Identification of Destabilizing Attacks in Power Systems

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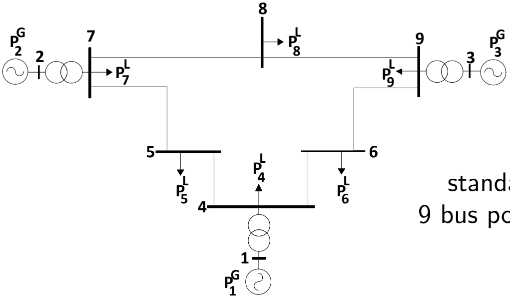
What is a destabilizing attack? (and why you should care?)



standard IEEE
9 bus power system

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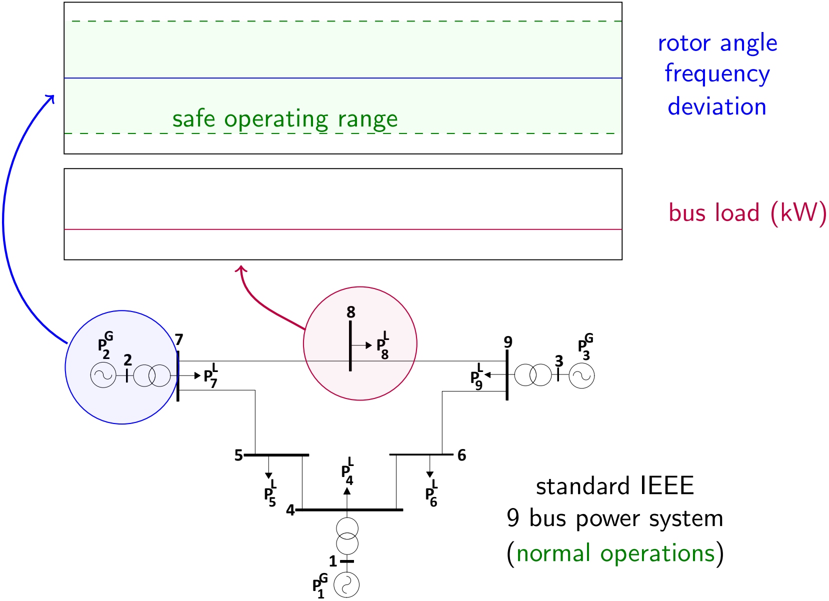

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(normal operations)

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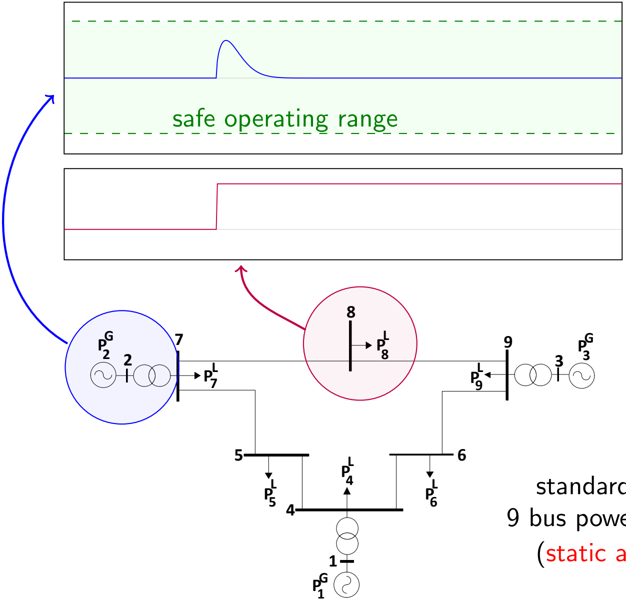

rotor angle frequency deviation

bus load (kW)

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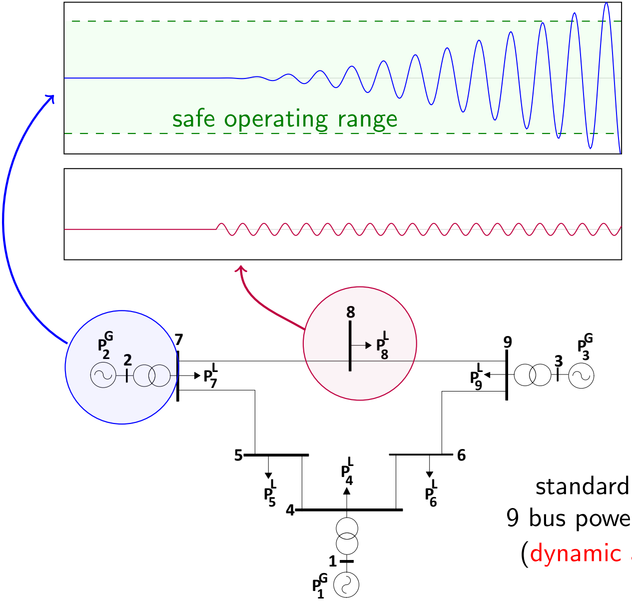

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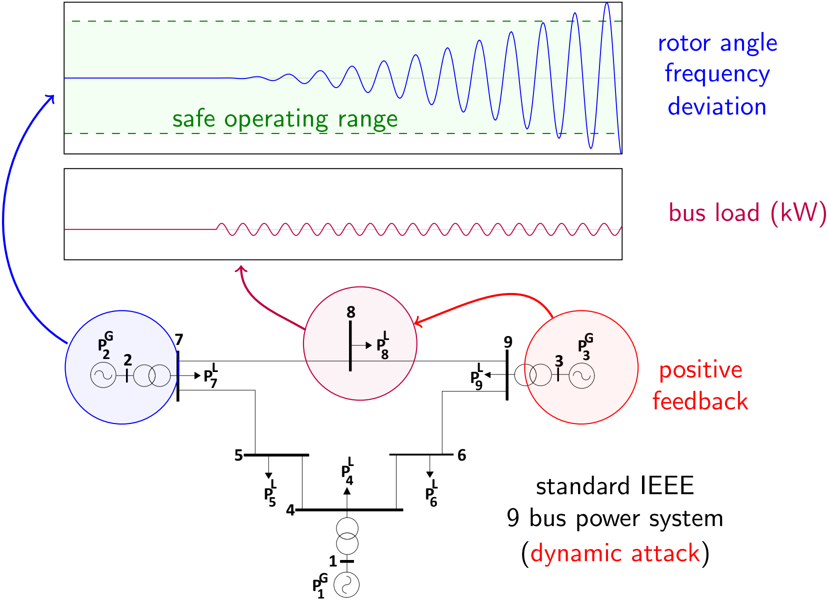

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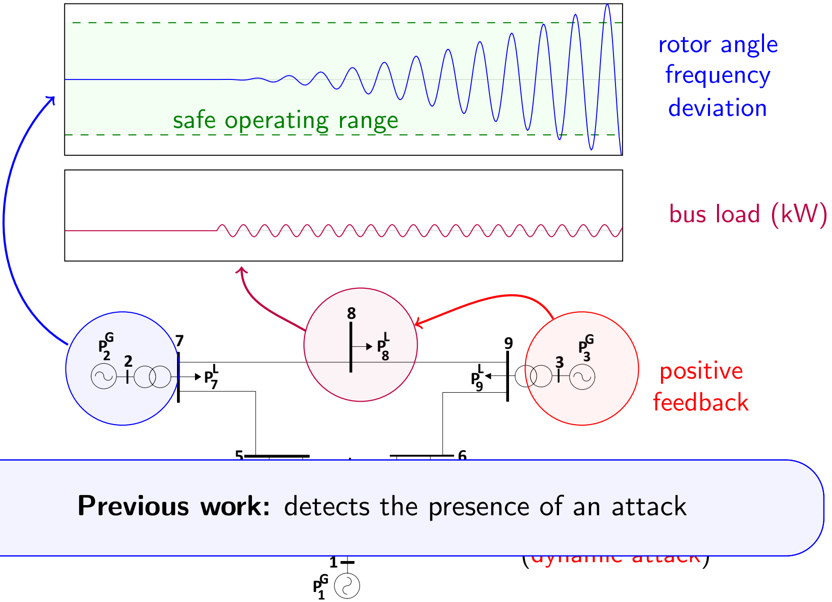
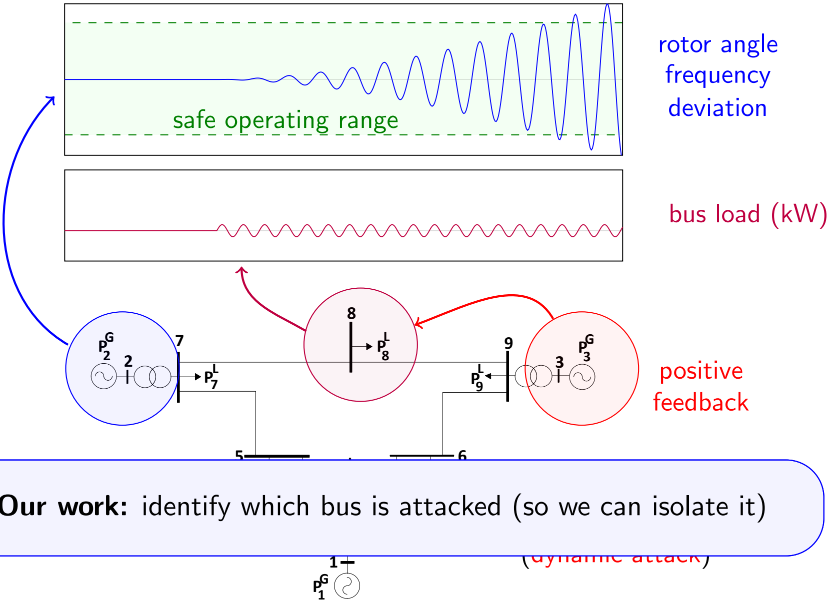


Previous work: detects the presence of an attack

What is a destabilizing attack? (and why you should care?)



Our work: identify which bus is attacked (so we can isolate it)

Outline

- Power system dynamics
  - Normal operation
  - Under attack
- Identifying the attack
  - Unscented Kalman Filter (UKF)
  - Joint state and variable estimation
  - Rank-1 approximate filter (our contribution)
    - Reduces computational complexity
    - Improves statistical efficiency
- Simulation results

System dynamics under normal conditions

With g generators and ℓ loads, model the power grid as:

$$\mathbf{x}_{t+1} = A\mathbf{x}_t + B\mathbf{u}_t + \epsilon. \tag{1}$$

where

$$\mathbf{x} = \text{vector of} \begin{cases} g \text{ generator voltage phase angles} \\ g \text{ generator rotor angular frequency deviation} \\ \ell \text{ load voltage phase angles} \end{cases}$$

$$\mathbf{u} = \text{vector of} \begin{cases} g \text{ power generation at all generator buses} \\ \ell \text{ power consumption at all load buses} \end{cases}$$

$A, B =$ highly structured matrices that depend on the grid's connectivity

$\epsilon \sim \mathcal{N}(0, Q)$ captures modeling and measurement errors

System dynamics under attack

Decompose the control into normal ($\mathbf{u}^n$) and attack ($\mathbf{u}^a$) components:

$$\mathbf{u} = \mathbf{u}^n + \mathbf{u}^a. \tag{2}$$

Assume the attacker uses a proportional controller

$$\mathbf{u}^a = A^p \mathbf{x} + \mathbf{u}^p, \qquad \text{where} \qquad A^p = \begin{bmatrix} 0 & 0 & -(D^L)^{-1} K^{LG} \\ 0 & 0 & 0 \end{bmatrix}. \tag{3}$$

D^L matrix of load damping coefficients (determined by power system).
$K^{LG}_{\ell,g}$ is the gain from the load ℓ to generator g (determined by attacker).

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Substituting into the system dynamics gives

$$\mathbf{x}_{t+1} = (A + BA^p)\mathbf{x}_t + B(\mathbf{u}^n_t + \mathbf{u}^p_t) + \epsilon. \tag{4}$$

Our goal: estimate the A^p matrix given a trajectory of $\mathbf{x}$s.
This tells us which load bus has positive feedback from which generator.

Naive solution: joint estimation with the UKF

Augment our system dynamics

$$\mathbf{x}_{t+1} = (A + BA^p)\mathbf{x}_t + B(\mathbf{u}_t^n + \mathbf{u}_t^p) + \epsilon$$

to include the new state variables

$$\begin{bmatrix} \mathbf{x}_{t+1} \\ \operatorname{vec} K_{t+1}^{LG} \end{bmatrix} = \begin{bmatrix} A + BA_t^p & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} \mathbf{x}_t \\ \operatorname{vec} K_t^{LG} \end{bmatrix} + \begin{bmatrix} B & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} \mathbf{u}_t^n + \mathbf{u}_t^p \\ \mathbf{u}_t^{LG} \end{bmatrix} + \begin{bmatrix} \epsilon \\ \epsilon^{LG} \end{bmatrix} \quad .$$

The resulting system is nonlinear.

We solve it with the Unscented Kalman Filter (UKF).

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Note that:

- $\mathbf{x}$ has $O(\ell + g)$ components (size of original problem)
- K^{LG} has $O(\ell g)$ components (size of new problem)

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Disadvantages of new problem:

- Computational cost is $O((\ell g)^3)$, much worse than $O((\ell + g)^3)$
- Not enough data for statistical efficiency

Our solution: joint estimation with rank-1 UKF

Assume that K^{LG} has rank 1:

$$K_t^{LG} = \mathbf{k}_t^L {\mathbf{k}^G}_t^\mathsf{T}.$$

This is reasonable because there will typically be few attacks.
Then the system dynamics become

$$\begin{bmatrix} \mathbf{x}_{t+1} \\ \mathbf{k}_{t+1}^L \\ \mathbf{k}_{t+1}^G \end{bmatrix} = \begin{bmatrix} A + BA_t^p & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & I \end{bmatrix} \begin{bmatrix} \mathbf{x}_t \\ \mathbf{k}_t^L \\ \mathbf{k}_t^G \end{bmatrix} + \begin{bmatrix} B & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & I \end{bmatrix} \begin{bmatrix} \mathbf{u}_t^n + \mathbf{u}_t^p \\ \mathbf{u}_t^L \\ \mathbf{u}_t^G \end{bmatrix} + \begin{bmatrix} \epsilon \\ \epsilon^K \\ \epsilon^L \end{bmatrix}.$$

Solve the system using the UKF.

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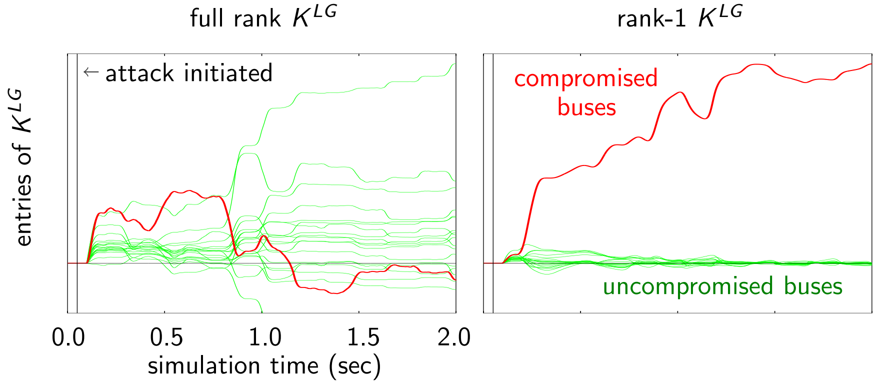
Note that:

- The size of the new state space is $O(\ell + g)$
- Computationally and statistically efficient

Simulation results (statistical efficiency)

Simulated attack on power system with 100 generators and 100 loads



The red line should be high and the green lines should be low.

The rank-1 approximation outperforms the full rank estimator

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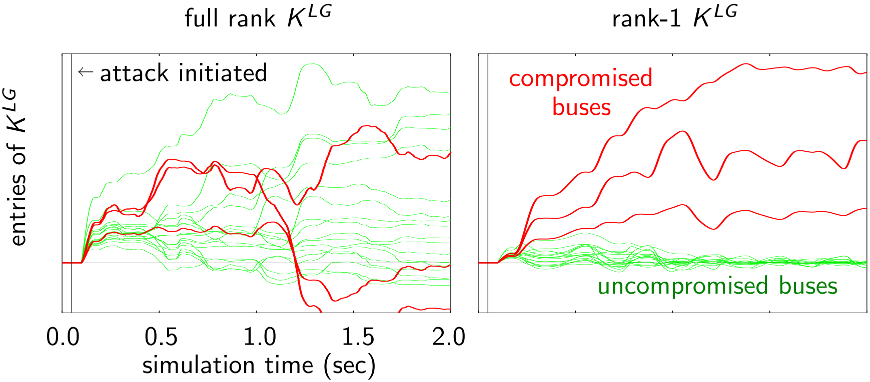

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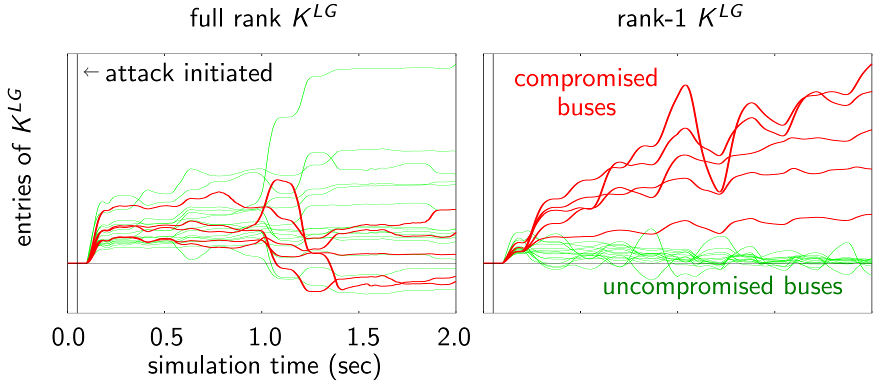

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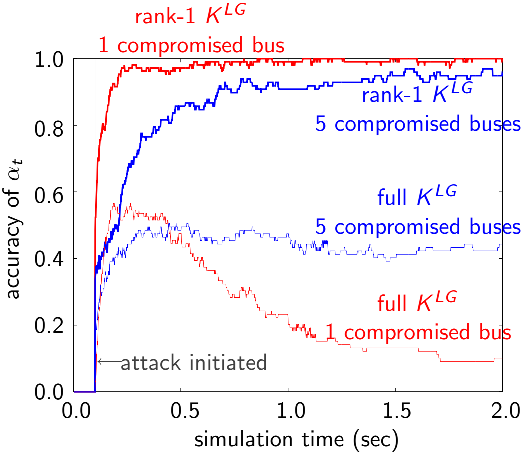
Simulation results (identification accuracy)

At any timestep t, our method has accuracy 1 if all the compromised buses have highest estimated K_t^{LG} entries; otherwise the method has accuracy 0

Repeat our experiment over 100 random configurations



Summary

- Previous methods could only detect attacks
- New method for identifying system buses under attack
  - joint estimation of system and attack parameters
  - solve with the Unscented Kalman Filter (UKF)
- Used a rank-1 approximation
  - better statistical efficiency
  - better computational efficiency

http://github.com/mikeizbicki/powergrid

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Questions?