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CENTER FOR ULTRA-WIDE-AREA RESILIENT ELECTRIC ENERGY TRANSMISSION NETWORKS

DOE Research Project: PMU-Based Voltage Stability

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Voltage Stability 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

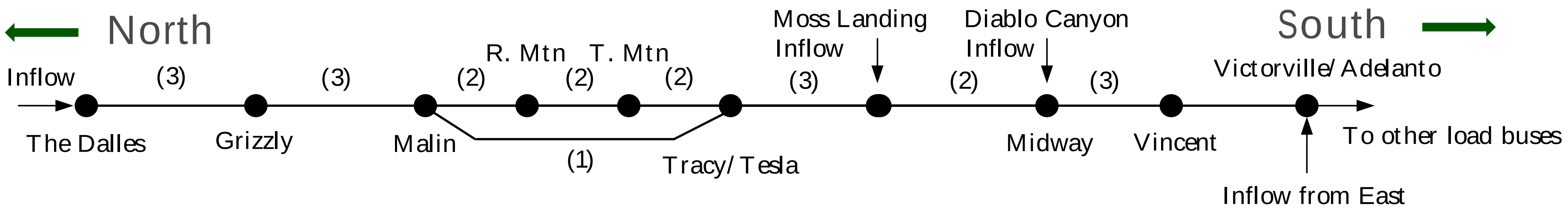
Increasing level of complexity →

Single load center, VIP model	Hybrid model, PMU based, high-voltage transmission grid	Full detailed model, SCADA based

- Goal – ***development of models and analysis techniques***: Hybrid, PMU-based, voltage stability mode with less computation than VSTAB-type programs but capable of handling more complex power transfer paths

Project Overview

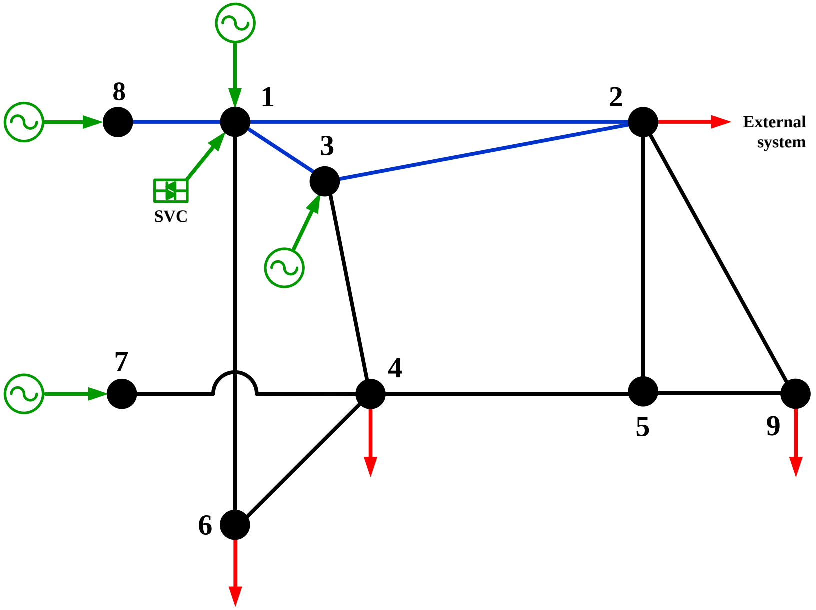
- Voltage stability of a complex transfer path (Pacific AC Intertie):

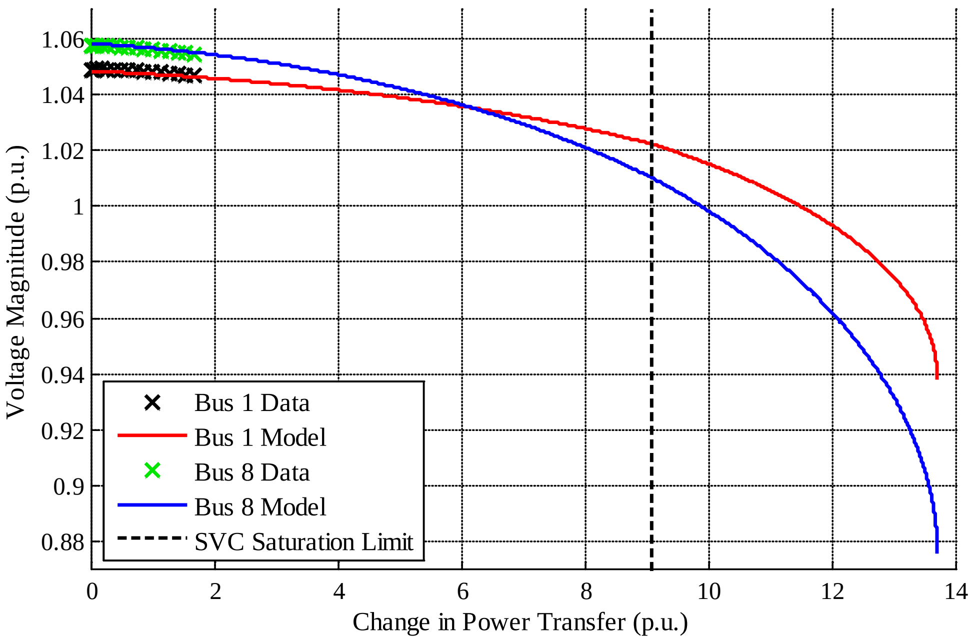


- Network characteristics:
  - Large number of injection and out-flow points
  - Load areas with multiple in-feeds
- Important information to know
  - PMU data: for obtaining actual voltage sensitivities, injections, and out-flows
  - Multiple vulnerabilities and reactive power supply at each location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

PMU-Based Voltage Stability for Central NY System

- 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

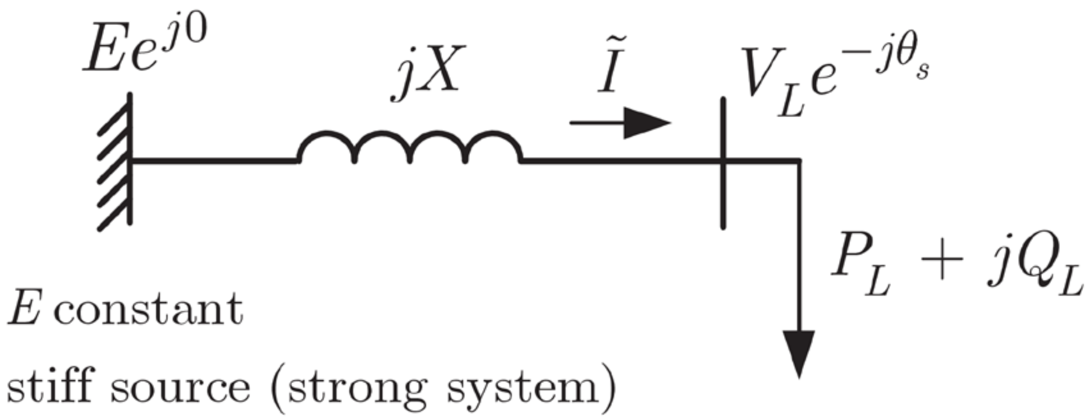




Voltage Stability Margin Calculation

- 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 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

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

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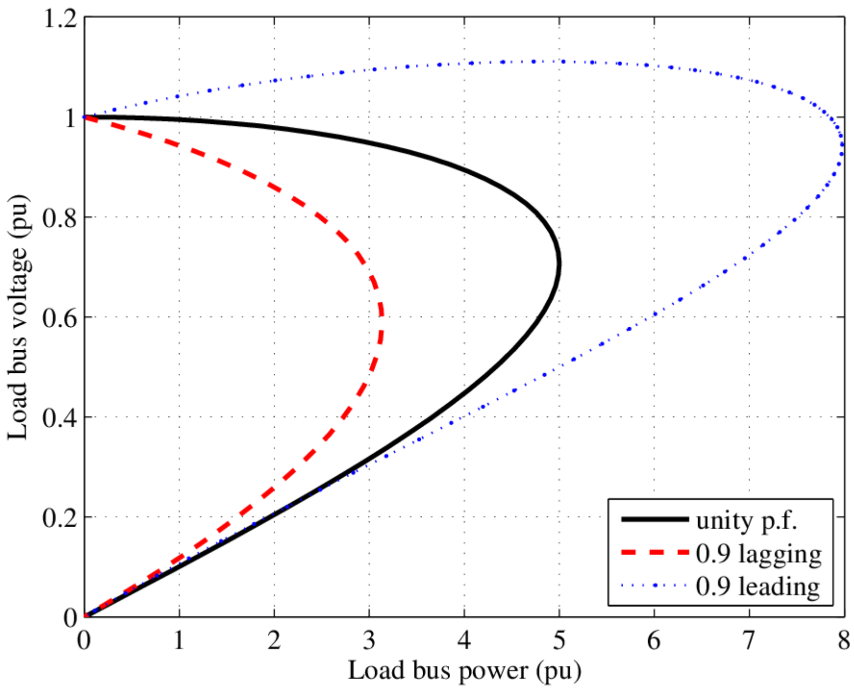
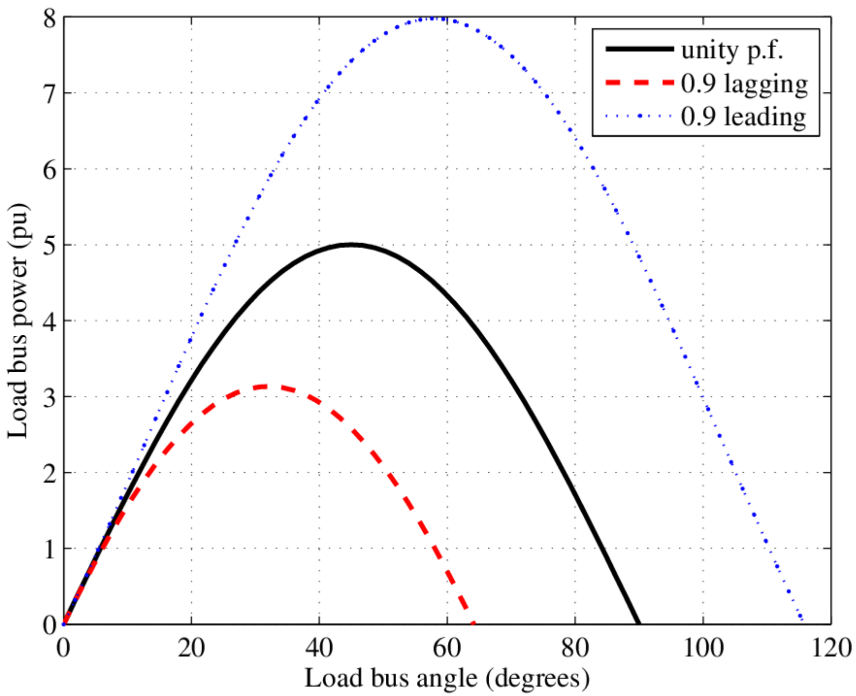
PV Curves and Angle Separation

- 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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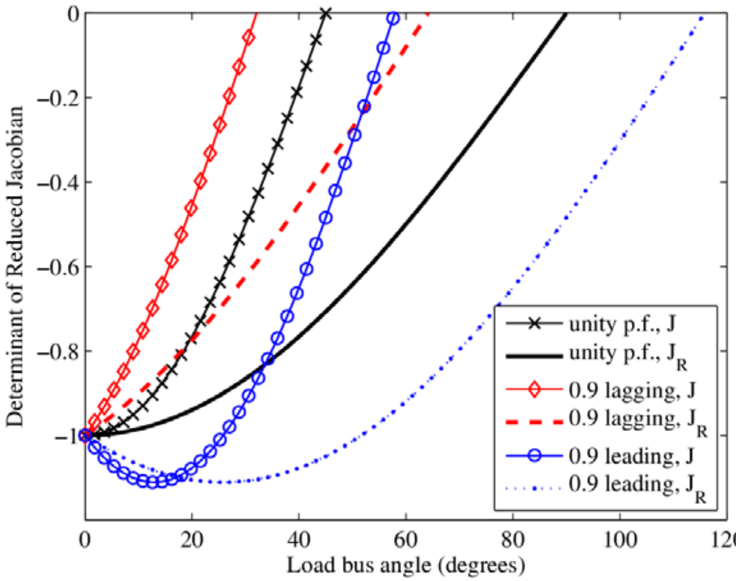
New Idea: Specify the Angle for VSA

- 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 at the maximum loading point:



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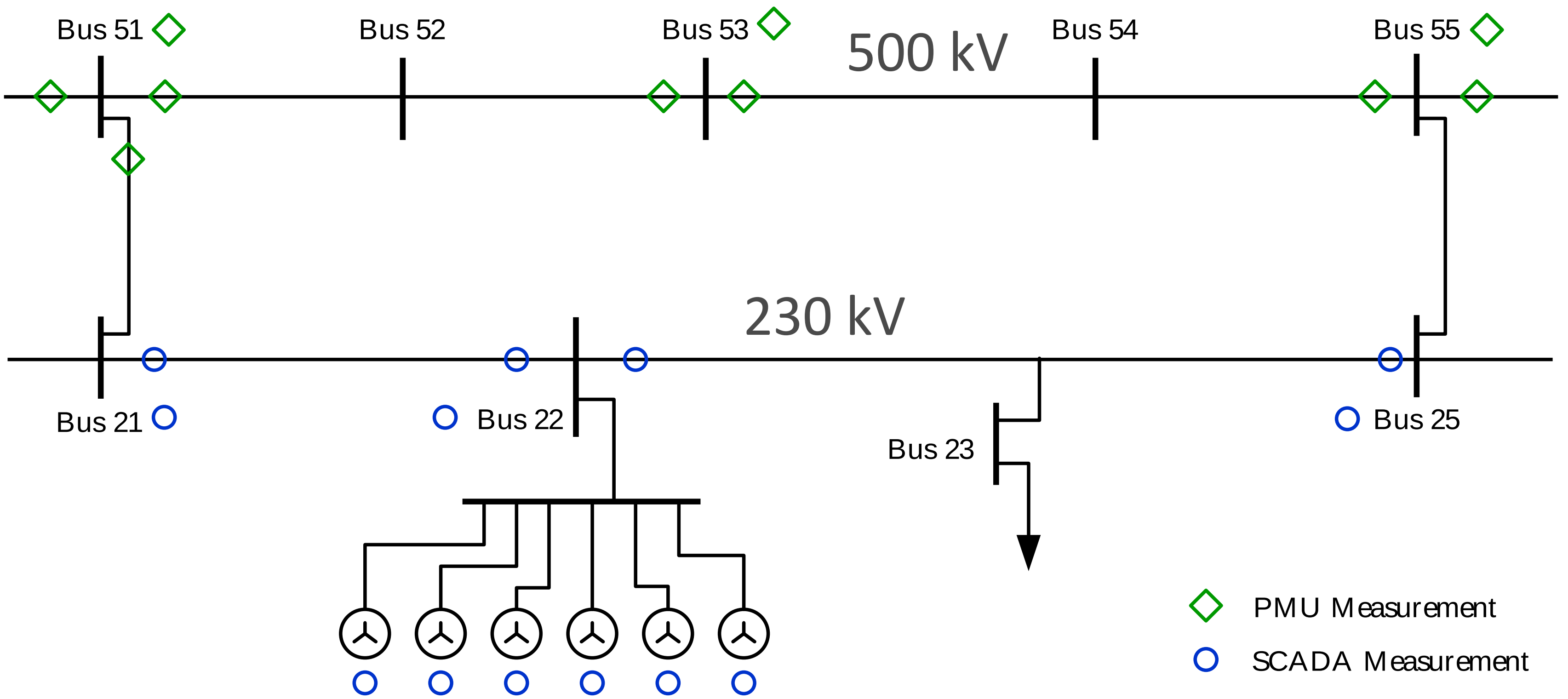
Advantages of *AQ*-Bus Method

- Calculate VS margins by increasing *AQ*-bus angle
- Accommodates multiple loads and generators
- Allows for various load types, such as 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

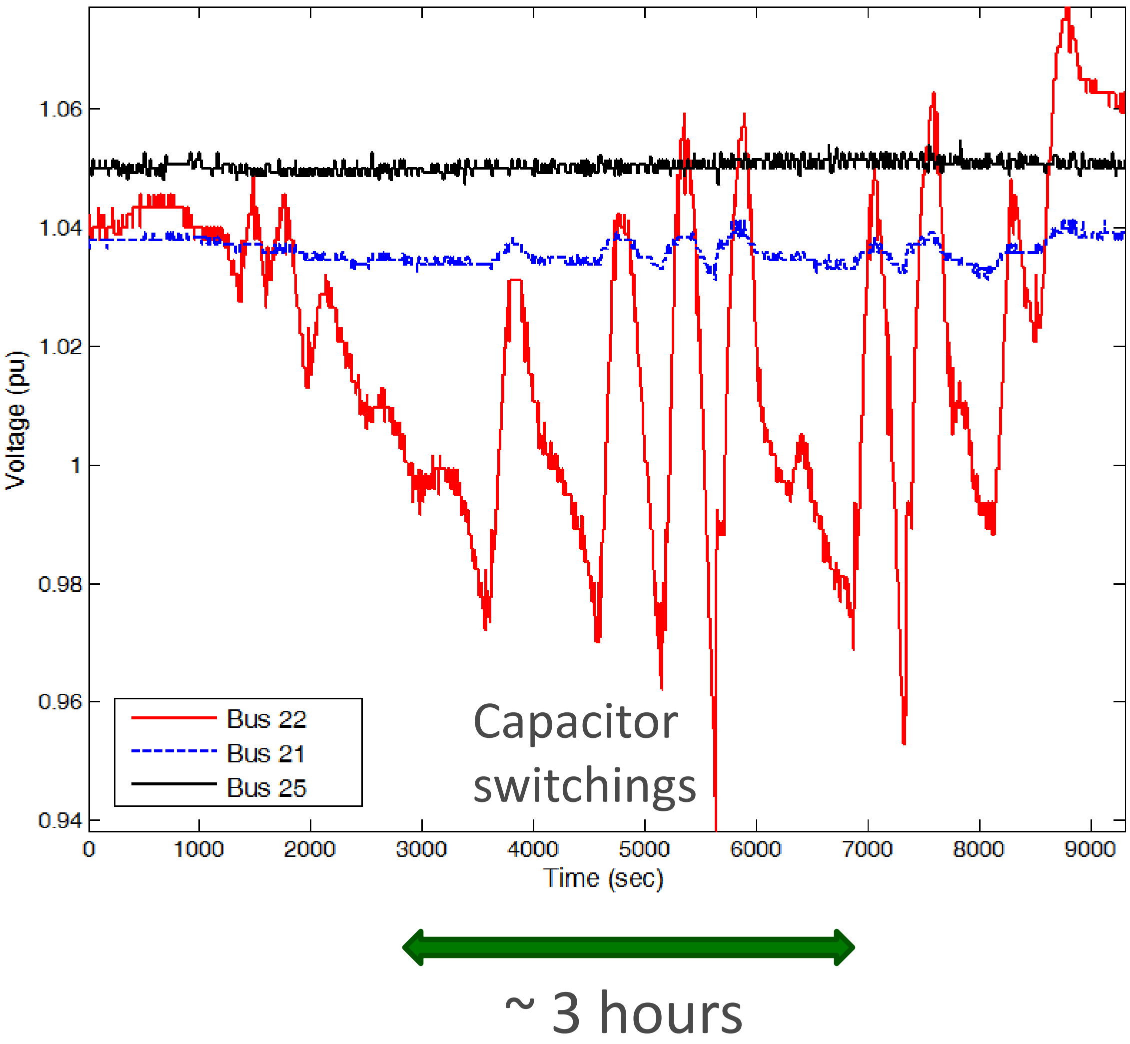
BPA Wind Farm Voltage Stability Study

- One-line diagram of a small portion of BPA system, with 6 wind farms connected to Bus 22.
- Connection from Bus 22 to Bus 21 is strong, but the link from Bus 22 to Bus 25 is weak.



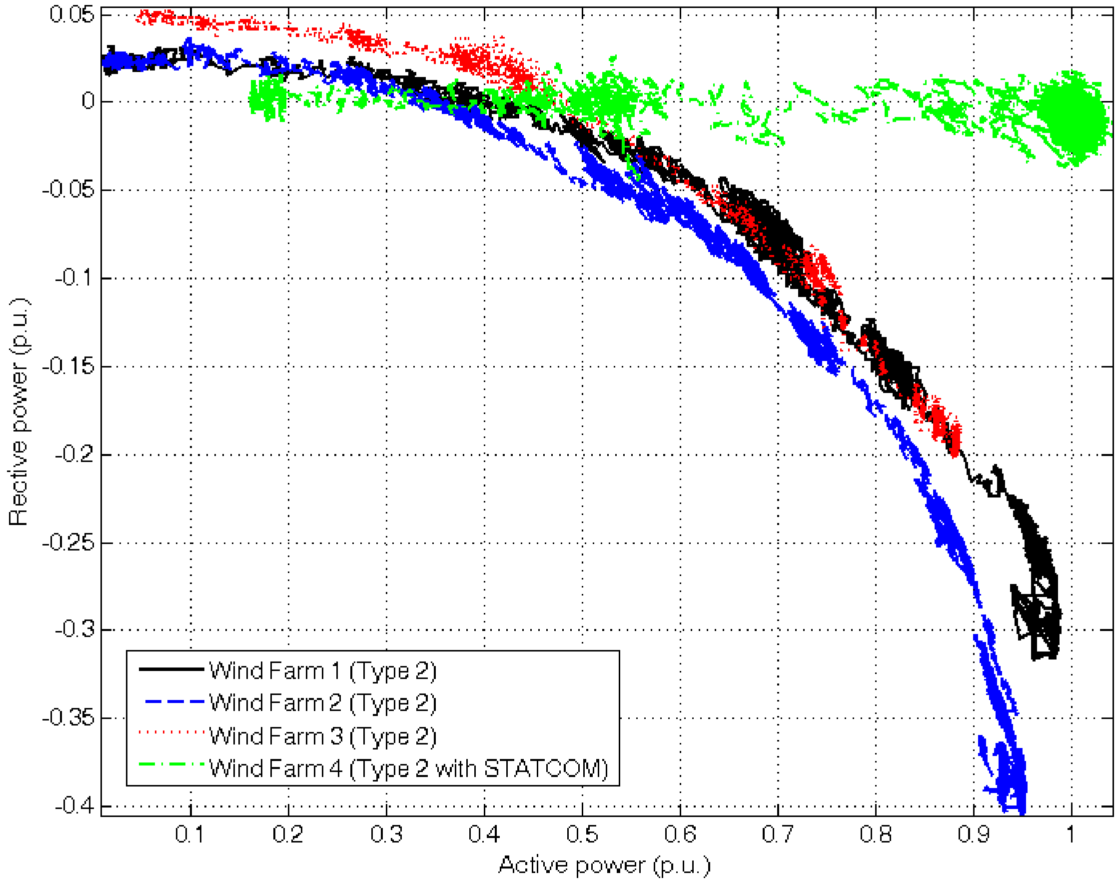
Voltage Variations with Outage of Strong Link

- SCADA data showing voltage response on Buses 21, 22, and 25, with Line 22-25 out of service. The voltage jumps are WTG trips.
- The project is to determine wind turbine reactive power control models and voltage stability limit.
- The wind farms cannot produce full output in this scenario.



Wind Farm PQ Relationship (Type 2 turbines)

- SCADA data showing the PQ characteristics of three wind farms (Type 2) connected to Bus 21.
- Note that the wind farm consumes reactive power as the active power is increased.
- The STATCOM on Wind Farm 4 mitigates this effect.



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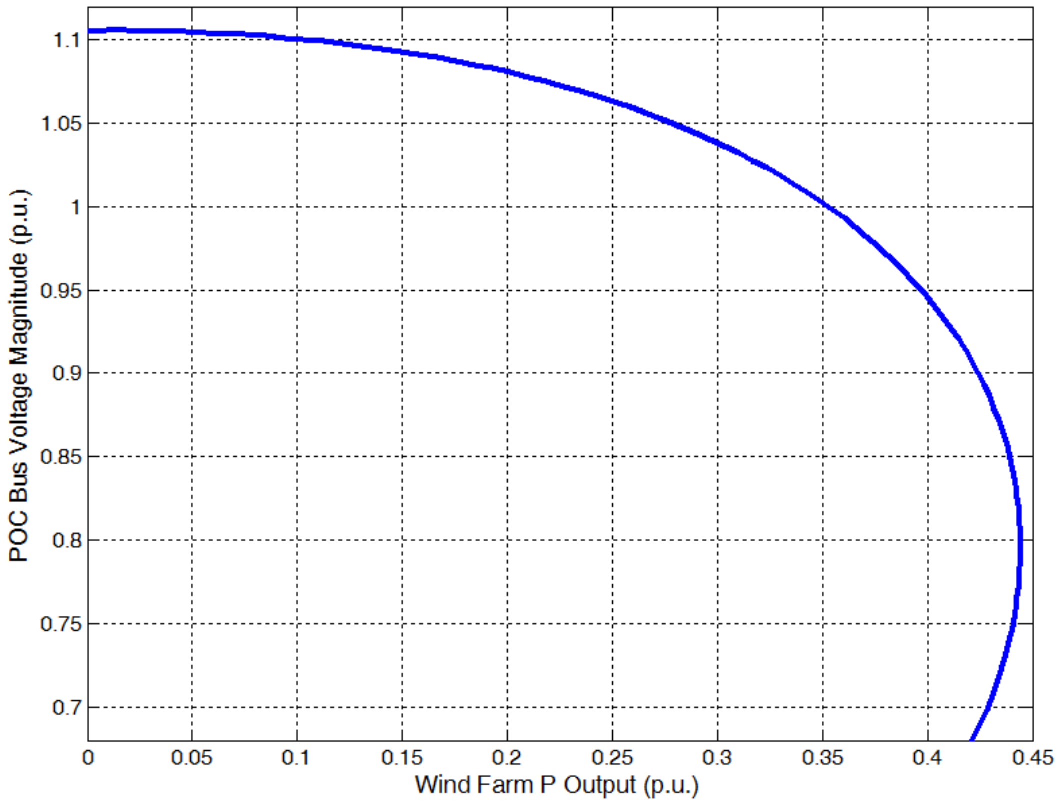
PV Curves for Strong Link Outage Scenario

- Steady-state PQ models for wind farms using SCADA data
- Included STATCOMs and shunt capacitors/reactors
- Wind speed uniform at all wind farms
- PV curve shows high voltage variability at the POC
- Wind farm output is limited by voltage stability



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Next Steps and Future Work

- Wind farm study:
  - Voltage stability under different wind scenarios
  - Effects of other line outages
  - Various levels of power transfer from Bus 21 to Bus 25
  - Using synchrophasor data
- Other potential study areas in WECC
  - Southern California Edison: Los Angeles
  - Olympic Peninsula in Washington State
- Development of a prototype for real-time voltage stability analysis using PMU data

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