Situational Awareness in Distribution Grid Using Micro-PMU Data

(Tasks 1.1 and 1.2)

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Agenda

- **Situational Awareness Using Distribution Synchrophasors**
  - Events in Distribution Systems
  - Event Detection
  - Event Classification
- **Use-Cases:**
  - Asset Monitoring
  - Protection System Diagnosis
- **Cyber Security & Situational Awareness**

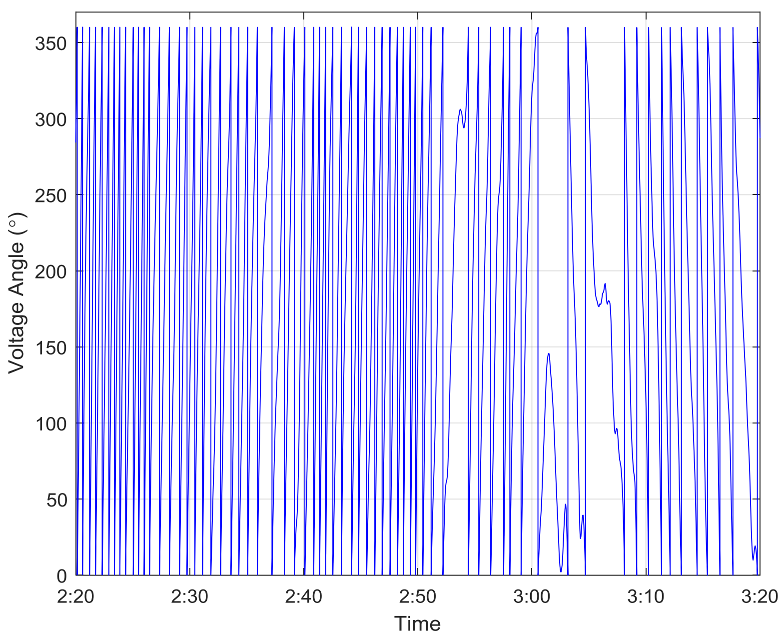
Our Focus: Sensors and Measurements

Data Recording:

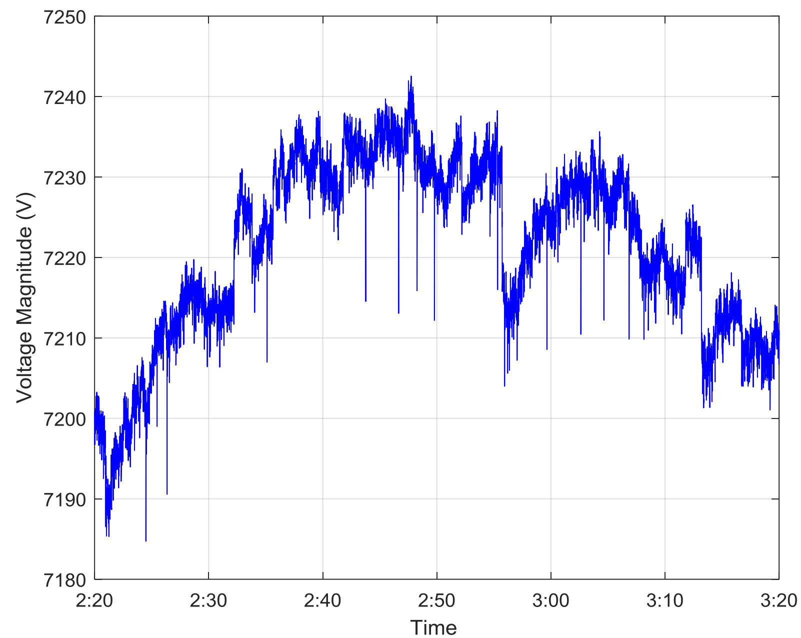
- Voltage Phasor
- Current Phasor

Features:

- Millisecond Reporting (120 Hz)
- 0.1 Accuracy



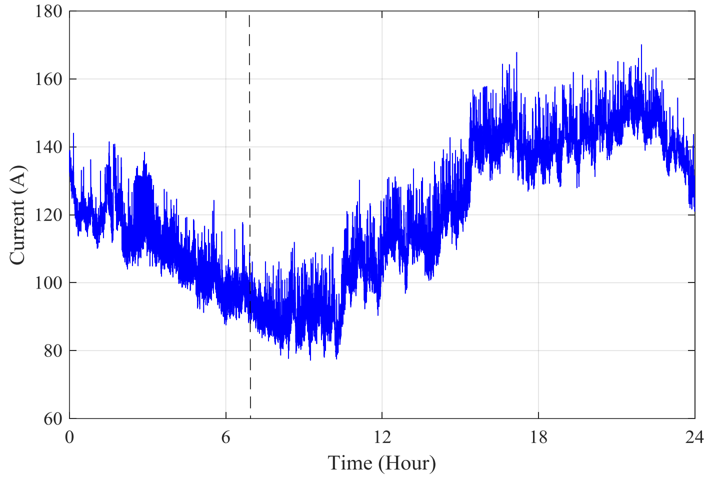
Voltage Angle



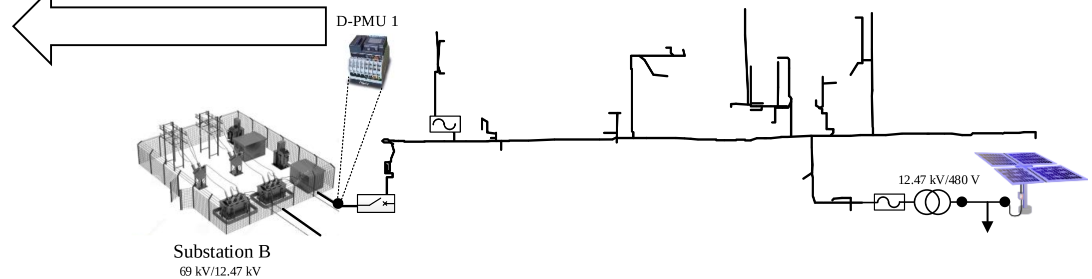
Voltage Magnitude

Events in Distribution Systems

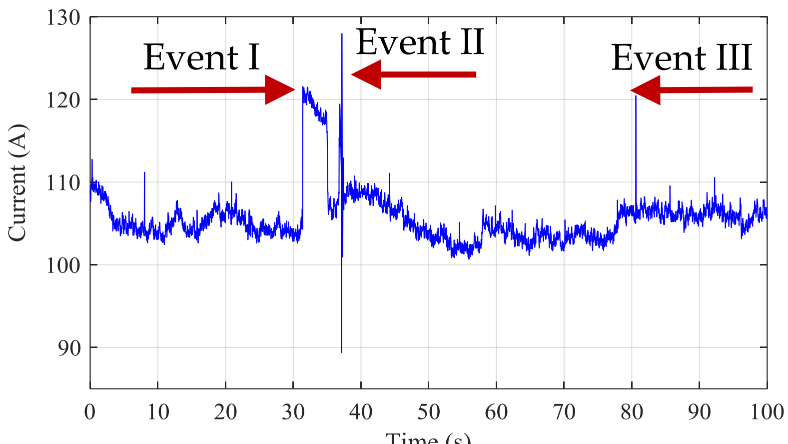
Data points: 10,368,000

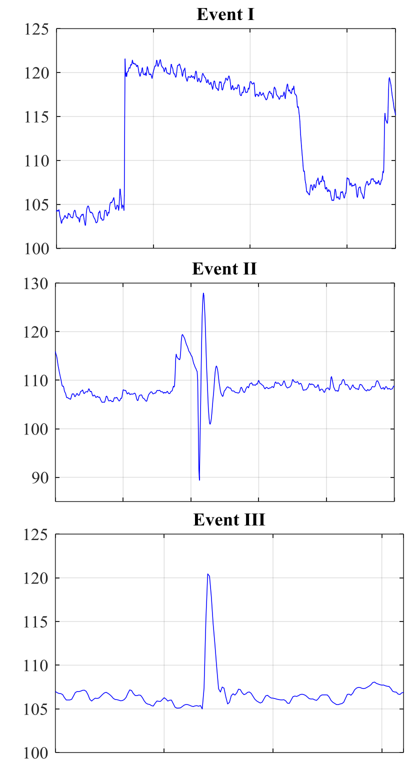


Current Magnitude of Phase A



Data Sequence: 100 seconds

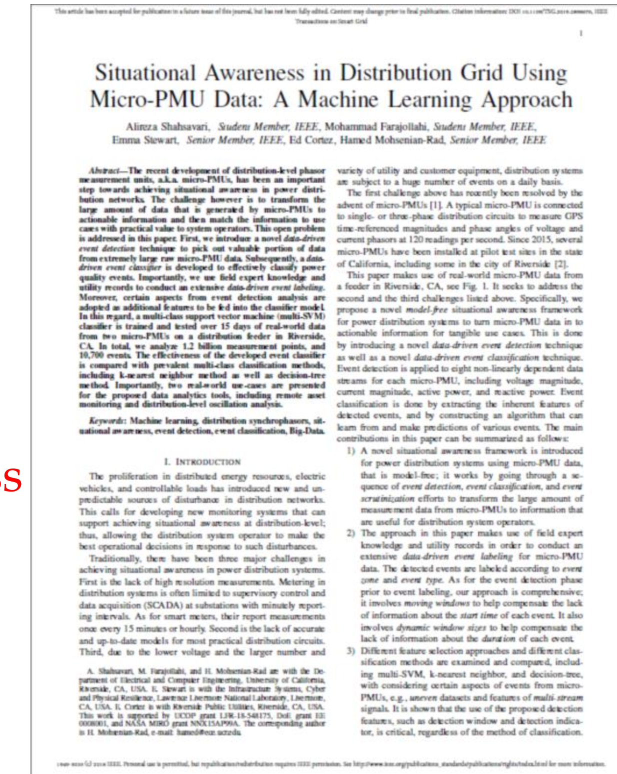




Application of Micro-PMUs:

- Capacitor Back Switching
- Fault Analysis
- Lightning Analysis
- Inverter Misoperation
- Event Detection
- Event Classification
- Impedance Calculation
- Topology Identification
- Event Source Location Identification
- …

Our Focus:
Situational Awareness with Application to Cybersecurity

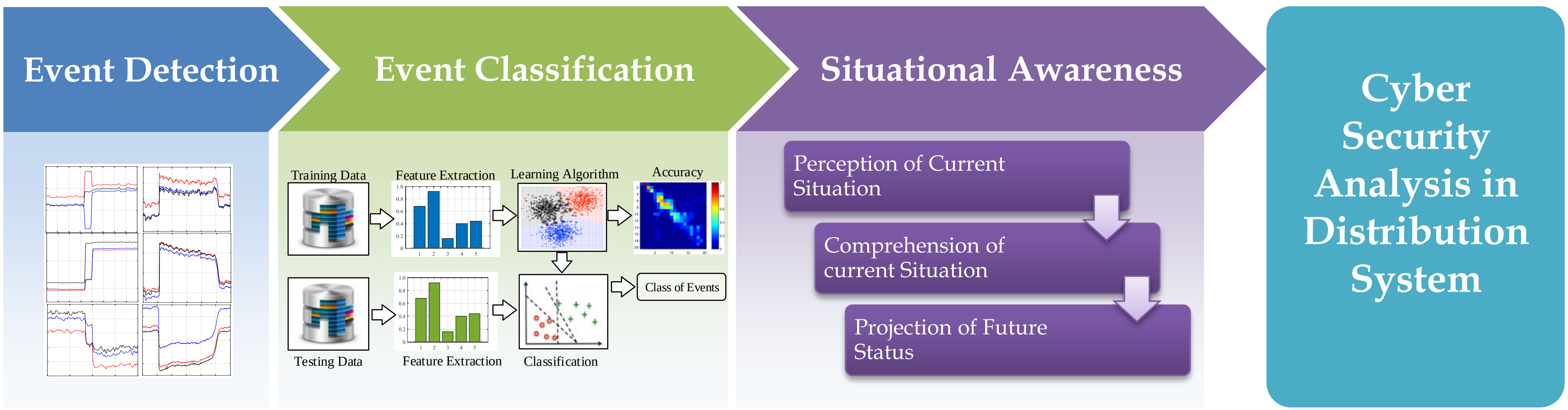

Situational Awareness in Distribution Grid Using Micro-PMU Data: A Machine Learning Approach

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

IEEE Power and Energy Magazine, May 2018

IEEE Trans. on Smart Grid, 2019

Situational Awareness and Cybersecurity in Distribution Systems



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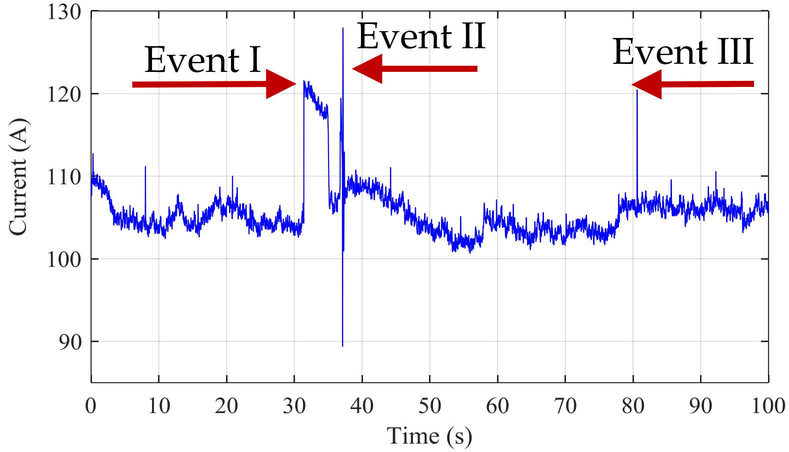
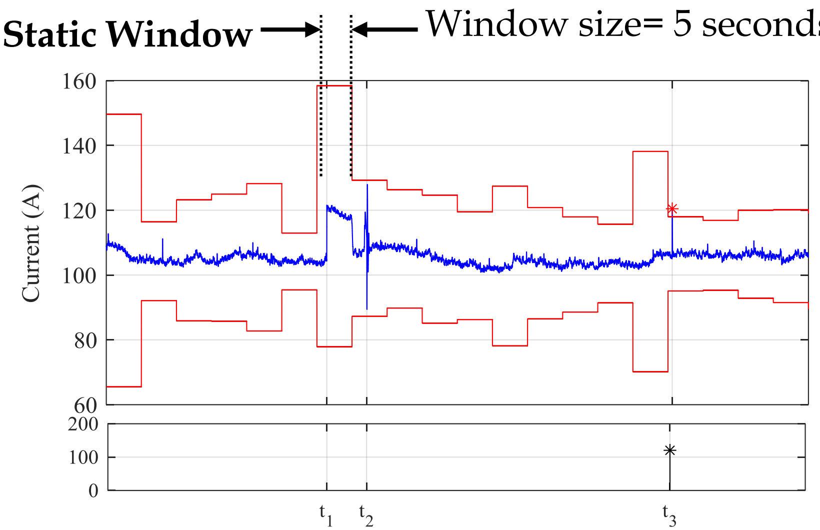
Events Detection: Method I, Absolute Deviation Around Median

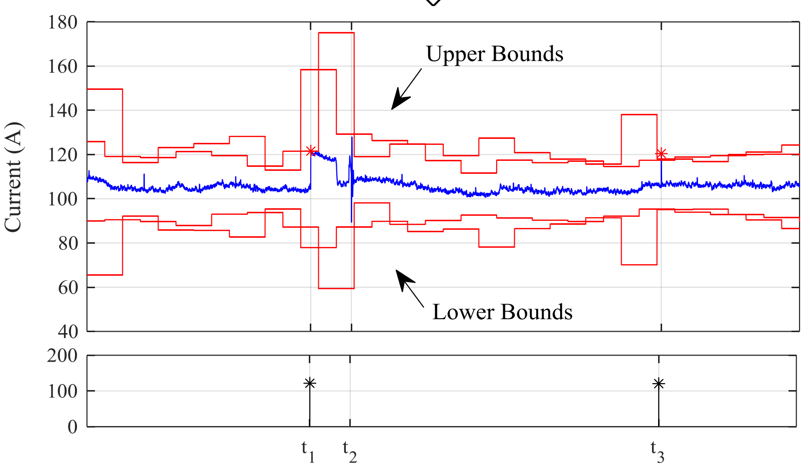
Data Sequence: 100 seconds



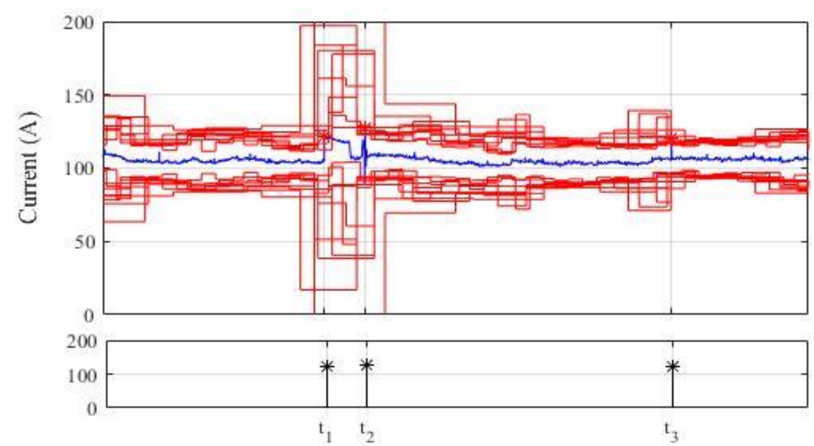
Static Window



Moving Window

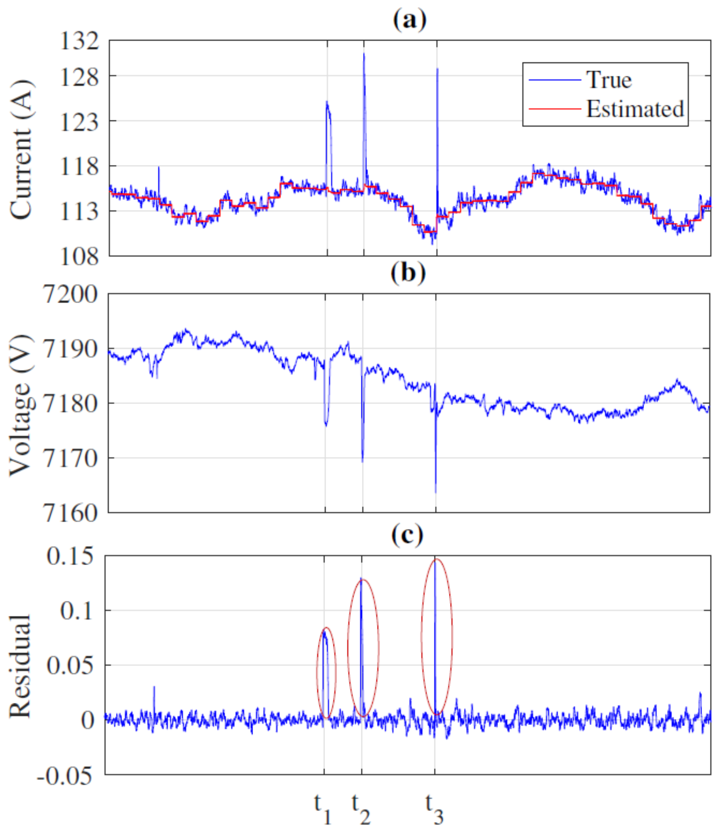


Dynamic Window Size and Moving Window

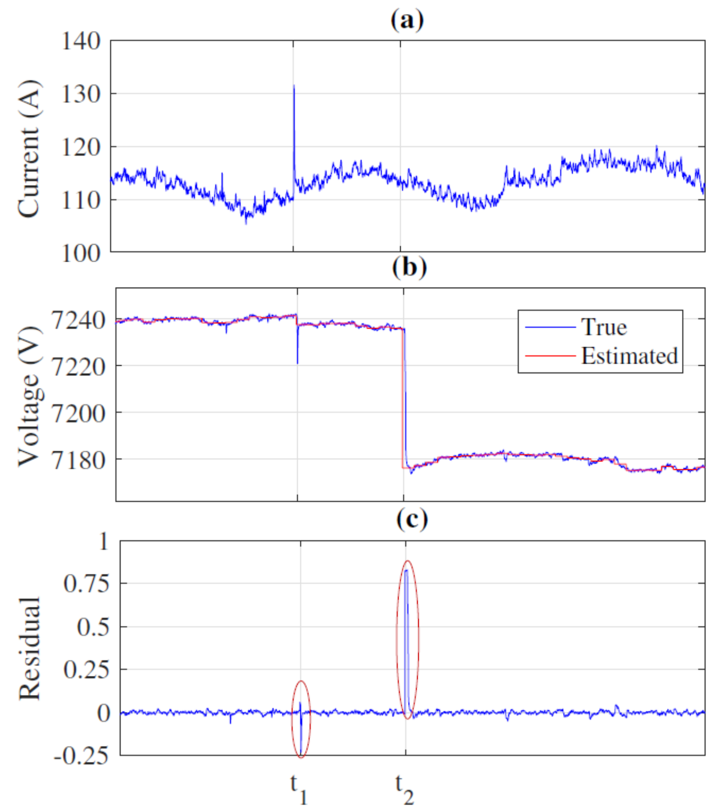


Events Detection: Method II, Residual Test on Non-Linear Estimation

Current Magnitude Estimation



Voltage Magnitude Estimation



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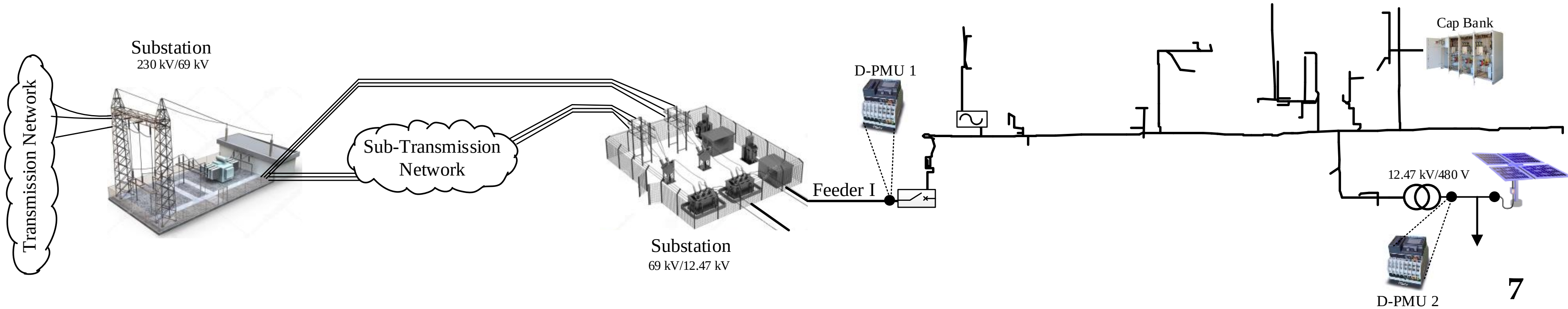
Event Classification

Event Labeling: Field Expert Knowledge and Utility Records

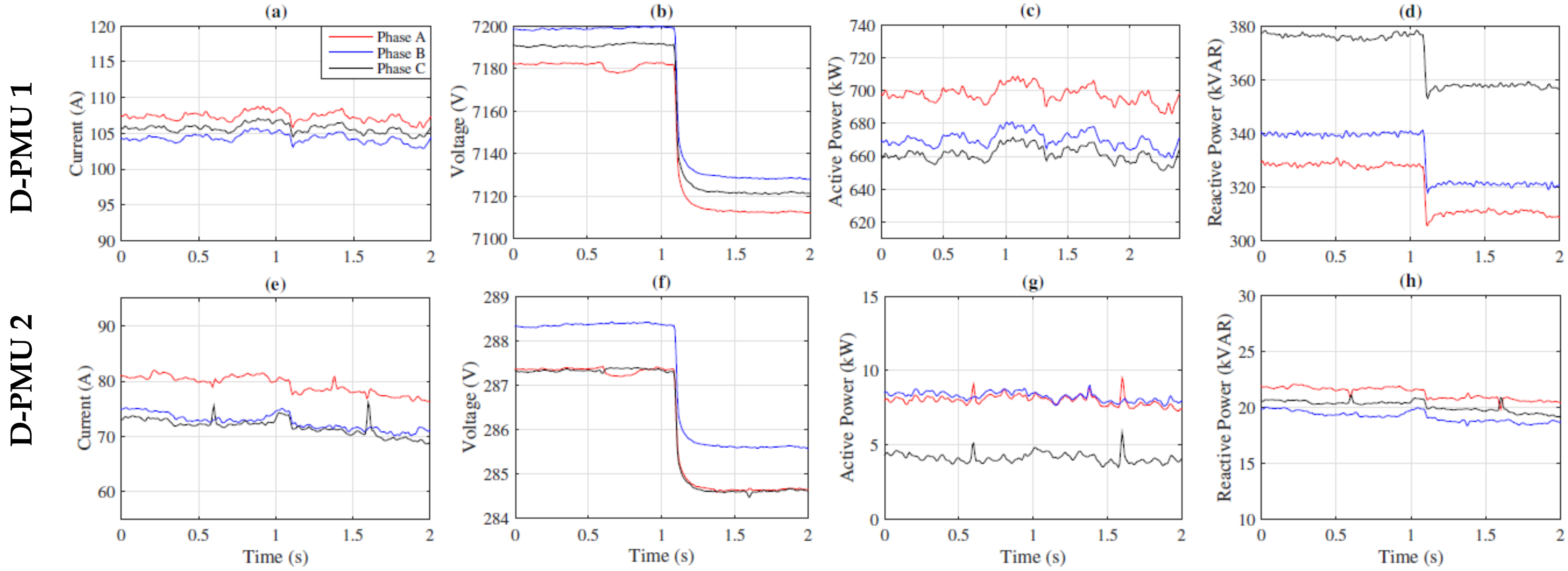
Provisions:

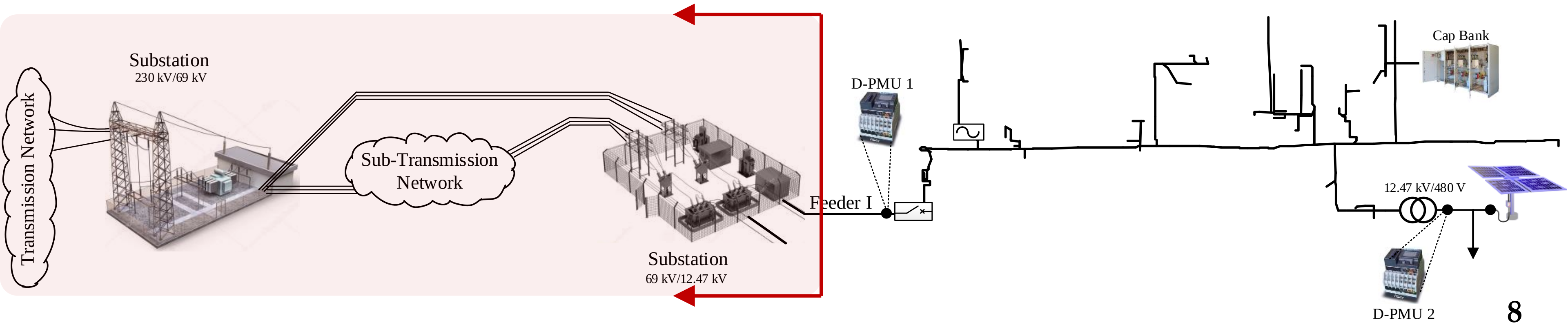
- Field knowledge of utility crew members
- Reviewing more than 1000 utility event logs for one year
- Computer simulation of the understudy feeders.
- Analysis of field data over three years.



Event Labeling

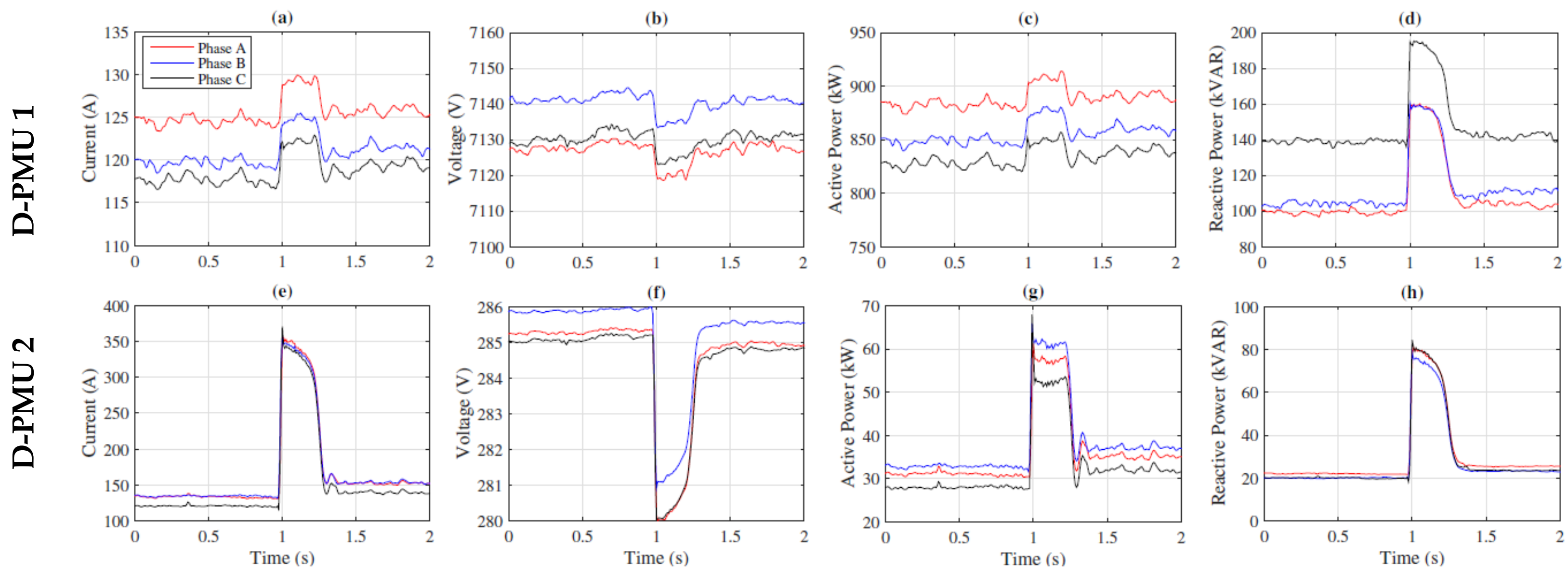
Class I: Events initiated from upstream of D-PMU 1:

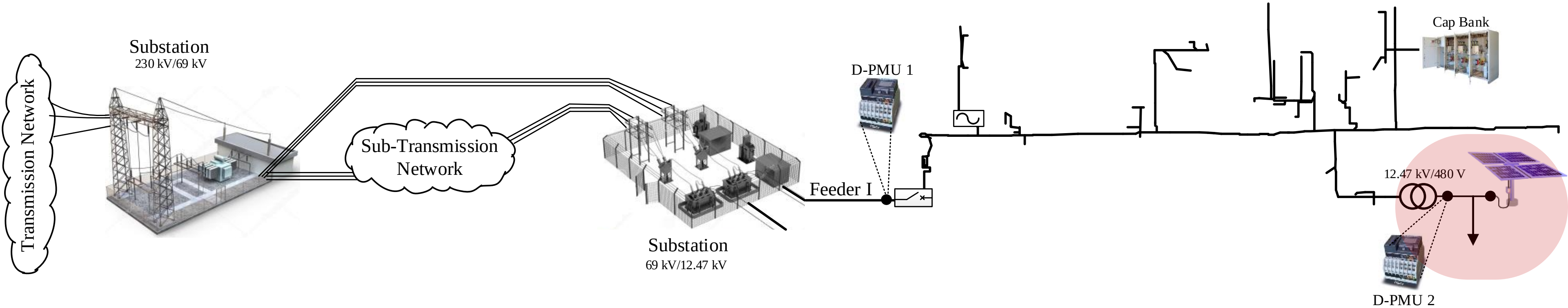




Event Labeling

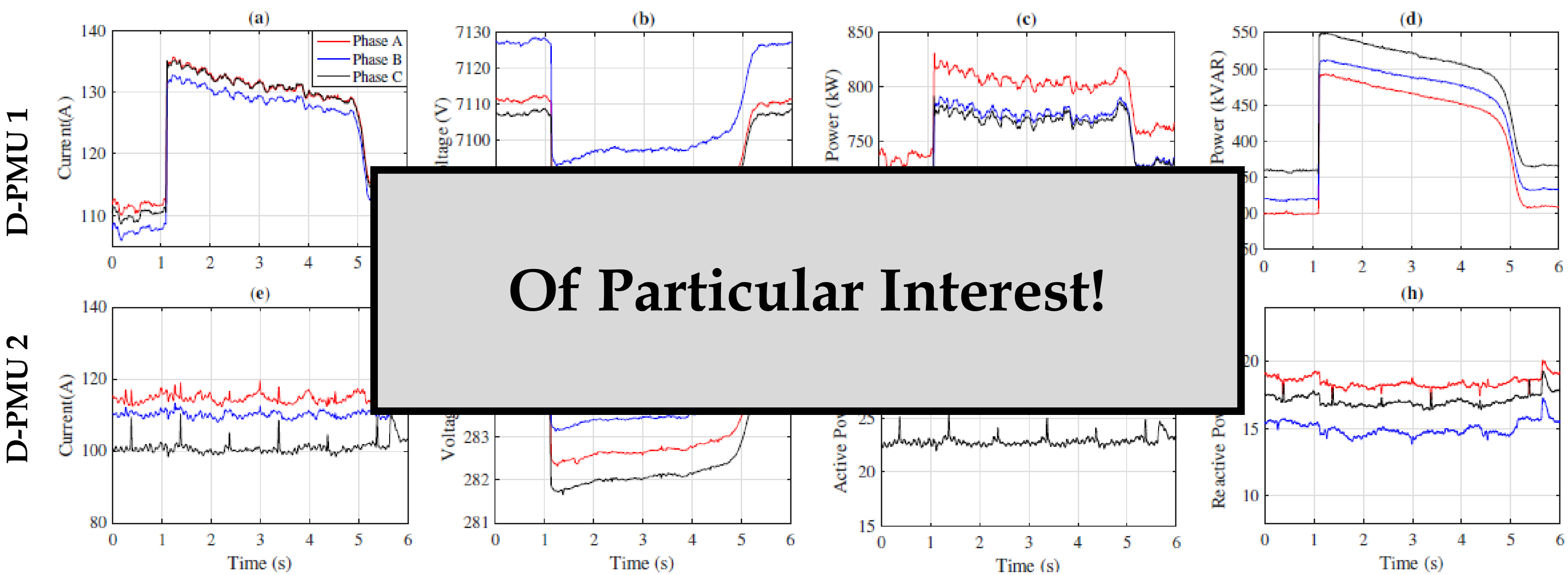
Class II: Events initiated from downstream of D-PMU 2:



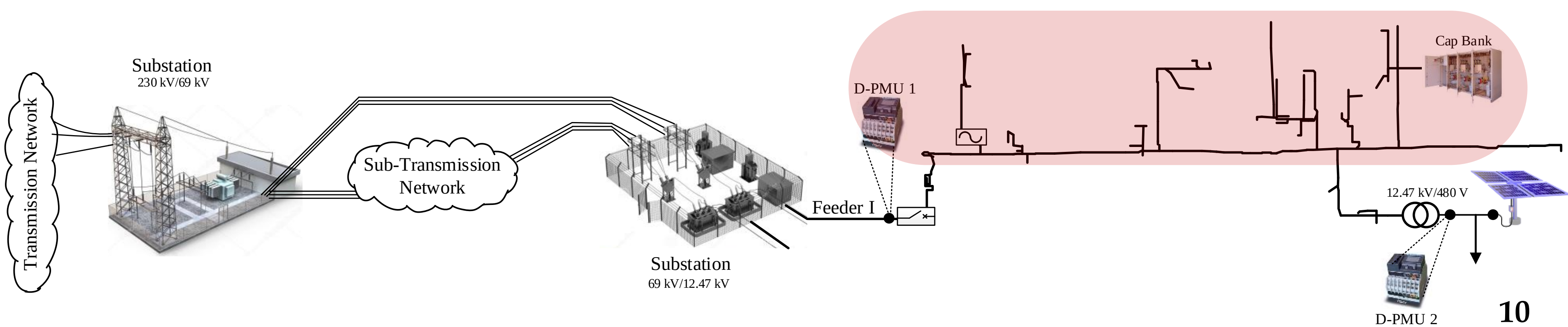


Event Labeling

Class III: Events initiated from somewhere between the two D-PMUs:



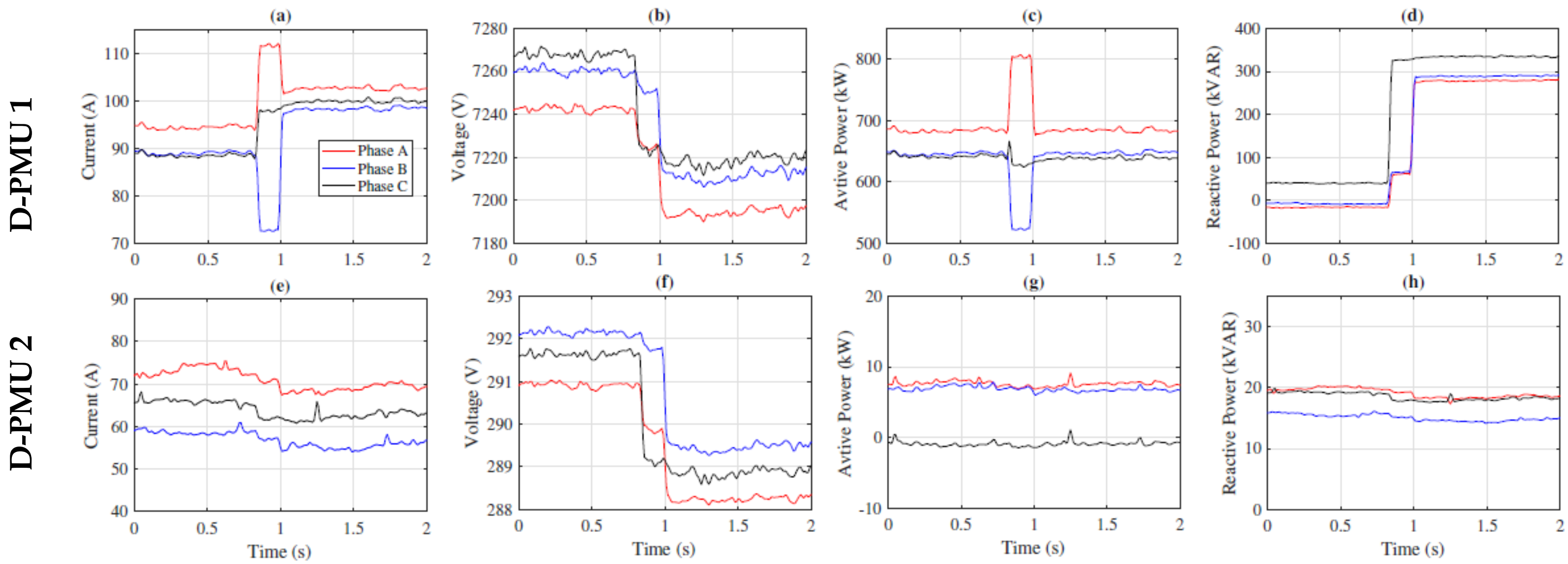
Of Particular Interest!

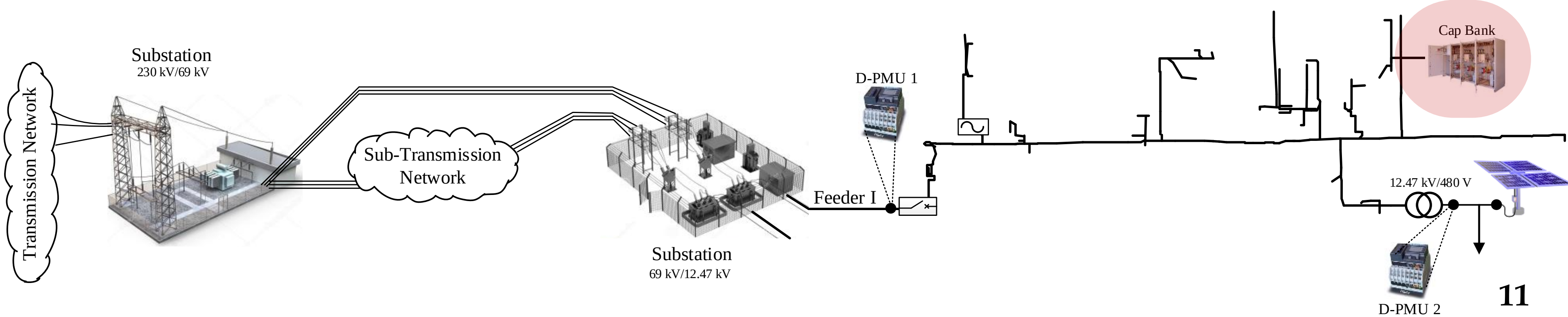


Event Labeling

Class III: Events initiated from somewhere between the two D-PMUs:

Class III.A: Capacitor Bank Switching

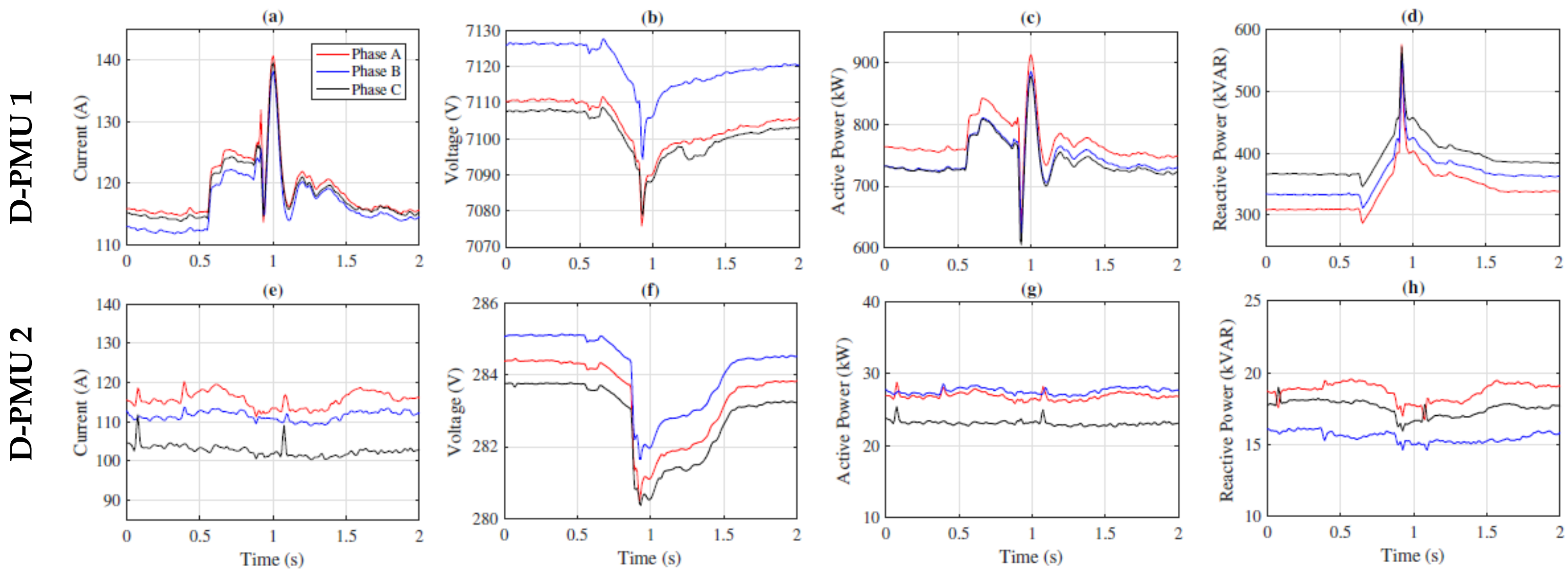


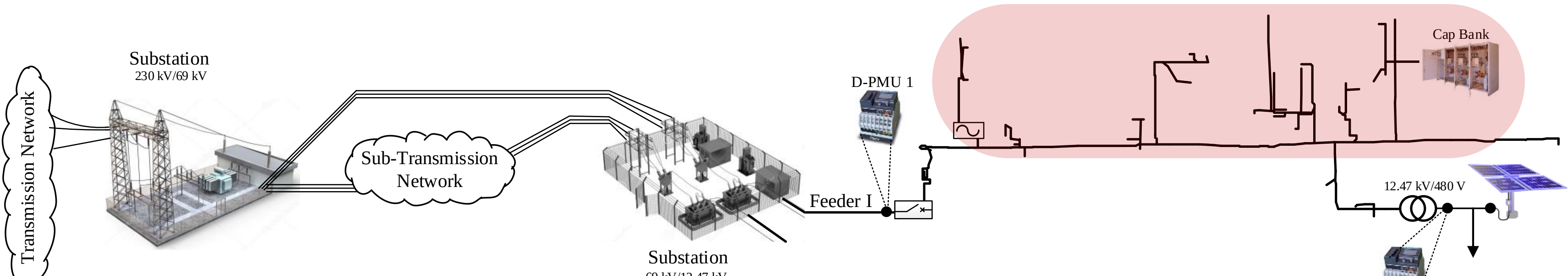


Event Labeling

Class III: Events initiated from somewhere between the two D-PMUs:

Class III.B: Momentary Oscillation





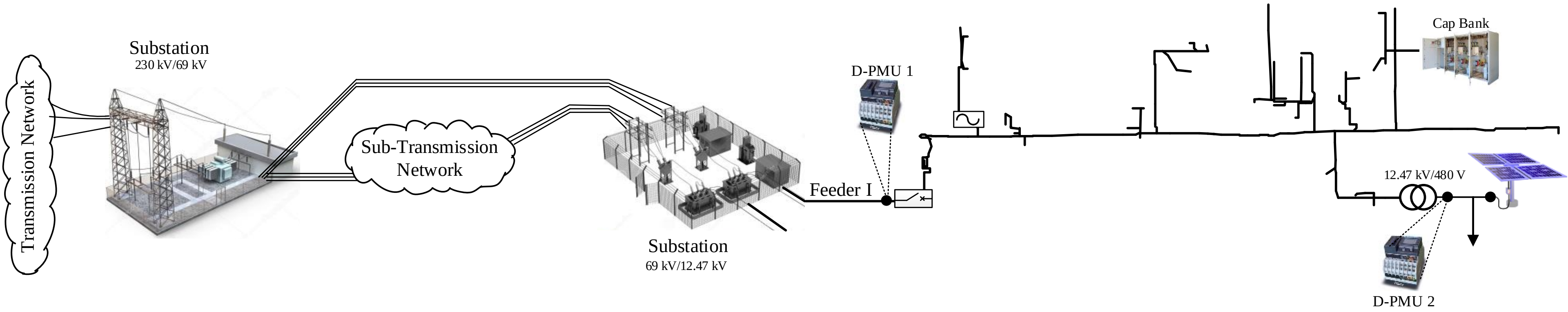
Event Labeling Summary

Layer I: Event Zone

- **Class I:** Events initiated from upstream of D-PMU 1
- **Class II:** Events initiated from downstream of D-PMU 2
- **Class III:** Events initiated from somewhere between the two D-PMUs

Layer II: Event Type

- **Class III.A:** Capacitor Bank Switching Events
- **Class III.B:** Momentary Oscillation
- **Class III.C:** Other Events



Feature Selection

- Single-Stream Features
  - Statistics, e.g., standard deviation
  - Difference, e.g., post-event and pre-event
- Multi-Stream Features
  - Correlation between any two signals
- Event Detection Features
  - Detection window size
  - Detection indicator

We consider data from two D-PMUs: Total number of signals is 8

Feature	Feature Description		Number
Single-stream	Statistics	std(D_i)	8
	Difference	$\lvert d_n - d_1 \rvert$	8
Multi-stream	Correlation	$corr(D_i, D_j)$	28
Detection	Detection Window	ω	1
	Detection Indicator	$\mathbb{I}\{D_i\}$	8

Total number of features: 53

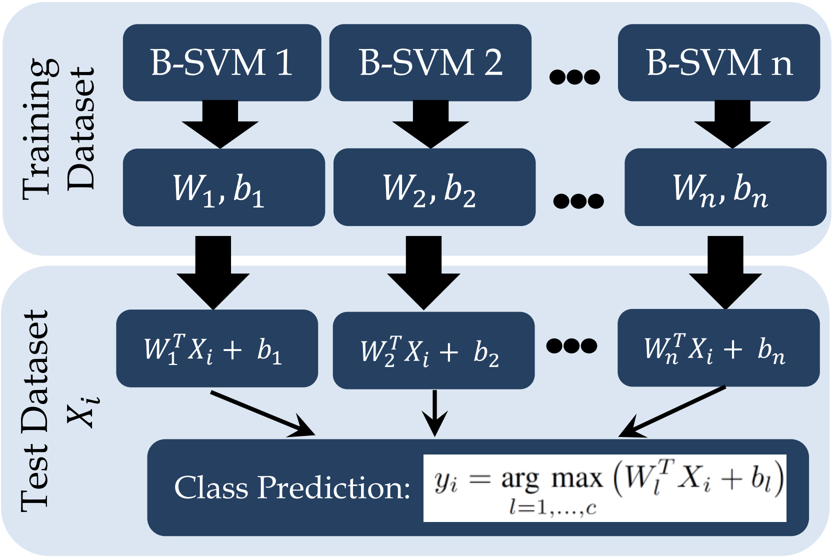
Event Classification Method:

1- Multi-Support Vector Machine (Multi-SVM)

- Binary Decomposition: One-against-all (OvA)

2- k-Nearest Neighbors (k-NN)

3- Decision-Tree (DT)



Summary of Analyzed Database:

- Data from two D-PMUs, during 15 days
- In total, 1.2 billion measurement points
- In total, 10,700 events (only 1% of the data points)
- Number of Events from Event Labeling

Class I	Class II	Class II
1,802	2,228	6,670

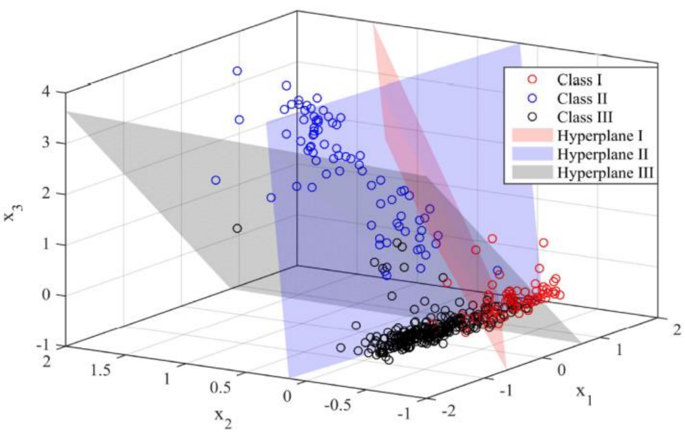
Class III.A	Class III.B	Class III.C
27	43	6,600

- Training dataset almost 4% for both layers

Illustrative Example of Multi-SVM Classification Results for Layer I:

Three dominant features among 53 features are selected to train and test classifier.

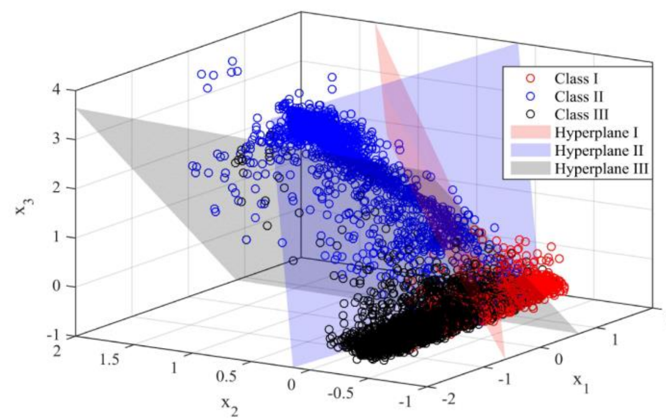
Training



Accuracy: 91.55%

Predicted Class \ Target Class	Class I	Class II	Class III
Class I	82.7% 67	5.8% 5	5.9% 16
Class II	0.0% 0	93.0% 80	0.4% 1
Class III	17.3% 14	1.2% 1	93.7% 254

Test

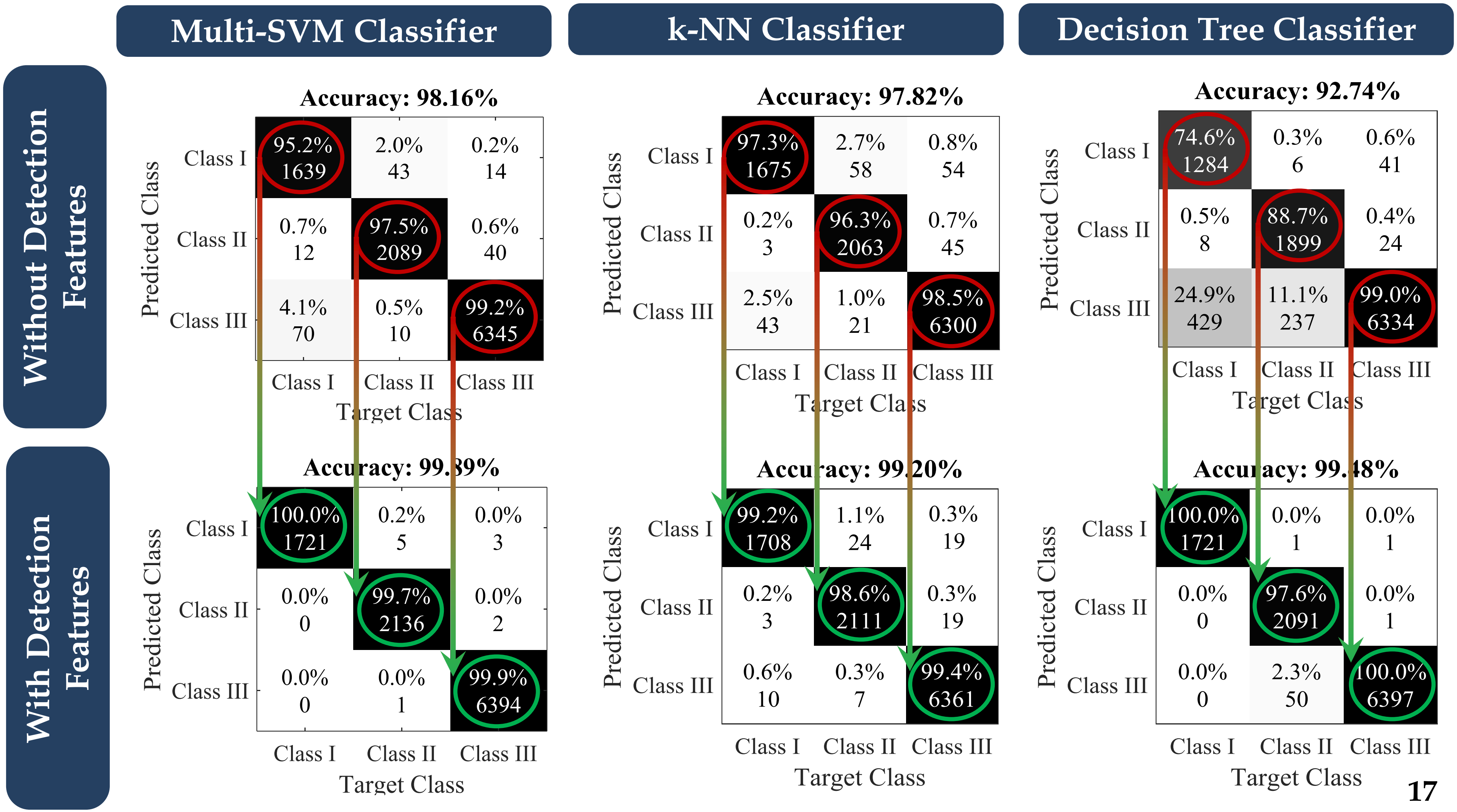


Accuracy: 89.57%

Predicted Class \ Target Class	Class I	Class II	Class III
Class I	70.7% 1216	4.8% 102	6.3% 404
Class II	0.1% 2	94.2% 2018	0.6% 37
Class III	29.2% 503	1.0% 22	93.1% 5958

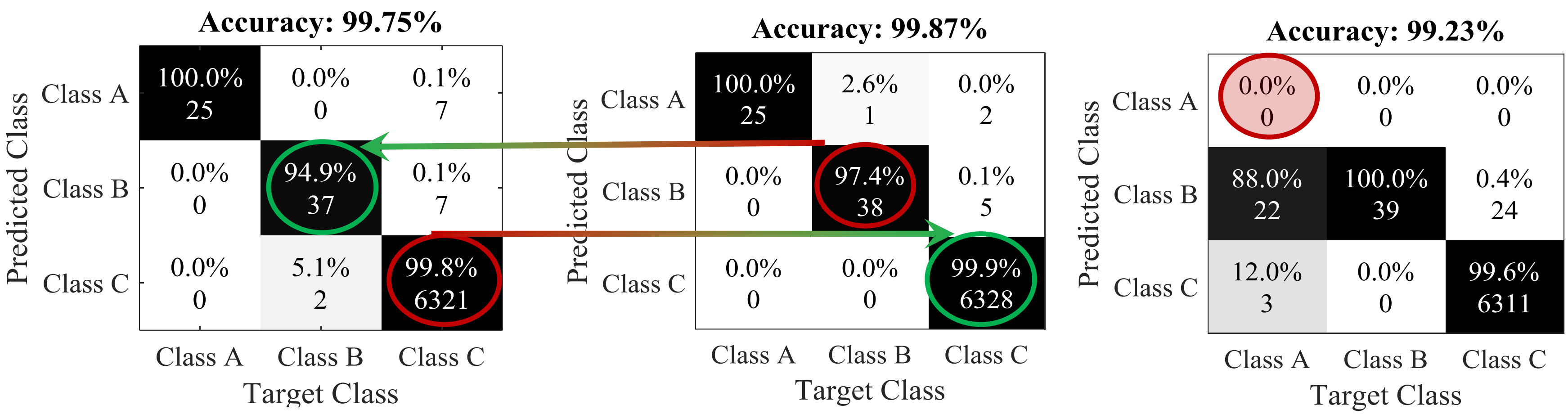
Classification Results for Test data of Layer I:

Impact of Detection Features



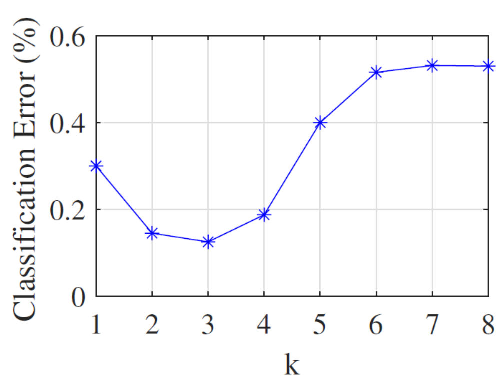
Classification Results for Test data of Layer II

Multi-SVM Classifier | **k-NN Classifier** | **Decision Tree Classifier**

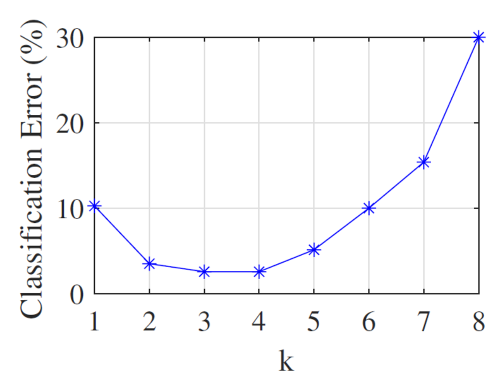


- The performance of k-NN classifier is highly sensitive to the choice of parameter k.

Overall Classification Error (%)



Classification Error in Class III.B (%)



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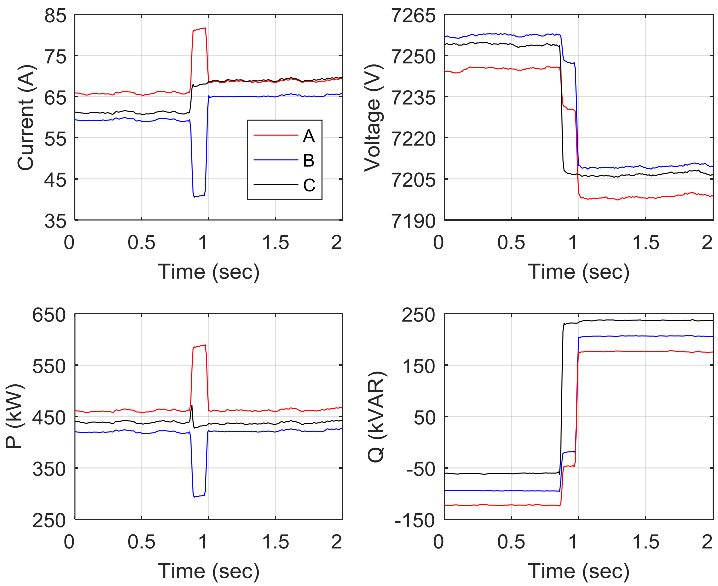
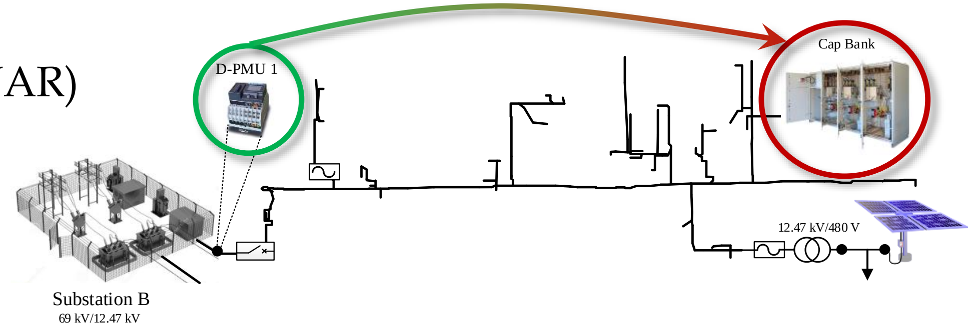
Three-Phase Switched Capacitor Bank:

- Switched capacitor bank three-phase (900 kVAR)
  - Controller: Volt-VAR Controller.

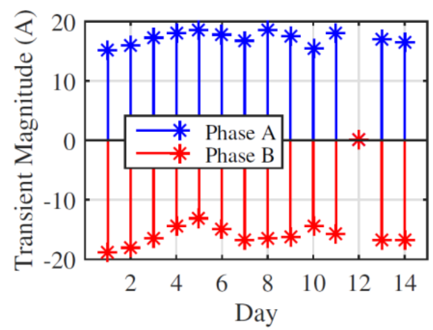
Switch off Event



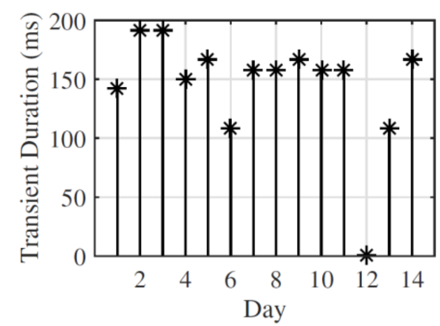
Remote Monitoring



Transient Current Magnitude

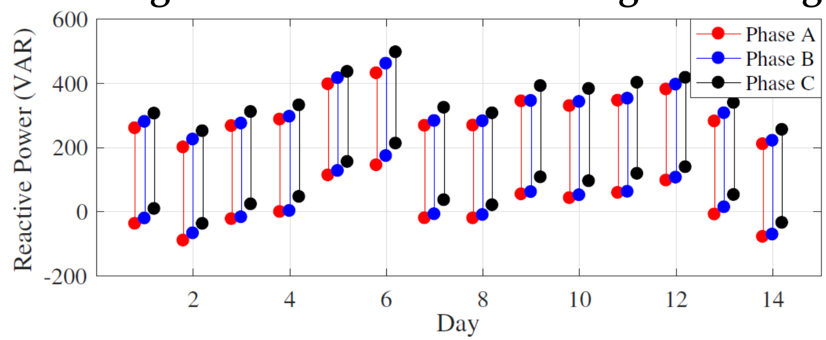


Duration of Transition



- **Two-Step 3-Phase Switch**
  - Step 1: Phase C (Zero Crossing)
  - Step 2: Phase A/B (Possible Malfunction)
- **Slightly Unbalanced Operation**
  - Likely fuse blowing on A and C

Change in Reactive Power During Switching



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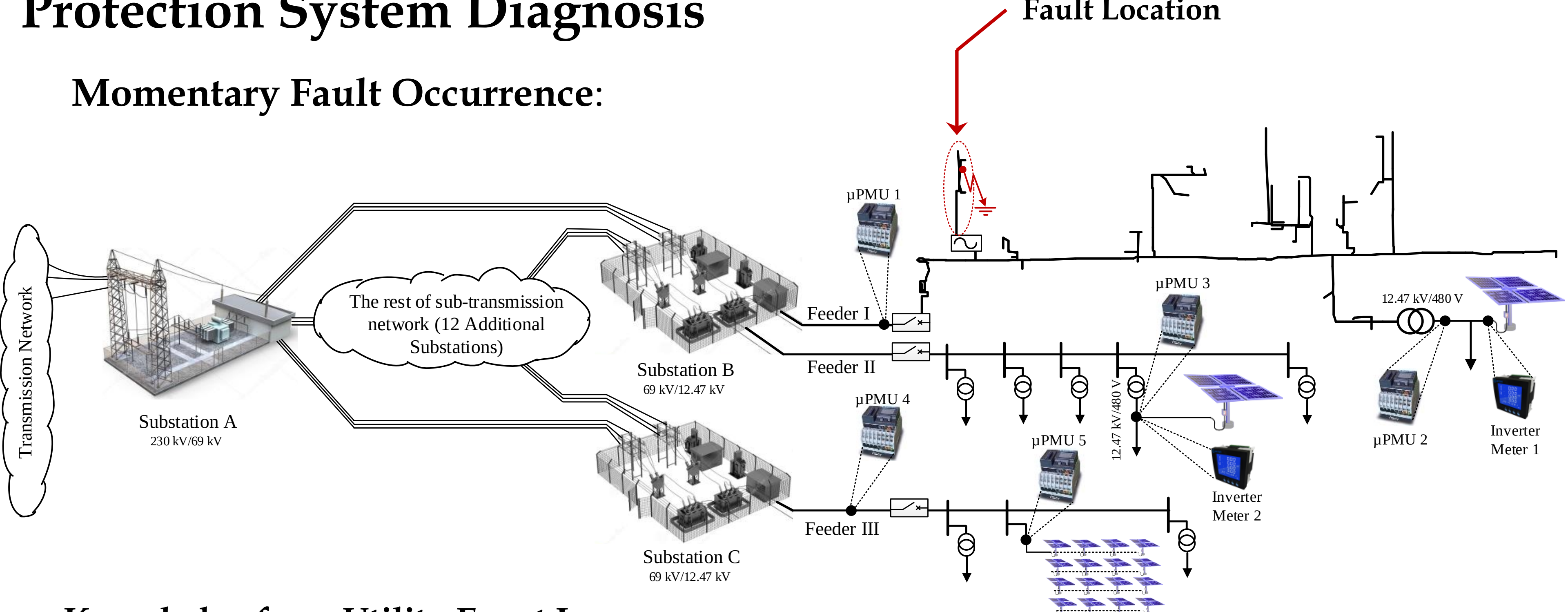
Protection System Diagnosis

Momentary Fault Occurrence:



Knowledge from Utility Event Log:

- **Fault Location:** Feeder I, in November 2016, almost 0.3 mile away from Substation B.
- **Event Source:** Blown fuse is founded in phase B and a diseased bird on pole.

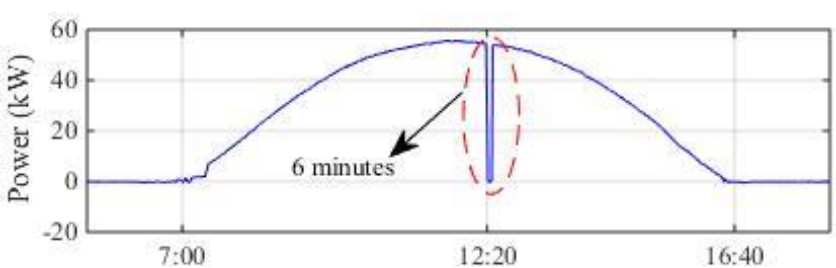
We are interested in answering the following questions

- What is the time-line of the fault?
- Possible miscoordination between lateral fuse and auto-recloser?
- Possible miscoordination between auto-recloser anti-islanding relay?

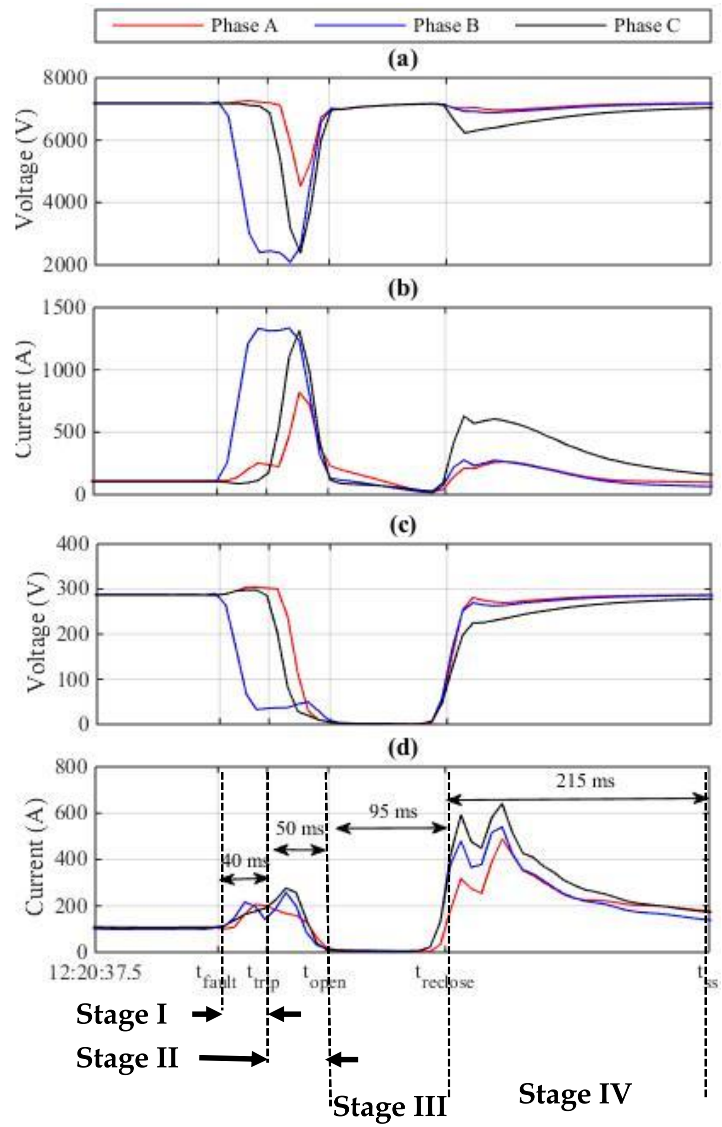
Fault Time-Line:

Stage I	• Voltage on phase B drops • Deviation in voltage on phases A and C
Stage II	• Recloser sends trip command to the circuit breaker • Three-phase circuit breaker operation transient
Stage III	• Feeder I is isolated • Current of D-PMU 1 decreases to zero (RLC circuit)
Stage IV	• First shot of recloser is finished • Feeder is reconnected to substation

Recloser-fuse coordination is Verified



Recloser Anti-islanding protection Miscoordination



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- Aspect 1: Attack Detection through Situational Awareness

Control Devices and Assets

Situational Awareness

Attack Detection

- Aspect 2: Vulnerability in Sensors and Monitoring System

Data Acquisition Level

Vulnerable Situational Awareness

Mohasinia's Research

References:

[1] A. Shahsavari, M. Farajollahi, E. Stewart, E. Cortez, H. Mohsenian Rad, "Situational Awareness in Distribution Grid Using Micro-PMU Data: A Machine Learning Approach", *IEEE Trans. on Smart Grid*, 2019.

[2] M. Farajollahi, A. Shahsavari, E. Stewart, H. Mohsenian Rad, "Locating the Source of Events in Power Distribution Systems Using Micro-PMU Data", *IEEE Trans. on Power Systems*, vol.33, pp. 6343 - 6354, May. 2018.

[3] A. Shahsavari, A. Sadeghi-Mobarakeh, E. Stewart, E. Cortez, L. Alvarez, F. Megala, H. Mohsenian Rad, "Distribution Grid Reliability versus Regulation Market Efficiency: An Analysis based on Micro-PMU Data," *IEEE Trans. on Smart Grid*, vol. 8, pp. 2916 - 2925, Jun. 2017.

[4] A. Shahsavari, M. Farajollahi, E. Stewart, H. Mohsenian Rad, "A Machine Learning Approach to Event Analysis in Distribution Feeders Using Distribution Synchrophasors," in *Proc. of IEEE Smart Grid Synchronized Measurements and Analytics*, College Station, TX, May. 2019.

[5] A. Shahsavari, M. Farajollahi, E. Stewart, C. Roberts, F. Megala, L. Alvarez, E. Cortez, H. Mohsenian Rad, "Autopsy on Active Distribution Networks: A Data-Driven Fault Analysis Using Micro-PMU Data," in *Proc. of IEEE PES NAPS*, Morgantown, WV, Sep. 2017.

[6] A. Shahsavari, M. Farajollahi, E. Stewart, A. Meier, L. Alvarez, E. Cortez, H. Mohsenian Rad, "A Data-Driven Analysis of Capacitor Bank Operation at a Distribution Feeder Using Micro-PMU Data," in *Proc. of IEEE Power & Energy Society Conference on Innovative Smart Grid Technologies (ISGT)*, Washington, DC, Apr. 2017.

[7] A. Shahsavari, M. Farajollahi, E. Stewart, C. Roberts, H. Mohsenian Rad, "A Data-Driven Analysis of Lightning-Initiated Contingencies at a Distribution Grid with a PV Farm Using Micro-PMU Data," in *Proc. of IEEE PES Society NAPS*, Morgantown, WV, Sep. 2017.

[8] A. Shahsavari, A. Sadeghi, E. Stewart, H. Mohsenian Rad, "Distribution Grid Reliability Analysis Considering Regulation Down Load Resources via Micro-PMU Data," *in proc. of IEEE International Conference on Smart Grid Communications*, Sydney, Australia, Nov. 2016.

Thank You!

Alireza Shahsavari