Analyzing Cascading Failures in Power Grids under the AC and DC Power Flow Models

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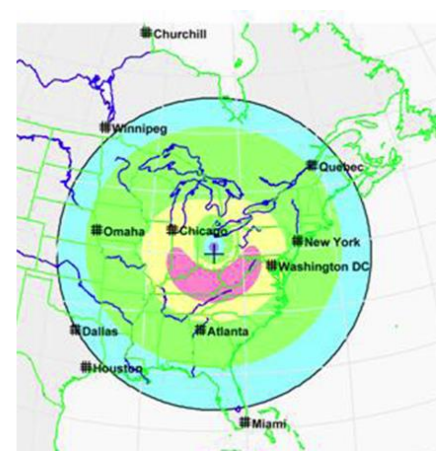
Failures

- Natural disasters

Satellite images show nighttime in Puerto Rico before the storm (above) and on 25 September (below), four days after the storm struck

- Electromagnetic Pulse (EMP) attack
- Physical attacks

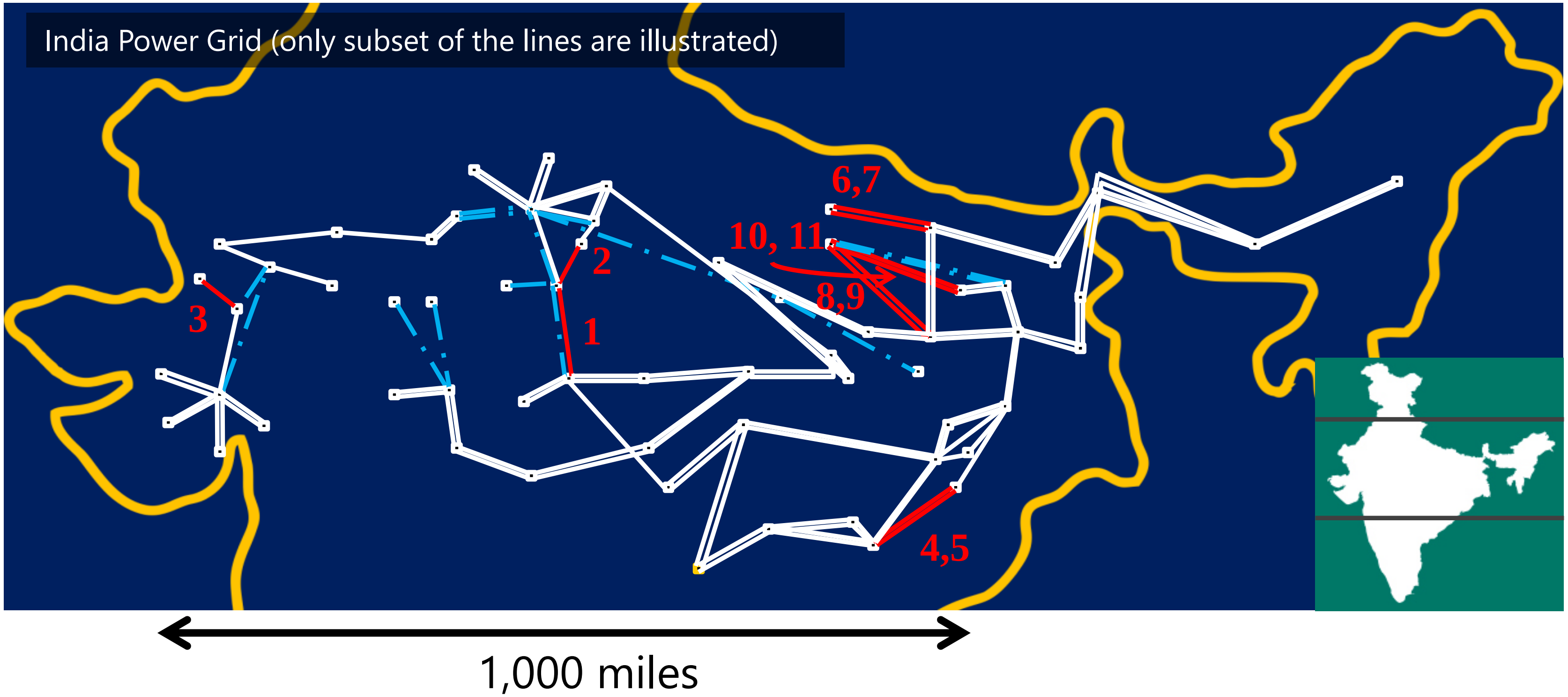


Power Grid Attack in San Jose

- “A sniper attack in April 2014 that knocked out an electrical substation near San Jose, Calif., has raised fears that the country's power grid is vulnerable to terrorism. ” –The Wall Street Journal

Cascading Failures in Power Grids

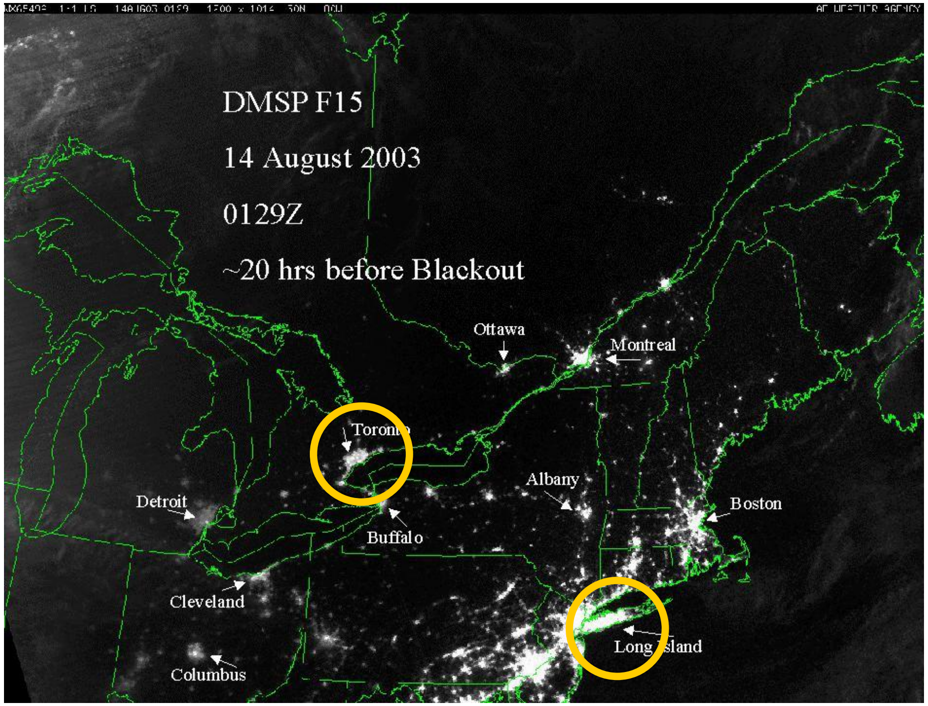
- Failures in a line or generator may results in further overloads
- Failures may cascade → Blackouts
- Sequence of line failures resulted in a blackout in July 2012 in India

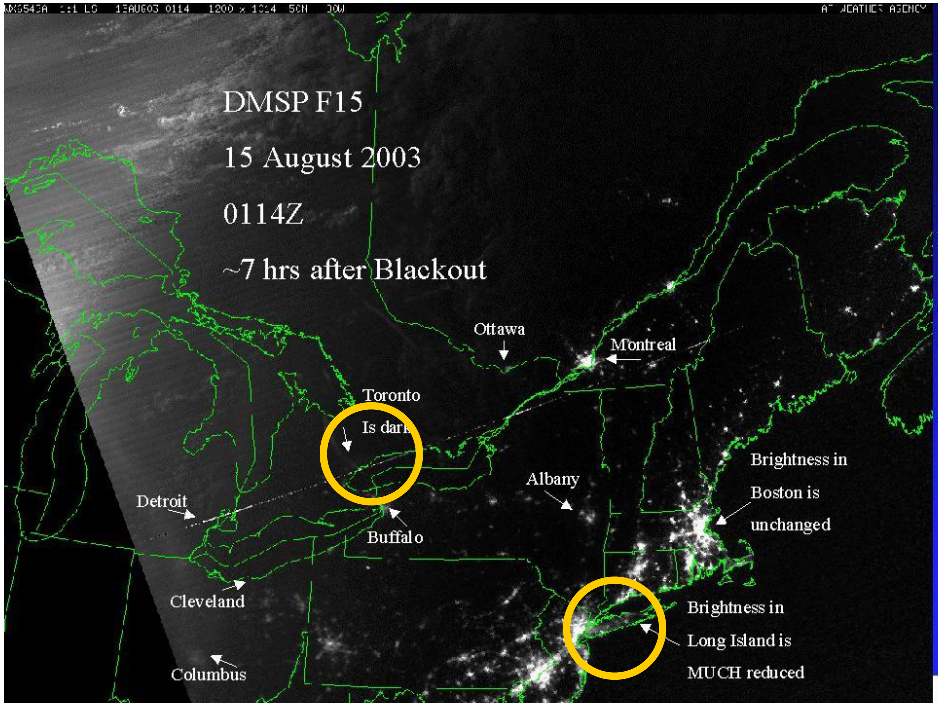


- Cascades do not necessarily develop contiguously

August 2003 Blackout in the US & Canada

- Started with a power plant failure
- Failures cascade and caused a large scale blackout





- Have a significant effect on many interdependent systems

Related Work

- Cascading Failures in power grids has been studied before
  - Percolation Theory (Crucitti et. al. 2004; Buldyrev et. al. 2010; Xiao & Yeh 2011; Chassin & Posse 2005)
    - Contiguous cascade models
    - Do not capture the properties of the cascades in power grids
  - Linearized DC Power Flows (Dobson et al. 2001-2016; Hines et al. 2007-2016; Gao et al. 2011; Bienstock et. al. 2010; Bernstein et. al. 2014; Soltan et. al. 2014; Buldyrev et. al. 2016)
    - Linearized power flow model approximating the AC power flows
    - Capture several properties of the cascades in power grids → noncontiguous
    - Neglect several operational constraints on voltages and reactive power flows
  - Non-linear and more accurate AC power flows (Bienstock 2016)
    - Most accurate model for describing the state of the grid in steady-state
    - AC power flows are costlier to solve → about 10x slower
    - Often times the equations do not result in a solution → require adjusting supply/demand
    - Much more difficult to obtain theoretical bounds using AC power flows
    - Studied much less

Our Contribution

- Is deploying the AC power flows necessary for studying cascades in power grids? → Why the DC approximation is not enough?
- How the DC approximation extends in approximating the cascades under the AC power flows?
- Developed a cascade simulator based the AC power flow model
- Rigorously compared the evolution of cascades and their severity based on the AC and DC power flows
  - In four publicly available power grid test cases including the IEEE 30-, 118-, 300-bus systems and the Polish grid (about 3000-bus system)
  - For three different cascade processes based on different line outage rules and supply/demand balancing rules

Outline

- AC and DC Power Flow Models
- Cascade Model
- Simulation Results
- Concluding Remarks

AC Power Flows

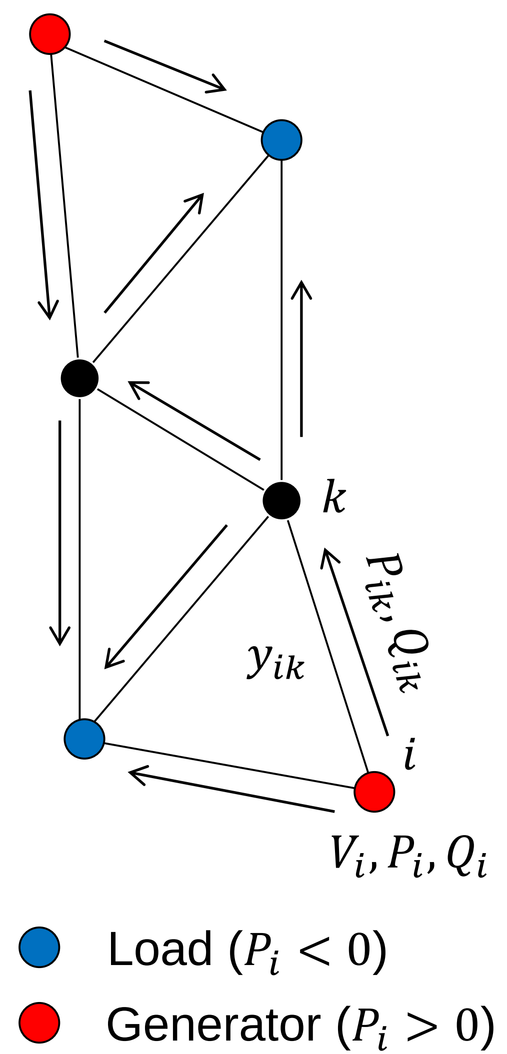
- Algebraic equations in the phasor domain
- Present the grid by a connected graph $G = (N, E)$
- $V_i = |V_i|e^{\mathbf{i}\theta_i}$
  $|V_\mathrm{i}|$ is the voltage magnitude
  θ_i is the voltage phase angle
- Transmission line (i, k) is characterized by series admittance $y_{ik} = g_{ik} + \mathbf{i}b_{ik}$
- The active and reactive power flows:

$$P_{ik} = |V_i|^2 g_{ik} - |V_i||V_k| g_{ik} \cos\theta_{ik} - |V_i||V_k| b_{ik} \sin\theta_{ik}$$

$$Q_{ik} = -|V_i|^2 b_{ik} + |V_i||V_k| b_{ik} \cos\theta_{ik} - |V_i||V_k| g_{ik} \sin\theta_{ik}$$

and $\theta_{ik} = \theta_i - \theta_k$

- Active and reactive power at node i:
  $P_i = \sum P_{ik}$, $Q_i = \sum Q_{ik}$
- Define: $|f_{ik}| \coloneqq |P_{ik} + \mathbf{i}Q_{ik}|$

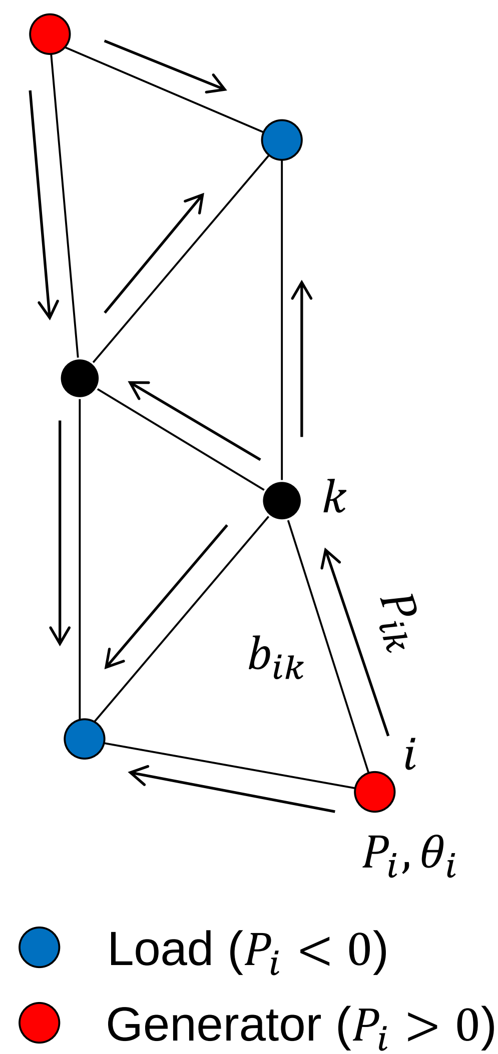


Power Flows - DC Approximation

- In the stable state of the system
  - $|V_i| \approx 1\, p.u.$ for all i
  - $\left|\frac{g_{ik}}{b_{ik}}\right| \ll 1$ for all lines $\Rightarrow y_{ik} \approx \boldsymbol{i} b_{ik}$
  - $\theta_{ik} \ll 1 \Rightarrow \cos(\theta_{ik}) \approx 1$ and $\sin(\theta_{ik}) \approx \theta_{ik}$
- The power flow equations reduce to

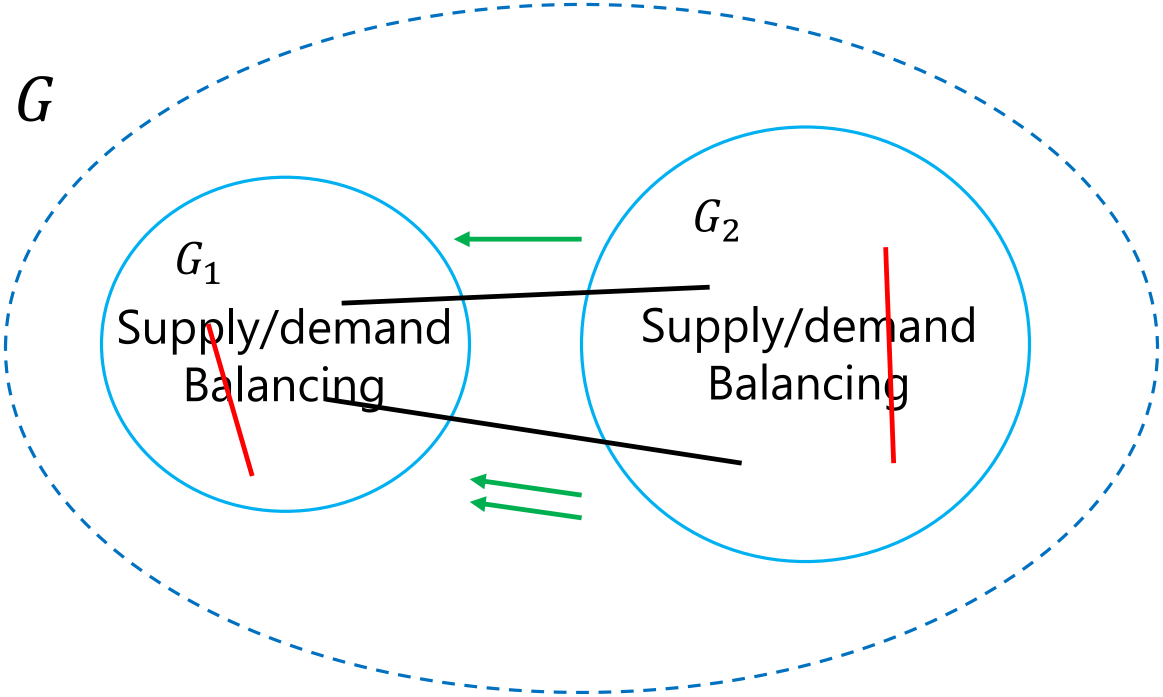
$$f_{ik} := P_{ik} = -b_{ik}(\theta_i - \theta_k)$$
$$\sum_k P_{ik} = P_i$$

- The DC power flow model neglects:
  - Reactive powers Q_{ik}
  - Voltage Magnitudes $|V_i|$
  - Line conductance values g_{ik} → lossless lines
- Name "DC" is because of similarity to the DC equations in resistive networks



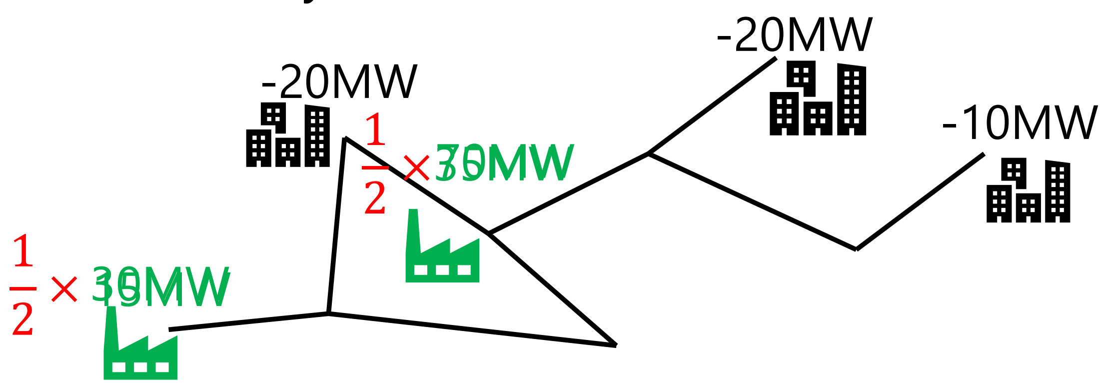
Cascading Failures Model

- **Input:** Connected network graph G with balanced supply and demand
- **Failure Event:** At time step $t = 0$, a failure of a subset of lines occurs
- **Until no more lines fail do:**
  - Adjust the total demand to the total supply within each component of G
  - Use the power flow model to compute the flows in G
  - Remove the lines from G according to a given outage rule

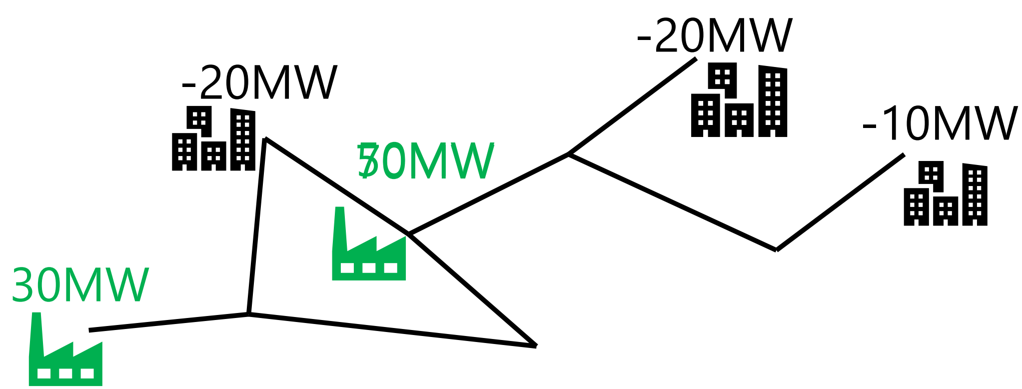


Supply/Demand Balancing Rules

- **Shedding and curtailing:** the amount of power supply/demand is reduced at all nodes by a common factor → common in previous works



- **Separation and adjusting:** Excess supply or demand nodes are separated from the grid from smallest to largest → closer to reality



Line Outage Rules

- **Deterministic:** A line l fails when the magnitude of the power flow on that line $|f_l|$ exceeds its capacity

- **Probabilistic:** A line l fails with probability p_l at each stage of the cascade

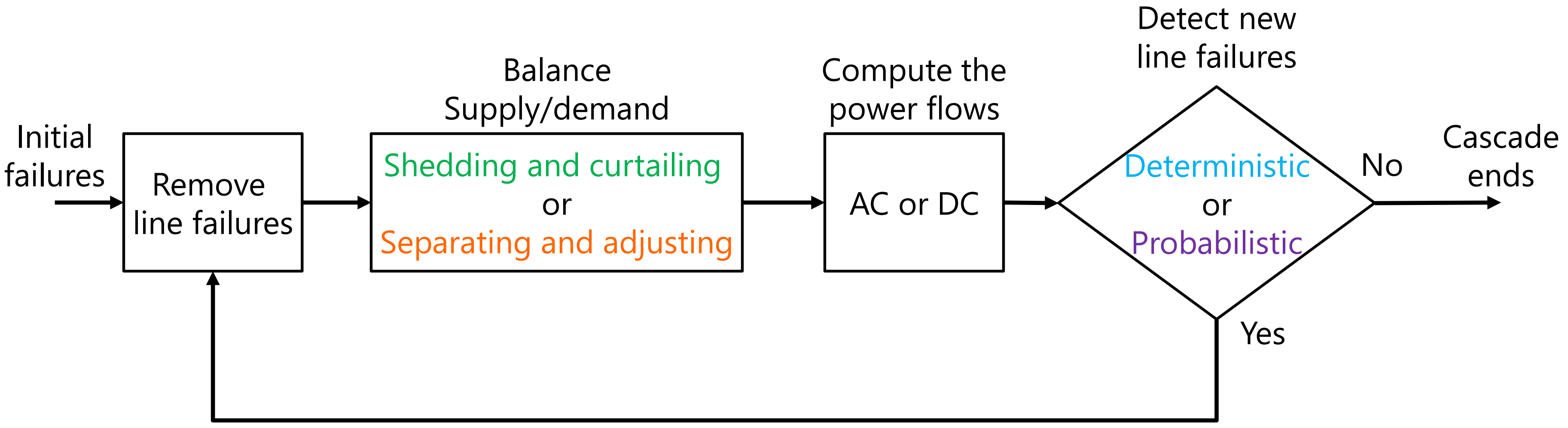
$$p_l = \begin{cases} 0, & \text{if } |f_l| < \xi_l \\ \dfrac{|f_l| - \xi_l}{c_l - \xi_l}, & \text{if } \xi_l \le |f_l| < c_l \\ 1, & \text{if } |f_l| \ge c_l \end{cases}$$

Cascade Processes

I. Cascade with the shedding and curtailing balancing rule and the deterministic line outage rule

II. Cascade with the separating and adjusting balancing rule and the deterministic line outage rule

III. Cascade with the shedding and curtailing balancing rule and probabilistic line outage rule

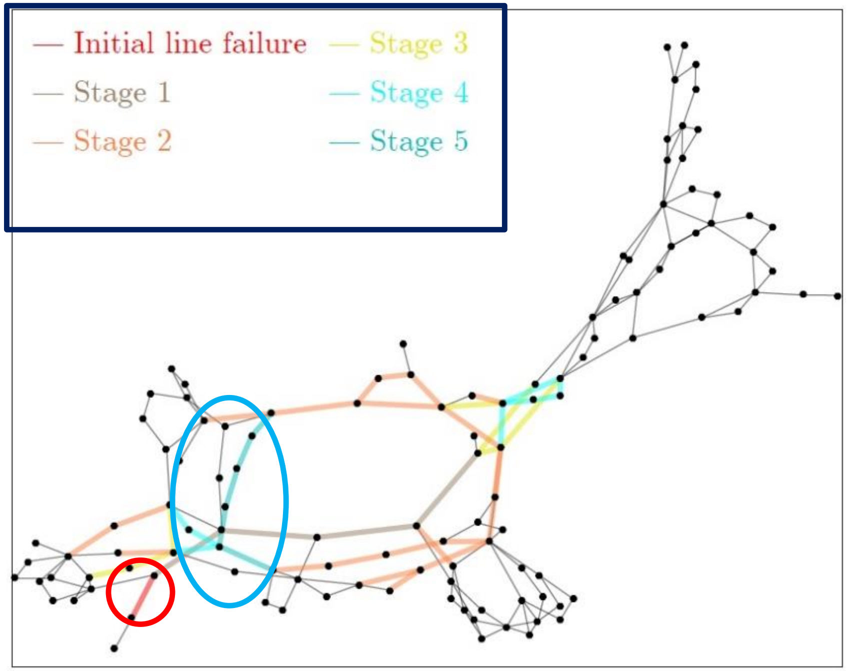


Simulation Results

Cascades Based on AC vs DC

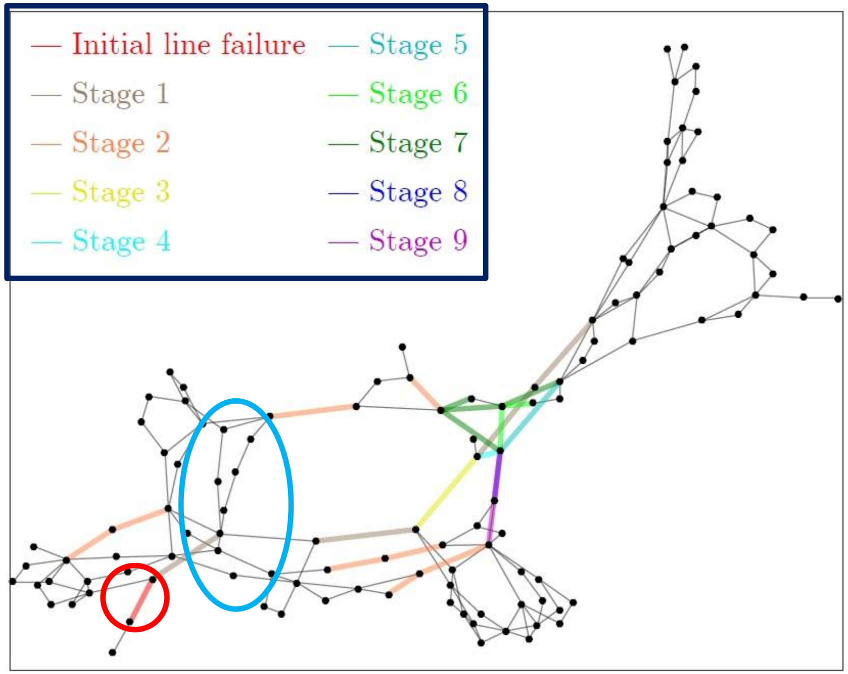
- Cascade initiated by a single line failure in the IEEE 118-bus system

5 stages



AC Cascading Failures Model

9 stages



DC Cascading Failures Model

- Result in quite different scenarios

Metrics

- **Node-loss ratio (N_G):** the ratio of the total number of failed nodes (i.e., nodes in dead components) at the end of the cascade to the total number of nodes

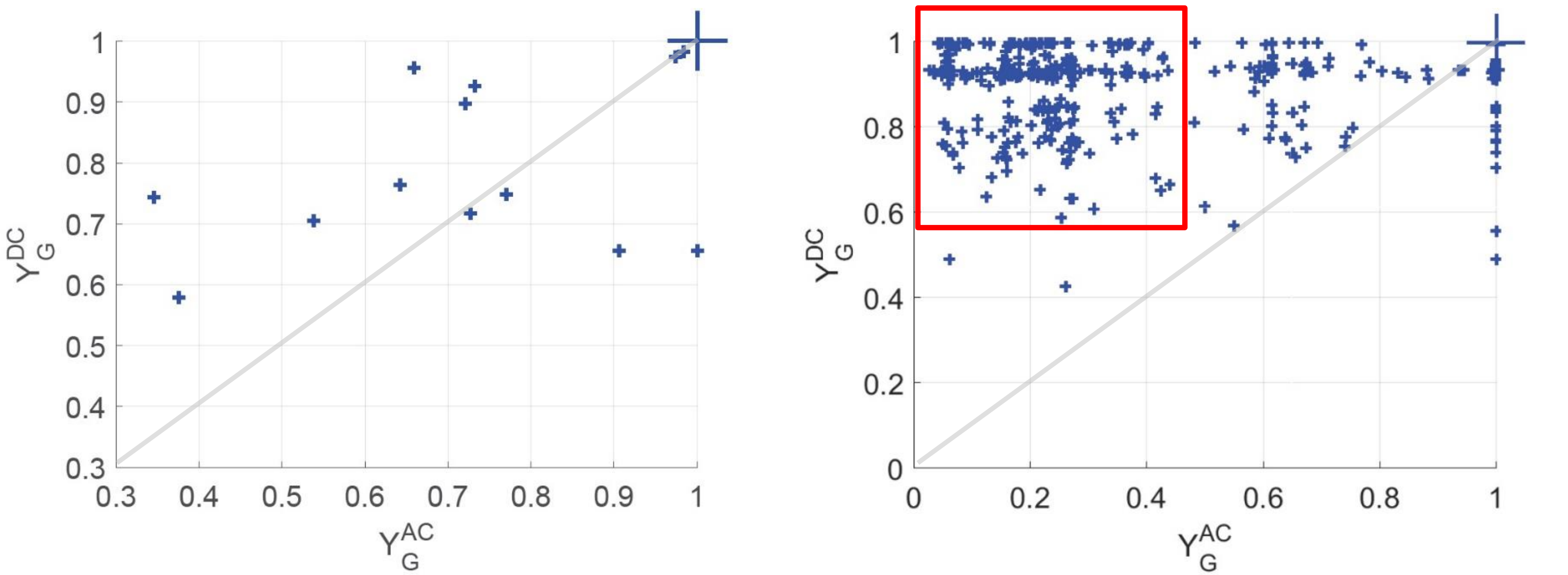
- **Line-loss ratio (L_G):** the ratio of the total number of failed lines at the end of the cascade to the total number of lines

- **Yield (Y_G):** the ratio of the demand supplied at the end of the cascade to the initial demand

- **Line-vulnerability ratio (R_l):** the total number of cascading failures in which line l is overloaded over the total number of cascading failures simulations.

AC vs DC Cascade Models Comparison

- Cascades initiated by single line failures
- Yield (Y_G): the ratio of the demand supplied at the end of the cascade to the initial demand



(a) IEEE 118-bus (b) Polish Grid

- Similar yield for small networks. However, for large networks the DC cascade model tends to overestimate the yield

AC vs DC Cascade Models Comparison

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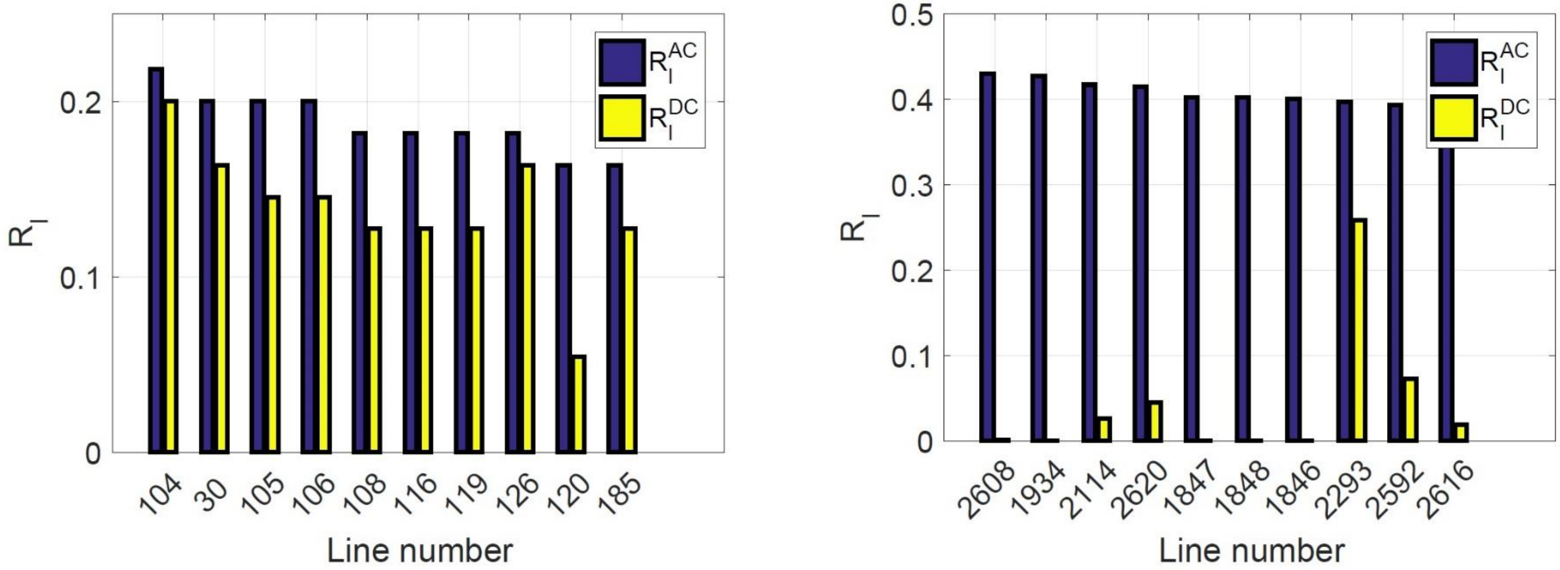

(a) IEEE 118-bus (b) Polish Grid

- Agree on the most vulnerable lines under the line-vulnerability ratios in small networks, most of the time. However, for larger networks they tend to detect different sets of lines

AC vs DC Cascade Models Comparison

- Cascades initiated by single line failures
- Yield (Y_G): the ratio of the demand supplied at the end of the cascade to the initial demand
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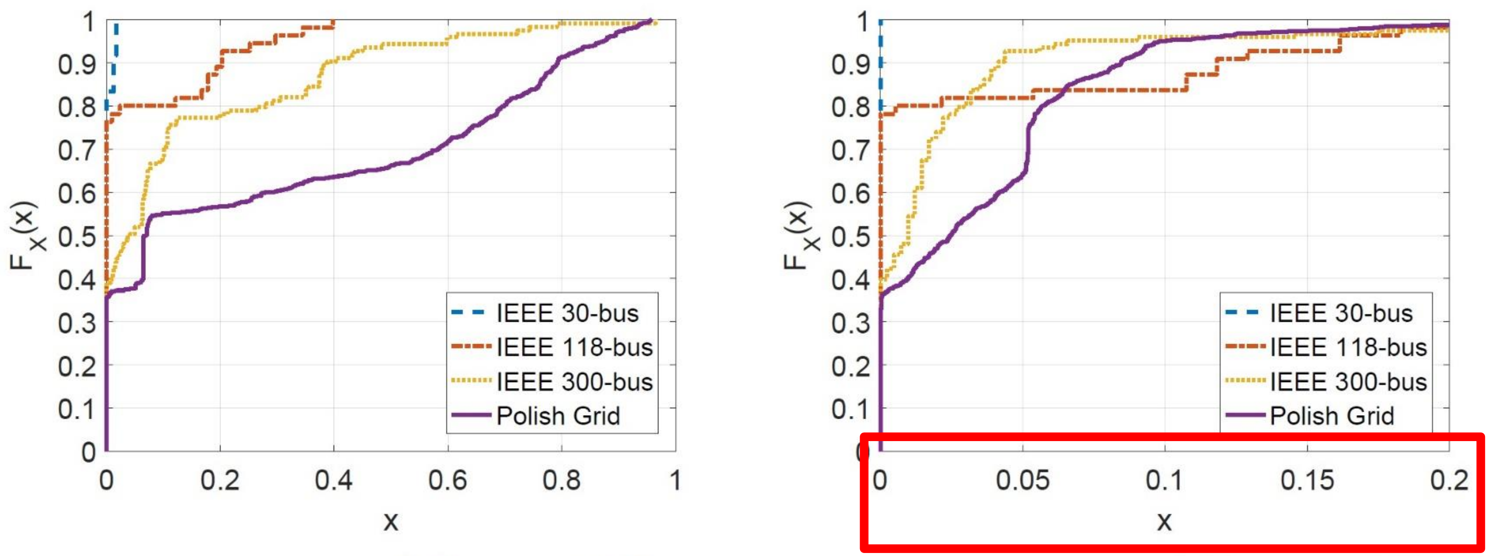
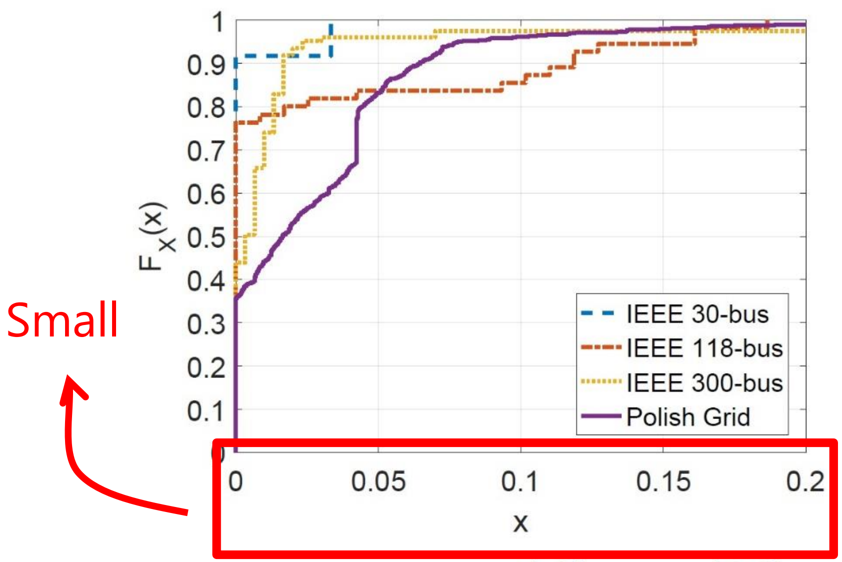


(a) $X := |Y_{\mathcal{G}}^{\mathrm{AC}} - Y_{\mathcal{G}}^{\mathrm{DC}}|$ (b) $X := |L_{\mathcal{G}}^{\mathrm{AC}} - L_{\mathcal{G}}^{\mathrm{DC}}|$

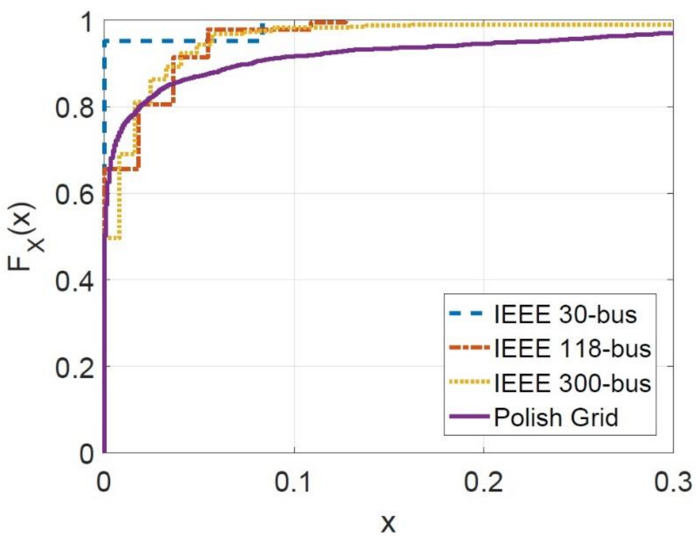
Small

AC vs DC Cascade Models Comparison

- Cascades initiated by single line failures
- Node-loss ratio ($N_{\mathcal{G}}$): the ratio of the total number of failed nodes (i.e., nodes in dead components) at the end of the cascade to the total number of nodes
- Line-vulnerability ratio (R_l): the total number of cascading failures in which line l is overloaded over the total number of cascading failures simulations.



(c) $X := |N_{\mathcal{G}}^{\mathrm{AC}} - N_{\mathcal{G}}^{\mathrm{DC}}|$



(d) $X := |R_l^{\mathrm{AC}} - R_l^{\mathrm{DC}}|$

Main Lessons Learned

- The cascade process I based on the AC and DC flow models:
  - Similar line- and node-loss ratios (i.e., total number of line and node failures) most of the time
  - Similar yield for small networks. However, for large networks (e.g., the Polish grid) the DC cascade model tends to overestimate the yield
  - Agree on the most vulnerable lines under the line-vulnerability ratios in small networks, most of the time. However, for larger networks (i.e., the Polish grid) they tend to detect different sets of lines

Different Cascade Processes

I. Cascade with the shedding and curtailing balancing rule and the deterministic line outage rule
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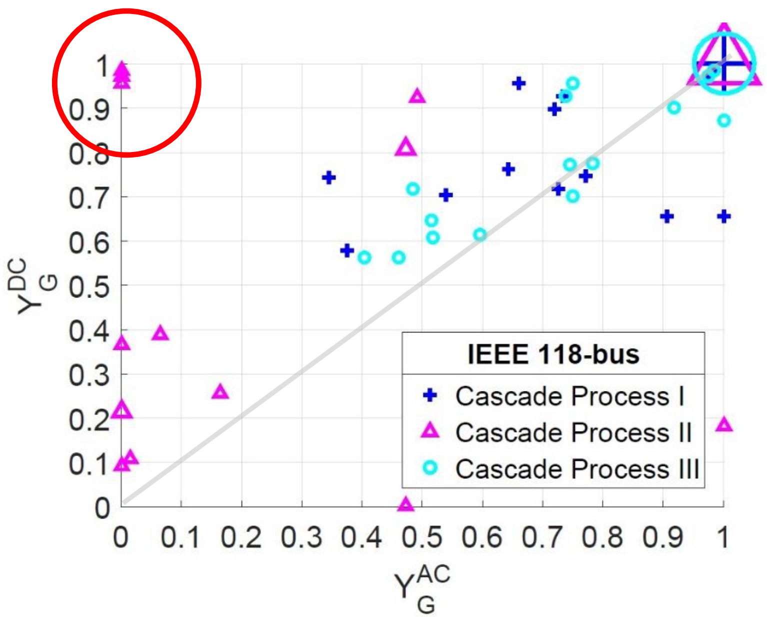
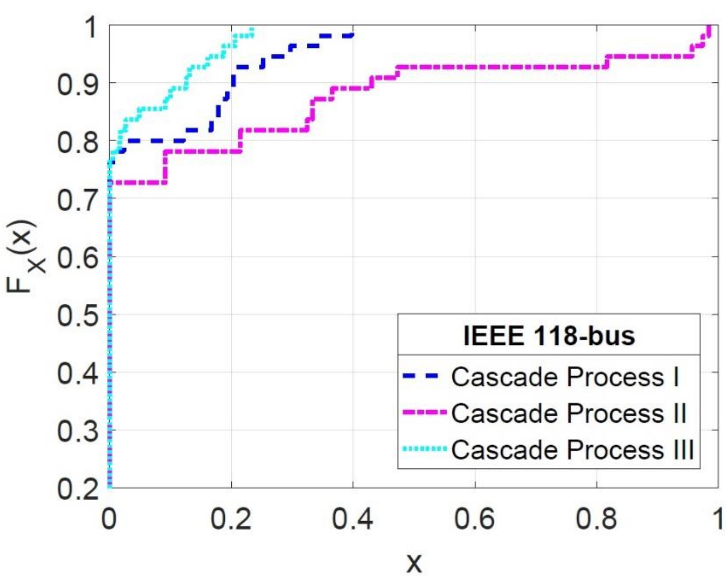


(a) $Y_{\mathcal{G}}^{\mathrm{AC}}$ vs $Y_{\mathcal{G}}^{\mathrm{DC}}$



(b) $X := |Y_{\mathcal{G}}^{\mathrm{AC}} - Y_{\mathcal{G}}^{\mathrm{DC}}|$

Different Cascade Processes

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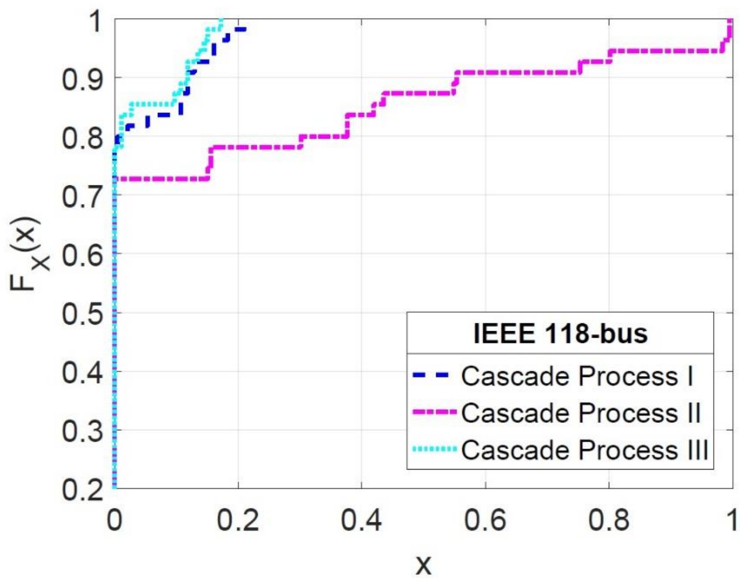
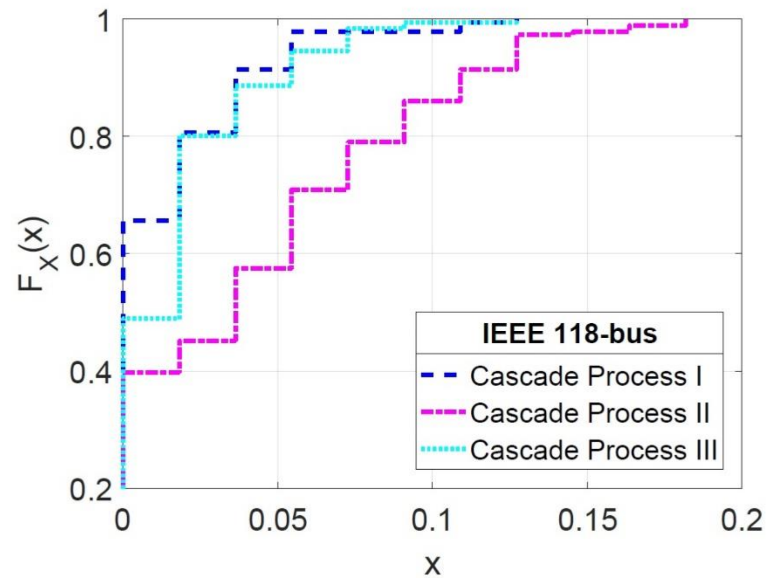


(a) $X := |L_{\mathcal{G}}^{\mathrm{AC}} - L_{\mathcal{G}}^{\mathrm{DC}}|$



(b) $X := |R_l^{\mathrm{AC}} - R_l^{\mathrm{DC}}|$

Main Lessons Learned

- The cascade process II based on the DC power flow model could significantly underestimates the severity of the cascade compared to the cascade based on the AC model
- The cascade process III provides similar differences based on the AC and DC power flows to cascade process I → Probabilistic outage rule does not make a lot of difference

Conclusions

- Due to the *voltage constraints*, the *divergence problems*, and the *reactive power flows*, the cascades based on the AC power flow model are more severe compared to the cascades based on the DC power flow model
- The DC model may underestimate the severity of the cascade, especially for larger networks
- Special care should be taken when drawing conclusions based on the DC cascade model in power grids
- "Cascading failures simulator in power grids," Available: https://github.com/TUDelftNAS/AC-Cascade-Sim

Thank You!

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