Early warning signs of instability in the statistical properties of PMU data

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US Northeast and Canada
August 14, 2003
50 million people
California, Arizona, Mexico
September 8, 2011
5 million people
Northern India
July 30, 2012: 350 million people
July 31, 2012: 700 million people
Officials said it would take at least 12 hours to repair the system and restore power to the capital Dhaka [AP]
Washington DC, April 7, 2015
Inadequate Situational Awareness

The 2003 Blackout Report stated, “A principal cause of the August 14 blackout was a lack of situational awareness, which was in turn the result of inadequate reliability tools and backup capabilities.”\textsuperscript{109} Similarly, the instant inquiry determined that inadequate real-time situational awareness contributed to the cascading outages. In
Critical Slowing Down

Early-warning signals for critical transitions

Marten Scheffer¹, Jordi Bascompte², William A. Brock³, Victor Brovkin⁵, Stephen R. Carpenter⁶, Vasilis Dakos¹, Hermann Held⁶, Egbert H. van Nes¹, Max Rietkerk⁷ & George Sugihara⁸
Power systems are constantly “bumped” by randomness

Can that statistical responses to these bumps, measured in PMU data, tell us about the health of the grid?
Statistics can be useful indicators


See also:
Susuki and Mezic, IEEE Trans. Power Syst., 2012 (and others)
How can we find the useful* statistical early warning signs?

*Useful: A sign that shows up early enough that we might actually be able to do something about it, even if there is measurement noise
Model a power grid using stochastic differential equations

\[ \dot{x} = f(x, y) \]

\[ 0 = g(x, y, u) \]

Differential equations. (swing eqs., governors, exciters, etc.)

Algebraic equations

r.v. for stochastic load perturbations

\[ \dot{u} = -Eu + C\xi \]

Loads modeled as Ornstein–Uhlenbeck process

Ind. Gaussian r.v.s, 1% std. dev.

Encodes corr. time of load fluctuations
And solve to find the variance and autocorrelation of voltages and currents.

\[ A\sigma_z + \sigma_z A^T = -BB^T \]

\[ \text{E} \left[ \begin{bmatrix} z(t) \\ z^T(s) \end{bmatrix} \right] = \exp \left[-A|t-s|\right] \sigma_z \]  

Lyapunov eq.
and choose a time delay for autocorrelation measurements
Check to make sure that the analytical and numerical line up
And add measurement noise

Which we can subsequently filter to largely regain our original signal, with the interesting side-effect that some of the variance now appears as autocorrelation.
At key locations, we can see clear signs of instability in Autocorrelation and Variance

How do we measure “detectability” to distinguish useful statistical signals from non-useful ones?
Which statistics provide useful (detectable) early warning?
Variance of voltages

Not useful
Detectability
Useful
Why is variance in voltage useful?
Autocorrelation of currents

Not
useful

Detectability

Useful
Can we use these signals to build a control system?
A (simple) control system

Every few minutes: Compute critical values for voltage variance based on First Passage Probability

PMUs → Real time: Check for proximity to critical statistics → Adjust P/Q resources to restore statistics

PMUs

PMUs

PMUs
Apply to 39 bus test case
Statistical feedback allows us to make better control decisions relative to voltage-magnitude-based control.
In summary

- **Autocorrelation** and **variance** are, *sometimes*, useful indicators of proximity to instability.

- Variances of **voltages near loads** are consistently good indicators of proximity to voltage collapse, even when voltage magnitudes are not.

- Autocorrelations of **currents near generators** (particularly smaller ones) are generally good indicators of system-wide stability issues (e.g., inter-area oscillations—Hopf bifurcation).

- These statistics can be used to design statistical control systems that can **improve voltage stability**.
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