resiliency assessment for investment policy on power systems

Moving from security to resiliency in Chilean network for the case of earthquakes

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Introduction: Economies Life-Lines Interdependence
Introduction: Chile is a country of Earthquakes

- 1575 Valdivia 8.5
- 1730 Valparaíso 8.7
- 1751 Concepción 8.5
- 1835 Concepción 8.5
- 1868 Arica 9.0
- 1906 Valparaíso 8.2
- 1922 Vallenar 8.5
- 1943 Coquimbo 8.2
- 1960 Valdivia 9.5
- 1985 Santiago 8.0
- 1995 Antofagasta 8.0
Introduction: Chile is a country of Earthquakes

CHILE (SUR)
Desde Cauquenes a Temuco

Históricos de terremotos representados
(1) Pacífico Mw: 8.8 / Profundidad: 30 km [27/02/2010] -> Tsunami destructor
(2) Lebú Ms: 7.3 [21/05/1960]
(3) Los Aromos Ms: 7.3 [22/05/1960]
(4) Collipulli Ms: 7.3 / Profundidad: 45 km [14/02/1962]
(5) Cañete Ms: 7.3 [19/06/1960]
(6) Contulmo Ms: 7.7 / Profundidad: 6 km [10/05/1975]
(7) Carahue Ms: 7.1 / Profundidad: 36 km [18/08/1974]

Desde Temuco a Chiloé
Epicentro en el Pacífico (de arriba a abajo):
* Ms: 7.4 / Profundidad: 55 km [01/11/1960]
* Ms: 8.5 / Mw: 9.5 [22/05/1960] -> Tsunami destructor
* Ms: 7.3 / Profundidad: 33 km [13/03/1967]
* Ms: 7 / Profundidad: 40 km [13/07/1961]

Leyenda
- SEN_220kV
- SEN_154kV
- SEN_110kV
- SEN_66kV
- SEN_500kV
- SEN_345kV
- Epicentro de Terremoto
China, Haiti, Indonesia, Italy, Japan, Mexico, Philippines, Turkey, and the US have experienced severe earthquakes that resulted in serious damages to their energy supply infrastructure, see Zhang (2018) [1], Barrientos (2018) [2].
Resiliency Curve: 2010 Chilean earthquake
Outline

1. Problem
2. Assessment
3. Solving approach
4. Results
“Maximize the resilience of the Electricity Network, where the measure is the energy not supplied (ENS), using as decision variable alternative investments for network enhancement”

Two ways to model the system’s fragility:

- Resilience: Consider high impact low probability (HILP) scenarios (earthquakes-blizzards-storms-hurricanes)
- Probabilistic security (reliability): Risk neutral, minimize ENS subject to operational failure rates

<table>
<thead>
<tr>
<th>Resilience</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>HILP</td>
<td>Risk neutral</td>
</tr>
<tr>
<td>All failures after the shock</td>
<td>Failures occur throughout the oper-</td>
</tr>
<tr>
<td></td>
<td>ation</td>
</tr>
<tr>
<td>Concerned with customer interruption and infrastructure recovery</td>
<td>Concerned with interruption time</td>
</tr>
</tbody>
</table>
Main issue: “Endogenous two stage stochastic mixed integer program”

The Discrete Optimization problem is formulated as:

\[
\begin{align*}
\min_x & \quad \{\mathbb{E}_\xi[ENS(x, \xi)]\} \\
\text{s.t.} & \quad \sum_{i=1}^m a_i x_i \leq b, \\
& \quad x_i \in \{0, u_i\}, \quad \forall i \in M,
\end{align*}
\]  

(1)

- Here \(x_i\) represent all network enhancement decisions (adding new lines, anchoring/hardening substations, etc).
- \(a_i\) represent costs associated with implementation of \(x_i\) and \(b\) is the budget allowed to be spent in system’s resilience.
- \(\xi\) is the realization of uncertainty: Pair of hazard and damage state of network components.
- We assume that the function \(ENS(x, \xi)\) is unknown, but we can estimate \(ENS(x, \xi_i)\) via a simulation experiment.
Resilience Assessment: $ENS(x, \xi)$

- Simulation of the system is accounted using the Unit Commitment model: “Mixed Integer Linear model that solves the dispatch of the generating units for each period on the time horizon.”
- With a slight modification of [3] on the power balance restriction and the cost function we get the post earthquake operation simulation model:

\[
\sum_{e \in i^+} f_e^t - \sum_{e \in i^-} f_e^t + \sum_{g \in G(i)} P_{g}^t = d_{i}^t + ENS_{i}^t, \; \forall i \in V, \; \forall t \in T,
\]  

\[
\sum_{t \in T} \sum_{g \in G} (P_{g}^t cp_{g} + vu_{g}^t cu_{g} + vd_{g}^t cd_{g}) + \sum_{i \in V} ENS_{i}^t c_{ens}.
\]  

- This new formulation is what we call PCED (post-contingency economic dispatch).
In the case of earthquakes, we need to model, firstly, their magnitudes and locations and, secondly, their attenuation profile.

For the attenuation we use the model proposed by Boroschek, which offers a more accurate representation for Chile [4].

Boroschek proposes that peak ground acceleration (PGA) attenuation at any position \( r \) from the earthquake’s epicenter follows (4).

\[
\log_{10}(PGA(r, h, M)) = -1.86 + 0.26M + 0.01h - 0.01R + 0.31 - (1.52 - 0.10 + M) + \log_{10}(R) \tag{4}
\]

Where \( M \) is the earthquake’s magnitude in the Gutenberg-Richter scale. Given the hypocenter \((ex, ey, h)\), then

\[
r = \sqrt{(ex - x)^2 + (ey - y)^2} \quad \text{and} \quad R = \sqrt{r^2 + (0.07 \cdot 10^{0.36 \cdot M})^2}.
\]

The results is on units of \([g]\), the gravity acceleration constant.
Damage scenario modeling for earthquake case
All the same, but without earthquakes the security assessment model only takes into account the hourly failure rates on its components, using historical data.

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure rate (occ/yr)</th>
<th>Restoration time (normal) [h]</th>
<th>Restoration time (hazard) [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-km line</td>
<td>0.8</td>
<td>28</td>
<td>56</td>
</tr>
<tr>
<td>Substation</td>
<td>0.2</td>
<td>21</td>
<td>42</td>
</tr>
<tr>
<td>Generator</td>
<td>5</td>
<td>58</td>
<td>116</td>
</tr>
</tbody>
</table>
**UC problem:** optimizes system operation in intact system

**PCED problem 1:** re-dispatches system operation after the earthquake occurs

**PCED problem 2:** re-dispatches system operation after a small fault occurs

**Final results** are composed of all previous results

**Figure:** Interactions between UC and PCED models.
At an upper layer, we consider a heuristic procedure to solve these discrete decision problems. The Industrial Strength COMPASS was first proposed in Nelson (2009) [5].

Use a three stage procedure:

- Global phase: Niching Genetic Algorithm (NGA).
- Local phase: COMPASS algorithm converges to a locally optimal solution according to confidence parameters.
- Clean-up phase: Ranking and Selection (R&S) procedure.
### Chilean case study: SEN year 2024

<table>
<thead>
<tr>
<th>Gen Cap. (per technology)</th>
<th>35.6 [GW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydro</td>
<td>30%</td>
</tr>
<tr>
<td>Solar</td>
<td>8%</td>
</tr>
<tr>
<td>Wind</td>
<td>6%</td>
</tr>
<tr>
<td>Coal</td>
<td>21%</td>
</tr>
<tr>
<td>Gas</td>
<td>20%</td>
</tr>
<tr>
<td>Oil</td>
<td>13%</td>
</tr>
</tbody>
</table>

| Peak Demand               | 11.3 [GW] |
| Number of lines           | 71        |
| Number of nodes (simplified) | 42        |
Chilean case study: SEN year 2024

Investment options considered:

| Lines | (6,8) = Cautin-Charrua  
|       | (9,6) = Ciruelos-Cautin  
|       | (9,32) = Ciruelos-Pichirropulli  
|       | (11,7) = Cruc.+Enc.-CerrN+LAGuirr  
|       | (18,13) = Laberinto+Domeyko-Cumbre  
| Seismic buses or DG | 1 = Alto Jahuel  
|                   | 7 = Cerro Navia+Lo Aguirre  
|                   | 8 = Charrua  
|                   | 11 = Crucero+Encuentro |
## Resiliency vs Reliability Investments

<table>
<thead>
<tr>
<th>Solution</th>
<th>Value [MWh]</th>
<th>Solution</th>
<th>Value [GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 - 7</td>
<td>348</td>
<td>11 - 7</td>
<td>42.2</td>
</tr>
<tr>
<td>18 - 13</td>
<td>392</td>
<td>7</td>
<td>43.2</td>
</tr>
<tr>
<td>9 - 32</td>
<td>523</td>
<td>1</td>
<td>43.5</td>
</tr>
<tr>
<td>6 - 8</td>
<td>580</td>
<td>8</td>
<td>44.5</td>
</tr>
<tr>
<td>9 - 6</td>
<td>617</td>
<td>11</td>
<td>44.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base</td>
<td>696</td>
<td>Base</td>
<td>46.0</td>
</tr>
</tbody>
</table>
Loss versus Budget

CEENS improvement vs budget

- SEN
- NoHVDC
- FixedHVDC
Resiliency Curve Distribution: Base vs HVDC
Conclusions and Remarks

- For earthquake case studies, resiliency prescription policy is better approach than security policy.
- New methodologies and models show that probabilistic security standards should be updated, breaking the risk neutral paradigm.
- Models developed show great flexibility to model different investments, the complex system’s dynamics and different kinds of natural hazards, in a straightforward manner.
- However the heuristic does not provide convergence guarantees, it has shown for reasonable size investment budgets, and smaller size instances that it is very robust to deliver optimal and near optimal solutions in practice.
Zhang
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APEC Workshop, Santiago, Chile. 2018. Deputy Director, Earthquake Prediction Department, China Earthquake Networks Center

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IEEE Transactions on power systems. 2006
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International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake.

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Questions?
Thank you!