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Capturing Real-Time Power System Dynamics: Opportunities and Challenges

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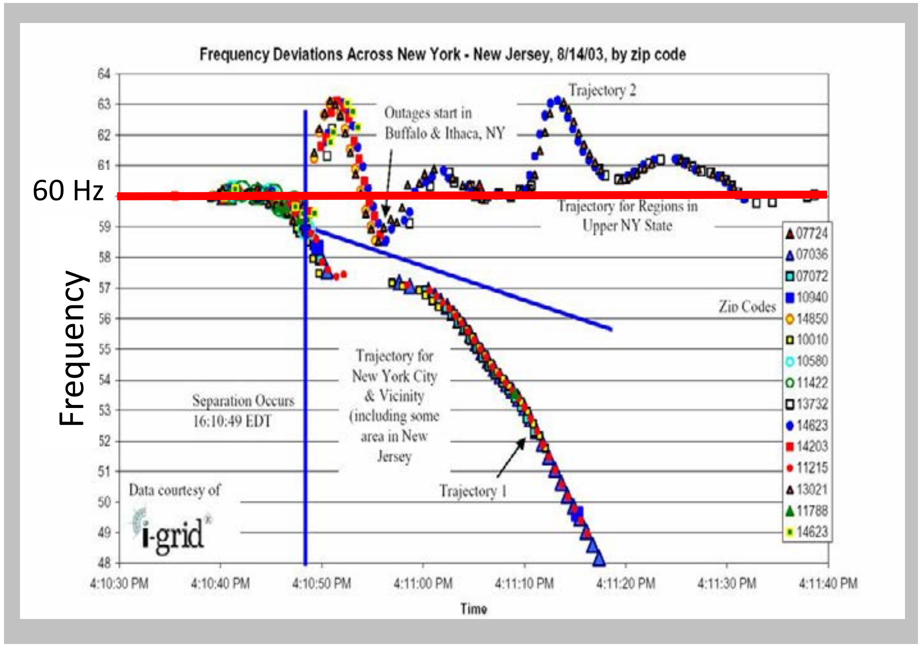
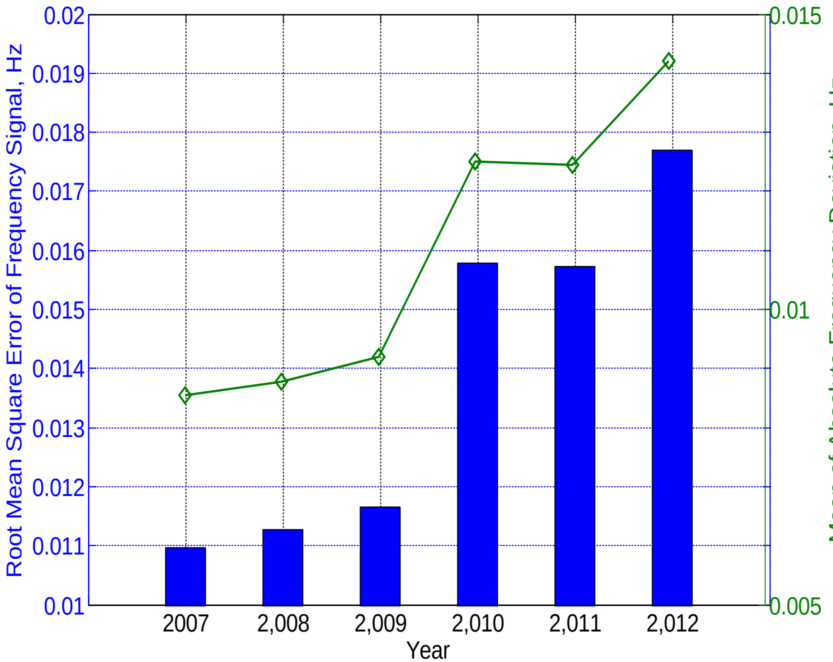
Frequency trending away from nominal requires tools capturing real-time dynamics

- Dynamic state estimation vs. traditional static state estimation
- Dynamic security assessment
- Dynamic model validation

(all identified as killer apps in NASPI phasor roadmap, https://www.naspi.org/Badger/content/File/FileService.aspx?fileID=539)



Emergency situation



Normal operation

Dynamic paradigm for grid operation and planning

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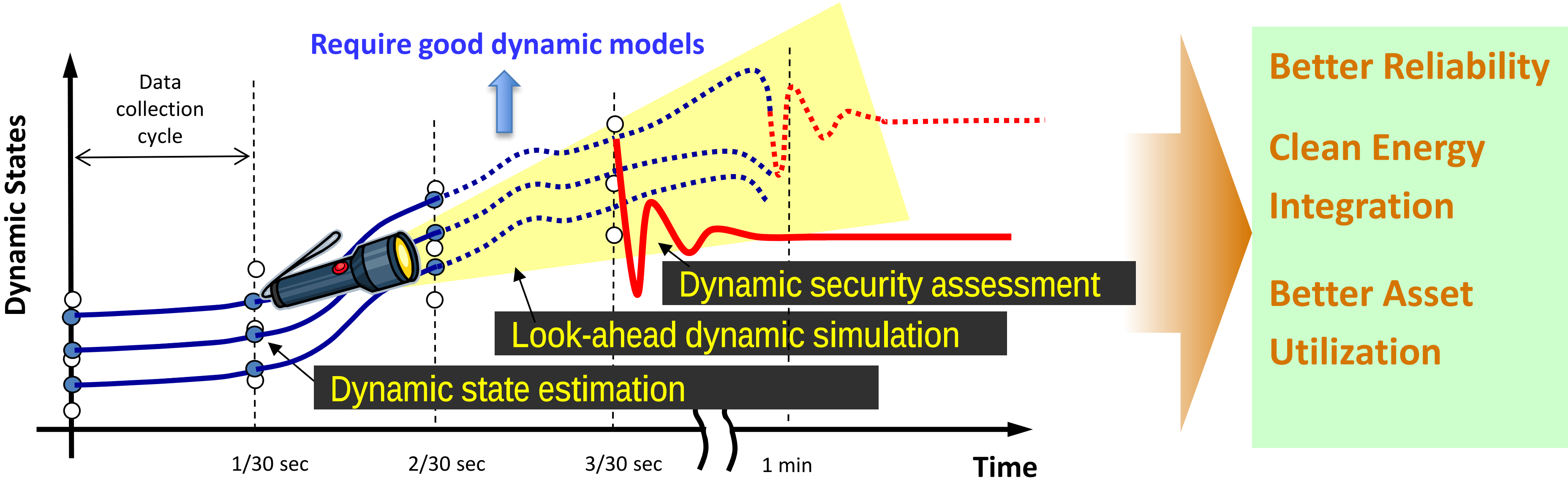
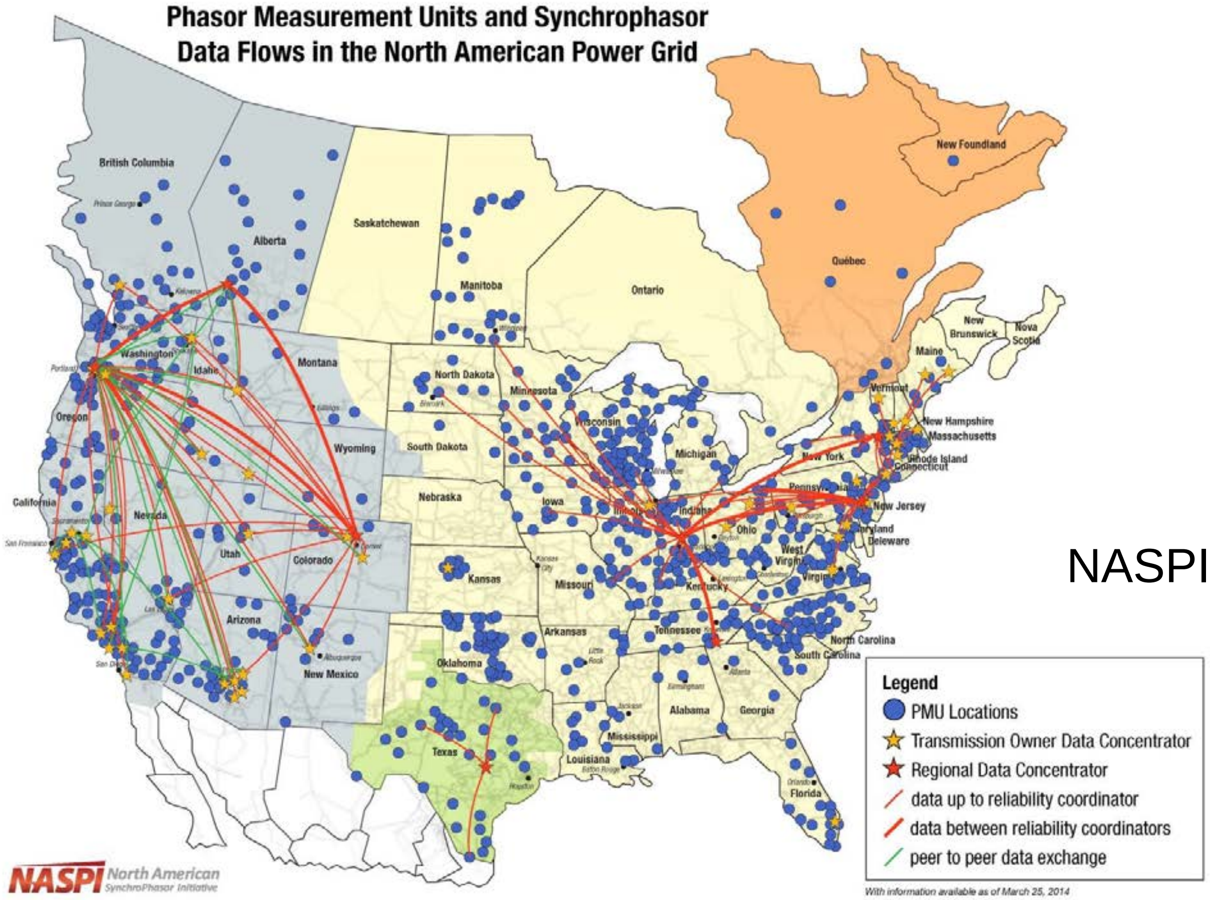
- **National Driver**: clean and efficient power grid as well as being affordable, reliable, and secure ➔ dynamic and fast
- **Technical Approach**: combine model prediction and measurement observations to determine where the grid is, where the grid is going, and where the grid could be (what-ifs).



Phasor measurement offers great opportunities for capturing dynamics

- Time-synchronized, high-speed measurement at 30 samples per second, able to capture the majority of grid dynamics



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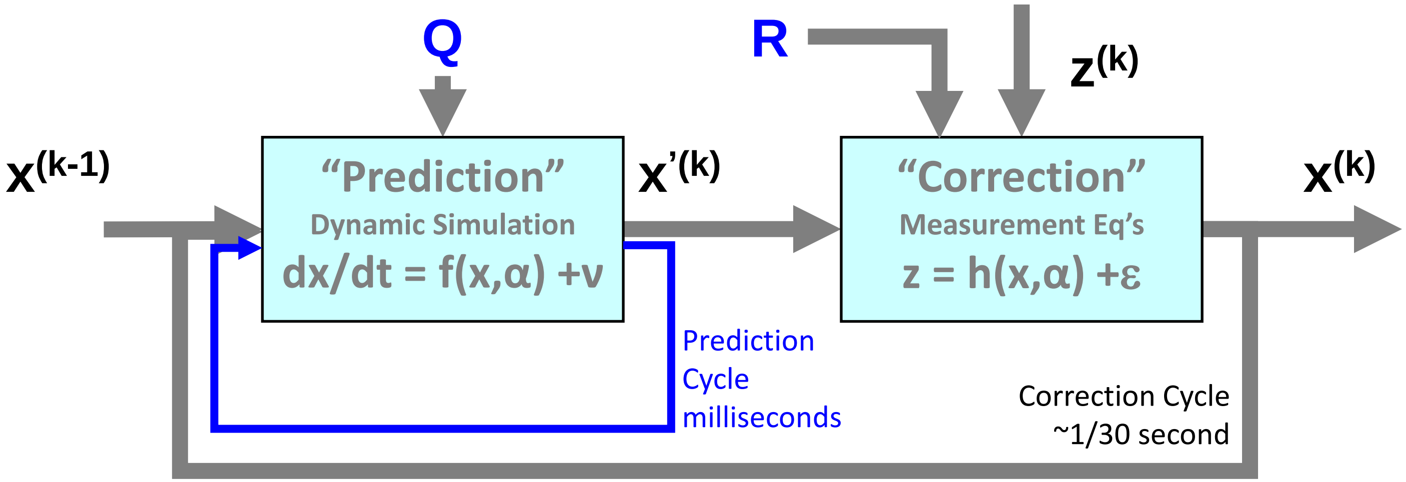
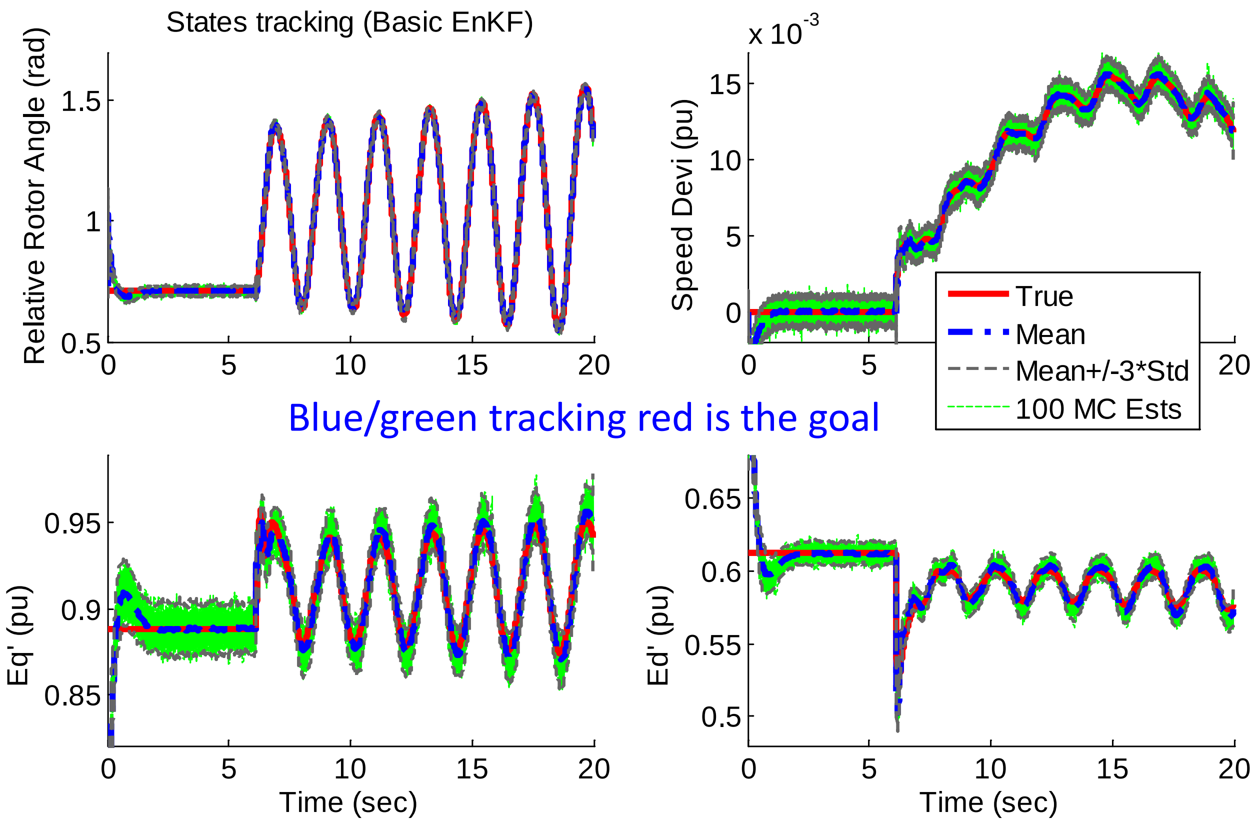
General formulation of dynamic state estimation

- Two-step process
  - Prediction through model simulation
  - Correction using real-time phasor measurement
- Mathematical algorithms: Extended Kalman Filter, Unscented Kalman Filter, Ensemble Kalman Filter, Particle Filter, …



Performance evaluation – estimation accuracy (Ensemble Kalman Filter)

- Excellent tracking with realistic evaluation conditions
  - 3% measurement noise; 40 ms measurement cycle (phasor measurement)
  - 5 ms interpolation cycle; modeling errors considered; unknown inputs; unknown initial states



Performance evaluation – computational speed (Ensemble Kalman Filter)

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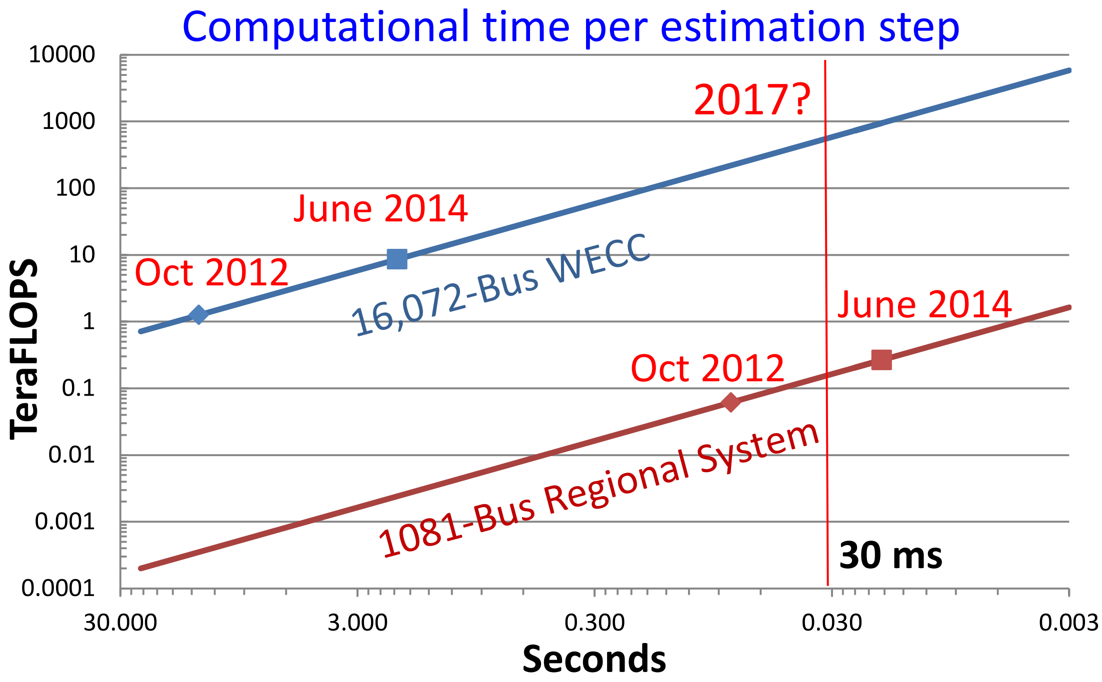
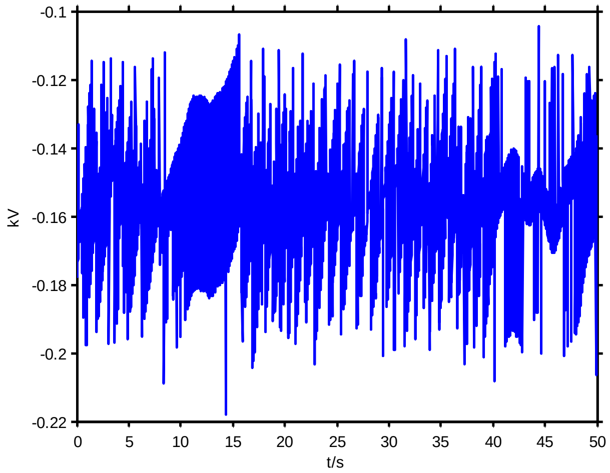
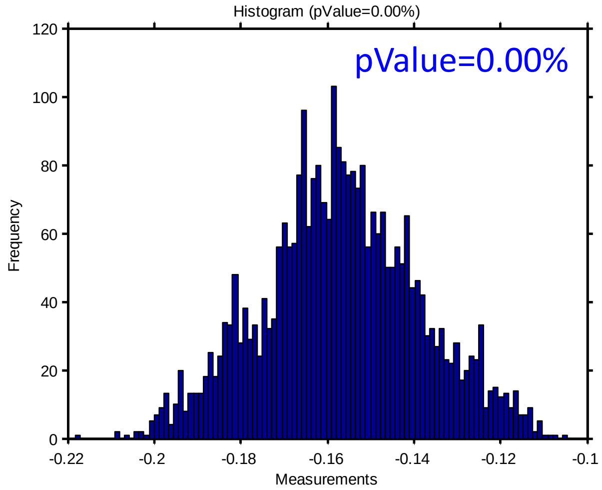
- Current codes scale to ~1,000 cores
- Current computational performance meets the real-time requirement for regional systems
- Challenge: real-time performance for interconnection-scale systems.

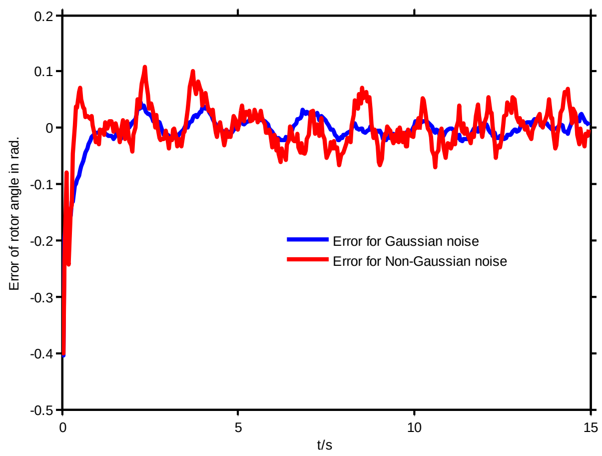


Performance evaluation – impact of non-Gaussian noises (Ensemble Kalman Filter)

- Non-Gaussian noise discovered in phasor measurements.
- Such non-Gaussian noises could result in large estimation errors.
- Challenge: new methods to accommodate non-Gaussian noises.





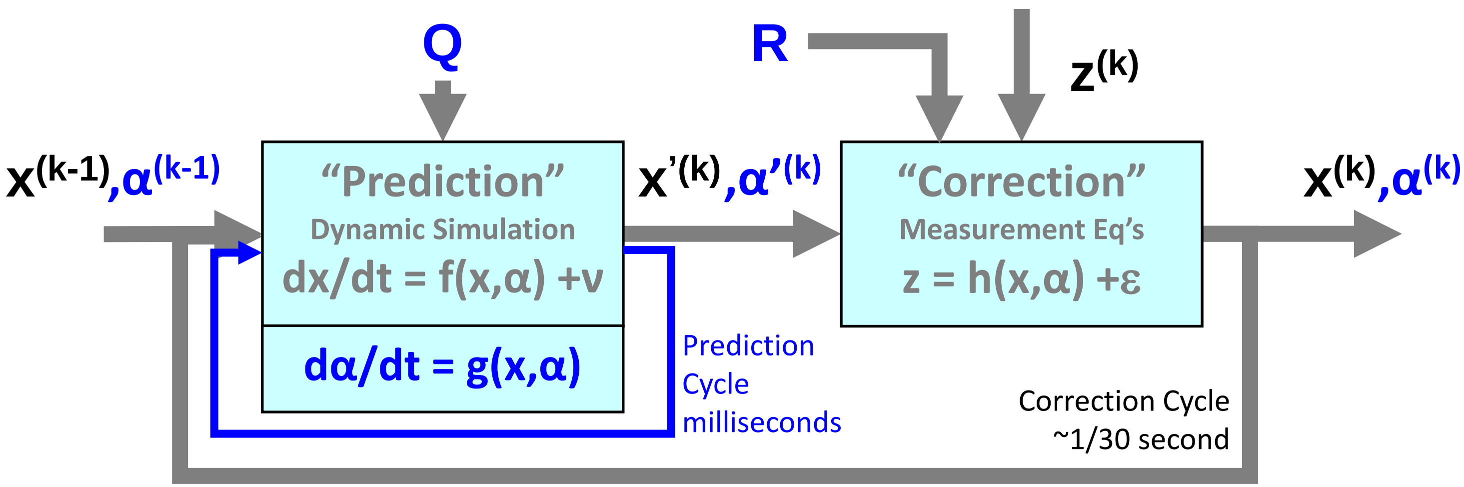


Filtering technology comparison for dynamic state estimation

	Extended Kalman Filter	Unscented Kalman Filter	Ensemble Kalman Filter	Particle Filter
Accuracy	The 2nd best with 0% diverged	33% diverged	The best with 0% diverged	20% diverged (PF 2000)
Efficacy of interpolation	High	High	Low	High
Number of samples needed	None	Small	Medium	Large
Sensitivity to missing data	Low	Low	Low	Low
Sensitivity to outliers	Low	Low	Medium	High
Computation time (non-parallel)	Shortest	Same order as EKF	longer than EKF	Same order as EnKF

Extending the formulation for dynamic model validation and calibration

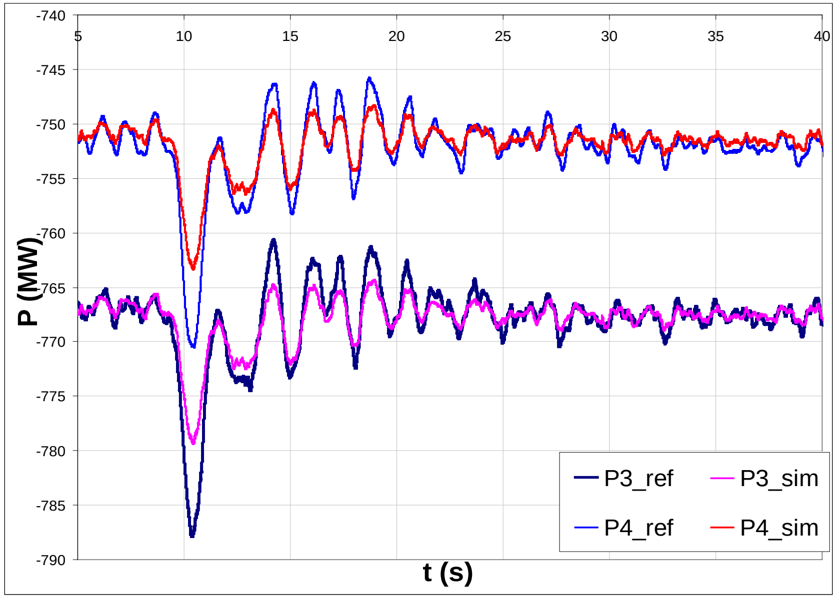
- Treating parameters as augmented states
  - **$d\alpha/dt = g(x,\alpha) = 0$**
- Dynamic states and parameters are estimated simultaneously, suitable for real-time applications

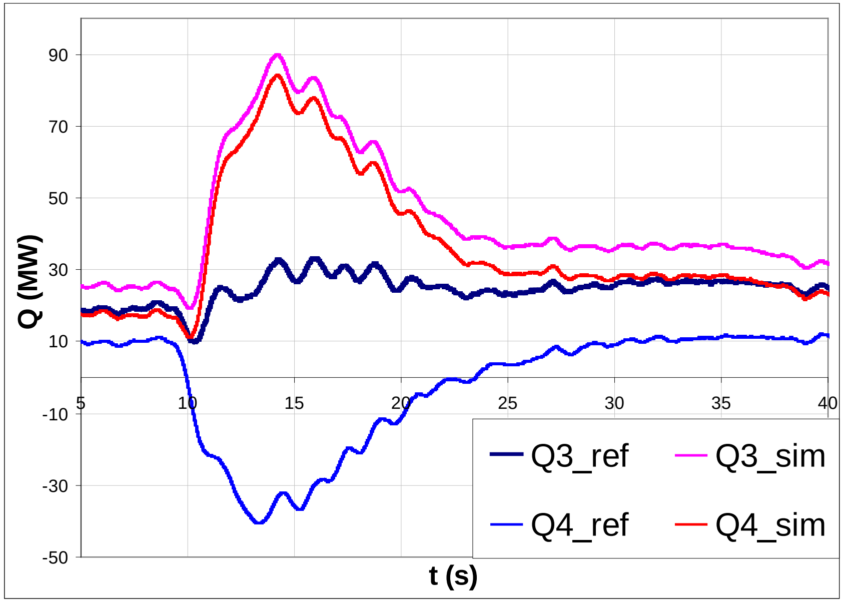


Calibration of Generator Dynamic Model

(Data from August 18 2002, 1500 MW Navajo units drop)

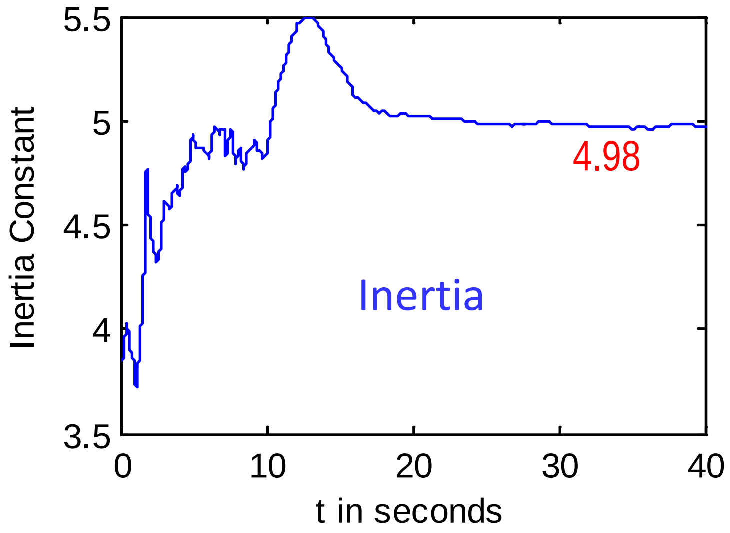
- Before calibration: Significant mismatch between simulation and measurement

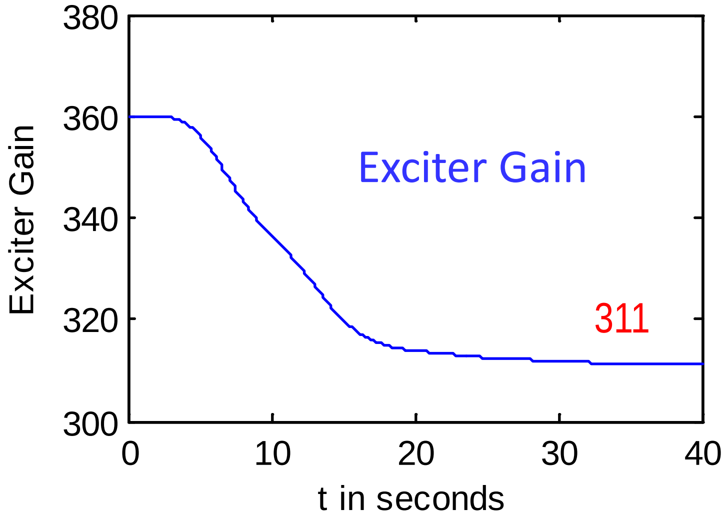


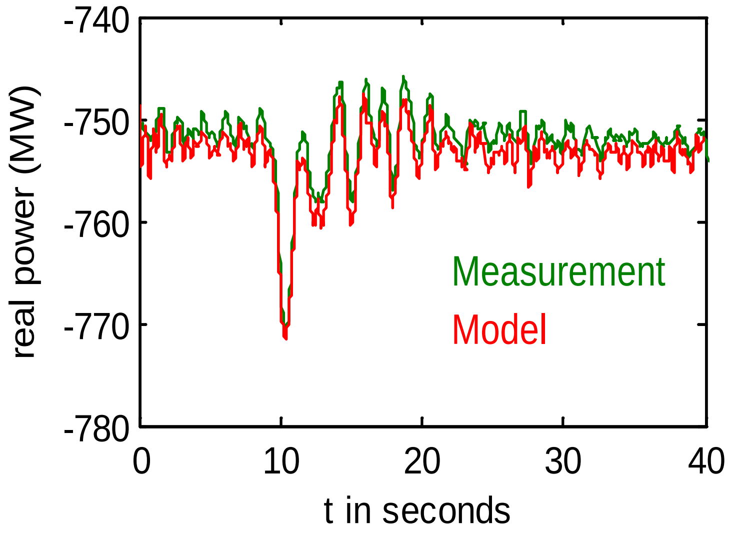


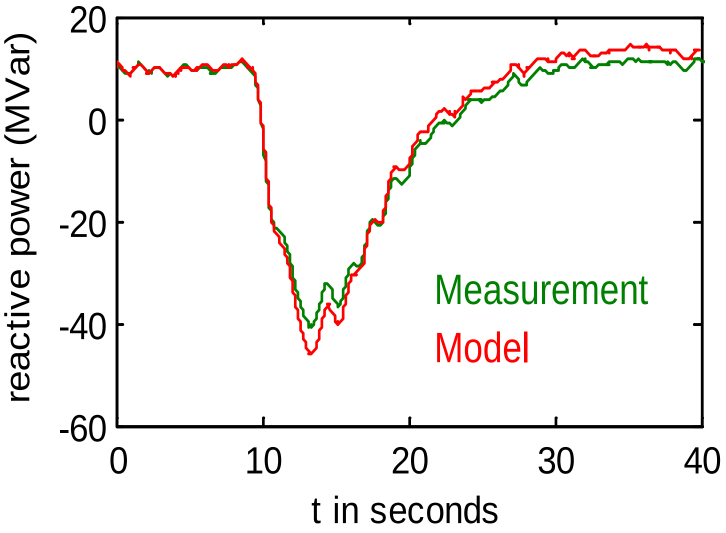
Calibration of Generator Dynamic Model
(Data from August 18 2002, 1500 MW Navajo units drop)

- After calibration: model and measurement match.









Multi-Event Model Verification: good match across multiple events after calibration

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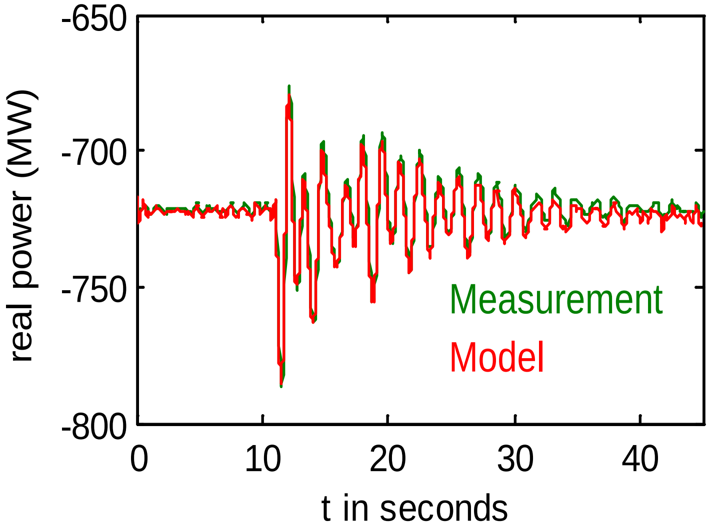
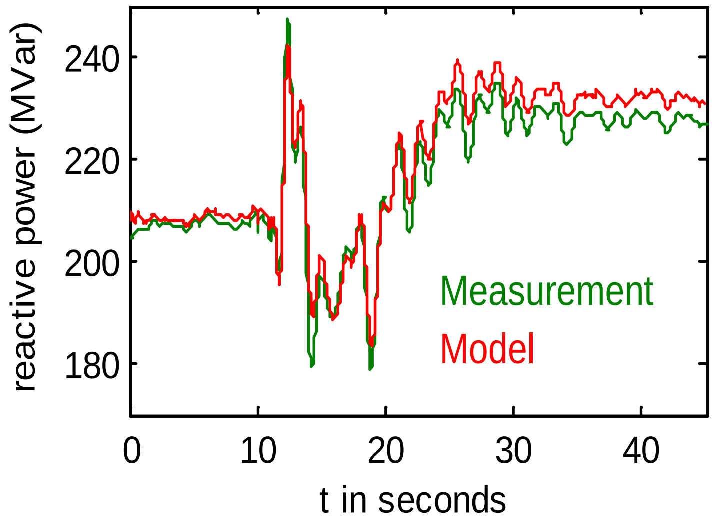
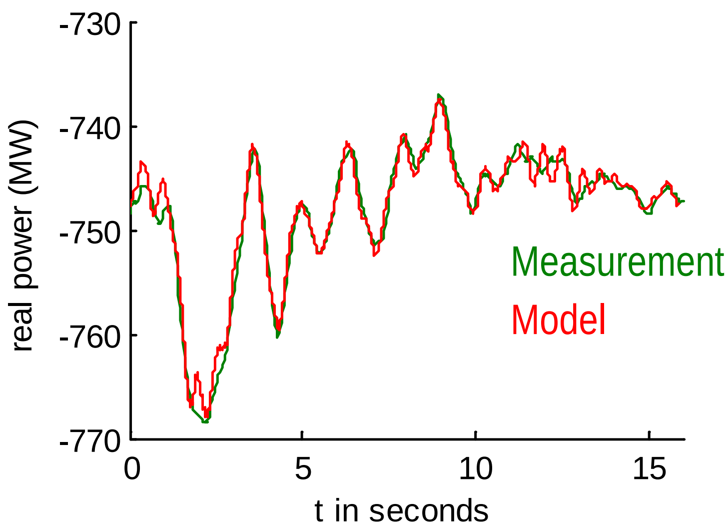
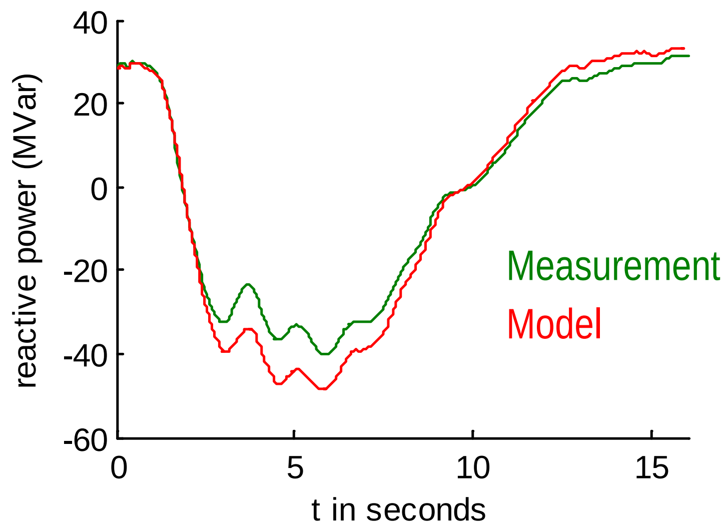




Event 1: July 16 2002, 2588 MW RAS generation drop





Event 2:Verification (July 28 2003, 1252 MW Palo Verde #3 trip and 1500 MW of other generation loss)

Summary

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- Capturing dynamics is necessary because the power grid is trending to be more dynamic (frequency deviates from nominal more often with larger amplitude).
- A dynamic paradigm is proposed to capture emerging dynamics and understand where the grid is, where the grid is going, and where the grid could be (what-ifs).
- Phasor measurements offer opportunities for implementation with Kalman filters.
  - Great performance for dynamic state estimation and dynamic model validation, ready for pilot testing and adoption.
- Challenges remain in real-time computational performance and non-Gaussian noise impact.

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Questions?