Geographically correlated failures in power grids: the ice storm case.

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Objective

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Development of a methodology to evaluate the reliability of the Chilean Power Grid in the event of ice storms.

Geographically Correlated Failures

July 2020, Chubut, Argentina. 55 high-voltage transmission towers were knocked down.

Feb 2010 , el Maule, Chile. A generation capacity of ~3,000 MW became immediately unavailable.

October 3rd 2015 Zhanjiang City, Philippines. Thyphoon Mujigae.

Expected to increase due to climate change:

Flows **Mudflows** **Wildfires** **Ice Storms** **Tropical Storms**

Geographically Correlated Failures

Wang, Y et al. "Research on resilience of power systems under natural disasters—A review." *IEEE Transactions on Power Systems* 31, no. 2 (2015): 1604-1613.

Typical Outage	**Outage due to Natural Disasters**
Single fault due to one component failure	Multiple faults due to catastrophic damage
No Stochastic feature involved in general analysis	Uncertainty & stochasticity with the process of natural disasters
No spatiotemporal correlation for the fault; fault happens randomly	Spatiotemporal correlation for the faults due to natural disasters
Most power generation units are working and stay connected	Power generation units may be out of service
Transmission & distribution network remain intact	Transmission & distribution network are damaged and incomplete
Only involve power grids infrastructure	Have interdependence with other infrastructures
Quick to repair and restore	Difficult to repair and restore

Geographically Correlated Failures (Dependent Failures)

Current Design Criteria ignore geographical correlation

- The security criteria N-1: meaning the network is design to provide the service even if one component have failed.
- Independent failures assumption: where two or more simultaneous failures have very low probability.

Using Montecarlo simulation and the Probabilistic Analysis method we can understand the consequences of ignoring dependence between failures.

Ice Storm

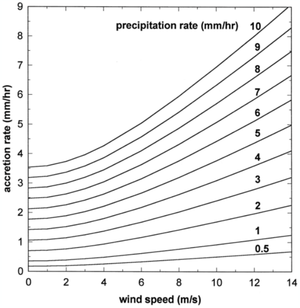
"The collapse of the towers caused the output of about 400 megawatts of power from the system, which was added to another 600 megawatts that the Atucha atomic complex stopped supplying since last Sunday due to a malfunction in the water pump system. The combined problems forced the government to make an urgent purchase of energy from Brazil to meet the electricity demand in the national interconnected system. In parallel, other imports from Uruguay and Chile are being evaluated."

Fuente: www.elciudadanoweb.com, Julio 2020.

Ice Storm - The Ice Thickness

- r: Precipitation rate $[mm/h]$
- w: the number of hours of freezing rain with precipitation rate P.
- v: Wind speed $[m/s]$.
- k: liquid water content of the rain-filled air $[g/m^3]$. Determinate by r.
- ρ_i: Ice density,
- ρ_0: Water density
- H : the hight of the component $[m]$.
- H_0: reference hight
- b: Factor de ajuste de la densidad del hielo

$$R_H = \frac{w}{\rho_i \pi}\left[(r\rho_r)^2 + (3.6vk)^2\right]^{1/2}\left(\frac{H}{H_0}\right)^b$$

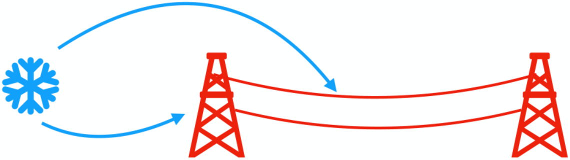


Uniform radial ice accretion rate for the simple model as a function of precipitation and wind speed, from (*).

(*) Jones, K. F. (1998). A simple model for freezing rain ice loads. Atmospheric research, 46(1-2), 87-97.

Ice Storm

- Ice and wind loads exert pressures on metal arms of the transmission tower. When the pressure exceeds the limit that the tower can withstand, the tower gets damaged and may eventually collapse.
- Similarly, ice and wind load combined can bend the transmission lines.



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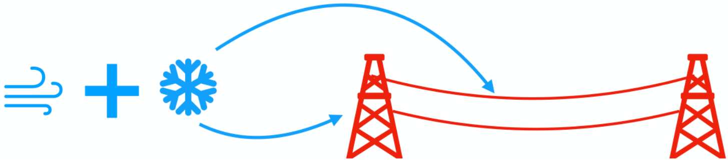


Ice Storm

- Freezing precipitation (r) and wind speed (v) probability distributions are derived on the basis of the peak over threshold (POT) model.
- In this method if the extreme value of an iid samples follows a Generalized Extreme Value (GEV) distribution then the excess of the sample follow a Generalized Pareto distribution (GPD).
- The POT model allows to estimate the parameters of the GDP, by studying the observation of local maxima.

Ice Storm - Wind and Ice Loads

- The transmission line wind load T_{L_v} is compute from the wind and the transmission line ice load T_{L_i} depends on the ice thickness R_H.[1]
- The tower wind load T_{L_v} is compute from the wind , while the transmission tower load T_{L_i} depends on the the ice thickness R_H and wind as well.[1]
- By sampling the precipitation rate r and the wind speed v, samples of the loads on tower and transmission lines can be obtained.

[1] Explicit and simple functions in Yang, H., Chung, C.Y., Zhao, J. and Dong, Z., 2013. A probability model of ice storm damages to transmission facilities. IEEE Transactions on power delivery, 28(2), pp.557-565.

Transmission lines loads

$$R_H = \frac{w}{\rho_i \pi} \left[(r\rho_r)^2 + (3.6vk)^2\right]^{1/2} \left(\frac{H}{H_0}\right)^b$$

$$T_{L_i} = \frac{\rho_{is}\pi g L}{89,2 \cdot 10^3}[(D + 2R_H)^2 - D^2],$$

$$T_{L_v} = \frac{g\vartheta S v^2 L}{3,6 \cdot 10^3}[D + 2R_H]$$

$$M_L = T_{L_i} + T_{L_v} + T_g$$

Transmission Tower loads

$$R_T = \frac{w}{\rho_i \pi}\left[(r\rho_r)^2 + (3.6vk)^2\right]^{1/2}\left(\frac{H}{H_0}\right)^b$$

$$T_{T_i} = 6 \cdot 10^{-4}\alpha_h \gamma A R_T$$

$$T_{T_v} = \frac{1}{2}v^2 \rho C_d A_f,$$

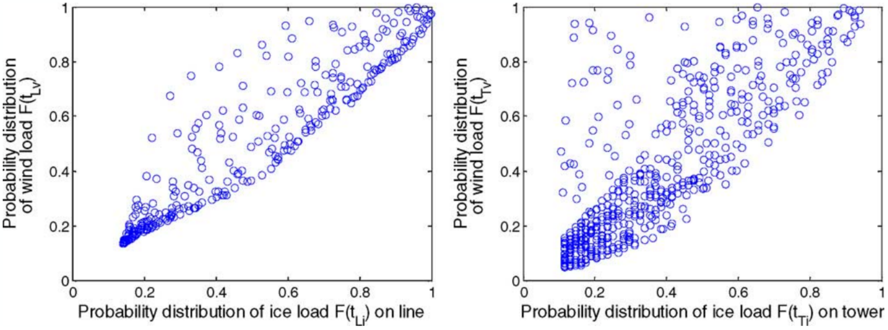
$$M_L = T_{T_i} + T_{T_v} + \Delta F_L$$

Ice Storm - Wind and Ice Loads[2]

- For the transmission lines, the T_{L_i}'s sample behaves as a GEV. The same applies to the T_{L_v}'s sample. But! They aren't independent.
- So by applying the inverse distribution of the GEV, couples uniform r.v. sample are obtained.
- The dependence of this pairs can be studied.
- The same argument applies to the tower's loads.

[2] Yang, H., Chung, C.Y., Zhao, J. and Dong, Z., 2013. A probability model of ice storm damages to transmission facilities. IEEE Transactions on power delivery, 28(2), pp.557-565.

Ice Storm - Wind and Ice Loads

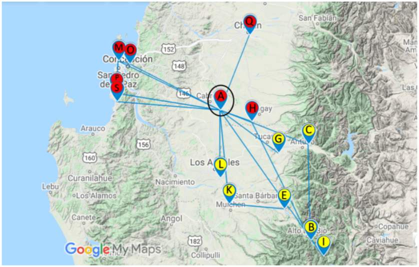


Ice Storm - Transmission line and tower failure probability

- After comparing several copula models for the dependences of the T_{L_i} and T_{L_v} the Clayton copula captures the dependence on the sample.
- So a bivariate distribution is obtained for the pair (T_{L_i}, T_{L_v}) using the marginal distributions GEV and the Clayton copula.
- The probability that a transmission line fails is given by the probability that the total load M_L exceeds the design load L_{max}. With $M_L = T_{L_i} + T_{L_v} + T_g$ where T_g is the dead weight.
- A similar argument applies to the tower's loads.

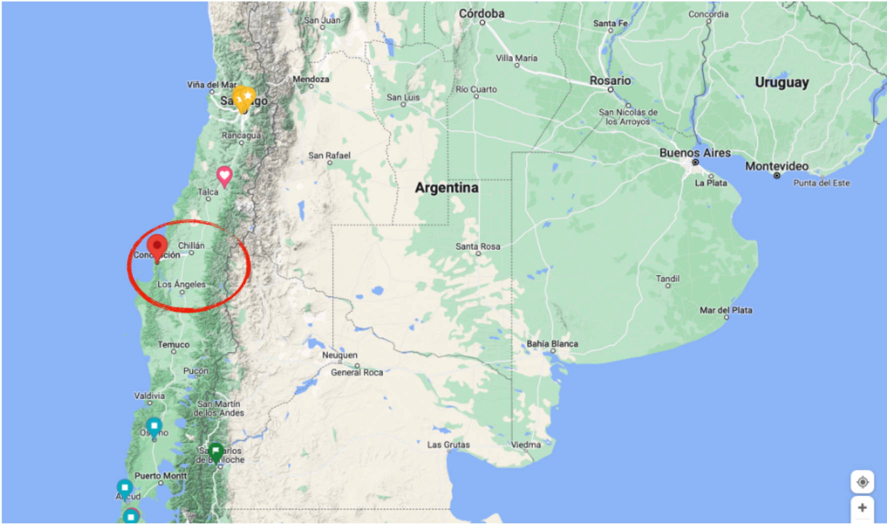
Ice Storm - Transmission line and tower failure probability

- Thus, knowing the parameters of an ice storm, in addition to the physical and geographical characteristics of a network, it is possible to determine the probability of failure of each of the components of the network under study.
- We consider the Chilean power system portion near Concepcion city that could be affected by ice storms.



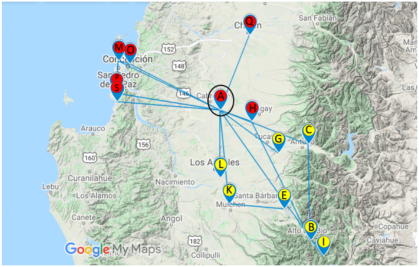
Chilean Electricity Grid in the Ñuble and Bío Bío Region. The energy sources are in yellow, the terminal nodes (the consumers) in red. Node A, enclosed in a black circle, is particularly important.

Ice Storm - Transmission line and tower failure probability



Ice Storm - Transmission line and tower failure probability

- Transmission lines are assume to connect nodes through straight lines. Every 100 [m] there is a transmission tower.
- Nodes in yellow are power generating facilities, while the red ones are demand nodes.
- The network is operational if
  - Each Terminal Node (red) is connected to at least one path with a Source Node (yellow),
  - the Charruá Central (A) (enclosed in black) is connected with at least 4 Source Nodes.
- Otherwise, the network will be considered inoperative.



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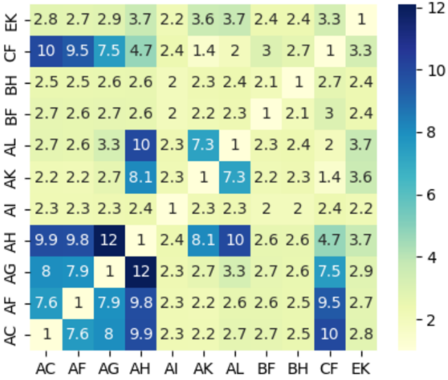
Ice Storm - Network element failures

- The vast majority of component pairs fail twice more often than the prediction with the independent assumption. Some pairs fail more than 10 times more often.
- The N-1 criteria ignores simultaneous failures while the independent assumption tends to give simultaneous failures relatively small probabilities. Both criteria dismiss simultaneous failures.



Ice Storm - Network Reliability result and assumptions

- Assumption on the occurrence on ice storm probability, two possibilities 10^{-3} and 10^{-6} the second for technical reasons.
- Simulations allow to estimate the network reliability, and evaluate posible improvements.
- The same accuracy with a crude MC will need $2{,}5 \cdot 10^8$, that is, $2,570$ times more simulations.

Sample size	10,000	20,000	50,000	70,000	100,000
Unreliability	4.06 10^-8	3.9 10^-8	2.44 10^-8	3.21 10^-8	3.29 10^-8
Variance	2.22 10^-16	2.09 10^-16	1.37 10^-16	1.76 10^-16	1.28 10^-16

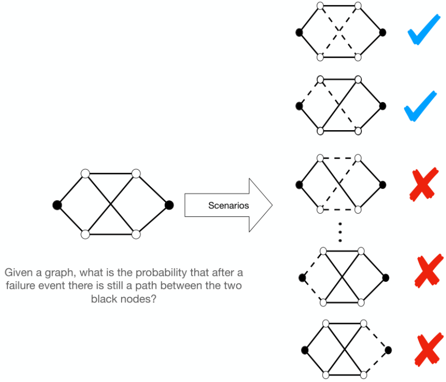
Computation with Ice storm probability of 10^-6

Ice Storm - What is the marshall-Olkin multivariate model

- The Marshall-Olkin model allows to simplify the failures simulations, in this model failures arise at a link level.
- Also Marshall-Olkin model allows to implement Important sampling method called Splitting.
- Allows to consider several geographical failures simultaneously.
- What is the Marshall-olkin model?

Network Reliability[3]

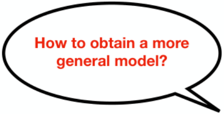
- There are several different connectivity measures. The expected connectivity is the reliability.
- If arcs fail independently and with the same probability p, there is a polynomial associated with the reliability.
- The reliability computation is $\#\mathcal{NP}$-complete!*

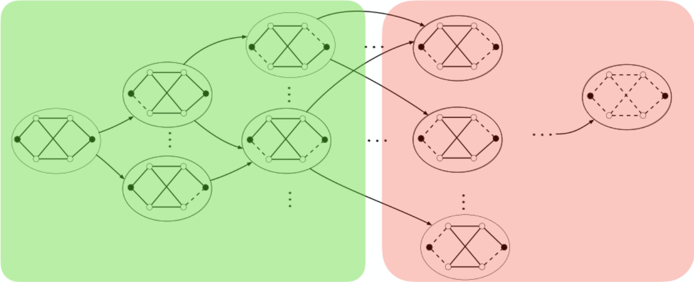


[3] Pérez-Rosés, H. (2018). Sixty years of network reliability. Mathematics in Computer Science, 12(3), 275-293.

Marshall-Olkin life-time model

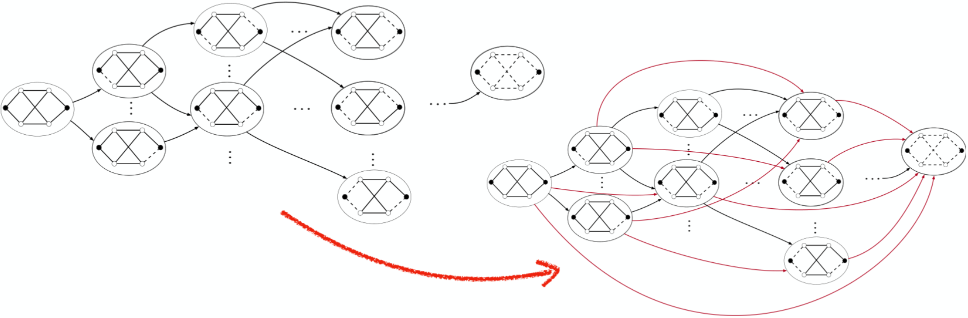
- We will consider random life-time for the components. Then for a static analysis we fix an instant $t = 1$.
- Let us consider a graph (N, E), where all edges have exponential life with the same parameter. Then for each arc $e \in E$, let T_e be the life of arc e, all iid as an $exp(\lambda)$.





Marshall-Olkin life-time model

- Marshall-Olkin Multivariate distribution $(T_{e_1}, \ldots, T_{e_n})$, with $T_e \sim exp(\lambda_e)$ life of component i. Does it have good properties? yes!:



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Marshall-Olkin Multivariate distribution $(T_{e_1}, \ldots, T_{e_n})$, with $T_e \sim exp(\lambda_e)$ life of component i. Does it have good properties? yes!:

1. Rare event simulation Botev, L'Ecuyer & Tuffin (2016) ✓
2. Integrate in stochastic optimization model for network design J.B., H. Cancela & E. Moreno (2014) ✓
3. Posible to estimate the parameter: Course of dimensionality but! under some assumptions Matus et al (2018) and many others ✓✗
4. Many other properties (Conference: Marshall Olkin Distributions - Advances in Theory and Applications 2013 Cherubini, Durante & Mulinacci) ✓
5. . Draw backs: correlation are only positive ✗

Marshall-Olkin life-time model[4]

The idea is to use shocks to represent the common-cause failures that arise in a network producing multiple failure in the system. For the two component case, we have:

- Let Z_1, Z_2 y $Z_{1,2}$ be independents exponential r.v. that represent the time a shock associated to sets of arcs $\{1\}, \{2\}$ and $\{1, 2\}$ arise.
- Assuming components start operative, let T_1 and T_2 lifetimes of the components 1 and 2 respectively.
- Then lifetimes are
  - $T_1 = \text{mín}\{Z_1, Z_{1,2}\} \sim exp(\lambda_{\{1\}} + \lambda_{\{1,2\}})$
  - $T_2 = \text{mín}\{Z_2, Z_{1,2}\} \sim exp(\lambda_{\{2\}} + \lambda_{\{1,2\}})$

[4] Marshall, A.,Olkin,I.: A multivariate exponencial distribution. Journal of the American Statistical Association 62, 30–44 (1967)

Thank you