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

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*To whom all blame is due

NASPI October Working Group Meeting
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NSF Awards ECCS-1254549, DGE-1144388,
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NY city, Nov. 9, 1965
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US Northeast and Canad
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
Photo: Bikas Das/AP Photo
IEEE Spectrum, Oct. 2012

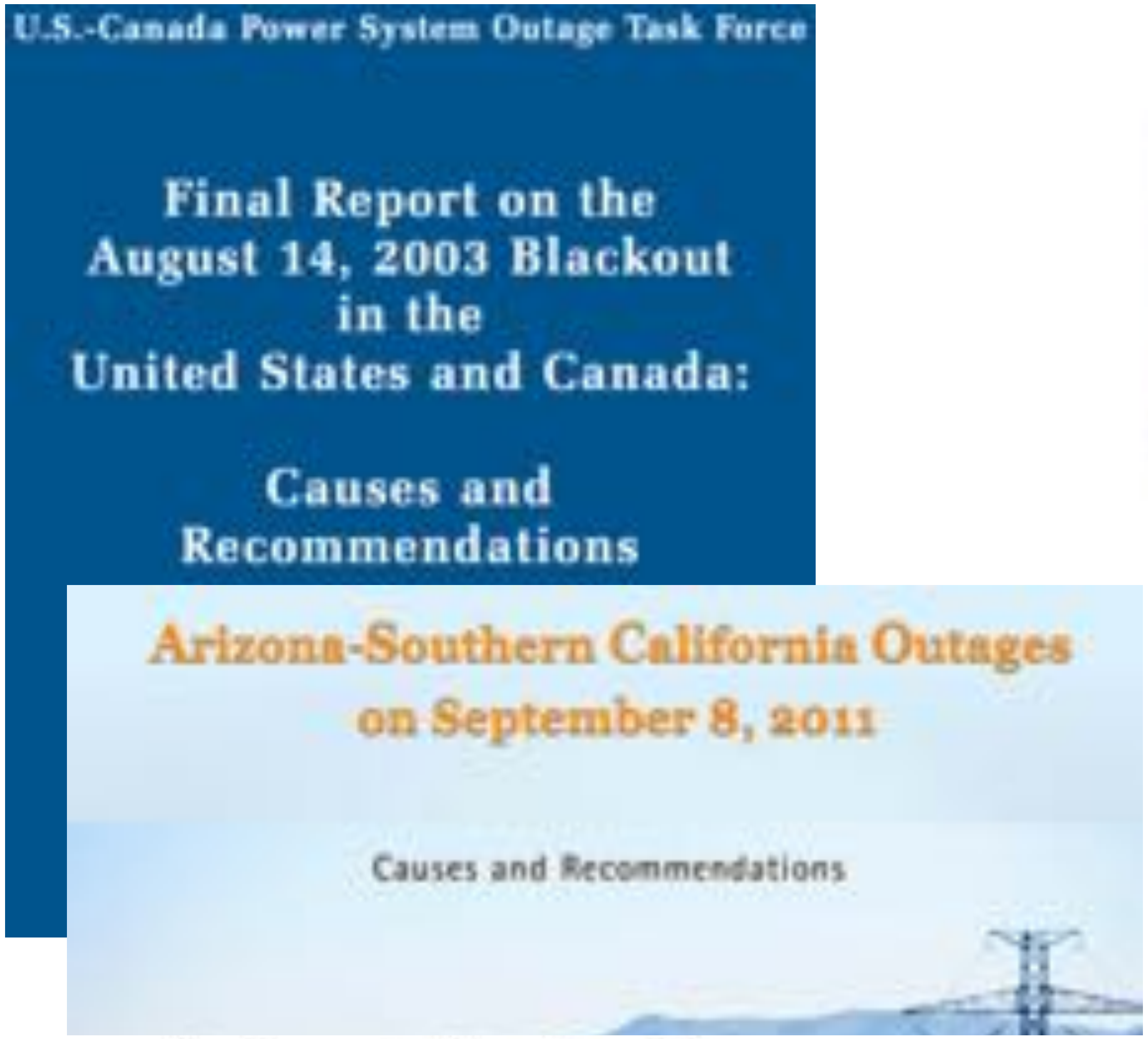
Bangledesh. 1 November 2014

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

washingtonpost.com

Situational Awareness

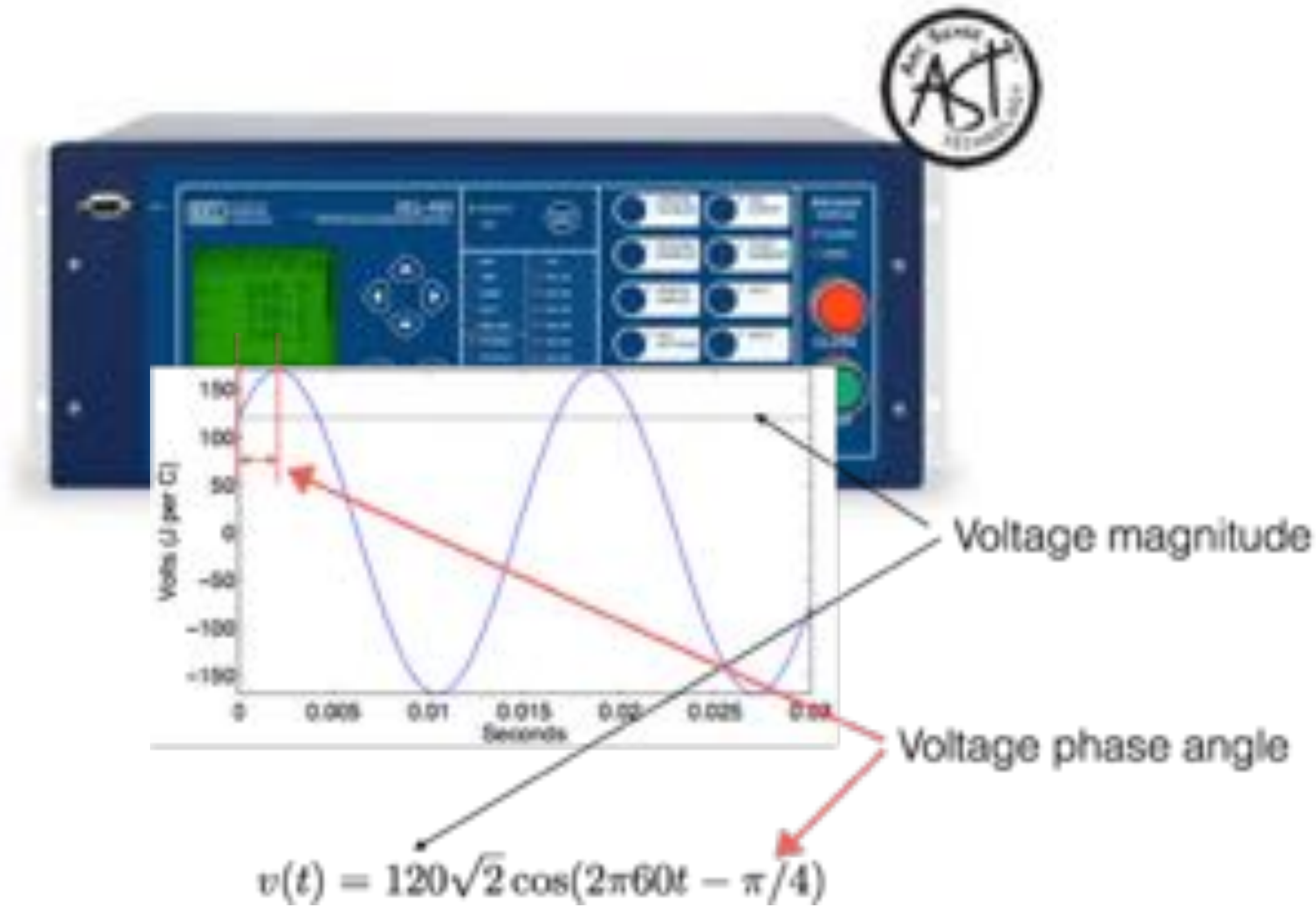

U.S.-Canada Power System Outage Task Force

Final Report on the August 14, 2003 Blackout in the United States and Canada:

Causes and Recommendations

Arizona-Southern California Outages on September 8, 2011

Causes and Recommendations



Inadequate Situational Awareness

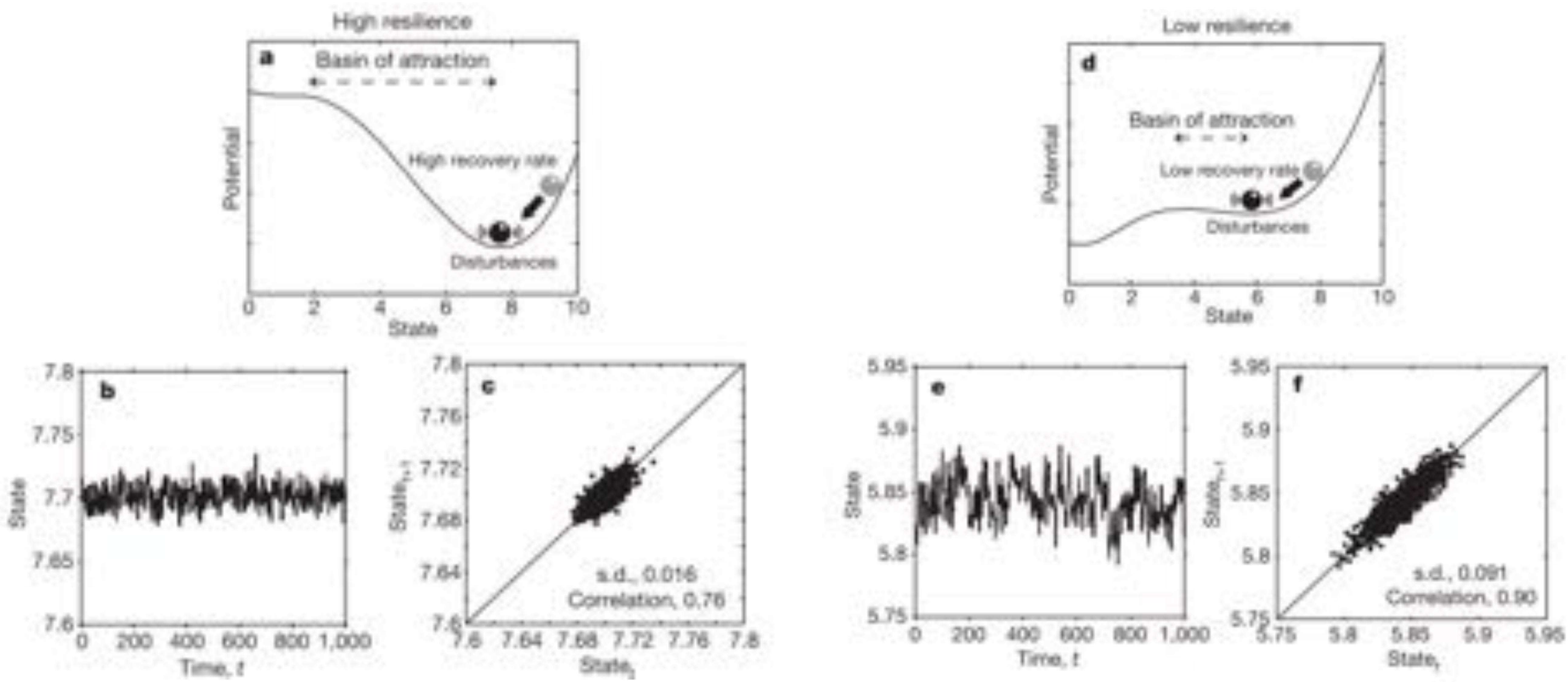
The 2003 Blackout Report stated, "A principal cause of the August 14 blackout was a lack of situational awareness, which was in turn the result of inadequate reliability tools and backup capabilities."[109] Similarly, the instant inquiry determined that inadequate real-time situational awareness contributed to the cascading outages. In

Critical Slowing Down

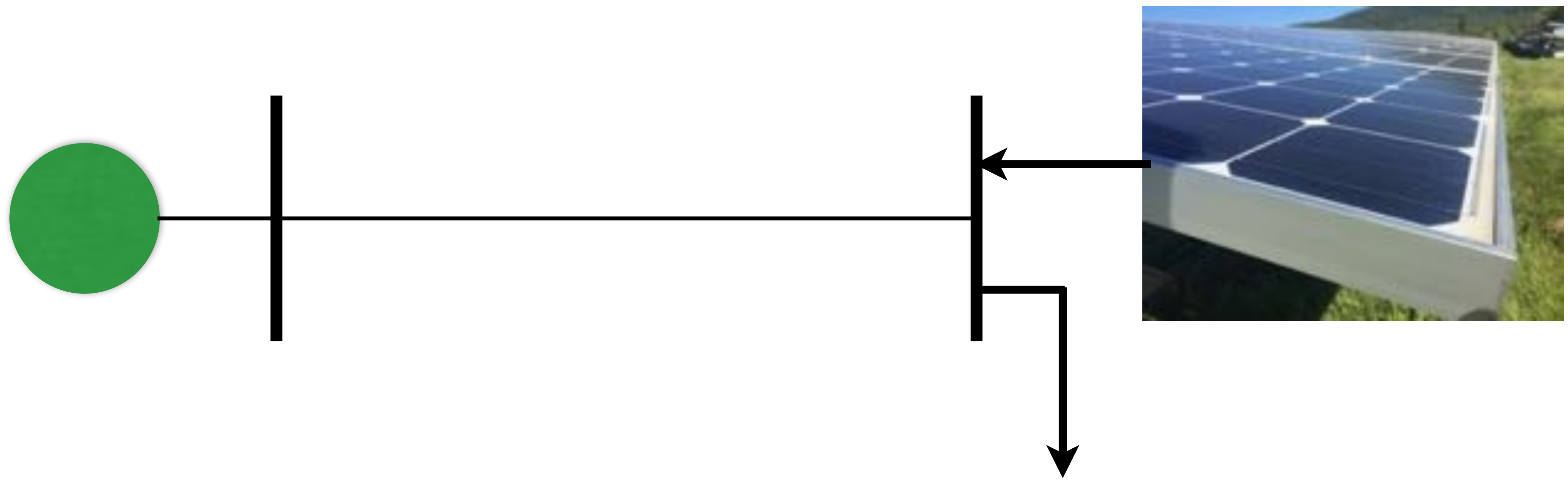
Vol 461|3 September 2009|doi:10.1038/nature08227 nature

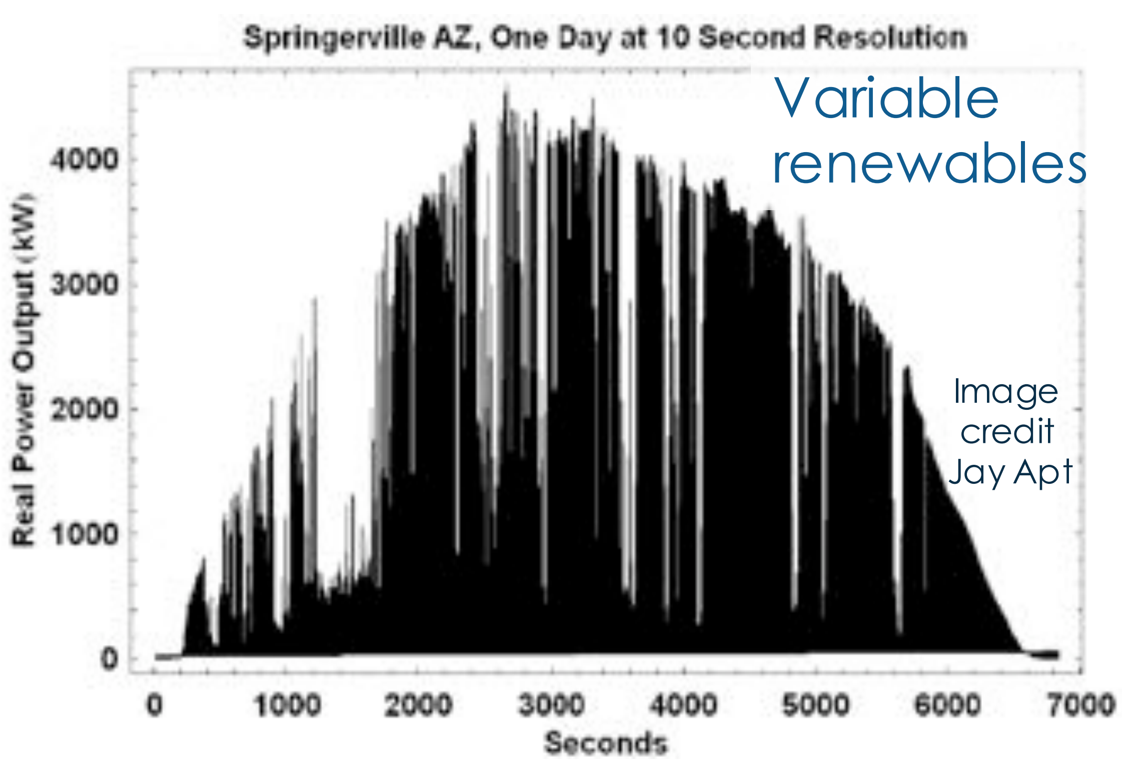
Early-warning signals for critical transitions

Marten Scheffer[1], Jordi Bascompte[2], William A. Brock[3], Victor Brovkin[5], Stephen R. Carpenter[4], Vasilis Dakos[1], Hermann Held[6], Egbert H. van Nes[1], Max Rietkerk[7] & George Sugihara[8]



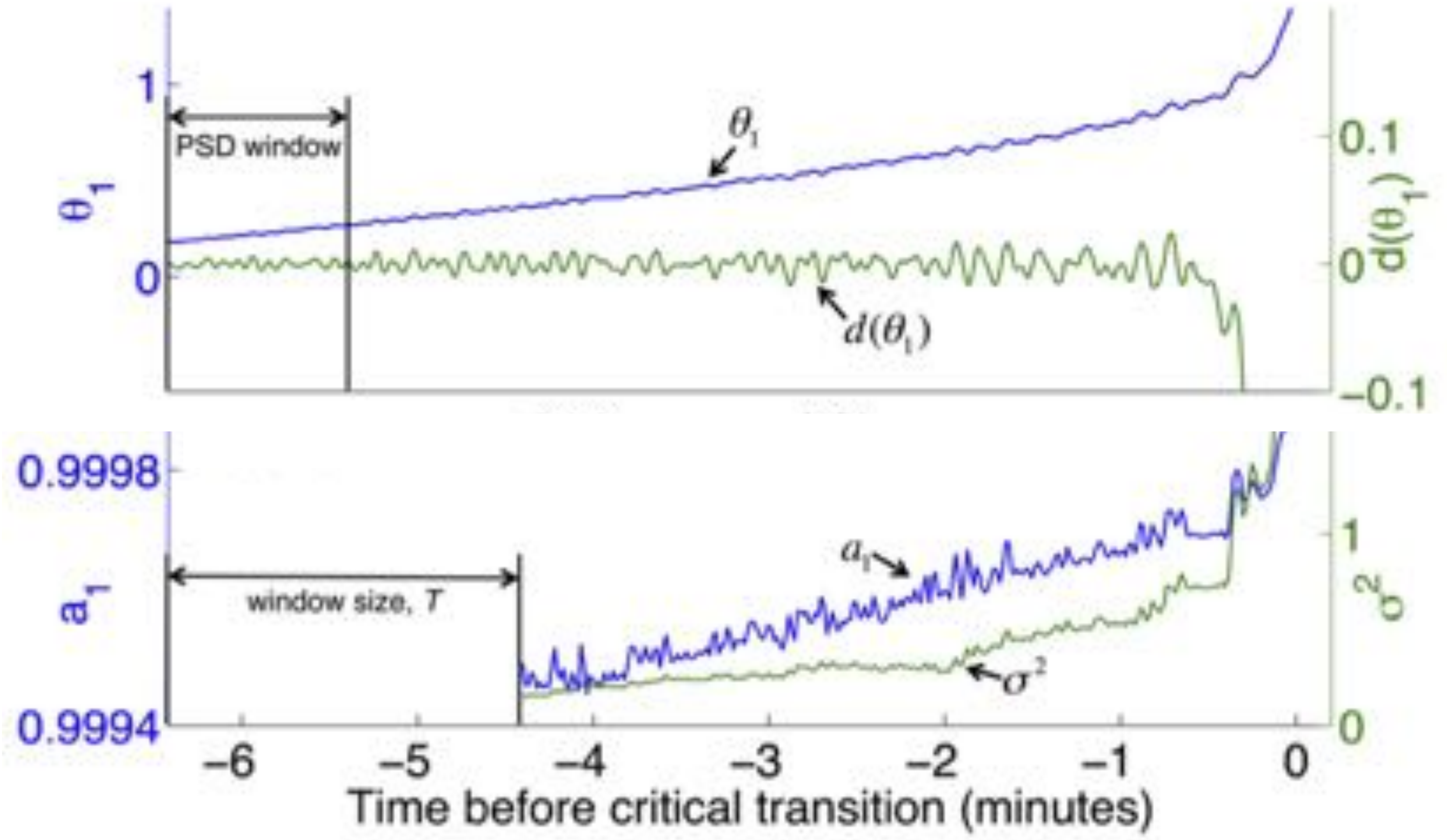
Power systems are constantly "bumped" by randomness





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

Statistics can be useful indicators



Cotilla-Sanchez, Hines, Danforth, IEEE Trans Smart Grid, 2012.

See also:

DeMarco and Berge, IEEE Trans on Ckt & Sys, 1987.

Dhople, Chen, DeVille, Domínguez-García, IEEE Trans on Ckt Sys, 2013

Podolsky and Turitsyn, arXiv:1307.4318, Jul. 2013.

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

$$\dot{\underline{x}} = f\left(\underline{x}, \underline{y}\right)$$

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

$$0 = g\left(\underline{x}, \underline{y}, \underline{u}\right)$$

Algebraic equations

r.v. for stochastic load perturbations

$$\dot{\underline{u}} = -E\underline{u} + C\underline{\xi}$$

Loads modeled as Ornstein–Uhlenbeck process

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

Encodes corr. time of load fluctuations

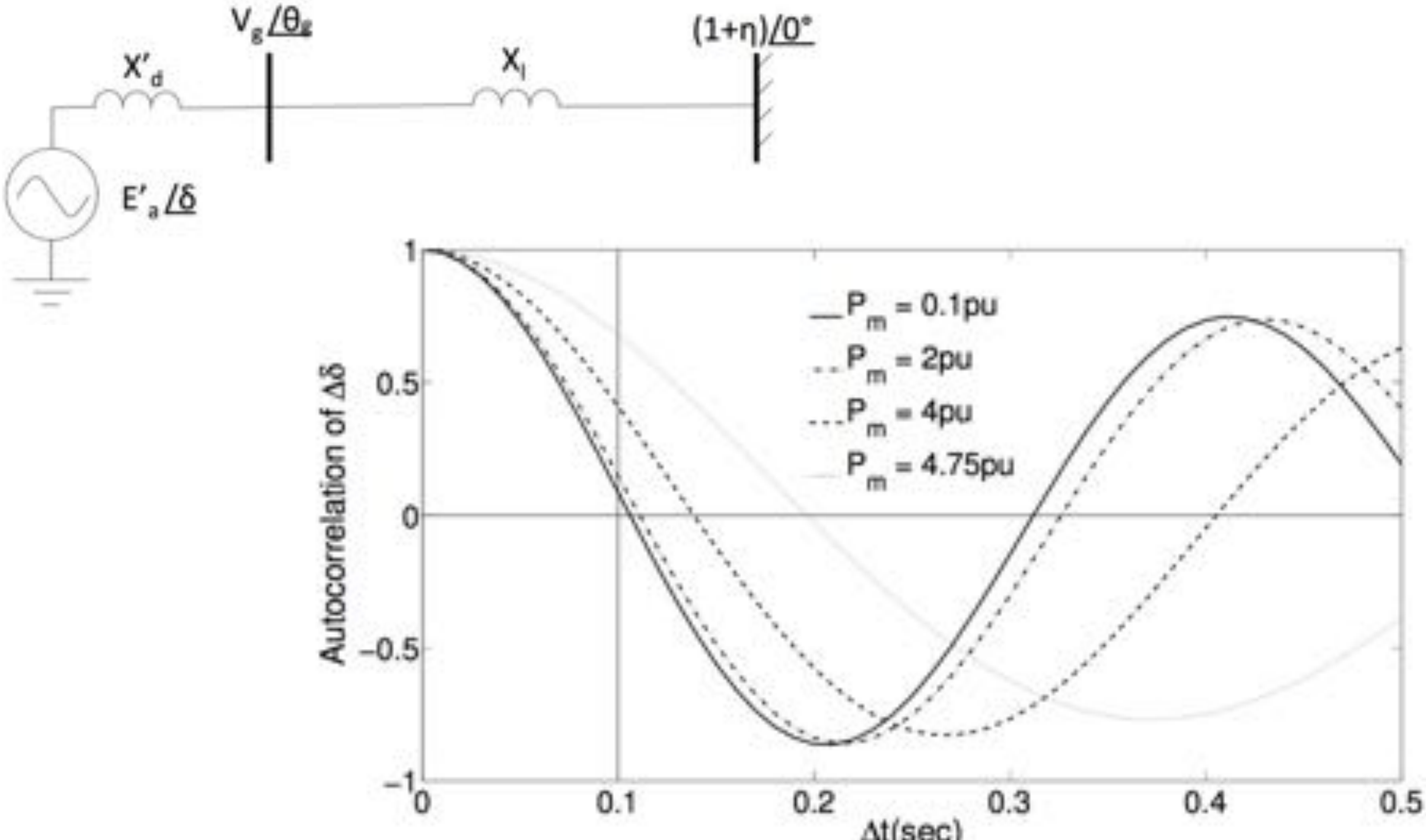
And solve to find the variance and autocorrelation of voltages and currents

$$A\sigma_{\underline{z}} + \sigma_{\underline{z}} A^T = -BB^T$$

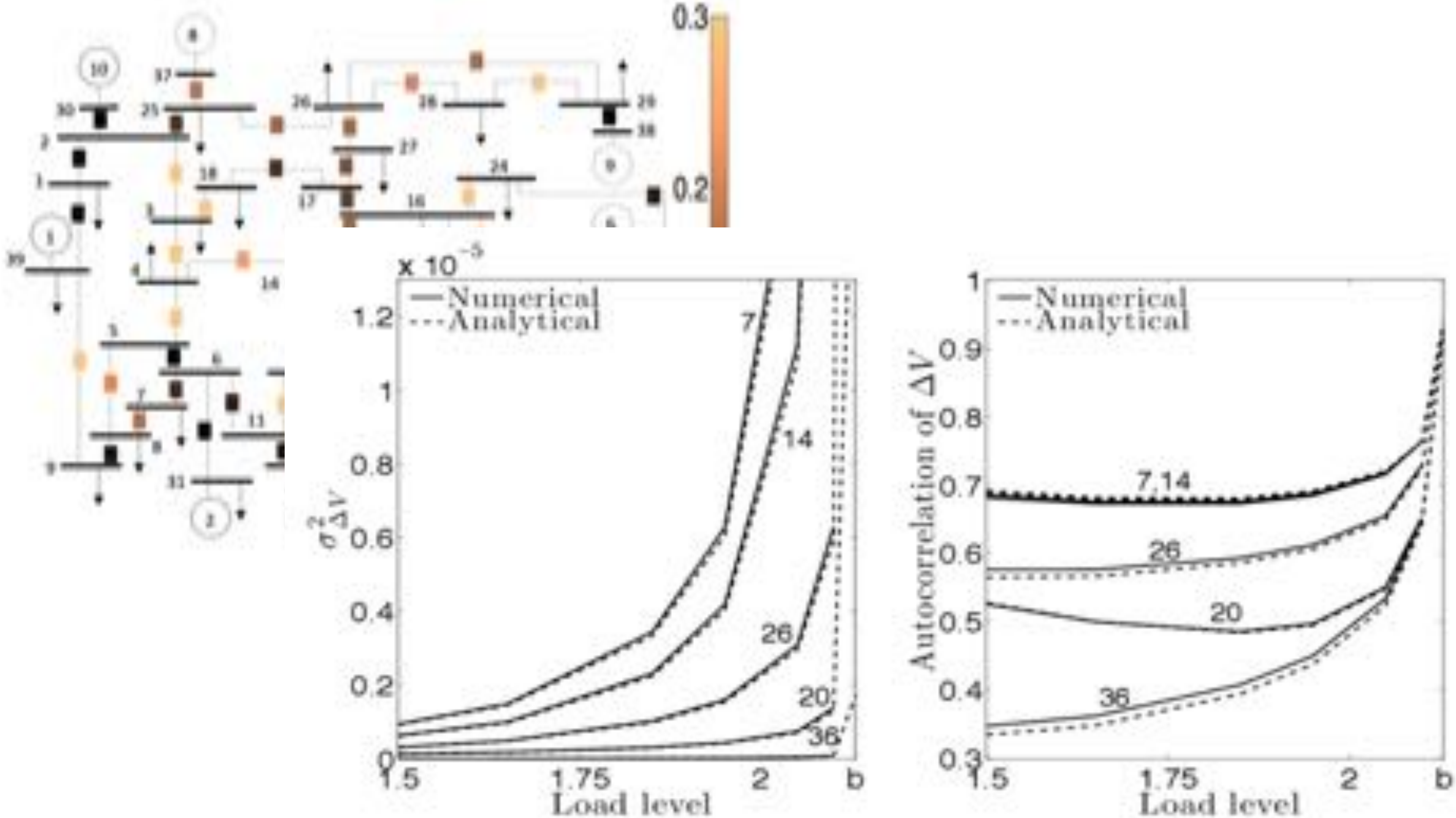
Lyapanov eq.

$$\mathrm{E}\left[\underline{z}\,(t)\,\underline{z}^T\,(s)\right] = \exp\left[-A|t-s|\right]\sigma_{\underline{z}}$$

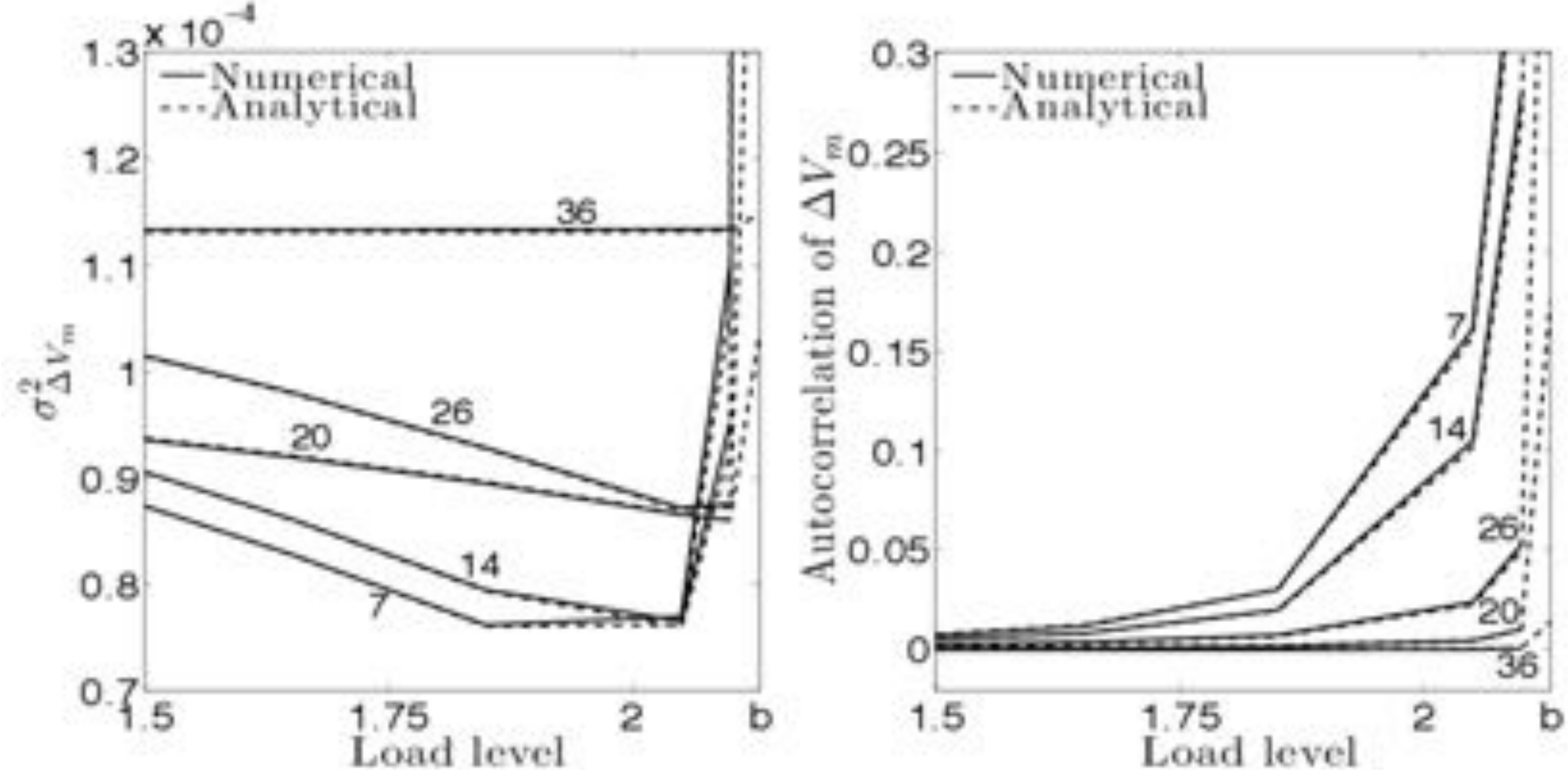
and choose a time delay for autocorrelation measurements



Check to make sure that the analytical and numerical line up



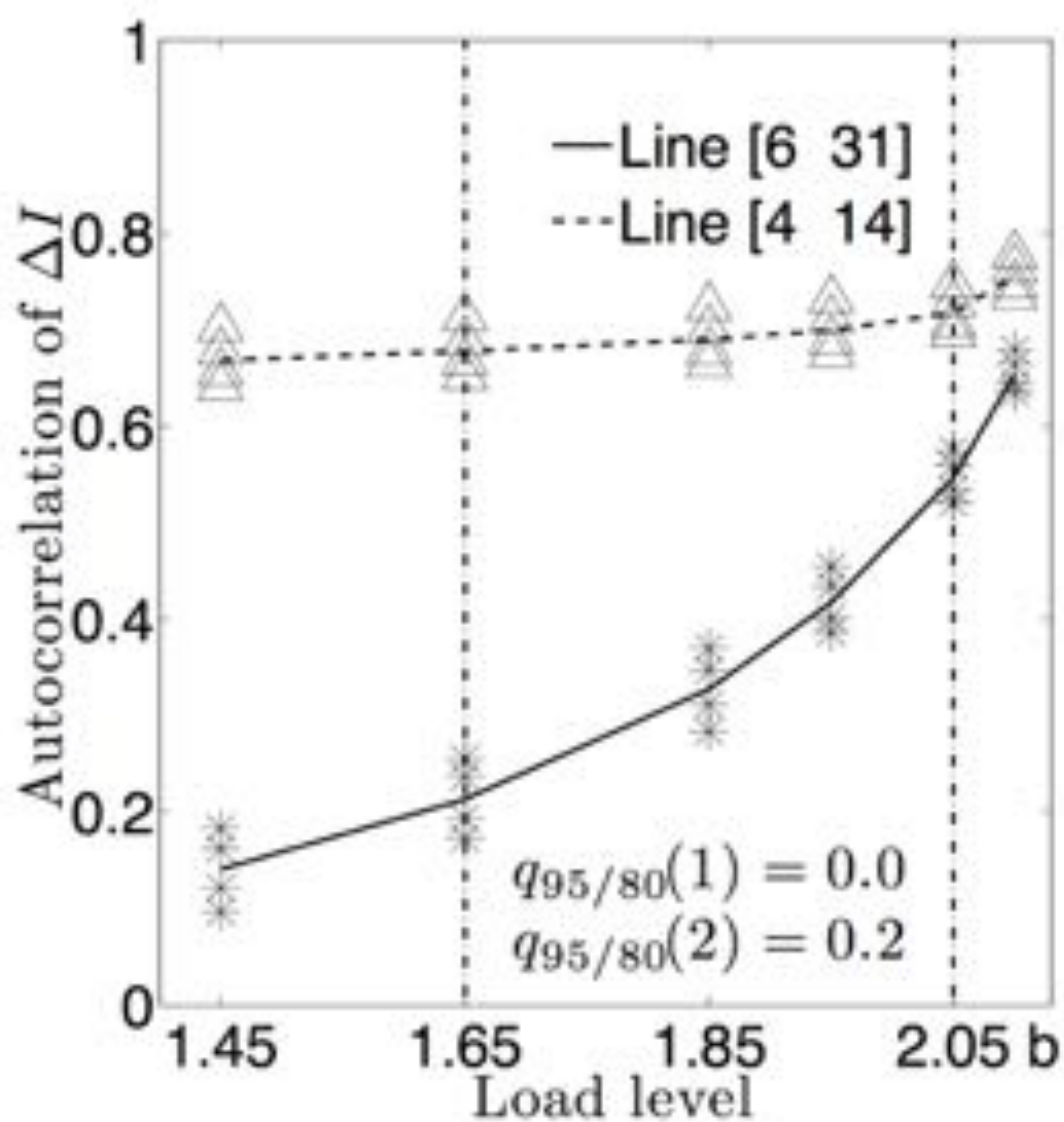
And add measurement noise



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.

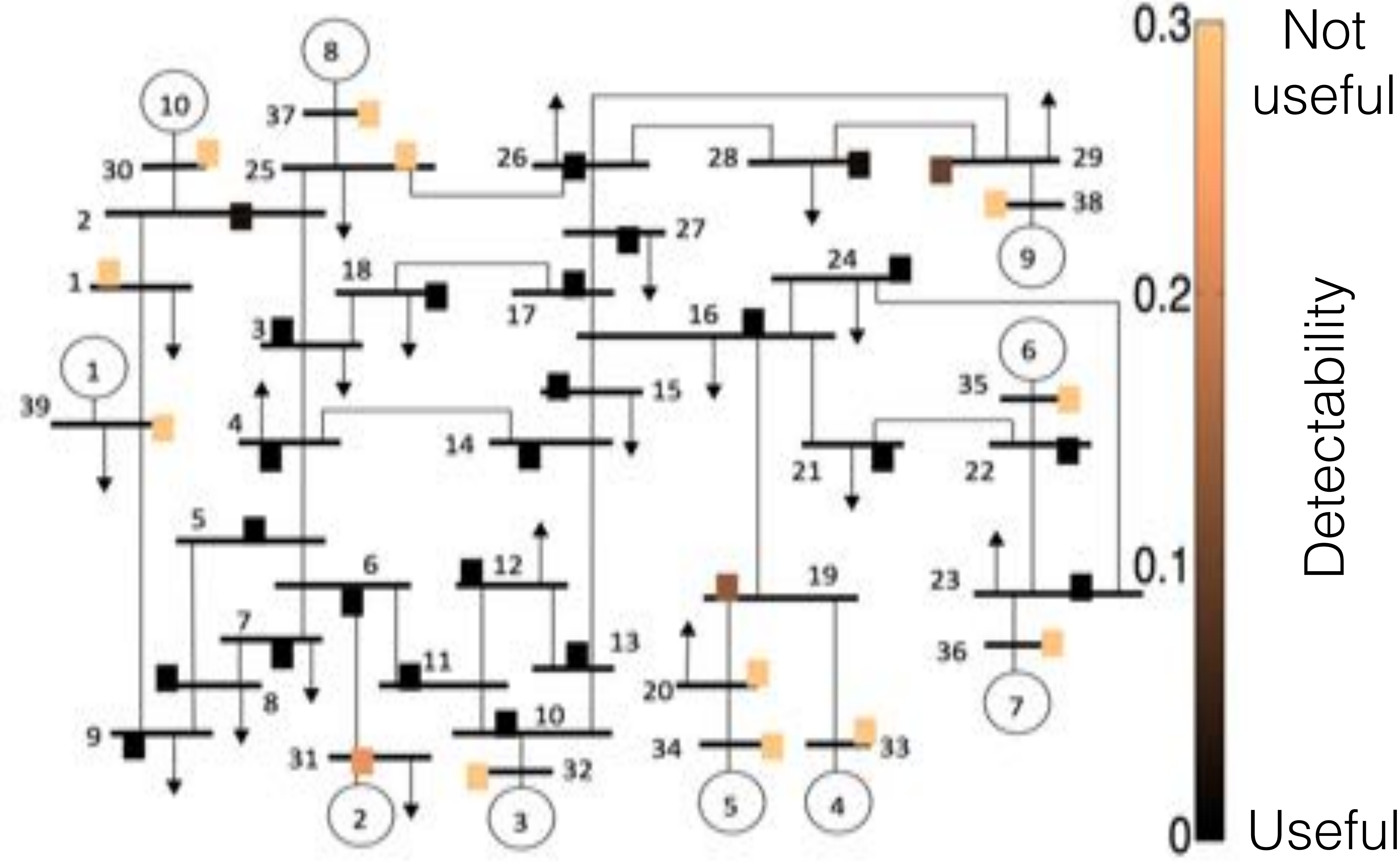
At key locations, we can see clear signs of instability in Autocorrelation and Variance

How do we measure
"detectability"
to distinguish
useful statistical signals
from non-useful ones?

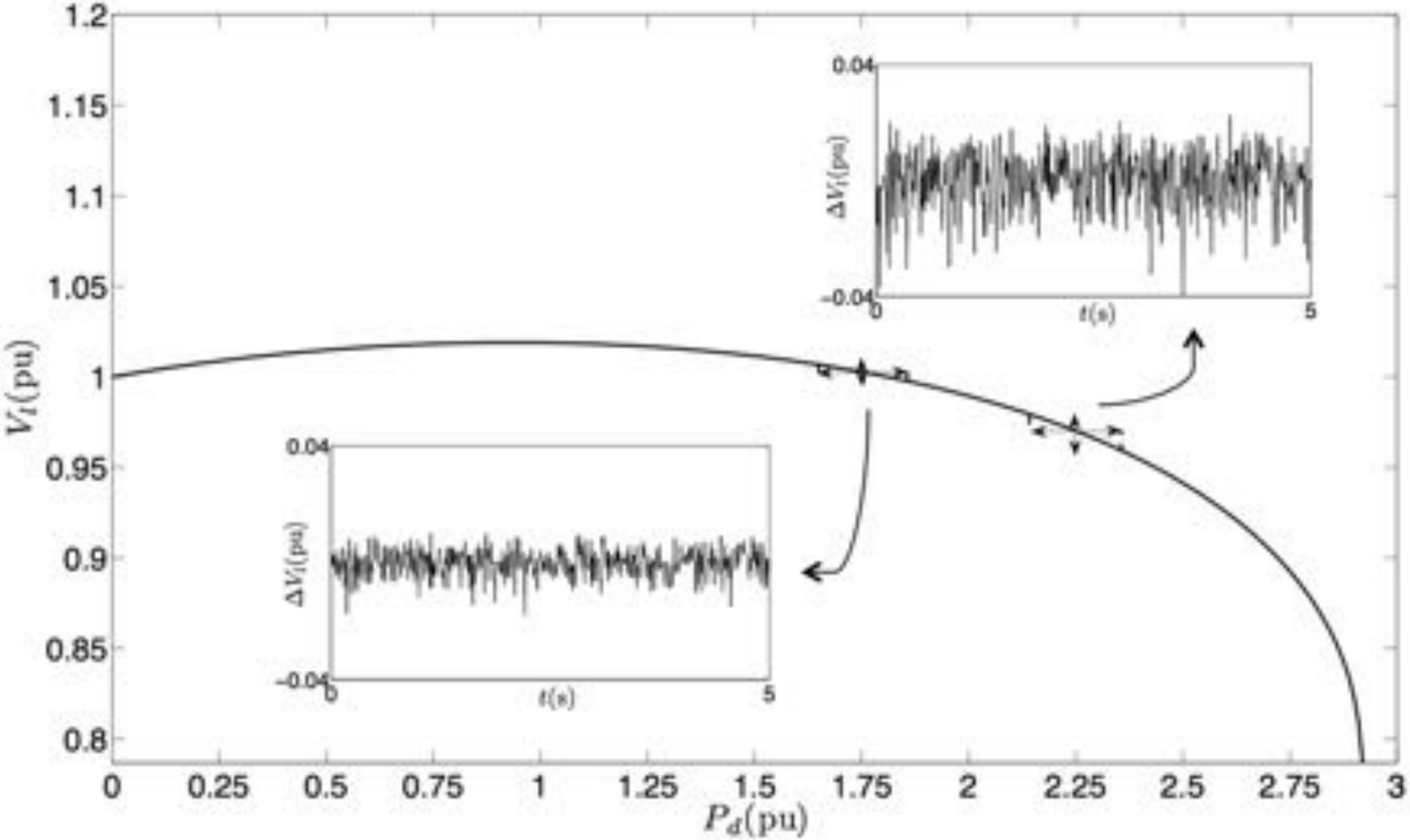


Which statistics provide useful (detectable) early warning?

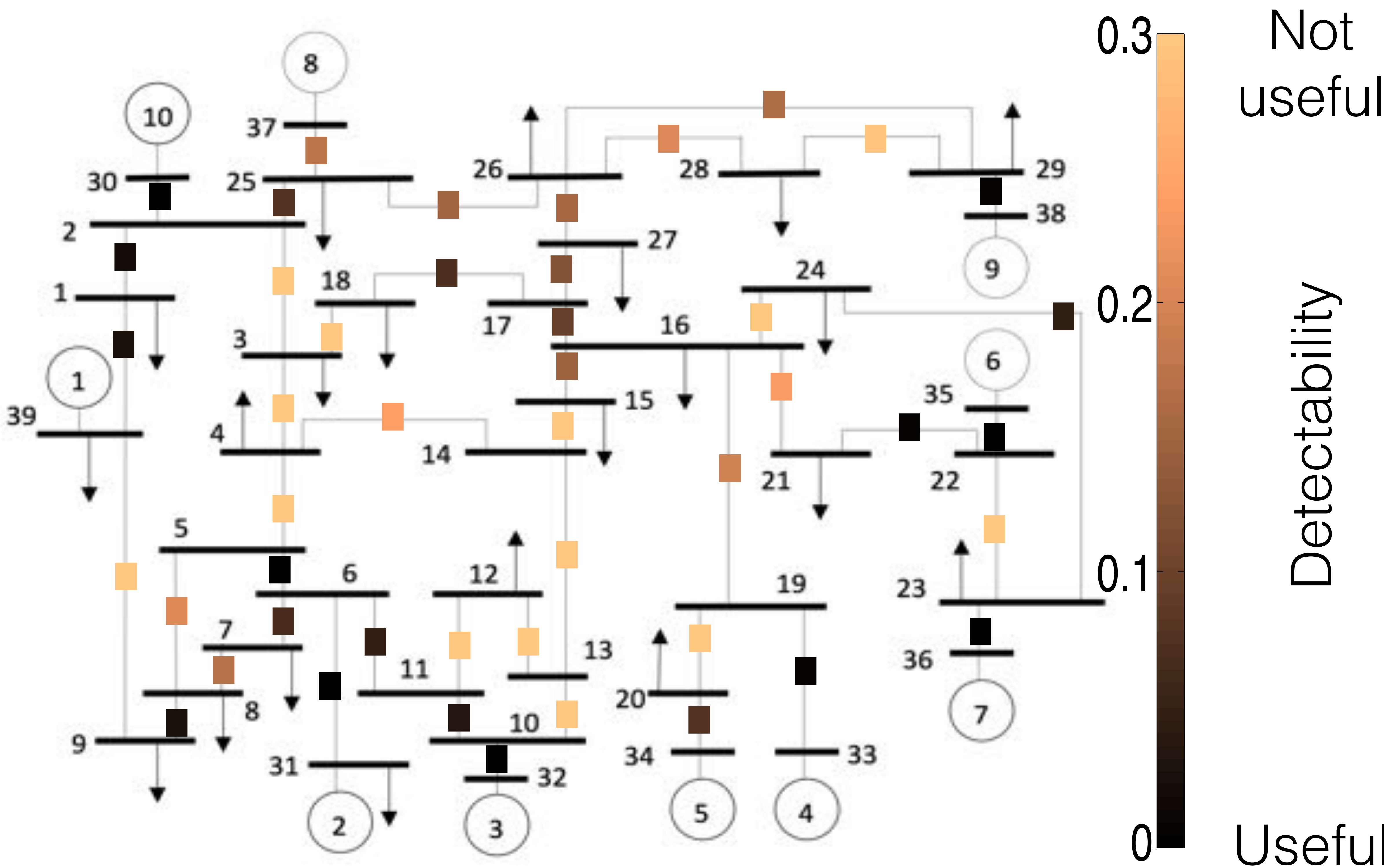
Variance of voltages



Why is variance in voltage useful?

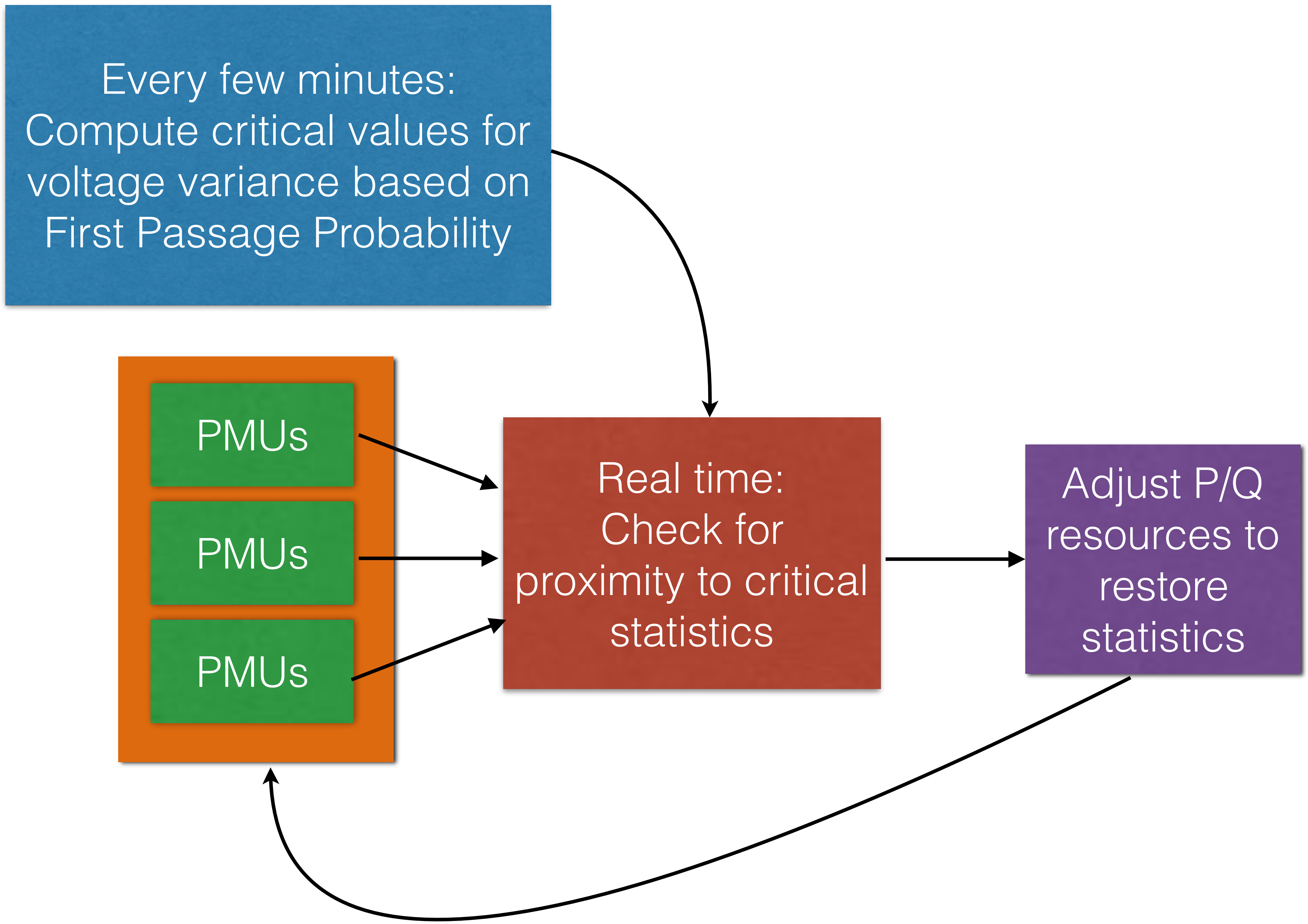


Autocorrelation of currents

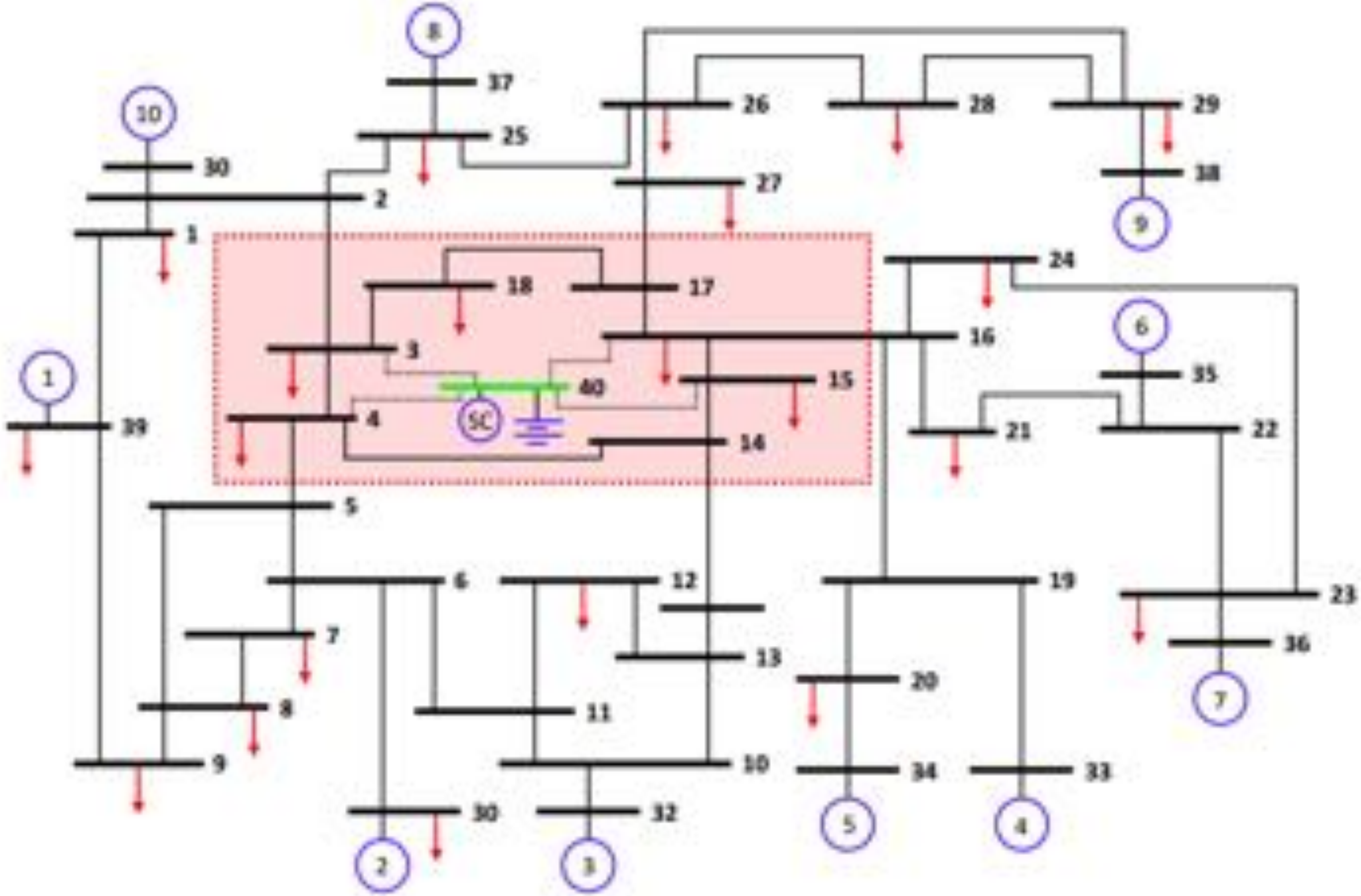


Can we use these signals to build a control system?

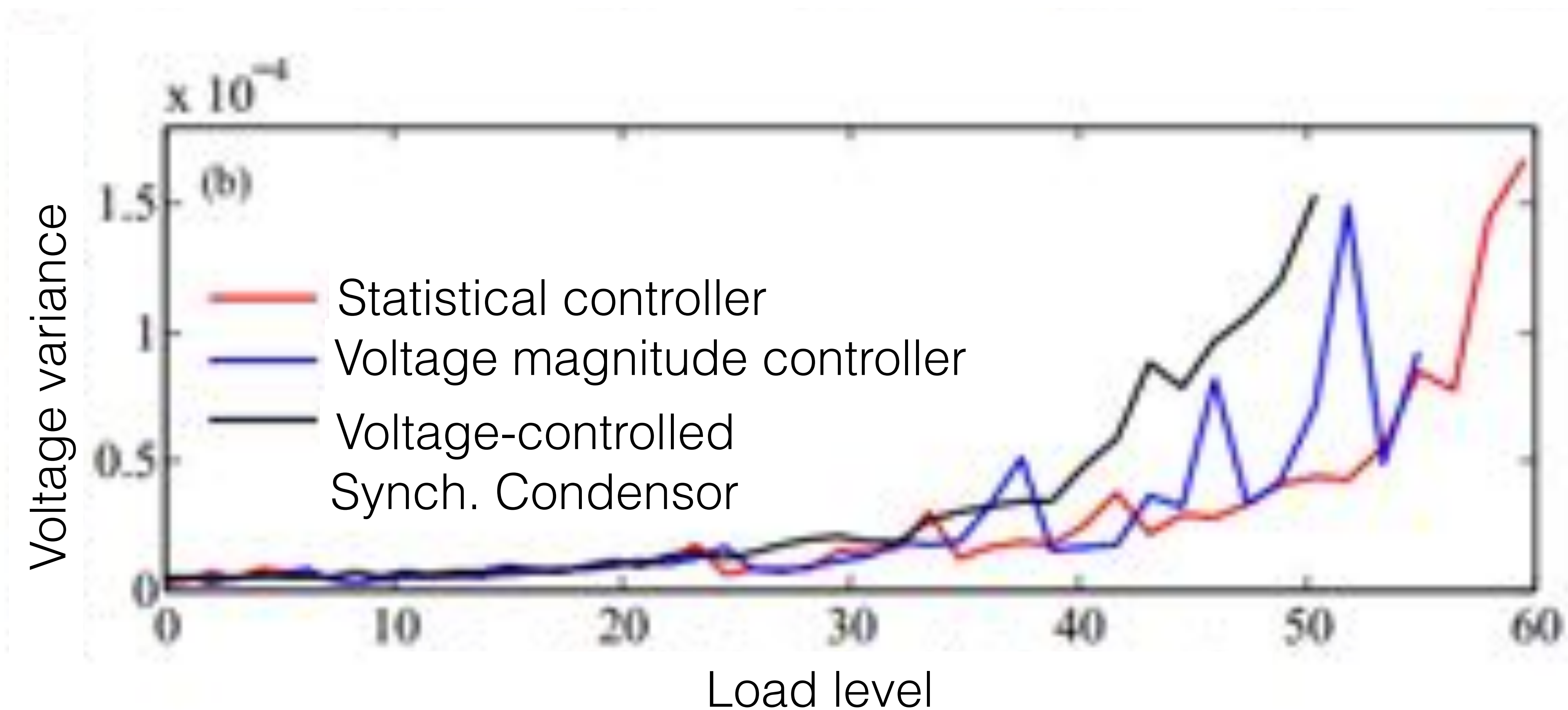
A (simple) control system



Apply to 39 bus test case



Statistical feedback allows us to make better control decisions relative to voltage-mangitude-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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NY city, Nov. 9, 1965
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