Event Detection and Localization in Distribution Grids with Phasor Measurement Units

Paper No: 17PESGM510

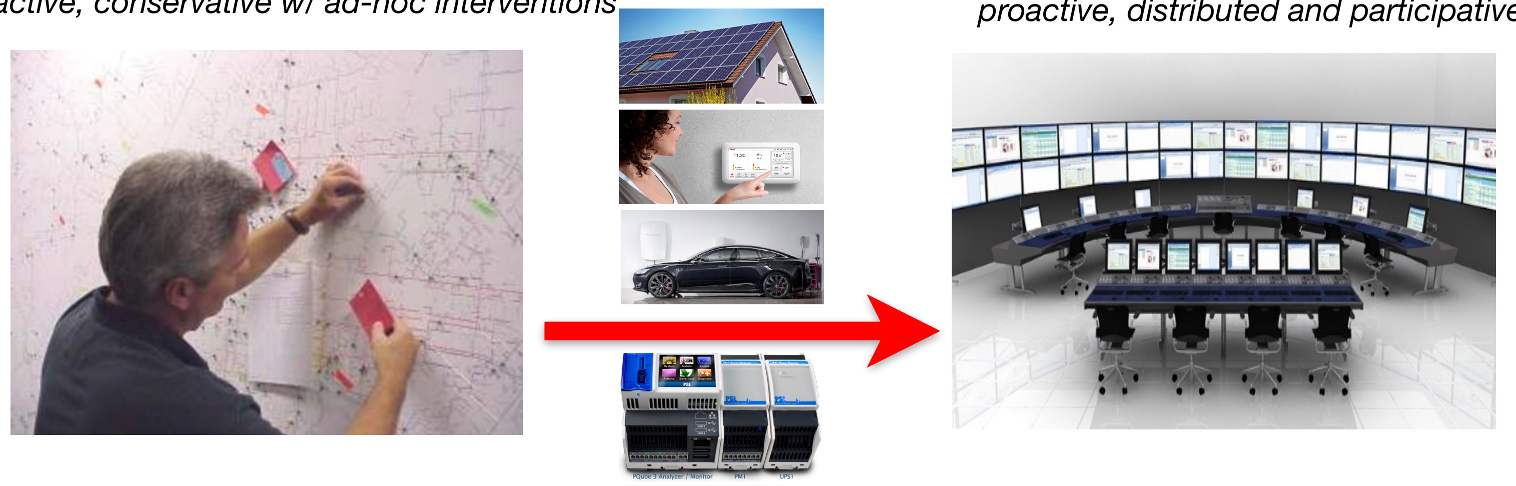
Omid Ardakanian[*], Ye Yuan[†], **Roel Dobbe**[‡], Alexandra von Meier[‡], Steven Low[§], and Claire Tomlin[‡]

[*]University of Alberta, [†]Huazhong University of Science and Technology, [‡]University of California, Berkeley, [§]California Institute of Technology

Introduction

Central operator
reactive, conservative w/ ad-hoc interventions

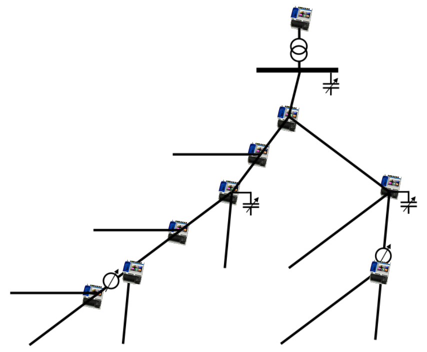
Real-time monitoring & automatic control
proactive, distributed and participative



Synchrophasor data provide unprecedented insights into the operating state of the system which can be used to uniquely determine the system model (i.e. the admittance matrix) and quickly identify the critical events, e.g. switching operations, tap changes, and faults

Goal: given time-synchronized voltage and current phasor measurements in a polyphase distribution network, recover the admittance matrix Y and detect any changes due to events (faults, reconfiguration, etc)

➔ Y must be sparse and symmetric



Formulation

Ohm's Law for successive time slots 1…K:

$$\underbrace{\begin{bmatrix} I_1(1) & \dots & I_1(K) \\ I_2(1) & \dots & I_2(K) \\ \vdots & \ddots & \vdots \\ I_N(1) & \dots & I_N(K) \end{bmatrix}}_{I_{\text{bus}}^K} = Y_{\text{bus}} \underbrace{\begin{bmatrix} V_1(1) & \dots & V_1(K) \\ V_2(1) & \dots & V_2(K) \\ \vdots & \ddots & \vdots \\ V_N(1) & \dots & V_N(K) \end{bmatrix}}_{V_{\text{bus}}^K}.$$

Challenges:

1. V_{bus}^K is low rank => standard least square does not work, it has infinite number of solutions;
2. Measurement error;
3. Limited deployment of sensors.

Identification Algorithm

Step 1: Use similarity transformation to re-arrange data matrices:

$$\mathcal{T} V_{\text{bus}}^K = \begin{bmatrix} \mathbb{V}_1 \\ \mathbb{V}_2 \end{bmatrix}, \qquad \mathcal{T} I_{\text{bus}}^K = \begin{bmatrix} \mathbb{I}_1 \\ \mathbb{I}_2 \end{bmatrix}.$$

Step 2: Compute $X = \mathbb{V}_1 \mathbb{V}_2^\dagger$.

Step 3: Rewrite Ohm's law as

$$\begin{bmatrix} \mathbb{I}_1 \\ \mathbb{I}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbb{Y}_{11} & \mathbb{Y}_{12} \\ \mathbb{Y}_{12}^\top & \mathbb{Y}_{22} \end{bmatrix}}_{\mathbb{Y}} \begin{bmatrix} X\mathbb{V}_2 \\ \mathbb{V}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbb{Y}_{11}X + \mathbb{Y}_{12} \\ \mathbb{Y}_{12}^\top X + \mathbb{Y}_{22} \end{bmatrix}}_{\mathbb{Y}_X} \mathbb{V}_2$$

Compute $\mathbb{Y}_X = \arg \min_{\mathcal{Y} \in \mathbb{C}^{D \times R}} \left\| \begin{bmatrix} \mathbb{I}_1 \\ \mathbb{I}_2 \end{bmatrix} - \mathcal{Y}\mathbb{V}_2 \right\|_2.$

Step 4: Obtain $\mathbb{Y}_{11}, \ \mathbb{Y}_{22}$

$$\mathbb{I}_1 = (\mathbb{Y}_{11}X + \mathbb{Y}_{12})\,\mathbb{V}_2$$
$$\mathbb{I}_2 = (\mathbb{Y}_{12}^\top X + \mathbb{Y}_{22})\,\mathbb{V}_2$$

$\longrightarrow$

$$C \triangleq \mathbb{I}_2 \mathbb{V}_2^\dagger - (\mathbb{V}_2^\dagger)^\top \mathbb{I}_1^\top X = -X^\top * \mathbb{Y}_{11} * X + \mathbb{Y}_{22}$$

$$\min \left\| \begin{bmatrix} \text{vec}(\mathbb{Y}_{11}) \\ \text{vec}(\mathbb{Y}_{22}) \end{bmatrix} \right\|_0 \quad \text{s.t.: } [-X^\top \otimes X^\top \quad I] \begin{bmatrix} \text{vec}(\mathbb{Y}_{11}) \\ \text{vec}(\mathbb{Y}_{22}) \end{bmatrix} = \text{vec}(C), \quad \mathbb{Y}_{11} \in \mathbb{S}^{(D-R)\times(D-R)}, \mathbb{Y}_{22} \in \mathbb{S}^{R\times R}.$$

Convex relaxation

$$\min \left\| \begin{bmatrix} \text{vec}(\mathbb{Y}_{11}) \\ \text{vec}(\mathbb{Y}_{22}) \end{bmatrix} \right\|_1 \quad \text{s.t.: } [-X^\top \otimes X^\top \quad I] \begin{bmatrix} \text{vec}(\mathbb{Y}_{11}) \\ \text{vec}(\mathbb{Y}_{22}) \end{bmatrix} = \text{vec}(C), \quad \mathbb{Y}_{11} \in \mathbb{S}^{(D-R)\times(D-R)}, \mathbb{Y}_{22} \in \mathbb{S}^{R\times R}.$$

Step 5: Obtain $\mathbb{Y}_{12}$

$$\mathbb{Y}_{12} = \arg \min_{\mathcal{Y} \in \mathbb{C}^{(D-R)\times R}} \|(\mathbb{Y}_{11}X + \mathcal{Y})\,\mathbb{V}_2 - \mathbb{I}_1\|_2$$

Event Detection and Localization Algorithm

Detection Algorithm

$$e(k) = I_{\text{bus}}(k) - \hat{I}_{\text{bus}}(k) = I_{\text{bus}}(k) - Y_{\text{bus}}^0 V_{\text{bus}}(k)$$

Check if e(k) is white noise
if yes, continue;
otherwise, detect the event.

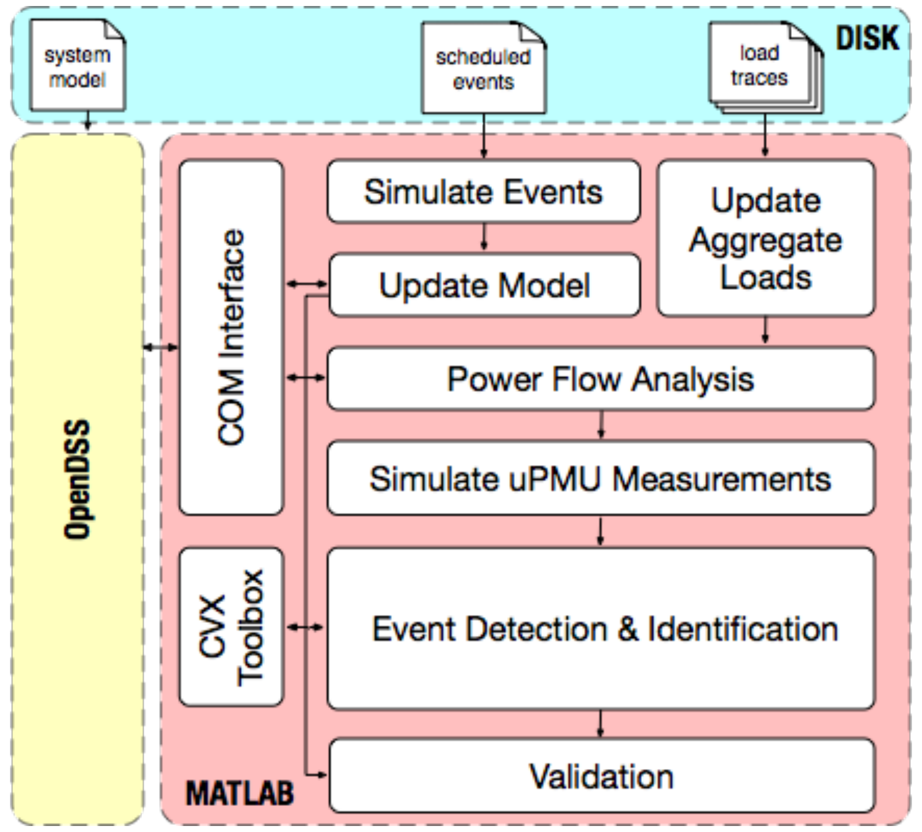
Event Localization Algorithm (requires a small no. of samples)

$$\min \|\Delta Y\|_1, \quad \Delta Y \triangleq Y_{\text{bus}}^1 - Y_{\text{bus}}^0$$
$$\text{s.t.: } I_{\text{bus}}^{t\to t+K} - Y_{\text{bus}}^0 V_{\text{bus}}^{t\to t+K} = \Delta Y V_{\text{bus}}^{t\to t+K}$$
$$\Delta Y \in \mathbb{S}^{D\times D}$$

$$I_{\text{bus}}^{t\to t+K} = [I_{\text{bus}}(t), I_{\text{bus}}(t+1), \dots, I_{\text{bus}}(t+K)]$$
$$V_{\text{bus}}^{t\to t+K} = [V_{\text{bus}}(t), V_{\text{bus}}(t+1), \dots, V_{\text{bus}}(t+K)]$$

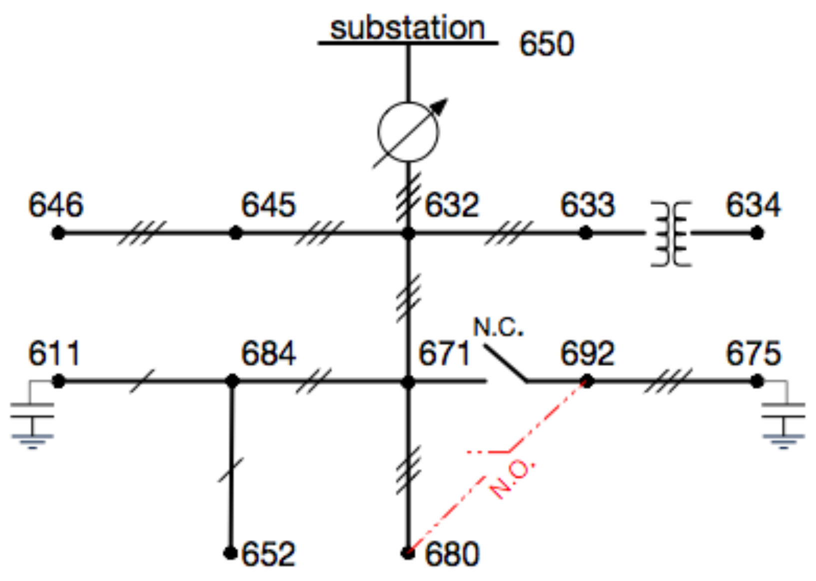
Experimental Setup

1. Compute real and reactive powers consumed at each node in every time slot
2. Simulate events at the specified times and update the admittance matrix
3. Perform power flow analysis for every time slot in OpenDSS
4. Add Gaussian white noise to the results to simulate phasor measurements
5. Solve the convex problems using the CVX toolbox to update the admittance matrix

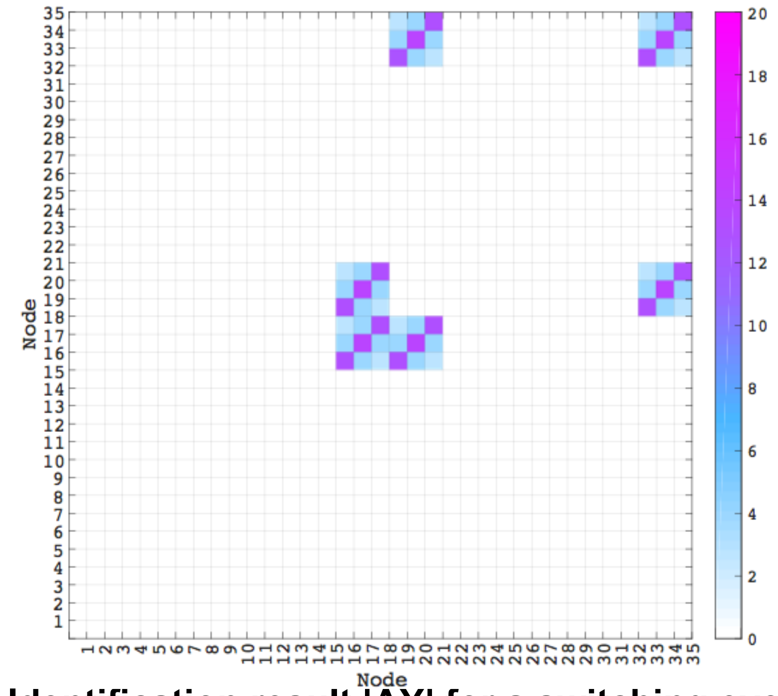


Example Results

- Performed extensive simulations on IEEE 13, 34, 37, and 123 test feeders
- Identified various events and pinpointed them to a small geographical area
- Studied sensitivity of the proposed techniques to the synchrophasor measurement error



Modified IEEE 13 bus test feeder



Identification result |ΔY| for a switching event

Further Information

Y. Yuan, O. Ardakanian, S. Low, and C. Tomlin, "On the inverse power flow problem," https://arxiv.org/abs/1610.06631, Tech. Rep., Oct. 2016.

-> For correspondence, *yye@hust.edu.cn*.