FRAMEWORKS FOR REALISTIC MODELING AND ANALYSIS OF POWER GRIDS

PhD Dissertation Defense

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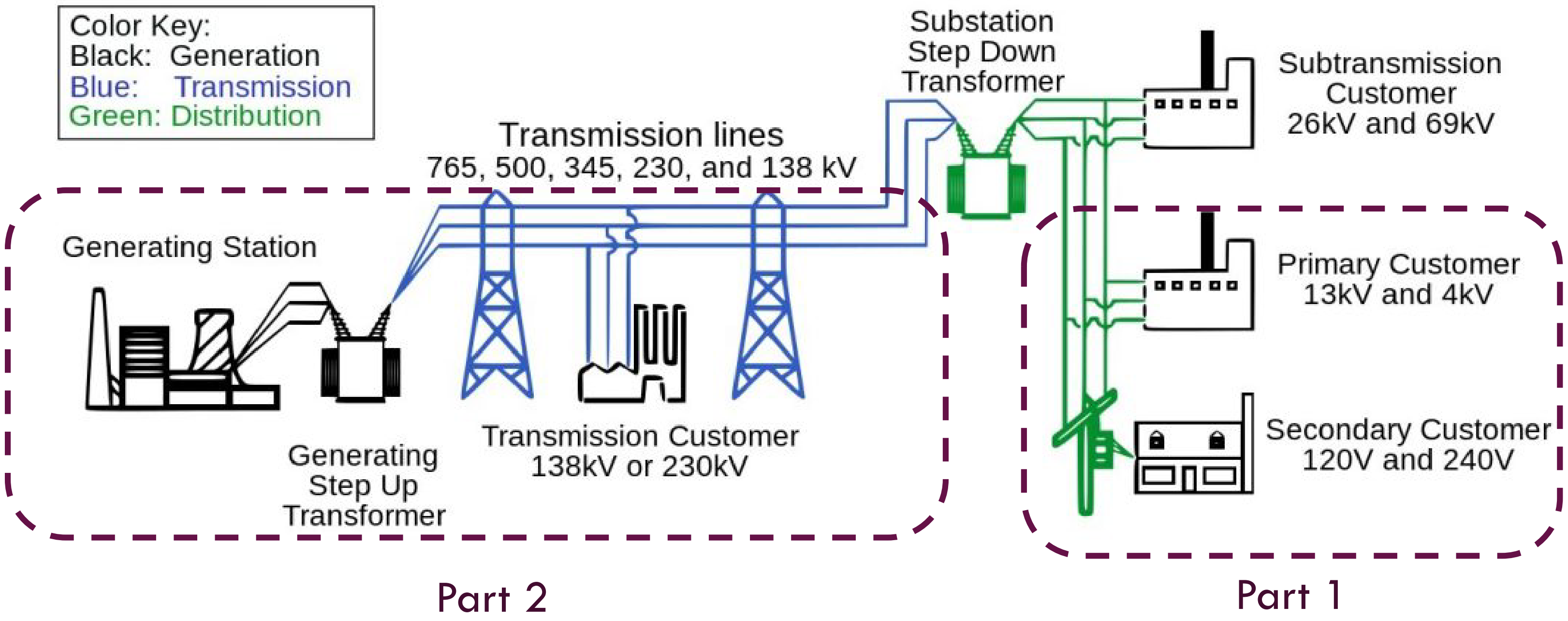
AGENDA

- Part 1: Distribution network creation framework (Realistic Modeling)
  - Motivation & problem definition
  - Proposed approach
  - Validation
  - Usage of framework
- Part 2: Cascading failure analysis framework (Realistic Analysis)
  - Motivation & overview of framework
  - Case study: targeted physical attack on Washington DC power grid.

THE POWER GRID

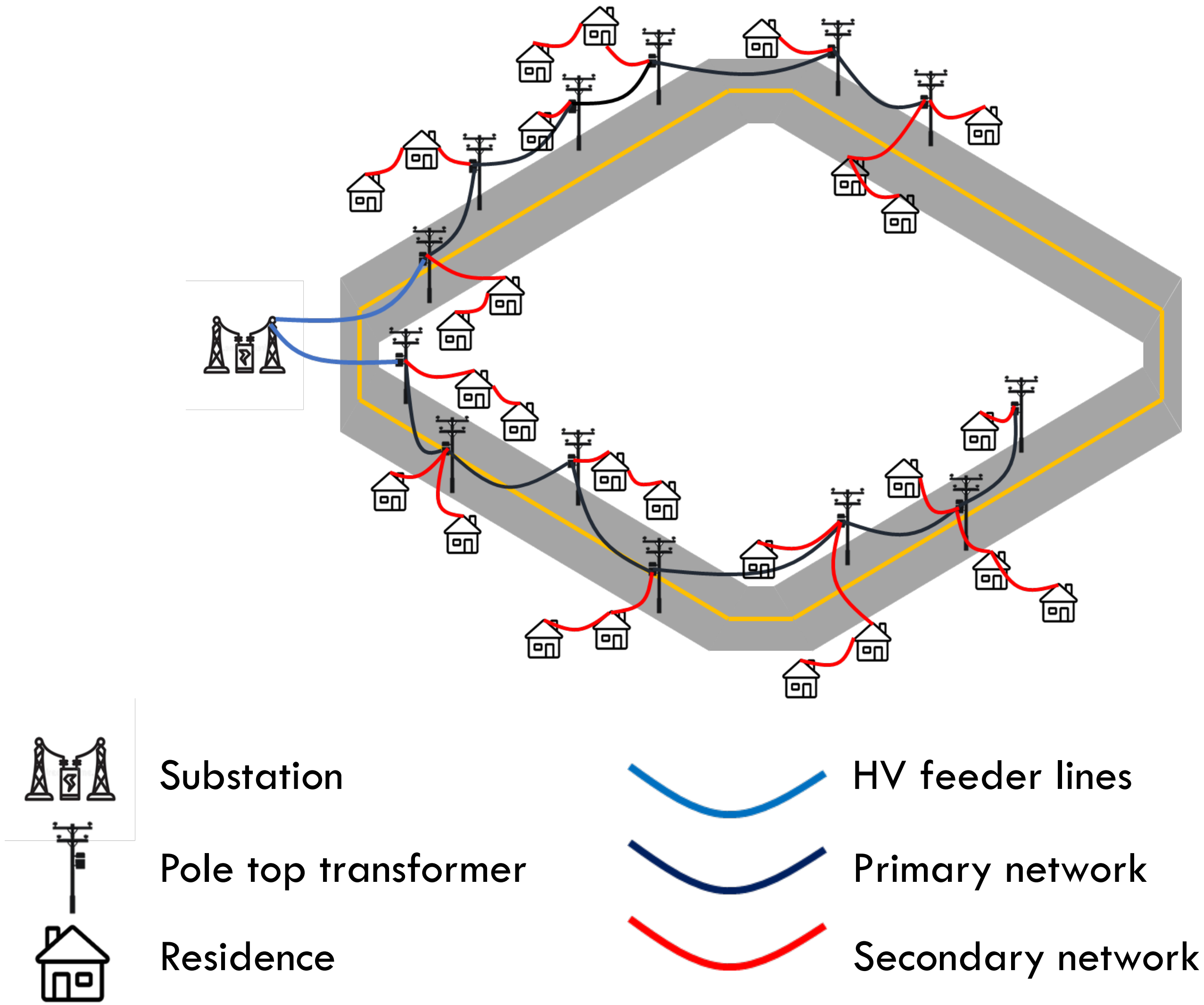
Power grid consists of

- Generation
- Transmission system
- Distribution system



DISTRIBUTION SYSTEM

- ❑ Voltage level is 33kV and lower.
- ❑ Composed of two networks
  - Medium voltage primary network.
  - Low voltage secondary network.
  - Substation connects primary through feeder lines.
- ❑ Transformers
  - Substation transformer
  - Pole-top transformer
- ❑ Distribution network is a tree.

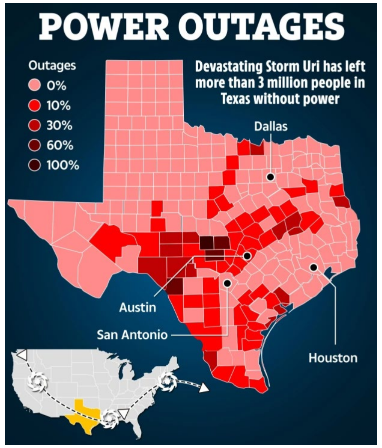


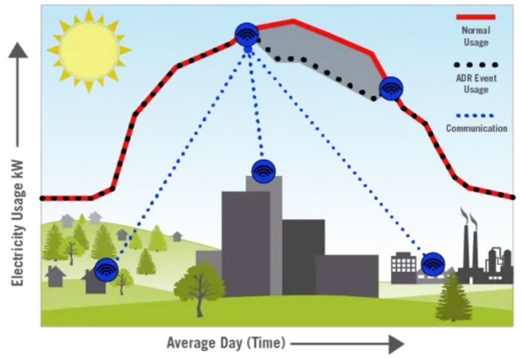
PART 1: FRAMEWORK TO CREATE SYNTHETIC DISTRIBUTION NETWORKS

1. R. MEYUR ET AL., "ENSEMBLES OF REALISTIC POWER DISTRIBUTION NETWORKS," PROCEEDINGS OF NATIONAL ACADEMY OF SCIENCES (PNAS), VOL. 119, NO. 42, 2022.
2. R. MEYUR ET AL., "CREATING REALISTIC POWER DISTRIBUTION NETWORKS USING INTERDEPENDENT ROAD INFRASTRUCTURE," 2020 IEEE INTERNATIONAL CONFERENCE ON BIG DATA (BIG DATA), 2020, PP. 1226-1235.
3. R. MEYUR ET AL., "STRUCTURAL VALIDATION OF SYNTHETIC POWER DISTRIBUTION NETWORKS USING THE MULTISCALE FLAT NORM," 14TH ACM/SPEC CONFERENCE ON PERFORMANCE ENGINEERING, 2023 (SUBMITTED AND UNDER REVIEW).

MOTIVATION

Aid public policy makers to deploy efficient plans for a decarbonized economy.



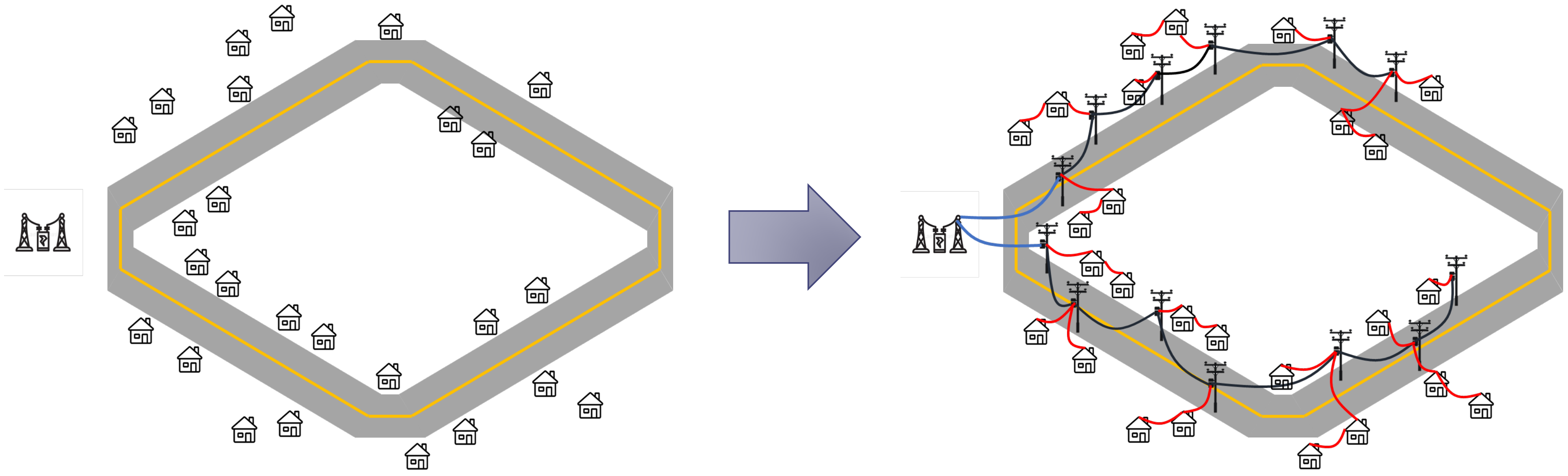


Utilities require emergency strategies to mitigate wide spread outages.

- Demand response program
- Direct load control

Extensive dataset of power distribution networks is necessary.

PROBLEM STATEMENT

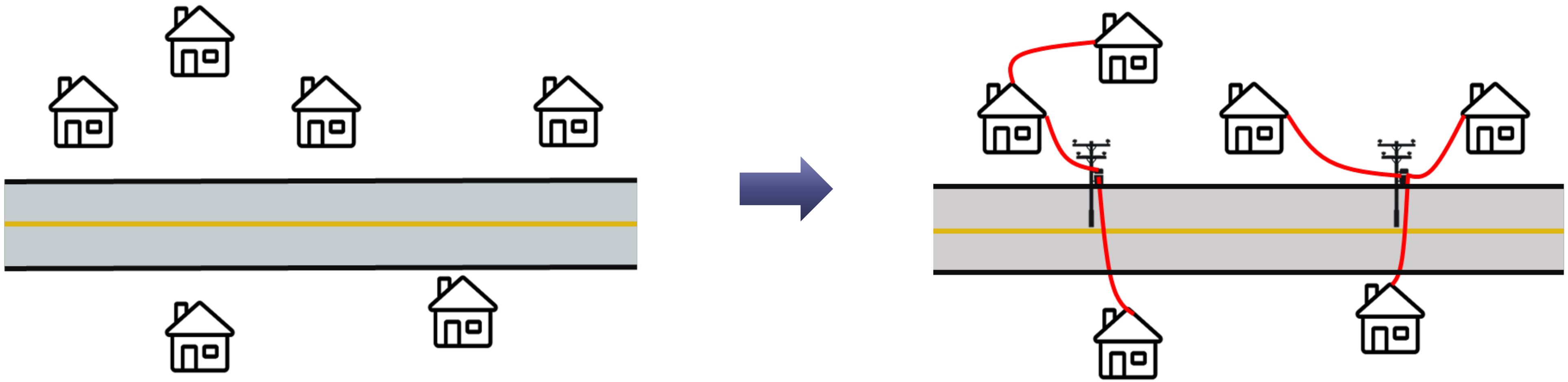


Problem: Given a set of residences and electric substations, construct a realistic power distribution network.

Assumption:
Distribution network follows road network.

Approach: two step bottom-up approach
- Construct secondary network.
- Construct primary network.

STEP 1: SECONDARY DISTRIBUTION NETWORK CREATION



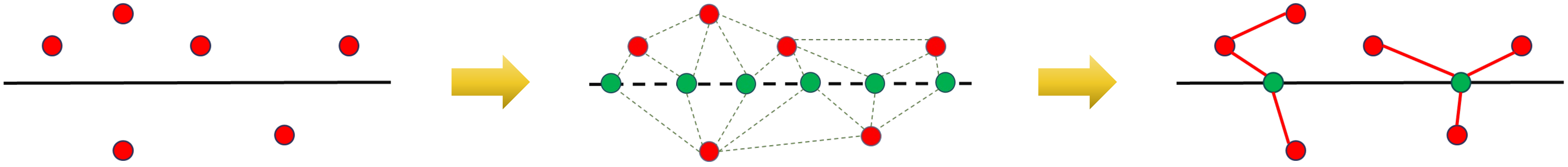
Given a road link and set of residences near it, construct the secondary distribution network.

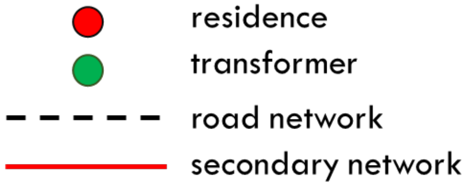
- Network is a forest of trees.
- Root nodes are transformers.
- Root nodes are along road link.

STEP 1: SECONDARY DISTRIBUTION NETWORK CREATION

Creating candidate edge set.

- ❑ Interpolate transformer locations along road link.
- ❑ Get candidate set of edges.

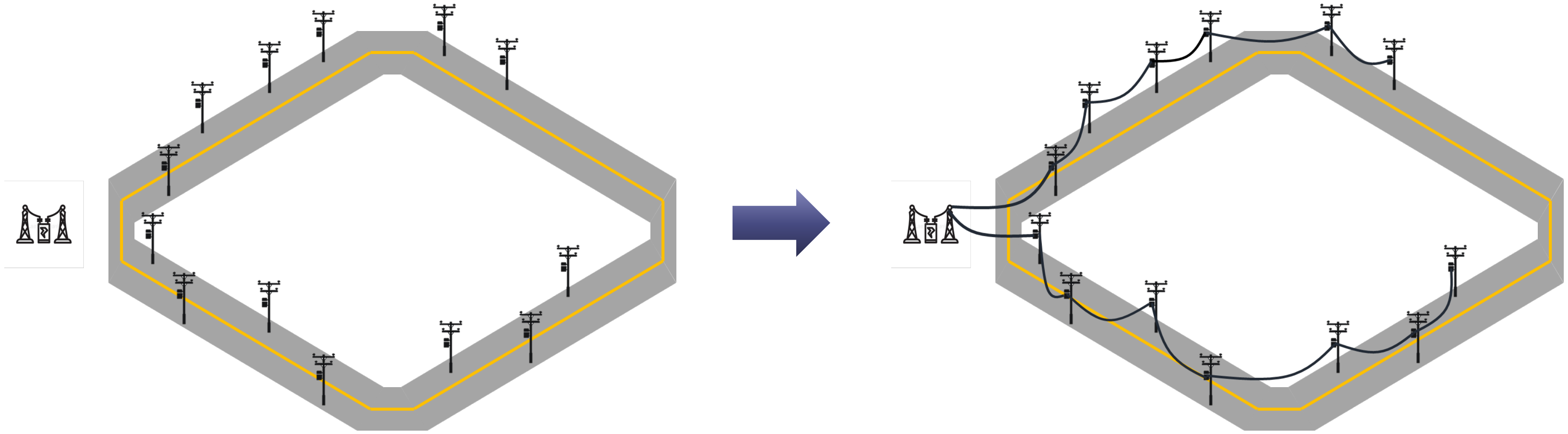




Mixed Integer Linear Problem (MILP)

- ❑ Select optimal edges from the candidate set.
- ❑ Satisfy the structural constraints.
- ❑ Minimize the total length of network.

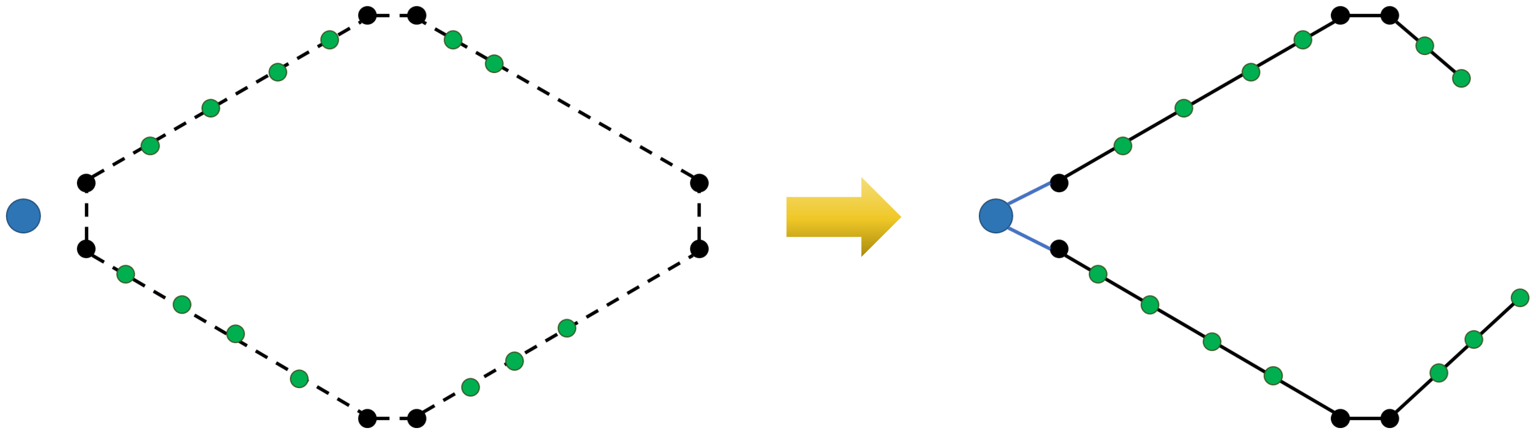
STEP 2: PRIMARY DISTRIBUTION NETWORK CREATION

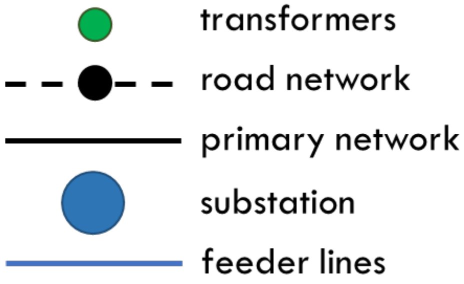


Given a set of transformers, substation and underlying road network, construct the primary distribution network.

- Network is a tree covering all transformers.
- The root node is the substation.
- Edges are chosen from the road network.

STEP 2: PRIMARY DISTRIBUTION NETWORK CREATION



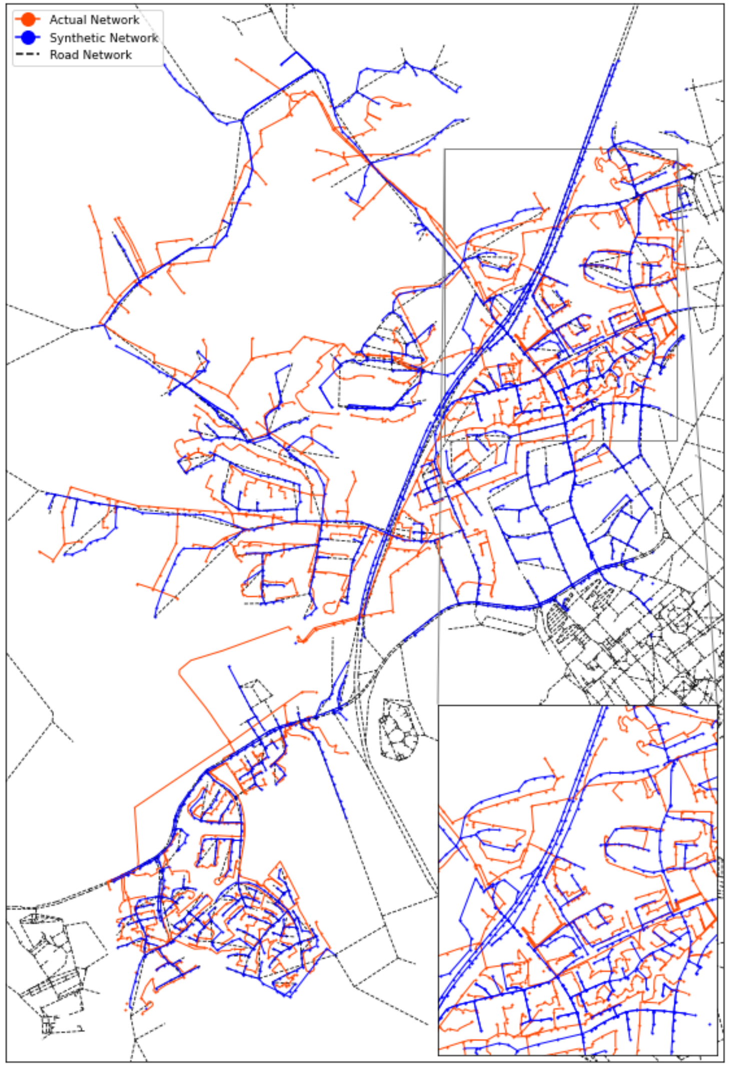


Mixed Integer Linear Problem (MILP)

- ❑ Select optimal edges from the road network edges.
- ❑ Satisfy the constraints.
  - Connect all transformers.
  - Output network is a tree rooted at substation.
  - Node voltages within ANSI limits (0.95-1.05 pu).
- ❑ Minimize the total length of network.

NETWORK VALIDATION

- We obtained actual power distribution networks of Blacksburg, Virginia.
  - Old dataset (before 2006).
  - Partial dataset of region from American Electric Power (AEP).
- Types of validation
  - Operational validation
  - Structural validation
  - Statistical validation

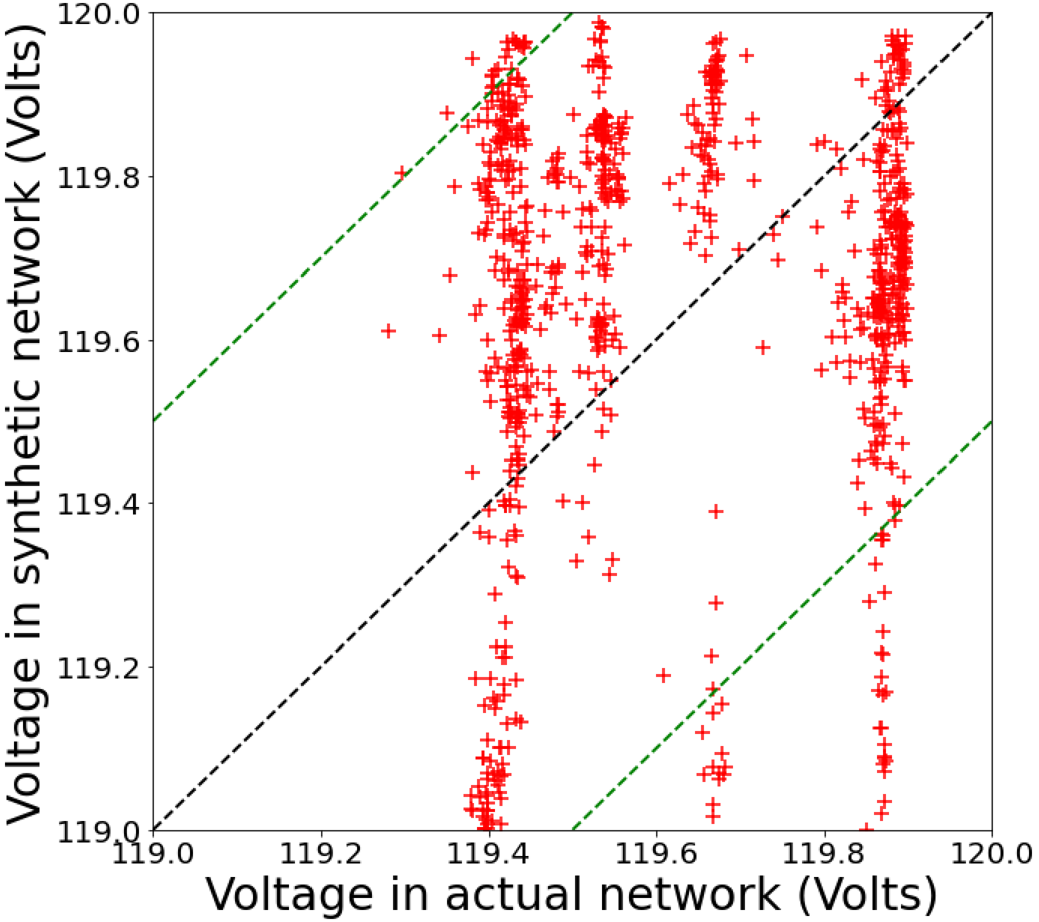


OPERATIONAL VALIDATION

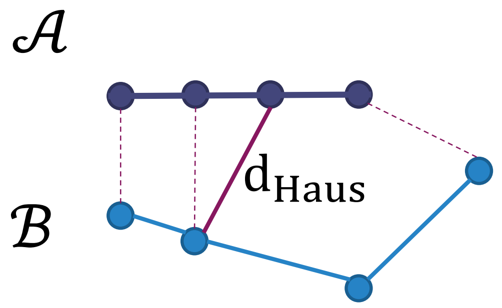
Compare voltage at residence nodes when

- They are connected to actual network.
- They are connected to synthetic network

Majority of residence voltages match within the $\pm 0.5\%$ tolerance margin.



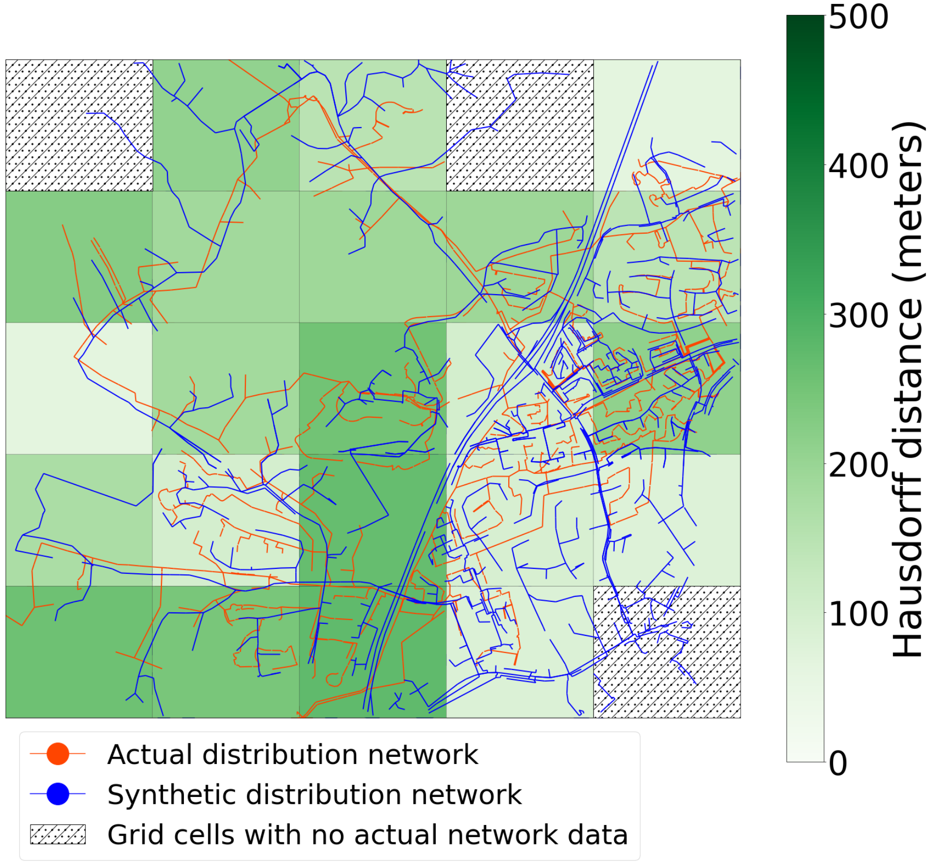
STRUCTURAL VALIDATION



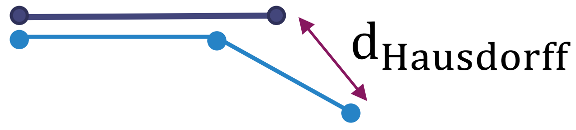
$$\mathrm{d}_{\mathrm{Haus}} = \max_{p \in \mathcal{A}} \min_{q \in \mathcal{B}} d(p,q)$$

Hausdorff distance

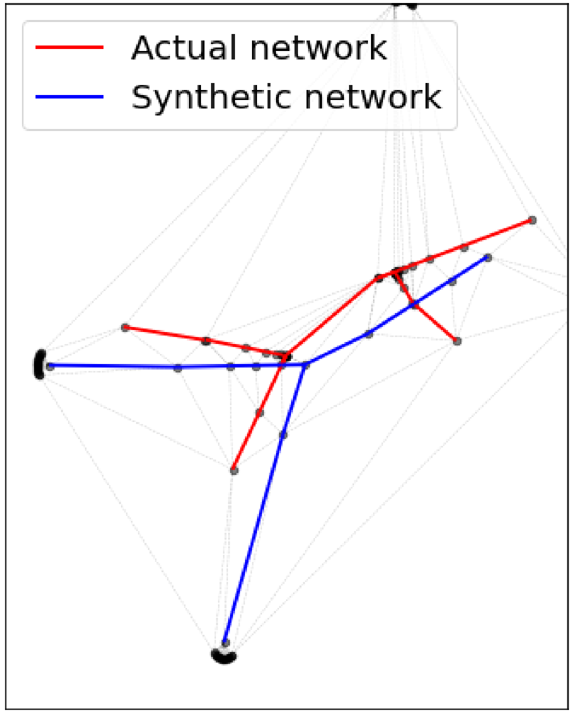
Maximum among all distances from point in $\mathcal{A}$ to closest point in $\mathcal{B}$

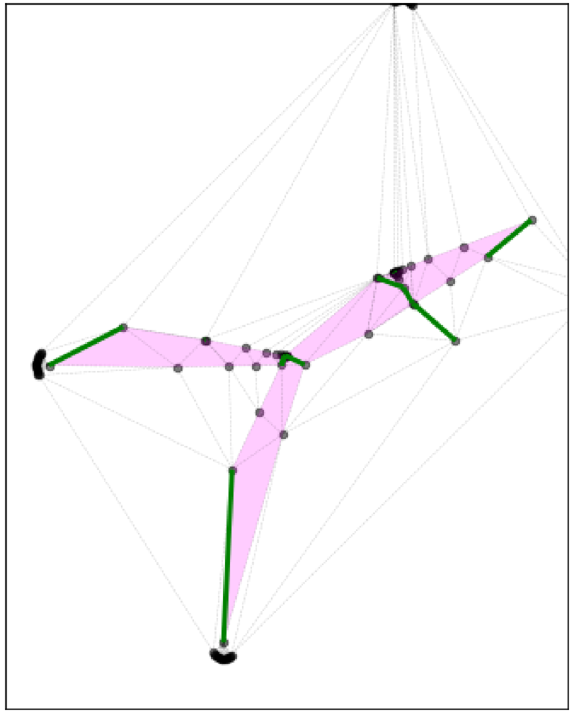


STRUCTURAL VALIDATION: USING SIMPLICIAL FLAT NORM



- Hausdorff distance only computes the maximum distance.
- We propose simplicial flat norm based distance metric which considers.
  - length deviation, and
  - area deviation.
- Good metric to compare planar graph structures or geometries.

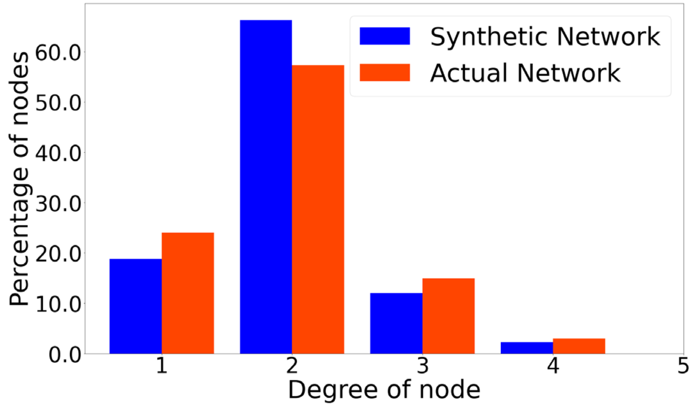




R. Meyur et al., "Structural Validation Of Synthetic Power Distribution Networks Using The Multiscale Flat Norm," 14th ACM/SPEC Conference on Performance Engineering, 2023 (submitted and under review).

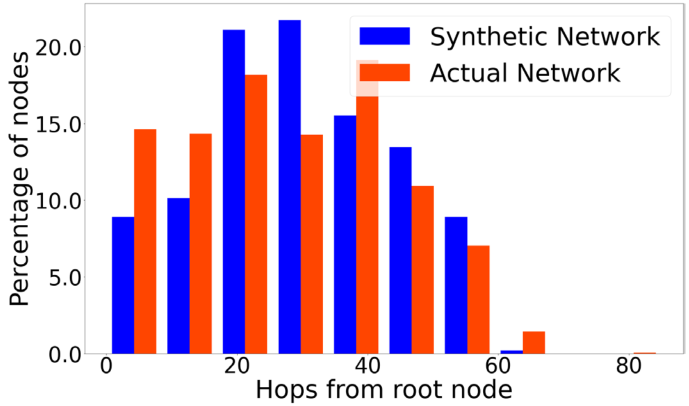
STATISTICAL VALIDATION

Degree distribution



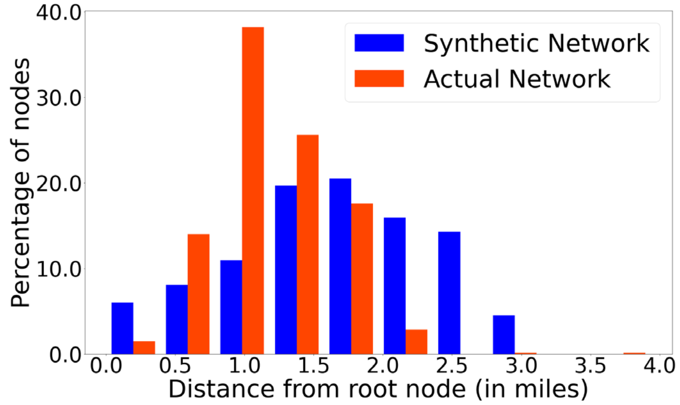
$\mathrm{KL_{div}} = 0.0208$

Hop distribution



$\mathrm{KL_{div}} = 0.0323$

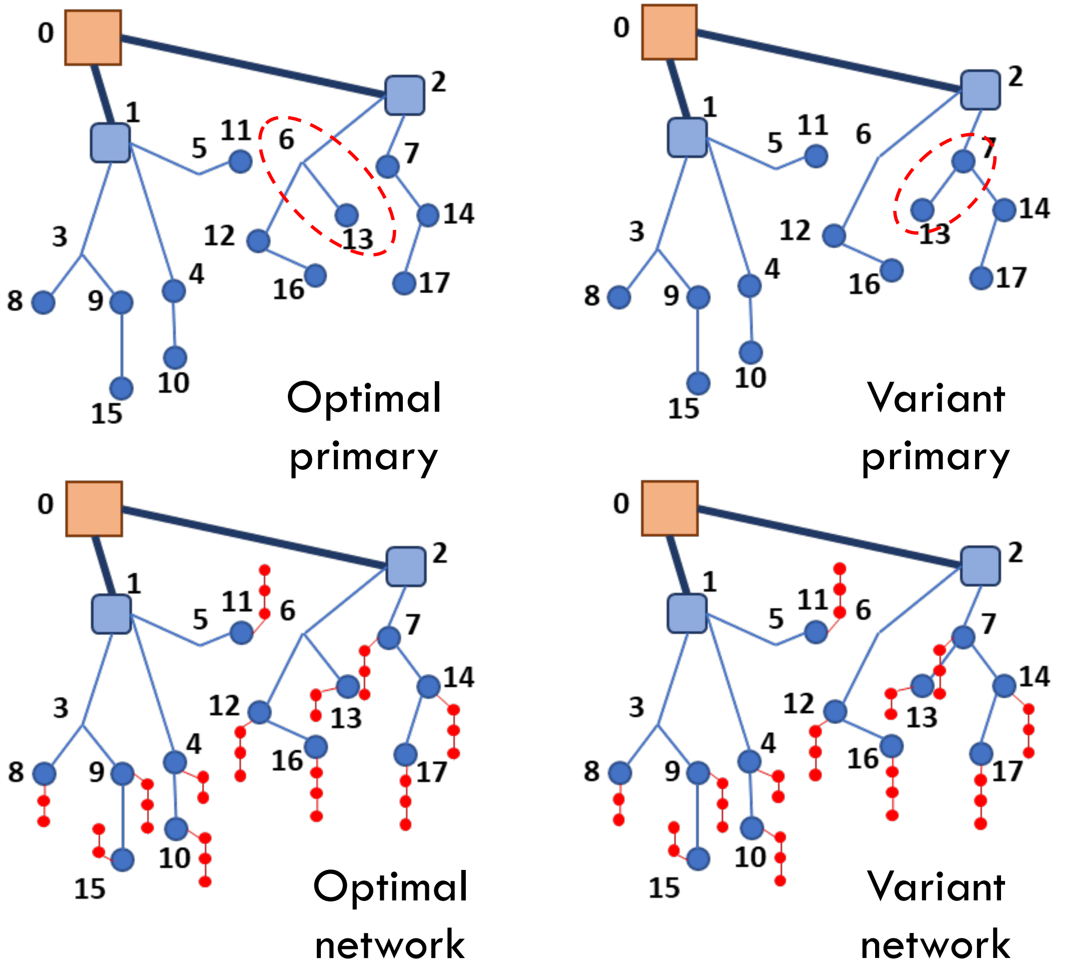
Reach distribution



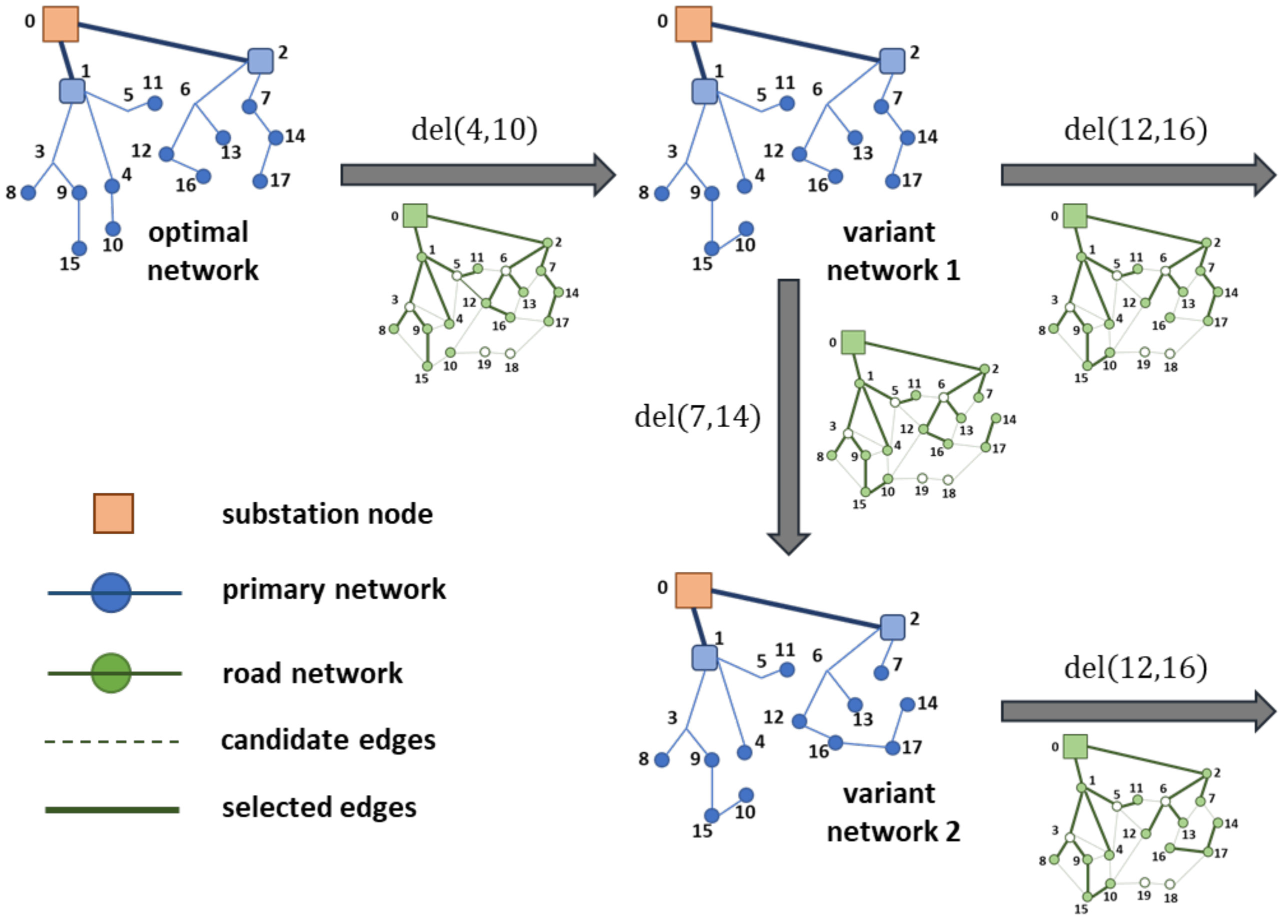
$\mathrm{KL_{div}} = 0.0096$

ENSEMBLE OF NETWORKS

- Is the optimal network the actual physical network?
- Create multiple feasible networks connecting the same nodes.
- **Simplified problem:** create an ensemble of primary networks and keep the secondary network intact.

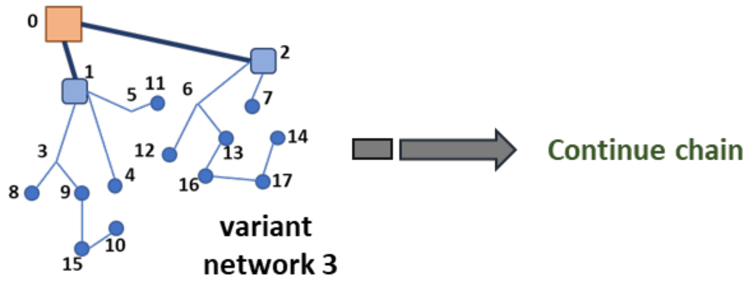


CREATING AN ENSEMBLE OF PRIMARY NETWORKS



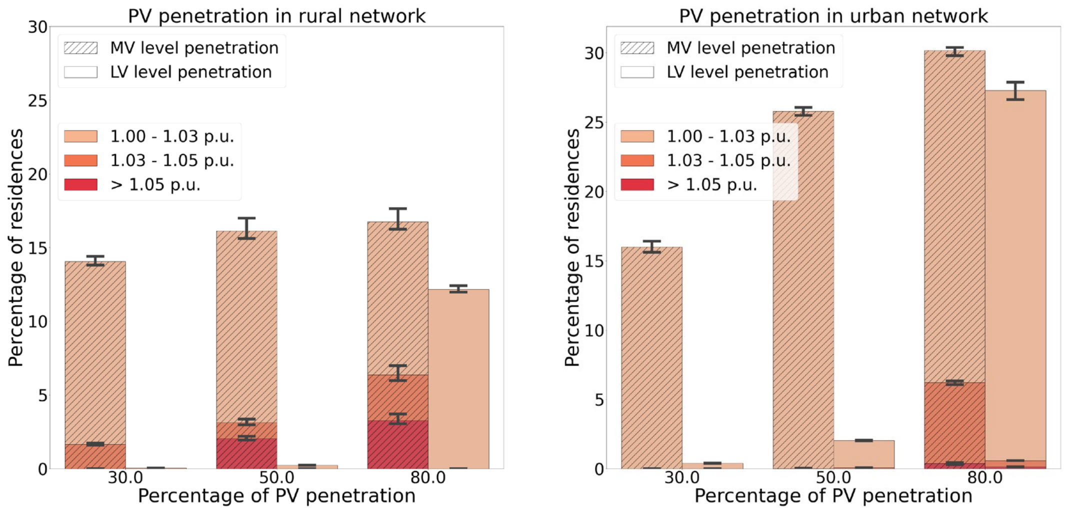
Procedure for creating variant network

- Delete a random edge from primary network.
- Solve a restricted version of primary network creation problem



USING SYNTHETIC NETWORKS TO ADDRESS PROBLEMS

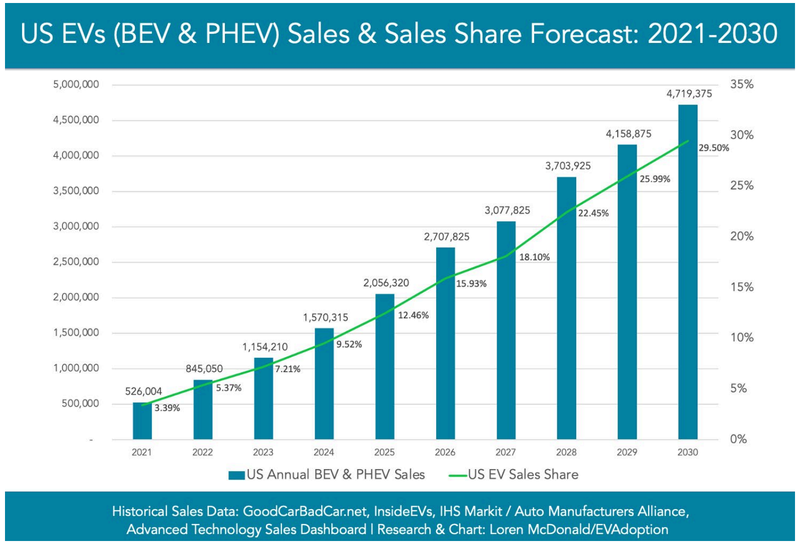
- ❑ Effect of photovoltaic (PV) penetration.
- ❑ Reliability aware residential EV charging strategy.
- ❑ Optimal placement of electric vehicle (EV) charging stations.
- ❑ Address equity and fairness problems in different demand response strategies.



USING SYNTHETIC DISTRIBUTION NETWORKS: RELIABILITY AWARE RESIDENTIAL ELECTRIC VEHICLE CHARGE SCHEDULING

1. R. MEYUR ET AL., “A RELIABILITY-AWARE DISTRIBUTED FRAMEWORK TO SCHEDULE RESIDENTIAL CHARGING OF ELECTRIC VEHICLES,” INTERNATIONAL JOINT CONFERENCE ON ARTIFICIAL INTELLIGENCE (IJCAI): SPECIAL TRACK ON AI FOR GOOD, VIENNA, AUSTRIA, JULY 2022.

MOTIVATION



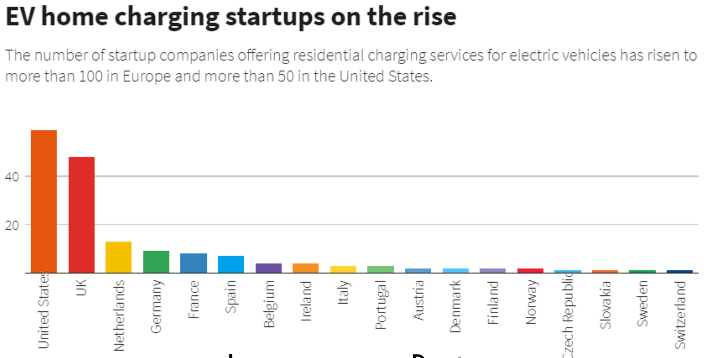
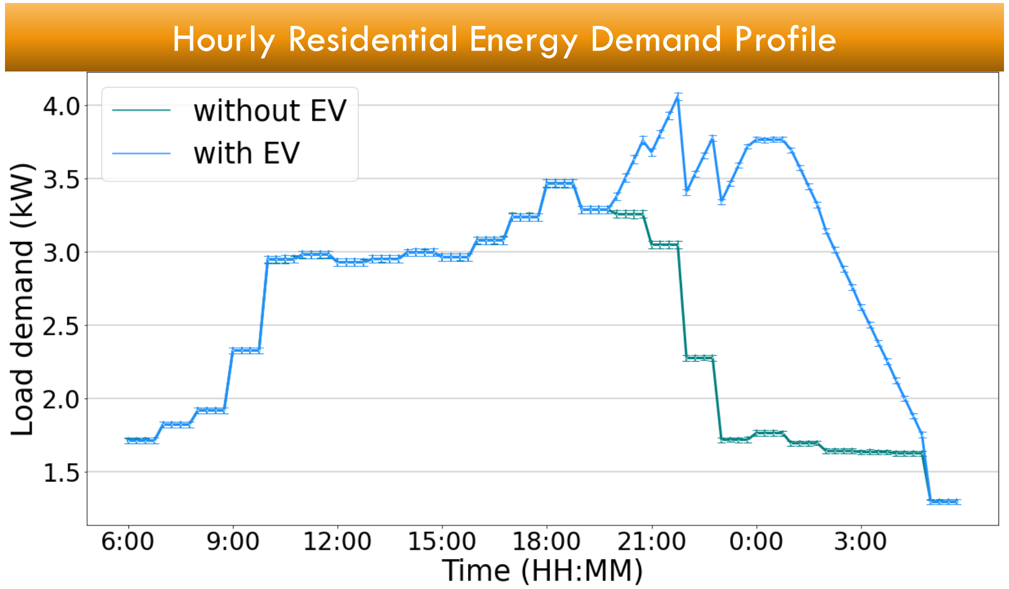
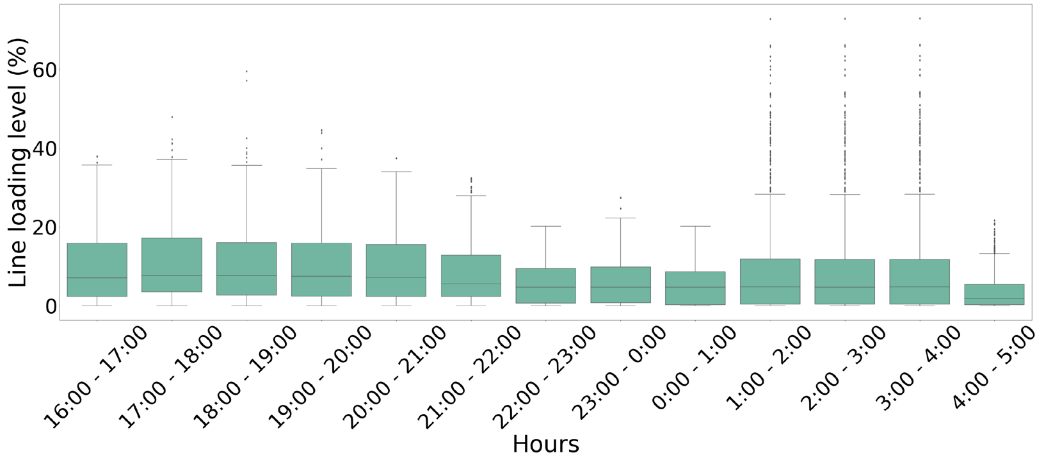


Image source: Reuters



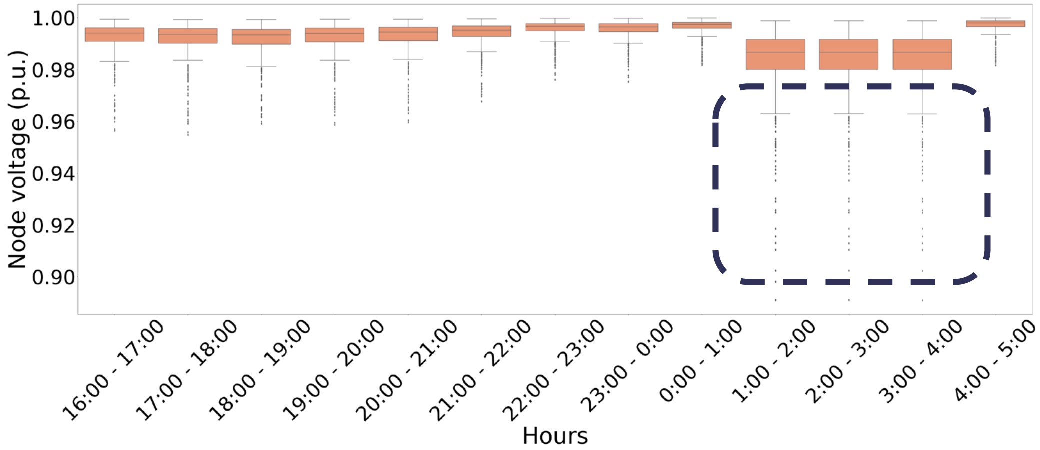
Residential EV charging accounts for a significant amount of increase in average household energy consumption

PROBLEM WITH CHARGING AT THE SAME TIME



Dominion Virginia Power Tariff (Off Peak Plan)

Time Interval (HH:MM)	00:00 – 05:00	05:00 – 15:00	15:00 – 18:00	18:00 – 00:00
Tariff ($/kWh)	0.07866	0.09511	0.21436	0.09511



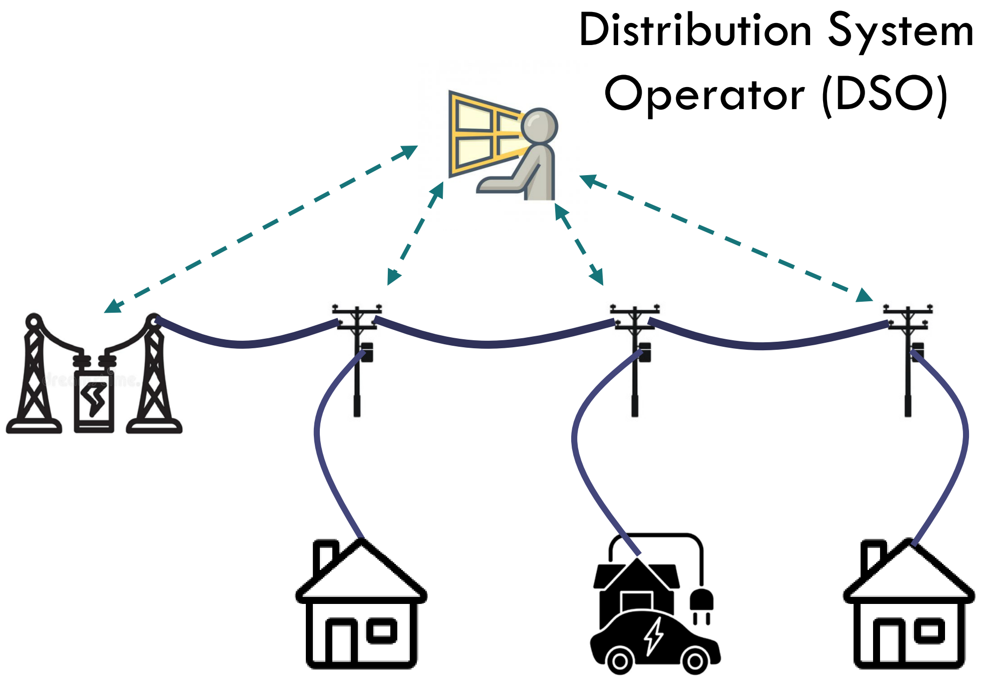
Reliable network

- Node voltages within acceptable limits (0.95 – 1.05 p.u.).
- Line power flows less than line capacities.

PROBLEM STATEMENT

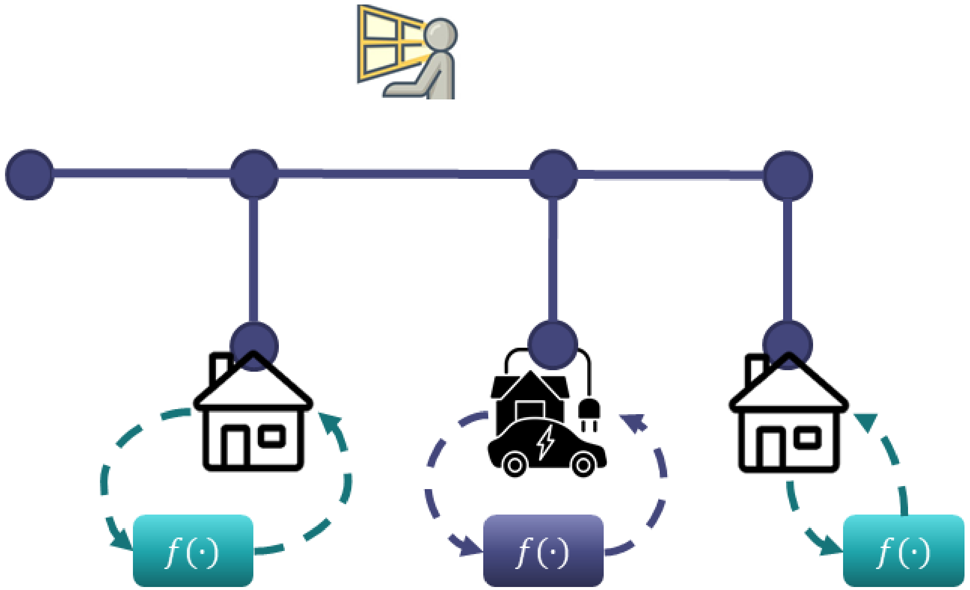
Find out the best schedule for residential EV charging which

- accommodates consumer preferences.
- maintains network reliability.



INDIVIDUAL APPROACH

- ❑ Each consumer solves own problem.
- ❑ No private information shared.
- ❑ No communication requirement.
- ❑ Optimal solution for individual consumer.
- ❑ Suboptimal or infeasible solution for DSO.



Individual optimization

CENTRALIZED APPROACH

- All consumers share personal information with DSO.
- High bandwidth for communication required.
- Optimal solution guaranteed for consumers and DSO.

Powering Smart Transportation

Smart Charging Infrastructure Pilot Program

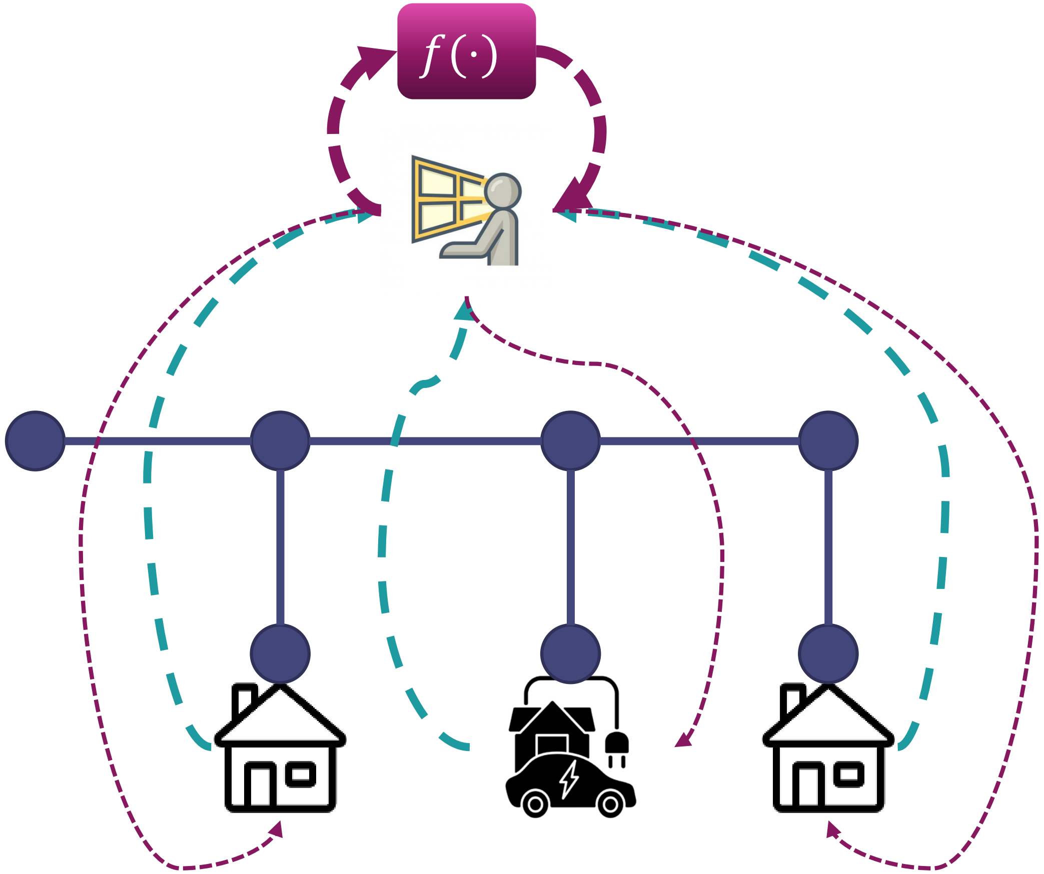
The Smart Charging Infrastructure Pilot (or "SCIP") Program supports electric vehicle (EV) adoption in Virginia and will inform the design of managed charging programs and other EV customer offerings in the future.

The SCIP Program provides rebates for qualifying EV charging stations, charging infrastructure and installation, commonly referred to as "make-ready," and network fees. See rebate amounts in the table below.

March 23, 2021 Update: *The DCFC and Multi-family rebate segments are fully subscribed.*

June 20, 2022 Update: *The SCIP Program will end December 31, 2022. All applications must be submitted by November 30, 2022. All charging stations must be installed, active and communicating data by December 31, 2022 to receive rebate payments.*

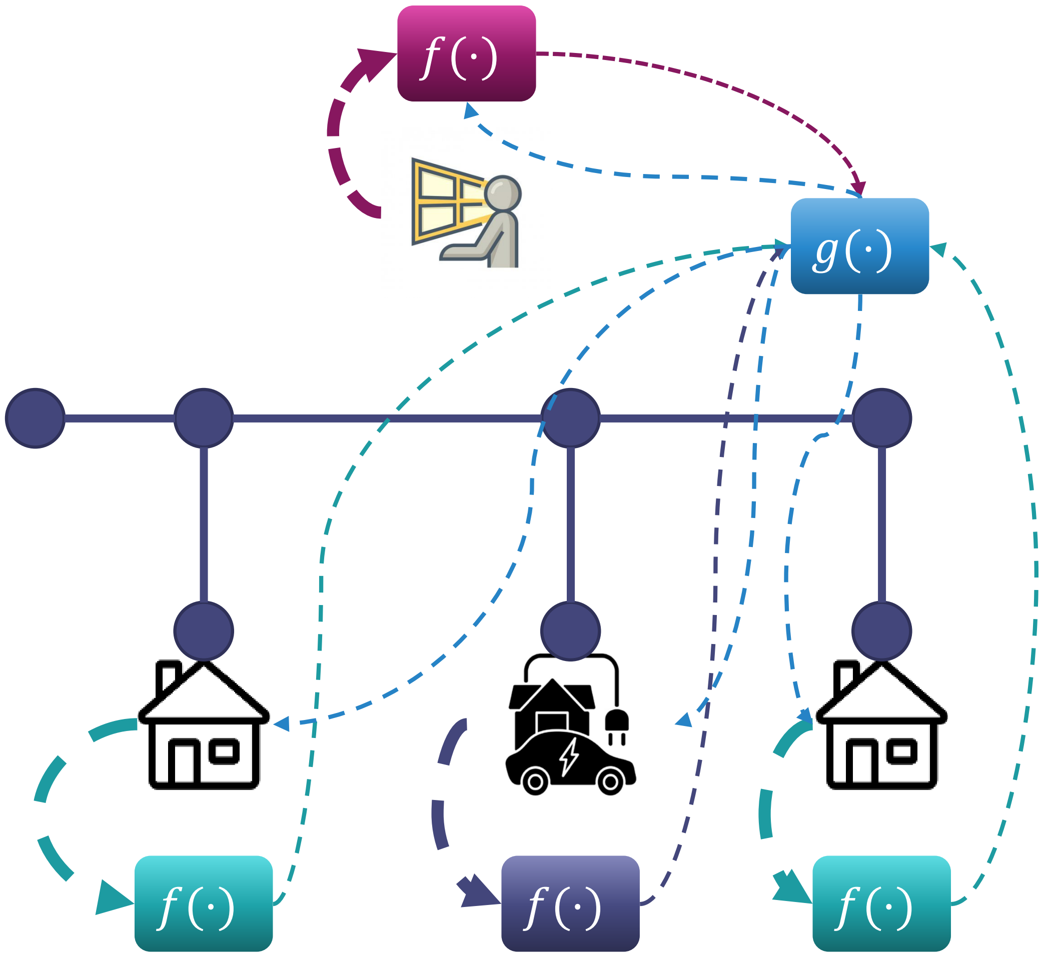
Source: Dominion Energy Smart Charger Rebate Plan



Centralized optimization

OUR APPROACH

- ❑ All consumers solve their own problem.
- ❑ DSO solves reliability problem.
- ❑ Optimal solutions are exchanged to reach consensus.
- ❑ Limited communication requirement.
- ❑ Limited exchange of information.
- ❑ Sub-optimal solution for consumers and DSO.
- ❑ Alternating Direction Method of Multipliers (ADMM) based approach guarantees convergence.



Distributed optimization

REVS: RELIABILITY AWARE EV CHARGE SCHEDULING

$$
\begin{aligned}
\min \quad & \sum_{t=1}^{T} c_i^t p_i^t \\
\text{over} \quad & p_i^t, s_i^t, z_i^t && \forall t \\
\text{s.t.} \quad & p_i^t = p_{i,0}^t + p_{i,\text{EV}}^t && \forall t \\
& p_{i,\text{EV}}^t = z_i^t P_{i,\text{EV}} && \forall t \\
& s_i^t = s_i^{t-1} + \frac{p_{i,\text{EV}}^t}{Q_{i,\text{EV}}} && \forall t \\
& z_i^t \in \{0,1\} && \forall t \\
& z_i^t = 0 \quad \forall t \le t_{\text{start}}, \ \forall t \ge t_{\text{end}} \\
& s_i^{t_{\text{start}}} = s_{i,\text{init}}, \ s_i^{t_{\text{end}}} \ge s_{i,\text{final}}
\end{aligned}
$$

Consumer optimization (MILP)

+

$$
\begin{aligned}
\min \quad & \sum_{t=1}^{T} C\left(\mathbf{p}^t\right) \\
\text{over} \quad & \mathbf{p}^t \\
\text{s.t.} \quad & \alpha \mathbf{1} \le -2\mathbf{R}\mathbf{p}^t + \mathbf{1} \le \beta \mathbf{1} && \forall t \\
& -\overline{\mathbf{f}} \le \mathbf{A}^{-1}\mathbf{p} \le \overline{\mathbf{f}} && \forall t
\end{aligned}
$$

DSO optimization (LP or QP)

→

$$
\begin{aligned}
\min \quad & \sum_{t=1}^{T} C\left(\mathbf{p}^t\right) + \sum_{i \in \mathcal{H}} \sum_{t=1}^{T} c_i^t p_i^t \\
\text{over} \quad & p_i^t, s_i^t, z_i^t && \forall t, \forall i \in \mathcal{H} \\
\text{s.t.} \quad & p_i^t = p_{i,0}^t + p_{i,\text{EV}}^t && \forall t, \forall i \in \mathcal{H} \\
& p_{i,\text{EV}}^t = z_i^t P_{i,\text{EV}} && \forall t, \forall i \in \mathcal{H} \\
& s_i^t = s_i^{t-1} + \frac{p_{i,\text{EV}}^t}{Q_{i,\text{EV}}} && \forall t, \forall i \in \mathcal{H} \\
& z_i^t \in \{0,1\} && \forall t, \forall i \in \mathcal{H} \\
& z_i^t = 0 && \forall t \le t_{\text{start}}, \forall i \in \mathcal{H} \\
& z_i^t = 0 && \forall t \ge t_{\text{end}}, \forall i \in \mathcal{H} \\
& s_i^{t_{\text{start}}} = s_{i,\text{init}} && \forall i \in \mathcal{H} \\
& s_i^{t_{\text{end}}} = s_{i,\text{final}} && \forall i \in \mathcal{H} \\
& p_i^t = 0 && \forall t, \forall i \notin \mathcal{H} \\
& \alpha \le 1 - 2\sum_j R_{ij} p_j^t \le \beta && \forall t, \forall i \\
& -\overline{f_k} \le \sum_j \left[\mathbf{A}^{-1}\right]_{kj} p_j^t \le \overline{f_k} && \forall t, \forall k \in \mathcal{E}
\end{aligned}
$$

Overall optimization (MILP or MIQP)

PROPOSED DISTRIBUTED APPROACH

DSO

Step 1: Update $\{\tilde{p}_i^t[l+1]\}_{t=1}^T \ \forall i$

$$\{\tilde{p}_i^t[l+1]\} = \min \sum_{i\in\mathcal{H}}\sum_{t=1}^T \frac{\kappa}{2}\left(\tilde{p}_i^t\right)^2 + \sum_{i\in\mathcal{H}}\sum_{t=1}^T \tilde{p}_i^t\left(\gamma_i^t[l] - \frac{\kappa}{2}\tilde{p}_i^t[l] - \frac{\kappa}{2}p_i^t[l]\right)$$

$$\text{s.t.} \quad \alpha \le 1 - 2\sum_j R_{ij}\tilde{p}_j^t \le \beta \quad \forall t, \forall i$$

$$-\overline{f_k} \le \sum_j \left[\mathbf{A}^{-1}\right]_{kj}\tilde{p}_j^t \le \overline{f_k} \quad \forall t, \forall k \in \mathcal{E}$$

Proprietary data
$\mathbf{A}, R, \alpha, \beta$

Step 2: Send $\{\tilde{p}_i^t[l+1]\}_{t=1}^T$ and receive $\{p_i^t[l+1]\}_{t=1}^T \ \forall i$

$\{\tilde{p}_i^t[l+1]\}_{t=1}^T$

$\{p_i^t[l+1]\}_{t=1}^T$

Step 3: Update $\{\gamma_i^t[l+1]\}_{t=1}^T \ \forall i$

$$\gamma_i^t[l+1] = \gamma_i^t[l] + \frac{\kappa}{2}\left(\tilde{p}_i^t[l+1] - p_i^t[l+1]\right)$$

Step 4: Check convergence

Consumer i

Step 1: Update $\{p_i^t[l+1]\}_{t=1}^T$

$$p_i^t[l+1] = \min \sum_{t=1}^T c_i^t p_i^t + \sum_{t=1}^T \frac{\kappa}{2}\left(p_i^t\right)^2 - \sum_{t=1}^T p_i^t\left(\gamma_i^t[l] + \frac{\kappa}{2}\tilde{p}_i^t[l] + \frac{\kappa}{2}p_i^t[l]\right)$$

$$\text{s.t.} \quad p_i^t = p_{i,0}^t + p_{i,\mathrm{EV}}^t \quad \forall t$$

$$p_{i,\mathrm{EV}}^t = z_i^t P_{i,\mathrm{EV}} \quad \forall t$$

$$s_i^t = s_i^{t-1} + \frac{p_{i,\mathrm{EV}}^t}{Q_{i,\mathrm{EV}}} \quad \forall t$$

$$z_i^t \in \{0,1\} \quad \forall t$$

$$z_i^t = 0 \quad \forall t \le t_{\mathrm{start}}, \forall t \ge t_{\mathrm{end}}$$

$$s_i^{t_{\mathrm{start}}} = s_{i,\mathrm{init}}, \quad s_i^{t_{\mathrm{end}}} \ge s_{i,\mathrm{final}}$$

Personal data
$\{p_{i,0}^t\}, P_{i,\mathrm{EV}}, Q_{i,\mathrm{EV}}, s_{\mathrm{init}}, s_{\mathrm{final}}, t_{\mathrm{start}}, t_{\mathrm{end}}$

Step 2: Receive $\{\tilde{p}_i^t[l+1]\}_{t=1}^T$ and send $\{p_i^t[l+1]\}_{t=1}^T$

$\{p_i^t[l+1]\}_{t=1}^T$

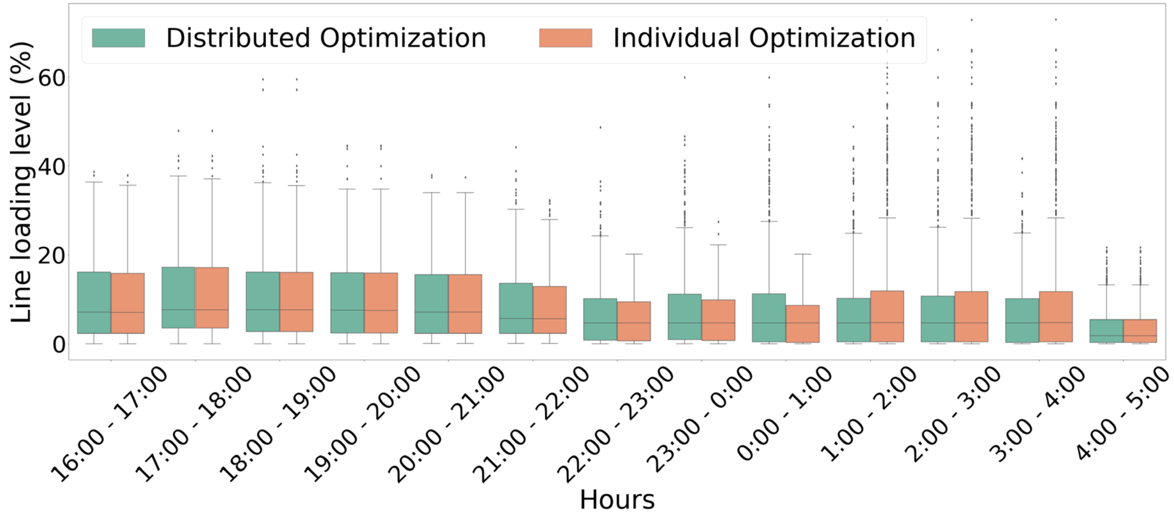
$\{\tilde{p}_i^t[l+1]\}_{t=1}^T$

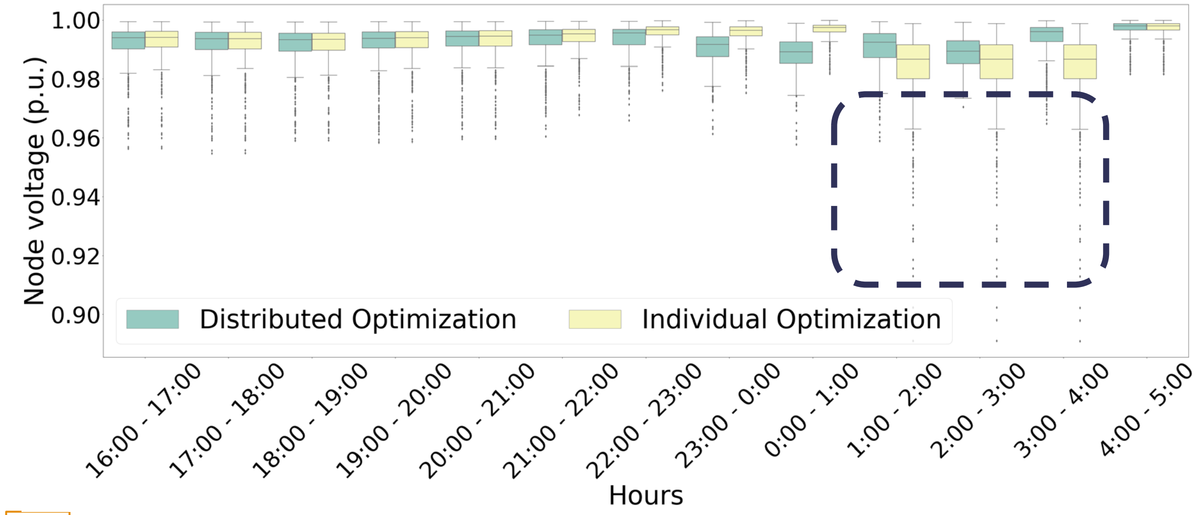
Step 3: Update $\{\gamma_i^t[l+1]\}_{t=1}^T$

$$\gamma_i^t[l+1] = \gamma_i^t[l] + \frac{\kappa}{2}\left(\tilde{p}_i^t[l+1] - p_i^t[l+1]\right)$$

Step 4: Check convergence

RESULTS





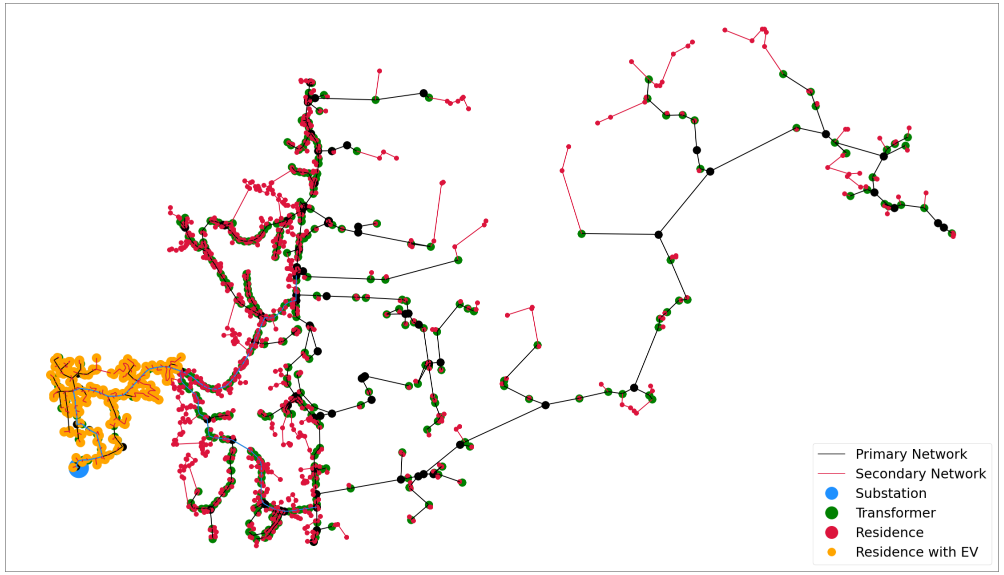
Electricity hourly tariff rates

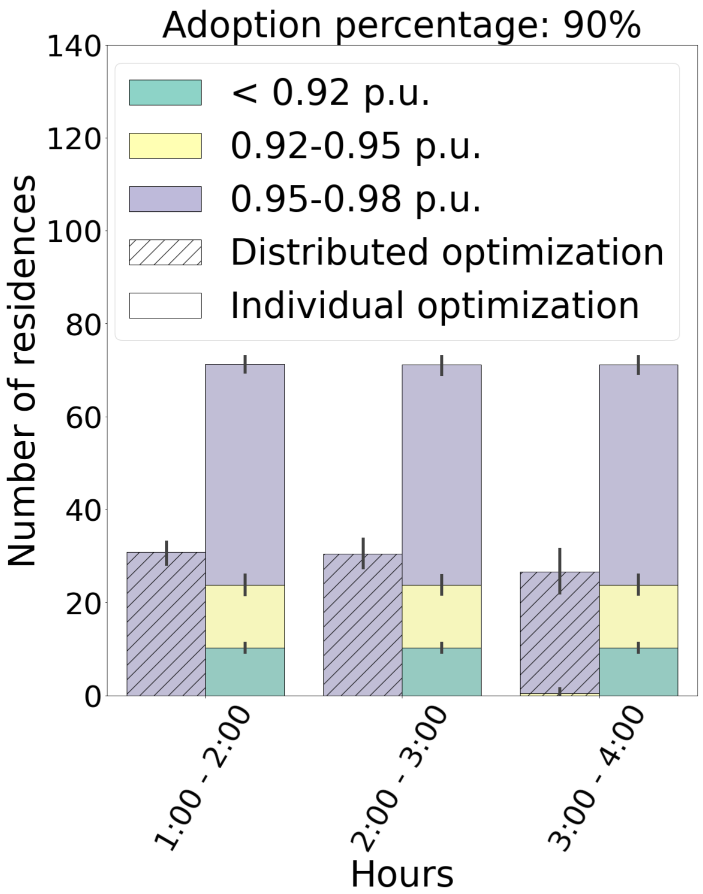
Time Interval (HH:MM)	**00:00 – 05:00**	**05:00 – 15:00**	**15:00 – 18:00**	**18:00 – 00:00**
Tariff ($/kWh)	0.07866	0.09511	0.21436	0.09511

Key observations

- Line limits are not violated even at high EV adoption levels.
- Voltage limits are violated when EV charging is done in an uncoordinated way.

RESULTS





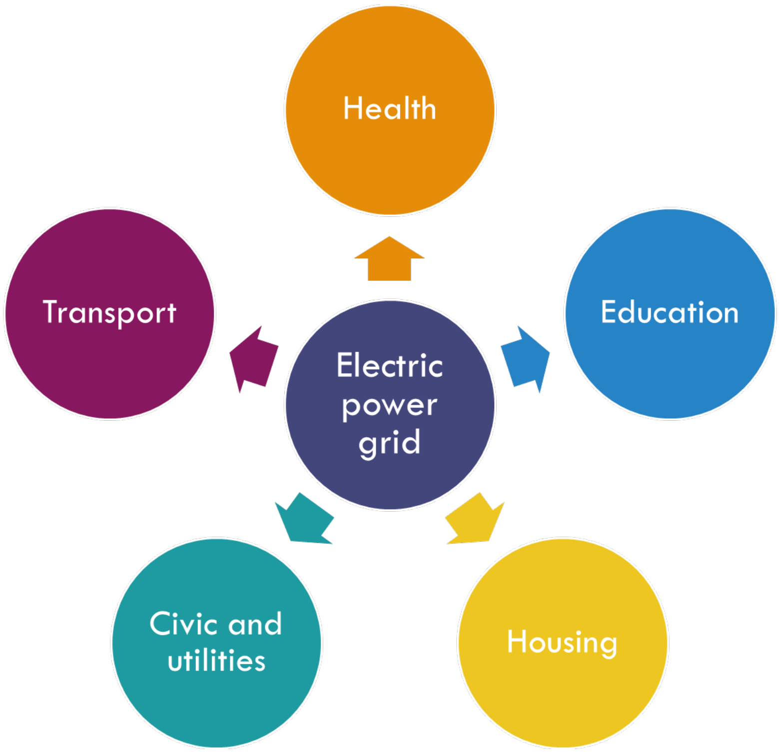
- We study impact of 90% EV adoption in a residential community.
- Individual optimization is compared to the proposed distributed approach.

Higher level of reliability attained if consumers coordinate with the DSO

PART 2: CASCADING FAILURE ANALYSIS FRAMEWORK

1. R. MEYUR ET AL., “VULNERABILITY OF THE POWER GRID TO TARGETED ATTACKS: THE ROLE OF REALISTIC REPRESENTATIONS,” PROCEEDINGS OF NATIONAL ACADEMY OF SCIENCES (PNAS), 2022 (**IN PREPARATION FOR SUBMISSION**).
2. R MEYUR ET AL., “CASCADING EFFECTS OF TARGETED ATTACKS ON THE POWER GRID,” COMPLEX NETWORKS AND THEIR APPLICATIONS VII. PP. 155–167 (2018).
3. R. MEYUR (2020). A BAYESIAN ATTACK TREE BASED APPROACH TO ASSESS CYBER-PHYSICAL SECURITY OF POWER SYSTEM. IN 2020 IEEE TEXAS POWER AND ENERGY CONFERENCE (TPEC) (PP. 1–6).

MOTIVATION



Disruption of electric power causes significant impact on the economy.

Image source: CNN News

Sniper attacked 17 transformers in Metcalf substation in Coyote, California on April 16, 2013 causing $15 million worth damage.

Image source: Reuters

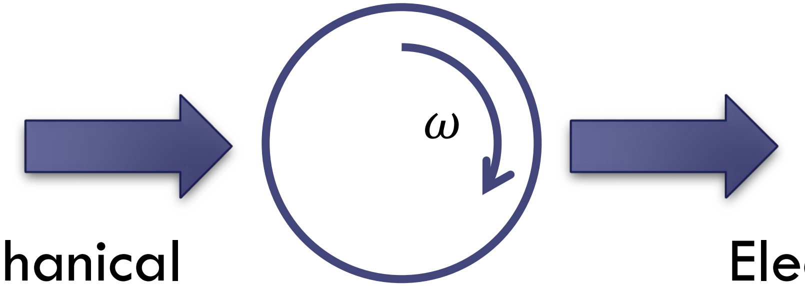
Image source: CBS News

Hurricanes and wildfires cause power grid damages every year.

Identify critical nodes in the power grid to prevent cascading outages and blackout.

PRELIMINARIES: ROTOR ANGLE STABILITY

Generator

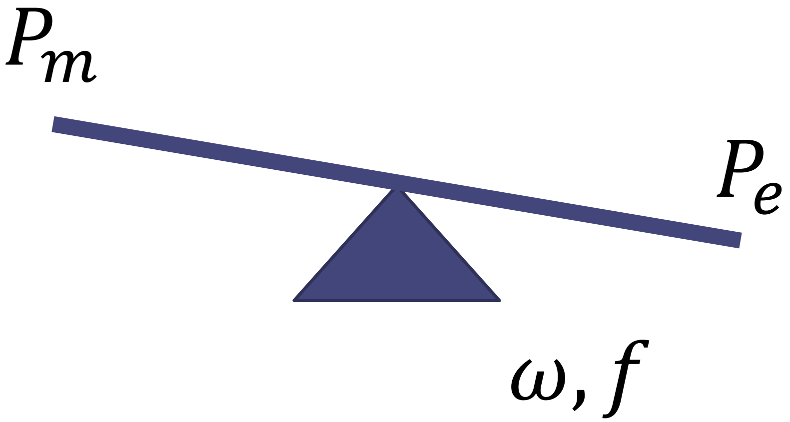


Mechanical power input P_m

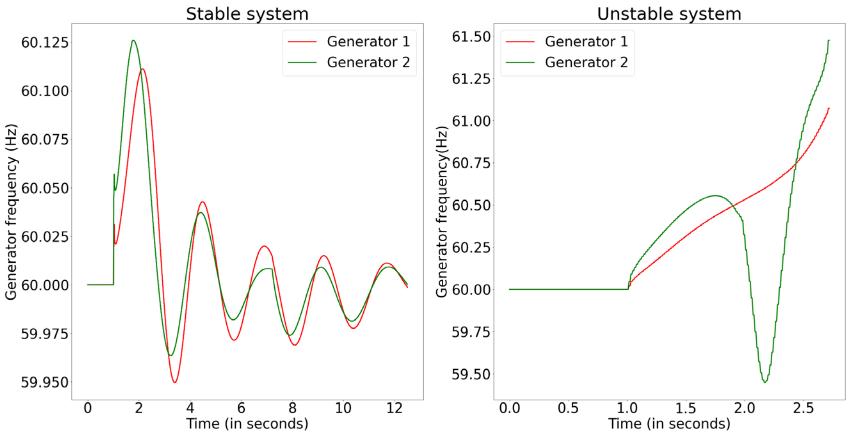
Electrical power output P_e

$$M\frac{d^2\theta}{dt^2} = M\frac{d\omega}{dt} = P_m - P_e$$

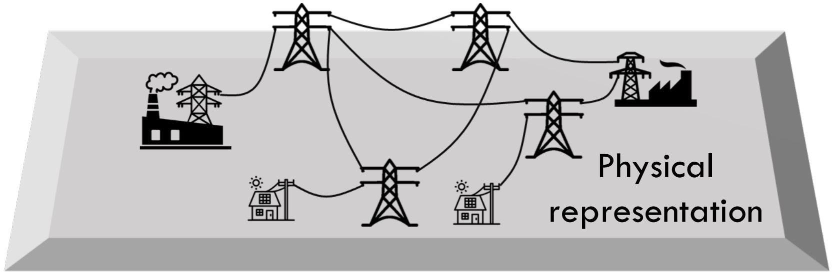
Generator speed ω determines frequency f of power grid

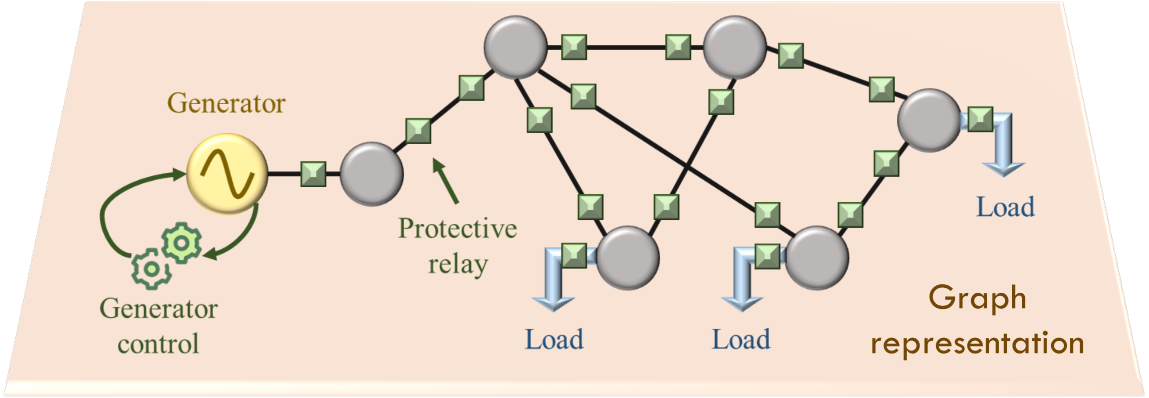


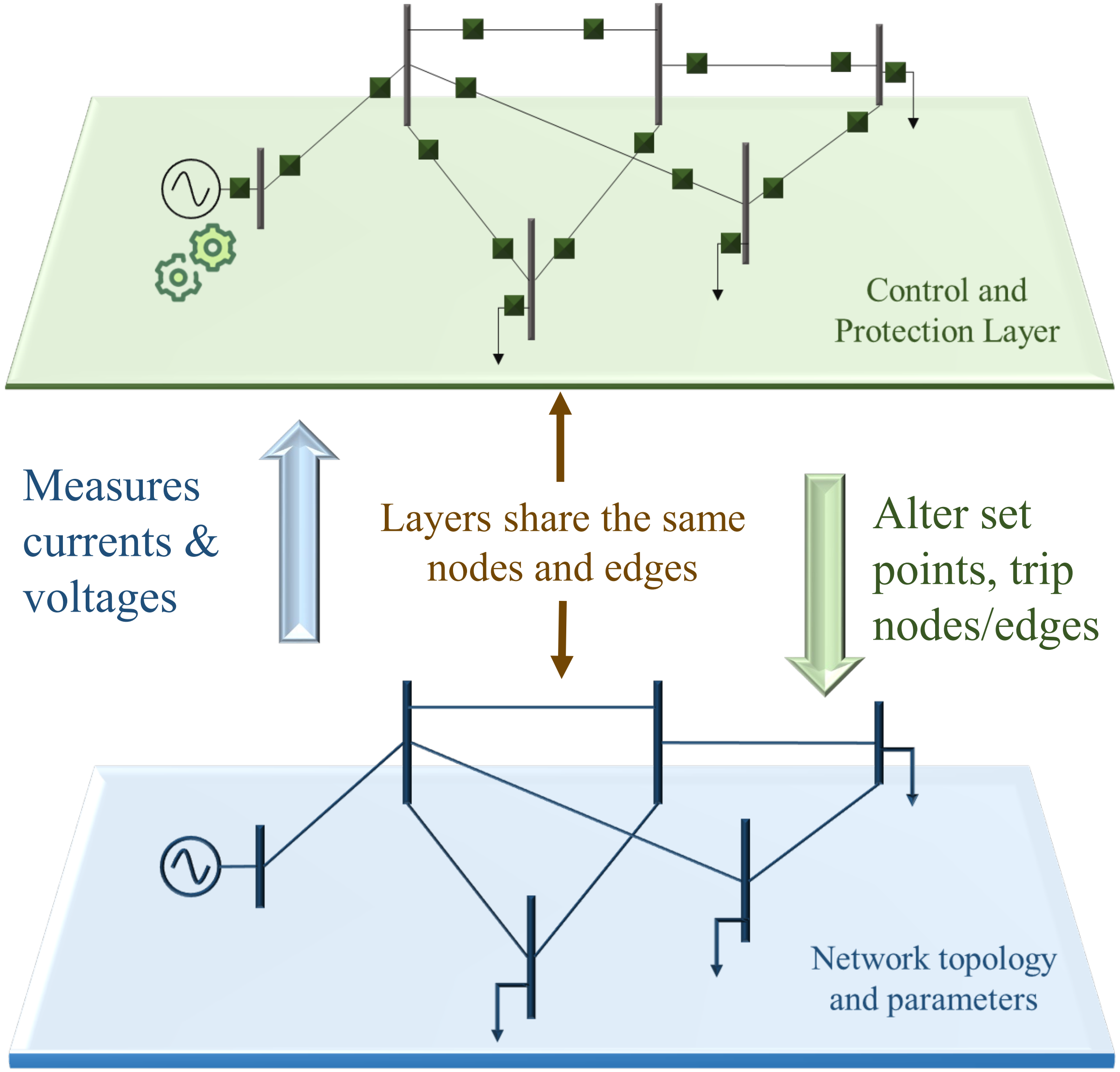
Rotor angle stability is determined by load & generation balance.



PRELIMINARIES: MULTIPLE LAYERS IN POWER GRID



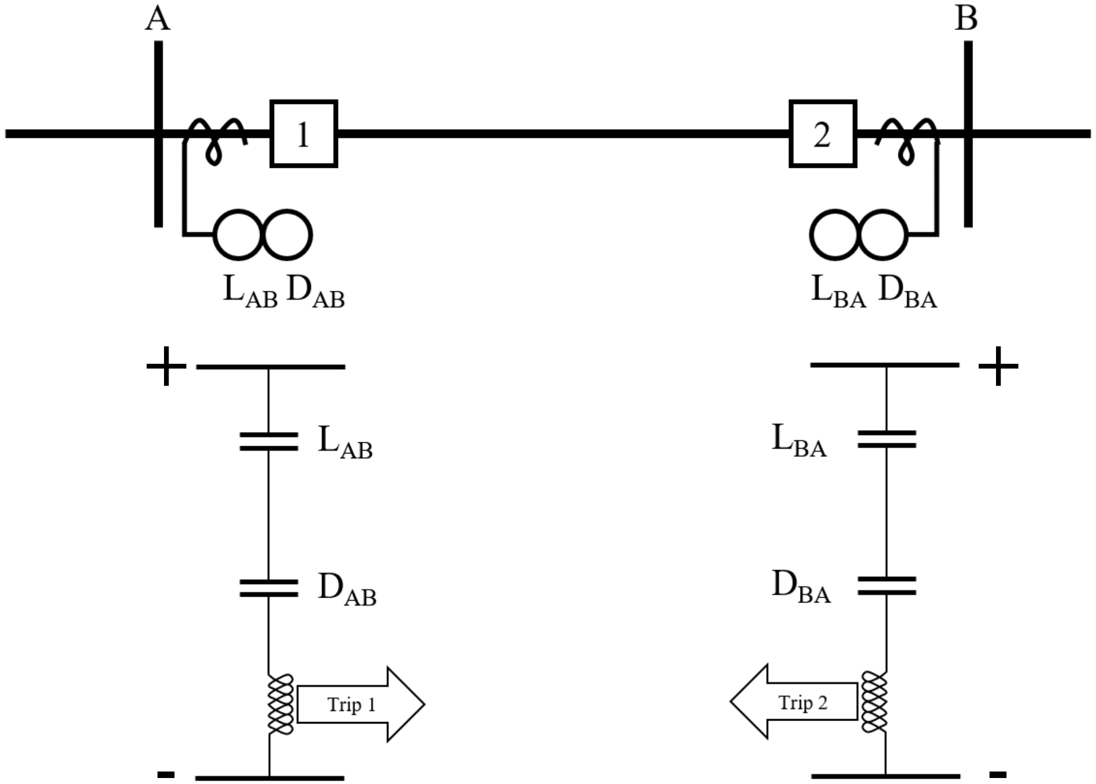




Failure of nodes & edges are determined by the action of protection & control systems

PRELIMINARIES: PROTECTIVE RELAYS IN POWER GRID

Electrical fuse wire is the simplest protection system.

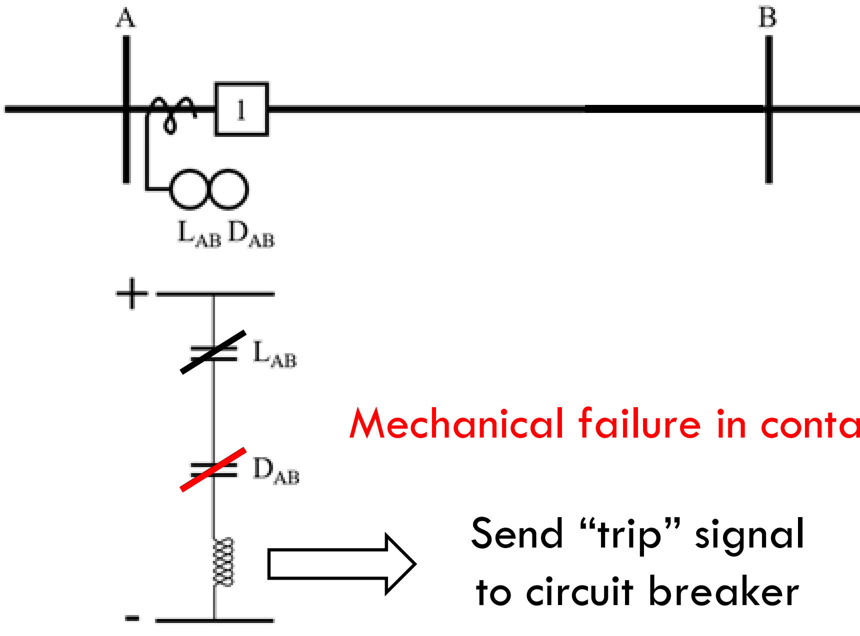


Faults – abnormal current in power grid.

Protection to equipment during faults.

- **Sensor**: measures current, voltage.
- **Relay**: detects the fault.
- **Circuit Breaker** (CB): isolates the equipment.

OUR NOVELTY: HIDDEN FAILURE MODEL IN PROTECTIVE RELAYS

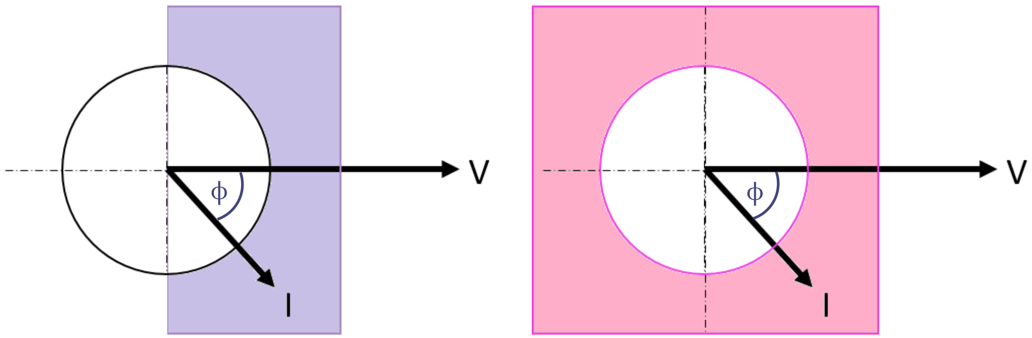


Mechanical failure in contact

Send "trip" signal to circuit breaker

Directional overcurrent relay

Sends a trip signal to circuit breaker if
- Current is above pickup value, and
- Current flows from A to B



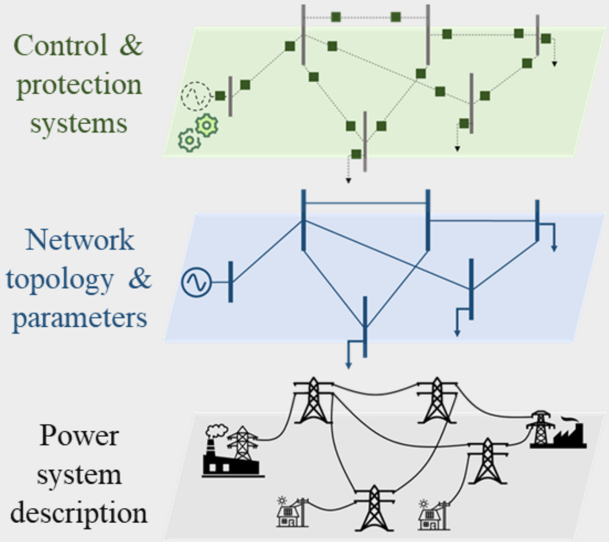
Normal operation
Trips only if current in the shaded region

Hidden failure in directional contact
Trips irrespective of current direction

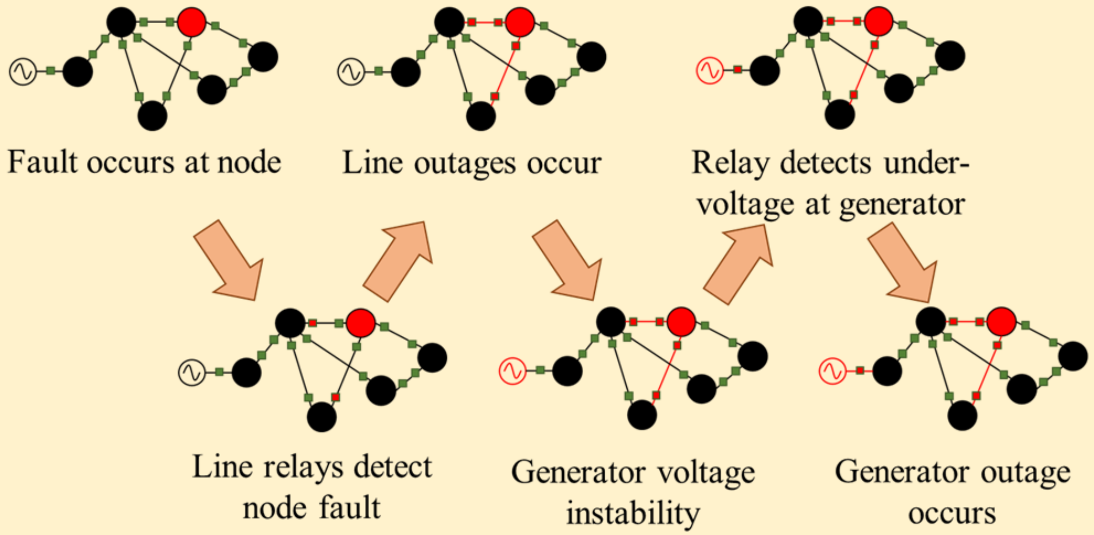
Failure remains hidden until the measured current exceeds pickup value

CASCADING FAILURE ANALYSIS FRAMEWORK

Input: power grid information



Framework for cascading failure analysis



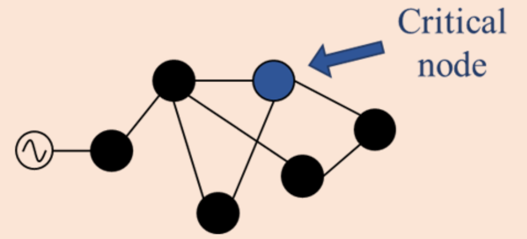
Input: disturbance model

Hurricanes
Forest fires
Cyber attack
Physical attack

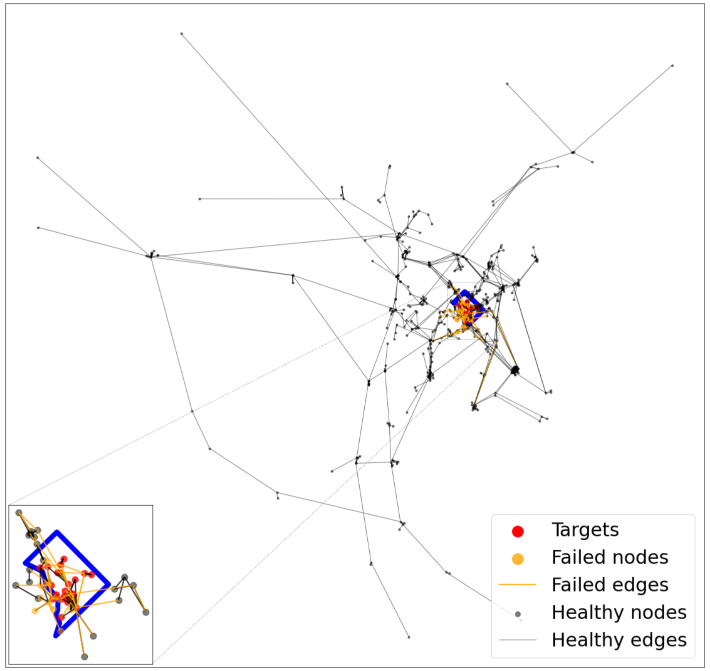
Output: impact evaluation

- Number of node outages.
- Probability of power system collapse.

Vulnerability & criticality analysis

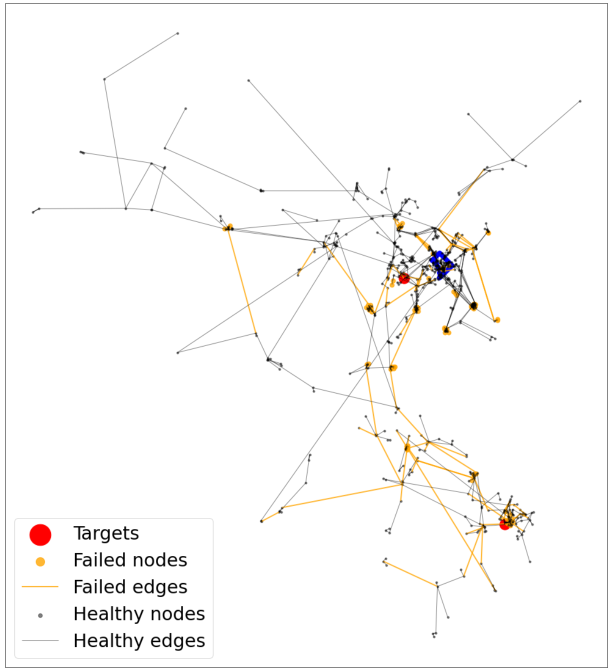


CASE STUDY: PHYSICAL ATTACK ON WASHINGTON DC POWER GRID



Large scale attack

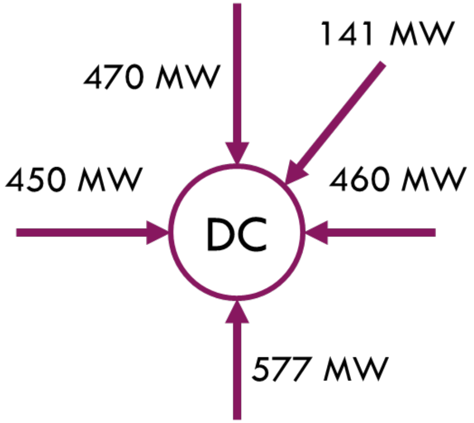
- Entire Washington DC is targeted.
- Large loss of property.
- Limited cascaded outage outside DC.

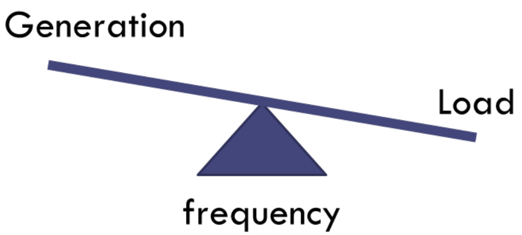


Coordinated attack on particular substations

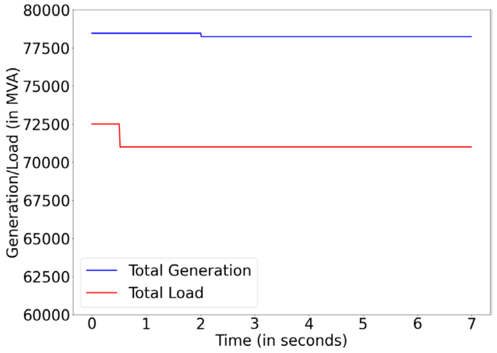
- Limited property damage.
- Widespread cascaded outages.
- Just targeting 2 nodes can cause a blackout!!!

DISCUSSION

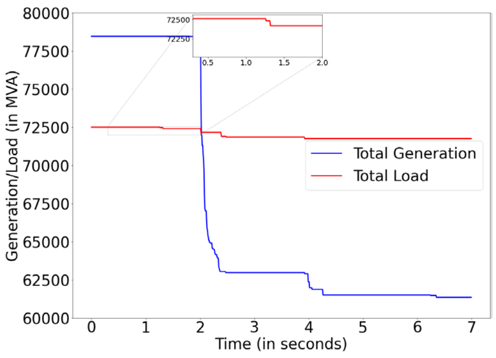




Large scale attack

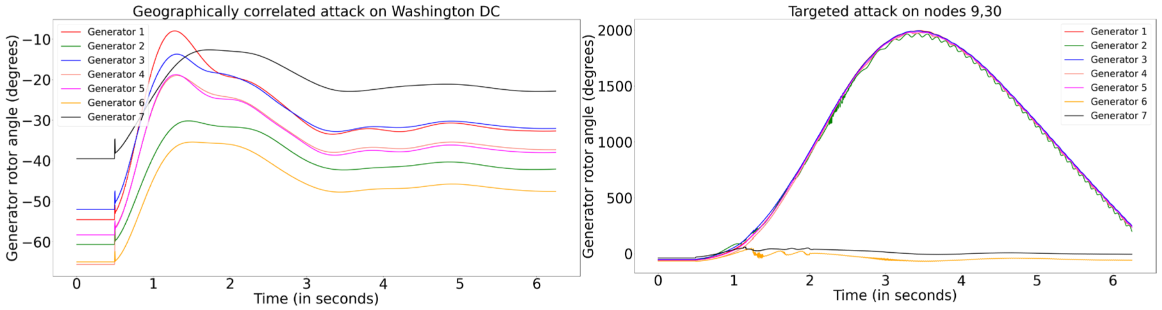


Coordinated attack

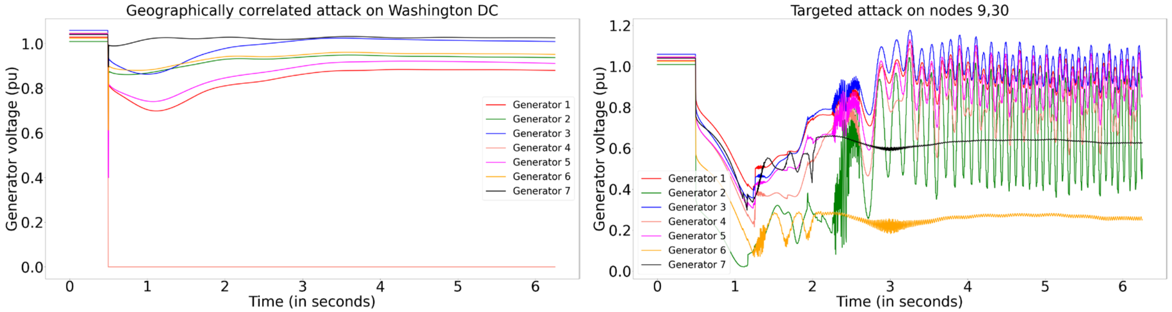


Large scale attack

Coordinated attack



Generator rotor angles

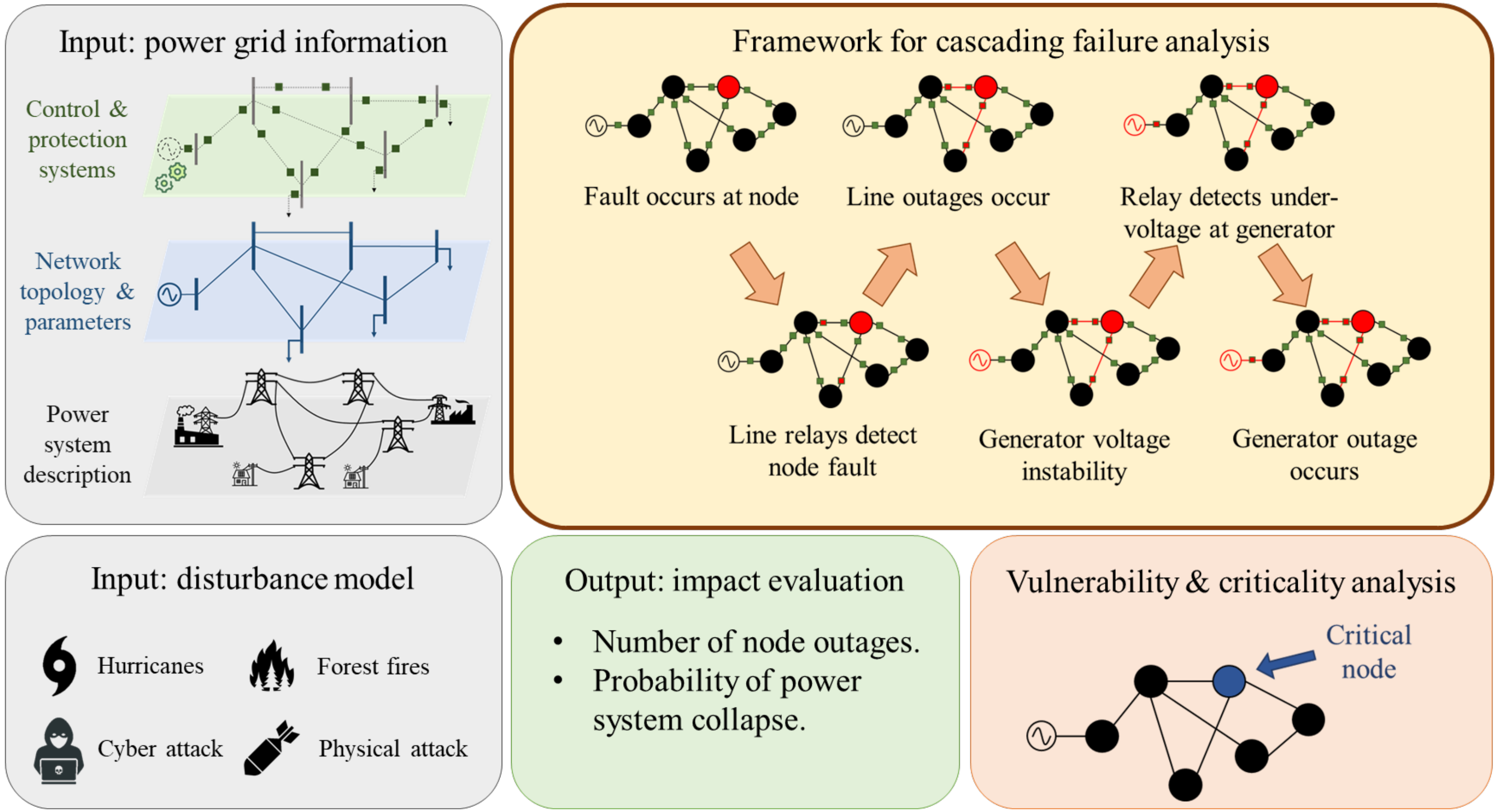


Generator voltage magnitudes

- Targeted attack interrupts the import of power from nearby areas.
- Large scale attack in Washington DC removes load inside the region.

SUMMARY AND CONCLUSIONS

- ❑ Generalized framework
  - Assess vulnerability of the power grid to any type of input disturbance.
  - Requires only the starting node(s) of failure.
- ❑ Multiple parallel runs
  - Run multiple simulations to generate failure scenarios.



QUESTIONS