Real-Time Voltage Stability Monitoring using PMUs

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The research questions:

1. How to detect the inception of a voltage collapse?

2. How to take the optimal control actions against voltage collapse?

Use PMU-data
Some key elements to voltage instability

Voltage:
• Large voltage drops in one or more buses.

Instability:
• Beyond the maximum deliverable power, the power and the voltage decrease together.

Dynamics:
• Predicting the evolution of the system - need to know underlying dynamics and structure of discrete events.

Loads:
• Load behavior often drives evolution to voltage instability, need to model the (net) loads.
We explore the following means to assess the voltage stability:

- **Lyapunov exponents** – measure the evolution of dynamic systems:
  - Simulated or estimated from PMU data
- **Thevenin equivalents** – estimate the maximum transferable power:
  - Calculated and/or estimated from PMU data.
- **Stability boundaries in parameter space:**
  - From measurements.
  - Utilize machine learning to construct these.
Research on Thevenin Equivalent Estimation

Old approaches: Measurement-based algorithms often solve eq’s from PMU data on the form:

\[ Ax = (b + D b) \]

New approach: consider disturbances on both sides – solve using total least squares.

\[ (A + D A)x = (b + D b) \]

Results: Case study showing improvements
The P-V curve from real PMU data

- Process and measurement noise, transients, large jumps.
- Loss of local generation can be viewed as net load increase.
- Overvoltage load shedding reduces the load even further.
- Need to take into account that net load increases and the protection.
The Q-V curve from real PMU data

- Increasing reactive power consumption
- Not clear how much Q margin exists, without supplemental estimation.
- As for the P-V curve, the PMU is not at the collapsing bus.
Testing algorithms in a real-time environment

- **Stream PMU-data**: Able to subscribe to stream data to Labview from PMUs sent by a PDC.
- **Implemented so far**:
  - Thévenin equivalent methods
  - Sensitivities
  - Lyapunov exponents
- **Testing by**:
  - Real PMU-data
  - RT-HIL PMUs for 5-bus system and Nordic32-models
PMU situated wrongly: We can see that the impedance margin is decreasing before the collapse, but we do not get any cross-over.

Dynamic behavior was a net load increase and then shedding.

Real-time execution of the algorithm(s).
Testing sensitivity calculation with Hardware in the Loop

- Nordic 32-model, monitoring two different load centers.
- Indicates which bus that is most voltage sensitive w.r.t transmitted line power.
Lyapunov exponents

• Rate of divergence between two starting points that are “near”.

• Use that voltage unstable system will have voltages that diverge from a starting point.

• If magnitude of voltage derivative is increasing (slope > slope) - rate of divergence is increasing.

• Positive Lyapunov exponent – (transiently) unstable.
Lyapunov exponents

Calculate either by:

- **Simulation**, start from a “near” point to the one of the real system and measure the divergence.

- **Signal-based**: Or, try to estimate the exponents from directly from measured signals.
Test of the LE algorithm – Unstable case

- Correctly indicates instability before collapse
- Dependent on chosen parameters in the algorithm, e.g. buffer length, dead-band.
Test of the LE algorithm – Stable case

• Correctly indicates stability.

• The exponent’s magnitude will decrease over time.
Important considerations with real-time PMU voltage stability monitoring

- System does not behave ideally. Impact from noise, transients, and discrete changes.
- Location of PMUs
- Machine learning to classify stability and control to alleviate voltage stability problems
Future work

• Combine *machine learning* scheme with one or more of the considered stability indicators

• Investigating *stabilizing control*.

• Investigate the *performance of the integrated prediction and control* methods.

• Test the feasibility of the above as a *RT application*. 