WARP: Wide Area Resilient Protection

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PROBLEM

- One wrong move by a protective relay during stressed operation can spell disaster for the power grid; Eg: '03 NE Blackout
- A "tipping point" for the '03 NE Blackout was a mis-operation by a distance relay on a 345kV circuit (Sammis-Star); (but hindsight is 20/20!)
- Can we in real-time, detect and correct mis-operations? Fast enough to avert an impending cascade?

KEY IDEAS

Relays today:

- Do not have global information on system stability, i.e. they are blind to the effect of their action on global stability of the system;
- Do NOT include dynamic state information in tripping decisions;
- Lock-out permanently after a pre-programmed sequence;
- Can mis-operate under extremely stressed conditions; No way to detect if operation was valid; No way to correct for mis-operations;
- Modern relays can be made to mis-operate by a cyber attack;
- A "D-uh" moment can be expensive!

What we propose:

- Supervise relay operation using dynamic state information and event "fingerprints" from wide-area measurement sets;
- Analytical approach based on energy functions to supervise relay operations associated with transmission lines;
- If relay operation is deemed "correct", do nothing. If relay operation is "incorrect", then correct (reverse) relay operation by switching in/out the system component; Resilience achieved by recovery from misoperations

How?

- Estimate the system's dynamic state from Phasor Measurement Unit (PMU) data;

$$\dot{x} = f(x, y, u, u_R)$$
$$0 = g(x, y, u, u_R)$$

- Given "measurements": some y's and z's = h(x,y), estimate x.
- f(.) represents ODE models of all dynamic units: (generators/exciters/prime-movers/control units);

* g (.) represents all the algebraic constraints (power-flow at each bus);

- Estimation needs to be accurate and robust – Instead of Kalman-based approaches, we use a Particle Filter; (speed-accuracy tradeoff)
- Estimated dynamic states are used to:

-- construct components of the system's energy functions which are very rich in dynamic information at the component level (such as generators, transmission lines, transformers, and loads)

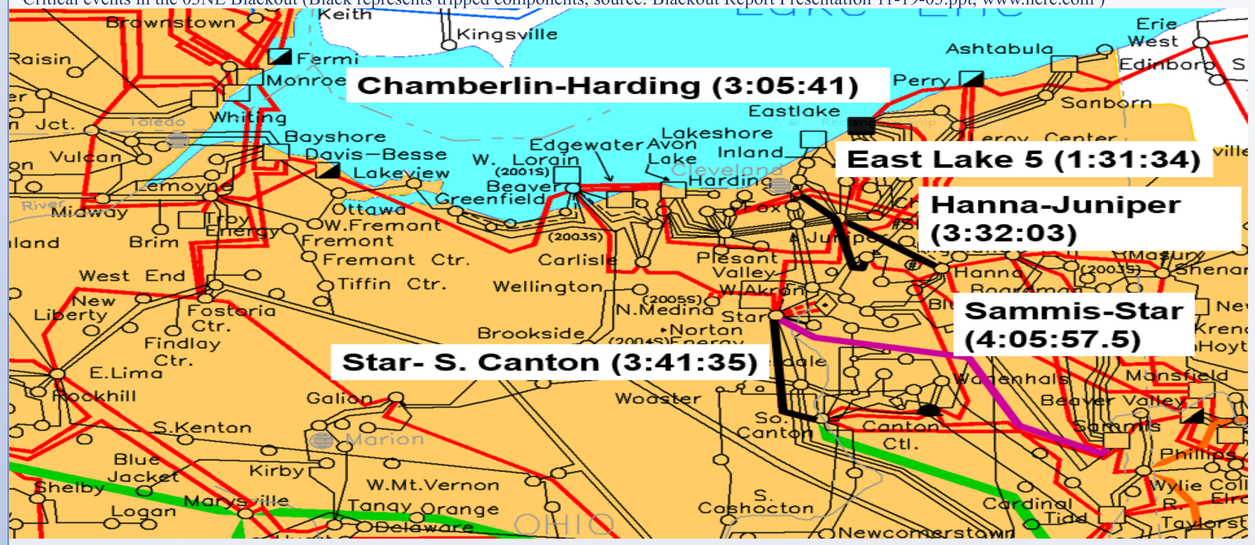
--detect and flag "events" that might be detrimental to system stability

--also used to forecast states in over a short time-horizon for look-ahead capabilities for

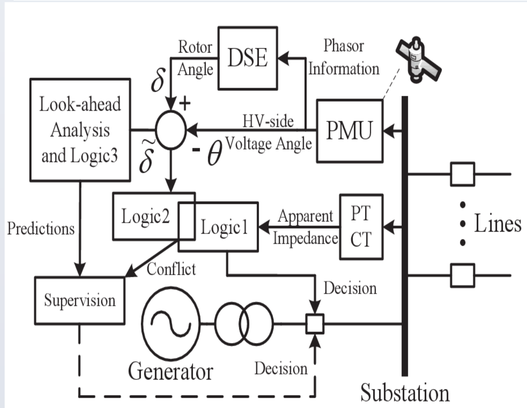
Challenge: Can we be "fast" enough? - For a clue, look at the time-stamps of events in the sample blackout log!

KEY ENABLER: DYNAMIC STATE ESTIMATION

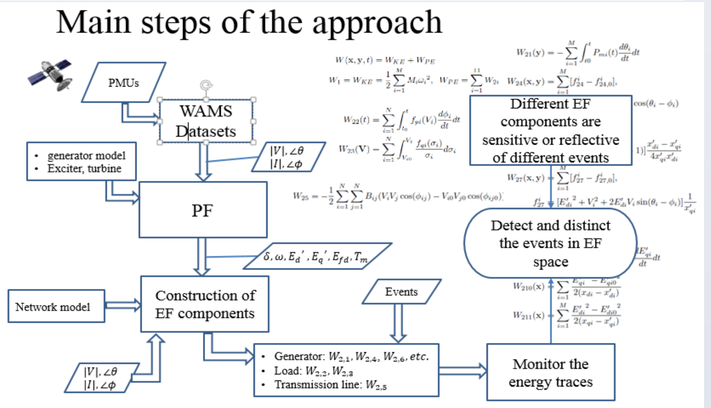
Critical events in the 03NE Blackout (Black represents tripped components, source: Blackout Report Presentation 11-19-03.ppt, www.nerc.com)

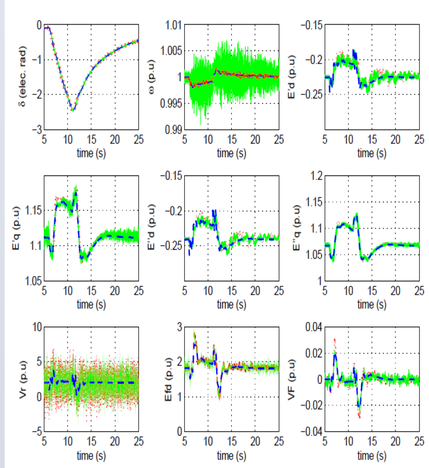


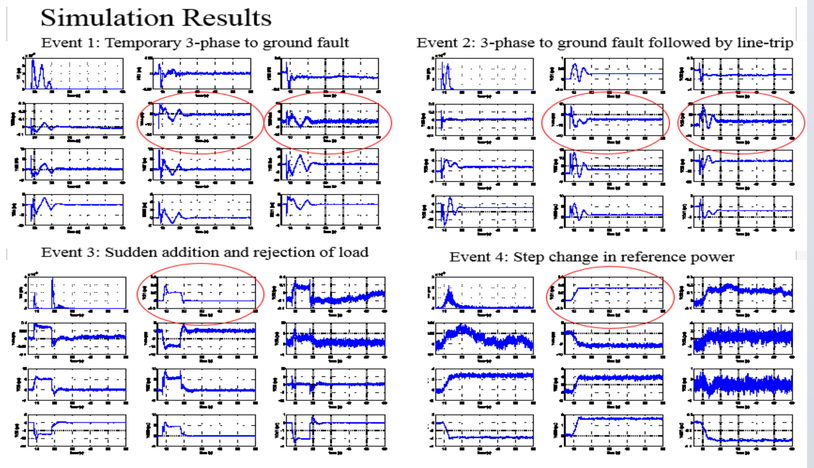
Scheme used to incorporate dynamic state information:



RESULTS (from [1], [2], and ongoing work)







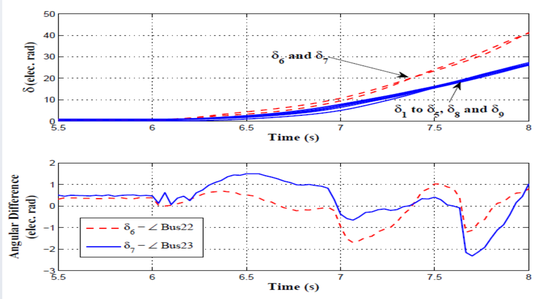
More Results/Observations

- State reconstruction also allows for prediction and early warning;
- Able to achieve 10-15 cycle (up to 0.25 s) look-ahead capabilities during power swings;
- Reconstructed states can also be used to directly assess (and predict) the damping of rotor angle swings. Table shows damping mode of local mode assessed using reconstructed states, for an unstable swing;

Modal damping of swings assessed via DSE

Report Time	Frequency (Hz)	Damping Ratio (%)
t=7.42s	1.096	-36
t=7.78s	1.192	-5.97
t=8.2s	1.202	-6.41
t=8.7s	1.259	-10.11

Global swing curves and system separations assessed with DSE



CONCLUSIONS/FUTURE WORK

- DSE allows for several possibilities that are being explored:
  - a direct look at system dynamics during stressed system operation;
  - construction of energy function components that can yield clues to event detection and classification;
  - ability to supervise both generator and transmission line relays from wide-area data sets;
- DSE also allows relays to gain a "slight" lead over impending system dynamics;
- The information extracted during this lead-time (modal damping, angular separations) can be used to make a more informed decision: i.e. opportune trip moments (for trips) or avert false trips (when detected)
- Impact of reversals in trip decisions on system dynamics and cascades needs to be studied
- Use of energy-function based event fingerprinting needs to be refined;

Acknowledgements

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References:

1. Y. Cui and R. G. Kavasseri, "A Particle Filter for Dynamic State Estimation in Multi-Machine Systems With Detailed Models", *IEEE Transactions on Power Systems (2015)*
2. R. G. Kavasseri, Y. Cui and S. Brahma, "A New Approach for Event Detection based on Energy Functions", *Proc. IEEE PES General Meeting*, National Harbor, MD, July 27-31, 2014

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