

A National Transmission Overlay (1.2)

James D. McCalley

Yifan Li

Iowa State University

jdm@iastate.edu



PSERC Future Grid Initiative
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Objective & Accomplishments

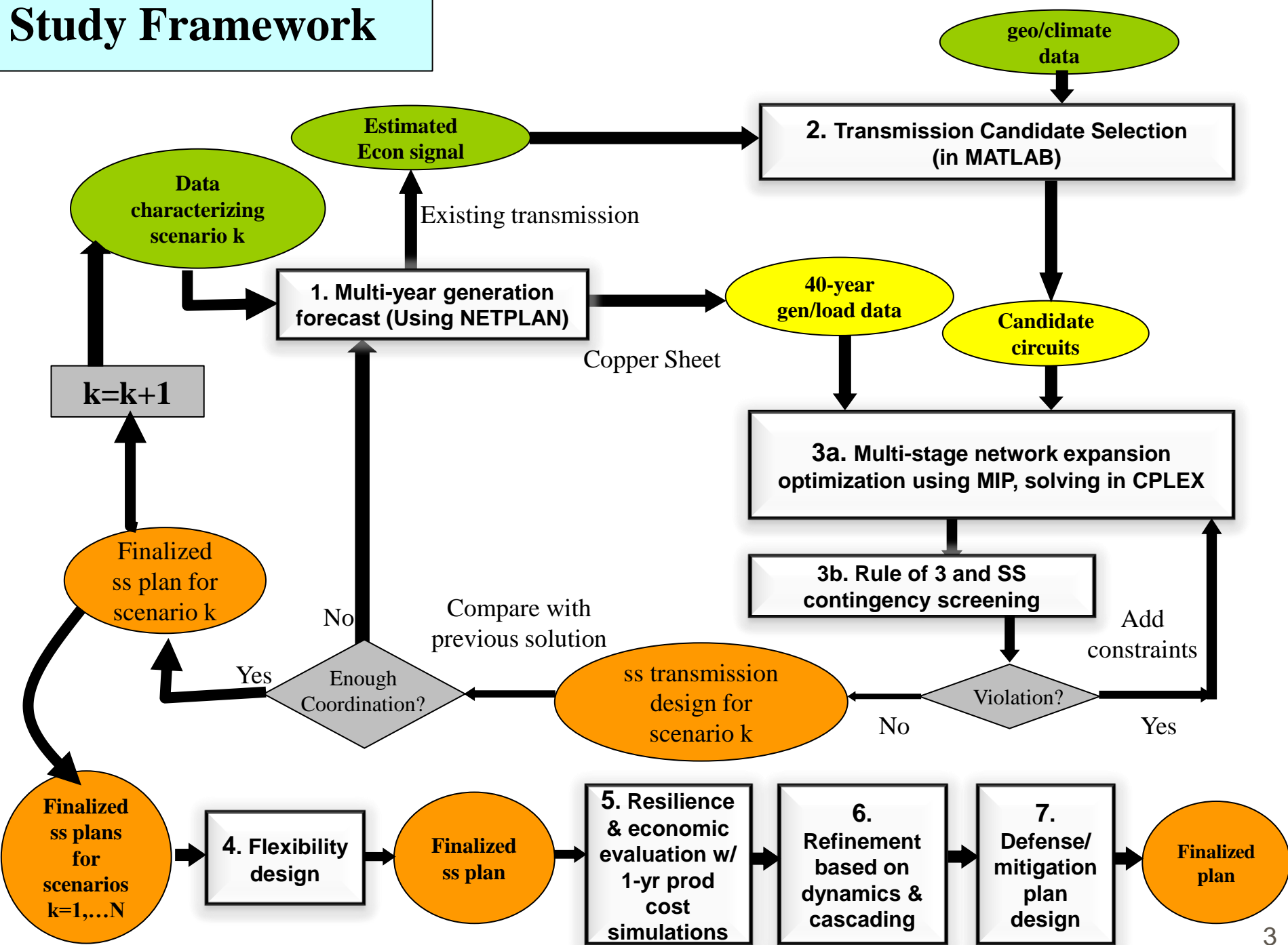
Objective:

- Develop interregional high capacity overlay design process to facilitate growth of renewables (wind, solar, geothermal) to 2050;
- Design and evaluate “good” U.S. transmission overlays for different futures;
- Quantify benefits to building a national transmission overlay

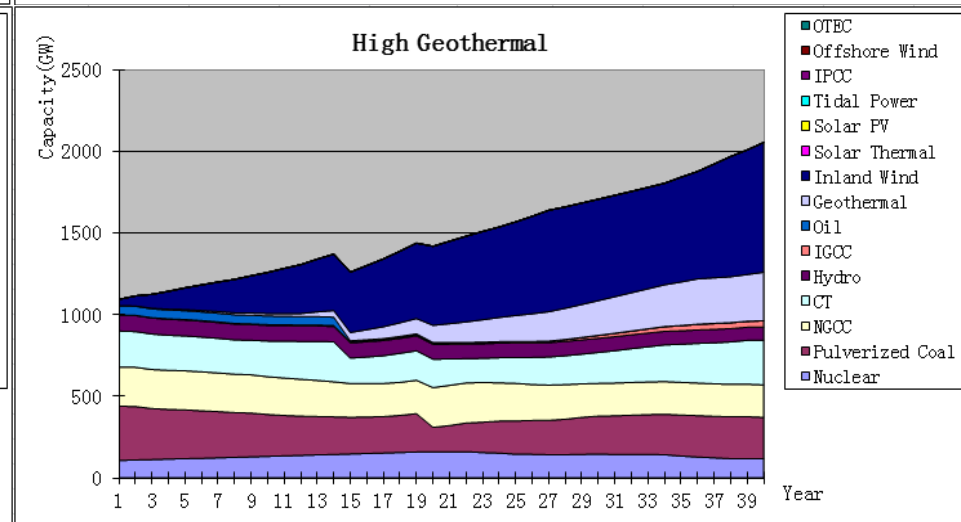
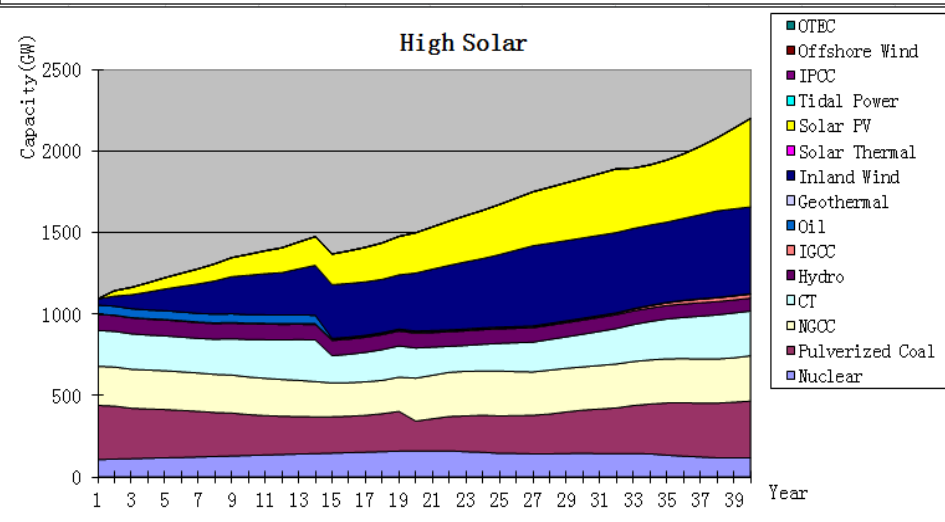
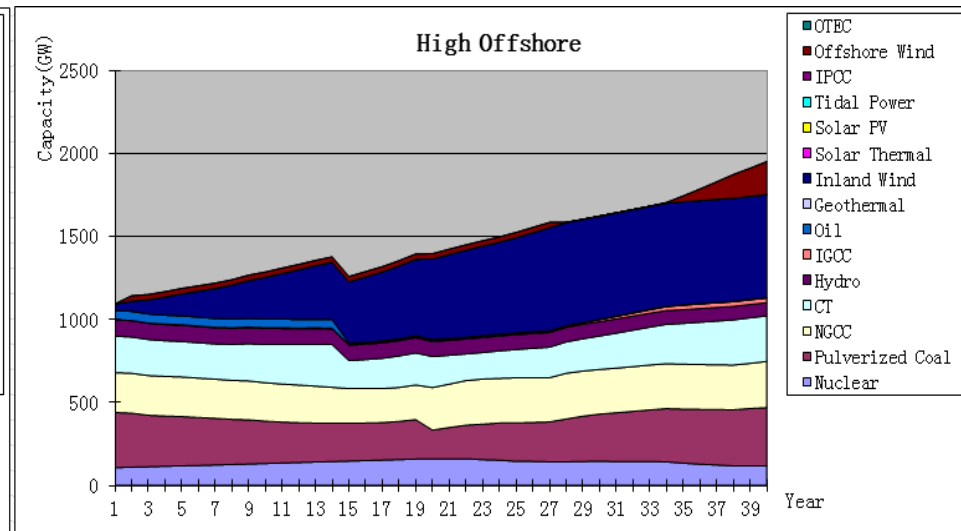
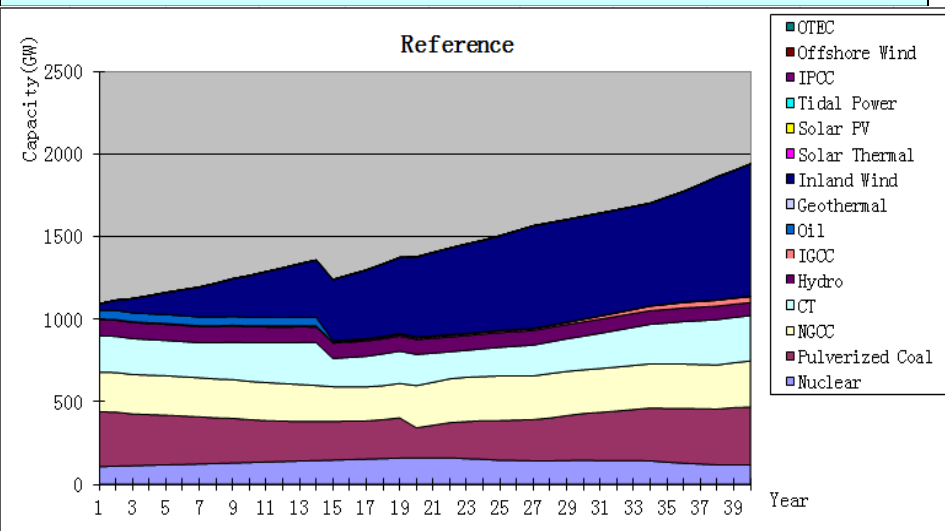
Accomplishments to date:

- Design process:
 - Candidate selection algorithm;
 - Multi-stage/circuit transmission optimization modeling approach;
- Developed 4 futures: ref, high off-shore, high solar, high geothermal
- Overlay designs for 4 futures
- Quantified steady state and dynamic benefits of overlay designs
- Investigate impacts of overlay on dynamics (Aliprantis)

Study Framework

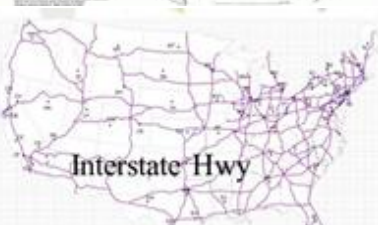
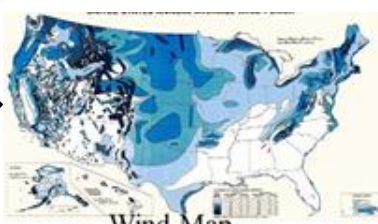
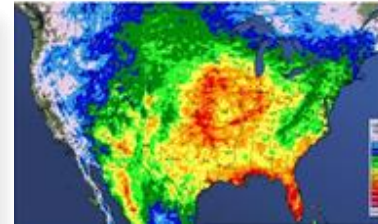
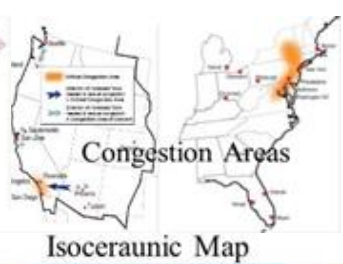


Four Futures



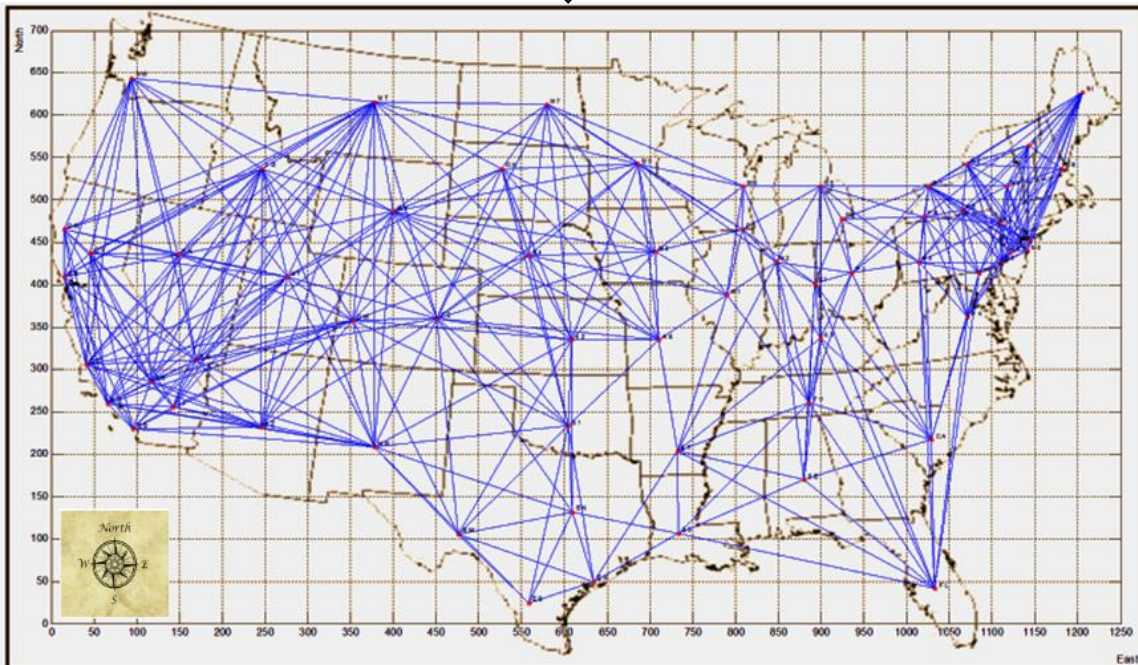
Four “high renewable” futures, very different in renewable generation type and amount, were designed using a 62 node US model, accurately representing existing generation, using representative data for future generation based on technology and location, in compliance with NERC’s regional reserve requirements.

Transmission Candidates



Iterative Reweighting Minimum Spanning Tree Algorithm

- Eliminates infeasible paths (reserve land, national parks, lightning areas...)
- Finds minimum "distance" tree which connects all nodes; stores selected arcs
- Develops weighted distance on selected arcs, where weights reflect
 - attributes facilitating transmission: existing trans, interstate hwy, rail;
 - attributes inhibiting transmission: terrain, pop density, forest, wind/ice;
 - economic impact;
- Repeat steps a-b, each time storing selected arcs



**383 Candidates,
N-1 connected set**

Network Expansion Optimization

Multi-stage transmission expansion optimization using disjunctive model, with an extension to allow multiple parallel circuit. Benders' decomposition is used to partition the problem into an investment master problem and 40 operational sub-problems:

$$\text{Min}_{\{x, f, g, \theta\}} \sum_{t \in \text{Hinv}} \sum_{ii=1}^{bk} \beta(t) 2^{ii-1} c_I(k) x_{kii}(t) + \sum_{t \in \text{H}} \beta(t) c_o g(t) \dots$$

Objective function includes T-investment & G-production costs. T-investment is function of technology, distance, substation.

Subject to

$$\sum_{k=(i,j)} f_k(t) - g_i(t) = d_i(t), \quad i=1, n \quad \forall t \in \text{H} \quad \dots \dots \dots \text{Nodal balance}$$

$$\left. \begin{aligned} f_k(t) - \gamma 0_k (\theta_i(t) - \theta_j(t)) &= 0, \\ k &= (i, j), j \in \Omega_i^0, i=1, n \quad \forall t \in \text{H} \\ -M_k(1 - S_k(t)) &\leq f_k(t) - \gamma_k (\theta_i(t) - \theta_j(t)) \leq M_k(1 - S_k(t)), \\ k &= (i, j), j \in \Omega_i^+, i=1, n \quad \forall t \in \text{H} \end{aligned} \right\} \dots \dots \dots$$

Represents impedance effects via DC power flow, but maintains linearity using disjunctive model extended to allow multiple parallel circuits.

$$S(t) = \sum_{i \in \text{Hinv}, i \leq t} x(i) \quad k = (i, j), j \in \Omega_i^0, i=1, n \quad \forall t \in \text{H} \quad \dots \dots \dots \text{Investment Accumulation}$$

$$\left. \begin{aligned} -f_k^{\max} S_k(t) &\leq f_k(t) \leq f_k^{\max} S_k(t), \\ -f 0_k^{\max}(t) &\leq f_k(t) \leq f 0_k^{\max}(t), \\ k &= (i, j), j \in \Omega_i^+, i=1, n \quad \forall t \in \text{H} \end{aligned} \right\} \dots \dots \dots$$

Transmission Capacity Constraints; AC capacities a function of distance

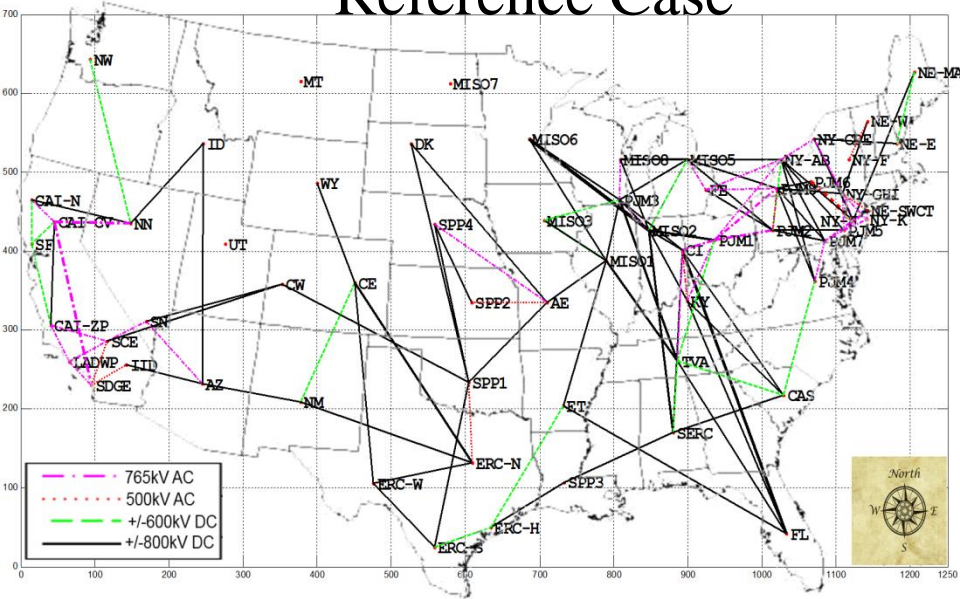
$$0 \leq g_i(t) \leq g_i^{\max}(t), \quad i=1, n \quad \forall t \in \text{H} \quad \dots \dots \dots \text{Generation Output Limit}$$

$$\theta_{ref}(t) = 0 \quad \dots \dots \dots \text{Reference bus angle set to be 0}$$

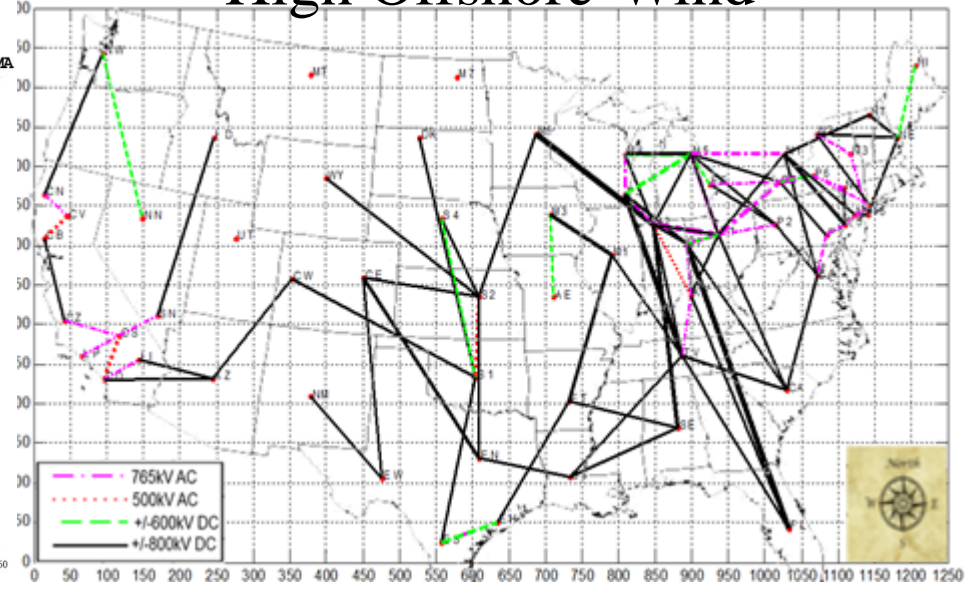
$$x(t), S(t) \in \{0,1\}^m \quad \dots \dots \dots \text{Binary decision variables}$$

Overlay Designs for Each Future

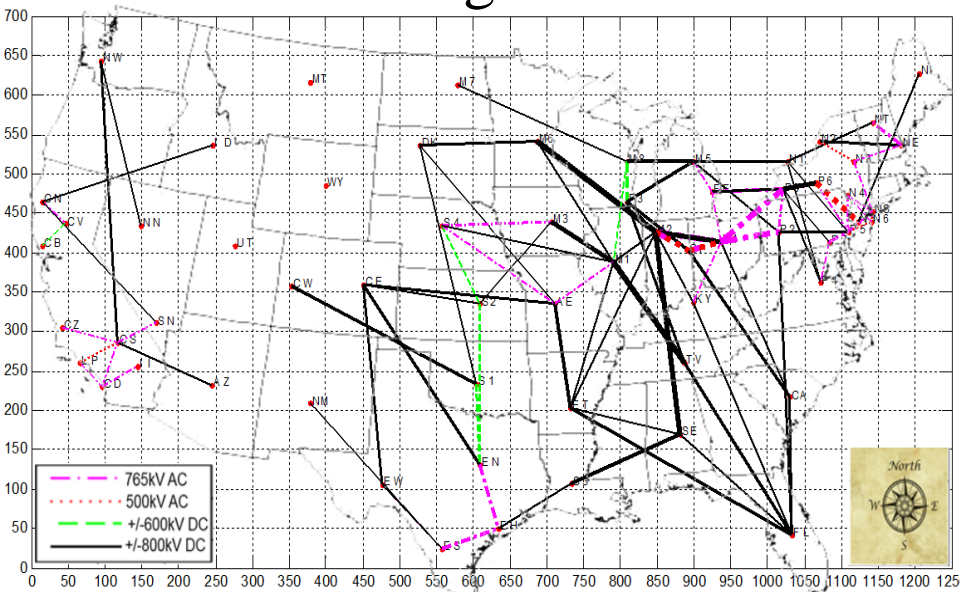
Reference Case



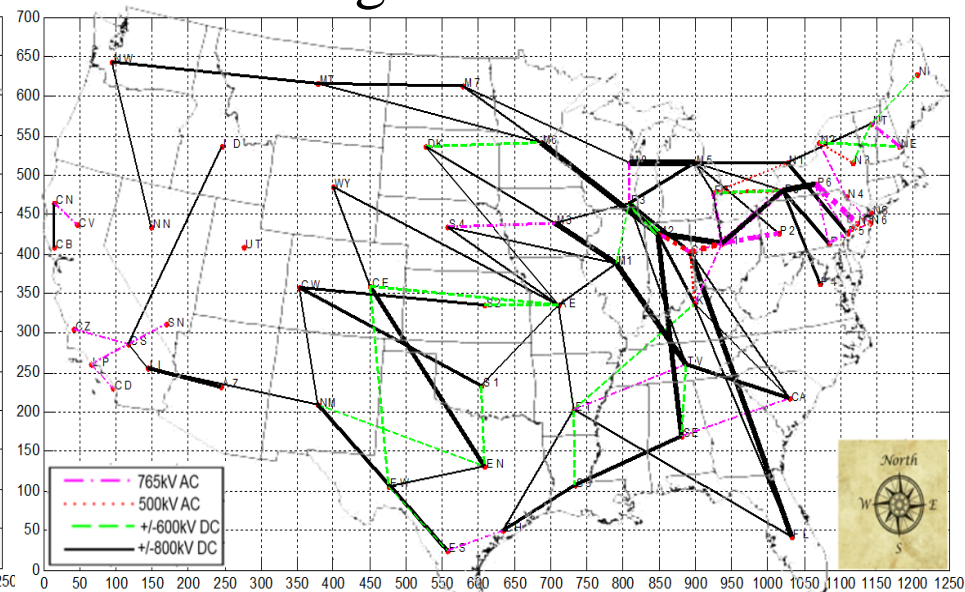
High Offshore-Wind



High Solar

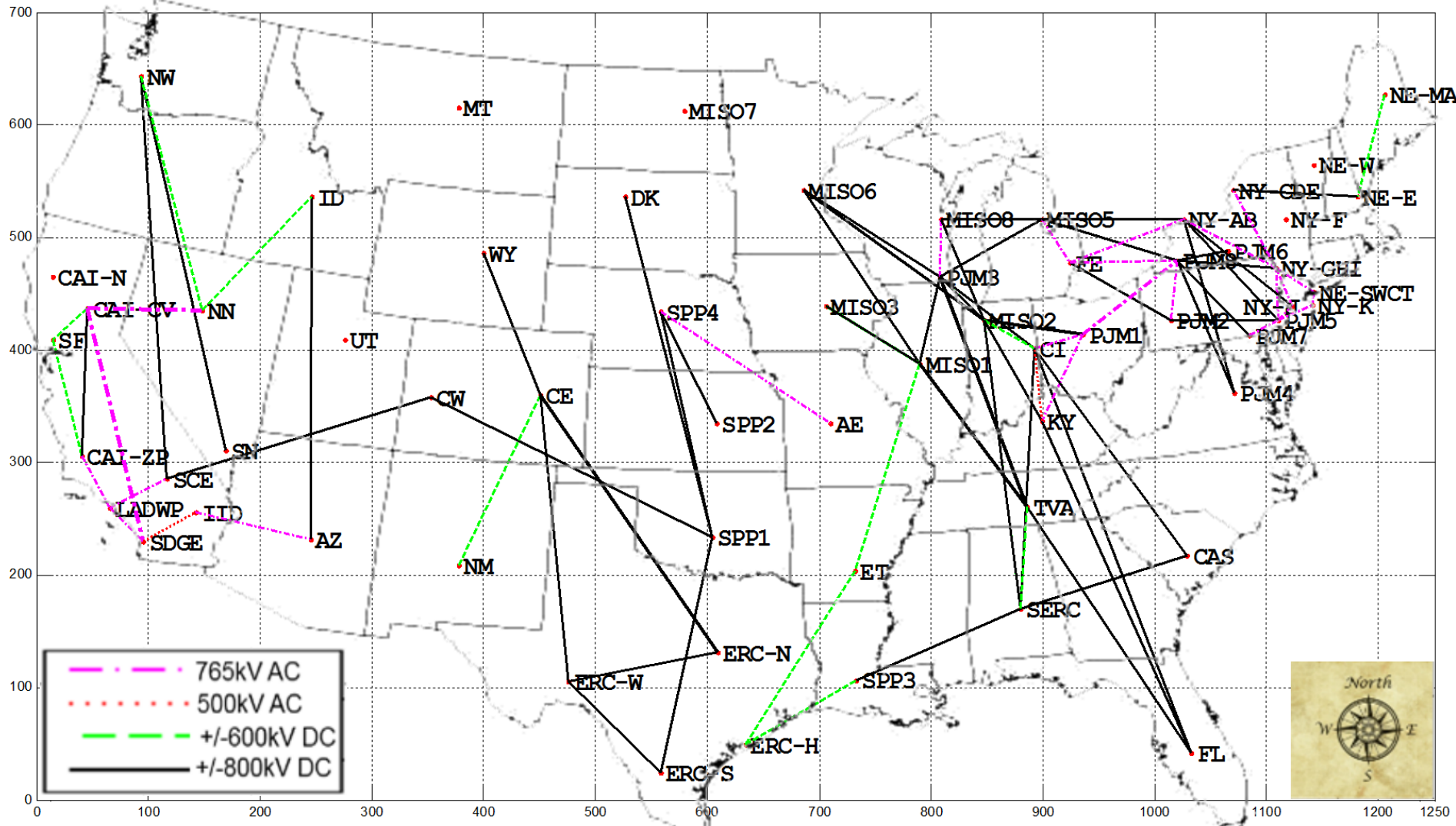


High Geothermal



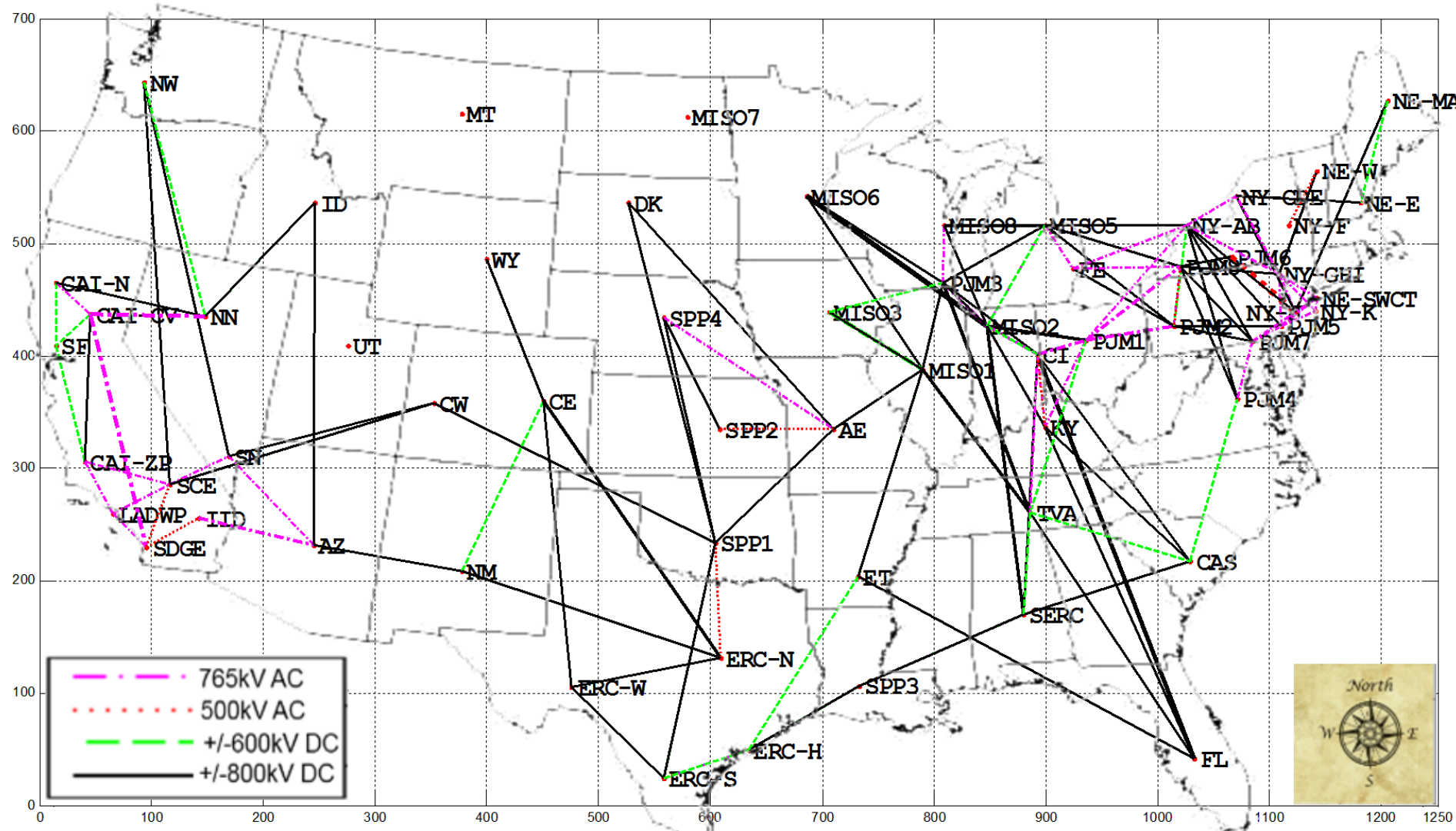
A Closer Look: The Reference Case

Transmission Overlay, yr 25: Major investments around Great Lakes, consistent with MISO-MTEP-2010 study results. 800kV DC lines supply SW, where limited renewable resources are available. WECC, EI, ERCOT interconnected near SPP.



A Closer Look: The Reference Case

Transmission Overlay, yr 40: Further investments in PJM, SERC and Arizona areas, to facilitate renewable generation increase and serve load centers.



Benefit Quantification:

Each overlay design evaluated under over 40 yrs, using NETPLAN solver. Results below indicate national transmission overlays benefit the overall U.S. electric system via lower costs & lower emissions.

TABLE I
BENEFIT OF TRANSMISSION OVERLAY#

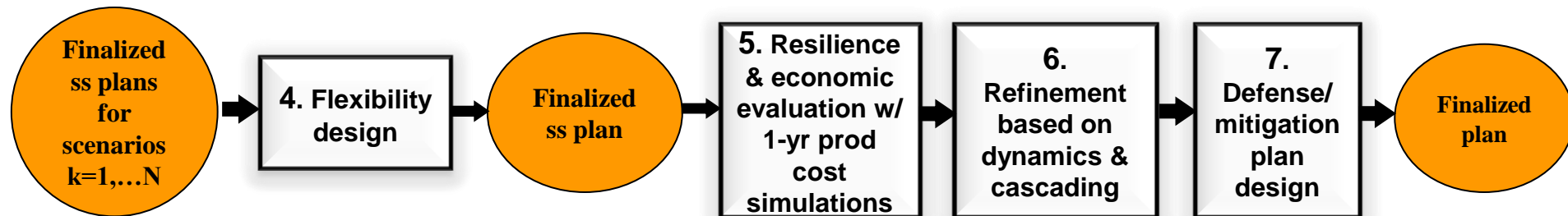
Case	Expanded Transmission				Fixed Current Transmission
	Ref.	High Off.	High Solar	High Geo.	
Gen. Inv. Cost(T\$)	1.766	1.731	1.752	1.735	2.523
Tran. Inv. Cost(T\$)	0.565	0.517	0.591	0.740	0
Gen. Prod. Cost(T\$)^	3.005	2.978	3.002	2.995	3.271
Total Cost(T\$)	5.336	5.226	5.345	5.470	5.794
Emission (10 ¹⁰ short ton)	5.135	5.448	5.072	5.112	5.812

#All costs have been discounted into 2010 dollars.

^The Generation Production costs include fuel costs and O&M costs.

Future Work:

- Flexibility design: to identify investments which minimize adaptation costs to future uncertainties.
- Analysis of resilience to very large scale “Katrina-like” events
- Refine design, particularly technology choice (AC vs DC, kV level) based on
 - Steady state and dynamic security studies,
 - Cascading.
- Develop defense plan



A National Transmission Overlay (1.2)

Dionysios Aliprantis
Hugo Villegas-Pico
Iowa State University
(dali@iastate.edu)



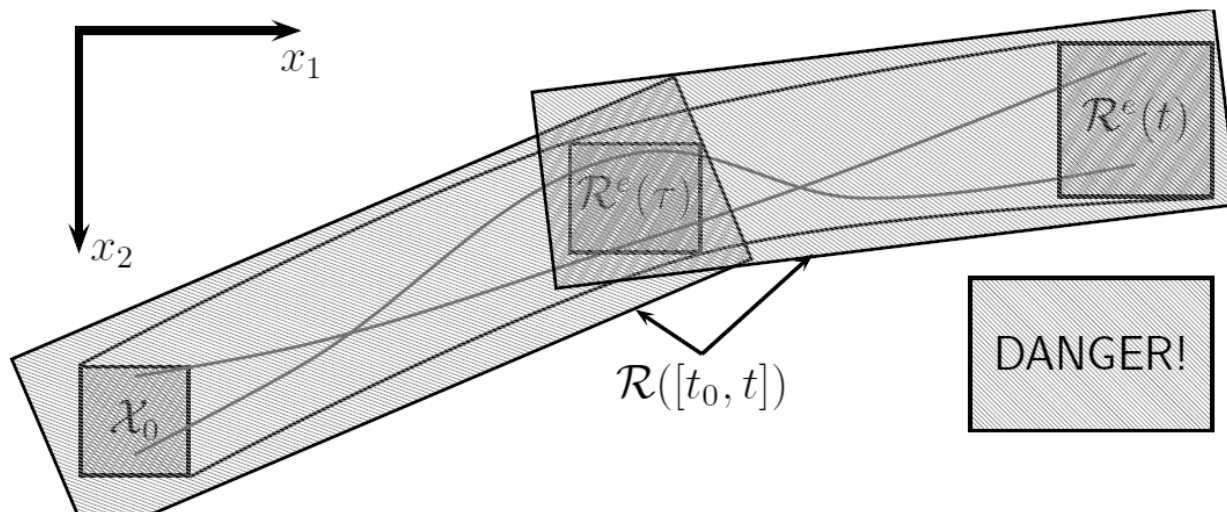
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Research Objectives

- Investigate impacts of new transmission overlay plans on power system dynamics.
- Metric of interest: frequency response.
- We model “slow” governor dynamics and impacts on average system frequency.
- We apply a computational technique for reachability analysis to model uncertainties in disturbances and system parameters.
- Calculate bounds of trajectories of frequency response with (E)HVAC/HVDC tie-lines.
- HVDC lines have frequency-sensitive controls.

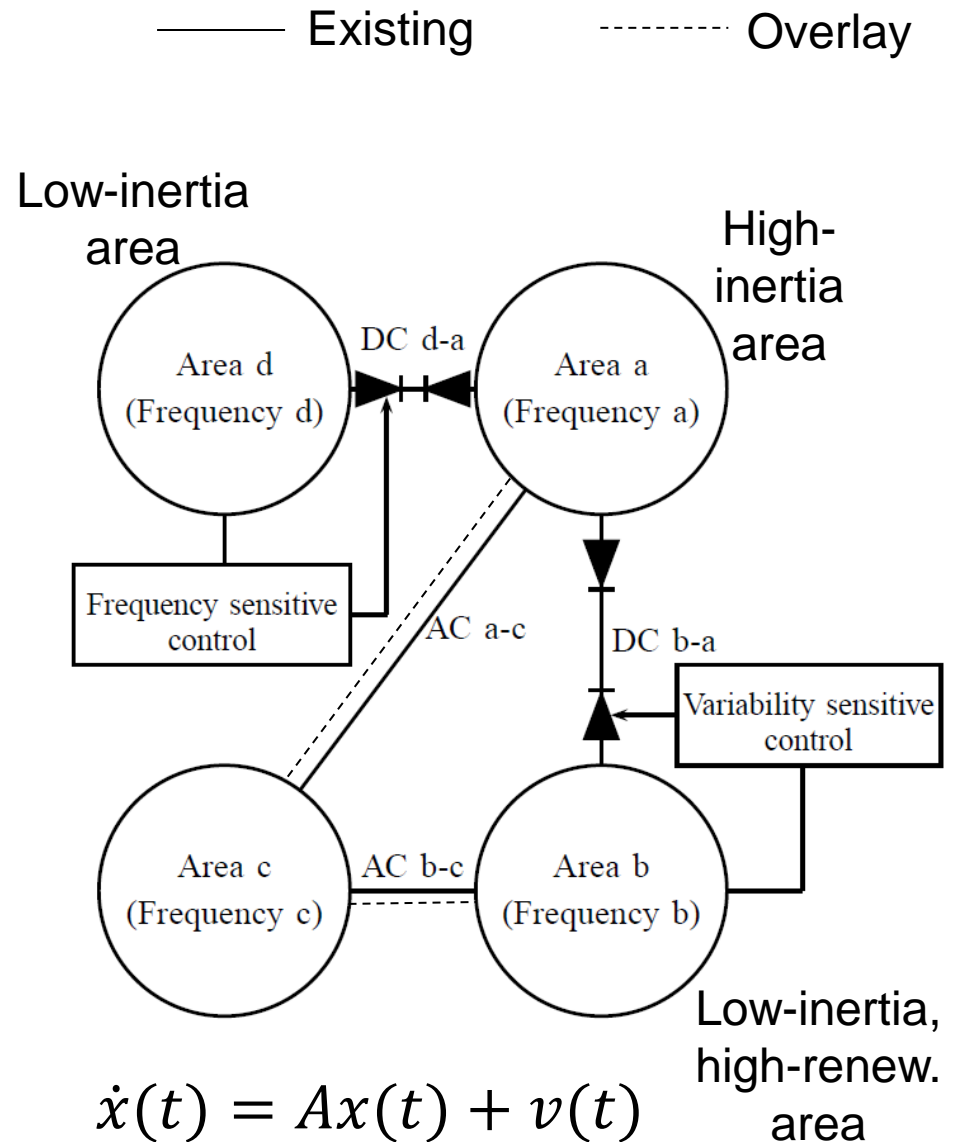
Reachability Analysis

- Reachability analysis yields bounds of solutions to an uncertain dynamic problem.
- Find a set (flow tube) that contains all possible trajectories.
- Run one study, calculating the evolution of the reachable set & capturing all possible scenarios.



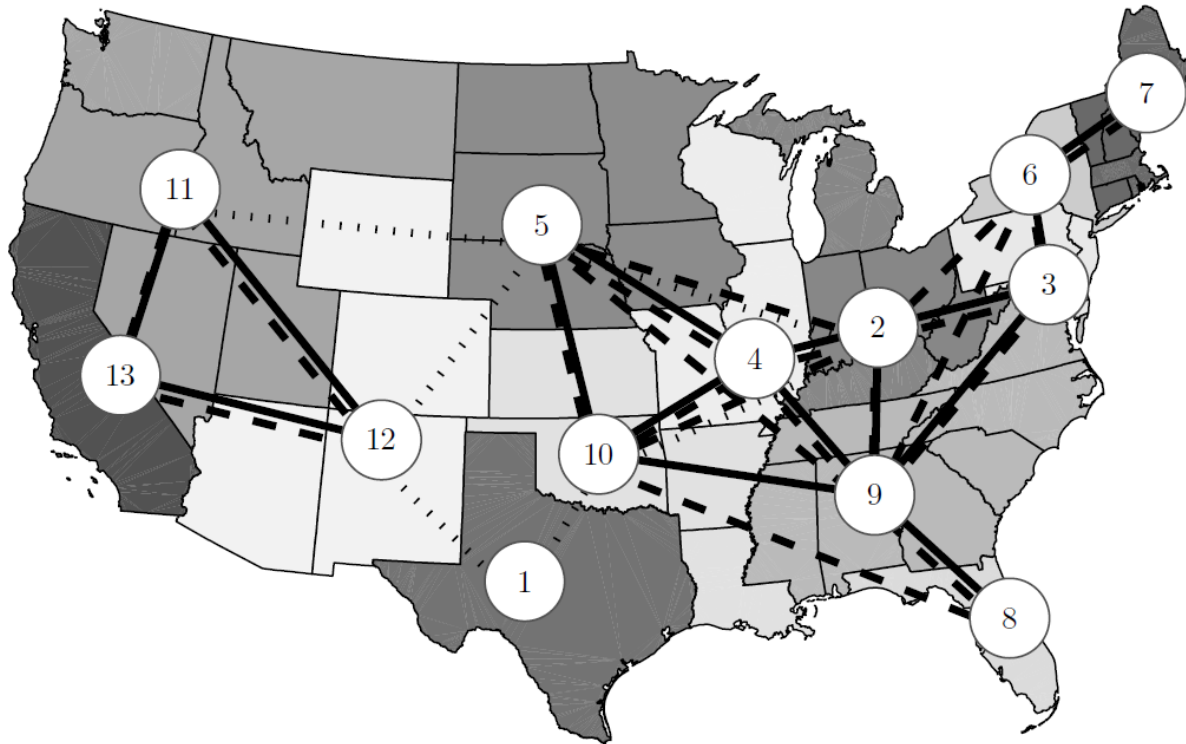
National Transmission Overlay Model

- High-capacity HVAC improves 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., areas a & d).
 - Control law that detects variability of renewable generation in one area (e.g., area b) and transfers to others with high inertia constant (e.g., area a).



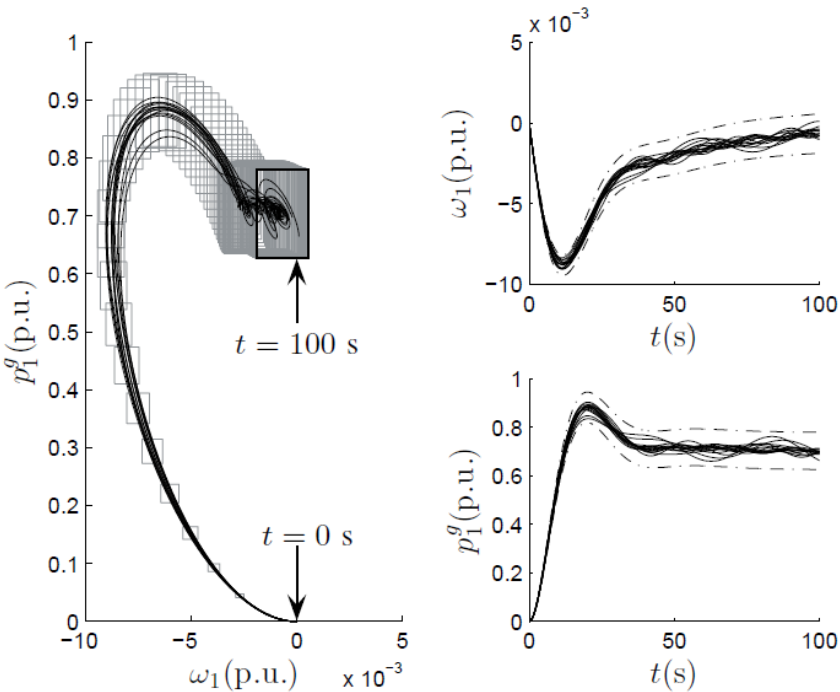
Example: Frequency-Sensitive HVDC

For simplicity, we model the U.S. power system as 13 regions:

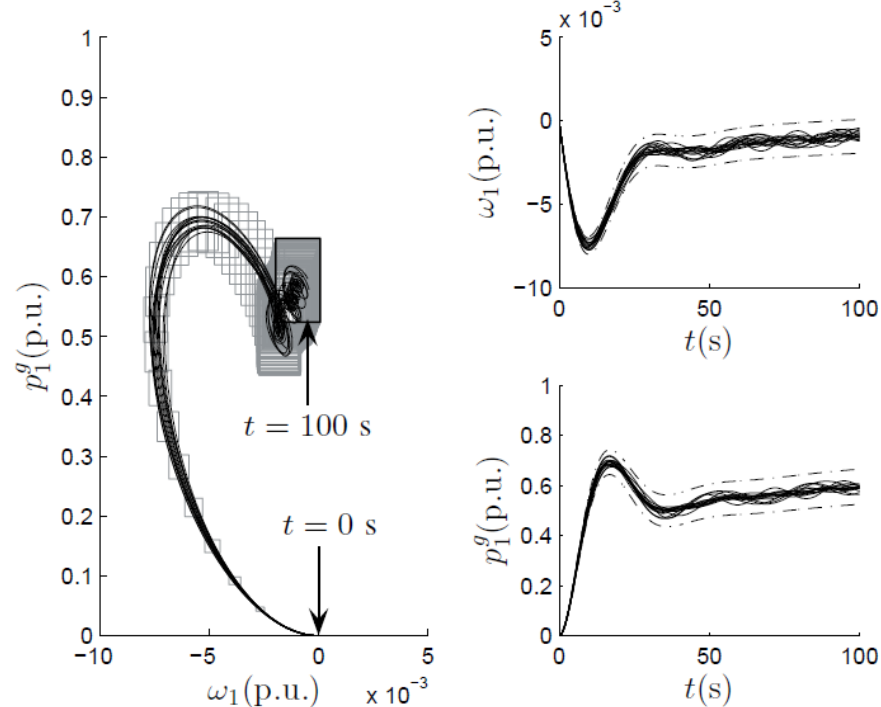


Simplified U.S. power system areas (not to scale) with across-area transmission capacity (solid) and studied HVAC (dashed) - HVDC (dotted) transmission overlays.

Example: Frequency-Sensitive HVDC

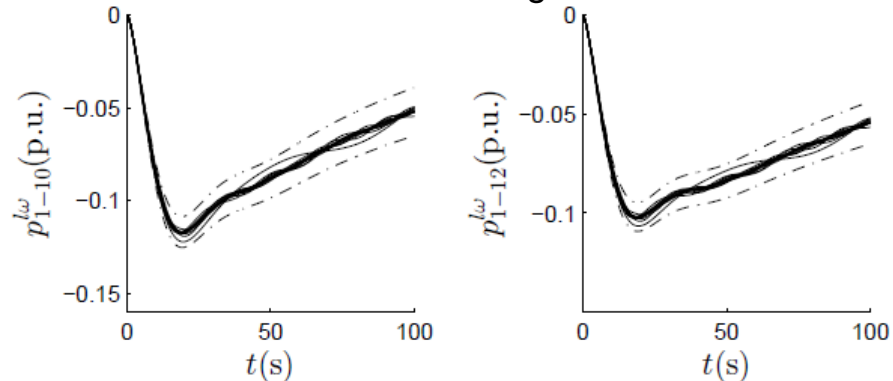


Region-1 frequency response **without** HVDC regulation.



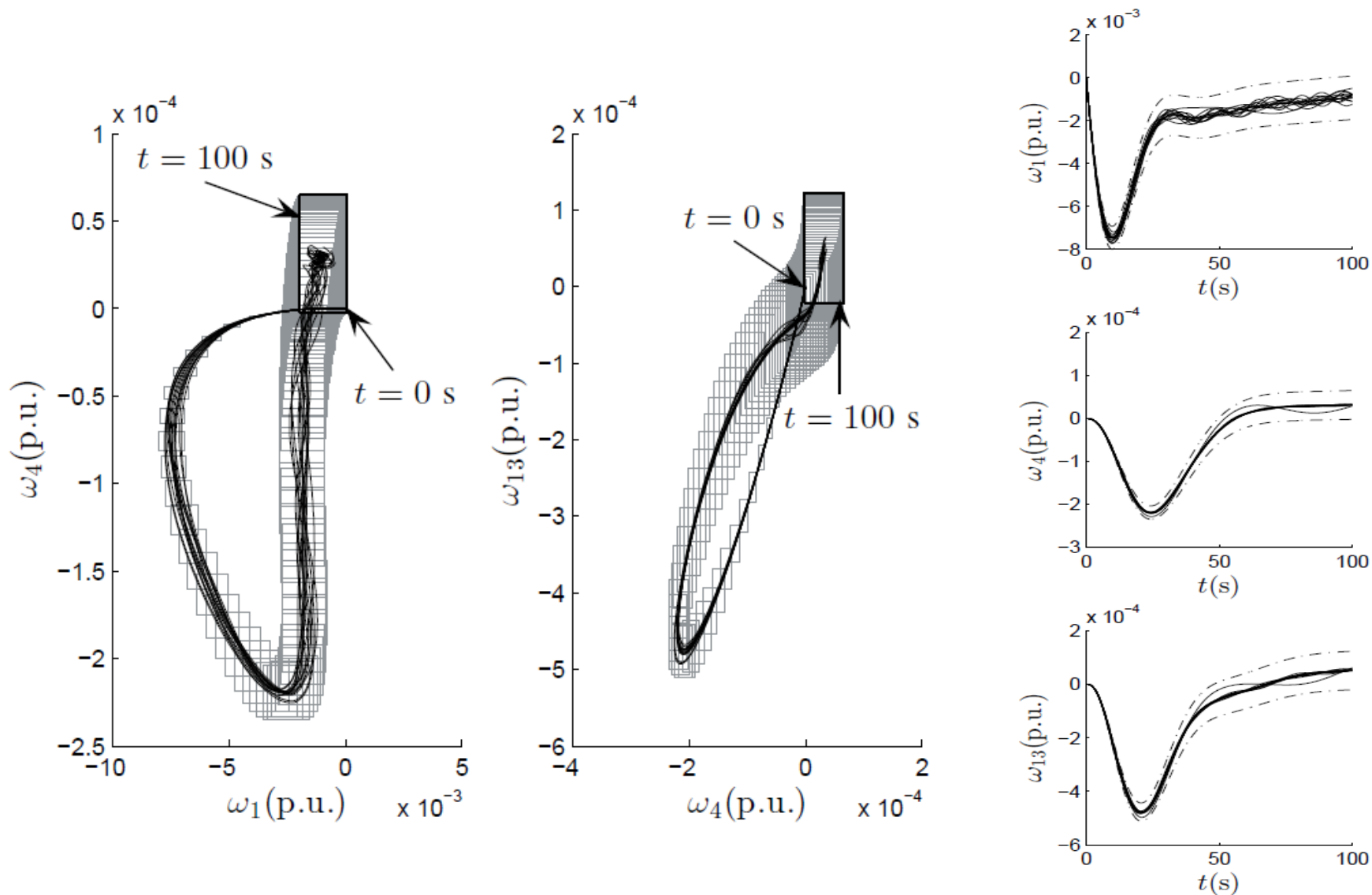
Region-1 frequency response **with** HVDC regulation.

Disturbance:
 Uncertain loss of generation in region 1
 $w_1^d \in [0.65, 0.75]$ p.u., with $S_B = 1000$ MVA
 and unity power factor.



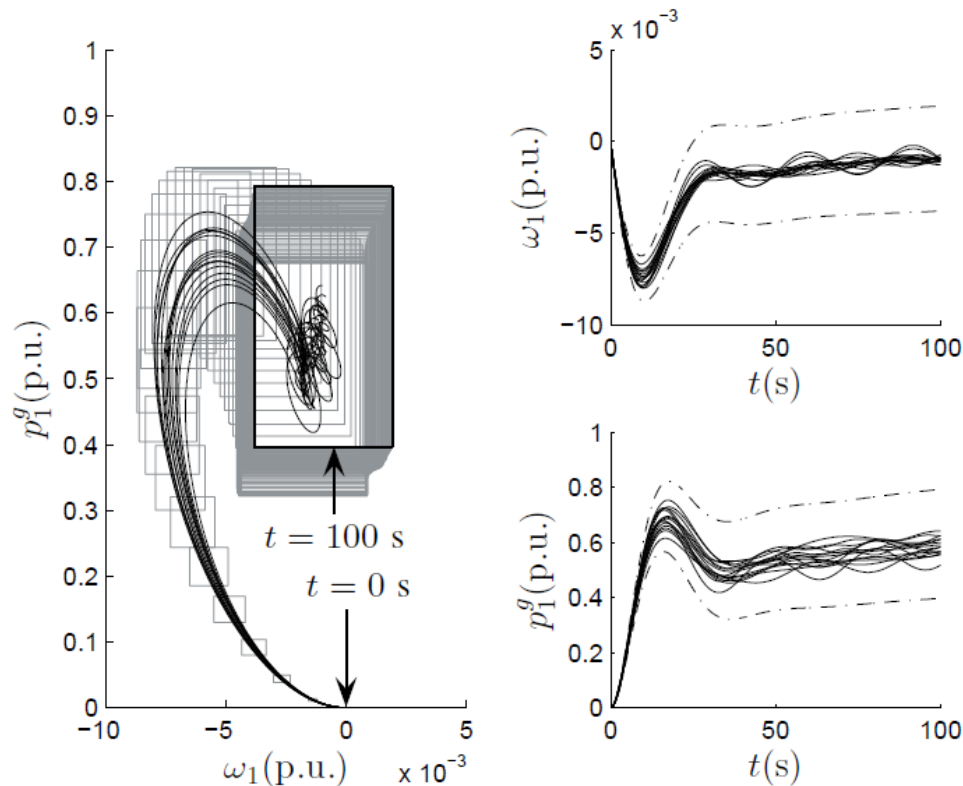
Region-1 HVDC power injections.

Example: Frequency-Sensitive HVDC



Impact on frequency of other regions (arbitrarily selected) when supporting region 1 by HVDC regulation.

Example: Frequency-Sensitive HVDC and Parameter Uncertainty

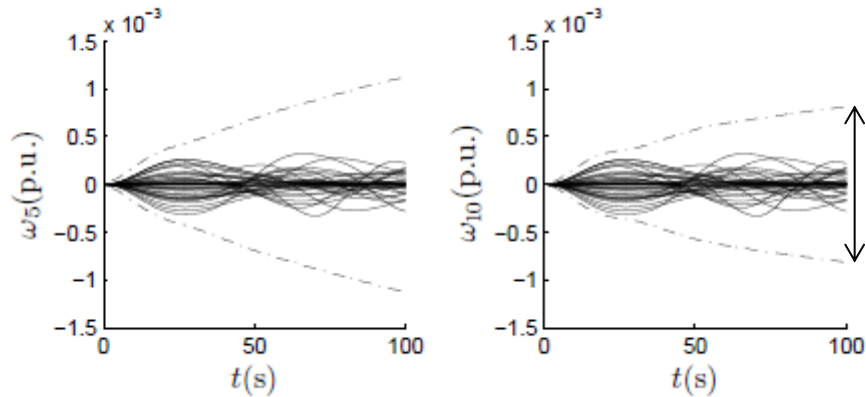


Region-1 frequency response
with HVDC regulation and inertia constant uncertainty ($\pm 5\%$ off nominal).

Disturbance:

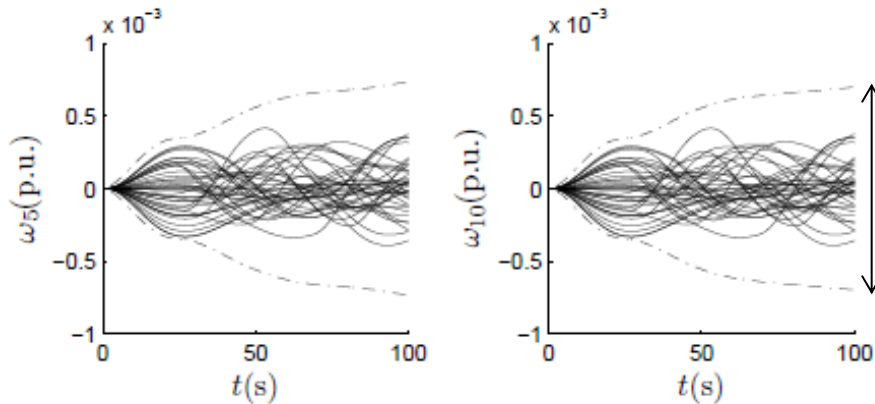
Uncertain loss of generation in region 1
 $w_1^d \in [0.65, 0.75]$ p.u., with $S_B = 1000$ MVA
 and unity power factor.

Example: Renewables Variability

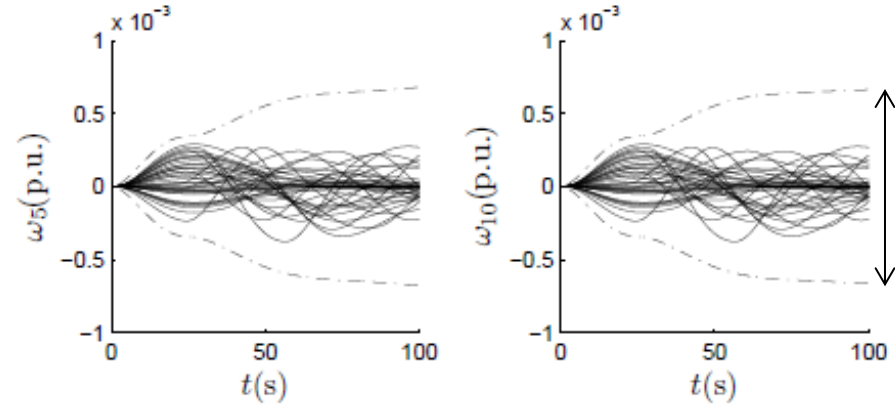


Frequency bounds of regions **without** HVAC-HVDC overlay.

Disturbance:
 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.



Frequency bounds of regions **with** HVAC overlay. (Improves bounds in ω_5 and ω_{10} .)



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

Conclusions

- A high-capacity HVDC overlay improves frequency response and can be used to “transmit variability.”
- A national transmission HVAC overlay improves “connectivity” among areas and the dynamic frequency response of areas with high renewable penetration.
- HVDC can transfer impacts to areas with higher inertia constants in a synchronous network (may improve governor response to frequency waves). Future work will entail more detailed modeling.
- Reachability analysis yields bounds of solutions to an uncertain dynamic problem.