# Situational Awareness Using Distribution Synchrophasors: Application to Asset Monitoring

Talk at WCGEC ESTAP, 4/11/2019

Hamed Mohsenian-Rad

Associate Professor, Electrical Engineering, University of California, Riverside
Associate Director, Winston Chung Global Energy Center
Director, UC-National Lab Center for Power Distribution Cyber Security

*Acknowledgements*: A. Shahsavari, M. Farajollahi, E. Stewart, E. Cortez,
A. Von-Meier, L. Alvarez, C. Roberts, F. Megala, Z. Taylor

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Distributed Energy Storage

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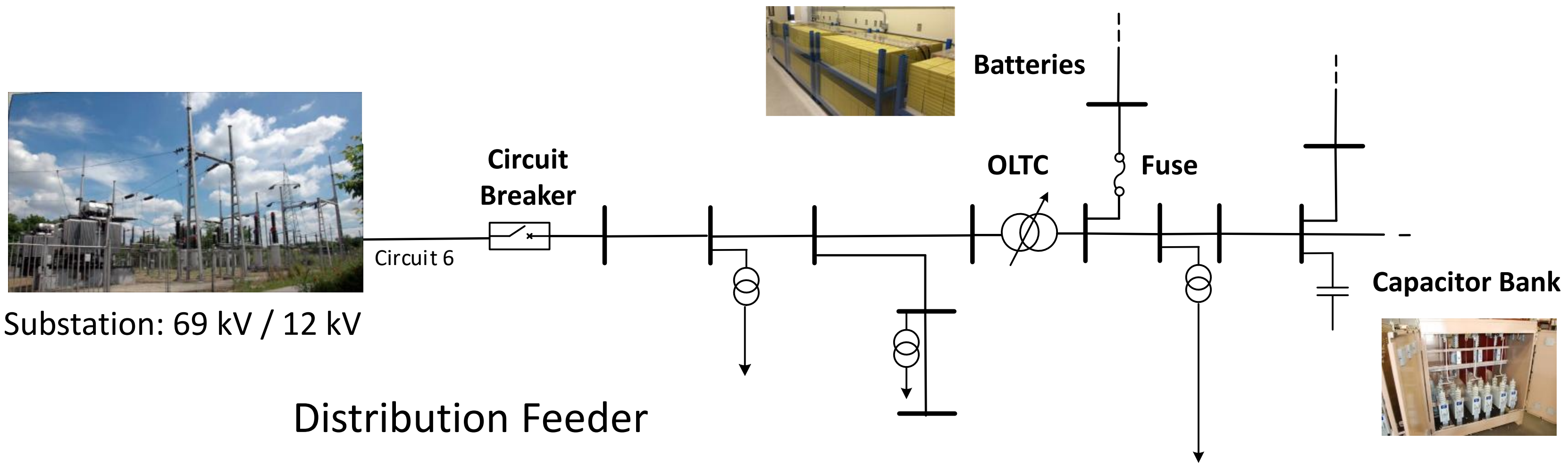
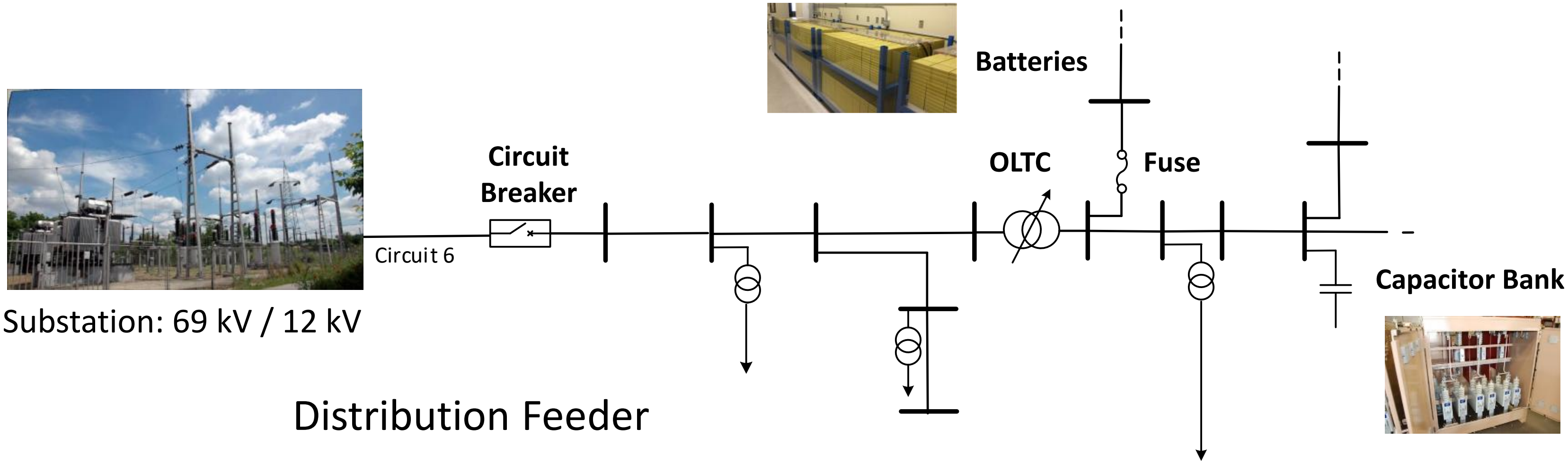
# Distributed Energy Storage Resources

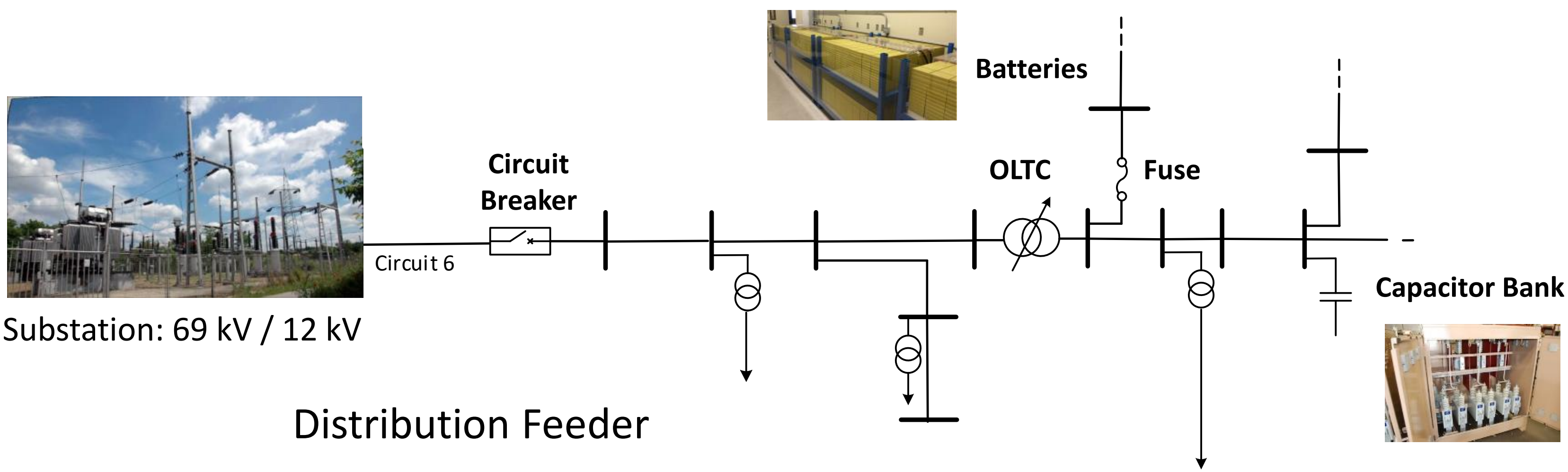


- They are often not monitored directly.



# Distributed Energy Storage Resources

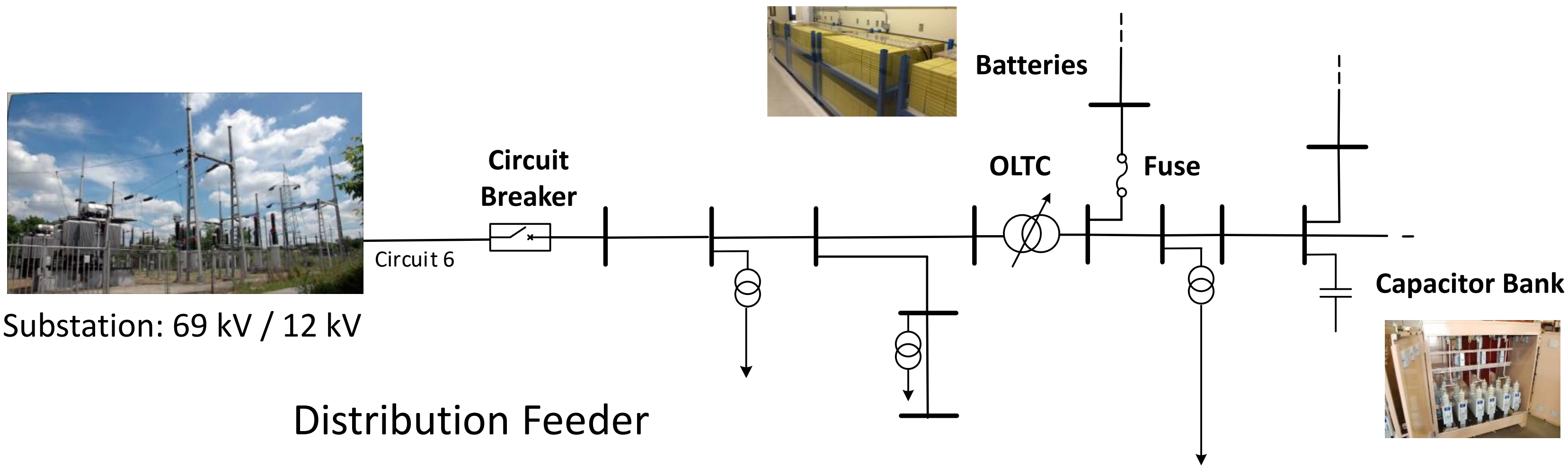
- They are often not monitored directly.
- They are potential targets for cyber attacks ➡ physical botnet



# Distributed Energy Storage Resources

- They are often not monitored directly.
- They are potential targets for cyber attacks → physical botnet
- We want to monitor their Health and Security?

Remotely!



# Distributed Energy Storage Resources

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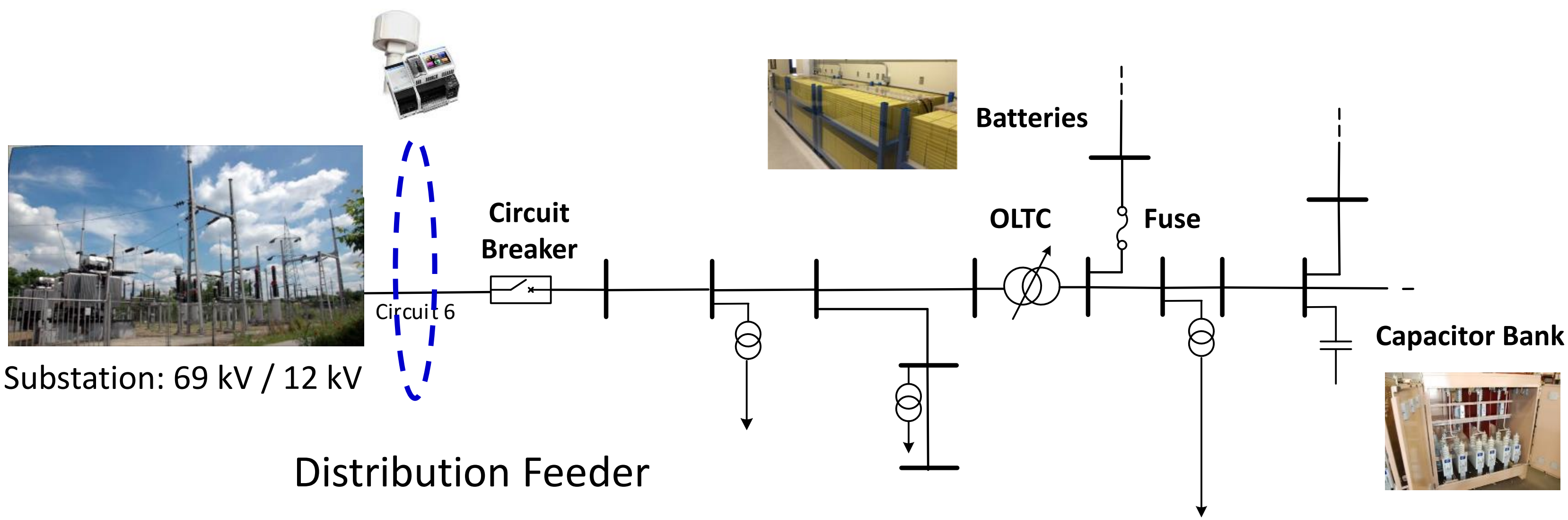
Remotely!

Micro-PMUs (GPS-equipped Phasor Sensors)

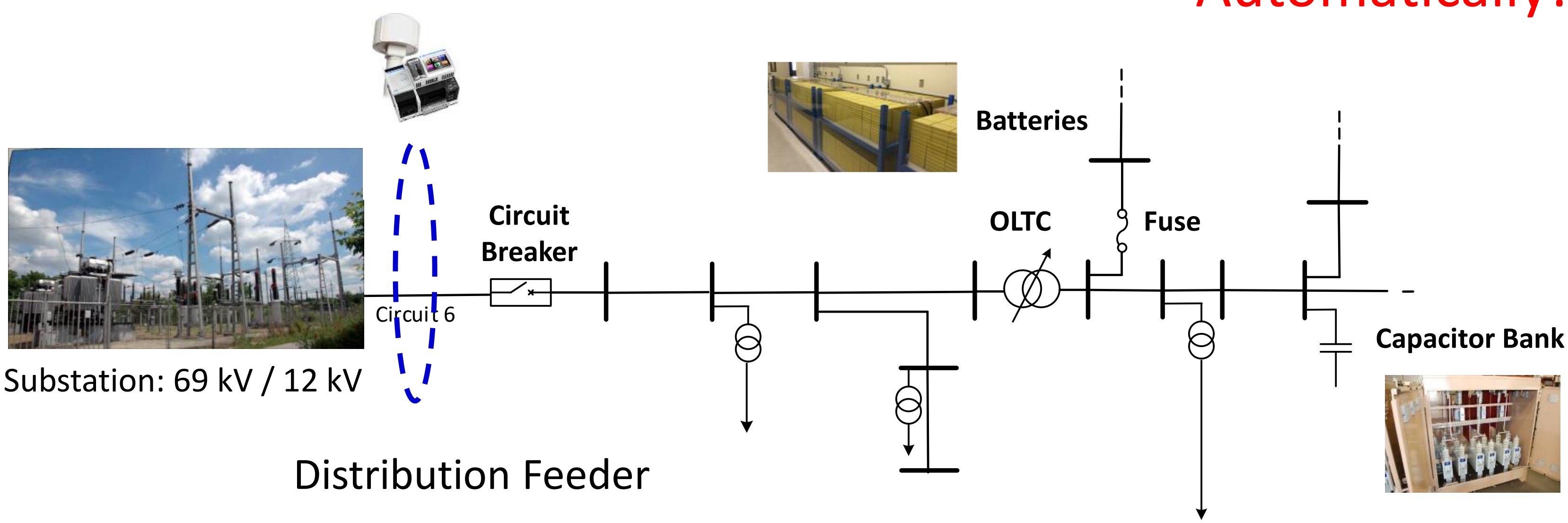


# Distributed Energy Storage Resources

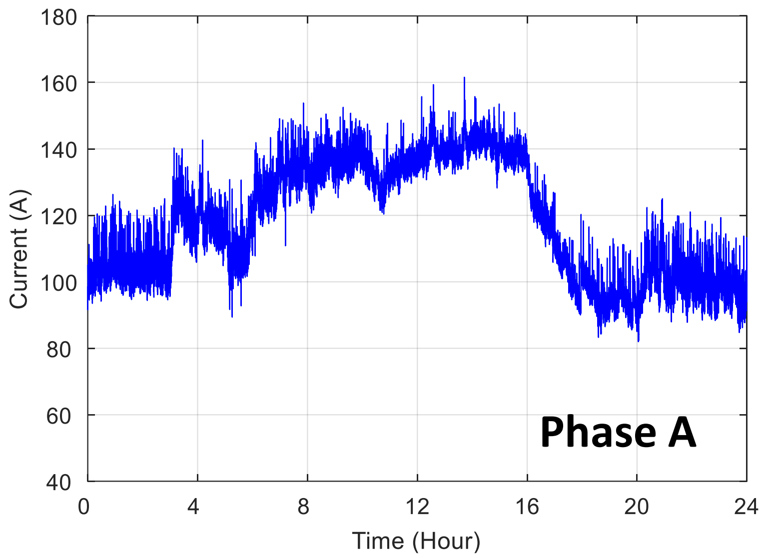
- They are often not monitored directly.
- They are potential targets for cyber attacks → physical botnet
- We want to monitor their Health and Security?

Remotely & Automatically!

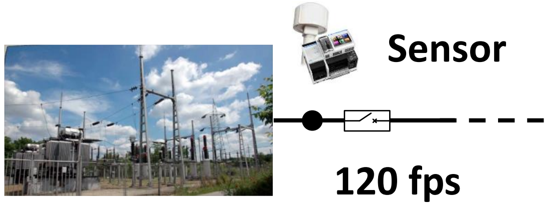
Micro-PMUs (GPS-equipped Phasor Sensors)



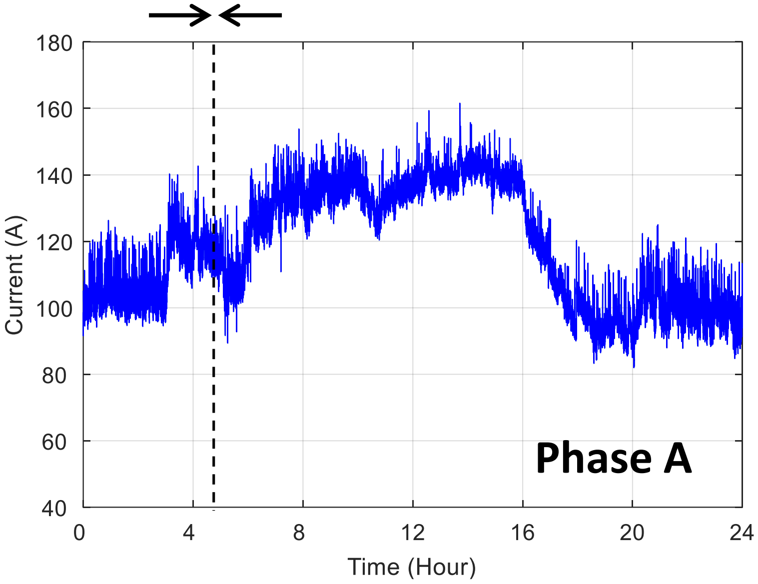
# Event-Driven Study




10,368,000 measurement points



# Event-Driven Study

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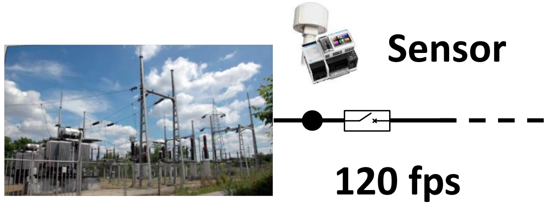
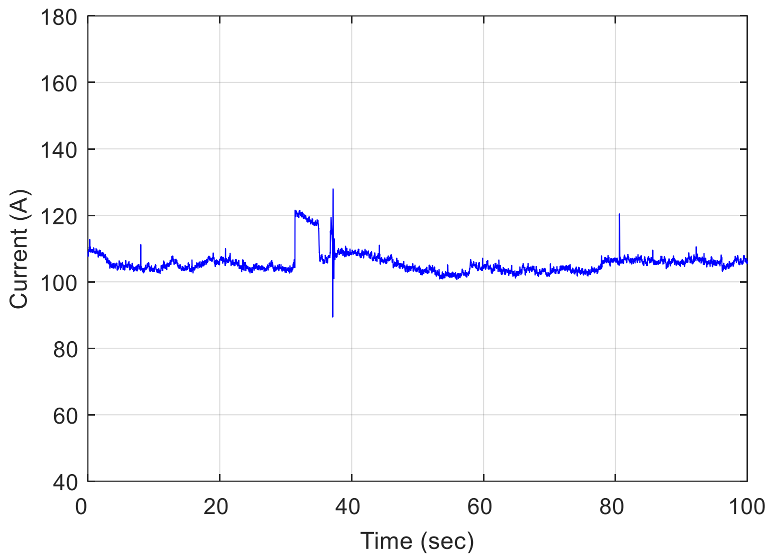
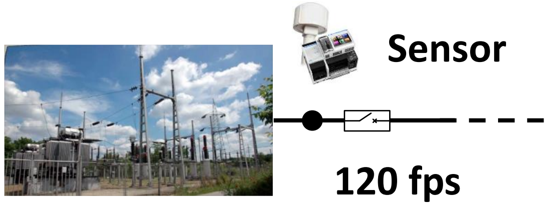
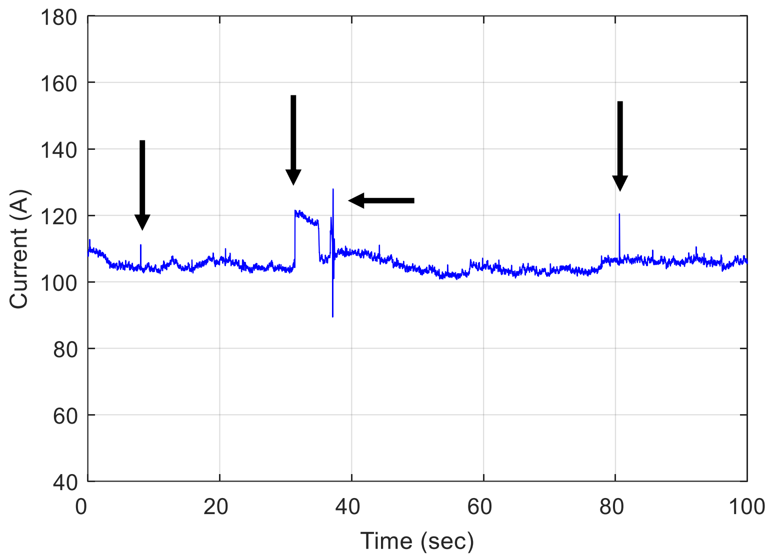


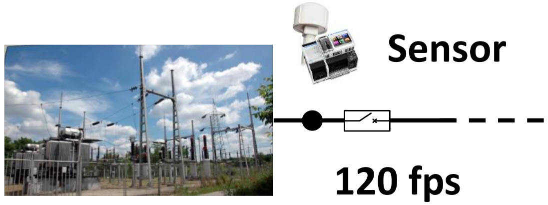
# Event-Driven Study



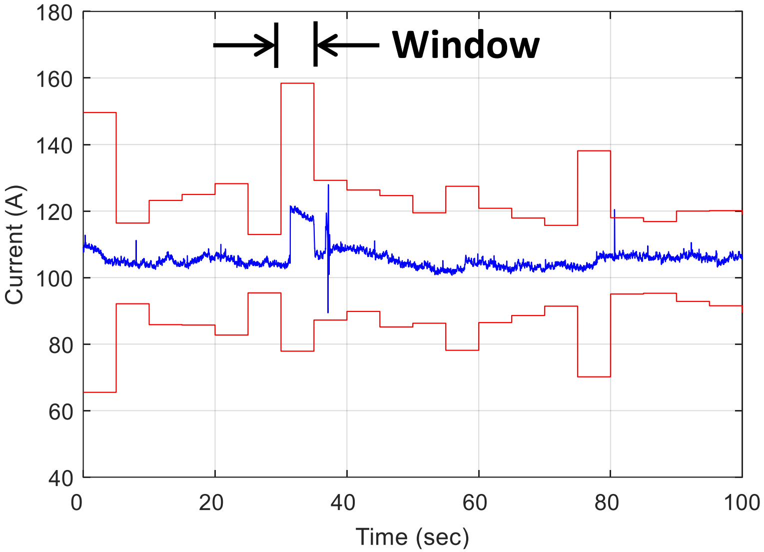



# Event-Driven Study



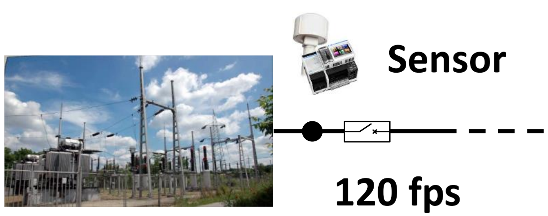



# Phase 1: Event Detection




**Anomaly Detection**

Absolute Deviation Around the Median



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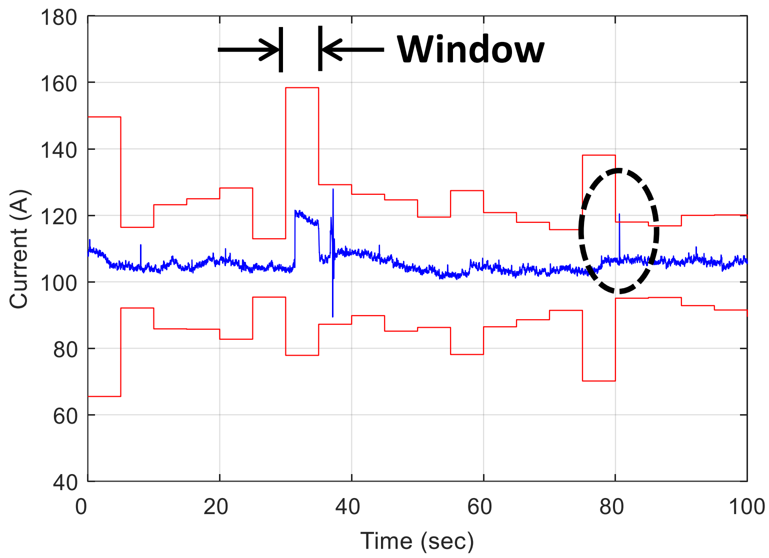
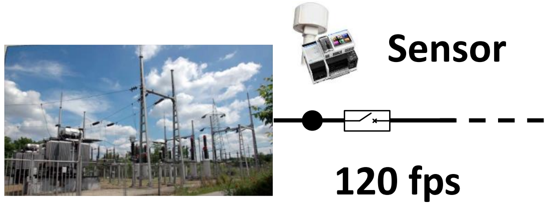



**Anomaly Detection**

Absolute Deviation Around the Median



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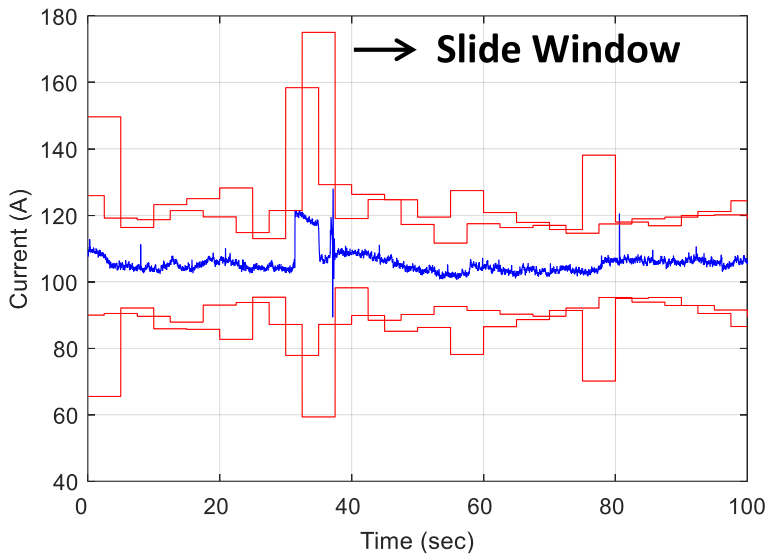
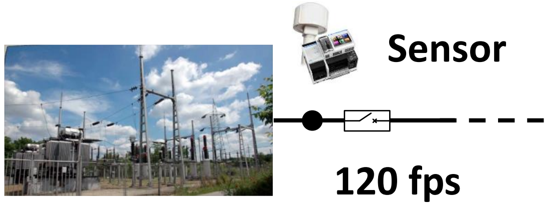



**Anomaly Detection**

Absolute Deviation Around the Median



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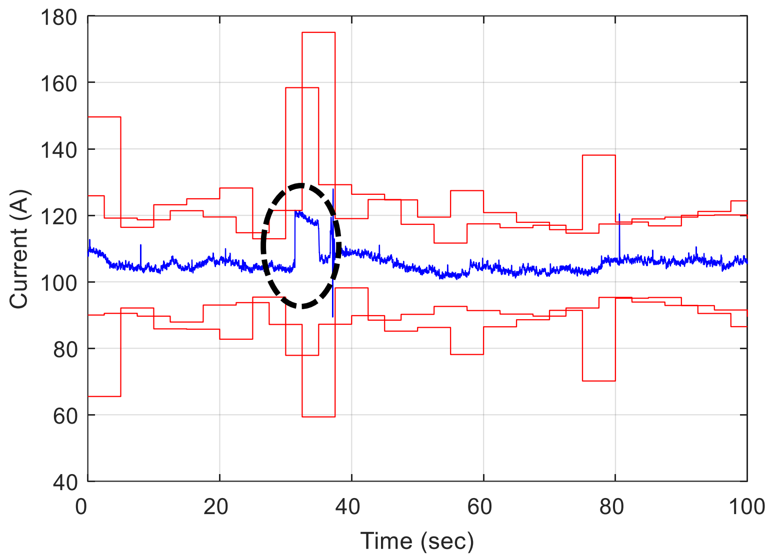


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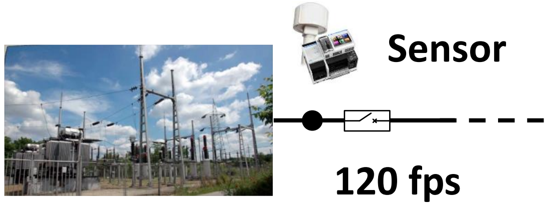
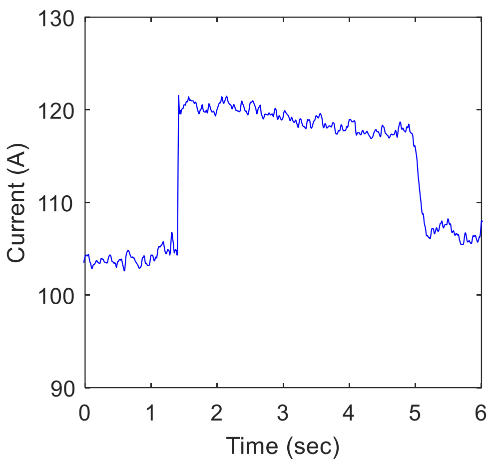
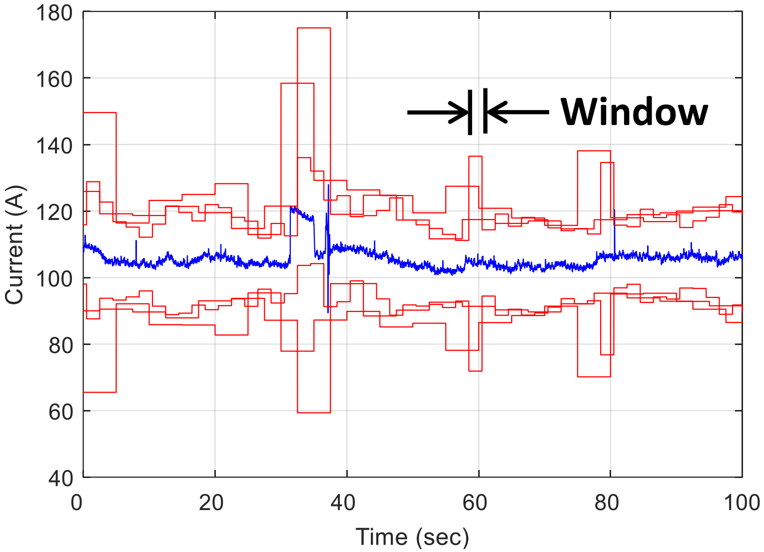


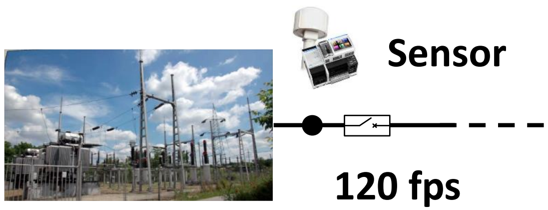

**Event 1**

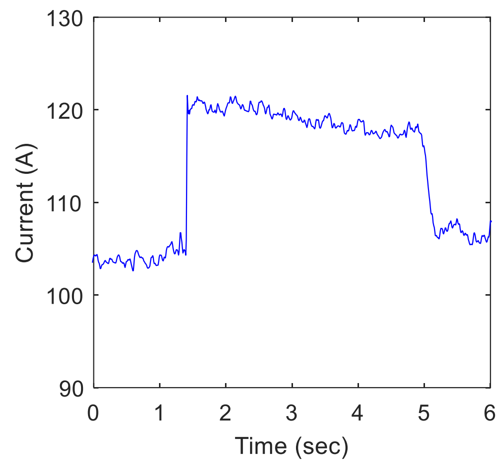
# Phase 1: Event Detection




**Anomaly Detection**

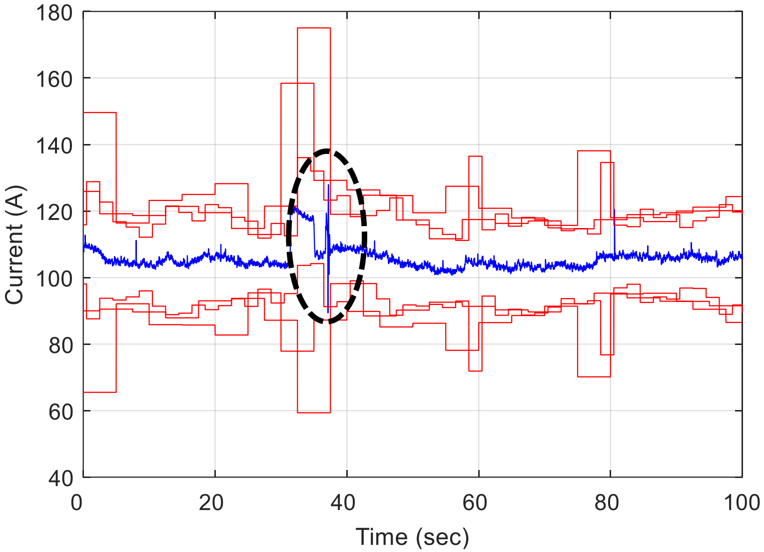
Absolute Deviation Around the Median



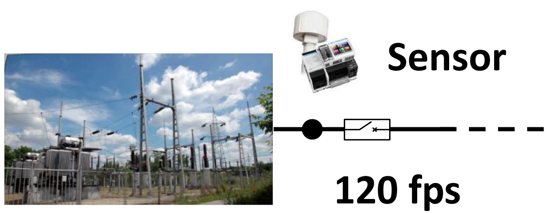

**Event 1**

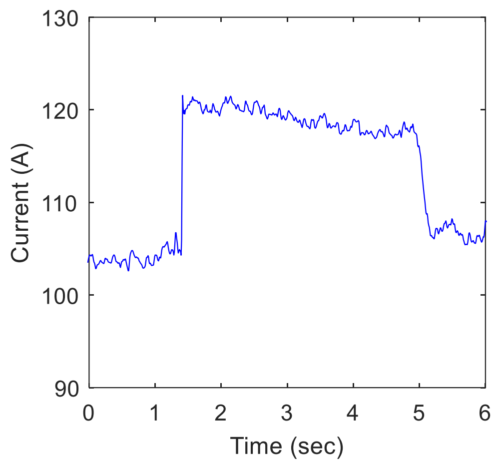
# Phase 1: Event Detection



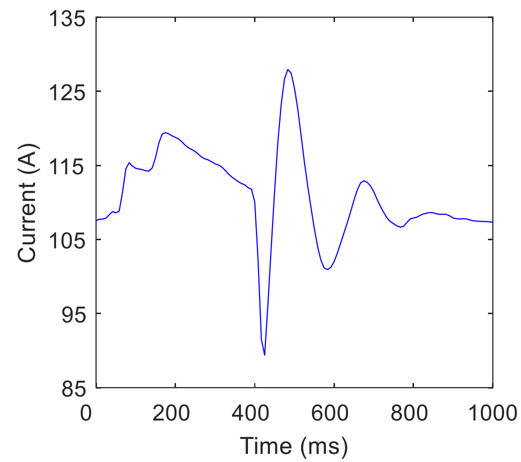

**Anomaly Detection**

Absolute Deviation Around the Median

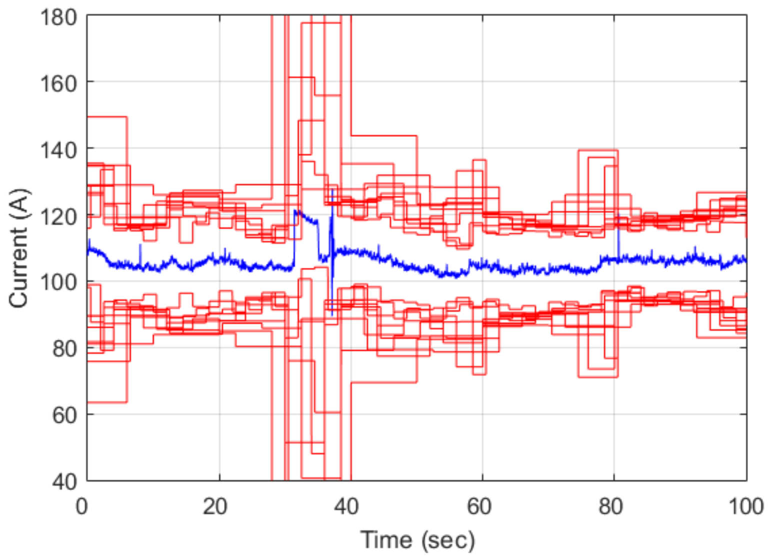



**Event 1**

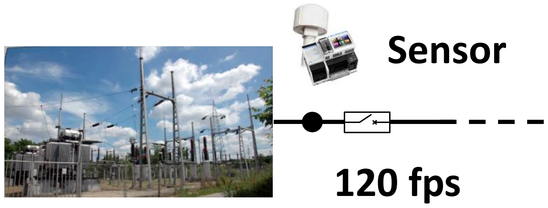


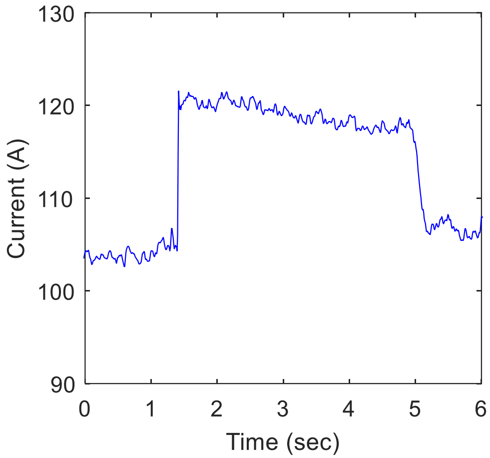

**Event 2**




**Anomaly Detection**

Absolute Deviation Around the Median

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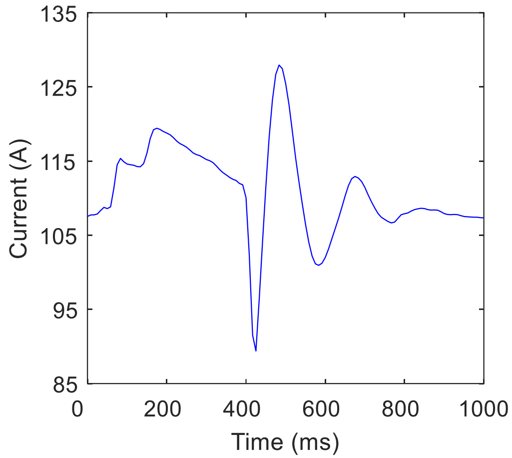
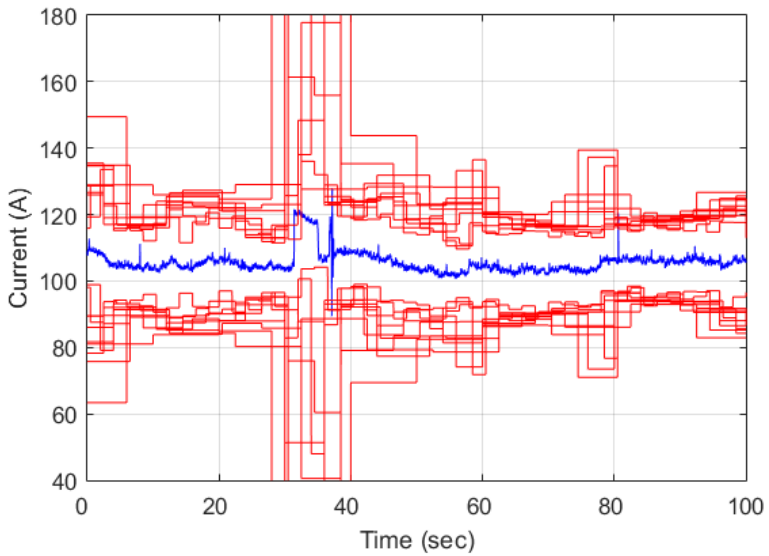


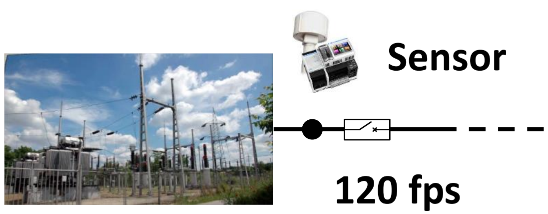

**Event 2**

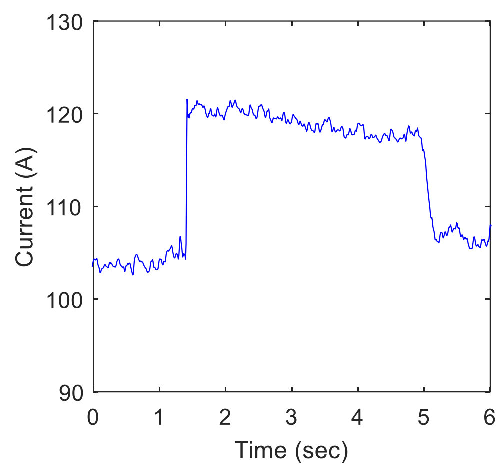
# Phase 1: Event Detection




**Anomaly Detection**

- Current ($I$)
- Voltage ($V$)
- Active Power ($P$)
- Reactive Power ($Q$)

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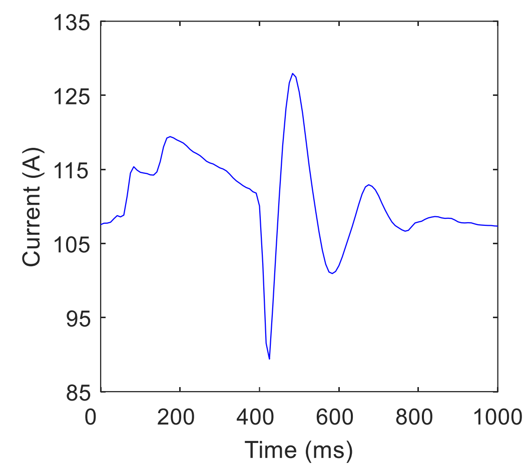
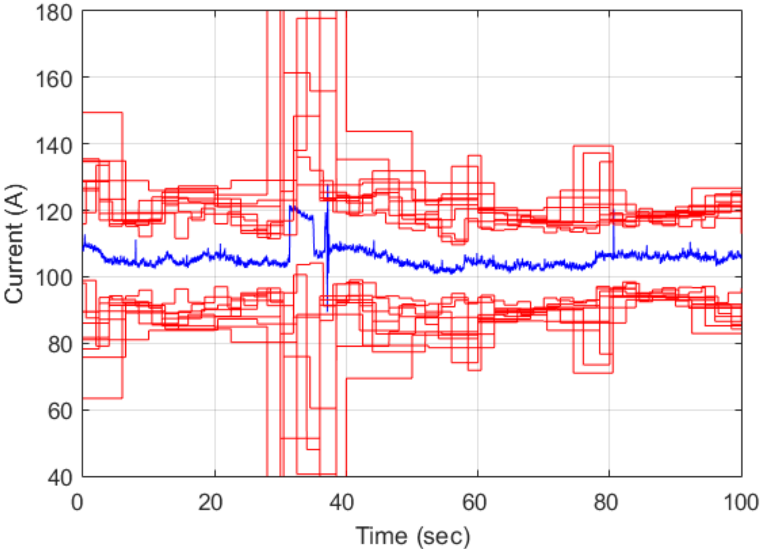
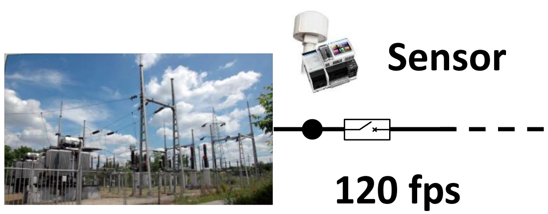
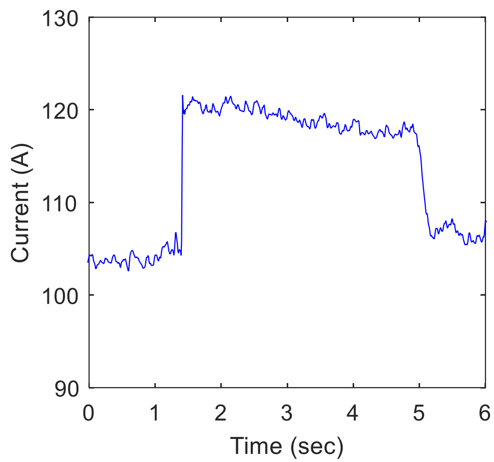



**Event 2**




**On Average: 500 Events Per Day Per Feeder**

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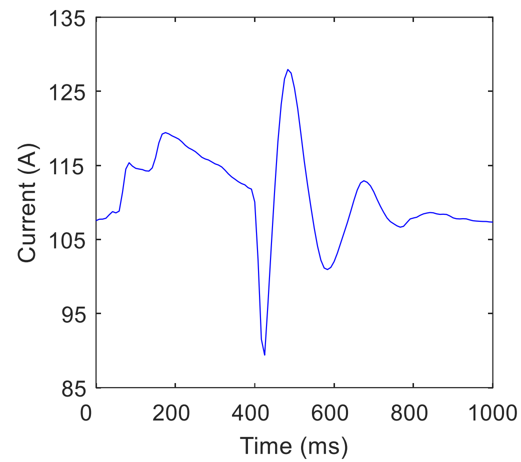
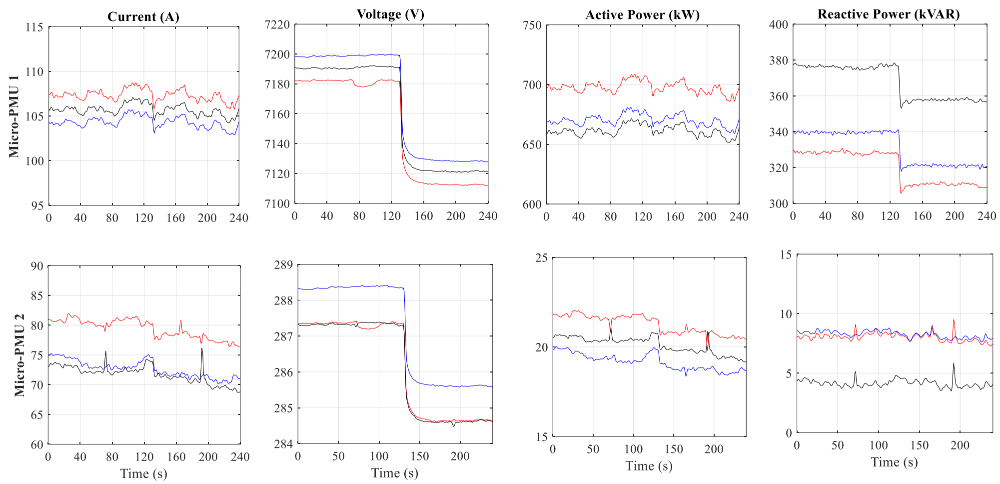
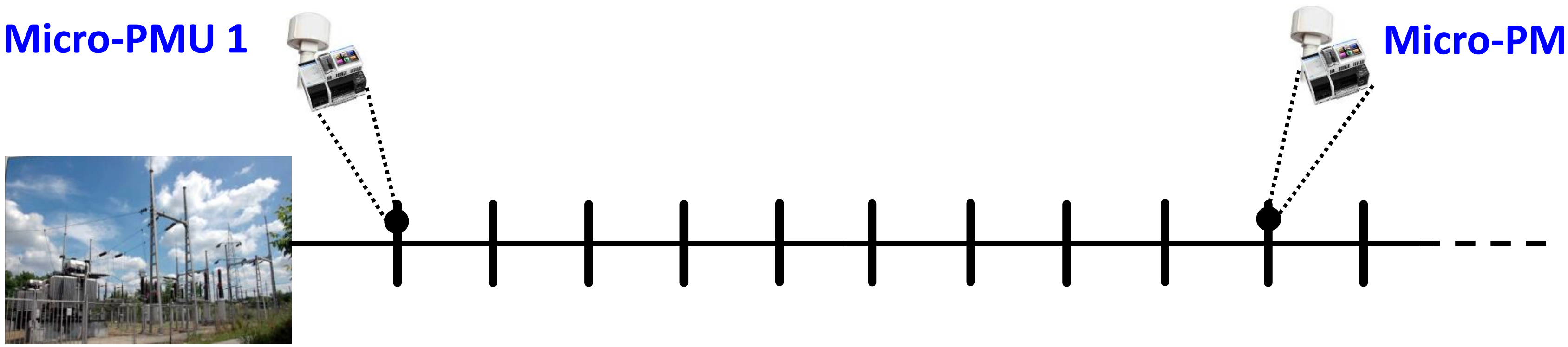


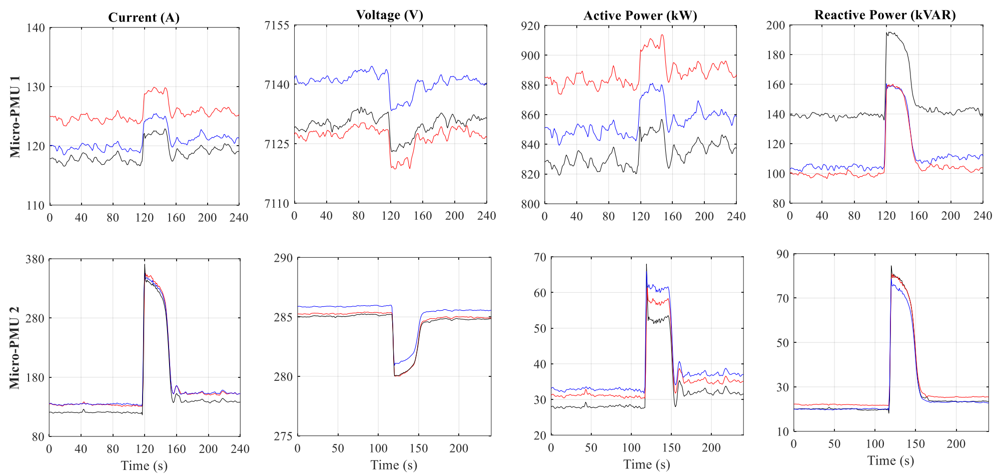

**Event 2**

# Phase 2: Event Classification

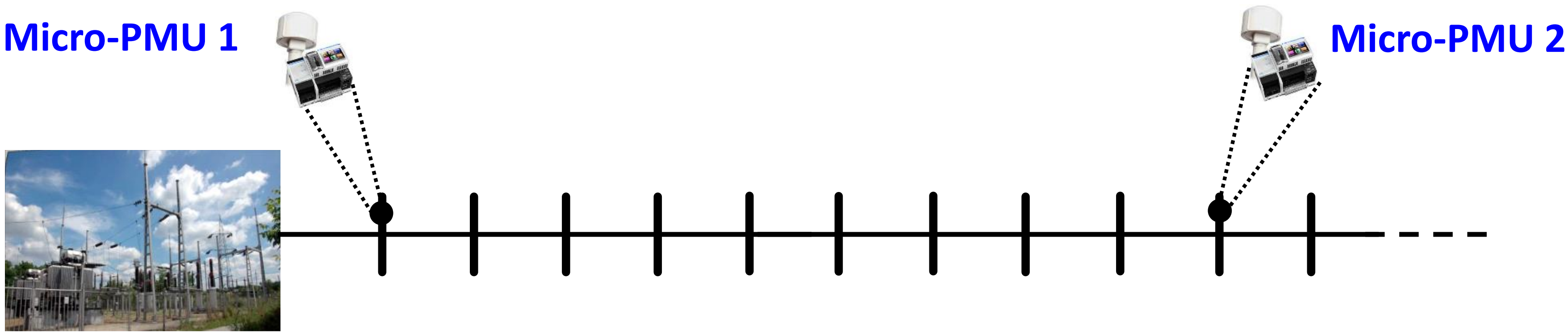
**Class 1**



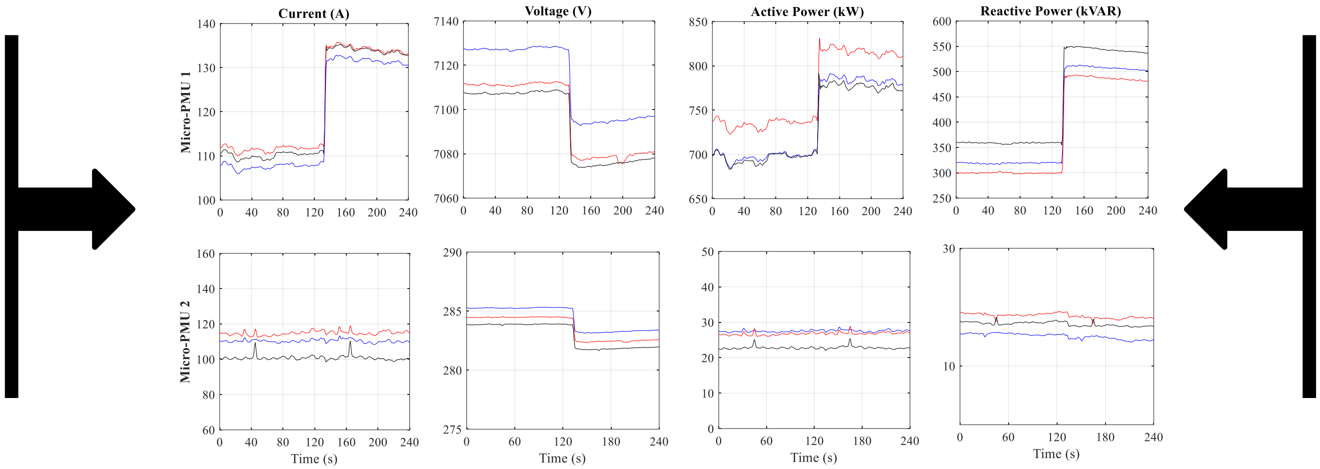




Current (A)
Voltage (V)
Active Power (kW)
Reactive Power (kVAR)
Micro-PMU 1
Micro-PMU 2
Time (s)
Time (s)
Time (s)
Time (s)

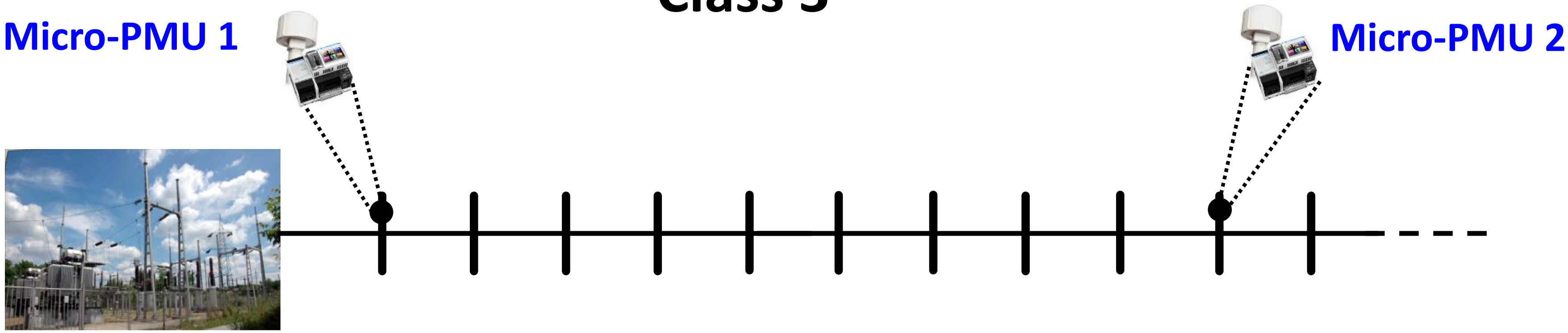
**Class 2**


Micro-PMU 1
Micro-PMU 2

# Phase 2: Event Classification




**Class 3**



# Phase 2: Event Classification

- **Methodology:**
  - Model Based
  - Data Driven
    - Unsupervised Classification
    - Supervised Classification
      - Labeling Training Samples (Classes 1, 2, and 3)
      - Feature Extraction

Utility Records

**Power Engineering**

2309 Events

# Phase 2: Event Classification

- **Classification Results:**
  - **Class 1**: 368 1434
  - **Class 2**: 296 1896
  - **Class 3**: 1645 5018

| Features | |
|---|---|
| Detection Window | $\min\{W\}$ |
| Detection Signal | $X_i \in \{I, V, P, Q\}$ |
| Statistics | $\sigma(X_i)$ |
| Difference | $\left|X_i^u - X_i^d\right|$ |
| Correlation | $\rho(X_i, Y_i)$ |

# Phase 2: Event Classification

- **Classification Results:**
  - **Class 1**: 368 1434
  - **Class 2**: 296 1896 → **Training Data**
  - **Class 3**: 1645 5018

| **Features** | |
|---|---|
| Detection Window | $\min\{W\}$ |
| Detection Signal | $X_i \in \{I, V, P, Q\}$ |
| Statistics | $\sigma(X_i)$ |
| Difference | $\lvert X_i^u - X_i^d \rvert$ |
| Correlation | $\rho(X_i, Y_i)$ |

# Phase 2: Event Classification

- **Classification Results:**

| | | |
|---|---|---|
| **Class 1**: | 368 | 1434 |
| **Class 2**: | 296 | 1896 |
| **Class 3**: | 1645 | 5018 |

**Test Data**

| **Features** | |
|---|---|
| Detection Window | $\min\{W\}$ |
| Detection Signal | $X_i \in \{I, V, P, Q\}$ |
| Statistics | $\sigma(X_i)$ |
| Difference | $\lvert X_i^u - X_i^d \rvert$ |
| Correlation | $\rho(X_i, Y_i)$ |

- **Classification Results:**

| | | |
|---|---|---|
| **Class 1**: | 368 | 1434 |
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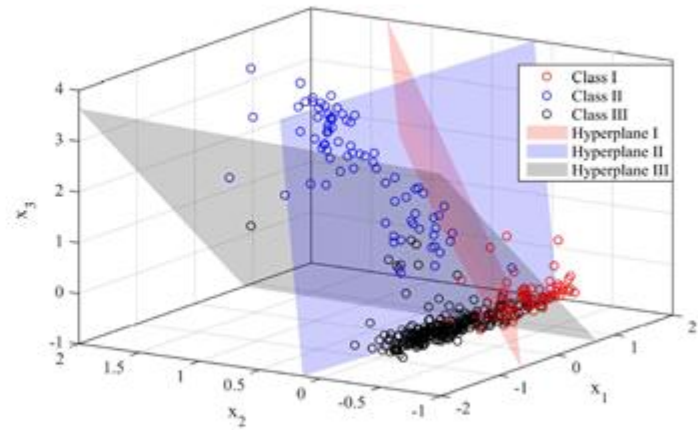
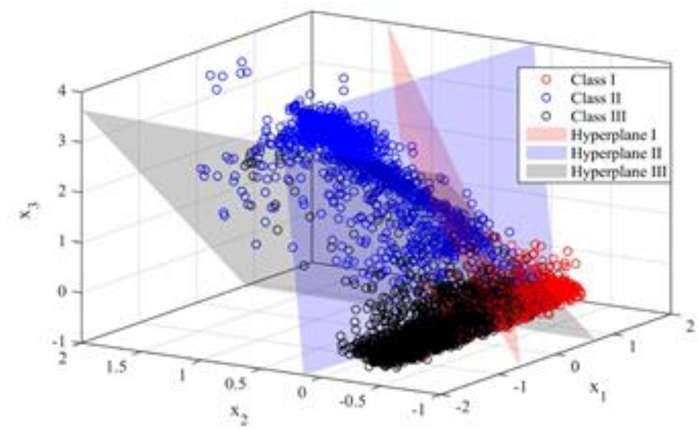



**Training Data**

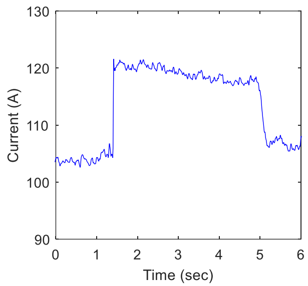



**Test Data**

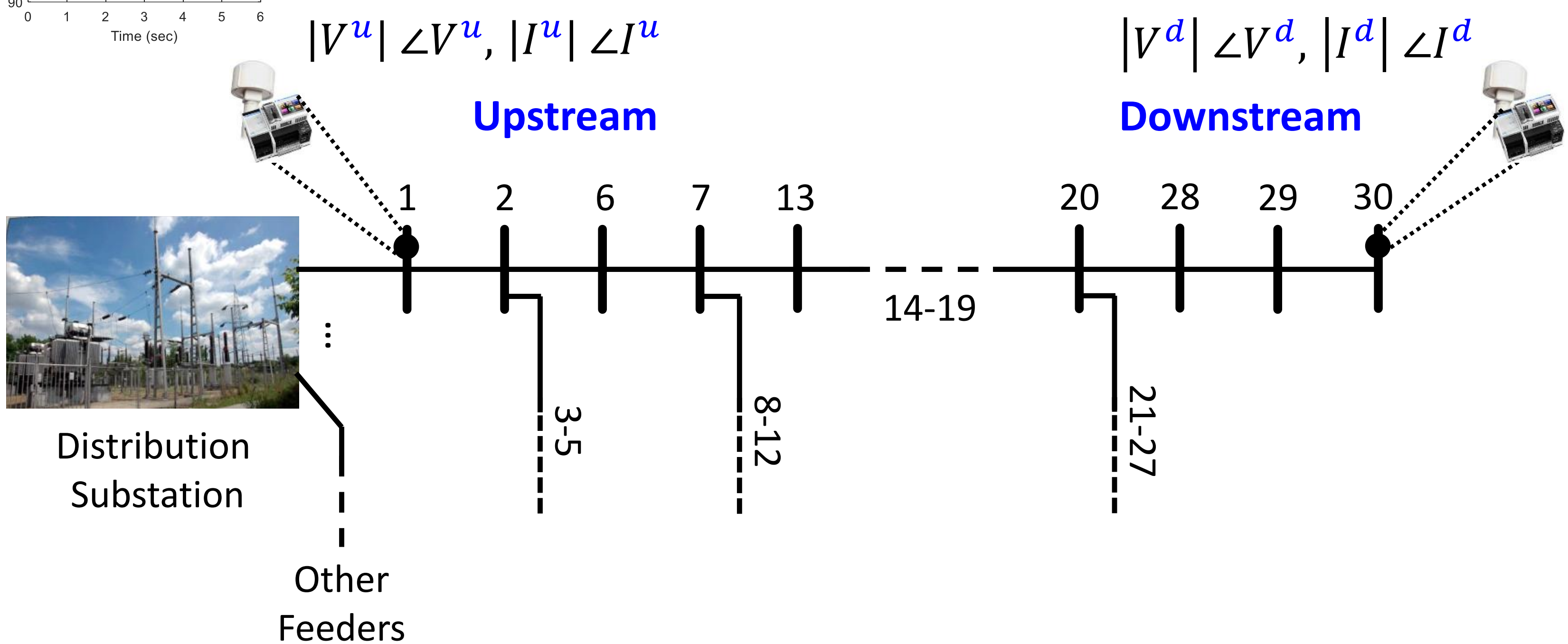
| **Features** | |
|---|---|
| Detection Window | $\min\{W\}$ |
| Detection Signal | $X_i \in \{I, V, P, Q\}$ |
| Statistics | $\sigma(X_i)$ |
| Difference | $\left\|X_i^u - X_i^d\right\|$ |
| Correlation | $\rho(X_i, Y_i)$ |

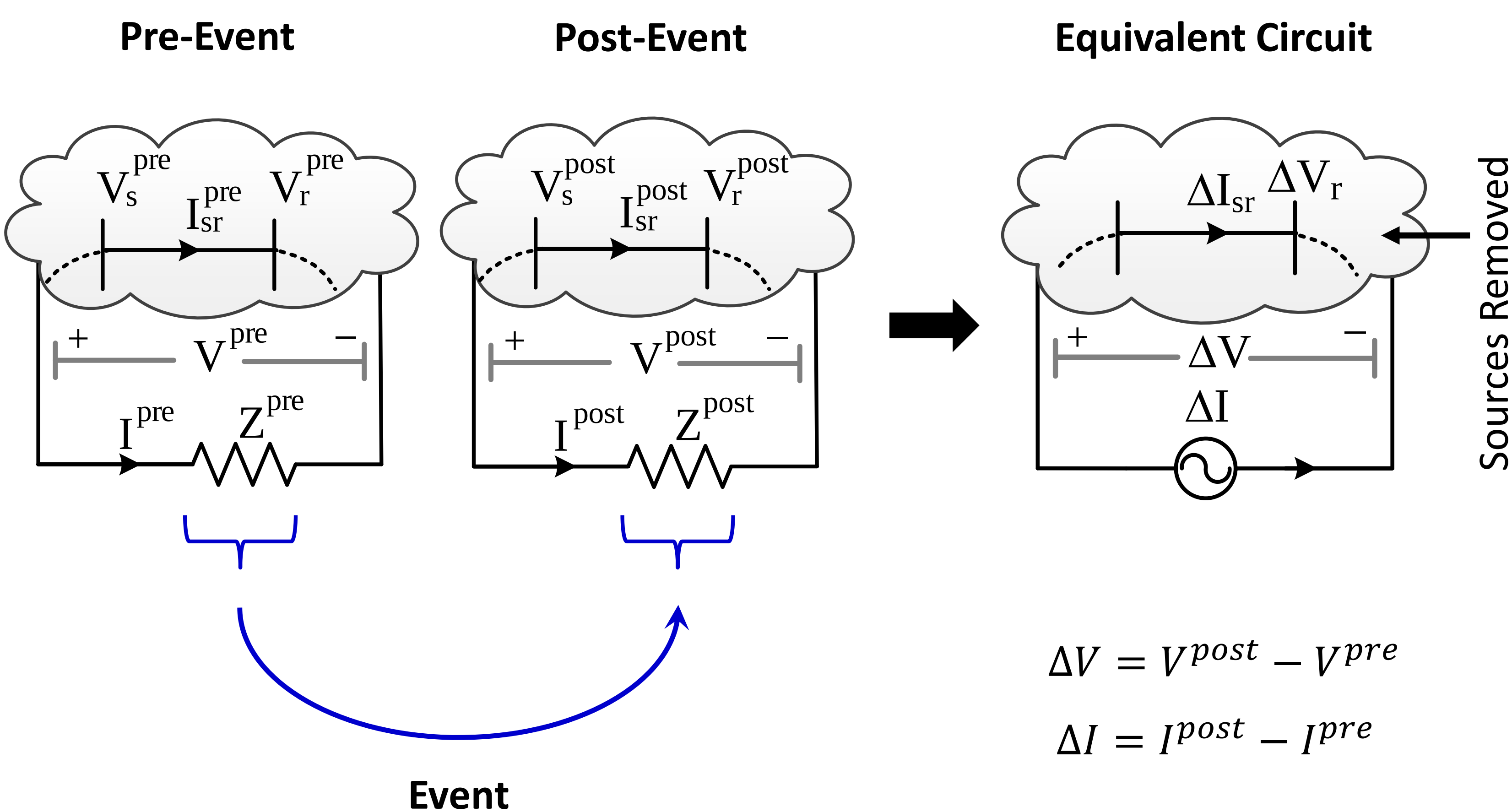
# Phase 3: Event Source Identification

**Class 3**




**Questions:** What is the source location of this event?





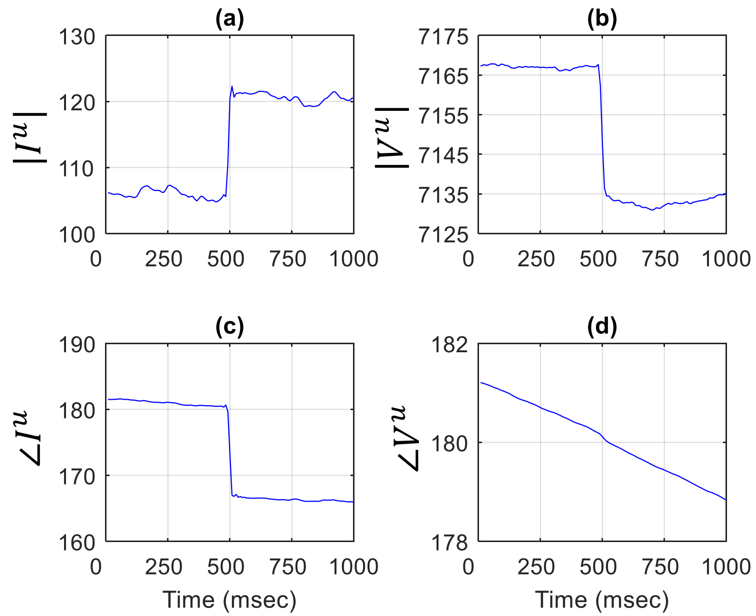

$$\Delta V = V^{post} - V^{pre}$$

$$\Delta I = I^{post} - I^{pre}$$

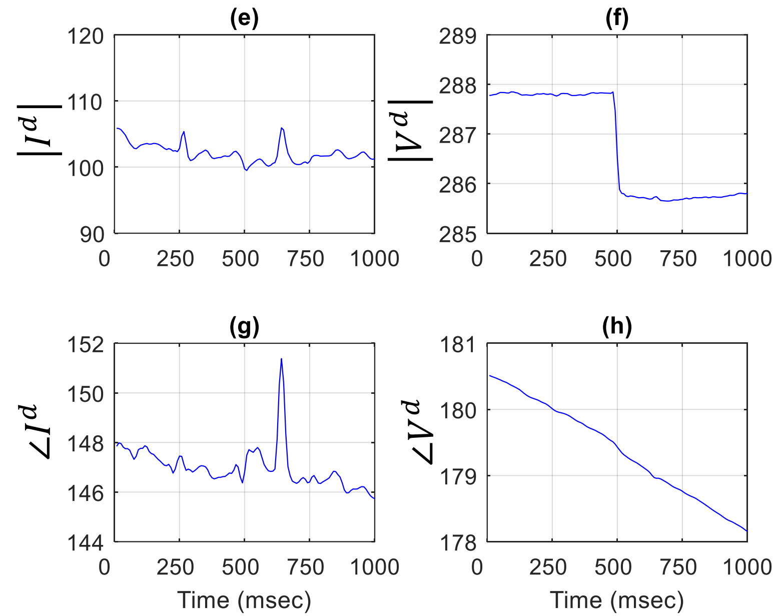
**Theoretical Foundation: Compensation Theorem**

# Step 3-1: Extract Differential Synchrophasors

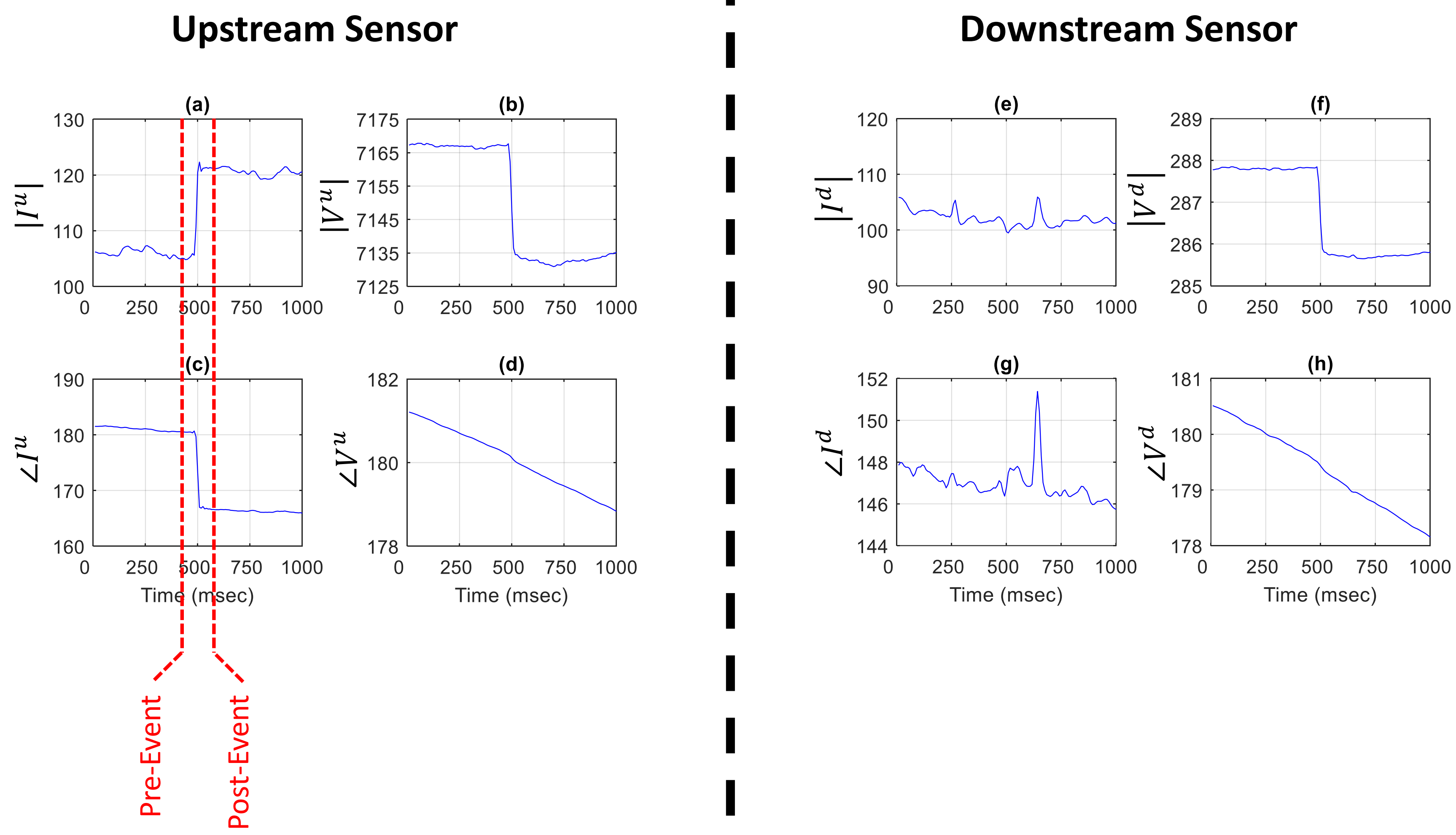
## Upstream Sensor




## Downstream Sensor

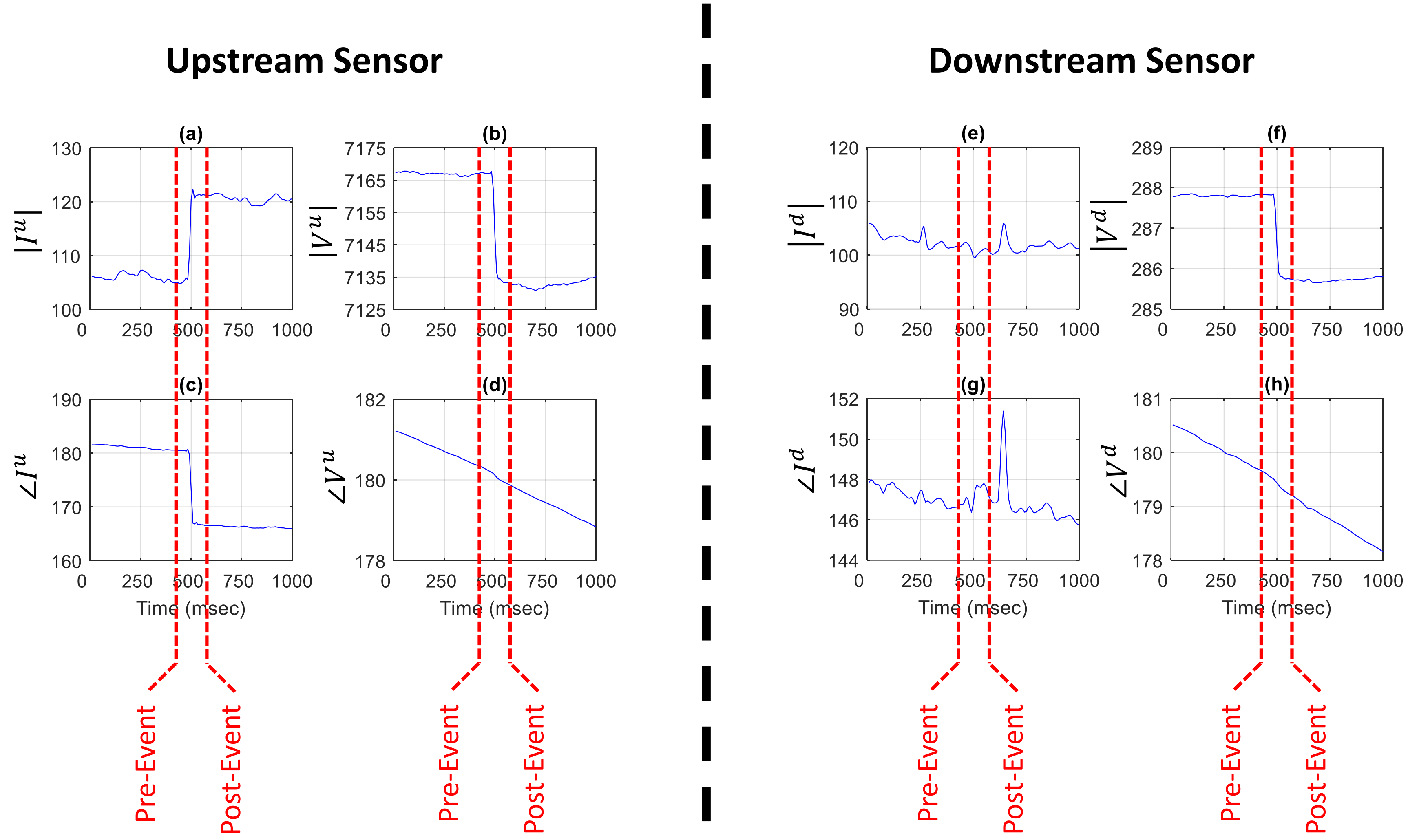


# Step 3-1: Extract Differential Synchrophasors




$|\Delta I^u| \angle \Delta I^u$

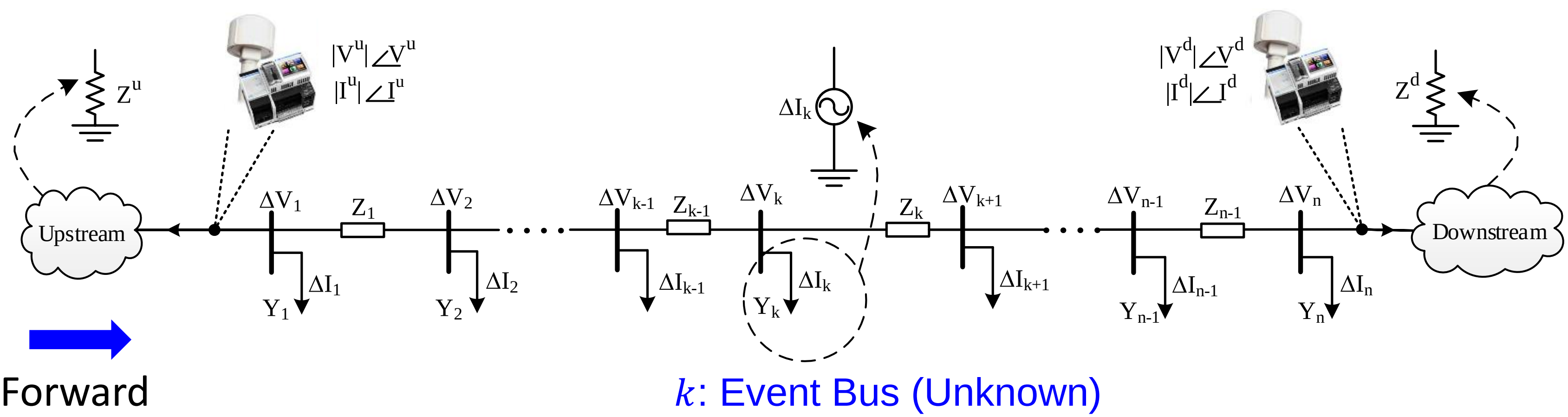
# Step 3-1: Extract Differential Synchrophasors




$|\Delta I^u| \angle \Delta I^u$ $|\Delta V^u| \angle \Delta V^u$ $|\Delta I^d| \angle \Delta I^d$ $|\Delta V^d| \angle \Delta V^d$

# Step 3-2: Forward Nodal Voltage Calculation

$$
\begin{aligned}
\Delta V_1^f &= \Delta V^u \\
\Delta V_2^f &= \Delta V_1^f + (\Delta I^u + Y_1 \Delta V_1^f) Z_1 \\
&\vdots \\
\Delta V_k^f &= \Delta V_{k-1}^f + (\Delta I^u + Y_1 \Delta V_1^f + \cdots + Y_{k-1} \Delta V_{k-1}^f) Z_{k-1} \\
\Delta V_{k+1}^f &\neq \Delta V_k^f + (\Delta I^u + Y_1 \Delta V_1^f + \cdots + Y_{k-1} \Delta V_{k-1}^f + Y_k \Delta V_k^f) Z_k \\
&\vdots \\
\Delta V_n^f &\neq \Delta V_{n-1}^f + (\Delta I^u + Y_1 \Delta V_1^f + \cdots + Y_{n-1} \Delta V_{n-1}^f) Z_{n-1}
\end{aligned}
\qquad \mathrm{I}
$$

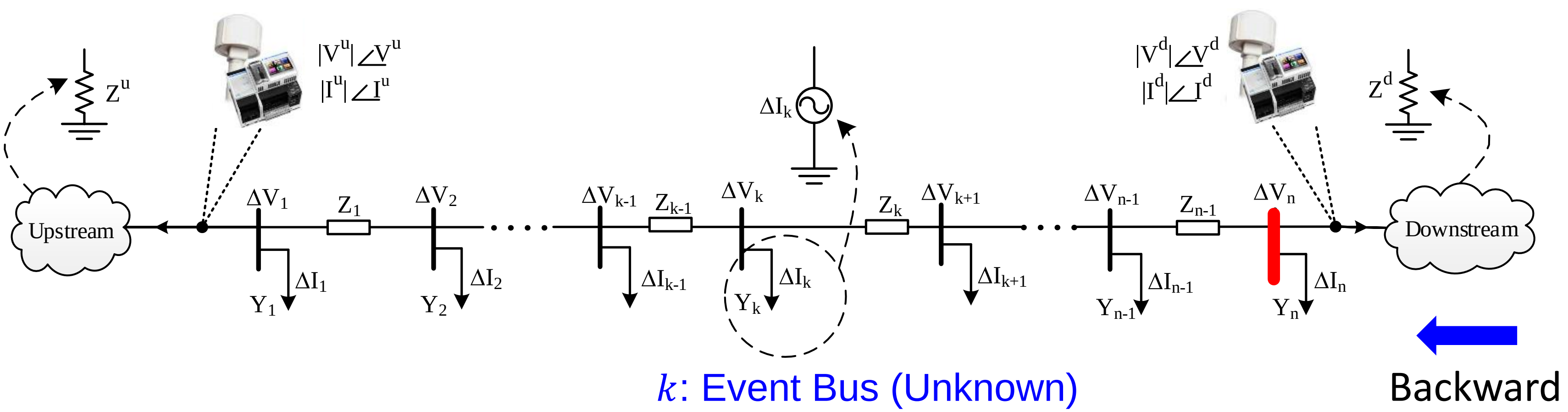



$k$: Event Bus (Unknown)

# Step 3-3: Backward Nodal Voltage Calculation

$$\Delta V_n^b = \Delta V^d$$
$$\Delta V_{n-1}^b = \Delta V_n^b + \left(\Delta I^d + Y_n \Delta V_n^b\right) Z_{n-1}$$
$$\vdots$$
$$\Delta V_k^b = \Delta V_{k+1}^b + \left(\Delta I^u + Y_n \Delta V_n^b + \cdots + Y_{k+1} \Delta V_{k+1}^b\right) Z_k$$
$$\Delta V_{k-1}^b \neq \Delta V_k^b + \left(\Delta I^u + Y_n \Delta V_n^b + \cdots + Y_{k+1} \Delta V_{k+1}^b + Y_k \Delta V_k^b\right) Z_{k-1}$$
$$\vdots$$
$$\Delta V_1^b \neq \Delta V_2^b + \left(\Delta I^u + Y_n \Delta V_n^b + \cdots + Y_2 \Delta V_2^b\right) Z_1$$

II




$k$: Event Bus (Unknown)

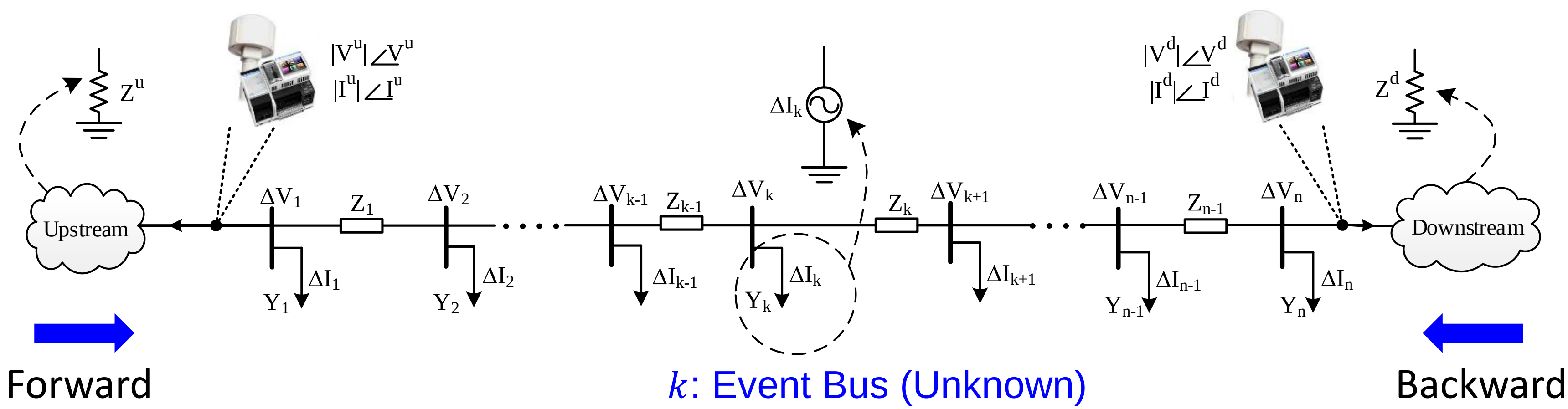
# Step 3-4: Analysis of Discrepancy Index

**Forward:** $\left\{\underbrace{\Delta V_1^f, \cdots, \Delta V_{k-1}^f, \Delta V_k^f}_{\text{Correct}}, \underbrace{\Delta V_{k+1}^f, \cdots, \Delta V_n^f}_{\text{Incorrect}}\right\}$

**Backward:** $\left\{\underbrace{\Delta V_1^b, \cdots, \Delta V_{k-1}^b}_{\text{Incorrect}}, \underbrace{\Delta V_k^b, \Delta V_{k+1}^b, \cdots, \Delta V_n^b}_{\text{Correct}}\right\}$

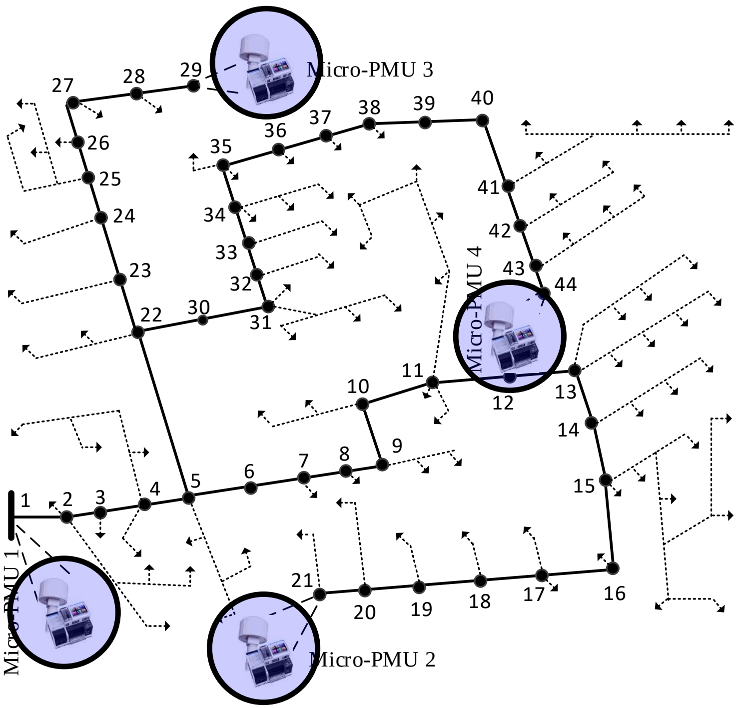
Discrepancy Index

$$k = \underset{i}{\operatorname{argmin}} \ \overbrace{\left|\Delta V_i^f - \Delta V_i^b\right|}^{\Phi_i}$$

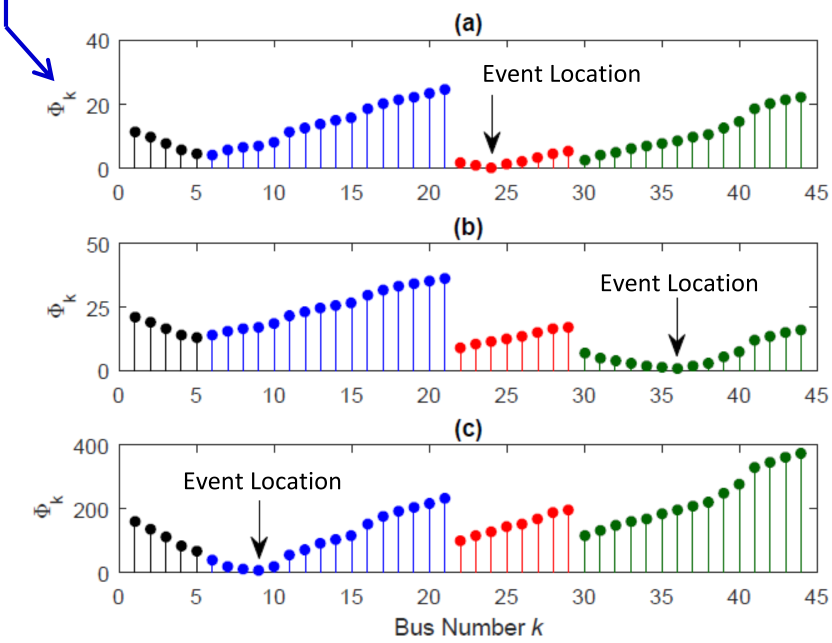


# Phase 3: Event Source Identification

IEEE 123-Bus Test System

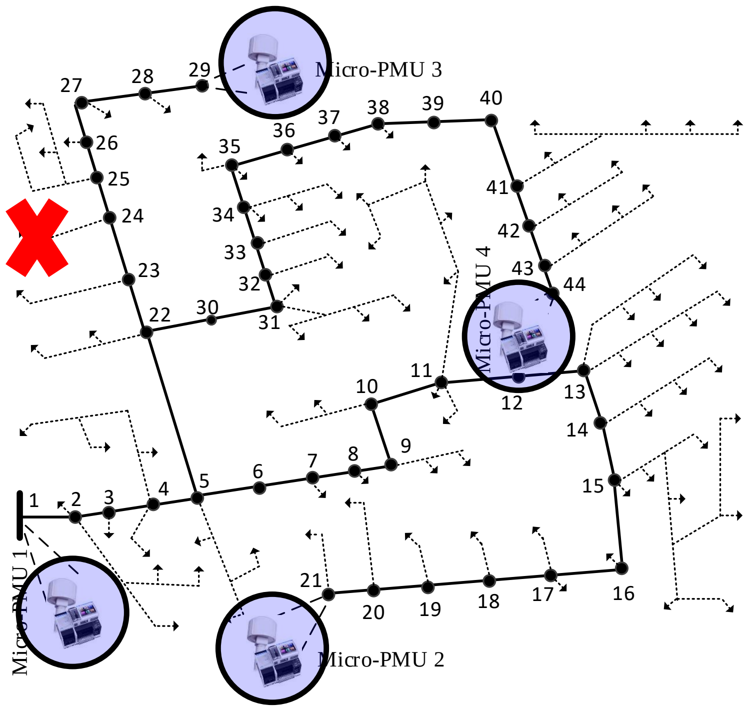



Discrepancy Index

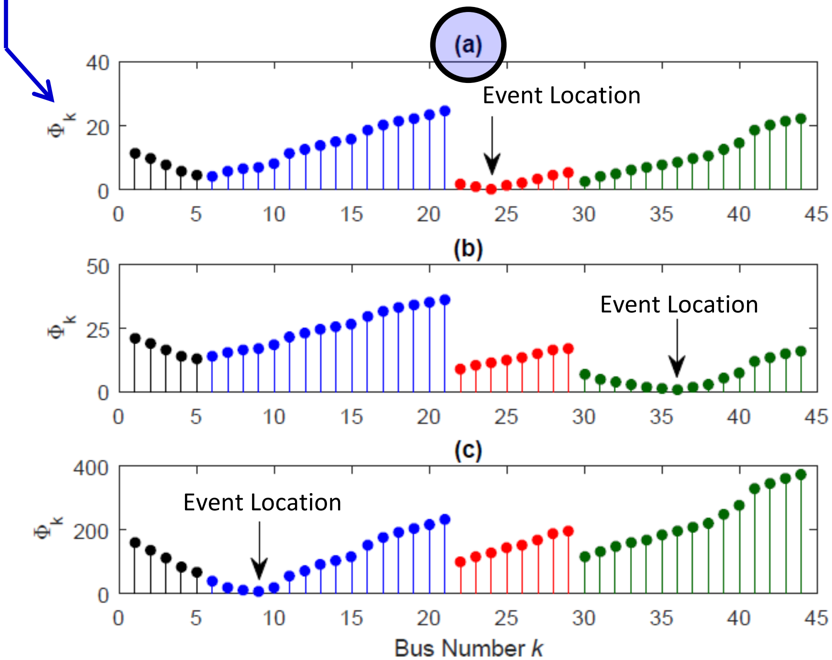


# Phase 3: Event Source Identification

IEEE 123-Bus Test System



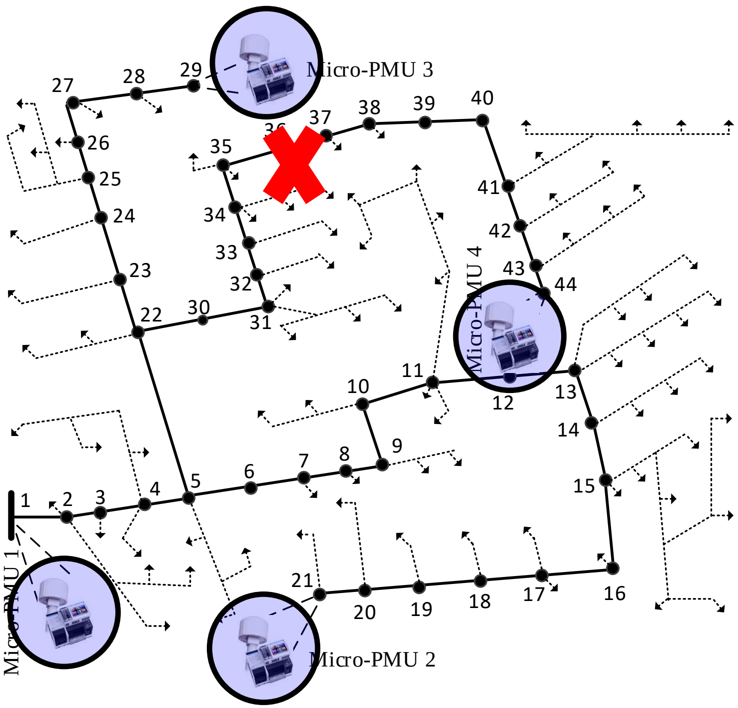

Discrepancy Index



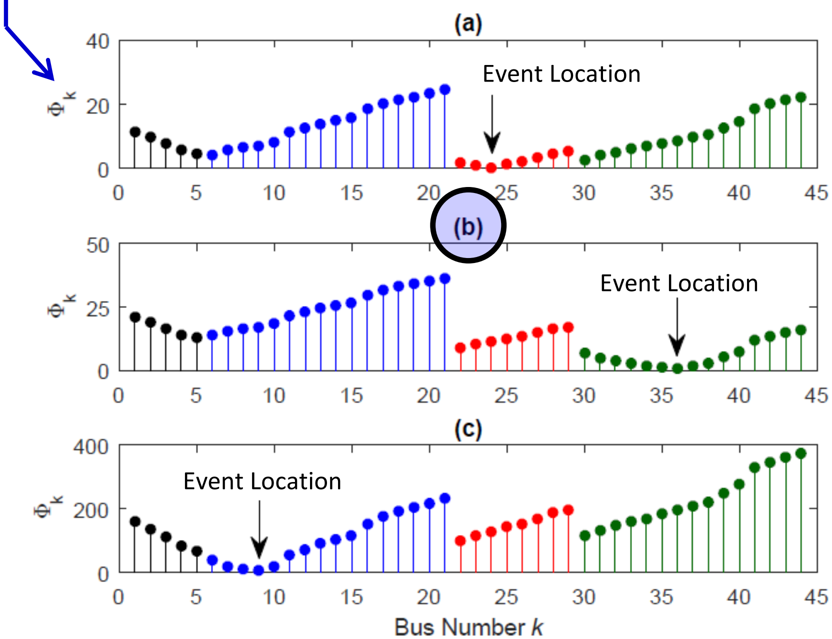

Event Source Location

# Phase 3: Event Source Identification

IEEE 123-Bus Test System

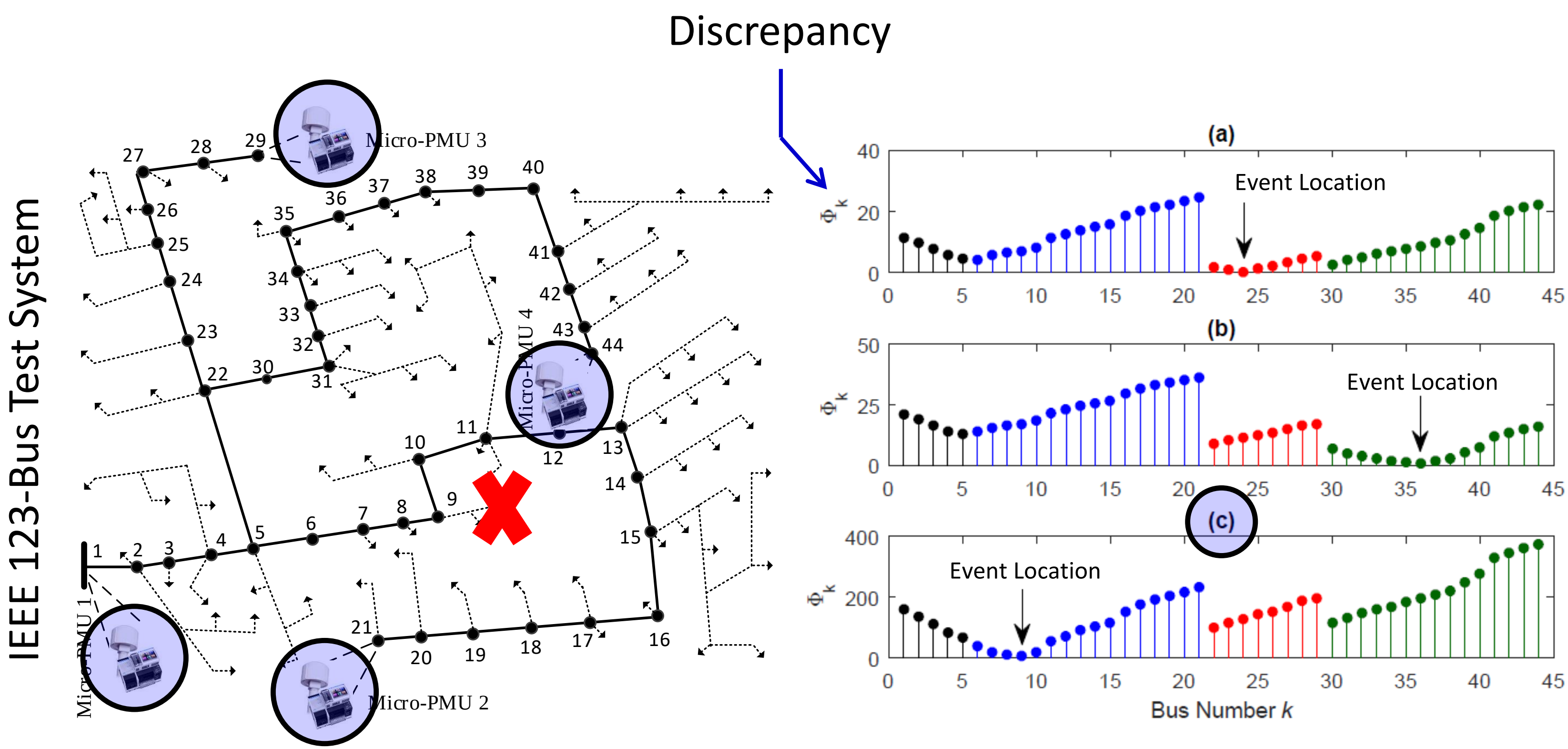



Discrepancy




Event Source Location

# Phase 3: Event Source Identification




Event Source Location

# Recap: Big Data?

- **Data-Analytics Package for Distribution Synchrophasors**
  - Event Detection
  - Event Classification
  - Event Source Identification

Billions of Data Points

Device-Specific Event Signatures

- **Case Study: Remote Asset Monitoring**

# Recap: Big Data?

- **Data-Analytics Package for Distribution Synchrophasors**
  - Event Detection
  - Event Classification
  - Event Source Identification

Billions of Data Points

Device-Specific Event Signatures

- **Case Study: Remote $\boxed{\text{Asset}}$ Monitoring**

Distributed Energy Storage

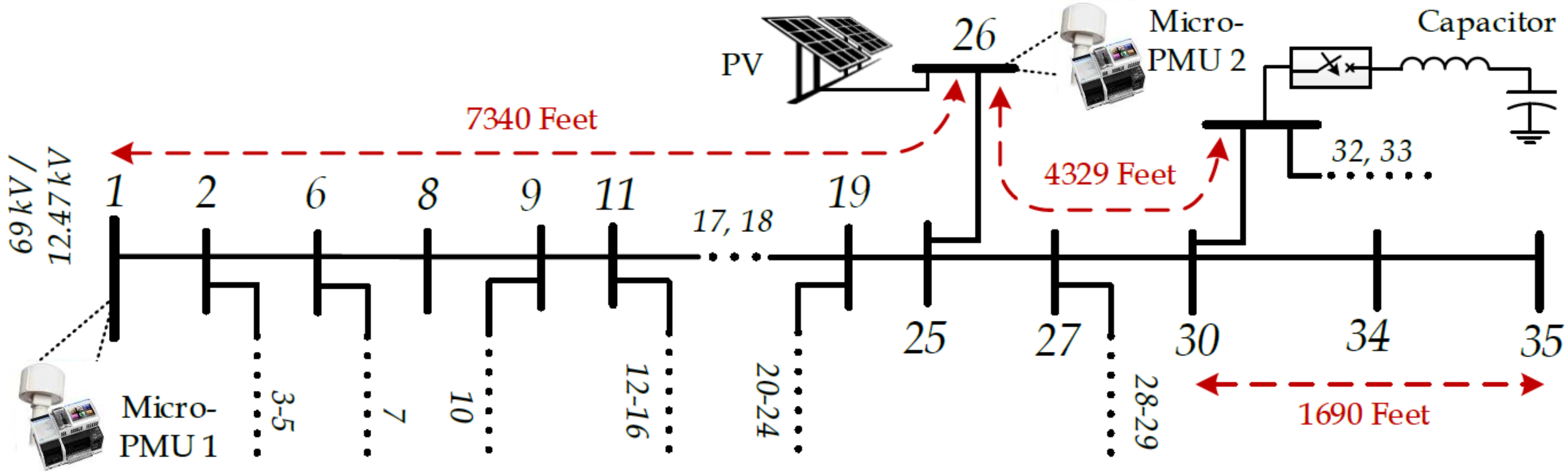
**Three-Phase Switched Capacitor Bank**

Rating: 3 x 300 kVAR = 900 kVAR

Volt/VAR Control

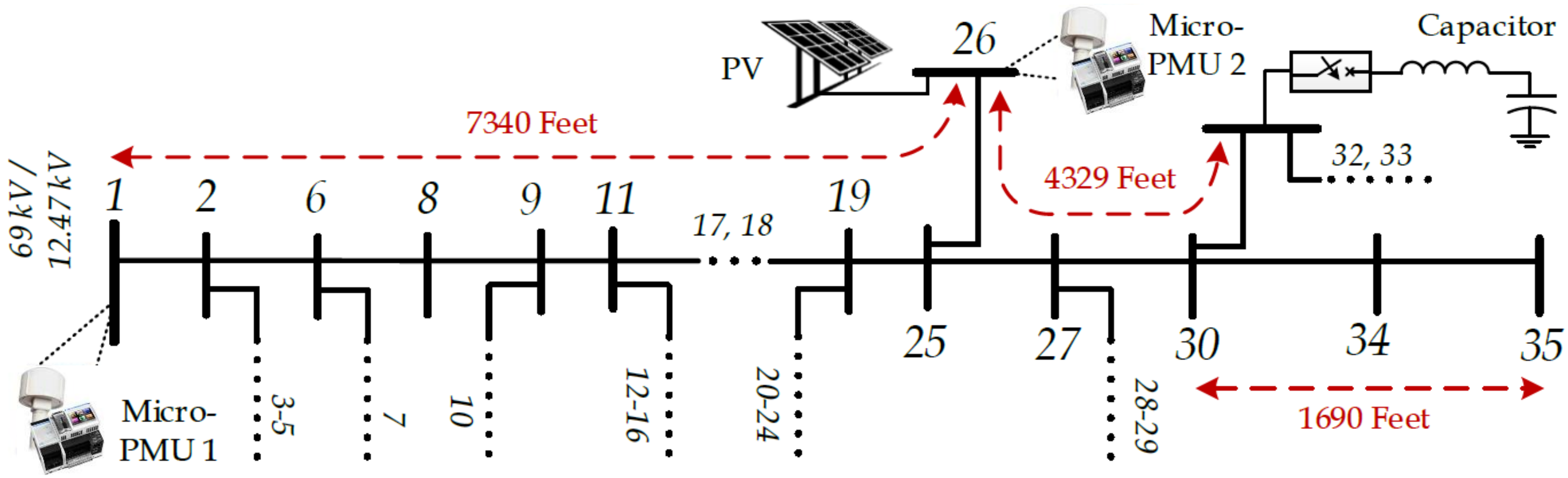
Onsite Switch On / Switch Off Controller

**No Monitoring**



**Typical Issues:**

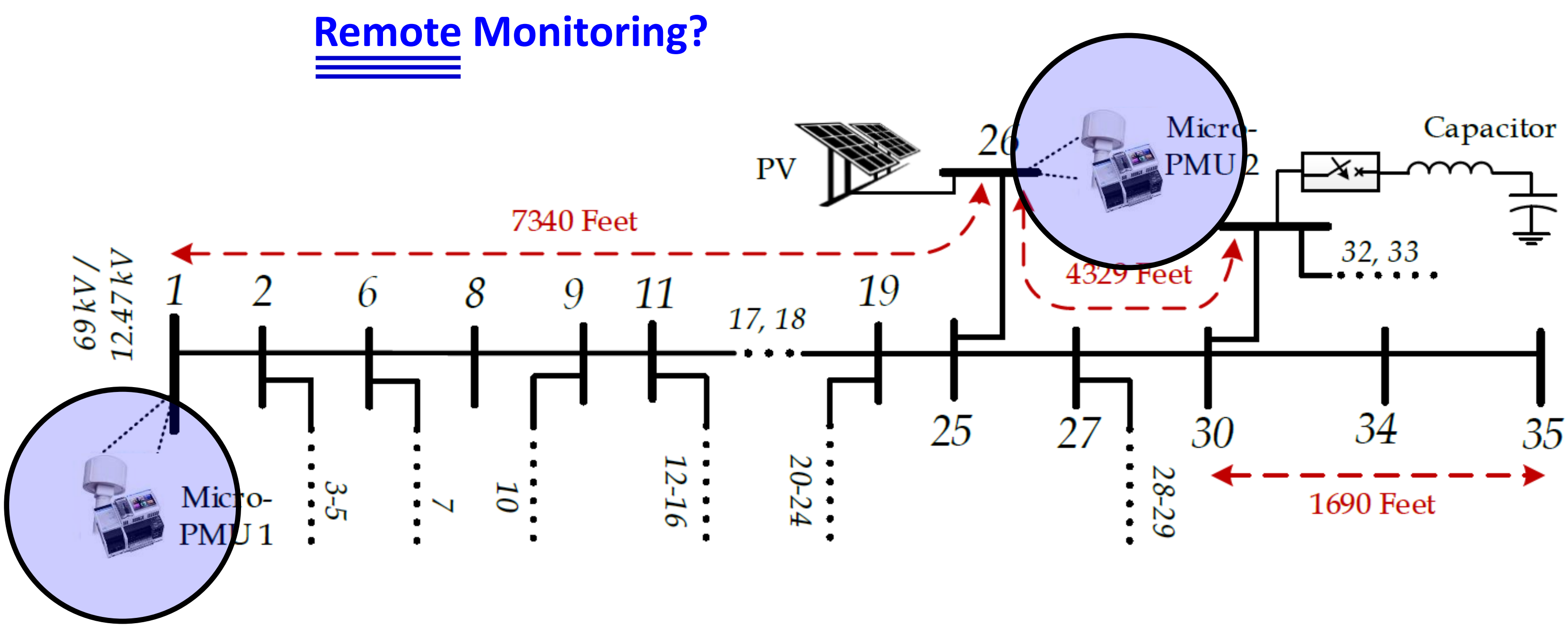
1. Unbalanced Operation (Fuses)
2. Switching Operation (Controllers)



# Case Study: (Remote) Asset Monitoring

**Typical Issues:**

1. Unbalanced Operation (Fuses)
2. Switching Operation (Controllers)

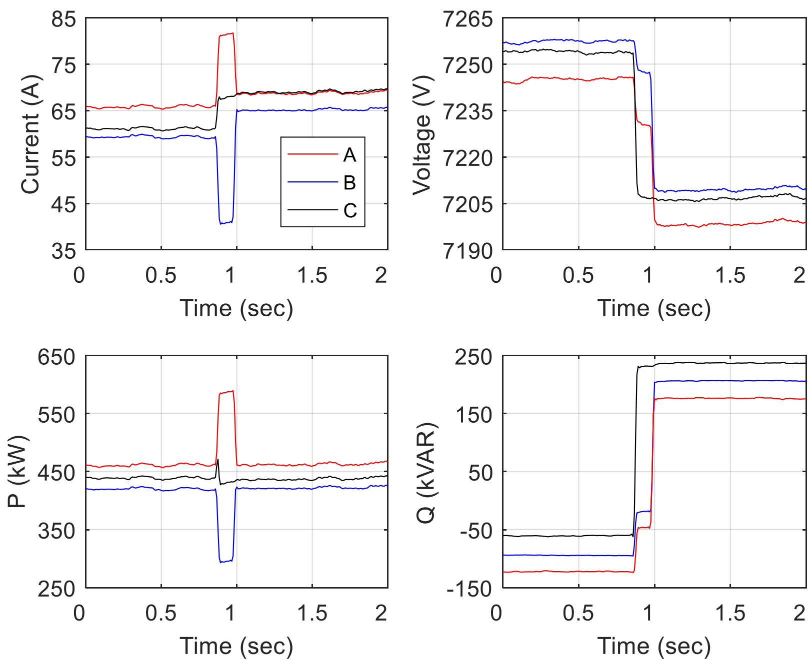


# Case Study: (Remote) Asset Monitoring

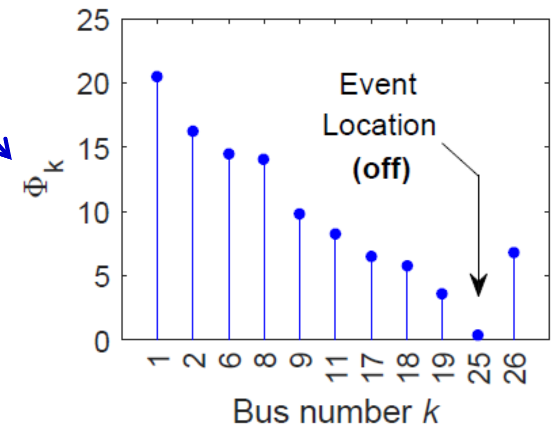
**Detection & Classification**

Discrepancy Index

**Switch Off Event**




**Location Identification**




**Event Bus: 25 (Correct)**

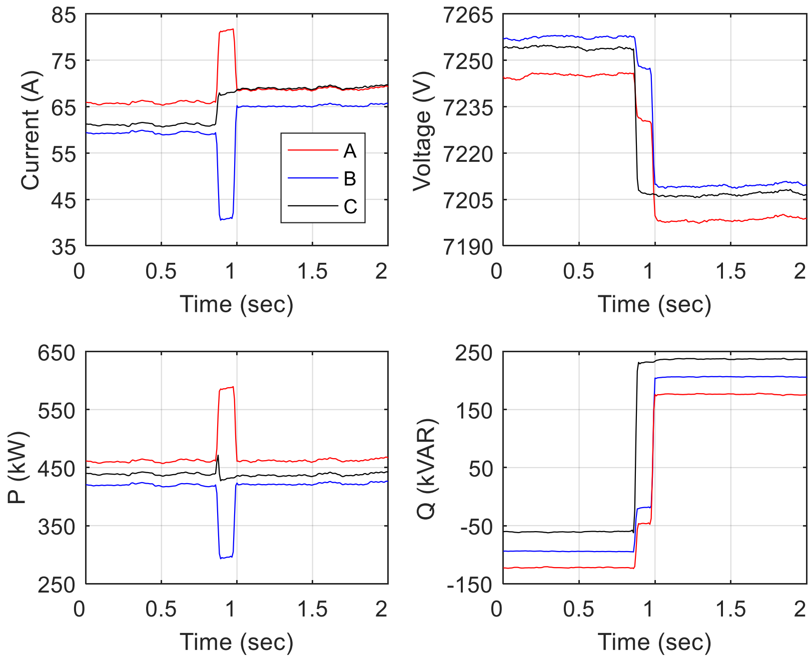
(Micro-PMU 1)

(Micro-PMU 2)

# Case Study: (Remote) Asset Monitoring

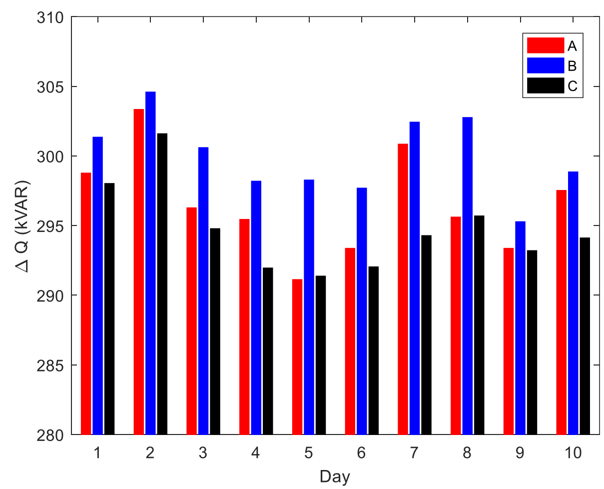
**Detection & Classification**

**Switch Off Event**




(Micro-PMU 1)

**Reactive Power Support**




**Slightly Unbalanced Operation**

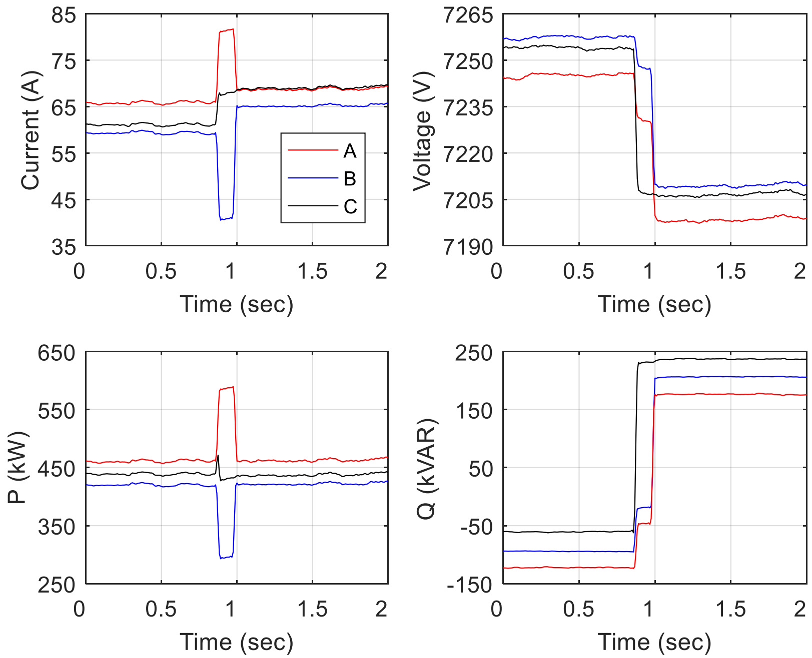
Phase B is always higher

Likely fuse blowing on C and A

# Case Study: (Remote) Asset Monitoring

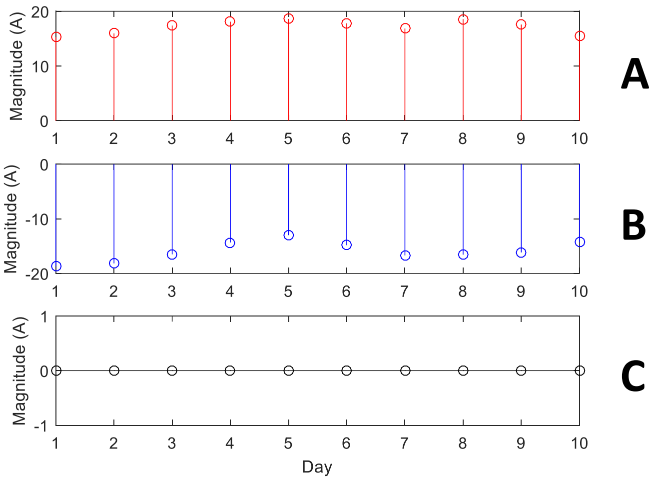
**Detection & Classification**

**Switch Off Event**




(Micro-PMU 1)

**Switching Transient**



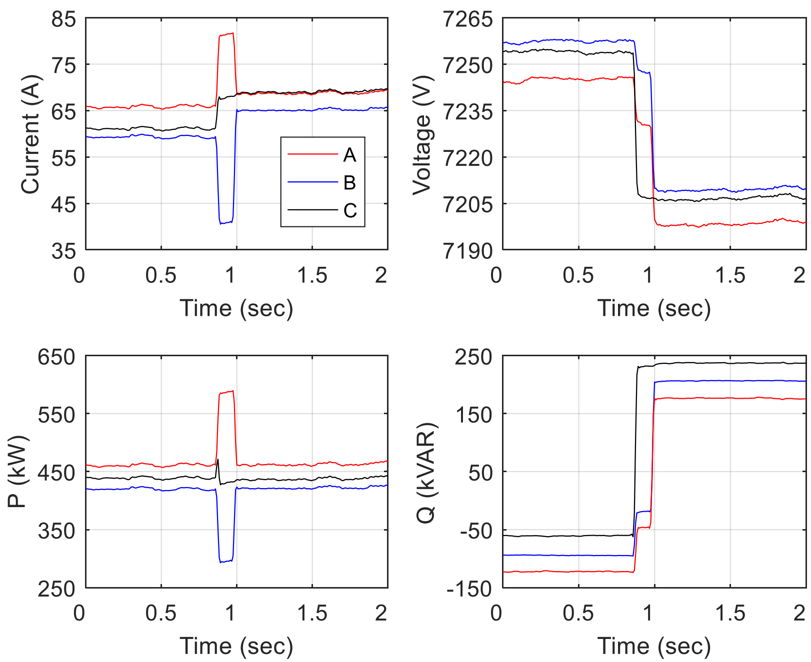

**Two-Step 3-Phase Switch**

**Step 1**: Phase C (Zero Crossing)

**Step 2**: Phase A/B (Possible Malfunction)

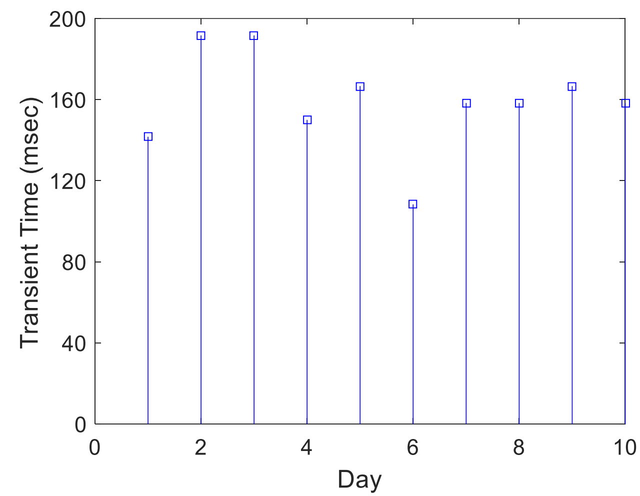
**Detection & Classification**

### Switch Off Event




(Micro-PMU 1)

### Switching Transient




**C $\longmapsto$ A/B**

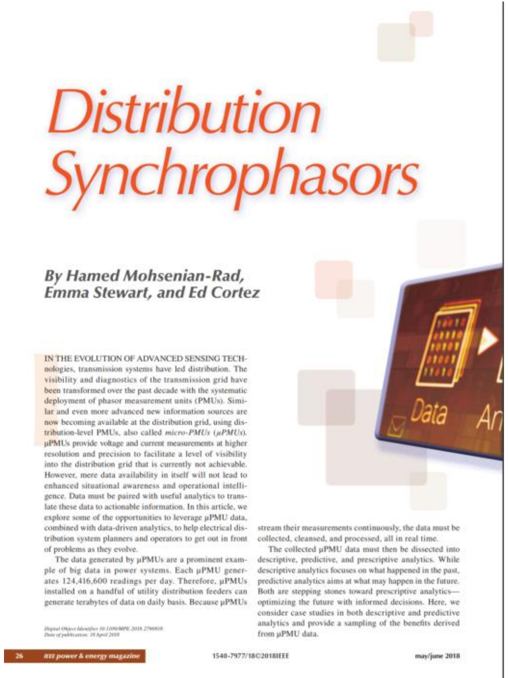
**Unbalanced System**

### Two-Step 3-Phase Switch

**Step 1**: Phase C (Zero Crossing)

**Step 2**: Phase A/B (Possible Malfunction)

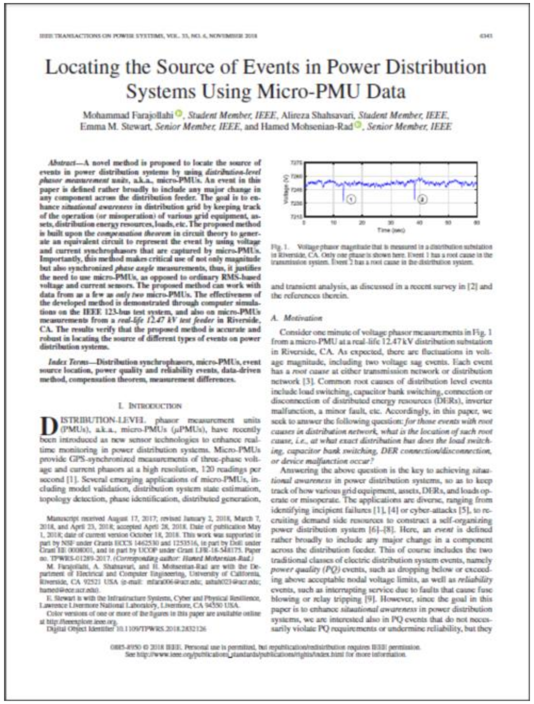
# Further Reading



Distribution Synchrophasors

By Hamed Mohsenian-Rad, Emma Stewart, and Ed Cortez

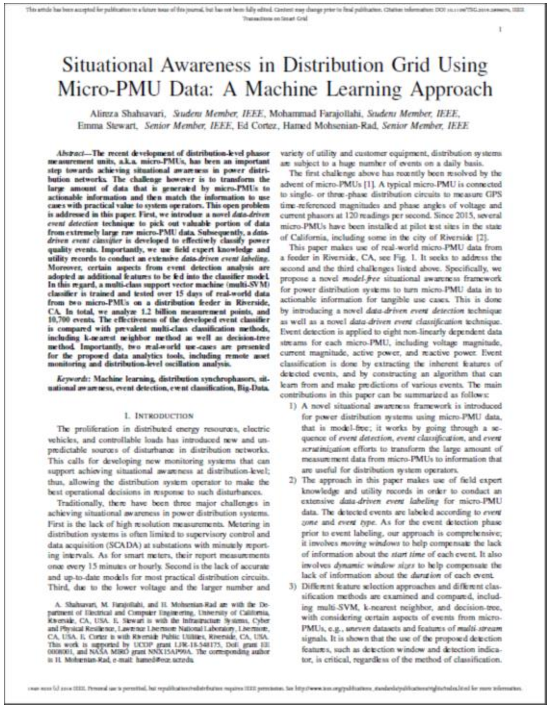
IEEE PES Magazine 2018



Locating the Source of Events in Power Distribution Systems Using Micro-PMU Data

Mohammad Farajollahi, Student Member, IEEE, Alireza Shahsavari, Student Member, IEEE, Emma M. Stewart, Senior Member, IEEE, and Hamed Mohsenian-Rad, Senior Member, IEEE

IEEE TPWRS 2018



Situational Awareness in Distribution Grid Using Micro-PMU Data: A Machine Learning Approach

Alireza Shahsavari, Student Member, IEEE, Mohammad Farajollahi, Student Member, IEEE, Emma Stewart, Senior Member, IEEE, Ed Cortez, Hamed Mohsenian-Rad, Senior Member, IEEE

IEEE TSG 2019

# Further Discussion

**Alireza Shahsavari**

**Mohammad Farajollahi**