Transmission Network Investment with Distributed Energy Resources and Distributionally Robust Security

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The Problem

Network Security (1)

- 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.

Network Security (2)

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.

Network Security (3)

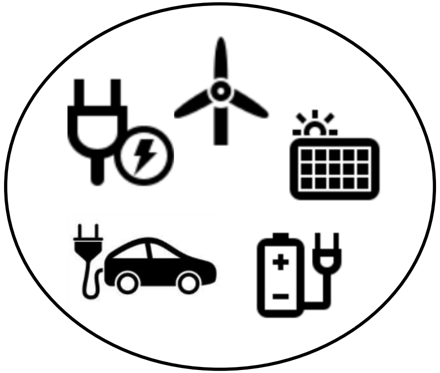
Distributionally Robust approach

- Minimization is made against the worst-case distribution within an ambiguity set.
- Ambiguity set is constructed using historical data (data driven).
- Acknowledges thee 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

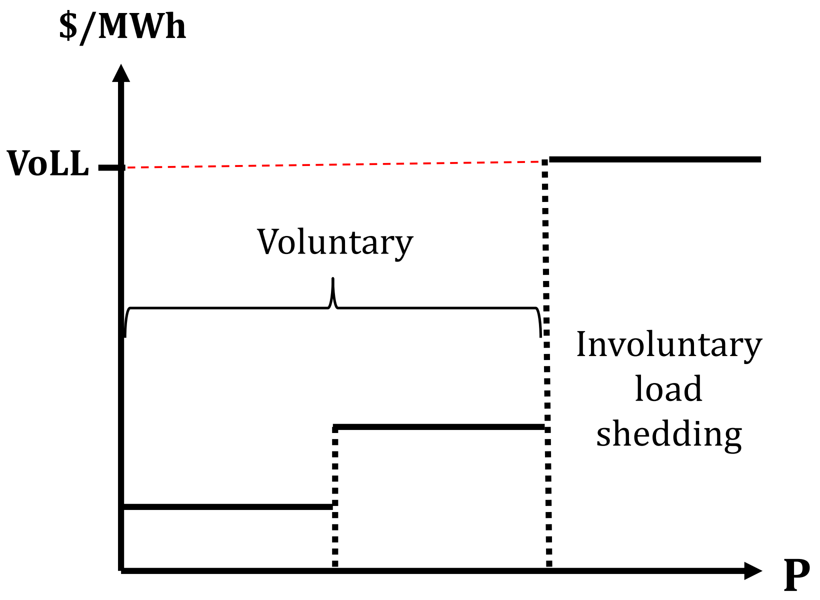
- Back up generation
- Distributed generation
- Flexible demand
- Storage technologies

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

DER's contribution to security (2)

Service #1: Demand reduction/DG increase.

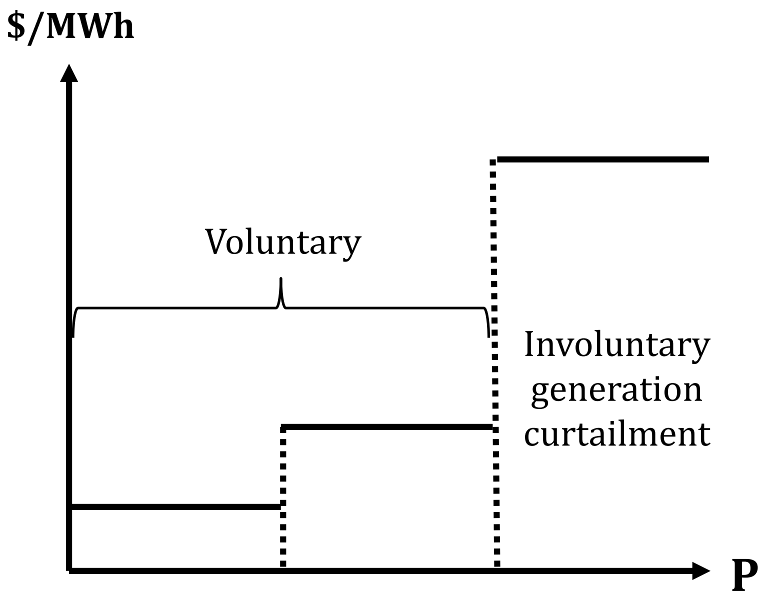
- Represented by a stepped cost.
- The last step is the VoLL.
- Voluntary services must be scheduled.
- Its cost is the supply curve offered by the aggregator.



DER's contribution to security (3)

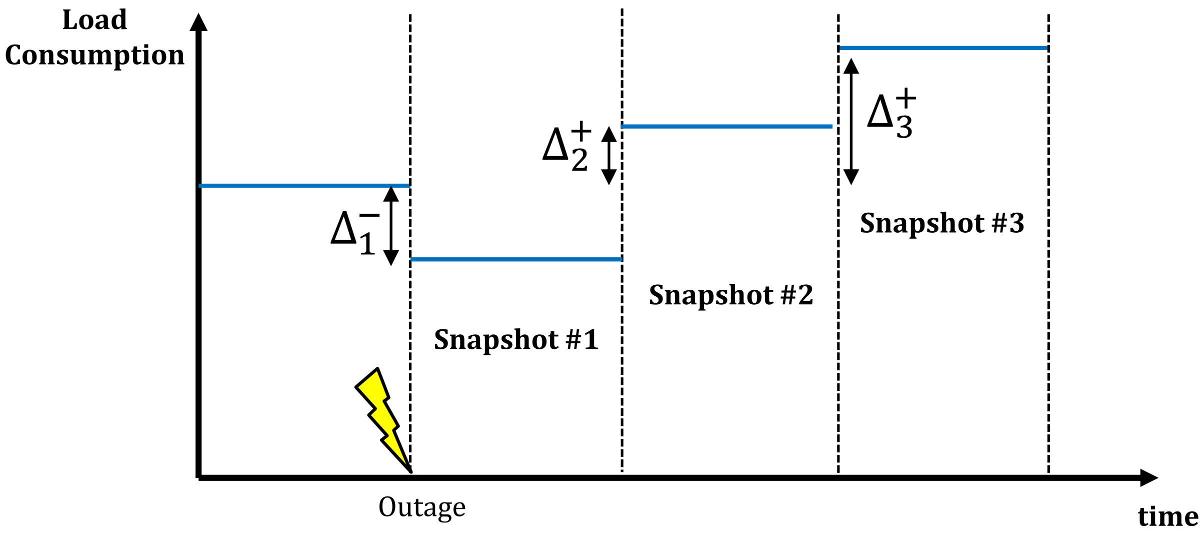
Service #2: DG reduction/demand increase.

- 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.



$$\delta \sum_i \Delta_i^- = \sum_i \Delta_i^+$$

$\delta > 1$ (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)

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

$s.t.$

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

Investment variables

Operation variables

Availability random vector

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 infraestructure

Formulation (4)

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

$s.t.$

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

Operation cost:

- Fuel Costs
- Reserves scheduling
- Scheduling of DER services

Formulation (5)

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

$$s.t.$$

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

Worst case expected cost of corrective actions:

- Reserves utilization
- Voluntary DER services utilization
- Load shedding and generation spillage

Formulation (6)

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

$$s.t.$$

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

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)

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

$s.t.$

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

- DC power flow
- Lines capacity
- Generators commitment
- Generators dispatch
- Nodal balance
- Scheduling of reserves and DER services

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):

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

Choosing matrix S and vector μ properly, we can get different approaches:

1. Robust.
2. Fixed probabilities.
3. Anything in between.

Solution methodology

Solution Methodology (1)

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

$$s.t. \quad g(x, y) = 0$$

Solution Methodology (2)

$$\min CI(x) + \sum_{t \in T} CO_t(y) + \Phi_t$$

$$s.t. \quad g(x, y) = 0$$

$$\Phi_t = \left\{ \begin{array}{l} \max\limits_{p \in \mathcal{P}_t} \sum\limits_{z \in \Omega} Q_t(x, y, z)\, p(z) \\ s.t. \\ \quad \left. \begin{array}{l} \sum\limits_{z \in \Omega} S_t(\vec{1} - z)\, p(z) \le \mu_t \\ \sum\limits_{z \in \Omega} p(z) = 1 \end{array} \right\} \forall t \in T \end{array} \right.$$

Solution Methodology (3)

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

$$s.t. \quad g(x, y) = 0$$

$$\alpha_t \geq Q_t(x, y, z) - \tau_t^T S_t(\vec{1} - z) \;\; \forall z \in \Omega, \mathrm{t} \in T$$

$$\tau_t \geq 0 \;\; \forall \mathrm{t} \in T$$

Solution Methodology (4)

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

$$s.t. \quad g(x, y) = 0$$

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

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

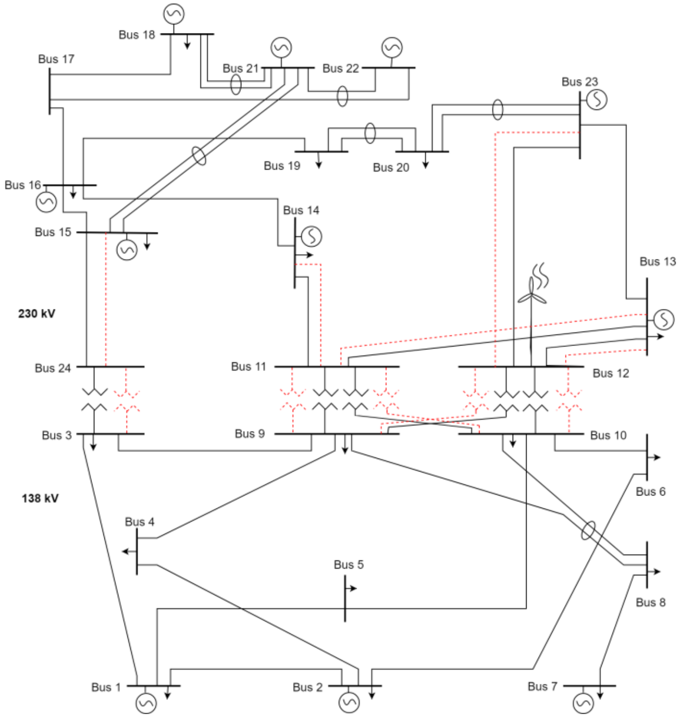
$$\tau_t \geq 0 \quad \forall t \in T$$

Iteratively approximated by Benders' cuts

Study Case: IEEE 24 bus RTS

Modified IEEE 24 bus system (1)

- 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:

Case	Involuntary curtailment	Voluntary DER services*	Ambiguity
Traditional N-1	No	No	Complete
Improved N-1	No	Yes	Complete
Stochastic	Yes	Yes	None
Distributionally robust	Yes	Yes	±30% Interval and bounded total failure rate.

*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.

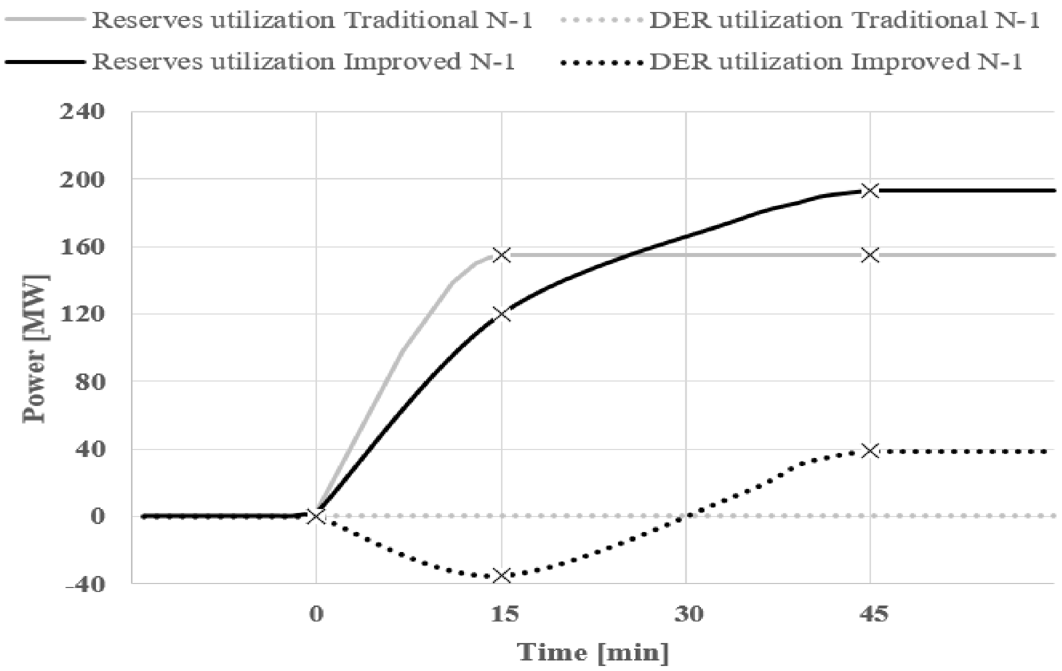
- As DER is prevented from providing security, high levels of redundancy in both transmission and generation were needed.

Case 2: Improved N-1

- Considerably less investment: only 5 assets (3 transformers an 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

Case	Investment	Planned Operation	Reserves Avail.	Demand Response Avail.	Demand Shifting Avail.	Corrective Contr. Util. Gen/Dem/Invol.	Total	Expected Corrective Costs (CvAR 1% on outages)	LOLE (hours)
Case #1	38.3	295.7	60.6	**-**	**-**	0.46/0/0.75	**395.8**	117.4	0.48
Case #2	27.1	289.3	19.1	15.5	0.17	0.31/0.59/0.61	**352.7**	142.1	0.40
Case #3	17.7	283.7	12.5	15.3	0.12	0.22/0.66/4.00	**334.1**	473.5	7.67
Case #4	19.1	283.5	12.7	15.4	0.14	0.22/0.64/2.75	**334.2**	346.6	4.06

**All costs are in M$/year.*

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

Case	Number of time blocks	Number of snapshots	Serial or Parallel	Execution Time [min]	Maximum RAM used
Baseline	10	2	Parallel	177	14
More time blocks	**20**	2	Parallel	289	16
More snapshots	10	**3**	Parallel	353	15
Serial solving	10	2	**Serial**	861	4

**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.

References

1. K. Moslehi and R. Kumar, *“A reliability perspective of the smart grid”.*
2. R. Moreno, D. Pudjianto, and G. Strbac, *“Transmission network investment with probabilistic security and corrective control”*
3. C. Zhao and R. Jiang, *“Distributionally Robust Contingency-Constrained Unit Commitment”.*

Acknowledgements

- Diego Alvarado was supported by Conicyt project FPCHA/MagísterNacional/2017-22171423.
- "Powered@NLHPC: This research was partially supported by the supercomputing infrastructure of the NLHPC (ECM-02)"

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