ON THE DYNAMICS OF TRANSMISSION CAPACITY AND LOAD LOSS DURING CASCADING FAILURES IN POWER GRIDS

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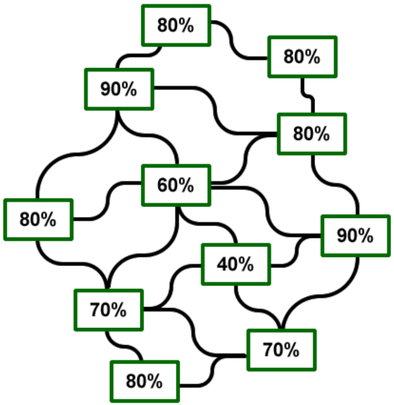
Cascading Failures in Power Grid : Overview



Network running normally

Source: Wikipedia

A few lines/generators trip initially → Loads shifted to nearby elements in the system → Nearby elements are overloaded beyond their capacity → Elements are tripped; load are shifted onto other elements → Cascading chain of failures starts, which can lead to system blackout

Outline of the Presentation

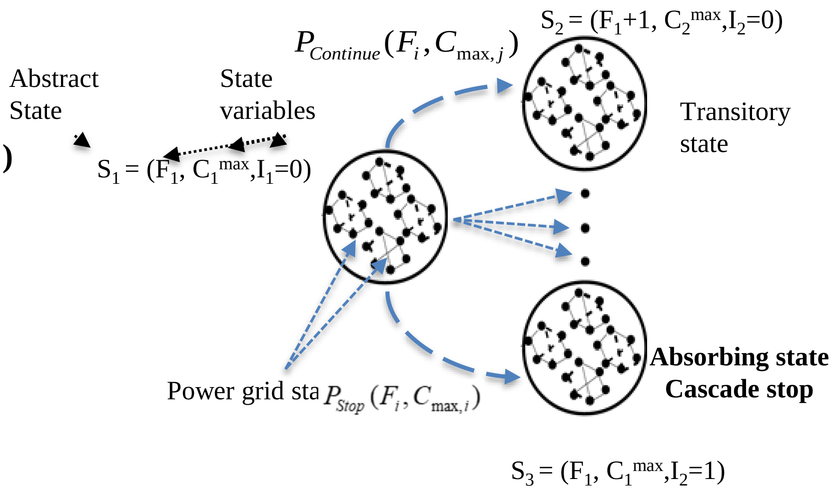
- Background works
- Contribution of this work
- Methodology
- Results
- Conclusions and Extensions

Background: Model for cascading failures: Markov chain based on a reduced state space of the power-grid variables

Main ideas of the *stochastic abstract-state evolution (SASE)* approach (1):

- Simplify the state space of the complex power system (**equivalence classes**)

Aggregate state variables: $\boldsymbol{S_i = (F_i, C_i^{\max}, I_i)}$



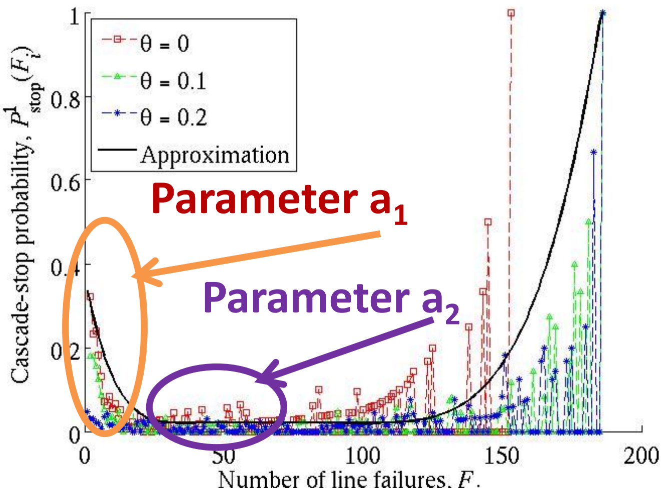
F: number of failed lines
***C**$_{max}$*: maximum capacity of failed lines
I: Cascade-stability of power grid

- Capturing the effects of the omitted variables through the transition probabilities and their parametric dependence on physical attributes and **operating characteristics** of the system.

1. Rahnamay-Naeini, M., Wang, Z., Ghani, N., Mammoli, A., & Hayat, M. M. (2014). Stochastic analysis of cascading-failure dynamics in power grids. *IEEE Transactions on Power Systems*, *29*(4), 1767-1779.

Background: Transition probabilities of MC are parameterized by grid's physical operating characteristics

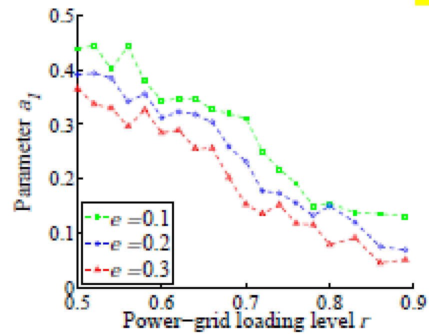
$P_{Stop}(F_i, C_{\max,i})$ is Data-driven and determined parametrically with the aid of Monte-Carlo power-flow-optimization



$$P^1_{Stop}(F_i) = \begin{cases} a_1\left(\dfrac{a_2 L - F_i}{a_2 L}\right)^4 + \varepsilon & 1 \le F_i \le a_2 L \\ \varepsilon & a_2 L \le F_i \le 0.6L \\ \min\left\{\left(\dfrac{F_i - 0.6L}{L - 0.6L}\right)^4 + \varepsilon, 1\right\} & 0.6L \le F_i \le L \end{cases}$$

The parameters are mapped to physical operating characteristics:

Transmission capacity estimation error	$e \in [0,1]$
Load shedding implementation constraints	$\theta \in [0,1]$
Power-grid loading level	$r \in [0,1]$



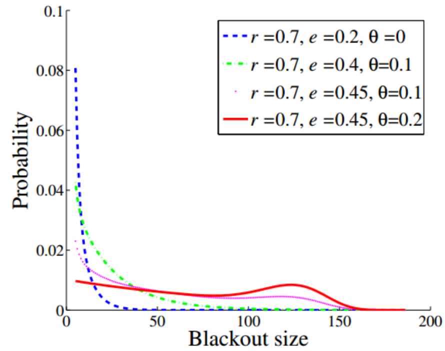
$P_{Stop}(F_i, C_{\max,i})$

Parametrized by the three physical operating characteristics

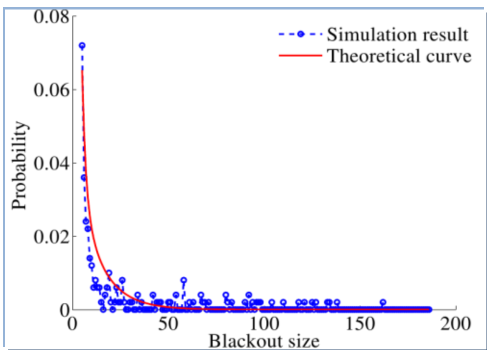
Background: Model can provide blackout-size distribution analytically for any initial condition

- Conditional probability that a power grid eventually reaches a state with ***n*** failures.

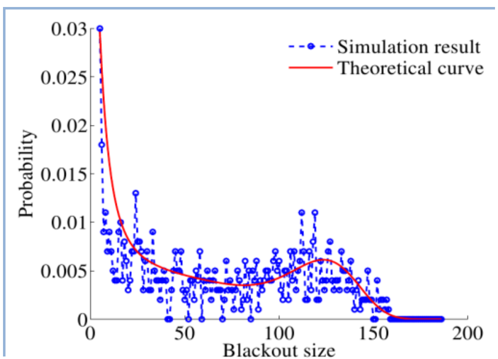
- Communication reliability limitations (e and q) and large loading levels (r) increase the probability of large blackouts.



- Model was validated using power system simulations



Normal operation of the power grid (**good** operating characteristics settings) Example of good scenario: **r=0.7,e=0.1,θ=0**



Operation of the power grid under stress (**bad** operating characteristics settings) Example of bad scenario: **r=0.7,e=0.45,θ=0.2**

Motivations for this work

In a recent study by cascading failure working group [1], following critical metrics for cascading failures were identified:

- **Size and distribution of the blackout size**
- **Amount of Load shedding** and Load shed distribution
- Critical transmission lines

1. P. Henneaux et al., "Benchmarking quasi-steady state cascading outage analysis methodologies," in 2018 IEEE International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), IEEE, 2018, pp. 1–6.

Contribution of this work

Steady state distribution of the transmission line failures are calculated analytically.

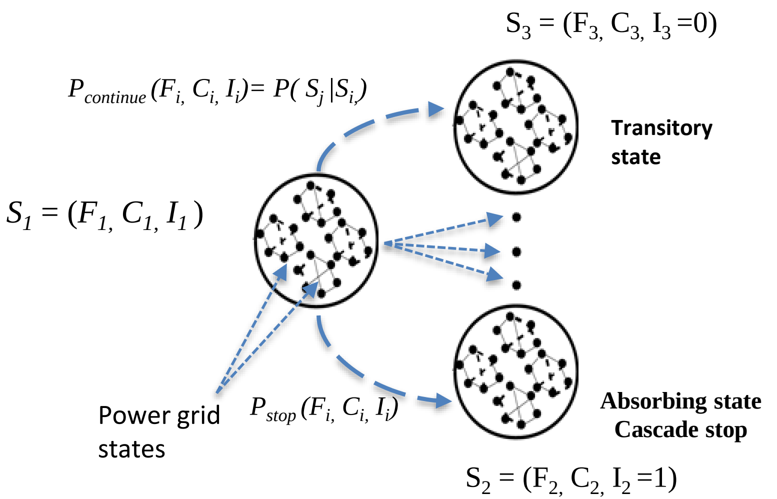
Average transmission capacity loss during cascading failures are calculated analytically. .

Amount of Load shed was calculated using the linear correlation between load shedding and capacity of the failed lines.

1. Rahnamay-Naeini, M., Wang, Z., Ghani, N., Mammoli, A., & Hayat, M. M. (2014). Stochastic analysis of cascading-failure dynamics in power grids. *IEEE Transactions on Power Systems*, *29*(4), 1767-1779.
2. P. Henneaux et al. , "Benchmarking quasi-steady state cascading outage analysis methodologies," in 2018 IEEE International Conference on Probabilistic Meth ods Applied to Power Systems (PMAPS), IEEE, 2018, pp. 1–6

Dynamics of transmission capacity and load loss

- Aggregate state variables: $\boldsymbol{S_i = (F_i, C_i, I_i)}$
  - $\boldsymbol{F_i}$: number of failed lines
  - $\boldsymbol{C_i}$: capacity of last failed lines
  - $\boldsymbol{I_i}$: Cascade-stability of power grid



- State transition probabilities of the Markov chain:

$$f(S_j|S_i) = \begin{cases} 1 & if\ F_j = F_i, C_j = C_i, I_j = I_i = 1, \\ P_{stop}(S_i) & if\ F_j = F_i, C_j = C_i, I_j = 1, \\ P(S_j|S_i) & if\ F_j = F_i + 1, C_j \in \mathcal{C}, I_j = 0, \\ 0 & otherwise. \end{cases}$$

Formulation allows to track the average transmission capacity loss

- $P(S_j|S_i)$ was formulated using $P_{stop}(S_i)$ as

$$P(S_j|S_i) = \Big(\alpha(C_j)^{\beta}(1 + \gamma C_i(C_j - C_{th}))\Big)(1 - P_{stop}(S_i))$$

- The parameters α, β, γ and C_{th} are calculated as described in [2].
- Here, C_{th} is a threshold in capacity values, where transmission lines with capacity lower than C_{th} are more vulnerable to failure in the next step.

1. Rezoan Ahmed Shuvro, Pankaz Das, Mahshid Rahnamay-Naeini, Francesco Sorrentino, Majeed M. Hayat. "On the Dynamics of Transmission Capacity and Load Loss during Cascading Failures in Power Grids", accepted at ISGT-Europe 2019.
2. Das, Pankaz, et al. "A data-driven model for simulating the evolution of transmission line failure in power grids." *2018 North American Power Symposium (NAPS)*. IEEE, 2018

Average transmission line failures and capacity loss in the steady state

- From the Markov chain, we calculate the distribution of the failed transmission lines of the power grid at the steady state

$$p(F_i|S_0) = \sum_{l=1}^{|\mathcal{C}|} \pi_{2(F_i-1)|\mathcal{C}|+2(l-1)+1}$$

- We calculate the expected number of transmission-line failures and the expected total capacity loss, given the initial condition, S_0 using the distribution of the failed transmission lines,

$$\mathsf{E}[F_i|S_0] = \sum_{F_i=1}^{M} F_i p(F_i|S_0).$$

$$\mathsf{E}[ATC_{F_i}|S_0] = \sum_{F_i=1}^{M} ATC_{F_i} p(F_i|S_0).$$

ATC_{Fi} is the average total capacity (ATC) loss with a total of F_i failures

Calculating average transmission capacity loss in the steady state

- we introduce the following recursion to calculate the average total capacity (ATC) loss during cascading failures

$$ATC_{F_j} = ATC_{F_i} + ACL_{F_j}$$

Here, ACL_{Fj} is the *average capacity loss* in the current state with F_j failures,
ATC_{Fi} is the average total capacity (*ATC*) loss with a total of F_i failures

- To calculate ACL_{Fj}, we need the marginal probabilities of initial line-failures with capacity C_i at the current state. After the occurrence of an initial event, we calculate the marginal probability at successive steps as follows,

$$P_{F_j}^{C_j} = \sum_{C_i \in \mathcal{C}} P(C_j \,|\, C_i) P(C_i)$$

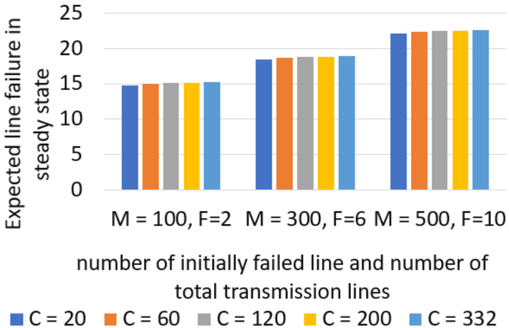
- P(C_j | C_i) = P(S_j |S_i) is obtained using the equation shown in previous slide
- P(C_j |C_i) equals P(S_j |S_i) because of our definition of the transition matrix

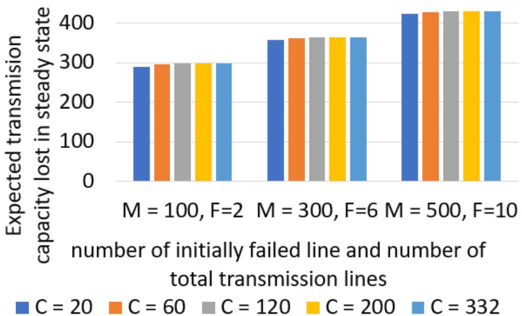
Then we calculate ACL_{Fj} using

$$ACL_{F_j} = \sum_{C_j \in \mathcal{C}} C_j P_{F_j}^{C_j}.$$

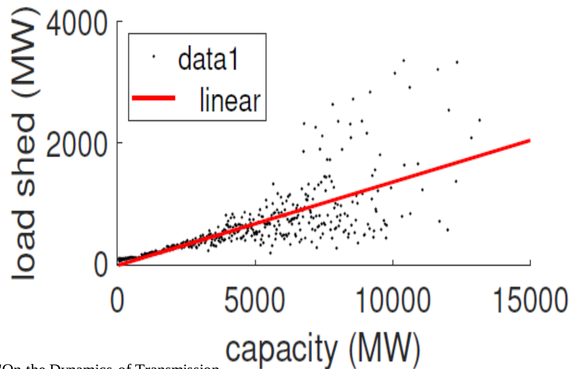
Prediction of expected loss in transmission capacity or loss in load delivery after initial trigger

- Expected number of line failure and expected transmission capacity loss for different total number of transmission lines, *M* and initially failed transmission lines, *F*





- Parametric prediction of load loss from average transmission capacity loss using linear regression using cascading failure data generated from simulation



1. Rezoan Ahmed Shuvro, Pankaz Das, Mahshid Rahnamay-Naeini, Francesco Sorrentino, Majeed M. Hayat. "On the Dynamics of Transmission Capacity and Load Loss during Cascading Failures in Power Grids", accepted at ISGT-Europe 2019.
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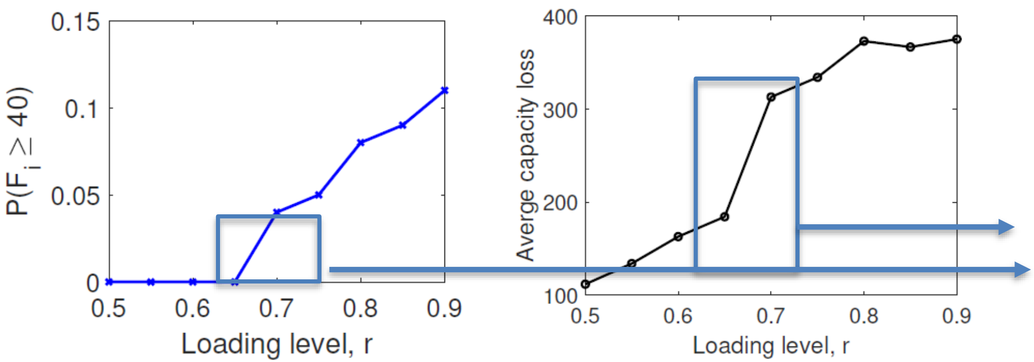
Model predicts critical initial triggers of cascading failures for a given set of grid operating settings

- $P(F_i \geq 40)$ and ATCL for various r, e = 0.45, θ = 0.2.
- For $r \geq 0.65$, the probability of a cascade increases with the grid loading level r



(a) $P(F_i \geq 40)$ (b) ATCL

Critical loading level above which a sharp transition in transmission line failure and average transmission capacity loss was observed

Critical initial conditions for various grid sizes

- Table below shows the severity of cascading failure for different values of *M* (total number of lines) and *F* (number of failed lines) (e.g., the red-colored zones indicate a cascade).

- We use a threshold of 300MW for ATCL (which corresponds to a small amount of load loss), above which we consider a cascading failure event. Note that the ATCL value was chosen arbitrarily for the purpose of classifying cascade events

- Expected transmission capacity loss during cascading failures for different total number of transmission lines, M and initially failed transmission lines, F (red indicates ≥300MW).

	M =100	M =200	M =300	M =400	M =500
F=2	290	262	236	214	196
F=3	315	296	270	247	228
F=4	336	324	301	279	259
F=5	355	349	330	309	289
F=6	375	371	357	337	318

Conclusions and Extensions

- This work allows to calculate the following analytically.

  - ✓ **The blackout size distribution**
  - ✓ **Average transmission capacity loss**
  - ✓ **Amount of load shed**

- Role of cyber threat on the resilience of the grid was captured in a subsequent paper.

- 'Balancing Smart Grid's Performance Enhancement and Resilience to Cyber Threat' (to be presented at the resilience week 2019).

- Currently we are working on devising optimal policies to mitigate cascading failures optimally.

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