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Sandia National Laboratories

A Model-free Approach for Estimating Service Transformer Capacity Using Residential Smart Meter Data

PVSC Area 9: Power Electronics and Grid Integration

Joseph A. Azzolini,

M. J. Reno, J. Yusuf

U.S. DEPARTMENT OF ENERGY NNSA

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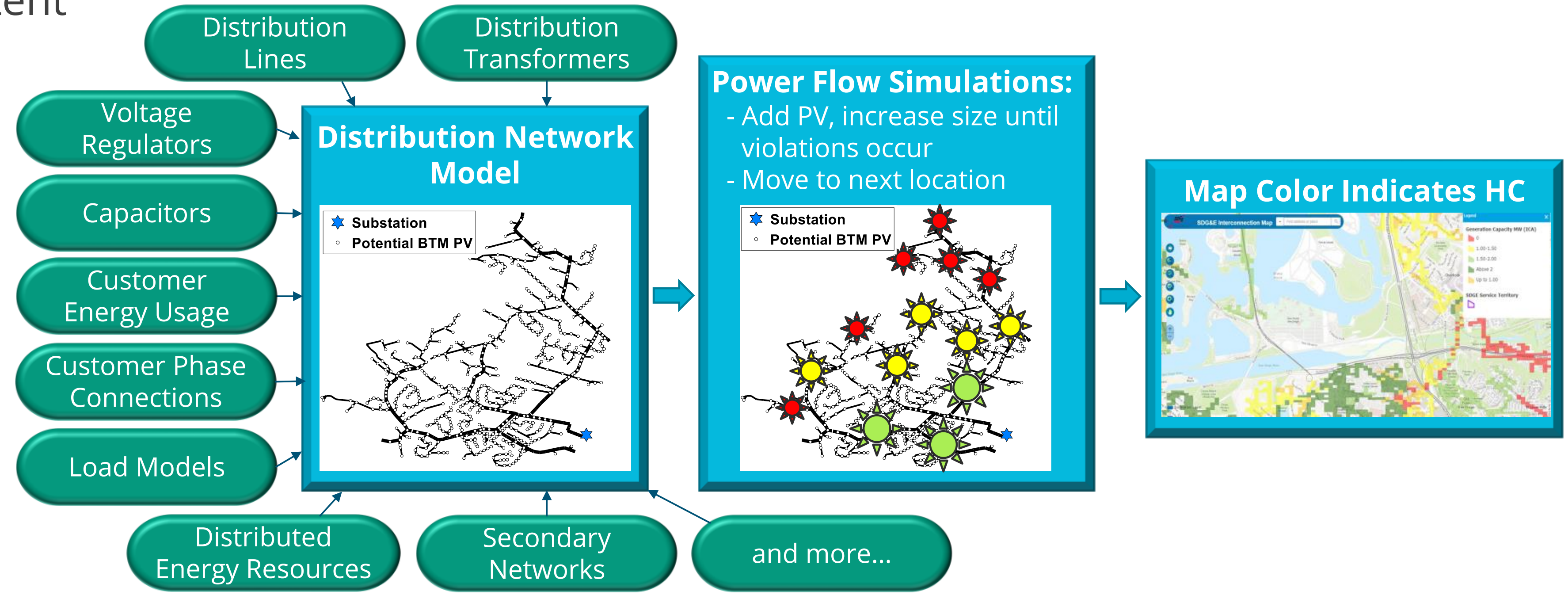
Background and Motivation

- Various planning and impact studies are required before PV systems can be interconnected with the grid to ensure safety and reliability are maintained
  - For residential PV, the most common limitations include **voltage** and **thermal** constraints
- However, as the pace of PV interconnection requests increases, conventional *model-based* approaches may not be sufficient:
  - They often require time-consuming simulations and highly detailed grid models
  - Residential PV are connected to low-voltage secondary circuits, where grid models are over-simplified or non-existent

Example **model-based** PV hosting capacity analysis (HCA)



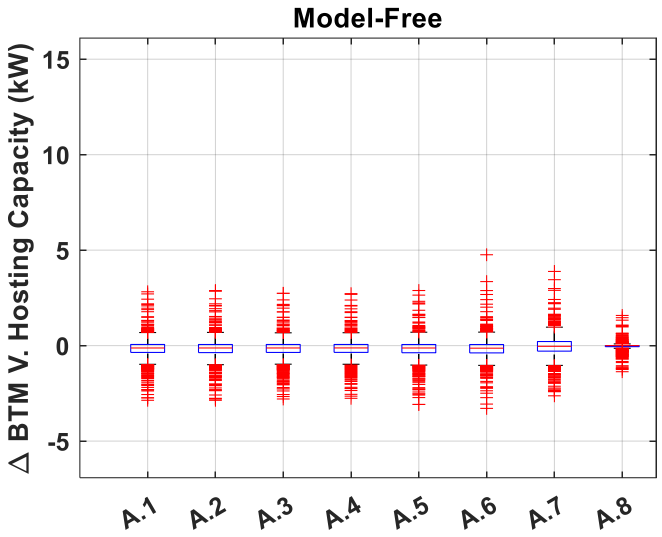
Background and Motivation

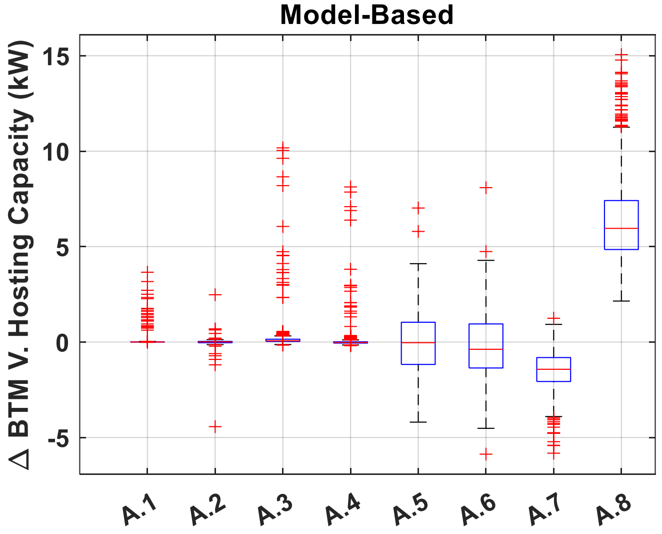
Model-free HCA for Assessing Voltage Constraints [1]:

- Accurate within 0.3 kW on average, and more robust to model errors

Conventional model-based HCA:

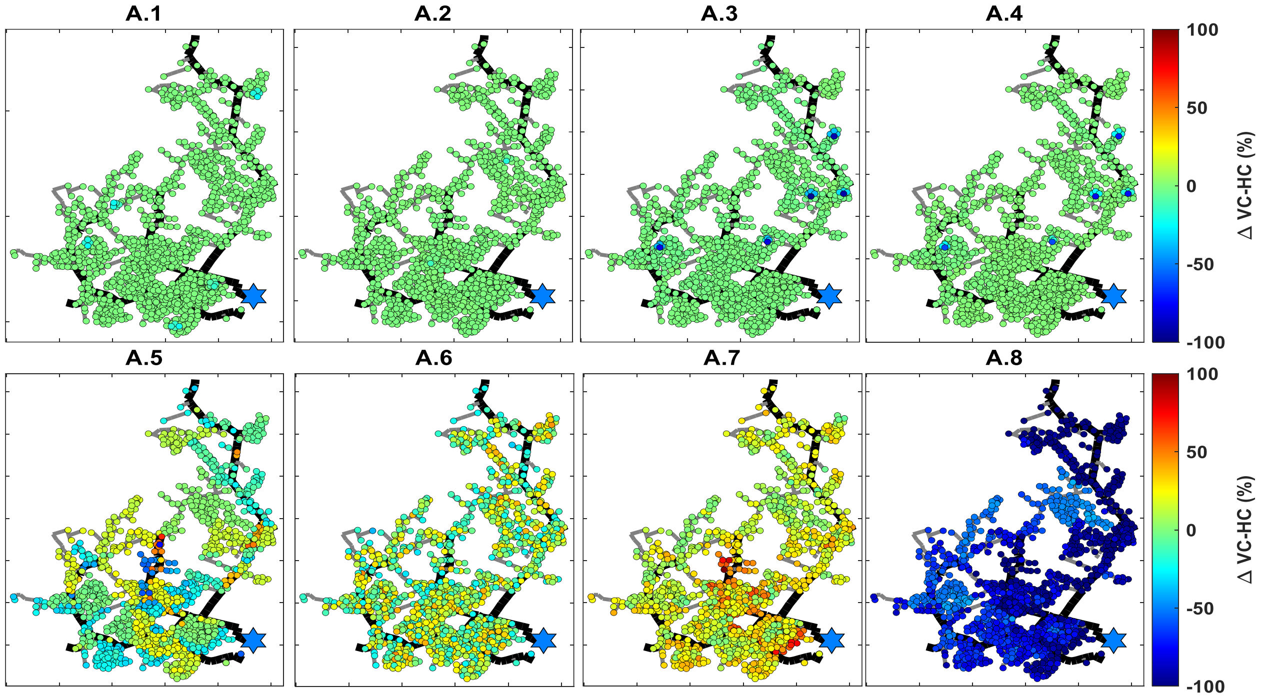
- HCA accuracy is *highly sensitive* to modeling errors [2]
  - Errors can have local or feeder-wide impacts





Model Error Scenarios

#	Error Type
A.1	Service Xfmr Size
A.2	Xfmr/Customer Pairing
A.3	Missing Existing PV
A.4	Missing Existing PV w/ Volt-VAR
A.5	Phase Labeling Errors
A.6	Service Line Lengths
A.7	Substation LTC Malfunction
A.8	Capacitor Malfunction



[1] J. Azzolini, M. Reno, J. Yusuf, S. Talkington, and S. Grijalva, "Calculating PV Hosting Capacity in Low-Voltage Secondary Networks Using Only Smart Meter Data," IEEE ISGT, 2023.

[2] J. Azzolini, S. Talkington, M. J. Reno, S. Grijalva, L. Blakely, and D. Pinney, "Improving Behind-the-Meter PV Impact Studies with Data-Driven Modeling and Analysis", *IEEE Photovoltaic Specialists Conference* (PVSC), 2022.

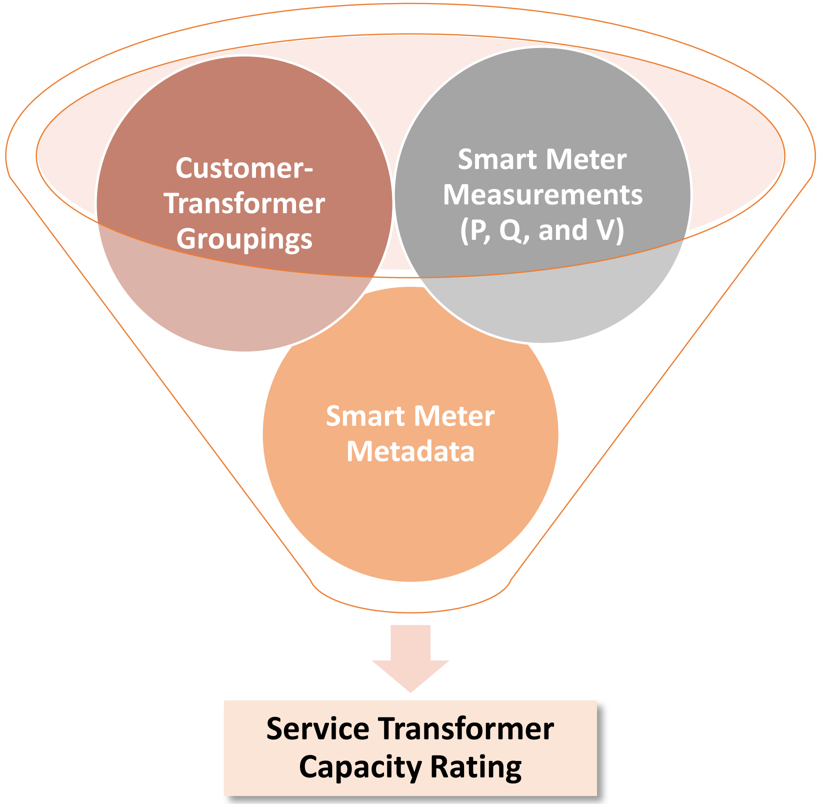
Model-free Service Transformer Capacity Estimation

Objective:

- Determine the rated capacity (in kVA) of all service transformers on a given radial distribution feeder *without* any topology information or grid models

Inputs:

- Smart meter data for all customers
  - Includes historical P, Q, V measurements and metadata (e.g., location, phase)
- Customer-transformer groupings
  - Previous [3] and ongoing work to determine these using smart meter data
- Lookup table of known transformer models (metadata)
  - kVA, R, and X for each transformer type



[3] L. Blakely and M. J. Reno, "Identification and Correction of Errors in Pairing AMI Meters and Transformers," in IEEE Power and Energy Conference at Illinois (PECI), 2021.

Model-free Service Transformer Capacity Estimation

The proposed approach has 3 main stages:

1) Aggregation for Service Transformer Measurements

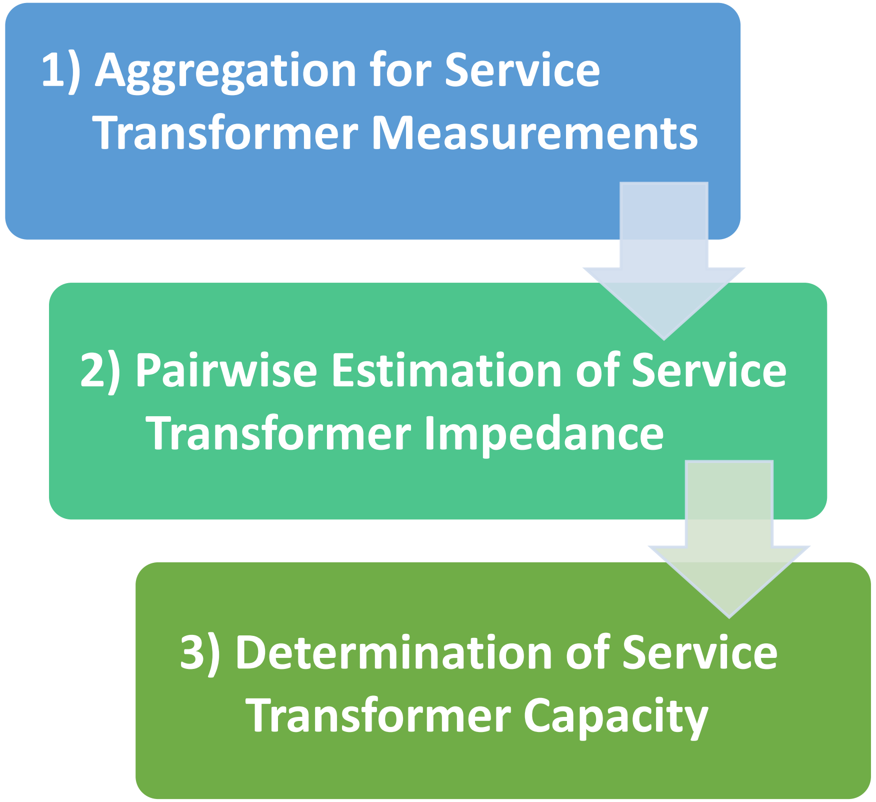
   -This stage generates estimates of the P, Q, and V measurements at the LV terminals of each service transformer using the smart meter data for the downstream customers connected to it

2) Pairwise Estimation of Service Transformer Impedance

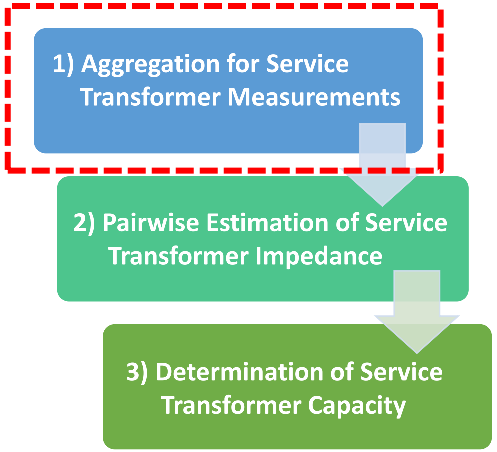
   -This stage creates multiple impedance estimates of each service transformer using the aggregated measurements from nearby transformers on the same phase

3) Determination of Service Transformer Capacity

   -This stage combines the multiple impedance estimates per transformer into a single prediction of rated capacity



Model-free Service Transformer Capacity Estimation



Aggregation example:

Apply linear voltage drop approximation to estimate the nearest upstream node voltage of neighboring customers:

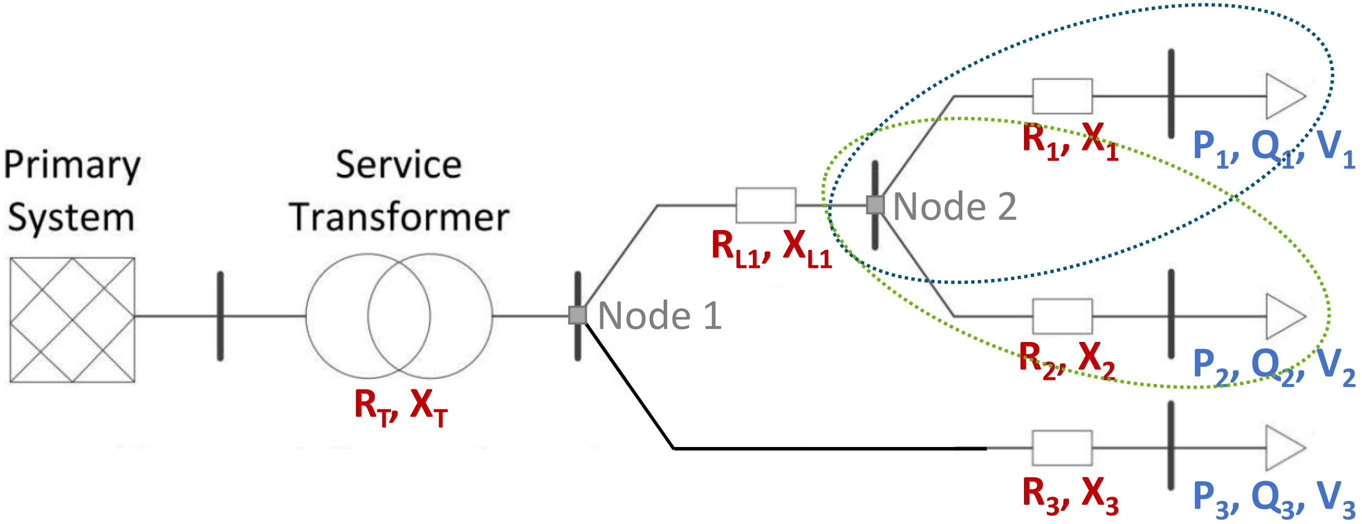
$$V_{Node2} = V_1 + R_1 I_{R1} + X_1 I_{X1} \quad (1)$$

$$V_{Node2} = V_2 + R_2 I_{R2} + X_2 I_{X2} \quad (2)$$

$$I_R = P/V \quad (3)$$

$$I_X = Q/V \quad (4)$$

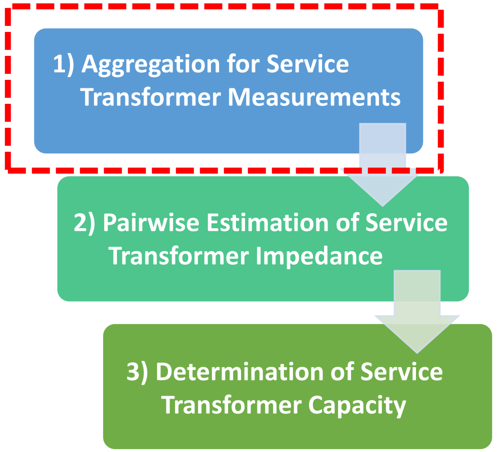
$$(V_1 - V_2) = -R_1 I_{R1} - X_1 I_{X1} + R_2 I_{R2} + X_2 I_{X2} \quad (5)$$



Solve linear regression problem (5) for branch R, X values, then calculate V_{Node2}:

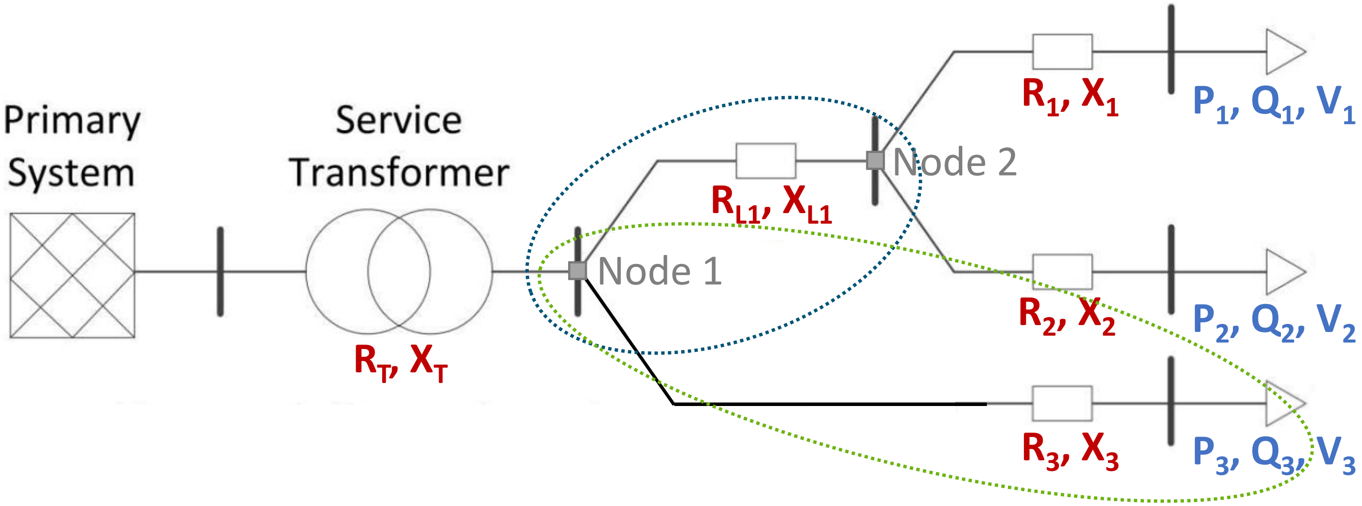
$$V_{Node2} = \frac{1}{N} \sum_{i=1}^{N} \left| \left| V_i + (R_i + jX_i)(I_{Ri} + jI_{Xi}) \right| \right|$$

Model-free Service Transformer Capacity Estimation

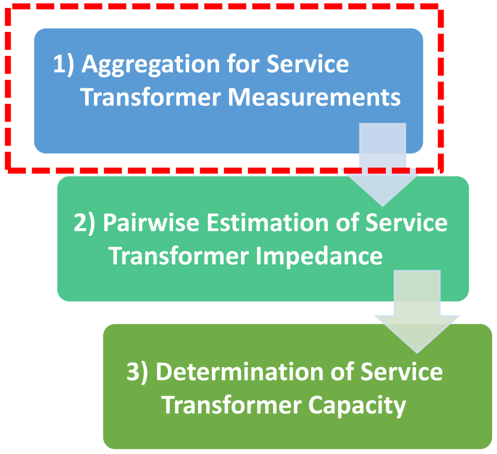


Aggregation example:

- The process can then be repeated to estimate the voltages at the LV terminals of the service transformer
- Sum the customer power measurements to estimate P, Q
- Average the customer coordinates for estimated location



Model-free Service Transformer Capacity Estimation

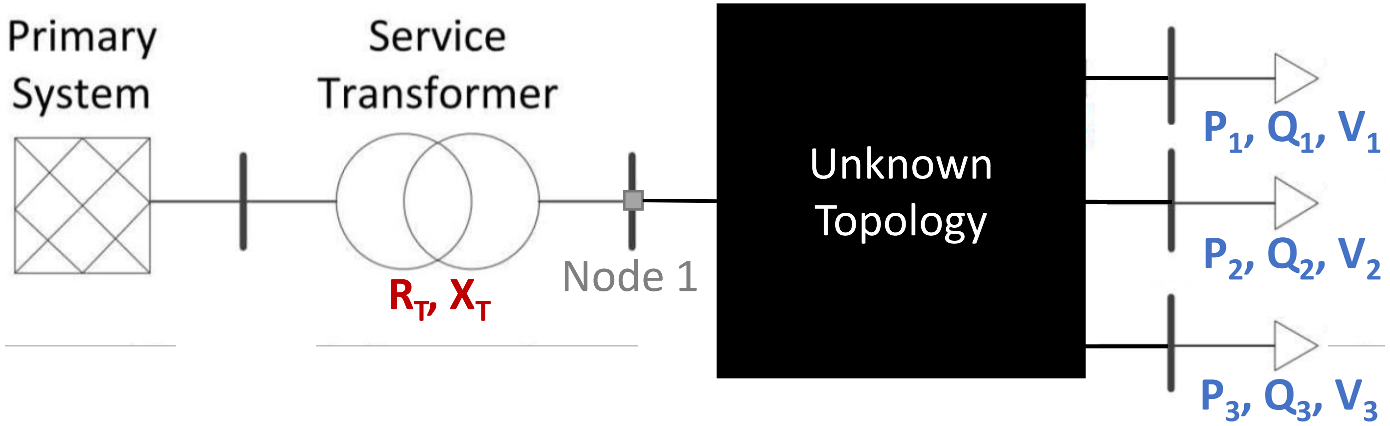


When topology is unknown:

- It is more challenging and requires more computing power to apply parameter estimation and estimate intermediate node voltages

Proposed solution:

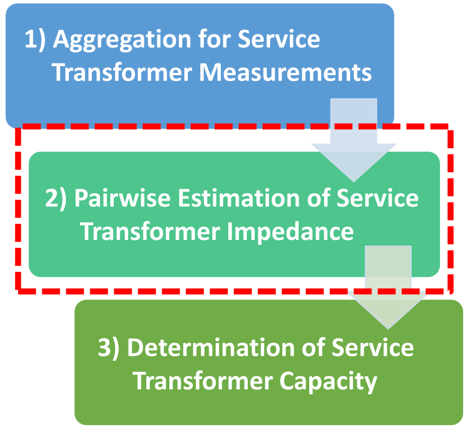
- Apply filter to ensure uni-directional power flow from the transformer to the customers
  - This guarantees that LV terminal voltage will be highest
- Estimate Node 1 voltage iteratively using every possible combination of customer pairs
- Whichever pair has the highest average estimated voltage is selected

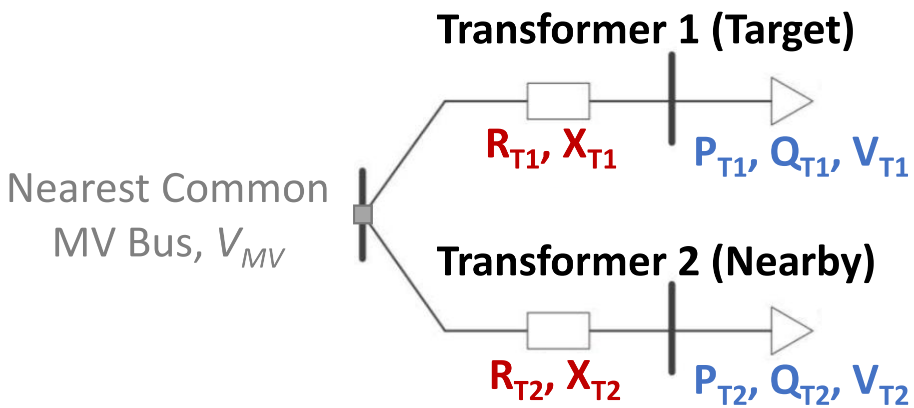


Model-free Service Transformer Capacity Estimation

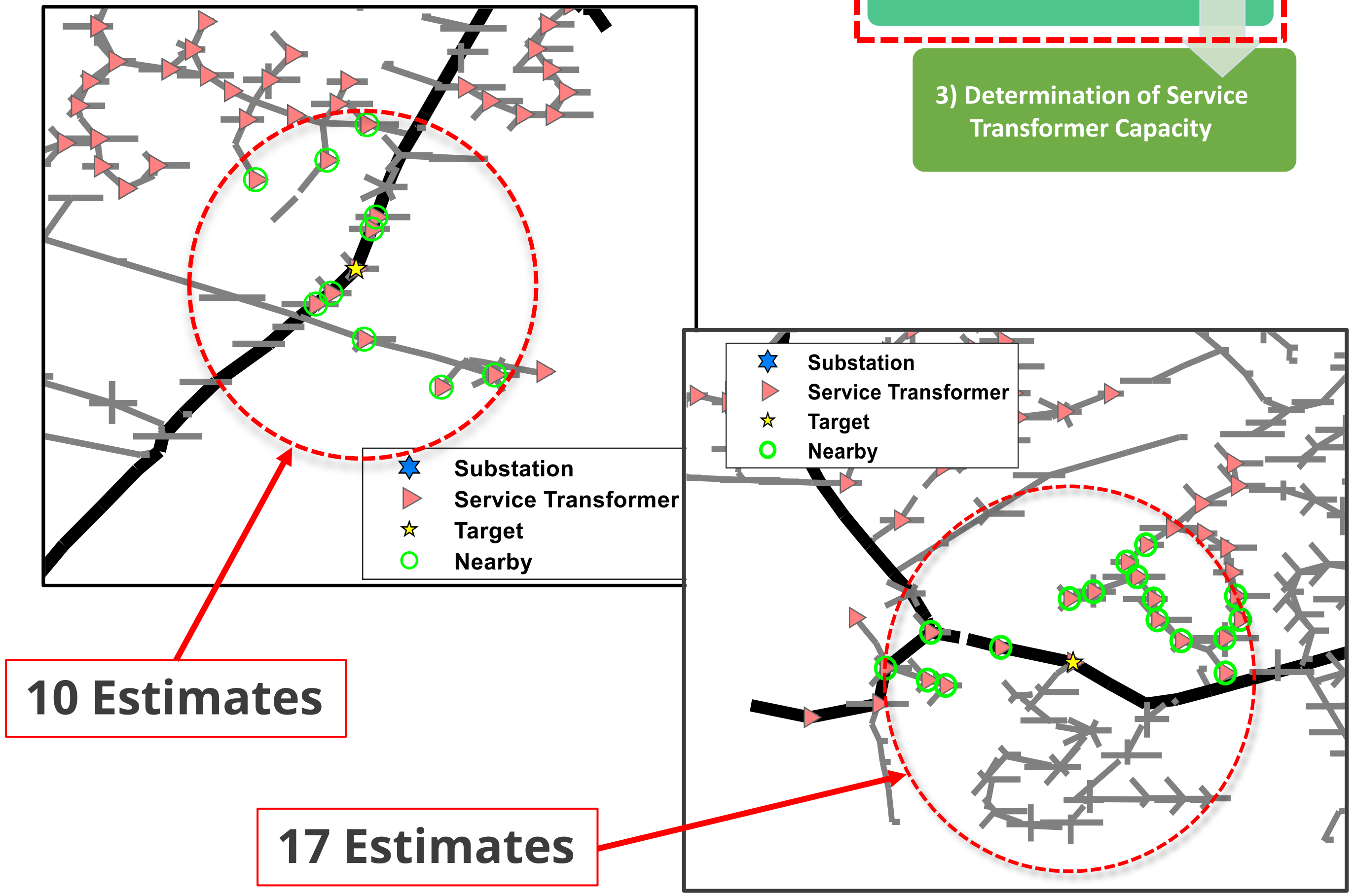
Pairwise Estimation of Service Transformer Impedance:

- The same parameter estimation approach can be applied to calculate the service transformer R and X values



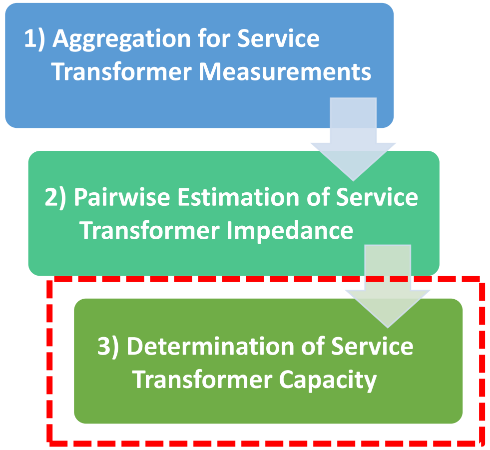


- Since the topology is unknown, multiple impedance estimates are generated for the target transformer by iteratively pairing it with nearby transformers (physically close)



Model-free Service Transformer Capacity Estimation

Determination of Service Transformer Capacity:



- The algorithm then uses a **weighted voting scheme** to combine the multiple estimates into a single kVA prediction, where the best matching R and X values (7) from the lookup table receives a vote

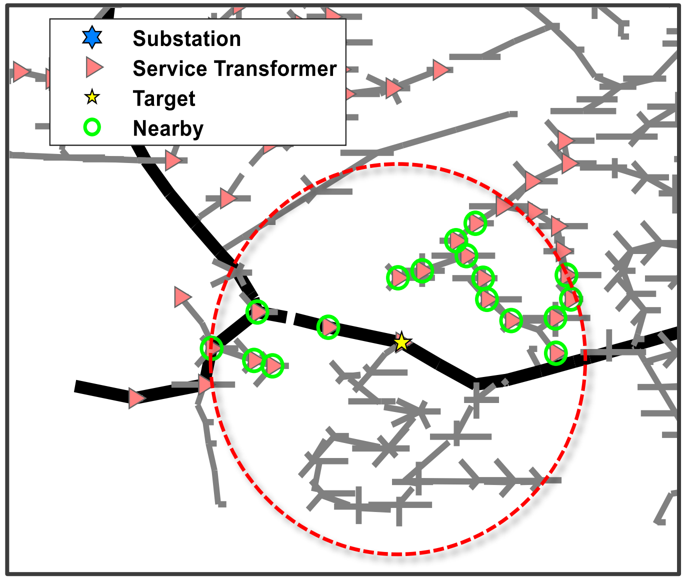
$$Error = \min\left(\left|R_{est} - R_{Lookup}\right| + \left|X_{est} - X_{Lookup}\right|\right) \quad (7)$$

- The votes are then weighted according to the RMSE of the linear regression models (8):

$$WF_t = \frac{1/(RMSE_t)}{sum(1/RMSE_T)} \quad (8)$$

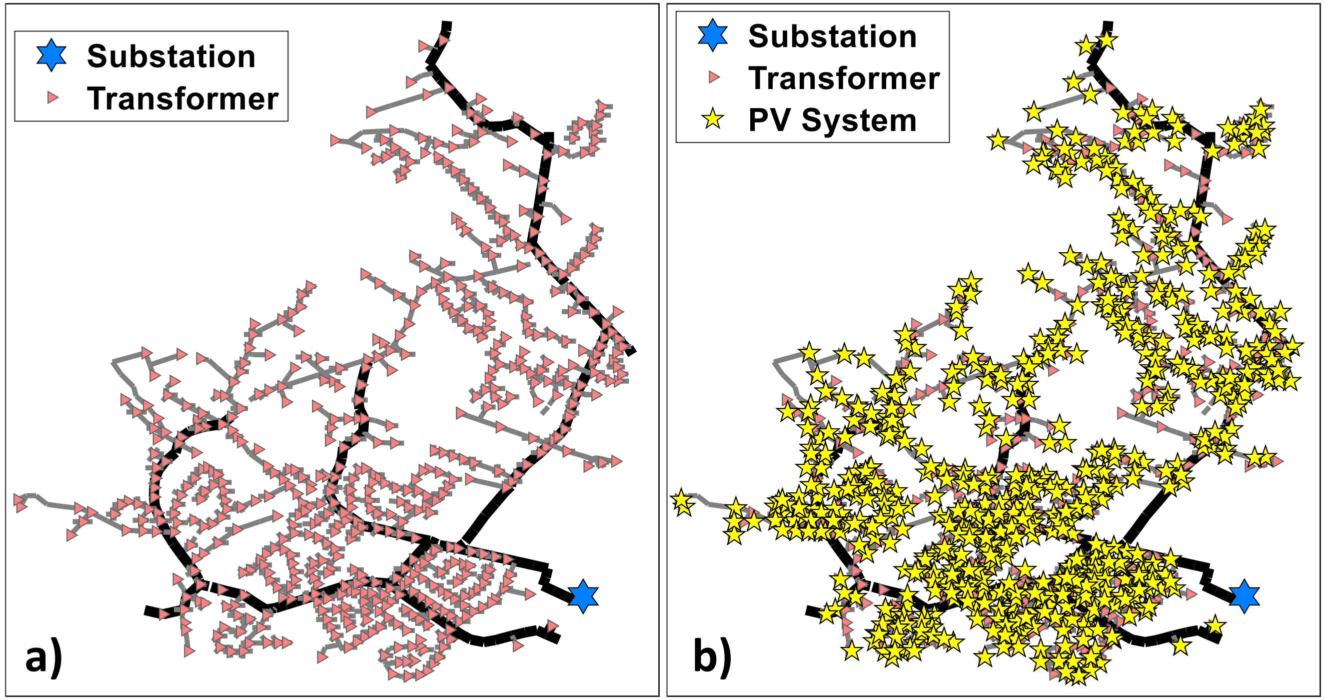
Transformer Types

ID	Rating (kVA)	*R* (Ω)	*X* (Ω)	Total in Ckt5
1	10.0	0.0979	0.1152	5
2	15.0	0.0634	0.0768	55
3	25.0	0.0346	0.0461	303
4	37.5	0.0215	0.0307	190
5	50.0	0.0150	0.0230	35
6	75.0	0.0092	0.0154	3

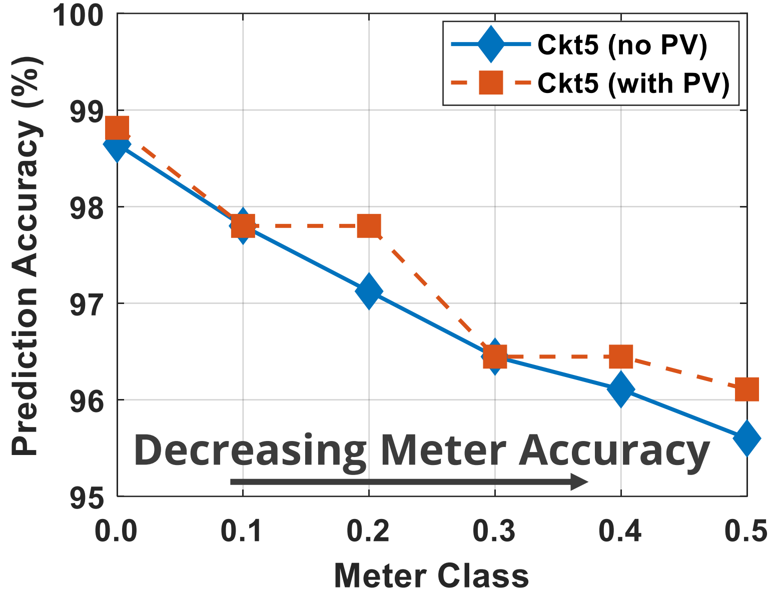


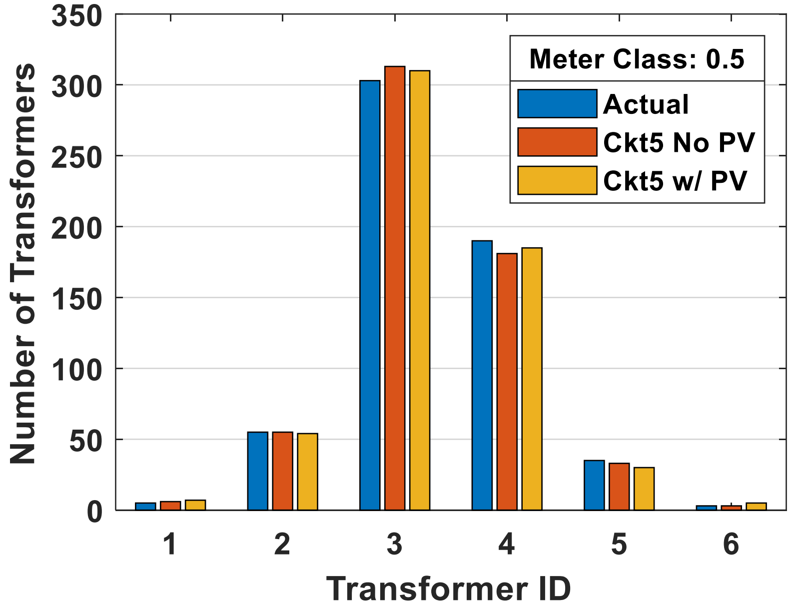
Results

- The algorithm was tested on two versions of the same circuit:
  - a) No PV
  - b) 701 distributed PV systems
- 591 service transformers; 1,379 customers



	Correct Predictions	Prediction Accuracy
Ckt5	583 / 591	98.65%
Ckt5 w/PV	584 / 591	98.82%





Conclusions

- The proposed algorithm uses smart meter measurements and metadata to estimate the rated capacity of all service transformers on a distribution feeder
- The algorithm was found to have an estimation accuracy of **>95% accuracy** regardless of the presence of existing PV systems
- Even under high levels of measurement noise, the algorithm estimated the total cumulative thermal capacity of service transformers on the circuit **within 1.01%**
- The results are promising, but future work is required to ensure accuracy is maintained over a diverse set of distribution circuits

THANK YOU

Questions?

Joseph A. Azzolini (jazzoli@sandia.gov)

For more project info, visit:
https://github.com/dpinney/omf/wiki/Models-~-hostingCapacity