Transmission Network Investment with Distributed Energy Resources and Distributionally Robust Security

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The Problem
Traditionally has been delivered by:

- Asset redundancy (more investment).
- Generation reserves.

Demand-side technologies can also contribute [1]:

- Through post-contingency corrective control.
- Taking advantage of Distributed Energy Resources (DER), including the flexibility of demand itself.
- Could displace the need for network redundancy.
Outages have been considered in two fashions in the context of planning [2]:

- **Deterministic:**
  - Widely used in the industry.
  - Likelihood of outages is neglected.
  - Impossible to balance pre- and post-contingency costs.

- **Probabilistic/stochastic:**
  - Can properly balance the costs of different corrective measures.
  - Assumes perfect information of reliability data.
Minimization is made against the worst-case distribution within an ambiguity set.

Ambiguity set is constructed using historical data (data driven).

Acknowledges the fact that failure rates are not completely known.

Can properly assess the contribution of different resources to security.
DER Services
DER’s contribution to security (1)

Aggregator
Offers under-contingency services acting on behalf of a group of people.

These services are physically provided by different resources:
- Back up generation
- Distributed generation
- Flexible demand
- Storage technologies

In case of a contingency the services would be delivered through corrective control.

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DER’s contribution to security (2)

Service #1: Demand reduction/DG increase.

- Represented by a stepped cost.
- The last step is the VoLL.
- Voluntary services must be scheduled.
- Its cost is the supply curve offered by the aggregator.
Service #2: DG reduction/demand increase.

- Represented by a stepped cost.
- The last step is involuntary.
- Voluntary services must be scheduled.
- Its cost is the supply curve offered by the aggregator.
DER’s contribution to security (4)

Service #3: Demand Shifting.

\[
\delta \sum_{i} \Delta_i^- = \sum_{i} \Delta_i^+ \\
\delta > 1 \text{ (Payback)}
\]
Formulation
Formulation (1)

\[
\min CI(x) + \sum_{t \in T} CO_t(y) + \sup_{p \in \mathcal{P}_t} \mathbb{E}_p \{ Q_t(x, y, z) \}
\]

s.t.
\[
g(x, y) = 0
\]
Formulation (2)

\[
\begin{align*}
\min CI(x) &+ \sum_{t \in T} CO_t(y) + \sup_{p \in P_t} \mathbb{E}_p\{Q_t(x, y, z)\} \\
\text{s.t.} & \quad g(x, y) = 0
\end{align*}
\]
Formulation (3)

\[\min CI(x) + \sum_{t \in T} CO_t(y) + \sup_{p \in \mathcal{P}_t} \mathbb{E}_p \{ Q_t(x, y, z) \}\]

\[s.t.\]
\[g(x, y) = 0\]

**Investment cost:**
- New network infrastructure
Formulation (4)

$$\min CI(x) + \sum_{t \in T} CO_t(y) + \sup_{p \in P_t} \mathbb{E}_p \{Q_t(x, y, z)\}$$

s. t.

$$g(x, y) = 0$$

**Operation cost:**
- Fuel Costs
- Reserves scheduling
- Scheduling of DER services
Formulation (5)

\[
\min CI(x) + \sum_{t \in T} CO_t(y) + \sup_{p \in P_t} \mathbb{E}_p\{Q_t(x, y, z)\}
\]

s. t.
\[
g(x, y) = 0
\]

Worst case expected cost of corrective actions:
- Reserves utilization
- Voluntary DER services utilization
- Load shedding and generation spillage
Formulation (6)

\[
\min CI(x) + \sum_{t \in T} CO_t(y) + \sup_{p \in \mathcal{P}_t} \mathbb{E}_p \{Q_t(x, y, z)\}
\]

\[
\text{s. t.} \quad g(x, y) = 0
\]

Minimum-cost corrective actions under contingency:
DC power flow – lines capacity – reserves and DER services utilization – power balance – ramping limits – maximum utilization of resources – energy payback
Formulation (7)

\[
\min CI(x) + \sum_{t \in T} CO_t(y) + \sup_{p \in \mathcal{P}_t} \mathbb{E}_p \{Q_t(x, y, z)\}
\]

s. t.

\[g(x, y) = 0\]
Ambiguity set selection

The ambiguity set consists of all probability distributions that satisfy a set of linear constraints on failure rates, given a support for the vector $z$ (that is, a set of contingencies considered):

$$\mathbb{E}_p(S_t \cdot (1 - z)) \leq \mu_t$$

Choosing matrix $S$ and vector $\mu$ properly, we can get different approaches:

1. Robust.
2. Fixed probabilities.
3. Anything in between.
Solution methodology
Solution Methodology (1)

\[
\begin{align*}
\min CI(x) + \sum_{t \in T} CO_t(y) + \sup_{p \in \mathcal{P}_t} \mathbb{E}_p \{ Q_t(x, y, z) \} \\
\text{s.t.} \quad g(x, y) = 0
\end{align*}
\]
Solution Methodology (2)

\[
\begin{align*}
\min & \quad CI(x) + \sum_{t \in T} CO_t(y) + \Phi_t \\
\text{s.t.} & \quad g(x, y) = 0 \\
\Phi_t & = \left\{ \max_{p \in P_t} \sum_{z \in \Omega} Q_t(x, y, z) p(z) \right. \\
\text{s.t.} & \quad \sum_{z \in \Omega} S_t(1 - z) p(z) \leq \mu_t \\
& \quad \sum_{z \in \Omega} p(z) = 1 \quad \forall t \in T
\end{align*}
\]
Solution Methodology (3)

\[
\min CI(x) + \sum_{t \in T} CO_t(y) + \mu_t \cdot \tau_t + \alpha_t \\
\text{s.t.} \quad g(x, y) = 0 \\
\alpha_t \geq Q_t(x, y, z) - \tau_t^T S_t(\vec{1} - z) \quad \forall z \in \Omega, t \in T \\
\tau_t \geq 0 \quad \forall t \in T
\]
Solution Methodology (4)

\[
\min CI(x) + \sum_{t \in T} CO_t(y) + \mu_t \cdot \tau_t + \alpha_t
\]

s.t. \[ g(x, y) = 0 \]

\[
\alpha_t \geq \max_{z \in \Omega} \{ Q_t(x, y, z) - \tau_t^T S_t(1 - z) \} \quad \forall t \in T
\]

\[
\tau_t \geq 0 \quad \forall t \in T
\]
Solution Methodology (5)

\[
\min CI(x) + \sum_{t \in T} CO_t(y) + \mu_t \cdot \tau_t + \alpha_t \\
\text{s.t. } g(x, y) = 0 \\
\alpha_t \geq \max_{z \in \Omega} \{ Q_t(x, y, z) - \tau_t^T S_t(\hat{1} - z) \} \ \forall t \in T \\
\tau_t \geq 0 \ \forall t \in T
\]

Iteratively approximated by Benders’ cuts
Study Case: IEEE 24 bus RTS
10 candidate transmission assets (redundancy), that connect high voltage exporting area to low voltage importing area.

- New 2000 MW of thermal generation.
- New 1800 MW of peak load.
- New 300 MW of wind generation.
- 40 combinations of wind and demand.
## Cases Description

- **Study cases:**

<table>
<thead>
<tr>
<th>Case</th>
<th>Involuntary curtailment</th>
<th>Voluntary DER services*</th>
<th>Ambiguity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional N-1</td>
<td>No</td>
<td>No</td>
<td>Complete</td>
</tr>
<tr>
<td>Improved N-1</td>
<td>No</td>
<td>Yes</td>
<td>Complete</td>
</tr>
<tr>
<td>Stochastic</td>
<td>Yes</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>Distributionally robust</td>
<td>Yes</td>
<td>Yes</td>
<td>±30% Interval and bounded total failure rate.</td>
</tr>
</tbody>
</table>

*Available on 10 nodes (demand disconnection 13%, DG disconnection 6%, shifting 5%).
Case 1: Traditional N-1

- Significant investment: 7 network assets (4 transformers and 3 lines).
- Highest amount of reserves held to deal with generation outages and network congestion.
- As DER is prevented from providing security, high levels of redundancy in both transmission and generation were needed.
Case 2: Improved N-1

- Considerably less investment: only 5 assets (3 transformers and 2 lines).
- Less generation reserves scheduled.
- DER services were capable of displacing need for investment and reserves.
Case 2: Improved N-1

Effects of demand shifting
Case 3: Stochastic

- Investment drops even further, to 3 assets (2 transformers and 1 line).

- Average amount of reserves held is considerably less than the previous case.

- DER and further post-contingency control actions significantly displaced redundancy.
Case 4: Distributionally robust

- When facing ambiguity in reliability data the models hedges against risk through:
  - Higher investment (1 extra line).
  - Higher volumes of operational measures (reserves and DER).

- The model is more protected against outages with higher impact (decision dependent).

- Assuming perfect information on reliability overestimates the amount of investment that can be displaced by demand services.
Out of sample analysis

- A two-level Monte Carlo simulation was carried out, first level chooses a probability distribution, the second one simulates outages.
- Number of random probability distributions: 3000.
- Number of simulated scenarios for each distribution: 10000 (considering outages beyond N-1).
- Used to compute expected utilization cost of corrective control.
- CVaR and LOLE were the risk metrics computed.
# Results summary

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Case #1</td>
<td>38.3</td>
<td>295.7</td>
<td>60.6</td>
<td>-</td>
<td>-</td>
<td>0.46/0/0.75</td>
<td>395.8</td>
<td>117.4</td>
<td>0.48</td>
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<tr>
<td>Case #2</td>
<td>27.1</td>
<td>289.3</td>
<td>19.1</td>
<td>15.5</td>
<td>0.17</td>
<td>0.31/0.59/0.61</td>
<td>352.7</td>
<td>142.1</td>
<td>0.40</td>
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<tr>
<td>Case #3</td>
<td>17.7</td>
<td>283.7</td>
<td>12.5</td>
<td>15.3</td>
<td>0.12</td>
<td>0.22/0.66/4.00</td>
<td>334.1</td>
<td>473.5</td>
<td>7.67</td>
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<tr>
<td>Case #4</td>
<td>19.1</td>
<td>283.5</td>
<td>12.7</td>
<td>15.4</td>
<td>0.14</td>
<td>0.22/0.64/2.75</td>
<td>334.2</td>
<td>346.6</td>
<td>4.06</td>
</tr>
</tbody>
</table>

*All costs are in M$/year.*

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Study Case: IEEE 118 bus
118 bus system: description

- 400 MW of peak load added to buses 60 and 62 and 500 MW added to bus 90.
- All 10 candidate assets chosen are lines (the ones that connect buses 60-62-90 with the rest of the system).
- Failure rate for generators was set to 0.1%.
- One outage per 100km per year was used in lines.
- 10 nodes providing demand services (10% of demand on load disconnection, 6% GD disconnection, 5% on load shifting).
118 bus system: results

<table>
<thead>
<tr>
<th>Case</th>
<th>Number of time blocks</th>
<th>Number of snapshots</th>
<th>Serial or Parallel</th>
<th>Execution Time [min]</th>
<th>Maximum RAM used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>10</td>
<td>2</td>
<td>Parallel</td>
<td>177</td>
<td>14</td>
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<tr>
<td>More time blocks</td>
<td>20</td>
<td>2</td>
<td>Parallel</td>
<td>289</td>
<td>16</td>
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<tr>
<td>More snapshots</td>
<td>10</td>
<td>3</td>
<td>Parallel</td>
<td>353</td>
<td>15</td>
</tr>
<tr>
<td>Serial solving</td>
<td>10</td>
<td>2</td>
<td>Serial</td>
<td>861</td>
<td>4</td>
</tr>
</tbody>
</table>

*All cases were solved using 2 x Intel Xeon E5-2660 10 cores each, and 48 GB of RAM.*
Conclusions

- The proposed model properly recognizes both the participation of DER in security and the limited knowledge of reliability data.
- We showed the advantages of the distributionally robust approach against N-1 and stochastic solutions.
  - The first undermines the value of DER displacing investment.
  - The latter is too optimistic.
- DER can not only replace reserves, but also enable the use of a more cost-effective kind.
1. K. Moslehi and R. Kumar, “A reliability perspective of the smart grid”.


3. C. Zhao and R. Jiang, “Distributionally Robust Contingency-Constrained Unit Commitment”.

References
Acknowledgements

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