Identification and Protection Against Critical Contingencies in Power Systems

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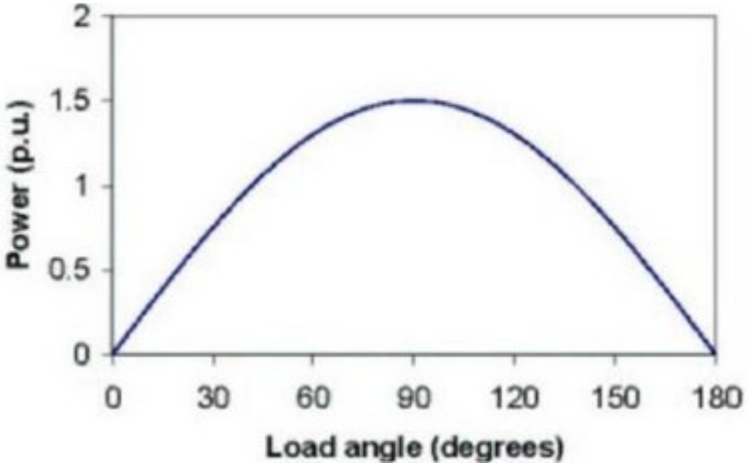
Power system fragility and resiliency

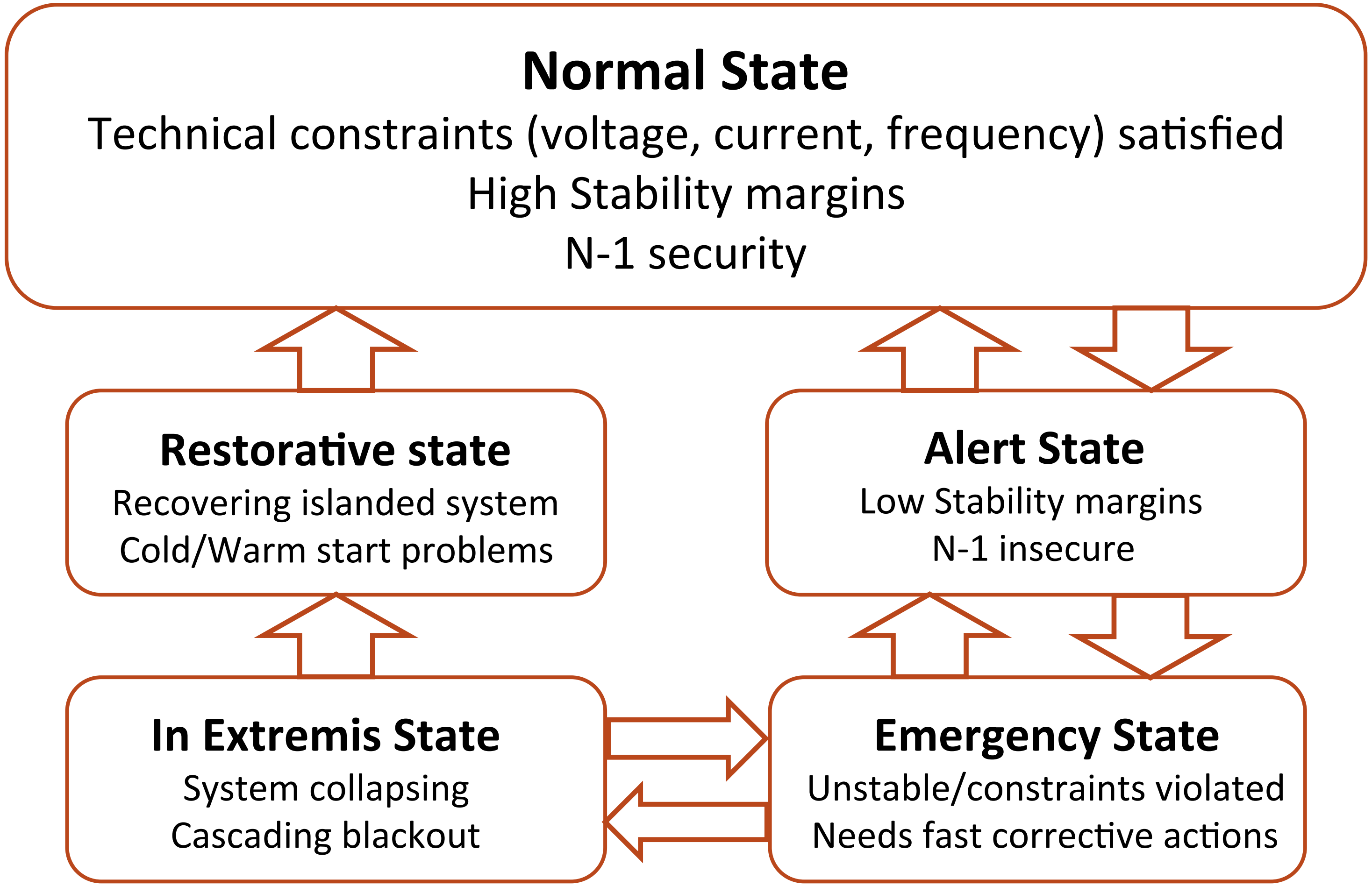
Power system is inherently fragile:

- Absorbs weak disturbances (N-1 contingencies)
- Loses stability after strong ones
  - Finite power line capacity + constant power controls
  - Inherently nonlinear phenomenon
- Resiliency: ability to recover after losing stability
  - Power interruptions: $80B/year damage to US economy



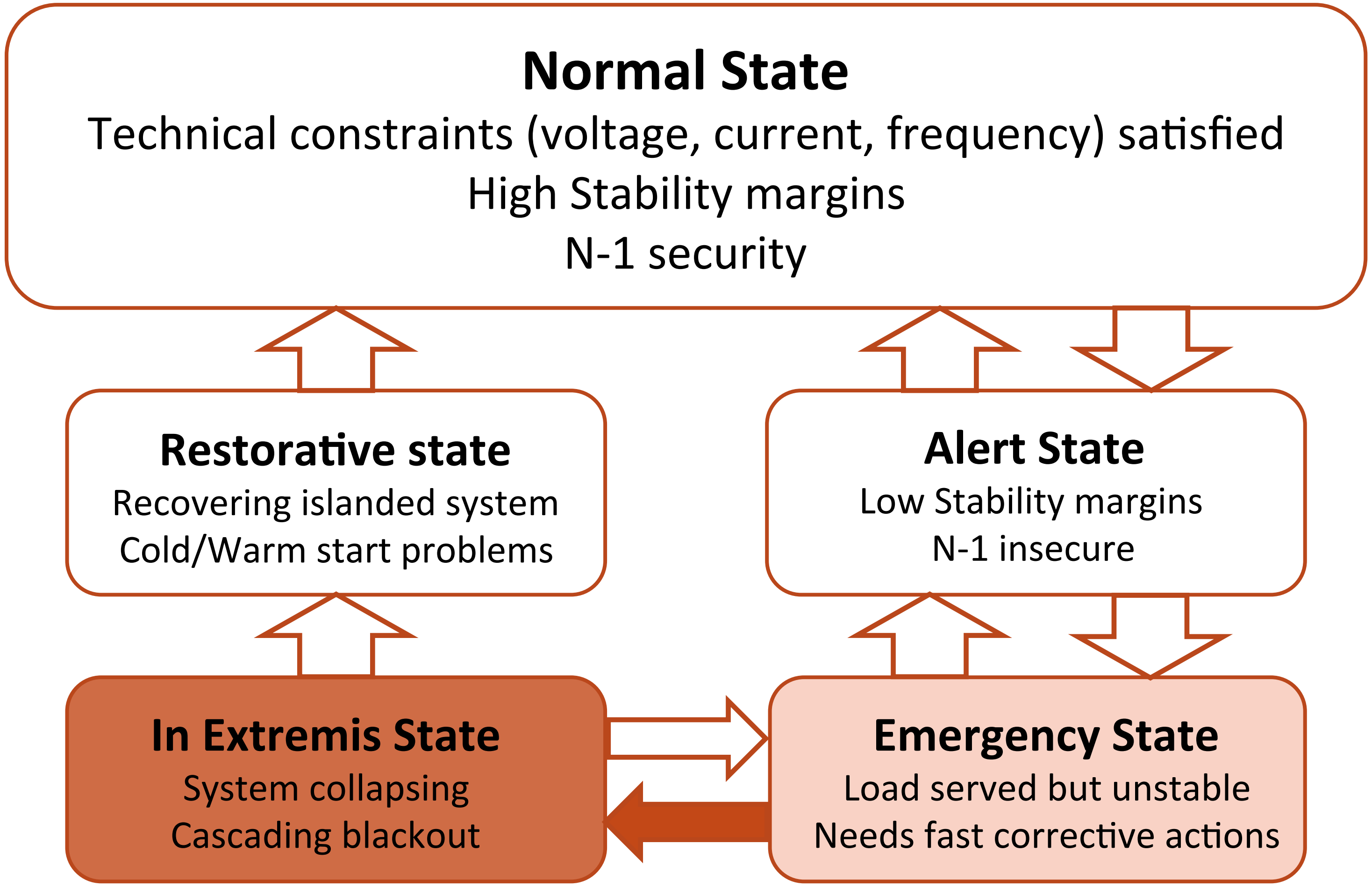
Power systems	Interpretation
Feasibility	Violation of constraints
Voltage stability	No equilibrium point
Small signal stability	Lack of asymptotic stability
Transient stability	**Convergence to equilibrium**

Dy Liaccio classification



- Proposed after 1965 blackout
- Foundation for:
  - Federal regulations
  - Emergency control system architecture

Fun dynamics problems



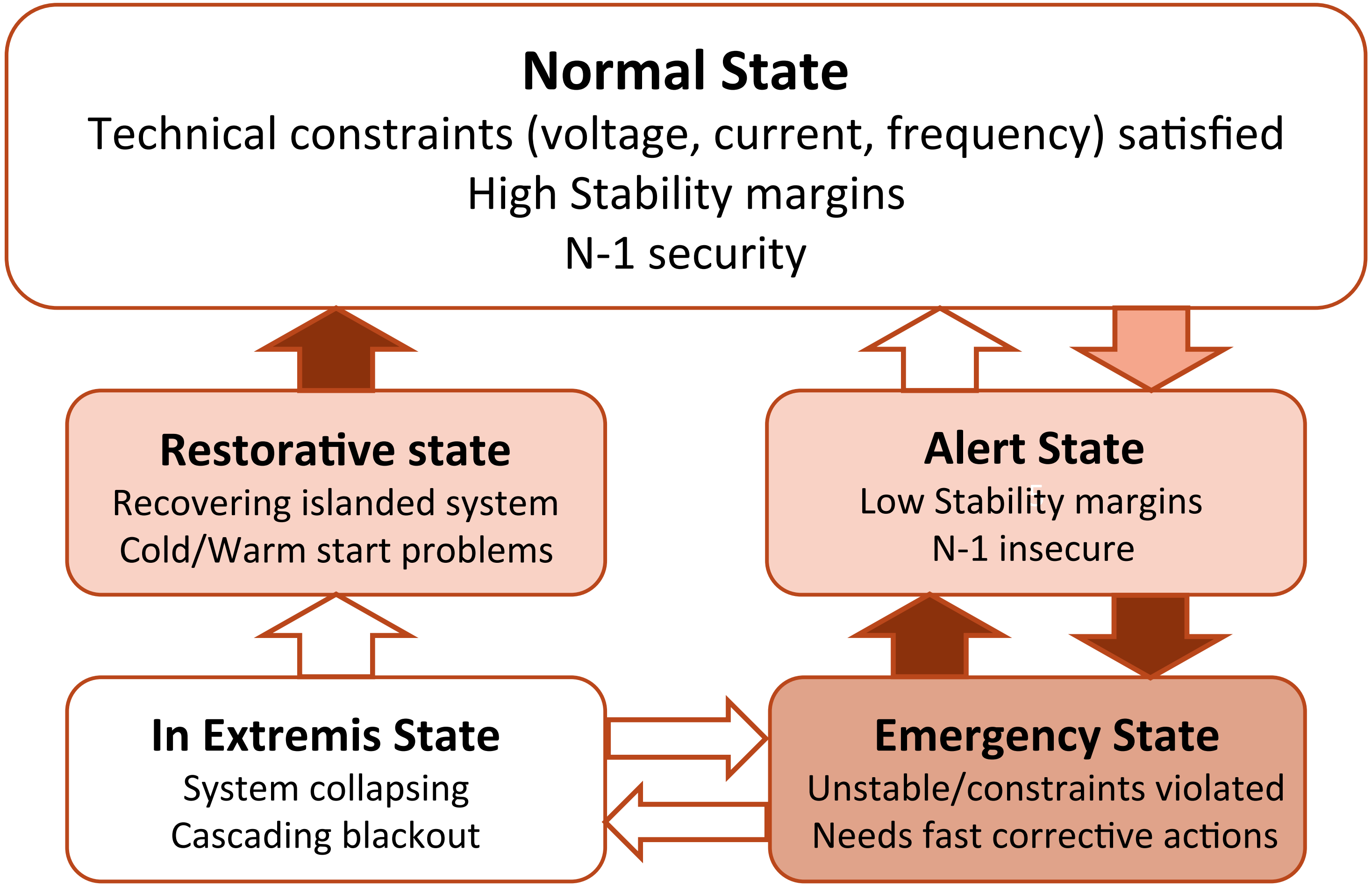
"Fun" problems:

- Rich in dynamics
- Finite-time collapse
- Infection-like cascades

However:

- Mostly "fantasy grid" studies
- Super-sensitive to details
- Not complex but complicated
- Huge role of human factor
- 2 year long post-mortem analysis of 1996 blackout

Relevant dynamics problems



Relevant problems

- Potential for industrial and societal impact
- Considered hard but important by engineers

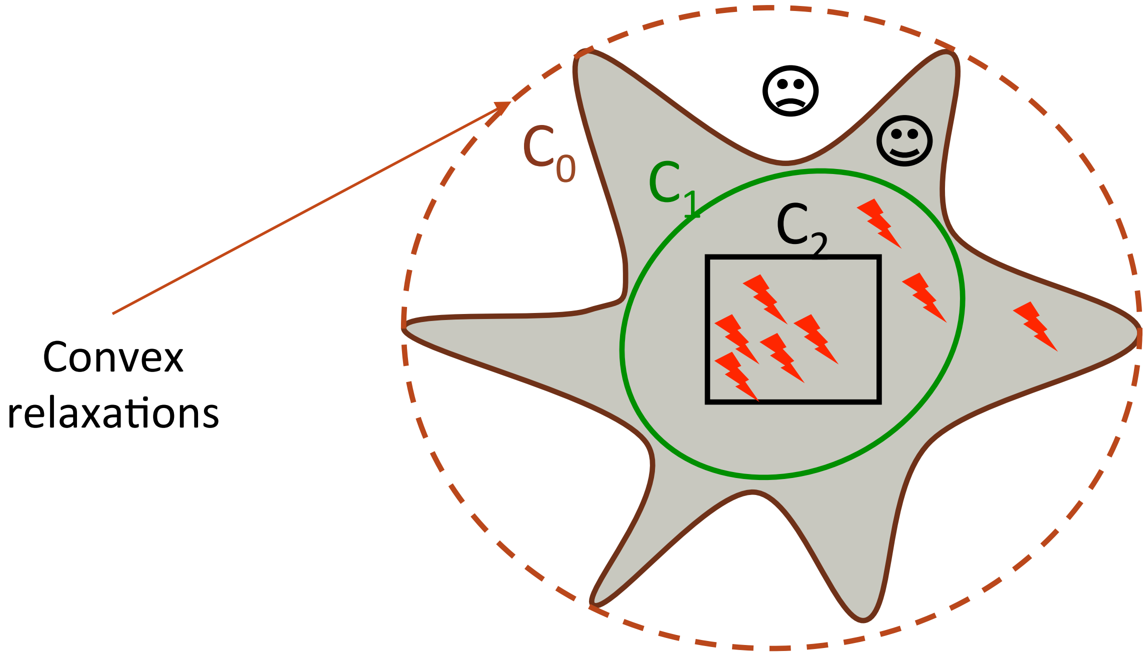
Specifically:

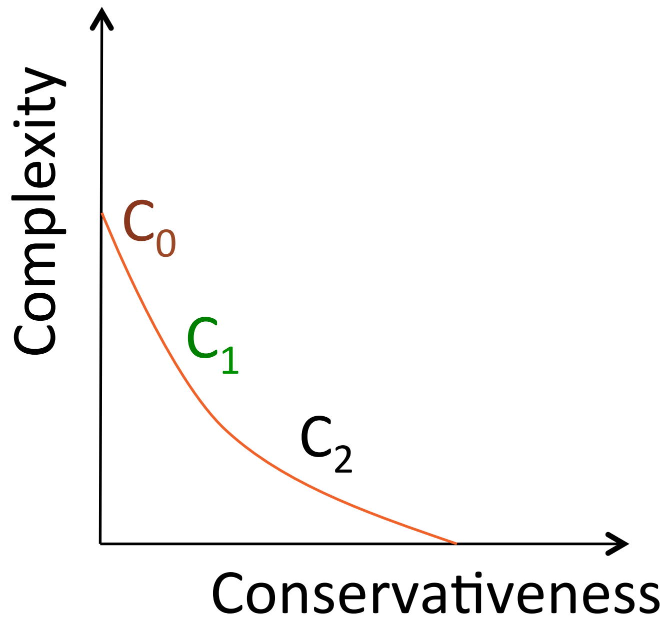
- Identification of dangerous contingencies
- Remedial action schemes
- Cold/warm start restoration
- Real-time topology control

Operational security: state of the art

- Offline screening and protection against some pre-selected contingencies
- Reliance on engineering judgement and heuristic algorithms
- **Can we do better ?**

Security certificates





Pre-compute security certificates → Filter safe contingencies → Process dangerous candidates

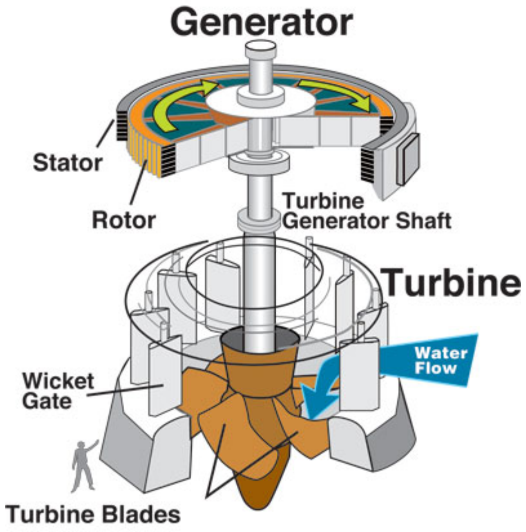
Reduce computational burden by offline pre-screening

Transient Stability

with Thanh Long Vu, Spyros Chatzivasileadis, Elena Gryazina

Swing equation

$$\frac{d\delta}{dt} = \omega$$



$$M\frac{d\omega}{dt} = p - D\omega - \nabla^T B \sin(\nabla\delta)$$

$\delta, \omega \in \mathbb{R}^n$: Generator rotor angles and velocities

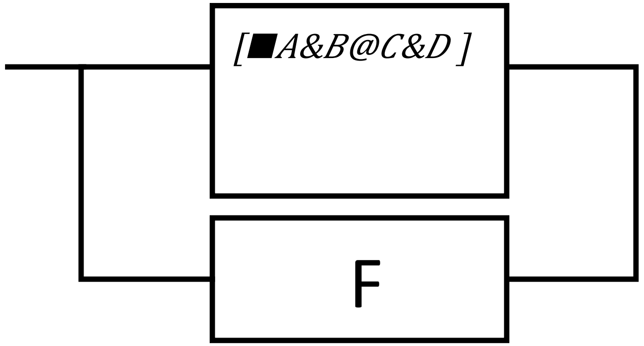
$p \in \mathbb{R}^n$: Mechanical power (torque)

$M = \mathrm{diag}(m) \in \mathbb{R}^{n\times n}$: Turbine inertia

$D = \mathrm{diag}(d) \in \mathbb{R}^{n\times n}$: damping/governor droop

$B = \mathrm{diag}(b) \in \mathbb{R}^{m\times m}$: line susceptance (normalized)

$\nabla \in \mathbb{R}^{m\times n}$: network incidence matrix



State-Space ``Lur'e'' Representation

$$\frac{dx}{dt} = Ax + BF(Cx)$$

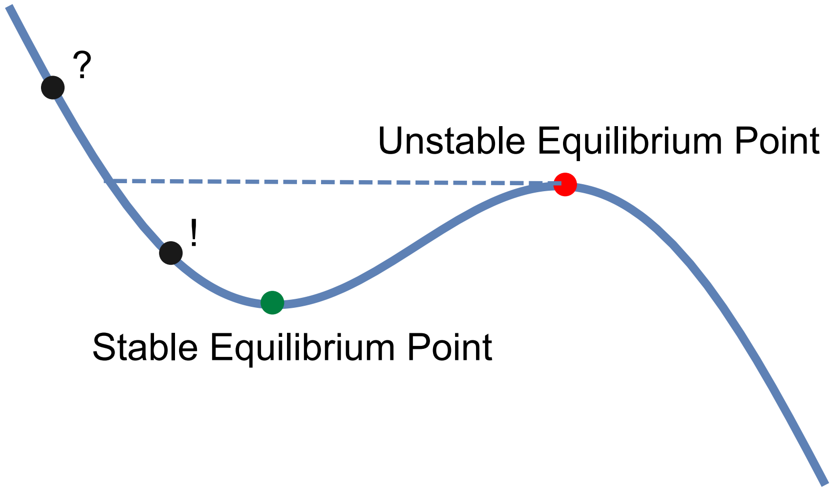
$$x = \begin{bmatrix} \delta - \delta_* \\ \omega \end{bmatrix}$$

$$F(z) = \sin(z) - z$$

Energy function

$$E = \frac{1}{2}\omega^T M \omega - b^T \cos(\nabla\delta) - p^T \delta$$

$$\frac{dE}{dt} = -\omega^T D \omega < 0$$



Stability certificate:

$$E(\delta,\omega) < E_{CUEP}$$

Many other Lyapunov functions out there!

$$V = \begin{bmatrix}\delta-\delta_* \\ \omega\end{bmatrix}^T Q \begin{bmatrix}\delta-\delta_* \\ \omega\end{bmatrix} - 1^T P\left(\cos(\nabla\delta) - \nabla\delta \sin(\nabla\delta_*)\right)$$

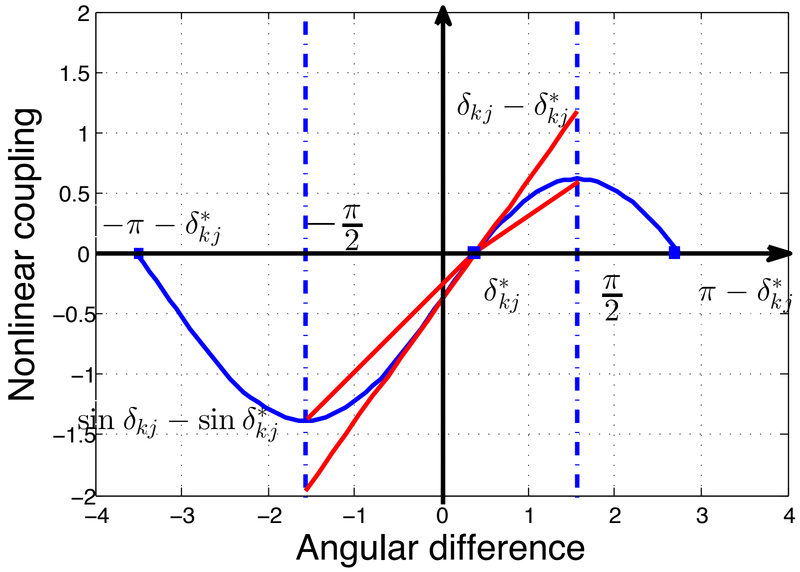
Long history:

- Lur'e and Postnikov '44
- Willems '71
- Pai '81
- Kamenetsky '87
- Hill '89
- Boyd '94
- Hiskens '97
- Rapoport '05
- …

Considered largely a theoretical possibility due to computational complexity

Lyapunov function family method

Bound nonlinearity around equilibrium → Construct Lyapunov Function → Certify invariance of bounded nonlinearity region

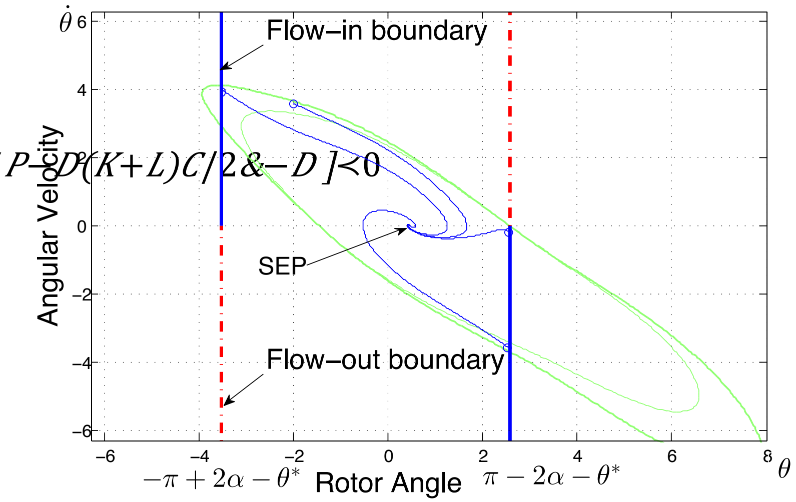


$$V = \begin{bmatrix} \delta - \delta^* \\ \omega \end{bmatrix}^T P \begin{bmatrix} \delta - \delta^* \\ \omega \end{bmatrix} \quad P > 0$$

$$\begin{bmatrix} A^T P + PA - C^T D K L C & PB - C^T D (K+L)/2 \\ B^T P - D(K+L)C/2 & -D \end{bmatrix} < 0$$

$$\Downarrow$$

$$dV/dt < 0$$

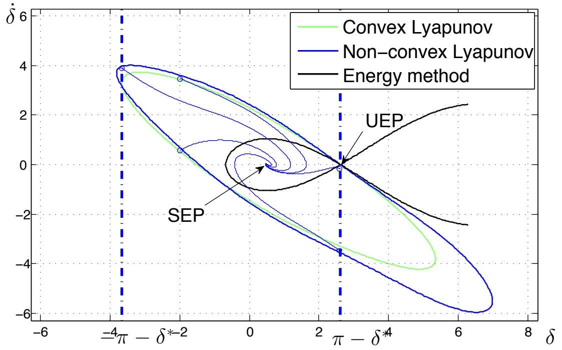


$$V(\delta, \omega) < V_{min}$$

Potentially more tractable and less conservative

Key features

Tractable

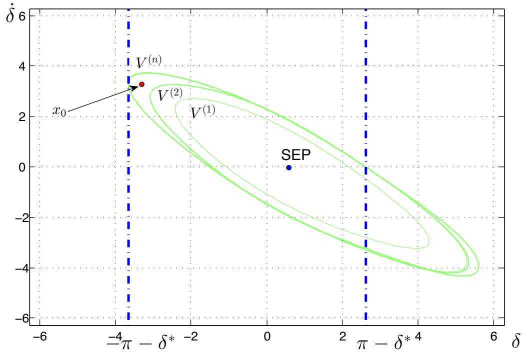


Relies on convex optimization

Scalable to 1000s of buses

TPWRS '15, PES GM '15

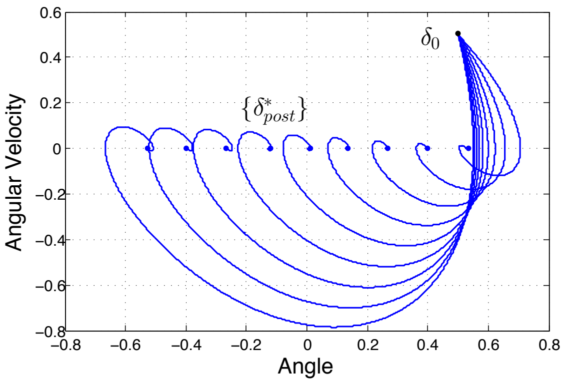
Adaptive



Huge set of certificates

Algorithms for adaptation to specific contingencies

Robust

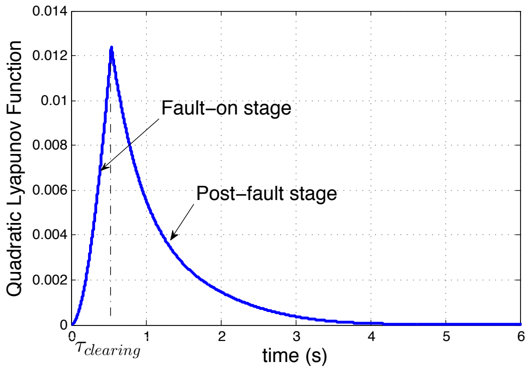


Allows for uncertainty in equilibrium point

Fast variations of wind

ACC '15, TAC '16

Simulation-free



No need in fault-on dynamics simulation

(reachability bounds)

TPWRS '16, TAC '16

Emergency control

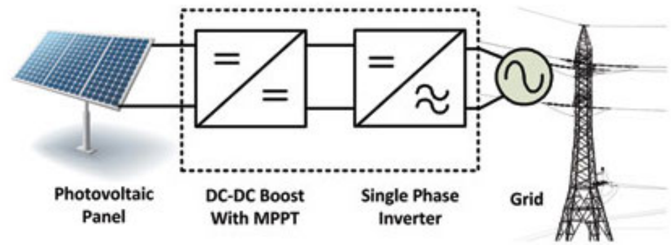
Key idea: adjust system dynamics in emergencies to restore stability

$$\begin{bmatrix} A^T P + PA - C^T D K L C & PB - C^T D(K+L)/2 \\ B^T P - D(K+L)C/2 & -D \end{bmatrix} \preceq 0$$

$$\begin{bmatrix} A^T P + PA - C^T D K L C & PB - C^T D(K+L)/2 \\ B^T P - D(K+L)C/2 & -D \end{bmatrix}$$

Virtual inertia and droop

$M d\omega/dt = p - D\omega - \nabla^T B \sin(\nabla\delta)$



ACC '16

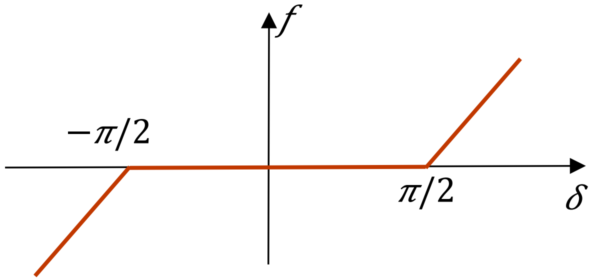
FACTS

$M d\omega/dt = p - D\omega - \nabla^T B \sin(\nabla\delta)$

PES GM '16

Fast Demand Response

$M d\omega/dt = p - D\omega - \nabla^T B \sin(\nabla\delta) + f(\delta)$

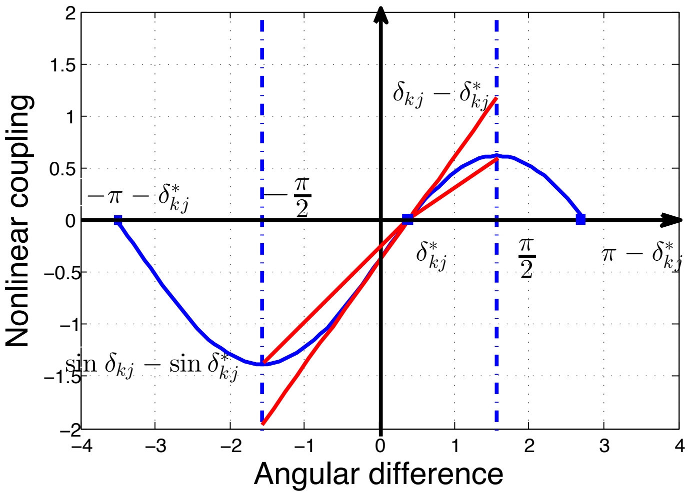


(ongoing)

Challenges & Opportunities: conservativeness

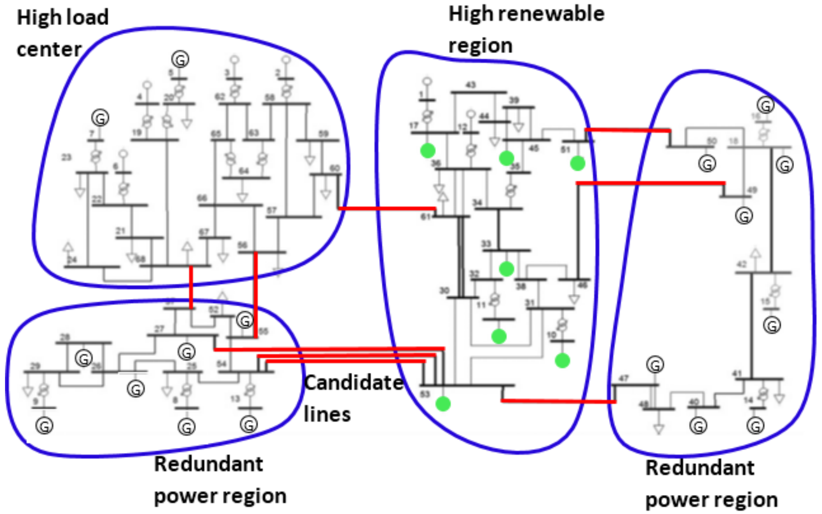
Sector bounds can be adapted as well

[■A↑T P+PA−C↑T DKLC&PB−C↑T D(K+L)/2 @B↑T P−D(K+L)C/2& −D]<0 ⇆ [■A↑T P+PA−C↑T DKLC&PB−C↑T D(K+L)/2 @B↑T P−D(K+L)C/2&−D

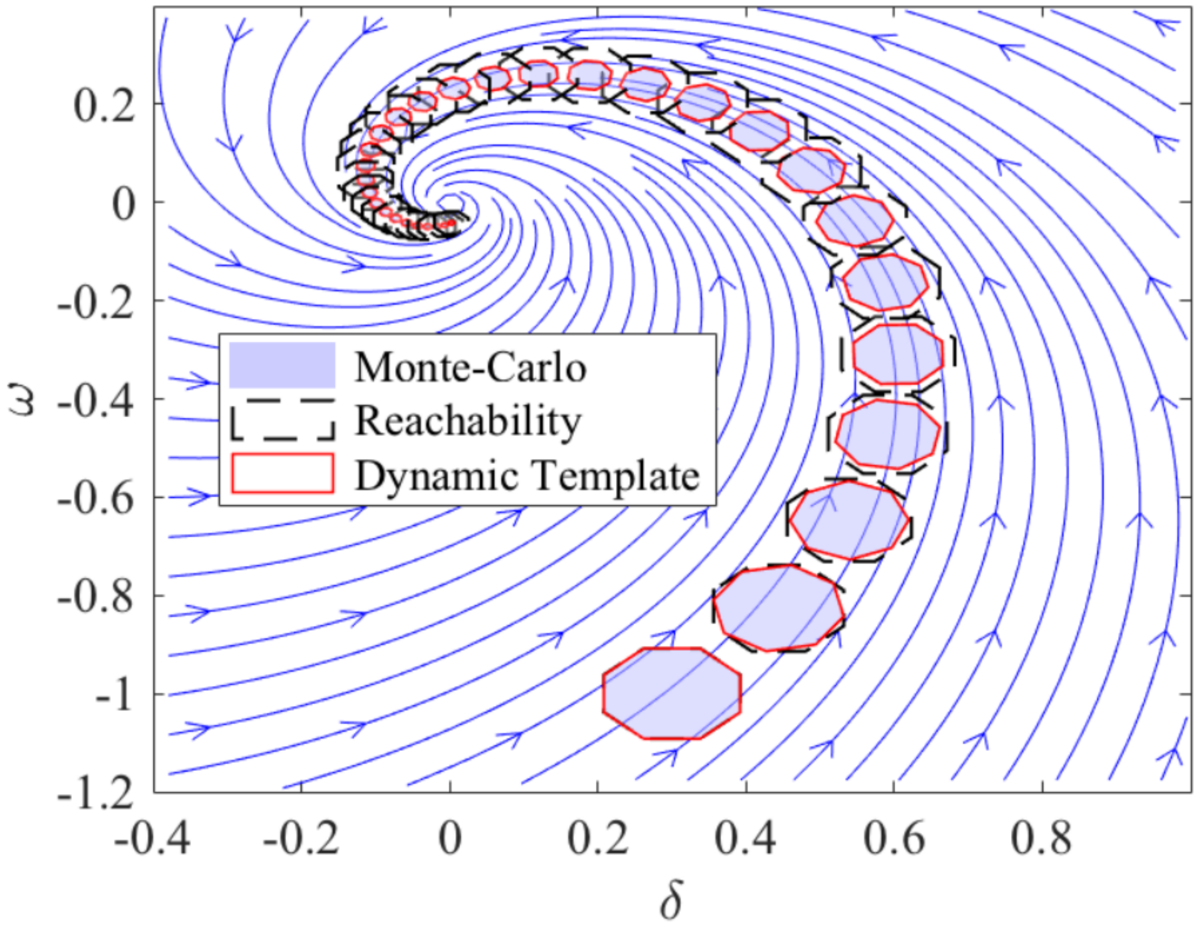


Ongoing project with Lena Gryazina

- Bilinear matrix inequality, hard to solve
- Only few angles oscillate strongly during contingencies
- Data-driven approaches combined with first-order methods



Beyond swing equation



Dynamic template algorithm:

- Represent a trajectory as a sequence of nonlinear equations (arbitrary complicated models)
- Use **linear programming** to characterize reachability sets
- Construct the uncertainty regions around any trajectory

Data-driven approaches:

- Millions of simulated trajectories accumulated by system operators. **Can this data be utilized in a non-heuristic way ?**
- Hierarchical certificate database (ongoing with LANL)