Cascading Outages, Relaying, and Wide-Area Distributed Control

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Normal Operation

Power flows from East and North

Loads are in the Western region
500 kV line tripped (human error)

Not normally a problem

But, could not reclose because of large standing angle

And, could not see angle

Heavy loads cause power flow directional change
Transformer overloads and trips

Multiple power flow changes

Lines become highly overloaded

San Diego fed primarily through single line to San Onofre Nuclear and it also is highly overloaded
San Onofre line overload duration leads to line trip

Large frequency swings

San Diego blackout
Path 44 During Cascade

From NERC Report
Relays During Major Disturbances

...low voltage, high power flows, power swings, abnormal frequency changes, rapid topology changes, ...

<table>
<thead>
<tr>
<th>Element</th>
<th>Challenges During Major Disturbance</th>
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<tr>
<td>Zone 1 distance</td>
<td>Power swing sensitivity</td>
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<td></td>
<td>Polarizing voltage memory</td>
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<td>Overreaching distances – zones 2, 3, 4</td>
<td>Load encroachment</td>
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<td>Instantaneous overcurrent</td>
<td>Power swing</td>
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<td>Undervoltage</td>
<td>Transient low voltage conditions</td>
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<td>Protecting the asset</td>
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<td>Differentials &amp; phase comparison</td>
<td>Immune to swings</td>
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</table>
Impedance During Major Disturbance

![Diagram of voltage and current relationships with impedances]

\[
Z = \frac{V_A}{I_L} = \frac{E_S}{E_S - E_R} (Z_S + Z_L + Z_R) - Z_S
\]
V => Z Impact

\[ \frac{E_S}{E_S - E_R} \]

- When \( E_R \) decreases, this term decreases
- When the angle between sources changes, this term decreases

\[ \frac{E_S}{E_S - E_R} = \frac{1}{2} \left(1 - j\cot\frac{\delta}{2}\right) \]
Impact of Relative Angle Variation

\[ \bar{Z} = \frac{\bar{Z}_T}{2} \left( 1 - j \cot \frac{\delta}{2} \right) - \bar{Z}_S \]

\[ k = \frac{E_S}{E_R} \]

\( \delta \) decreases

\( \delta \) = 180°

\( 0.5 \bar{Z}_T \)

\( \delta \) increases

\( \bar{Z} \)

\( Z \)

\( Z_L \)

\( Z_R \)

\( Z_S \)

\( R \)

\( X \)
Power Systems are Changing
Weaker and Intermittent Sources, “Stiffer” Loads, Longer Lines

- Less control over sources
- Faster dynamics
- Modern loads don’t brown out
SONGS Safety Net – Installed Now

Distance traveled in 1 processing interval

Start 0 / Finish 1

Power Flow (MW)

Time (s)

Safety Net Does Not Operate

Safety Net Operates

South Interconnection Opens

Non-credible N – 2 Outage Occurs
Central America – Installed Now

\[ y(t) = \sum_{i} A_{m_i} e^{\sigma_i t} \cos\left(2\pi f_{m_i} t + \phi_{m_i}\right) \]
SIPS / RAS

• Designed for specific applications
• Preplan the responses
• Do include state measurement & feedback
• Challenged by complex contingencies
Looking To The Future...

Ref: reference

Controller

Observer

System, G

Output
Power System Control For...

- Geographically large
- Nonlinear
- Undergoes structural changes
  - Intentional
  - Unintentional
Structure Drives Trajectory

\[ f_{d_{k-1}} \quad n(d_{k-1}) \quad x_{k-1} \quad f_{d_k} \quad n(d_k) \quad x_k \]
Keeping The System Constrained

- state
- equilibrium point
- operating boundary
- region of convergence
- existing-control boundary

Diagram showing a region in state space with an equilibrium point and boundaries.
Must Consider Contingencies

![Diagram with state and topology/parameter axes]
Contingencies Further Constrain The Operating Region
How To Design A Controller That

• Is designed for **nonlinear** systems
• Is **structural**, not signal based
• Stabilizes a **wide range** of contingencies
• Keeps states within **acceptable bounds**
• Minimizes the **cost** of controls
• Is **robust** and **resilient**
Biological Control Systems

Very efficient and resilient – large nonlinear, non-signal systems

• Redundant
• Modular
• Distributed
• Adaptable
• Feedback
• Diversity
• Learn / Memory

{Measuring}
{Modeling Predicting Assessing}
{Selection best actions}
Design Approach

• Don’t try to predict contingencies
• Instead, predict state evolution
  – Run in real-time
  – Iterative application, with feedback
  – At each iteration search for optimal control
• Why optimal control?
  – Because with control over the structure, we can stabilize any contingency
  – More interesting is to do so at minimum cost
Model Prediction Control – iter 1

- evolution
- modeling

predicted trajectory 1
predicted trajectory for no controls
predicted trajectory 2
reference trajectory

state

t_F, t_T

structure selection 1
structure selection 2
Model Prediction Control – iter 2

- Evolution
- Modeling

- Predicted trajectory 1
- Predicted trajectory 2
- Reference trajectory
- Predicted trajectory for no controls

State

Structure selection 1

Structure selection 2
Stabilizing the System
Rush-to-judgement vs. overthinking
Technology Enablers

• More, better, faster measurements
  – Synchrophasors
  – Time-domain
• Faster, more reliable networks
• Higher performance computing
• Real-time simulation advances
• Distributed systems
• Architectural changes - microgrids
From Research To ... The Very Practical

- Equipment Failure: 36%
- Settings / Logic / Design / As-left: 37%
- Unknown: 14%
- System: 13%

NERC Staff Analysis of System Protection Misoperations, December 2014
Getting The Settings Right

### Device Comparison

<table>
<thead>
<tr>
<th>Name</th>
<th>Feeder_A</th>
<th>Feeder_B</th>
<th>Feeder_C</th>
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<tbody>
<tr>
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<tr>
<td><strong>In Service</strong></td>
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<tr>
<td>Feeder_A</td>
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<td>Feeder_B</td>
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<td>Feeder_D</td>
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</tbody>
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Also Practical...

Time-Domain Protection

Faster tripping =>
- stays closer to equilibrium
- fewer contingencies
- less state variation
Conclusions

• Relays take quick action to isolate only faulted elements - but during a cascade asset removal can further weaken the system
• Special protection schemes increase reliability for specific situations
• Settings / logic / design are a cost-effective way to reduce cascade probability
• System level state-based control solutions of the future adapt to large order contingencies
• The “need for speed” – time domain protection
Some References

• Zweigle, G.; Venkathasubramanian, M.; “Transient Instability Mitigation For Complex Contingencies With Computationally Constrained Cost-Based Control”, IEEE Transactions on Smart Grid, July 2016
• Zweigle, G.; Blood, E.; ” Distributed Control With Local and Wide-Area Measurements for Mitigation of Cascading Outages”, IEEE N. American Power Symposium, September 2014.
• E.O. Schweitzer, III, B.Kasztenny, A.Guzman, V.Skendzic, M.V. Mynam, "Speed of Line Protection – Can We Break Free of Phasor Limitations?", WPRC 2014