Cascading Outages, Relaying, and Wide-Area Distributed Control

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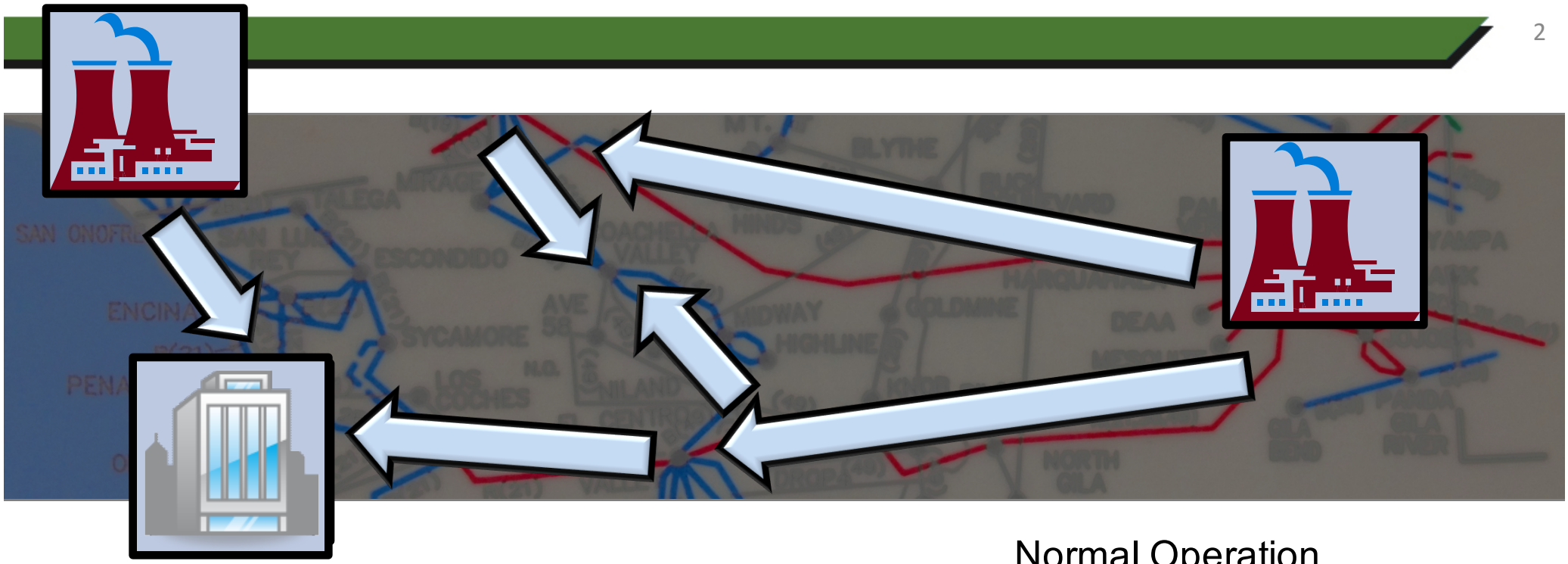
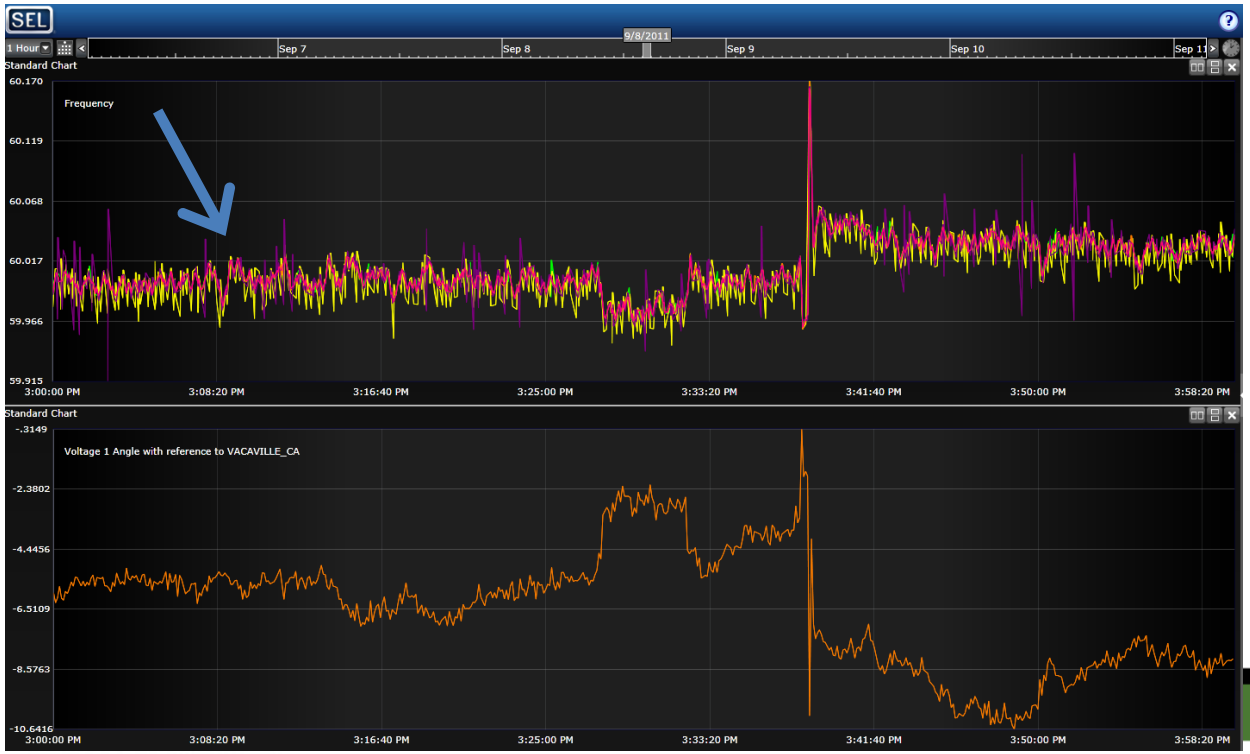
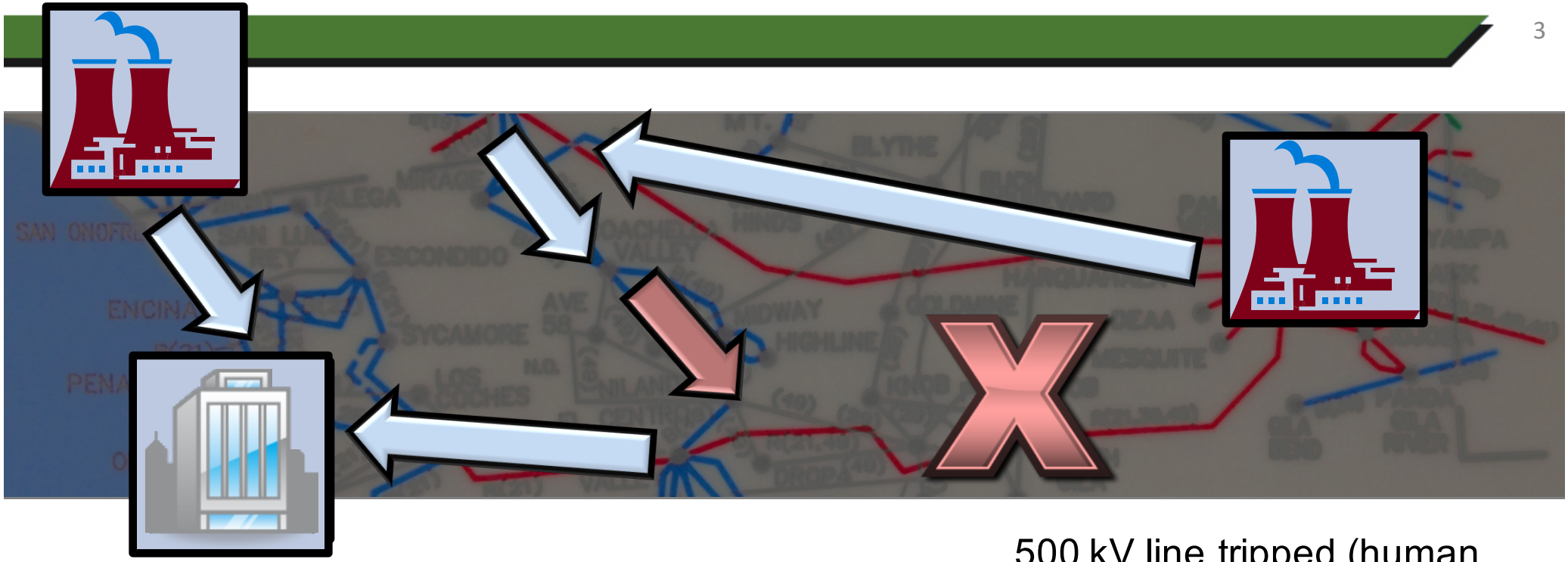


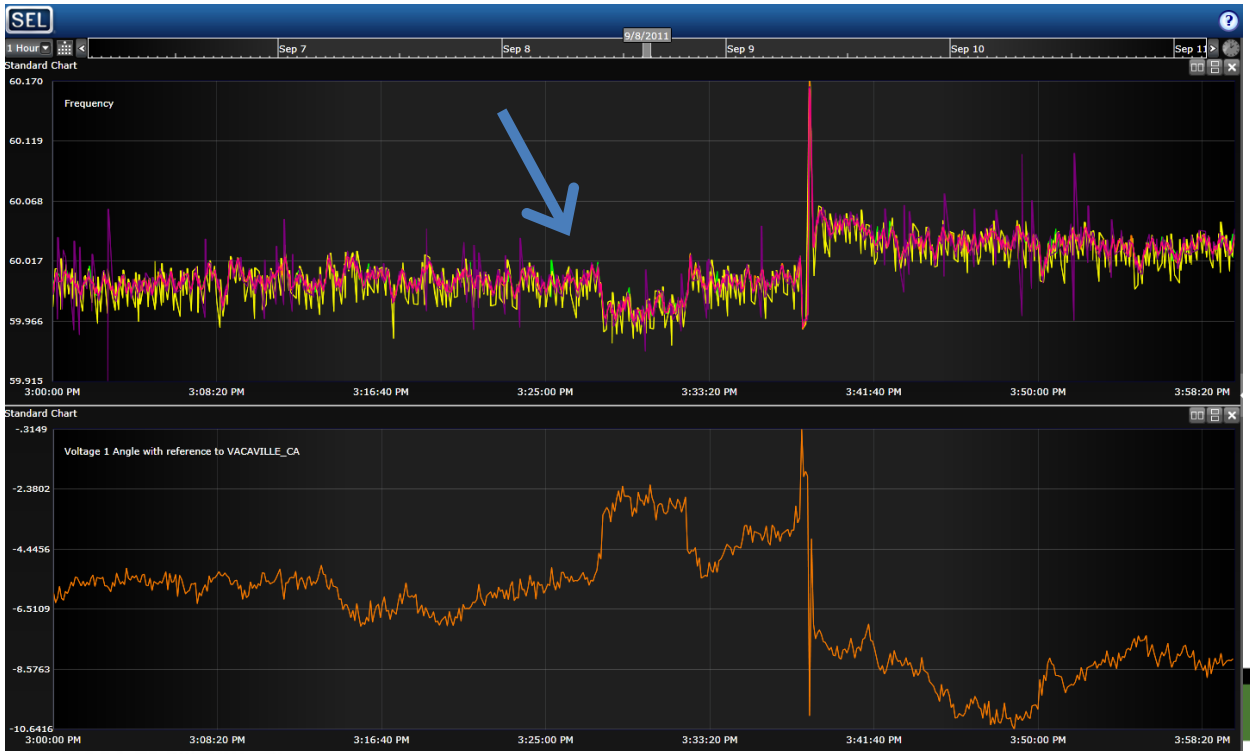


Normal Operation

Power flows from East and North

Loads are in the Western region





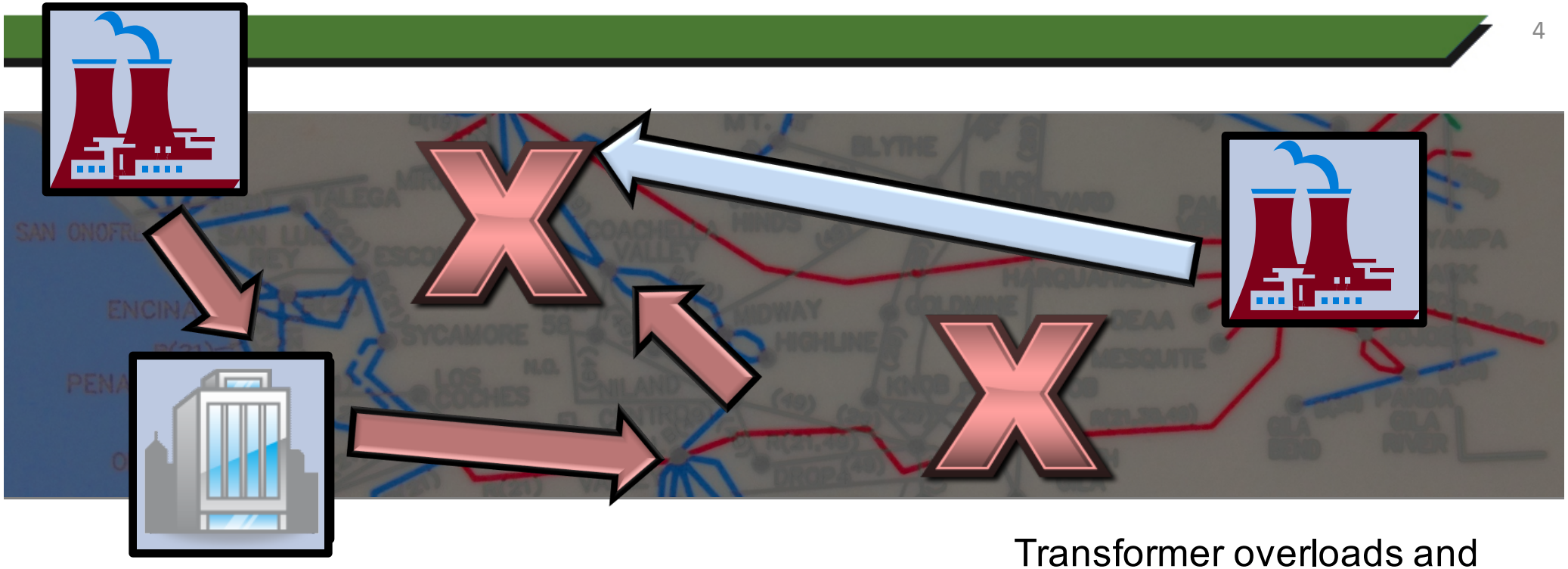
500 kV line tripped (human error)

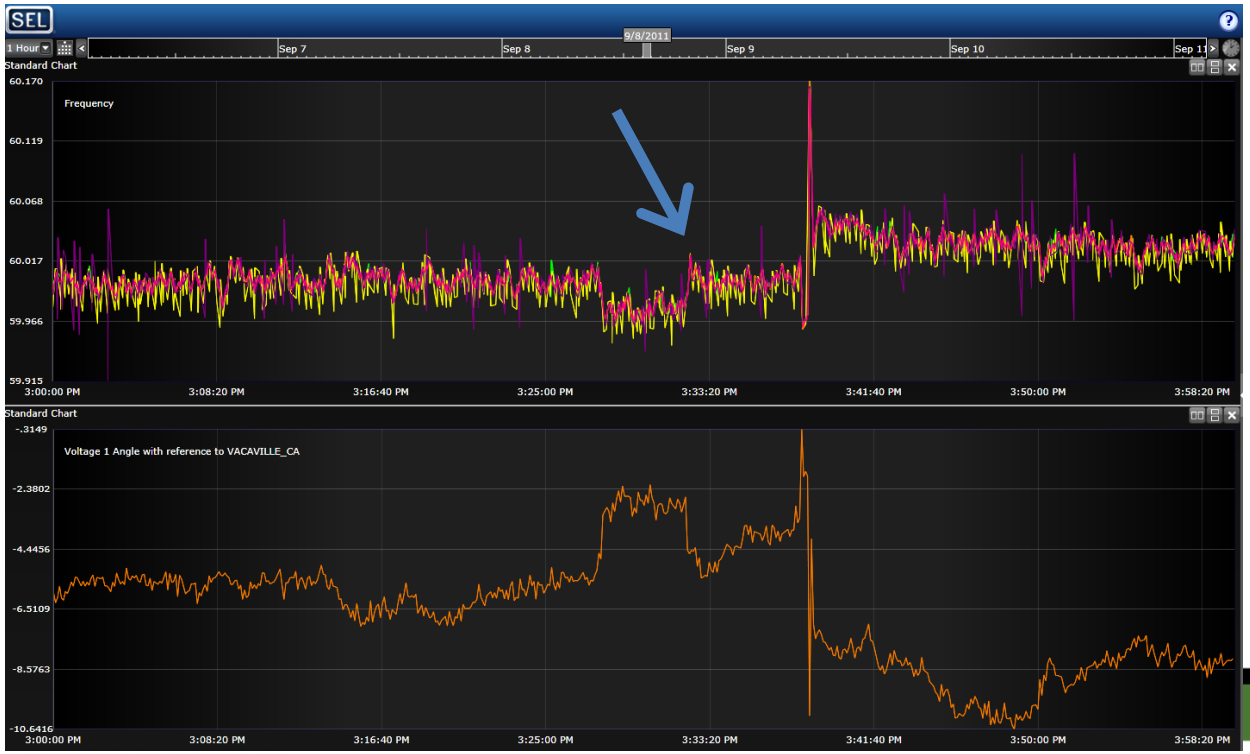
Not normally a problem

But, could not reclose because of large standing angle

And, could not see angle

Heavy loads cause power flow directional change



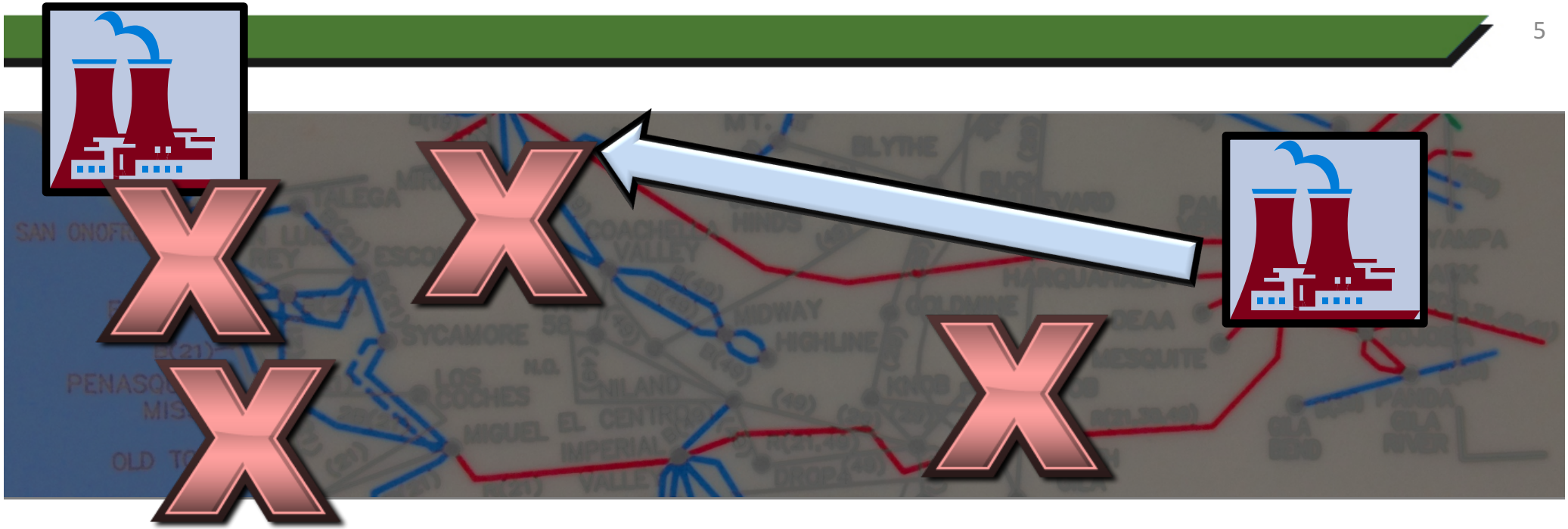


Transformer overloads and trips

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

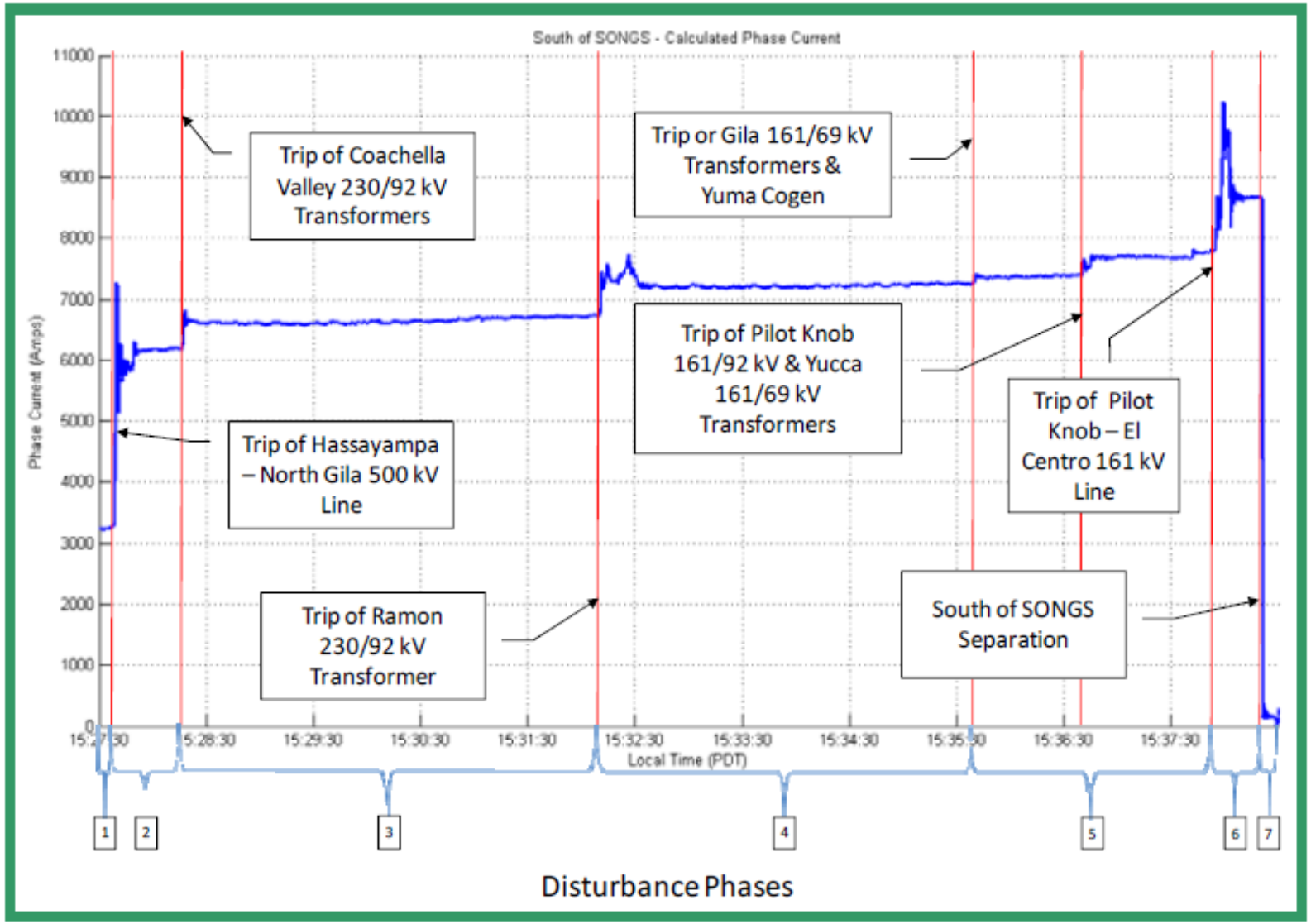


San Onofre line overload duration leads to line trip

Large frequency swings

San Diego blackout

Path 44 During Cascade



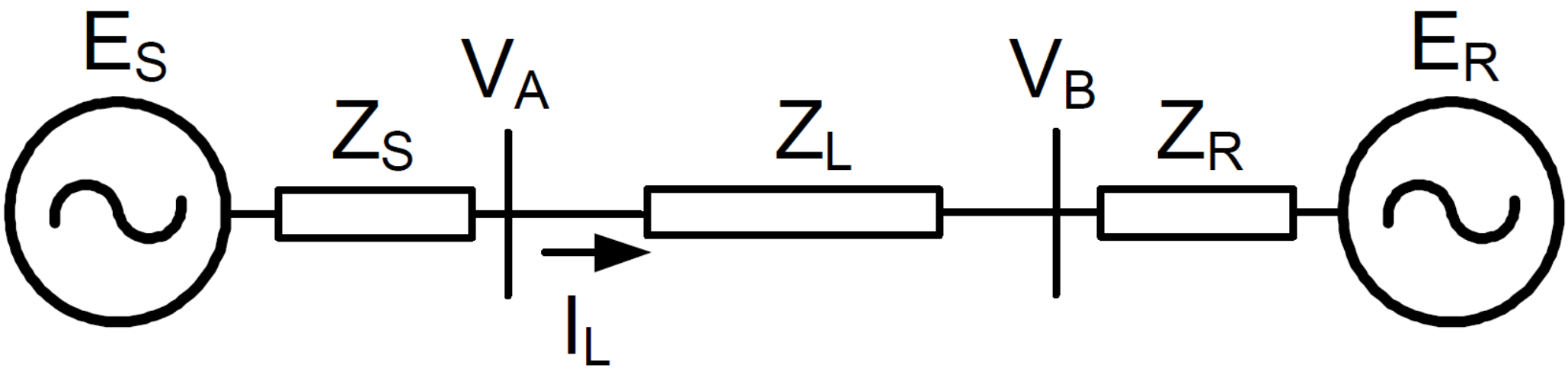
From NERC Report

Relays During Major Disturbances

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

Element	Challenges During Major Disturbance
Zone 1 distance	Power swing sensitivity Polarizing voltage memory
Overreaching distances – zones 2, 3, 4	Load encroachment
Instantaneous overcurrent	Power swing
Undervoltage	Transient low voltage conditions
Generator protection	Protecting the asset
Differentials & phase comparison	Immune to swings

Impedance During Major Disturbance



$$Z = \frac{V_A}{I_L} = \frac{E_S}{E_S - E_R}(Z_S + Z_L + Z_R) - Z_S$$

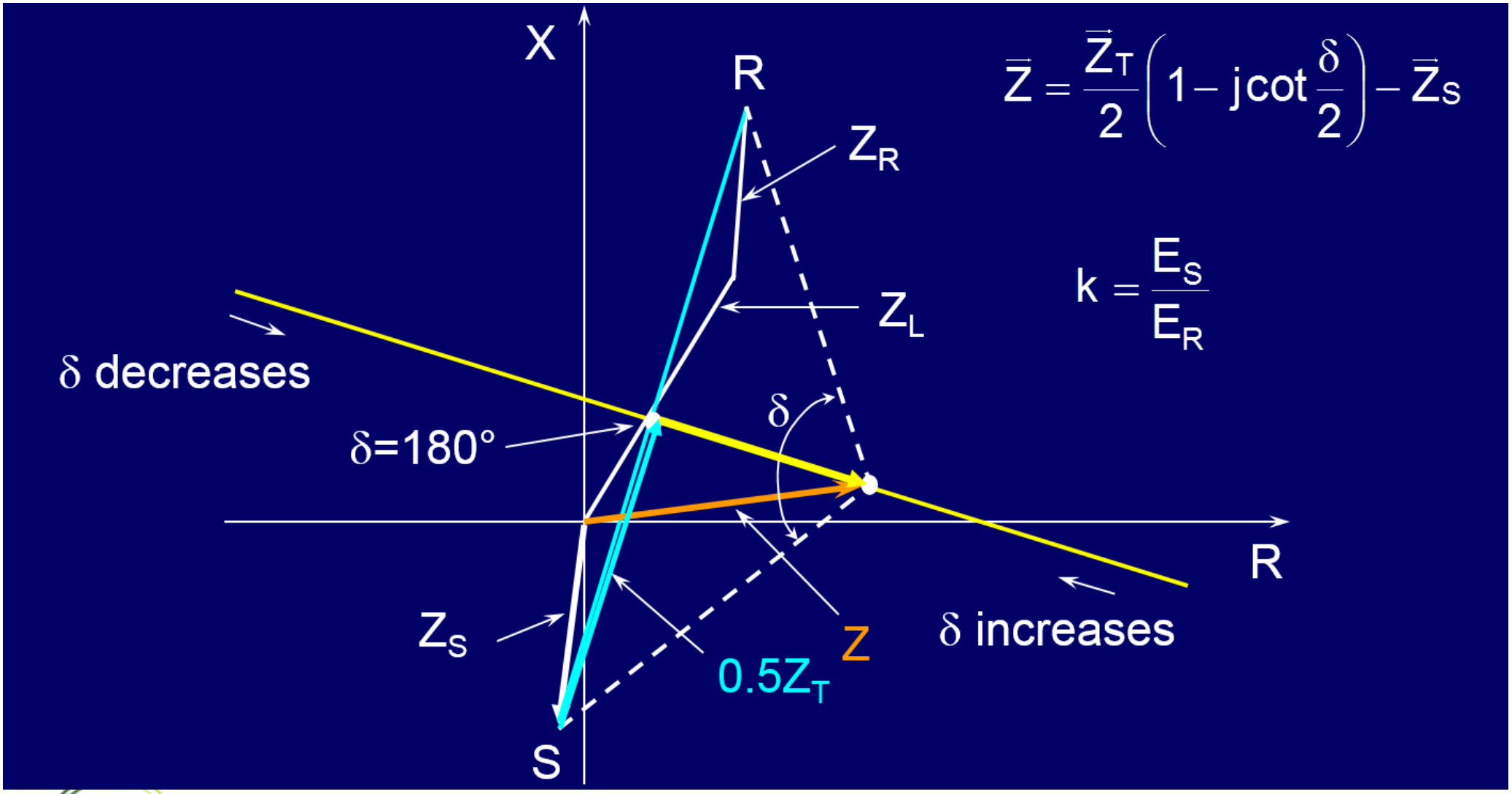
V => Z Impact

$$\frac{E_S}{E_S - E_R}$$

- 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



$$\vec{Z} = \frac{\vec{Z}_T}{2}\left(1 - j\cot\frac{\delta}{2}\right) - \vec{Z}_S$$

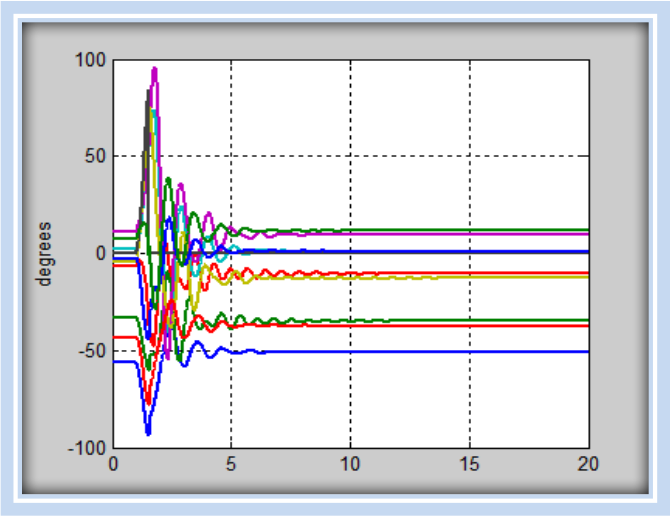
$$k = \frac{E_S}{E_R}$$

Power Systems are Changing

Weaker and Intermittent Sources, “Stiffer” Loads, Longer Lines

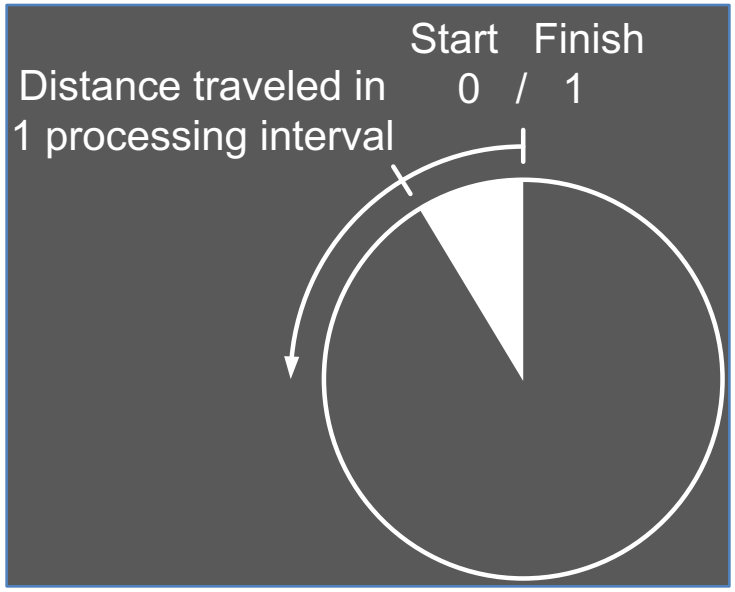
Less control over sources

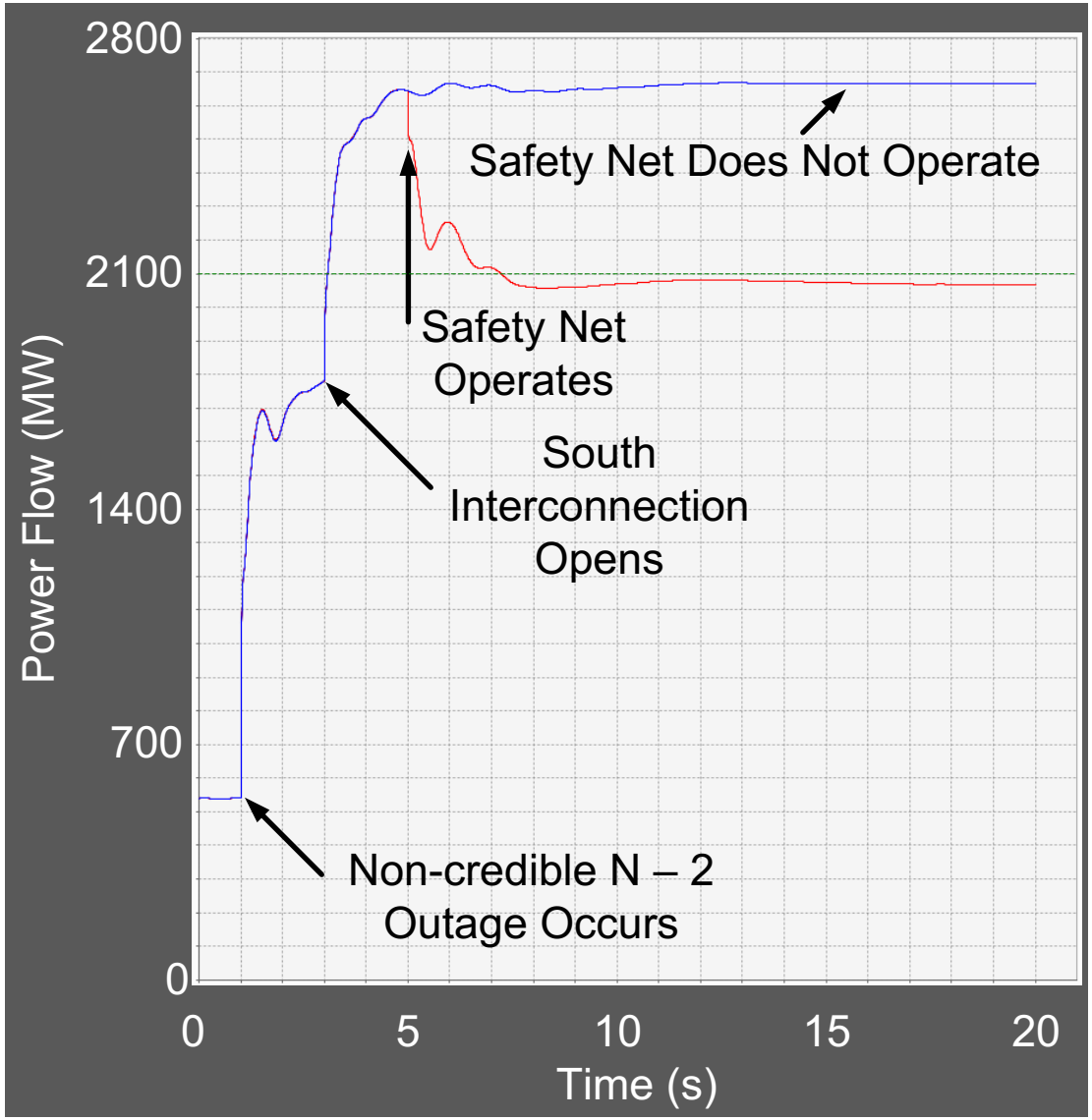
Faster dynamics



Modern loads don’t brown out

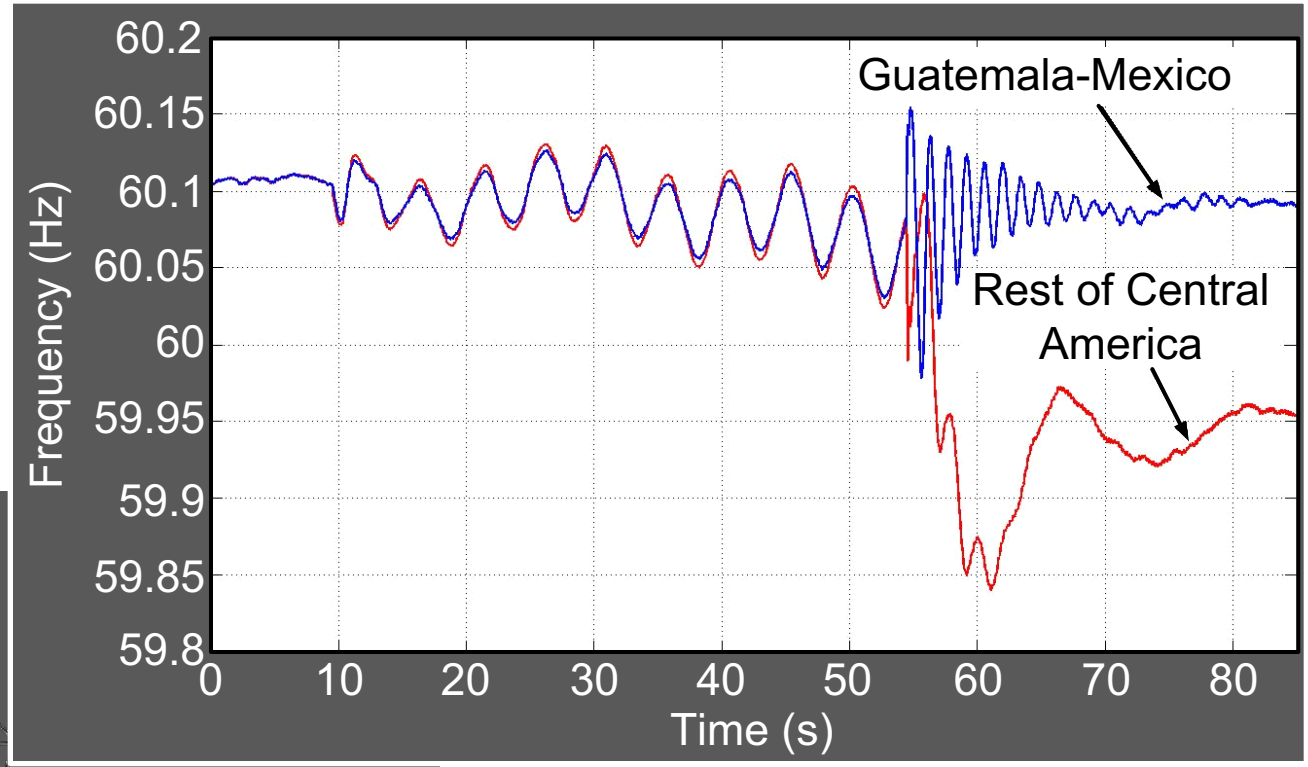
SONGS Safety Net – Installed Now

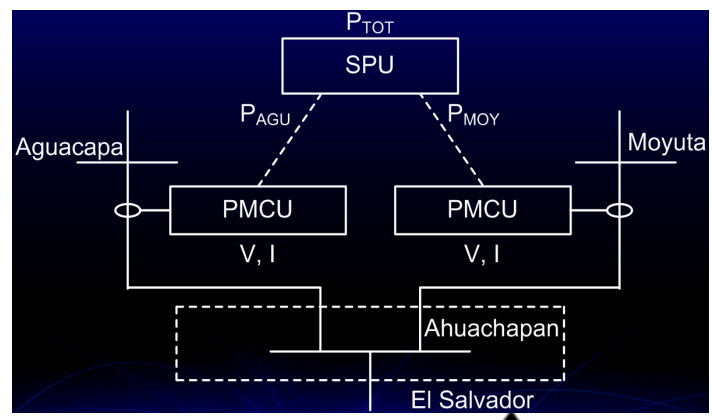




Central America – Installed Now

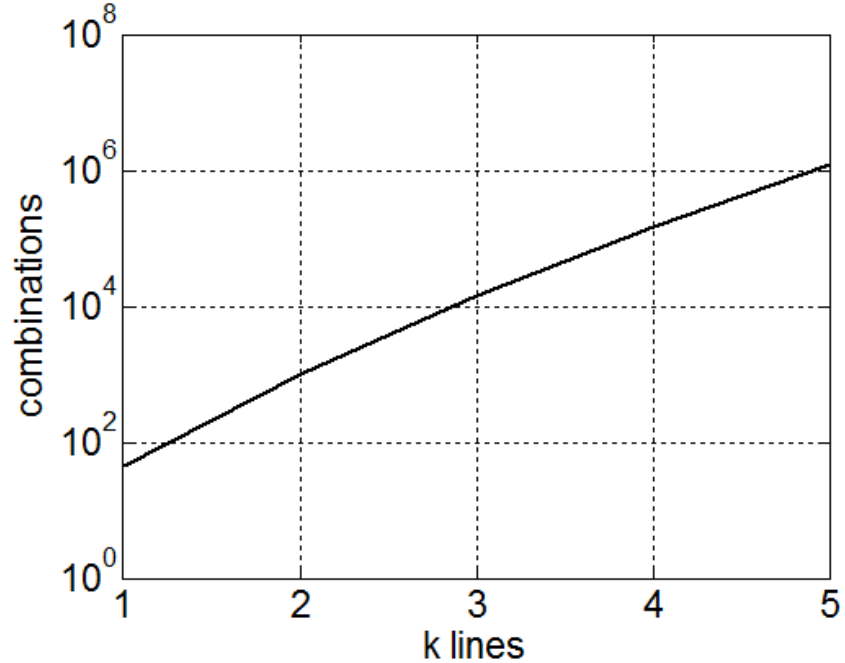
$$y(t) = \sum_i A_{m\_i} \quad e^{\sigma_i \cdot t} \cos\left(2\pi \cdot f_{m\_i} \cdot t + \phi_{m\_i}\right)$$



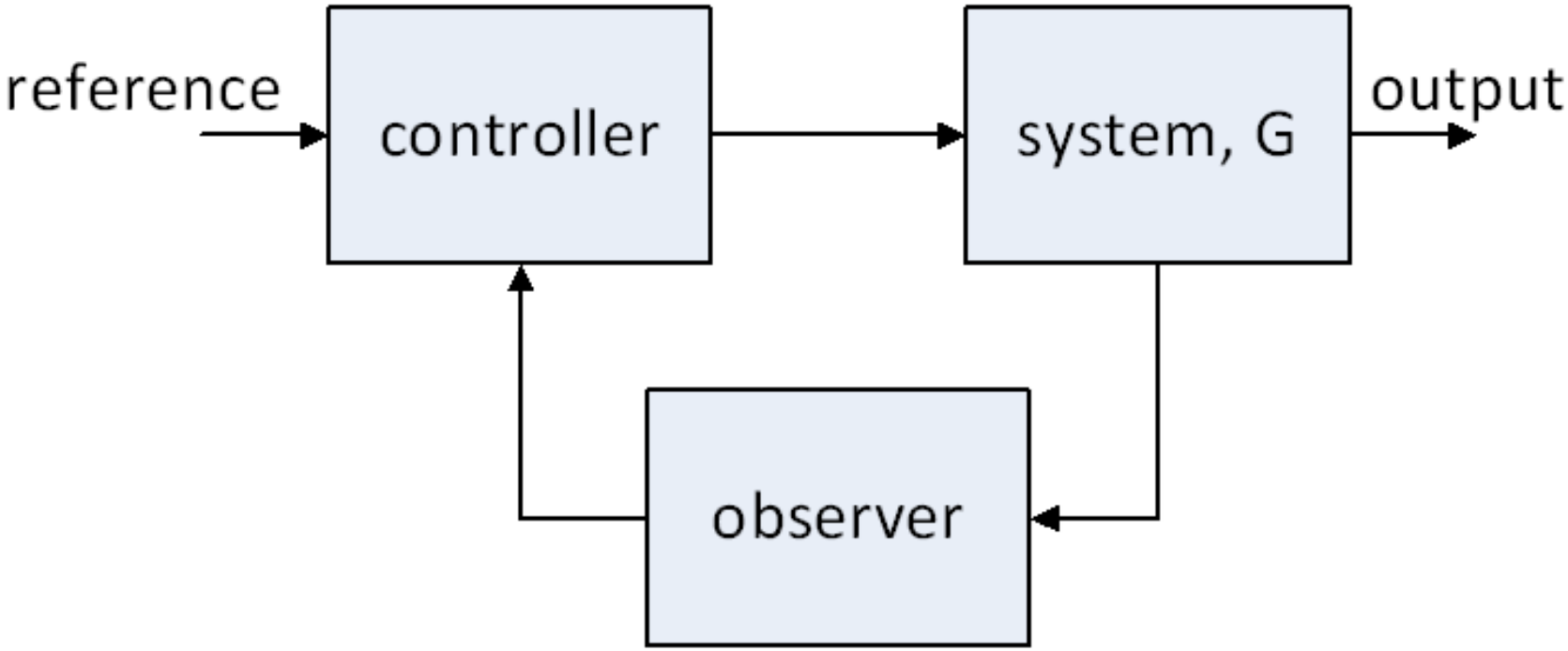


SIPS / RAS

- Designed for specific applications
- Preplan the responses
- Do include state measurement & feedback
- Challenged by complex contingencies

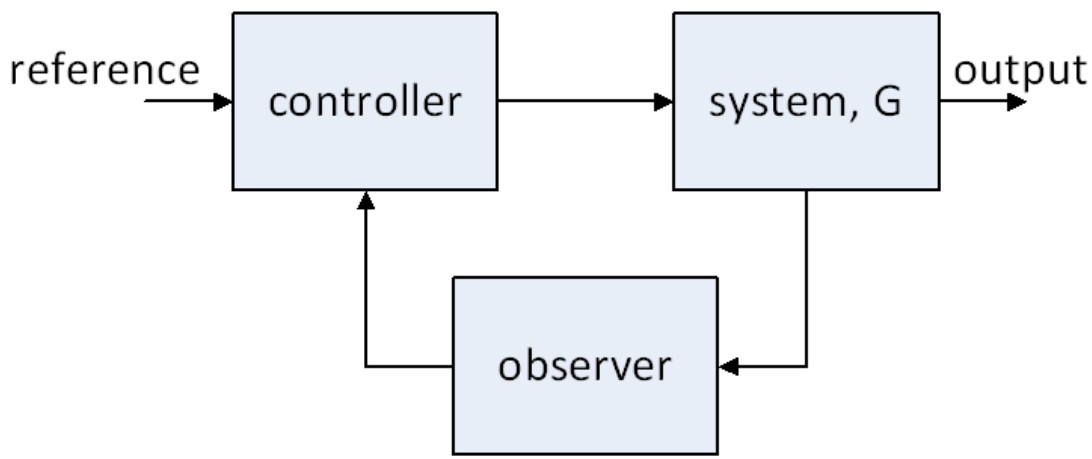


Looking To The Future…

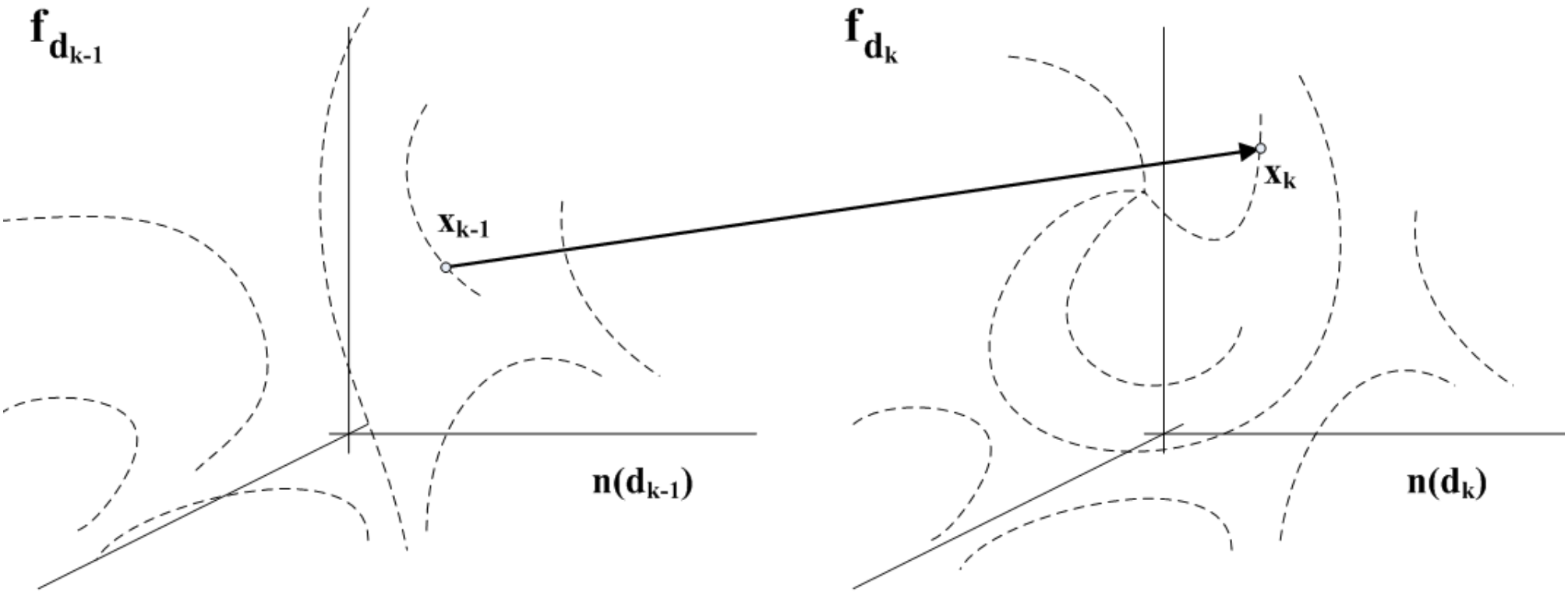


Power System Control For…

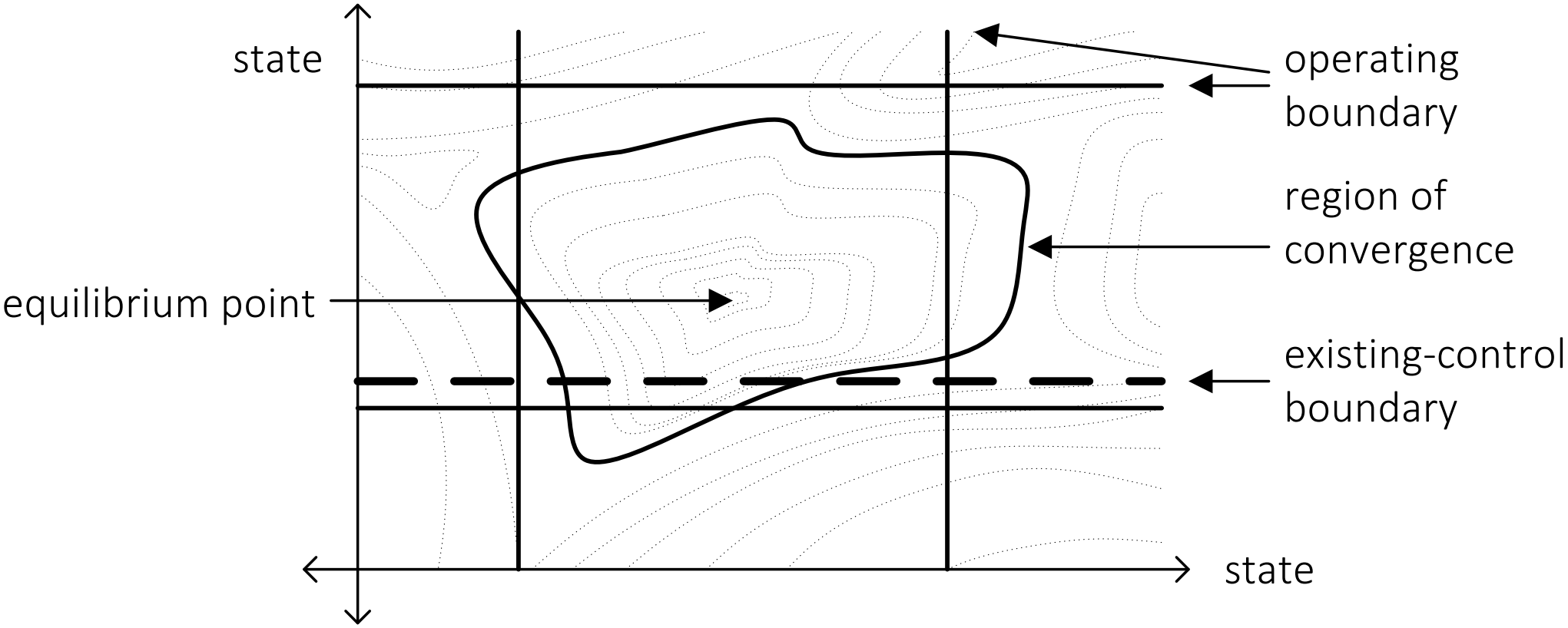
- Geographically large
- Nonlinear
- Undergoes structural changes
  - Intentional
  - Unintentional



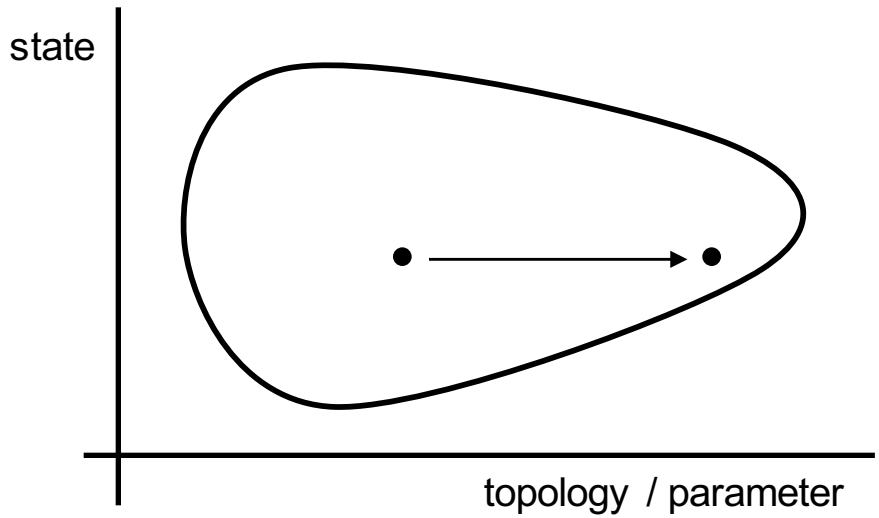
Structure Drives Trajectory

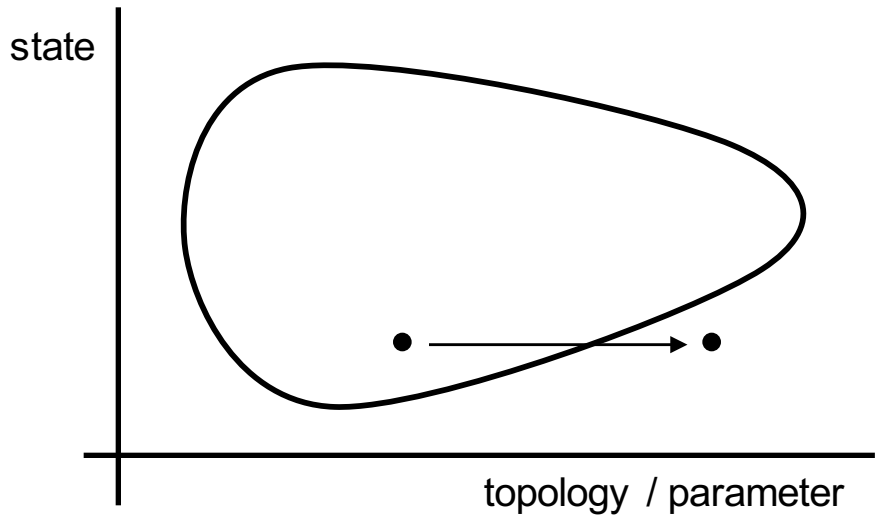


Keeping The System Constrained

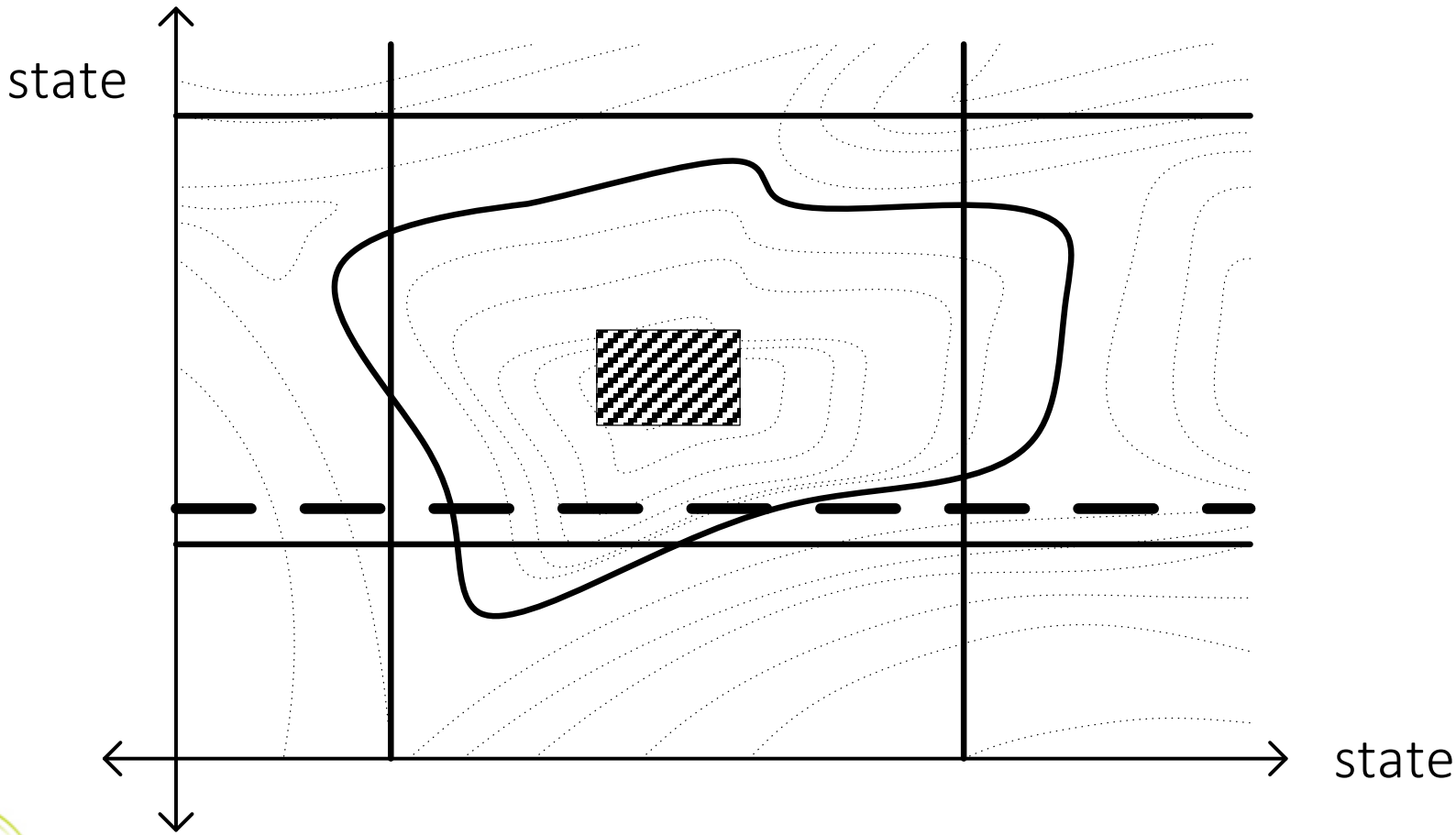


Must Consider Contingencies



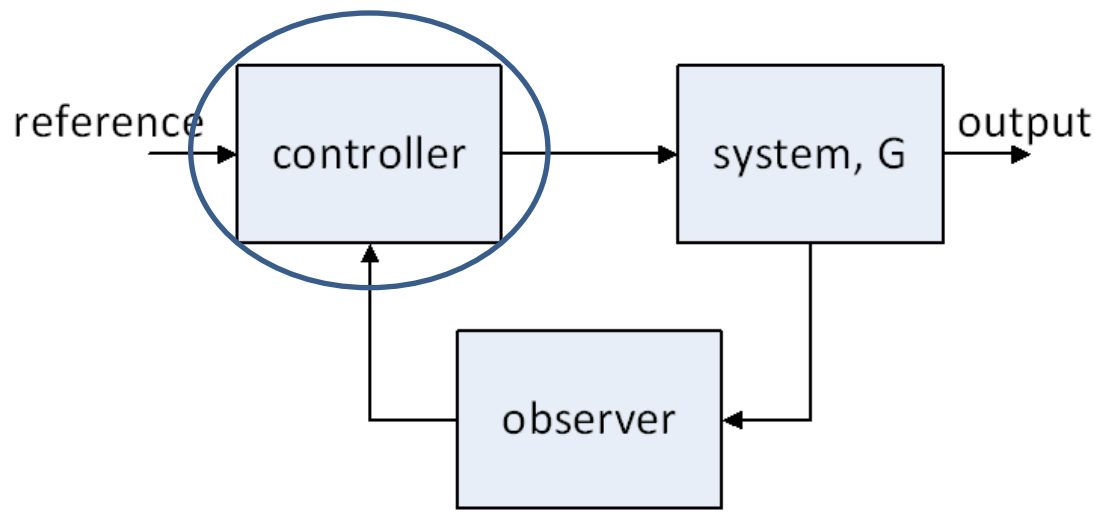


Contingencies Further Constrain The Operating Region



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

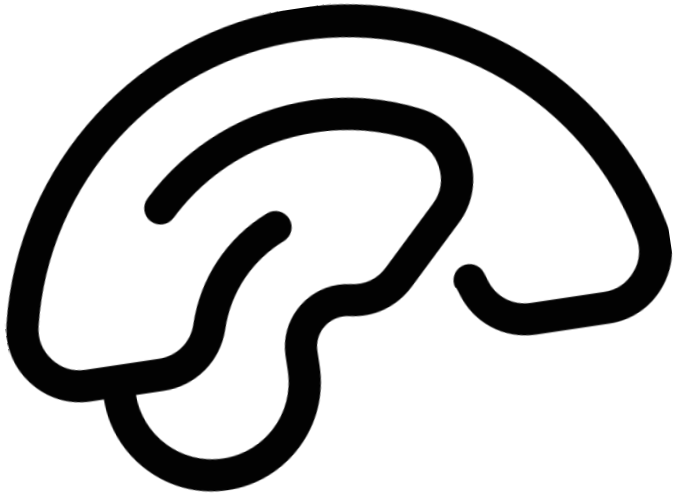


Biological Control Systems

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

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

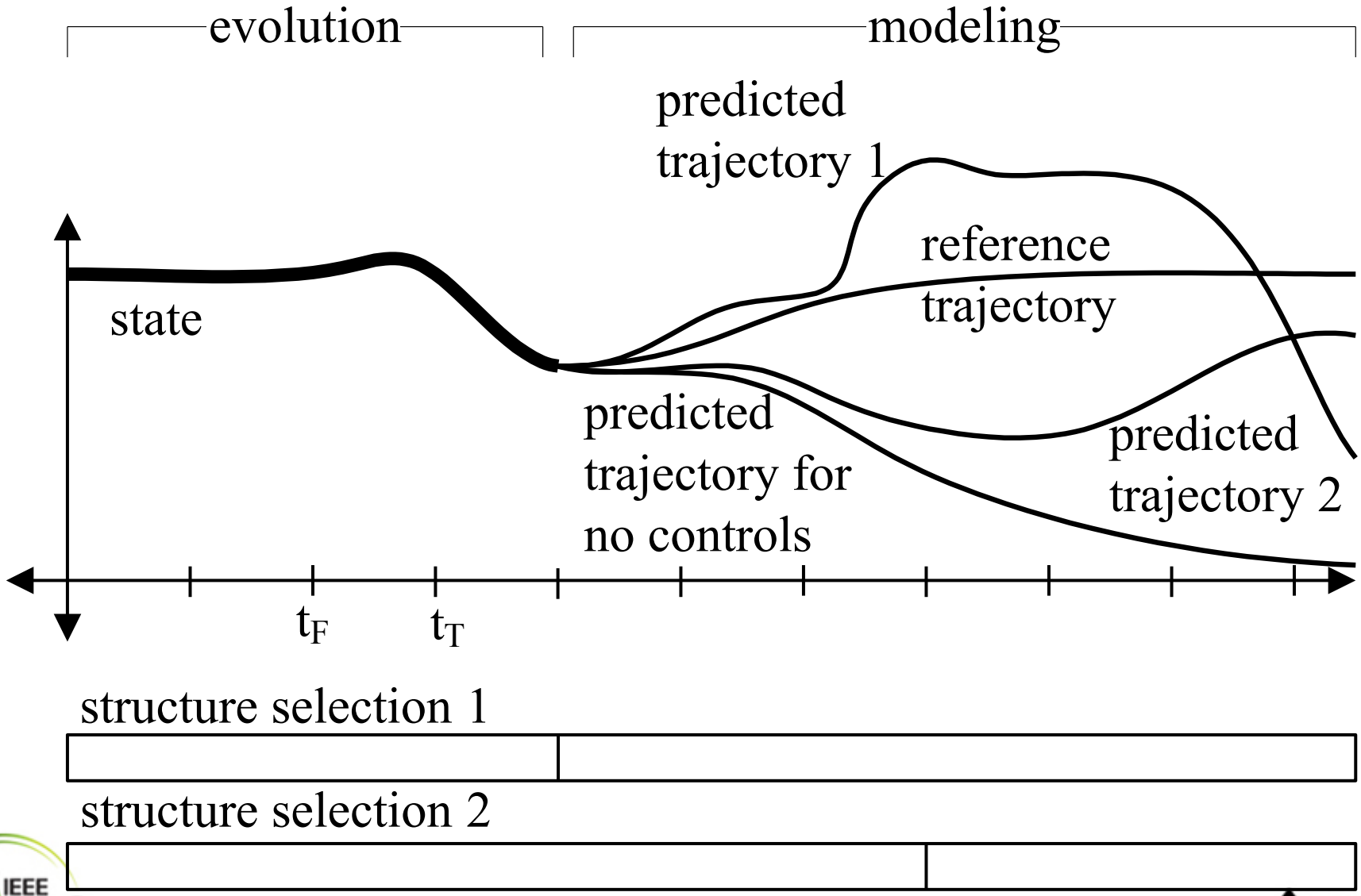
{Measuring}
{Modeling Predicting Assessing}
{Selection best actions}



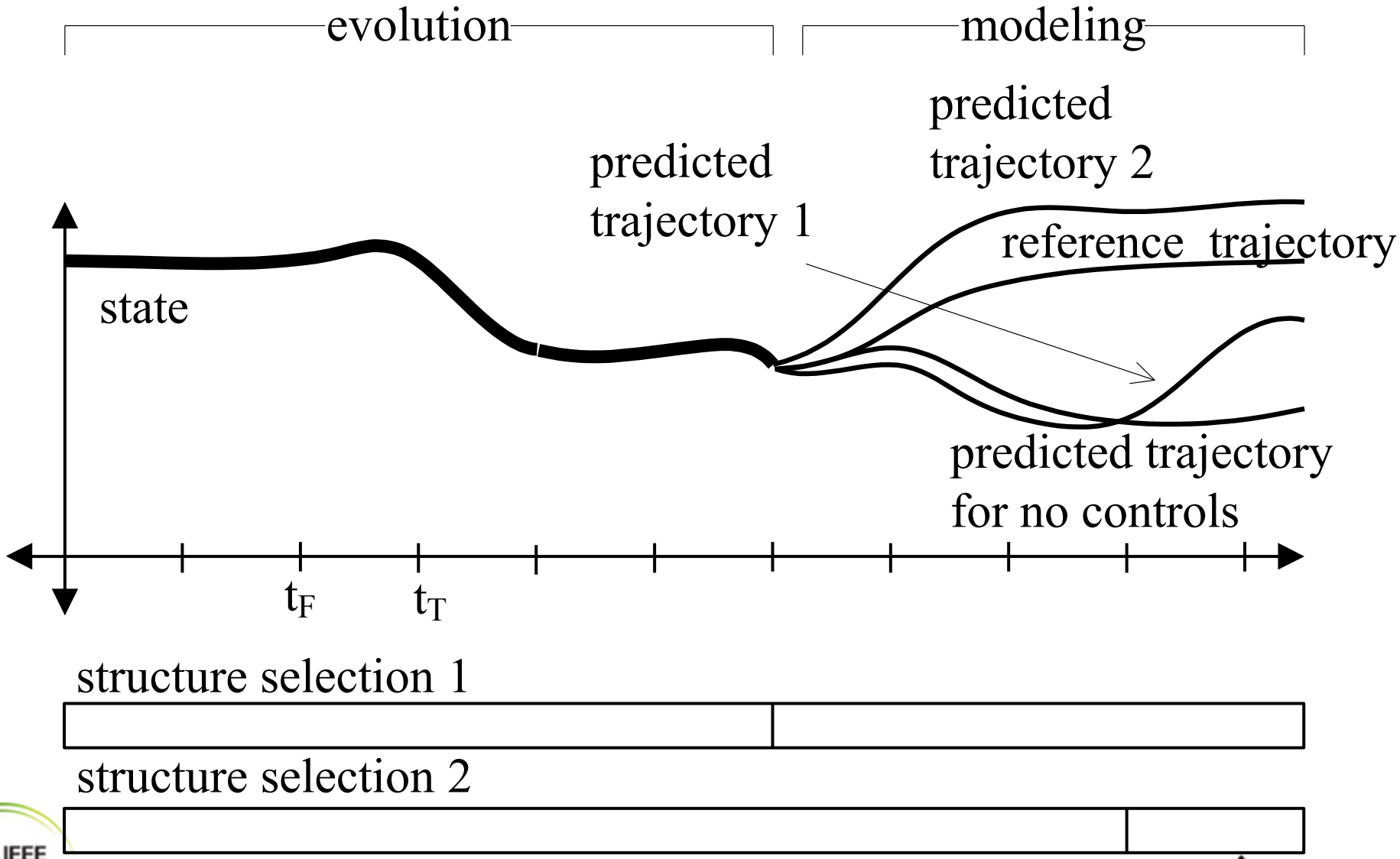
Design Approach

- 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

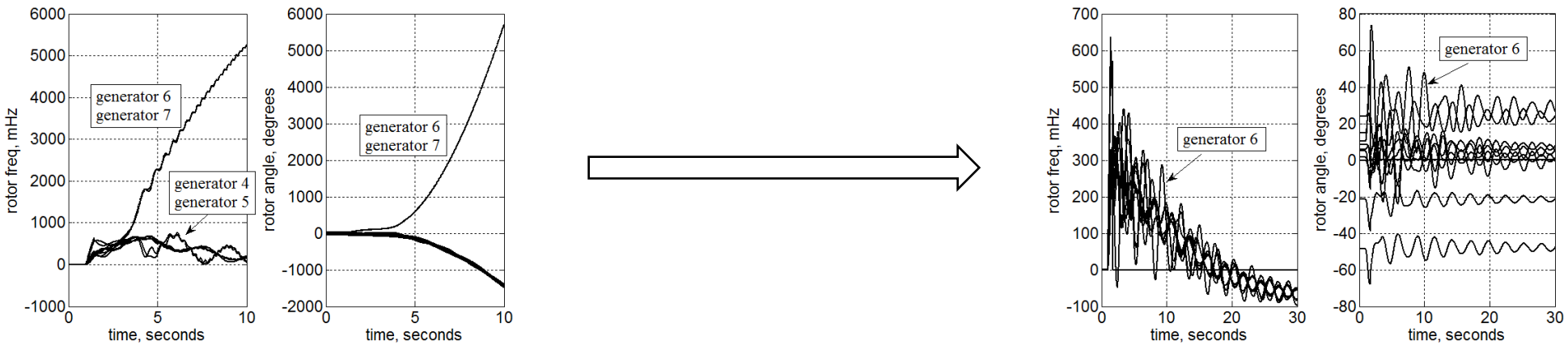
Model Prediction Control – iter 1

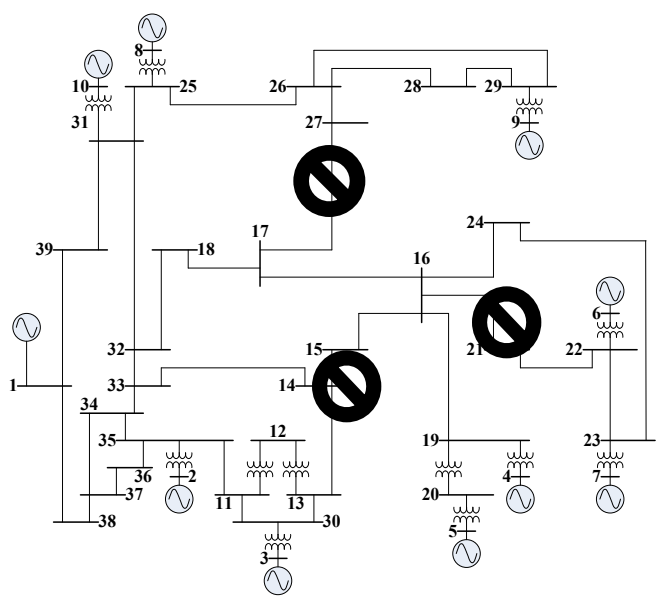


Model Prediction Control – iter 2

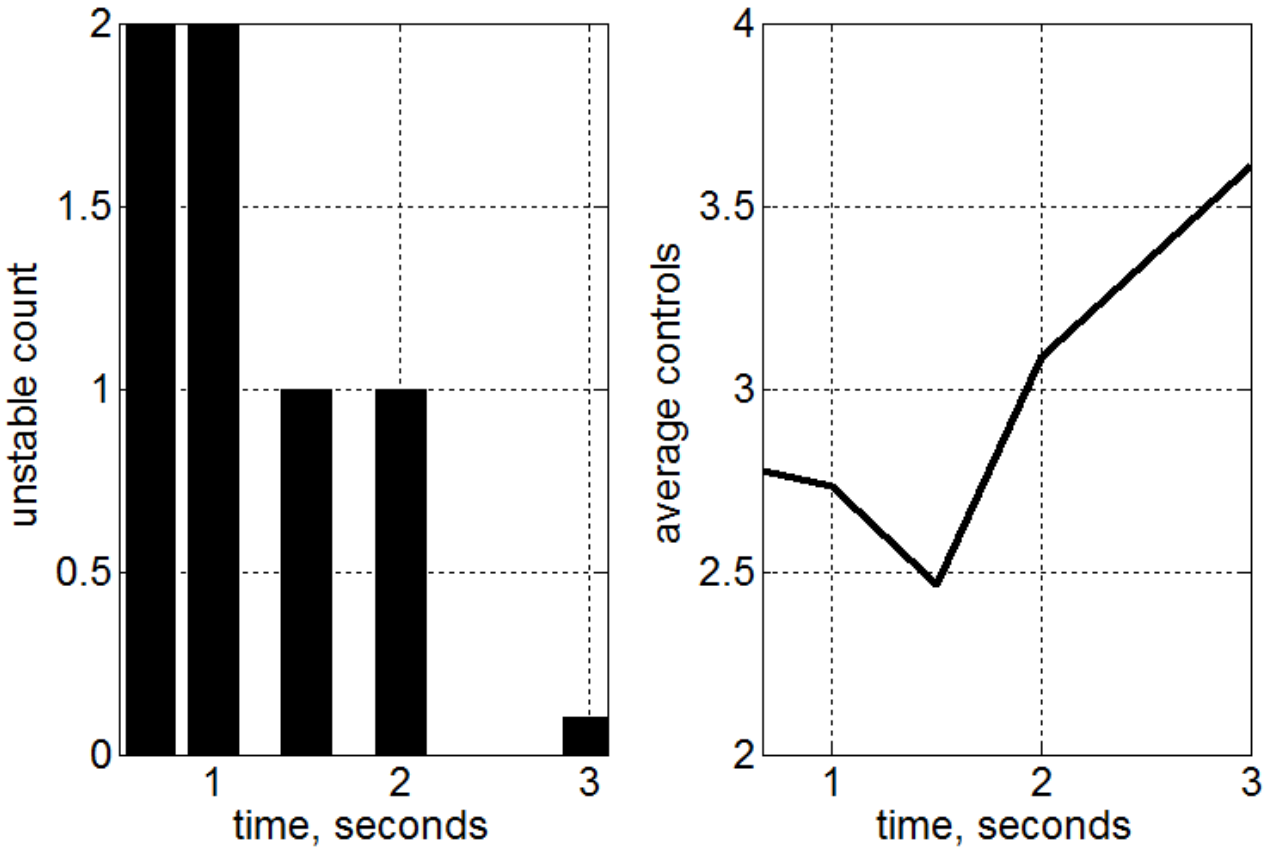


Stabilizing the System





Rush-to-judgement vs. overthinking

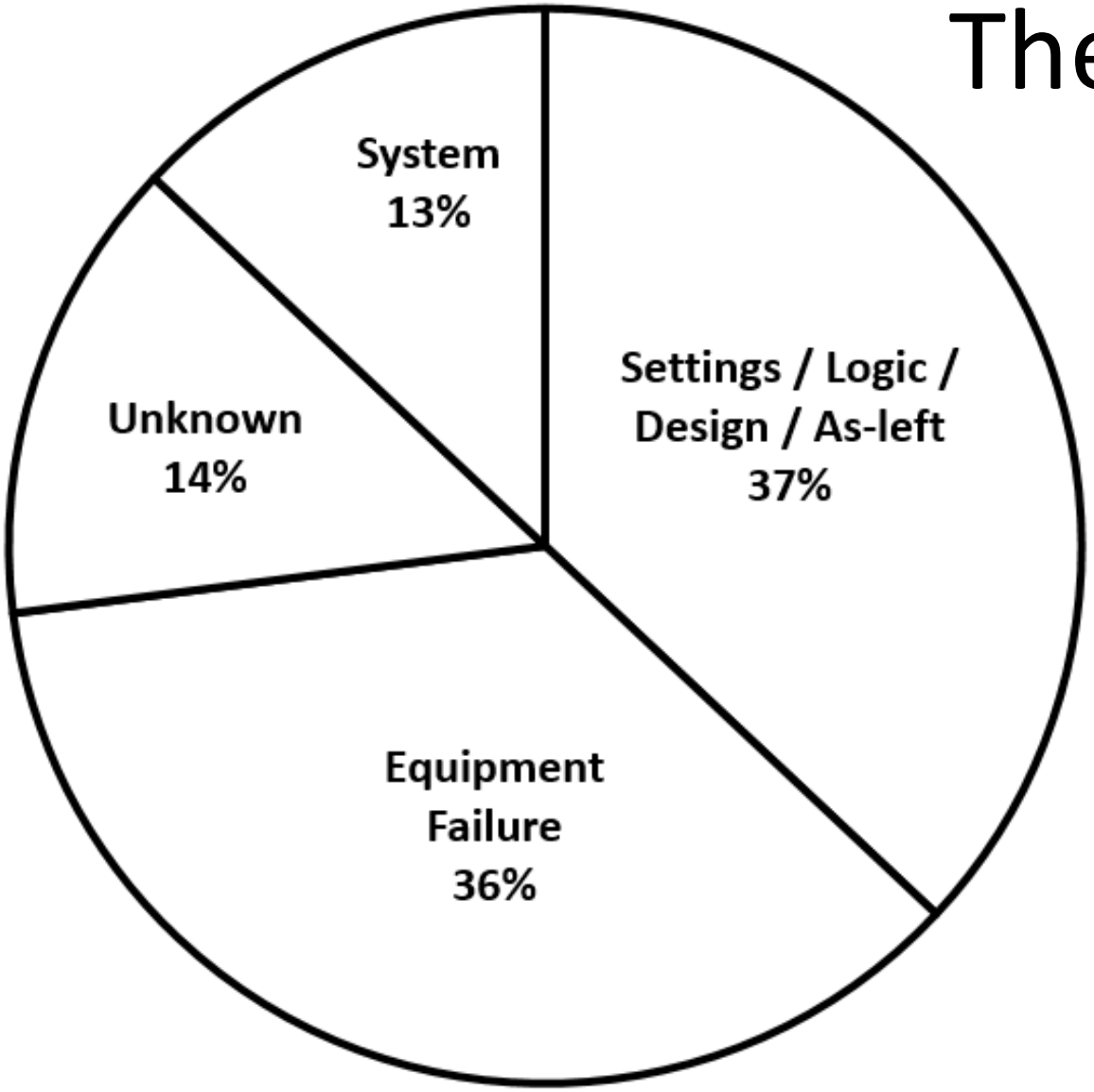


Technology Enablers

- More, better, faster measurements
  - Synchrophasors
  - Time-domain
- Faster, more reliable networks
- Higher performance computing
- Real-time simulation advances
- Distributed systems
- Architectural changes - microgrids

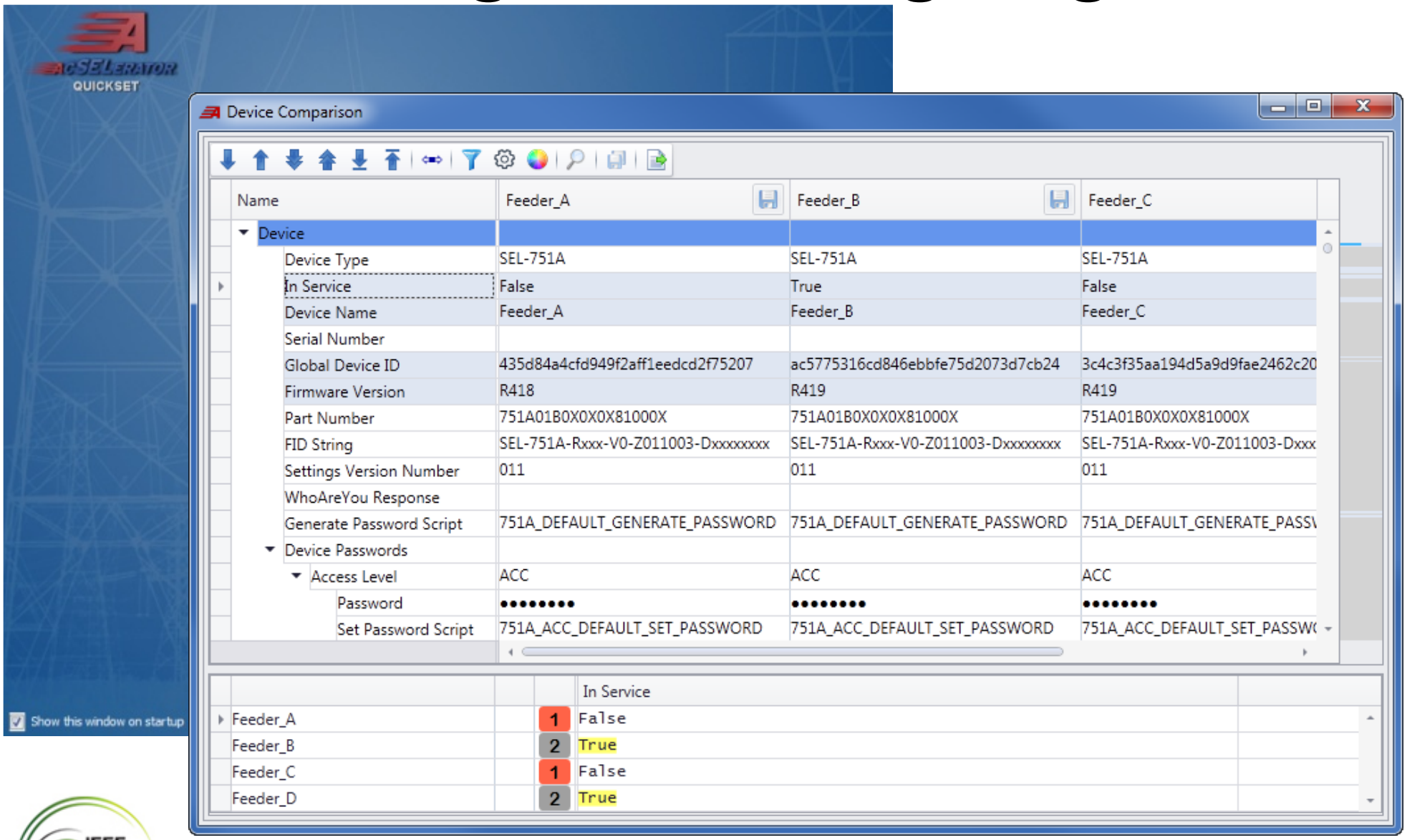
From Research To …

The Very Practical



NERC Staff Analysis of System Protection Misoperations, December 2014

Getting The Settings Right



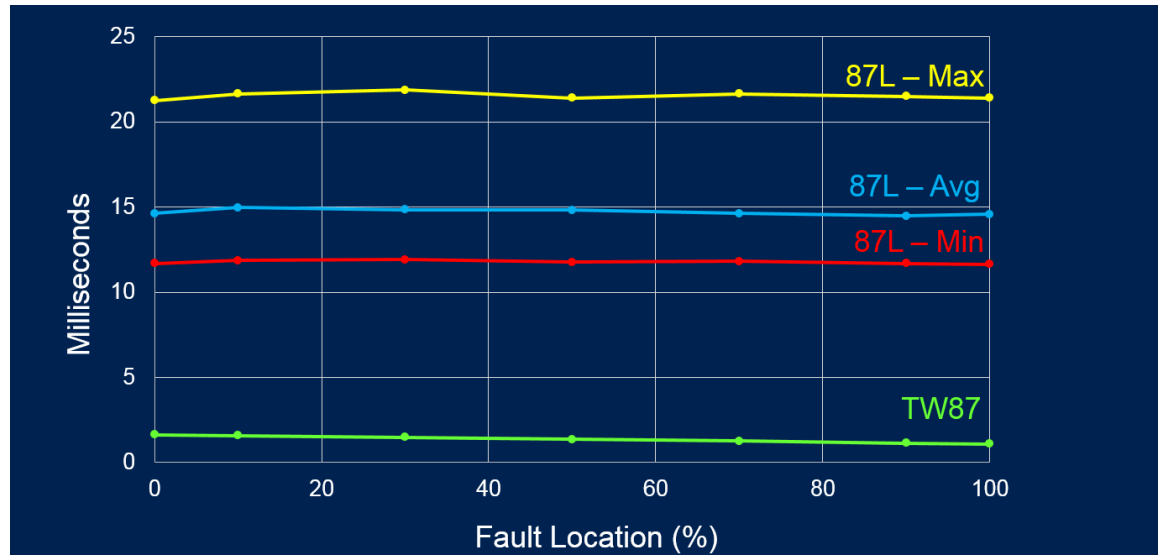
Name	Feeder_A	Feeder_B	Feeder_C
Device			
Device Type	SEL-751A	SEL-751A	SEL-751A
In Service	False	True	False
Device Name	Feeder_A	Feeder_B	Feeder_C
Serial Number			
Global Device ID	435d84a4cfd949f2aff1eedcd2f75207	ac5775316cd846ebbfe75d2073d7cb24	3c4c3f35aa194d5a9d9fae2462c20
Firmware Version	R418	R419	R419
Part Number	751A01B0X0X0X81000X	751A01B0X0X0X81000X	751A01B0X0X0X81000X
FID String	SEL-751A-Rxxx-V0-Z011003-Dxxxxxxxx	SEL-751A-Rxxx-V0-Z011003-Dxxxxxxxx	SEL-751A-Rxxx-V0-Z011003-Dxxx
Settings Version Number	011	011	011
WhoAreYou Response			
Generate Password Script	751A_DEFAULT_GENERATE_PASSWORD	751A_DEFAULT_GENERATE_PASSWORD	751A_DEFAULT_GENERATE_PASS
Device Passwords			
Access Level	ACC	ACC	ACC
Password	••••••••	••••••••	••••••••
Set Password Script	751A_ACC_DEFAULT_SET_PASSWORD	751A_ACC_DEFAULT_SET_PASSWORD	751A_ACC_DEFAULT_SET_PASSW

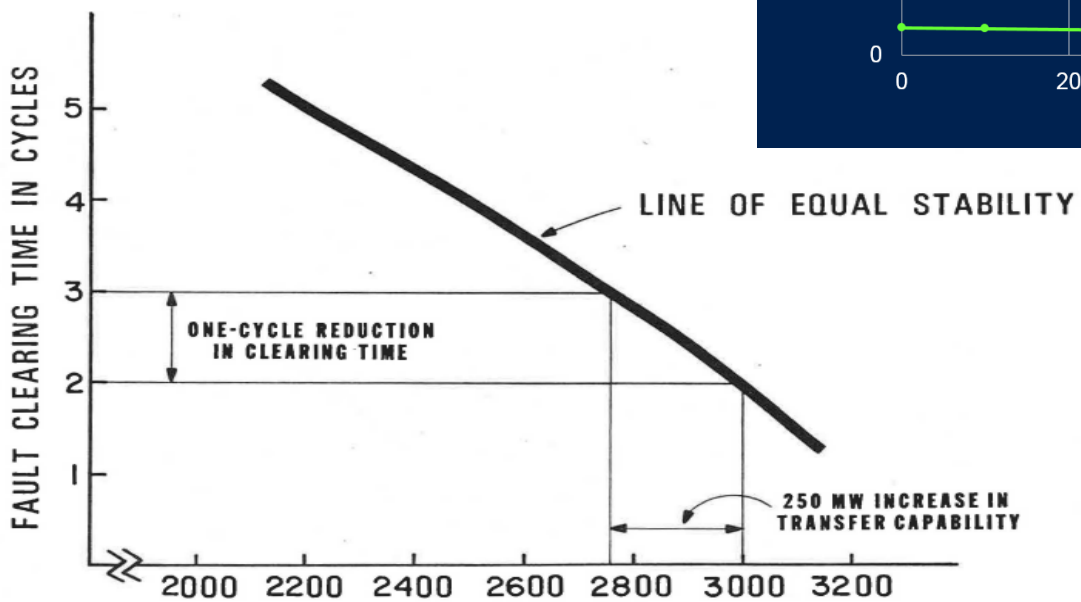
		In Service
Feeder_A	1	False
Feeder_B	2	True
Feeder_C	1	False
Feeder_D	2	True

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