DOE/OE Transmission Reliability Program

PMU-Based Voltage Stability

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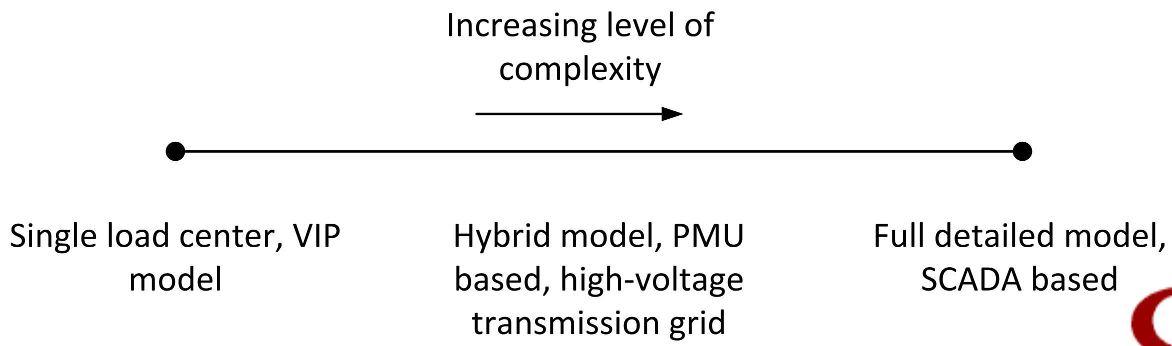
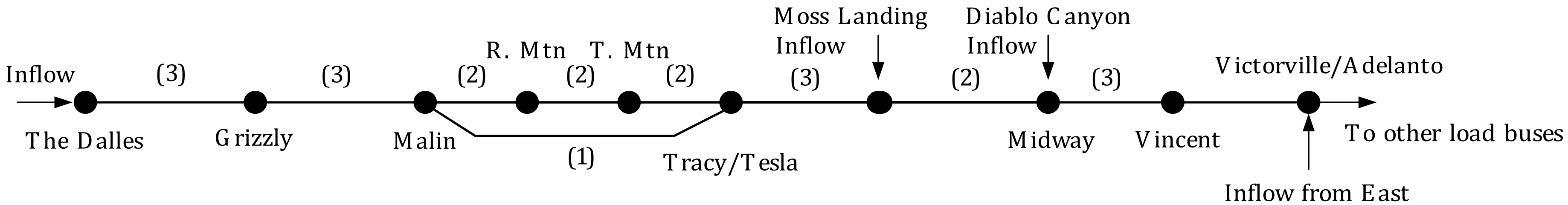
Project Objective

- Traditional voltage stability analysis (VSA) approaches:
  - Full-order detailed model: off-line or real-time analysis with SCADA measurements or SE solutions. High computation burden and dependent on the load model. Example: VSTAB program
  - Single-load, stiff-bus model: applicable to radial systems, dependent on load models. Example: voltage instability predictor (VIP) approach
- Goal: Hybrid, PMU-based, voltage stability mode with less computation than VSTAB-type programs but capable of handling more complex power transfer paths



Project Overview

- Voltage stability of a complex transfer path (Pacific AC Intertie):



- Network characteristics:
  - Large number of injection and out-flow points
  - Load areas with multiple in-feeds
- Important information to know
  - PMU data: for obtaining actual voltage sensitivities, injections, and out-flows
  - Multiple vulnerabilities and reactive power supply at each location
  - Flow sensitivities at injection and outflow points
  - Network parameters

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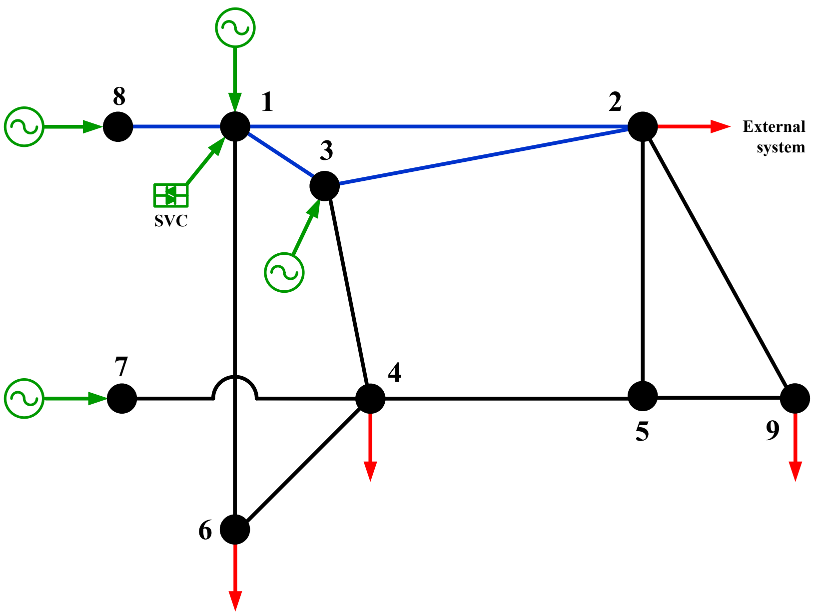
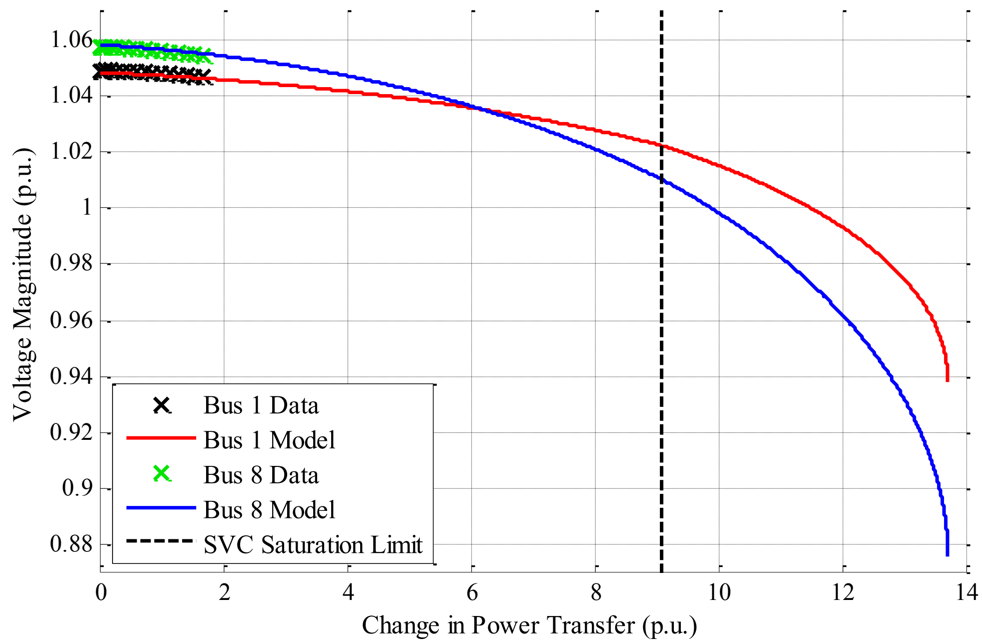
PMU-Based Voltage Stability for NY

- Use PMU data from loss-of-generation events to construct equivalent systems for the unobservable regions
- Compute PV curves of the transfer path using a PMU-based model





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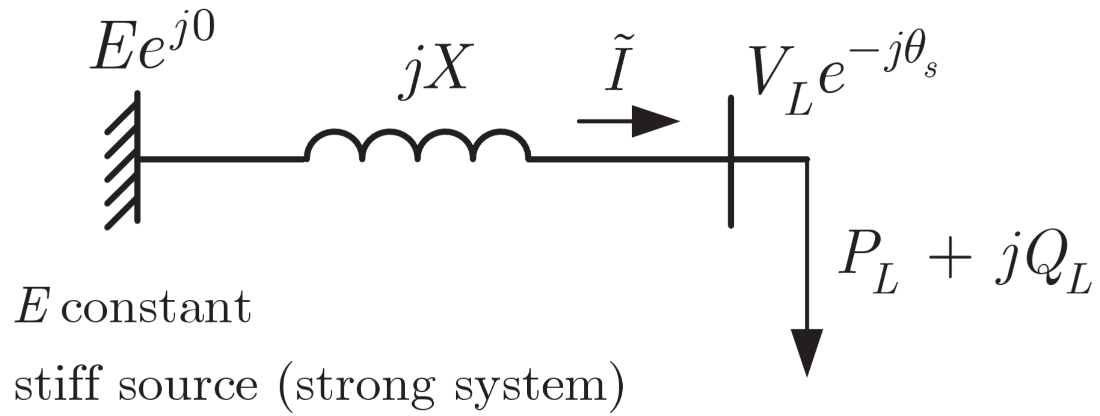
Voltage Stability Margin Calculation

- Difficulty in steady-state voltage stability (VS) margin calculation:
  - Singularity of power flow Jacobian at the voltage collapse point
  - Newton-Raphson iteration fails to converge, sometimes far from collapse
- Method of homotopy (continuation power flow):
  - Introduce a load parameter to remove singularity (increase the size of *J* by 1)
  - Special software using this approach to compute VS margins has been developed (Example: CPFLOW)
- Our approach:
  - Define a new bus type to directly remove the singularity from the Jacobian
  - Enables fast computation of PV curves and voltage stability margins
  - Retains all the features of conventional power flow methods

Single-Load, Stiff Bus System



- Treating the load bus as a PQ bus, the Jacobian is:

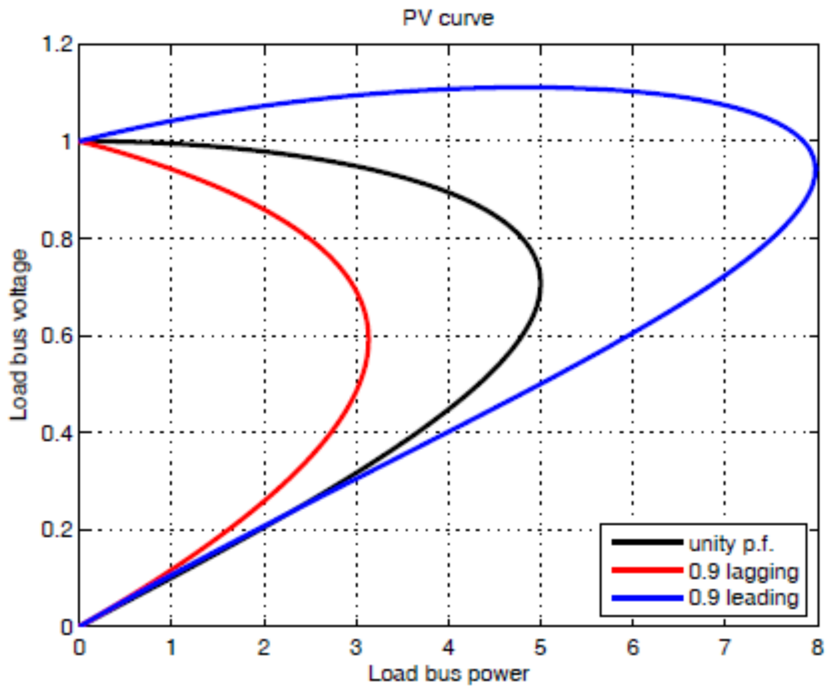
$$J = -\frac{1}{X}\begin{bmatrix} V_L E\cos\theta_s & E\sin\theta_s \\ V_L E\sin\theta_s & 2V_L - E\cos\theta_s \end{bmatrix}$$

- The Jacobian is singular when

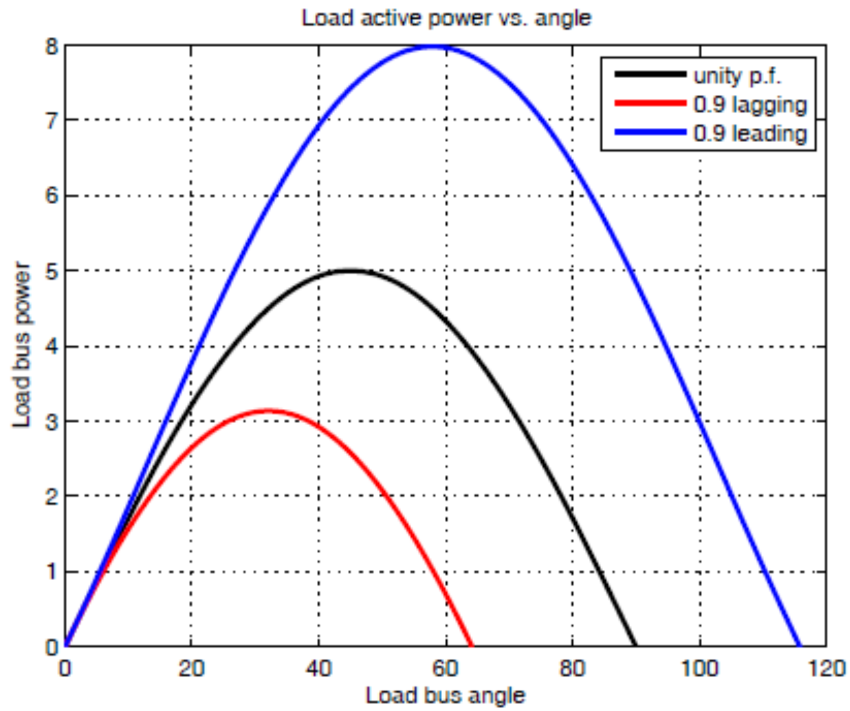
$$\det J = V_L E(2V_L\cos\theta_s - E)/X = 0$$

PV Curves and Angle Separation

- Single-load VSA with constant power factor:
- Load bus angle (angle separation) is seldom analyzed in VSA



PV Curves



Power vs. Angle Separation

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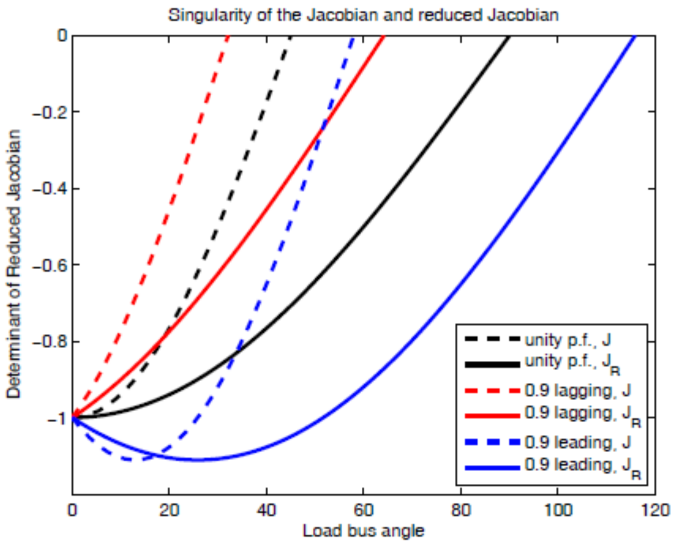
New Idea: Specify the Angle for VSA

- Specify load bus angle, so the number of unknowns is reduced by 1
- Remove load *P* equation (load power not enforced):

$$J = -\frac{1}{X}\begin{bmatrix} V_L E\cos\theta_s & E\sin\theta_s \\ V_L E\sin\theta_s & 2V_L - E\cos\theta_s \end{bmatrix}$$

- New matrix is nonsingular:



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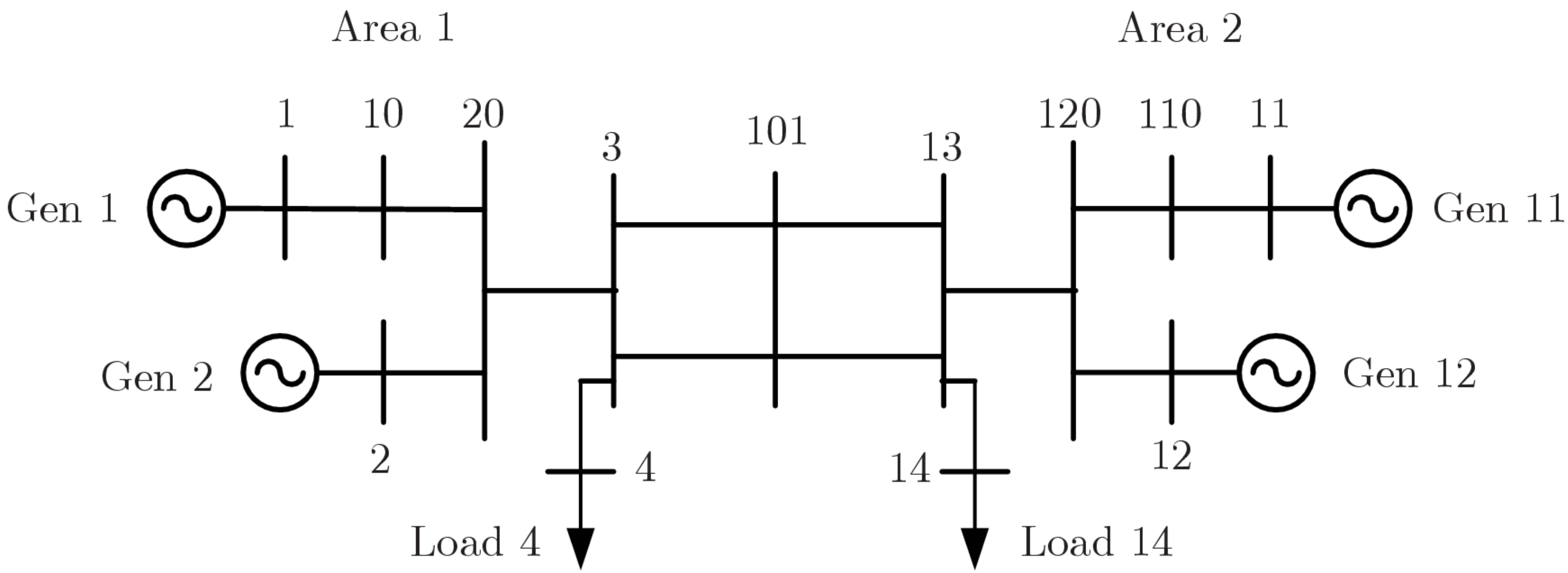
Advantages of *AQ* Bus Method

- Calculate VS margins by increasing *AQ* bus angle
- Accommodates multiple loads and generators
- Allows for constant power factor loads
- Includes all features of conventional power flow:
  tap changers, generator reactive power limits, sparse matrices, decoupled power flow, etc.
- Can be generalized to large power systems:

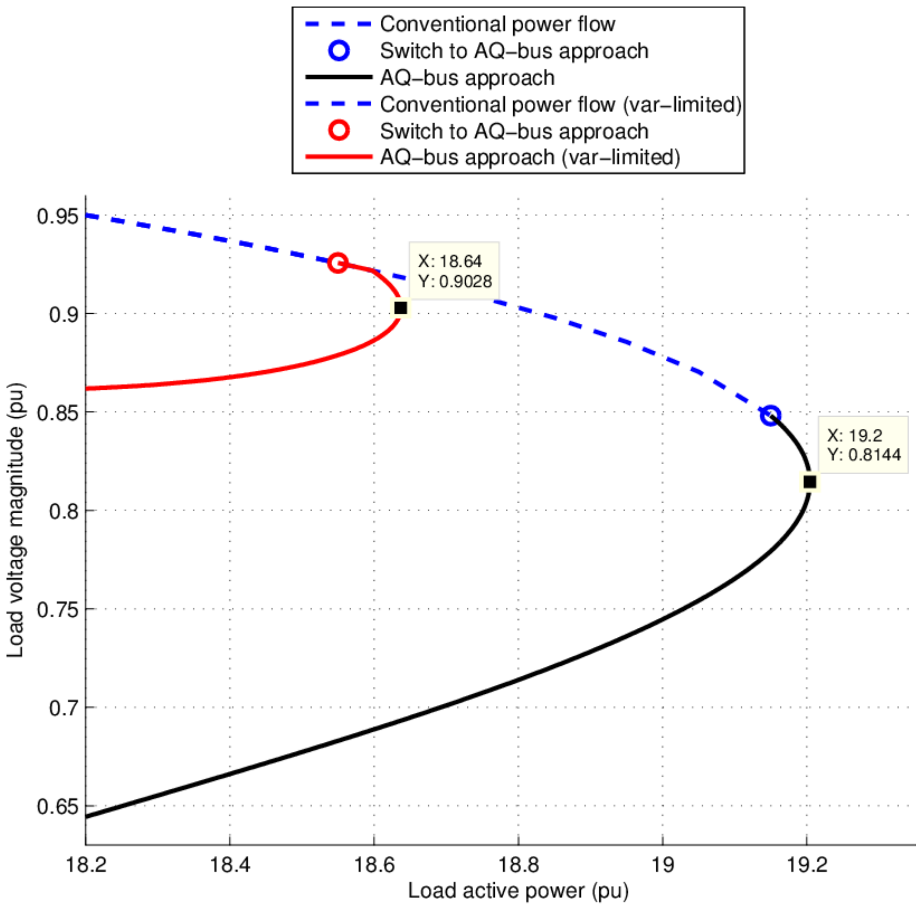
Bus types	Bus representation	Fixed values
PV	Generator buses	Fixed active power generation and bus voltage
PQ	Load buses	Fixed active and reactive power consumption
AV	Swing bus (generator)	Fixed angle (A) and voltage magnitude
AQ	Load bus	Fixed voltage angle and reactive power consumption

2-Area, 4-Machine System

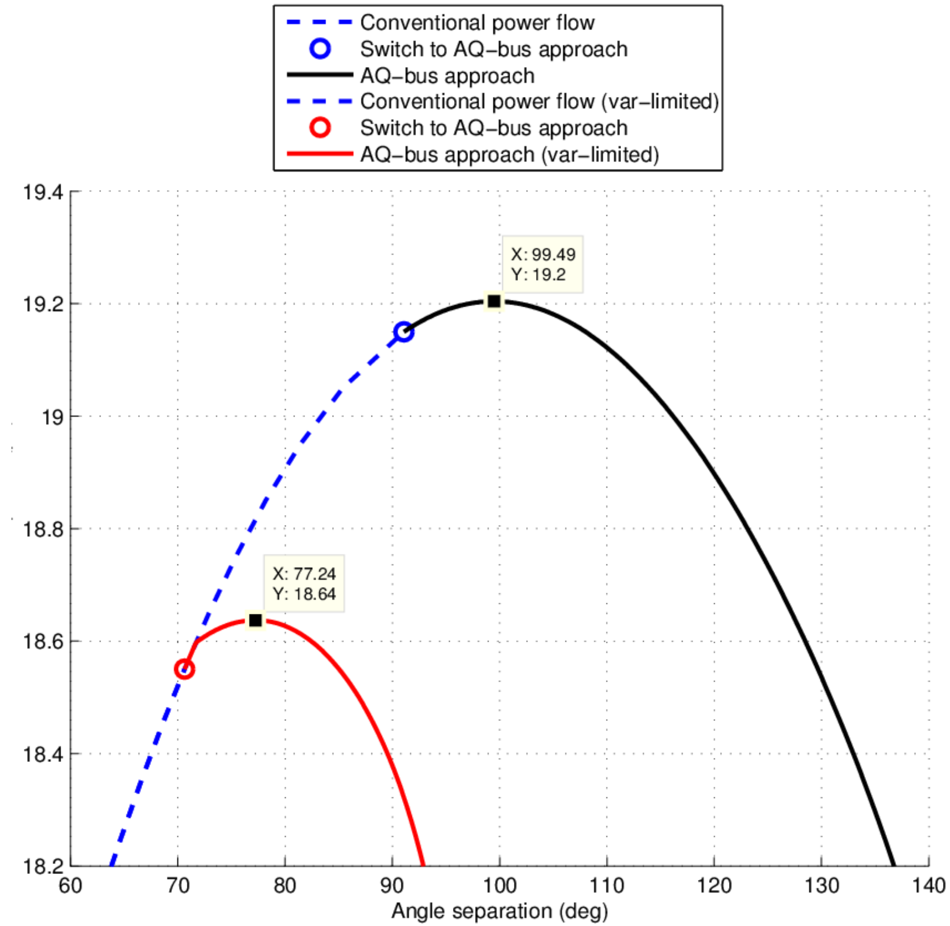


- Constant power factor load increase on Bus 14, with supply from Generator 1
- Base case: no var limit on generators
- Case 1: var limit on Generator 2

2-Area System with Var Limits

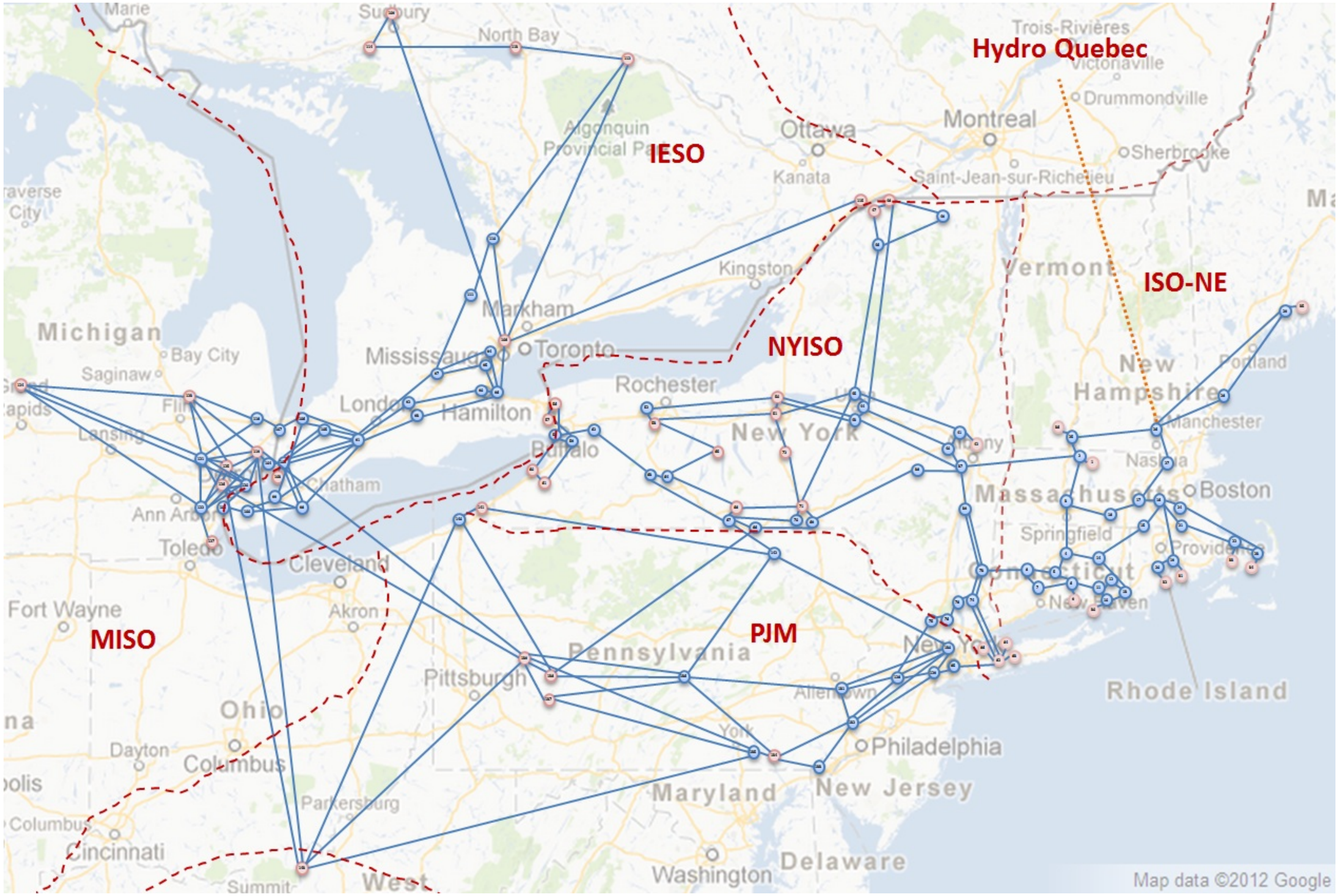


PV Curve



Power vs. Angle

Example: NPCC 48-Machine System



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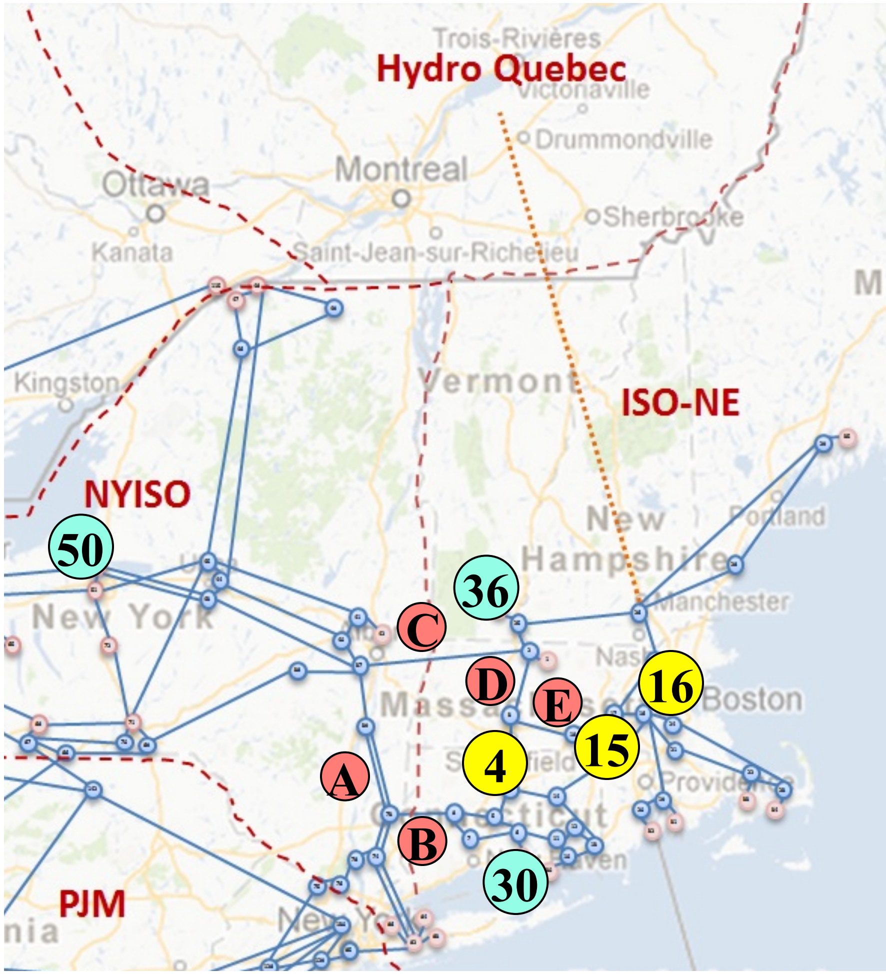
NPCC System: Contingency Analysis



Generator schedule for 48-machine system

Generator Bus #	Bus Type	β_k
50	AV (swing)	-
30	PV	0.10
36	PV	0.80

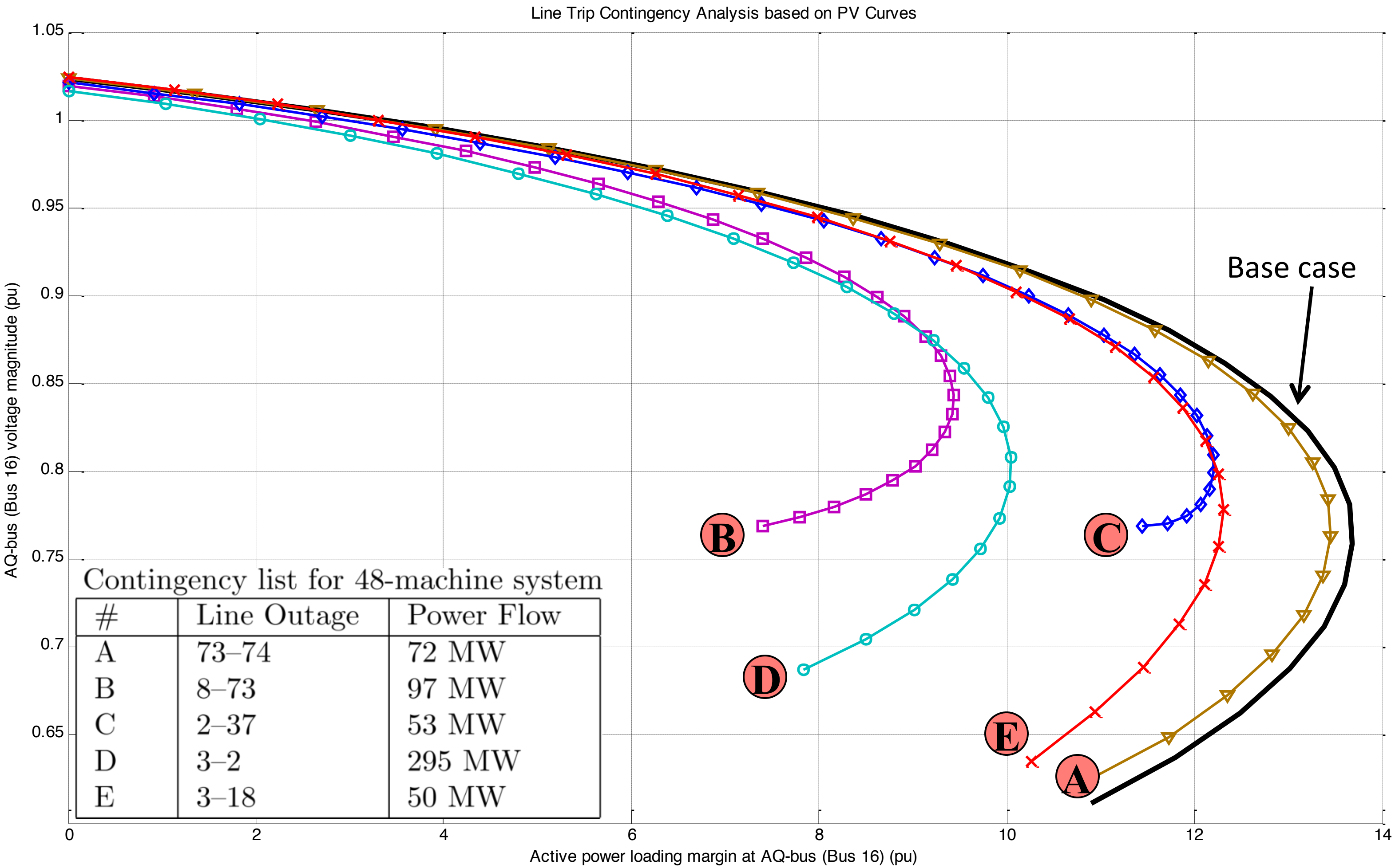
Load schedule for 48-machine system

Load Bus #	Bus Type	α_ℓ	Power Factor
16	AQ	-	0.95 lag
4	PQ	0.50	0.95 lag
15	PQ	0.25	0.95 lag

Contingency list for 48-machine system

#	Line Outage	Power Flow
A	73–74	72 MW
B	8–73	97 MW
C	2–37	53 MW
D	3–2	295 MW
E	3–18	50 MW

PV Curves & Contingency Analysis



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AQ Bus voltage magnitude (pu)

Active power margin (ΔP) at *AQ* Bus (pu)

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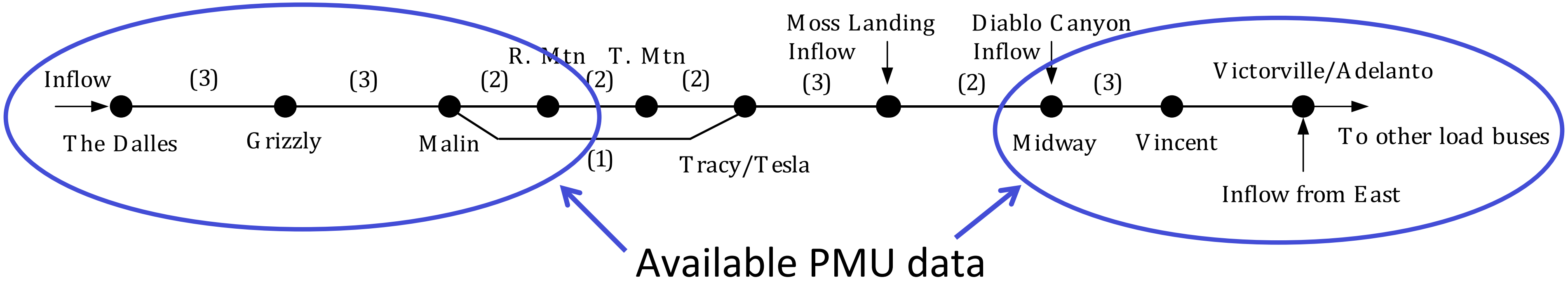
Application to WECC System

- Ongoing work with BPA and SCE to obtain PMU data
  - Establishing PMU-observable region
  - Choose study regions based on available data

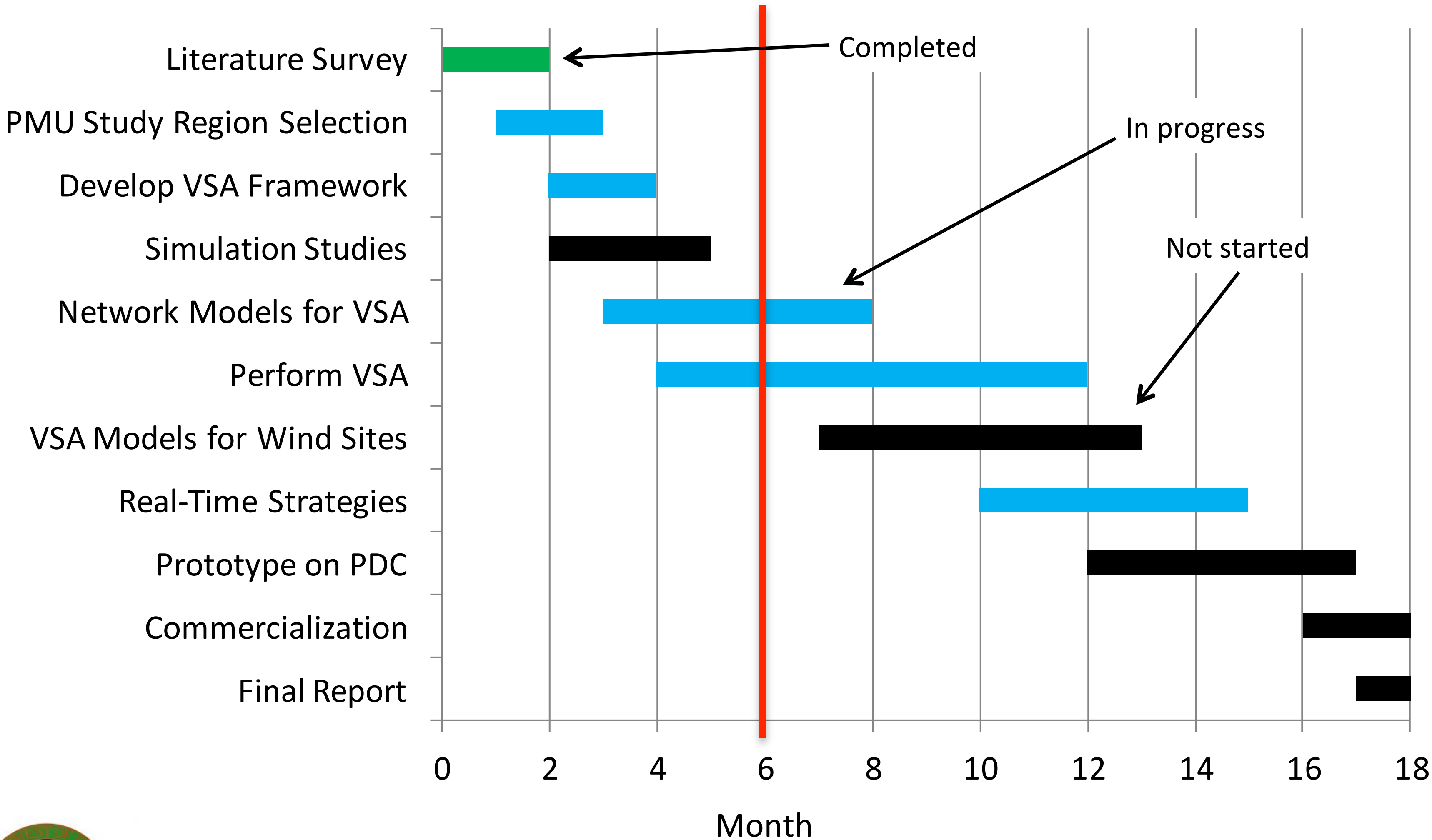


- Future work:
  - Plan to extend coverage with additional PMU data
  - Obtain PMU data from BPA, SCE, PG&E, and others
  - Require network parameters
  - Comparison of VS method with simulation studies

Project Status

- Start date: January 2013
- Accomplishments for this year:
  - Preliminary work on PMU-based VS models
  - Development of a new method for fast voltage stability margin computation (for real-time application)
  - Intellectual property disclosure filed with RPI Technology Commercialization division
  - Agreements in place with BPA and SCE for data-sharing
- Deliverables for this year:
  - Reports: Literature survey, PMU locations and study regions, and VSA framework (*AQ*-bus method)

Project Timeline



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Risk Factors & Future Plans

- Risk Factors:
  - Receiving input, participation, and feedback from system operator stakeholders
  - Obtaining good PMU data coverage and other data

- Ongoing/Future Plans:
  - Collect additional data (PMUs, network parameters)
  - Cross-correlate PMU data in a phasor state estimator
  - Validate PMU-based VS models with simulation studies
  - Apply *AQ*-bus method to WECC system with real data
  - Develop prototype software for real-time operation