An Affine Arithmetic Based Method for Voltage Stability Assessment of Power Systems with Intermittent Generation Resources

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Outline

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• Background review:
  – Voltage stability definitions and analysis techniques
  – Affine arithmetic-based power flow
• Affine arithmetic PV curve computation
• Simulation results and discussions
  – Case A: 5-Bus test system
  – Case B: 118-Bus test system
• Conclusions
• Future work
Motivation

• Intermittent renewable energy sources penetrating electricity grids:

2030 Projected Generation (TWh) in Ontario (source: OPA)

- Nuclear: 46%
- Gas: 14%
- Wind (uncertain): 20%
- Solar PV (uncertain): 10%
- Bionergy: 1.3%
- Water: 1.5%
- Conservation (uncertain): 7%
Motivation

• Uncertainties associated with wind power injections:
Motivation

• Uncertainties associated with wind power injections (http://ets.aeso.ca/):
Motivation

- Uncertainties associated with solar power injections (http://www.nrel.gov/):
Motivation

• Some available methods to deal with uncertainties are computationally inefficient and/or mathematically complex.
• Power system stability is affected by intermittent sources of power.
Objectives

• Develop computationally efficient methods based on AA for systems with intermittent renewable sources for stability assessment.

• Study the computational effort of the proposed methods using “realistic” test systems.
Voltage Stability Analysis

• Refers to the ability of the power system to maintain acceptable voltage levels in normal conditions and after the system is perturbed.

• Can be associated with short-term or long-term phenomena.
Voltage Stability Analysis

• Continuation power flows can be used to assess the maximum loadability:
AA-Based Power Flow

1. Start
2. Operating Condition Intervals
3. Computation of Central Values for Voltages and Angles
4. Computation of Affine Forms for Voltages and Angles
5. Computation of Affine Forms for Active and Reactive Powers
6. Contraction Algorithm
7. Compute Affine Forms for Reactive power Generated at PV Buses
8. Any Limit Violation? (Yes/No)
   - Yes: PV-PQ bus type switching
   - No: Print Bounds
9. End
AA-Based PV Curve Computation

- Load power equations:

\[
\hat{P}_{Li}(\lambda) = P_{Loi} + \hat{\lambda}\Delta P_{Li} \quad \forall i = 1, \ldots, N
\]

\[
\hat{Q}_{Li}(\lambda) = Q_{Loi} + \hat{\lambda}\Delta Q_{Li} \quad \forall i = 1, \ldots, N
\]

where:

\[
\hat{\lambda} = \lambda_o + \sum_{m \in N_{IG}} \frac{\partial \lambda}{\partial P_{Gm}} \bigg|_o \Delta P_{Gm} \mathcal{E}_{IGm} + \sum_{n \in N_{CV}} \frac{\partial \lambda}{\partial V_n} \bigg|_o \Delta V_n \mathcal{E}_{CVn}
\]
AA-Based PV Curve Computation

• Voltages and angles can be represented as:

$$\hat{V}_i = V_{oi} + \sum_{m \in N_{IG}} \frac{\partial V_i}{\partial P_{Gm}} \Delta P_{Gm} \varepsilon_{IGm} + \sum_{n \in N_{CV}} \frac{\partial V_i}{\partial V_n} \Delta V_n \varepsilon_{CVn} \quad \forall i \in N_Q$$

$$\hat{V}_n = V_{on} + \left(V_{\text{max}_n} - V_{on}\right) \varepsilon_{CVn} \quad \forall n \in N_{CV}$$

$$\hat{\theta}_i = \theta_{oi} + \sum_{m \in N_{IG}} \frac{\partial \theta_i}{\partial P_{Gm}} \Delta P_{Gm} \varepsilon_{IGm} + \sum_{n \in N_{CV}} \frac{\partial \theta_i}{\partial V_n} \Delta V_n \varepsilon_{CVn} \quad \forall i \in N_P$$
AA-Based PV Curve Computation

• Parametrization technique:
AA-Based PV Curve Computation

• The power flow equations are:

\[ P_{Gi} - P_{Loi} - \hat{\lambda} \Delta P_{Li} - \sum_{j=1}^{N} \hat{V}_i \hat{V}_j \left( G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \right) = 0 \quad \forall \ i, j = 1, \ldots, N \]

\[ Q_{Gi} - Q_{Loi} - \hat{\lambda} \Delta Q_{Li} - \sum_{j=1}^{N} \hat{V}_i \hat{V}_j \left( G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j) \right) = 0 \quad \forall \ i, j = 1, \ldots, N \]

• In compact form:

\[ A_{vs} \varepsilon_{vs} = C_{vs} \]

\[ C_{vs} = L_{vs} - \left( R_{vs} + q_{vs} \right) \]
AA-Based PV Curve Computation

• Linear programming formulation:

Min \[ \sum \varepsilon_{IG_{\text{min}}} + \sum \varepsilon_{CV_{\text{min}}} \quad \forall m \in N_{IG}, \forall n \in N_{CV} \]

st \[-1 \leq \varepsilon_{IG_{\text{min}}}, \varepsilon_{CV_{\text{min}}} \leq 1\]

\[ C_{VS_{\text{min}}} \leq A_{VS} \varepsilon_{VS_{\text{min}}} \leq C_{VS_{\text{max}}} \]

Max \[ \sum \varepsilon_{IG_{\text{max}}} + \sum \varepsilon_{CV_{\text{max}}} \quad \forall m \in N_{IG}, \forall n \in N_{CV} \]

st \[-1 \leq \varepsilon_{IG_{\text{max}}}, \varepsilon_{CV_{\text{max}}} \leq 1\]

\[ C_{VS_{\text{min}}} \leq A_{VS} \varepsilon_{VS_{\text{max}}} \leq C_{VS_{\text{max}}} \]
AA-Based PV Curve Computation

- Algorithm:
  1. Start
  2. Read system data and define intervals for intermittent sources of power
  3. Choose the PQ-bus voltage magnitude $V_p$ as varying parameter
  4. Compute central values of affine forms
  5. Compute affine forms for voltages, angles, and $\lambda$
  6. Compute power flow equations in affine form
  7. Rearrange the power flow equations
  8. Solve the resultant linear programming problems
  9. Compute the reactive power output of generators
  10. Check for any limit violation?
     - Yes: Convert concerned PV Buses into PQ Buses
     - No: Compute $\lambda_{\text{max}}$ and $\lambda_{\text{min}}$
  11. If $V_p = V_p + \Delta V_p$, then:
     - No: Stop
     - Yes: Print results and end

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Simulation Results

• Case A is a 5-bus test system. GEN 2 is assumed to be an intermittent power source, with a variation of ±50% with respect to its central output power.

• The voltage controlled by this generator is allowed to vary within ±2%.
Simulation Results

• Case A PV curves:

![Graph showing PV curves with markers for MC Lower Bound, MC Upper Bound, AA Lower Bound, and AA Upper Bound. The graph plots BUS 2 Voltage Magnitude (p.u.) against LOAD (MW).]

Difference:
- 0.803 % for Maximum λ
- 0.854 % for Minimum λ
Simulation Results

• Case A GEN 2 reactive power:
Simulation Results

• Case B is the 118-bus benchmark system.

• The synchronous generators located at buses 10, 25 and 49 are treated as intermittent power sources.

• The power at GEN 10 is allowed to vary within 450 and 585 MW, the power at GEN 25 within 220 and 286 MW, and the power at GEN 49 within 204 and 265.2 MW, which represent a 30% variation.
Simulation Results

• Case B PV curves:

Difference:
0.42 % for Maximum λ
0.83 % for Minimum λ
Simulation Results

• Case B GEN 6 reactive power:
Conclusions

• The proposed methodology is able to compute the bounds for the static load margins when the system presents uncertainties associated with intermittent sources of power such as wind and solar power.

• The obtained results presents reasonably accuracy when compared with those obtained using MC simulations, at significantly lower computational costs.

• The accuracy of the proposed method is questionable when the size of the intervals that models the corresponding uncertainties is very large.
Future Work

• AA-based transient stability:
Thanks!