Electric Energy Challenges of the Future:

A PSERC Future Grid Initiative Progress Report

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PSERC Future Grid Webinar
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PSERC Future Grid Initiative

- DOE-funded project entitled "The Future Grid to Enable Sustainable Energy Systems”(see http://www.pserc.org/research/FutureGrid.aspx)
- Objective: to investigate the requirements of an electric grid with high penetrations of sustainable energy systems and extensive reliance on cyber systems for sensing and communication.
- Focus: accomplishments in the thrust area “Electric Energy Challenges of the Future”

Robust and Dynamic Reserve Requirements

Kory Hedman with grad students Joshua Lyon and Fengyu Wang at Arizona State

Wide Area Control Systems

Mani Venkatasubramanian with researchers at Washington State

Integrating Transmission and Distribution Engineering Eventualities

Gerald Heydt with grad students B.J. Pierre and A. Salloum at Arizona State

A National Transmission Overlay: Design Process

Jim McCalley with grad students Yifan Li and Hugo Villegas at Iowa State

A National Transmission Overlay: Impacts on Power System Dynamics

Dionysios Aliprantis with grad student Hugo Villegas-Pico at Iowa State

Kory Hedman
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Outline

- Background and Motivation
- Current Industry Practices
- CAISO, ERCOT, and MISO
- Achievements
- Results
- Future Work

Background

- Reserve requirements (spinning and non-spinning reserve) are imposed inside day-ahead unit commitment to ensure sufficient backup capacity is available
  - Such requirements are used as proxy methods to ensure N-1 reliability
  - Traditional reserve requirements for unit commitment do not guarantee N-1 due to congestion
  - Congestion may prevent reserves from being deliverable when needed
- Choice of reserve requirements affects reliability and economic efficiency

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Project Motivation

- Ensuring sufficient reserves (quantity + location) will be increasingly more difficult with renewables
- Opportunities to improve existing reserve rules for market or vertically integrated environments
  - Develop robust and dynamic reserve requirements
  - Create reserve rules for renewables
  - Improve reserve deliverability by developing dynamic reserve zones
- Targeted results:
  - Improved economic efficiency and reliability
  - Improved management of resource uncertainty (renewables, demand, electric vehicles)

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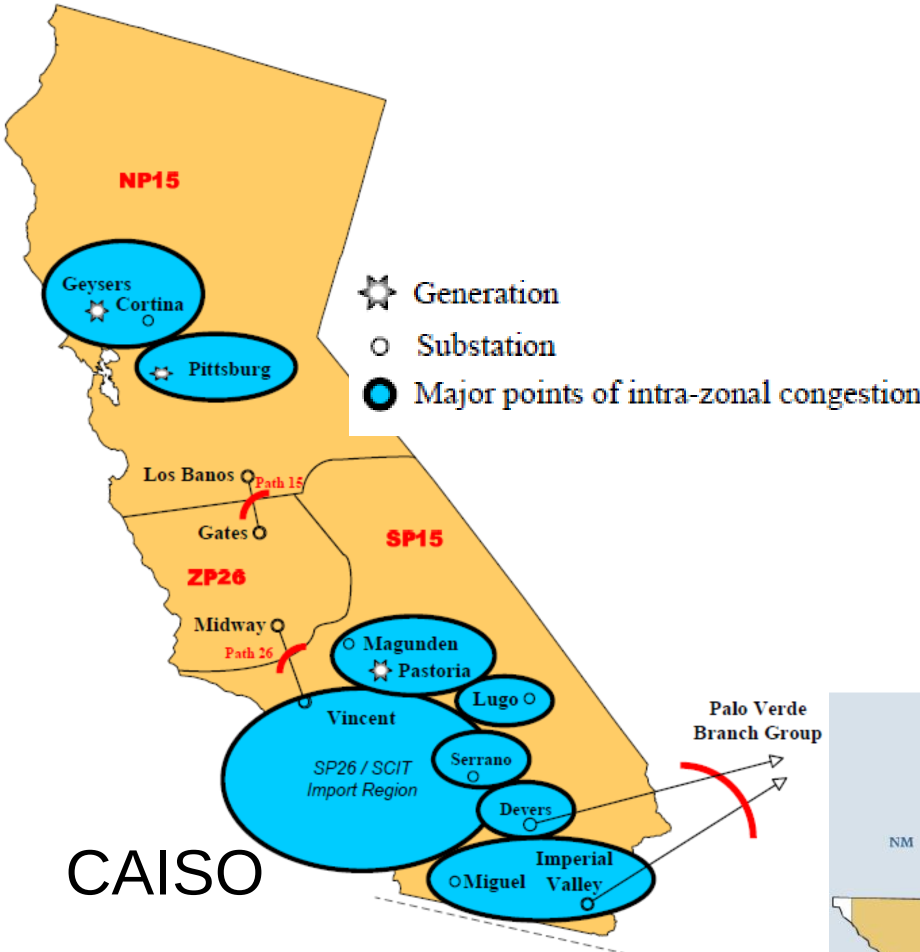
Current Industry Practices: Reserve Zones

- Reserve zone: a defined region of the grid with a specified reserve requirement
- Today's reserve zones are usually determined by:
  - Utility ownership
  - Identification of critical, congested paths
- Zones traditionally treated as static (i.e., are rarely updated; do not reflect a network's operational states)
- Example: Zones in Texas (i.e., ERCOT):
  - Defined such that each generator or load within the zone has a similar affect on *commercially significant constraints (CSC)*
  - ERCOT utilizes statistical clustering methods to determine zones

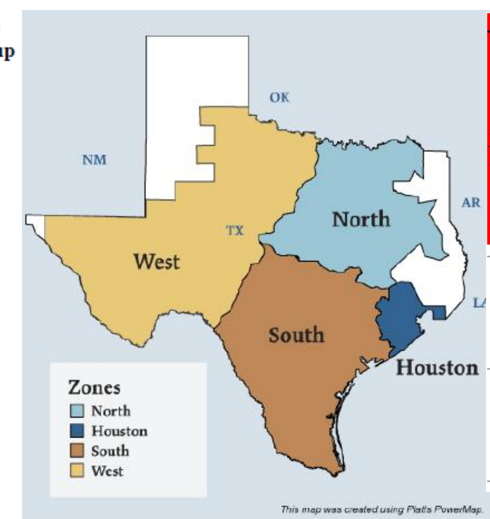
ERCOT, "ERCOT Protocols, Section 7: Congestion Management" [Online]. Available at www.ercot.com/content/mktrules/protocols/current/07-070110.doc, July, 2010.

CAISO, ERCOT, MISO's Reserve Zones



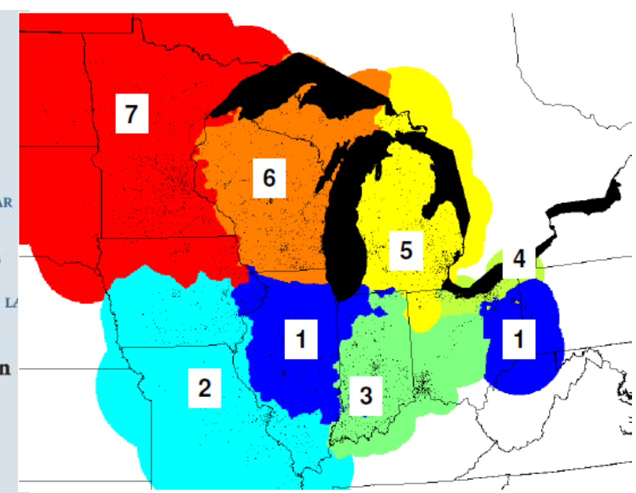
CAISO

- CAISO has 3 reserve zones
- Their reserve rules do not account for intra-zonal congestion
- Intra-zonal congestion is account for by other rules



ERCOT

MISO



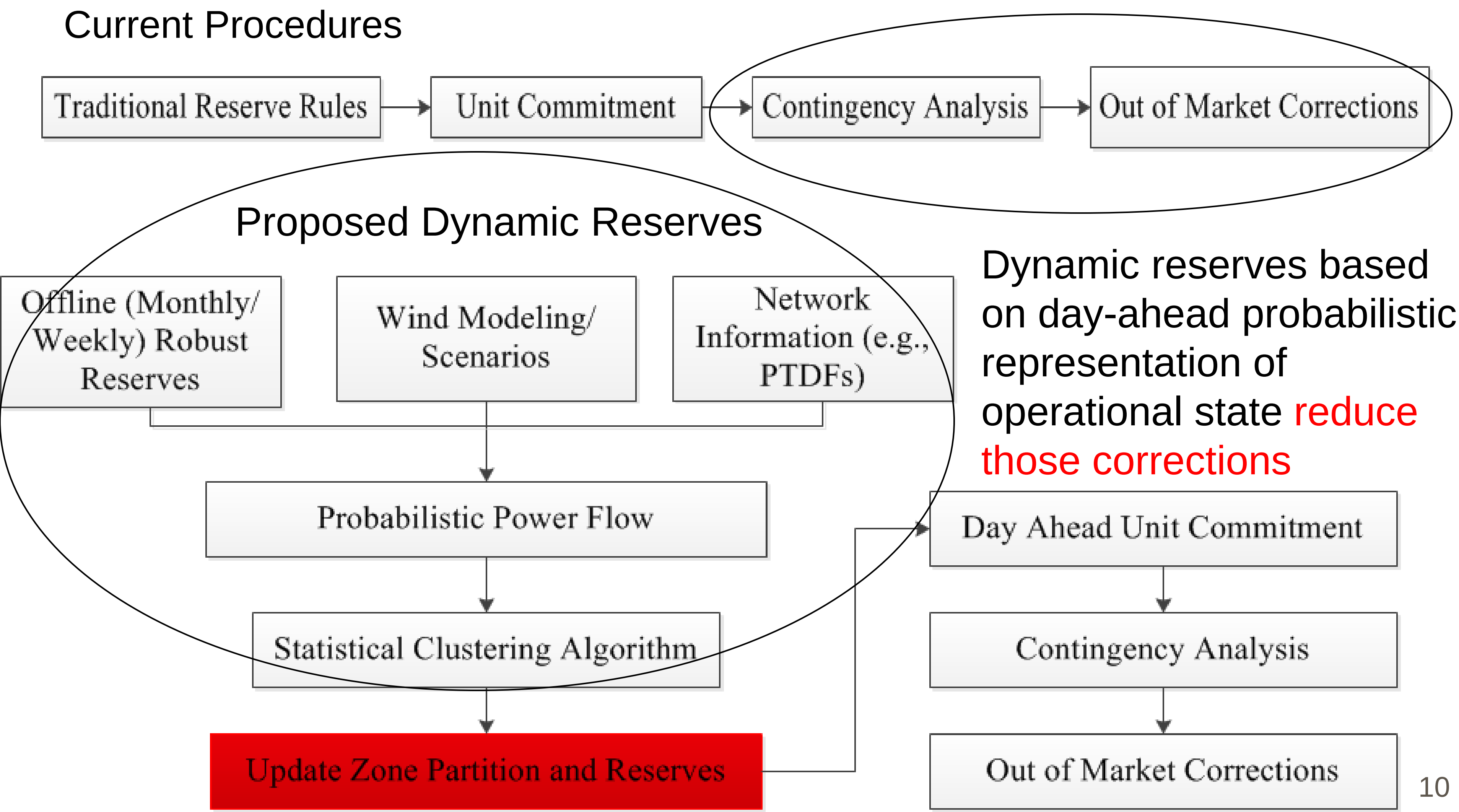
Area 1 is a part of PJM

Project Achievements

- Developed systematic ways to determine dynamic reserve requirements (zones and levels)
  - Improved reserve location/deliverability
  - Transitioned from static to dynamic (operational state dependent) rules
  - Developed reserve rules for renewable resources
  - Developed reserve rules for network topology changes
  - Results: improvements in market efficiency (reduced costly out of merit dispatch/out of market corrections) and reliability/reserve deliverability

Day Ahead Dynamic Reserves

Reserve rules that fail to achieve N-1 require costly out of merit dispatch/out of market corrections (operators must turn on additional generation)



Dynamic reserves based on day-ahead probabilistic representation of operational state reduce those corrections

Results: Reserve Deliverability Issues within Contingency Analysis

- Day-ahead unit commitment (IEEE 118 test system) with:
  - Traditional reserves: max(largest contingency, NREL's 3+5 rule) with forecasted wind
  - Two-stage stochastic program with traditional reserves and 10 wind scenarios modeled
  - Proposed dynamic reserves: zones based on PTDF and probabilistic power flow (with forecasted wind)
- Performed contingency analysis on N-1 and wind scenarios
- Tested 12 days from January to March
- **Reserve not capable of being delivered, which will then require *out of market/out of merit dispatch corrections:***

	Stochastic Programming (Single Zone) (MW)	Traditional Reserves (3 Zones) (MW)	Dynamic Reserves (3 Zones) (MW)	Percent Improvement
Expectation of Reserve Not Deliverable	4.25	4.23	2.17	48.7%

[1] F. Wang and K. W. Hedman, "A statistical clustering method to determine dynamic reserve zones for systems with renewable resources," In preparation.

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Reserve Rules Related to Congestion

- Congestion on zone interfaces dictates the ability to allow reserve sharing between zones
  - ISO New England allows zonal reserve sharing as a function of congestion
- Most reserve policies generally ignore intra-zonal congestion
- New reserve policies can better reflect system stress by relating it to congestion
  - The option to increase reserve or decrease congestion is embedded into the proposed optimization algorithm

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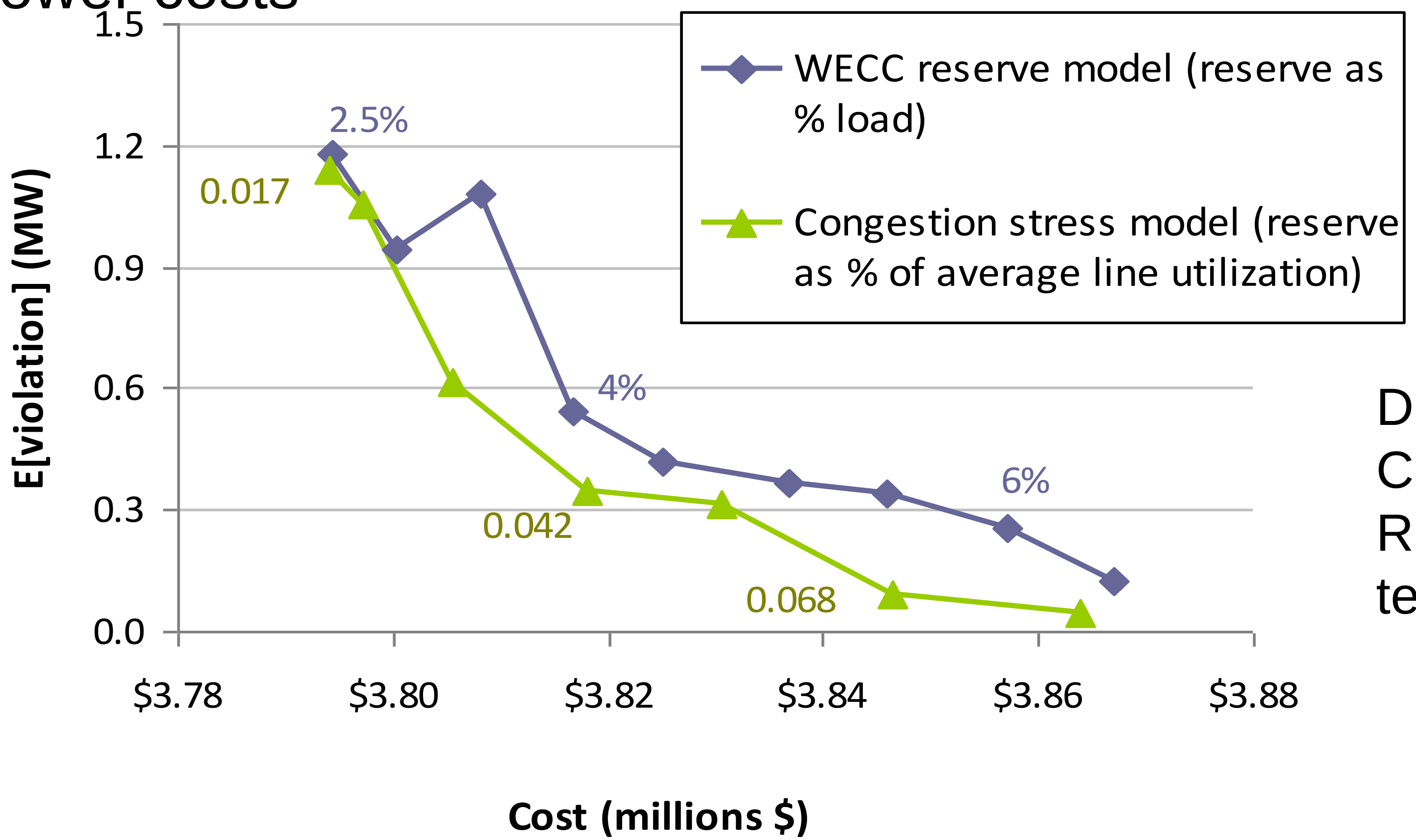
Reserve as a Function of Congestion

Green line: reserve rule as a function of congestion dominates WECC's reserve model: improved reserve deliverability with lower costs

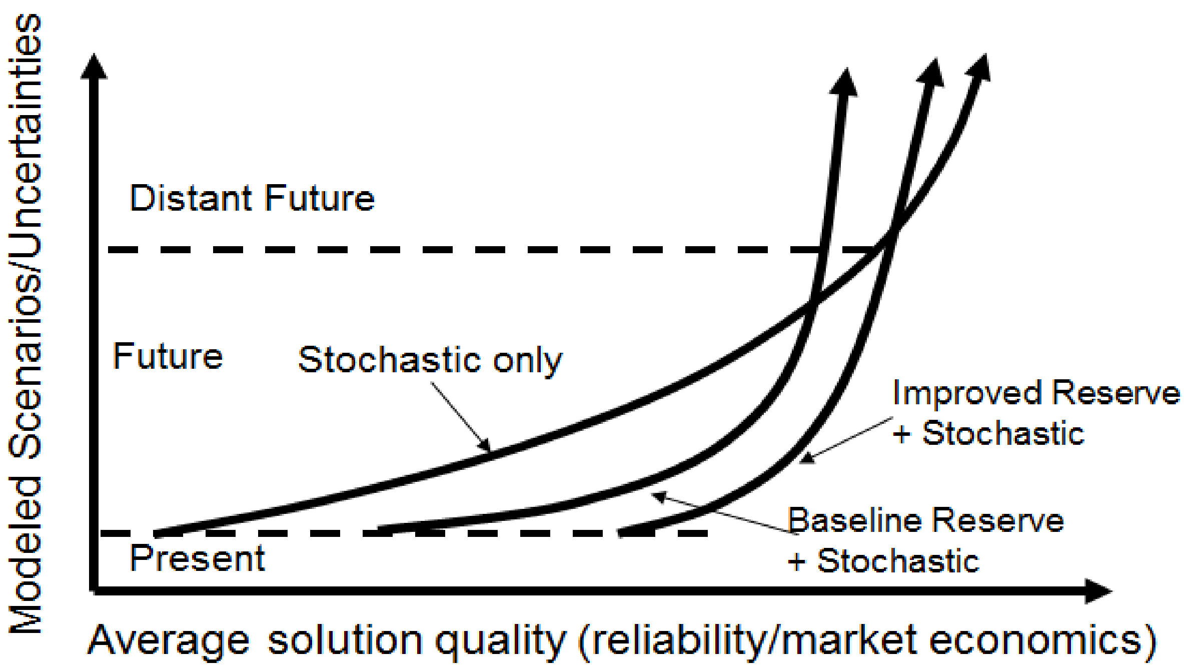


Day-ahead Unit Commitment Results (RTS96 test system)

[2] J. Lyon and K. W. Hedman, "Reserve requirements to efficiently mitigate intra-zonal congestion," In preparation.

Future Work

- Model refinement; market and risk analysis
- Combining dynamic reserve policies with a parallelizable stochastic unit commitment problem will improve convergence and solution quality



References

[1] F. Wang and K. W. Hedman, “Reserve zone determination based on statistical clustering methods,” *NAPS2012*.

[2] F. Wang and K. W. Hedman, “A statistical clustering method to determine dynamic reserve zones for systems with renewable resources,” In preparation.

[3] J. D. Lyon, K. W. Hedman, and M. Zhang, “Reserve requirements to efficiently mitigate intra-zonal congestion,” In preparation.

[4] J. D. Lyon, M. Zhang, and K. W. Hedman, “Dynamic reserve zones for distinct scenarios,” In preparation.

[5] J. D. Lyon, K. W. Hedman, and M. Zhang, "Embedding reserve zone partitioning into unit commitment,” In preparation.

Wide Area Control Systems

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Objectives

- Wide-area control designs for future power systems
- High percentage of renewable energy sources
- Fast wide-area monitoring systems with PMUs everywhere
- What control designs are feasible?
- Voltage stability issues at substations from reactive power demands of renewables and power electronic devices
- Small-signal stability problems from interactions of power electronic devices with the grid
- Transient stability concerns from unforeseen operating conditions and high order contingencies

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Accomplishments

- Developed a new wide-area hierarchical voltage controller
- Developed a new wide-area transient stability controller aimed at uncertain operating conditions of the future and for highly complex, unplanned for, large contingencies

Benefits

- Improved controls resulting from better real-time system data, thus taking advantage of new synchrophasor technologies
- Response to system events that is faster and more efficient with less load loss

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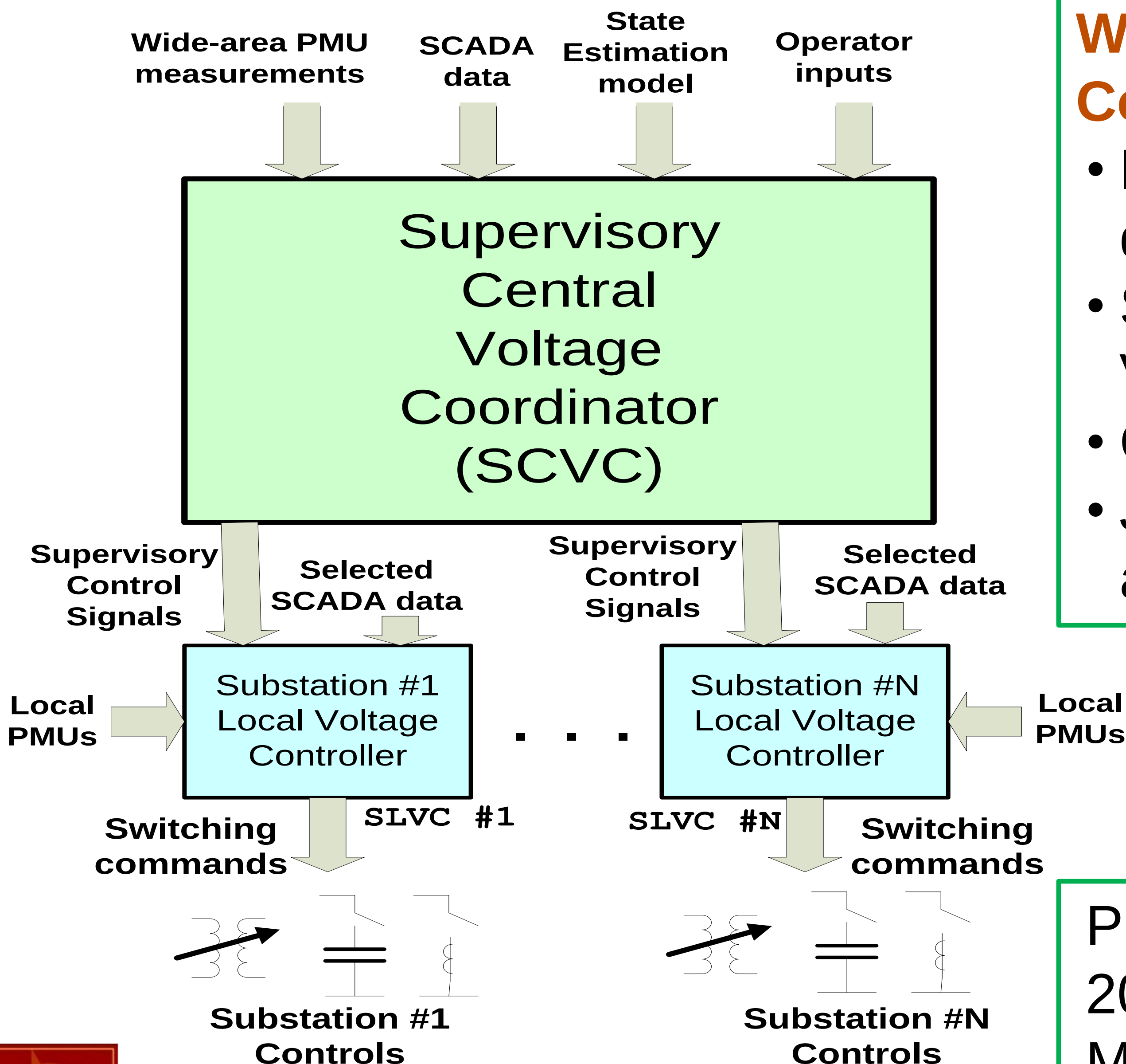

Wide-Area Voltage Controller

- Hierarchical design developed
- Substation Local Voltage Controllers
- Central Coordinator
- Javier Guerrero and Hong Chun

Presented in IEEE 2012 PES General Meeting paper

Small-Signal Stability

- Challenging problem from lack of models and from interaction of discrete and continuous dynamics
- Subsynchronous high frequency modes (5 Hz to 50Hz) from power electronic devices may be problematic
- High sampling frequency data may be needed
- Controls on power electronic side may be culprits
- Detection and isolation crucial
- Which substation(s)? Which controls?
- New algorithms for monitoring and analysis of subsynchronous modes developed
- Tested on 12.5 Hz SSR Mode seen in certain wind farms in Oklahoma Gas and Electric from DFR data at 5760 Hz sampling rate (NASPI February 2012 presentation)

Wide-Area Transient Stability Controller

- New model prediction based real-time angle stability control developed
- Suited for uncertain operating conditions of the future and for unplanned high order contingencies
- PMUs assumed everywhere
- Rotor machine angles assumed to be measured from synchronous machines
- Fast communication and computation assumed
- Stable or unstable? What control actions? Algorithms developed.
- Can stabilize highly complex contingencies
- Doctoral dissertation work of **Greg Zweigle**
- IEEE 2012 PES T&D Expo paper, IEEE PES Trans paper

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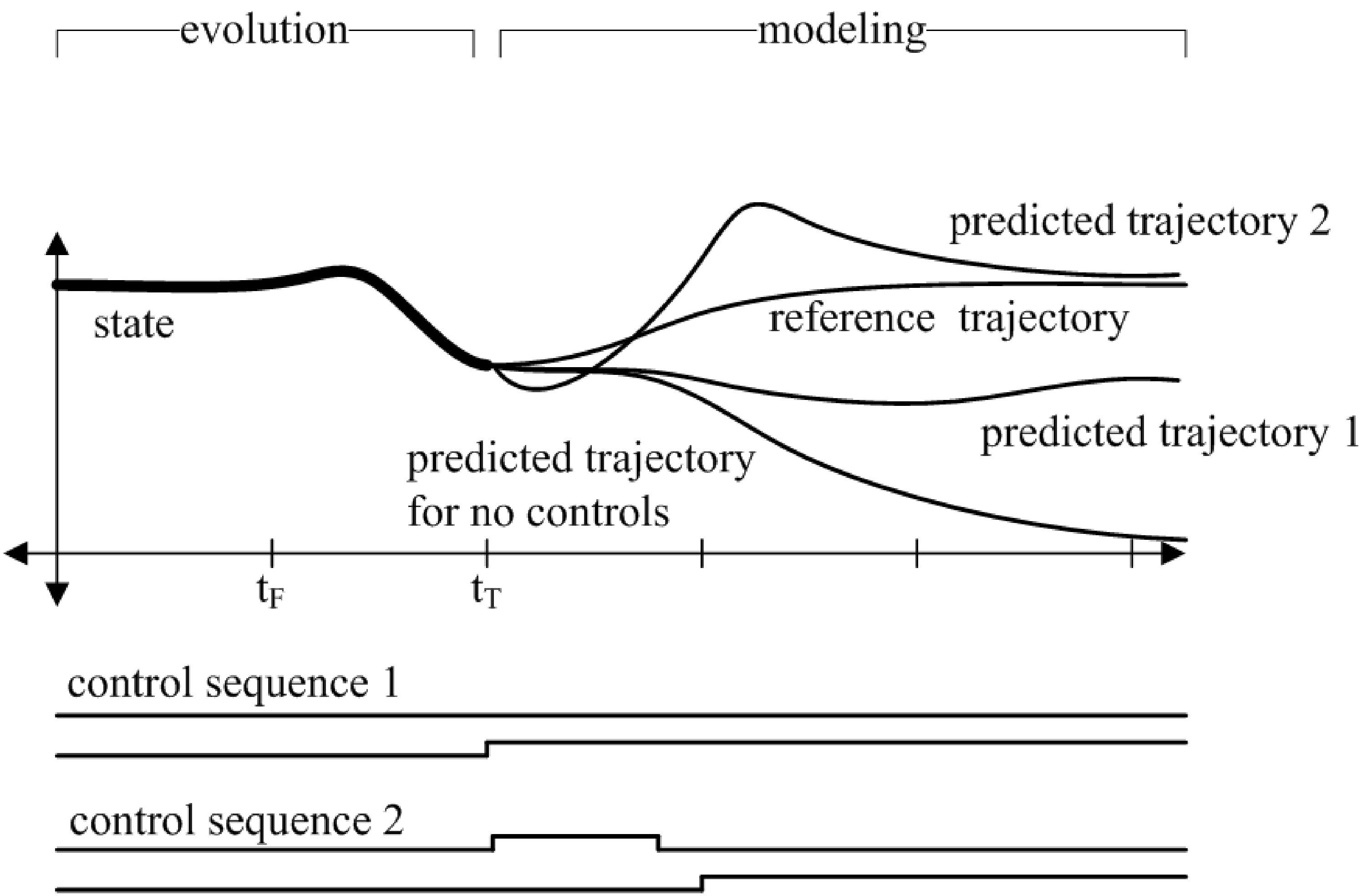
Wide-Area Transient Stability Controller

- Investigate stabilization of large contingencies
- Difficult to pre-plan for these cases
- Leverage advances in synchrophasors
  - Network measurements
  - Emerging generator measurements
- Leverage advances in computing power & high speed communication networks
- Model prediction formulation proposed
- Don't try to predict contingencies
- Instead, predict state evolution
  - Run in real-time
  - Iterative application, with feedback
  - At each iteration, search for optimal control

Model Prediction Control (MPC)



MPC & Transient Stability

- MPC originally for chemical process control
- Previously applied for slower power system phenomena
    - Voltage stability control
    - Small-signal rotor angle control
- Must act within seconds
- Doesn't require as many control options
- Communications and computers getting faster

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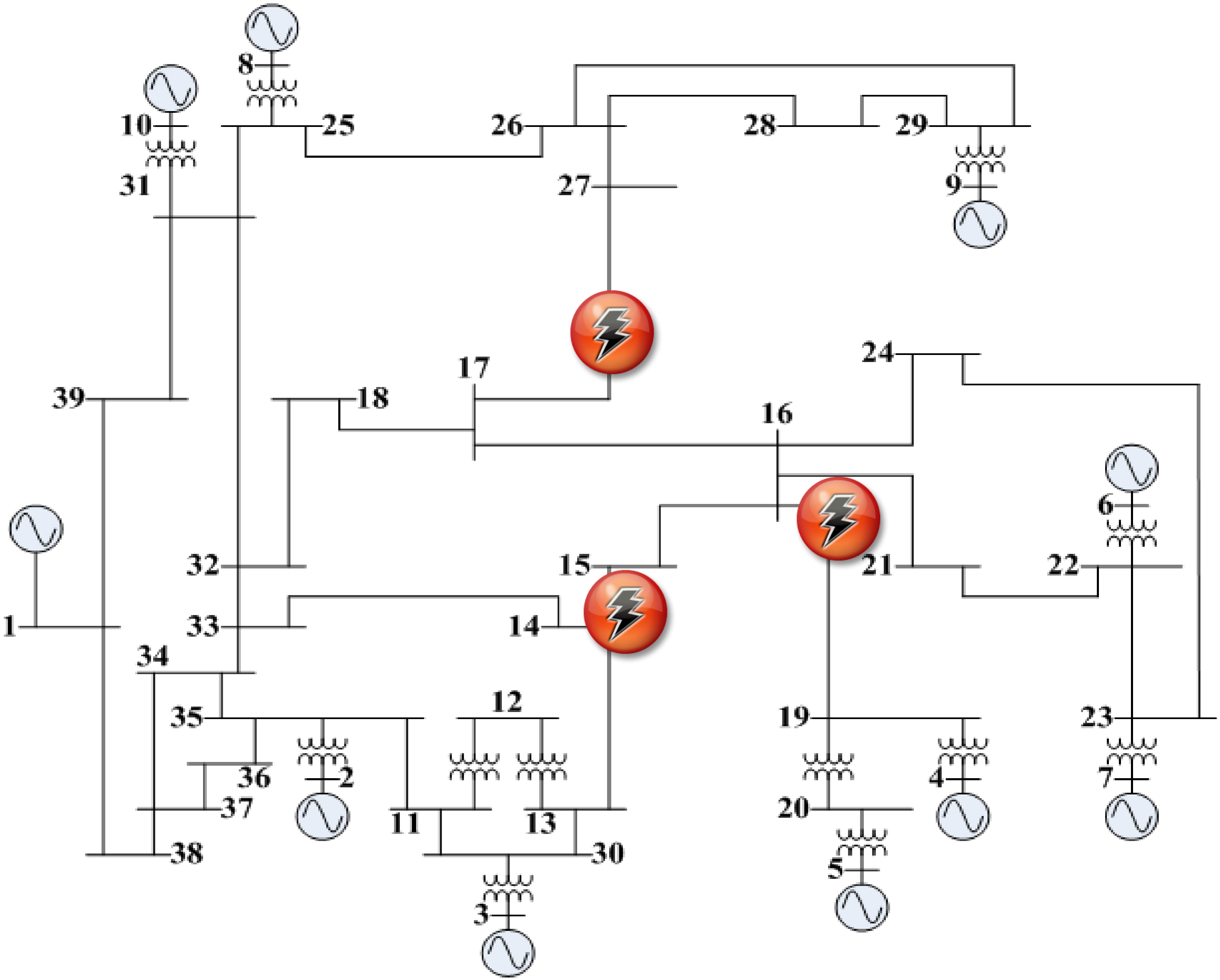
Transient Stability Controller Goal

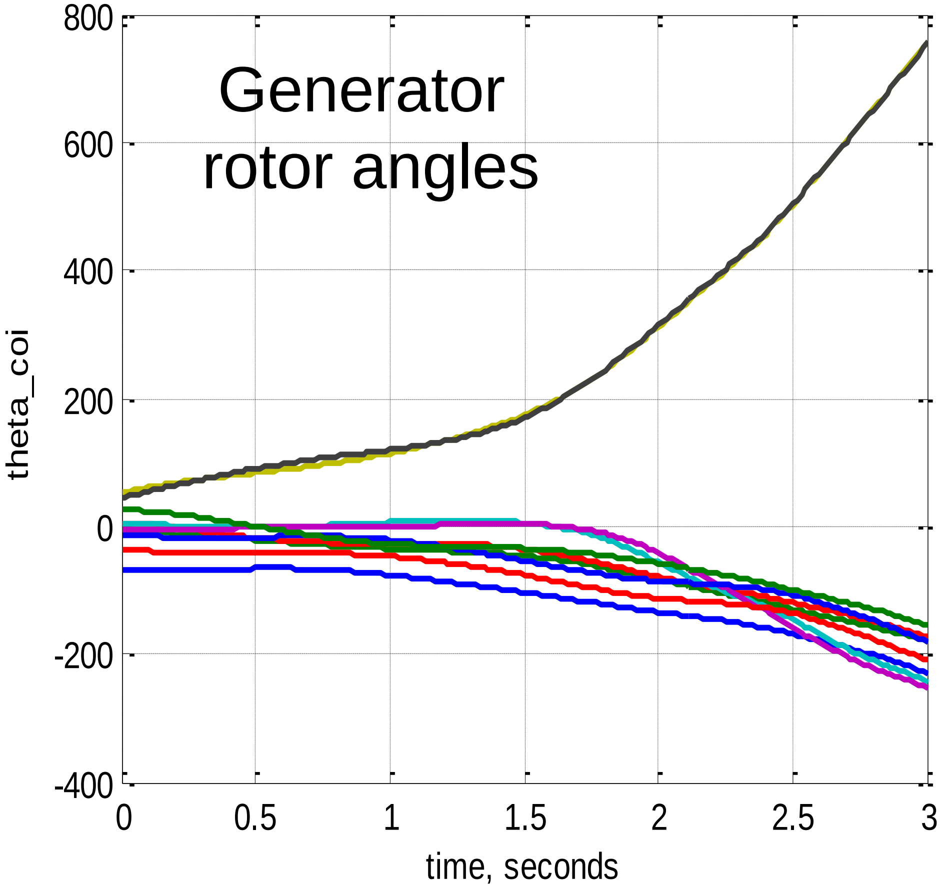
After large contingencies, effect recovery to stable operating point through rapid and minimal system changes, while also keeping the system within specified constraints on

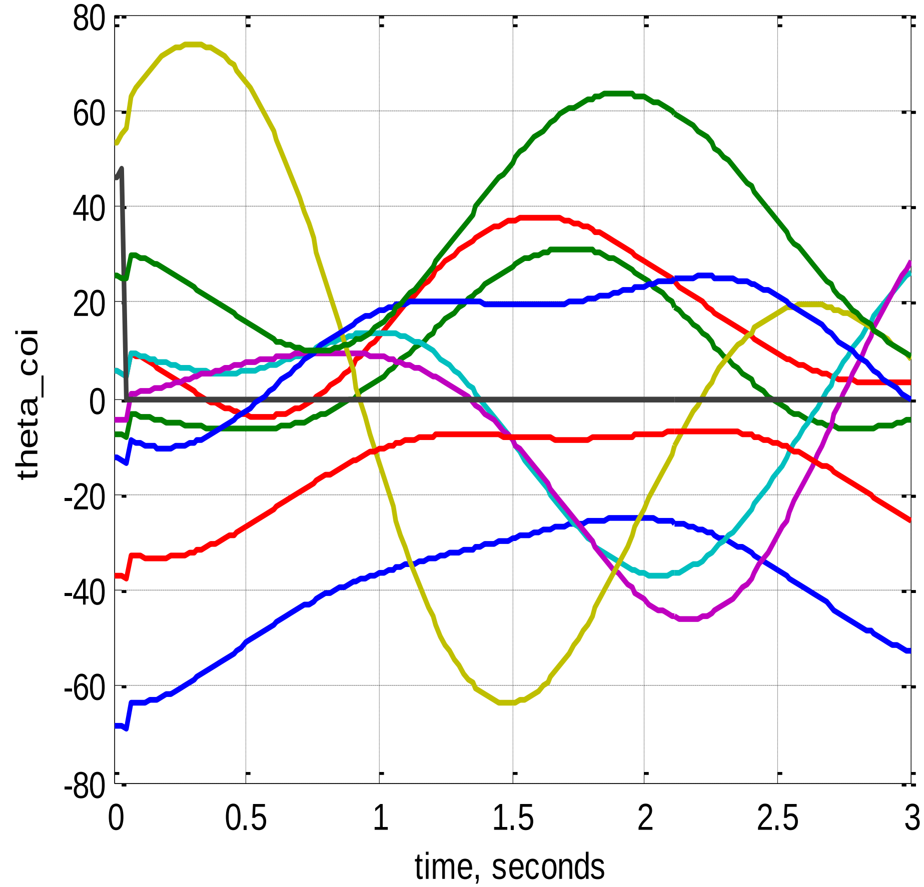
- **acceptable voltage deviations and**
- **acceptable frequency fluctuations.**

Triple Line - Faults and Cleared



Iteration 1 Prediction Sequences





No controls

State Cost = 0.08

Control Cost = 2

Total Cost = 0.16

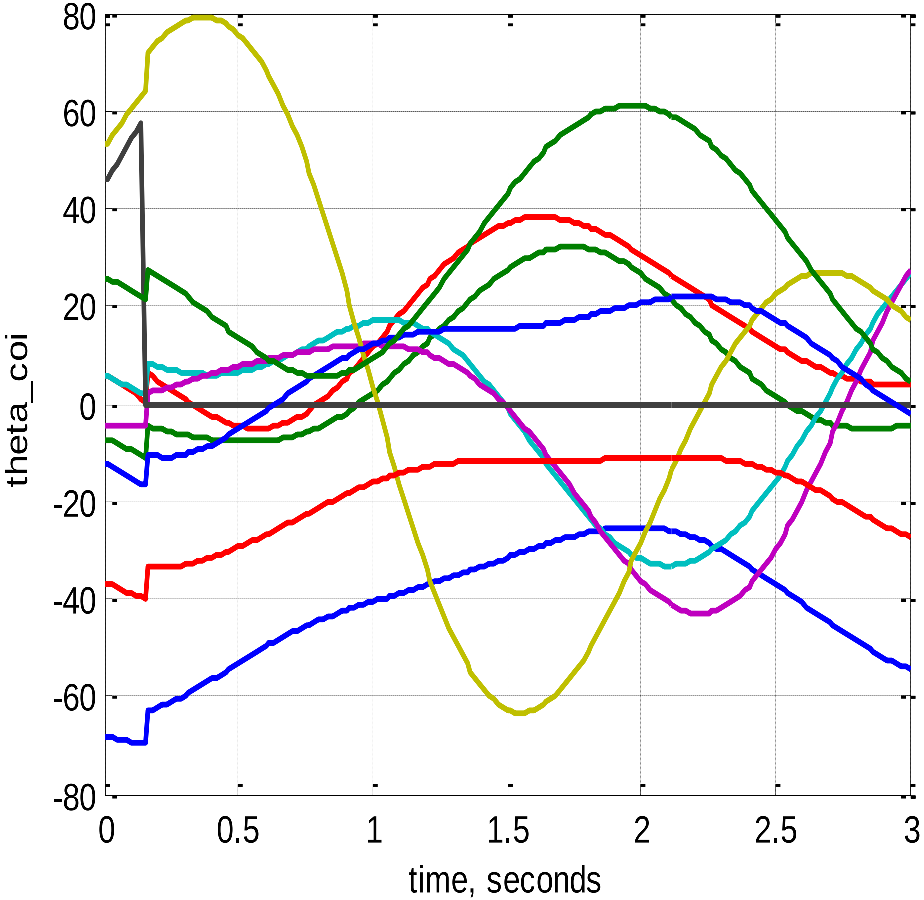
Trip G7, then no control

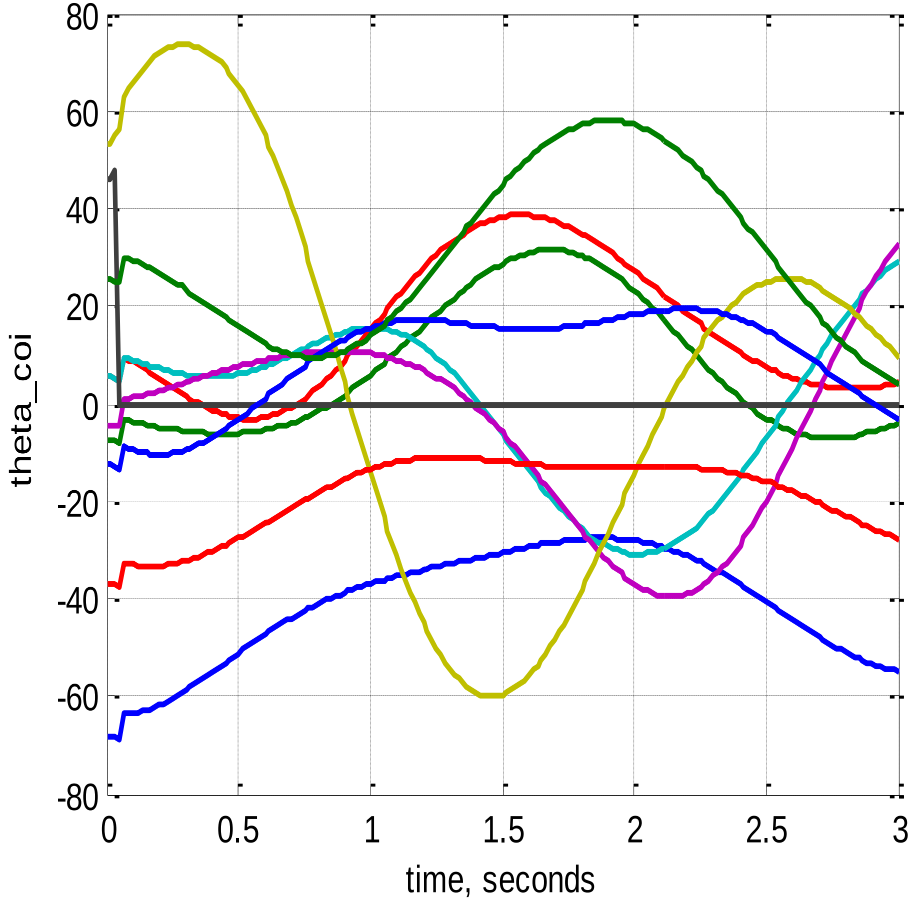
State Cost = 0.007

Control Cost = 3

Total Cost = 0.021

Iteration 1 Prediction Sequences





<u>Comp 31-32, then trip G7</u>

State Cost = 0.007

Control Cost = 4

Total Cost = 0.28

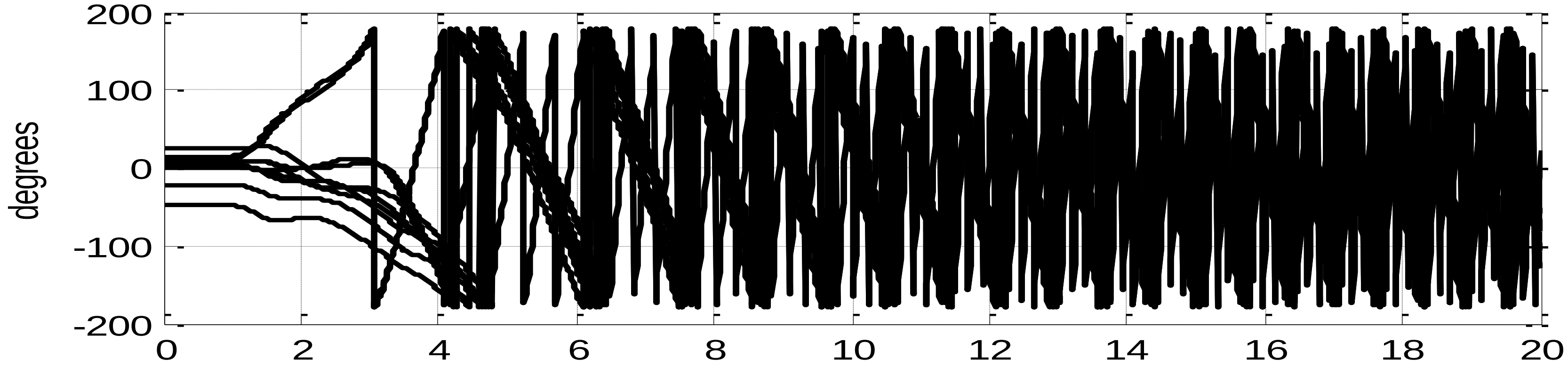
<u>Trip G7, then comp 31-32</u>

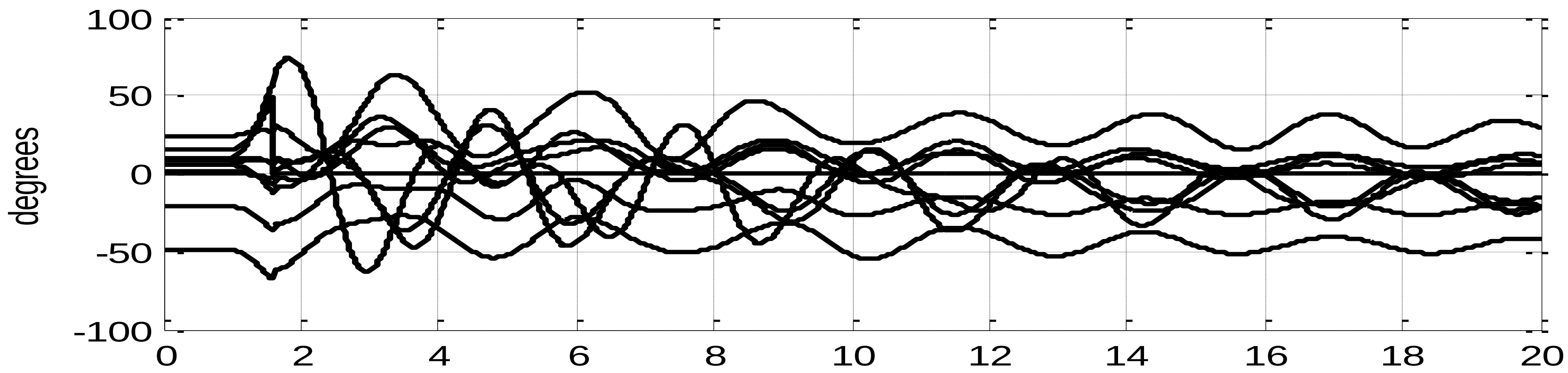
State Cost = 0.006

Control Cost = 4

Total Cost = 0.024

Machine Angles Before and After Control





Future Work

- This project focused on control designs for future power systems
- **How to get to the future?**
- Transition road map needed
- Control designs with combination of SCADA and PMUs
- Control designs with increasing availability of fast communication networks
- Road from here to the future needs to be planned out
- Implementations in phases
- Start working with utilities on actual designs and implementations

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Publications

- V. Venkatasubramanian, H. Chun, J. Guerrero, F.Habibi-Ashrafi, and A. Salazar. *Hierarchical two-level voltage controller for Southern California Edison*. Proceedings of IEEE PES General Power Meeting, San Diego, CA, July 2012.

- G. Zweigle, and V. Venkatasubramanian. *Model Prediction Based Transient Stability Control*. Proceedings of IEEE PES Transmission and Distribution Conference and Exposition, Orlando, FL, May 2012.

- G. Zweigle, and V. Venkaatsubramanian, *Wide-area Optimal Control of Electric Power Systems with Application to Transient Stability for Higher Order Contingencies,* IEEE Transactions on Power Systems, to appear.

Integrating Transmission and Distribution Engineering Eventualities

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Accomplishment: Analysis of advantages and disadvantages of selected innovative transmission technologies

- **HVDC multiterminal systems** and application in the WECC system (making the Pacific DC Intertie a three terminal system)
- **HVDC meshed networks** and application in Southern California – Mexico – Arizona (alleviating stress in the adjacent 500 kV system, and effectuating a tie with CFE-Mexico)
- **Integration of HTLS** and **compact phase overhead transmission** in the contemporary AC system – with examples
- **Six phase overhead transmission** systems, and the integration of those circuits into the existing three phase AC network

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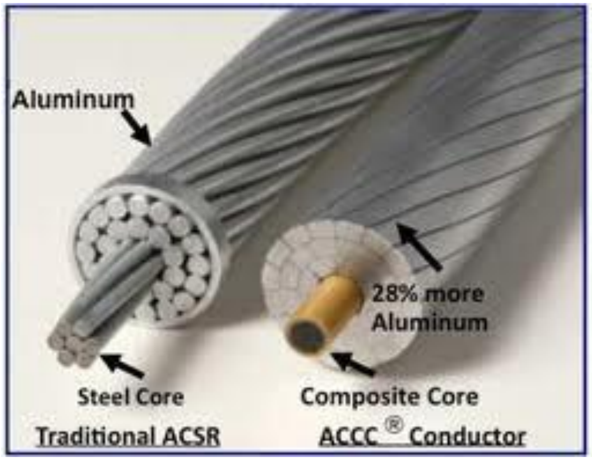
High Temperature Low Sag Conductors

- Advantages
  - Increased current carrying capabilities (~2x typical conductor)
  - Construction advantages (e.g., no new tower design, short reconductoring time)
  - Less sag
  - Higher power handling capacity
  - No increase in right of way width
- Disadvantages
  - Expensive
  - Less experience with this conductor
  - If operated at higher currents, greater I2R losses



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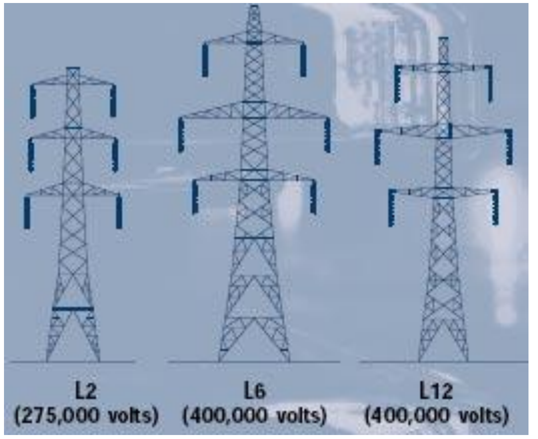
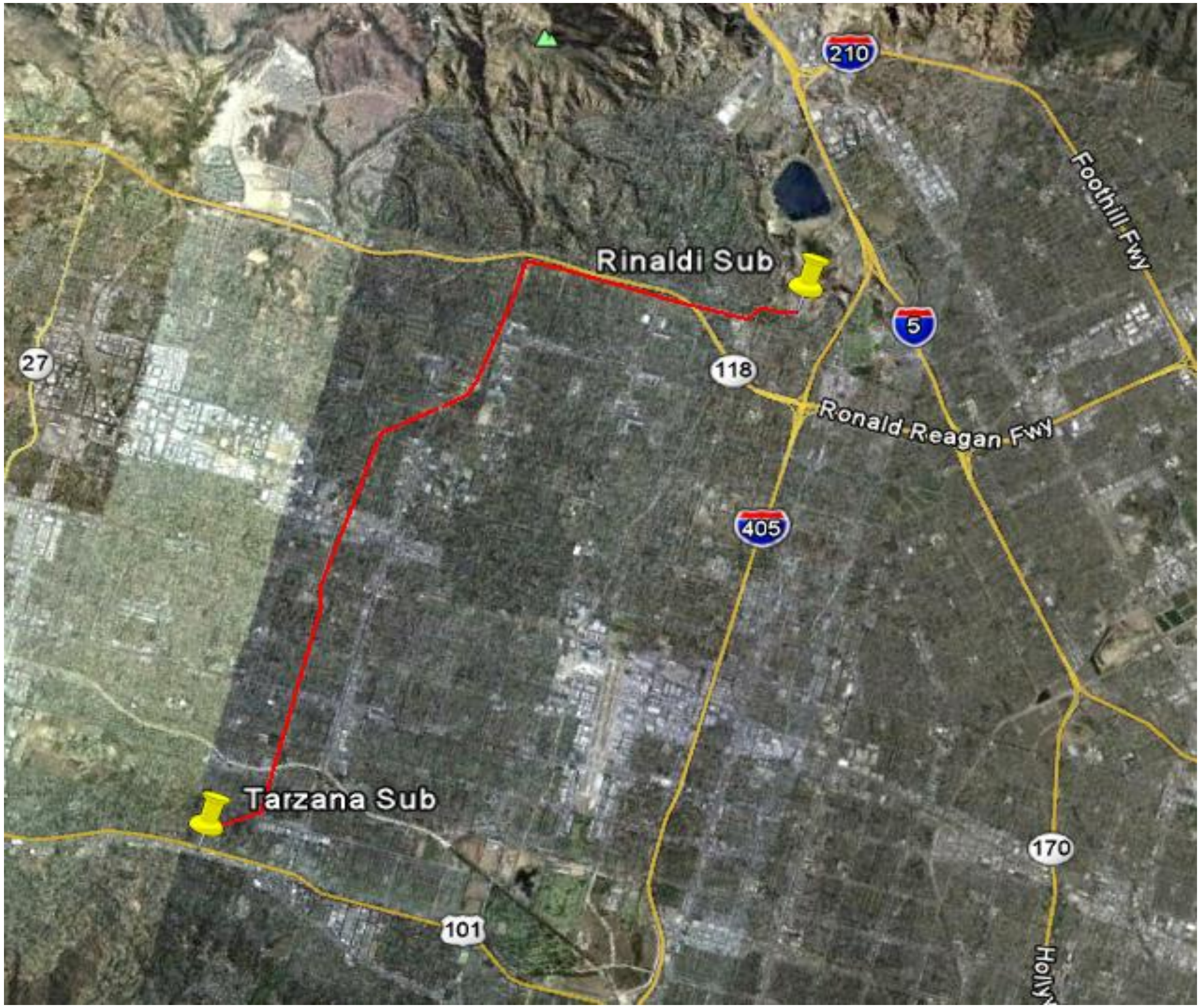
Compact Designs:
Reducing the distance between phases

- Advantages
  - Increases mutual coupling thus decreasing positive sequence reactance ($X^{+} = X_s - X_m$)
  - Increases power flow on the line
  - Decreased ROW and tower size
- Disadvantages
  - Worse lightning protection (BIL)
  - Decreased safety in live line maintenance
  - Must comply with NESC standards – and possibly local or state standards



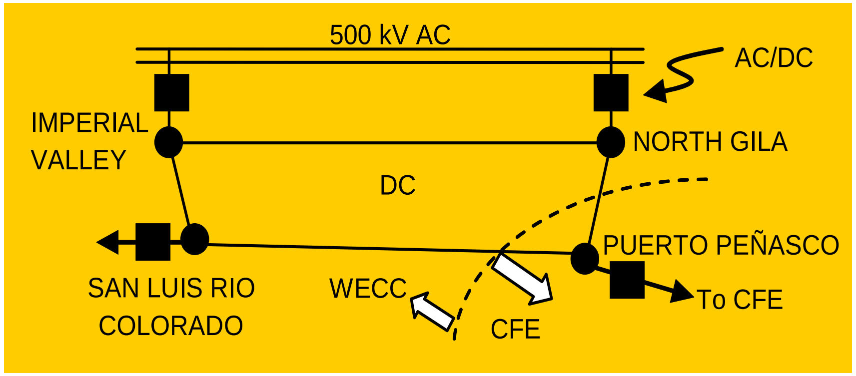
Example: Reconductoring Rinaldi-Tarzana 230 kV with HTLS



- A short line, ~18 miles
- Typical HTLS reconductoring
- Long term thermal limit improved
- Security limit not impacted
- Voltage limit not impacted
- Limitations imposed by the loading of adjacent circuits and components at Tarzana

Relieves a WECC critical path.
Losses increase under heavy loading.

Example: A HVDC Meshed Network in Southern California – Arizona - Mexico



A comparison of simulation results for two illustrative implementations of HVDC transmission

*To retain all lines in thermal and security limits

Case considered	Location of increased loading	Permissible increase in base case loading MW *
WECC system base case with no added HVDC	Imperial Valley and San Luis Rio Colorado	992
Same with added meshed HVDC	Imperial Valley and San Luis Rio Colorado	3350

Meshed HVDC illustration in the WECC system

* Maximum for the indicated conductor

Converter stations				
Station	Interconnection Region	Technology	Voltage Rating	Control type
North Gila, AZ	WECC	VSC	±500 kV	Current
Imperial Valley, CA	WECC			Voltage
San Luís RC, Sonora	WECC			Current
Puerto Peñaso, Sonora	CFE			Current

HVDC transmission		
Length (km)	North Gila – Imperial Valley	Imperial Valley – San Luis RC
	114	96
	San Luis RC – Puerto Peñasco	Puerto Peñasco – North Gila
	170	181
Conductor	Falcon (1590 kcmil)	
Configuration	2 lines	
Conductor/ pole	2	
Voltage rating	± 500 kV	
Power rating*	2.63 GW	

Utilization of a current controlled HVDC system at the US-Mexico border to: parallel 500 kV critical circuits; asynchronously connect CFE-Mexico to the US and also CFE-Sonora to CFE-Baja California. Enhances security of the southwest AC grid.

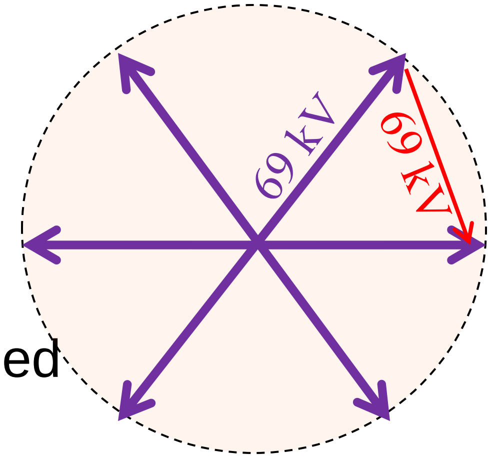
Innovative Concepts for Bulk Power Transmission

Objectives for innovative grid technology development

- Minimize cost
- Maximize conductor and insulating systems in overhead and underground transmission
- Maximize space utilization
- Maximize use of investment in transmission assets / designing a favorable cost-benefit ratio
- Permit solutions to transmission problems that have few viable alternatives
- Alleviate critical transmission paths
- Design new asynchronous connections for specialized applications
- Note: New applications arise from new materials (e.g., dielectrics, insulators), advances in power electronics and other technology developments

Innovative Concepts for Transmission Systems

(1) High phase order cables



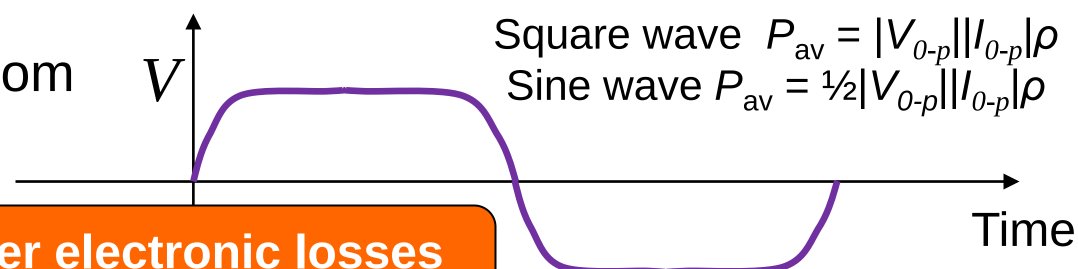
In a six phase system, line-neutral and line-line voltage magnitudes are the same. Cable systems can be designed with less dielectric stress

- Lower line-line voltage
- High power transmission
- Low electromagnetic impact
- In higher phase order systems, some of these advantages are magnified
- Higher reliability (single pole out)
- Potentially narrower ROW, trenches and conduits

Challenges: protection, innovative interfaces to the three phase system, loss of phase operation, innovative cable designs

(2) Nonsinusoidal waveform applications

- Utilize dielectric / insulation systems maximally (not like a sine wave)
- Utilizes the conductor ampacity more fully
- Can be generated electronically – we already have the electronic interface in many cases
- Low frequency outlet feeders from wind farms and PV generation



Square wave $P_{av} = |V_{0\text{-}p}||I_{0\text{-}p}|\rho$

Sine wave $P_{av} = ½|V_{0\text{-}p}||I_{0\text{-}p}|\rho$

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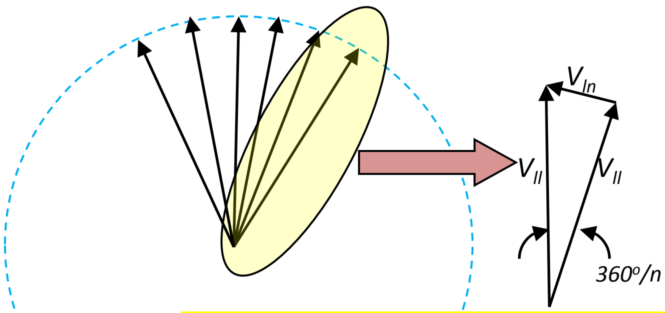
Challenges: mitigate power electronic losses and cost, lower RFI

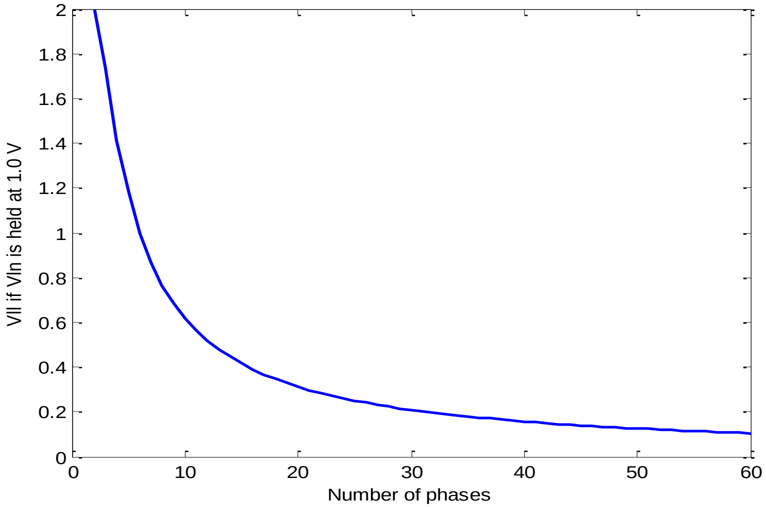
Innovative Concepts for Transmission Systems

(3) High phase order, compact phase designs for overhead and cable transmission

Low phase to phase voltages which can be combined with phase compaction to give high power capacity for a given spatial occupancy (*cables* or *overhead*)



$$|V_{ll}| = \sqrt{2(1-\cos(360/n))}\,|V_{ln}|$$



- Potential for operation under loss of a phase
- Low electromagnetic impact
- Maximal use of space
- "Positive sequence" impedance of the cable can be simply calculated using Toeplitz matrices. AC calculations simplified analogous to symmetrical component calculations.

Challenges: interface with the three phase system

(4) Integrated – innovative technologies for bulk power applications

- Combine several innovative technologies to obtain enhanced transmission characteristics
- AC and DC subsystems to obtain benefits of both
- Realize asynchronous interconnections at high power levels
- Permit islanding and connection of North American interconnections

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For More Information

- Pierre, B. J.; G. T. Heydt. *Increased Ratings of Overhead Transmission Circuits Using HTLS and Compact Designs*. Proceedings of North American Power Symposium, Champaign, IL, September 2012.
- Salloum, A.; G. T. Heydt. *Innovative HVDC Connections in Power Transmission Systems*. Proceedings of the IEEE PES Transmission and Distribution Engineering Conference and Exposition, Orlando, FL, May 7-10, 2012.

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National Transmission Overlay: Design Process

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Research Objectives and Accomplishments

- Design a U.S. interregional transmission overlay to facilitate the growth of wind, solar, nuclear, geothermal, and clean-coal generation over the next 40 years.
- Develop an associated design process and necessary tools

Motivation

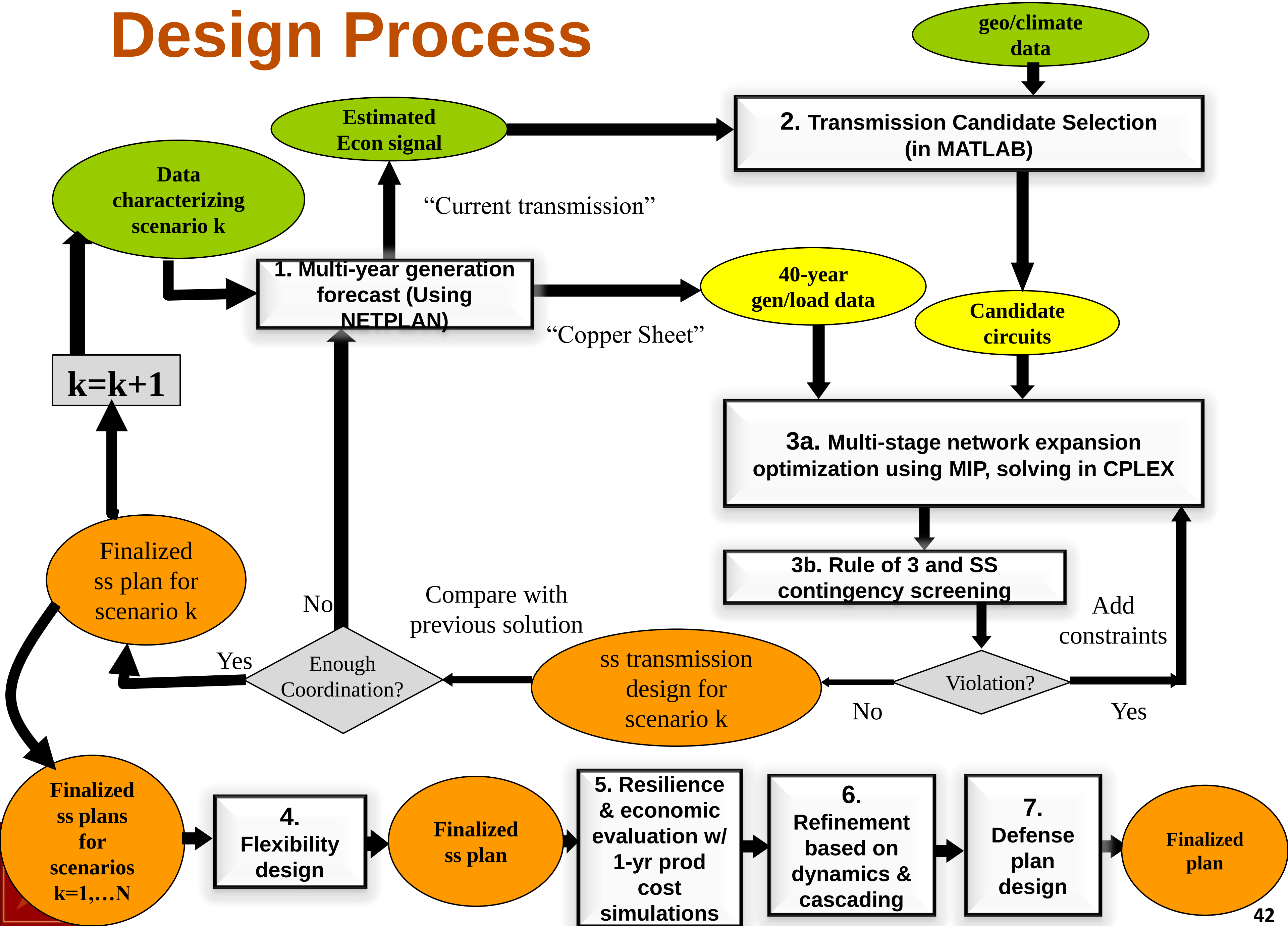
High-capacity interregional transmission is mainly motivated by high-renewable penetration because…

- Locational dependence.
- Renewable energy can be moved only by electric transmission.
- Transmission costs comprise a relatively small percent of long-term power system cost.

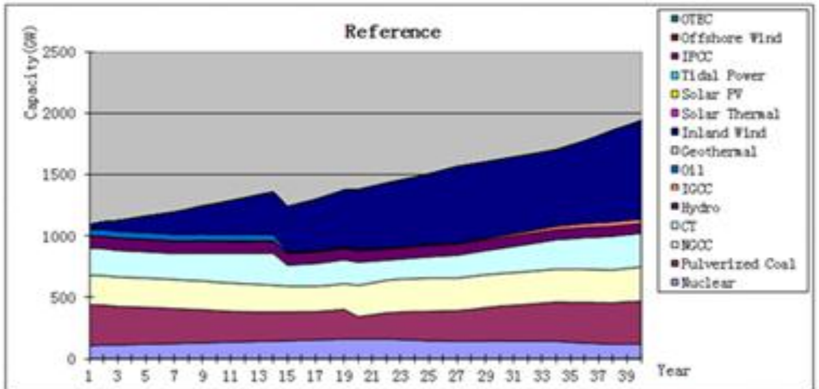
A white paper last year indicated potential benefits; further investigation was warranted.

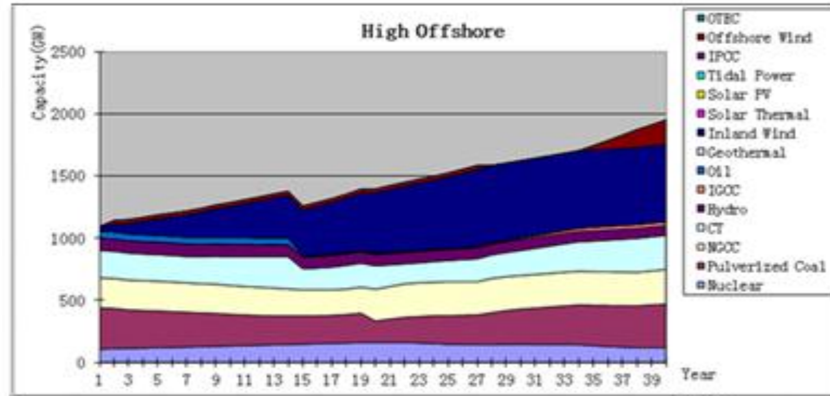
See "Transmission Design at the National Level: Benefits, Risks and Possible Paths Forward,"
http://pserc.org/research/FutureGrid/broadanalysis/GridEnablers.aspx

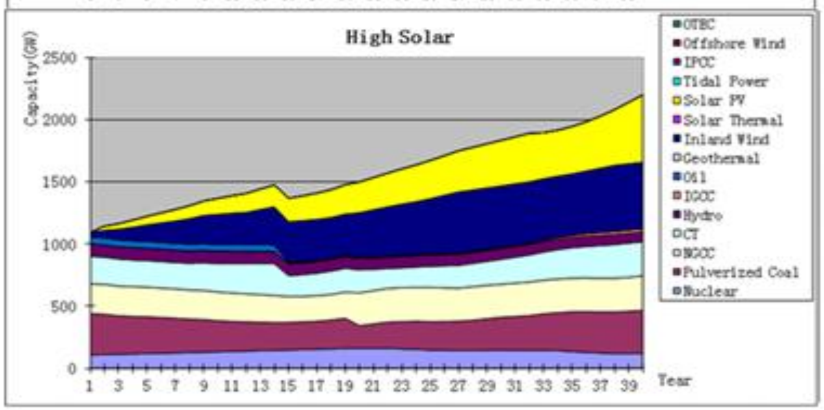
Design Process

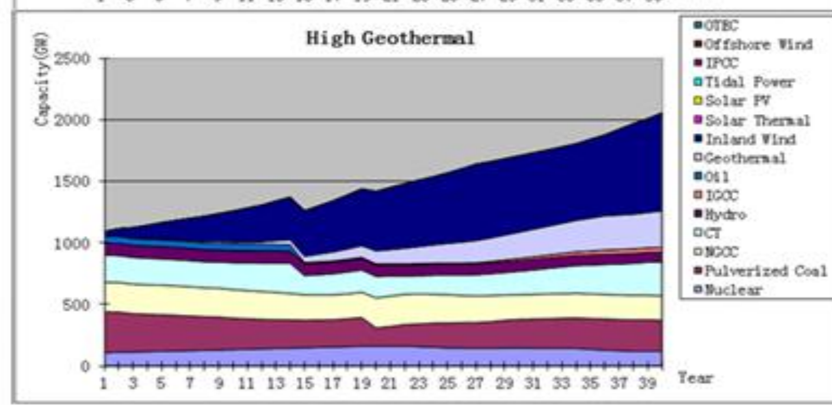


Results of Step 1: Scenarios 1-4

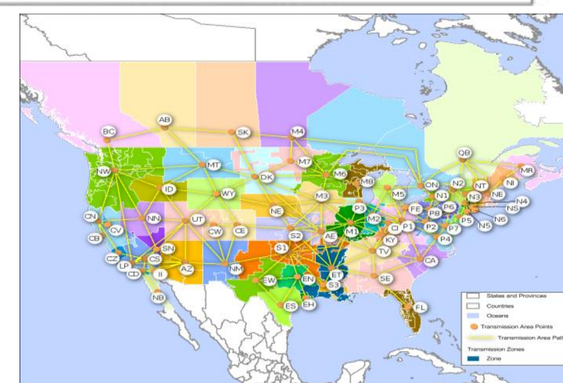








- **National dataset: 62 nodes each with right mix of existing gen technologies, existing interregional transmission modeled.**
  - **Location-specific gen investment costs & capacity factors**
    - **15 mature or developing generation technologies**



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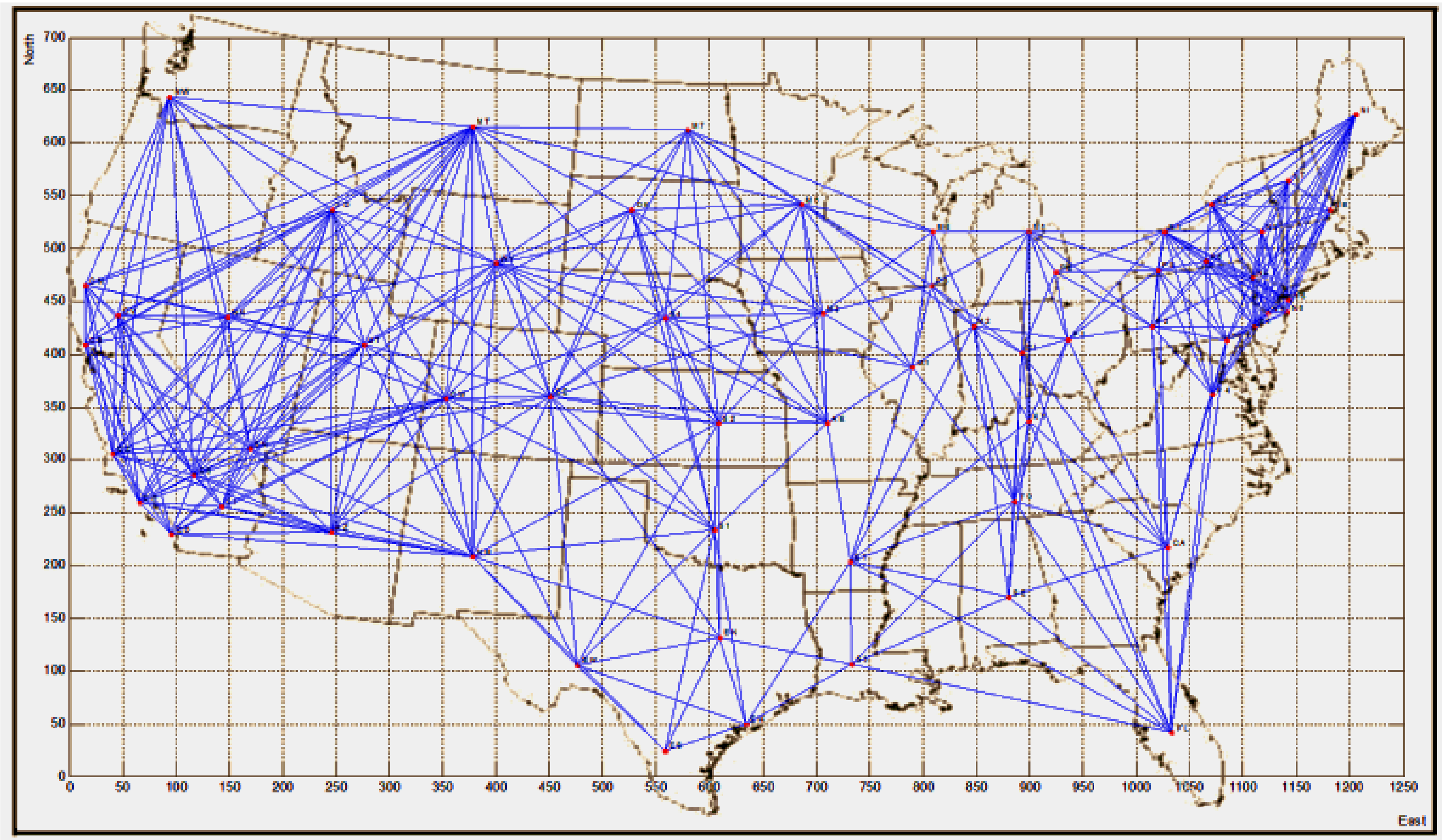
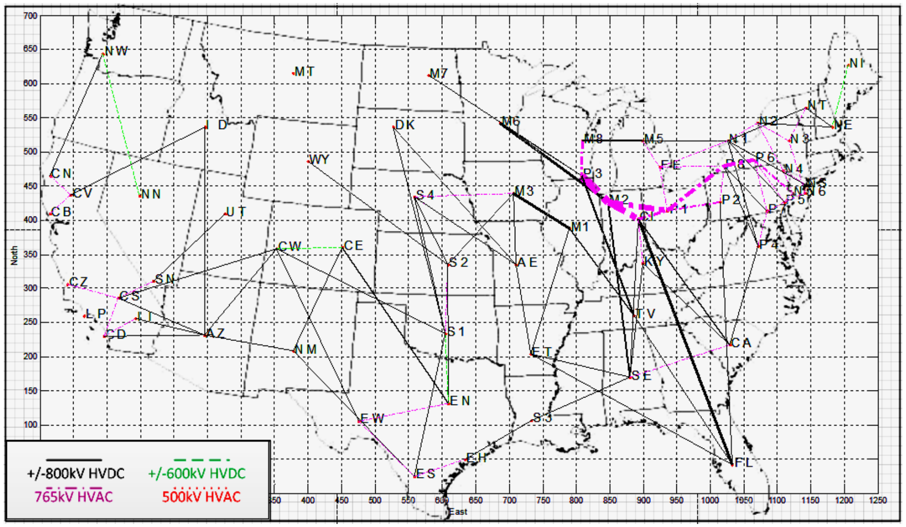
Results of Step 2: 371 Transmission Circuit Candidates

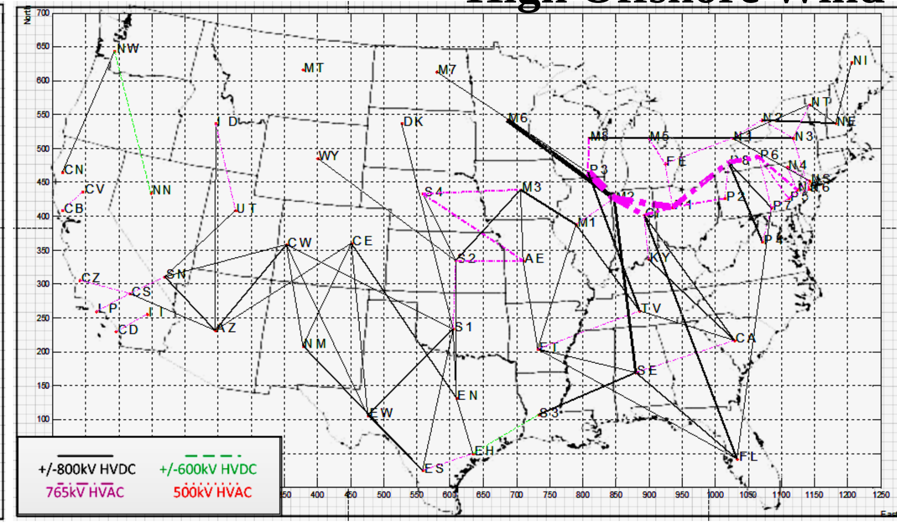


Results of Step 3a: Optimal Designs-Four Scenarios

Reference Case

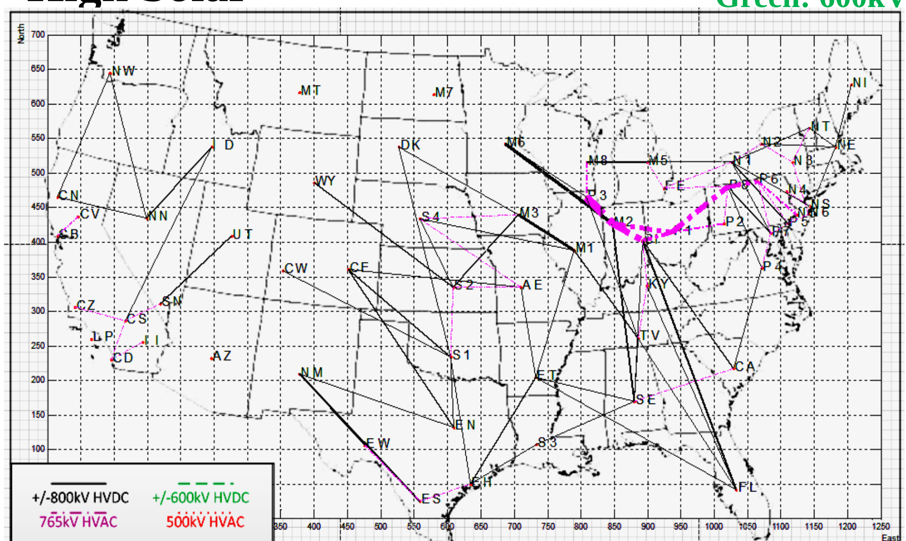


High Offshore Wind

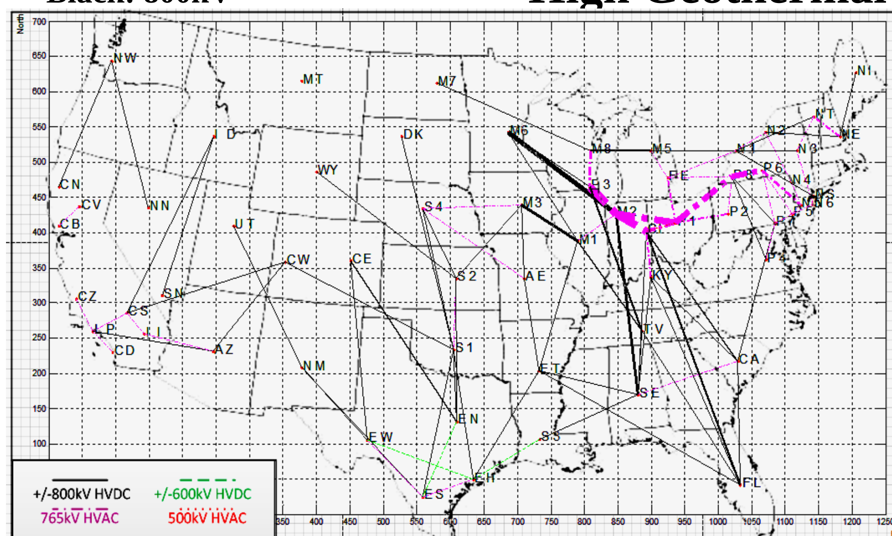


Red: 500kV
Green: 600kV
Purple: 765kV
Black: 800kV

High Solar



High Geothermal



Results of Step 3a: Top 34 Capacity Investments for Reference Case

101 paths received capacity expansion.

M1-M8: MISO
P1-P8: PJM
CI: Central Indiana
N1-N3: New York
NW: Northwest
NN,SN: N., S. Nevada
S1-S4: SPP
EN, EW, ES: Ercot N, W, S
EH: Ercot southeast
NE: New England
SE: Southeast
CE, CW: Colorado E, W
FL: Florida
TV: TVA
NT, NI, NS: Northeast
ET: Entergy
CA: Carolina
NM: New Mexico

Year invested	Tchnlgy	Arc #	# of Lines	From	To	Distance	Cpcty per Line (GW)	Cpcty (GW)	Cost per Line (2010 $M)	Total Cost (2010 $M)
15	765kV	287	19	P3	M2	183	3.00	57.0	847.56	16103.64
15	765kV	329	10	P8	P6	204	2.79	27.9	787.75	7877.52
15	765kV	277	10	P1	P8	185	2.98	29.8	712.07	7120.72
15	765kV	164	10	M2	CI	112	4.17	41.6	462.24	4622.48
20	765kV	287	9	P3	M2	183	3.00	27.0	847.56	7628.04
20	765kV	167	7	M2	P1	176	3.08	21.5	674.99	4724.95
20	765kV	194	6	M8	P3	100	4.49	26.9	398.73	2392.38
15	765kV	311	5	P6	N5	106	4.32	21.6	524.30	2621.50
6	+/-600kV	266	1	NW	NN	403	3	3	2012.80	2012.80
11	+/-600kV	332	1	S1	EN	237	3	3	1450.59	1450.60
11	+/-600kV	237	1	NI	NE	223	3	3	1855.95	1855.96
15	+/-600kV	343	1	S3	SE	472	3	3	2240.51	2240.51
16	+/-600kV	77	1	CW	CE	243	3	3	1816.02	1816.02
20	+/-800kV	170	3	M3	M1	339	6	18	2802.41	8407.26
15	+/-800kV	338	2	S2	M3	492	6	12	3277.38	6554.76
15	+/-800kV	123	2	FL	CI	949	6	12	5106.23	10212.46
20	+/-800kV	163	2	M1	TV	338	6	12	2858.95	5717.89
22	+/-800kV	182	2	M6	M2	610	6	12	3960.77	7921.55
36	+/-800kV	182	2	M6	M2	610	6	12	3960.77	7921.55
3	+/-800kV	206	1	N1	NT	385	6	6	3207.82	3207.82
5	+/-800kV	109	1	ET	FL	779	6	6	4625.83	4625.83
8	+/-800kV	102	1	EH	S3	384	6	6	2946.72	2946.73
8	+/-800kV	35	1	CE	EN	791	6	6	4276.71	4276.71
9	+/-800kV	44	1	CI	CA	512	6	6	3779.43	3779.43
10	+/-800kV	356	1	SE	M2	589	6	6	3930.82	3930.82
10	+/-800kV	193	1	M8	M5	370	6	6	2997.16	2997.16
10	+/-800kV	176	1	M5	N1	259	6	6	2661.48	2661.48
11	+/-800kV	193	1	M8	M5	370	6	6	2997.16	2997.18
11	+/-800kV	14	1	CA	P4	371	6	6	3217.28	3217.28
12	+/-800kV	324	1	P7	P8	245	6	6	2790.90	2790.90
12	+/-800kV	35	1	CE	EN	791	6	6	4276.71	4276.71
13	+/-800kV	356	1	SE	M2	589	6	6	3930.82	3930.82
13	+/-800kV	289	1	P3	TV	598	6	6	3661.67	3661.67
13	+/-800kV	238	1	NM	CE	447	6	6	3169.20	3169.20

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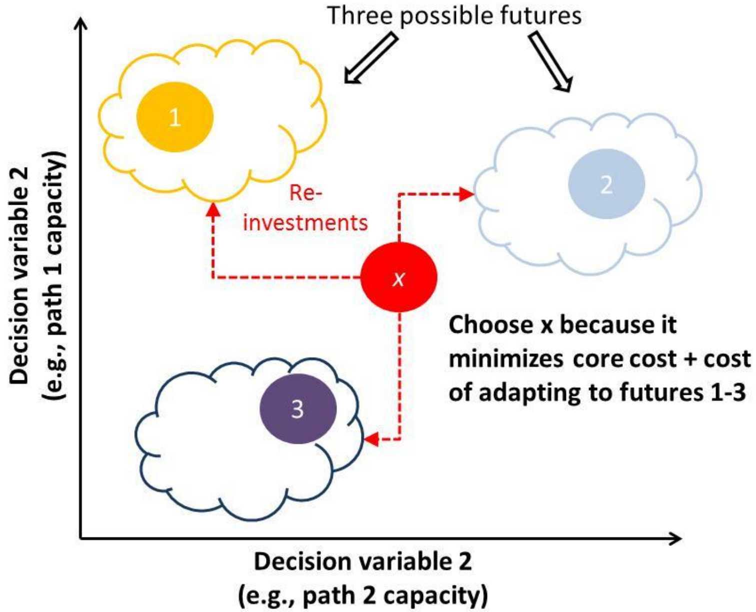
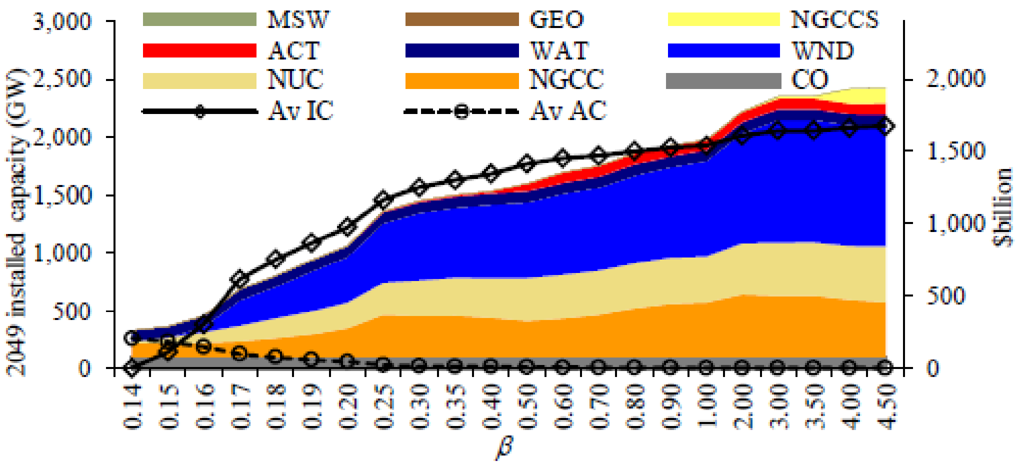
Tool for Step 4: Flexibility Design





Identifies an investment that is "core" in that the total "CoreCost" plus the cost of adapting it to the set of envisioned futures is minimum.

Minimize:

CoreCosts($\underline{x}^f$)+β[Σ_i AdaptationCost($\Delta\underline{x}_i$)]

Subject to:

Constraints for scenario i=1,…N: $\underline{g}_i(\underline{x}^f+\Delta\underline{x}_i)\leq\underline{b}_i$

$\underline{\mathbf{x}}^f$: Investments common to all scenarios i

$\Delta\underline{\mathbf{x}}_i$: Additional investments needed to adapt to scenario i

Research Benefits

1. Integration of 6 new planning tools
   - **(a) Path selection: an iterative reweighting spanning tree algorithm to identify good candidates for transmission expansion paths based on right of way availability, economic benefit potential, land type, climate and population density, altitude, and isoceraunic conditions**
   - **(b) Transmission optimizer: multi-period, multi-technology T-expansion planning model, implemented as a linear mixed-integer program;**
   - **(c) Dynamics: reachability approach whereby design decisions for frequency dynamics are informed considering uncertainties**
   - **(d) NETPLAN: a generation-transmission expansion planning software modeling interdependencies between electric network, the fuel systems, and the transportation systems (passenger and freight);**
   - **(e) Resilience planning: identifies designs that are resilient to large-scale disturbances (such as the Katrina/Rita hurricanes of 2005);**
   - **(f) Flexibility planning: identifies designs capable of adapting at low cost to future uncertainties.**
2. Inform dialogue on a heavy-transmission future scenario

Potential Uses of Research Results

- Enhance expansion planning processes
  - Interregional planning studies
  - Intra-regional planning studies
- Informs policy development: building transmission is effective and inexpensive
- Raises an important societal question: if economic and environmental benefits are attractive, why do we not do it ?

National Transmission Overlay: Impacts on Power System Dynamics

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Research Objectives and Accomplishments

- How a new transmission overlay can improve the power system dynamics to uncertain scenarios?
  - Focus on “slow” governor dynamics and impacts on average system frequency.
  - Apply a computational technique for reachability analysis to model uncertainty in disturbances and system parameters.
  - Calculate bounds of trajectories of frequency response with EHVAC/HVDC tie-lines.

Benefits and Importance

- Presents the benefits of a national transmission overlay for improving power system dynamics (frequency) under uncertainties.
- Reachability analysis approach for planning decisions based on frequency dynamics.
- Compares the benefits of using HVDC vs. EHVAC for dynamic improvement of the future power system.

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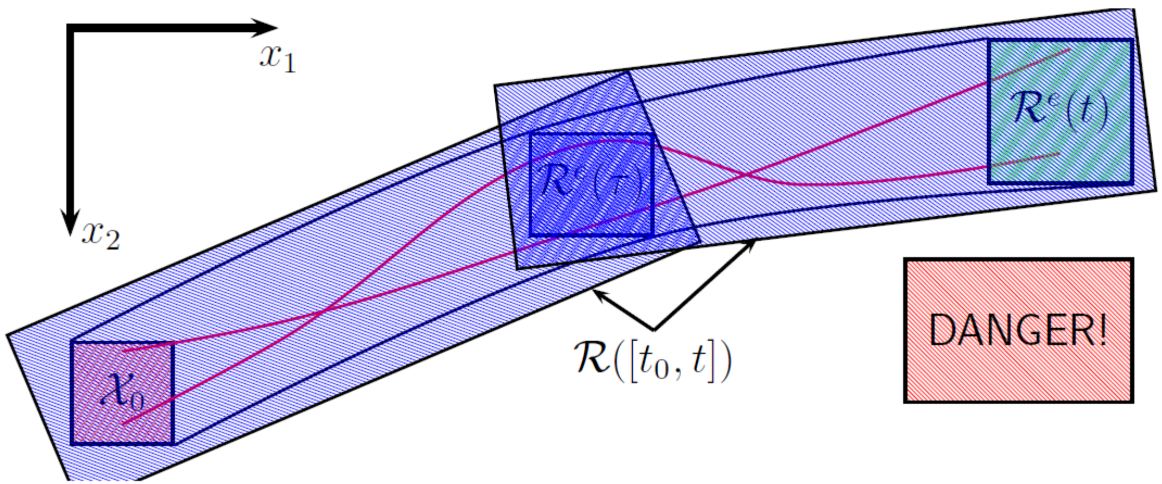
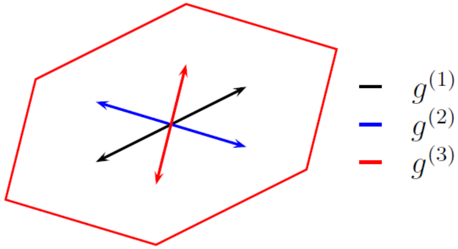
Reachability Analysis

- Reachability analysis yields bounds of solutions to an uncertain dynamic problem.
- Find a set that contains all possible trajectories.
- Run one study, calculating the evolution of the reachable set, and capturing all possible scenarios at once.



- Zonotopes are used to represent sets.



An Example

- Dynamic equation of a single area "governor" dynamics [3].
- Uncertain parameters: inertia h, damping factor d, load-generation unbalance ω^d (disturbance).

$$\frac{d\omega}{dt} = -\frac{1}{2h}\left(d + \frac{k_g f}{r_c}\right)\omega + \frac{1}{2h}p_g - \frac{1}{2h}w^d$$

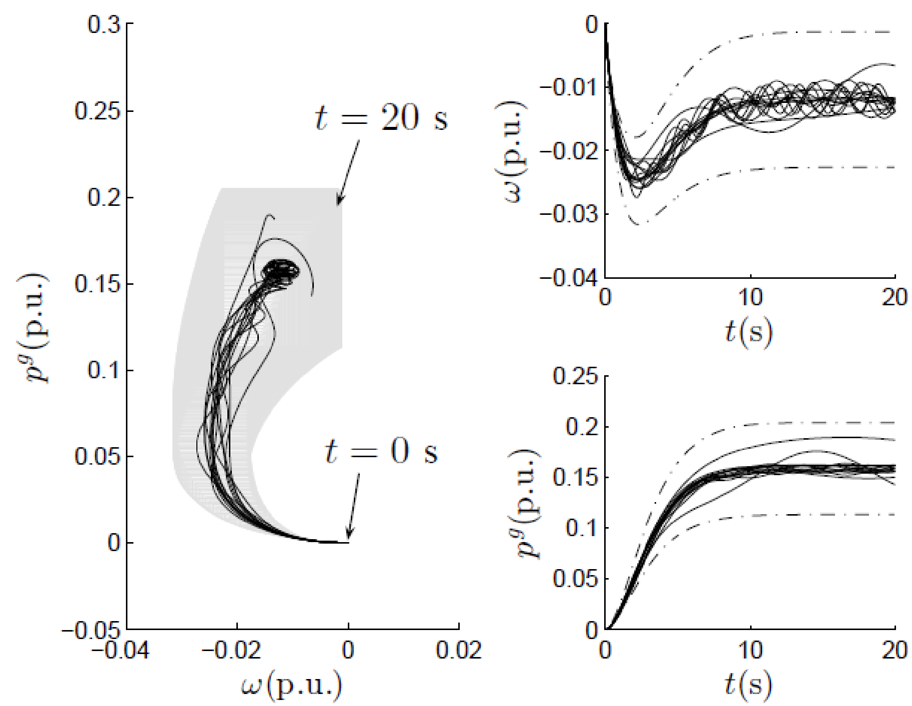
$$\frac{dp^g}{dt} = -\frac{k_g(1-f)}{r_c\tau_g}\omega - \frac{1}{\tau_g}p^g\,,$$

$$h \in \boldsymbol{h} = [3.9, 4.1]$$

$$d \in \boldsymbol{d} = [1.8, 2.2]$$

$$\boldsymbol{w}^d = [0.2, 0.3]$$

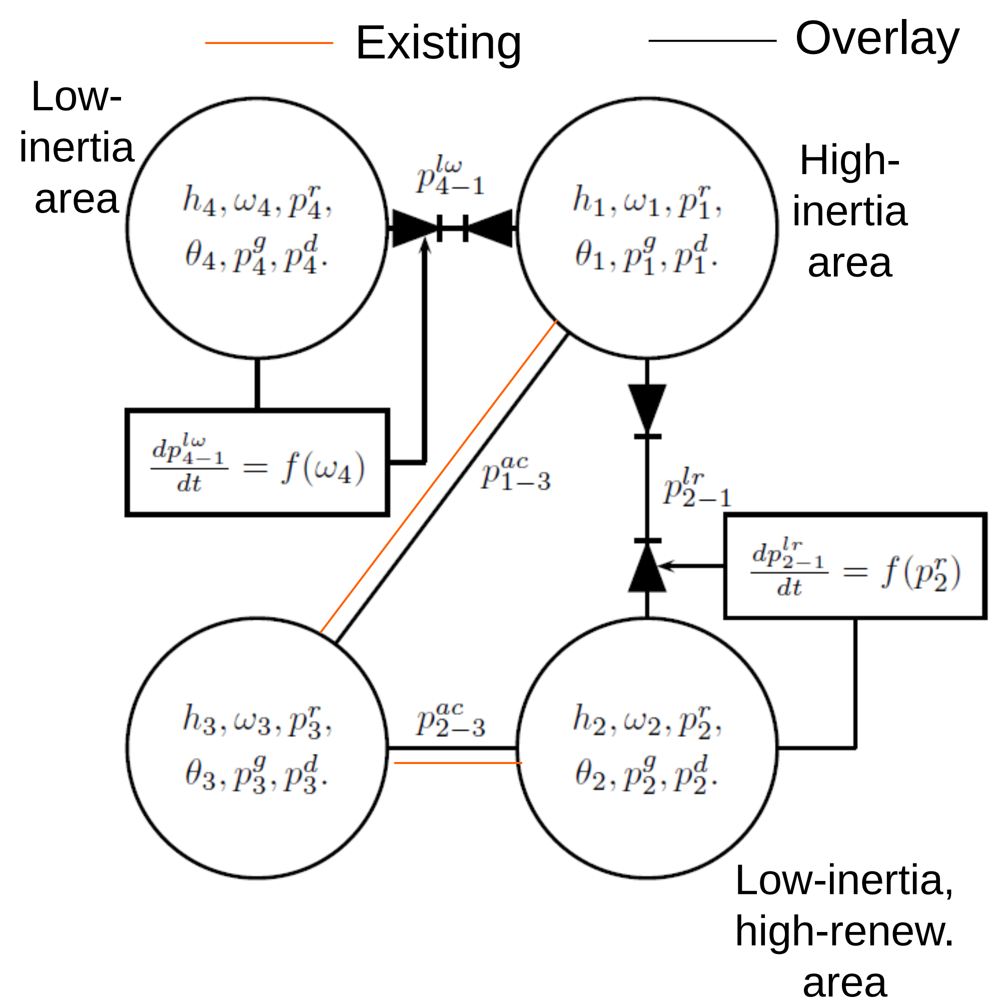
Note that ω^d is time-varying within the prescribed bound.



National Transmission Overlay Model

- High-capacity HVAC improves the connectivity among synchronously connected areas.

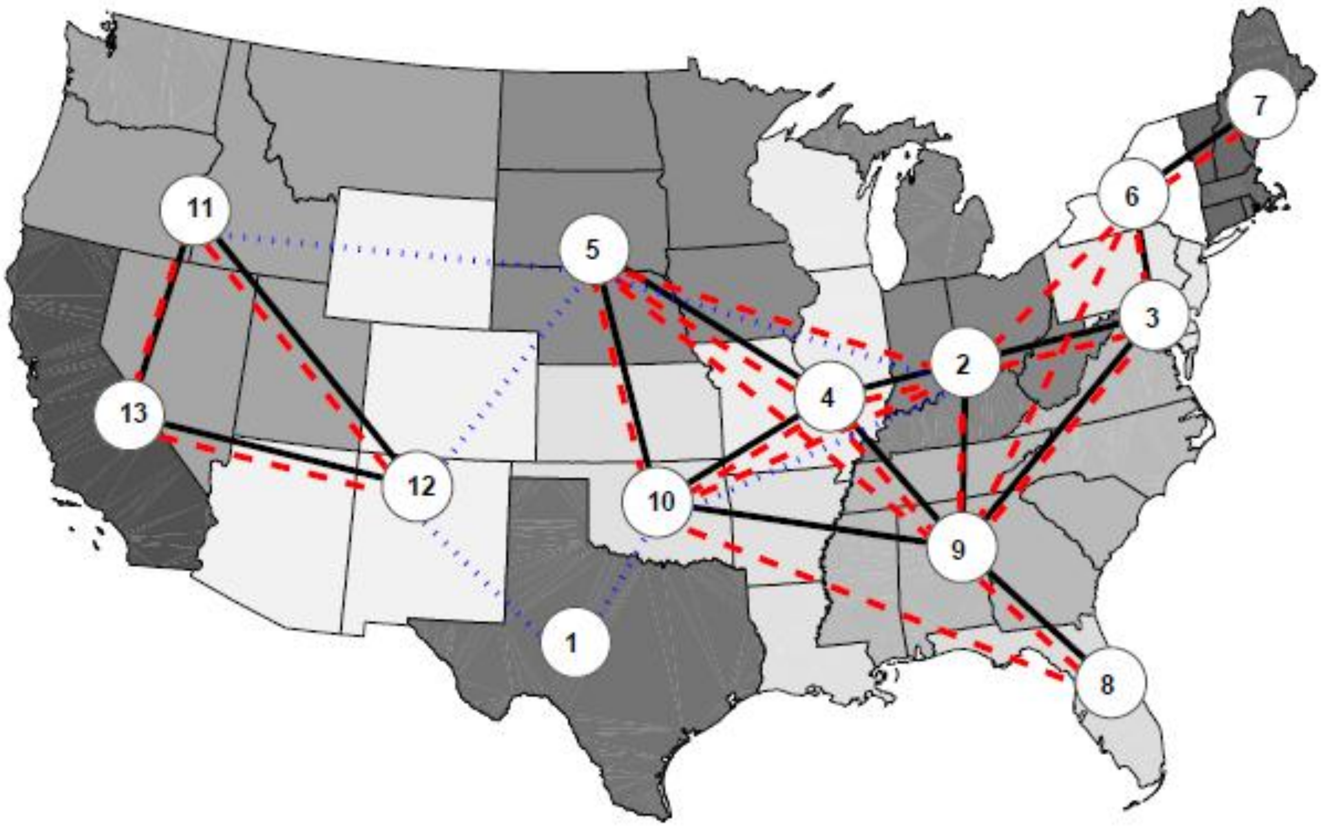
- High-capacity HVDC can be used for frequency regulation:
  - Control law that emulates governor response implemented between asynchronously connected areas (e.g., between areas 1 & 4).
  - Control law that detects variability of renewable generation in one area (e.g., area 2) and transfers to others with high inertia constant (e.g., area 1).



$$\frac{d\omega_i}{dt} = \frac{1}{2h_i}\left(p_i^g + p_i^r - p_i^d - p_i^{ac} + p_i^{dc\omega} + p_i^{dcr}\right)$$

Example: Frequency-Sensitive HVDC

For simplicity, we illustrate the U.S. system modeled by 13 areas.

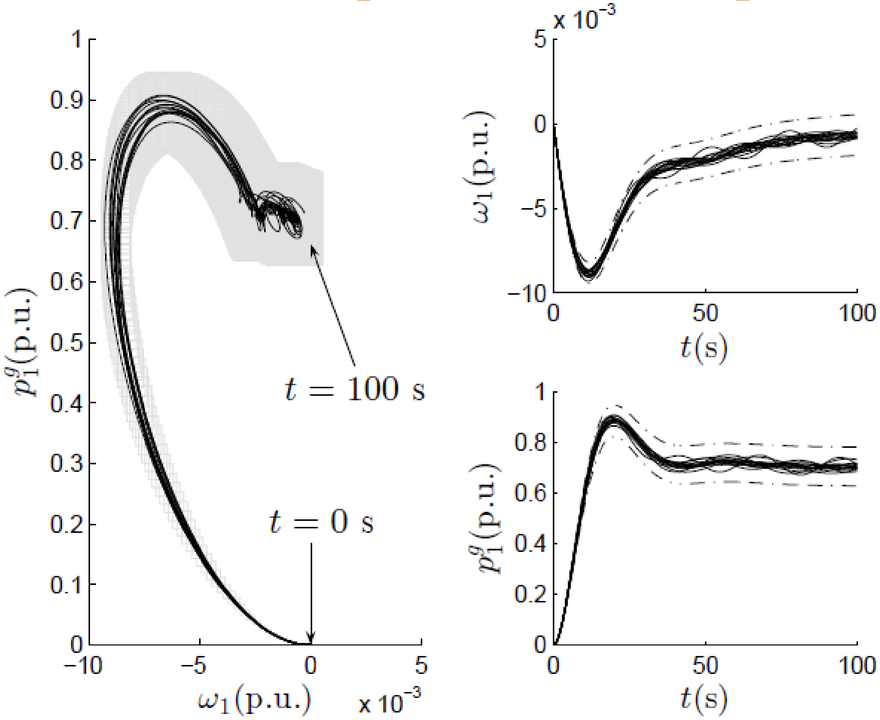


-Areas with high renewable penetration (e.g. 1,5,10,13).

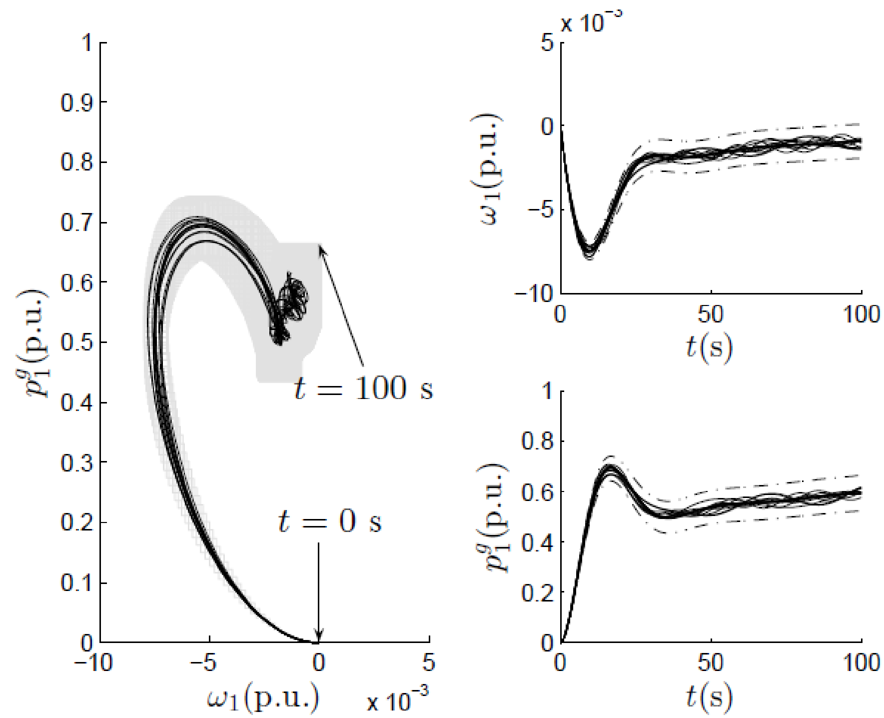
- Areas with high inertia constants (e.g. 2,9).

Simplified U.S. power system areas (not to scale) with across-area transmission capacity (solid) and studied HVAC (dashed) - HVDC (dotted) transmission overlays.

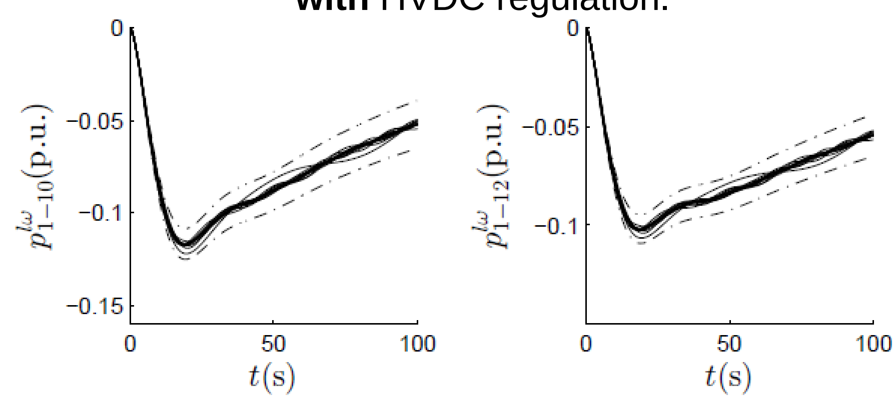
Example: Frequency-Sensitive HVDC



Area-1 frequency response
without HVDC regulation.



Area-1 frequency response
with HVDC regulation.



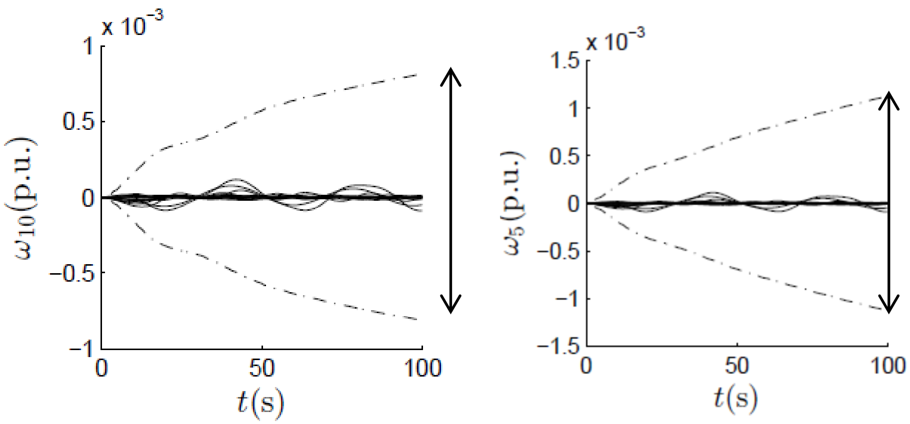
Area-1 HVDC power injections.

Disturbance:

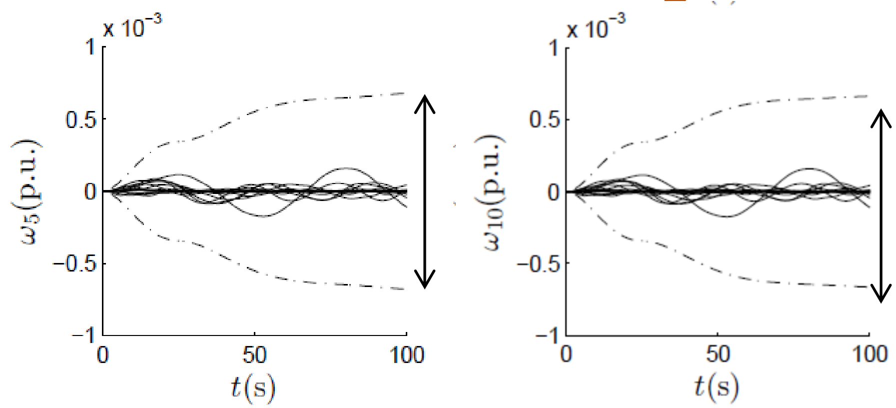
We simulate an uncertain loss of generation in area 1 **without** and **with** support of the other interconnections.

$w_1^d \in [0.65, 0.75]$ p.u., with $S_B = 1000$ MVA and unity power factor.

Example: Renewables Variability



Frequency bounds of areas
without HVAC- HVDC overlay.



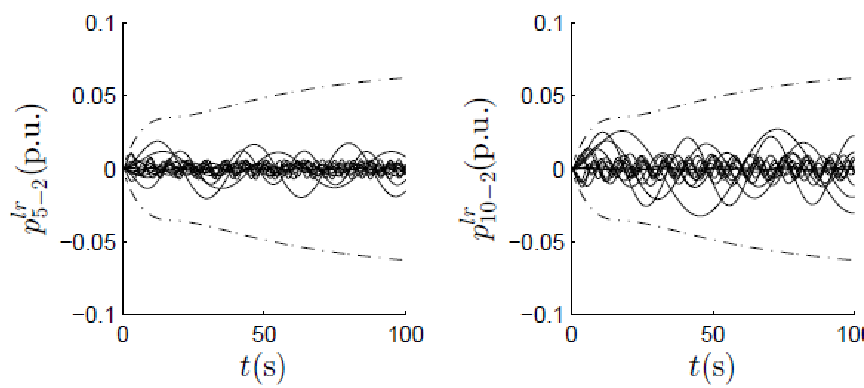
Frequency bounds of areas
with HVAC and HVDC overlay.
(Improved bounds in ω_5 and ω_{10} than HVAC alone)

Disturbance:

We simulate how frequency bounds can be **improved** by adding a HVAC and HVDC overlay that interconnects areas of high renewable penetration with areas of conventional generation.

Uncertainty in renewable-generation power in areas 5 and 10. p_5^r, $p_{10}^r \in [-0.1, 0.1]$ p.u. with $S_B = 1000$ MVA and unity power factor.

HVDC lines are set to transmit 50% of variability.



HVDC transmitting variability from area 5 to 2
and from area 10 to 2.

Potential Uses of Research Results

- Strategic planning for power system dynamic improvement:
  - link interconnections with high capacity HVDC for control and regulation,
  - link areas adequately to distribute the impacts of variability of renewable sources.
- Can all the glitches related to high renewable penetration be mitigated by a national transmission overlay?

Future Research

- *Implementation of flexibility design*: This part of the design process is essential for overlay development, because otherwise, uncertainties of future scenarios can have significant influence on the result. We have developed and tested our flexibility design methods on a generation expansion process only. We need to extend this work to make it applicable to transmission designs.
- *Dynamic analysis*: We have only begun to explore the applicability of our zonotope-based reachability design and will need additional funding to use it within an overall dynamic security assessment that is needed to understand the dynamical implications of an overlay.
- *Defense plan design*: The overlay should introduce little or no new risks to operating the power system. To ensure this, a defense plan is needed whereby outages of multiple overlay elements would trigger mitigation measures to avoid uncontrolled cascading. Design of such a defense plan will require coordination between HVDC controls and actuation of rapid network reconfigurations.

Publications completed or in-progress

- V. Krishnan, J. McCalley, S. Lemos, and J. Bushnell, "Nation-wide transmission overlay design and benefits assessment for the US," to appear in *Energy Policy*, 2013.
- Y. Li and J. McCalley, "A disjunctive model for transmission expansion planning," under development for journal submission.
- Y. Li and J. McCalley, "Design of a high capacity interregional transmission overlay for the US," under development for journal submission.
- H. Villegas-Pico and D. C. Aliprantis, "Design verification of voltage ride-through capability of wind turbines with fully-rated converters." Under development for journal submission.
- H. Villegas-Pico and D. C. Aliprantis, "Assessment of power system speed dynamics by a national transmission overlay in a high renewable penetration scenario." Under development for conference submission.
- Y. Li, "Design of high capacity interregional transmission systems," Ph.D. dissertation, in progress.
- H. Villegas-Pico, "Reachability methods for power system dynamic analysis," Ph.D. dissertation, in progress.

Feedback on this Webinar

Send your comments and questions to the individual researchers and/or to pserc@asu.edu.

Where do you see this research being useful in creating a future grid that enables sustainable energy systems?

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