Real-Time Monitoring of Distribution Systems: Challenges

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Outline

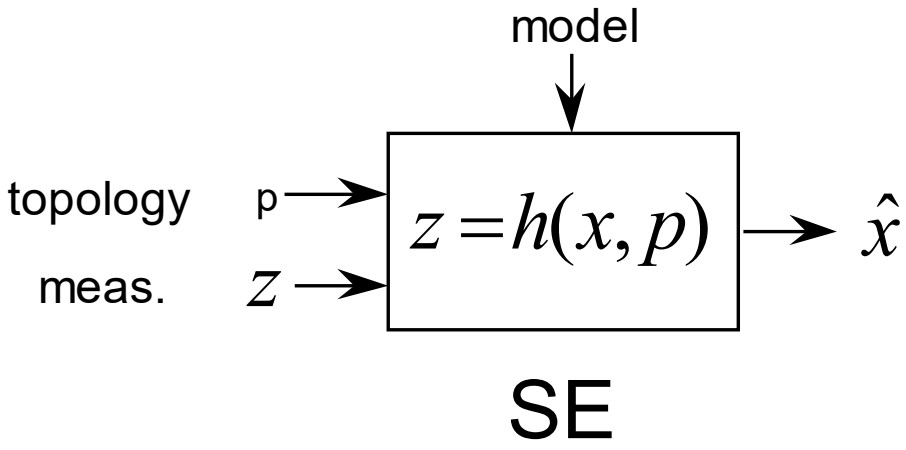
Focus: Why is it taking so long to develop these Tools?

- Phase I: Initial Research
  - Challenges on Distribution System for Real-time Monitoring
  - Branch Current Based State Estimation (BCSE)
- Phase II: Recognizing & Addressing Challenges
  - Business Case?
  - Addressing practical Issues
- Phase III: Improving Performance
  - Why DSSE does not perform as expected in practice?

Phase I: Research

- Motivation:
  - No tools were available

- Tool: **State Estimation**



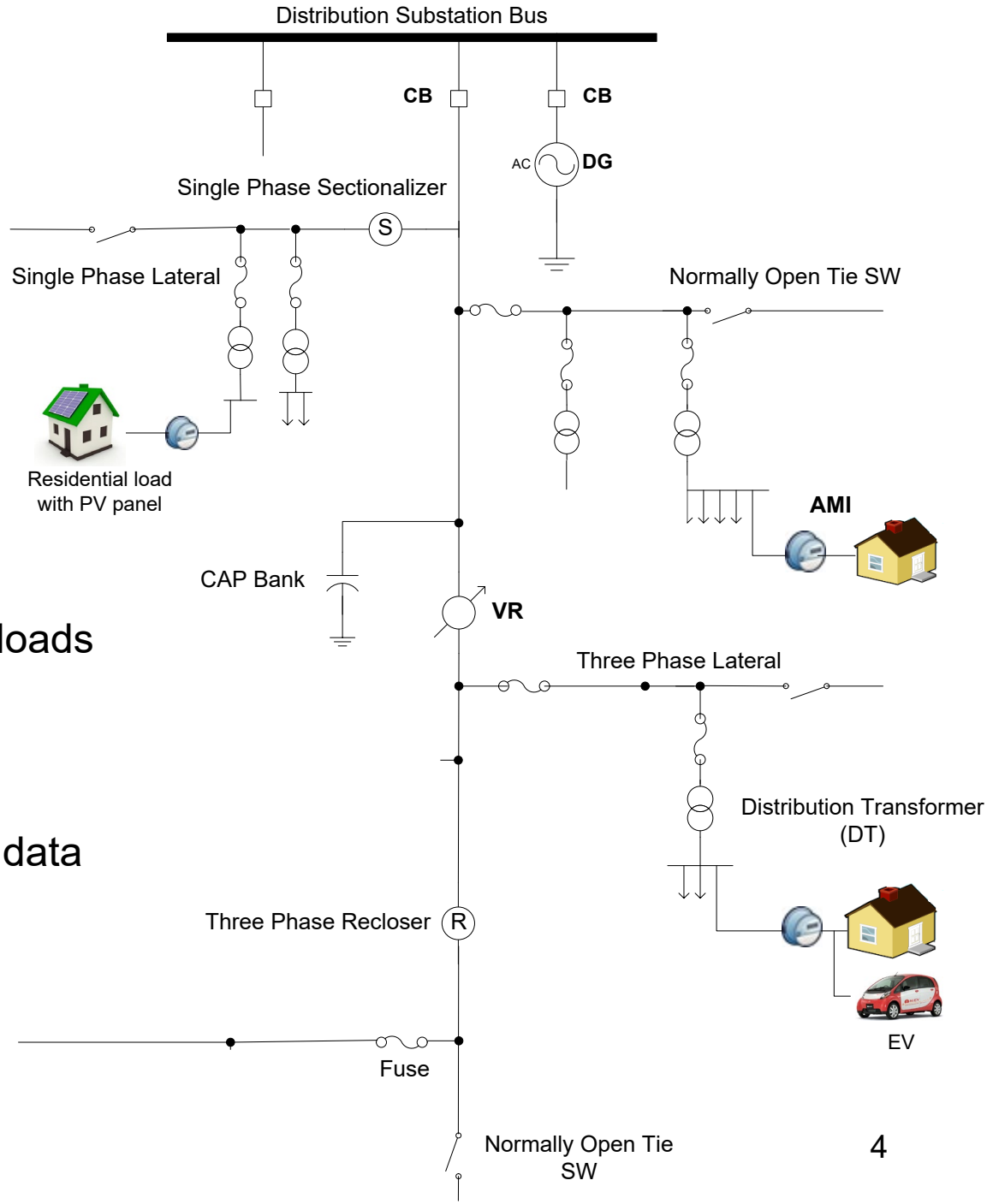
Challenges for SE

(a) System

- Multi-phase System
- Multi-phase unbalanced loads

(b) Data

- Very few measurements
- Limited accuracy of load data



Distribution Feeder

12.47kV, 3 miles
6.9 MW Peak
1240 Customers
299 Transformers

Challenge: Scale!

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Dist Sys State Estimation (DSSE)

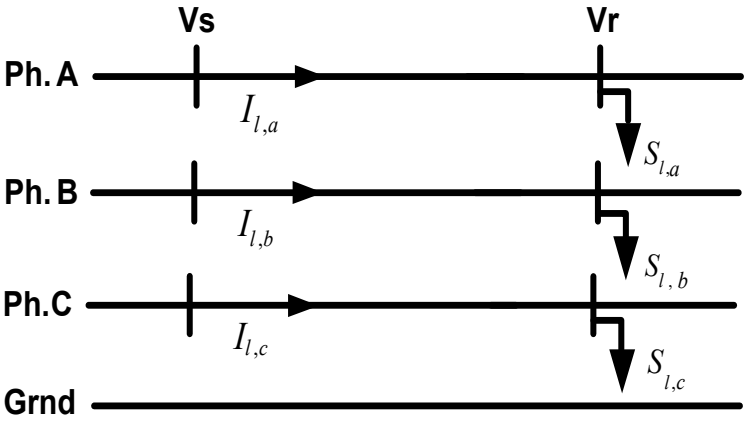
- **Approach: WLS**

$$\min_{x} \quad J(x) = \sum_{i=1}^{m} w_i (z_i - h_i(x))^2 = [z - h(x)]^T W [z - h(x)]$$

Good choice [1]

Challenges

- Challenge: Multi-phase unbalanced system
  - Line Model



$$\begin{bmatrix} V_{r,a} \\ V_{r,b} \\ V_{r,c} \end{bmatrix} = \begin{bmatrix} V_{s,a} \\ V_{s,b} \\ V_{s,c} \end{bmatrix} - l \begin{bmatrix} z_{aa} & z_{ab} & z_{ac} \\ z_{ba} & z_{bb} & z_{bc} \\ z_{ca} & z_{cb} & z_{cc} \end{bmatrix} \begin{bmatrix} I_{l,a} \\ I_{l,b} \\ I_{l,c} \end{bmatrix}$$

- → **3 phase coupled model with low x/r ratio**

- Loads

  can be three, two, or single-phase

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- Challenge: Limited Measurements

  Load data:

- historical load data!
- loads are cyclic with a daily pattern

→Load data → pseudo measurements for SE

→Minimum meas: meas at the feeder head

Branch Current SE

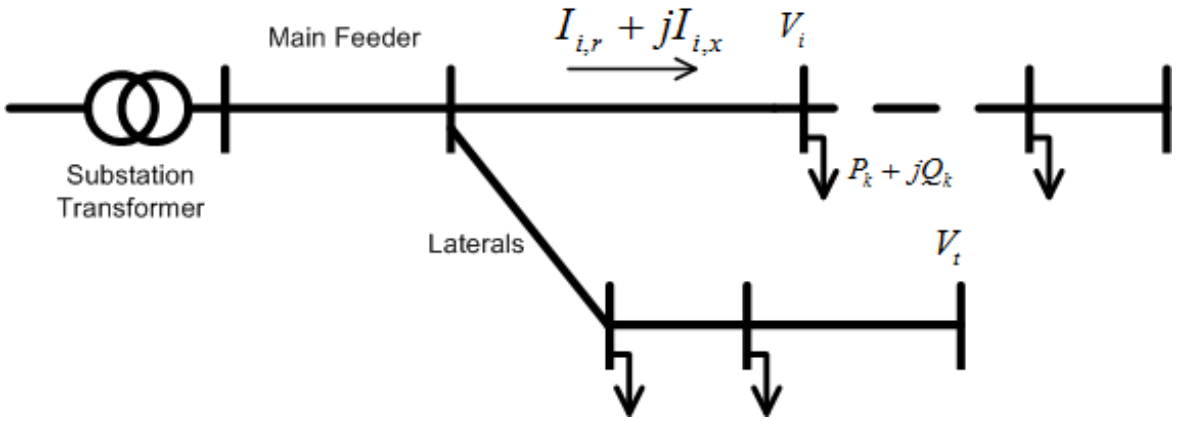
- Challenge: Computational Burden

3 phase coupled model -> cannot adopt decoupled SE

Branch Current SE

→ The BCSE

- branch currents as the system state $\boldsymbol{x}$ *(for radial feeders)*



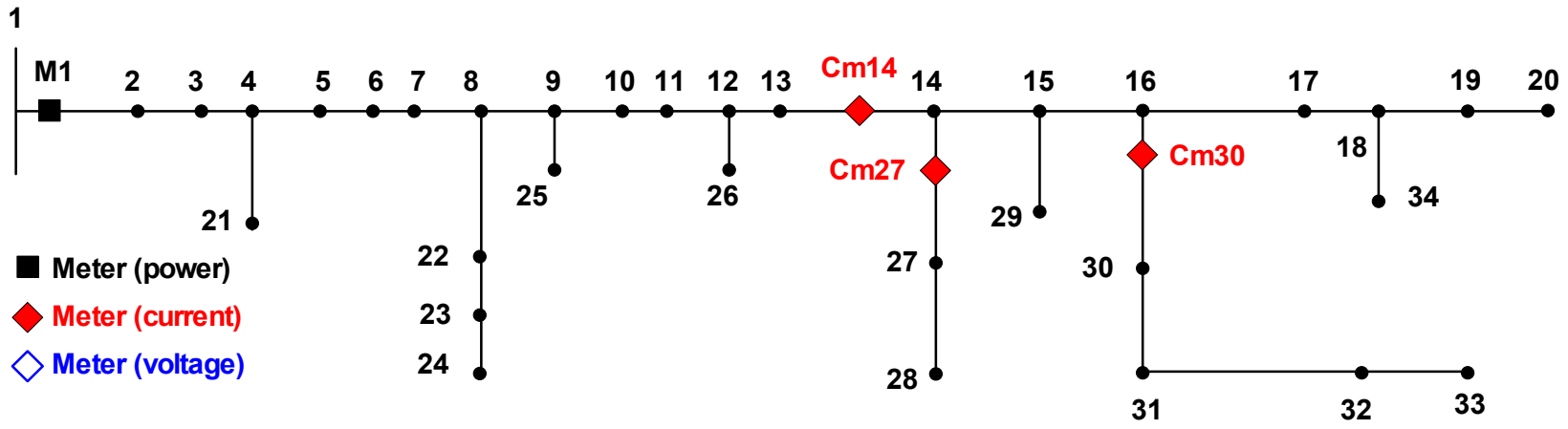
$$x_i = [I_{r,i}, I_{x,i}]$$

- Convert measurements to equivalent current measurements

→ ***Meas Jacobian H is constant and decoupled!***

Case Study

- IEEE 34 node radial test feeder

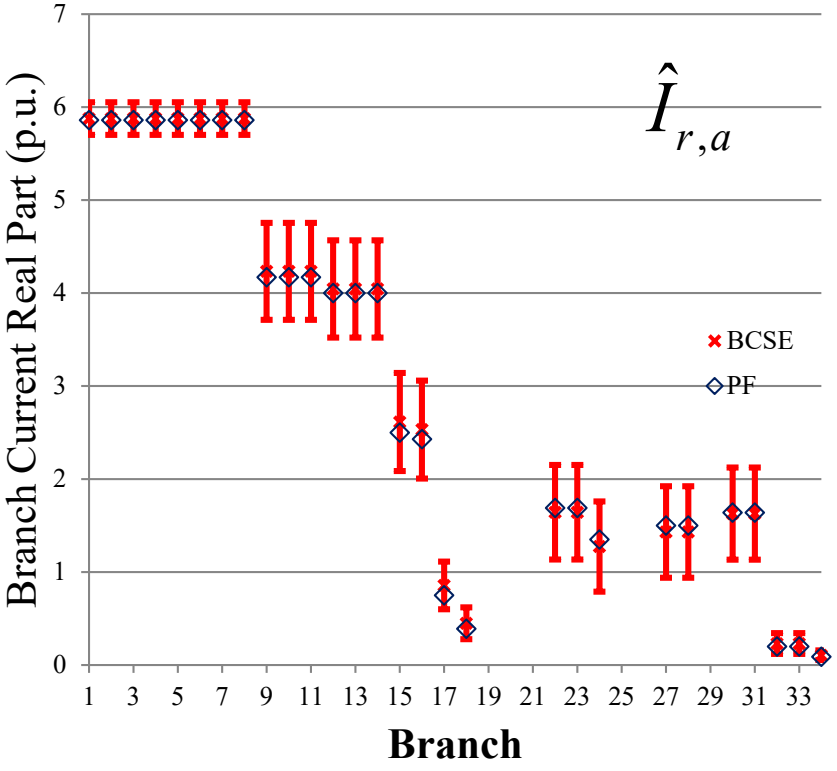


- Test cases
  - ***Case 1:*** Power and voltage measurements (M1) at the substation and forecasted load data.
  - ***Case 2*****:** Case 1 plus three CMs at branches: Cm14, Cm27, and Cm30.

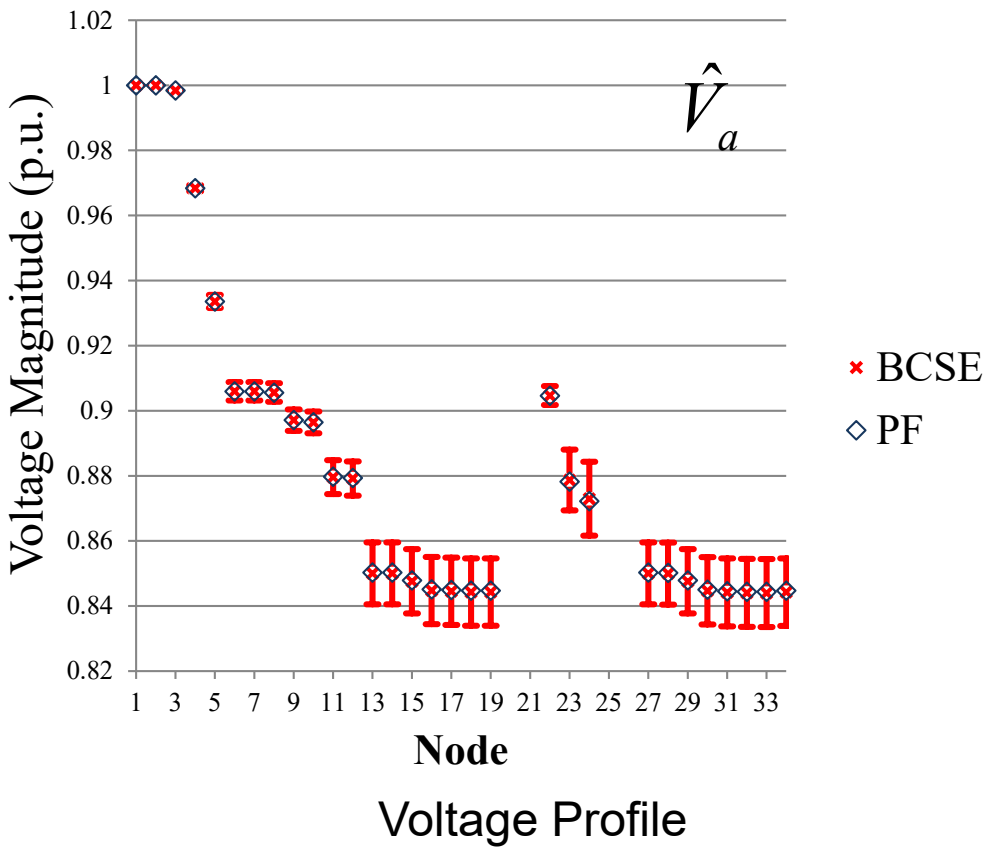
    - 3% error for real-time measurement
    - 50% error for load estimation

Simulation Results

Case 1 - Phase A



Ir_a



Voltage Profile

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Phase II: Application

Challenge:

- **Had to explain to industry why they need SE**

Phase II: Application

- **Opportunity**
- AMI

Jame Hollland

Mainly for Energy Metering

Phase II: Application

- **Opportunity**
- AMI

- **New Application (Business Case):**

  Conservation Voltage Reduction (CVR)

  → Need: - monitor voltages (at PCC) → **SE**
  - Volt/Var control (VVC)

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Contribution

- Load Estimation Using AMI data
- Meter Placement:

  Measurements needed to obtain good voltage estimates

Load Estimation

- Load Estimation using AMI data

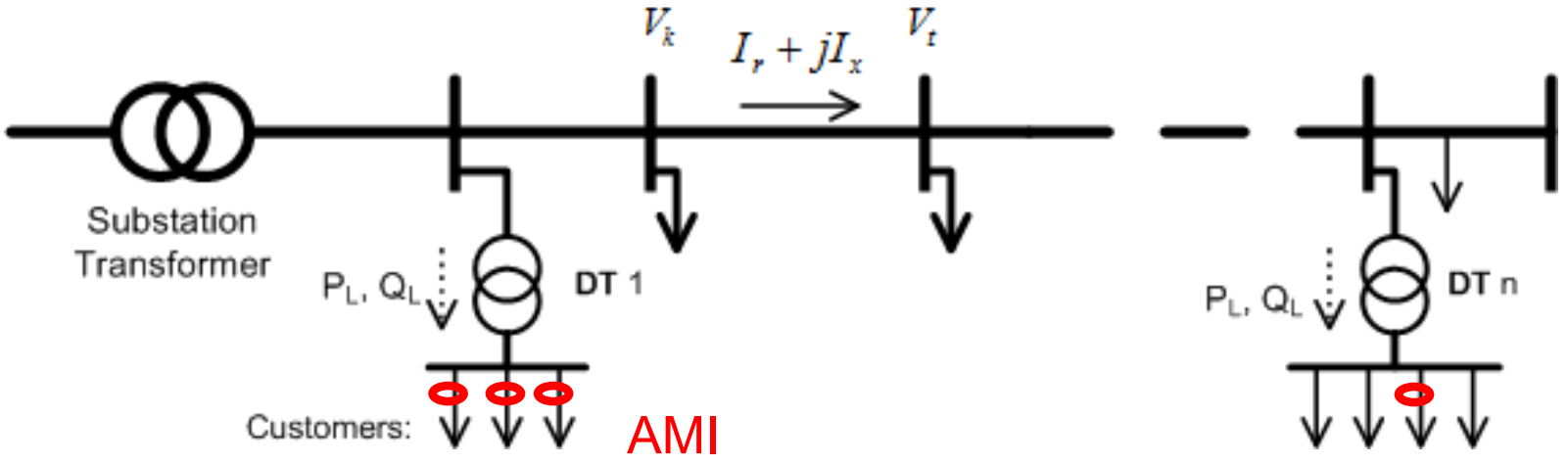
Challenges:

- AMI is not designed for real-time monitoring

- millions of customers to monitor

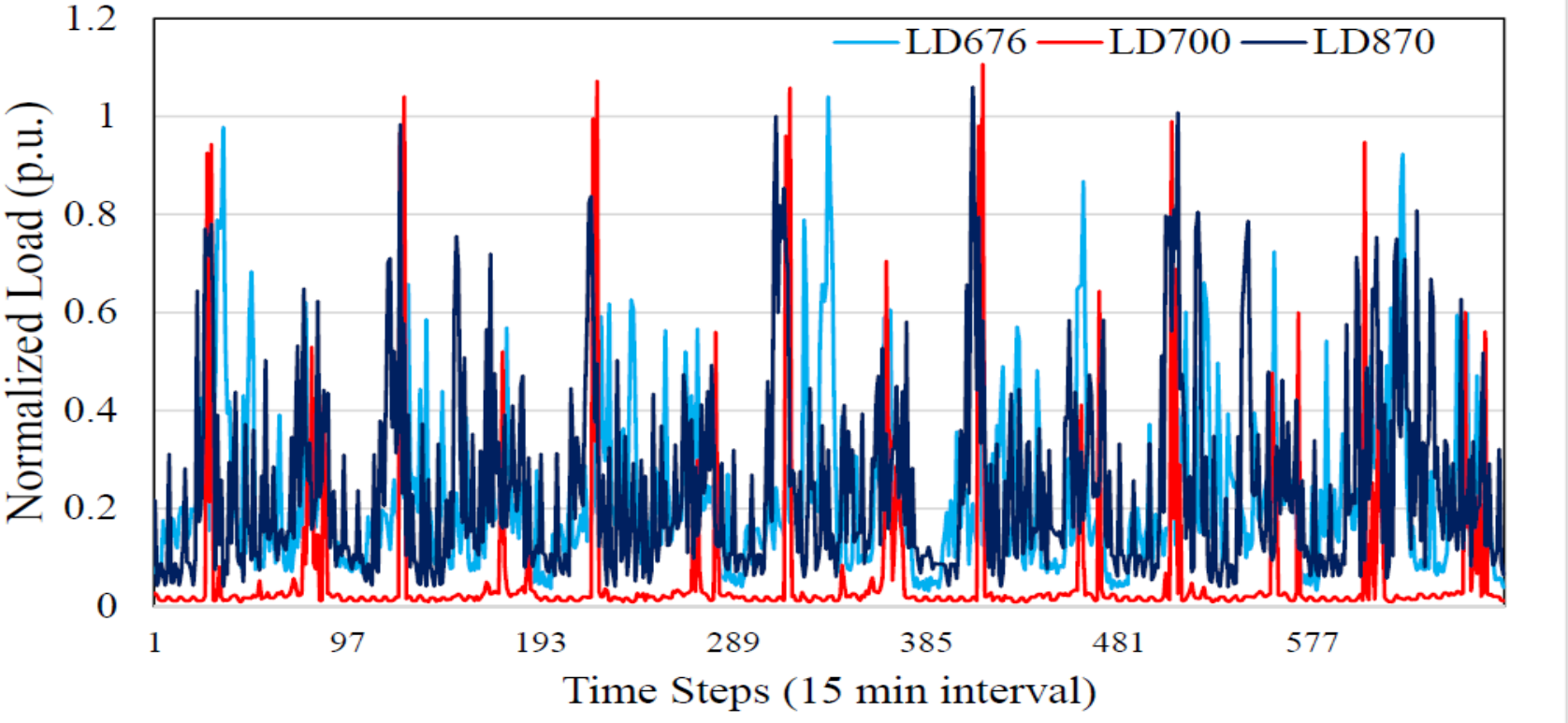
Load Estimation

- Load Estimation using AMI data



- For SE, load of Distribution Transformers (DT) is needed.
- Loads: real and reactive power $P_i + jQ_i$.

Load Profiles from AMI



N. Lu, Et al. "Smart meter data analysis," *T&D Conf 2012*

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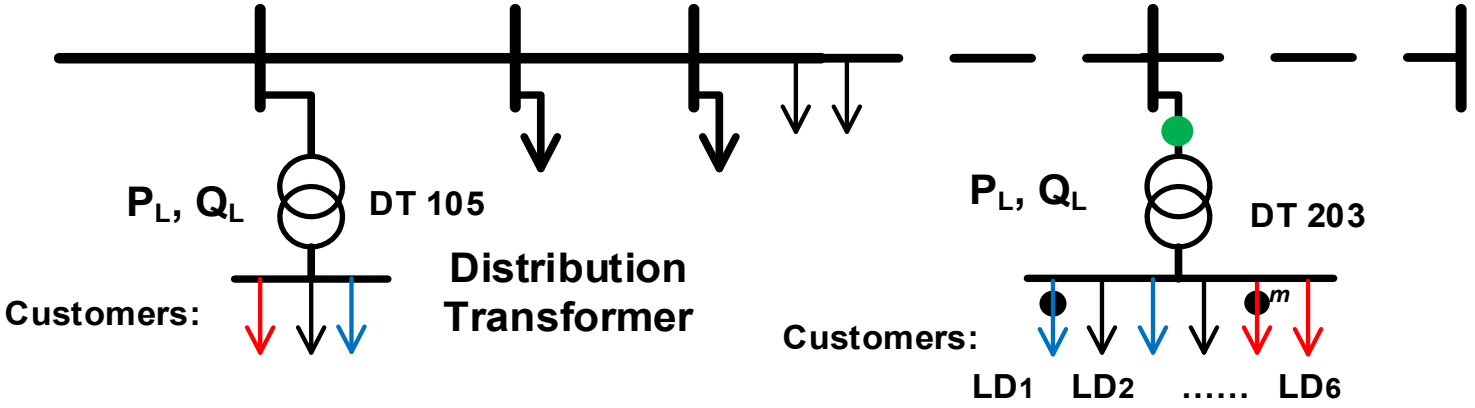
Load Estimation

- Step 1: Load Clustering
  - Finding similar customers by clustering analysis
- Step 2: Load Estimation
  - statistical models

[4] U. Singh and M. Baran, 2016

Load Clustering

Total Customers: 22



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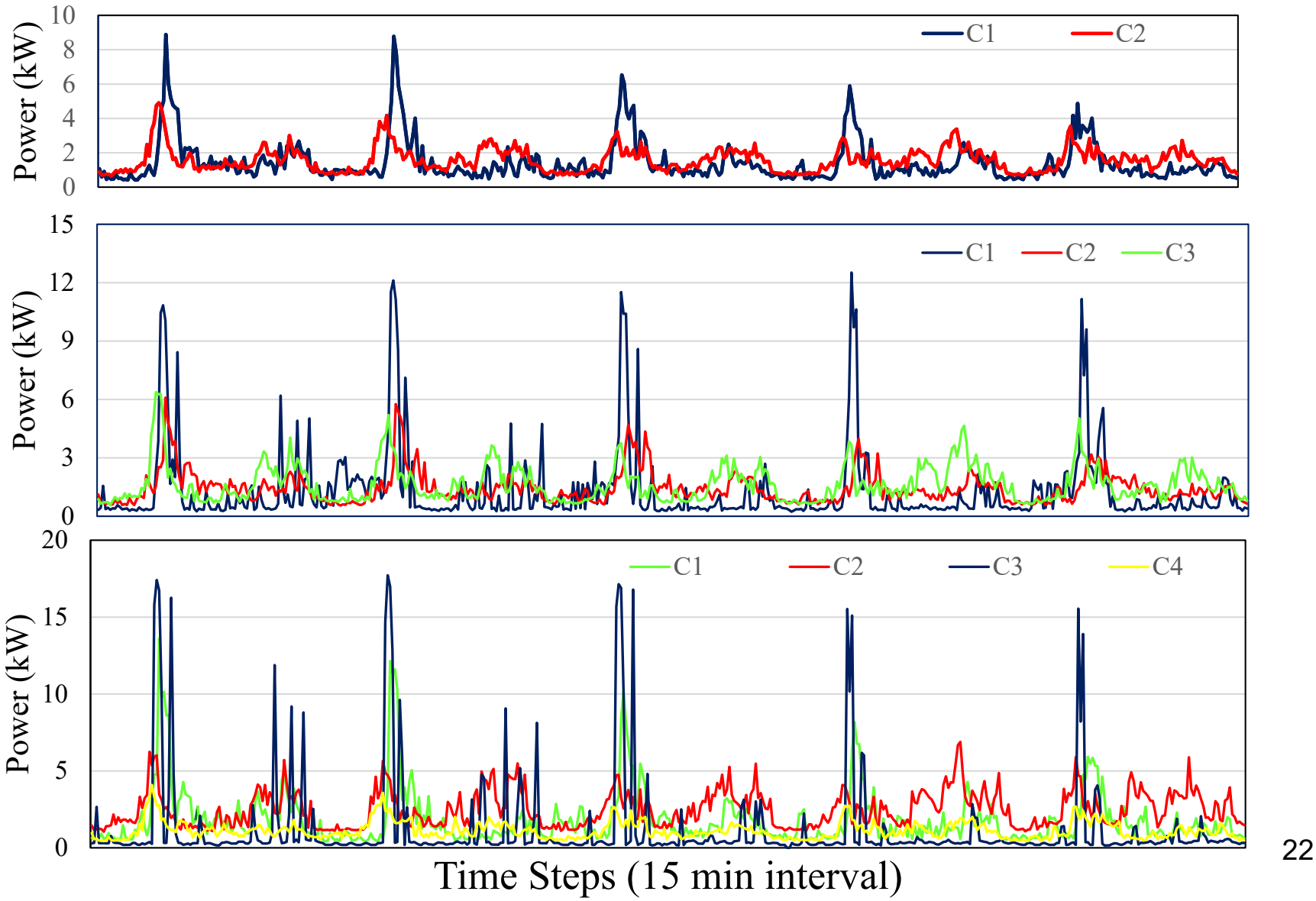
Load Clustering



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Load Models

- *Historical Model: Load Model with Daily Harmonics*

$$y(t) = \beta_0 + \sum_{i=1}^{N_h} \beta_i \cos(\frac{2\pi ti}{n}) + \sum_{j=1}^{N_h} \beta_j \sin(\frac{2\pi tj}{n}) + R_t$$

$$R_t = \varphi_1 R_{t-1} + \varphi_2 R_{t-2} + \varepsilon$$

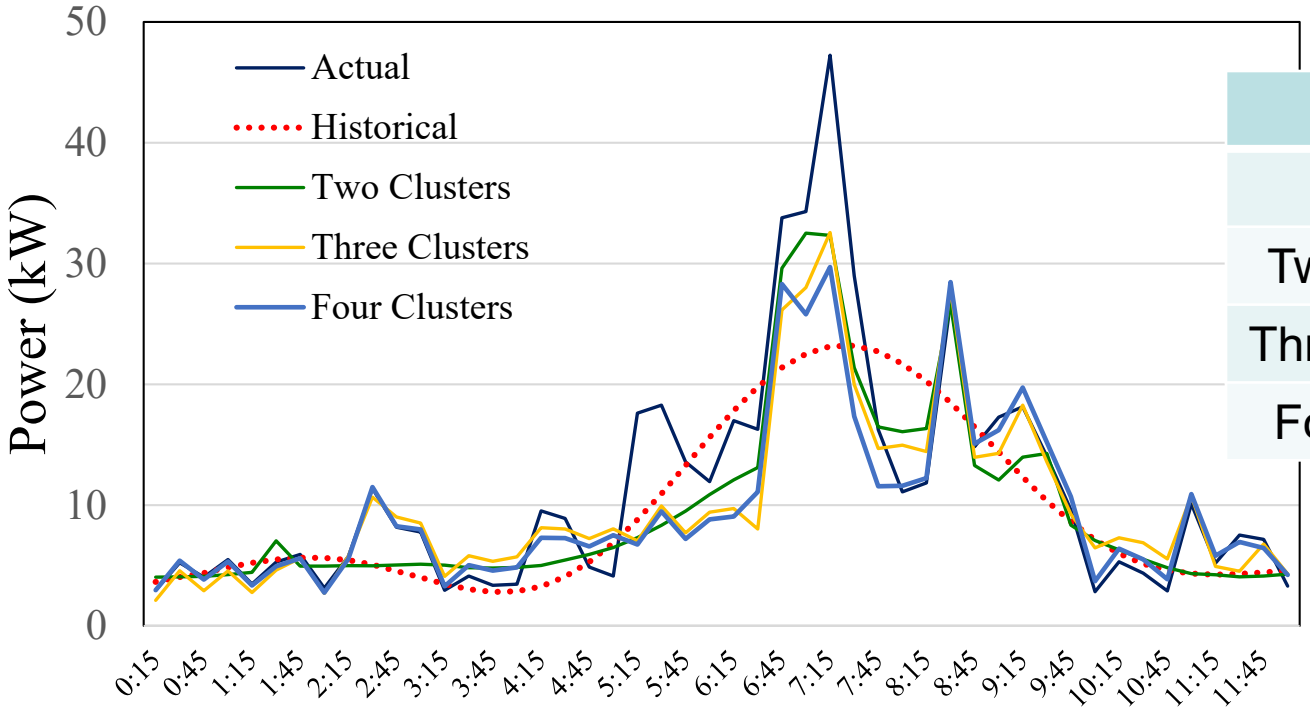
- *Load Estimation: Load Model with Real-time Data*

$$y(t) = \beta_0 + \sum_{i=1}^{N_h} \beta_i \cos(\frac{2\pi ti}{n}) + \sum_{j=1}^{N_h} \beta_j \sin(\frac{2\pi tj}{n}) + \sum_{k=1}^{N_C} \beta_{t,C_k} P_{t,C_k} + R_t$$

$$R_t = \varphi_1 R_{t-1} + \varphi_2 R_{t-2} + \varepsilon$$

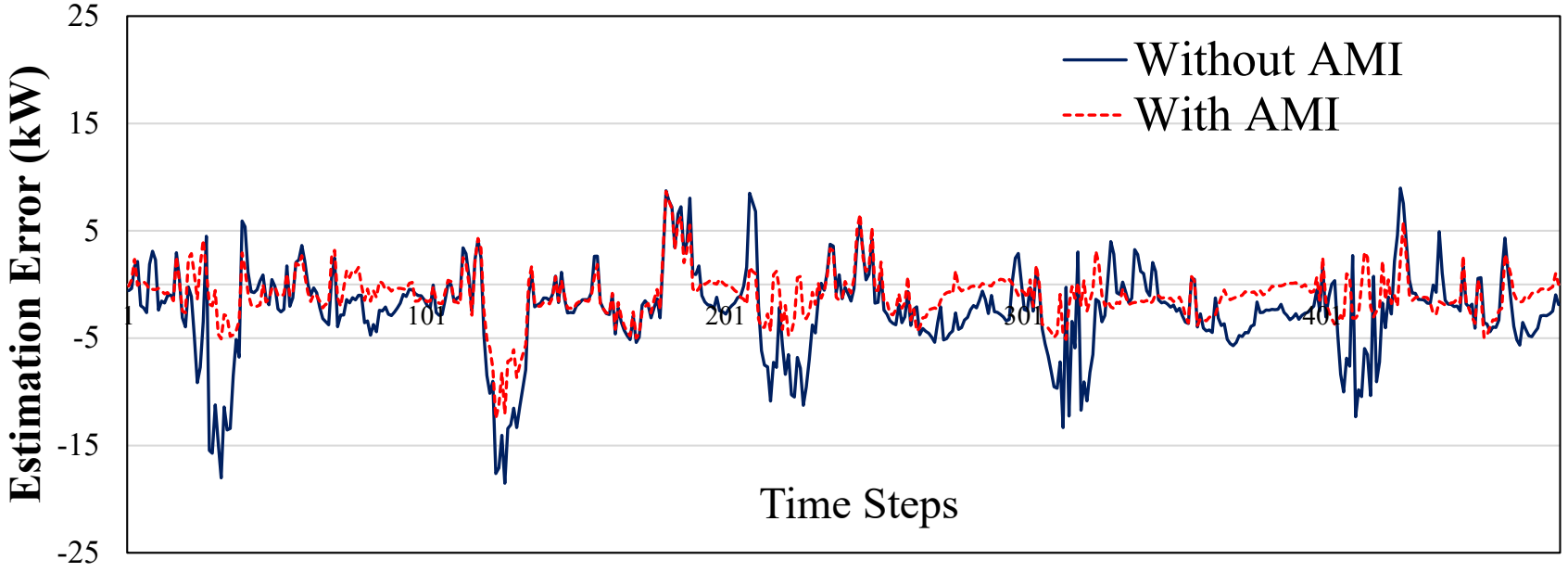
AMI Data from Each Cluster

Load Estimation



Model	RMSE
Historical	4.87
Two Clusters	3.88
Three Clusters	3.41
Four Cluster	3.38

Performance



Real-time measurements from AMI improves the load estimation accuracy by 48% (in MAPE & RMSE).

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Meter Placement

- Meter Placement: Measurements Needed to obtain *good estimate*

- Objective: *Interested quantity*: voltages at PCC

  measure: variance of voltage estimate

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Meter Placement for VVC

- Real-Time measurements
  - Number of measurements and their location
  - Type of measurements, i.e. voltage, current, and power

Meter Placement Problem

Determine the meters that needs to be placed on a given feeder such that the SE with these measurements can estimate the voltages within desired accuracy (+/- 1 V) .

Meter Placement Problem

$$\min f_O = \sum_{i=1}^{n} C_i(d_i)$$

$$s.t. \quad \max\left\{\hat{\boldsymbol{\sigma}}_V\right\} \le \bar{\sigma}_V$$

$$\mathbf{M}_1(\hat{\mathbf{x}}, \mathbf{z}) = 0$$

$$\hat{\boldsymbol{\sigma}}_V = \mathbf{M}_2(\hat{\mathbf{x}}, \mathbf{z})$$

$$d_i \in \{0,1\}$$

where:

- d_i :decision variable of that measurement
- C_i :cost function of the measurement
- $\hat{\mathbf{x}}$:estimated system state
- $\mathbf{z}$:measurements for SE
- $\hat{\boldsymbol{\sigma}}_V$:voltage standard deviation
- $\mathbf{M}_1$:SE mapping

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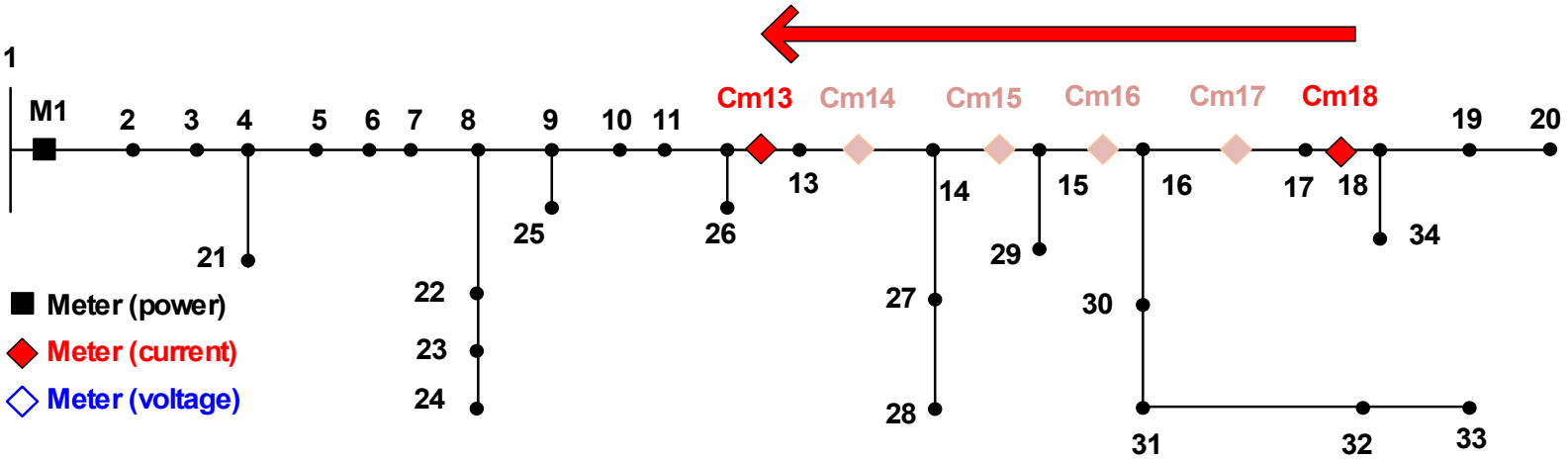
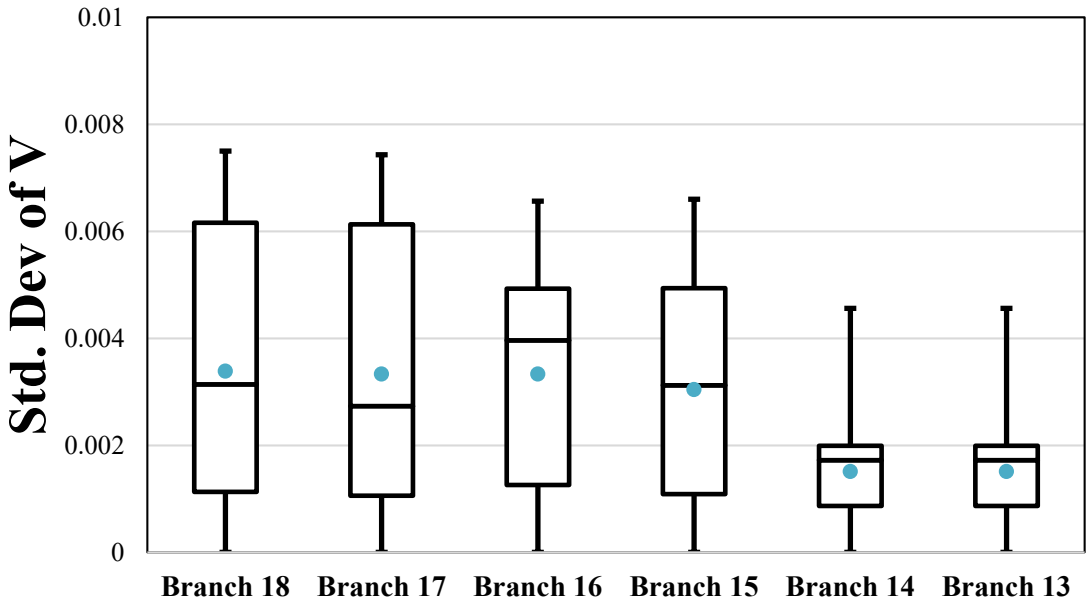
Solution Approach

- This is a difficult problem

⇒ Use Sensitivity to determine good places for each measurement type

Sensitivity Analysis

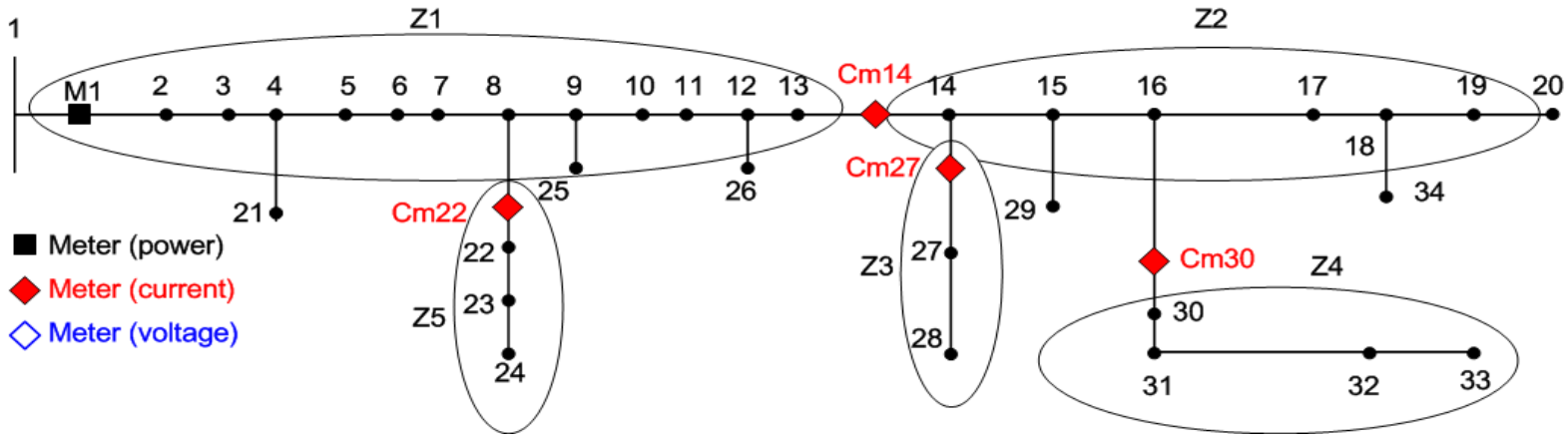




Placing the CMs close to the beginning of the substation/ the beginning of the lateral/ before big loads.

Meter Placement Rules

- **Rule 1**: Determine the load zones along the feeder
  with similar loading &
  Put CMs in the beginning of each load zones



- **Rule 3**: 'Put VMs at the end of the main feeder and laterals

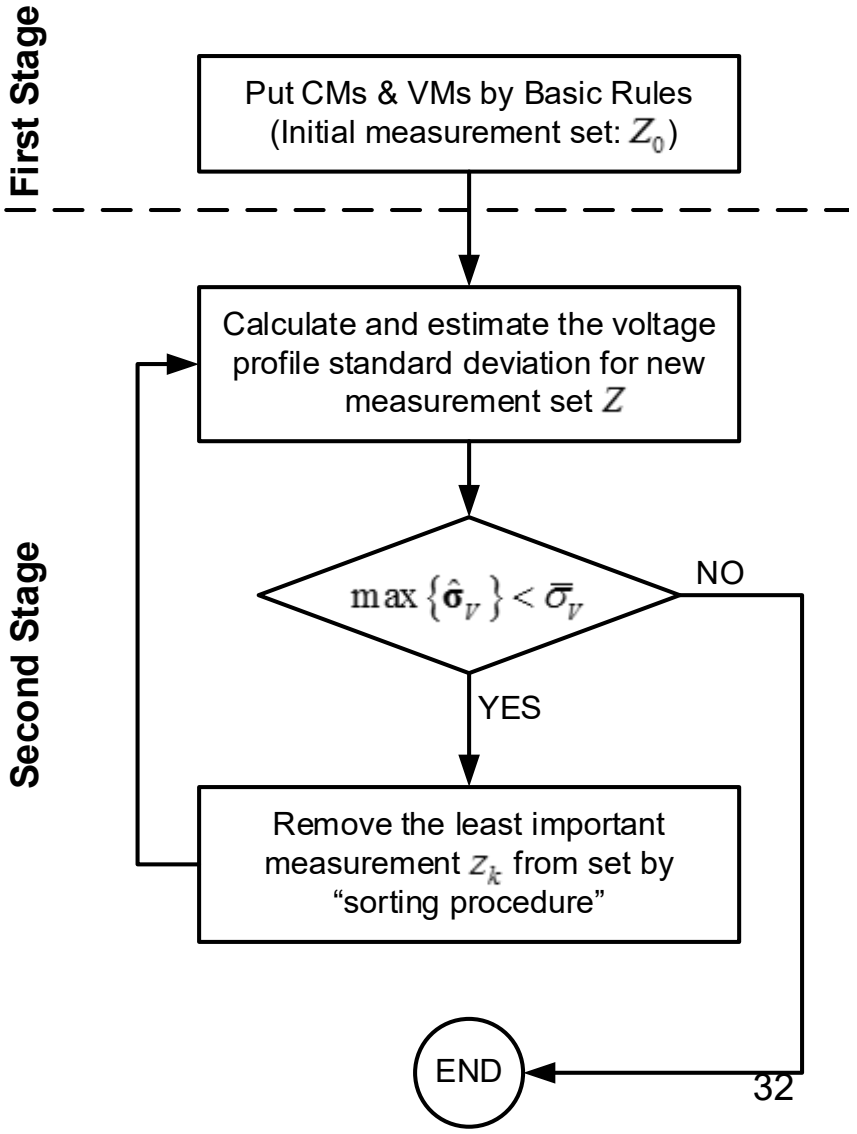
Meter Placement Scheme

Stage 1:

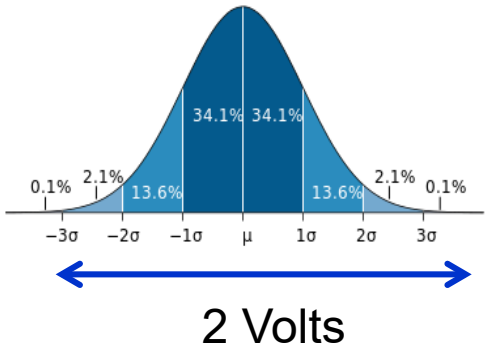
Put VMs and CMs based on the Rules

Stage 2:

Meter Elimination

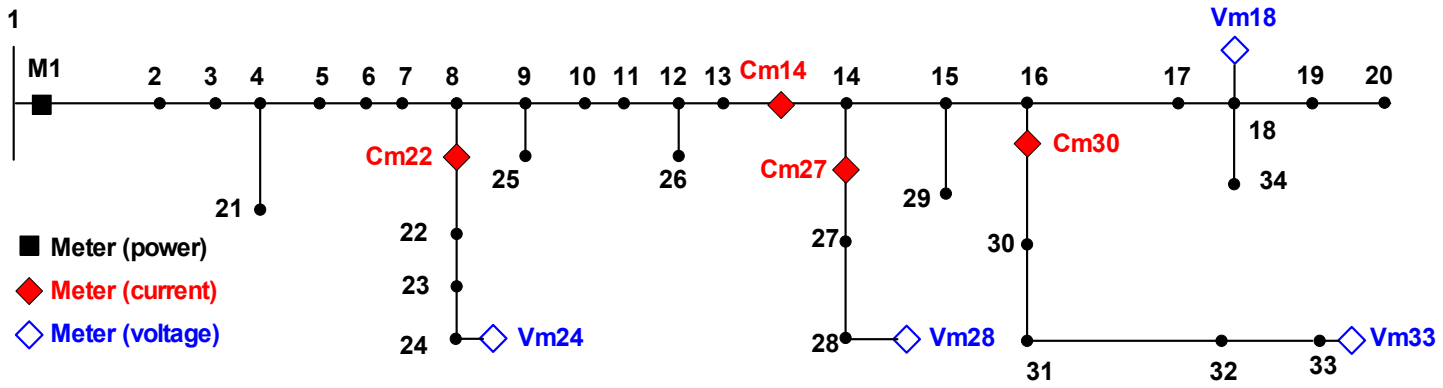


- Target value $\bar{\sigma}_V$

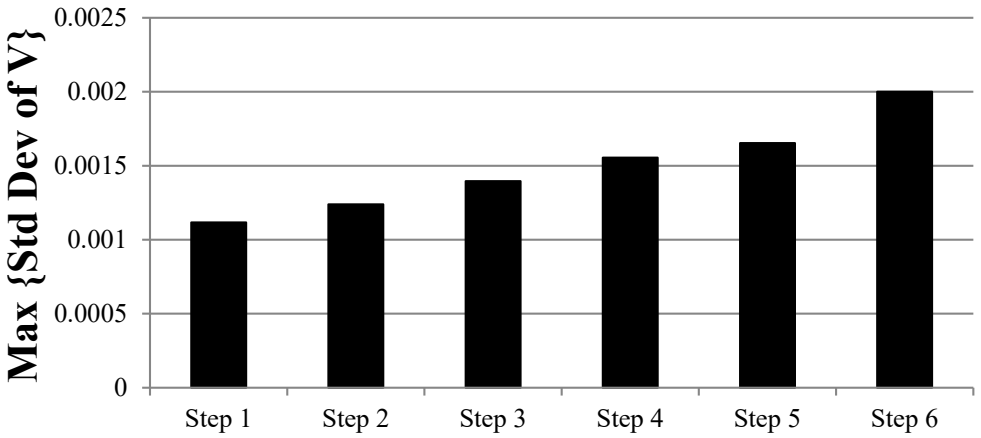


Case Study

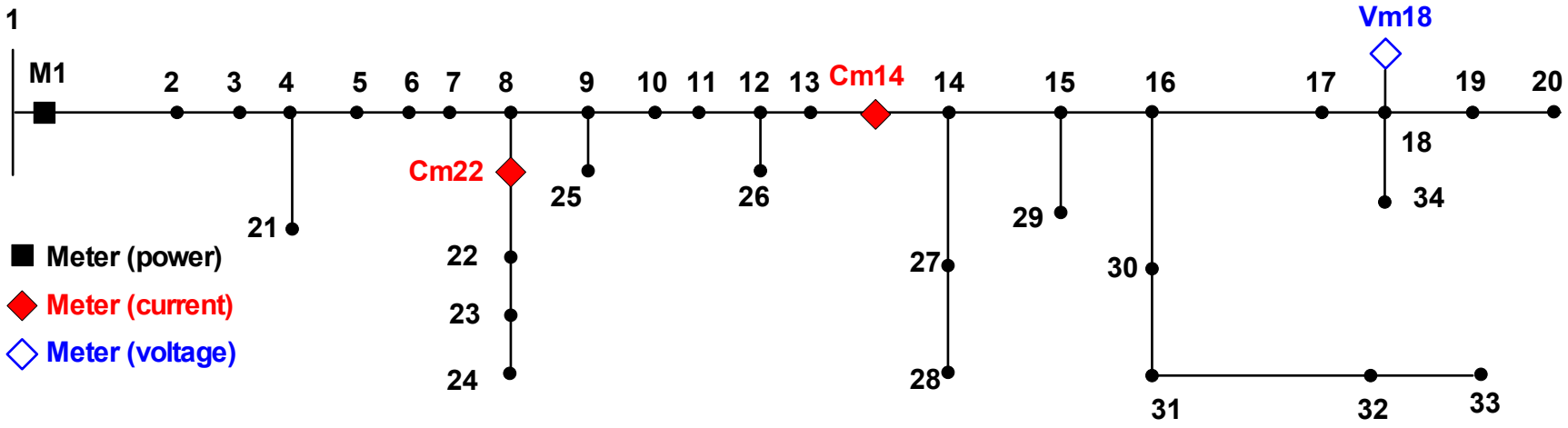
- Step1: placing all VMs and CMs



- Step2: Meter Elimination

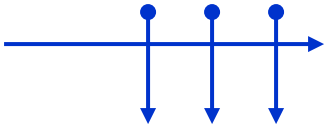


Final Measurement Set



Other Efforts

- Different Estimation Approaches:
  - Bayesian
  - Forecast Assisted State Estimation



- Load Estimation

- Detailed Feeder Model

Review paper

A Survey on State Estimation Techniques and Challenges in Smart Distribution Systems
K. Dehghanpour, Z. Wang, et all, IEEE TSG, March 2019

Phase III: State-of-Art

- Two main approaches adopted

  - PF

  - WLS

Phase III: State-of-Art

- Challenges
  - Renewables: intermittency

Phase III: State-of-Art

- Challenges

  - DSSE Performance
    - Good estimation for interested quantities (voltage at PCC)
    - General: should work on all types systems (feeders)
    - Reliable performance
    - Should not diverge
    - Have diagnostic tools

  - Bad data and topology processing

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- Project: SE performance
  - Issue: SE performs well on some of the systems but not some others
  - Goal: Identify the main factors contributing to poor performance
  - Approach: Can ML help?

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Papers

1. R. Singh, B. Pal, and R. Jabr, “Choice of estimator for distribution system state estimation,” IET Gen. Trans. Dist., 2009.
2. M. Baran and A. Kelley, “A branch-current-based state estimation method for distribution systems,” *IEEE TPWS,* Feb. 1995.
3. *V. Zamani, and M. Baran*, “Feeder Monitoring for Volt/VAR Control in Distribution Systems”, IEEE PES GM 2014
4. *U. Singh, V. Zamani, and M. Baran, “* On-line Load Estimation for Distribution Systems with AMI” IEEE PES GM 2014
5. D. Ablakovic, I. Dzafic, R. A. Jabr, and B. C. Pal, “Experience in distribution state estimation preparation and operation in complex radial distribution networks,” *IEEE PES GM,* 2014

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Thank You