) = v_1(t) - v_2(t)$

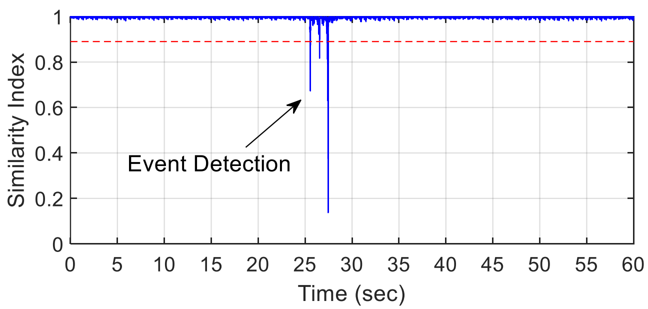


$i(t) = i_1(t) - i_2(t)$

$$A(t) = \text{Area} = \left| \int_{i(\tau=t-T)}^{i(\tau=t)} v(t)\, di(t) \right|$$

$$S(t) = 1 - \left| \frac{A(t) - A(t-T)}{\max\{A(t), A(t-T)\}} \right|$$

Similarity Index



[4] M. Izadi and H. Mohsenian-Rad, "Characterizing synchronized Lissajous curves to scrutinize power distribution synchro-waveform measurements," in ***IEEE Trans. on Power Systems***, vol. 36, no. 5, pp. 4880-4884, Sept 2021.

Synchro-Waveform Data Analysis

- **Situational awareness** with synchro-waveform data:
  - Data Size Per WMU: **3,981,312,000 Readings Per Day**
  - One Pair of WMUs: 8 Billion Data Points Per Day
  - Event-Driven Data Analytics:
    - **Event Detection**
    - **Event Location Identification**
    - **Event Characterization / Classification**

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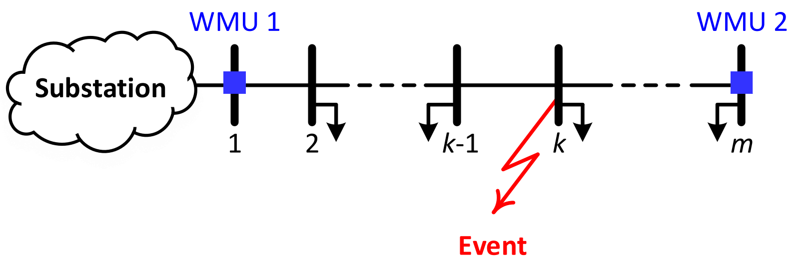
Event Location Identification

- Finding the Cause of Transient Events:



Event Location Identification

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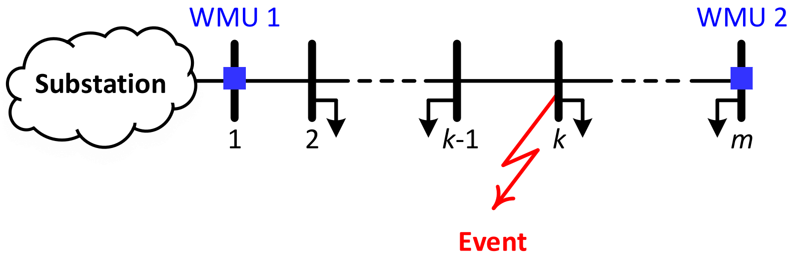

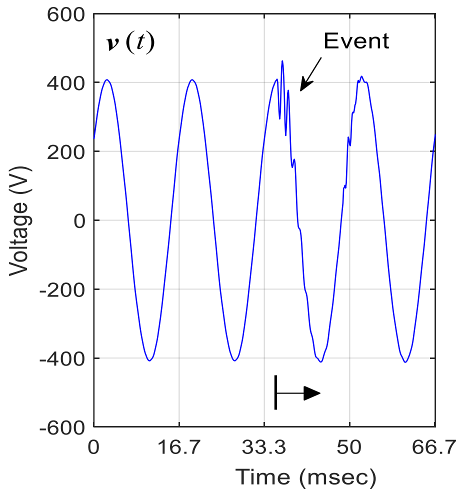

Event Location Identification

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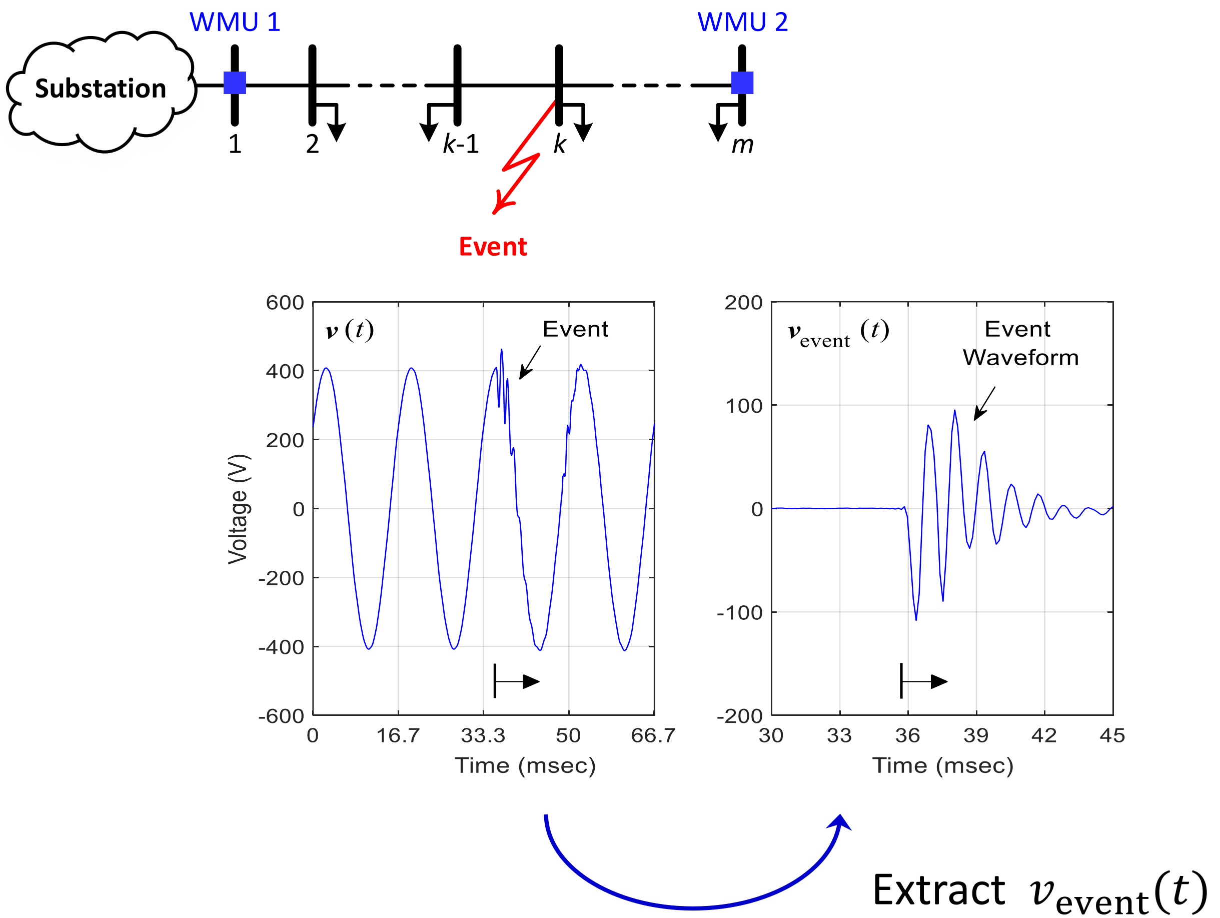

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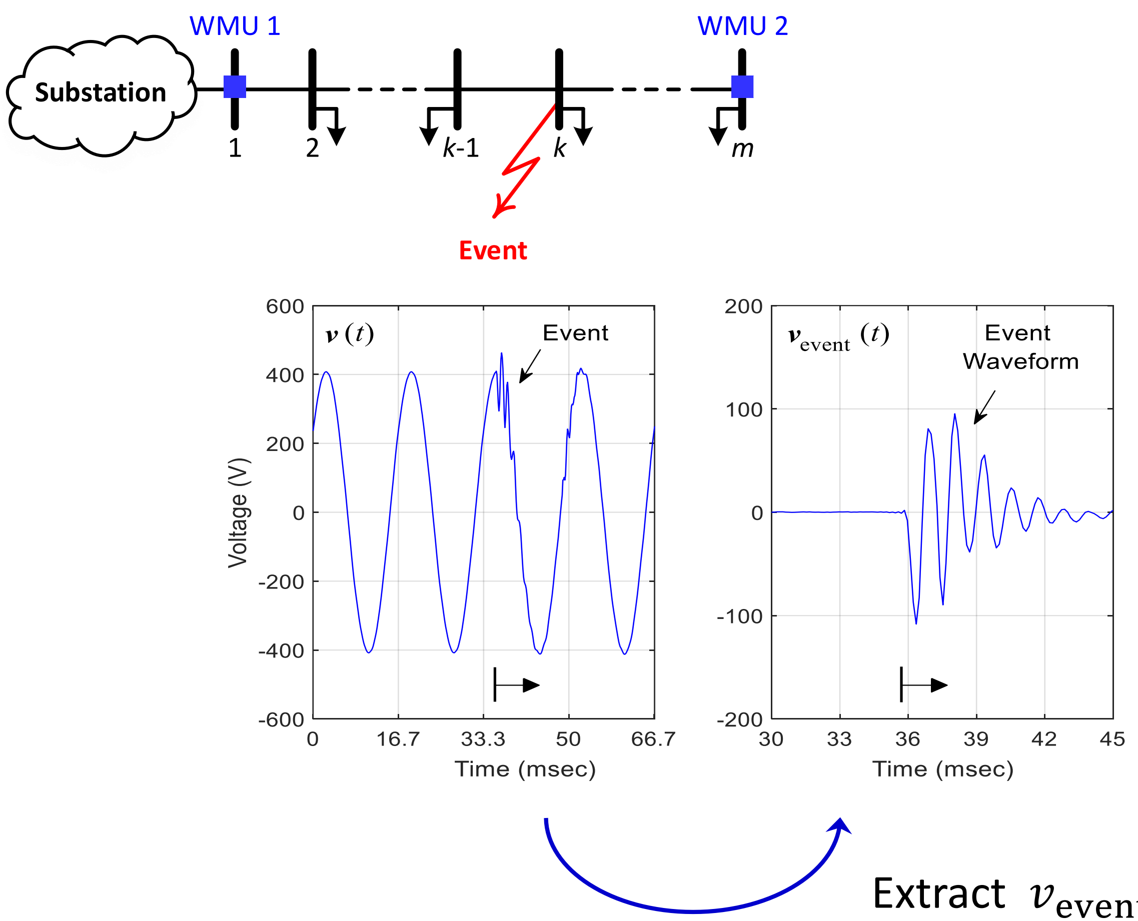


Extract $v_{\text{event}}(t)$

Modal Analysis

Number of Modes

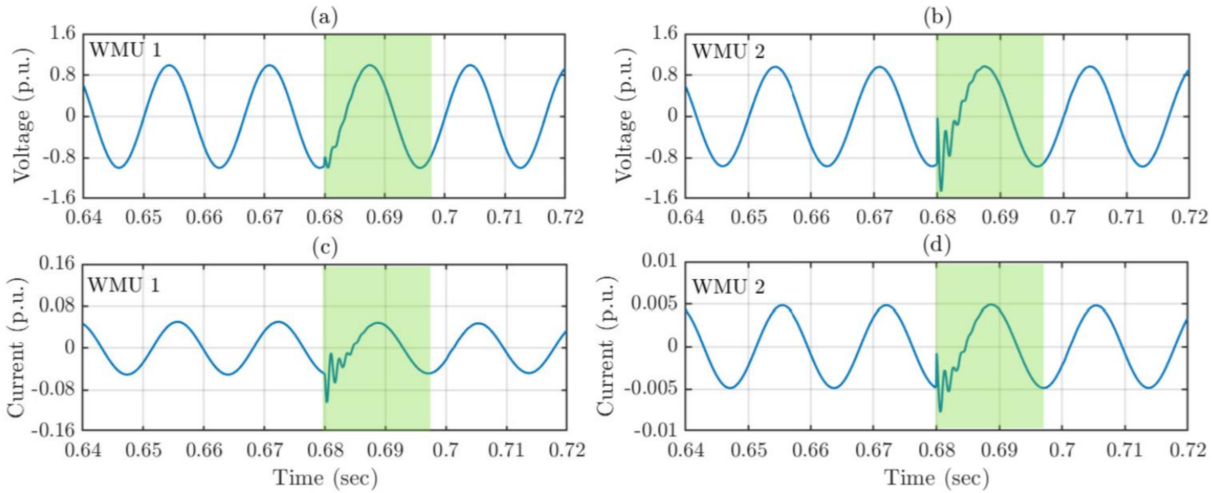
$$\sum_{p=1}^{P} A_{p,m}\, e^{\sigma_p t} \cos(2\pi f_p t + \theta_p)$$

Damping Sinusoidal Modes
$(f_p, \sigma_p, A_{p,m}, \theta_p)$

- Multi-Signal Modal Analysis:

WMU 1 WMU 2

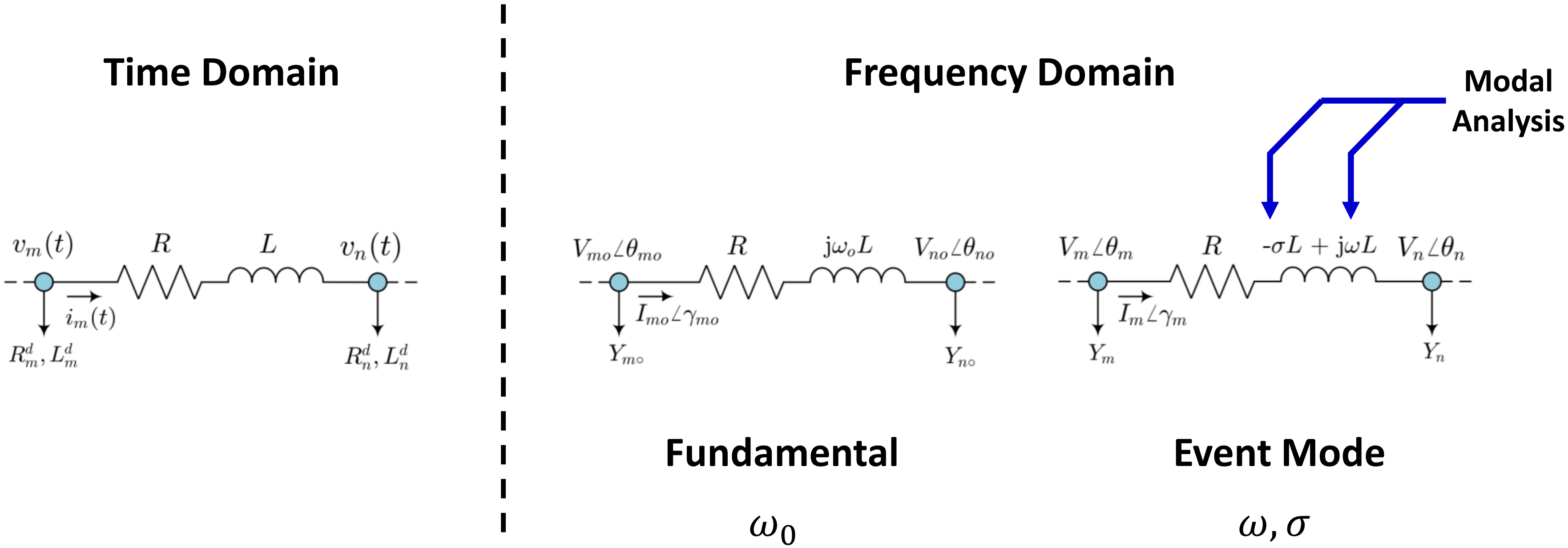
$v_1(t), i_1(t), v_2(t), i_2(t)$



WMU	Signal	Frequency (Hz)	Damping Rate (Hz)	Magnitude (p.u.)	Phase Angle (deg.)
1	Voltage	60.00 / 747.72	0.00 / -624.30	0.98 / 0.20	0.00 / 0.00
	Current			0.04 / 0.06	-25.19 / 82.43
2	Voltage			0.96 / 0.92	-0.49 / -1.07
	Current			0.004 / 0.004	-25.96 / -3.23

* The two most dominant modes are separated with a slash.

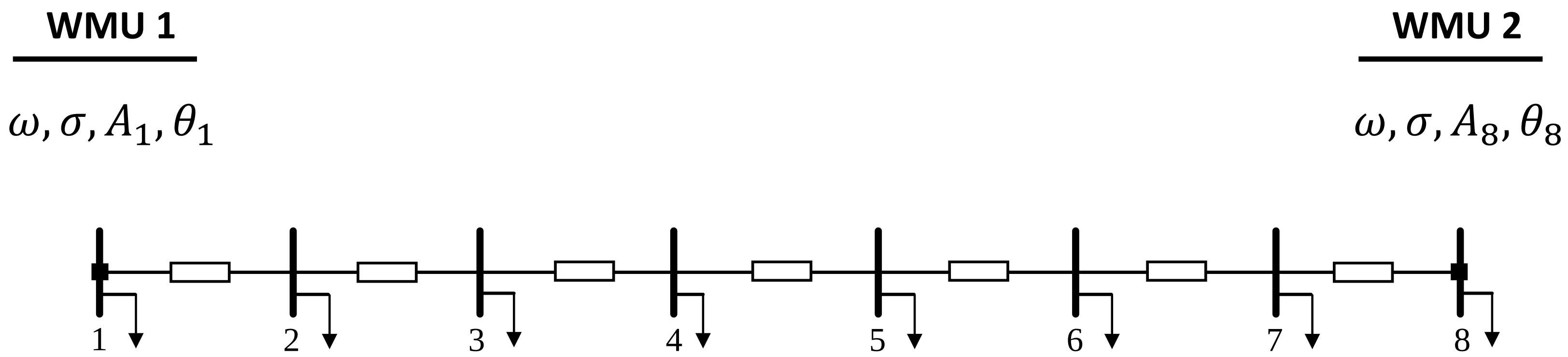
Event Location Identification



- Accordingly, we can solve the circuit in “event mode”.
    - This means solving the circuit based on ω, σ (instead of over ω_0)

Event Location Identification

- Circuit model under the event mode[5]:



[5] M. Izadi and H. Mohsenian-Rad, "synchronous waveform measurements to locate transient events and incipient faults in power distribution networks," in ***IEEE Trans. on Smart Grid***, vol. 12, no. 5, pp. 4295-4307, Sept 2021.

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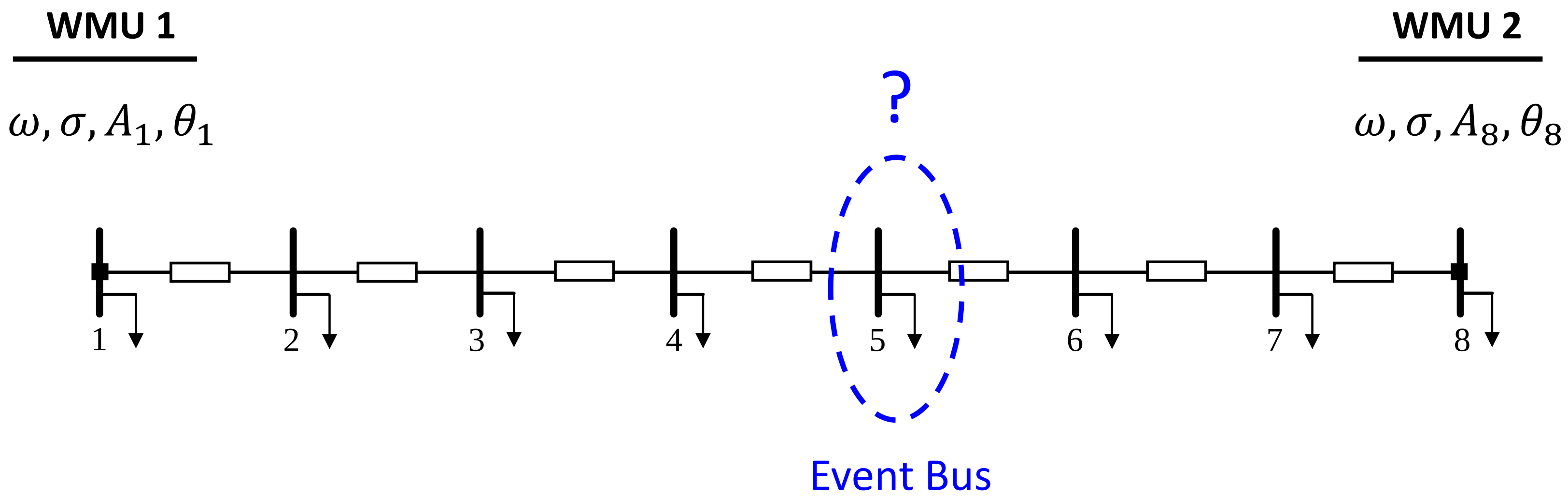

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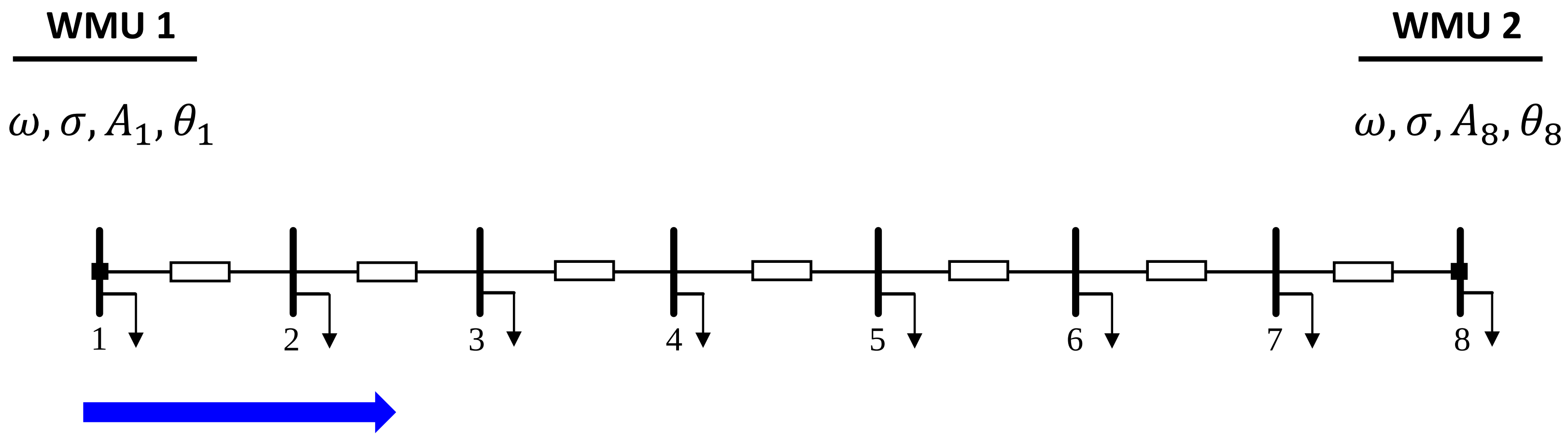

Step 1: Forward Sweep (Event Mode)

$V_1^f, V_2^f, \ldots, V_7^f, V_8^f$

(Phasors in Event Mode; *not* in Fundamental Mode)

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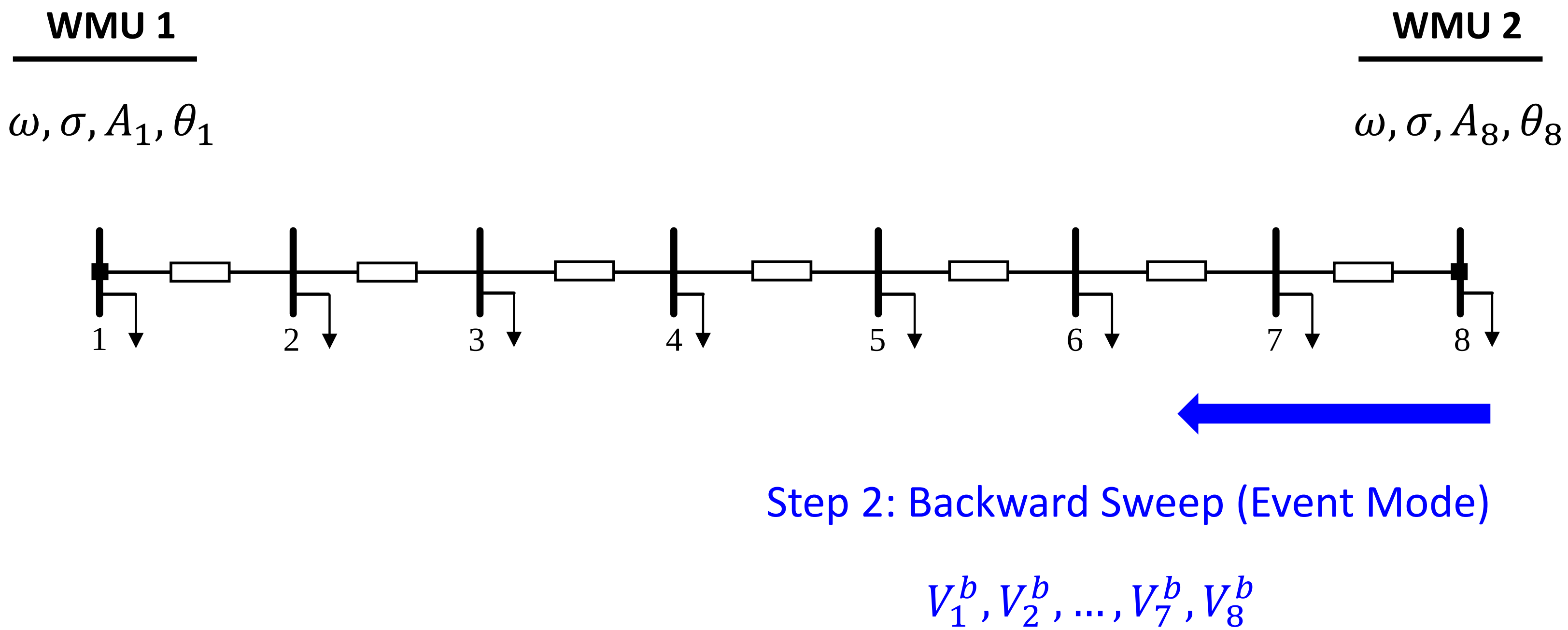

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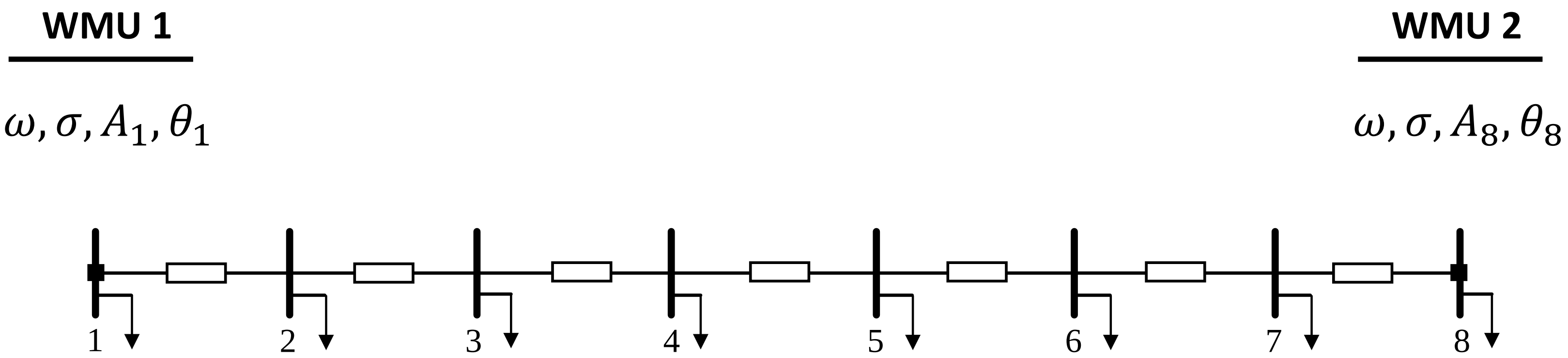

Step 3:

$$k^* = \underset{i}{\operatorname{argmin}}\ \Psi_i \qquad \text{where} \qquad \Psi_i = \left| V_i^f - V_i^b \right|, \qquad i = 1, \ldots, 8.$$

↑ Discrepancy

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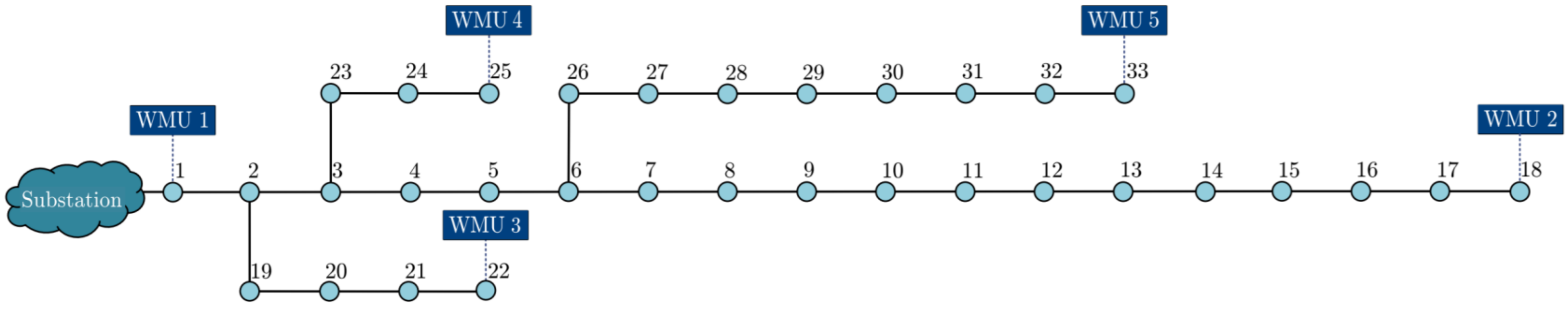
Event Location Identification

- We may have more than two WMUs available:



- Several Options:

  1) WMU 1 and WMU 2

  2) WMU 1 and WMU 3

  3) WMU 1 and WMU 4

  4) WMU 1 and WMU 5

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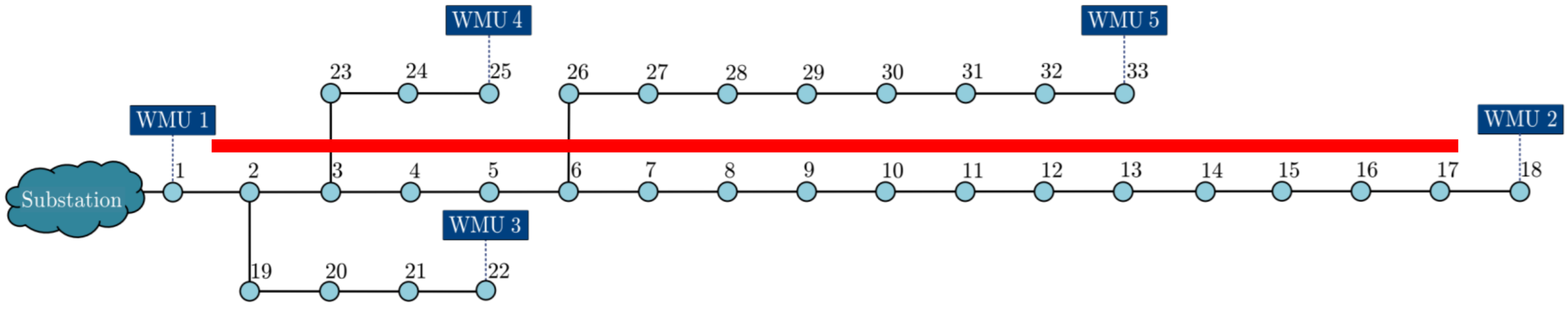

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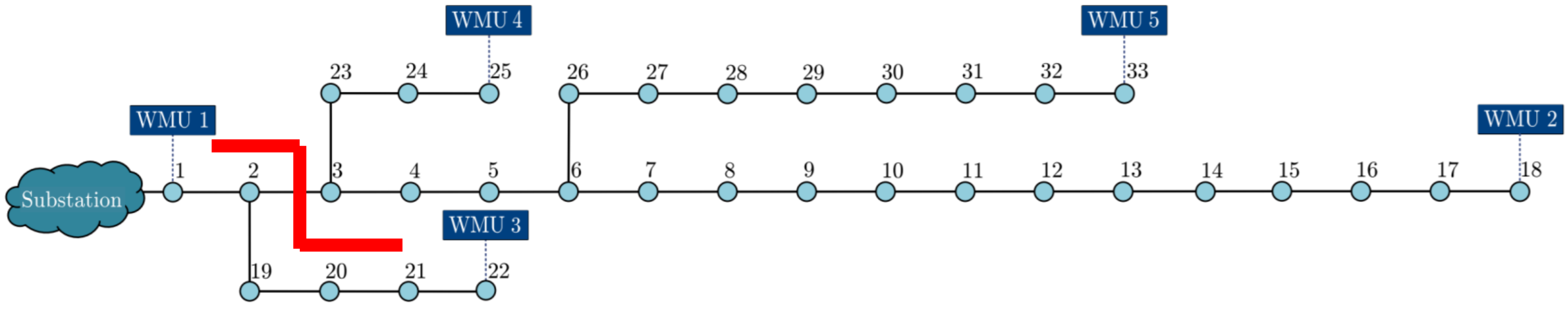

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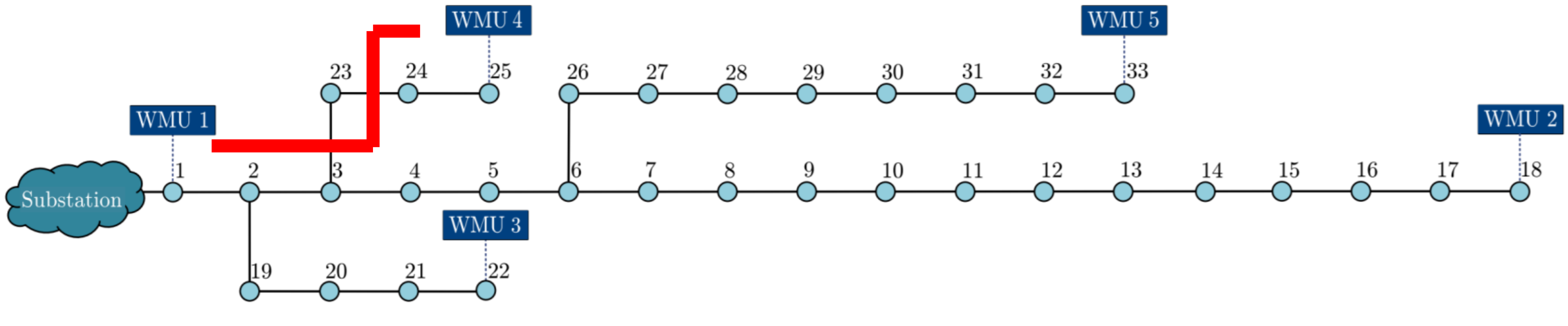

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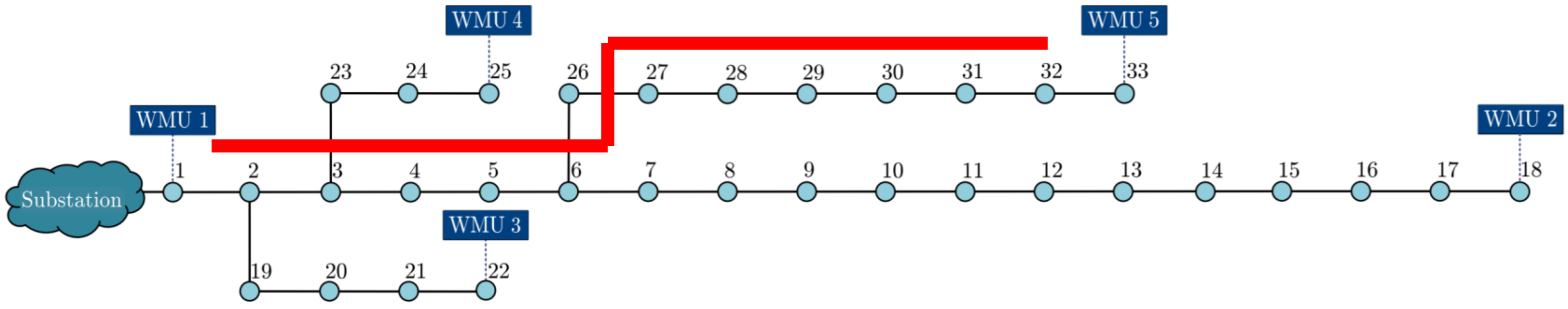

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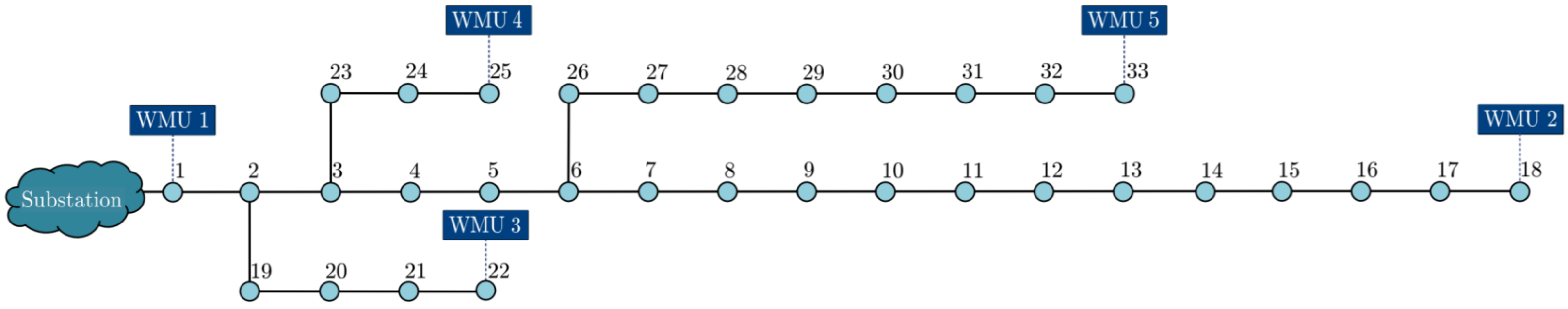


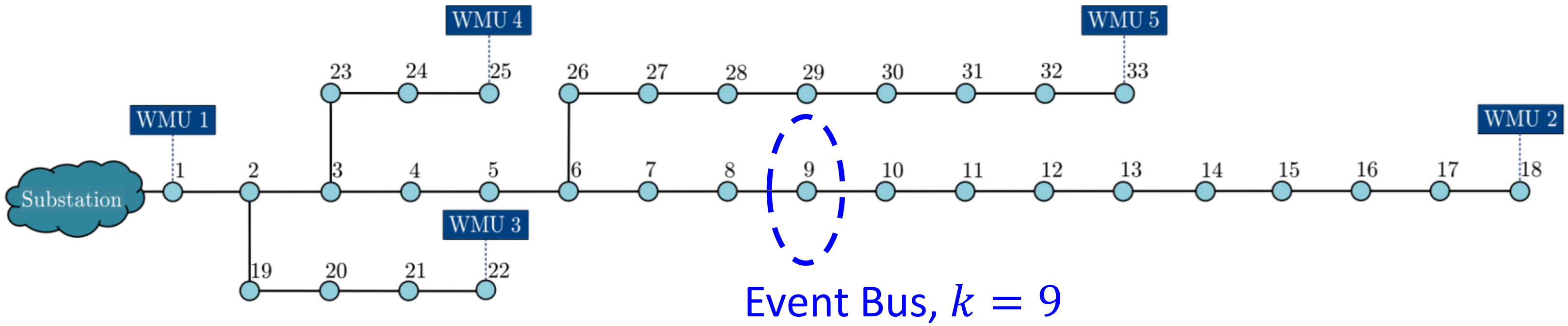
- Several Options:

1) WMU 1 and WMU 2
2) WMU 1 and WMU 3
3) WMU 1 and WMU 4
4) WMU 1 and WMU 5

$$k^* = \underset{i}{\operatorname{argmin}} \sum_{s=2}^{5} \Psi_i^{1,s}$$

Event Location Identification

- IEEE 33-Bus Test System (PSCAD Simulations)[5]:



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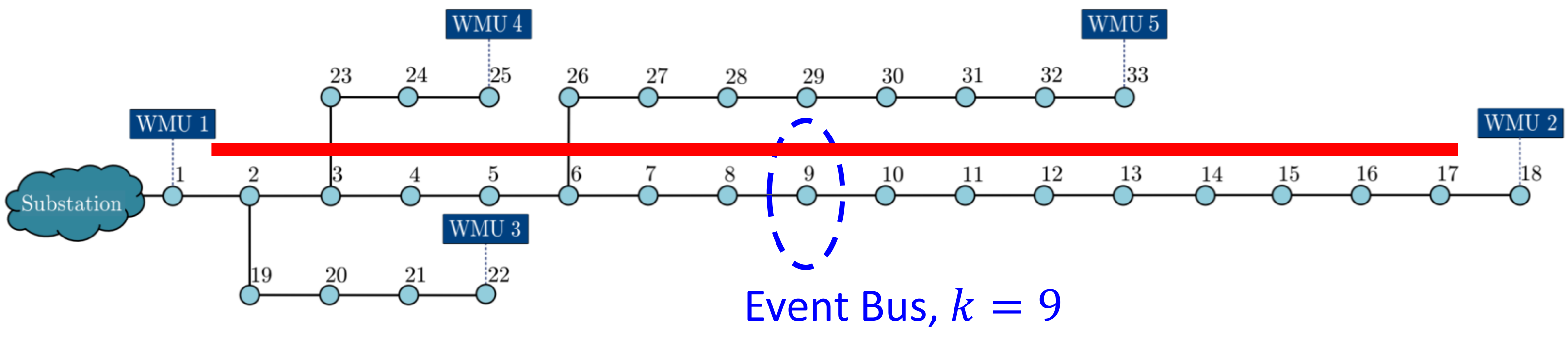
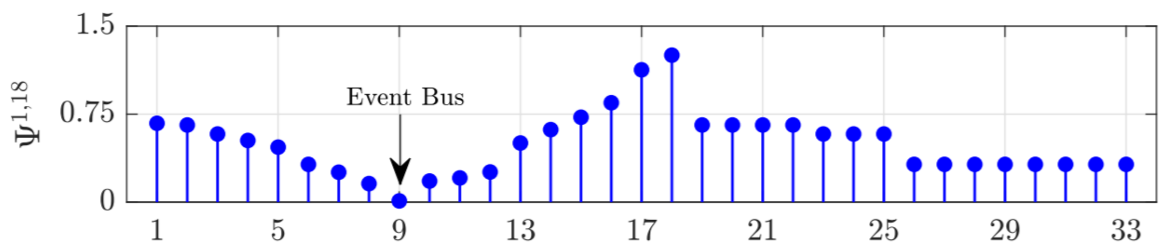


WMUs 1 and 2



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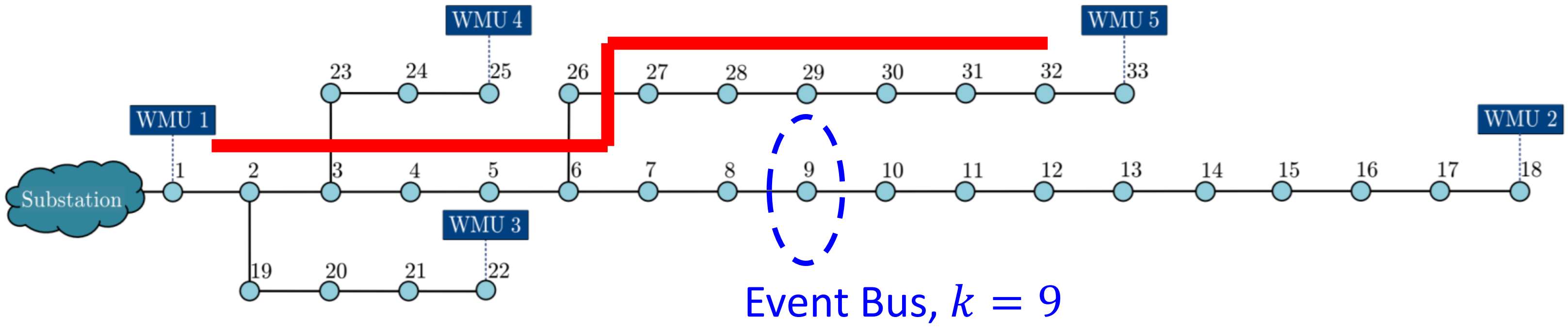
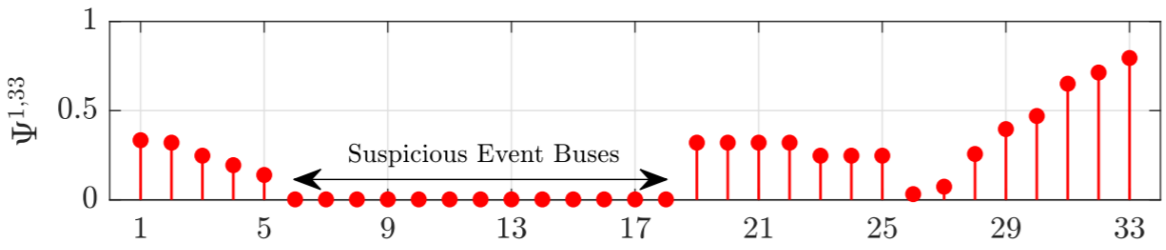


WMUs 1 and 3



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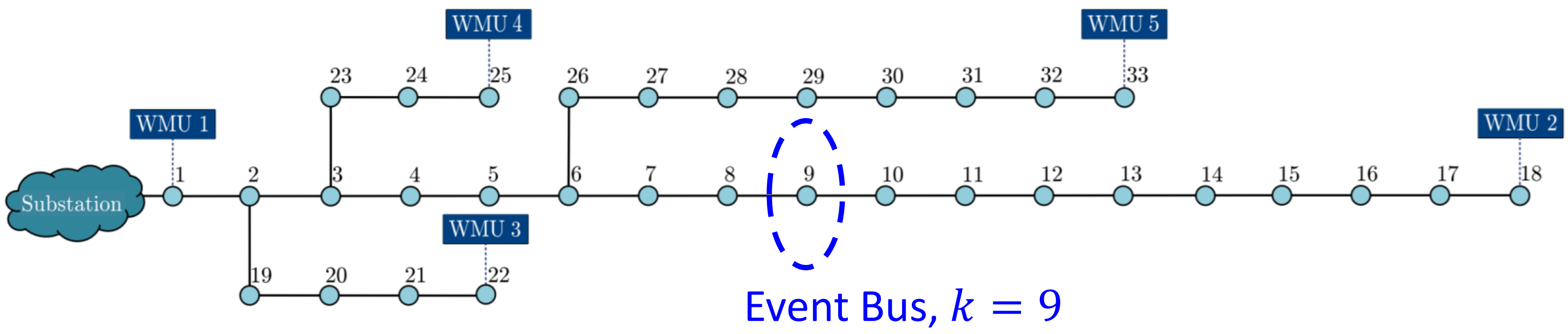
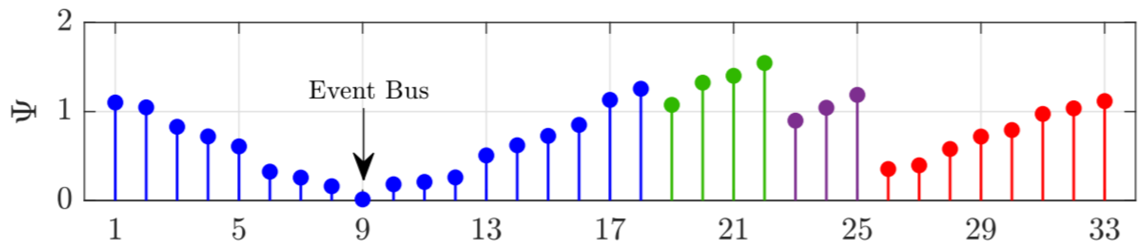


All *Five* WMUs



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Event Location Identification

- Impact of *Harmonic Distortion* and *Measurement Noise*:

THD (%)	SNR (dB)	Correct Bus	Neighboring Bus	Other Bus
1	80	100.0 %	0.0 %	0.0 %
	50	100.0 %	0.0 %	0.0 %
	20	86.8 %	5.8 %	7.4 %
2	80	100.0 %	0.0 %	0.0 %
	50	99.9 %	0.1 %	0.0 %
	20	84.4 %	7.5 %	8.1 %
3	80	100.0 %	0.0 %	0.0 %
	50	99.8 %	0.2 %	0.0 %
	20	85.5 %	6.2 %	8.3 %

- Impact of *Error in Line Parameters*:

Error (%)	Correct Bus	Neighboring Bus	Other Bus
25	100.0 %	0.0 %	0.0 %
50	98.9 %	1.1 %	0.0 %
75	93.0 %	7.0 %	0.0 %
100	85.8%	14.2 %	0.0 %

Sensitivity Analysis

Synchro-Waveform Data Analysis

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Event Characterization

- Example Feature Extraction in Waveform Measurements[1]:
  - Angle, Magnitude, and Duration
  - Number of Affected Phases
  - Transient Oscillations
  - Transient Impulses
  - Fault-Specific Features
  - Changes in Steady-State Characteristics
  - Time, Season, and Location
  - Other Basic Features
  - Graphical Features

Event Characterization

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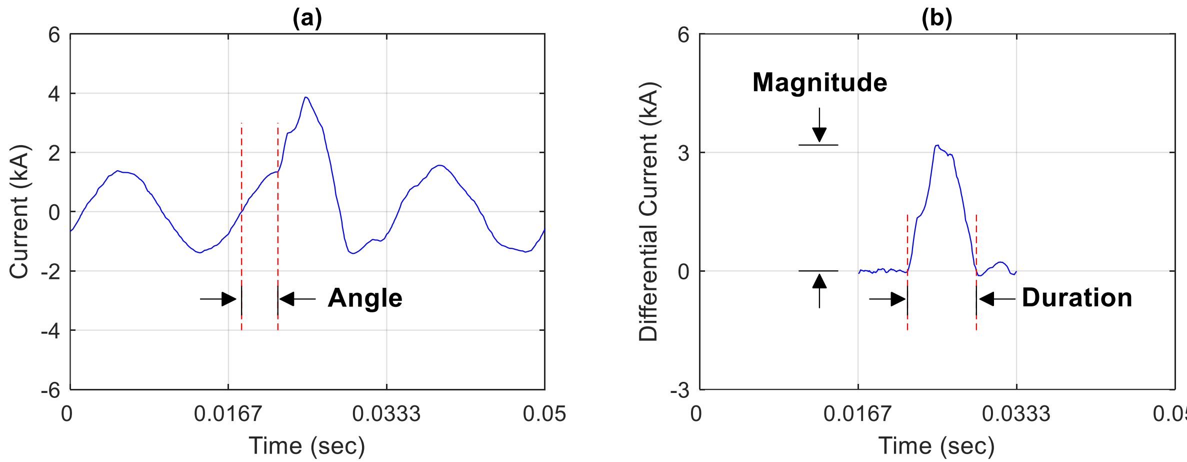
  - Other Basic Features
  - Graphical Features ⟵

Angle, Magnitude, and Duration

- These basic features can be obtained for most events.

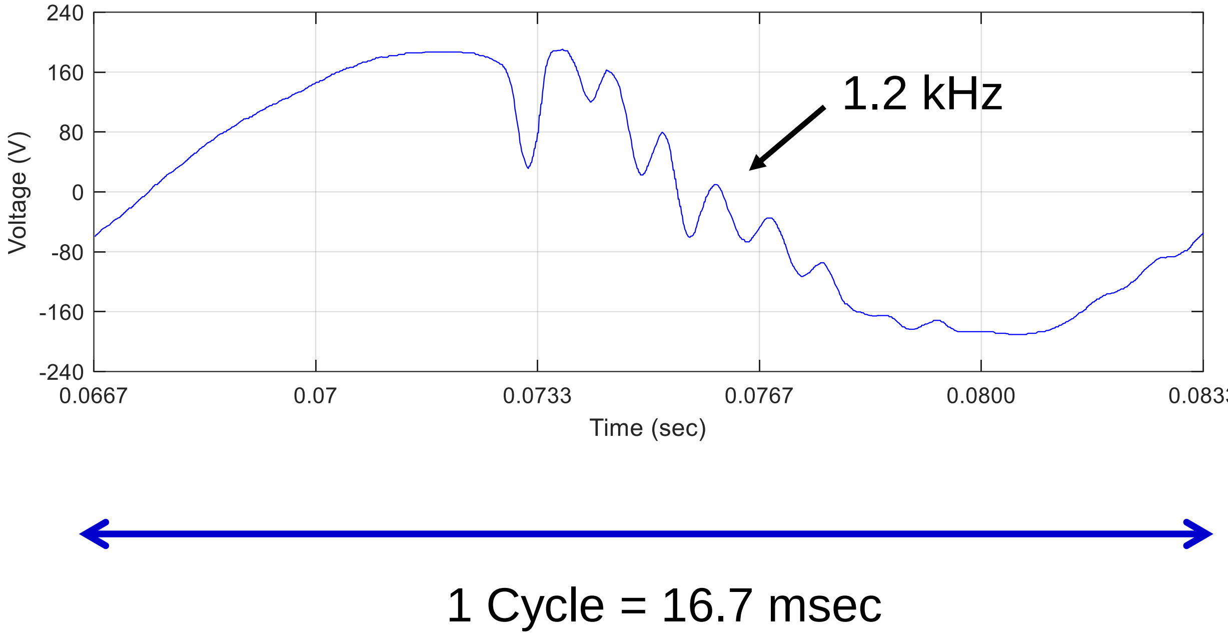
- An example for these three features for the case of a current waveform measurement during a self-clearing fault is shown below.



Original waveform   Differential waveform

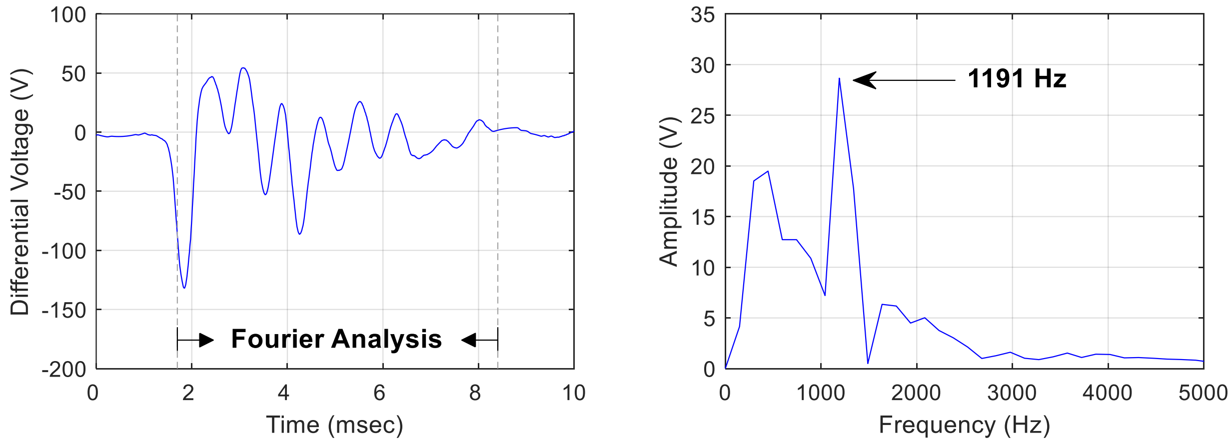
Transient Oscillations

- Transient oscillations in waveform measurements are described by the *magnitude*, *duration*, and *dominant frequency* of the oscillations.



Transient Oscillations

• The frequency of oscillations in waveform measurements can be obtained by using *modal analysis*; including the use of Fourier Analysis.

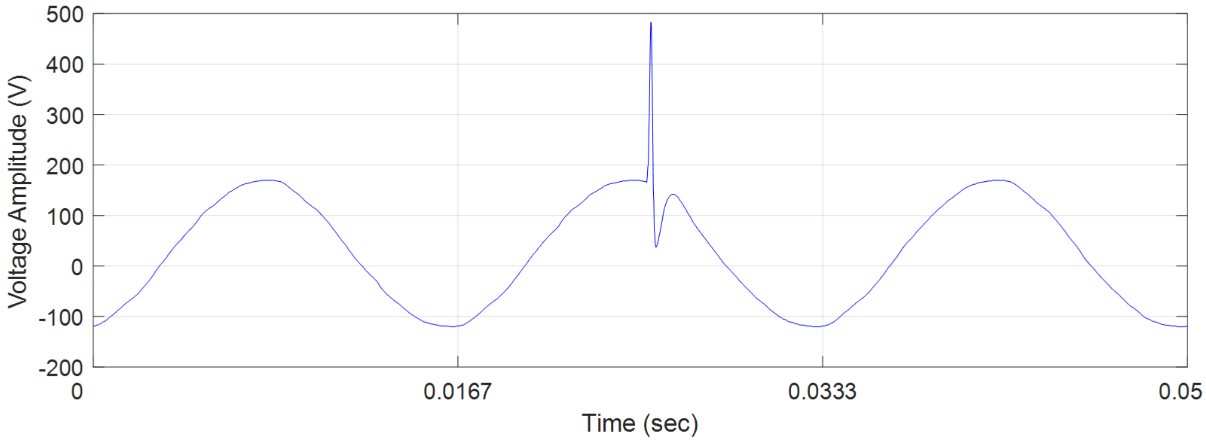


• The *dominant frequency* is about 1.2 KHz.

Transient Impulses

- An *impulsive transient* is a sudden change in the waveform of voltage, current, or both, that is typically unidirectional in polarity.

- A common cause of impulsive transients is *lightning strike*.



Graphical Features

- The Lissajous graphs can serve as *images* with graphical characteristics.

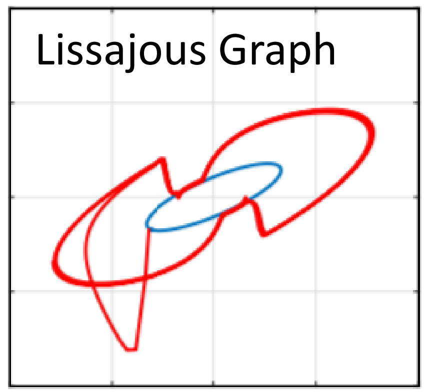
Location 1 / WMU 1

$v_1(t), i_1(t)$

Location 2 / WMU 2

$v_2(t), i_2(t)$

$v(t) = v_1(t) - v_2(t)$



$i(t) = i_1(t) - i_2(t)$

Event Characterization

<u>Graphical Features</u>

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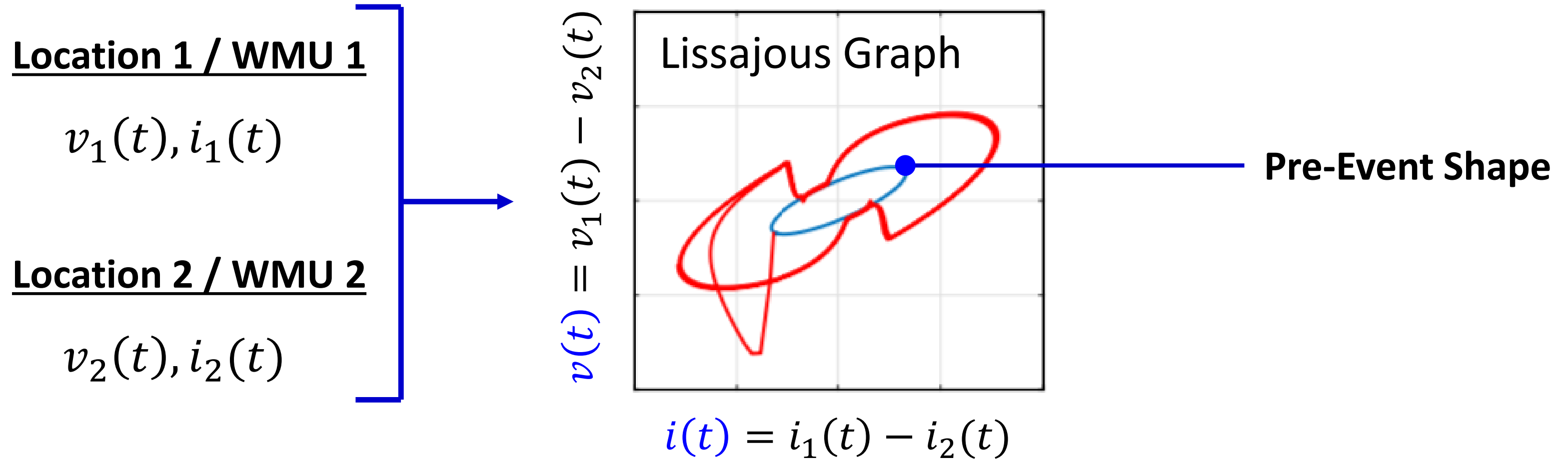

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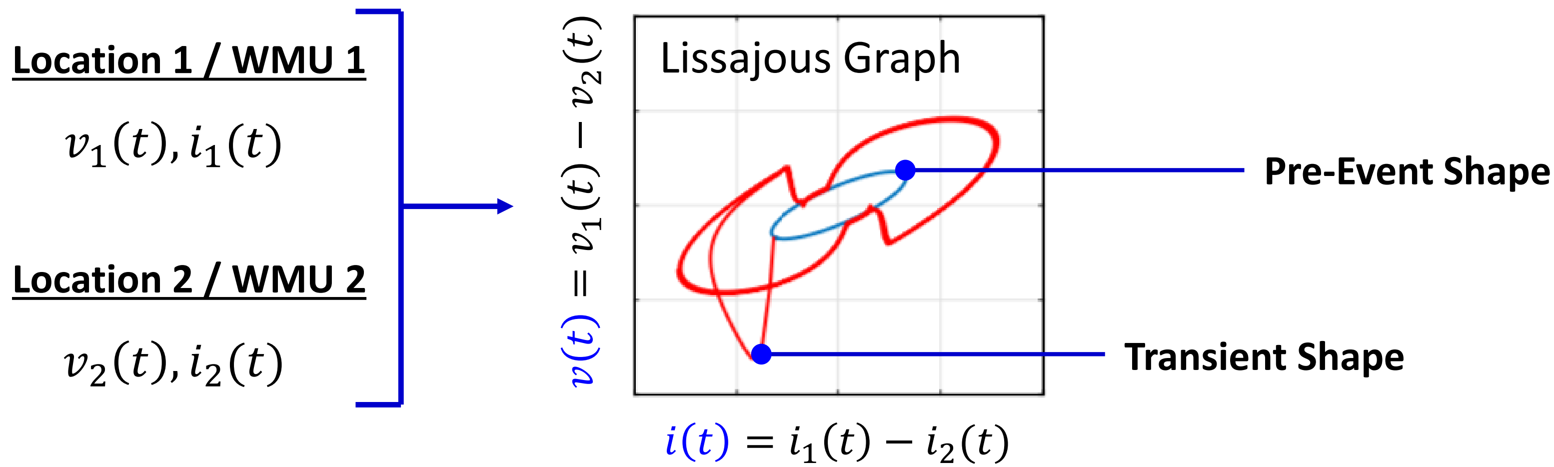

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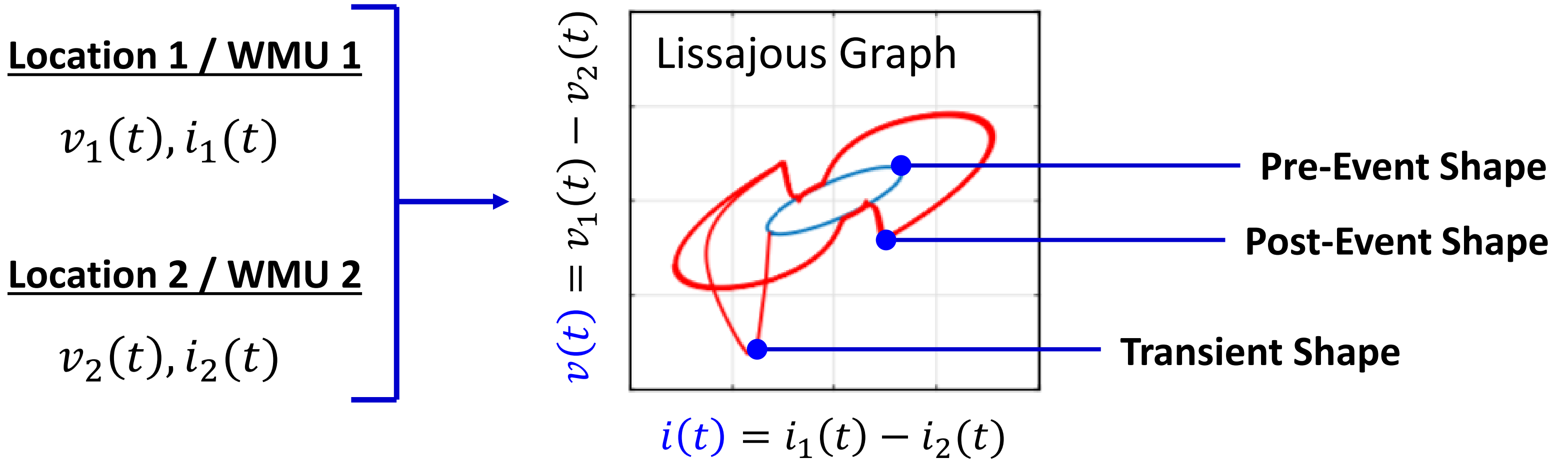
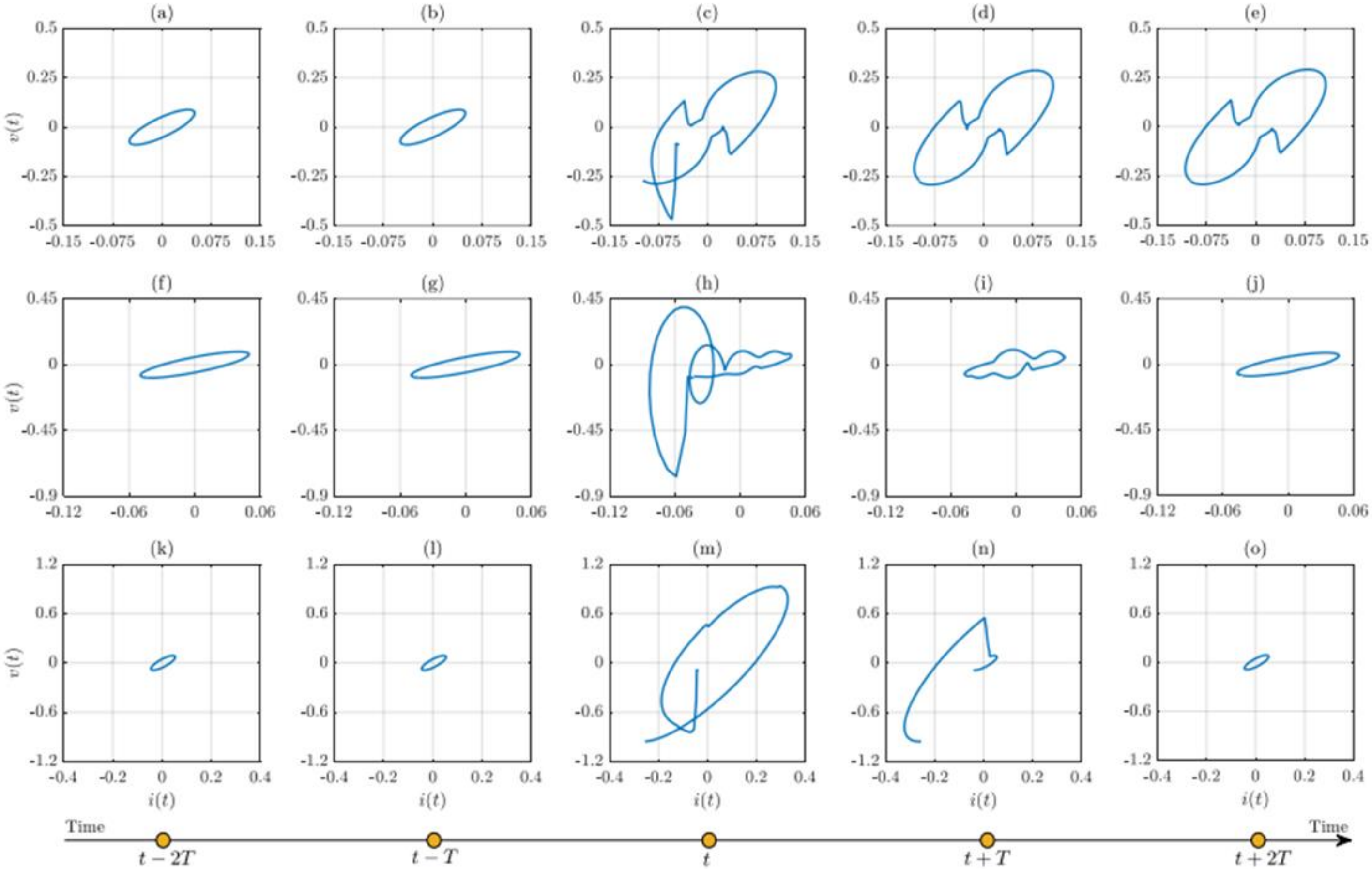


- Characterization/Classification[6]:

High Impedance Fault

Capacitor Bank Switching

Incipient Fault



[6] M. Izadi, H. Mohsenian-Rad, " Synchronized Lissajous-based method to detect & classify events in synchro-waveform measurements in power distribution networks," in ***IEEE Trans. on Smart Grid***, vol. 13, no. 3, pp. 2170-2184, May 2022.

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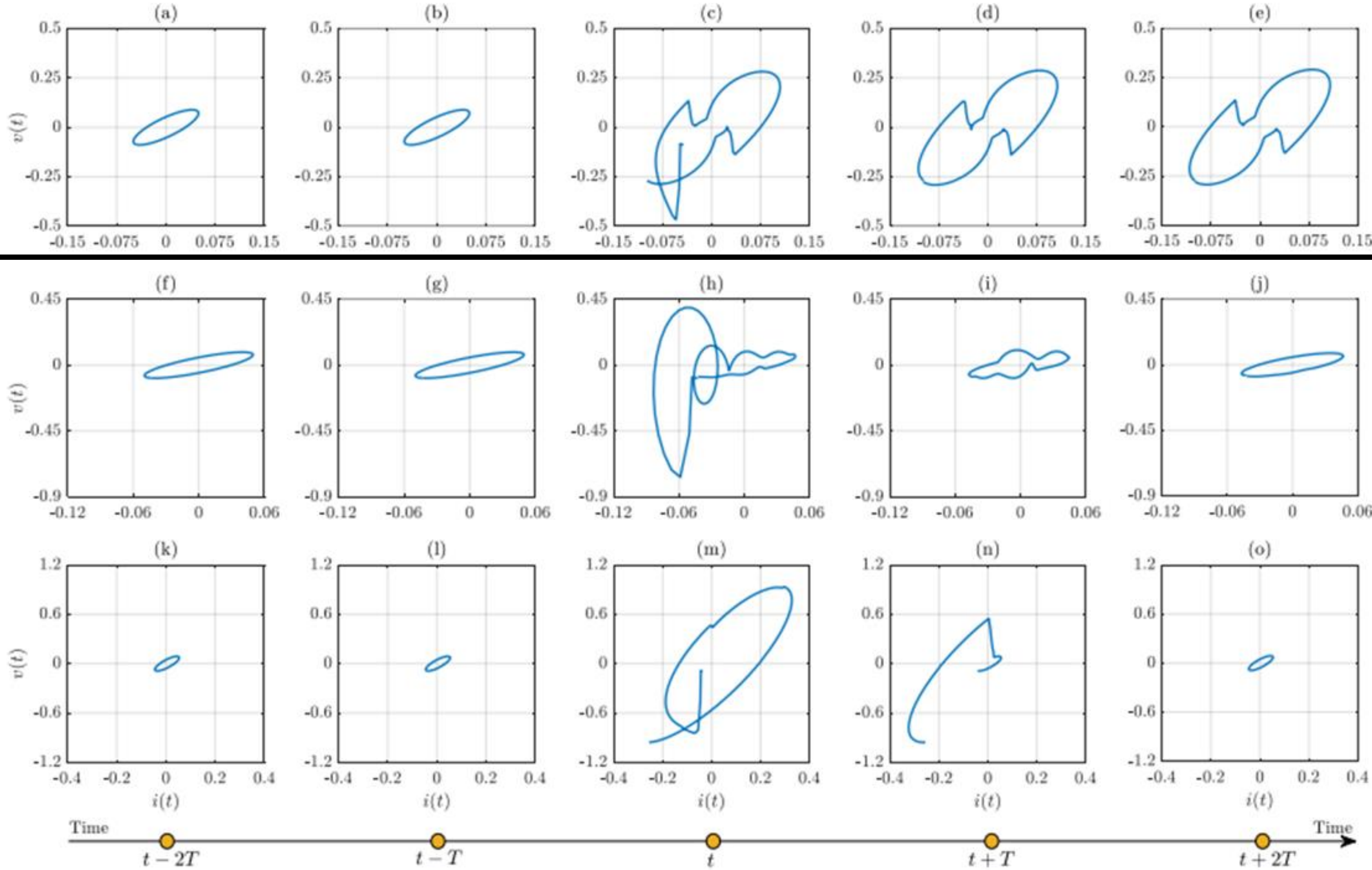

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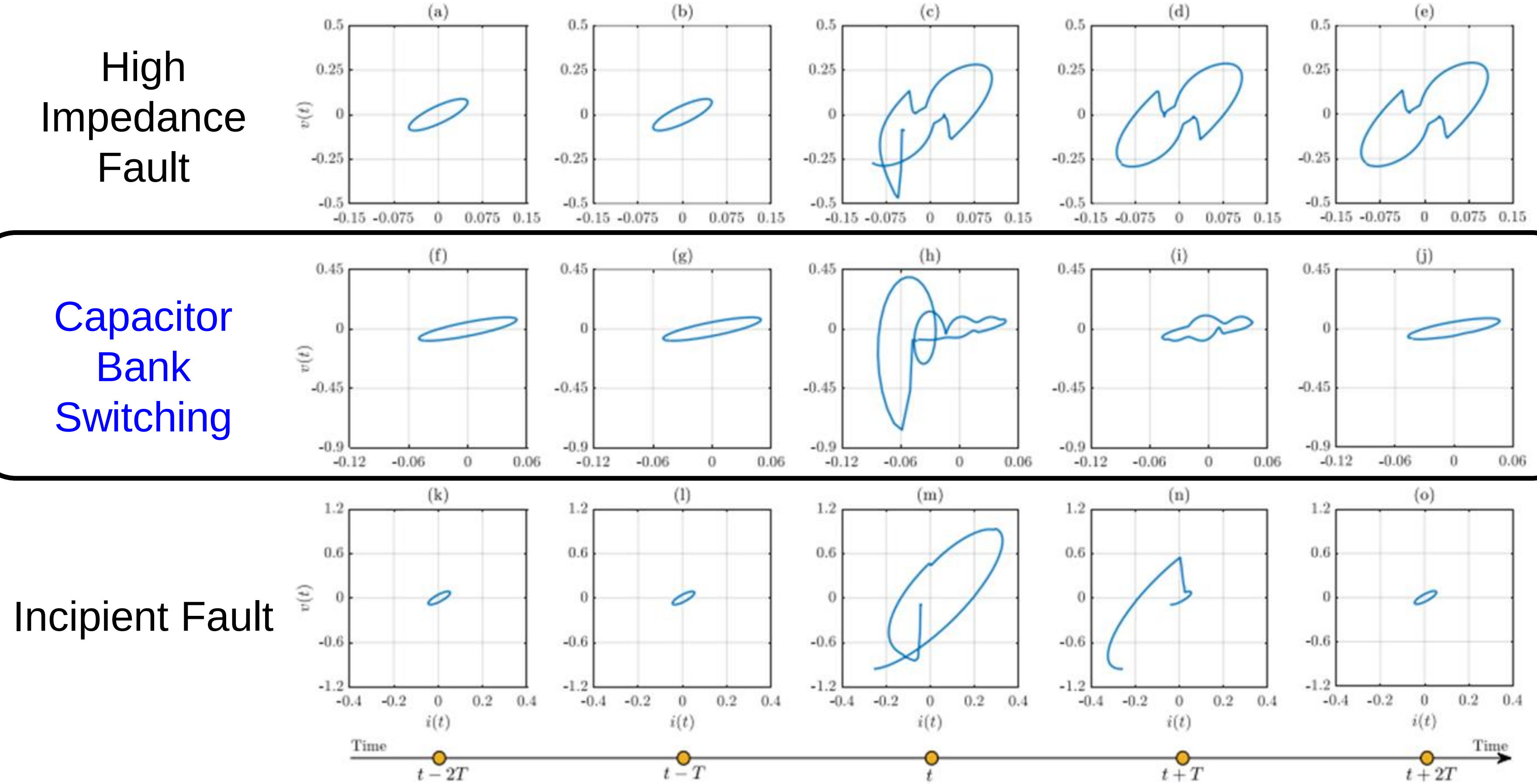

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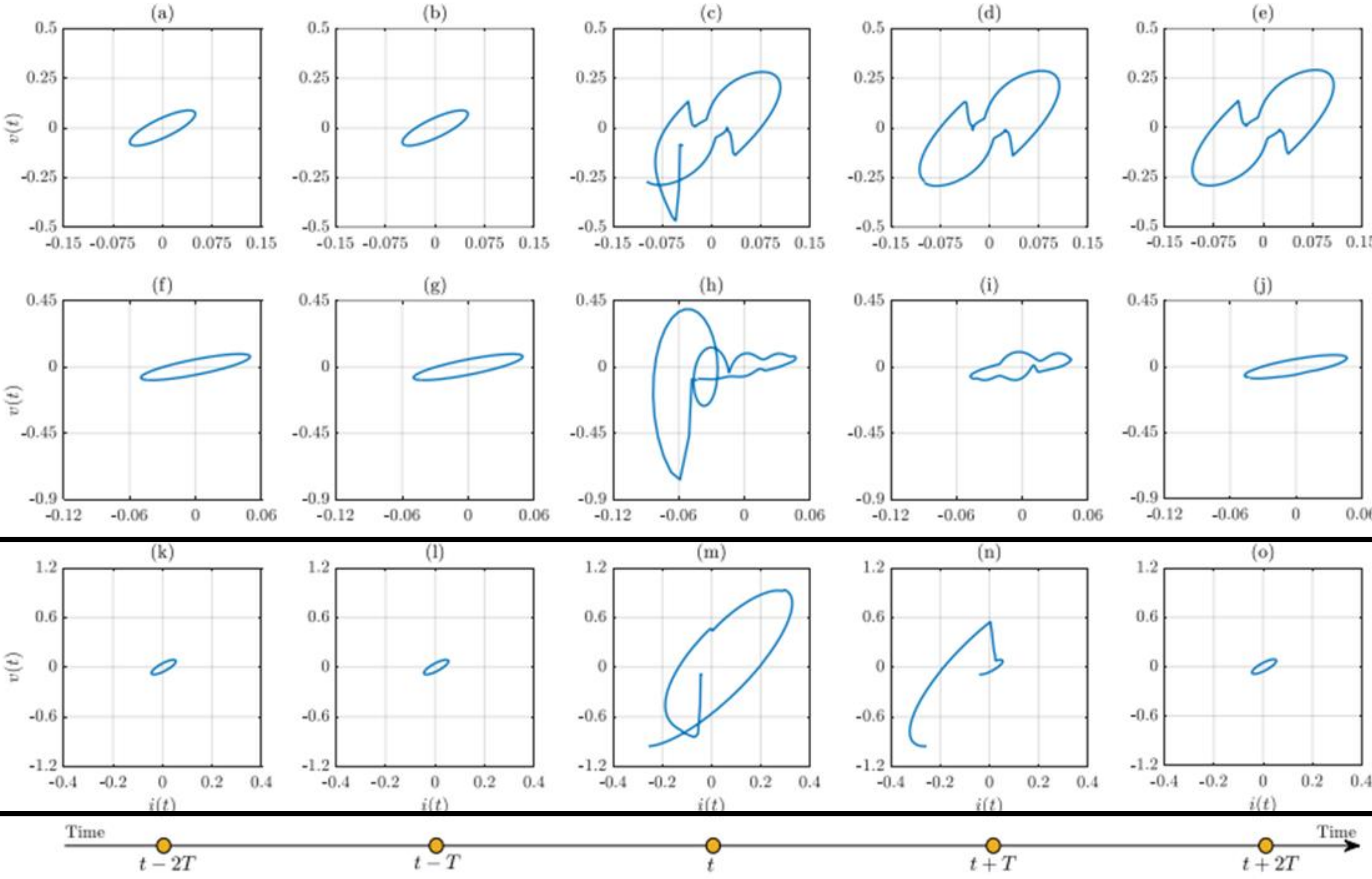
Capacitor Bank Switching

Incipient Fault



[6] M. Izadi, H. Mohsenian-Rad, " Synchronized Lissajous-based method to detect & classify events in synchro-waveform measurements in power distribution networks," in ***IEEE Trans. on Smart Grid***, vol. 13, no. 3, pp. 2170-2184, May 2022.

- Classification with Convolutional Neural Network (CNN)[6]:

Confusion Matrix:

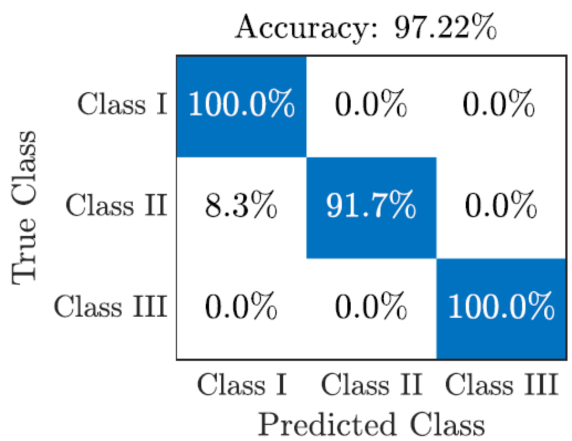


Image Processing

Performance:

Class	Precision	Sensitivity	Specificity	F_1 Score
I	100.0%	92.3%	100.0%	96.0%
II	100.0%	100.0%	100.0%	100.0%
III	94.4%	100.0%	96.8%	97.1%

[6] M. Izadi, H. Mohsenian-Rad, " Synchronized Lissajous-based method to detect & classify events in synchro-waveform measurements in power distribution networks," in ***IEEE Trans. on Smart Grid***, vol. 13, no. 3, pp. 2170-2184, May 2022.

Synchro-Waveform Data Analysis

- Applications of Situational awareness with synchro-waveform data:
  - **Event Detection**
  - **Event Location Identification**
  - **Event Characterization / Classification**

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Incipient (*Early-Stage*) Faults

- **Overhead Line**
- **Underground Cable**
- **Capacitor Bank**
- **Transformer**
- **Inverters**
- **Power Electronics**

⋮

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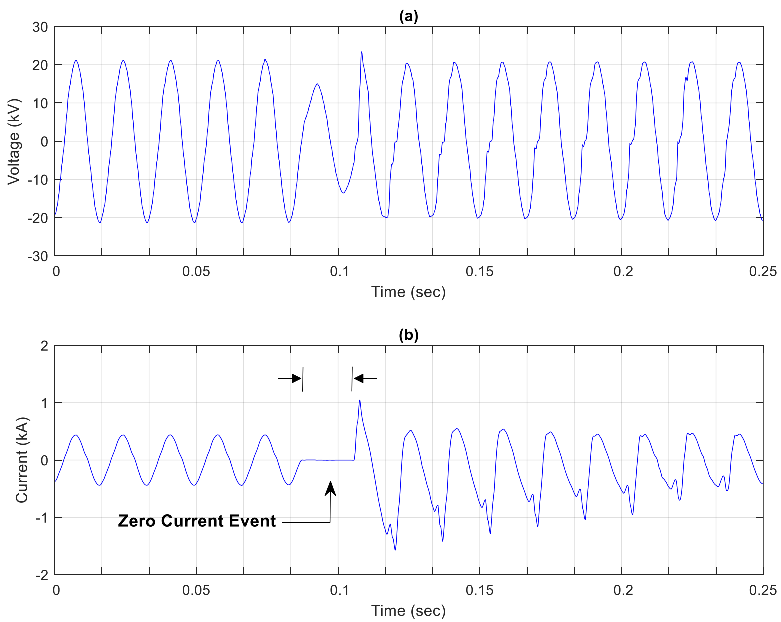
⋮

Unique Signatures



Lance Irwin 2010

- Applications of Situational awareness with synchro-waveform data:
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  - **Event Characterization / Classification**

Incipient (*Early-Stage*) Faults

- Overhead Line — Wildfire Monitoring[7]
- Underground Cable
- Capacitor Bank
- Transformer
- Inverters
- Power Electronics
⋮

[7] H. Mohsenian-Rad, "Synchro-Waveforms in Power Distribution with Application to Wildfire Monitoring," Panel Presentation, *IEEE PES General Meeting*, July 2021.

Synchro-Waveform Data Analysis

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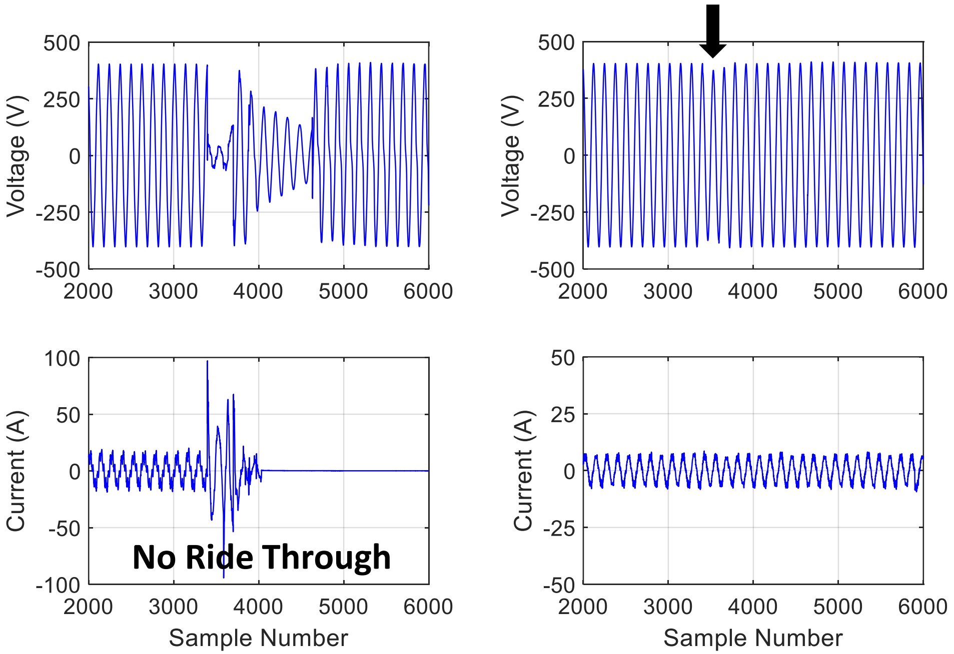
⋮

Inverter Response



Inverter 1 **Inverter 2**

Synchro-Waveform Data Analysis

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Incipient (*Early-Stage*) Faults
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Incipient (*Early-Stage*) Faults

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- Inverters
- Power Electronics
⋮

Analysis of Oscillations

- Oscillation Source Detection
- Sub-synchronous and Super-Synchronous
⋮

Synchro-Waveform Data Analysis

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Incipient (*Early-Stage*) Faults

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⋮

Analysis of Oscillations

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- Sub-synchronous and Super-Synchronous

⋮

Protection Systems

- Relay Coordination
- Differential Protection

⋮

Synchro-Waveform Data Analysis

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Incipient (*Early-Stage*) Faults

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⋮

Analysis of Oscillations

- Oscillation Source Detection
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⋮

Protection Systems

- Relay Coordination
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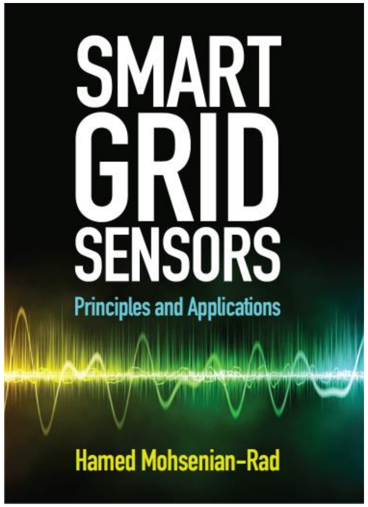
⋮

And More!

- Chapter 4: Waveform and Power Quality Measurements and Their Applications

Textbook on Smart Grid Sensors:
- Working Principles
- Sample Data Sets
- Data-Driven Methods

Synchro-phasors
Synchro-waveforms
Smart meters
Building sensors
Power and energy
Probing
⋮



Cambridge University Press
April 2022
348 Pages
120 Examples
150 Exercise Questions
Solutions Manual
Instructional Slides
Data Sets

- And the references cited on the slides.

Thank You!

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