

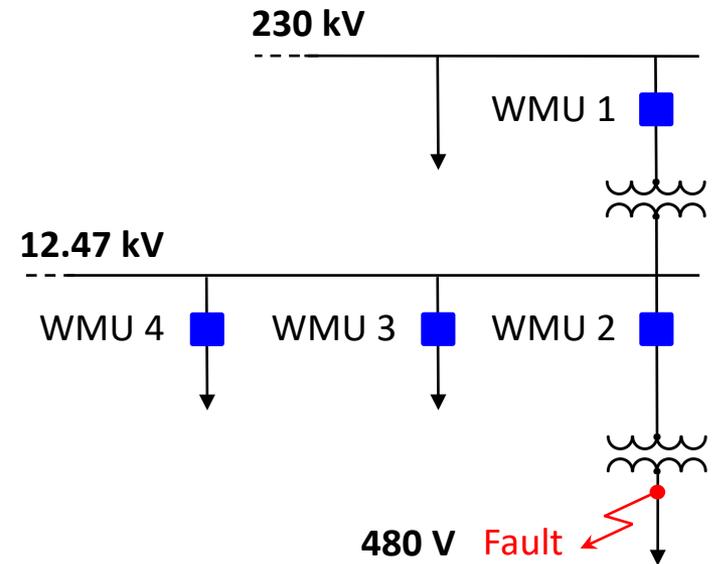
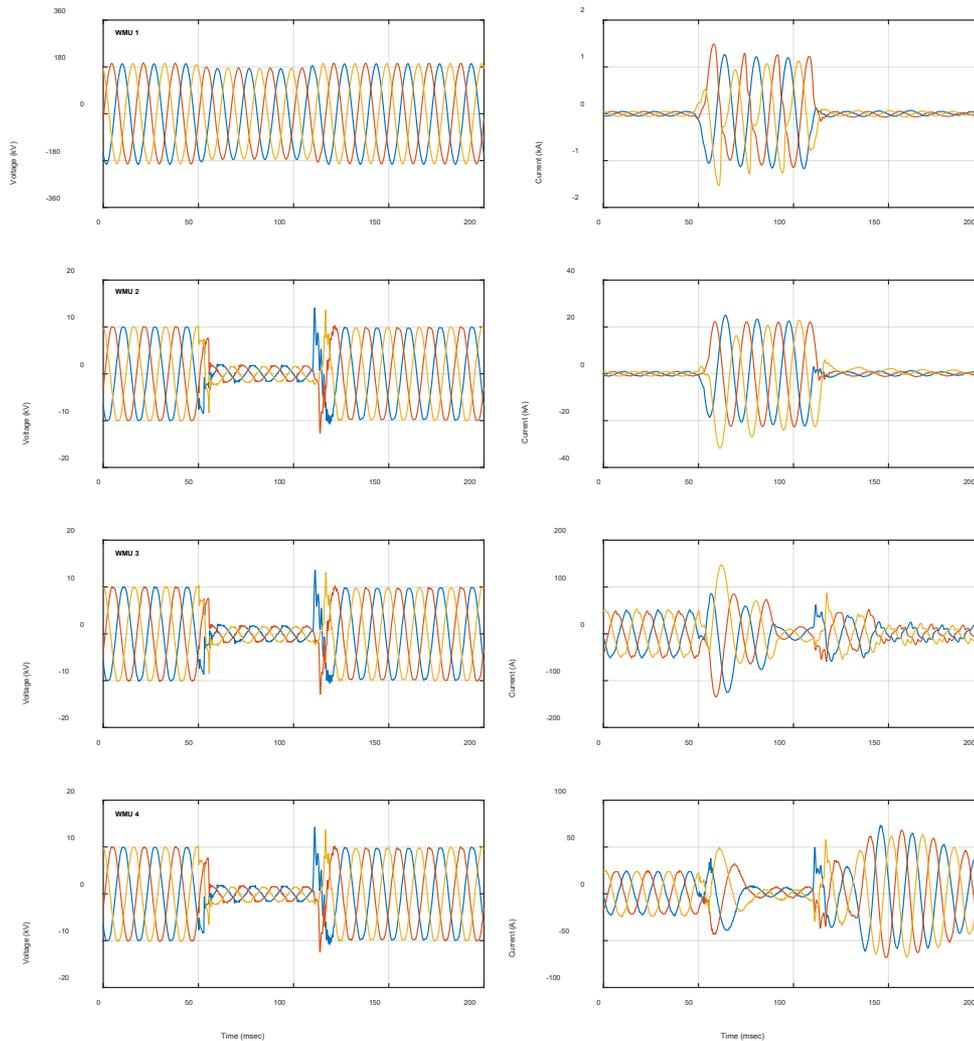
# Continuous (Gapless) Recording of Synchro-waveforms: Field Experiments and Case Studies

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

Professor and Bourns Family Faculty Fellow  
Department of Electrical and Computer Engineering  
University of California, Riverside

*Collaborators:* Alex McEachern (McEachern Lab), Richard Kirby (SEL), Manuel Cahuich (SEL), Chris Mullins (PMI), Narges Ehsani (UCR), Fatemeh Ahmadi (UCR), Zong-Jhen Ye (UCR), Hossein Mohsenzadeh (UCR), Milad Izadi (UCR), Wilsun Xu (UA), Mladen Kezunovic (TAMU), Farnoosh Rahmatian (NG)

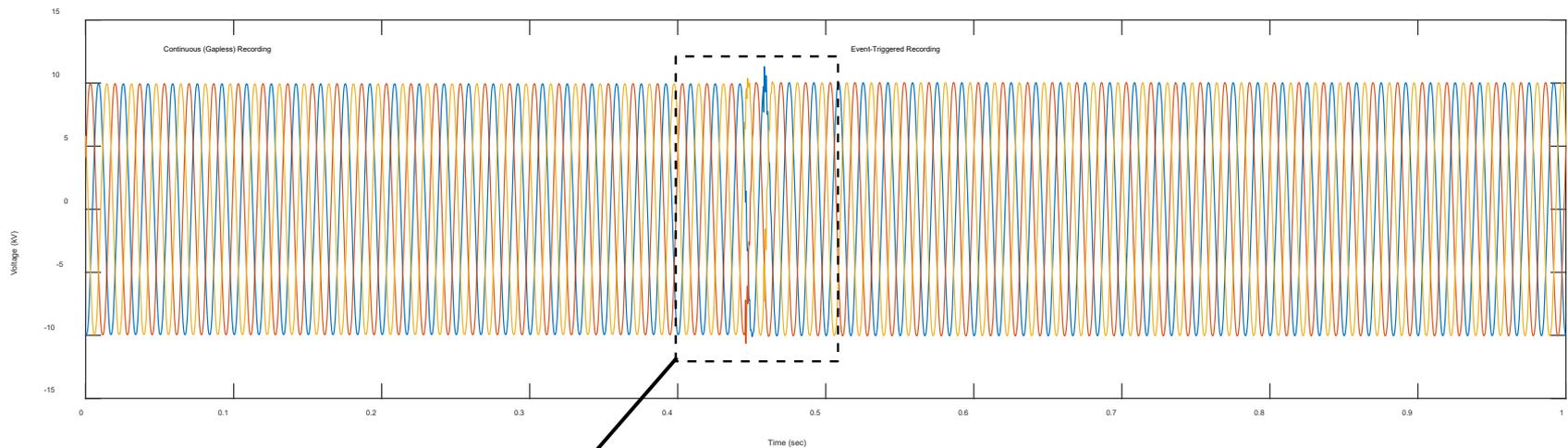
# Synchro-Waveforms



(Same Fault/Event at Different Locations)

WMU: Waveform Measurement Unit

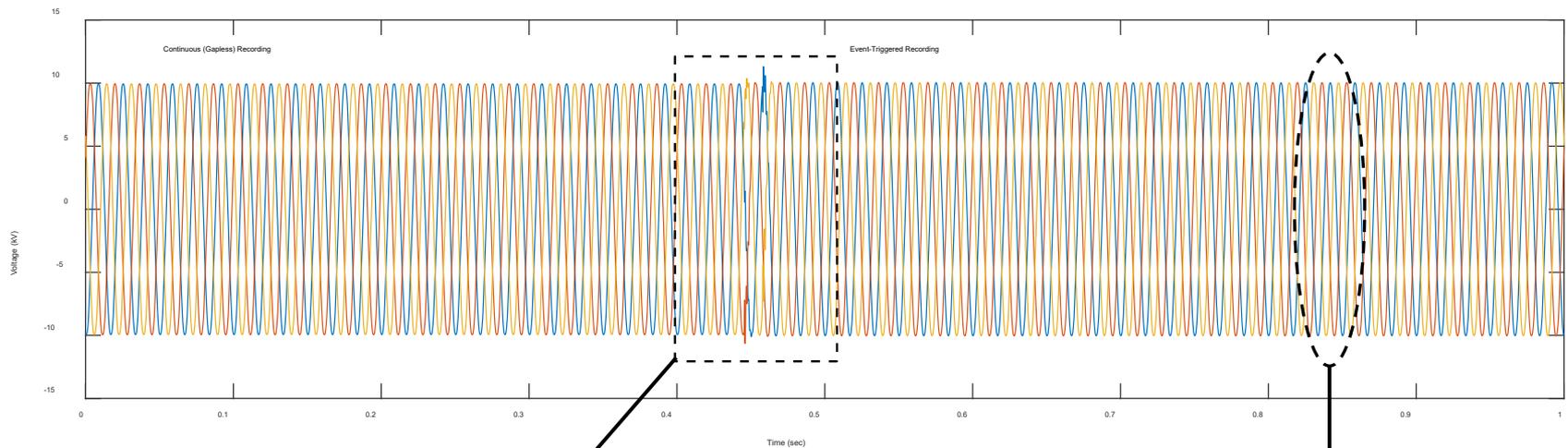
# Continuous vs. Event-Triggered Recording



## Event-Triggered Waveform Capture:

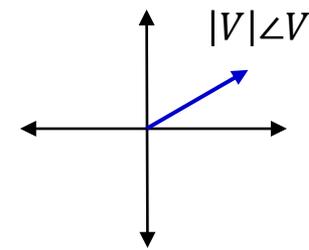
- Power Quality Meters
- Digital Fault Recorders

# Continuous vs. Event-Triggered Recording



Event-Triggered Waveform Capture:

- Power Quality Meters
- Digital Fault Recorders

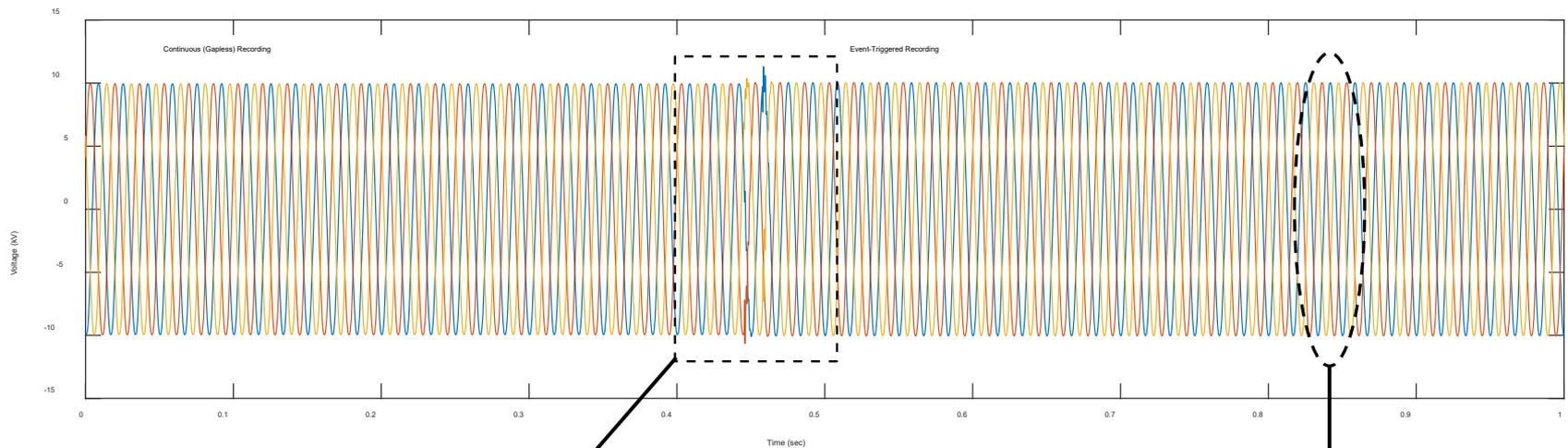


Phasor  
Extraction

Continuous *Phasor* Recording:

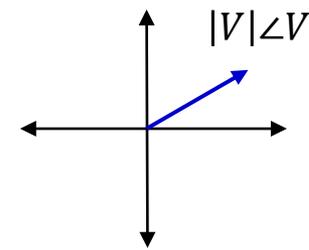
- Phasor Measurement Units

# Continuous vs. Event-Triggered Recording



Event-Triggered Waveform Capture:

- Power Quality Meters
- Digital Fault Recorders



Phasor  
Extraction

Continuous *Phasor* Recording:

- Phasor Measurement Units

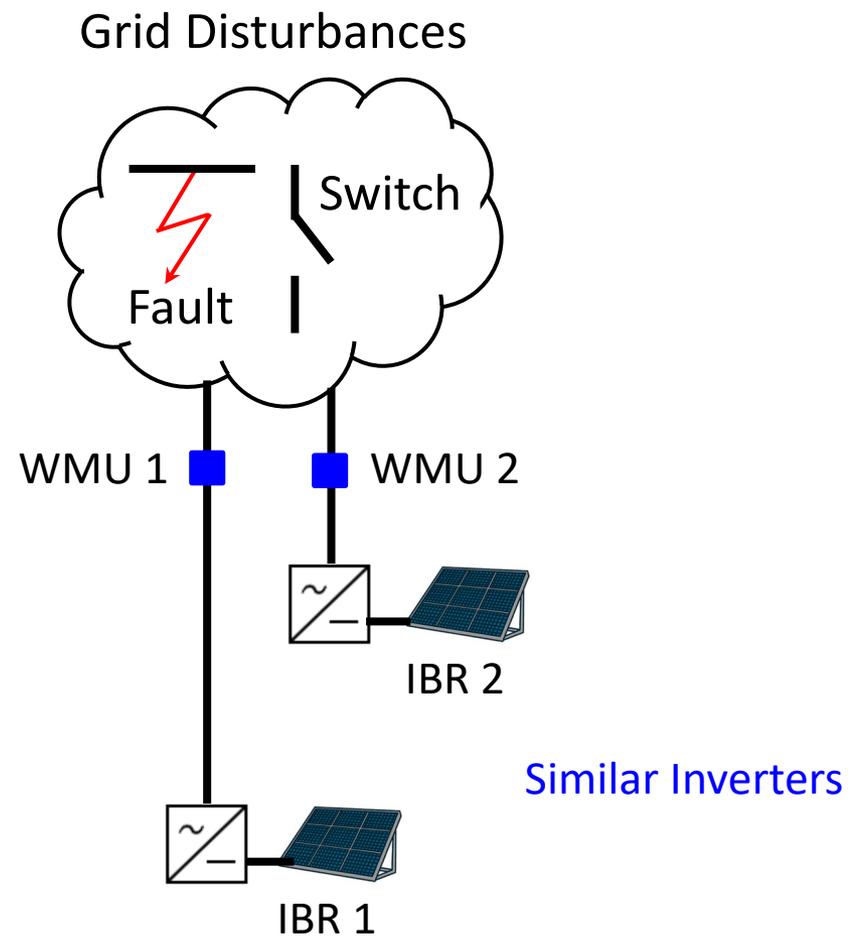
Not Yet Common for *Waveform* Measurements

# Continuous vs. Event-Triggered Recording

- In event-triggered waveform capture, there is ***no guarantee*** that all the informative cycles of the synchro-waveforms are captured at each WMU.
  - A ***tight event-capture criteria*** can result in losing important information.
  - A ***loose event-capture criteria*** can frequently trigger waveform capture where information of interest is not contained, causing additional overhead in data processing.
- Ultimately, the sole advantage of event-triggered waveform capture is to cope with the ***limitations of data storage and communication***.

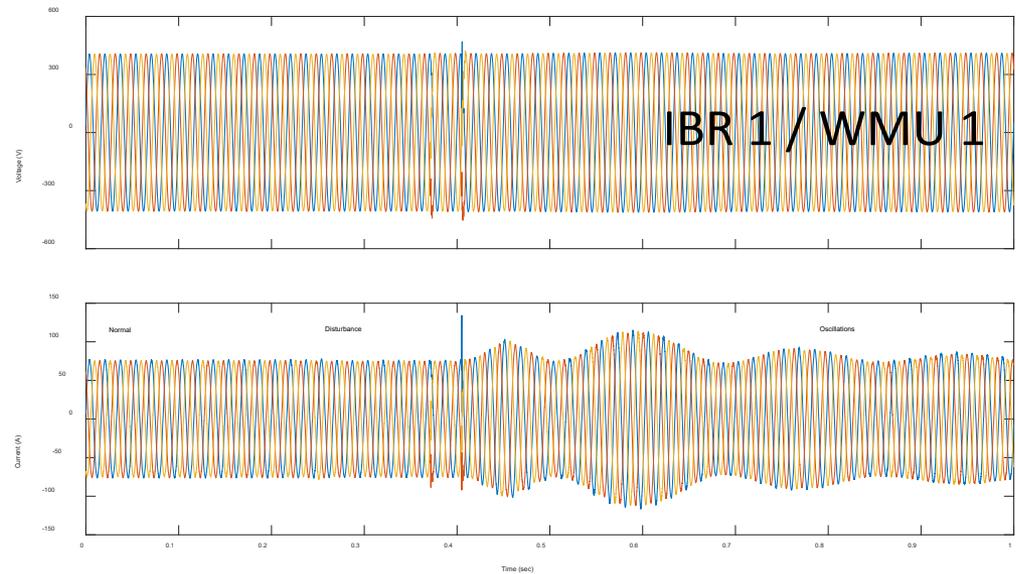
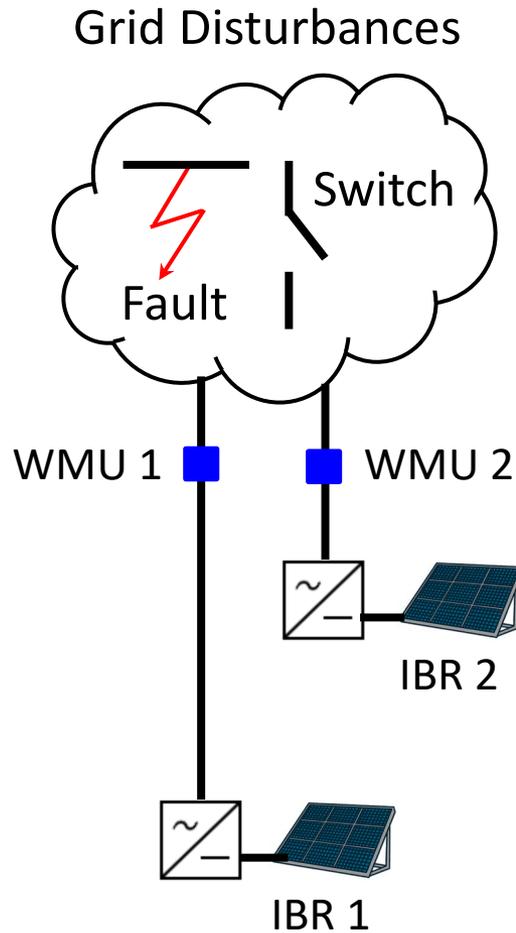
# Continuous vs. Event-Triggered Recording

- Example:



# Continuous vs. Event-Triggered Recording

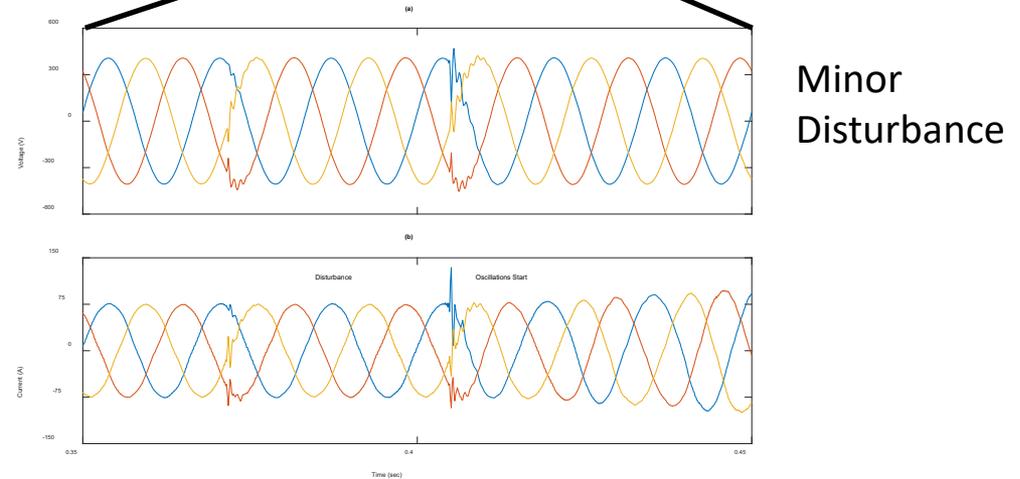
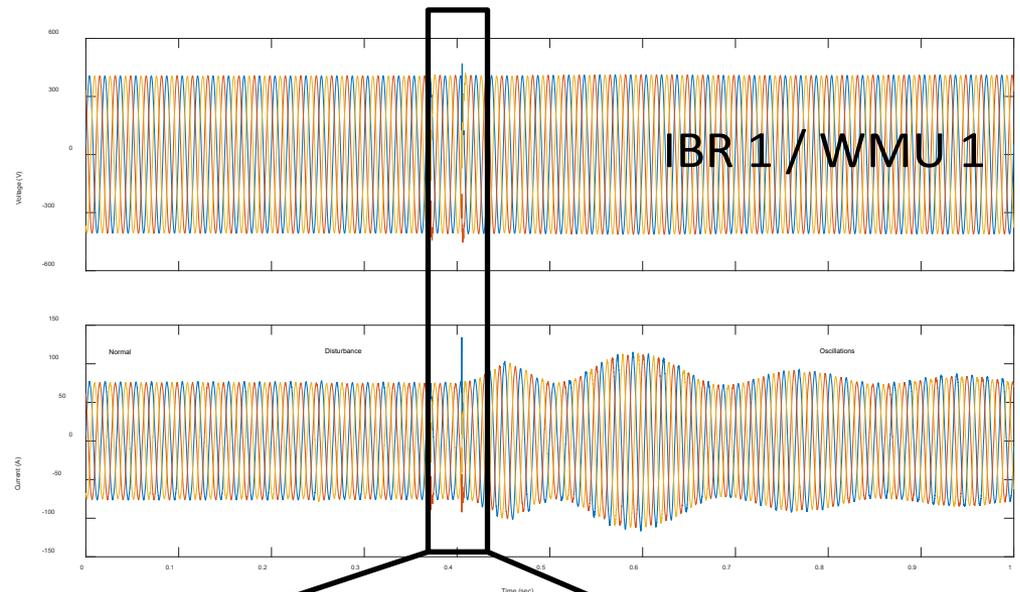
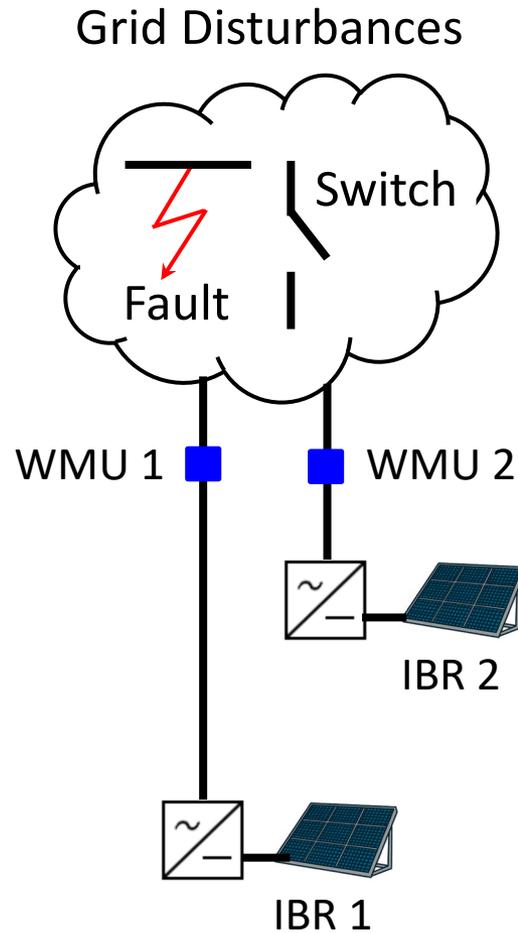
- Example:



Similar Inverters

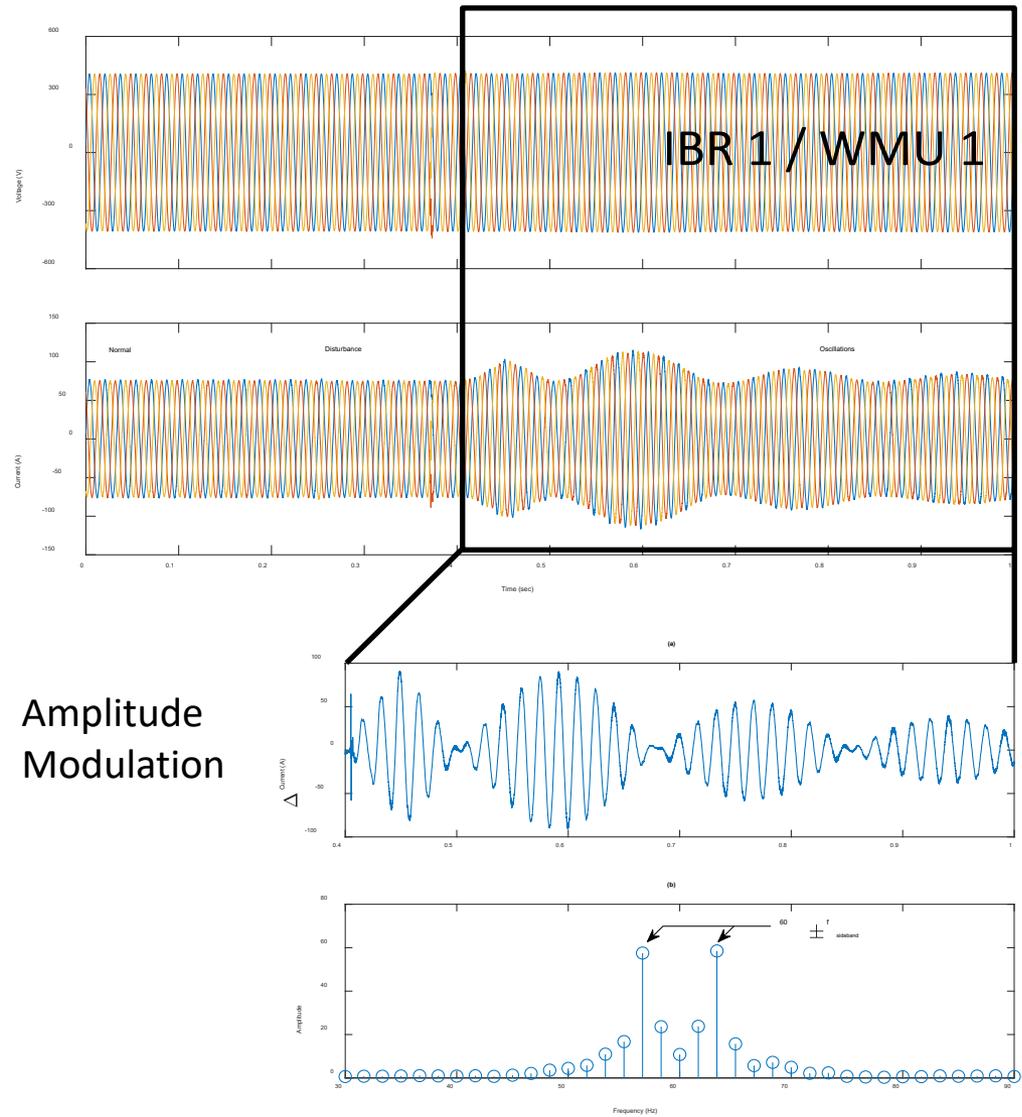
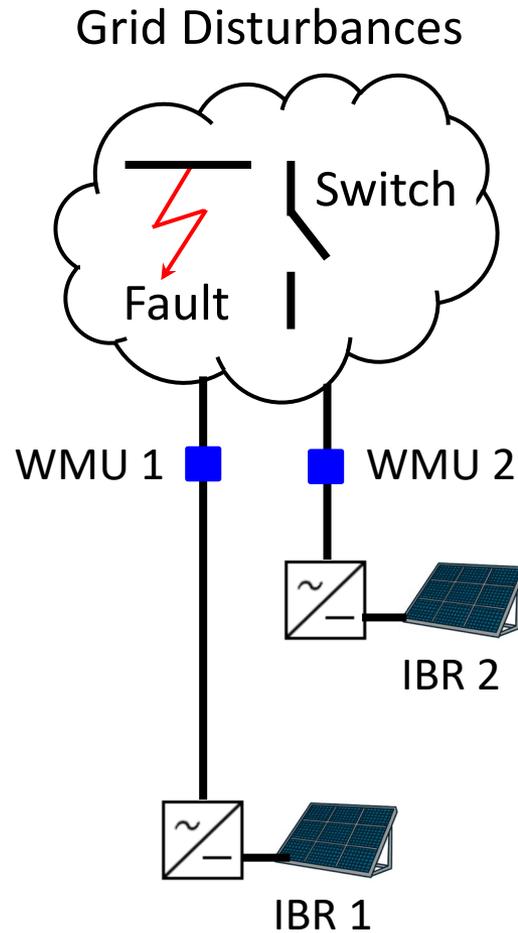
# Continuous vs. Event-Triggered Recording

- Example:



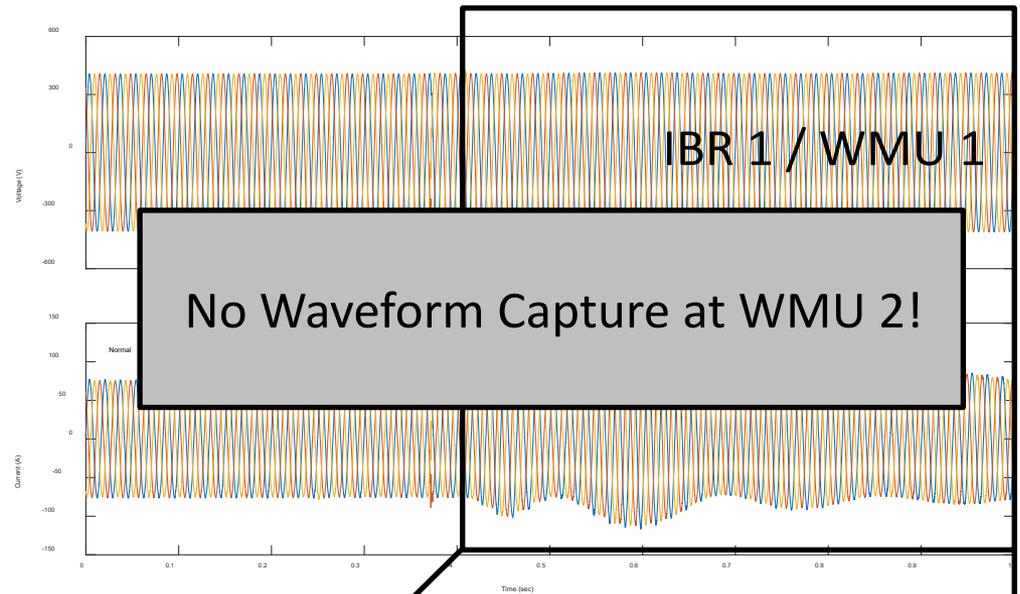
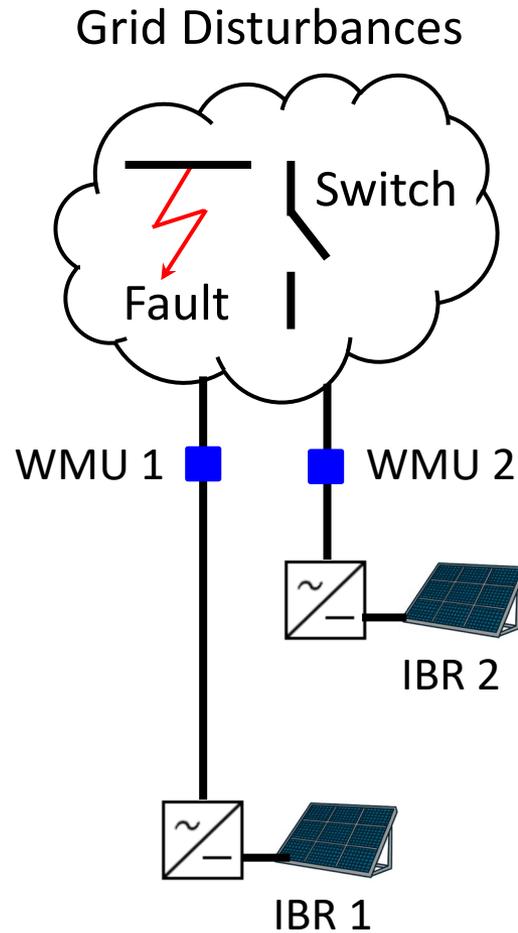
# Continuous vs. Event-Triggered Recording

- Example:

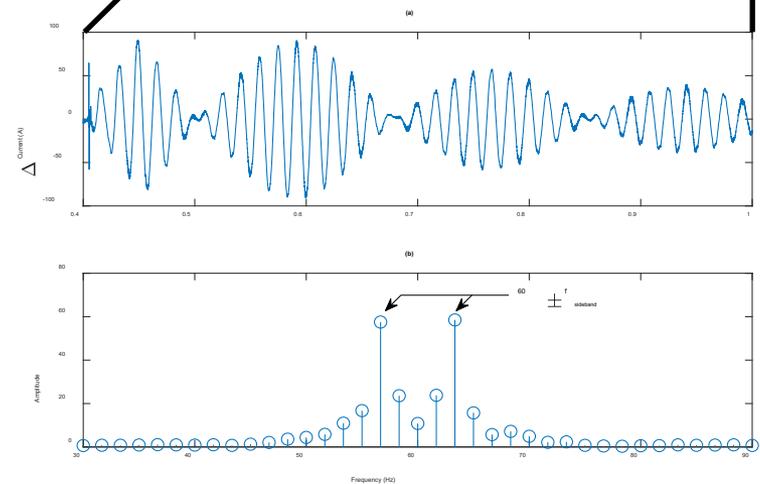


# Continuous vs. Event-Triggered Recording

- Example:



Amplitude Modulation



# Examples for Continuous (Gapless) Recording

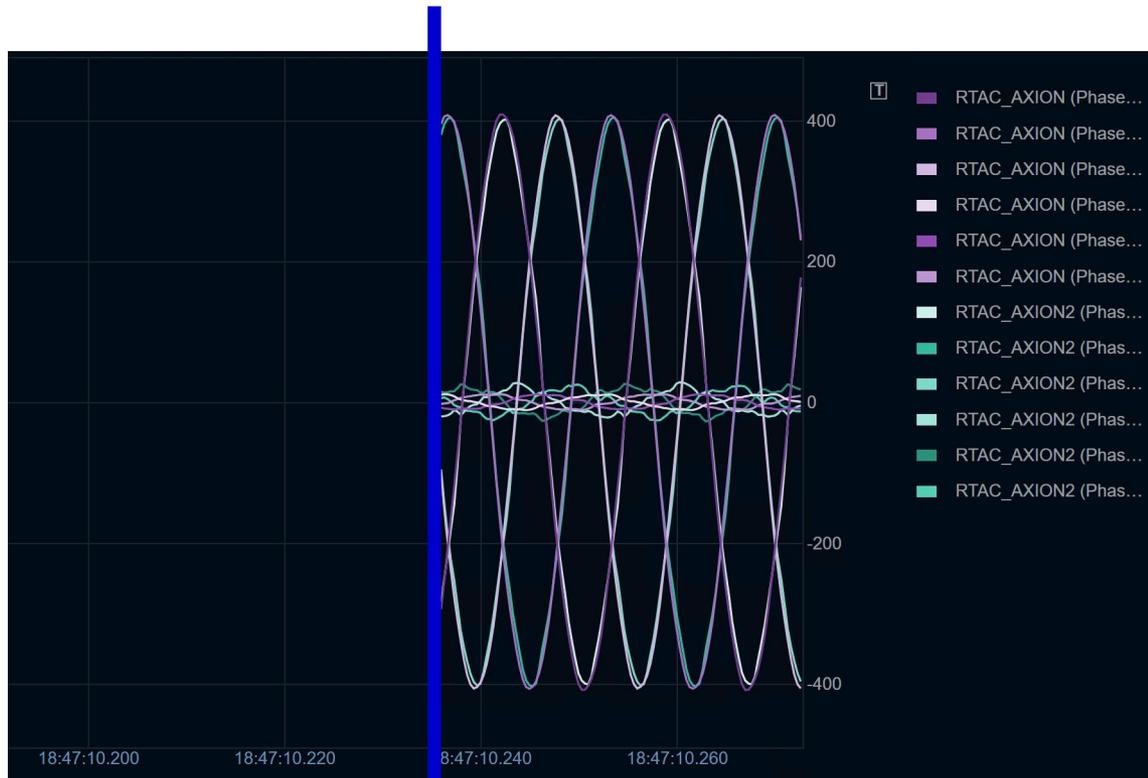
- **Local Recording** (Example: McEachern's GridSweep)

 GridSweep-6-10_2022-10-31_00-13-00_UTC	4/8/2024 7:51 AM	CSV File	4,362 KB
 GridSweep-6-10_2022-10-31_00-14-00_UTC	4/8/2024 7:51 AM	CSV File	4,362 KB
 GridSweep-6-10_2022-10-31_00-15-00_UTC	4/8/2024 7:51 AM	CSV File	4,361 KB
 GridSweep-6-10_2022-10-31_00-16-00_UTC	4/8/2024 7:51 AM	CSV File	4,361 KB
 GridSweep-6-10_2022-10-31_00-17-00_UTC	4/8/2024 7:51 AM	CSV File	4,361 KB
 GridSweep-6-10_2022-10-31_00-18-00_UTC	4/8/2024 7:51 AM	CSV File	4,362 KB
 GridSweep-6-10_2022-10-31_00-19-00_UTC	4/8/2024 7:51 AM	CSV File	4,362 KB
 GridSweep-6-10_2022-10-31_00-20-00_UTC	4/8/2024 7:51 AM	CSV File	4,361 KB
 GridSweep-6-10_2022-10-31_00-21-00_UTC	4/8/2024 7:51 AM	CSV File	4,361 KB
 GridSweep-6-10_2022-10-31_00-22-00_UTC	4/8/2024 7:51 AM	CSV File	4,362 KB
 GridSweep-6-10_2022-10-31_00-23-00_UTC	4/8/2024 7:51 AM	CSV File	4,361 KB
 GridSweep-6-10_2022-10-31_00-24-00_UTC	4/8/2024 7:51 AM	CSV File	4,361 KB
 GridSweep-6-10_2022-10-31_00-25-00_UTC	4/8/2024 7:51 AM	CSV File	4,361 KB
 GridSweep-6-10_2022-10-31_00-26-00_UTC	4/8/2024 7:51 AM	CSV File	4,361 KB
 GridSweep-6-10_2022-10-31_00-27-00_UTC	4/8/2024 7:51 AM	CSV File	4,361 KB
 GridSweep-6-10_2022-10-31_00-28-00_UTC	4/8/2024 7:51 AM	CSV File	4,361 KB
 GridSweep-6-10_2022-10-31_00-29-00_UTC	4/8/2024 7:51 AM	CSV File	4,362 KB
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 GridSweep-6-10_2022-10-31_00-33-00_UTC	4/8/2024 7:51 AM	CSV File	4,362 KB
 GridSweep-6-10_2022-10-31_00-34-00_UTC	4/8/2024 7:51 AM	CSV File	4,362 KB
 GridSweep-6-10_2022-10-31_00-35-00_UTC	4/8/2024 7:51 AM	CSV File	4,362 KB
 GridSweep-6-10_2022-10-31_00-36-00_UTC	4/8/2024 7:51 AM	CSV File	4,362 KB
 GridSweep-6-10_2022-10-31_00-37-00_UTC	4/8/2024 7:51 AM	CSV File	4,362 KB
 GridSweep-6-10_2022-10-31_00-38-00_UTC	4/8/2024 7:51 AM	CSV File	4,362 KB

← Each File: One Minute

# Examples for Continuous (Gapless) Recording

- **Local Recording** (Example: McEachern's GridSweep)
- **Streaming through Ethernet** (Example: SEL's Axion)



Screenshot  
at Data Server

Stream Starts

# Examples for Continuous (Gapless) Recording

- **Local Recording** (Example: McEachern's GridSweep)
- **Streaming through Ethernet** (Example: SEL's Axion)
- **Streaming to Cloud** (Example: PMI's Seeker)

The screenshot shows a JupyterLab interface. On the left is a file browser for the directory '/ 3\_22\_2024 /'. It contains a table of files:

Name	Last Modified
2024_03_04_11_37_36_WMU...	15 days ago
2024_03_13_14_32_51_WMU1...	14 days ago
2024_03_13_14_32_51_WMU2...	14 days ago
2024_03_20_17_07_59_WMU1...	14 days ago
2024_03_20_17_08_00_WMU...	14 days ago
2024_03_20_17_38_09_WMU1...	14 days ago
2024_03_20_17_38_10_WMU1...	14 days ago

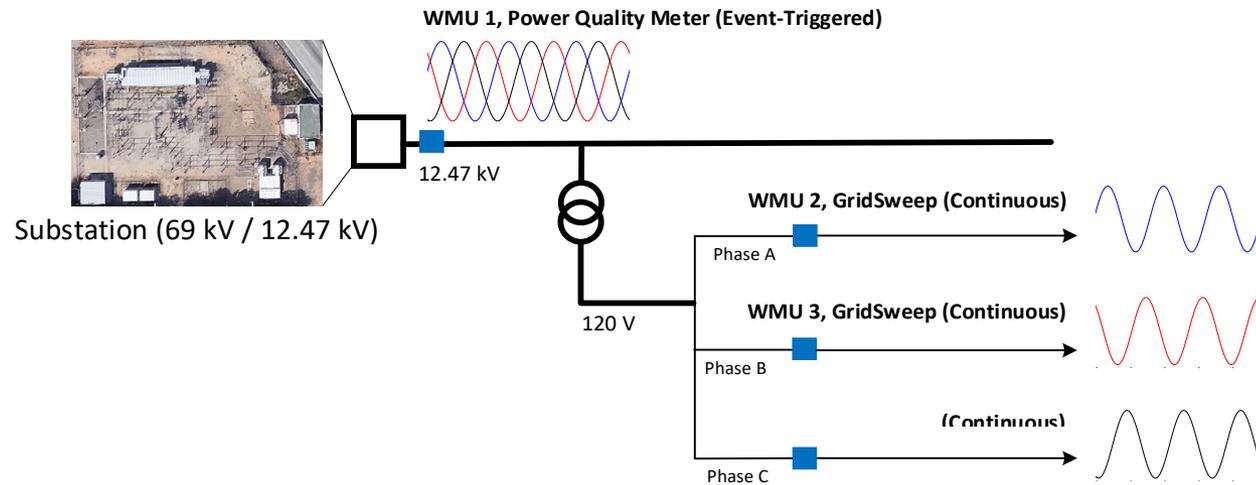
On the right is a code editor for a Python 3 (ipykernel) environment. The code is as follows:

```
33 return pq.query(request)
34
35 # Function to save data to CSV
36 def save_to_csv(data, timestamps, filename):
37     with open(filename, 'w', newline='') as csvfile:
38         csvwriter = csv.writer(csvfile)
39         csvwriter.writerow(['Timestamp', 'V1', 'I1', 'V2', 'I2', 'V3', 'I3']) # Wri
40
41     for timestamp, v1, i1, v2, i2, v3, i3 in zip(timestamps, *data):
42         csvwriter.writerow([timestamp, v1, i1, v2, i2, v3, i3])
43
44
45 # Define parameters
46 path = "/mnt/process/600000"
47 pq = precision_query(path)
48
```

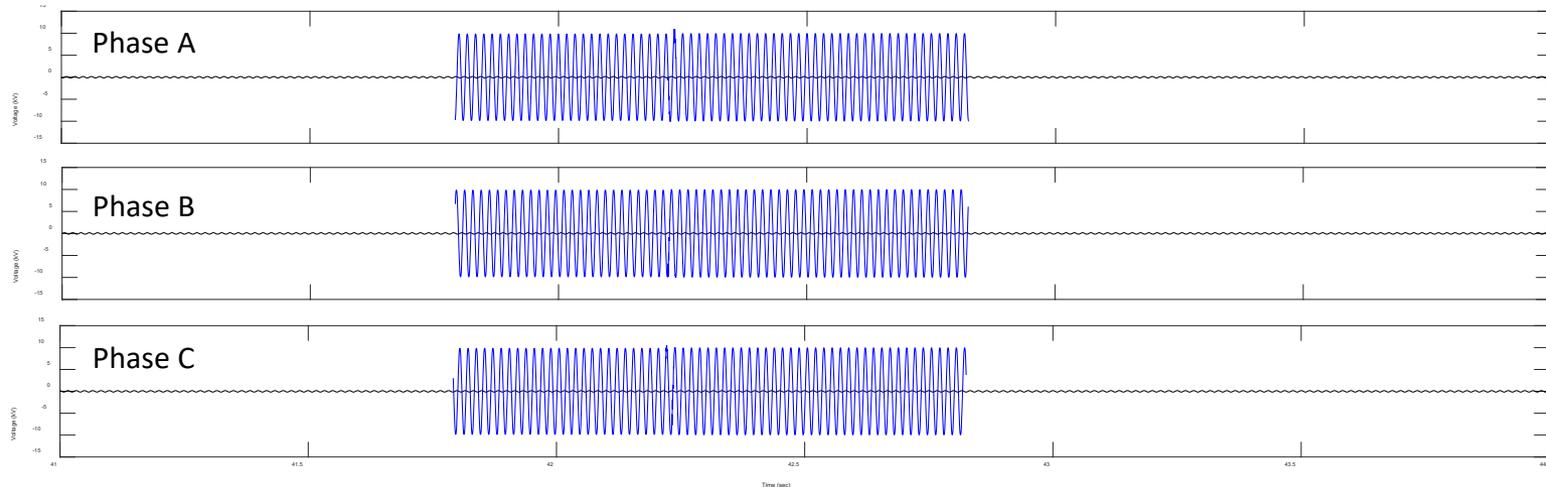
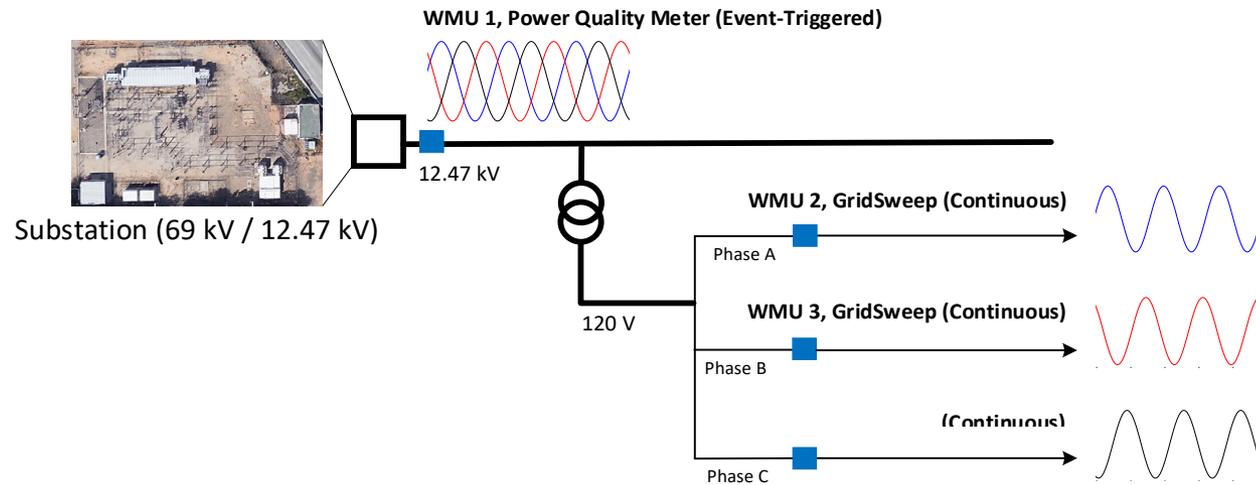
Cloud Data Files

Cloud-based Python Code

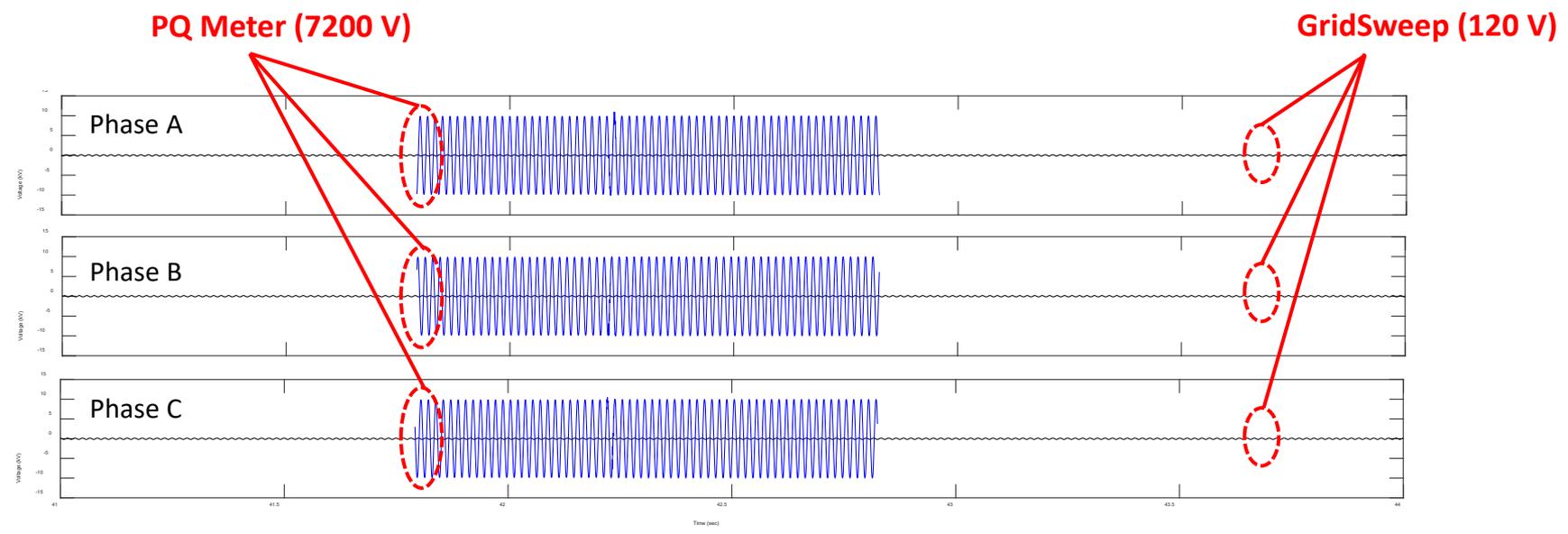
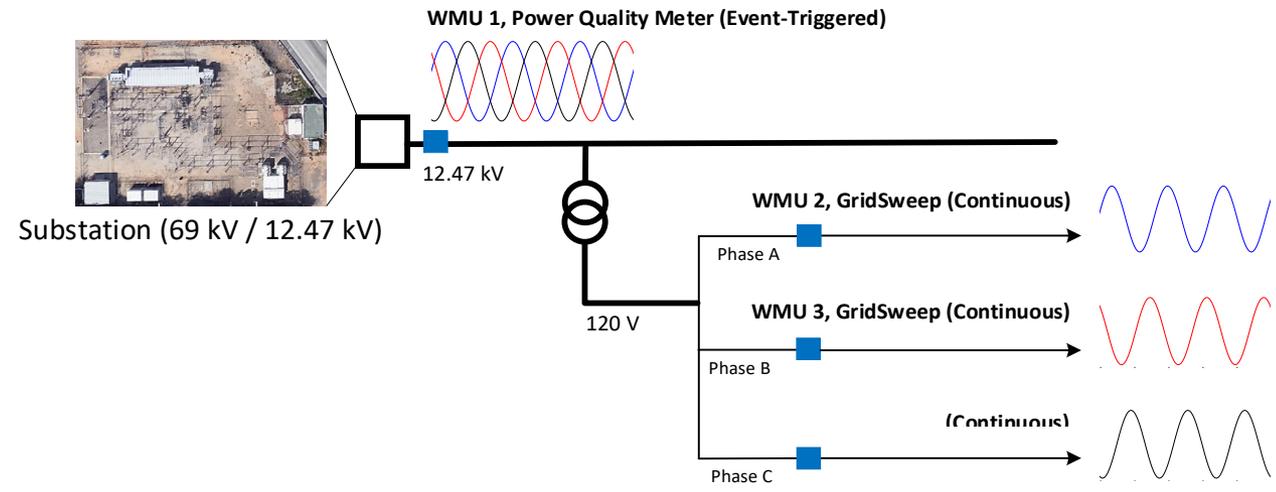
# Case Study 1: Low Voltage vs. Medium Voltage WMUs



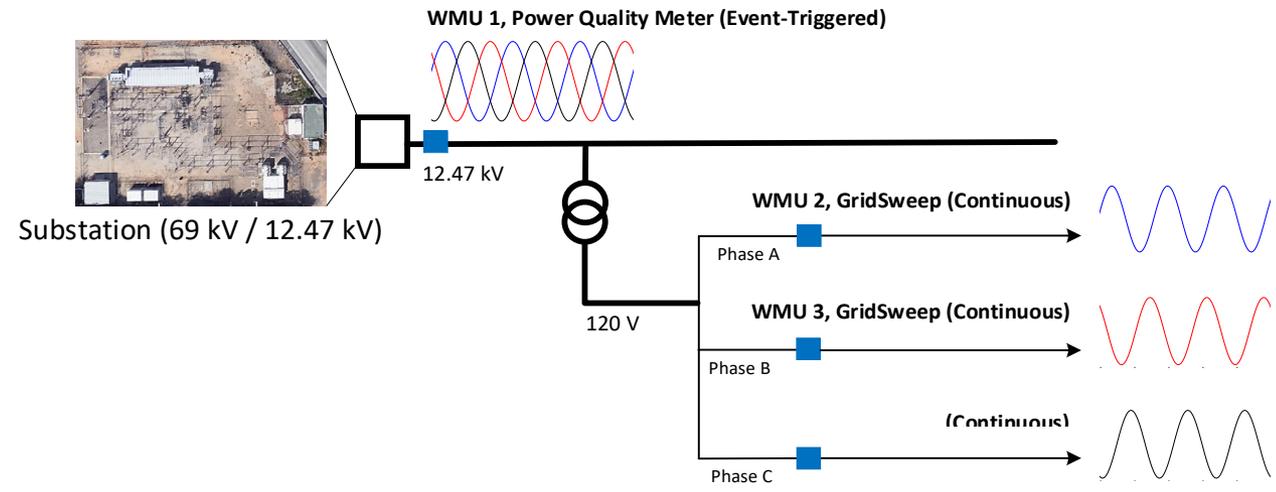
# Case Study 1: Low Voltage vs. Medium Voltage WMUs



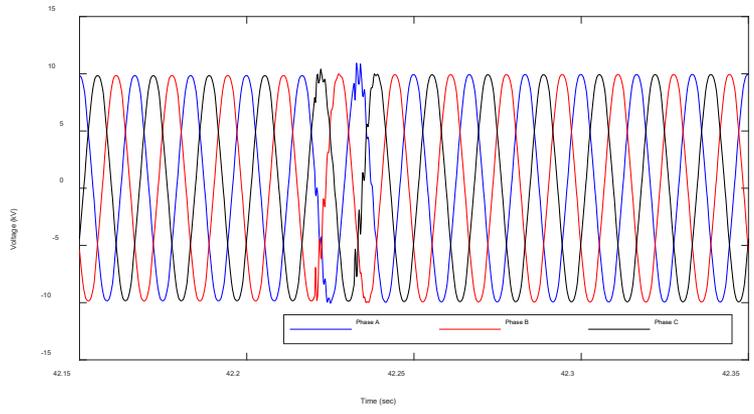
# Case Study 1: Low Voltage vs. Medium Voltage WMUs



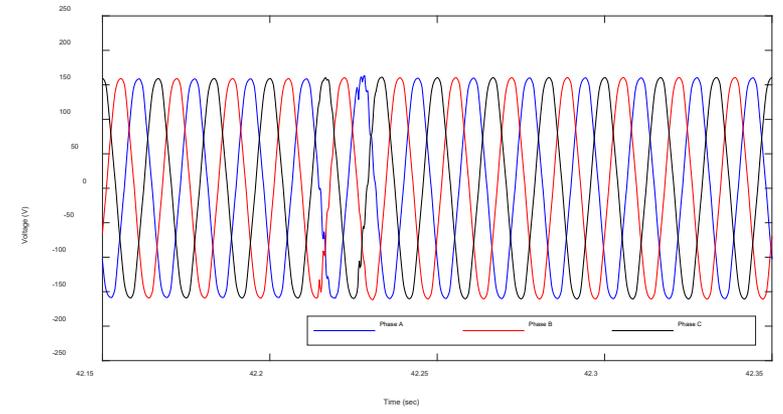
# Case Study 1: Low Voltage vs. Medium Voltage WMUs



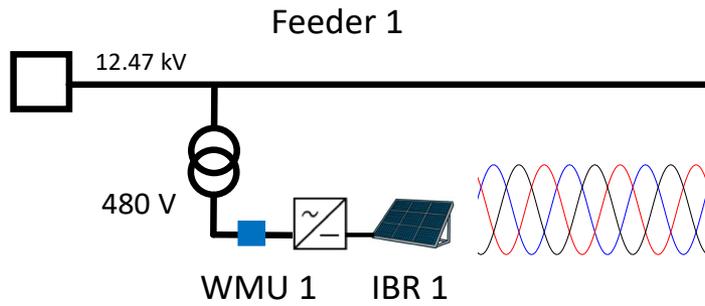
Substation (Event-Triggered)



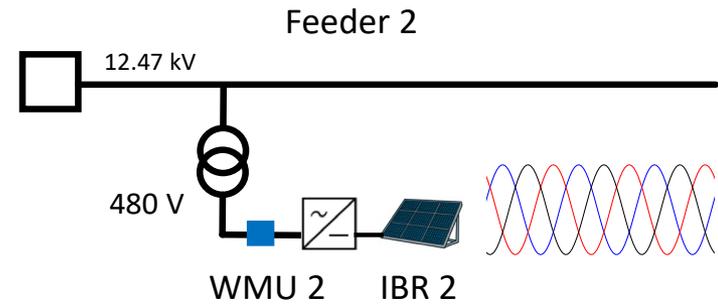
Power Outlet (Continuous/Gapless)



# Case Study 2: WMUs at IBRs

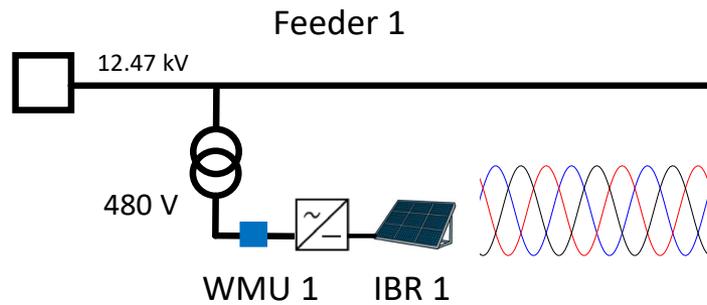


(SEL 735 – Event-Triggered)

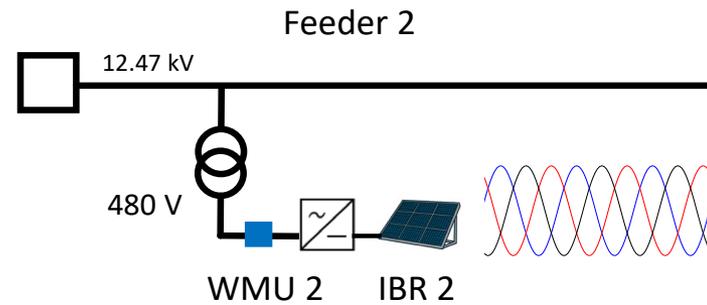


(SEL 735 – Event-Triggered)

# Case Study 2: WMUs at IBRs

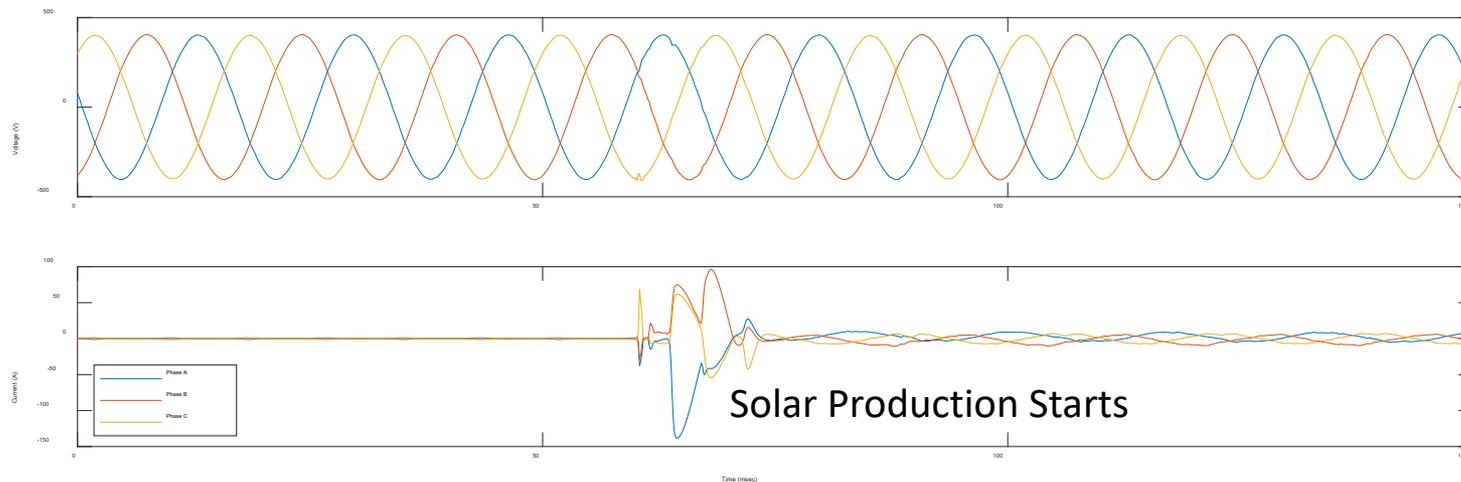


(SEL 735 – Event-Triggered)

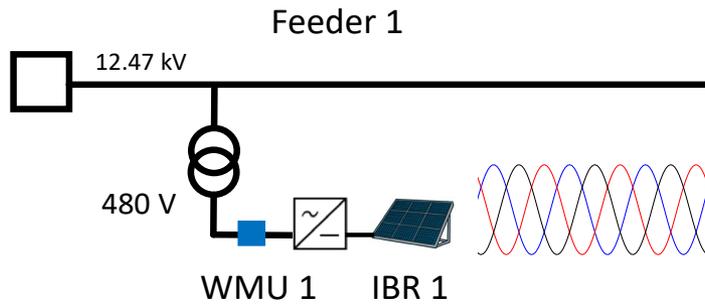


(SEL 735 – Event-Triggered)

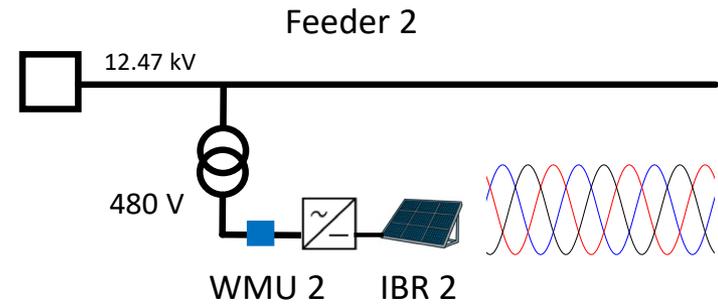
**Occasional Trigger:** *At one IBR once every several weeks.*



# Case Study 2: WMUs at IBRs

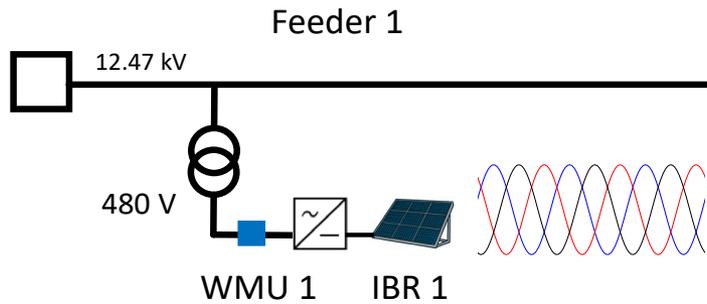


(SEL Axion – Continuous)

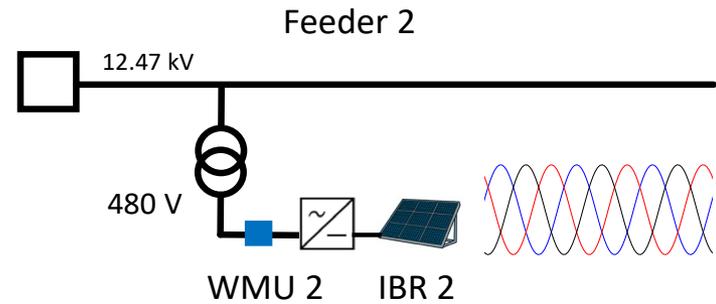


(SEL Axion – Continuous)

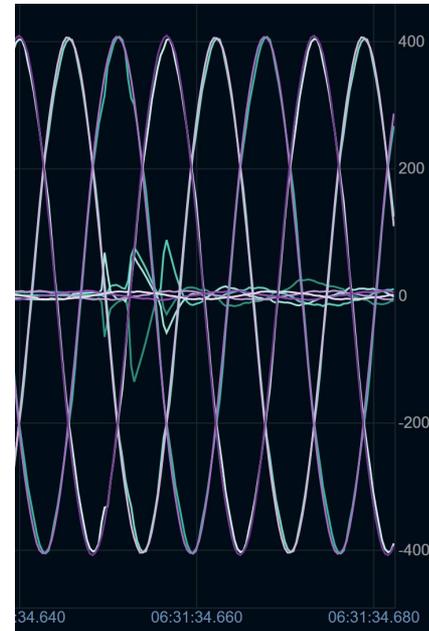
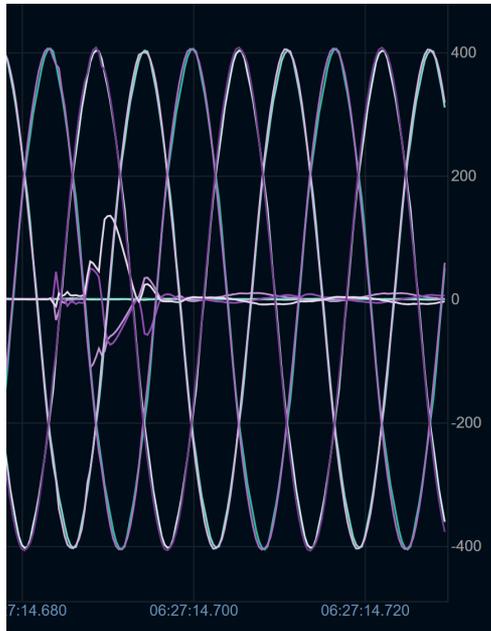
# Case Study 2: WMUs at IBRs



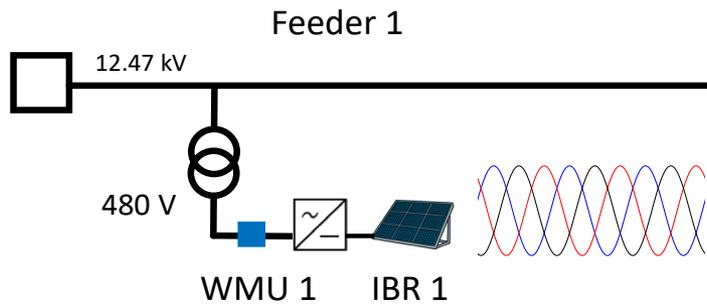
(SEL Axion – Continuous)



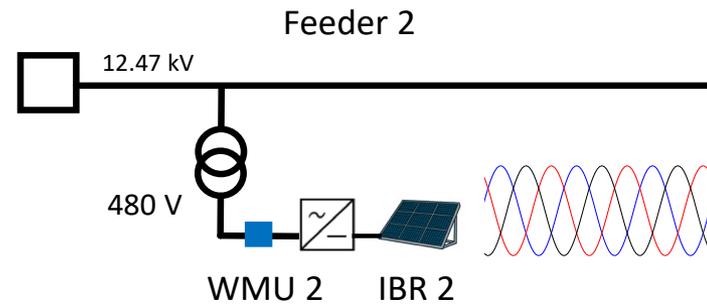
(SEL Axion – Continuous)



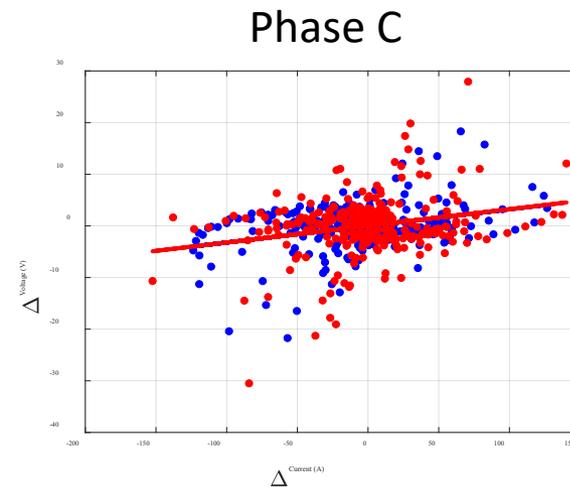
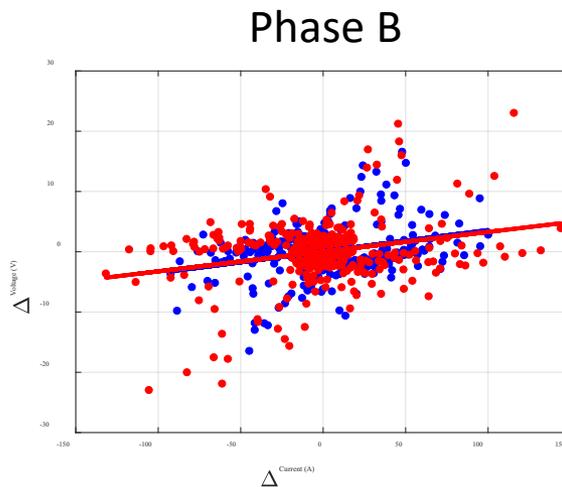
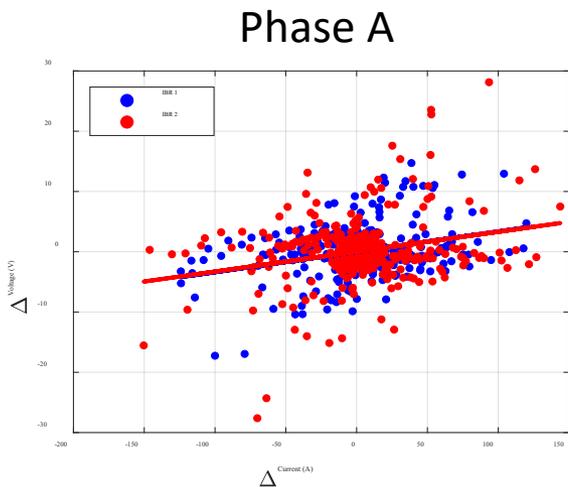
# Case Study 2: WMUs at IBRs



(SEL Axion – Continuous)

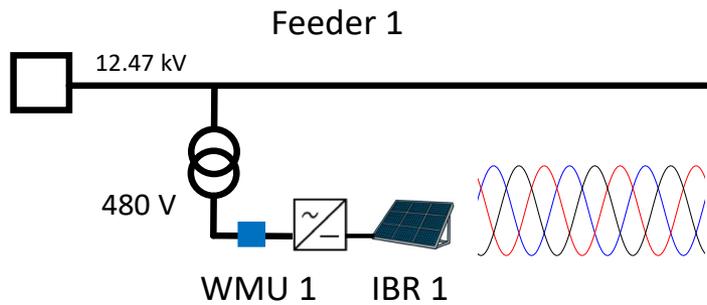


(SEL Axion – Continuous)

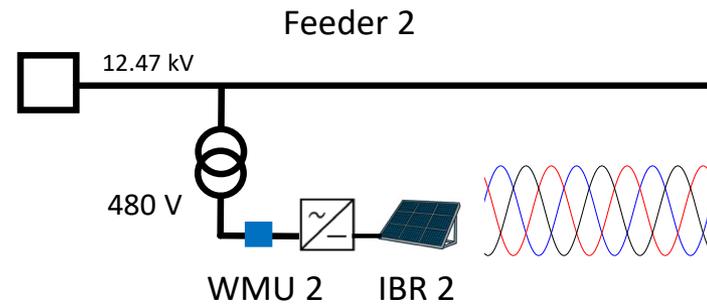


$\Delta$ : Differential Voltage and Current

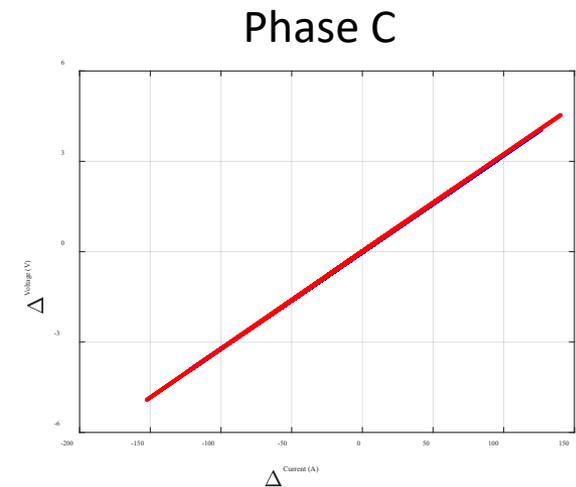
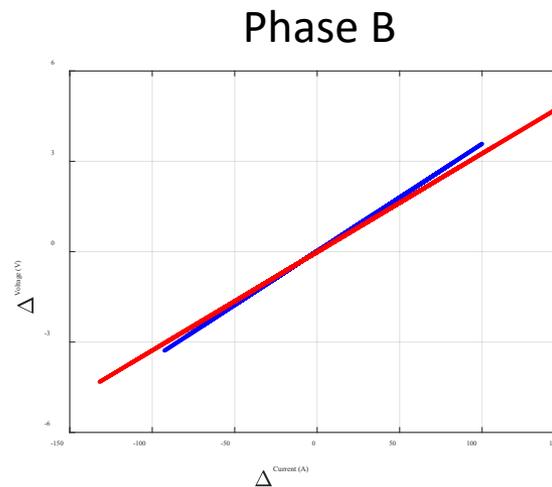
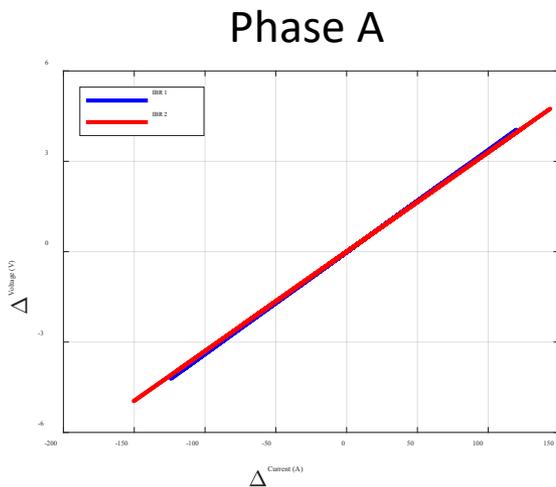
# Case Study 2: WMUs at IBRs



(SEL Axion – Continuous)

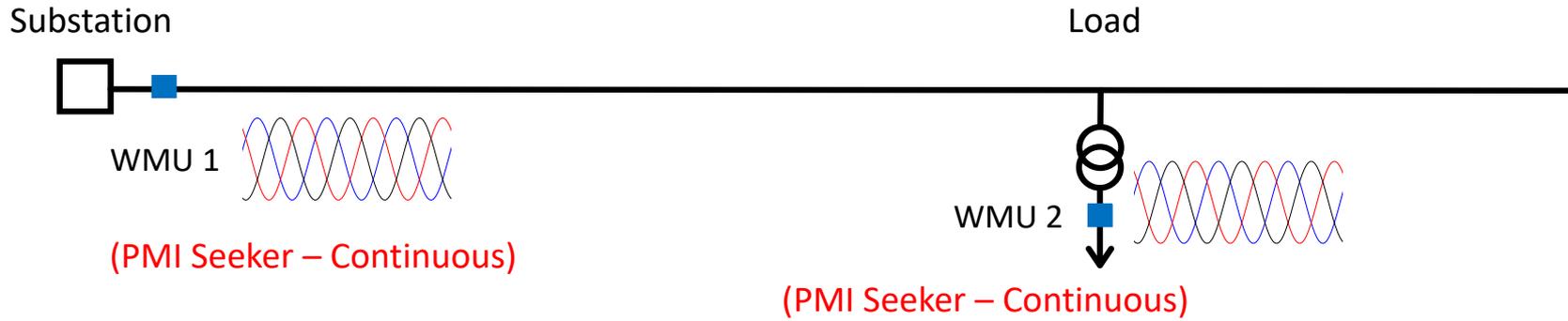


(SEL Axion – Continuous)



$\Delta$ : Differential Voltage and Current

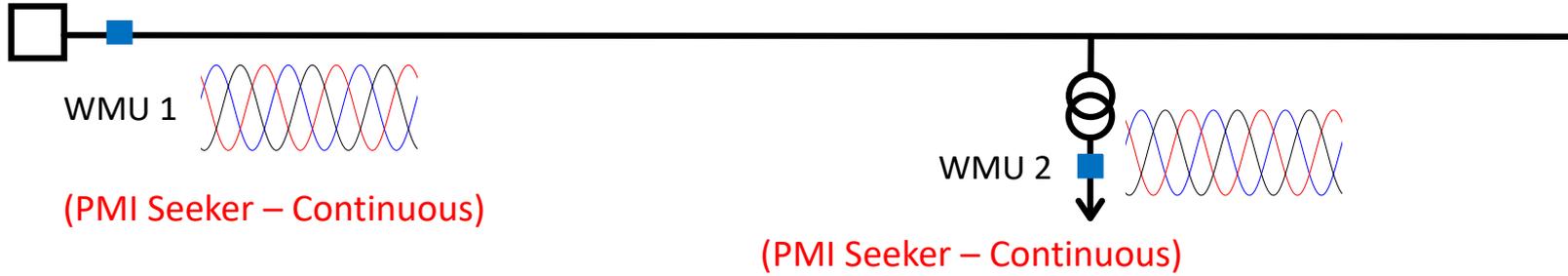
# Case Study 3: Event Region Identification



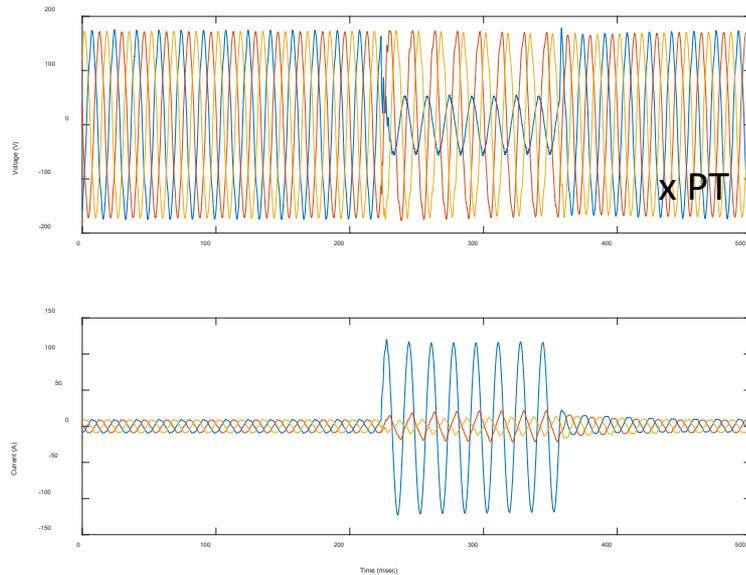
# Case Study 3: Event Region Identification

Substation

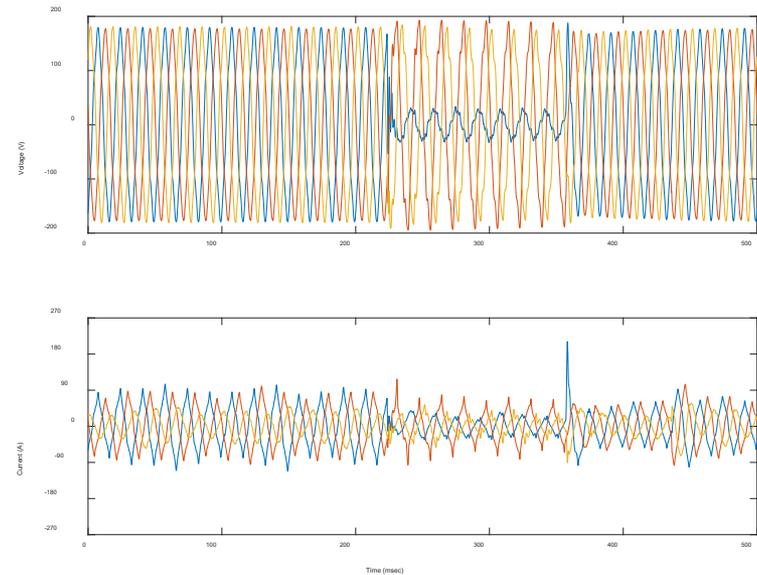
Load



WMU 1



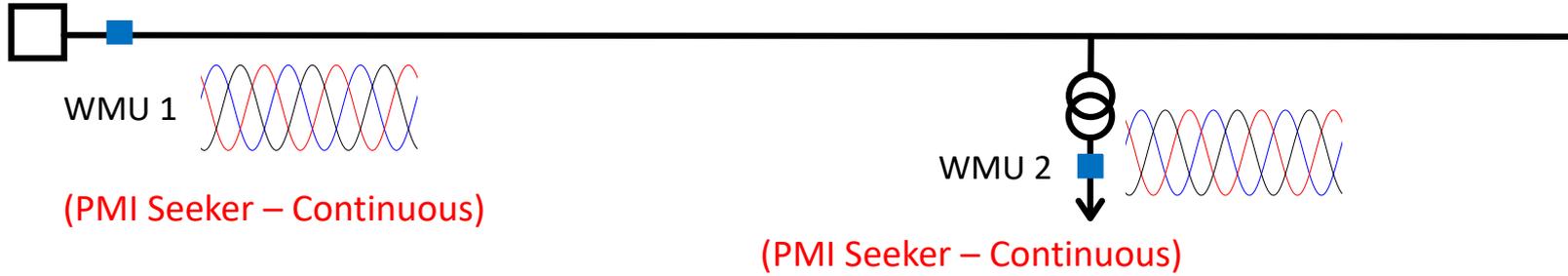
WMU 2



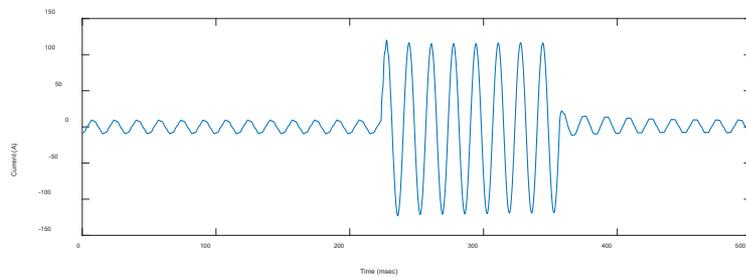
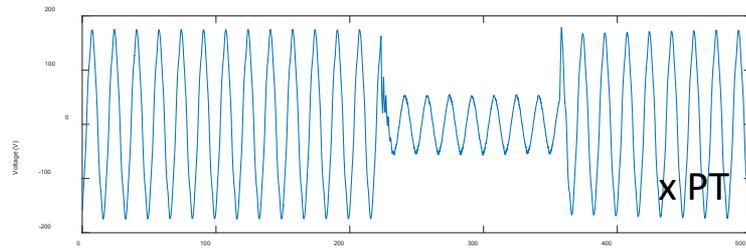
# Case Study 3: Event Region Identification

Substation

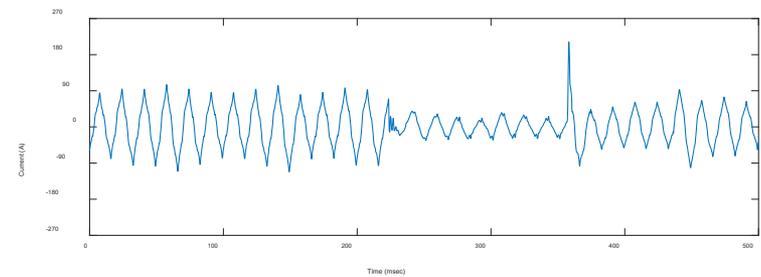
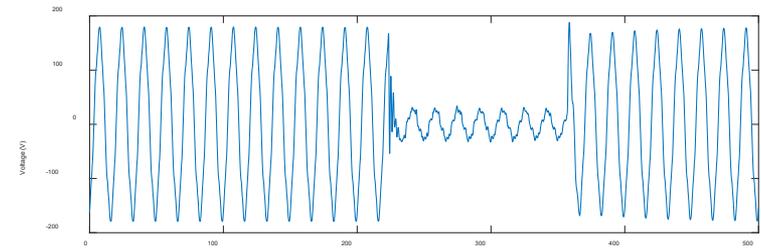
Load



WMU 1



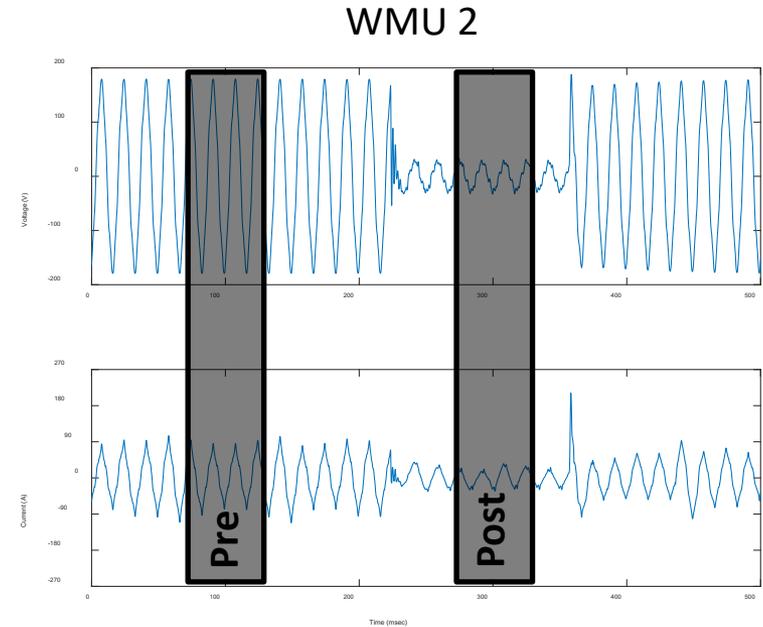
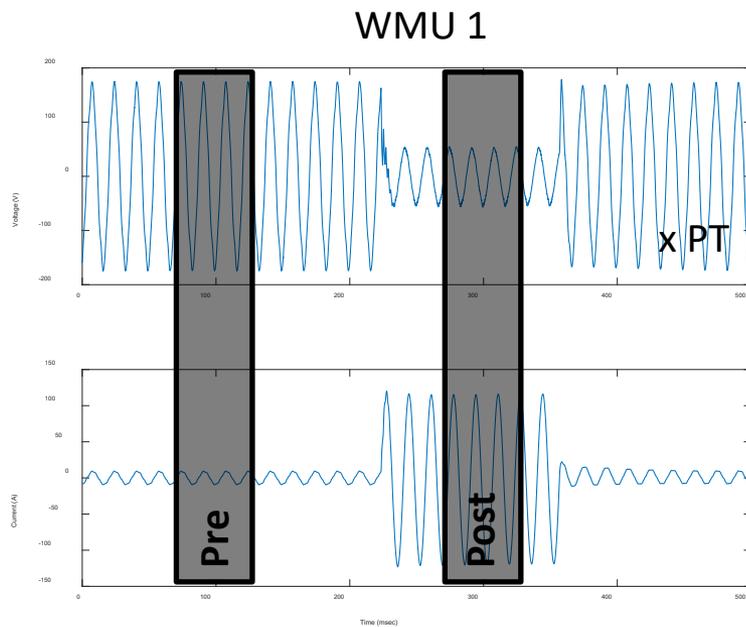
WMU 2



# Case Study 3: Event Region Identification

Substation

Load



[Farajollahi, et. al, IEEE Trans. on Power Systems, 2018]

# Thank You!

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Homepage: [www.ece.ucr.edu/~hamed](http://www.ece.ucr.edu/~hamed)