Secure Dynamic State Estimation Using PMU data under Model Uncertainty and Cyber Attacks

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Outline

Dynamic State Estimation

- Discrete-time nonlinear system

$$\begin{cases} \boldsymbol{x}_k = \boldsymbol{f}(\boldsymbol{x}_{k-1}, \boldsymbol{u}_{k-1}) + \boldsymbol{q}_{k-1} \\ \boldsymbol{y}_k = \boldsymbol{h}(\boldsymbol{x}_k, \boldsymbol{u}_{k-1}) + \boldsymbol{r}_k \end{cases}$$

- Dynamic state estimation:

  given $\boldsymbol{x}_{k-1}$ and $\boldsymbol{y}_k$, estimate $\boldsymbol{x}_k$

- For power systems:
  - $\boldsymbol{x}$: internal states of generators
  - $\boldsymbol{y}$ comes from synchrophasors

Challenge 1: Model Uncertainty

- Power system model can be inaccurate
  - unknown inputs

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{B}_w\boldsymbol{w} + \phi(\boldsymbol{x}, \boldsymbol{u})$$

  - unavailable inputs (not measured or difficult to measure)
  - parameter inaccuracy
- Are more detailed models always better?
  - difficult to validate and calibrate
  - higher computational burden

Challenge 2: Cyber Attacks against PMU Measurements

- National Electric Sector Cybersecurity Organization Resource (NESCOR) failure scenarios
  - measurement data compromised due to PDC authentication compromise
  - communications compromised between PMUs and control center
- Different types of attacks against measurements
  - data integrity attack
  - denial of service attack
  - replay attack

Kalman Filters

- Extended Kalman Filter
  - used for linearized model
  - need to calculate Jabobian
- Unscented Kalman Filter
  - used for nonlinear model
  - no need to calculate Jabobian
  - numerical stability problem
- Cubature Kalman Filter
  - used for nonlinear model
  - large system with high nonlinearity
  - better numerical stability

Dynamic Observers

- Real system dynamics

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{B}_w\boldsymbol{w} + \phi(\boldsymbol{x}, \boldsymbol{u})$$

- Observer dynamics

$$\dot{\hat{\boldsymbol{x}}} = \boldsymbol{A}\hat{\boldsymbol{x}} + \boldsymbol{B}\boldsymbol{u} + \phi(\hat{\boldsymbol{x}}, \boldsymbol{u}) + \boldsymbol{L}\big(\boldsymbol{y} - \boldsymbol{h}(\hat{\boldsymbol{x}})\big)$$

- Observer design

$$\begin{bmatrix} \boldsymbol{A}^\top\boldsymbol{P} + \boldsymbol{P}\boldsymbol{A} + (\epsilon_1\rho + \epsilon_2\mu)\boldsymbol{I}_n - \sigma\boldsymbol{C}^\top\boldsymbol{C} & \boldsymbol{P} + \frac{\varphi\epsilon_2 - \epsilon_1}{2}\boldsymbol{I}_n \\ \left(\boldsymbol{P} + \frac{\varphi\epsilon_2 - \epsilon_1}{2}\boldsymbol{I}_n\right)^\top & -\epsilon_2\boldsymbol{I}_n \end{bmatrix} < 0$$

$$\boldsymbol{L} = \frac{\sigma}{2}\boldsymbol{P}^{-1}\boldsymbol{C}^\top$$

W. Zhang, H. Su, H. Wang, and Z. Han, “Full-order and reducedorder observers for one-sided lipschitz nonlinear systems using riccati equations,” *Commun. Nonlinear Sci. Numer. Simul.*, vol. 17, no. 12, pp. 4968–4977, 2012.

A Realistic Scenario for Dynamic State Estimation

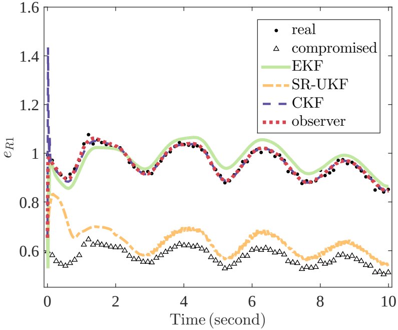
- 16-machine 68-bus system
- Power system is modeled as 10th order nonlinear system
- Gaussian Process noise and measurement noise
- Model uncertainty
  - unknown $\boldsymbol{B}_w \boldsymbol{w}$

$$\boldsymbol{w}(t) = \begin{bmatrix} 0.5\cos(\omega_u t) \\ 0.5\sin(\omega_u t) \\ 0.5\cos(\omega_u t) \\ 0.5\sin(\omega_u t) \\ -e^{-5t} \\ 0.2\, e^{-t}\cos(\omega_u t) \\ 0.2\cos(\omega_u t) \\ 0.1\sin(\omega_u t) \end{bmatrix}$$

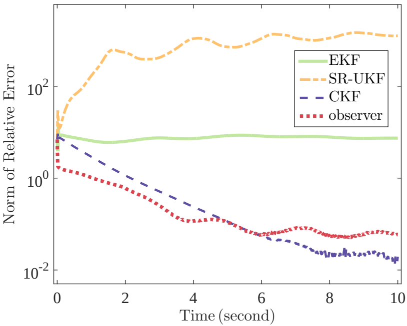
  - estimator only knows steady-state values of T_m and E_{fd}
  - reduced admittance matrix is the steady-state one within 1 second after fault
- Initial guess of the states is far from the real states

Data Integrity Attack

Data integrity attack: 8 out of 64 measurements are scaled by k or $1/k$ ($k = 0.6$)

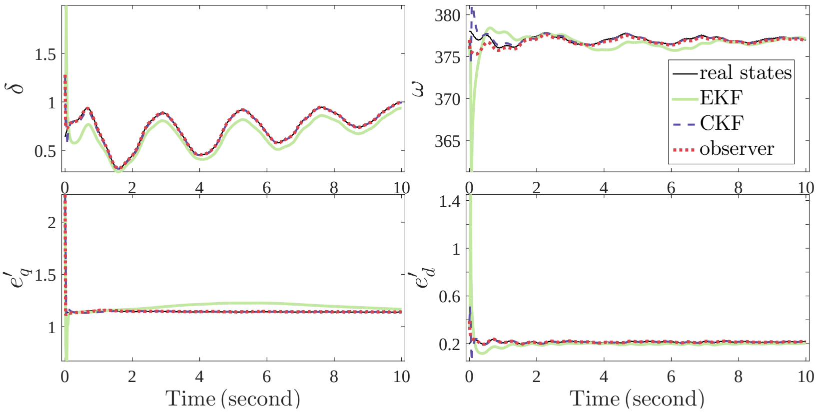


Compromised measurements e_{R1}



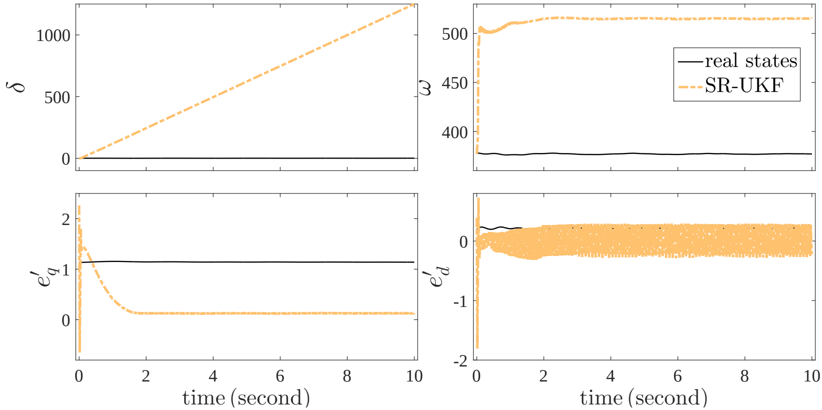
Norm of relative error of states

Data Integrity Attack (cont'd)



Estimation from EKF, CKF, and observer

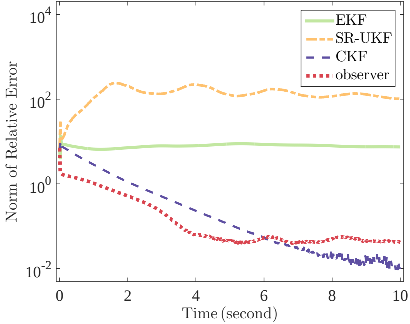
Data Integrity Attack (cont'd)



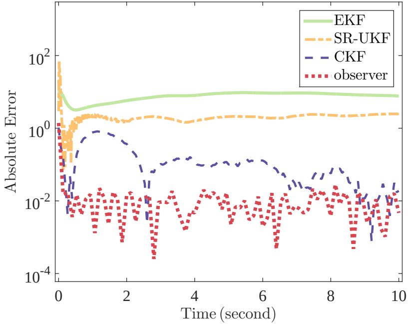
Estimation from SR-UKF

Denial of Service Attack

8 measurements do not update for $t \in [3s, 6s]$



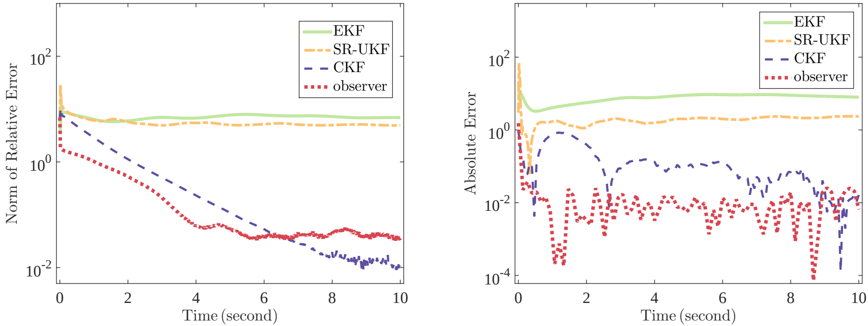
Norm of relative error of states



Absolute error of measurements

Replay Attack

8 measurements for $t \in [3\text{s}, 6\text{s}]$ equal those $t \in [0\text{s}, 3\text{s}]$



Norm of relative error of states

Absolute error of measurements

Conclusion

- We design a realistic scenario for DSE with significant model uncertainty and cyber attacks
- We compare different estimation approaches
  - observers are more robust to model uncertainty and cyber attacks
  - observers have theoretical guarantee for convergence
  - observers are easier to implement

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THANK YOU!