Data-Driven Analysis of Events in Distribution Synchrophasors

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Acknowledgements: M. Farajollahi, A. Shahsavari, E. Stewart, E. Cortez,
Scope

• **Focus: Micro-PMU Data Streams**

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

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• **Use Cases:**
  - Remote Asset Monitoring
  - Load Modeling
  - Protection System Diagnosis

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Main Focus in This Presentation

Focus in This Presentation
Events in Distribution Systems

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

Sensor

Micro-PMU
(Riverside, CA)
Events in Distribution Systems

Event Signature

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

Sensor

Micro-PMU
(Riverside, CA)

120 fps
Events in Distribution Systems

**Event Signature**

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

Sensor

120 fps

Micro-PMU

(Riverside, CA)
Events in Distribution Systems

On Average: 500 Events Per Day Per Feeder
Event Detection

Residue Test in Nonlinear Estimation

Absolute Deviation Around Median

Session #10: Wednesday, 2:30 p.m. - 3.45 p.m.
Event Types

Micro-PMU 1

Micro-PMU 2
Event Types

Micro-PMU 1

Micro-PMU 2
Event Types

Hamed Mohsenian-Rad
Data-Driven Analysis of D-PMU Events
UC Riverside
Event Types

Data-Driven Analysis of D-PMU Events

Micro-PMU 1

Micro-PMU 2
Event Classification

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

- **Classification Results:**

<table>
<thead>
<tr>
<th>Class</th>
<th>Training Data</th>
<th>Test Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>368</td>
<td>1434</td>
</tr>
<tr>
<td>Class 2</td>
<td>296</td>
<td>1896</td>
</tr>
<tr>
<td>Class 3</td>
<td>1645</td>
<td>5018</td>
</tr>
</tbody>
</table>

---

*Diagram showing scatter plots for training and test data with hyperplanes marked for different classes.*
Event Classification

- **Classification Results:**

<table>
<thead>
<tr>
<th>Class</th>
<th>Detection Signal</th>
<th>Detection Window</th>
<th>Statistics</th>
<th>Difference</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>( X_i \in {I, V, P, Q} )</td>
<td>( \min{W} )</td>
<td>( \sigma(X_i) )</td>
<td>(</td>
<td>X_i^u - X_i^d</td>
</tr>
</tbody>
</table>

Confusion Matrix

<table>
<thead>
<tr>
<th>Target Class</th>
<th>Predicted Class</th>
<th>100%</th>
<th>1.8%</th>
<th>0.1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td>1.8%</td>
<td>0.1%</td>
</tr>
<tr>
<td>0%</td>
<td>98.1%</td>
<td>0%</td>
<td>98.1%</td>
<td>0.0%</td>
</tr>
<tr>
<td>0%</td>
<td>0.1%</td>
<td>0%</td>
<td>0.1%</td>
<td>99.9%</td>
</tr>
</tbody>
</table>
Problem Statement

Questions:
1. What is the source location of this event?
2. What can we learn from this event?
Background: Compensation Theory

\[ \Delta V = V_{\text{post}} - V_{\text{pre}} \]

\[ \Delta I = I_{\text{post}} - I_{\text{pre}} \]
Step 1: Extract Differential Synchrophasors

**Upstream Sensor**

(a) $|I_u|$ vs. Time (msec)

(b) $|V_u|$ vs. Time (msec)

(c) $\angle I_u$ vs. Time (msec)

(d) $\angle V_u$ vs. Time (msec)

**Downstream Sensor**

(e) $|I_d|$ vs. Time (msec)

(f) $|V_d|$ vs. Time (msec)

(g) $\angle I_d$ vs. Time (msec)

(h) $\angle V_d$ vs. Time (msec)
Step 1: Extract Differential Synchrophasors

Upstream Sensor

| $|I_u|$ | $|V_u|$ | $|I_d|$ | $|V_d|$ |
|---|---|---|---|
| ![Graph](image1.png) | ![Graph](image2.png) | ![Graph](image3.png) | ![Graph](image4.png) |

Pre-Event | Post-Event

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

Downstream Sensor

Pre-Event | Post-Event

$|\Delta I^d| \angle \Delta I^d$ | $|\Delta V^d| \angle \Delta V^d$
Step 2: Forward Nodal Voltage Calculation

\[ \Delta V_1^f = \Delta V_u \]
\[ \Delta V_2^f = \Delta V_1^f + (\Delta I_u + Y_1 \Delta V_1^f)Z_1 \]
\[ \vdots \]
\[ \Delta V_k^f = \Delta V_{k-1}^f + (\Delta I_u + Y_1 \Delta V_1^f + \cdots + Y_{k-1} \Delta V_{k-1}^f)Z_{k-1} \]
\[ \Delta V_{k+1}^f \neq \Delta V_k^f + (\Delta I_u + Y_1 \Delta V_1^f + \cdots + Y_{k-1} \Delta V_{k-1}^f + Y_k \Delta V_k^f)Z_k \]
\[ \vdots \]
\[ \Delta V_n^f \neq \Delta V_{n-1}^f + (\Delta I_u + Y_1 \Delta V_1^f + \cdots + Y_{n-1} \Delta V_{n-1}^f)Z_{n-1} \]

\( k \): Event Bus (Unknown)
Step 3: Backward Nodal Voltage Calculation

\[
\begin{align*}
\Delta V_n^b &= \Delta V^d \\
\Delta V_{n-1}^b &= \Delta V_n^b + (\Delta I_d + Y_n \Delta V_n^b)Z_{n-1} \\
&\vdots \\
\Delta V_{k}^b &= \Delta V_{k+1}^b + (\Delta I_u + Y_n \Delta V_n^b + \cdots + Y_{k+1} \Delta V_{k+1}^b)Z_k \\
\Delta V_{k-1}^b &\neq \Delta V_k^b + (\Delta I_u + Y_n \Delta V_n^b + \cdots + Y_{k+1} \Delta V_{k+1}^b + Y_k \Delta V_k^b)Z_{k-1} \\
&\vdots \\
\Delta V_1^b &\neq \Delta V_2^b + (\Delta I_u + Y_n \Delta V_n^b + \cdots + Y_2 \Delta V_2^b)Z_1
\end{align*}
\]

\(k\): Event Bus (Unknown)
Step 4: Event Location Identification

Forward: \( \{ \Delta V_1^f, \ldots, \Delta V_{k-1}^f, \Delta V_k^f, \Delta V_{k+1}^f, \ldots, \Delta V_n^f \} \)

Backward: \( \{ \Delta V_1^b, \ldots, \Delta V_{k-1}^b, \Delta V_k^b, \Delta V_{k+1}^b, \ldots, \Delta V_n^b \} \)

\( k = \arg\min_i |\Delta V_i^f - \Delta V_i^b| \)

\( k: \) Event Bus (Unknown)
Feeder with Laterals

Extended Method: \[ k = \arg\min_i \sum_{j=1}^{m-1} \sum_{s=j+1}^{m} |\Delta V_i^j - \Delta V_i^s| \]
Simulation Results

(a) Event at Bus 24; (b) Event at Bus 36; (c) Event at Bus 9
Importance of Measuring Phase Angle

\[ V_{\text{post}} - V_{\text{pre}} = \Delta V \]

Case A: Small \( \alpha \)

Case B: Large \( \alpha \)
Scope

• Focus: Micro-PMU Data Streams

• Data-Analytics Package for Distribution Synchrophasors
  • Event Detection
  • Event Classification
  • Event Identification

• Use Cases: Remote Asset Monitoring
  Load Modeling
  Protection System Diagnosis
Case Study 1: (Remote) Asset Monitoring

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 1: (Remote) Asset Monitoring

Detection & Classification

Switch Off Event

Discrepancy

Location Identification

Event Bus: 25 (Correct)

(Micro-PMU 1)
Case Study 1: (Remote) Asset Monitoring

- **Analysis of Events Over Two Weeks:**

  Change in Reactive Power During Switching:

  Transient Overshoot Current During Switching:

  **Two-Step 3-Phase Switching:**
  - Step 1: Phase C (Zero Crossing)
  - Step 2: Phase A/B (Possible Malfunction)
Case Study 2: Static Load Modeling

- Feeder Aggregated Load Model:

\[ P_{mk} = P_{mh} \left( \frac{V_{mk}}{V_{mh}} \right)^{np} \]

\[ Q_{mk} = Q_{mh} \left( \frac{V_{mk}}{V_{mh}} \right)^{nq} \]
Case Study 2: Static Load Modeling

- **Individual Load Models:**

\[
P_{m_k} = P_{m_h} \left( \frac{V_{m_k}}{V_{m_h}} \right)^{n_p}
\]

\[
Q_{m_k} = Q_{m_h} \left( \frac{V_{m_k}}{V_{m_h}} \right)^{n_q}
\]

\[
P_{m_k} = P_{m_h} \left( \frac{V_{m_k}}{V_{m_h}} \right)^{n_{p,i}} 
\quad i = 1, 2, \ldots, n
\]

\[
Q_{m_k} = Q_{m_h} \left( \frac{V_{m_k}}{V_{m_h}} \right)^{n_{q,i}}
\]
Case Study 2: Static Load Modeling

- Example:

<table>
<thead>
<tr>
<th>Configuration</th>
<th>SW1</th>
<th>SW2</th>
<th>SW3</th>
<th>SW4</th>
<th>SW5</th>
<th>SW6</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>m1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
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<td>[0 , t1 ]</td>
</tr>
<tr>
<td>m2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>[t1 , t2 ]</td>
</tr>
<tr>
<td>m3</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>[t2 , t3 ]</td>
</tr>
<tr>
<td>m4</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>[t3 , t4 ]</td>
</tr>
<tr>
<td>m5</td>
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<td>0</td>
<td></td>
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<td>1</td>
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<tr>
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<tr>
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<td>1</td>
<td>1</td>
<td>[t10 , t11]</td>
</tr>
</tbody>
</table>
Further Reading

IEEE T. on Power Systems 2018

IEEE T. on Power Systems 2019
Further Reading (Cont.)