Enhancing Power Grid Stability through Analytics: Information is Power, and Power is Information

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What Drives the "Smart" Grid?

- Premise #1: the grid has long been pretty smart (Edison, Tesla, Steinmetz *et al* were no dummies).
- But… many challenges in the North American power grid revolve around coordinating a commodity that moves near speed-of-light, across large geographic distances. Trend of last 15 years of utility restructuring – ship more power, over longer distances.
- Challenge grows if we want to fully exploit renewable resources: wind in great plains, solar in southwest.

What Drives the "Smart" Grid?

- Premise #2: As well operated as grid may have been, new communication, measurement, and computation technologies open door to do better.
- Specifically – key need flagged after Northeastern U.S. blackout of Aug. 2003 – more "situational awareness."
- In grid, this translates to accurately measuring 1000's of time-varying quantities, over 1000's of square miles, *WHILE PRECISELY ALIGNING ALL THESE MEASUREMENTS IN TIME (e.g. at ~4 PM, I see voltage drop 8% in Chicago, 8% in Cleveland – to the fraction of a second, which happened first?)*

What Drives the "Smart" Grid?

- Premise #3: new technology is providing measurement data by the boatload. Job of grid engineers becomes one of using this data to increase efficiency and reliability, and quality of future infrastructure planning.
- Popular press has focused on the new measurement hardware residential customers see – so-called "smart meters" (and the press has not always been good).
- Largely unseen by general public has been a technology revolution at the grid level – wide rollout of "synchro-phasor" measurements.

What's Next for the Smart Grid?

- Conceptually, synchrophasor measurements are pretty simple, but pay-off is huge.
- They collect same voltage, current, frequency & power measurements we've always made, but on steroids. LOTS of them, highly accurate, 30 times/second, and precisely synchronized in time no matter how distant.
- If North American grid of 2003 lacked situational awareness, by 2013 most of U.S. grid will be copiously self aware. But critical need for data interpretation… How to productively ***use*** this "big data"?

What's Next for the Smart Grid?

Power is Information

- Refrain in many quarters of the power grid today says that we must "extract knowledge from data."
- Extracting value from voluminous measurements benefits from "big data" manipulation know-how that crosses many fields. Indeed, details of algorithm described later in this talk rests on underlying computation very similar to that used by Netflix "Cinematch" film suggestion software. But…
- In this presenter's opinion, successful data mining for grid applications still requires understanding of the engineering and physics of the electric power.

Voltage Instability Monitoring Using Sychrophasor Data

To illustrate these ideas in more depth, following is a sample of on-going project: “Voltage Instability Monitoring using Synchrophasor-Data”

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- Computational results to follow are research of UW-Madison PhD student, Mr. JongMin Lim.

Voltage Instability

- Motivation: among challenges to reliable grid operation is avoidance of an instability phenomena known as "voltage collapse," a culprit in many major blackouts.
- Need to avoid this problem can drive major infrastructure investments. In my home of state of Wisconsin, a controversial transmission line through center of the state capital city of Madison was justified largely based on its contribution to avoidance of voltage instability.

Voltage Instability

Feb. 2009 Testimony to WI PSC, by ATC's Manager for Transmission Planning, Mr. Jamal Khudai, docket 137-CE-147, under "Need for the Project":

- "The transmission system in Dane Co. … is marginally adequate under normal operating conditions. Low voltage conditions are projected to occur in the 2015-2020 period with the system intact… If not addressed, these issues lead to non-convergence of the power flow model (the problem doesn't 'solve'), which indicates voltage collapse conditions. No significant thermal violations are projected in this period under system intact or system normal conditions."

http://psc.wi.gov/apps35/ERF_view/viewdoc.aspx?docid=107754

Voltage Instability Monitoring Using Sychrophasor Data

- Concerns for voltage instability problems acute in areas seeing rapid expansion of renewable generation; e.g. Columbia River Gorge, Southern California Edison (hence work w/BPA and LBL).

- General objective: condense 100’s to 1000’s of measurements, updated 30 times/sec.
into an operational grid “Stress Monitor.”

- Current state-of-the art relies on output once-per-five minute state estimator. New analytic methods seeks real-time monitoring, less prone to erroneous assumptions on network topology.

Geometric Insight into Voltage Instability Monitoring

- Approach to be describe here seeks to estimate conditioning of power flow equations through singular value decomposition (SVD) of matrices constructed of windowed measurement data.

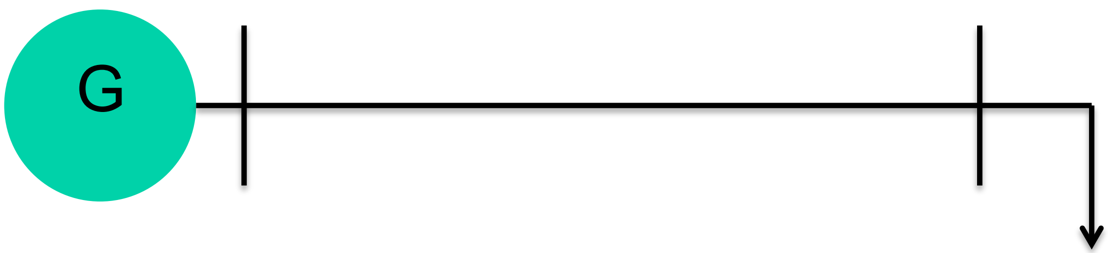
- For the non-specialist, much of the approach can be seen from a geometric perspective.

- A simple two degree of freedom power system example allows use to explicitly picture this geometric perspective, hopefully allowing intuition into the more abstract singular value analysis.

Geometric Insight into Voltage Instability Monitoring

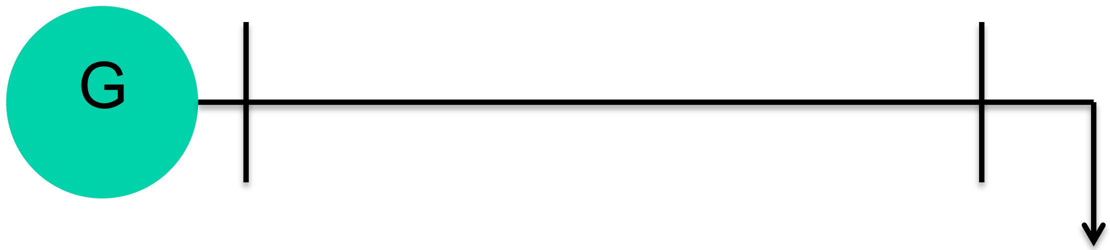
- Consider simple one-line power system, with one load, active power demand, P, reactive power demand Q. One generator, that holds its voltage magnitude constant, and adjusts its power output to meet load.

- Then only two variables: voltage magnitude at load bus (denote V), and relative phase angle (denote δ).



Load Demand:
Active Power P
Reactive Power Q

Geometric Insight into Voltage Instability Monitoring



Load Demand:
Active Power P
Reactive Power Q

- Steady state operating point defined by a (δ, V) pair that defines the operating point for this little system. Dynamics of grid determined by motion of (δ(t), V(t)) in time. In full detail, we'd need a third variable, a ω(t), but neglect here for simplicity.

Important Aside, Looking Ahead to Application…

- The new measurement technologies alluded to in opening slides – “synchrophasor measurements” or “PMUs” – are precisely these of δ’s and V’s!

Again, key improvements in recent years have been:

- Cost-effective means to simultaneously measure 1000’s of these, 30 times per second, precisely synchronized in time across 100’s and 1000’s of miles;

- Cost-effective, high-bandwidth communication to gather huge numbers of measurements to a control centers – “Phasor Data Concentrators.”

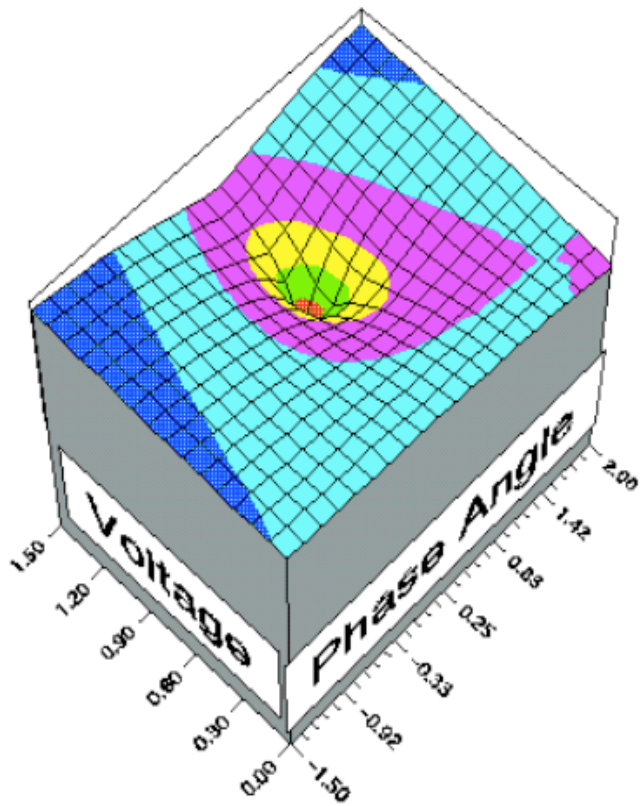
Geometric Insight into Voltage Instability Monitoring

- Technical point: modest modeling approximations, vector field that defines dynamics of power system state, $\mathbf{x}(t) = (\delta(t), V(t))$, is exactly integrable.

- Hence there exists a well defined scalar function of state, we'll denote $\Phi(\mathbf{x})$, with properties much like energy in a dissipative mechanical system (think of a rolling ball on hilly surface):
  (i) stable equilibria are local minima of energy;
  (ii) once any outside force is removed, energy is non-increasing along motion away from the equilibrium.

Geometric Insight into Voltage Instability Monitoring

- Viewed in $\mathbf{x}$ = (δ, V) plane, color contour plot of $\Phi(\mathbf{x})$ appears as below.



Geometric Insight into Voltage Instability Monitoring

- Added insights require understanding of nature of disturbances in the electric power grid, and how these translate to our geometric picture…
- In normal operation, the three bulk power grids of the U.S. are exceptionally stable. Vast majority of time, customer sees steady voltage & frequency (e.g., the 120 V rms of your wall outlet, at 60 cycles per second).
- But underlying is continuous variation in load levels and in generation MW outputs. And not infrequently, there are failures of equipment.

Geometric Insight into Voltage Instability Monitoring

- 24-hour load cycle of variation in customer demand, and generation changes in response, smoothly deforming the energy contour. Typical time scale much slower than dynamics $\rightarrow$ the rolling ball "tracks" the minimum energy point.
- Failure of large transmission line or generator is a major "kick" to the system. Visualize a quake, (nearly) instantaneously shifting underlying energy contour.
- Sufficient redundancy built into grid to survive these "contingencies," albeit in degraded configuration. Safety margins temporarily reduced.

Geometric Insight into Voltage Instability Monitoring

- Third class of "disturbance," usually not of concern ***unless margins are reduced…***
- On top of slow, 24-hour cycle of variation, aggregate customer load at a major substation displays fast time scale random variation (milliseconds-to-minutes). Reflects aggregate behavior of 10's or 100's of thousands of individual devices, switched on/off by humans, or by very local automatic control systems.
- Weather dependent power generation (e.g., wind and photovoltaic) add to this fast time scale random variation of "inputs" to power system.

Geometric Insight into Voltage Instability Monitoring

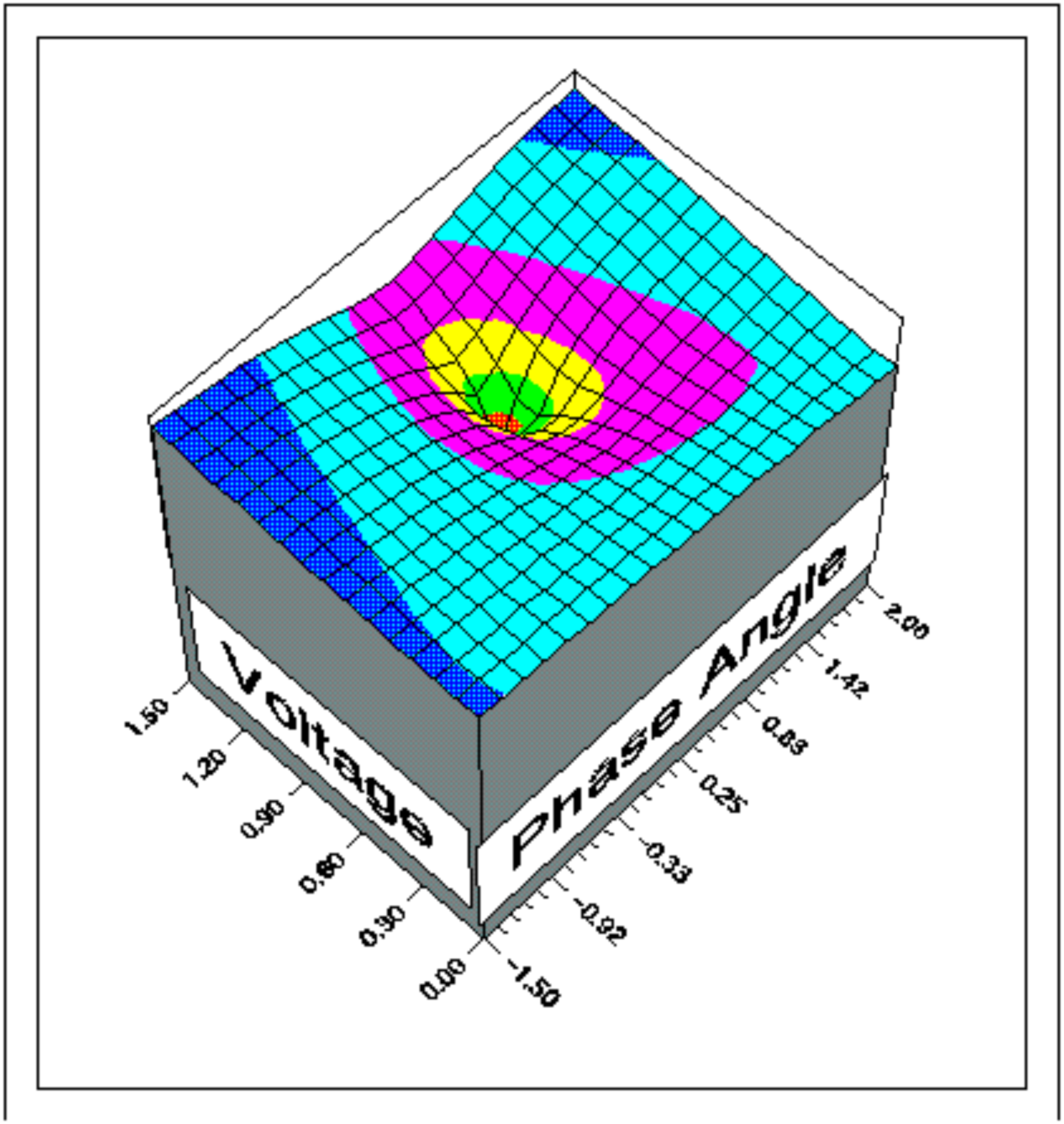
- First principles imply that load variations should appear as sum of filtered random jump processes; measurement literature of ‘80’s & 90’s suggests modeling simply as filtered white noise.

- Improved studies in recent years suggest refinement as Ornstein-Uhlenbeck stochastic process.

- Conceptual picture remains that of rolling ball on potential energy contours, continuously disturbed by forces in form of a “small noise” process.

Geometric Insight into Voltage Instability Monitoring

- Impact: our rolling ball of the power system state is never exactly at equilibrium. Rather, it is a diffusion process, continuously randomly wandering.
- Under “good” operating conditions, this wandering of the state is confined to a small neighborhood of the equilibrium point
- But what happens if the system is stressed, either by a major equipment outage, or by high, increasing demand in the 24-hour load cycle? (a hot afternoon , and more and more air conditioners go on...)


Voltage
Phase Angle
1.50
1.20
0.90
0.60
0.30
0.00
-1.50
-0.92
-0.33
0.25
0.83
1.42
2.00

Geometric Insight into Voltage Instability Monitoring

Key Observations:

- Voltage collapse is the final loss of the stable operating point, with path of state divergence being one of primarily declining voltage magnitude.
- As operating conditions worsen, curvature of the potential well about the equilibrium lessens. For a fixed magnitude variation in stochastic load (e.g., fixed variance if modeled as a simple zero random process), the variation of system state in response, ($\delta(t)$, $V(t)$) increases in magnitude.

From Geometric Insight to Analytic Tools

- For the simple example previous, the potential quantity plotted, $\Phi(\mathbf{x})$, was the integral of power flow equations, ubiquitous in power grid engineering.

- As hence $\nabla\Phi(\mathbf{x})$ corresponds to the power flow equations. The local curvature of $\Phi(\mathbf{x})$ about the equilibrium, $\nabla^2\Phi(\mathbf{x})$, therefore corresponds to the power flow Jacobian.

- From an algebraic equation viewpoint, the linearized approximation mapping from variations in load, to variations in system state, is the inverse of this power flow Jacobian.

From Geometric Insight to Analytic Tools

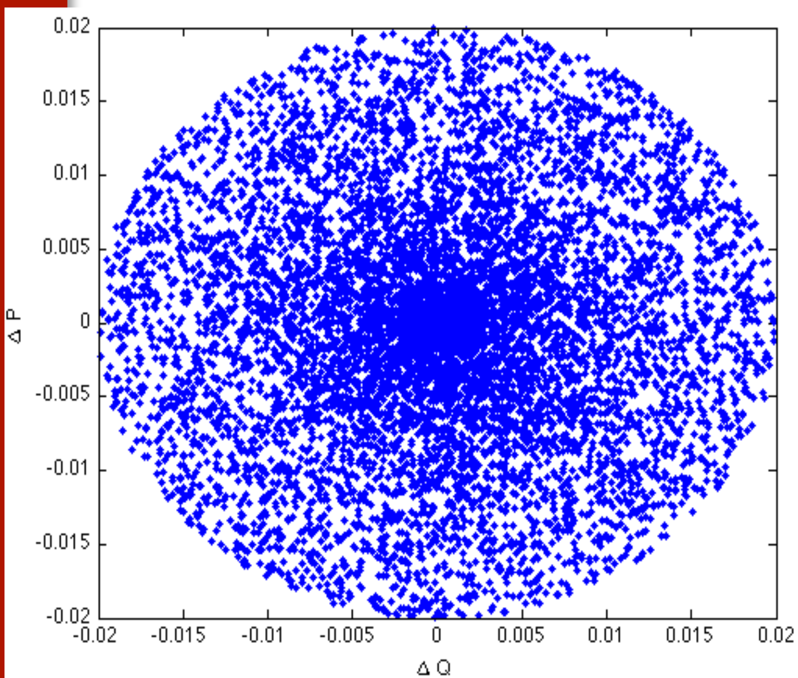
- Long been recognized that if the operating point evolves towards condition at which the Jacobian is singularity, the grid is at risk of voltage collapse.
- Existing methods require full network data, explicitly constructing the Jacobian in software (order of computation – eastern synchronous grid in U.S. is ~80,000 nodes, associated Jacobian is order 10^5)
- Alternative here is a ”model free” approach. View power grid as analog power flow solver. Estimate conditioning of power flow via behavior of measured outputs, with persistent excitation of load variation.

Motivation of Proposed Algorithm

- As motivation, consider idealized picture of load variation: a vector in $\Re^n$, randomly varying in time. At 30 Hz, one might view each new load vector as selected from within a scaled unit sphere in $\Re^n$
- Standard results in linear algebra imply that a square linear map, acting on a sphere of "input" points, yields an ellipse in the set of "output" points.
- The lengths and directions of the axes of this output ellipse are easily computed from the singular value decomposition of the matrix associated with the linear map.

Motivation of Proposed Algorithm

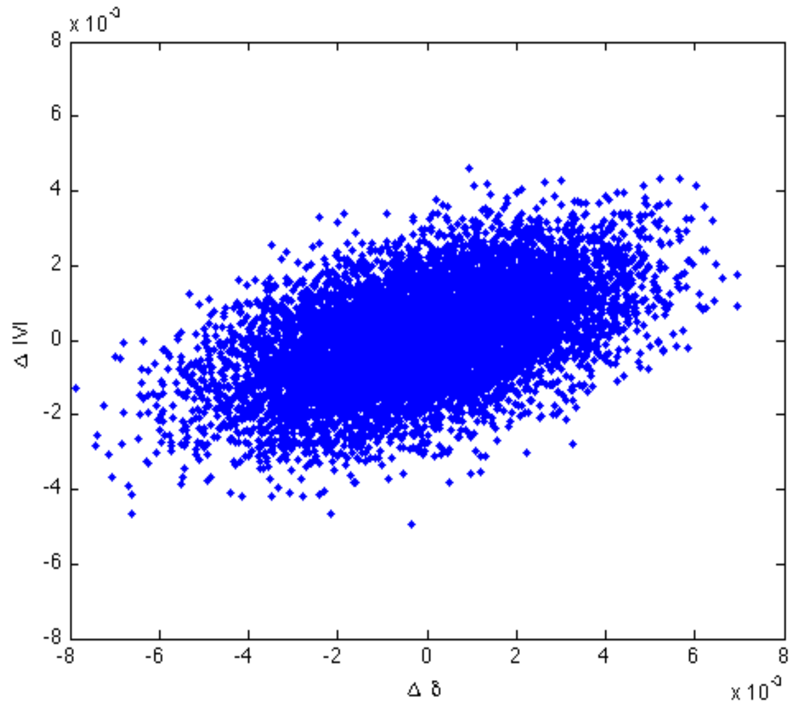
- Fast stochastic load variation "persistently excites" motion about operating point, allowing estimate of system conditioning via ellipse formed in output space.



$\Delta P - \Delta Q$ Input Load Variation

Power System

Power Flow Solution



$\Delta\delta - \Delta V$ Output Response

Proposed Algorithm

- In our problem, we get to observe the measurements output points, 30 times per second (more realistically, we get measurements of perhaps 5-15% of the total number of states)
- We want to estimate length of major axis, and flag if it becomes too large, indicating that the inverse of the power flow Jacobian is becoming ill-conditioned.

Proposed Algorithm

- At time L, insert the newest measurement column into PMU data matrix and delete the oldest column. PMU data matrix maintains its number of columns (i.e. fixed length moving window)

$$\begin{bmatrix} \Delta\underline{\delta}_L \\ \Delta|\underline{V}_L| \end{bmatrix} = \begin{bmatrix} \underline{\delta}_L \\ |\underline{V}_L| \end{bmatrix} - Base\,State$$

$$\left[\boxed{\begin{matrix} \Delta\underline{\delta}_1 & \Delta\underline{\delta}_2 & \Delta\underline{\delta}_3 & \cdots & \Delta\underline{\delta}_L \\ \Delta|\underline{V}|_1 & \Delta|\underline{V}|_2 & \Delta|\underline{V}|_3 & \cdots & \Delta|\underline{V}|_L \end{matrix}} \begin{matrix} \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \end{matrix}\right]$$

PMU data Matrix

Proposed Algorithm

- Proposed conditioning measure is extremely simple – at each time step, just compute largest singular value of this sliding window array.

$$\begin{bmatrix} \Delta \underline{\delta}_{L+1} \\ \Delta |\underline{V}_{L+1}| \end{bmatrix} = \begin{bmatrix} \underline{\delta}_{L+1} \\ |\underline{V}_{L+1}| \end{bmatrix} - Base\,State$$

$$\left[\begin{array}{c|cccccc|cc} \Delta\underline{\delta}_1 & \Delta\underline{\delta}_2 & \Delta\underline{\delta}_3 & \cdots & \Delta\underline{\delta}_L & \Delta\underline{\delta}_{L+1} & & \cdots & \cdots \\ \Delta|\underline{V}|_1 & \Delta|\underline{V}|_2 & \Delta|\underline{V}|_3 & \cdots & \Delta|\underline{V}|_L & \Delta|\underline{V}|_{L+1} & & \cdots & \cdots \end{array}\right]$$

PMU data Matrix

Proposed Algorithm

- At each update, a rank one change to the data matrix (offers opportunities for efficient computation, even in very large dimension data sets).

$$\begin{bmatrix} \Delta \underline{\delta}_{L+2} \\ \Delta |\underline{V}_{L+2}| \end{bmatrix} = \begin{bmatrix} \underline{\delta}_{L+2} \\ |\underline{V}_{L+2}| \end{bmatrix} - Base\,State$$

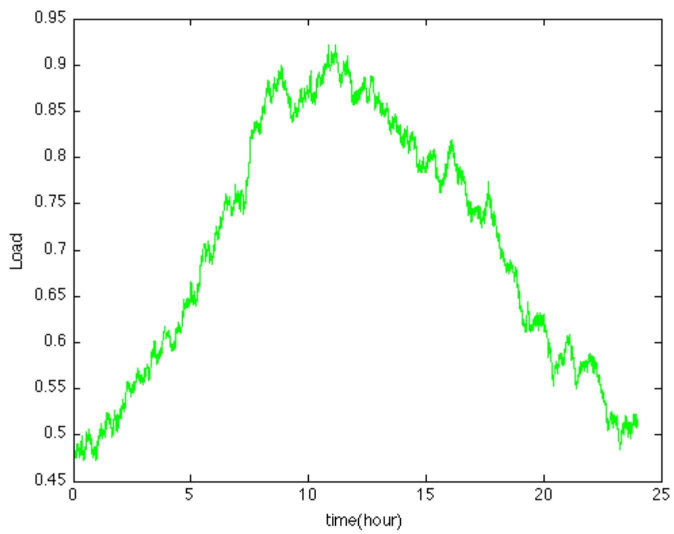
$$\left[\begin{array}{cc|cccccc|c} \Delta\underline{\delta}_1 & \Delta\underline{\delta}_2 & \Delta\underline{\delta}_3 & \cdots & \Delta\underline{\delta}_L & \Delta\underline{\delta}_{L+1} & \Delta\underline{\delta}_{L+2} & & \cdots \\ \Delta|\underline{V}|_1 & \Delta|\underline{V}|_2 & \Delta|\underline{V}|_3 & \cdots & \Delta|\underline{V}|_L & \Delta|\underline{V}|_{L+1} & \Delta|\underline{V}|_{L+2} & & \cdots \end{array}\right]$$

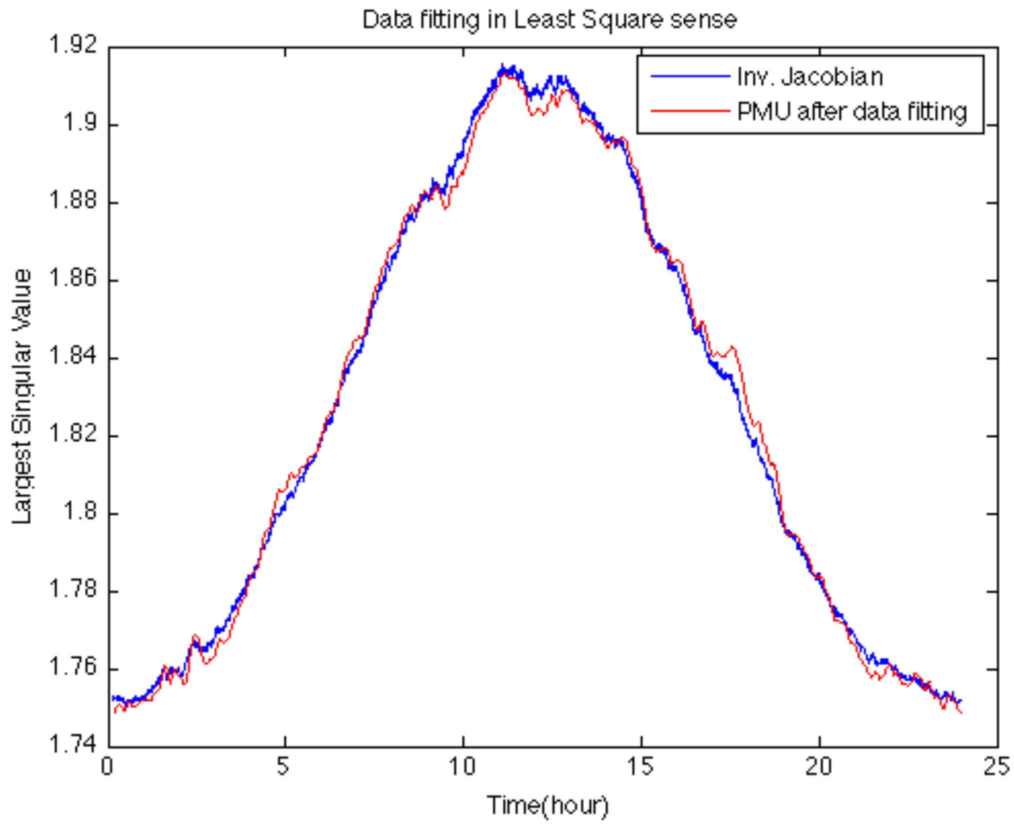
PMU data Matrix

Synthetic Test Case Performance

- Synthetic systems allow comparison of "measurement based" computation to idealized computation utilizing full Jacobian Information. Here IEEE 14 bus case:

"Input" data below: 24-hr load cycle, with random variation

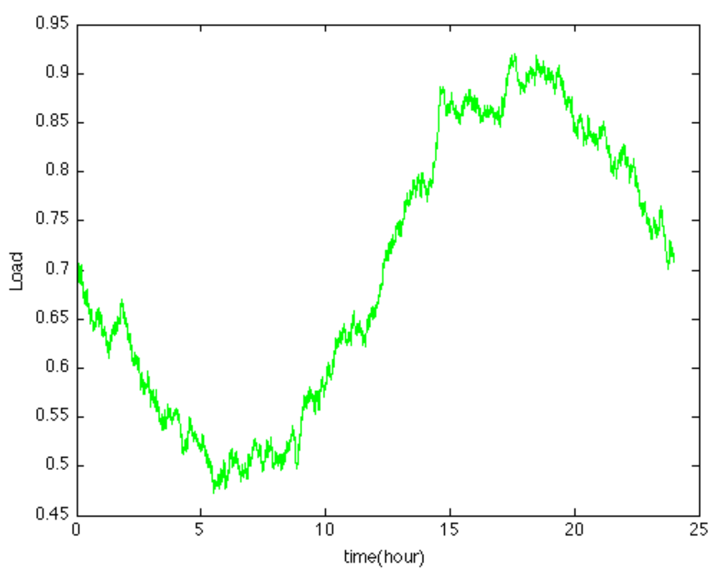


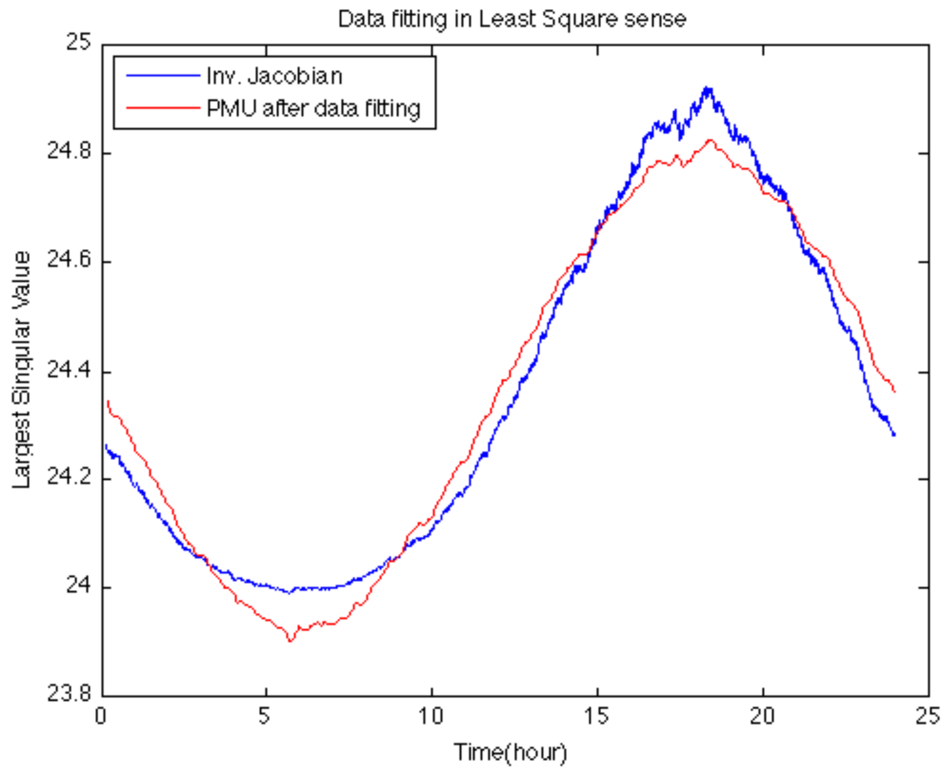


Synthetic Test Case Performance

- Synthetic systems allow comparison of "measurement based" computation to idealized computation utilizing full Jacobian Information. Here IEEE 300 bus case:

"Input" data below: 24-hr load cycle, with random variation





Conclusions/Take Away Points

- A revolution in power grid measurement is currently in progress, providing precisely synchronized, high bandwidth data across broad geographic area.
- Opens opportunity to accurately track the dynamic "stress" on the power grid, providing the situational awareness sought after 2003 Northeast blackout.
- The algorithms and "analytics" underlying these tools share features with those applied to more unstructured consumer preference prediction.

Conclusions/Take Away Points

- While loosely terming proposed approach as "model free," characterization of grid stability still requires deep understanding of grid structure & physics.
- True goal is to use measurements to lessen risk that parameters populating model miss real time changes.
- Ultimate goal will be optimal blend of *a priori* information (fully populated model – today's approach in grid control centers), with the type of model free, purely measurement-based algorithm proposed here.