Synchro-Waveforms: A New Frontier in Advanced Smart Grid Sensing and Data Analytics

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Agenda

- **Part 1) Introduction, Technology, and Real-World Data**
- **Part 2) Data Analytics Methods**
- **Part 3) Applications – Current and Future**

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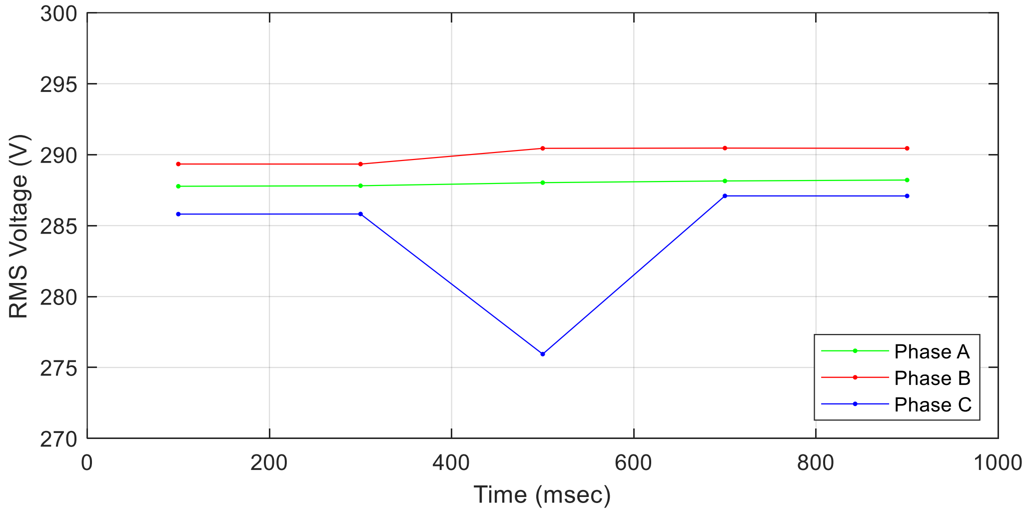
- **Part 1) Introduction, Technology, and Real-World Data**
- **Part 2) Data Analytics Methods**
- **Part 3) Applications – Current and Future**

Part 1) Introduction, Technology, and Real-World Data

- The following topics are discussed in **Part 1**:
  - Waveform Measurements: Comparison with Other Smart Grid Data
  - Waveform Measurement Units (WMUs)
  - Synchro-waveforms
  - Sampling Rates and Resolution
  - Field Installations and Sensor Technologies

Part 1.1) Waveform Measurements

- Consider the following “high-resolution” **SCADA** measurements:

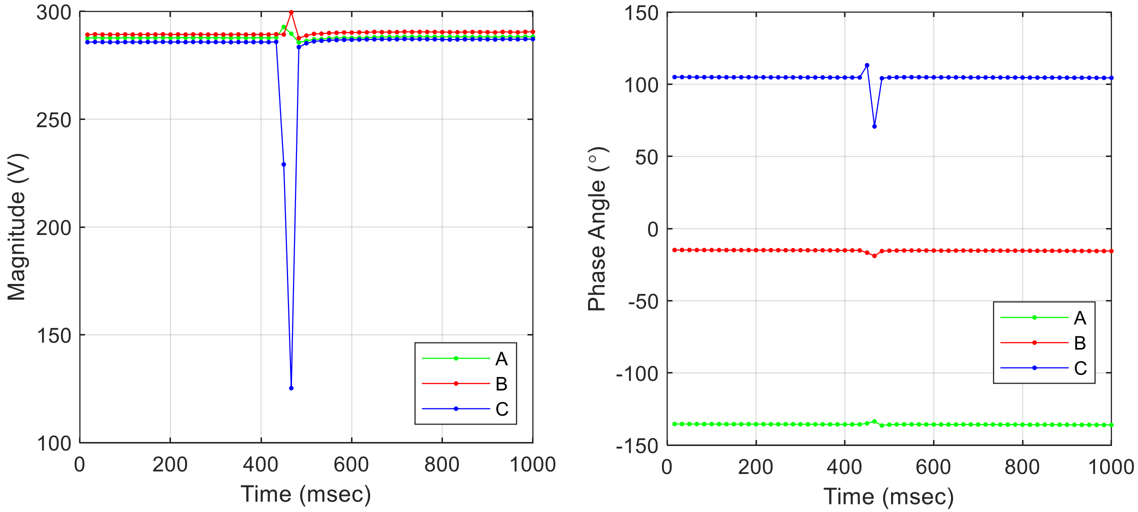


- RMS-Voltage is measured at five readings per second (5 / second).

- In practice, SCADA measurements are *even less granular* in time.

Part 1.1) Waveform Measurements

- The **PMU** measurements (**phasors**) during the *same period*:

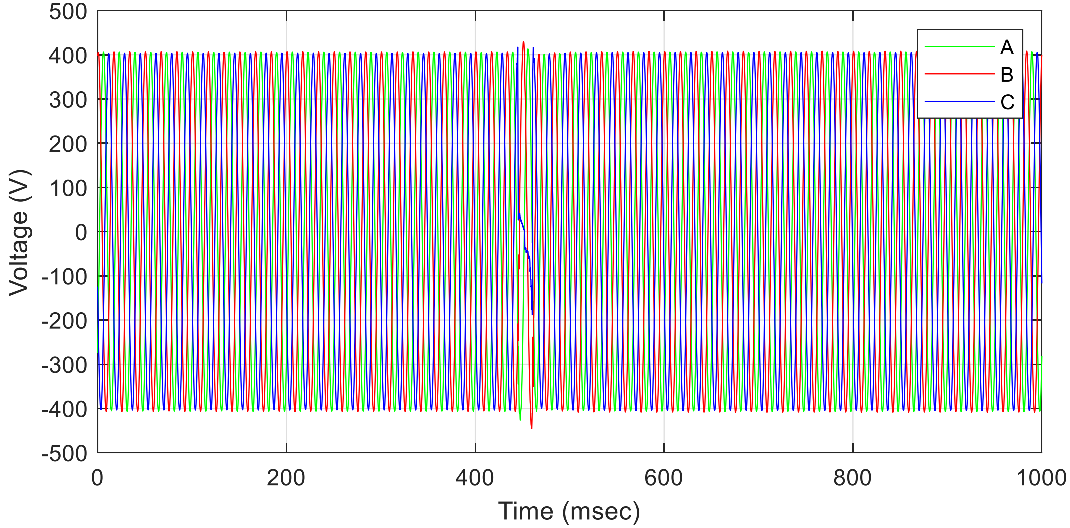


- Phasors are measured at 60 readings per second (60 / second).

- In practice, PMUs have 10 to 120 readings per second.

Part 1.1) Waveform Measurements

- The **WMU** (?) measurements (**waveforms**) during the *same period*:

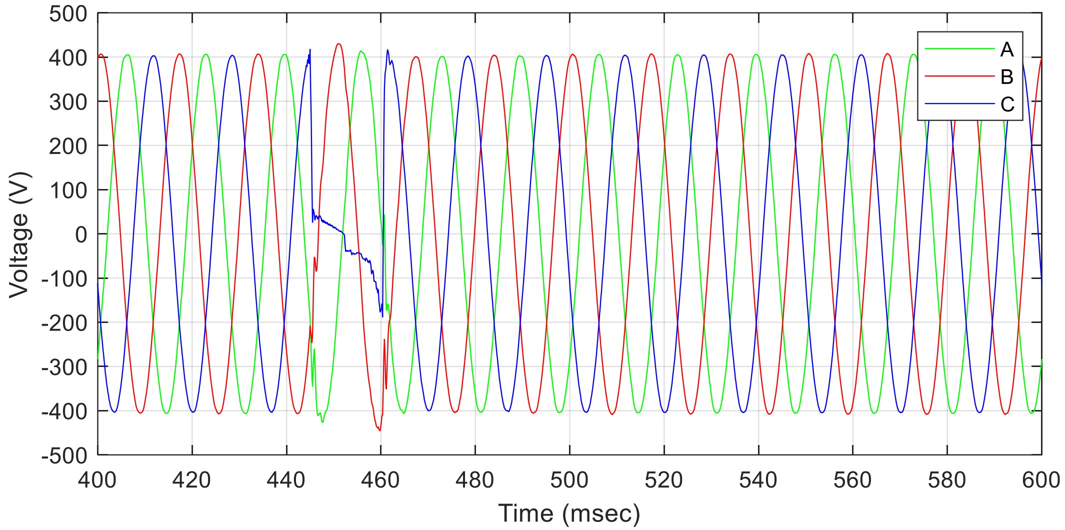


- Waveforms are measured at 128 readings per cycle (128x60 / second).

- We can see something happened between 400 msec and 600 msec.

Part 1.1) Waveform Measurements

- If we *zoom in* the **waveforms** measurements between 400 ms – 600 ms:

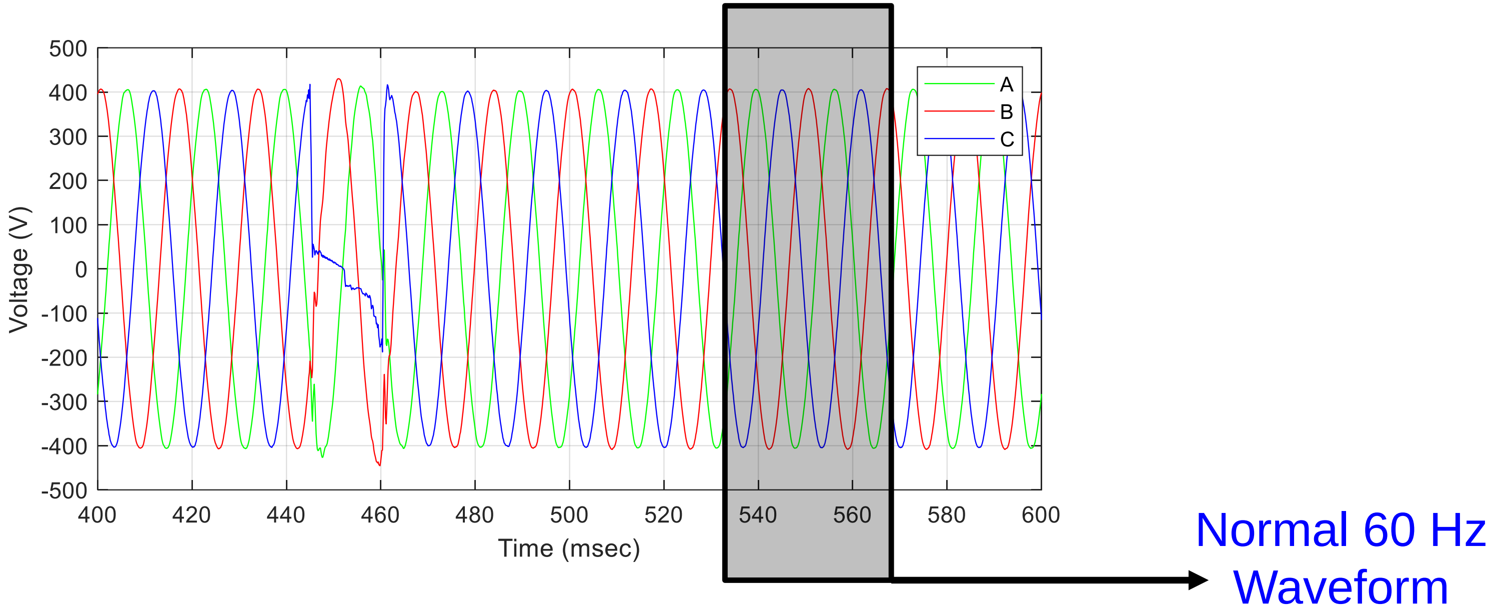


- There was a *momentary fault* in the system at phase C.

- We *almost entirely lost voltage* for about 18 milliseconds.
    - SCADA and PMUs *cannot* capture this *major but short-lasting* issue.

Part 1.1) Waveform Measurements

- If we *zoom in* the **waveforms** measurements between 400 ms – 600 ms:



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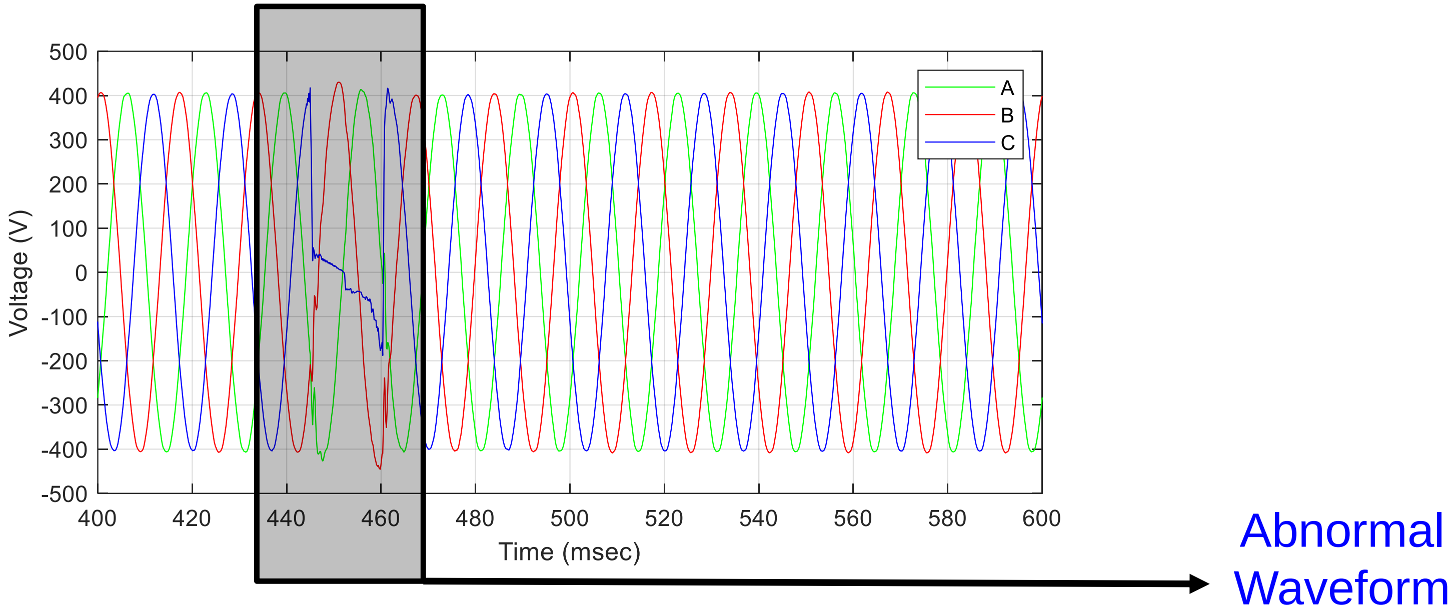

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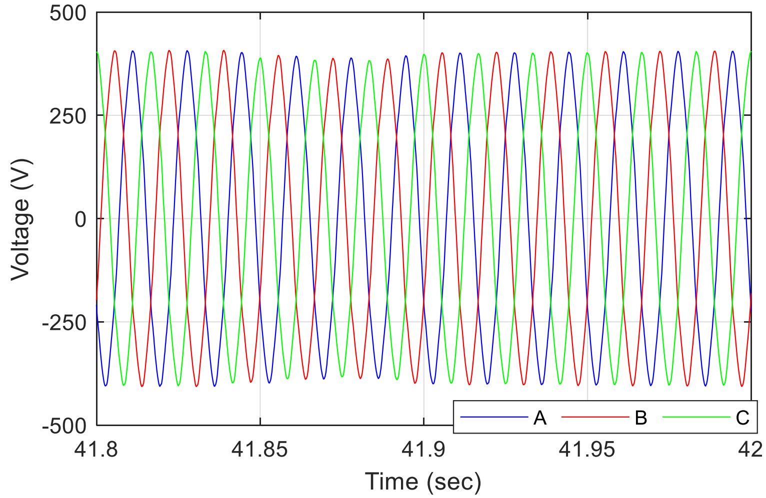
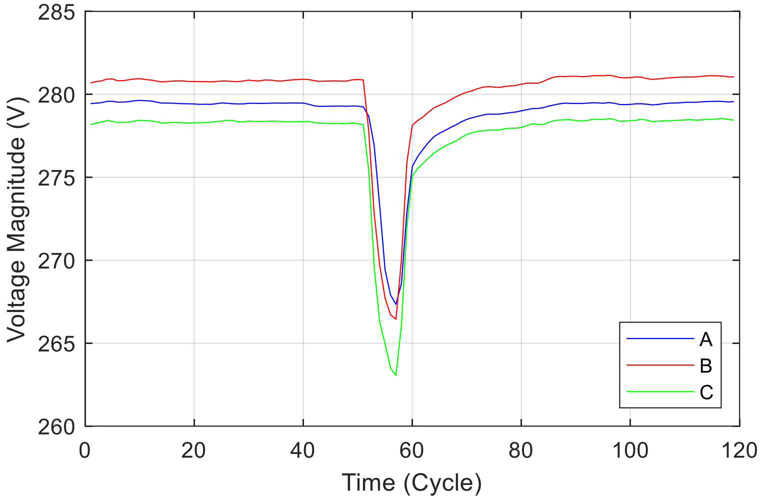
- We *almost entirely lost voltage* for about 18 milliseconds.
  - SCADA and PMUs *cannot* capture this *major but short-lasting* issue.

Part 1.1) Waveform Measurements

- Another Example (Voltage Sag):



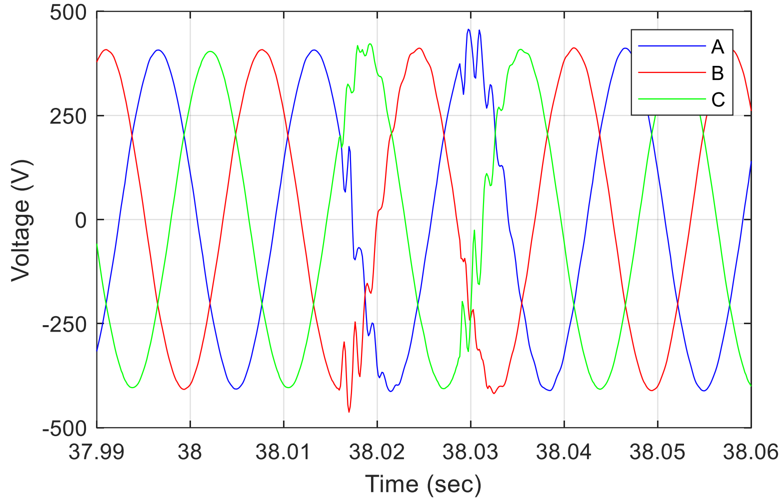
Waveform



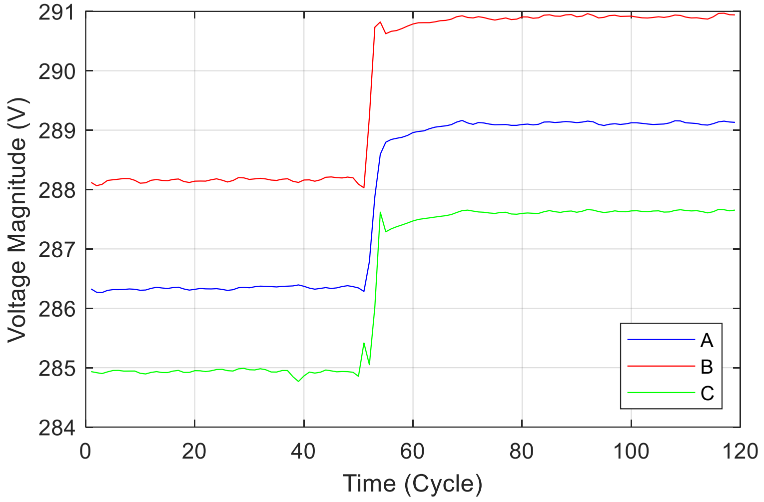
Phasor (Magnitude)

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

- Another Example (Resonance):



Waveform



Phasor (Magnitude)

- With PMUs, we do *not notice* the resonance in the phasors.

Part 1.2) Waveform Measurement Unit

- The device to measure waveform measurements:

  - **WMU**: Waveform Measurement Unit[1]

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

- WMU is a general and new term. The actual sensor might be called:

  - Power Quality Meter

  - Point-on-Wave (POW) Sensor (They all measure waveform)

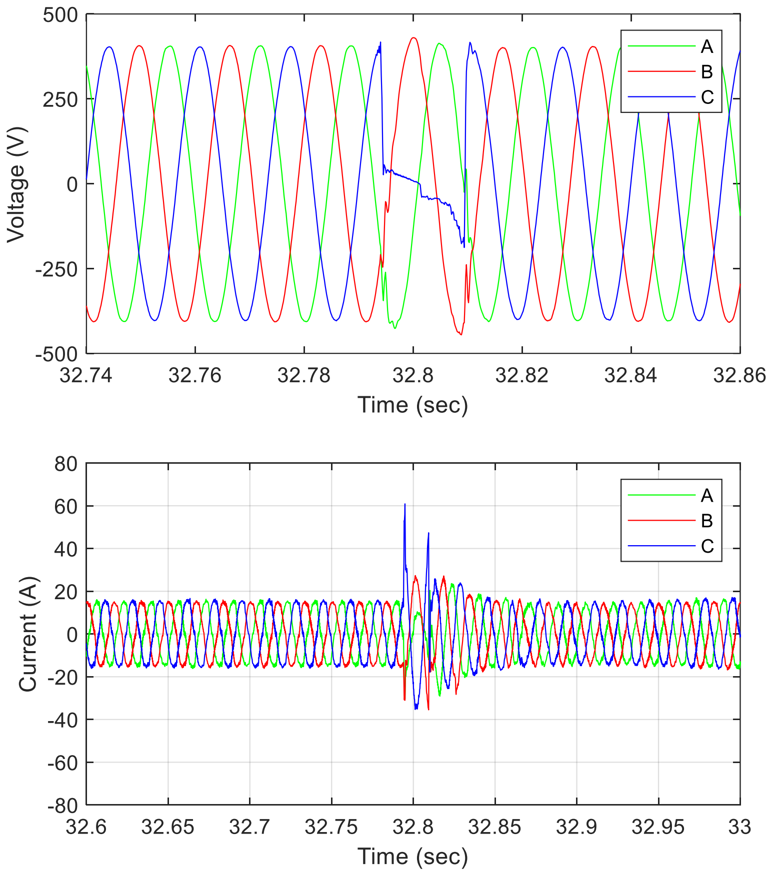
  - Digital Fault Recorder (DFR)

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

Part 1.2) Waveform Measurement Unit

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

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



Part 1.3) Synchro-Waveforms

- Just like PMUs, we can equip WMUs with GPS time-synchronization.

- Two Concepts:

Synchro-Phasors = Phasors + Time Synchronization

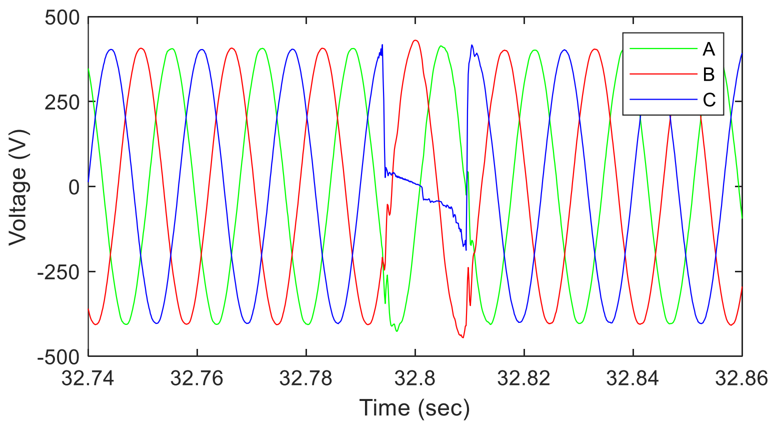
Synchro-Waveforms = Waveforms + Time Synchronization

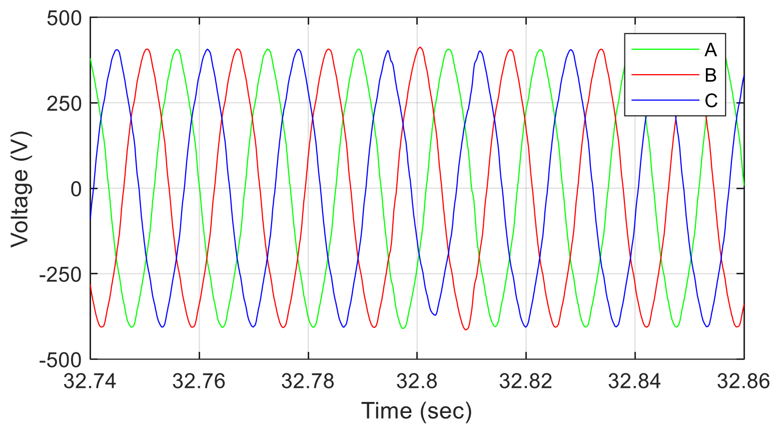
PMU GPS Antenna

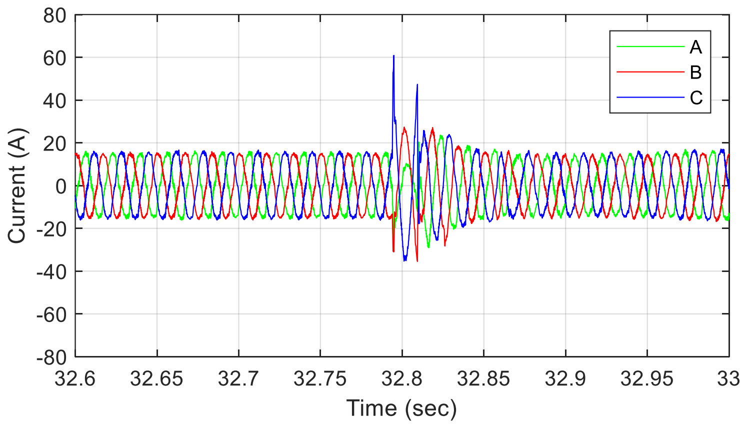
WMU GPS Antenna

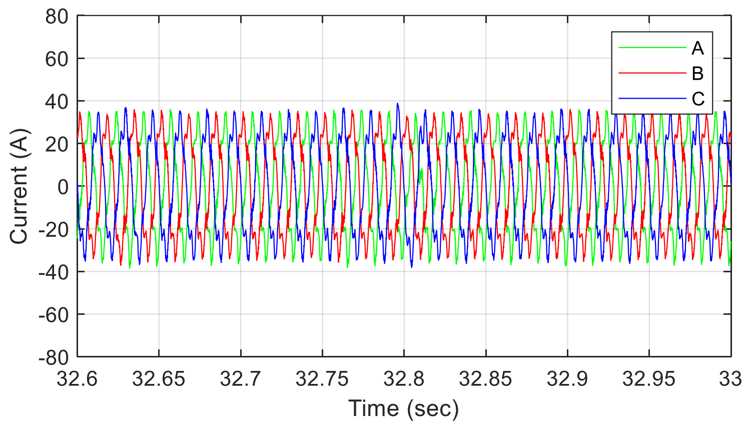
Part 1.3) Synchro-Waveforms

- Synchro-Waveforms for the example that we saw before:







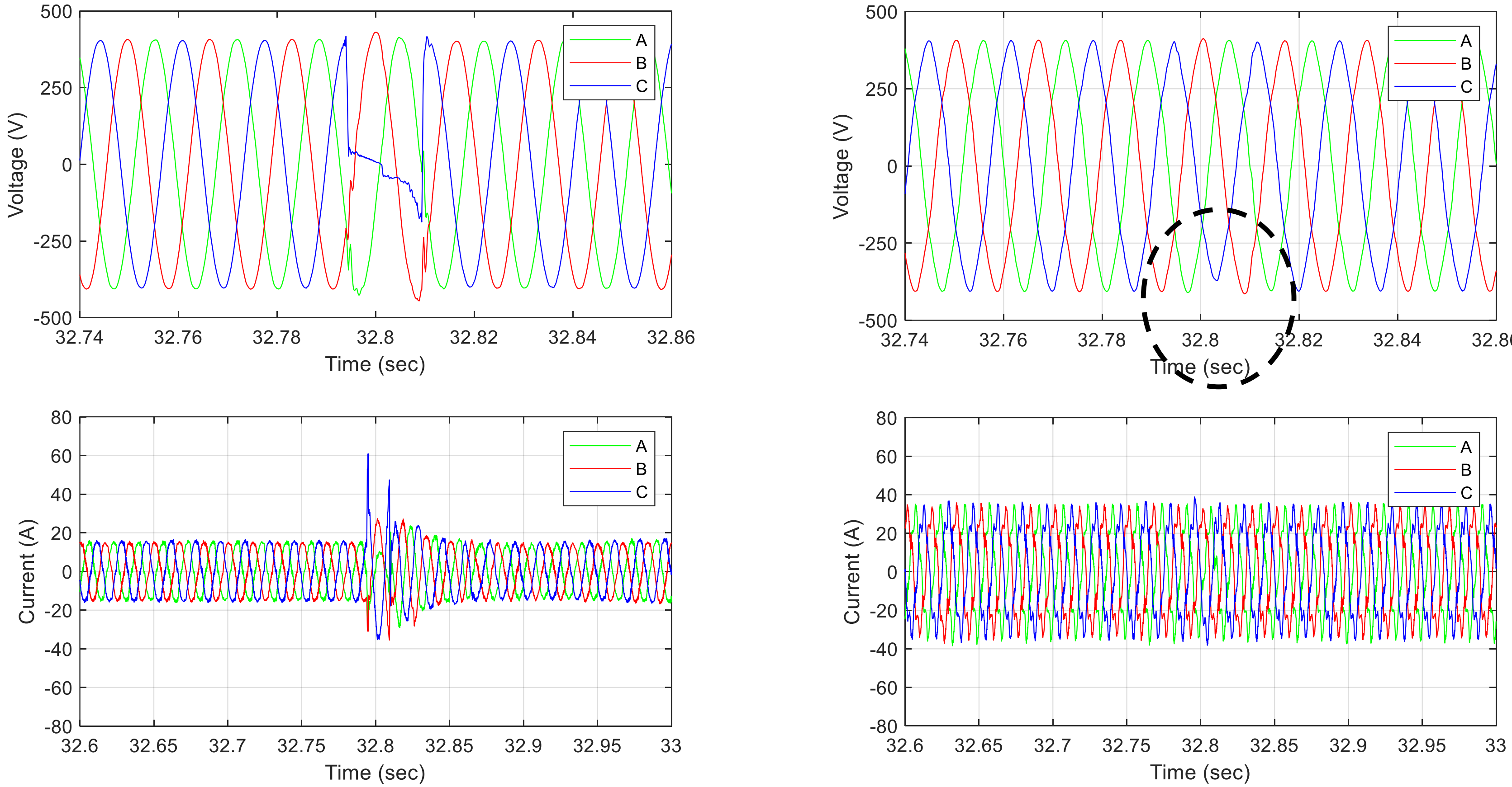


WMU 1 ⟷ **WMU 2**

Time Synchronized

Part 1.3) Synchro-Waveforms

- Synchro-Waveforms for the example that we saw before:



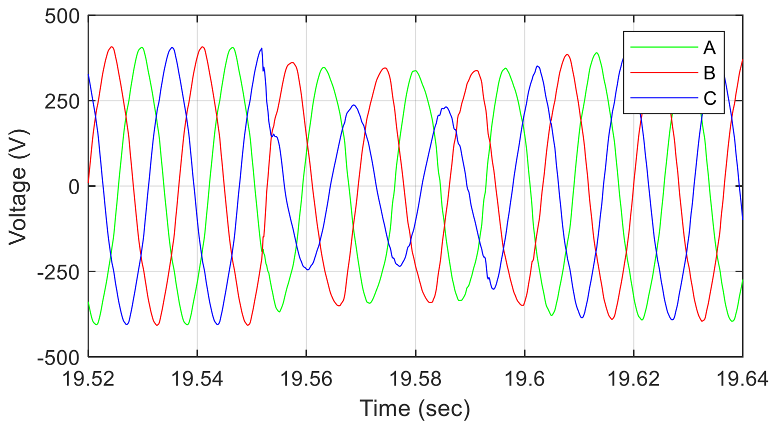
WMU 1 ⟷ **WMU 2**

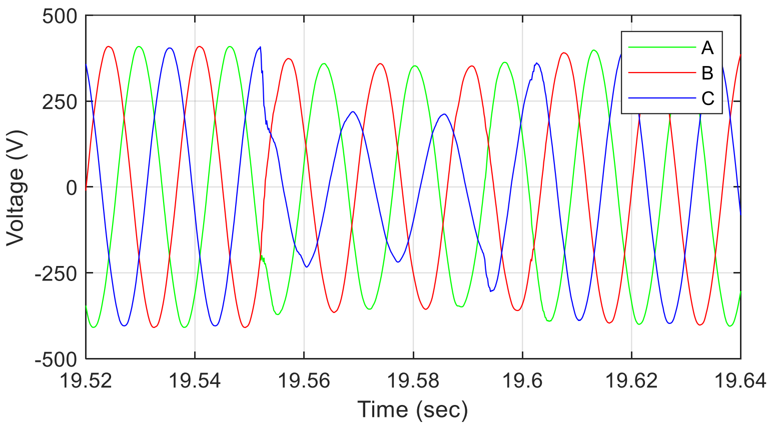
Time Synchronized

Part 1.3) 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.

- Another Example - Synchro-Waveforms:



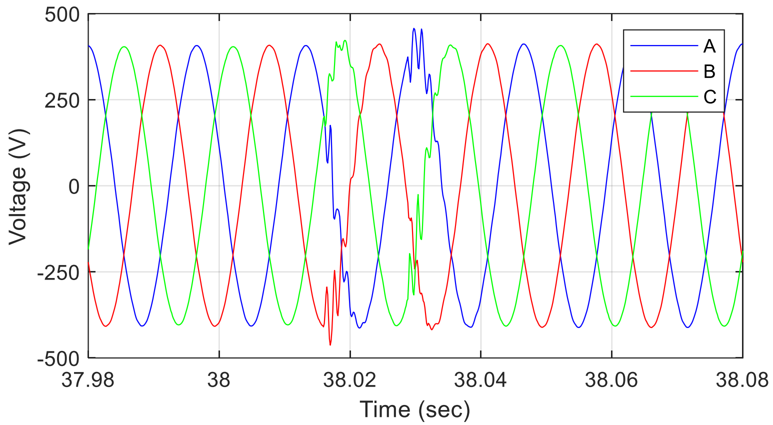


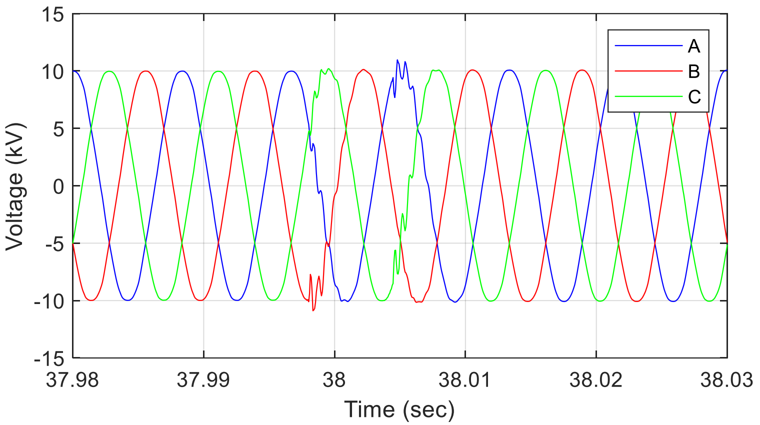
WMU 1 **WMU 2**

Time Synchronized

Part 1.3) Synchro-Waveforms

- Synchro-Waveforms in the example with Resonance:





WMU 1

Time Synchronized

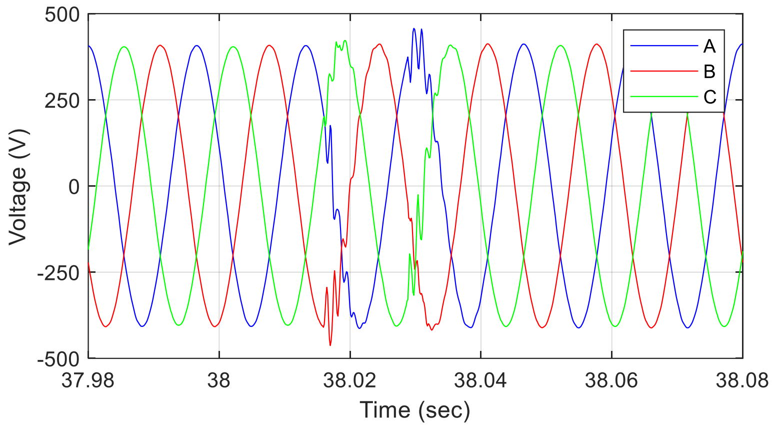
WMU 3

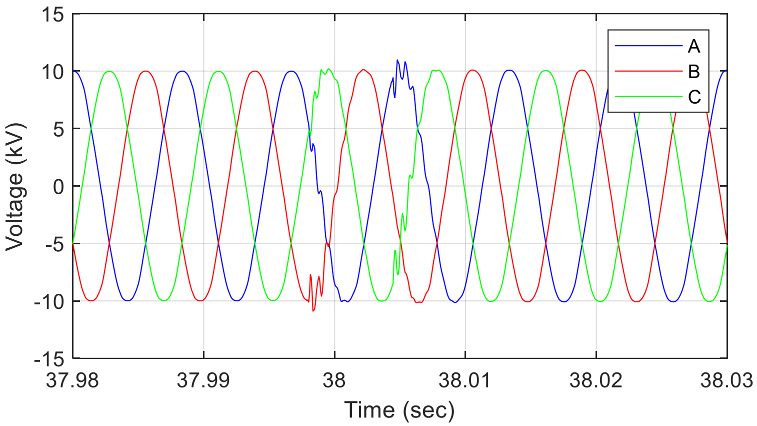
Another Location

(Also, Different Voltage Level)

Part 1.3) 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.)

Part 1.4) Sampling Rates and Resolution

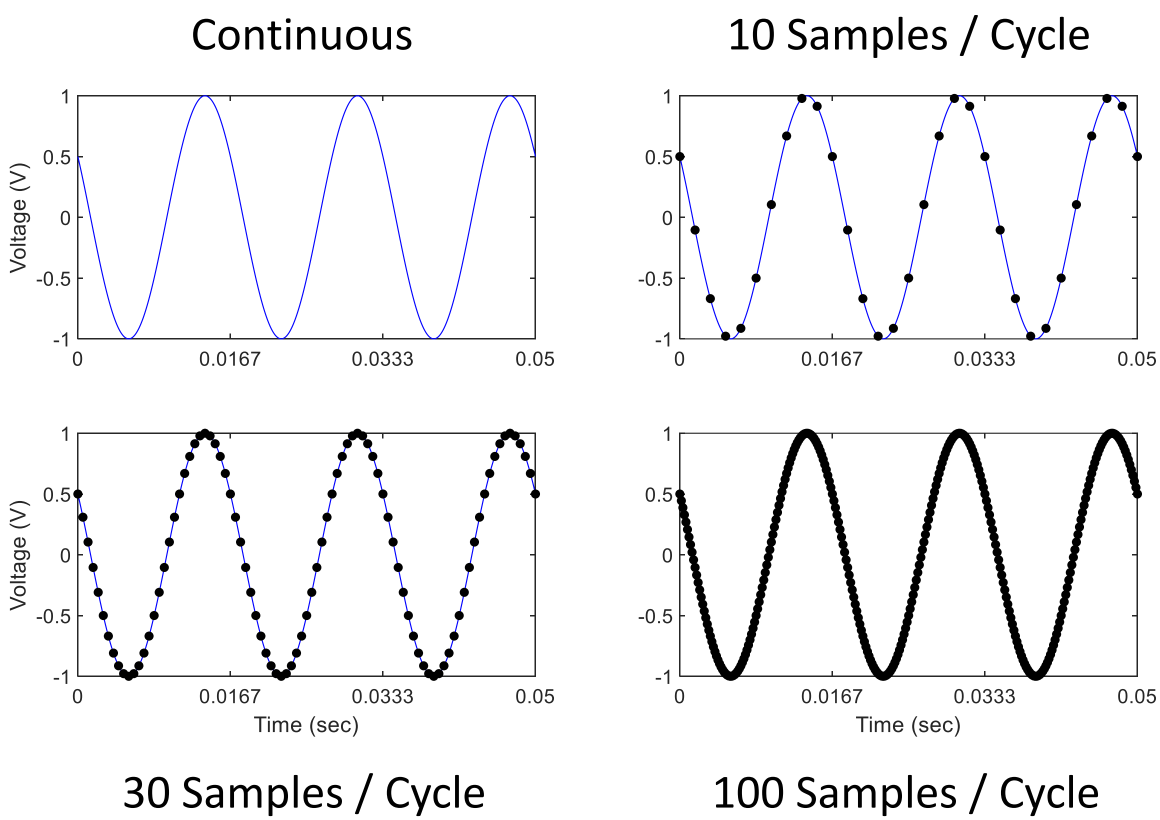
- Digital sensors make *discrete measurements* at a fixed sampling rate.

- The sampling rate of a sensor is indicated in *samples per second* or *samples per cycle* of the AC signal. For example, the sampling rate can be 10 samples per cycle, i.e., 10×60=600 samples per second.

- Even if the measured voltage or current wave is purely sinusoidal, its reconstruction requires a minimum sampling rate, namely twice the frequency of the signal, according to the Nyquist-Shannon sampling theorem. For example, the minimum required sampling rate for a 60 Hz purely sinusoidal voltage wave is 120 samples per second (2 / cycle).

Part 1.4) Sampling Rates and Resolution

- A continuous sinusoidal voltage wave $v(t)$ versus its discrete (sampled) version $v[k]$ under different sampling rates:



Part 1.4) Sampling Rates and Resolution

- Common sampling rates for WMUs in practice:
  - 32 Samples Per Cycle
  - 64 Samples Per Cycle
  - 128 Samples Per Cycle ← The rate for our examples so far.
  - 512 Samples Per Cycle
  - 1024 Samples Per Cycle (Not Common)

- Trade-off between Better Resolution vs Data Management:

Part 1.5) Field Installations and Sensor Technologies

- WMUs can be installed at Substations:

Outside

Medium Voltage Installations

(Three-Phase) (12.47 kV)

Inside

Part 1.5) Field Installations and Sensor Technologies

- WMUs can be installed at Assets and DERs:

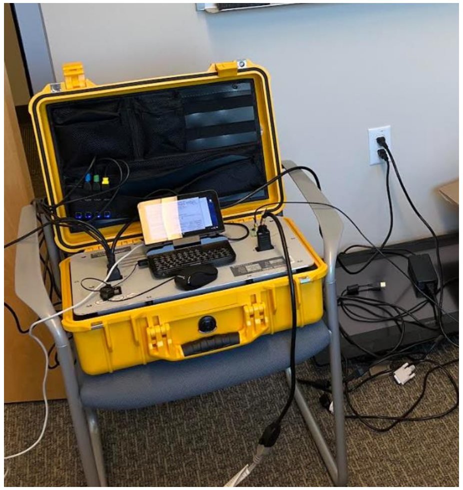
PV Inverters

Low Voltage Installations

(Three-Phase) (480 V)

Part 1.5) Field Installations and Sensor Technologies

- WMUs can be installed at Power Outlets:



My Office

(DoE GtidSweep Project)

Low Voltage Installations

(Single-Phase) (120 V)

- The nature of the data and the related principles are the same.

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Part 2) Data-Analytics Methods

- The following topics are discussed in **Part 2**:
  - Event Detection
    - Single Waveform
    - Multiple Synchronized Waveforms
  - Feature Extraction
  - Event Classification
  - Event Location Identification

Part 2.1) Event Detection

- Waveform sensors operate at very high sampling rates, such as at 128 samples per cycle, i.e., 128x60 = 7,680 samples per second.

- At such high sampling rate, a waveform sensor generates **3,981,312,000 samples per day** from a single three-phase voltage and current sensor.

- This is a huge amount of data to report. Therefore, in practice, most samples are *discarded shortly after they are collected* and as soon as they have gone through a light-weight analysis inside the sensor.

  - Instead, the waveform is captured (event-triggered waveform capture) only if the waveform is somewhat *unusual* and thus *worthy of further examination*.

  - This is done when an *event* is detected.

Part 2.1) Event Detection

- Once an event is detected, i.e., we notice *something unusual* in the waveform, the sensor stores the waveform data over several cycles:

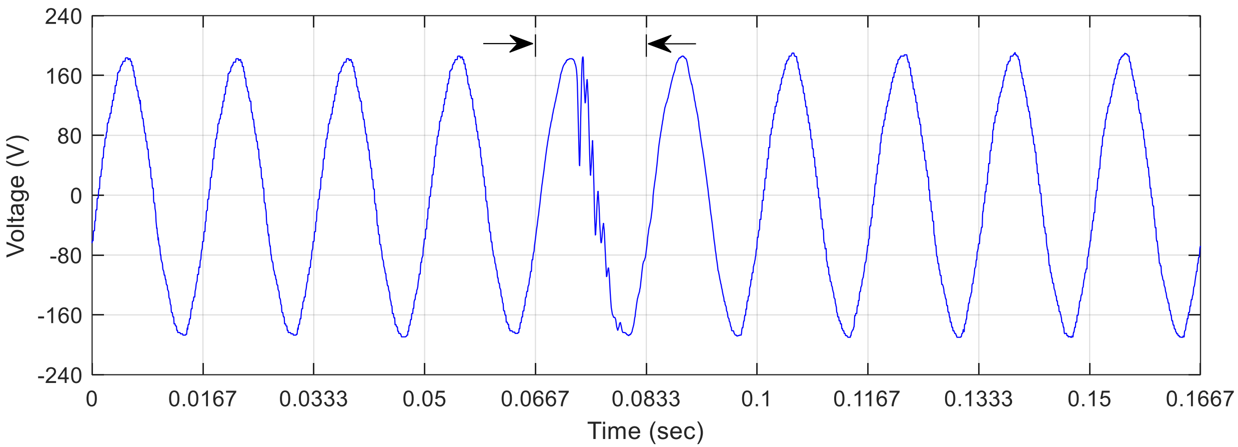
  - starting from C_{before} cycles *before* the event

  - ending by C_{after} cycles *after* the event

- Parameters C_{before} and C_{after} can be adjusted.

Part 2.1) Event Detection

- Consider the voltage measurement across 10 cycles:

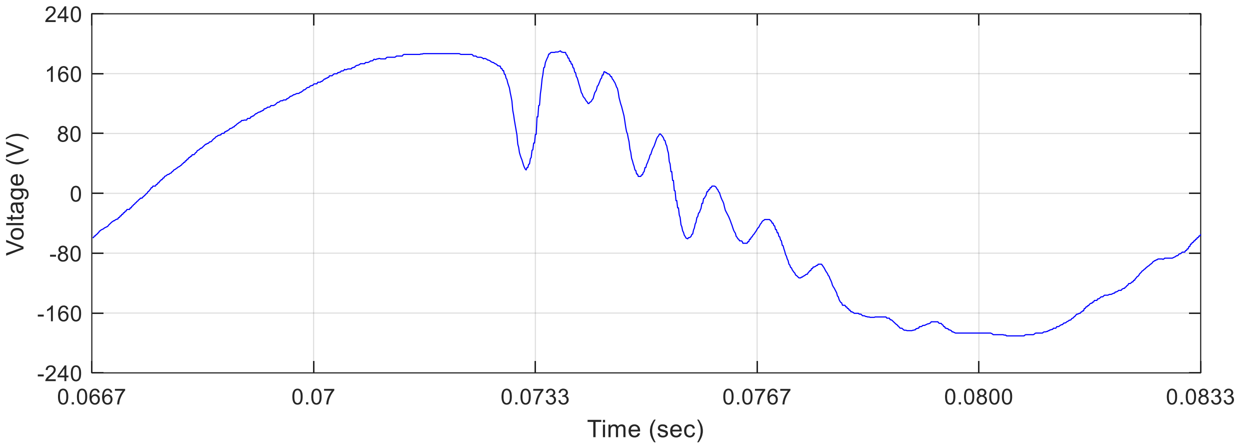


- Waveform capture:

  - starts at $C_{\text{before}} = 4$ cycles before the distorted cycle

  - ends at $C_{\text{after}} = 5$ cycles after the distorted cycle

- In this example, the waveform is highly distorted during cycle #5:



- The distortion is due to a *momentary ringing event* that was caused by resonances formed between a capacitor bank and an inductive load during an upstream fault in a distribution system[1].

Event Detection in Waveform Measurements

- There are different methods to detect an event to *trigger* event capture.

- The main idea in most waveform event detection methods is to *compare* the measured waveform with a *reference* waveform.

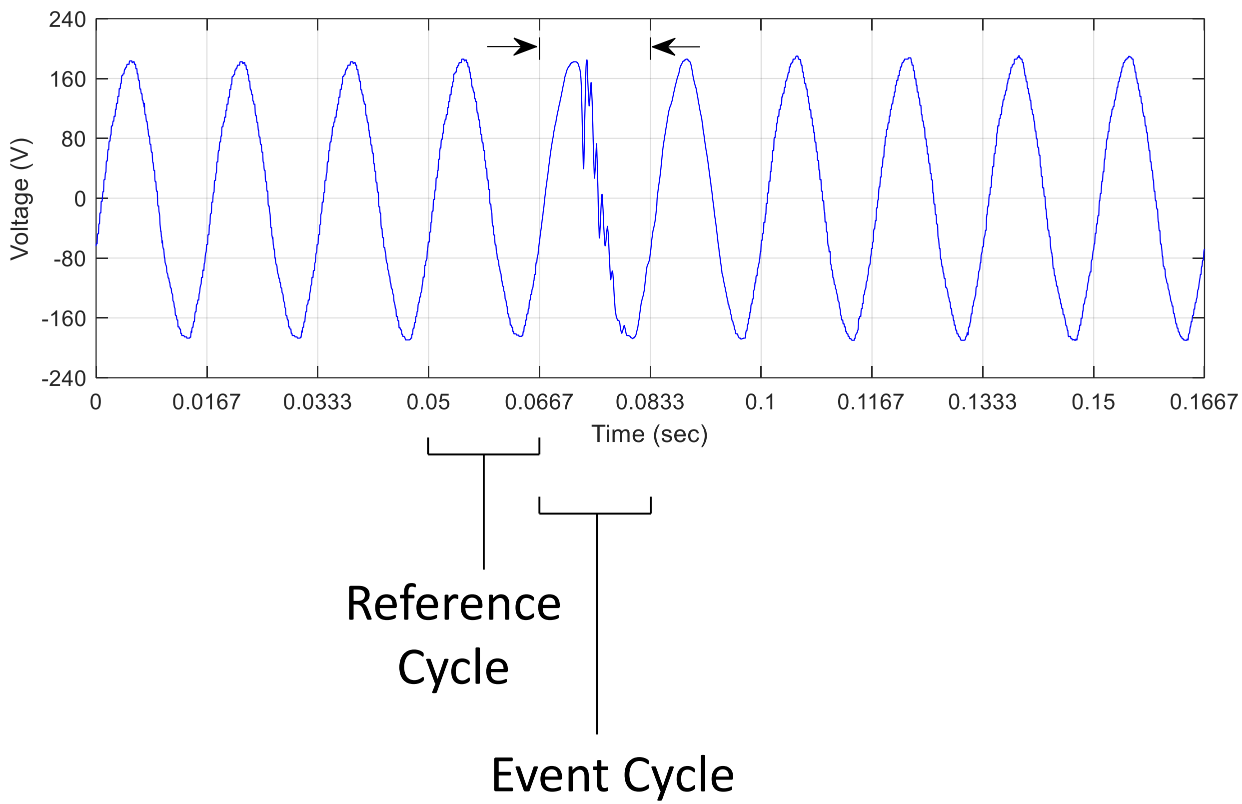
To represent the *normal* behavior of the system.

- If there is a considerable difference between the measured waveform and the reference waveform, then it can infer *abnormal* behavior.

which in turn can *trigger* an event capture.

Part 2.1) Event Detection

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



Part 2.1) Event Detection

- There are different ways to compare two cycles of waveforms, such as[1]:
  - Comparing THD
  - Comparing RMS
  - Point-to-Point Comparison
  - Comparing Sub-Cycle RMS
  - Differential Waveform
  - Neutral Current Waveform
  - Other Factors and Methods

Part 2.1) Event Detection

- There are different ways to compare two cycles of waveforms, such as[1]:
  - Comparing THD
  - Comparing RMS
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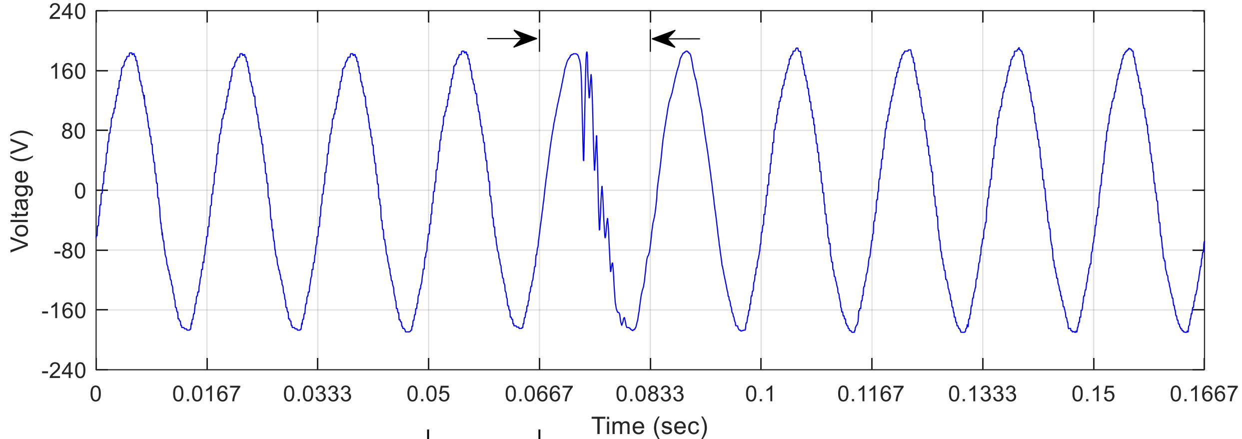
  - Comparing Sub-Cycle RMS
  - Differential Waveform
  - Neutral Current Waveform
  - Other Factors and Methods
- Next, we discuss *some* of these methods.

Comparing THD

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



THD < 1%

THD = 16%

THD = Total Harmonic Distortion

Comparing THD

- What matters here is the *change* in THD from one cycle to the next:

$$\Delta\text{THD} = \text{THD}(\text{Current Cycle}) - \text{THD}(\text{Previous Cycle})$$

- Importantly, the value of THD by itself is not important.

- Thus, it is rather a *change* in THD that indicates a *change* in waveform. In this regard, we can check the following inequality to detect an event:

$$|\Delta\text{THD}| \geq \alpha_{\text{THD}}$$

Comparing THD

- Parameter α_{THD} is a predetermined threshold.

- For example, if we set $\alpha_{\mathrm{THD}} = 5\%$, then we detect an event if the THD in each cycle of the waveform suddenly changes by 5% or more.

- Note that, both *positive changes* and *negative changes* in THD are of interest here because both indicate changes in wave-shape.

- A negative change in THD indicates *reduction* in waveform distortion.

    - Meaning that the source of distortion is removed or mitigated.

Differential Waveform

• This method investigates the abnormalities that are *superimposed* to the normal voltage or normal current waveforms during an event.

• 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, i.e., $T = 1/60$ second for a 60 Hz waveform; and N is a small integer number, such as 1, 2, 3, 4, or 5.

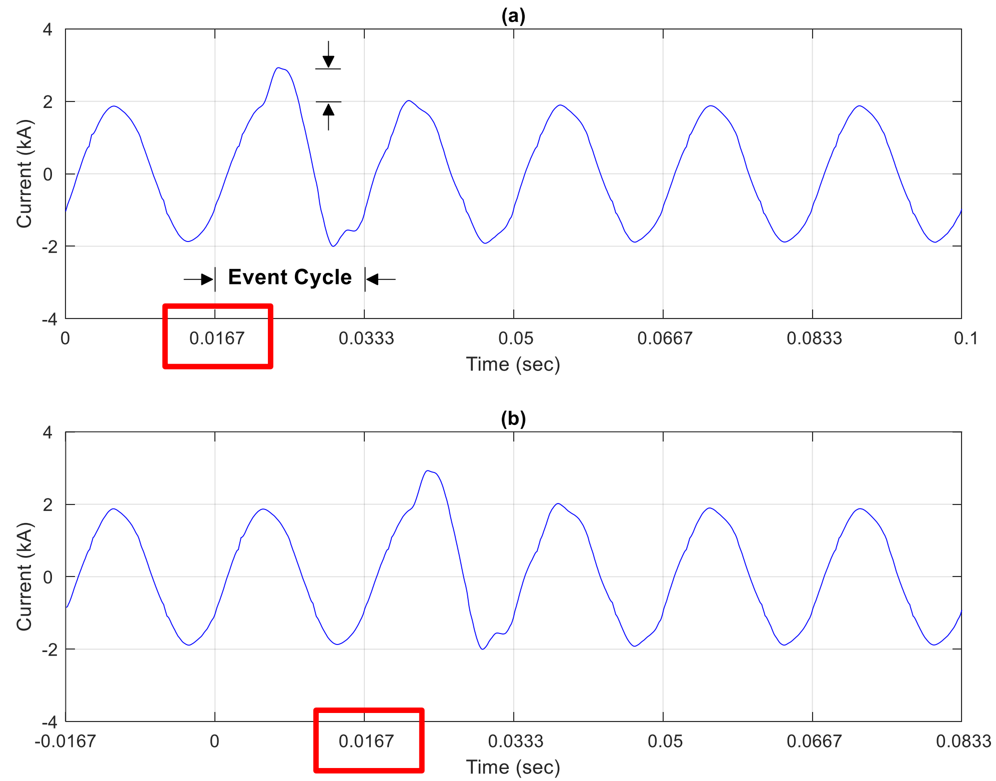
• We can detect an event based on the characteristics of $\Delta x(t)$.

Differential Waveform

- Consider the current waveform measurements below:

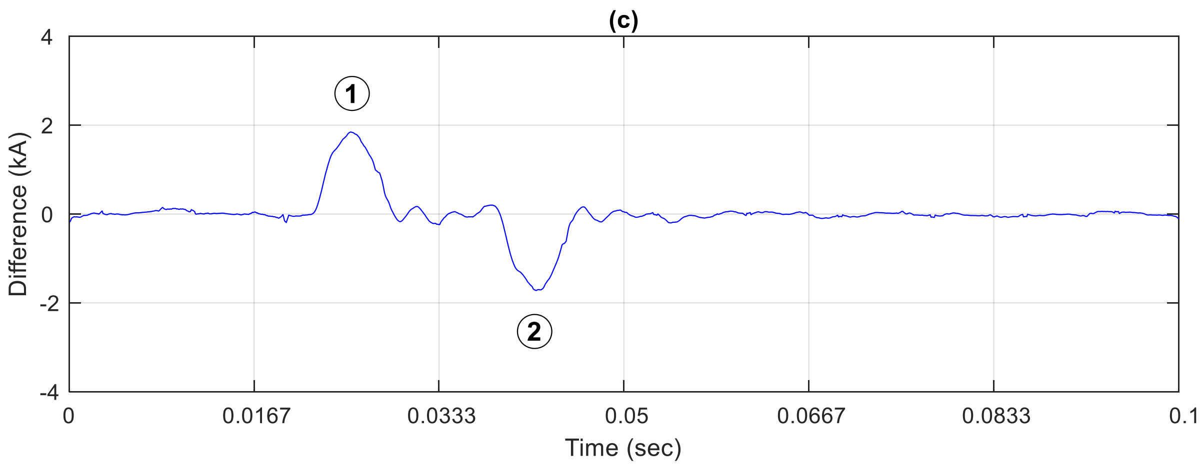
$x(t)$

$x(t-T)$



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. (Q: Why?)

Differential Waveform

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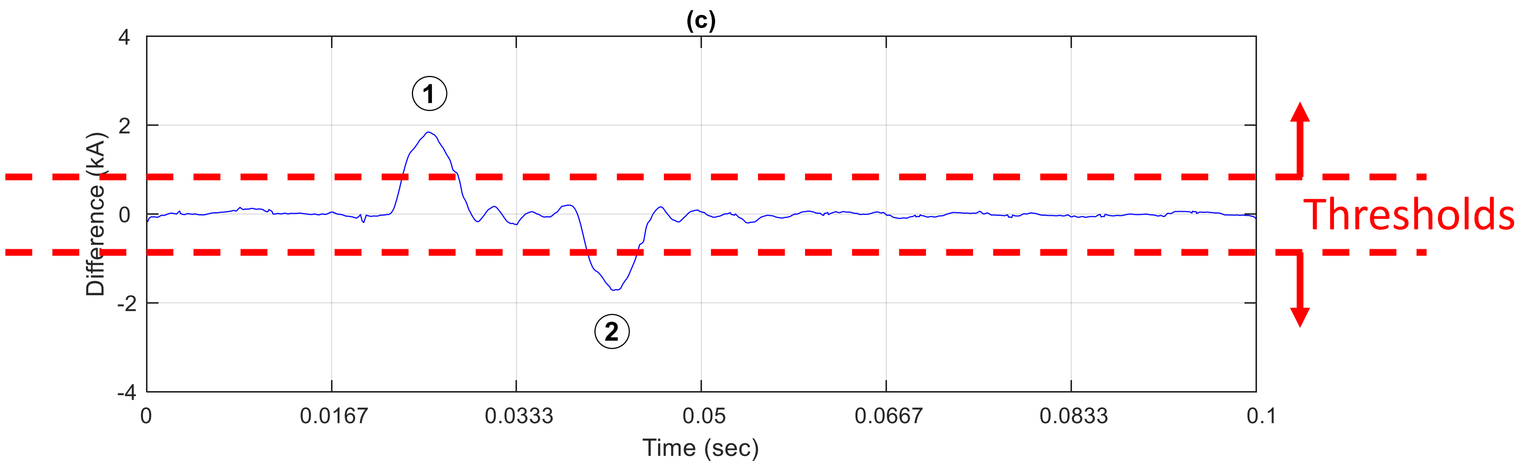

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Neutral Current Waveform

• Many events are *asymmetric* and take place only in one phase, such as in the case of a single-phase-to-ground fault. Even if an event occurs in all three phases, it is unlikely that it affects all three phases equally.

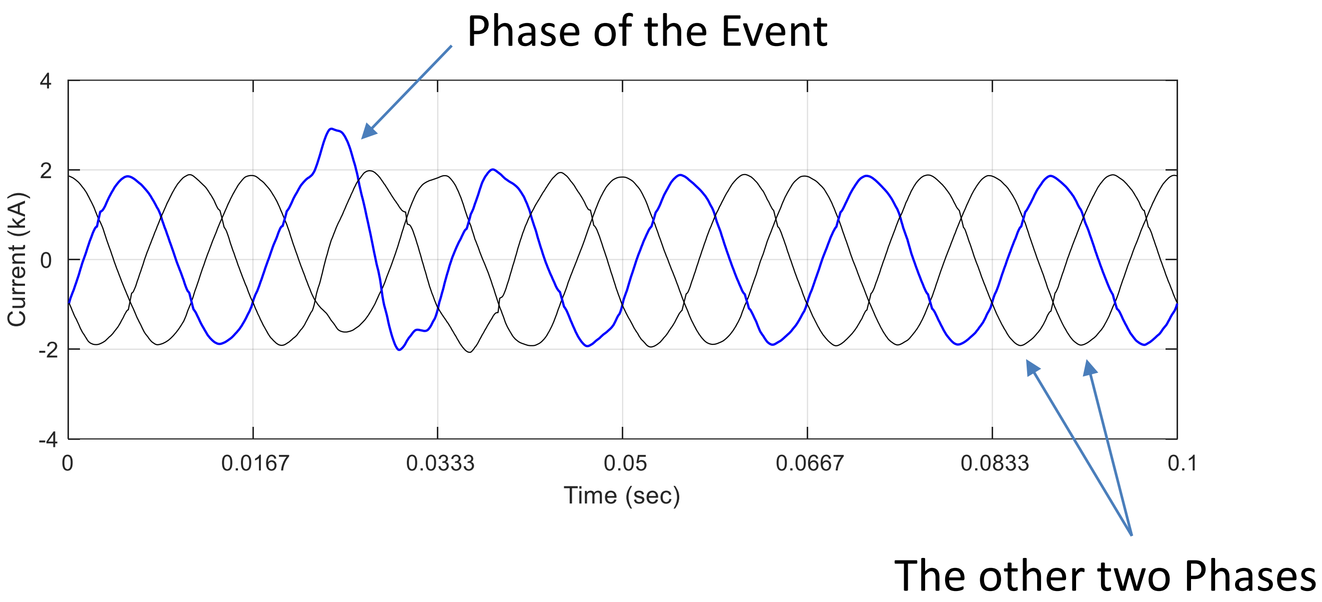
• Therefore, we may detect an event in waveform measurements by examining the *neutral current* (either measured or calculated):

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

• **Note**: This is relevant only to three-phase waveform measurements.

Neutral Current Waveform

- Consider the following three-phase current waveform measurements:



Neutral Current Waveform

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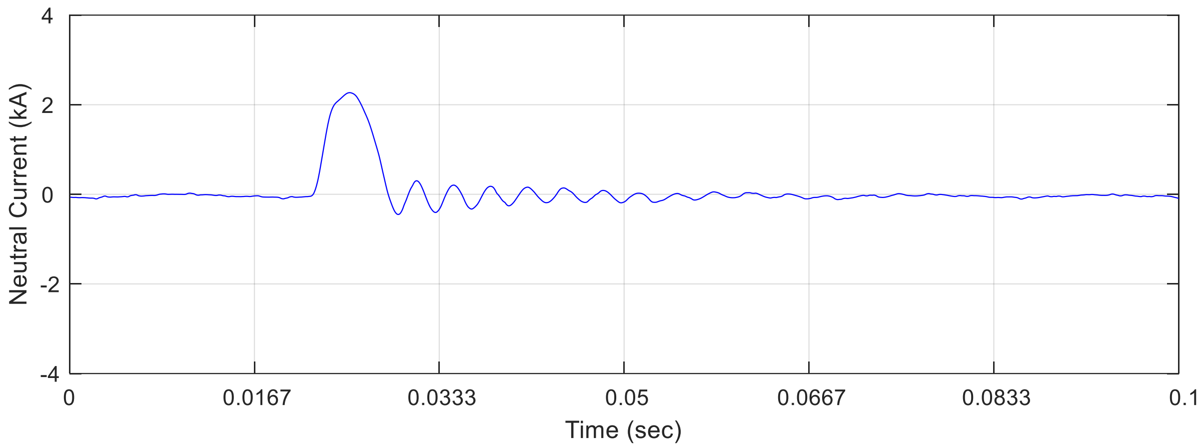

• The event creates a significant signature in the neutral current waveform during the event. This signature can be used to detect the abnormality.

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

Neutral Current Waveform

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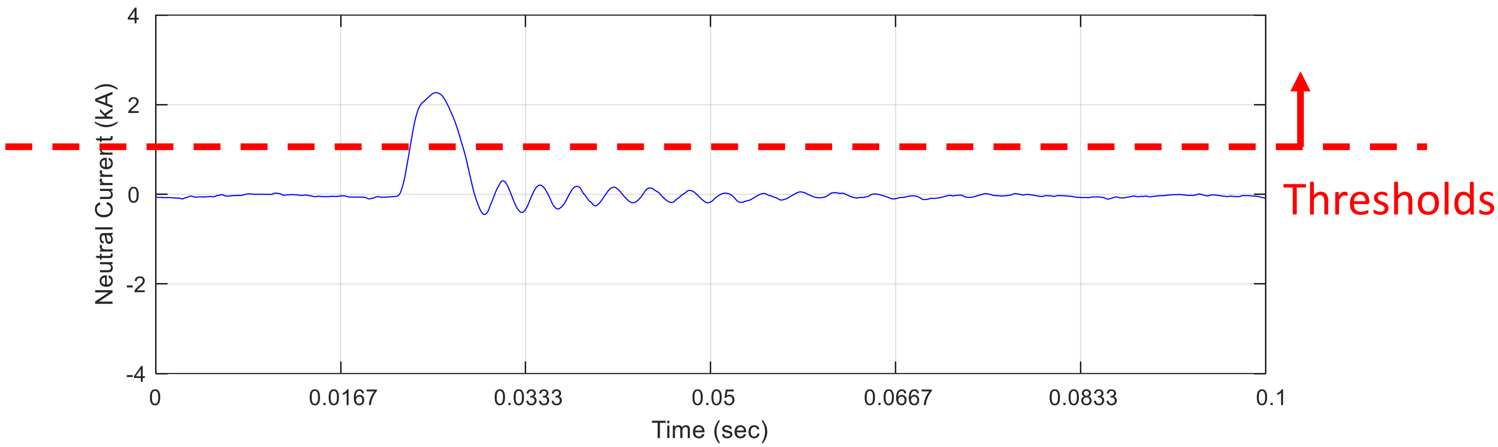

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Part 2.1) Event Detection – Synchronized Waveforms

- The methods so far can detect an event in any single waveform.
- 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: $i_2(t)$

Part 2.1) Event Detection – Synchronized Waveforms

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- 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.

Part 2.1) Event Detection – Synchronized Waveforms

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- 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: $i_2(t)$

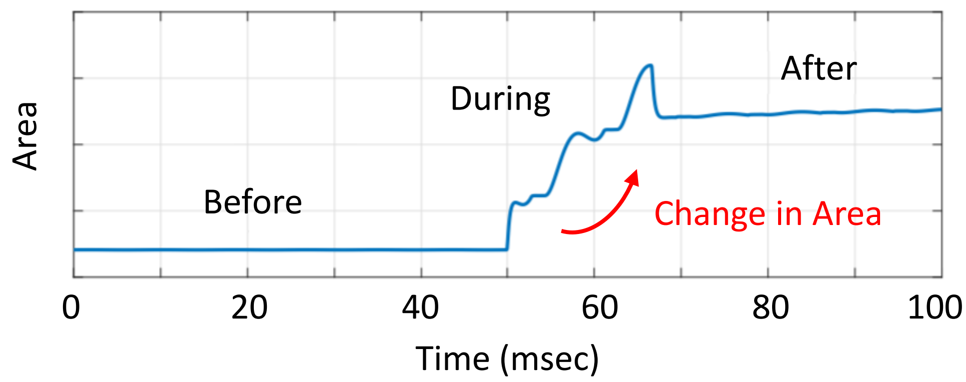
Detect

We can look for event in *all* waveforms.

- Detection[2]:

Event Detection

(Plus Other Methods)

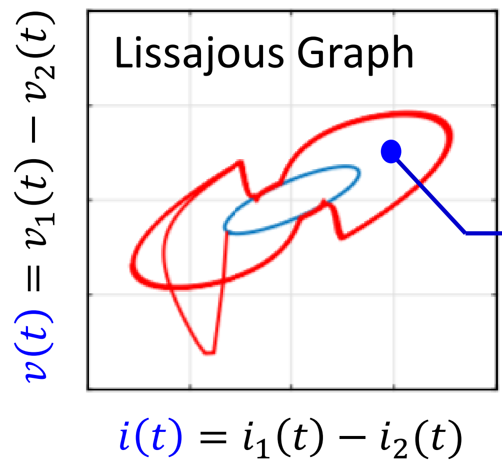


Location 1 / WMU 1

$v_1(t), i_1(t)$

Location 2 / WMU 2

$v_2(t), i_2(t)$



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

(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.

Part 2.2) Feature Extraction

• Given the many events that may take place every day, we need a way to *translate* the waveform measurements during events into useful information that can help diagnose issues, discover hidden patterns and unknown correlations, and make recommendations.

• The key to achieving this goal is to define *quantitative features* that can characterize each event and allow *signature evaluation*, event classification, pattern recognition, and statistical analysis.

• Some of them are *generic* and can be defined for almost any event in waveform measurements, regardless of the exact type of the event.

• Some are defined only for certain types of events, such as *certain faults*[1].

Part 2.2) Feature Extraction

- Several features have been defined in the literature[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

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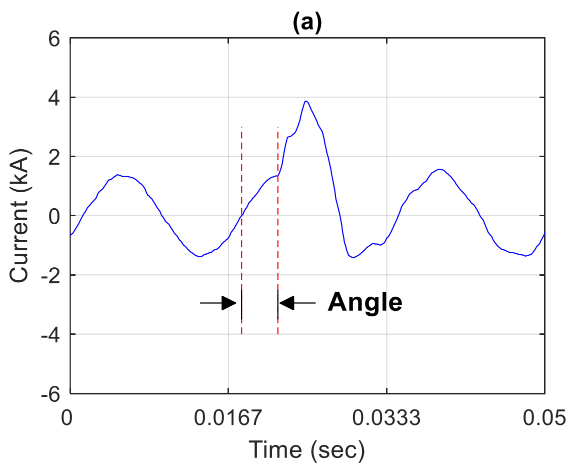
  - Changes in Steady-State Characteristics
  - Time, Season, and Location
  - Other Basic Features
  - Graphical Features

(Next, we discuss *some* of them.)

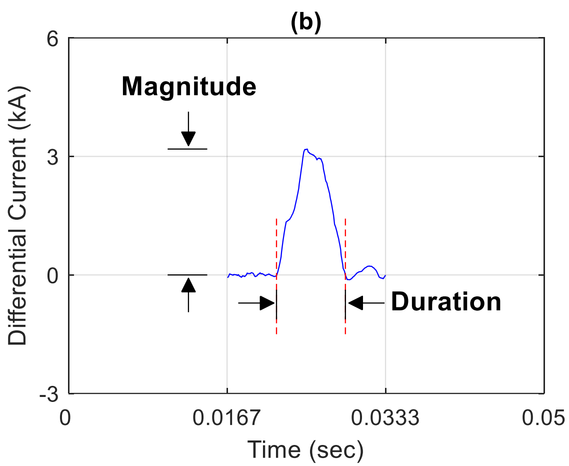
Angle, Magnitude, and Duration

• 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.



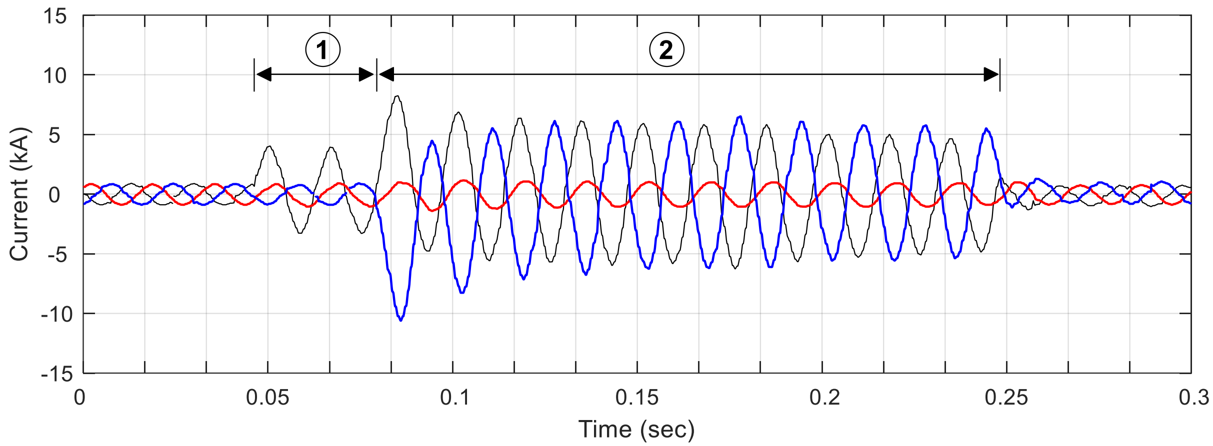
Original waveform



Differential waveform

Number of Affected Phases

• An event in waveform measurements may affect 1 phase (A, B, or C), 2 phases (A and B, A and C, or B and C), or all 3 phases (A and B and C).

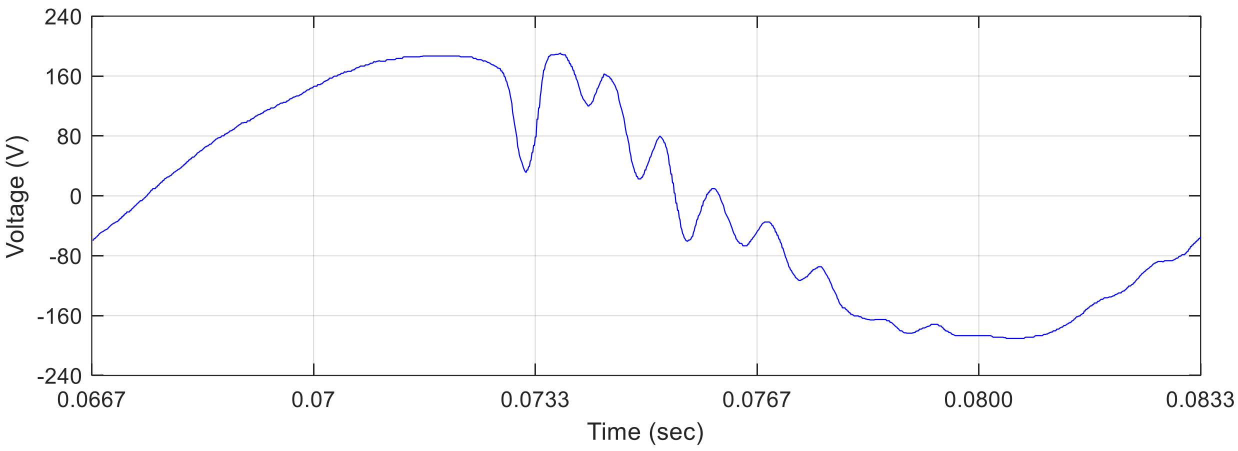


• This fault is *initially single-phase*, during the period that is marked as 1 . It then (after about two cycles) evolves into a second phase, during the period that is marked as 2 , before it is cleared by a protective device.

Transient Oscillations

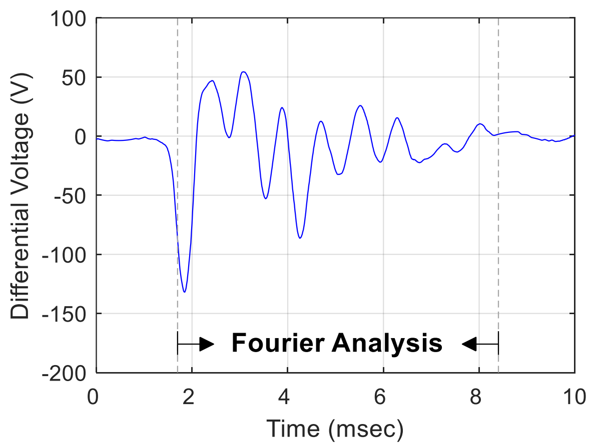
• Many events in power systems create *transient oscillations* in voltage waveforms and/or current waveforms. The duration of transient oscillations may vary from a few microseconds to several milliseconds.

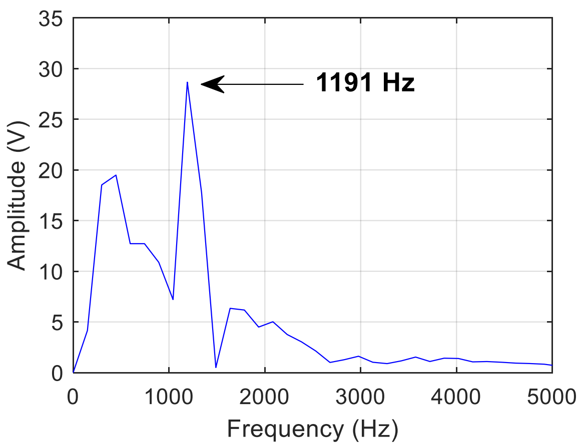
• Transient oscillations in waveform measurements are described by the *magnitude*, *duration*, and *dominant frequency* of the oscillations.



Transient Oscillations

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



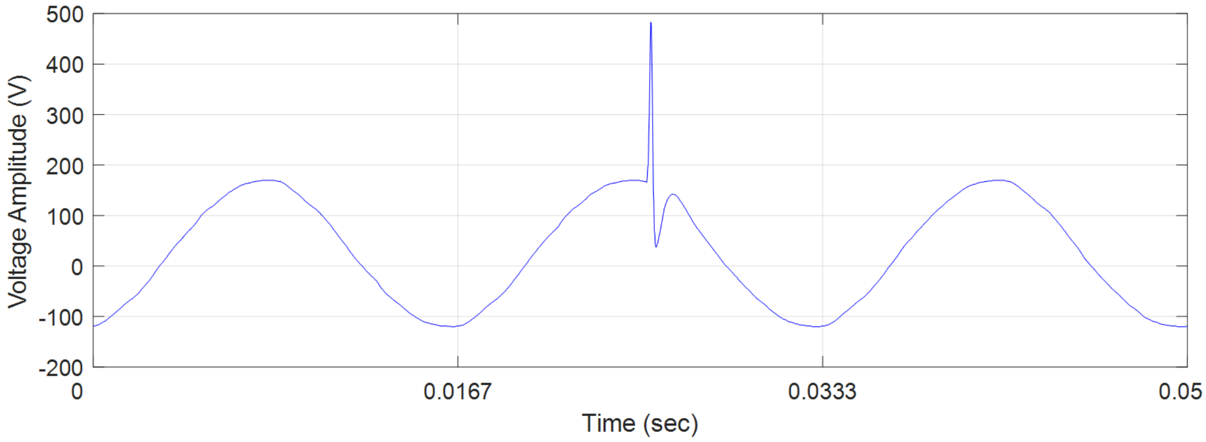


• The *dominant frequency* is about 1.2 KHz.

Transient Impulses

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

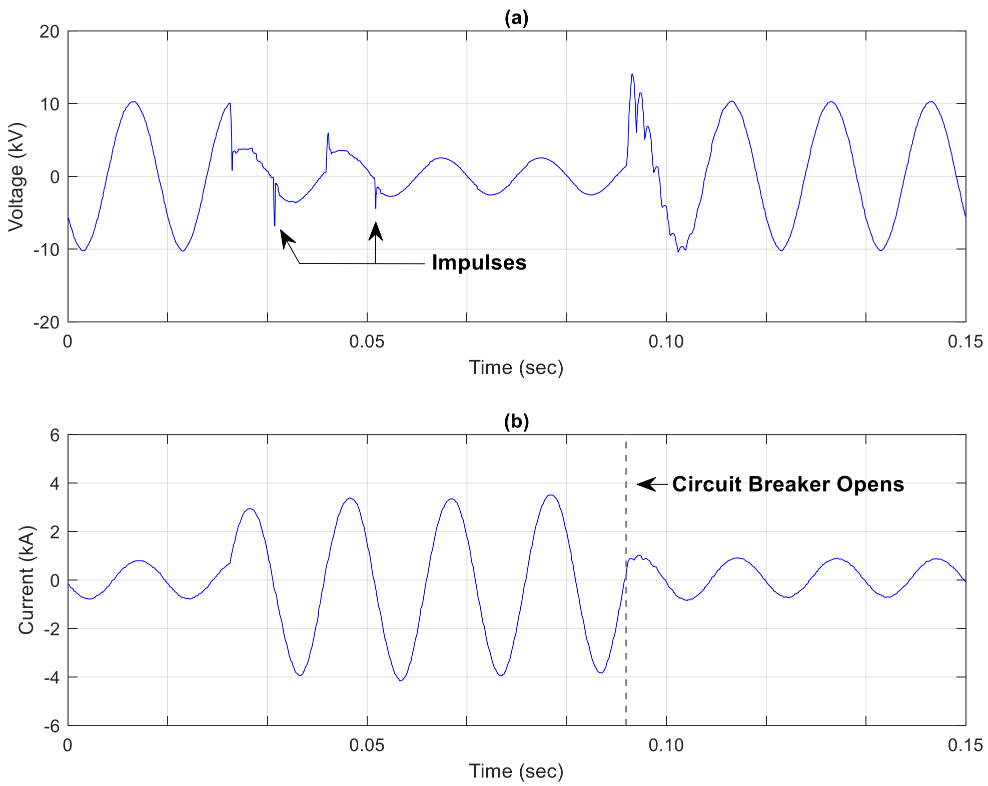
- The most common cause of impulsive transients is *lightning strike*.



Transient Impulses

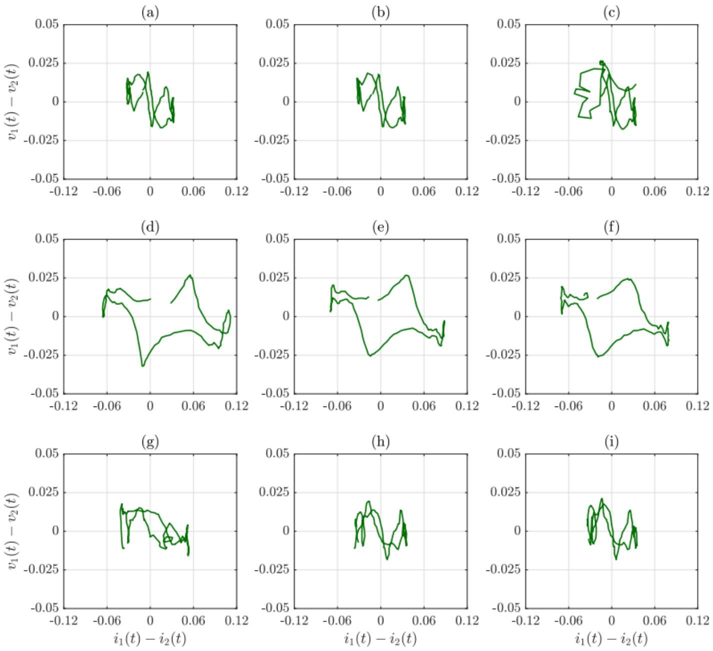
- However, certain faults may also create transient impulses.

Fault in an underground cable (at cable terminator)



Graphical Features

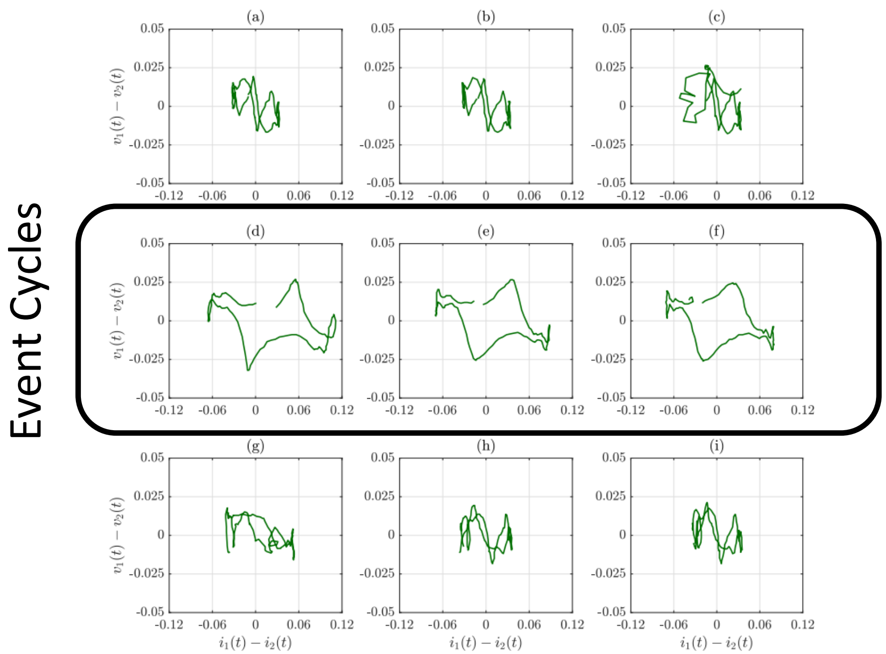
• The shape of each waveform, or the Lissajous graph (of synchronized waveforms) can serve as *images* with graphical characteristics.



Synchronized Lissajous Graph

Graphical Features

• The shape of each waveform, or the Lissajous graph (of synchronized waveforms) can serve as *images* with graphical characteristics.

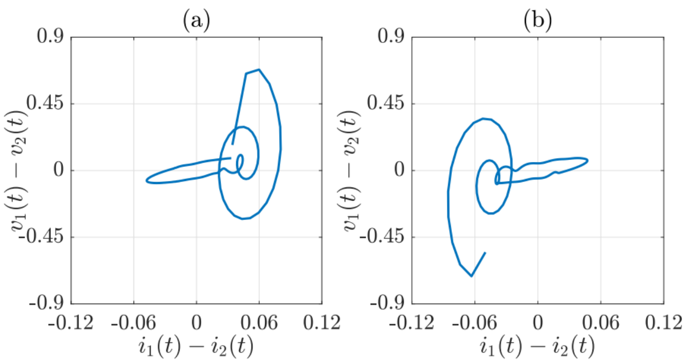


Synchronized Lissajous Graph

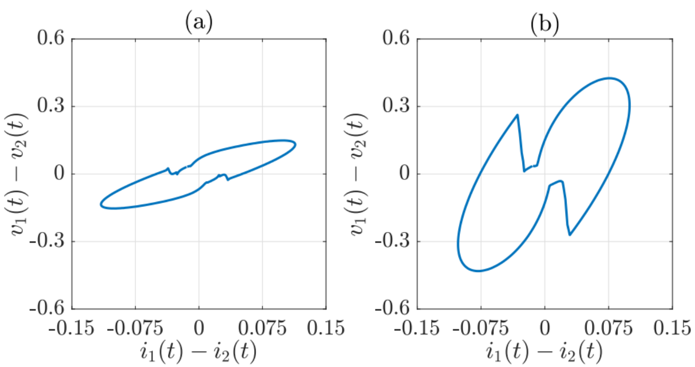
Part 2.3) Event Classification

- Characterization/Classification[3]:

  Image Processing Using Convolutional Neural Networks (CNN).



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



Same Event, *Different Locations*
(Inflated Images)

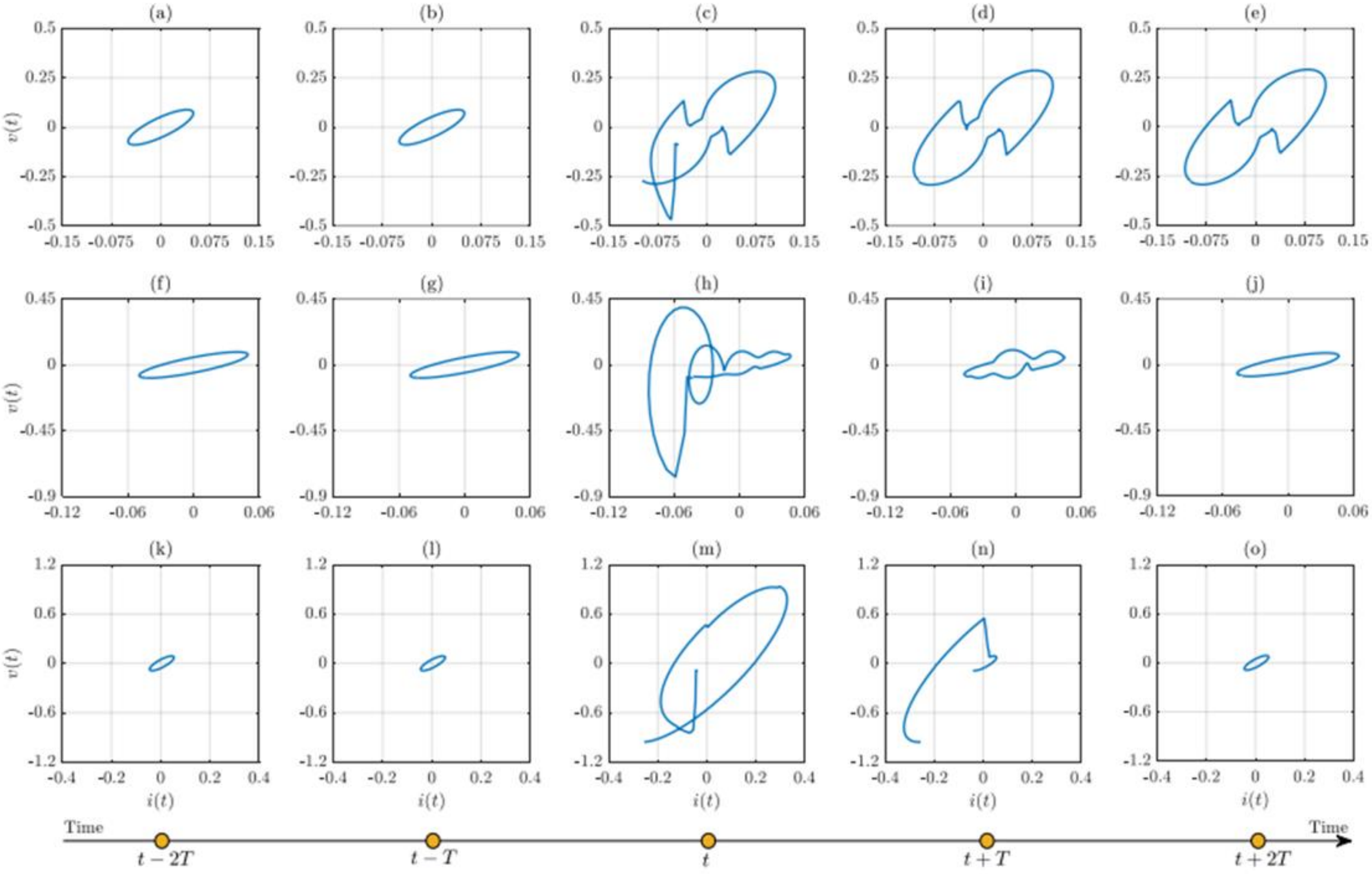
[3] M. Izadi, H. Mohsenian-Rad, " Synchronized Lissajous-based method to detect & classify events in synchro-waveform measurements in power distribution networks," in ***IEEE Trans. on Smart Grid***, vol. 13, no. 3, pp. 2170-2184, May 2022.

- Characterization/Classification[3]:

High Impedance Fault

Capacitor Bank Switching

Incipient Fault



[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.

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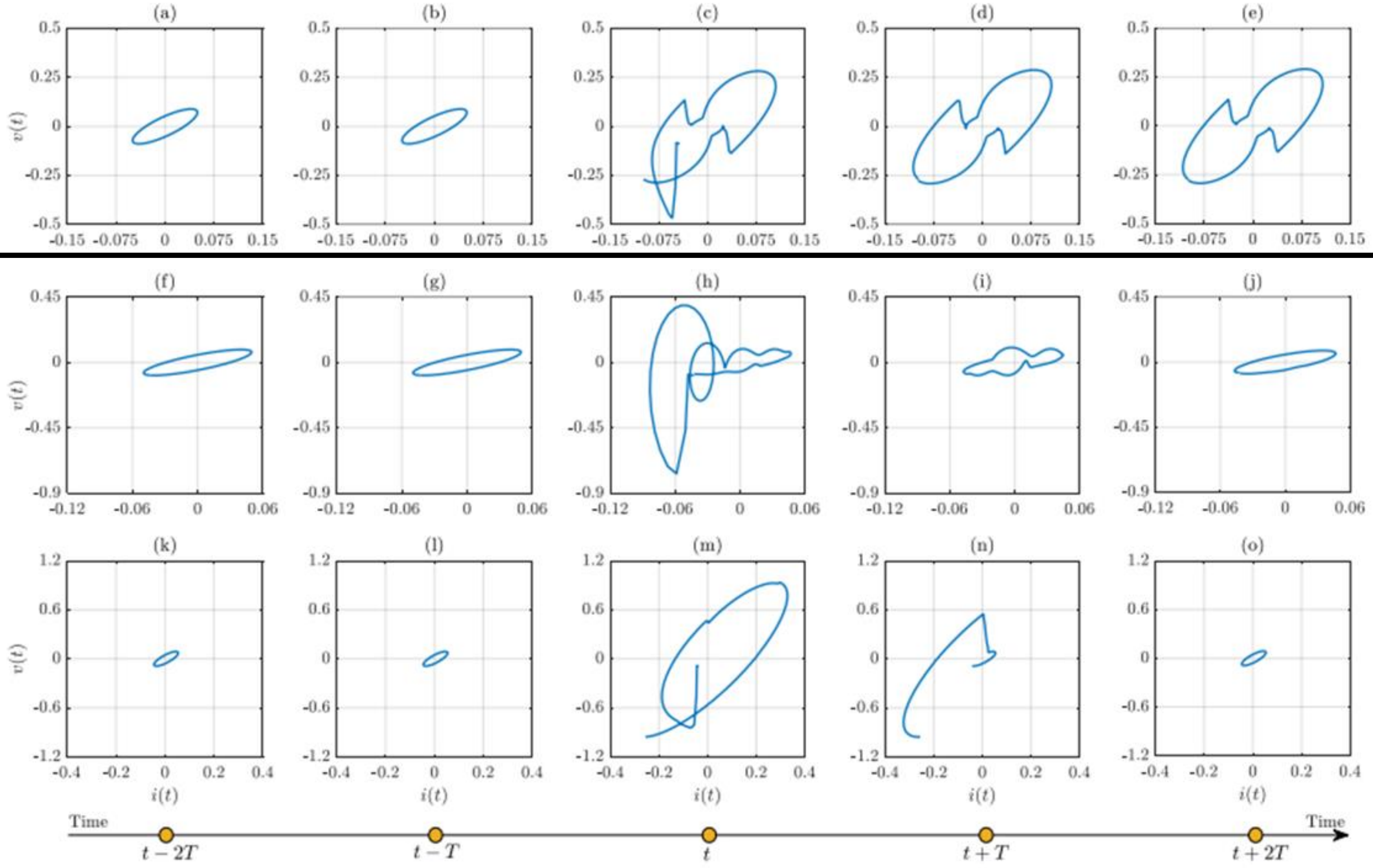

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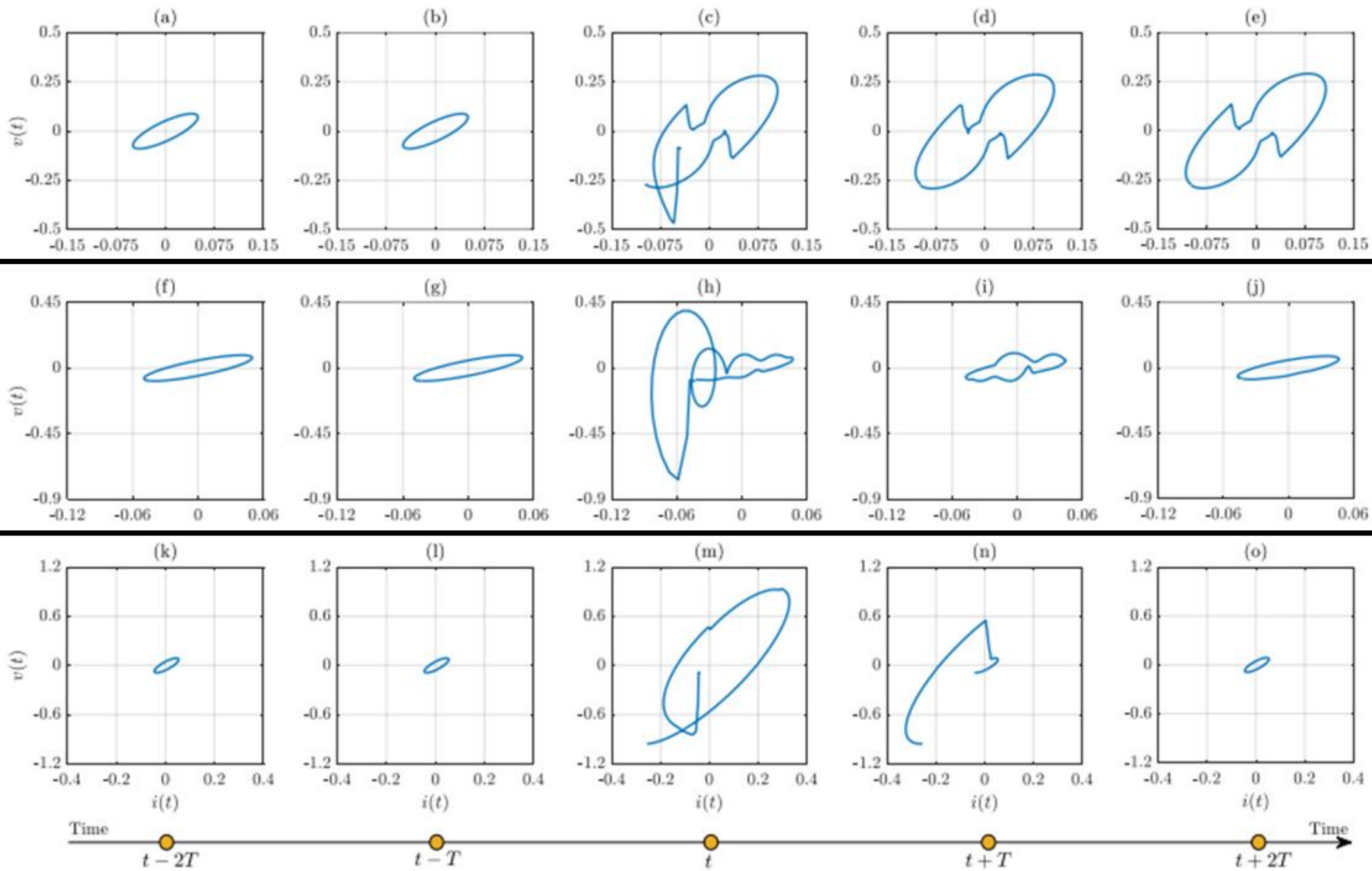

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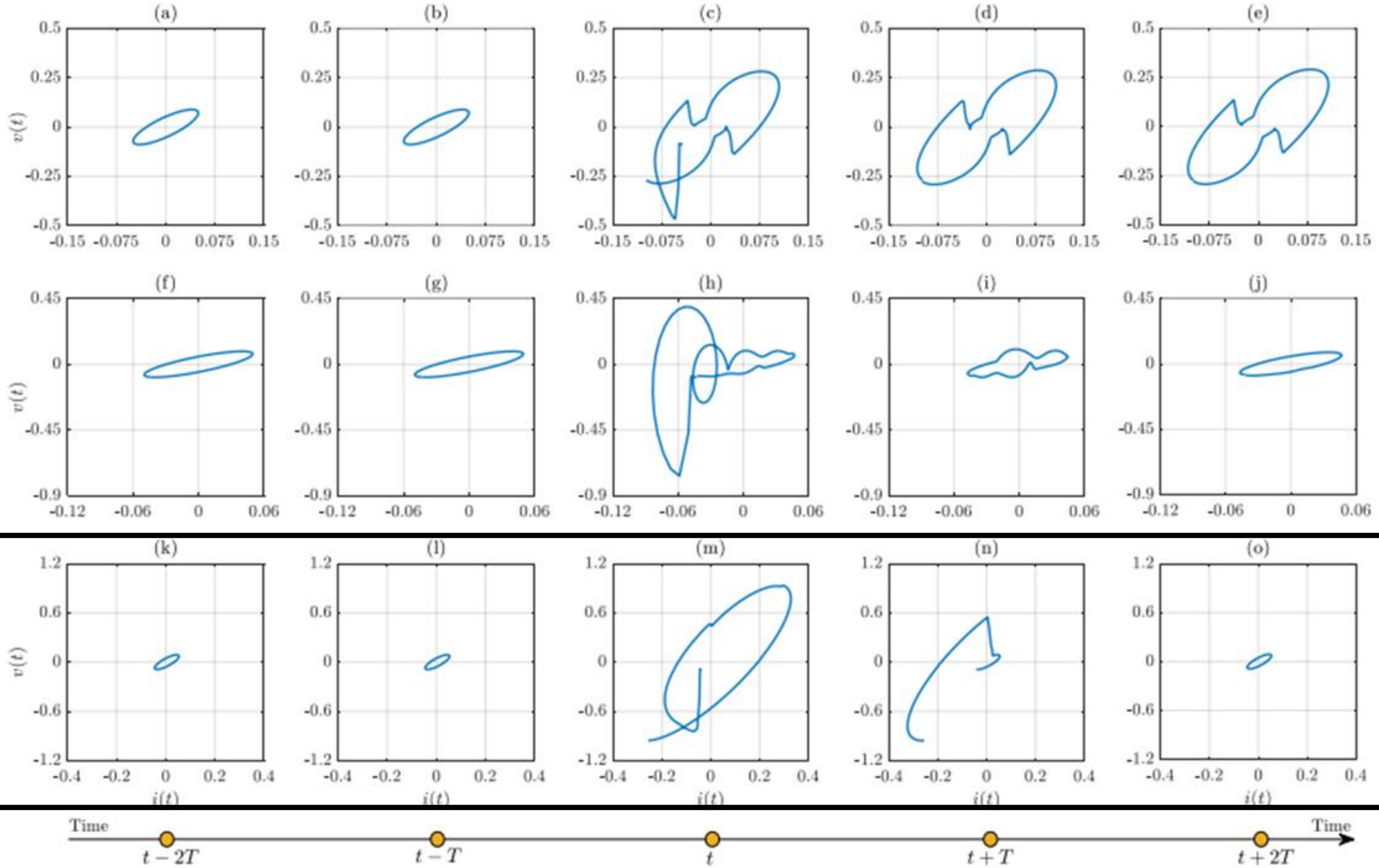


[3] M. Izadi, H. Mohsenian-Rad, " Synchronized Lissajous-based method to detect & classify events in synchro-waveform measurements in power distribution networks," in ***IEEE Trans. on Smart Grid***, vol. 13, no. 3, pp. 2170-2184, May 2022.

- Characterization/Classification[3]:

Confusion Matrix:

Accuracy: 97.22%

True Class \ Predicted Class	Class I	Class II	Class III
Class I	100.0%	0.0%	0.0%
Class II	8.3%	91.7%	0.0%
Class III	0.0%	0.0%	100.0%

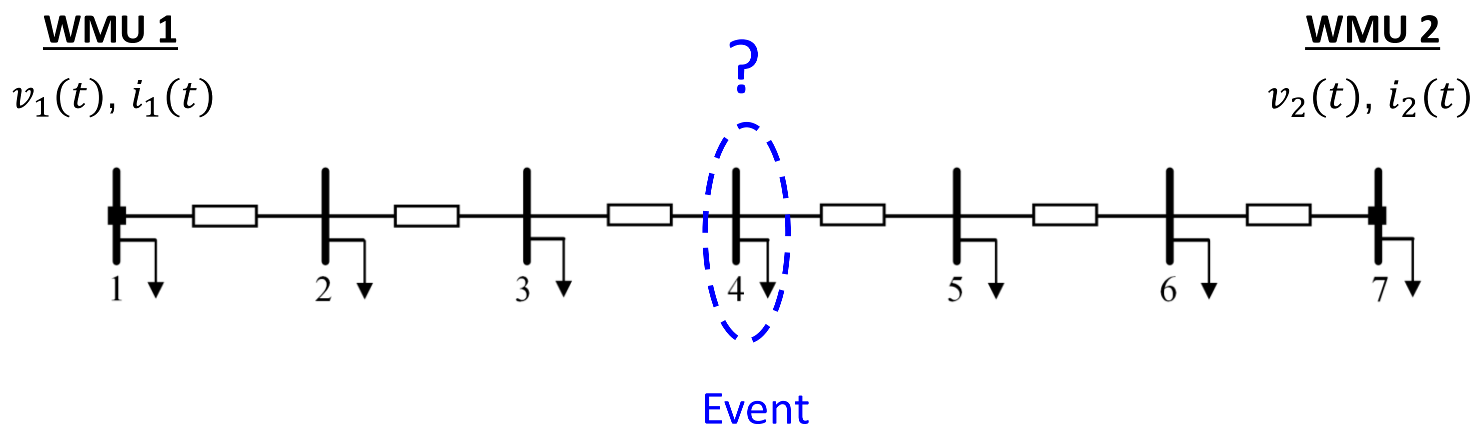
Performance:

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%

[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.

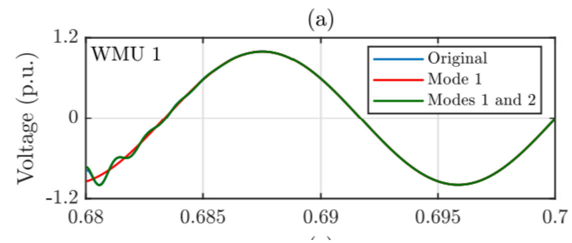
Part 2.4) Event Location Identification

- The objective is to identify the network bus where the event occurs.
  - The event occurs *somewhere between* the two WMUs
  - The two WMUs see the impact of the events at their locations.
  - Can we identify the *event bus* based on $v_1(t)$, $i_1(t)$, $v_2(t)$, $i_2(t)$?



- This can be achieved by first conducting a multi-signal modal analysis[4]:

Multi-Signal Modal Analysis



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

<u>WMU 1</u>

$v_1(t), i_1(t)$

<u>WMU 2</u>

$v_2(t), i_2(t)$

Number of Modes

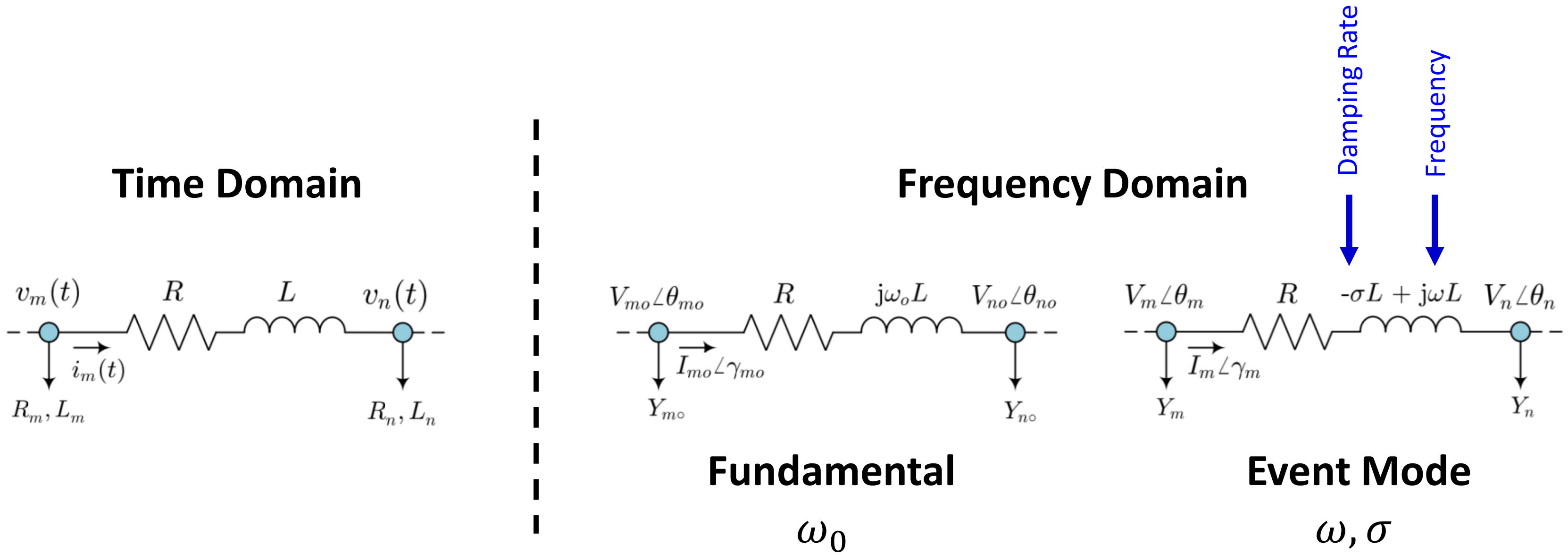
$$v_1(t) \approx \sum_{p=1}^{P} \underbrace{A_{p,m}\, e^{\sigma_p t} \cos(2\pi f_p t + \theta_p)}_{\text{Damping Sinusoidal Modes } (f_p, \sigma_p, A_{p,m}, \theta_p)}$$

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

[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. 4295-4307, September 2021.

Part 2.4) Event Location Identification

- This is followed by the analysis of the circuit in the event mode[4]:



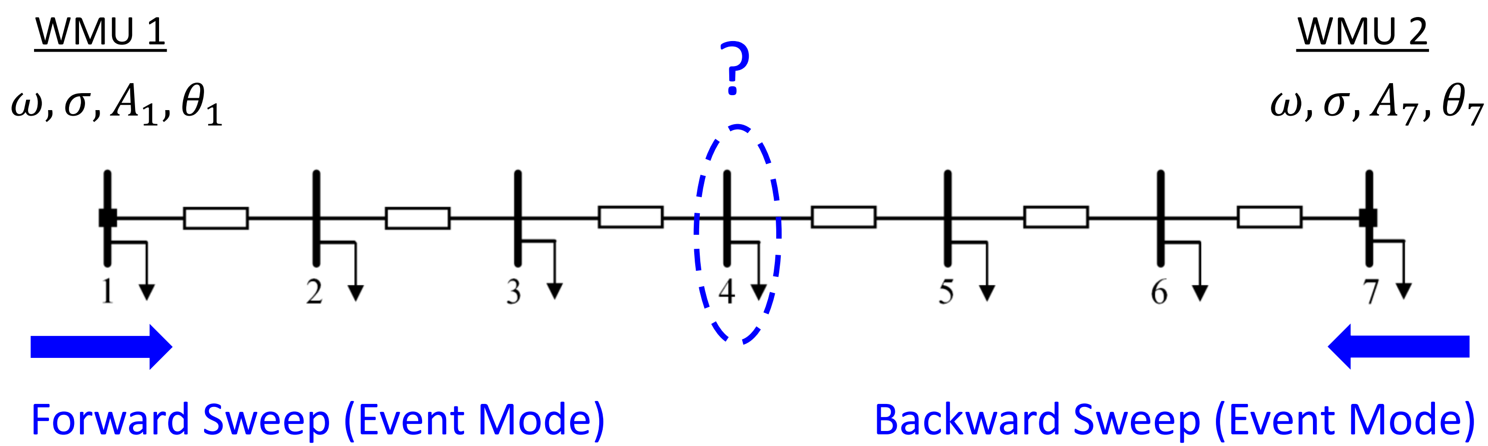
[4] M. Izadi and H. Mohsenian-Rad, “synchronous waveform measurements to locate transient events and incipient faults in power distribution networks," in ***IEEE Trans. on Smart Grid***, vol. 12, no. 5, pp. 4295-4307, September 2021.

Part 2.4) Event Location Identification

- By conducting a forward sweep from WMU 1 and a backward sweep from WMU 2, we can obtain a discrepancy index at each bus[4]:

Discrepancy

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



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Agenda

- **Part 1) Introduction, Technology, and Real-World Data**
- **Part 2) Data Analytics Methods**
- **Part 3) Applications - Current and Future**

Part 3) Applications - Current and Future

- The following topics are discussed in **Part 3**:
    - Asset Monitoring
    - Wildfire Monitoring
    - Other Applications:
        - Sub-synchronous Resonance
        - Protection,
        - …

Faults in Underground Cables

• Failures in underground cables are gradual and take place over time.

• They are often caused by *moisture penetration* into the *cable splice* (connection of two cables), which results in breakdown of the cable insulation.

Example cable joints at the time of installation, for connecting and splicing medium and high voltage underground cables.

www.powerandcables.com

• The water produces an *arc*; but then the arc quickly evaporates water, which in turn *extinguishes the arc*, making the fault *self-clearing*[1].

Faults in Underground Cables

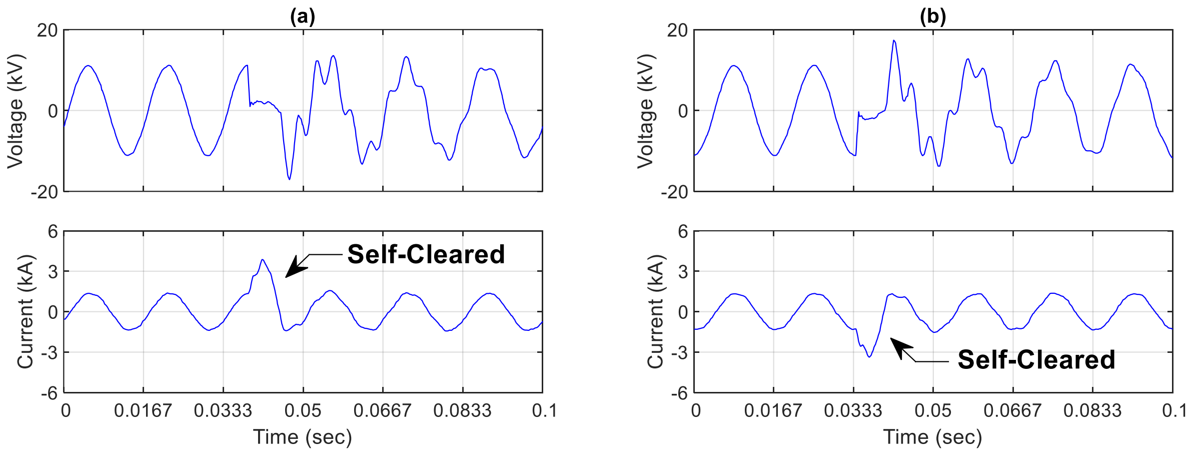
• The self-healing nature of the above fault means that *it does not trigger any overcurrent protection device*; hence, it can go unnoticed for a while.

• However, these incipient faults may ultimately turn into permanent faults after self-clearing many times and *gradually damaging the cable*.

• Once they turn permanent, they will cause the operation of the power system protection devices; losing service for several utility customers.

Faults in Underground Cables

• Her are the voltage and current waveforms during two *sub-cycle self-clearing faults* in the *same* underground cable[5].

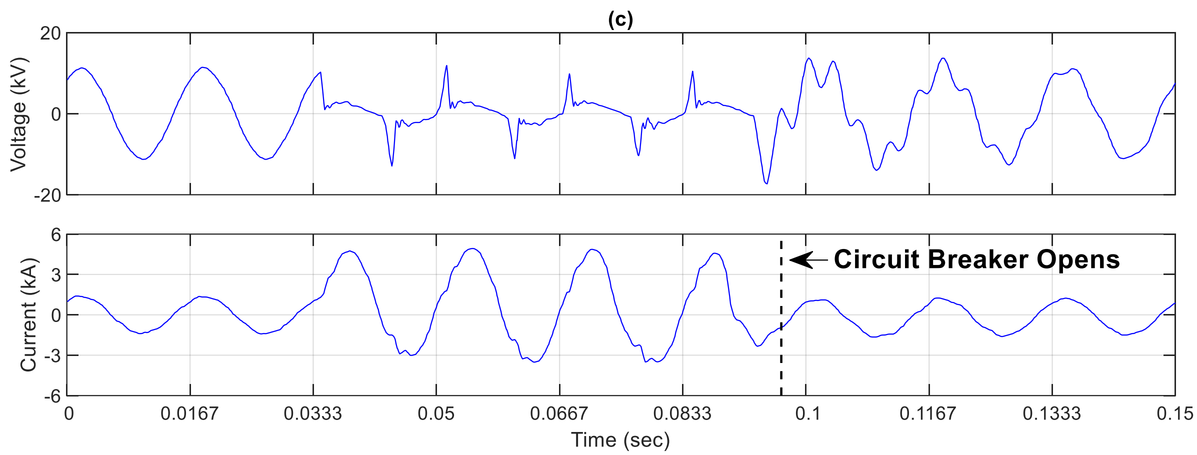


• The second fault takes place only about *1.5 hours after* the first fault.

[5] 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.

Faults in Underground Cables

• Two days later, yet another fault took place on the same underground cable. This time the fault lasted for 3 cycles, and it was cleared by an over-current circuit breaker which isolated the faulted area[5].



• The first two *incipient faults* were followed by a *permanent fault*.

[5] 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.

<u>Faults in Overhead Lines</u>

- Failures in overhead transmission and distribution lines are often due to short-circuit conditions that can be caused in different ways, such as:
    - Tree contact
    - Animal contact
    - Traffic accidents
    - Lightning

Faults in Overhead Lines

- Failures in overhead transmission and distribution lines are often due to short-circuit conditions that can be caused in different ways, such as:
  - Tree contact
  - Animal contact
  - Traffic accidents
  - Lightning
- Some of these causes are *sudden* with *no precursor* conditions.

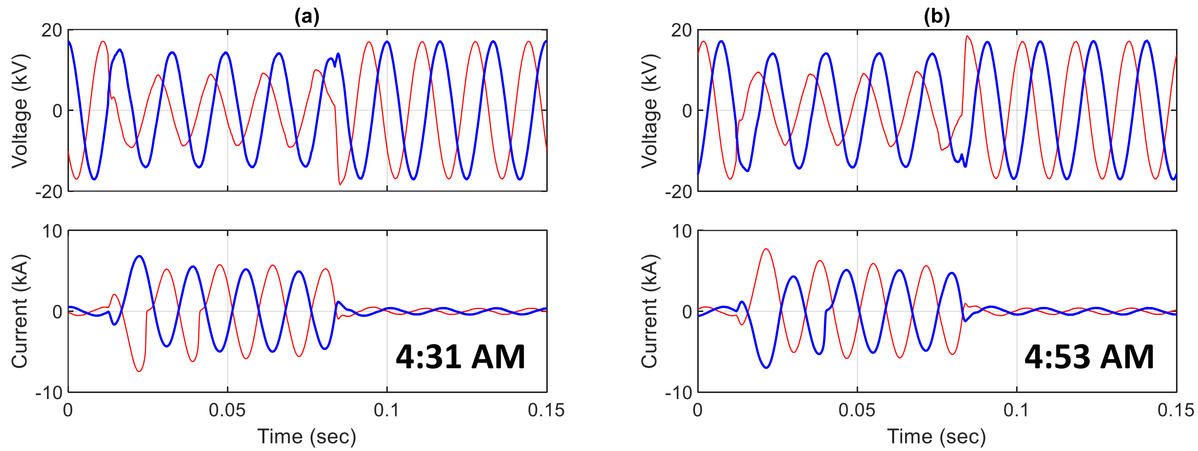
Faults in Overhead Lines

- Failures in overhead transmission and distribution lines are often due to short-circuit conditions that can be caused in different ways, such as:
    - Tree contact
    - Animal contact
    - Traffic accidents
    - Lightning

- However, some other causes may *repeat* and *evolve* into a major outage. For example, this can happen to tree contacts, due to *growth in vegetation* or during *storms and windy weather* conditions.

Faults in Overhead Lines

• Two faults that are caused by *tree contacts* to an overhead line during *windy* weather conditions[6]. The first fault happened at 4:31 AM. The second fault happened at 4:53 AM. Both faults affected only two phases.

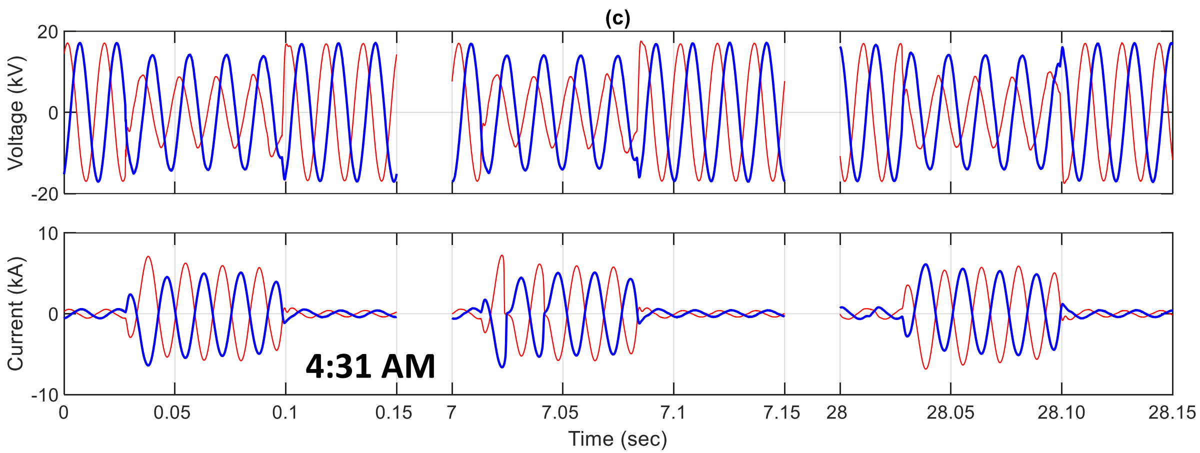


• Both faults were cleared by the circuit breakers in the power system.

[6] U.S. Department of Energy and Electric Power Research Institute, "DOE/EPRI National Database Repository of Power System Events," https://pqmon.epri.com/see_all.html.

Faults in Overhead Lines

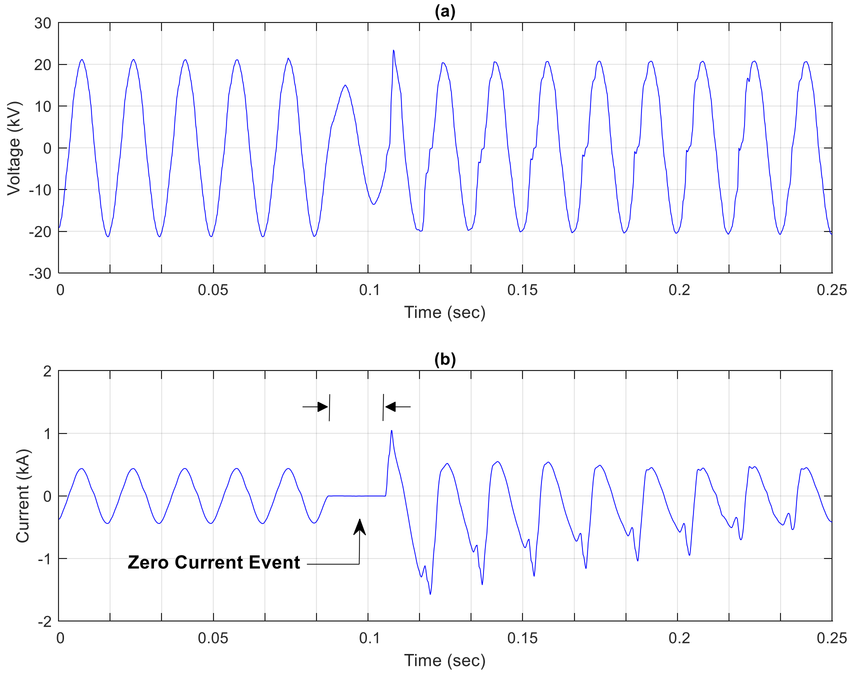
• As the storm intensified, so did the frequency of the faults by tree contacts. For instance, at 5:01 AM, *three separate faults* took place *within one min*. All of them lasted about 4 cycles before they were cleared by the re-closer.



[6] U.S. Department of Energy and Electric Power Research Institute, "DOE/EPRI National Database Repository of Power System Events," https://pqmon.epri.com/see_all.html.

Faults in Transformers

• Voltage and current waveforms are shown during a transformer tap changer incipient failure[7]. The fault occurred *during tap changing*.



[7] L. A. Irwin, "Real Experience Using Power Quality Data to Improve Power Distribution Reliability," in Proceedings of the IEEE International Conference on Harmonics and Quality of Power, Sep. 2010.

Faults in Transformers

- Initially, the fault occurred occasionally, and the duration of the *zero current period* was less than one cycle.

- However, over several days, the abnormality took place *more frequently* and *repeated* multiple times every day.

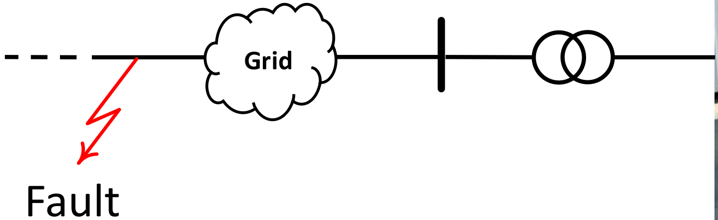
- The duration of the *zero current period* also gradually increased.

- When technicians inspected the tap changer, they discovered *a pin that was shearing* and causing *arcing* during the travel of the tap changer[7].

[7] L. A. Irwin, "Real Experience Using Power Quality Data to Improve Power Distribution Reliability," in Proceedings of the IEEE International Conference on Harmonics and Quality of Power, Sep. 2010.

Impact of Faults on DERs

- Q: How do different equipment and devices *respond* to a fault?
- Answering this question is particularly critical when it comes to *inverter-based resources*, such as most DERs (Distributed Energy Resources).
- Examples of inverter-based resources include PVs, wind turbines, stationary batteries, and grid-connected electric vehicles.

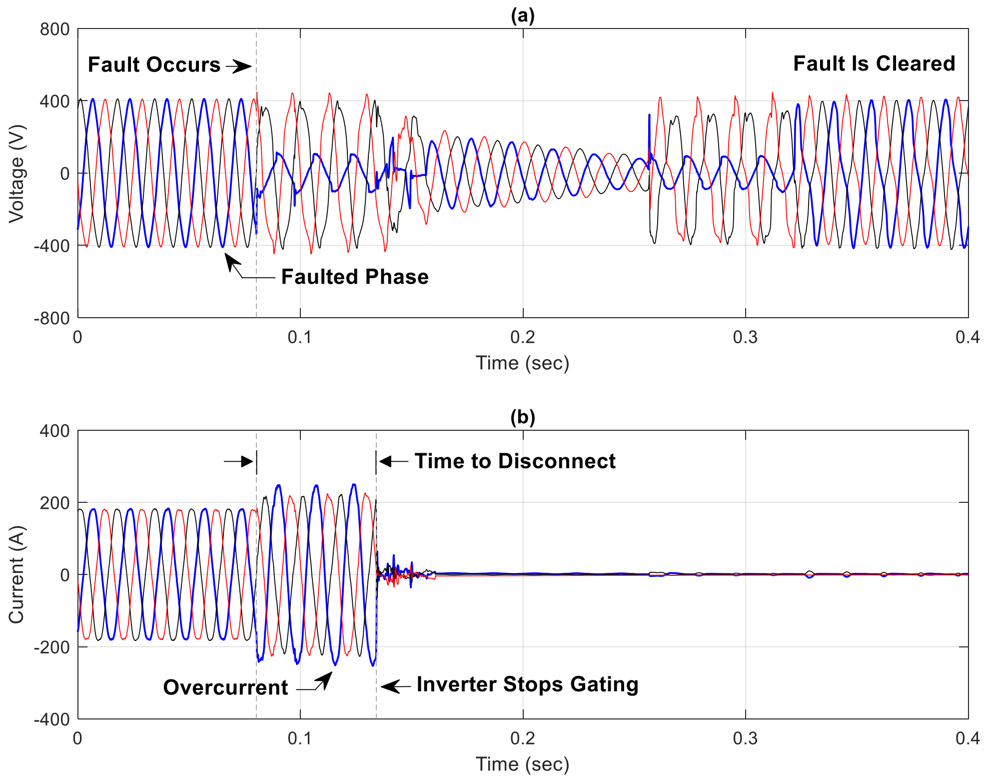


Inverter

Solar Panels

Impact of Faults on DERs

• The voltage and current waveforms of a three-phase 480 V solar PV inverter during a fault are shown below.



Impact of Faults on DERs

•The fault occurs on one phase (thick blue curve) at 0.0802 seconds, as marked by the first vertical dashed line.

• It immediately creates a *sudden drop in voltage* on the faulted phase.

• The fault also causes a surge in current at the PV unit, which quickly reaches as high as 140% of the pre-fault current.

• This ultimately causes the *inverter's protection system* to act.

• The fault is later cleared after a few cycles, *yet the PV unit stays disconnected for the next three minutes*, not shown here.

Part 3.2) Wildfire Monitoring

- Wildfire in California in 2020[8]:
  - Death: 33
  - Economic Cost: $12 Billion

www.npr.org

- Many of the California wildfires are caused by electric power issues[9]:

	FIRE NAME *(CAUSE)*	DATE	COUNTY	ACRES	*STRUCTURES*	DEATHS
1	**CAMP FIRE** *(Powerlines)*	November 2018	Butte	153,336	**18,804**	85
2	**TUBBS** *(Electrical)*	October 2017	Napa & Sonoma	36,807	**5,636**	22
3	**TUNNEL - Oakland Hills** *(Rekindle)*	October 1991	Alameda	1,600	**2,900**	25
4	**CEDAR** *(Human Related)*	October 2003	San Diego	273,246	**2,820**	15
5	**NORTH COMPLEX** *(Under Investigation)**	August, 2020	Butte, Plumas, & Yuba	318,935	**2,352**	15
6	**VALLEY** *(Electrical)*	September 2015	Lake, Napa & Sonoma	76,067	**1,955**	4
7	**WITCH** *(Powerlines)*	October 2007	San Diego	197,990	**1,650**	2
8	**WOOLSEY** *(Under Investigation)*	November 2018	Ventura	96,949	**1,643**	3
9	**CARR** *(Human Related)*	July 2018	Shasta County, Trinity	229,651	**1,614**	8
10	**GLASS FIRE** *(Under Investigation)**	September 2020	Napa & Sonoma	67,484	**1,520**	0
11	**LNU LIGHTNING COMPLEX** *(Under Investigation)**	August 2020	Napa, Solano, Sonoma, Yolo, Lake, & Colusa	363,220	**1,491**	6
12	**CZU LIGHTNING COMPLEX** *(Lightning)*	August 2020	Santa Cruz, San Mateo	86,509	**1,490**	1
13	**NUNS** *(Powerline)*	October 2017	Sonoma	54,382	**1,355**	3
14	**THOMAS** *(Powerline)*	December 2017	Ventura & Santa Barbara	281,893	**1,063**	2
15	**OLD** *(Human Related)*	October 2003	San Bernardino	91,281	**1,003**	6

[8] https://www.fire.ca.gov/incidents/2020/

[9] https://www.fire.ca.gov/media/t1rdhizr/top20_destruction.pdf

Part 3.2) Wildfire Monitoring

- Vegetation Caused Burning of a Power Line[10]

- A tree branch broke and fell on a single-phase section of a line.

- It caused a momentary fault that was cleared by a recloser.

1 Hour

- Another momentary fault occurred and it was cleared.

16 Hours

- Multiple intermittent momentary faults occurred and cleared.

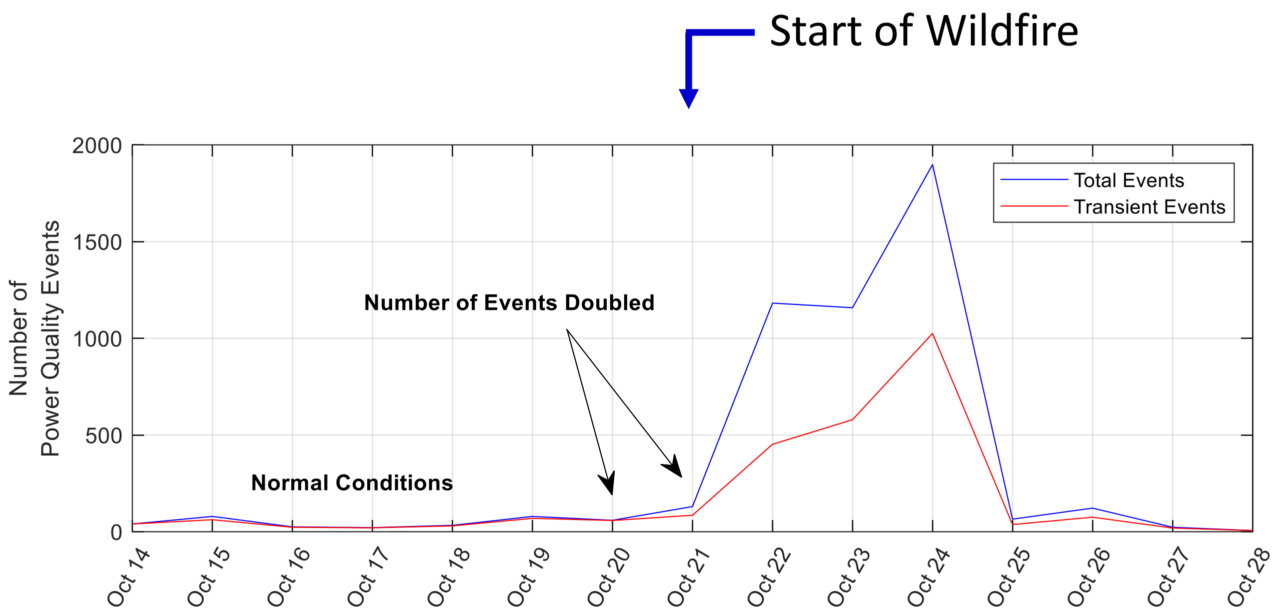
8 Hours

- Final fault burned the power line down.

24 Hours!

[10] J. A. Wischkaemper, C. L. Benner, B. D. Russell, K. Muthu Manivannan, “Application of Advanced Electrical Waveform Monitoring and Analytics for Reduction of Wildfire Risk”, in *Proc. of IEEE ISGT*, Washington, DC, 2014.

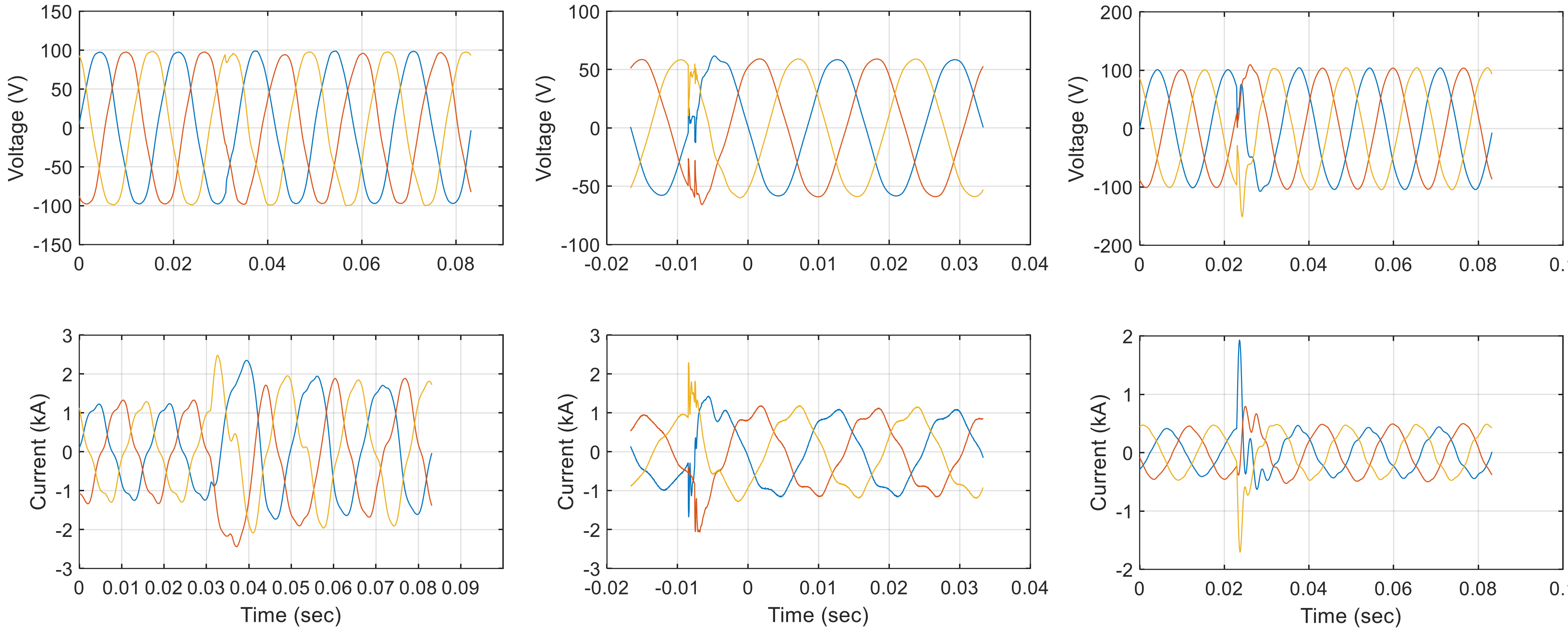
- Number of events during a wildfire in California:



- Wildfires create *huge footprints on power quality events*.

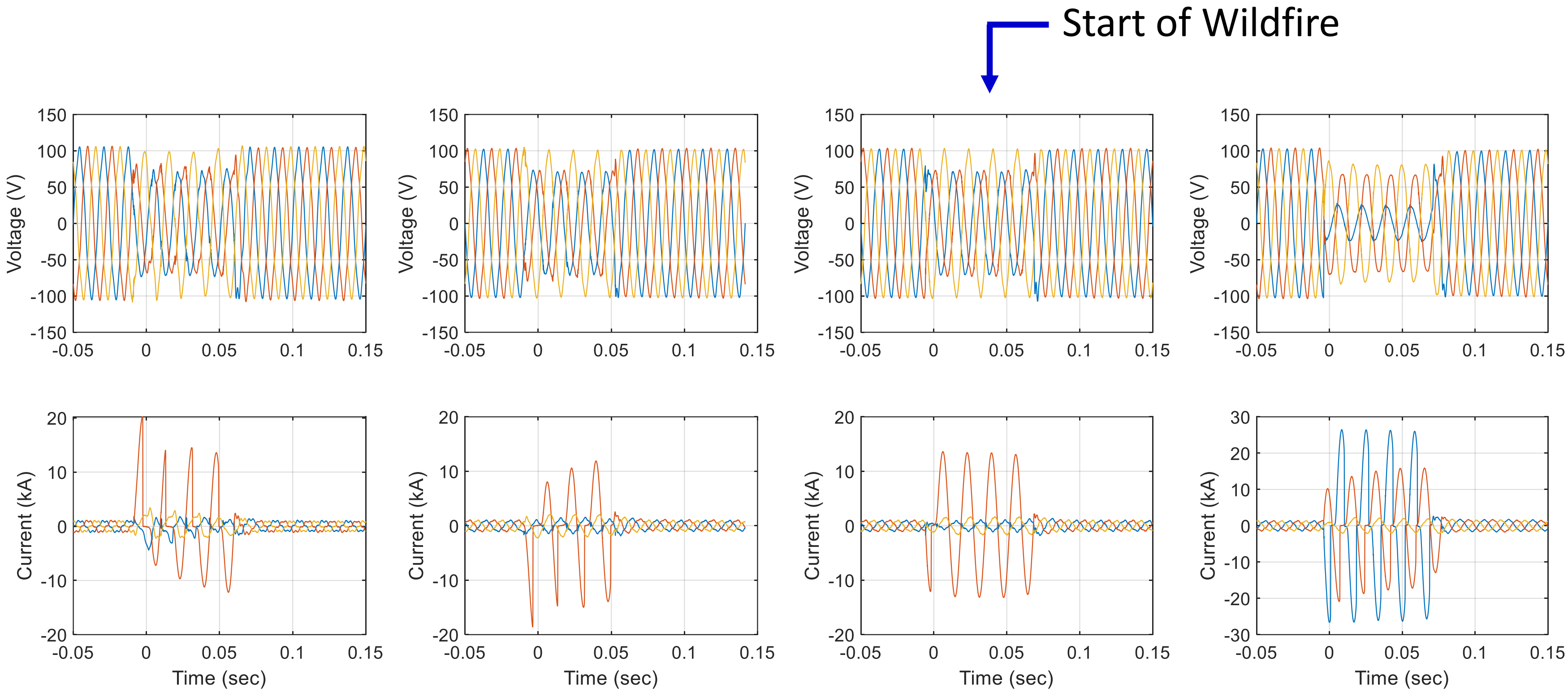
Part 3.2) Wildfire Monitoring

- Examples of various events during the period on the last slide:



Part 3.2) Wildfire Monitoring

- Possible Precursors (Ongoing Research):



23:38:05.8700	00:27:52.6680	00:35:53.7700	00:49:53.5960
Day 21	Day 22	Day 22	Day 22

Part 3.3) Other Applications

- Detecting Sub-synchronous and Super-Synchronous Resonance.
  - Incidents with 20 Hz and 80 Hz oscillations[11].
  - Cannot be detected by SCADA or PMU (fundamental) measurements.

- Enhanced Protection with Multi-Location Waveform Analysis[12].
  - Differential protection, relay coordination, distributed protection, etc.

[11] B. Gao, Y. Wang, W. Xu, and G. Yang, "Identifying and ranking sources of SSR based on the concept of subsynchronous power," *IEEE Trans. Power Delivery*, vol. 35, no. 1, pp. 258–268, Feb. 2020.

[12] W. Xu, Z. Huang , X. Xie, and C. Li, "Synchronized Waveforms – A Frontier of Data-Based Power System and Apparatus Monitoring, Protection, and Control, " *IEEE Trans. Power Delivery*, vol. 37, no. 1, February 2022.

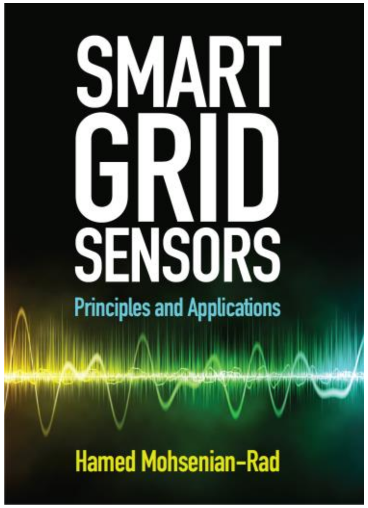
Further Reading

- 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
⋮



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Thank You!

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