Synchro-Waveforms in Power Distribution Systems: Field Data, Data-Analytics, and Use Cases

IEEE SGSMA (May 24, 2022)

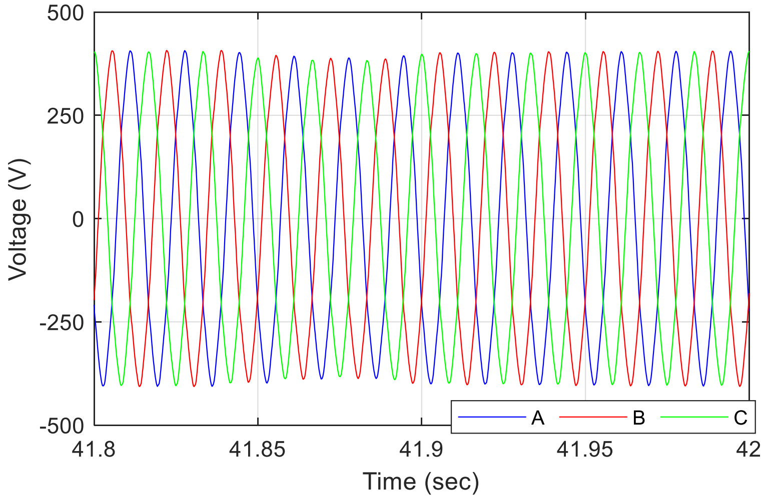
Hamed Mohsenian-Rad*, Ph.D., IEEE Fellow*

Professor and Bourns Family Faculty Fellow
Department of Electrical Engineering, University of California, Riverside
Associate Director, Winston Chung Global Energy Center

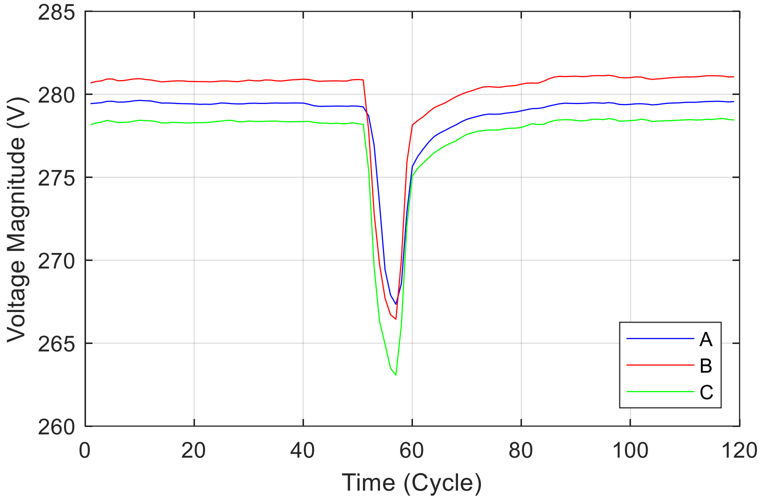
Acknowledgement: Milad Izadi (Ph.D. Student)

Waveform: Real-World Examples

- Example 1 (Voltage Sag):



Waveform



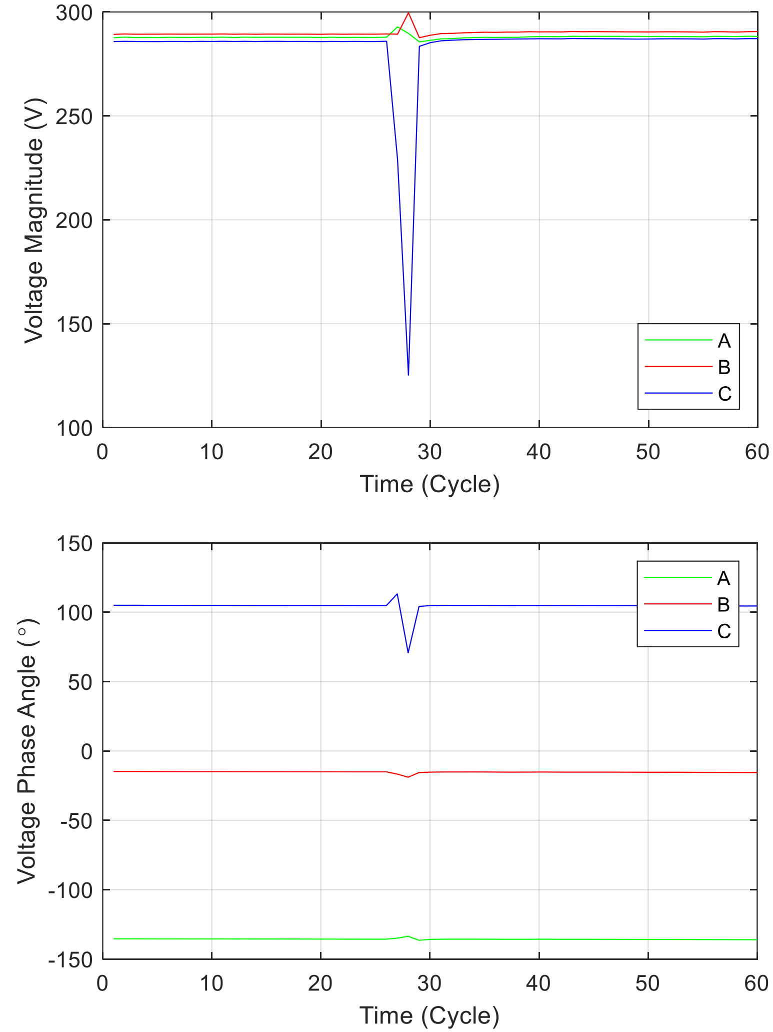
Phasor

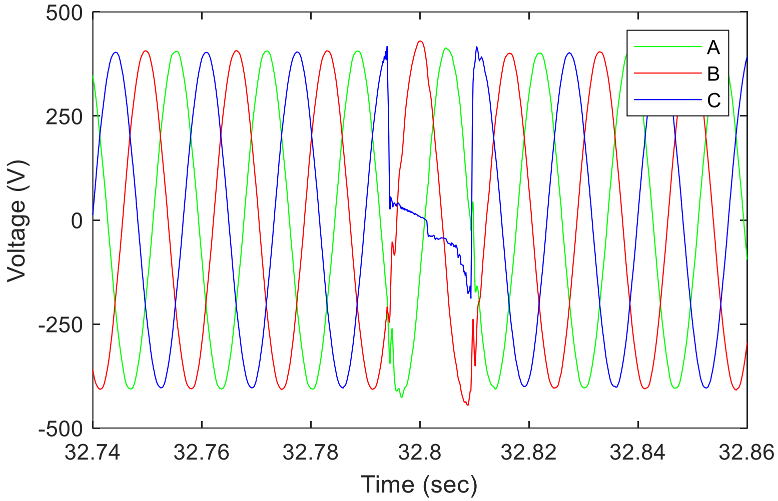
- Looking at voltage waveform may *not* be necessary in this example.

Waveform: Real-World Examples

- Example 2 (Fault):

Phasor

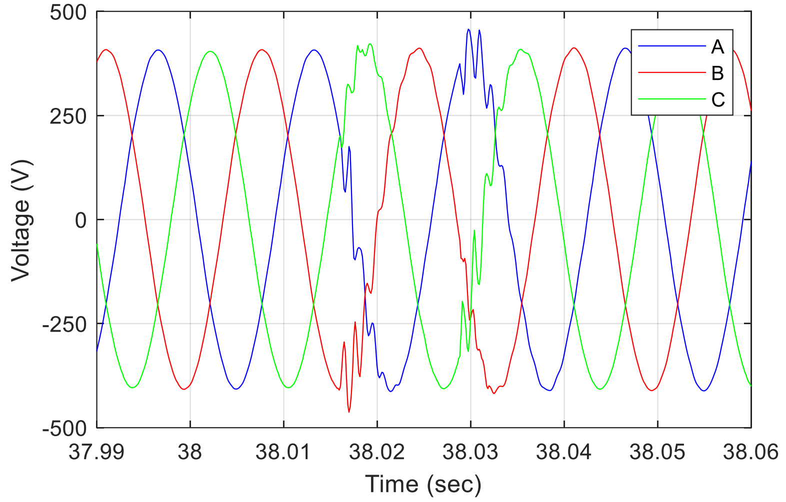




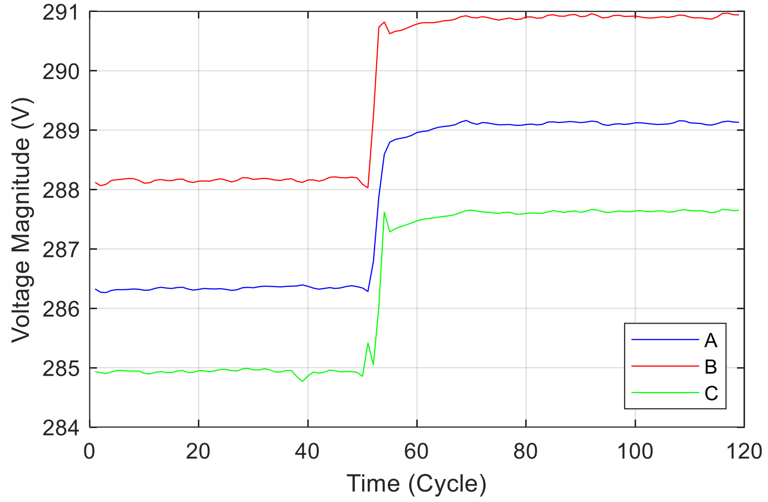
Waveform

- Waveform shows much more details about the event.

- Example 3 (Resonance):



Waveform



Phasor

- We *do not notice* such high-frequency resonance in the phasors.

Synchro-Waveforms

- These are just a few examples of comparing waveforms and phasors.

- Two Concepts:

  Synchro-Phasors = Phasors + Time Synchronization

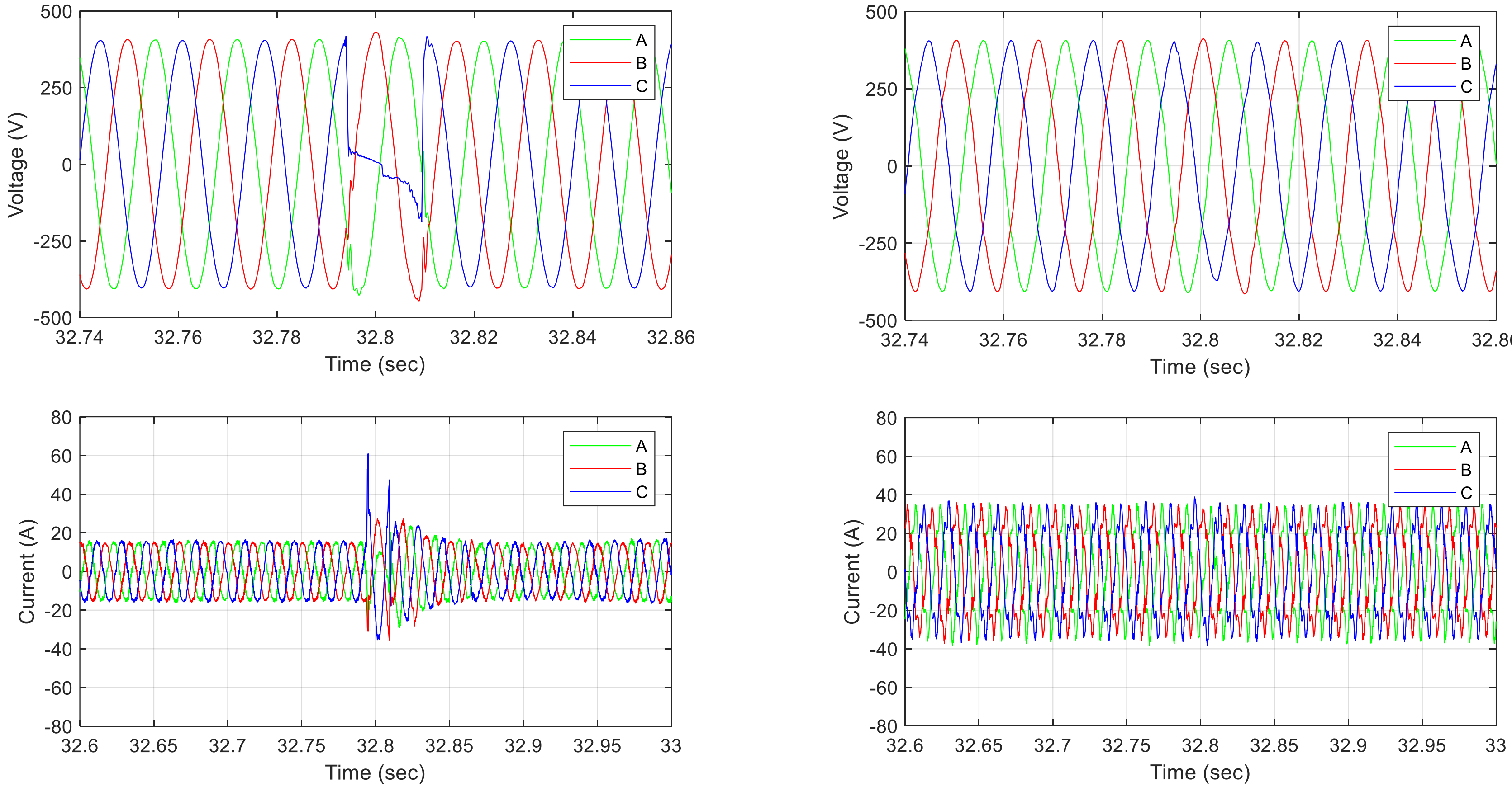
  Synchro-Waveforms = Waveforms + Time Synchronization

- We can generally refer to the sensors that measure synchro-waveforms as Waveform Measurement Units (WMUs[1]), in contrast to PMUs.

- **WMUs**: PQ Meters, DFRs, etc. [*with Time-Synchronization*]

[1] a.k.a SWMU, see A. F. Bastos, et. al, "SynchroWaveform Measurement Units & Applications", *IEEE PESGM 2019*.

- Synchro-Waveforms in Example 2 (Fault):

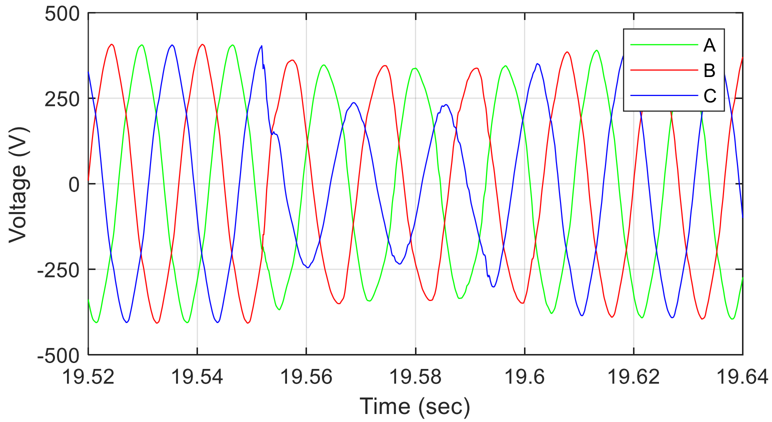


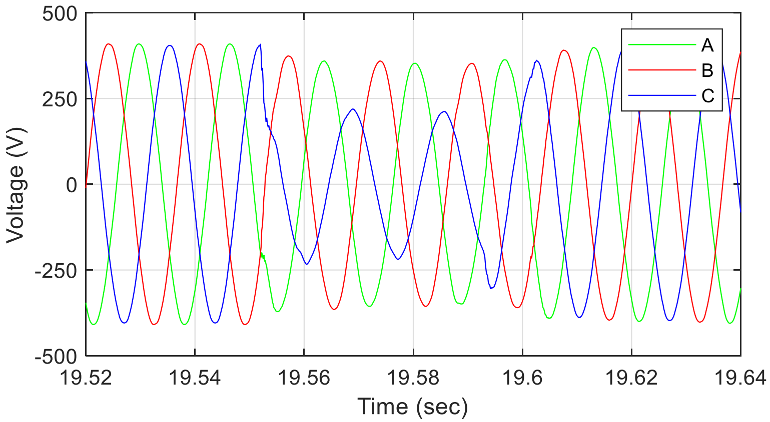
WMU 1 ⟷ **WMU 2**

Time Synchronized

Synchro-Waveforms

- The last fault was seen *very differently* by WMU 1 and WMU 2.
- But there are other faults that are seen *very similarly* by these two WMUs.
- Example 4 (Another Fault) - Synchro-Waveforms:



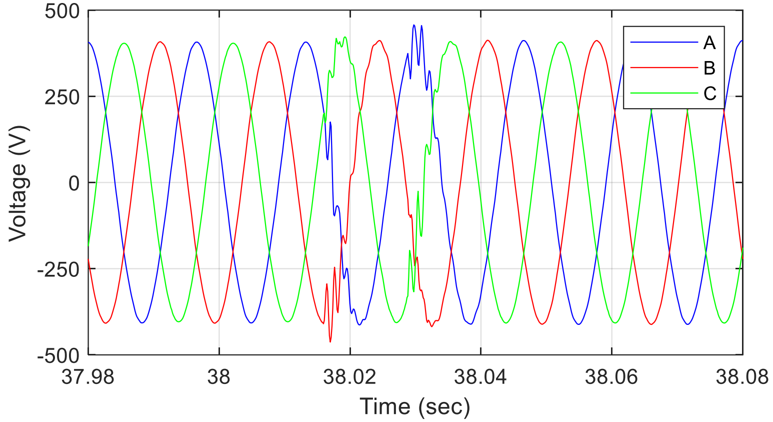


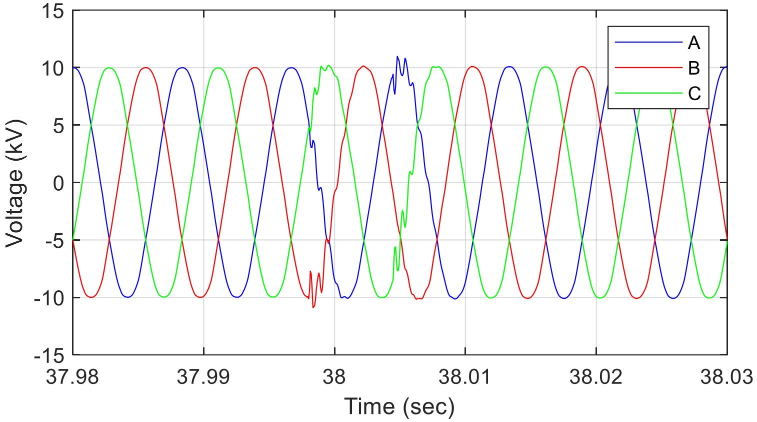
WMU 1 **WMU 2**

Time Synchronized

Synchro-Waveforms

- Synchro-Waveforms in Example 3 (Resonance):

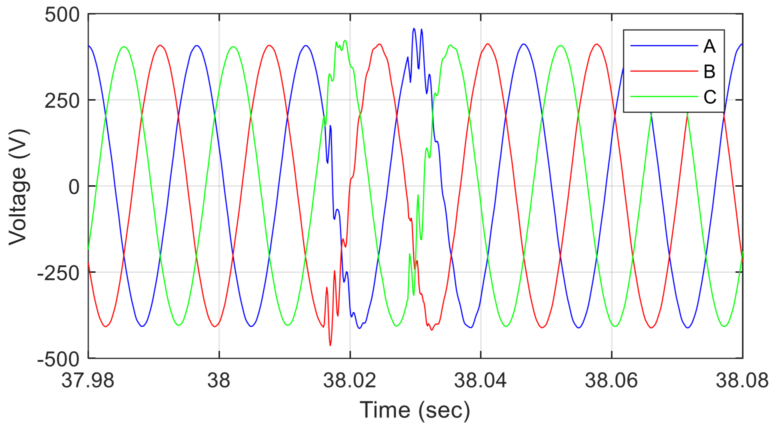


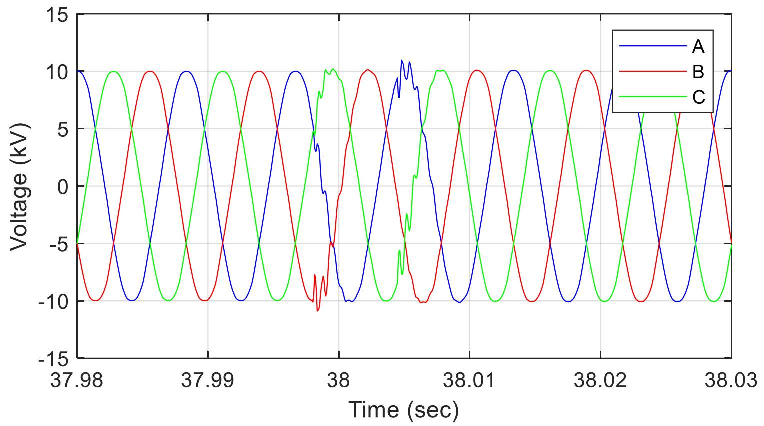


WMU 1 ⟷ **WMU 3**

Time Synchronized

- Synchro-Waveforms in Example 3 (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.)

Situational Awareness with Synchro-Waveforms

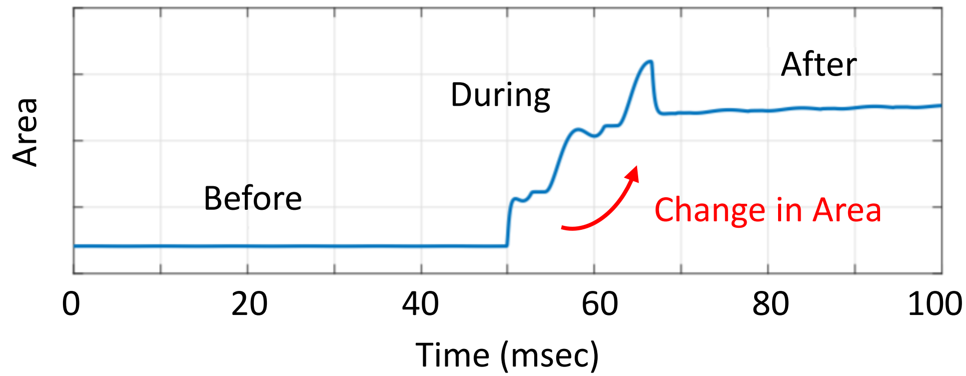
- Analysis of waveform disturbances using synchro-waveforms:
  - **Detection**
  - **Characterization / Classification**
  - **Location Identification**

Situational Awareness with Synchro-Waveforms

- Detection[2]:

Event Detection

(Plus Other Methods)



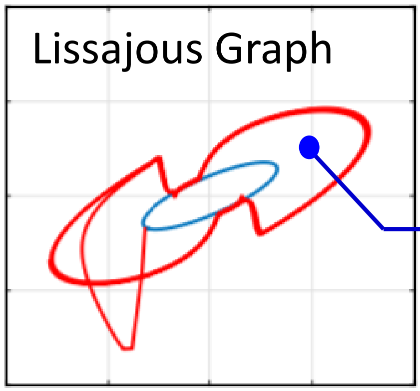
Location 1 / WMU 1

$v_1(t), i_1(t)$

Location 2 / WMU 2

$v_2(t), i_2(t)$

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



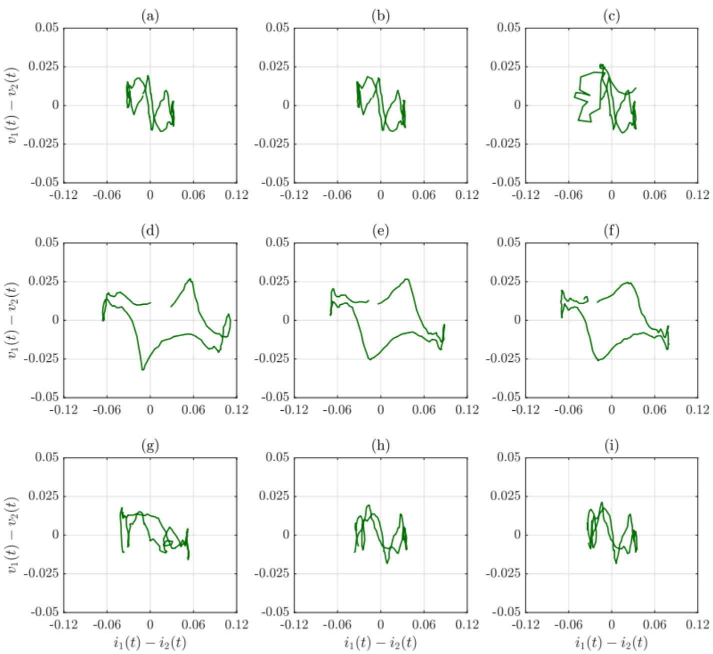
$i(t) = i_1(t) - i_2(t)$

$$\text{Area} = \left| \int_{i(t=0)}^{i(t=T)} v(t)\, di(t) \right|$$

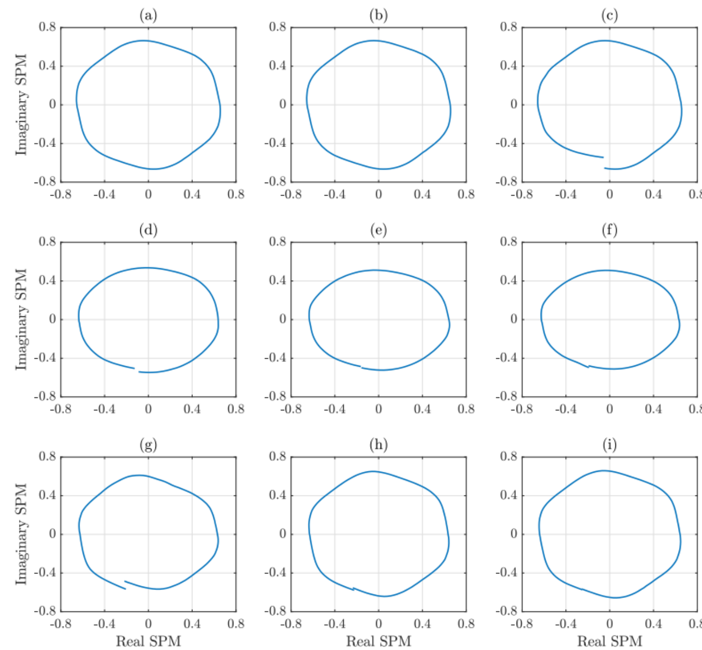
(Or Other Metrics)

[2] 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.

- Characterization/Classification[3]:



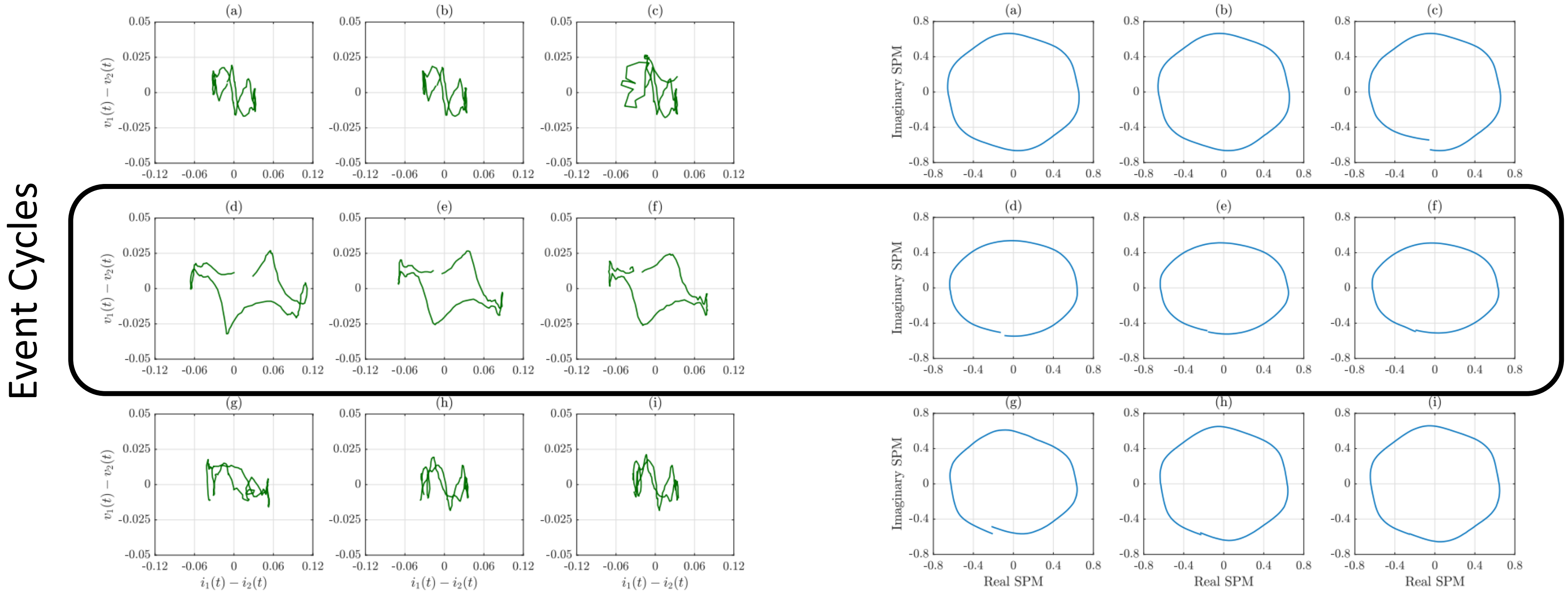
Synchronized Lissajous Graph



Space-Phasor Model

[3] 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.

- Characterization/Classification[3]:



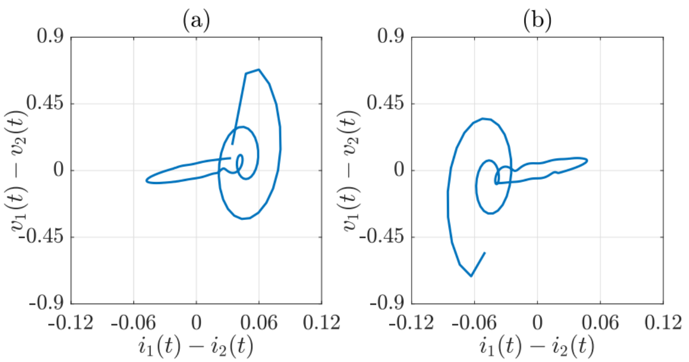
Synchronized Lissajous Graph

Space-Phasor Model

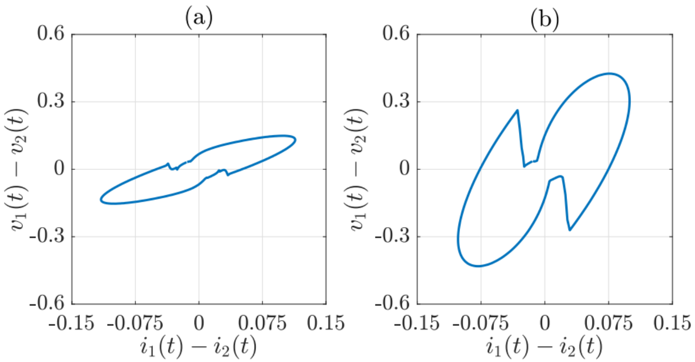
[3] M. Izadi, H. Mohsenian-Rad, " Synchronized Lissajous-based method to detect & classify events in synchro-waveform measurements in power distribution networks," in ***IEEE Trans. on Smart Grid***, vol. 13, no. 3, pp. 2170-2184, May 2022.

- Characterization/Classification[3]:

  Image Processing Using Convolutional Neural Networks (CNN).



Same Event, *Different Firing Angles*
(Mirrored Images)

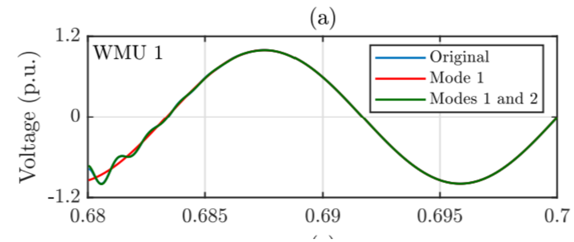


Same Event, *Different Locations*
(Inflated Images)

[3] 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.

- Location Identification[4]:

Multi-Signal (Synchronized) Modal Analysis



Event starts at $t = 0.68$ sec (Sub-Cycle Event)

WMU 1

$v_1(t), i_1(t)$

WMU 2

$v_2(t), i_2(t)$

Number of Modes

$$v_1(t) \approx \sum_{p=1}^{P} A_{p,m}\, e^{\sigma_p t} \cos(2\pi f_p t + \theta_p)$$

Also for $i_1(t), v_2(t), i_2(t)$

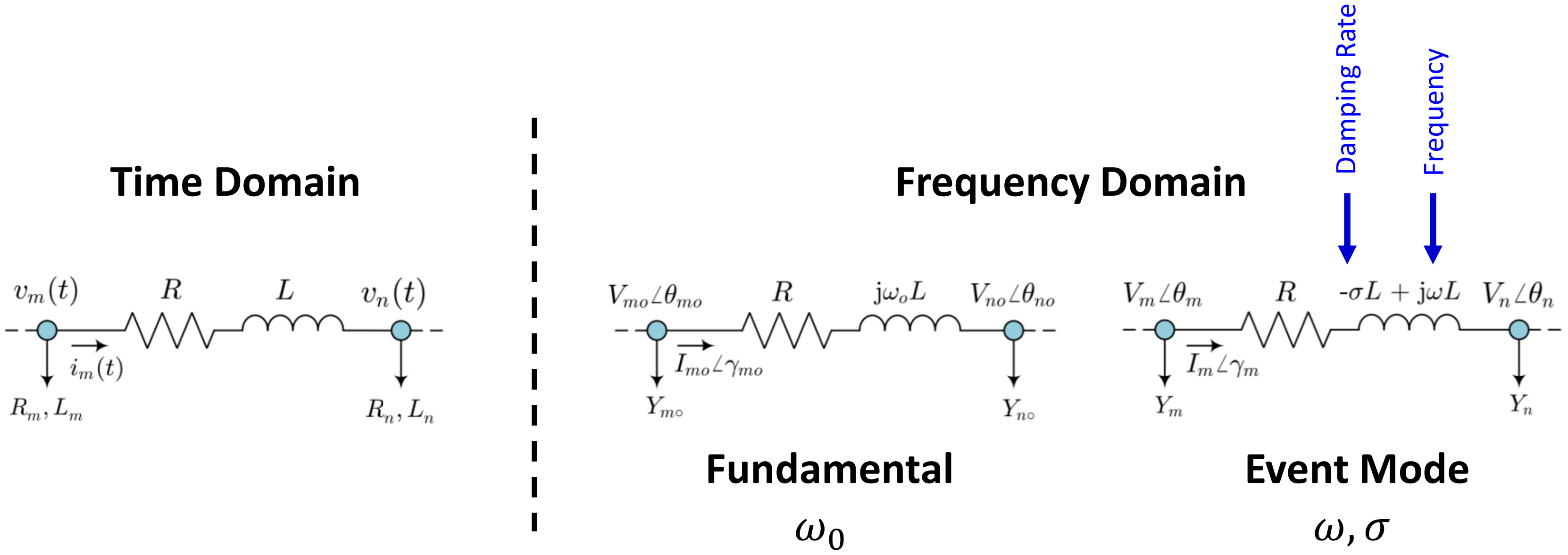
Damping Sinusoidal Modes $(f_p, \sigma_p, A_{p,m}, \theta_p)$

[4] 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, Sept 2021.

Situational Awareness with Synchro-Waveforms

- Location Identification[4]:

  Analysis of Circuit at Event Mode.



[4] 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, Sept 2021.

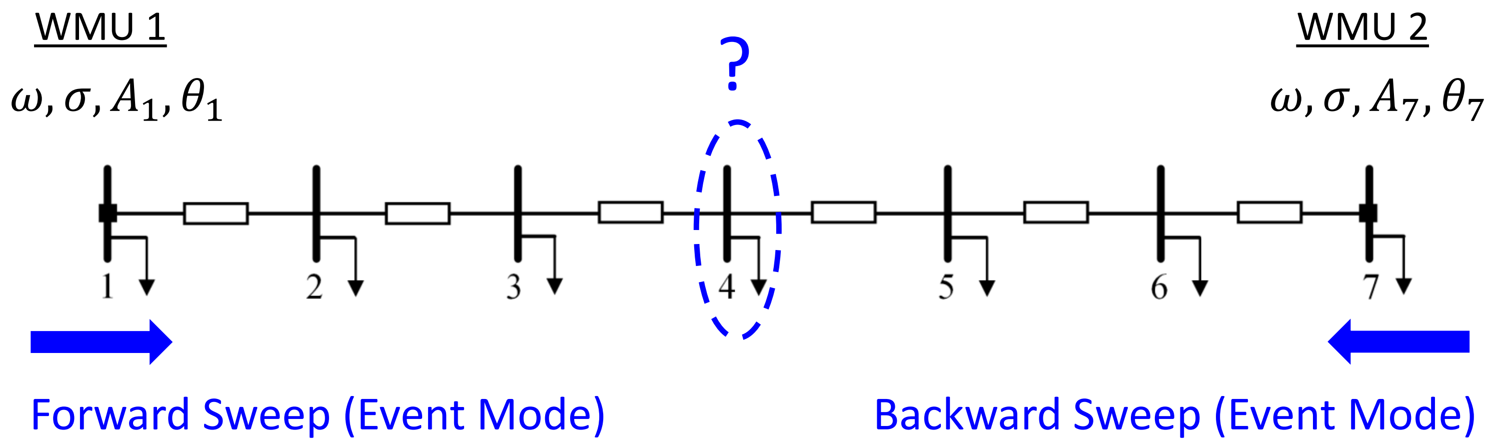
- Location Identification[4]:

Forward/Backward Method.

Discrepancy

$$k^* = \underset{i}{\text{argmin}}\ \Psi_i$$

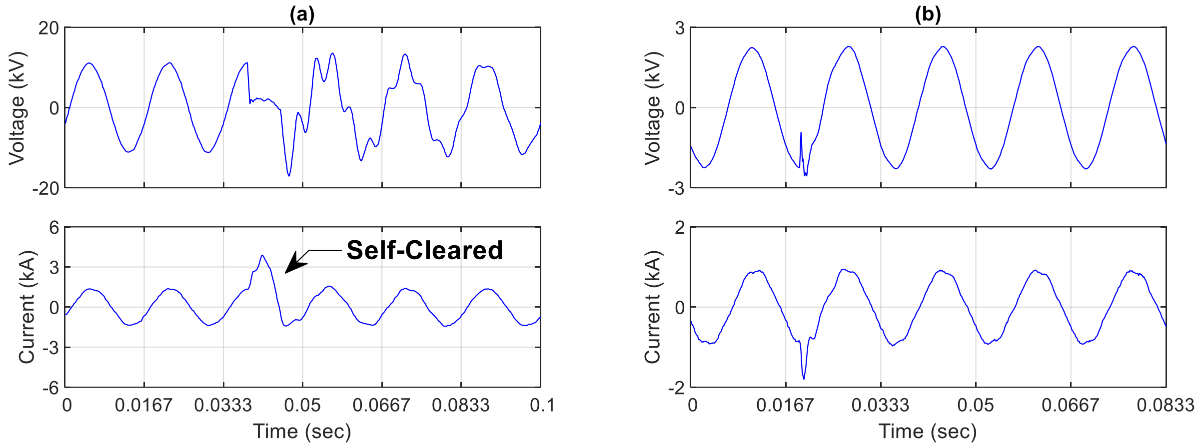
$$\text{where}\quad \Psi_i = \left|V_i^f - V_i^b\right|,\quad i = 1, \dots, 7.$$



[4] 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, Sept 2021.

Potential Use Cases: (Remote) Incipient Faults

- Transient Signatures: Asset Monitoring, Wildfire Detection[5], etc.



Power Lines[6] **Capacitor Bank**[7]

- Using *synchronized waveform measurements* helps with more effective detection, characterization, classification, and location identification.

[5] H. Mohsenian-Rad, "Synchro-Waveforms in Power Distribution with Application to Wildfire Monitoring " Panel Presentation, *IEEE Power and Energy Society General Meeting*, July 26, 2022.

[6] S. Kulkarni, S. Santoso, and T. A. Short, "Incipient Fault Location Algorithm for Underground Cables," *IEEE Transactions on Smart Grid*, vol. 5, no. 3, pp. 1165–1174, May 2014.

[7] S. Santoso, and D. D. Sabin, "Power Quality Data Analytics: Tracking, Interpreting, and Predicting Performance," in *Proc. of the IEEE Power and Energy Society General Meeting*, Jul. 2012.

Conclusions

- Synchro-Waveforms: new frontier in power grid situational awareness.
- Examples: transient sub-cycle and few-cycle disturbances.
- New method: Detection and Characterization
  - Image processing and analysis of synchronized Lissajous graphs
- New method: Location Identification
  - Analysis of the sub-cycle event mode(s)
- The results show accurate and robust performance.
- Synchro-waveforms have great potential in incipient fault analysis.

Further Reading

Synchro-Waveform Analysis:

[1] 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, p. 4880, Sept 2021.

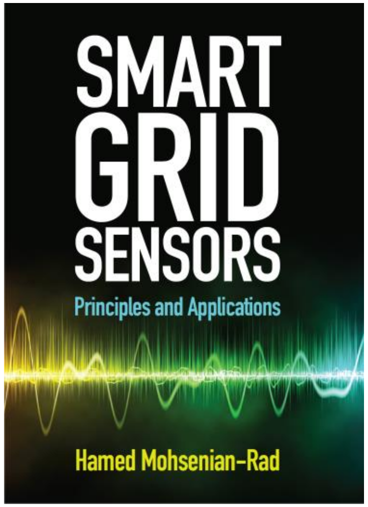
[2] M. Izadi and H. Mohsenian-Rad, "Synchronized Lissajous-based method to detect & classify events in synchro-waveform measurements in power distribution networks," in ***IEEE Trans. on Smart Grid***, vol. 13, pp. 2170, May 2022.

[3] 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, Sept 2021.

Textbook on Smart Grid Sensors:

- Working Principles
- Sample Data Sets
- Data-Driven Methods

  Synchro-phasors
  Synchro-waveforms
  Smart Meters
  SCADA
  Sensors in Buildings
  Device and Asset Sensors
  Probing and Perturbation
  Off-Domain Data
  ⋮



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

Thank You!

Hamed Mohsenian-Rad, *Ph.D., IEEE Fellow*

Professor and Bourns Family Fellow
Department of Electrical and Computer Engineering
University of California, Riverside
E-mail: hamed@ece.ucr.edu
Homepage: www.ece.ucr.edu/~hamed