PMU Data Analytics for Power Distribution

First Session

Hamed Mohsenian-Rad, University of California, Riverside
**Nonintrusive Load Modeling Using Micro-PMUs**

Asja Derviskadic, Swiss Federal Institute of Tech of Lausanne
**Synchronized Sensing for Wide-Area Situational Awareness of Power Distribution Networks**

Second Session

Wei Zhou, Huazhong University of Science and Technology
**DPMU for Harmonic State Estimation**

Moosa Moghimi Haji, University of Alberta
**Estimating Distribution System Parameters using DPMU and Smart Meter Data**
Nonintrusive Load Modeling Using Micro-PMUs

Smart Grid Comm 2019, Beijing, China

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

Background: Events in Micro-PMU Data Streams

Event Signature

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

12 kV

Micro-PMU
(Riverside, CA)

120 Million Data Points Per Day

Sensor

120 fps
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On Average: 500 Events Per Day Per Feeder

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(Riverside, CA)
Background: Events in Micro-PMU Data Streams

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120 fps

Micro-PMU (Riverside, CA)
**Previous Results**

1. Event Detection and Event Classification (Machine Learning):

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![Graphs showing current, voltage, active power, and reactive power over time for different phases and events.]

**Upstream Event (Sub-transmission or Transmission)**

Previous Results

1. Event Detection and Event Classification (Machine Learning):

Switching Event (Distribution)

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1. Event Detection and Event Classification (Machine Learning):

Switching Event (Distribution)

2. Event Location Identification (Hybrid Model-Based):

\[ |I|, \angle I \quad V, \angle V \]

Previous Results

2. Event Location Identification (Hybrid Model-Based):

\[ |\Delta I^u| \angle \Delta I^u \quad |\Delta V^u| \angle \Delta V^u \]

\[ |\Delta I^d| \angle \Delta I^d \quad |\Delta V^d| \angle \Delta V^d \]

Previous Results

2. Event Location Identification (Hybrid Model-Based):

\[ |\Delta I^u_1| \angle \Delta I^u_1 \]

\[ k: \text{Event Bus (Unknown)} \]

Previous Results

2. Event Location Identification (Hybrid Model-Based):

\[ k = \arg \min_{i} \left| \Delta V_i^f - \Delta V_i^b \right| \]

2. Event Location Identification (Hybrid Model-Based):

\[ k = \arg \min_i |\Delta V_i^f - \Delta V_i^b| \]

Observations

- We used only two micro-PMUs

- We can **remotely** and **automatically** monitor all **load switching events**

  ![Diagram](image)

  - Pointer of Metering at Feeder Head
  - 1: Open
  - 0: Closed

- Therefore, we can keep track of switching configurations.
Observations

- We used only two micro-PMUs
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![Diagram showing substation with micro-PMUs and load switch configurations.]

- 1: Open
- 0: Closed
Observations

- We used only two micro-PMUs
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Therefore, we can keep track of switching configurations.

Q: What can we do with this?
Observations

- We used only two micro-PMUs

- We can **remotely** and **automatically** monitor all **load switching events**

- Therefore, we can keep track of switching configurations.

Q: What can we do with this?

A: **Nonintrusive Load Modeling**
Noninvasive Load Modeling

- Feeder Aggregated Load Model:

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

\[ Q_{mk} = Q_{mh} \left( \frac{V_{mk}}{V_{mh}} \right)^{nq} \]

Switching Configuration Number

A Variation of the **ZIP Model**.

- Constant Impedance
- Constant Power
- Constant Current
• **Individual Load Models:**

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

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

- **Individual Load Models:**

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

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

Switching Event

Switching Configuration Number

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

\[
Q_{m_k} = Q_{m_h} \left( \frac{V_{m_k}}{V_{m_h}} \right)^{n_{q,i}}
\]
Step 1: Circuit Model Equations

- **Complex Power Conservation:**

  \[ S_{m_k} = \sum_{i=1}^{n} \left( S_{i}^{l,m_k} \times SW_{i}^{m_k} \right) + \sum_{j=1}^{n} Z_j \left( \sum_{d=j}^{n} \left( S_{d}^{l,m_k} \right)^* \times SW_{d}^{m_k} \right) \]

  \[ \text{Current in Line } j \]

  \[ \text{Total Load} \]

  \[ \text{Total Loss} \]

  \[ \text{Switching Configuration} \]

  \[ \text{Substation} \]

  \[ V_{m_k}, P_{m_k}, Q_{m_k} \]

  \[ Z_1, Z_2, \ldots, Z_n \]

  \[ \text{SW}_1, \text{SW}_2, \ldots, \text{SW}_n \]

  \[ S_{1}^{l,m_k}, S_{2}^{l,m_k}, \ldots, S_{n}^{l,m_k} \]

  Parameter \( SW_{i}^{m_k} \) is one if the individual load \( i \) is turned on during switching configuration \( m_k \); and zero otherwise.
Step 1: Circuit Model Equations

- **KVL:**

\[
V_i^{m_k} = V_{m_k} - \sum_{j=1}^{i} Z_j \left( \sum_{d=j}^{n} \frac{S_{d}^{l,m_k}}{V_{d}^{l,m_k}} \right) SW_d^{m_k}
\]

Voltage at Substation

Voltage Drop at Line \( j \)

# of Equations = \( n \)
Step 1: Circuit Model Equations

- **Combined Equations:**
  \[
  S_{mk} = \sum_{i=1}^{n} \left( S_{i,mk}^l W_i^m \right) + \sum_{j=1}^{n} Z_j \left| \sum_{d=j}^{n} \left( \frac{S_{d,mk}^l}{V_{d,mk}^l} \right)^* \times SW_d^m \right|^2 
  \]
  \[
  V_{l,mk}^l = V_{mk} - \sum_{j=1}^{i} Z_j \left( \sum_{d=j}^{n} \left( \frac{S_{d,mk}^l}{V_{d,mk}^l} \right)^* \times SW_d^m \right), i = 1, \ldots, n
  \]

  **Unknowns:** $S_{i,mk}^l$ and $V_{l,mk}^l$ for $i = 1, \ldots, n$

- **For any switching configuration $m_k$:**

<table>
<thead>
<tr>
<th>Number of Equations:</th>
<th>Number of Unknowns:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n + 1$</td>
<td>$n + \sum_{i=1}^{n} SW_i^m$</td>
</tr>
</tbody>
</table>
Step 2: Load Model Equations

- For any two distinct switching configurations $m_k$ and $m_h$:

$$S^{l,m_k}_i = p^{l,m_h}_i \left( \frac{|V^{m_k}_i|}{|V^{m_h}_i|} \right)^{n_{p_i}} + j q^{l,m_h}_i \left( \frac{|V^{m_k}_i|}{|V^{m_h}_i|} \right)^{n_{q_i}}$$

**Necessary Condition:**
$$\sum_{k=1}^{c} SW_i^{m_k} \geq 2$$

**Additional Unknowns:**
$$n_{s_i} = n_{p_i} + j n_{q_i} \quad \text{for} \quad i = 1, \ldots, n$$
Step 3: Solving the System of Equations

• Given \( c \) distinct switching configurations:

\[
\begin{align*}
\text{# of Unknowns:} & \quad n \times c + \sum_{k=1}^{c} \sum_{i=1}^{n} SW_i^{mk} + n \\
\text{# of Equations:} & \quad c \times (n + 1) + \sum_{i=1}^{n} \sum_{k=1}^{c} SW_i^{mk} - n
\end{align*}
\]

**Theorem:** We need to observe at least \( c_{min} = 2n \) distinct switching configurations to solve the nonintrusive individual load modeling problem.
Illustrative Example

<table>
<thead>
<tr>
<th>Configuration</th>
<th>SW₁</th>
<th>SW₂</th>
<th>SW₃</th>
<th>SW₄</th>
<th>Time</th>
</tr>
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<tbody>
<tr>
<td>m₁</td>
<td>1</td>
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<td>0</td>
<td>0</td>
<td>[0 , t₁]</td>
</tr>
<tr>
<td>m₂</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>[t₁ , t₂]</td>
</tr>
<tr>
<td>m₃</td>
<td>0</td>
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<td>0</td>
<td>1</td>
<td>[t₂ , t₃]</td>
</tr>
<tr>
<td>m₄</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>[t₃ , t₄]</td>
</tr>
<tr>
<td>m₅</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>[t₄ , t₅]</td>
</tr>
<tr>
<td>m₆</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>[t₅ , t₆]</td>
</tr>
<tr>
<td>m₇</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>[t₆ , t₇]</td>
</tr>
<tr>
<td>m₈</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>[t₇ , t₈]</td>
</tr>
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<table>
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<tr>
<th>Circuit Model</th>
<th># of Equations</th>
<th># of Unknowns</th>
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<tbody>
<tr>
<td></td>
<td>40</td>
<td>52</td>
</tr>
<tr>
<td>Load Model</td>
<td>16</td>
<td>4</td>
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<tr>
<td>Combined</td>
<td>56</td>
<td>56</td>
</tr>
</tbody>
</table>

\[ Z_{sub} = 1.6+j0.9 \]
\[ S_1 = 0.8+j1.3 \]
\[ S_2 = 0.2+j0.7 \]
\[ S_3 = 1.4+j1.1 \]

(a) Voltage Magnitude (pu) vs. Time (sec)
(b) Voltage Angle (Degrees) vs. Time (sec)
(c) Real Power (W) vs. Time (sec)
(d) Reactive Power (kVAR) vs. Time (sec)

Hamed Mohsenian-Rad
Nonintrusive Load Modeling Using Micro-PMUs
UC Riverside
Extension 1: Distribution Feeder with Laterals

<table>
<thead>
<tr>
<th>Configuration</th>
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<th>SW₂</th>
<th>SW₃</th>
<th>SW₄</th>
<th>SW₅</th>
<th>SW₆</th>
<th>Time</th>
</tr>
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<tbody>
<tr>
<td>m₁</td>
<td>1</td>
<td>0</td>
<td>1</td>
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<td>0</td>
<td>0</td>
<td>[0 , t₁]</td>
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<tr>
<td>m₂</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
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<td>[t₁ , t₂]</td>
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<tr>
<td>m₃</td>
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<td>[t₂ , t₃]</td>
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<tr>
<td>m₄</td>
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<td>[t₃ , t₄]</td>
</tr>
<tr>
<td>m₅</td>
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<tr>
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<tr>
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<tr>
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<tr>
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<td>[t₈ , t₉]</td>
</tr>
<tr>
<td>m₁₀</td>
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<td>[t₉ , t₁₀]</td>
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<td>1</td>
<td>1</td>
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<td>[t₁₀ , t₁₁]</td>
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<td>1</td>
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<td>1</td>
<td>[t₁₁ , t₁₂]</td>
</tr>
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<tr>
<th>Circuit Model</th>
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<tbody>
<tr>
<td></td>
<td>84</td>
<td>120</td>
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<tr>
<td>Load Model</td>
<td>42</td>
<td>6</td>
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<tr>
<td>Combined</td>
<td>126</td>
<td>126</td>
</tr>
</tbody>
</table>

**Voltage Angle (Degree)**

**Voltage Magnitude (pu)**
Extension 2: Redundant Switching Configurations

<table>
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<th>SW₄</th>
<th>SW₅</th>
<th>SW₆</th>
<th>Time</th>
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<tbody>
<tr>
<td>m₁</td>
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<td>1</td>
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<tr>
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<td>1</td>
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<td>[t₁₂]</td>
</tr>
</tbody>
</table>

- We solve an “estimation” problem.

Error in Line Impedances

<table>
<thead>
<tr>
<th>Error in Line Impedance</th>
<th>5%</th>
<th>10%</th>
<th>15%</th>
<th>20%</th>
<th>25%</th>
<th>30%</th>
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</thead>
<tbody>
<tr>
<td>Error in Estimating $n_p$</td>
<td>0.09</td>
<td>0.93</td>
<td>1.30</td>
<td>1.98</td>
<td>2.54</td>
<td>3.38</td>
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<tr>
<td>Error in Estimating $n_q$</td>
<td>0.78</td>
<td>1.95</td>
<td>3.23</td>
<td>5.34</td>
<td>9.16</td>
<td>11.87</td>
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</table>

In Presence of Error in Measurements

- # of Equations: 258
- # of unknowns: 246
Extension 3: Identifying Erroneous Switching Status

<table>
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<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>
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<tr>
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</tr>
<tr>
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<td>1</td>
<td>[t₁, t₂]</td>
</tr>
<tr>
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<tr>
<td>m₉</td>
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<td>[t₈, t₉]</td>
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<td>m₁₀</td>
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<td>[t₉, t₁₀]</td>
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<td>1</td>
<td>1</td>
<td>[t₁₁, t₁₂]</td>
</tr>
</tbody>
</table>

- Residual Test (In Presence of Two Erroneous Configurations):

![Circuit Diagram](image)

(a) Normalized Residual vs. Circuit Model Equation
(b) Normalized Residual vs. Circuit Model Equation
Conclusions

• Install a few micro-PMUs at feeder head and end buses.

• Remotely and automatically Identify:
  • ZIP Model for all individual loads across the distribution feeder.

• AMI / Smart Meters:
  • Not Available: Our Approach is a Replacement
  • Available: Our Approach is an Oversight
    • AMI Failure
    • Electricity Theft
    • Cybersecurity
    • ...

Non-Intrusive
Further Reading

IEEE T. on Power Systems 2018

IEEE T. on Smart Grid 2019
Application of Load Switching Events in Steady-State Load Modeling in Power Distribution Networks

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Abstract—A novel event-based method is proposed to nonintrusively load modeling in power distribution systems. The method integrates steady-state load modeling with micro-PMUs to extract the desired information. The event-based method involves micro-PMUs to monitor the load profiles and extract the parameters of each load. The method then integrates these parameters with steady-state load modeling to create a more accurate model of the distribution network.

Keywords—Load modeling, micro-PMUs, event-based method, power distribution systems.

1. INTRODUCTION

A recent IEEE report [1] has found that the majority of the utilities are using meter-based methods to estimate the parameters of their load models. Measurement-based load modeling can be classified static and dynamic. One focus in this paper is on static load modeling, where the goal is to estimate the parameters of the so-called ZIP load models.

An important issue in measurement-based static load modeling is the estimation of the ZIP load parameters. These are typically estimated using a ZIP model in the static load modeling process. However, the challenge is implementing this idea in a way that is efficient and reliable. In this paper, we propose an event-based method for nonintrusively load modeling in power distribution systems.

In the event-based method, micro-PMUs are used to monitor the load profiles and extract the parameters of each load. The method then integrates these parameters with steady-state load modeling to create a more accurate model of the distribution network.

II. EXAMPLES

Consider a distribution feeder with N [2] loads as shown in Fig. 1(a). Depending on which individual loads are on and which individual loads are off, there can be a total of 2^N − 1 possible load configurations in this feeder. However, the challenge is implementing this idea in a way that is efficient and reliable. In this paper, we propose an event-based method for nonintrusively load modeling in power distribution systems.

IEEE T. on Power Systems 2019

Hamed Mohsenian-Rad
Nonintrusive Load Modeling Using Micro-PMUs

IEEE PES Magazine 2018