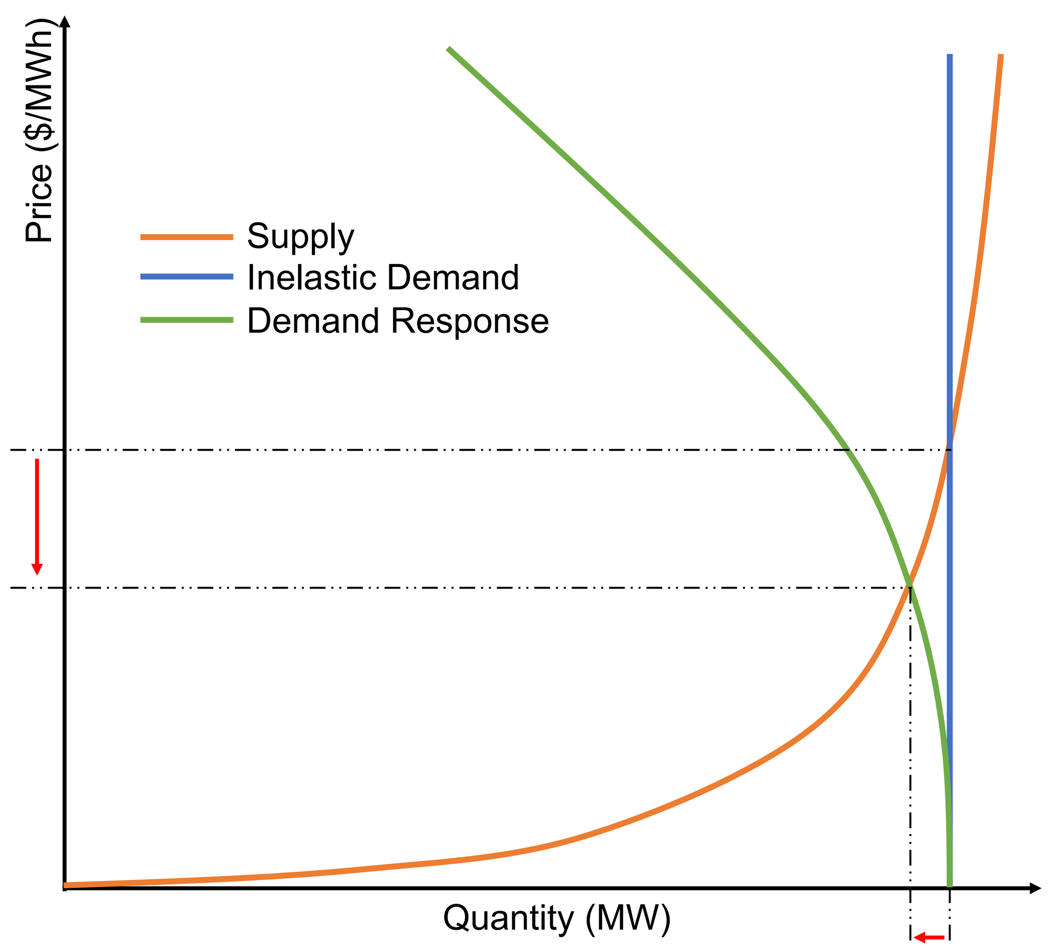
Sandia National Laboratories

Evaluating Demand Response (DR) Opportunities for Power Systems Resilience Using MILP and MINLP Formulations

Motivation

- Catastrophic events result in \$18-70 billion/year in consequences and recovery costs in the U.S.
- Large industrial consumers can improve power grid resilience by modulating their load during these extreme events



Goal of Our Study

Quantifying the tradeoff between required capital investment in the grid and the benefits of potential demand response (DR) partnerships can help process facilities make operational or investment decisions in support of these arrangements.

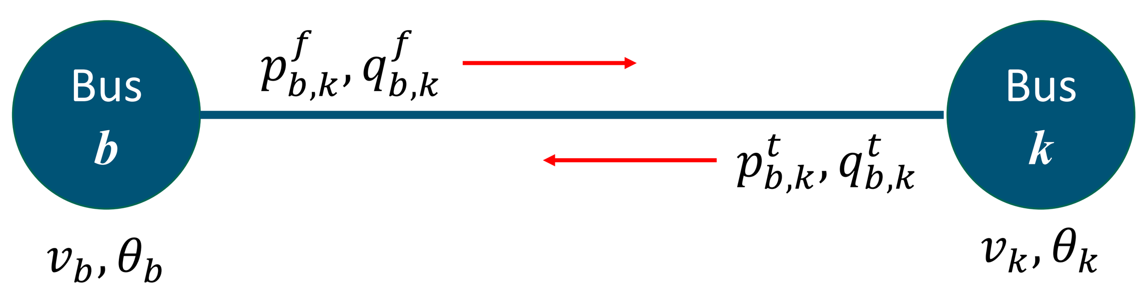
Technical Approach

- Construct 100 weather-event scenarios with N line-outages per scenario
- Solve a stochastic programming approach to assess the value of DR compared to transmission line hardening for uncertain, extreme events
- Compare the AC power flow (nonconvex MINLP) with the DC approximation (MILP) formulation for transmission hardening versus DR contracts on an AC power grid

AC Power Flow versus DC Power Flow Formulation

AC Power Flow (ACPF) Formulation Nonconvexities:

$$p^f_{b,k} = G^1_{b,k}v_b^2 - v_b v_k(G^2_{b,k}\cos(\theta_b-\theta_k) - B^2_{b,k}\sin(\theta_b-\theta_k))$$
$$p^t_{b,k} = G^4_{b,k}v_k^2 - v_b v_k(G^3_{b,k}\cos(\theta_b-\theta_k) - B^3_{b,k}\sin(\theta_b-\theta_k))$$
$$q^f_{b,k} = -B^1_{b,k}v_b^2 + v_b v_k(B^2_{b,k}\cos(\theta_b-\theta_k) + G^2_{b,k}\sin(\theta_b-\theta_k))$$
$$q^t_{b,k} = -B^4_{b,k}v_k^2 + v_b v_k(B^3_{b,k}\cos(\theta_b-\theta_k) + G^3_{b,k}\sin(\theta_b-\theta_k))$$



DC Power Flow (DCPF) Formulation Assumptions:

- Resistance << Reactance (implies G << B)
- Nominal Voltage Magnitude (|V| ≈ 1 per-unit)
- Small Voltage Angle Difference ($\sin(\theta_b - \theta_k) \approx \theta_b - \theta_k$)

Transmission Line Hardening versus Demand Response (DR):

$$\min |Y|_{true}$$

s.t.

ACPF (or DCPF) Constraints and other Operational Limits

$$\begin{bmatrix} X^H_{s,l} \\ p^f_{b,k}, p^t_{b,k}, q^f_{b,k}, q^t_{b,k} \\ -\bar{\Theta} \le \theta_b - \theta_k \le \bar{\Theta} \end{bmatrix} \veebar \begin{bmatrix} \neg X^H_{s,l} \\ p^f_{b,k}, p^t_{b,k}, q^f_{b,k}, q^t_{b,k} = 0 \end{bmatrix}$$

Line-outages per scenario *s*

$Y_l \overset{true}{\Longleftrightarrow} X^H_{s,l}$ **Line selected for hardening**

$$\begin{bmatrix} X^D_{s,b} \\ (1-\Delta_b)P^L_b \le p^L_{s,b} \le P^L_b \end{bmatrix} \veebar \begin{bmatrix} \neg X^D_{s,b} \\ p^L_{s,b} = P^L_b \end{bmatrix}$$

$X^D_{s,b}$ *is false* **Buses in scenario *s* not candidates (or selected) for DR**

$Z_b \overset{true}{\Longleftrightarrow} X^D_{s,b}$ **Buses selected for DR**

$|Z|_{true} \le N_z$ **Limit on buses selected for DR**

For increasing values of N_z, Computes minimum number of lines to harden to ensure feasible operations across all weather-event scenarios

Solution Technique

DCPF-Based Approach:

→ MILP Formulation with Big-M Transformations
→ Solve with Commercial B&B (Gurobi)
→ Approximation is Solved Exactly

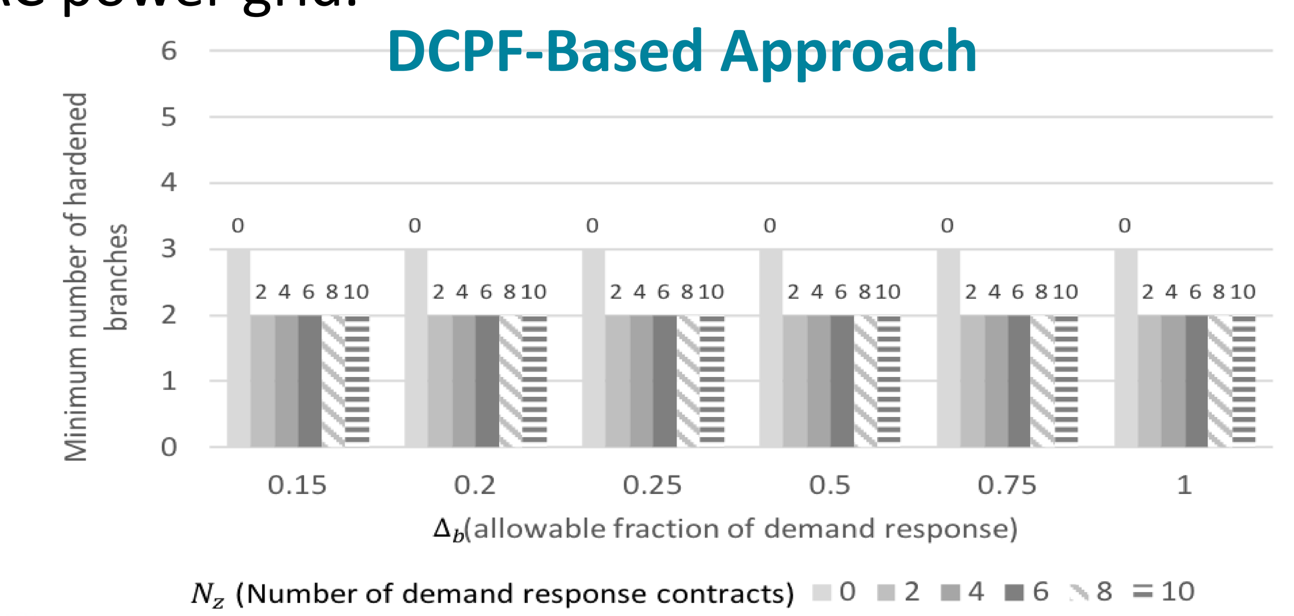
ACPF-Based Approach:

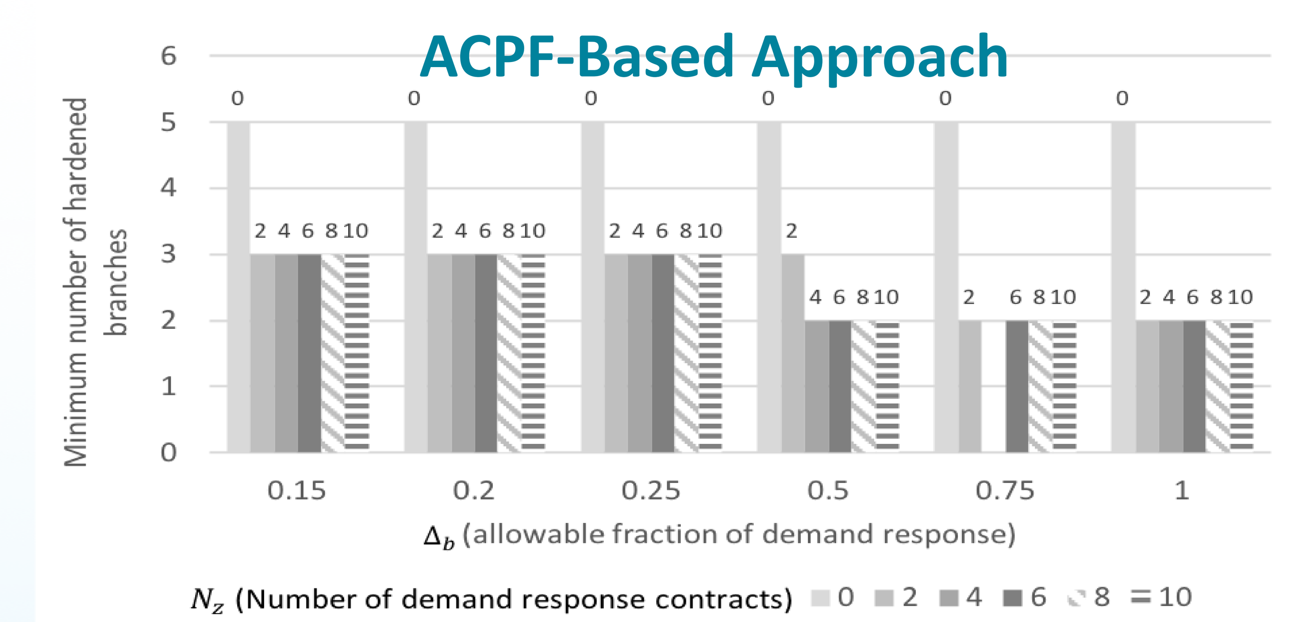
→ Nonconvex MINLP Formulation with Big-M
→ Solve with Multi-Tree Approach
- Lower-Bounding: MISOCP (Solve with Gurobi)
- Upper-Bounding: NLP (Solve with IPOPT)

→ If Zero Gap, then Formulation is Solved Globally

Summary Results

DCPF-based approach results in solutions that are suboptimal and, at times, infeasible for operations on an AC power grid.





dataset: pglib_opf_case30_as (pglib-opf v19.01)

Future Work

Improve Scalability of MINLP (see poster: "Decomposing Optimization Based Bounds Tightening via Graph Partitioning")

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NNSA National Nuclear Security Administration
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SAND No. ___________

Michael Bynum mlbynum@sandia.gov
Anya Castillo arcasti@sandia.gov
Jean-Paul Watson jwatson@sandia.gov
Carl D. Laird cdlaird@sandia.gov

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