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Applications of Bilevel Mixed-Integer Programming to Power Systems Resilience

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Outline

- Motivation
- Modeling
  - Network model
  - Generalized disruption model
  - Multi-regime System Operator (defender) model
    - Grid-connected, cascade, islanding
- Bilevel formulation
  - Benders decomposition
- Resource dispatch
  - Controllable DGs, islanding capabilities
  - Trilevel formulation – solution approach

Cyberphysical disruptions

Hurricane Maria (September 2017)

- Customers facing blackouts for months

Metcalf Substation (April 2013)

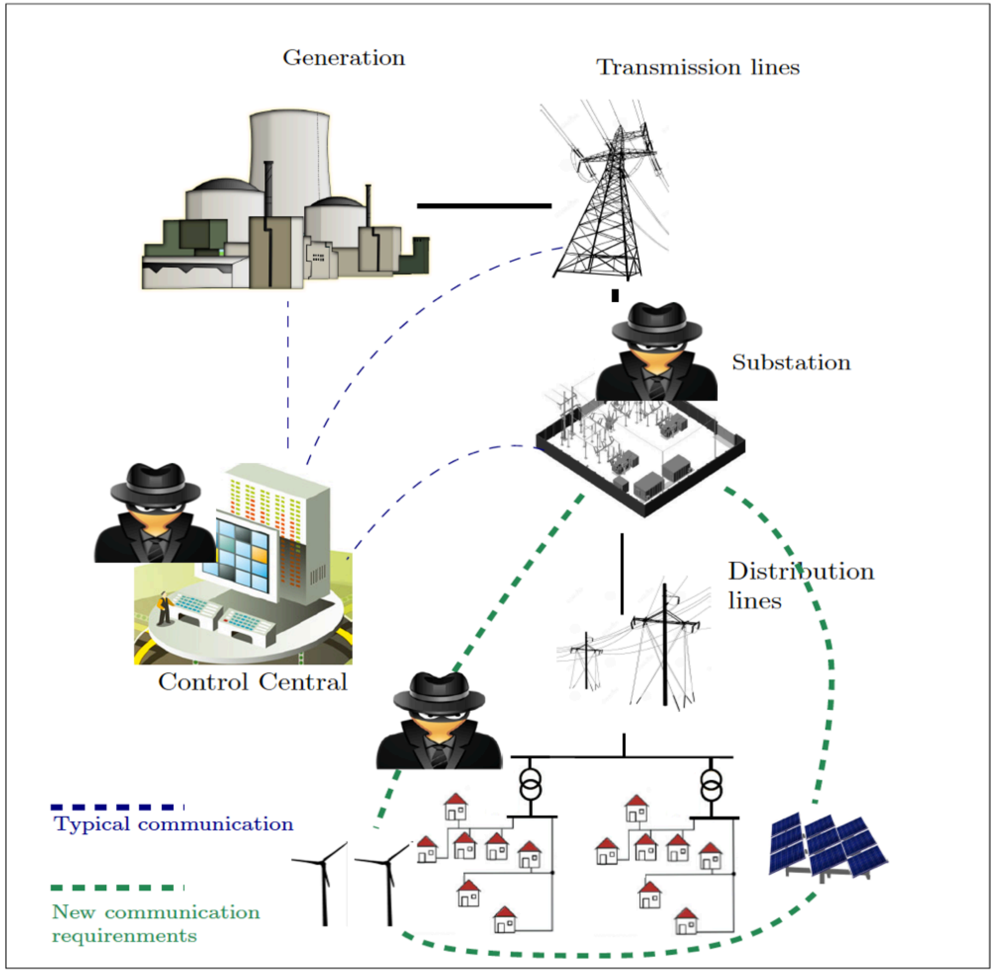
- Sniper attack on 17 transformers
- Telecommunication cables cut
- 15 million $ worth of damage
- 100 mn $ for security upgrades

Ukraine attack (Dec 2015-2016)

- First ever blackouts caused by hackers
- Controllers damaged for months

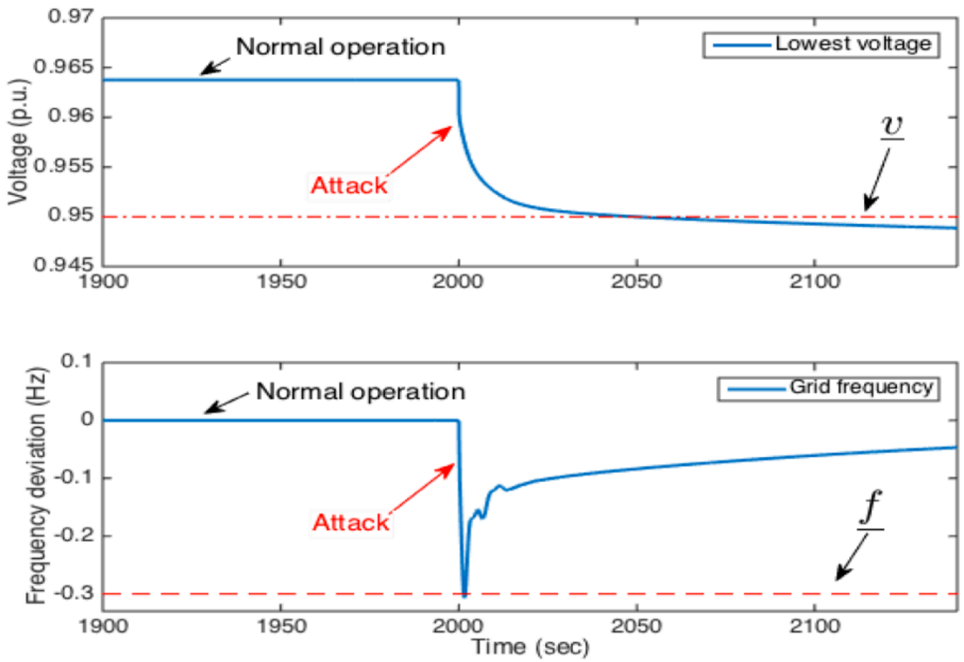
Attack scenarios

NESCO Vulnerabilities (EPRI):



Authorized Employee Issues Invalid Mass Remote Disconnect
Invalid Access Used to Install Malware Enabling Remote Internet Control
Meter Authentication Credentials are Compromised and Posted on Internet
Weak Encryption Exposes AMI Device Communication
Known but Unpatched Vulnerability Exposes AMI Infrastructure
Inadequate Access Control of DER Systems Causes Electrocution
DER SCADA System Issues Invalid Commands
Denial of Service Attack Impairs NTP Service

=> supply-demand imbalance (sudden / prolonged)



Three regimes of SO operation

Grid-connected regime

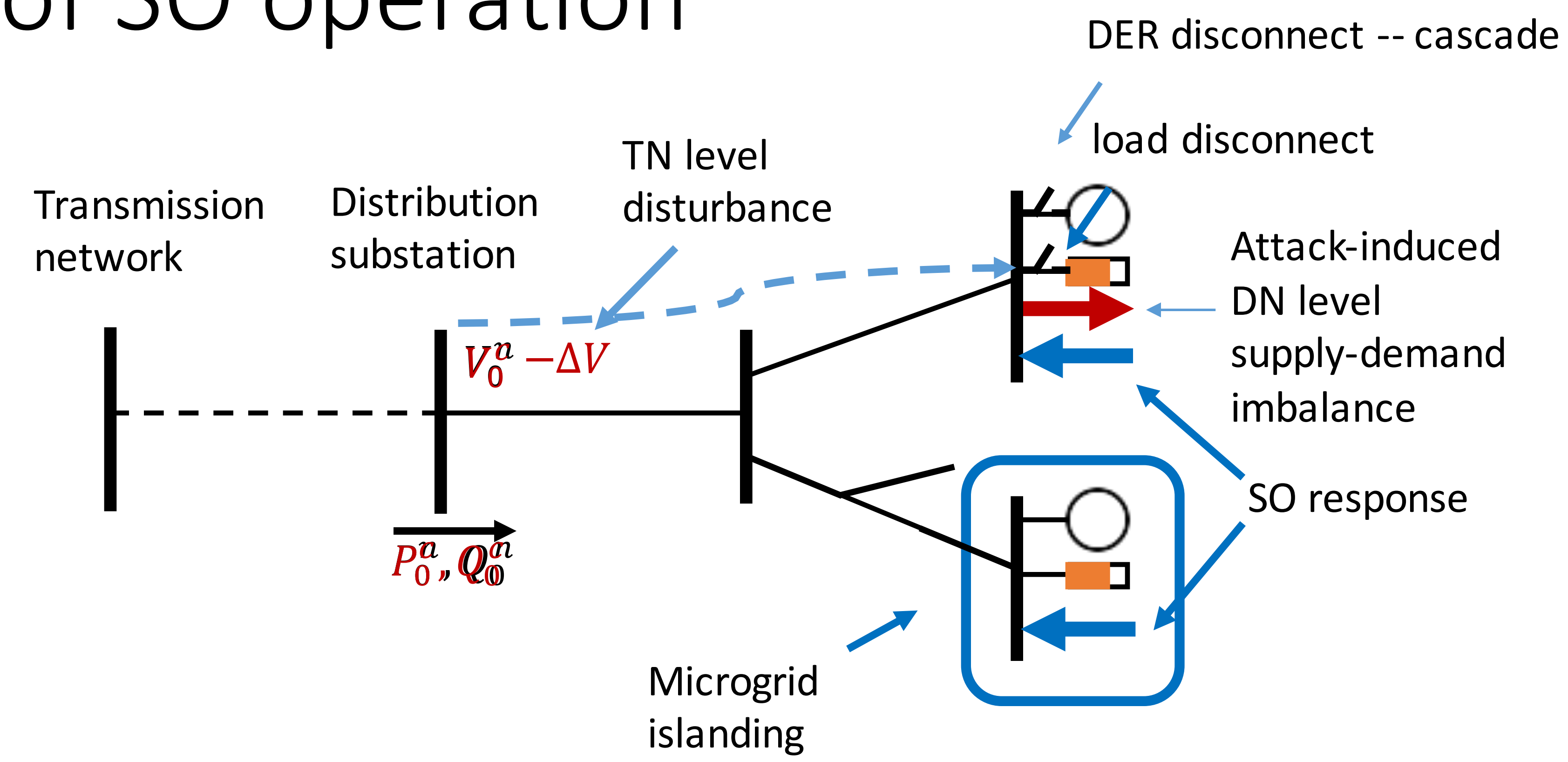
- Can absorb the impact of disturbances

Islanding mode regime

- Larger disturbances may force microgrid islanding

Cascade regime

- High severity voltage excursions, then more DER disconnects (cascades), more load shedding



When TN and DN level disturbances clear, the system can return to its nominal regime

Our approach

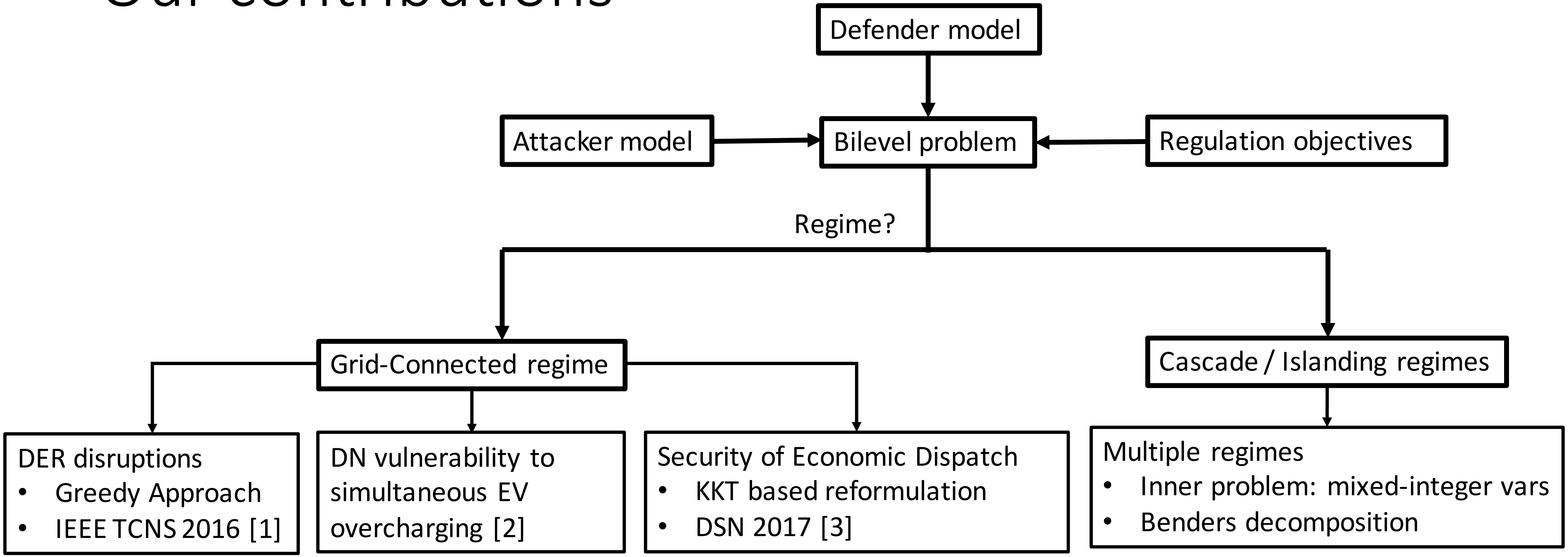
Most attacker-defender interactions can be modeled as

- Supply-demand imbalance induced by attacker
- Control (reactive and proactive) by the system operator

- Abstraction: Bilevel (or multilevel) optimization problems
    - Flexible to allow for both continuous and discrete variables
    - Good solution approaches: Duality, KKT conditions, Benders cut, MILP
    - Provide practically useful insights to determine critical scenarios

- Supplements simulation based approaches
    - For example, co-simulation of cyber and power simulators

Our contributions



[1] Shelar D. and Amin. S - "Security assessment of electricity distribution networks under DER node compromises”
[2] Shelar D., Amin. S and Hiskens I. – “Towards Resilience-Aware Resource Allocation and Dispatch in Electricity Distribution Networks”
[3] Shelar D., Sun P., Amin. S and Zonouz S. - “Compromising Security of Economic Dispatch software”

Related Work (partial)

(T1) Interdiction and cascading failure analysis of power grids

- R. Baldick, K. Wood, D. Bienstock: Network Interdiction, Cascades
- A. Verma, D. Bienstock: N-k vulnerability problem
- D. Papageorgiou, R. Alvarez, et al.: Power network defense
- X. Wu, A. Conejo: Grid Defense Planning

(T2) Cyber-physical security of networked control systems

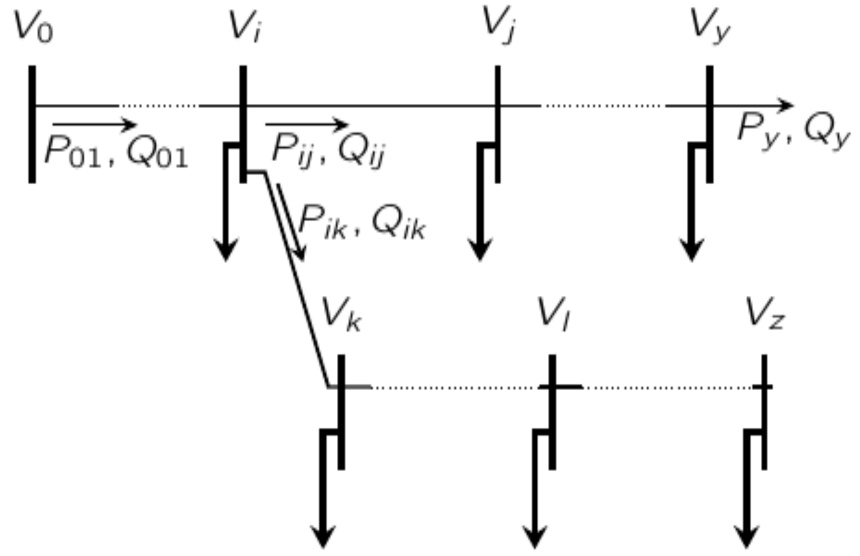
- E. Bitar, K. Poolla, A Giani: Data integrity, Observability
- H. Sandberg, K. Johansson: Secure control, networked control
- B. Sinopoli, J. Hespanha: Secure estimation and diagnosis
- T. Basar, C. Langbort: Network security games

Network model

Power flow on tree networks - Baran and Wu model (1989):

- $\mathcal{G} = (\mathcal{N}, \mathcal{E})$– tree network of nodes and edges
- $\overline{pc}_i, \overline{qc}_i$ - real and reactive nominal power demand at node i
- $\overline{pg}_i, \overline{qg}_i$ - real and reactive nominal power from uncontrollable generation at node i

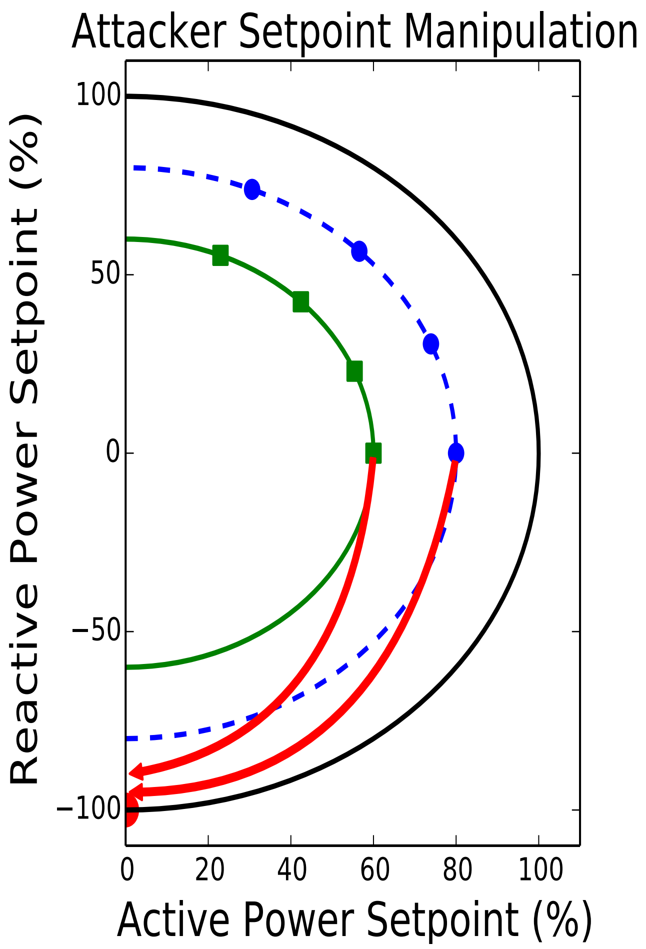
- V_i - voltage magnitude at node i
- $\mathrm{z}_{ij} = \mathrm{r}_{ij} + \mathbf{j}\mathrm{x}_{ij}$ - impedance on line (i, j)
- P_{ij}, Q_{ij} - real and reactive power from node i to node j
- p_i, q_i - net real and reactive power consumed at node i



Generalized disruption model

Attacker strategy: $a = (\delta, pd^a, qd^a, \Delta V_0)$

- δ: attack vector, with $\delta_i = 1$ if node i is attacked and 0 otherwise
- Satisfy $\sum_i \delta_i \leq M$ (attacker's resource budget)
- pd_i^a, qd_i^a - attacker's active/reactive power disturbance at node i (general model: captures various attack scenarios)
- ΔV_0: voltage drop at substation node
  - Due to physical disturbance or temporary fault in the TN



Attacker strategy:

- Which nodes to compromise?
- What set-points to choose?

Defender model: Grid-connected regime

Defender response: $d = (\beta)$

- $\beta_i \in \left[\underline{\beta_i}, 1\right]$: load control parameter at node i
  - $pc_i = \beta_i \, \overline{pc}_i, \quad qc_i = \beta_i \, \overline{qc}_i$

$\overline{pc_i}, \overline{qc_i}$ - nominal power demand at node i

Defender response:

How much load control should be exercised?

Defender model: Cascade regime

Defender response: $d = (\beta, kc, kg)$

- kc_i = 0 if load is connected, 1 otherwise.
- kg_i = 0 if uncontrolled DG is connected, 1 otherwise.

- Voltage constraints for connectivity:

$$kc_i = 0 \implies V_i \in \left[\underline{V_c}_i, \overline{V_c}_i\right]$$
$$kg_i = 0 \implies V_i \in \left[\underline{V_g}_i, \overline{V_g}_i\right]$$

← voltage bounds for load (resp. generation) connectivity

Defender response:

Which loads and DGs to disconnect?

Defender model: Islanding regime

Defender response: $d = (\beta, kc, kg, pr, qr, km)$

- pr, qr - dispatch of resources (DERs)
- km_{ij} = 1, if line $(i, j) \in \chi$ is open, 0 otherwise.

χ - set of lines which can be disconnected to form microgrids

- Microgrid formation affects power flows and voltages:

$$km_{ij} = 1 \implies \begin{cases} P_{ij} = Q_{ij} = 0 \\ V_j = V^{\text{nom}} \end{cases}$$

$$km_{ij} = 0 \implies pr_j = 0, qr_j = 0$$

Defender response:

Which lines to disconnect?

Power flow constraints before disruption

- Net power consumed at a node

$$p_i = pc_i - pg_i$$
$$q_i = qc_i - qg_i$$

- Linear Power flows (LPF)

$$P_{ij} = \sum_{k:j \to k} P_{jk} + p_i$$
$$Q_{ij} = \sum_{k:j \to k} Q_{jk} + q_i$$

- Voltage drop equation

$$V_j = V_i - (\mathrm{r}_{ij} P_{ij} + \mathrm{x}_{ij} Q_{ij})$$

$$V_0 = V_0^{\mathrm{nom}}$$

Power flow constraints after disruption

- Net power consumed at a node

$$p_i = pc_i - pg_i + \delta_i pd^{a^\star}_i$$
$$q_i = qc_i - qg_i + \delta_i qd^{a^\star}_i$$

- Linear Power flows (LPF)

$$P_{ij} = \sum_{k:j \to k} P_{jk} + p_i$$
$$Q_{ij} = \sum_{k:j \to k} Q_{jk} + q_i$$

- Voltage drop equation

$$V_j = V_i - (\mathrm{r}_{ij} P_{ij} + \mathrm{x}_{ij} Q_{ij})$$

$$V_0 = V_0^{\mathrm{nom}} - \Delta V_0$$

Power flow constraints after SO dispatch

- Net power consumed at a node

$$p_i = pc_i - pg_i + \delta_i pd^{a^\star}_i - pr_i$$
$$q_i = qc_i - qg_i + \delta_i qd^{a^\star}_i - qr_i$$

- Linear Power flows (LPF)

$$P_{ij} = \sum_{k:j\rightarrow k} P_{jk} + p_i$$
$$Q_{ij} = \sum_{k:j\rightarrow k} Q_{jk} + q_i$$

- Voltage drop equation

$$V_j = V_i - (\mathrm{r}_{ij} P_{ij} + \mathrm{x}_{ij} Q_{ij})$$

$$V_0 = V_0^{nom} - \Delta V_0$$

Losses

Cost of active power supply : $L_{\mathrm{AC}}(x) \equiv W_{AC} P_0$

Loss of voltage regulation :
where $t_i \geq |V_i - V^{\mathrm{nom}}|$

$$L_{\mathrm{VR}}(x) \equiv W_{\mathrm{VR}} \sum_{i \in N} t_i \, ,$$

Cost incurred due to load control : $L_{\mathrm{LC}}(x) \equiv \sum_{i \in N} W_{\mathrm{LC},i} (1 - \beta_i)$

Loss in Grid-Connected regime : $L^{GC\ regime}(x) = L_{\mathrm{AC}}(x) + L_{\mathrm{VR}}(x) + L_{\mathrm{LC}}(x)$

Attacker-Defender problem [AD] - Bilevel formulation

$$[\text{AD}]\ \mathcal{L} := \max_{a \in \mathcal{A}} \min_{d \in \mathcal{D}} L^{\text{GC regime}}(x(a, d))$$

- Powerflows, DER capabilities, voltage bounds
- Defender model (resources and capabilities)
- Attacker model (resources and capabilities)

System State $x = (p, q, P, Q, V)$

Attacker-Defender problem [AD] – Cascade regime

$$[\text{AD}]\ \mathcal{L} := \max_{a \in \mathcal{A}} \min_{d \in \mathcal{D}} L^{\text{CS regime}}\,(x(a,d))$$

- Powerflows, DER capabilities, voltage bounds
- Defender model (resources and capabilities)
- Attacker model (resources and capabilities)

Where $L^{\text{CS regime}}(x) \equiv L^{\text{GC regime}}(x) + L_{\text{SD}}(x)$

- Cost of load shedding

$$L_{\text{SD}}(x) \equiv \sum_{i \in \mathcal{N}} W_{\text{SD},i}\, k c_i$$

- $W_{\text{SD},i}$: cost of unit load shedding

Attacker-Defender problem [AD] – Islanding regime

$$[\text{AD}]\ \mathcal{L} := \max_{a \in \mathcal{A}} \min_{d \in \mathcal{D}} L^{\text{MI regime}}(x(a,d))$$

- Powerflows, DER capabilities, voltage bounds
- Defender model (resources and capabilities)
- Attacker model (resources and capabilities)

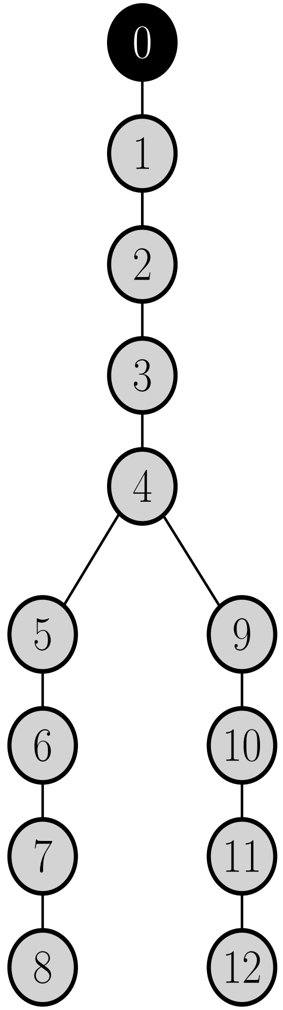
Where $L^{\text{MI regime}}(x) \equiv L^{\text{GC regime}}(x) + L_{\text{MG}}(x)$

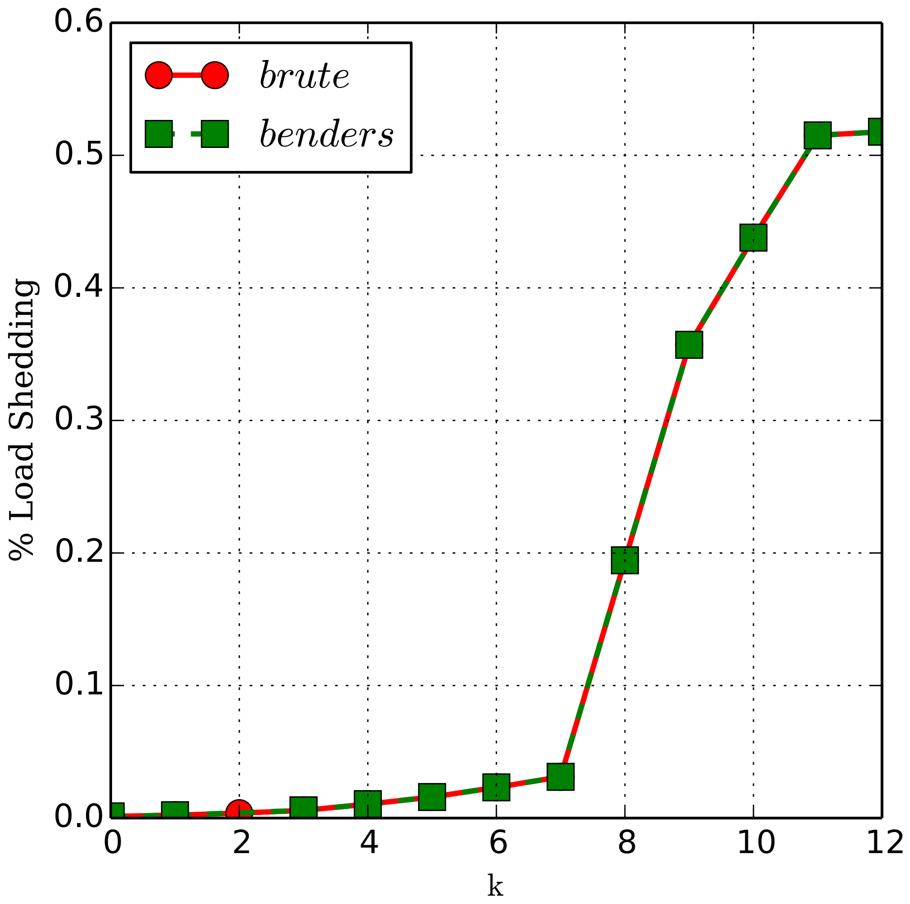
- Cost of microgrid islanding

$$L_{\text{MG}}(x) \equiv \sum_{(i,j) \in \chi} W_{\text{MG},ij}\, km_{ij}$$

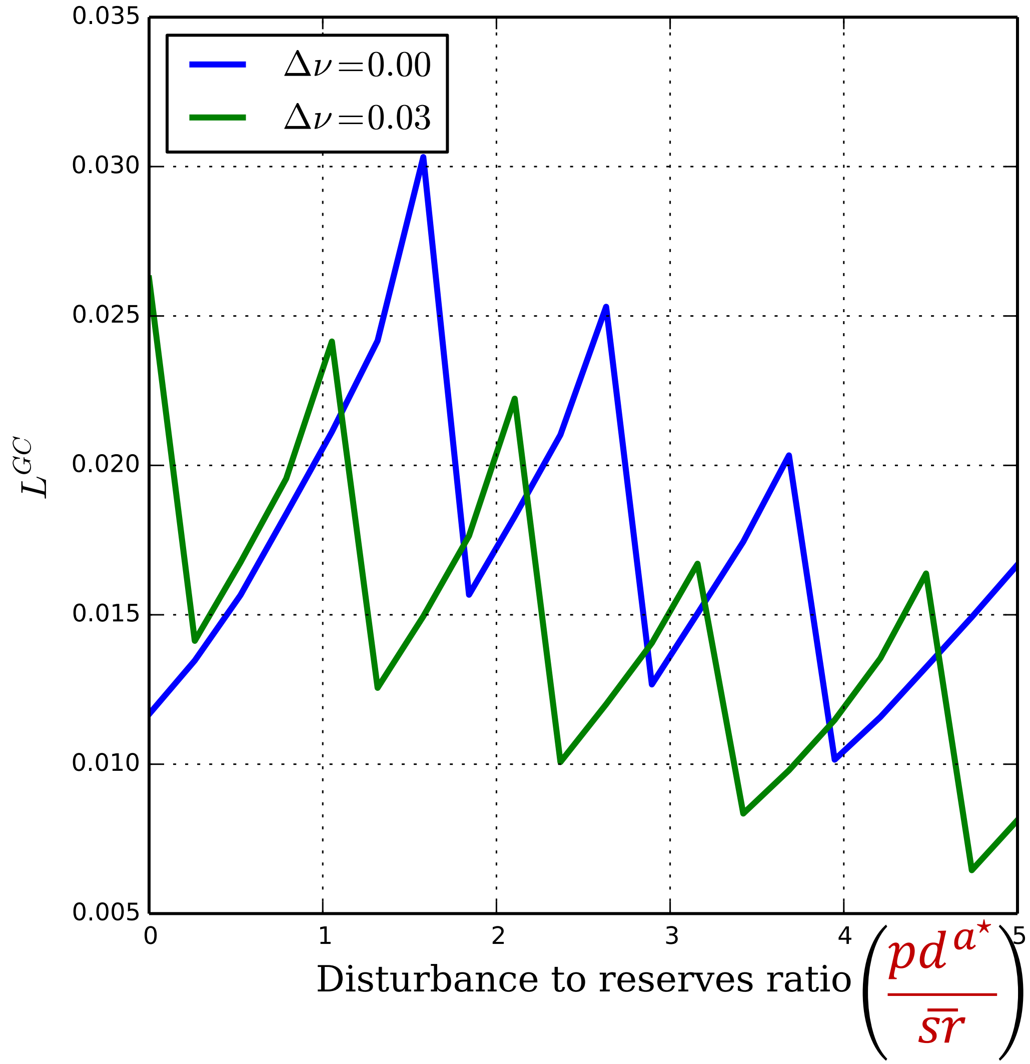
- $W_{\text{MG},ij}$: cost of a single microgrid island formation at node j

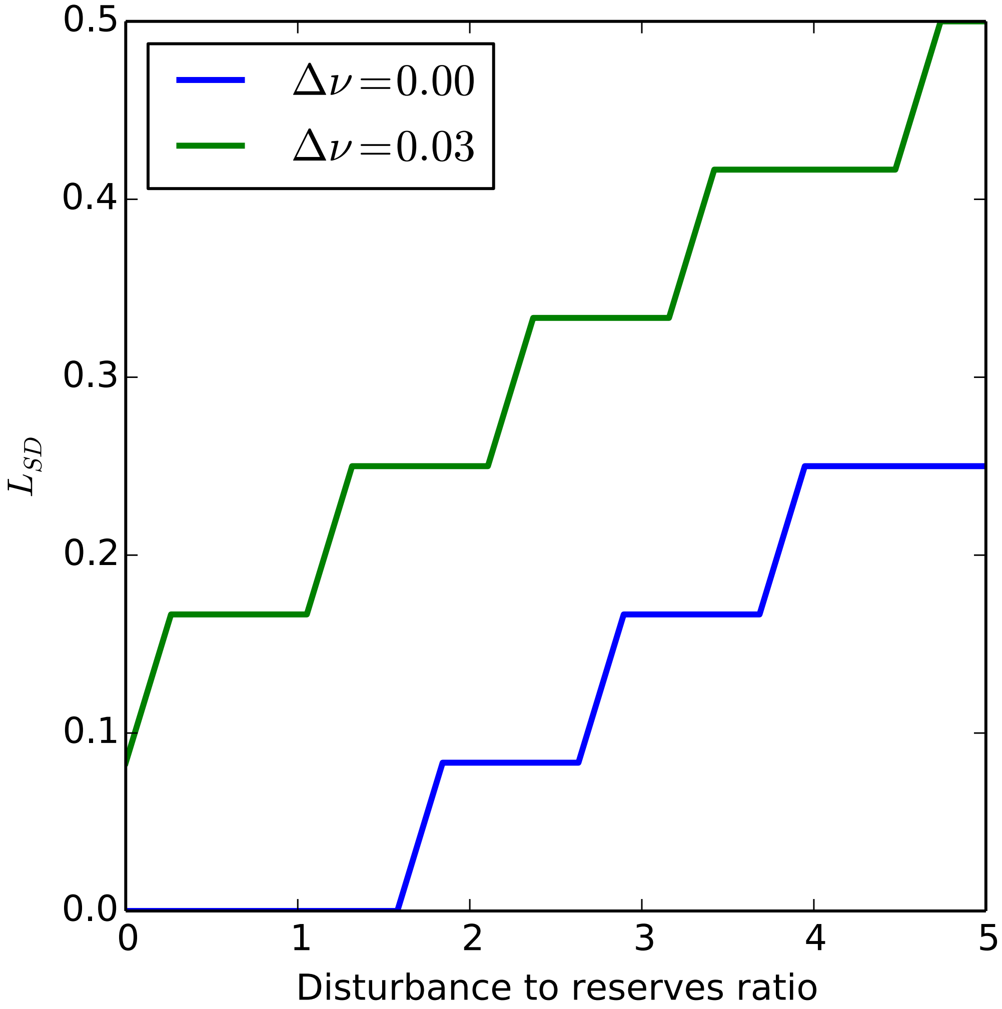
Benders cut approach



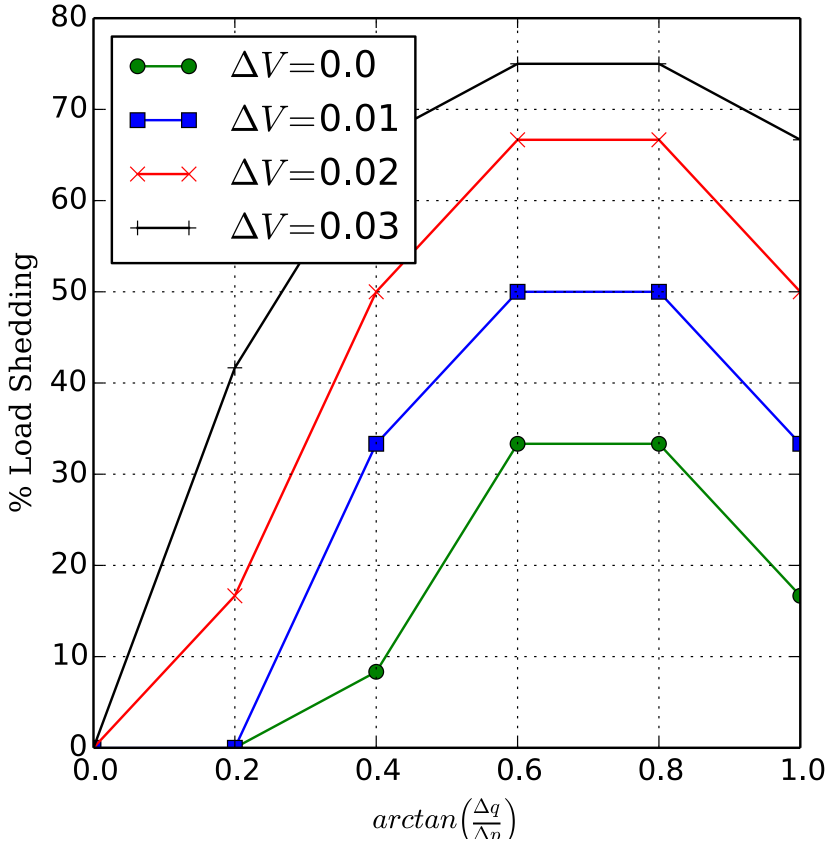


Computational results for Cascade regime





Load shedding vs $\frac{\Delta q}{\Delta p}$



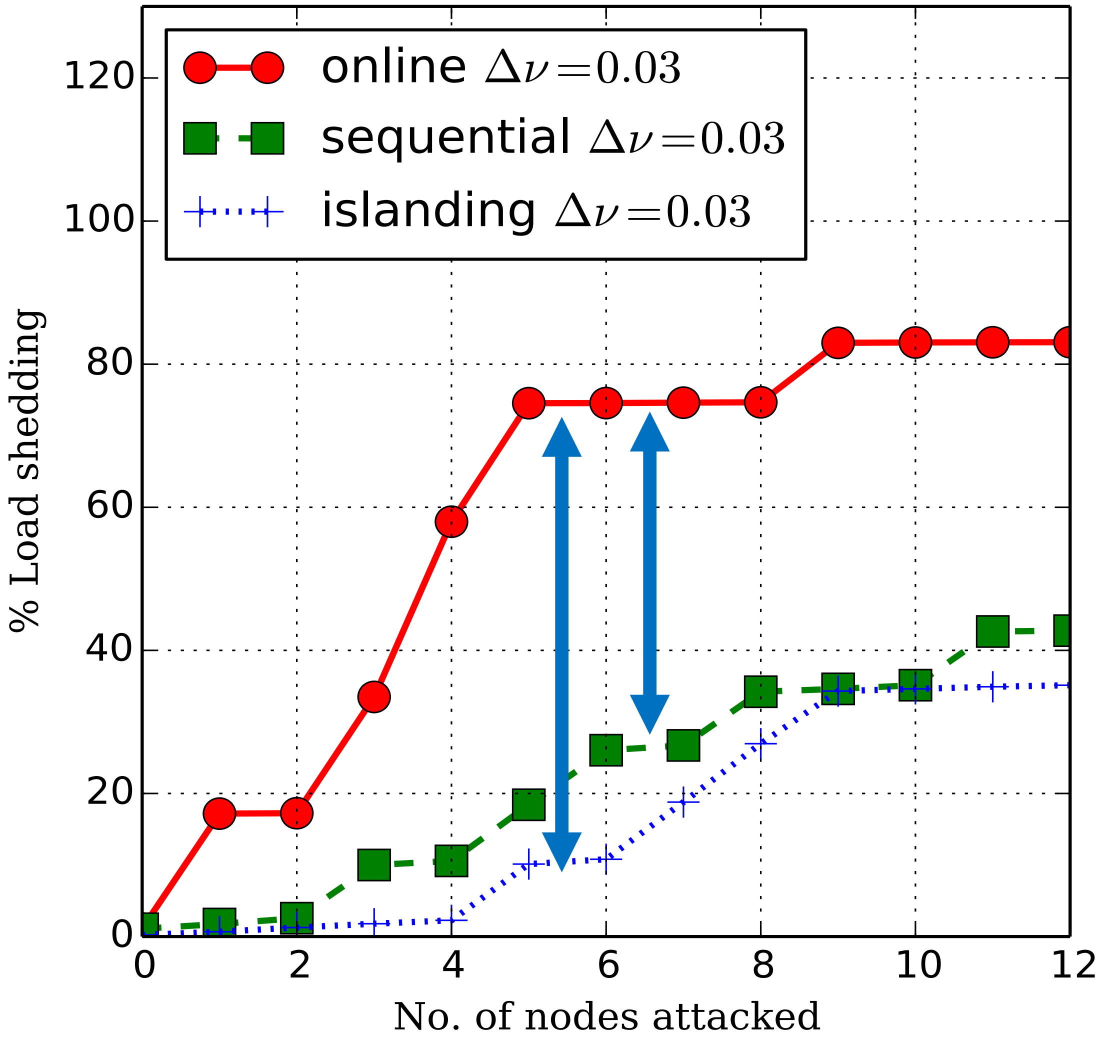
No response - (multi-round) cascade

Worst-case loss under no defender response

An algorithm

- Initial contingency
- For r = 1,2,…
  - Compute new power flows
  - Determine a single loads or DG that maximally violates its voltage bounds
  - Disconnect that device accordingly

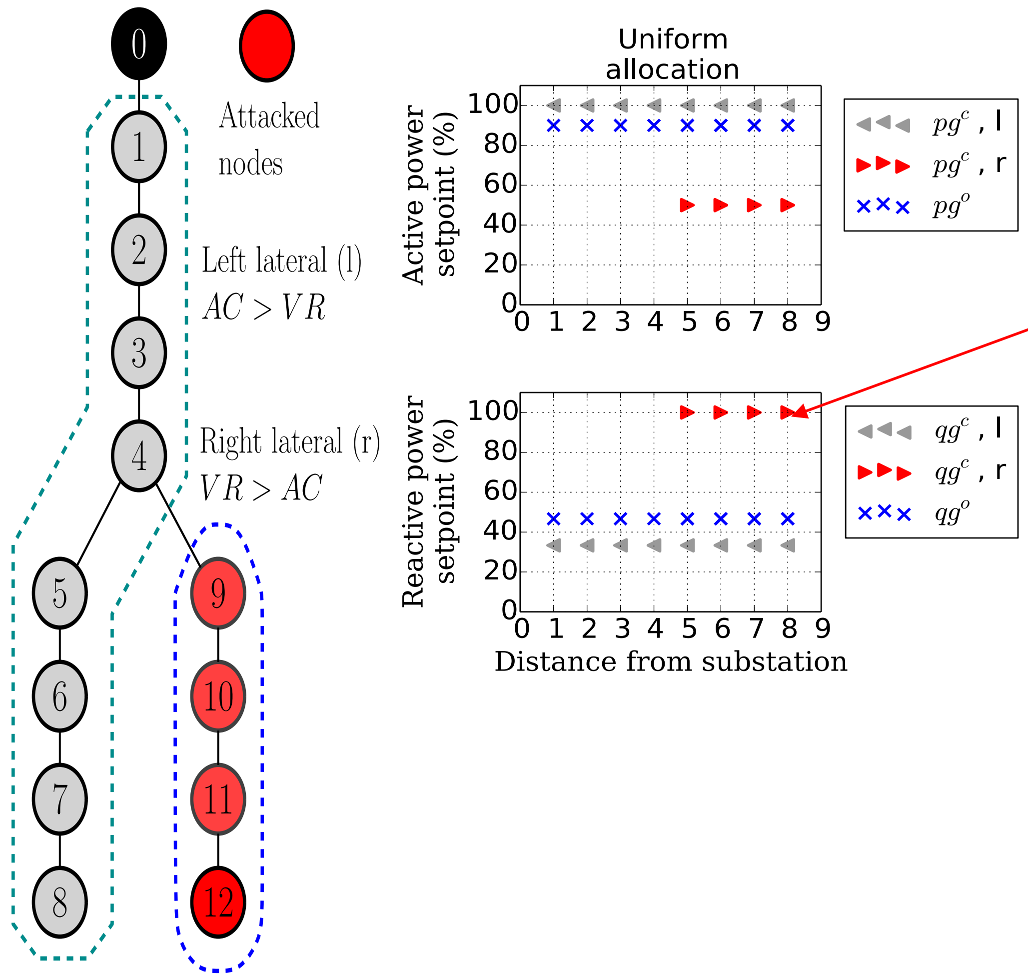
Online vs Sequential vs Islanding



Value of timely
disconnections
islanding

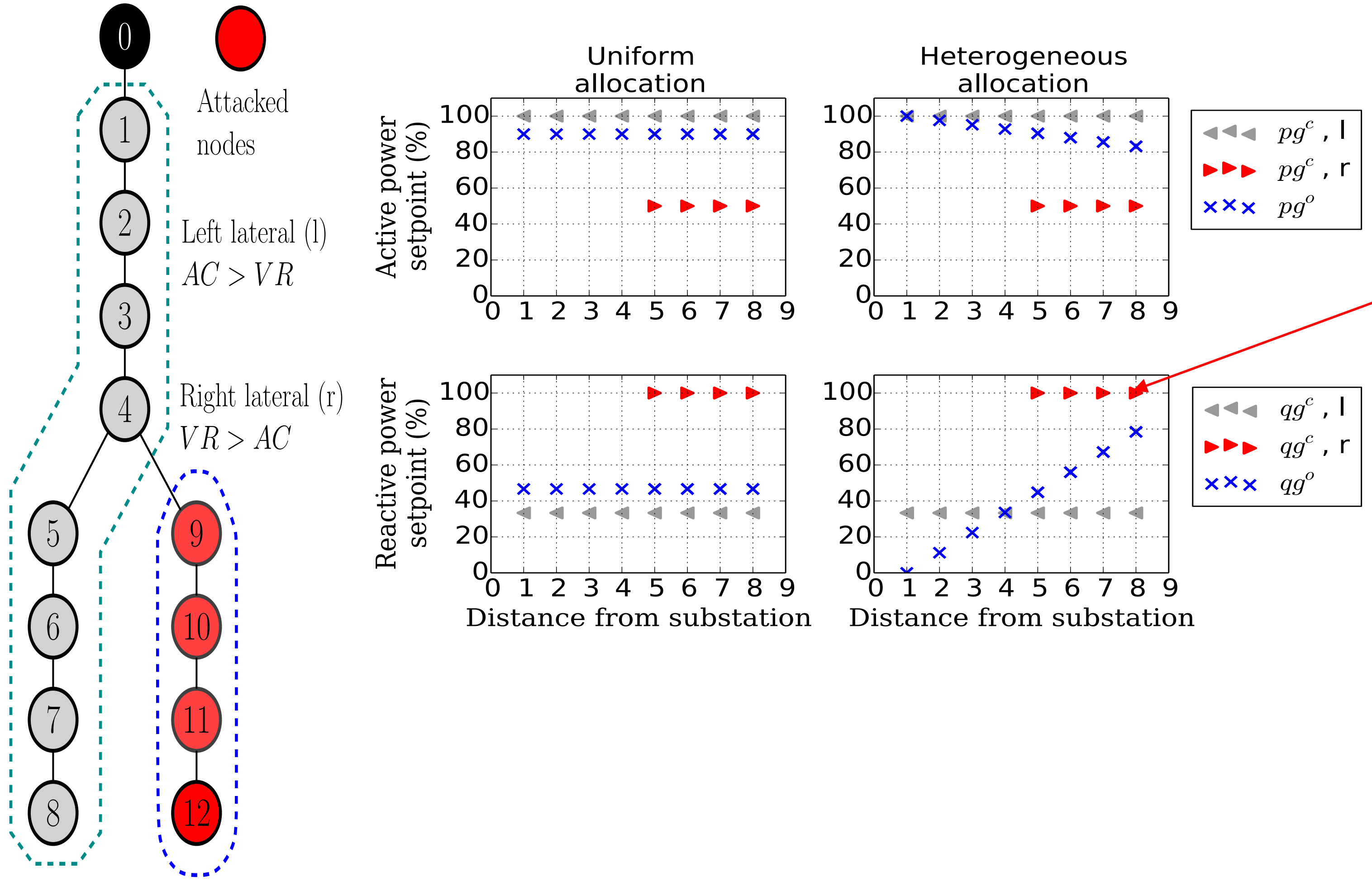
Defender Response and Allocation: Diversification

Special case of $\chi = \{(0,1)\}$



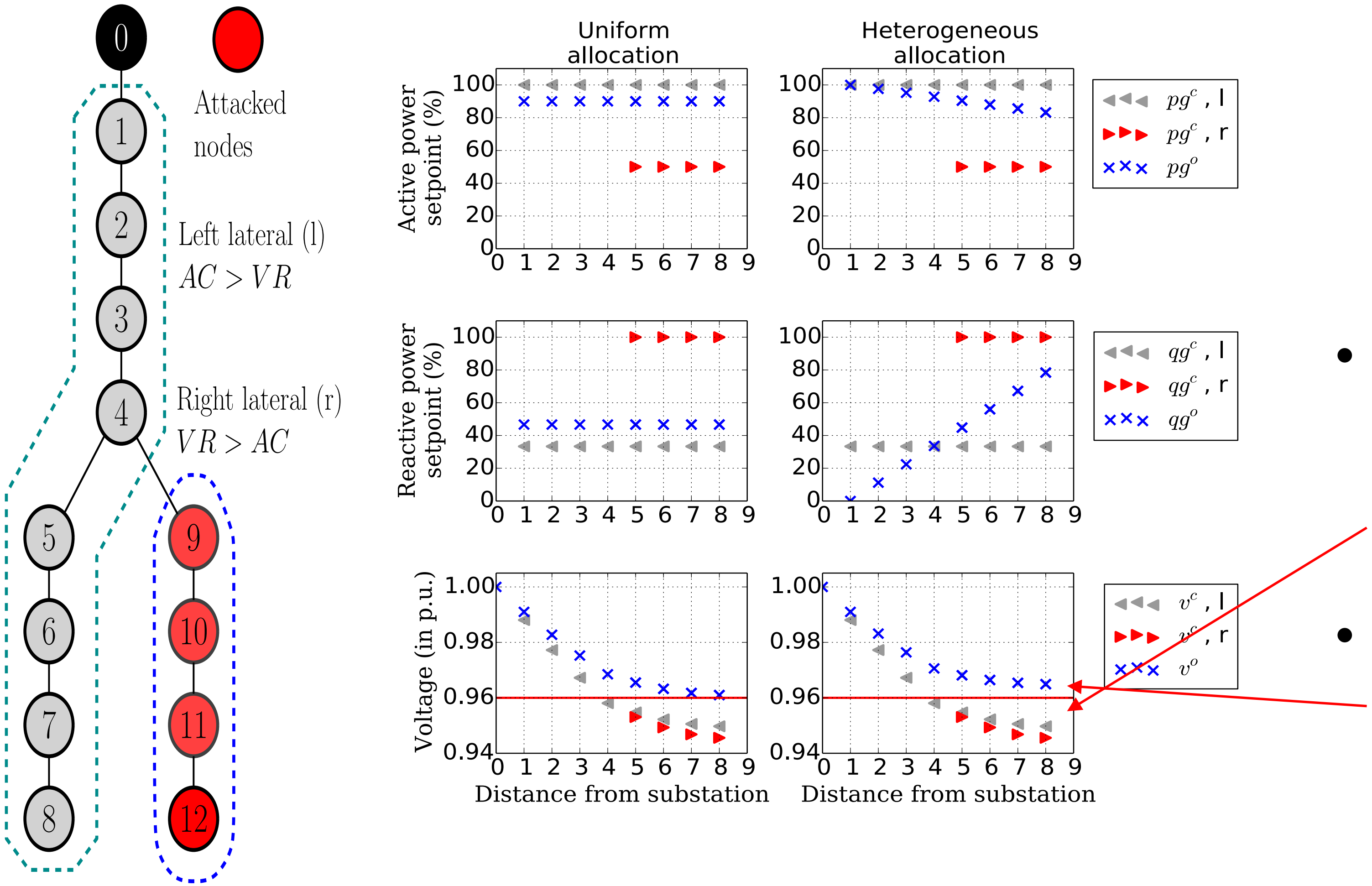
- Some DERs contribute to L_{VR} more than L_{AC}, and vice versa

Defender Response and Allocation: Diversification



- Diversification holds for "heterogeneous allocation" with downstream DERs with more reactive power

Defender Response and Allocation: Diversification



- Post-contingency losses are the same for uniform vs. heterogeneous resource allocations
- Pre-contingency voltage profile is better for heterogeneous resource allocation

Heterogeneous resource allocation can support more loads than uniform one.

Big picture: Where does it all fit?

$$\min_{r \in \mathcal{R}} C_{alloc}\left(x^{o}(r)\right) + \max_{a \in \mathcal{A}} \min_{d \in \mathcal{D}} L\left(x^{c}(r, a, d)\right)$$

- Powerflows, DER capabilities, voltage bounds
- Defender model (resources and capabilities)
- Attacker model (resources and capabilities)

Resilience-Aware Optimal Power Flow (RAOPF)

Resiliency-Aware OPF - Trilevel formulation

Voltage deviation model

$$V^{nom} - V_0^c = -V^{reg}(P_0^o - P_0^c)$$

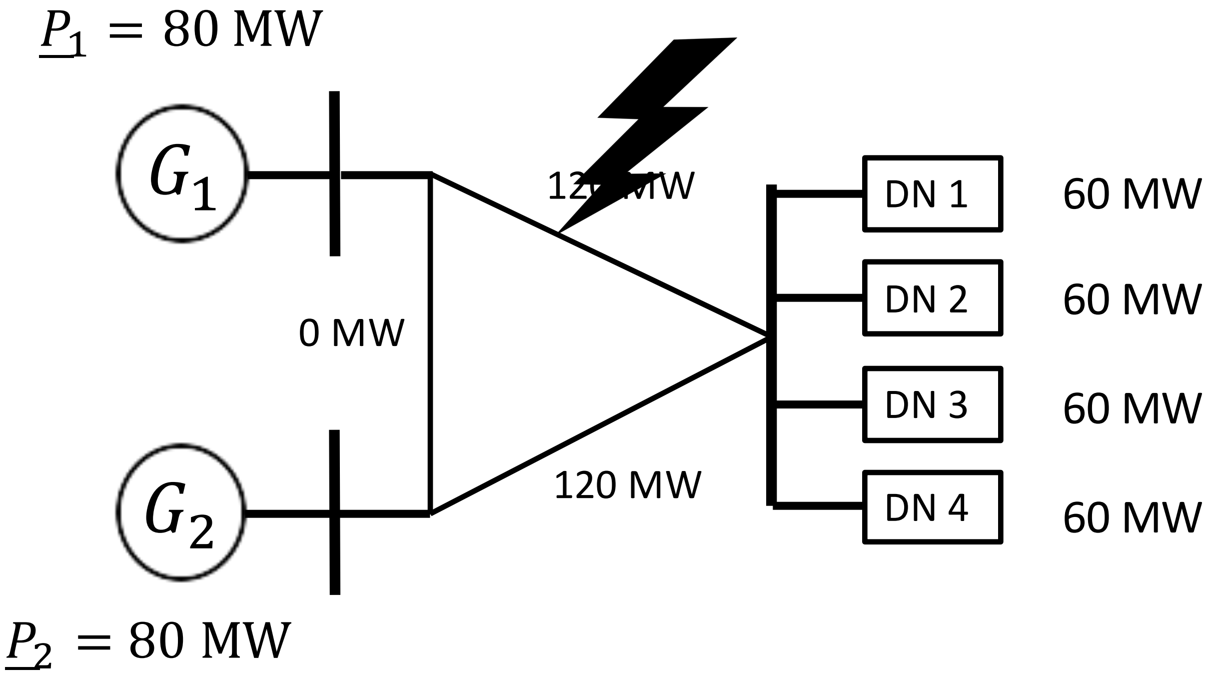
Frequency deviation model

$$f^{nom} - f^c = -f^{reg}(Q_0^o - Q_0^c)$$

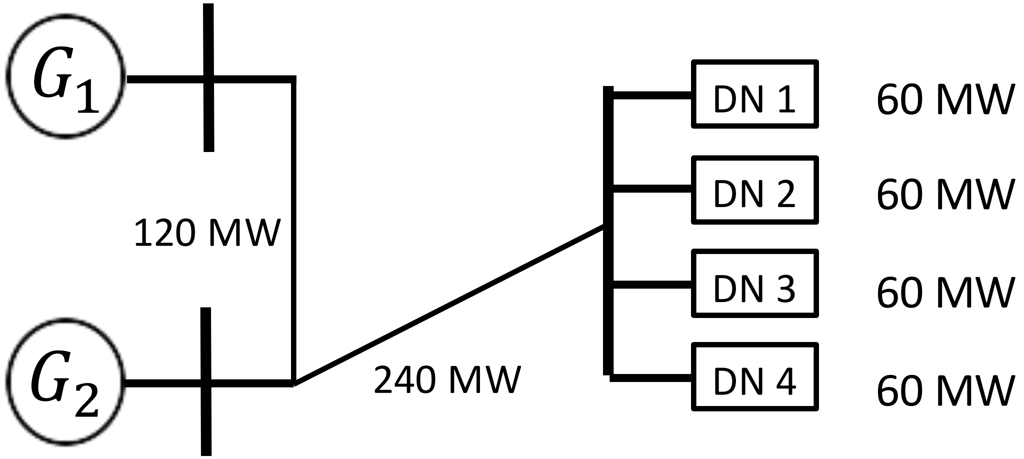
Pre-contingency resource allocation

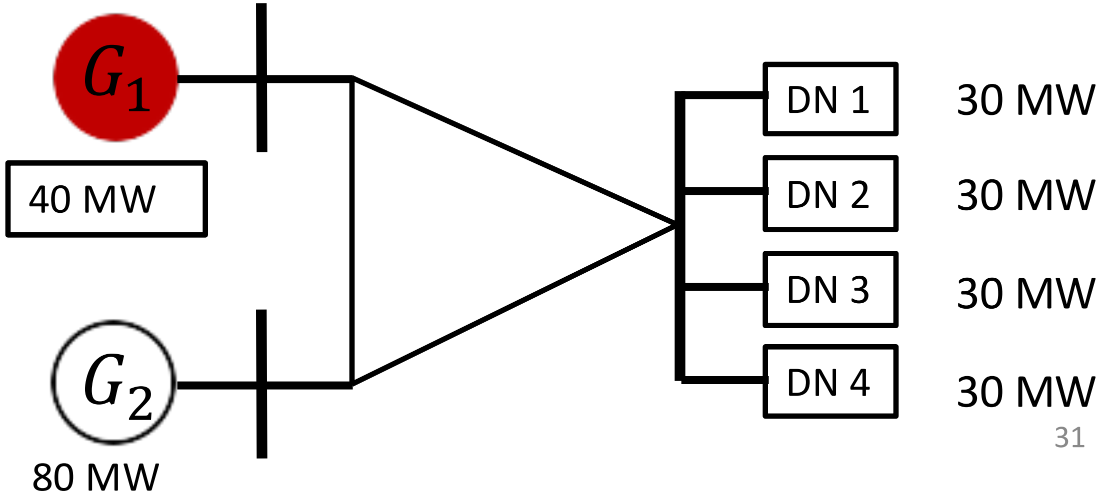
$$r = (pr^o, qr^o)$$

Final example: DN resiliency is indeed important



- Normal operating scenario
- Lightning strikes - recloser opens temporarily
- Voltage drops at the DN substations
- Microgrid islanding reduces net load
- Infeasible power flow in TN





Summary

- Resource allocation and dispatch in electricity DNs
    - under strategic cyber-physical failures
    - trilevel mixed-integer formulation
- Multi-regime defender response
- Application of Benders cut approach for solving bilevel MILPs
- Structural results on worst-case attacks and tradeoffs for defender response

Future work

- Design of decentralized defender response using message passing
- Power restoration over multiple time periods

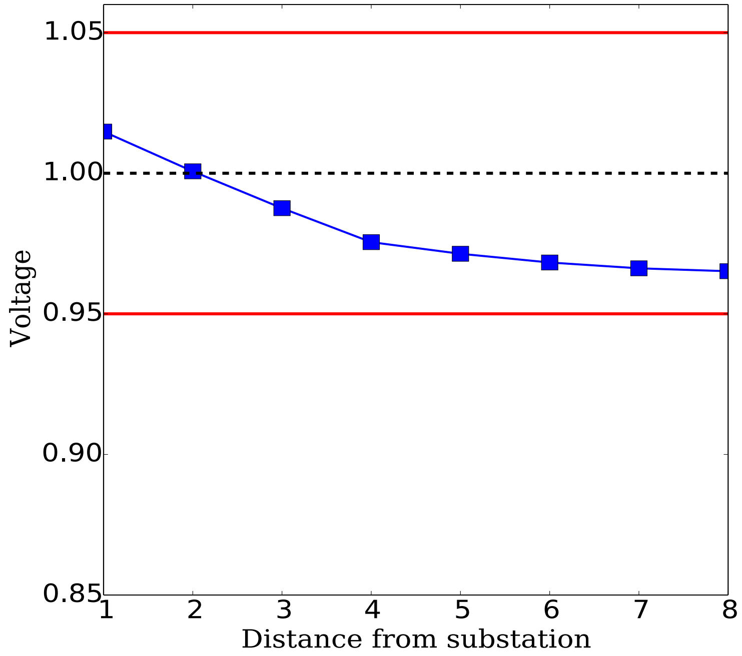
Optimal attacker set-points

Typically,

- Small line losses: in comparison to power flows
- Small impedances: sufficiently small line resistances

Assume for simplicity:

- No reverse power flows: power flows from substation to downstream



What are optimal attacker set-points?

Proposition: For a defender action ϕ, and given attacker choice of δ, the optimal attacker disturbance is given by:

$$pd^{a^\star} = pg_i^o, \quad qd^{a^\star} = qg_i^o + \overline{\boldsymbol{sg}}_{\boldsymbol{i}} \text{ (in case of attack on DERs)}$$

$$pd^{a^\star} = pce_i^o, \quad qd^{a^\star} = qce_i^o \text{ (in case of attack on EVs)}$$

Benders cut approach

Proposition (Bienstock 2009)
Optimal value attack problem for a **fixed attack cardinality** is equivalent to a minimum cardinality attack problem for a **fixed target loss value**.

Benders cut approach

Optimal value attack problem for a **fixed attack cardinality** is equivalent to a minimum cardinality attack problem for a **fixed target loss** value.

L_{target} : minimum loss that the attacker wants to inflict upon the defender

Attacker Master problem

- Initialize with no cuts

$$\min \sum_i \delta_i$$

$$\text{s.t. cuts}$$

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

Defender problem

$$\min_{d \in \mathcal{D}} L(x)$$

s.t.

- Powerflows, DER capabilities, voltage bounds
- Defender model (resources and capabilities)

Benders cut

- Let δ^{iter} be fixed attacker strategy for current iteration
- Let ϕ_I (resp. ϕ_C) denote a defender response with fixed integer variables
- Then the inner problem becomes a linear program (LP)

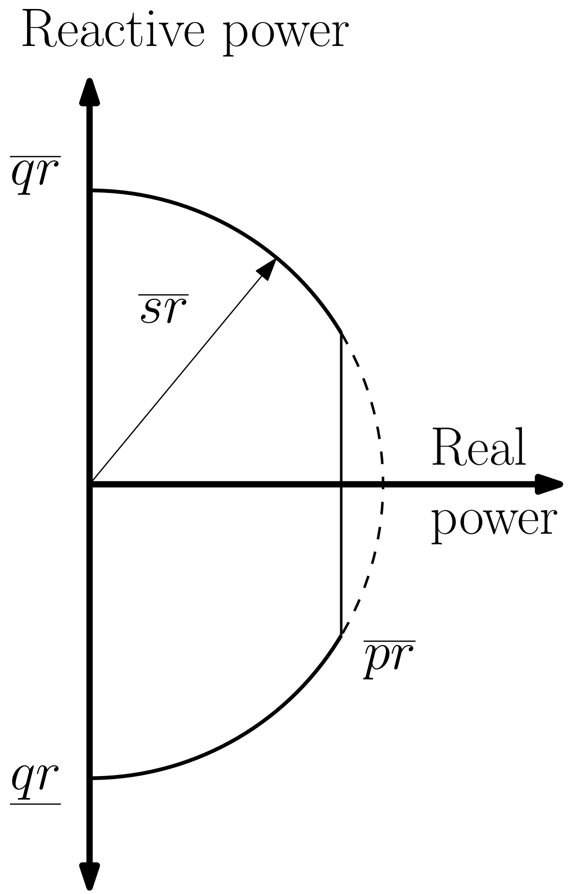
$$LP\left(\delta^{iter}, \phi_I\right) \equiv \quad \begin{aligned} &\min\ c^T y \\ &s.t.\ Ay \geq b \\ &\qquad Cy = d + Q\delta^{iter} \end{aligned}$$

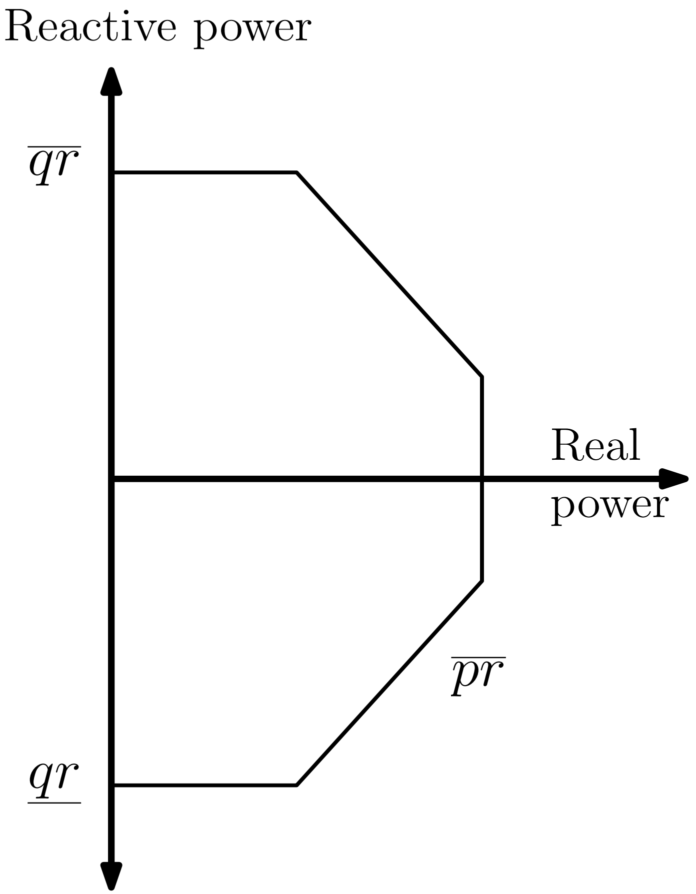
- Let $(\lambda^\star, \alpha^\star)$ be the optimal dual variable solution to this LP.

Benders cut is given by : ${\lambda^\star}^T b + {\alpha^\star}^T (d + Q\delta) \geq L_{target}$

- This cut eliminates δ^{iter} from feasible space of attacker strategies

Controllable distributed generation model





$0 \leq pr_i \leq \overline{pr}_i,$

$pr_i^2 + qr_i^2 \leq \bar{s}\bar{r}_i^2$

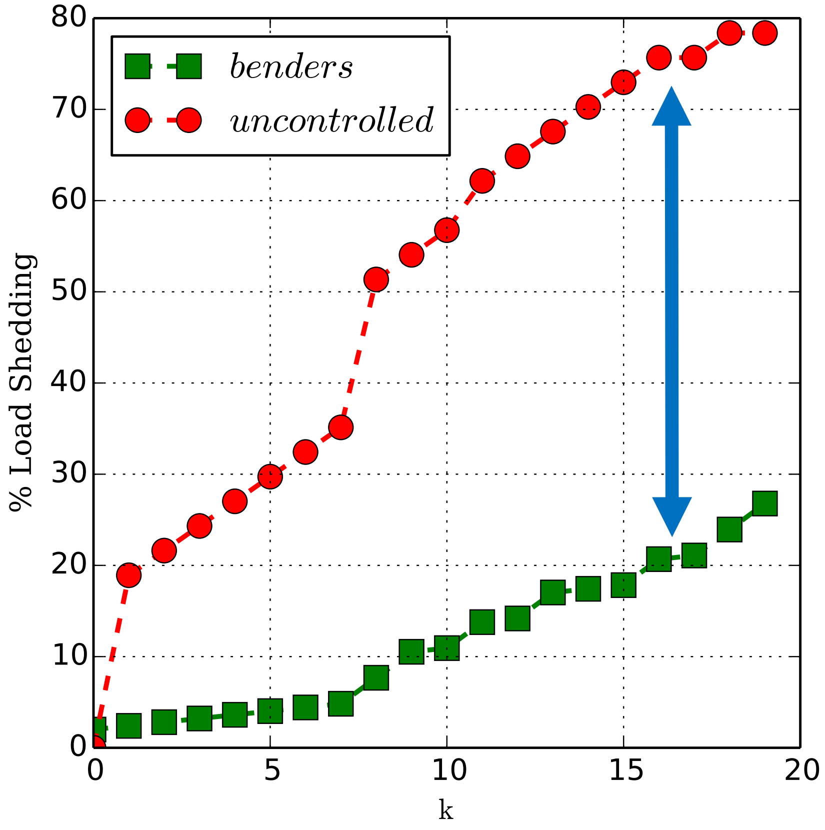
$\overline{pr}_i$ - maximum active power capacity

$\bar{s}\bar{r}_i$ - apparent power capability of inverter

Polytopic model used for computational simplicity

Uncontrolled cascade vs Sequential

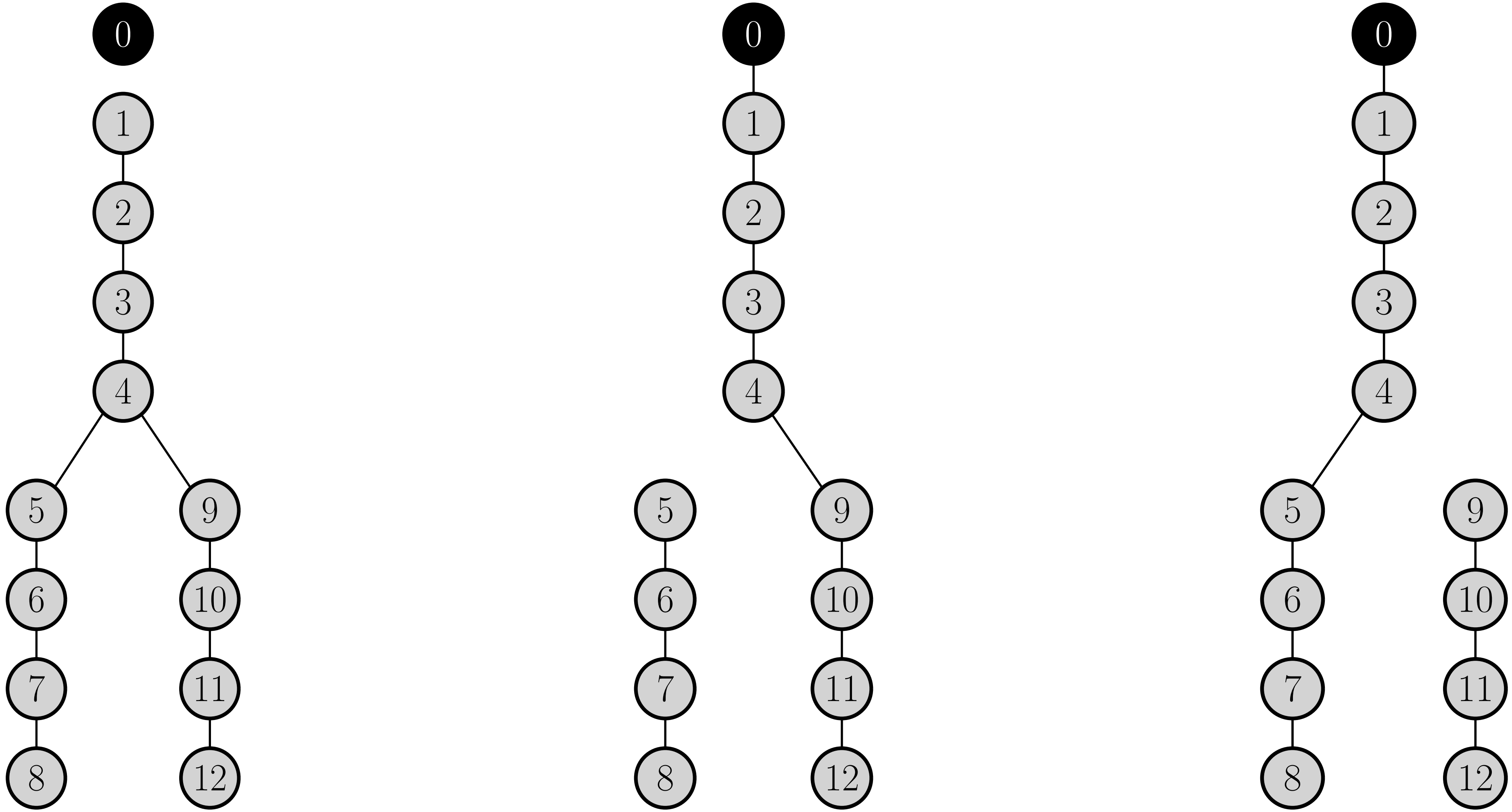
N = 37 nodes



Value of timely response

Microgrid island formation

- $\chi = \{(0,1), (4,5), (4,9)\}$
- 3 out of $8 = 2^{|\chi|}$ possible configurations – 13 node network



Linear power flows after dispatch

Net power consumed at a node i

$$p_i = pc_i - pg_i - pr_i + \delta_i pd^{a\star}_i$$
$$q_i = qc_i - qg_i - qr_i + \delta_i qd^{a\star}_i$$

Power flow on line $i \to j$

$$P_{ij} = \sum_{k:j \to k} P_{jk} + p_i$$

$$Q_{ij} = \sum_{k:j \to k} Q_{jk} + q_i$$

Voltage drop equations

$$V_j = V_i - (r_{ij} P_{ij} + x_{ij} Q_{ij})$$

$$V_0 = V_0^o - \Delta\nu$$

Islanding regime (cont'd)

Updated constraints

- An (emergency) distributed generator is started at node j in a microgrid island

$$|pr_j| \leq \bar{sr}_j \, km_{ij}$$
$$|qr| \leq \bar{sr}_j \, km_{ij}$$

Where pr_j, qr_j is active and reactive power output; $\bar{sr}_j$ is the apparent power capability of the emergency generator at node j

- The net power flow into the node j from the substation is 0, i.e.

$$km_{ij} = 1 \implies P_{ij} = Q_{ij} = 0$$

- The nodal voltage at node j is the nominal voltage,

$$V_j = \begin{cases} V_i - \left(r_{ij}P_{ij} + x_{ij}Q_{ij}\right), & \text{if } km_{ij} = 0 \\ V^{\text{nom}}, & \text{otherwise.} \end{cases}$$

What's next?

- What is a good resiliency metric?
  - Allowable $\Delta(V, p, q)$ without exceeding target 20% L_{SD}

- General case $|\chi| > 1$
  - Diversification?
  - Solution approach for RAOPF (trilevel)?

Resiliency-aware Resource Allocation

Stage I - Allocation of DERs over radial networks

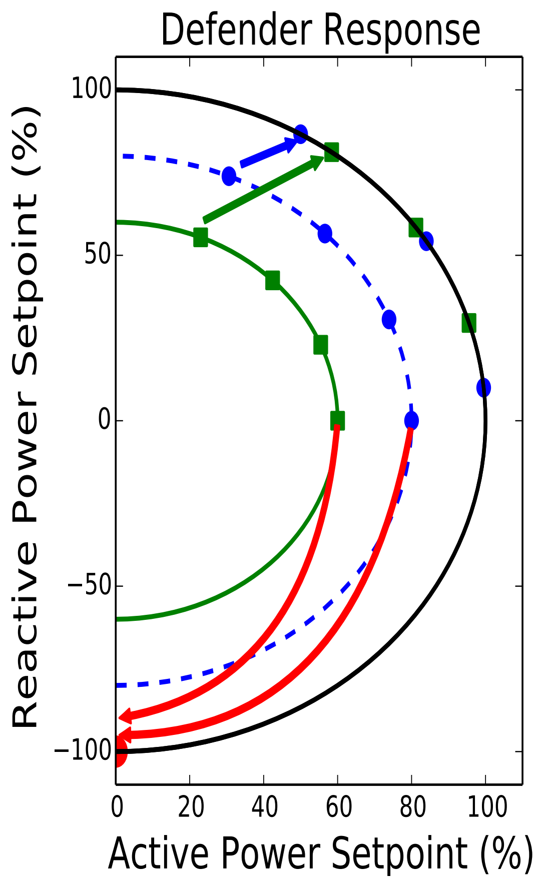
a. Size and location
b. Active and reactive power setpoints (x^n)?

Stage II - Adversarial node disruptions

a. Which nodes to compromise (δ)?
b. Set-point manipulation (sp^a)?

Stage III - Optimal dispatch / response (x^c)

a. Maintain voltage
b. Exercise load control or not



Goals:

1. Determine the best resource allocation
2. Identify vulnerable / critical nodes
3. Determine optimal dispatch post-contingency

Microgrid formation (cont'd)

Updated constraints

$$p_i = pc_i - pg_i - pr_i + \delta_i pd^{a^\star}_i \ - pe_i$$
$$q_i = qc_i - qg_i - qr_i + \delta_i qd^{a^\star}_i \ - qe_i$$

$$|P_{ij}| \leq \overline{Cap}_{ij}(1 - km_{ij})$$
$$|Q_{ij}| \leq \overline{Cap}_{ij}(1 - km_{ij})$$

$$|v_j - v^{nom}| \leq (1 - km_{ij})$$
$$|v_j - \left(v_i - 2(r_{ij}P_{ij} + x_{ij}Q_{ij})\right)| \leq km_{ij}$$

- An emergency generator of microgrid is on only if it is in islanded state

$$\left|pe_j\right| \leq \overline{se}_j \ km_{ij}$$
$$\left|qe_j\right| \leq \overline{se}_j \ km_{ij}$$