U.S. DEPARTMENT OF ENERGY
Electricity Delivery & Energy Reliability

Advanced Grid Modeling 2014 Peer Review

Dynamic Paradigm for Grid Operations

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Collaborating Organizations: Binghamton University, Powertech Labs
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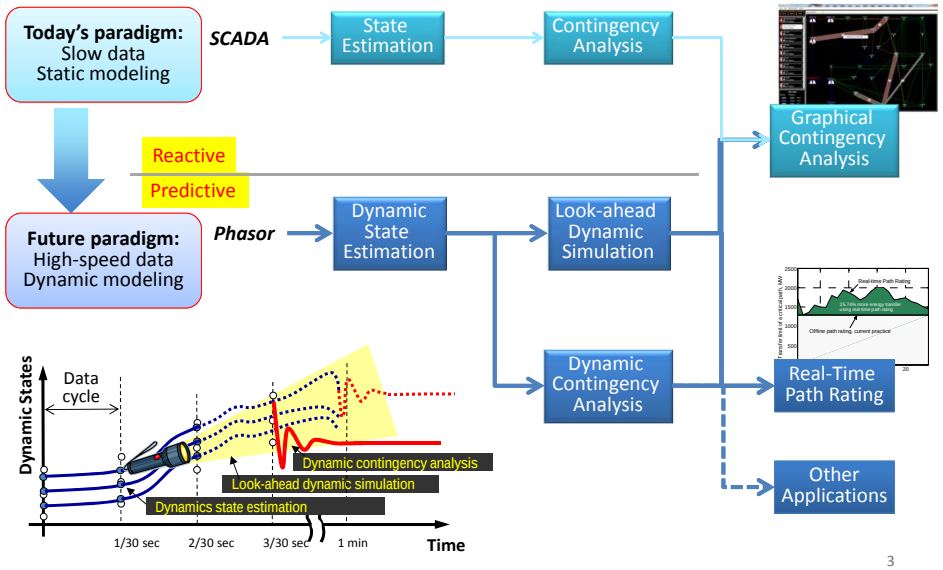
Presentation outline

- Project Purpose: Capturing Dynamics
- Significance and Impact
- Technical Approach – A Dynamic Paradigm for Operation
- Technical Accomplishments
  - Dynamic State Estimation
  - Look-Ahead Dynamic Simulation
  - Dynamic Contingency Analysis
    - Transient Stability
    - Voltage Stability
- Synergistic Work
- Summary
- Contacts

Capturing dynamics:
Enable grid operations from reactive to predictive



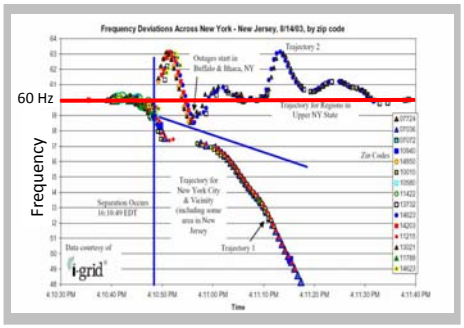
Projects and teams

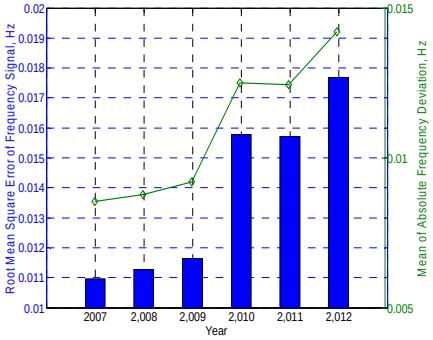
- Dynamic Paradigm for Grid Operations
  - Henry Huang, Ning Zhou (Binghamton University), Steve Elbert, Shuai Lu, Da Meng, Shaobu Wang, Ruisheng Diao
- Look-Ahead Dynamic Simulation
  - Shuangshuang Jin, Ruisheng Diao, Di Wu, Yousu Chen
- Dynamic Contingency Analysis
  - Yousu Chen, Mark Rice, Shuangshuang Jin, Kurt Glaesemann
- Non-Iterative Voltage Stability Analysis
  - Yuri Makarov, Bharat Vyakaranam, Da Meng, Pavel Etingov, Tony Nguyen, Di Wu, Zhangshuan (Jason) Hou, Shaobu Wang, Steve Elbert, Laurie Miller

See project details on posters…

Trend of frequency variance

- Traditional state estimation does not accurately capture the system's dynamic status
  - During emergency situations, frequency is significantly off nominal 60Hz
  - During normal operation, frequency tends to deviate more often from 60Hz

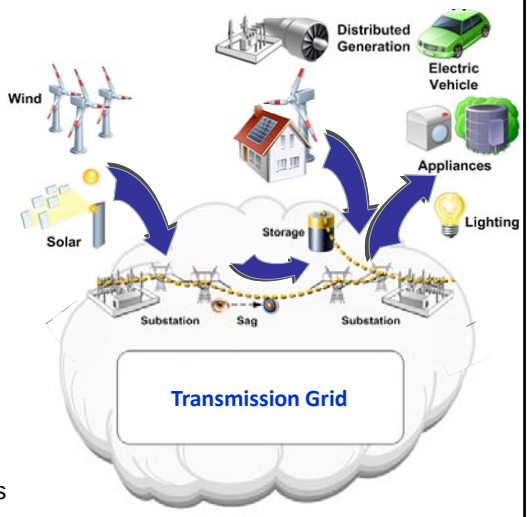




Challenges in future power grid operations

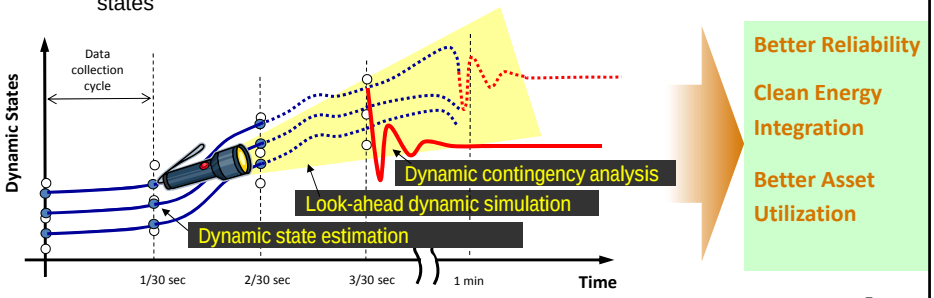
"Grid evolution meets information revolution"

- **Grid Evolution** – stochastic & dynamic
  - Generation: intermittent renewable energy, distributed generation
  - Demand: smart loads, plug-in hybrids
  - Other: storage, new market design/incentives
- **Information Revolution** – data rich but information scarce
  - Large number of phasor measurement units, smart meters, and intelligent devices
  - Requirements of cyber security



Dynamic paradigm for grid operation

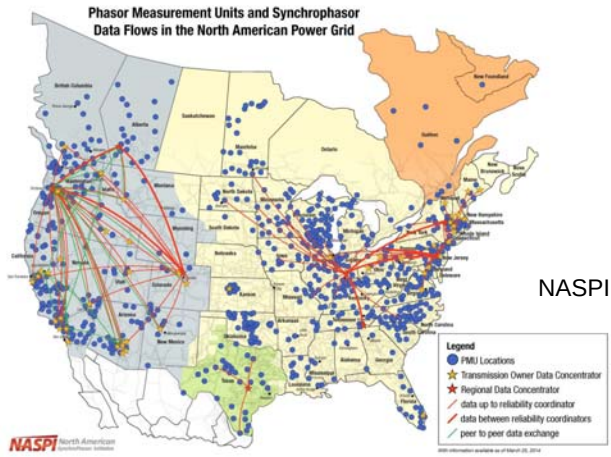
- **National Driver**: clean and efficient power grid as well as being affordable, reliable, and secure ➔ dynamic and fast operation
- **Technical Approach**: combine model prediction and measurement observations to determine where we are, where we are going, and what-ifs
  - Fuse models and data with nonlinearity, discontinuity, model deficiency, and data sparsity
  - Develop Advanced Kalman Filter and HPC codes to estimate states and models
  - Solve a large number of ODE systems to predict future states and alternative states



Enabling factor –

Phasor measurement

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

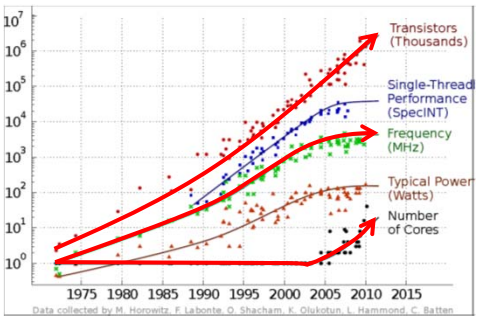


NASPI: www.naspi.org

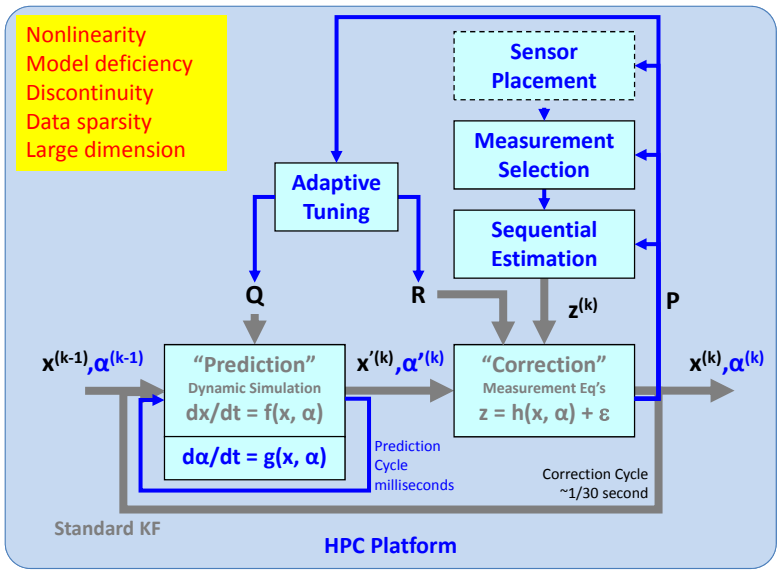
Enabling factor –

Computing technology

- CMOS technology hitting its limits due to power dissipation for the increased clock speed (4-6 GHz)
- Moore's Law still applies – multiple-core processors (parallel computers)
  - PCs: Two-, four-, and eight-cores
  - HPCs: 100s~1,000s cores
  - Forthcoming high-end parallel systems expected to offer million cores
- <u>Parallel computing becomes a fundamental technique</u>

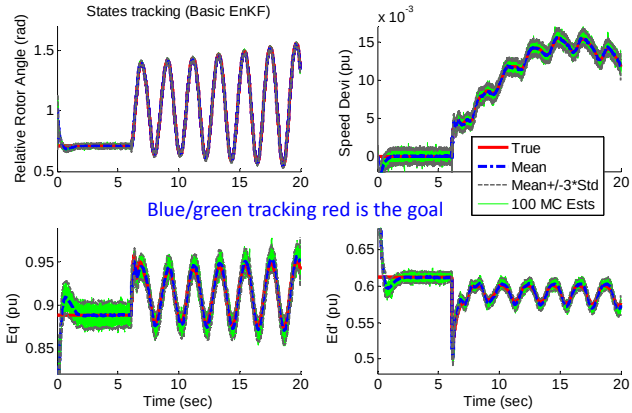


Advanced Kalman Filter for dynamic state estimation



Performance evaluation – estimation accuracy

- 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

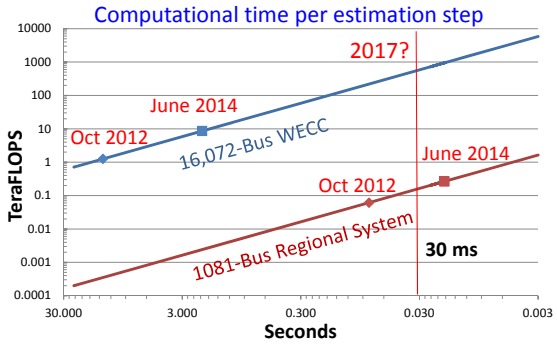


Filtering technology assessment

	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

Computational performance – scalability

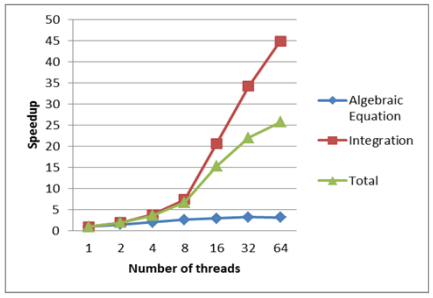
- Current codes scale to ~1,000 cores
- Current computational performance meets the real-time requirement for regional systems
- Performance is expected to be real-time soon for interconnection-scale systems



Look-Ahead Dynamic Simulation

- Performance evaluation with the WECC system

Time distribution for WECC system (Simulation length: 30s with 0.005s time step)			
# of threads	Algebraic Equation	Integration	Total
1	13.26	218.87	232.14
2	8.99	111.97	120.95
4	6.46	57.49	63.96
8	5.07	29.58	34.65
16	4.58	10.64	15.22
32	4.14	6.41	10.55
64	4.16	4.88	9.04

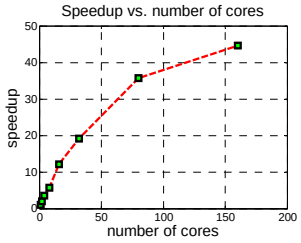


- 13x faster compared to a commercial tool with sequential computing

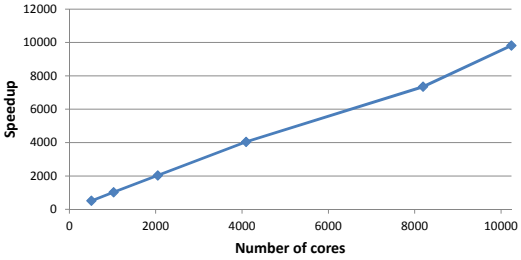
Dynamic Contingency Analysis

- Solving a large set of Differential Algebraic Equations
- Computational challenge is load balancing – dynamic load balancing vs. static load balancing

Commercial Tool on HPC via Virtual Machine

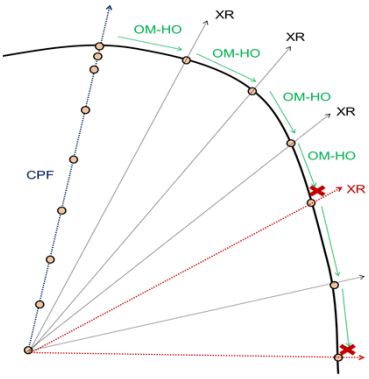


Native HPC Implementation



Voltage Stability Analysis

- Objectives:
  - Generate voltage stability boundary (VSB) accurately and quickly
  - Use parallel computing to further enhance speed
  - Provide connectivity to commercial tools such as PowerWorld

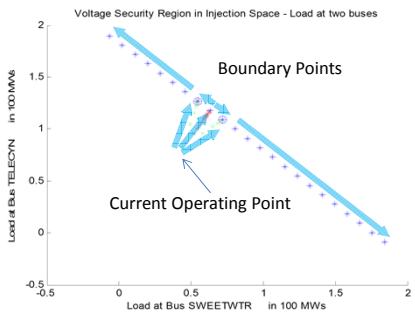


- A combination of methods to explore the VSB:
  - Continuation power flow (CPF)
  - New PNNL method based on the X-ray theorem (XR)
  - Orbiting method (OM) - a direct VSB tracing procedure
  - High-order numerical methods (HO)

Voltage Stability Analysis –

Computational performance

- Minimizing the CPF runs results in great improvement in computational performance
  - 5.6x speedup for WECC-sized system in this example
- Parallel computing version is being implemented and expected to further improve the performance

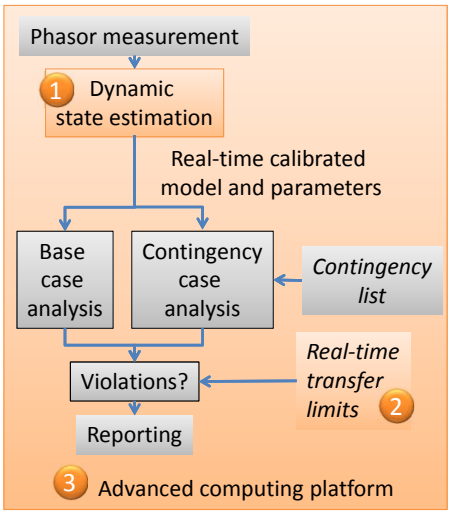


System	Total simulation time		Continuation power flow (CPF)			Boundary orbiting method (BOM)		
	BP[1]	Time(s)	Runs	Time (s)	ATR (s)[2]	Runs	Time (s)	ATR (s)
WECC 2014 (19331 buses)	26	887	3	575	191	25	416	16.6
CAISO (3535 buses)	9	38.6	3	28.9	9.6	8	8.8	1.1
Central America (1985 buses)	8	24.8	3	23.1	7.7	7	1.1	0.17

[1]Boundary Points
[2]Average Time per Run (s)

Use cases of dynamic paradigm

- Real-time predictive grid operation with calibrated model and parameters for faster response and control
- Effective management of large-scale integration of smart grid technologies such as renewable generation, demand response, electric vehicles, and distributed generation
- Better asset utilization to maximize power transfer capabilities and defer transmission expansion



Synergistic work

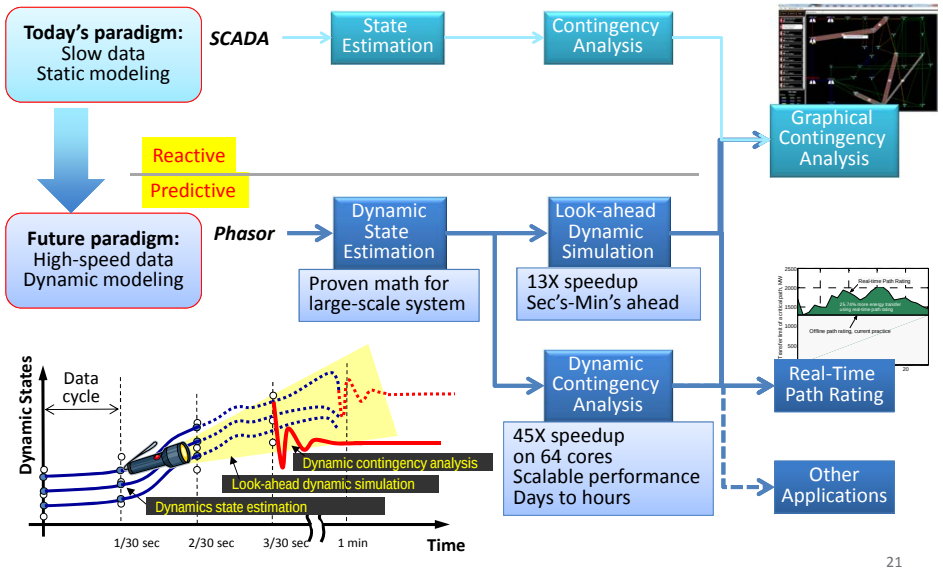
- M2ACS Predictive Modeling, DOE-ASCR
  - Stochastic modeling and data assimilation
- GridPACK™, DOE-OE
  - Parallel computing library for efficient development and better compatibility
- Non-Wire Methods for Congestion Management, DOE ARPA-E
  - Transient and voltage stability analysis
  - Asset utilization improvement through real-time path rating

See project details on posters…

Summary

- Grid evolution meeting information revolution ➔ grid operations transition from static & slow to dynamic & fast
  - Enabling technologies are computation advancement and data development
- A dynamic paradigm is necessary to capture emerging dynamics and understand where the grid is, where the grid is going, and where the grid could end up
  - Dynamic state estimation based on Advanced Kalman Filter
  - Look-ahead dynamic simulation
  - Dynamic contingency analysis of transient and voltage stability
- This paradigm is expected to facilitate integration of new generation and load for a more reliable, efficient, and cleaner power grid

Capturing dynamics:
Enable grid operations from reactive to predictive



Contacts

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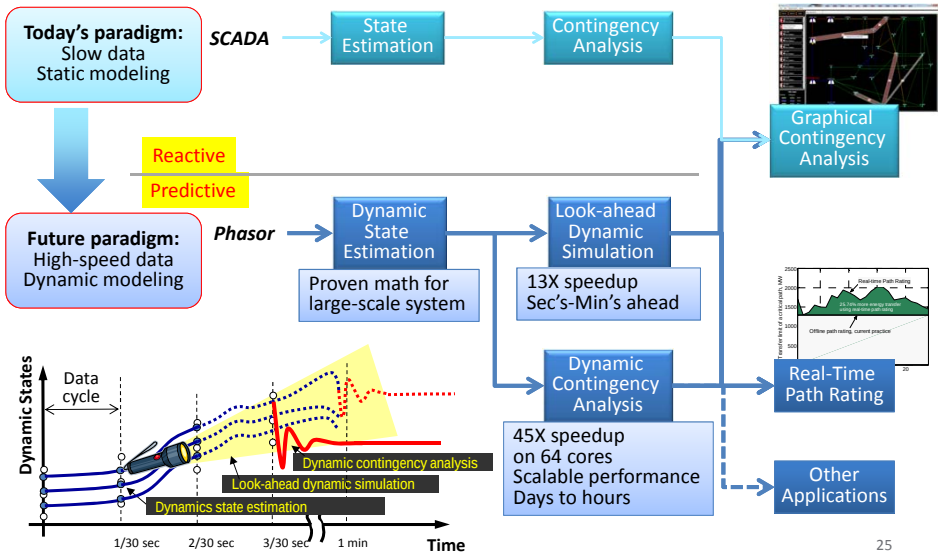
- Dynamic Contingency Analysis
  - Yousu Chen, 206-528-3062, yousu.chen@pnnl.gov
- Non-Iterative Voltage Stability Analysis
  - Yuri Makarov, 509-372-4194, yuri.makarov@pnnl.gov

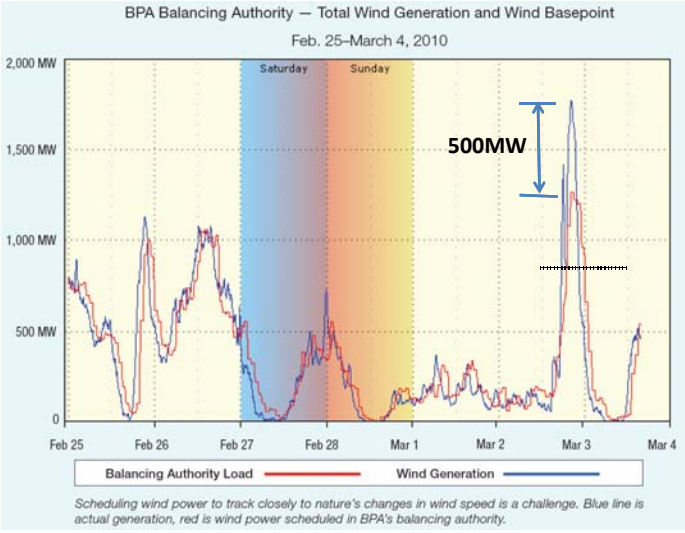
Questions?

Backup slides

Capturing dynamics:
Enable grid operations from reactive to predictive



Mitigate intermittency of renewable energy

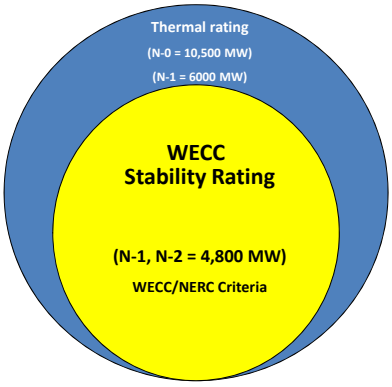


Source: BPA Fact Sheet, "BPA's wind power efforts surge forward," March 2010

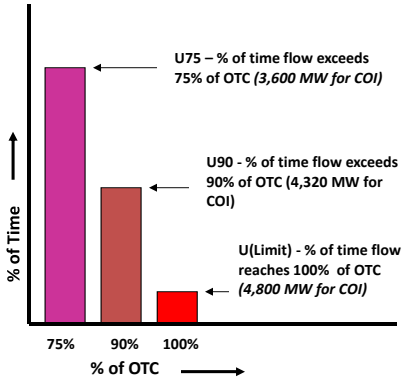
Improve asset utilization

Transfer Capacity Example – California Oregon Intertie (COI)

Path Ratings



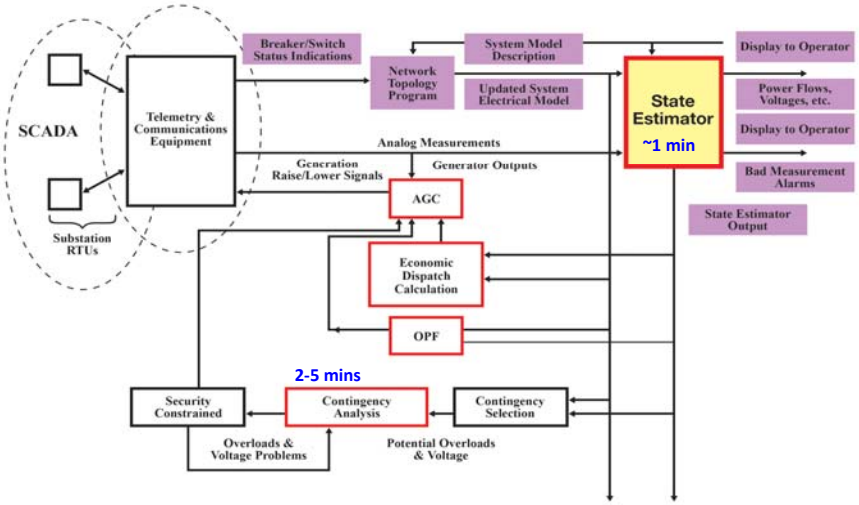
U75, U90 and U(Limit)



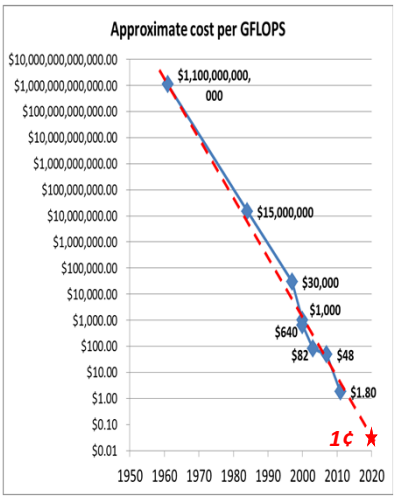
Source : Western interconnection 2006 congestion management study

Today's power grid operation paradigm

- Steady-state model based: static and slow paradigm



Computers are more affordable



Data Source: http://en.wikipedia.org/wiki/FLOPS

- 1997
- **IBM Deep Blue**
  - 11.38 GFLOPS, >$100M

- 2005 (8 years later)
- **Sony VAIO GRT-290Z**
  - 6 GFLOPS, ~$2,000

- 2012 (15 year later)
- **LG Optimus 4X HD P880**
  - 24 GFLOPS, $600