Analyzing, Understanding, and Mitigating Cascading Failures

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Outline

1 2003 U.S.-Canada Blackout

2 Understanding Cascading Failure

3 Mitigating Cascading Failure
## Major Blackouts in US

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Load lost (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov. 9, 1965</td>
<td>Northeast</td>
<td>20,000</td>
</tr>
<tr>
<td>Jul. 13, 1977</td>
<td>New York</td>
<td>6,000</td>
</tr>
<tr>
<td>Jan. 17, 1994</td>
<td>California</td>
<td>7,500</td>
</tr>
<tr>
<td>Jul. 2, 1996</td>
<td>Western US</td>
<td>11,743</td>
</tr>
<tr>
<td>Aug. 10, 1996</td>
<td>Western US</td>
<td>30,489</td>
</tr>
<tr>
<td>Sept. 4, 2011</td>
<td>Western US</td>
<td>7,899</td>
</tr>
</tbody>
</table>
Before Blackout

- Transfers high to northeast U.S. + Ontario: not unusual and not above transfer limits
- Critical voltage day: voltage within limits
- Frequency: typical for a summer day
- System within limits prior to 3:05pm on both actual and contingency basis
Phase 1: Normal Afternoon Degrades: 12:15pm–2:14pm EDT

- Cause: Tree contact causing a short circuit to ground
- Unexpected failures
- Highly Optimized Tolerance
Phase 2: FE’s Computer Failures: 2:14pm–3:59pm EDT

- 2:14pm FE alarm and logging software failed
- 2:20pm Several FE remote EMS terminals failed
- 2:27pm Star-South 345-kV line tripped
- 2:41pm Primary FE control system server hosting the alarm function failed
- 2:54pm FE back-up computer failed and all functions running on it stopped

Interdependent network:

physical system ⇔ control center
Phase 3: Three FE 345-kV Line Failures: 3:05pm–3:57pm EDT

- 3:05pm Harding-Chamberlin 345-kV (44% emergency rating)
- 3:32pm Hanna-Juniper 345-kV (88%)
- 3:41 Star-South Canton 345-kV (93%)

Due to tree contact; Line flows below emergency rating
After 345-kV lines were lost, at 3:39pm FE’s 138-kV lines around Akron began to overload and fail.

16 overloaded and tripped out of service.
Phase 5: 345-kV Transmission System Cascade in Northern Ohio and South-Central Michigan

345-kV Sammis-Star Tripping

Sammis-Star Tripping by Zone 3 Relay

<table>
<thead>
<tr>
<th>Zone 3 Tripped Lines</th>
<th>State</th>
<th>Trip Time (EDT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Sammis - Star (345 kV)</td>
<td>Ohio</td>
<td>16:05:57 EDT</td>
</tr>
<tr>
<td>2 Star (138 kV) Transformer #6 Star - Dixie (345 kV)</td>
<td>Ohio</td>
<td>16:06:01 EDT</td>
</tr>
<tr>
<td>3 Ohio/CTL - Waovier (138 kV)</td>
<td>Ohio</td>
<td>16:08:58 EDT</td>
</tr>
<tr>
<td>4 Gilaire - Orchere (345 kV)</td>
<td>Ohio</td>
<td>16:08:59 EDT</td>
</tr>
<tr>
<td>5 Richland - Waxon - Mclroy (138 kV)</td>
<td>Ohio</td>
<td>16:09:00 EDT</td>
</tr>
<tr>
<td>6 Arcenia - Howard (138 kV)</td>
<td>Ohio</td>
<td>16:09:00 EDT</td>
</tr>
<tr>
<td>7 Tangy - Kirby (138 kV)</td>
<td>Ohio</td>
<td>16:09:01 EDT</td>
</tr>
<tr>
<td>8 E. Lima - Fowmu (345 kV)</td>
<td>Ohio</td>
<td>16:09:31 EDT</td>
</tr>
<tr>
<td>9 Argenta - Houth+(345 kV)</td>
<td>Michigan</td>
<td>16:10:36 EDT</td>
</tr>
<tr>
<td>10 Argenta - Timpkin (345 kV)</td>
<td>Michigan</td>
<td>16:10:36 EDT</td>
</tr>
<tr>
<td>11 Argenta - Verona (138 kV)</td>
<td>Michigan</td>
<td>16:10:37 EDT</td>
</tr>
<tr>
<td>12 Detroit - Island Road (138 kV)</td>
<td>Michigan</td>
<td>16:10:37 EDT</td>
</tr>
<tr>
<td>13 Verona - Battric (138 kV)</td>
<td>Michigan</td>
<td>16:10:37 EDT</td>
</tr>
<tr>
<td>14 Argenta - Monnow (138 kV)</td>
<td>Michigan</td>
<td>16:10:38 EDT</td>
</tr>
</tbody>
</table>
Phase 6: Full Cascade 4:10pm–4:13pm EDT
Phase 6: Full Cascade 4:10pm–4:13pm EDT

4:10:39pm

4:10:44pm

4:10:45pm

4:13pm
The blackout shut down 263 power plants (531 units) in the US and Canada, most from the cascade after 4:10:44pm, but none suffered significant damage.
When the cascade was over at 4:13pm, over 50 million people in the northeast US and the province of Ontario were out of power.

- System-wide disturbances that affect many customers across a broad geographic area are rare event
- More frequently than expected
- How to explain the power law distribution?

Note: The circles represent individual outages in North America between 1984 and 1997, plotted against the frequency of outages of equal or greater size over that period.

Source: Adapted from John Doyle, California Institute of Technology, “Complexity and Robustness,” 1999. Data from NERC.
Hindsight bias: inclination, after an event has occurred, to see the event as having been predictable, despite there having been little or no objective basis for predicting it, prior to its occurrence

Wide variety of initial outages (triggers)

Many mechanisms in cascading: Power flow redistribution and static overloads; Control or protection malfunction or function not suited to conditions; Oscillations; Voltage collapse; Transient instability; Operational or planning errors, no situational awareness; Unusual or poorly understood interactions
Existing Approaches

- Analyze historical data: need long observation time for good statistics for rare large blackouts; no modeling assumptions
- Analyze the phenomenon:
  - Analyze detailed failures and interactions in a single blackout after it occurs
  - Analyze a section of most probable or high risk failures
- Simplified model: Analyze a simplified power system model to explain the bulk properties of cascading failures, rather than modeling all of the equipment in detail; analyze one or only a few of the cascading mechanisms (e.g. OPA)
- Idealized model: Develop an idealized, even tractable model to reveal fundamental properties of complex power system (e.g. CASCADE, interaction model)
- High-level Statistical model: Statistically model the overall progression of cascading failures, while neglecting details of the interactions; simple and tractable (Branching process model)
Self-organized Criticality (SOC)

- Two competing mechanisms dominate:
  - Large events slowly but steadily become more probable
  - The probability of future large events decreases when a large event occurs
- The system is driven towards criticality

Examples: Sandpile; earthquakes; financial crisis
Simplified Model–OPA Model

- Fast dynamics: cascading blackouts
  - Random line outage
  - DC load flow model with LP re-dispatch

- Slow dynamics: load increase and system upgrade

- Treat power system as a complex system
  - made up of multiple interconnected elements
  - capacity to change and learn from experience
# Simplified Model–OPA Model

## Analogy with the sandpile

<table>
<thead>
<tr>
<th></th>
<th><strong>power system</strong></th>
<th><strong>sandpile</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>system state</td>
<td>fractional overloads</td>
<td>gradient profile</td>
</tr>
<tr>
<td>driving force event</td>
<td>load increase</td>
<td>addition of sand</td>
</tr>
<tr>
<td>relaxing force event</td>
<td>line upgrade</td>
<td>gravity</td>
</tr>
<tr>
<td>cascade</td>
<td>line outage</td>
<td>sand topples</td>
</tr>
<tr>
<td></td>
<td>cascading lines</td>
<td>avalanche</td>
</tr>
</tbody>
</table>

![Graph showing rank versus load shed](attachment:graph.png)

OPA on WECC and NERC data
Idealized Model: CASCADE

- All $n$ components are initially unfailed and have initial loads $L_1, L_2, \cdots, L_n$ that are independent random variables uniformly distributed in $[L_{\text{min}}, L_{\text{max}}]$. 
- Add the initial disturbance $D$ to the load of each component. State counter $i = 0$.
- Test each unfailed component for failure: For $j = 1, \cdots, n$, if component $j$ is unfailed and its load $> L_{\text{fail}}$ then component $j$ fails. Suppose $M_i$ components fail in this step.
- If $M_i = 0$, stop; the cascading process ends.
- If $M_i > 0$, then increment the component loads according to the number of failures $M_i$: Add $M_i P$ to the load of each component.
Idealized Model: CASCADE

initial load range \([L_{\text{min}}, L_{\text{max}}] = [0.5, 8.5]\)
failure load \(L_{\text{fail}} = 9.5\)
initial disturbance \(D = 3\)
load increment \(P = 1\)
iteration counter \(i\)

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>component number</th>
<th>(i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>6</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>initial random load (L_j)</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>9</td>
<td>10</td>
<td>7</td>
<td>4</td>
<td>initial disturbance (D) added</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>11</td>
<td>12</td>
<td>9</td>
<td>6</td>
<td>1 and 3 fail; (2P) added</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>12</td>
<td>13</td>
<td>10</td>
<td>7</td>
<td>2 fails; (P) added</td>
<td>3</td>
</tr>
<tr>
<td>15</td>
<td>13</td>
<td>14</td>
<td>11</td>
<td>8</td>
<td>4 fails; (P) added</td>
<td>4</td>
</tr>
</tbody>
</table>

cascade ends with 1, 3, 2, 4 failed

- integer loads used for convenience only.
- loads above \(L_{\text{fail}} = 9.5\) indicate failure.

Figure 2: Mean number of components failed \(ES\) as a function of average initial component loading \(L\). Note the change in gradient at the critical loading \(L = 0.8\). There are \(n = 1000\) components and \(ES\) becomes 1000 at the highest loadings.

Figure 1: Log-log plot of distribution of number of components failed \(S\) for three values of average initial load \(L\). Note the power law region for the critical loading \(L = 0.8\). \(L = 0.9\) has an isolated point at \((1000, 0.80)\) indicating probability 0.80 of all 1000 components failed. Probability of no failures is 0.61 for \(L = 0.6\), 0.37 for \(L = 0.8\), and 0.14 for \(L = 0.9\).
Idealized Model: Interaction Model

- strong coupling between components in complex systems (a failure in one or more components can lead to cascading failures which may have catastrophic consequences on the functioning of the system)
- Quantitatively study the interactions of components
- Study how these interactions influence cascading failure

**Table : Outage Data**

<table>
<thead>
<tr>
<th>Generation</th>
<th>Generation 1</th>
<th>Generation 2</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>cascade 1</td>
<td>$L_0^{(1)}$</td>
<td>$L_1^{(1)}$</td>
<td>$L_2^{(1)}$</td>
</tr>
<tr>
<td>cascade 2</td>
<td>$L_0^{(2)}$</td>
<td>$L_1^{(2)}$</td>
<td>$L_2^{(2)}$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>cascade $M$</td>
<td>$L_0^{(M)}$</td>
<td>$L_1^{(M)}$</td>
<td>$L_2^{(M)}$</td>
</tr>
</tbody>
</table>
Idealized Model: Interaction Model

- Interaction matrix: conditional probability that one component failure causes another

Topology of 118-bus system

Directed interaction network

- Identify links and components that play important role in propagation of blackouts
Idealized Model: Interaction Model

- Generate initial failures randomly
- Only use information in interaction matrix
- Study influence of component interactions
- Investigate possible mitigation measures
Idealized Model: Interaction Model

- Compare distribution of simulation and data
- Mitigate cascading risk by removing crucial interactions

Line distribution for 118-bus system

Mitigation effect by removing interactions
**Statistical Model: Branching Process**

- Describe overall propagation of cascades
- Ignore all details of cascading; simple and tractable
- Simple propagation mechanism: an outage independently causes other outages by sampling from many others, each with small probability → the number of caused outages of an outage approximately follows Poisson distribution (Galton-Watson branching process with Poisson offspring distribution)

- Markov chain
- Two assumptions
  - Independent
  - Identically distributed (offspring distribution)
- Offspring mean indicates criticality
  - $\lambda < 1$, subcritical
  - $\lambda = 1$, critical
  - $\lambda > 1$, supercritical
Statistical Model: Branching Process

How do we test branching process?

<table>
<thead>
<tr>
<th>Table: Outage Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>generation 0</td>
</tr>
<tr>
<td>cascade 1</td>
</tr>
<tr>
<td>cascade 2</td>
</tr>
<tr>
<td>...</td>
</tr>
<tr>
<td>cascade $M$</td>
</tr>
</tbody>
</table>

PDF of $Z_0 + \text{average propagation } \lambda \xrightarrow{\text{branching process}} \text{PDF of } Y$

- Line outages propagate
- Load shed propagates
Verify if GW branching process can statistically describe how blackouts propagate by comparing distribution estimated by branching process and empirically.

Line distribution for 118-bus system
\[ \hat{\lambda} = 0.40 \]

Load distribution for 118-bus system
\[ \hat{\lambda} = 0.44 \]
Statistical Model: Branching Process

- Consider multiple outages

**Empirical joint distribution**

**Estimated joint distribution**

**Marginal distribution of line outages**

**Marginal distribution of load shed**
Framework for Mitigating Cascading Failure

- Identify possible initiating events, their spread, and severity.
- Identify existing resources in the system that might be sufficient to prevent a cascading outage in planning and online environments.
- Apply effective islanding techniques in planning and online environments.
- If a blackout can’t be prevented, identify an effective blackstart technique.
Unsuccessful and Successful Stories

Unsuccessful story:

- 2011 WECC System: Peak demand and lower than peak generation $\rightarrow$ sizeable voltage deviation $\rightarrow$ equipment failure and a cascade
- 2012 Indian Blackout: Unscheduled interchanges $\rightarrow$ highly loaded tie lines; Inadequate operator relief actions $\rightarrow$ overloaded tie lines tripped by relays; Resulting power swings split the system

Successful story:

- 2008 UK Network: Two large generators tripped within 2 minutes and another two generators tripped; Frequency dropped to 48.795 Hz; Under-frequency relays operated successfully at 48.8 Hz and disconnected 546 MW of demand; Frequency was recovered
Controlled Islanding

- Last resort
- Three critical problems
  - Where to separate? (i.e. the separation points to form sustainable islands)
  - When to separate? (i.e. separation timing)
  - What to do after separation? (i.e. post-separation control actions in formed islands, e.g. generation adjustment and load shedding)

<table>
<thead>
<tr>
<th>Stages</th>
<th>Main Tasks</th>
<th>Addressed Problems</th>
</tr>
</thead>
</table>
| Offline Analysis /OFA (in the planning stage) | • Identify elementary coherent groups of generators and potential separation boundaries forming sustainable islands  
• Place SRs and synchrophasors.  
• Develop a post-separation control strategy for each potential island | Study “where”, “when”, and “what”          |
| Online Monitoring /ONM (periodically) | • Monitor oscillations between elementary coherent groups  
• Predict currently probable separation boundaries from those pre-determined in the OFA stage. | Solve “where” and study “when”             |
| Real-time Control/RTC (in real time) | • Use real-time synchrophasor data to estimate the separation risk on each boundary predicted in the ONM stage  
• Form islands at a boundary when its risk exceeds a preset threshold  
• Perform post-separation control strategies from the OFA stage in islands | Solve “when” and “what”                    |
Where to Separate?

WECC 179-bus System

Graph Representation
Complex systems: complex in that they are diverse and made up of multiple interconnected elements and adaptive in that they have the capacity to change and learn from experience.

The Whole > Part 1 + Part 2 + ···

When the whole is too complex to handle, why not split it into small pieces.
References

- J. Qi, K. Sun, and S. Mei, “An interaction model for simulation and mitigation of cascading failures,” submitted to IEEE.
- J. Qi and K. Sun, “Estimating the propagation of several cascading outages with multi-type branching processes,” submitted to IEEE.
- Task Force on Understanding, Prediction, Mitigation and Restoration of Cascading Failures, “Mitigation and prevention of cascading outages: methodologies and practical applications”.