Synchrophasor Detectives

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SAMSI Workshop

Scientific Problems for the Smart Grid

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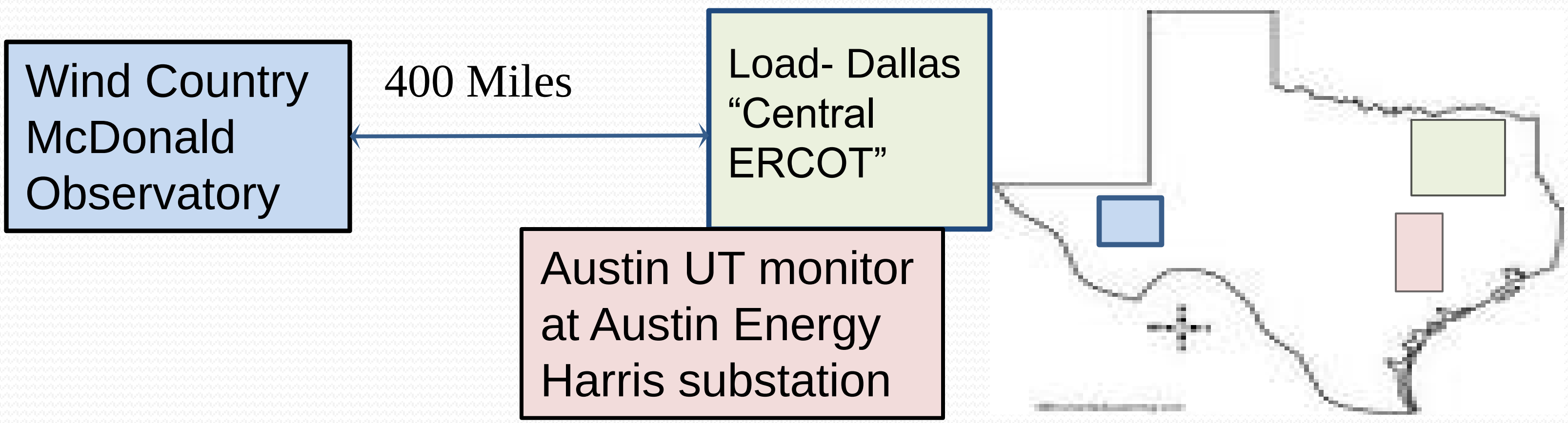
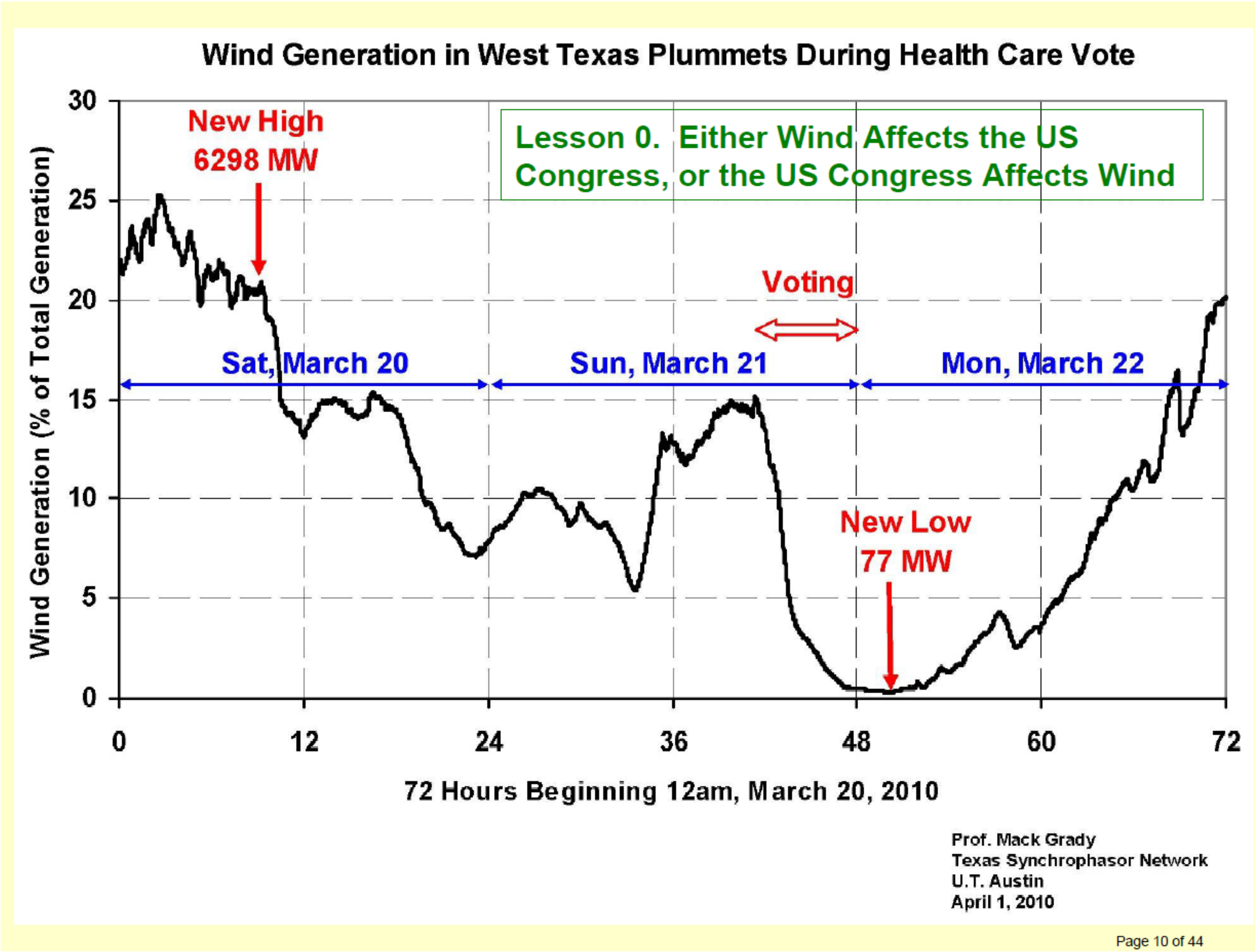
BRADLEY DEPARTMENT
OF ELECTRICAL & COMPUTER ENGINEERING

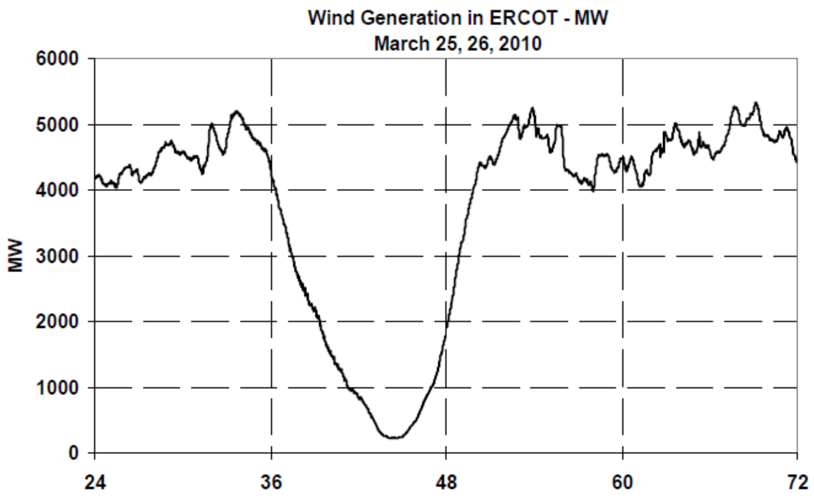
- Just as new telescopes (Hubble) or new microscopes (STEM) have shown us thing we did not predict, wide area - time synchronized - measurements have produced a few surprises.
- The next two slides are from Mack Grady UT Austin (with his permission) The title comes from his second slide



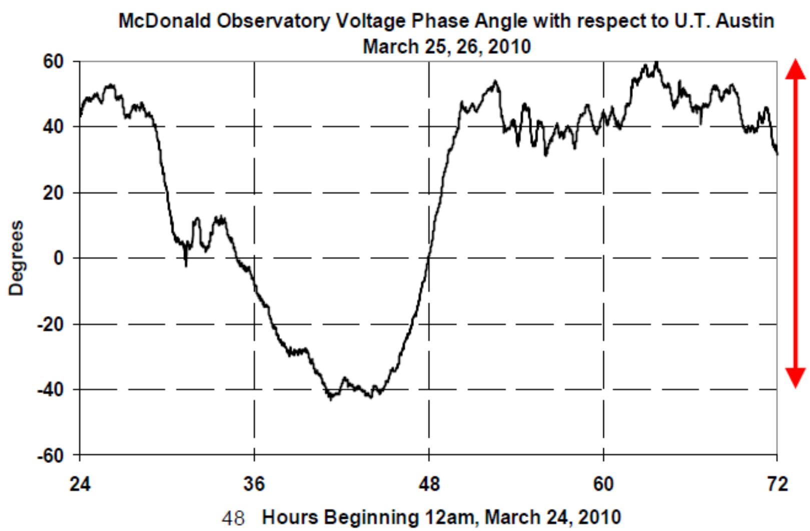

Wind Generation in West Texas Plummets During Health Care Vote
Wind Generation (% of Total Generation)
New High
6298 MW
Lesson 0. Either Wind Affects the US Congress, or the US Congress Affects Wind
Voting
Sat, March 20
Sun, March 21
Mon, March 22
New Low
77 MW
30
25
20
15
10
5
0
0
12
24
36
48
60
72
72 Hours Beginning 12am, March 20, 2010
Prof. Mack Grady
Texas Synchrophasor Network
U.T. Austin
April 1, 2010
Page 10 of 44

Lesson 1. Every Day has Synchrophasor Surprises

You must become a synchrophasor detective



Wind generation and West Texas phase angle can go through large daily swings



West Texas voltage phase angle swings nearly 100º and back with respect to U.T. Austin in about 24 hours

Lesson 2 again from Texas

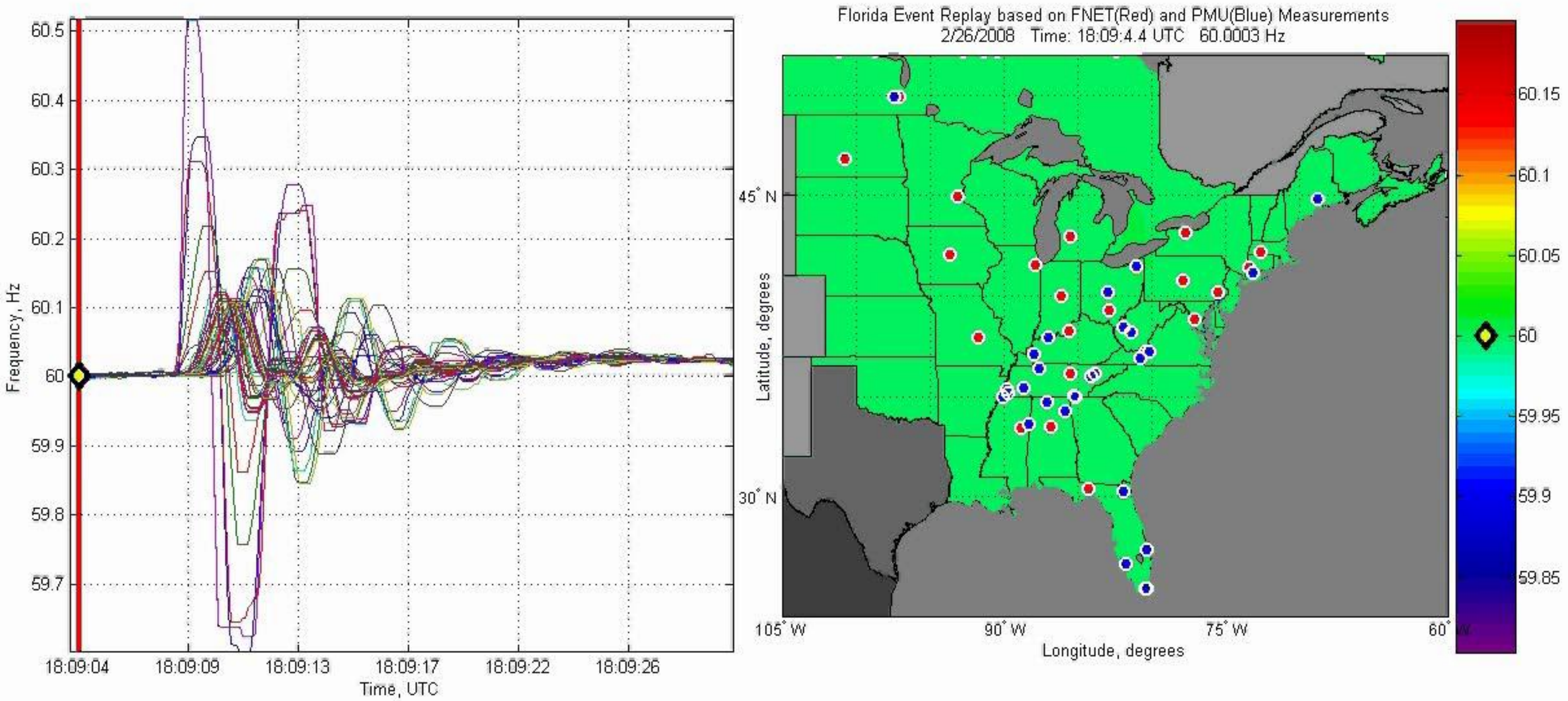
- A load rejection test in Texas in July 1993 with PMUs at four sites* exhibited an effect described by the authors as "Note the delay detecting the transient between the point closest to the plant – Venus and the furthest - Robinson…….The propagation phenomenon is not clear. It is not electrical in nature because of the time delay"

Initially a critic claimed the instruments were not calibrated correctly

* D. Faulk and R. J. Murphy," Comanche peak unit no. 2 100% load rejection test-underfrequency and system phasor measurements across TU electric system", Proc Conf Protective Relay Engineers, 1994 College Station, TX

NY Times June 8,2009

- On Feb. 26, 2008, a short circuit in a Miami electric power substation and an operator's error gave managers of the nation's electrical grids a glimpse of an uneasy future. The events triggered a chain reaction of power plant and transmission line outages in the state, unleashing sharp swings in voltages and power frequency that blacked out power for nearly 1 million customers in southern and central Florida for up to four hours.
- A video depicting the Florida incident's rippling spread has been created by Virginia Polytechnic Institute and State University's electrical and computer engineering department, which caught the disturbance on its first-generation grid frequency monitoring network. Some grid executives have downloaded the video on their laptops as a kind of horror flick for engineers of what could happen.

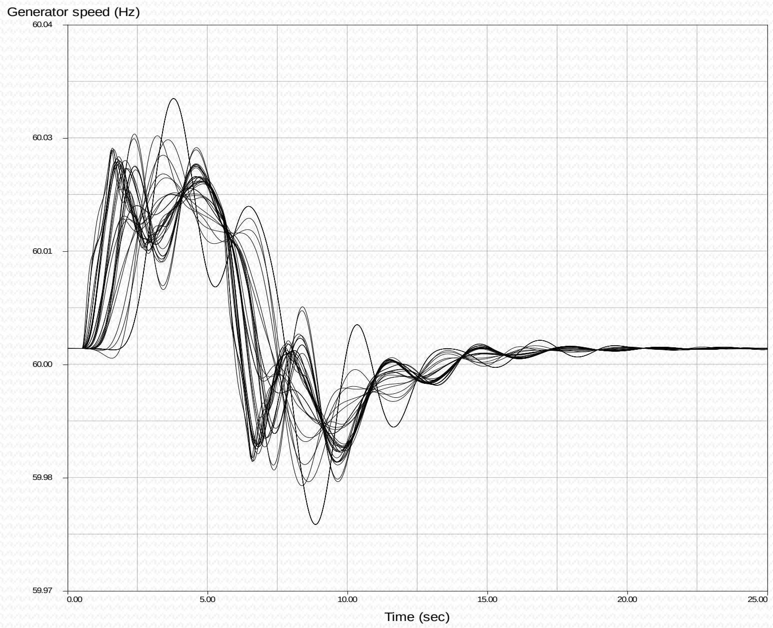


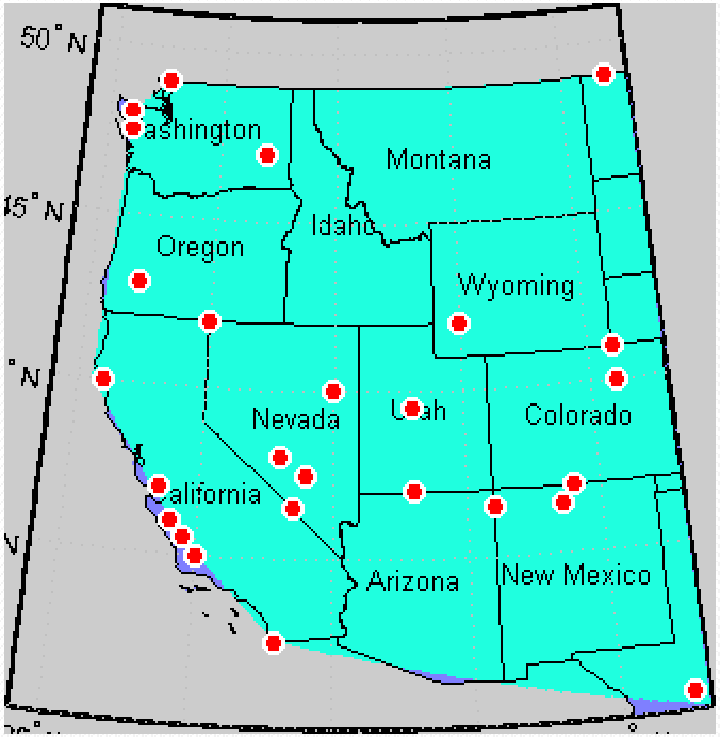
Florida Event Replay based on FNET(Red) and PMU(Blue) Measurements
2/26/2008 Time: 18:09:4.4 UTC 60.0003 Hz
Frequency, Hz
Time, UTC
Latitude, degrees
Longitude, degrees
60.5
60.4
60.3
60.2
60.1
60
59.9
59.8
59.7
18:09:04
18:09:09
18:09:13
18:09:17
18:09:22
18:09:26
45° N
30° N
105° W
90° W
75° W
60° W
60.15
60.1
60.05
60
59.95
59.9
59.85

- One view of this is that these waves must have existed in the past and caused no trouble so there is nothing to worry about.
- Besides “what could you hope to do about it anyway”
- The waves can cause incorrect relay operation but it is hard to predict exactly where.
- Nevertheless academics continue to be interested.

Prompted by FERC CEII (critical energy infrastructure information-Order Nos. 702, 630, 630-A, 643, 649 and 683) We seek a model system which exhibits waves. 127 Bus WECC model from 1990’s created for a DC Infeed study.

- Real power disturbance initiated by loss of 375MW in Los Angeles followed by recovery of the 375MW after 5 seconds





Control of Waves

- From the Telegrapher's equation for electromechanical waves # the idea of terminating the system in its characteristic "impedance" emerged*." Impedance" is the ratio of angle to frequency, This lead to "zero reflection" and zero transmission" controllers*. Ideally they depend on finding
- $$\frac{\partial \theta(x,t)}{\partial x}$$
- Approximations to this term have been suggested and applied to a modified version of the IEEE 145 bus 50 machine system. A zero transmission controller (controllable energy storage represented by load modulation where the load changes in response to local frequency and power variation on the local line) was added at bus 93 ● (Case 1) and three similar controllers were used at bus 67, 82 and 128. (Case 2) ^ ●

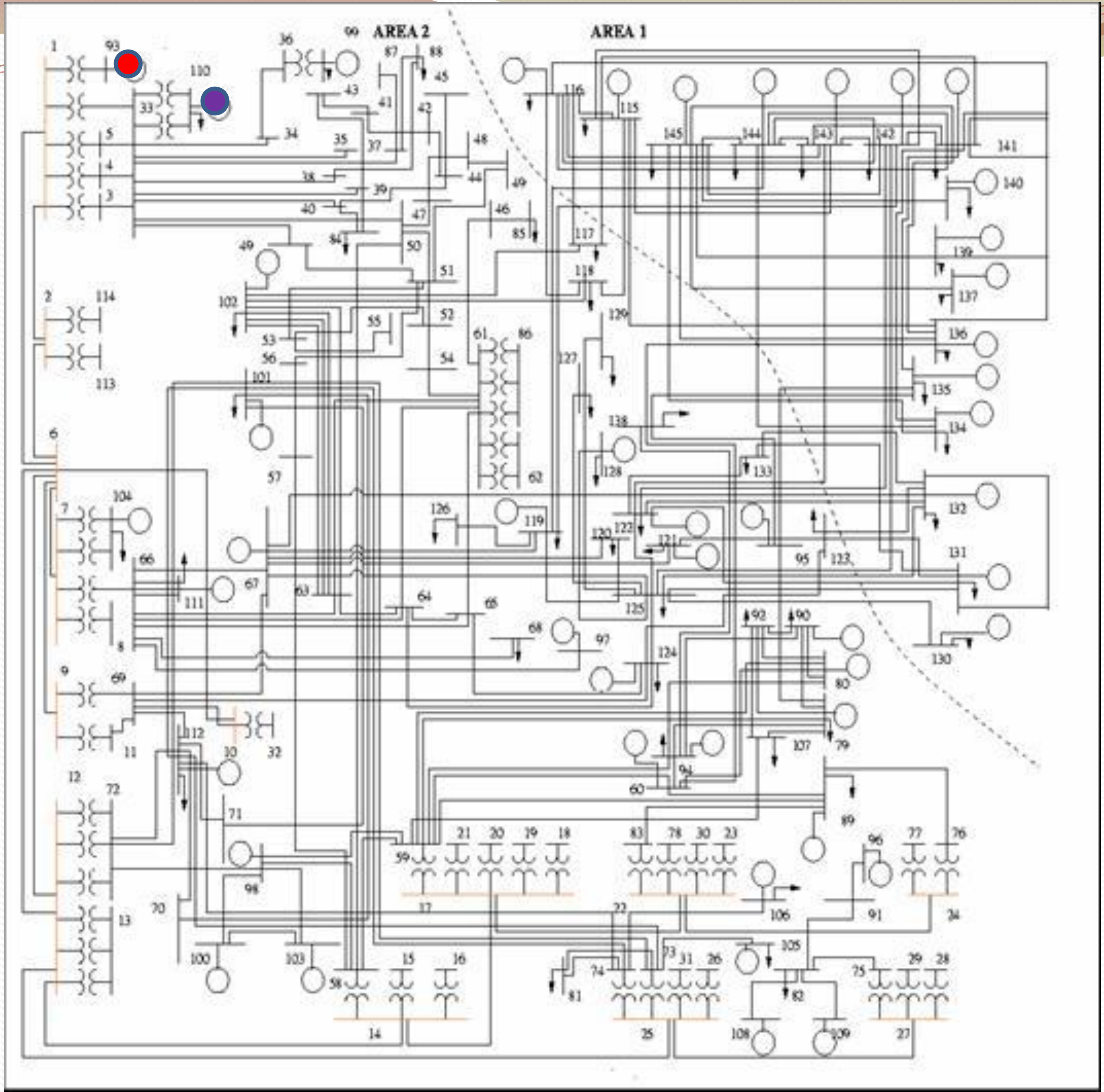
M Parashar, " Continuum Modeling of Electromechanical Dynamics in Power Systems", PhD Thesis Dissertation, Cornell University, 2003

*B. C. Lesieutre , E Scholtz, G. C. Verghese, "Impedance Matching Controllers to Extinguish Electromechanical Waves in Power Networks", Proc of 2002 IEEE Conference on Control Applications

^Xing Wei BS Dissertation," Control of disturbance in power system", Southwest Jiao Tong University EE, June 2010

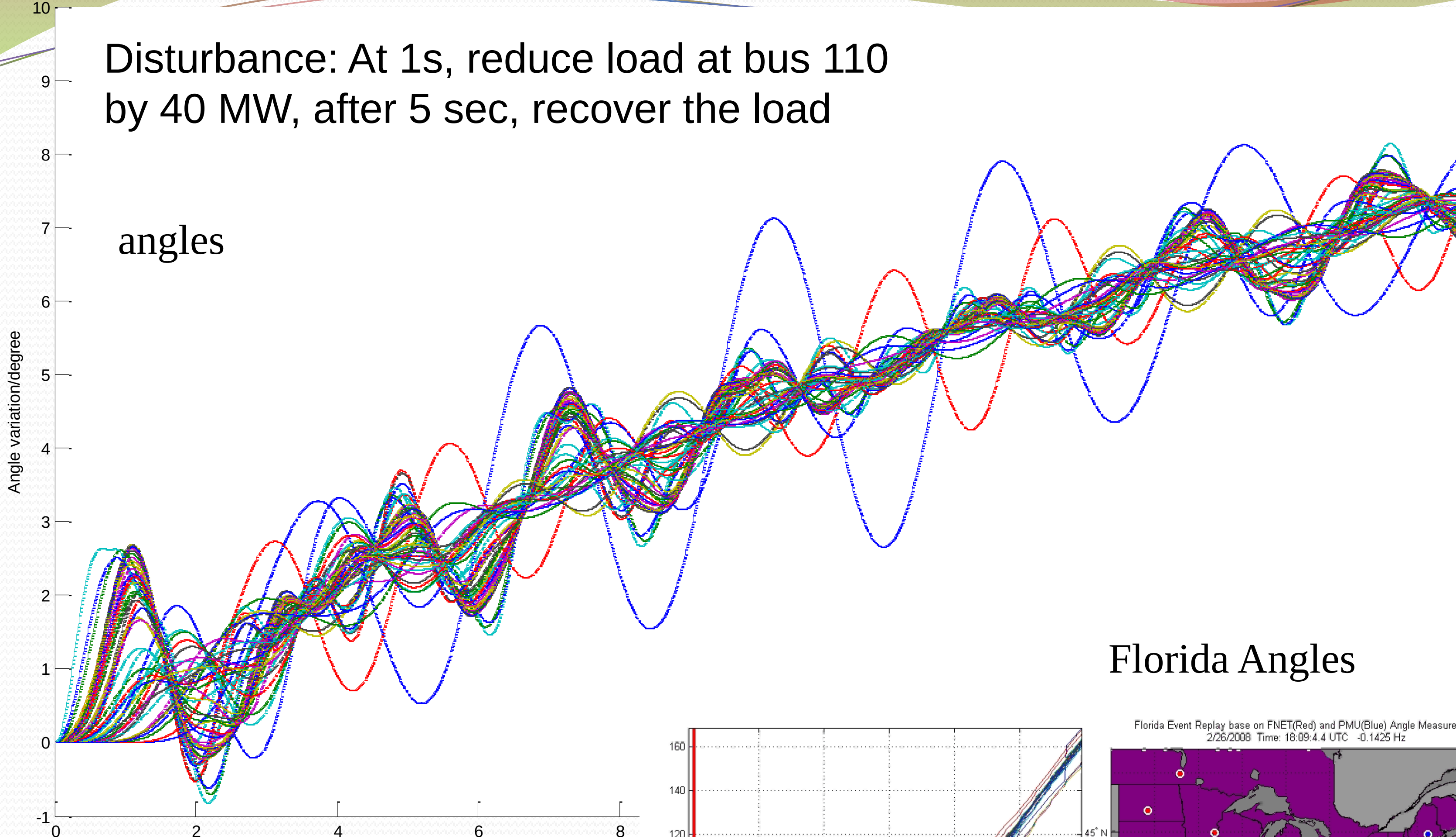
Case 1

Zero transmission controller close to the disturbance



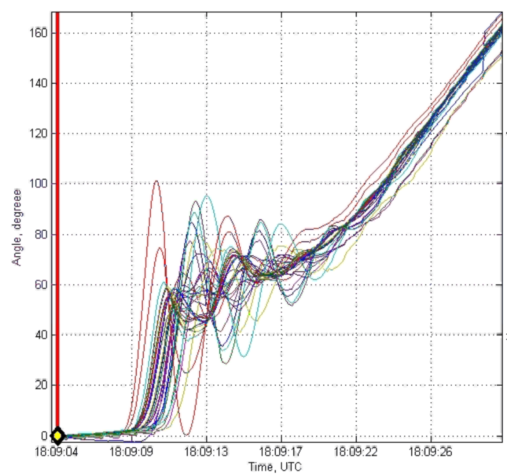
Disturbance: At 1s, reduce load at bus 110 by 40 MW, after 5 sec, recover the load

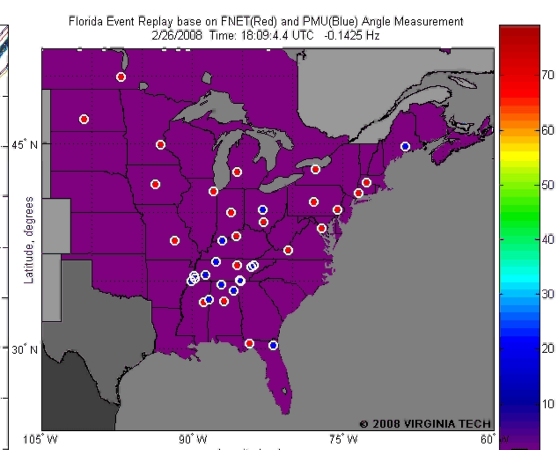
angles



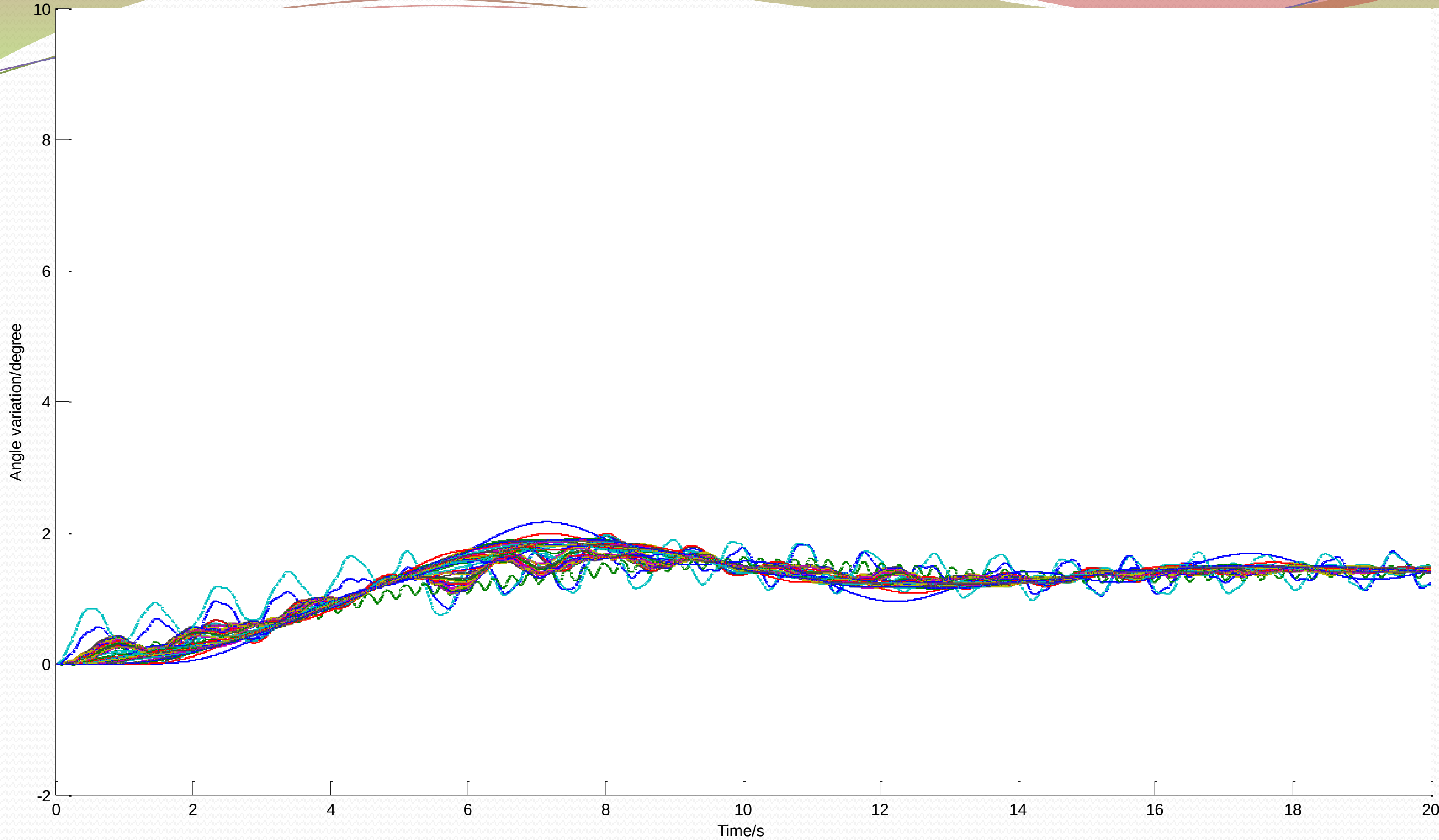
Without control

Florida Angles

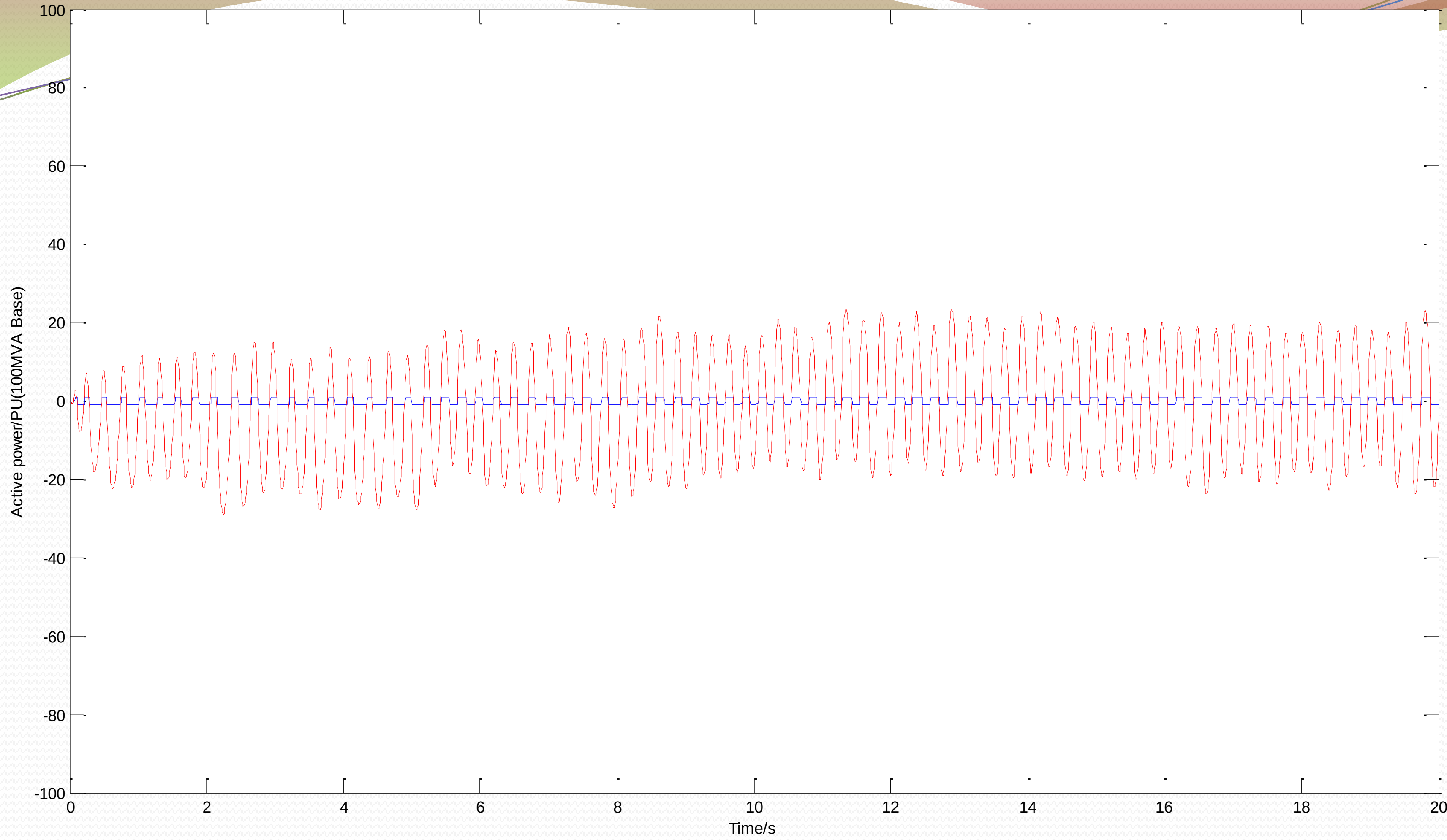




VirginiaTech
Invent the Future



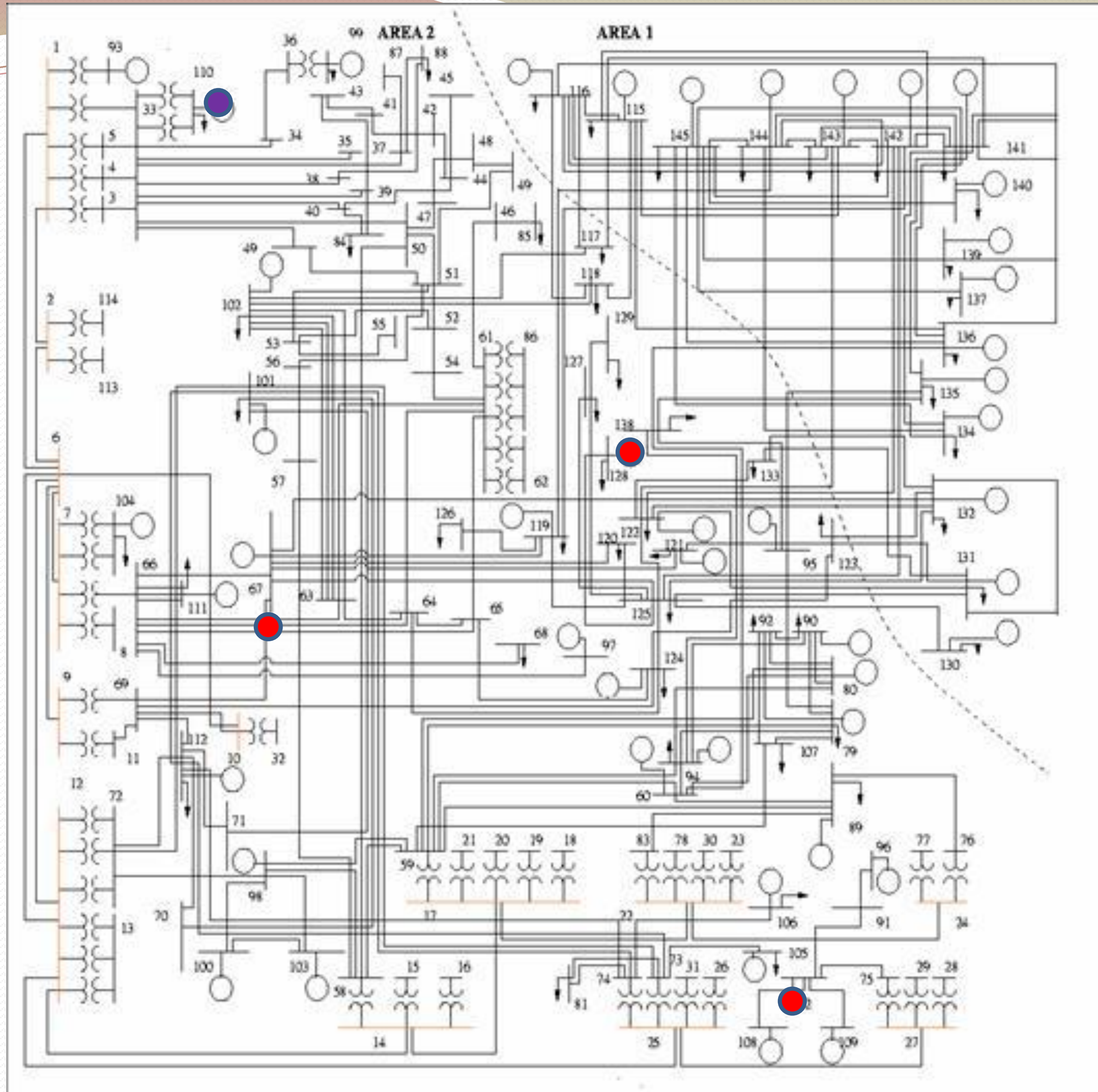
With one Zero transmission controller(ZTC) at bus 93

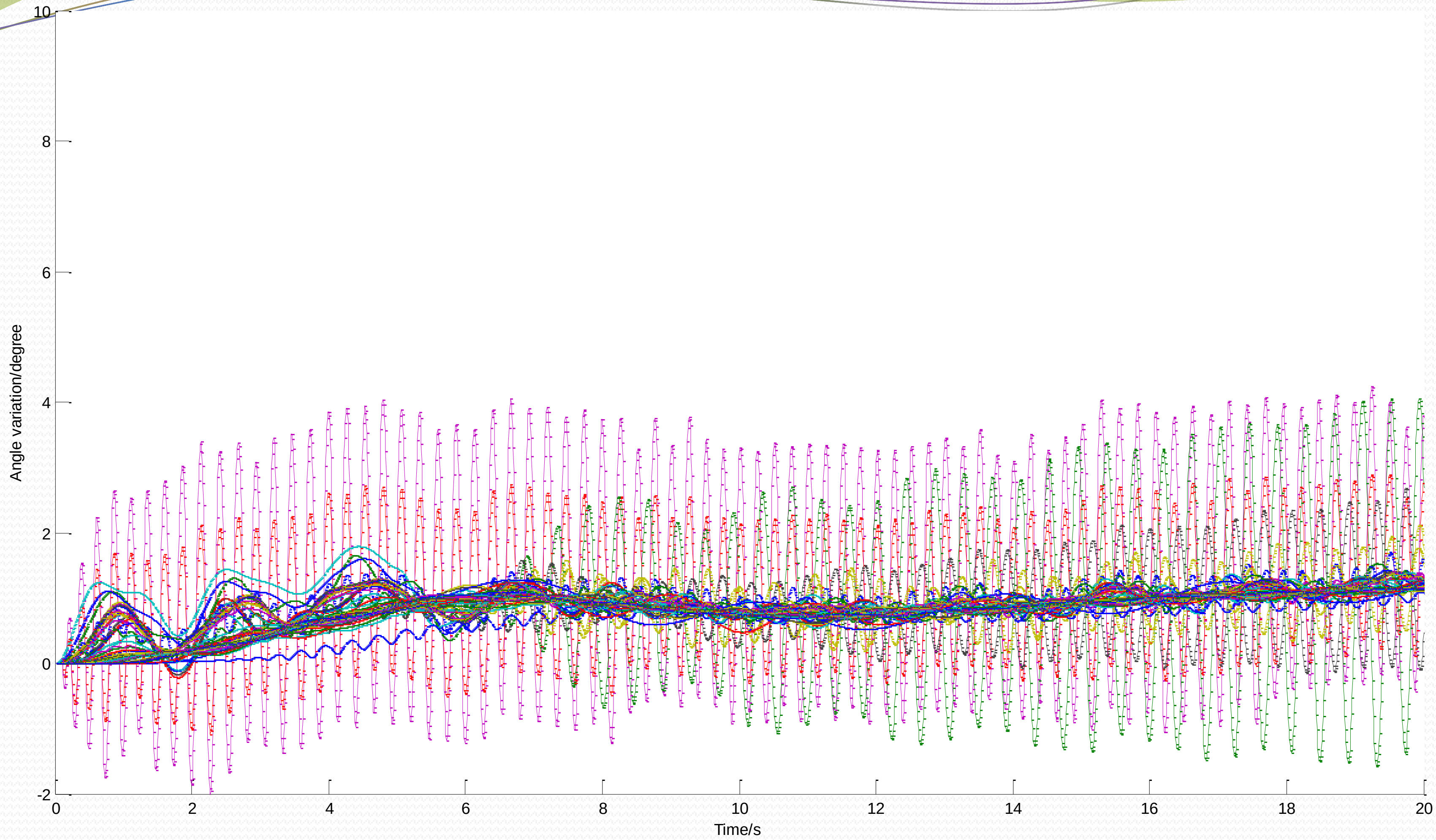


Output(The limit of the controller output is ± 80MW) of the controller(blue) and the desired power of the controller (red)

Case 2

Three zero transmission controllers further from disturbance





With three ZTCs at bus 67, 82, and 128

The angle of the buses where the controllers are installed have the larger amplitude

The controllers are saturating as in slide 14

DOE Demonstration Project

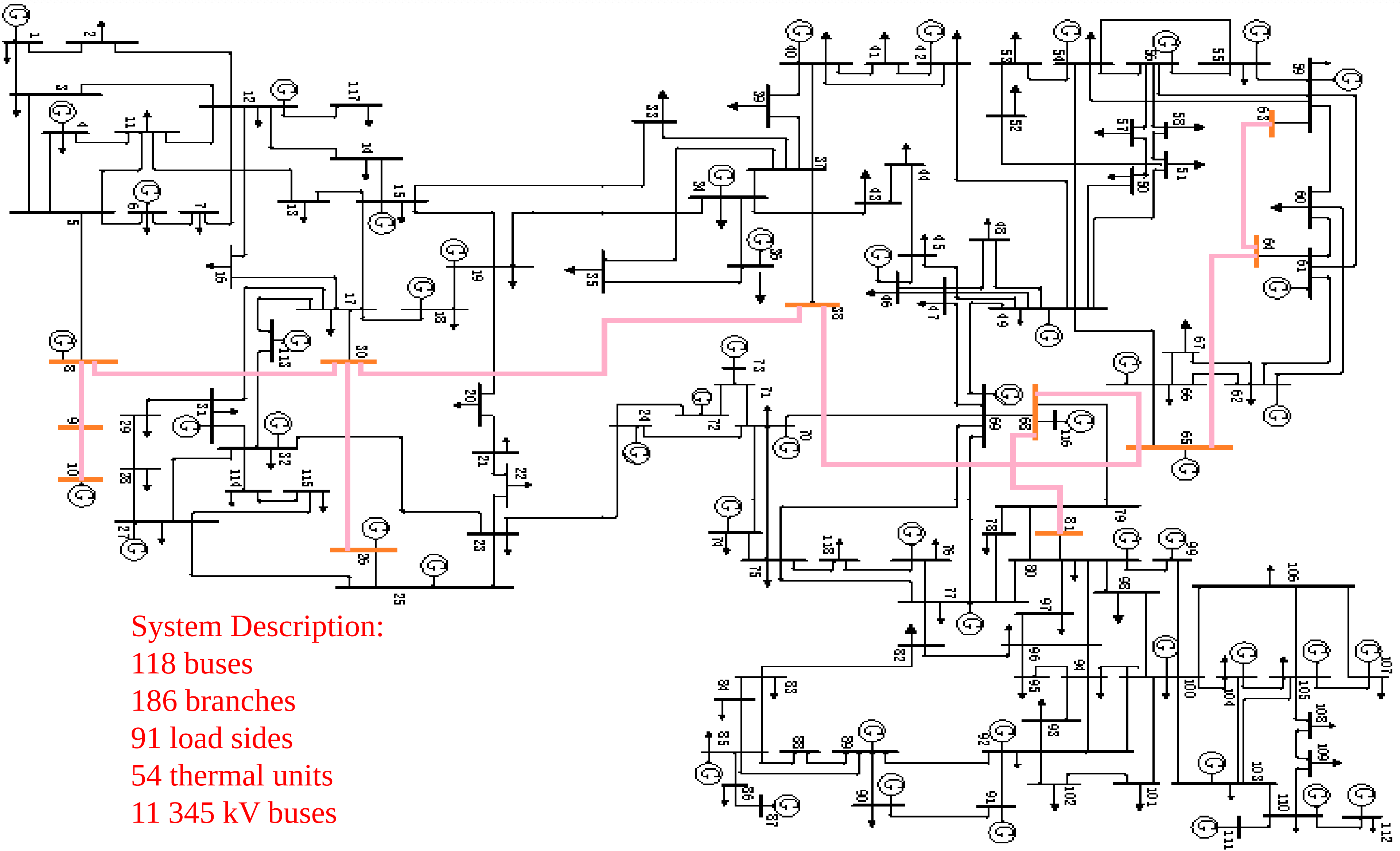
- SYNCHROPHASOR BASED TRACKING THREE PHASE STATE ESTIMATOR AND ITS APPLICATIONS
  - Virginia Tech University, Blacksburg, VA
  - Dominion Virginia Power   Quanta Technology
- Three phase, PMU only, All 500kV buses, every 1/30 sec.
- Time tagged measurements transmitted over a Sonnet network produce a truly dynamic estimate
- Linear
  - Measurements, z, are complex voltages and currents
  - The estimate of the voltages, x, is a linear combination of the measurements which only changes when the topology changes

$$\hat{x} = Mz$$

  - A topology processor uses measurements and time tagged breaker status to detect breaker opening to change M

- At the moment each new estimate is computed without regard to the previous estimate.
- To identify bad data and detect events in the system it is important to have an observation residual, the difference between the predicted measurement and the actual measurement.
- Again with CEII in mind, we use the IEEE 118 bus system which has 11 345kV buses and 107 138 kV buses as a model system

One-line Diagram of IEEE 118-bus Test System



System Description:
118 buses
186 branches
91 load sides
54 thermal units
11 345 kV buses

The issue: predict the next set of measurements

- If we measured all the injections at the 345kV buses we might write

$$x(n+1) = \Phi x(n) + \Gamma w(n)$$

$$z(n+1) = Hx(n)$$

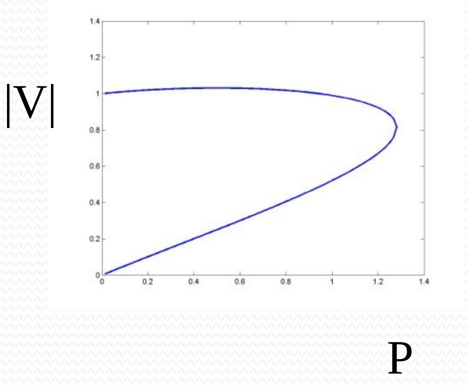
- and imagine we measure both z(n) and w(n). But unfortunately we do not have the luxury of measuring all of w(n). We do not even measure all 500kV currents (Dominion)
- ARMA: predict the next measurement from prior estimates.
- Each $\hat{x}(n) = Mz(n)$

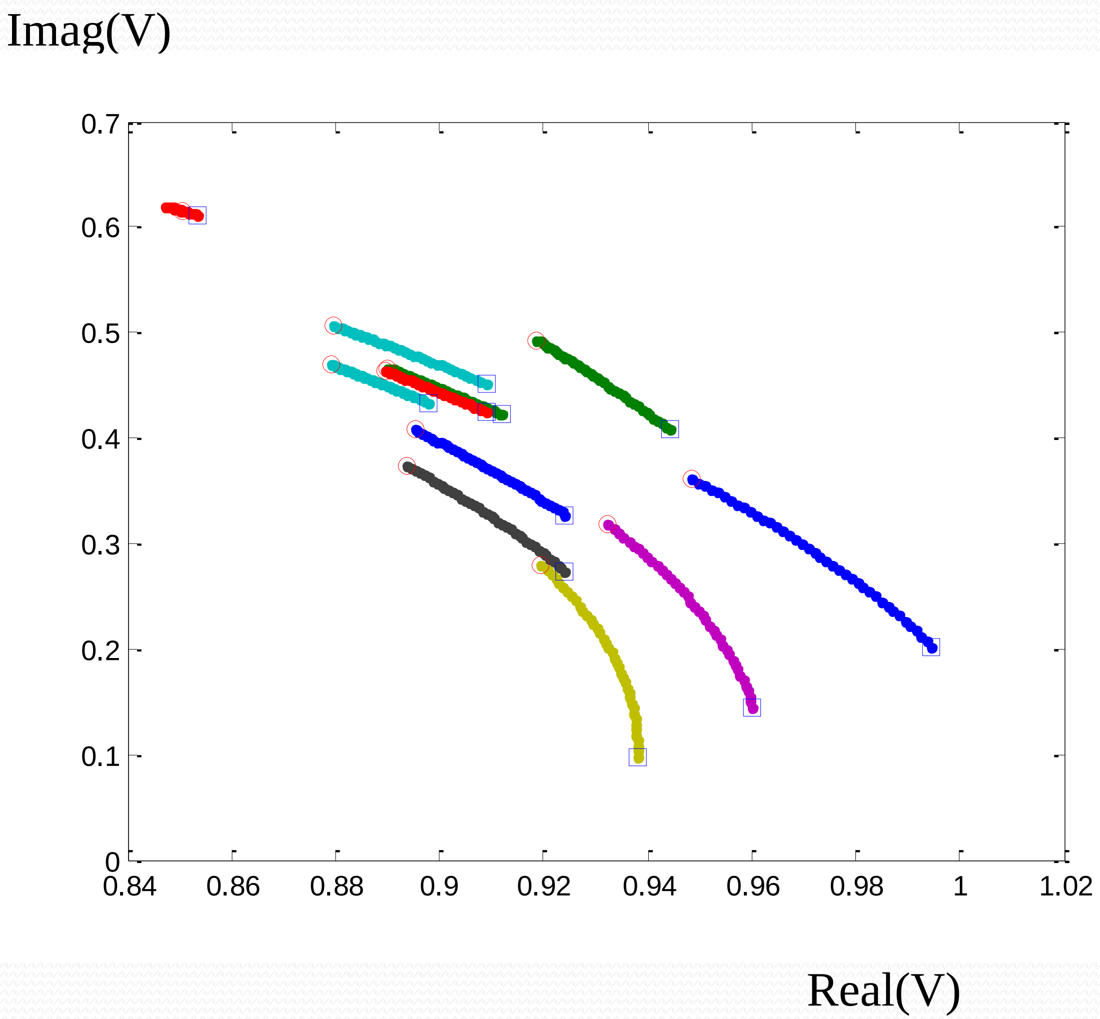
$$\tilde{x}\ (n+1) = \Theta_1 \hat{x}(n) + \Theta_2 \hat{x}(n-1) + \cdots \Theta_{r+1} \hat{x}(n-r)$$

$$residual = Mz(n+1) - \tilde{x}(n+1)$$

Morning Load pick-up   60% load increase in one hour

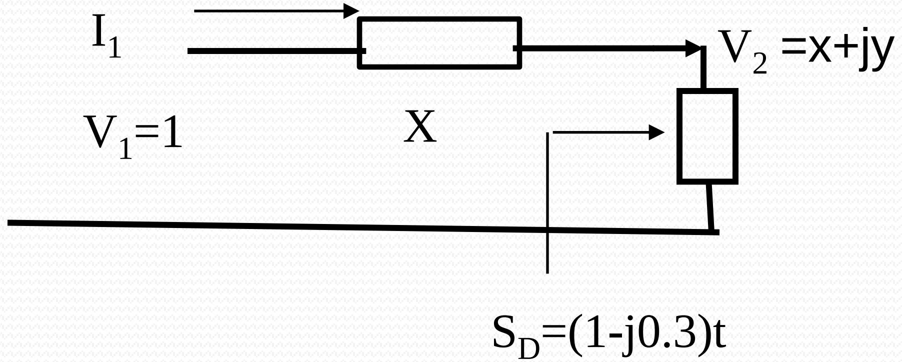
Circle - start
Square – end
Complex voltages on 345 kV buses
These voltages are essentially quadratic
$v_k(t) \sim= a_k + b_k t + c_k t^2$
Nose curves are under the same assumption of load increase at constant power factor





Why the curves are quadratic

- Load is increased at constant power factor X=0.5, β=-0.3



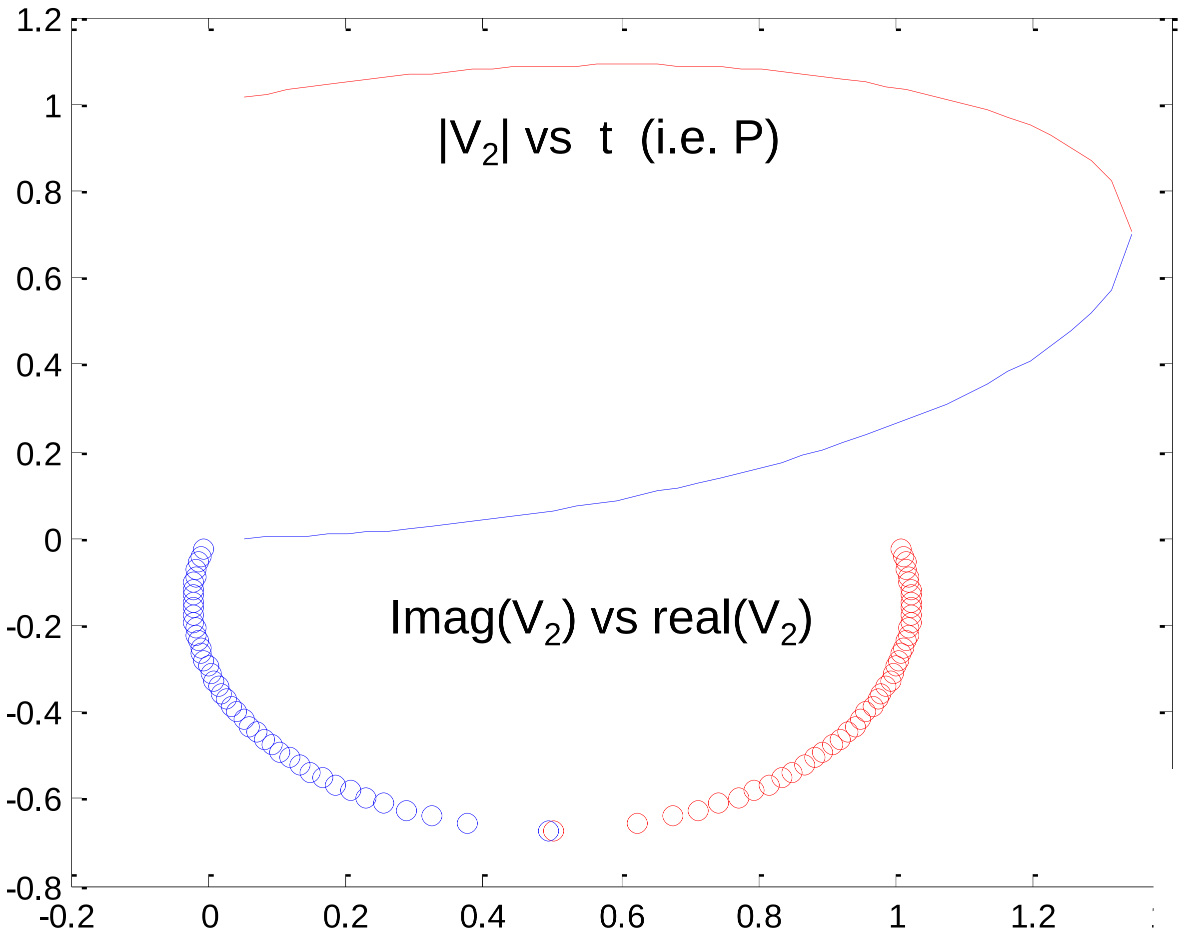
$$I = \frac{1 - x - jy}{jX}$$

$$I^* = \frac{1 - x + jy}{-jX}$$

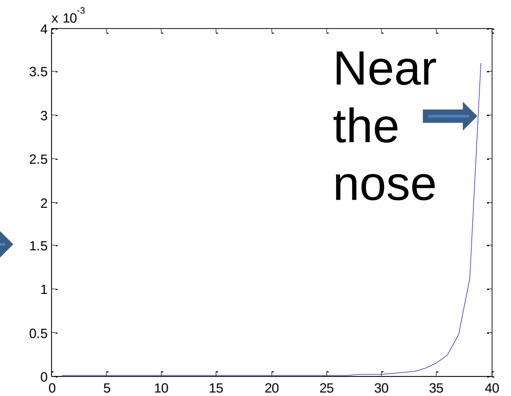
$$x + jy - x^2 - y^2 = -j0.5t - .15t$$

$$y = -0.5t$$

$$x^2 - x + 0.25t^2 - 0.6t = 0$$



Error in quadratic fit scale 10^{-3}



- Let y(t) be an nth order polynomial

$$y(t) = \alpha_n t^n + \alpha_{n-1} t^{n-1} + \alpha_{n-2} t^{n-2} + \cdots \alpha_1 t + \alpha_0$$

$$\begin{bmatrix} y(n) \\ y(n-1) \\ \vdots \\ y(1) \\ y(0) \end{bmatrix} = \begin{bmatrix} 1 & n & n^2 & \cdots & n^n \\ 1 & n-1 & (n-1)^2 & \cdots & (n-1)^n \\ \vdots & \vdots & \vdots & \cdots & \\ 1 & 2 & \cdots & 2^{n-1} & 2^n \\ 1 & 1 & \cdots & 1 & 1 \end{bmatrix} \begin{bmatrix} \alpha_0 \\ \alpha_1 \\ \vdots \\ \alpha_{n-1} \\ \alpha_n \end{bmatrix}$$

$$\mathbf{y} = \mathbf{V}\boldsymbol{\alpha}$$

The first row of V^{-1} $b^T = [b_n\ b_{n-1}\ b_{n-2}\ \ldots\ b_2\ b_1]$

$$b^T \mathbf{y} = b^T \mathbf{V}\boldsymbol{\alpha} \quad b^T V = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$b_n y(n) + b_{n-1} y(n-1) + b_{n-2} y(n-2) \cdots + b_1 y(1) = \alpha_0 = y(0)$$

For all a's y satisfies the same ARMA model, b's are the binomial coefficients*

Examples: n=5, b=[-1 6 -15 20 -15 6]

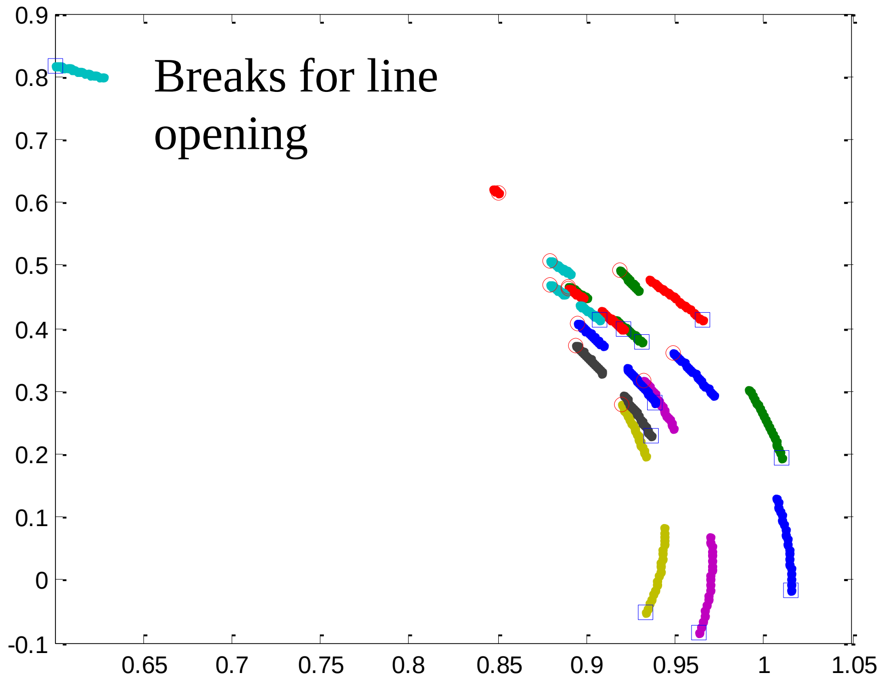
y(n)=6y(n-1)-15y(n-2)+20y(n-3)-15y(n-4)+6y(n-5)-y(n-6)

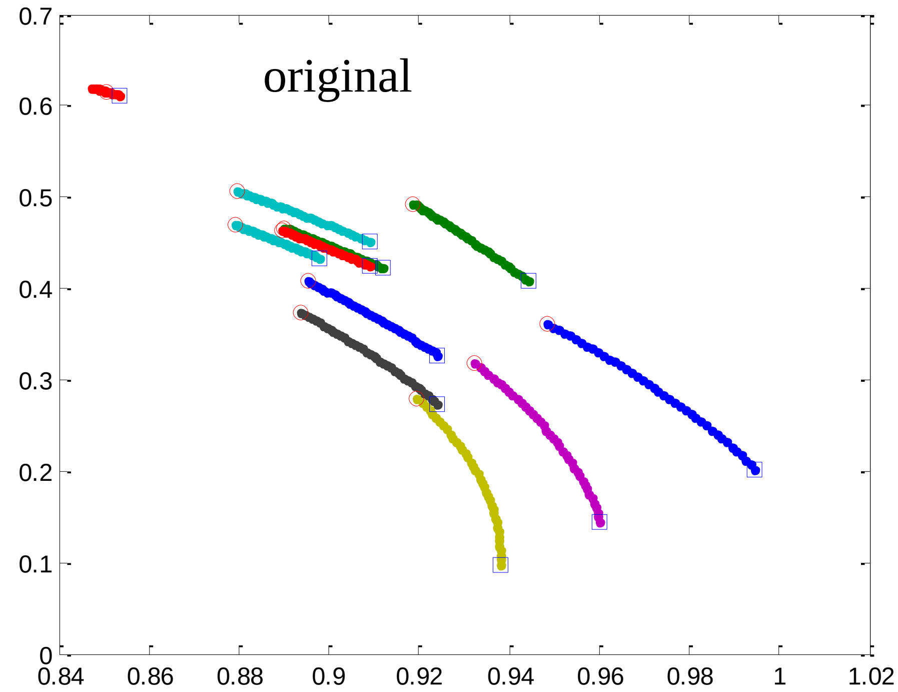
n=2

y(n)=3y(n-1)-3y(n-2)+y(n-3)   predictor for all quadratic voltages

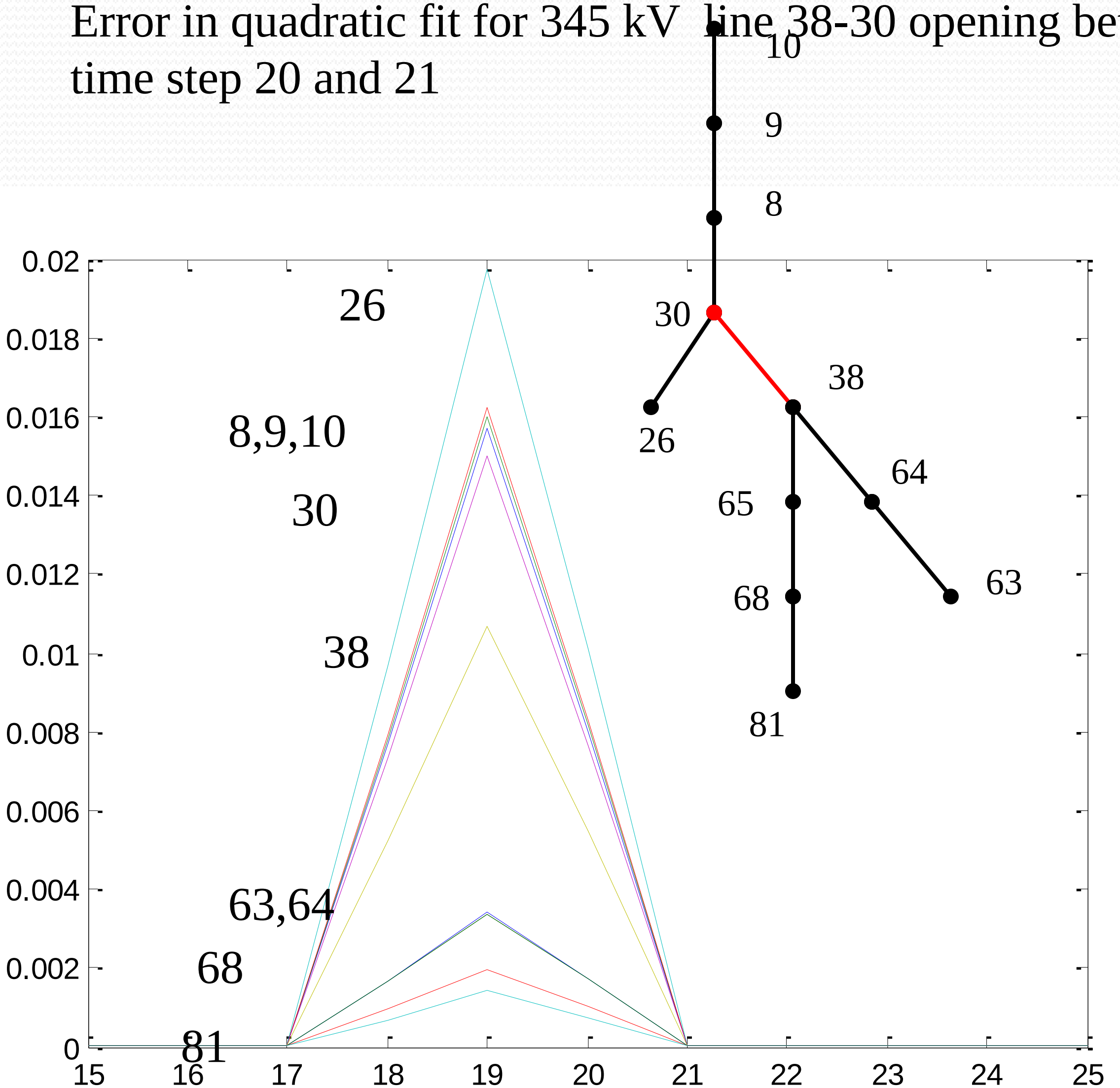
*A Eisinberg and P. Pugliese, "Exact Inversion of a Class of Vandermonde Matrices", Proc 5th SIAM Conference on Applied Algebra, June 1994

345 kV Line opening



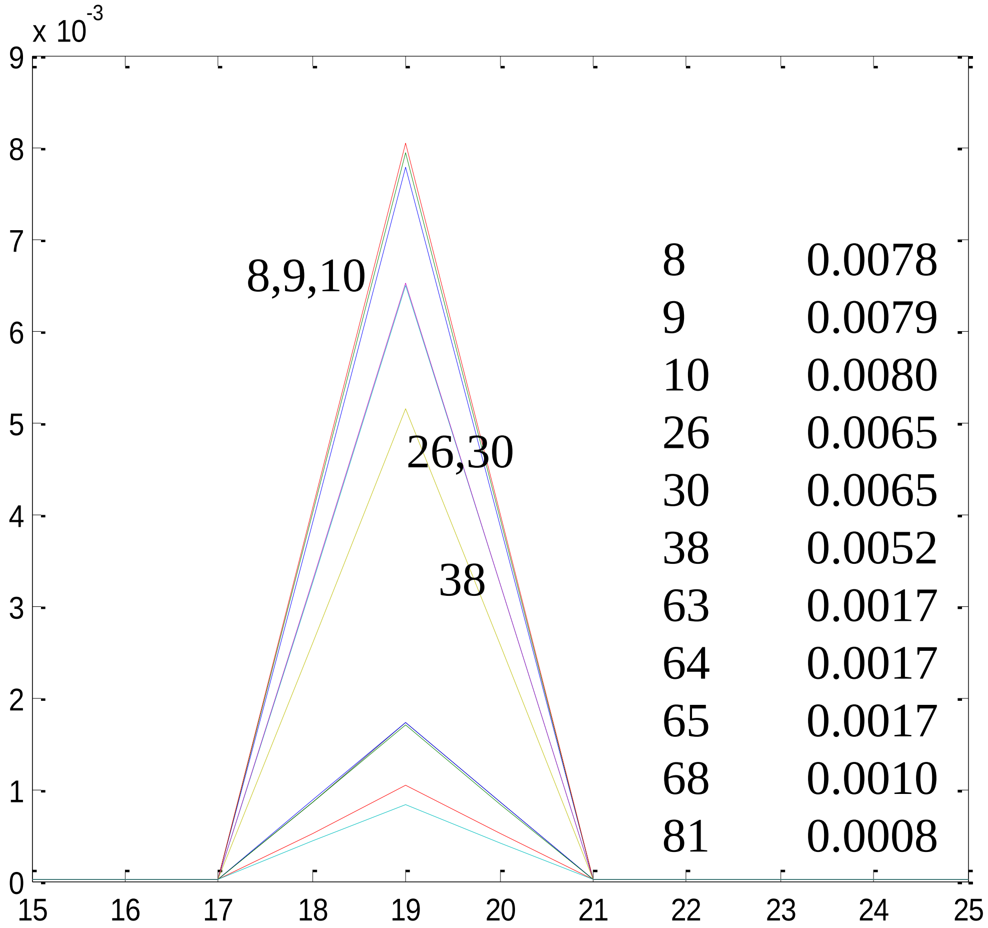


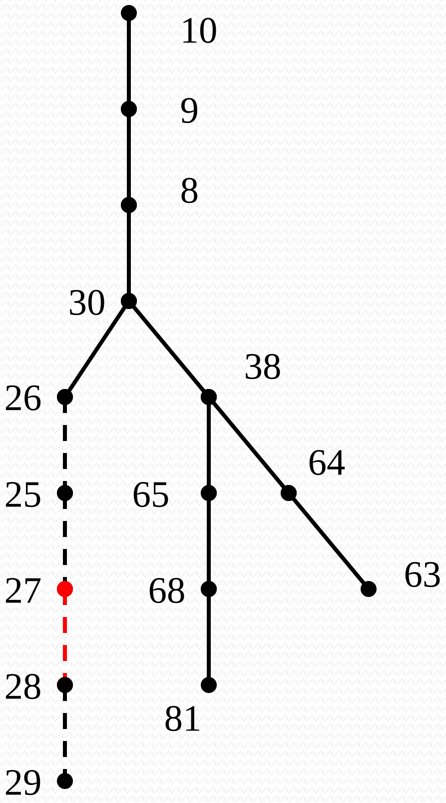
Error in quadratic fit for 345 kV line 38-30 opening between time step 20 and 21



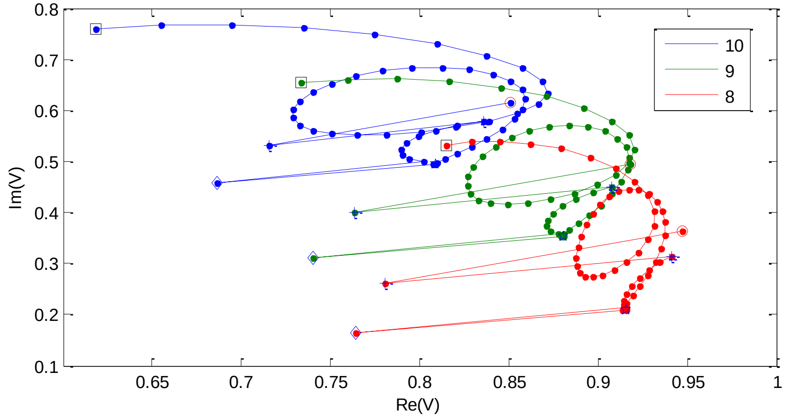
8	0.0157
9	0.0160
10	0.0162
26	0.0197
30	0.0150
38	0.0107
63	0.0034
64	0.0034
65	0.0034
68	0.0020
81	0.0014

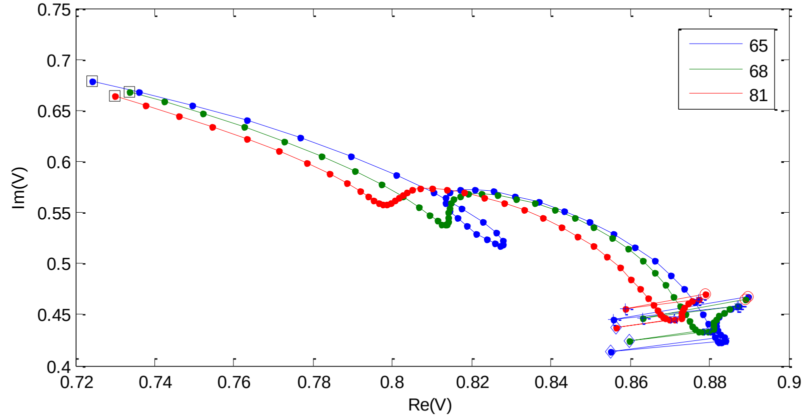
Now open a 138kV line 27-28

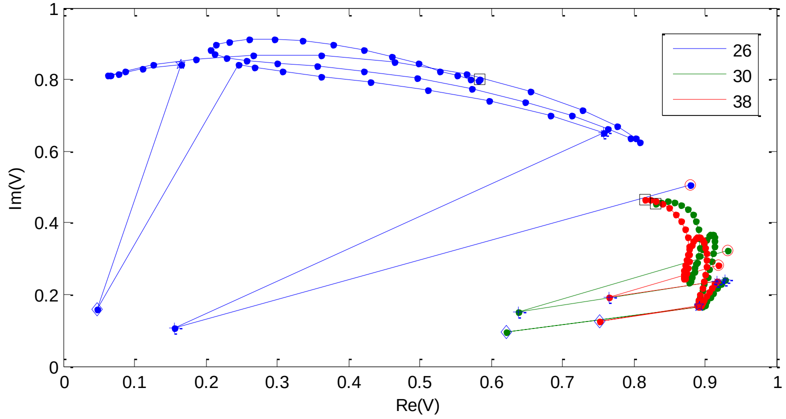


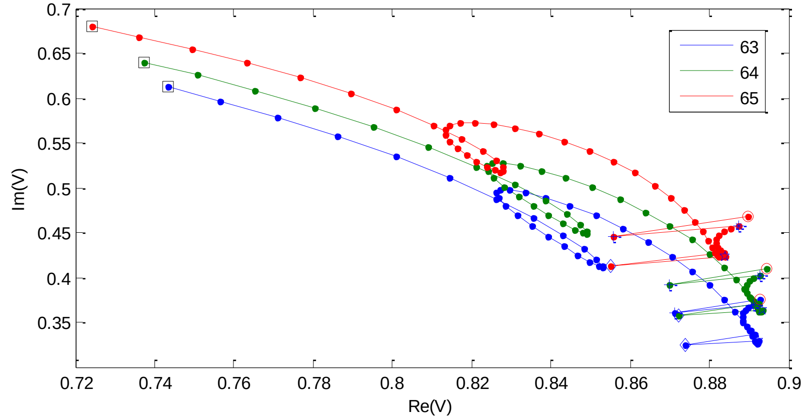


A quiz: Speed up What happened?
Nine 345 kV complex bus voltages in the 118 bus system at 30 times a sec plotted in the complex plane

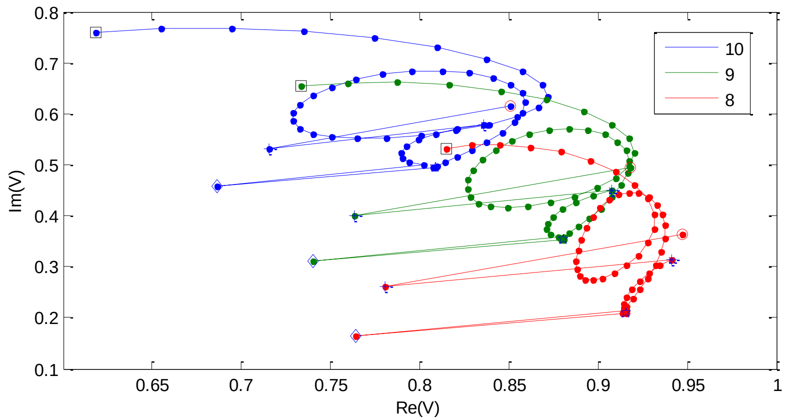


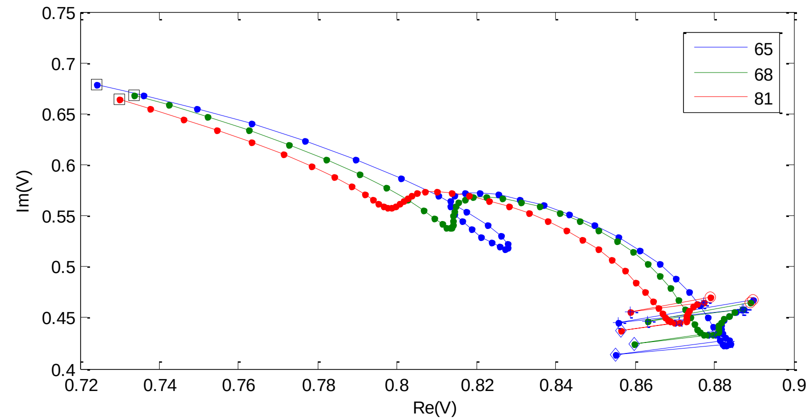


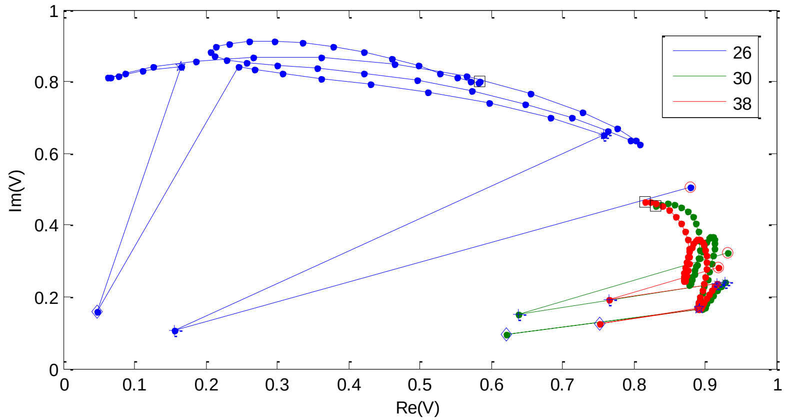


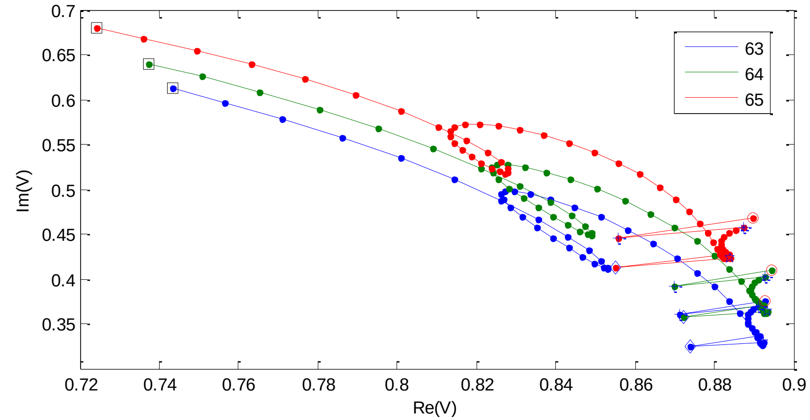


Answer: Three Phase Fault on Line 26-30 with Unsuccessful High Speed Reclose

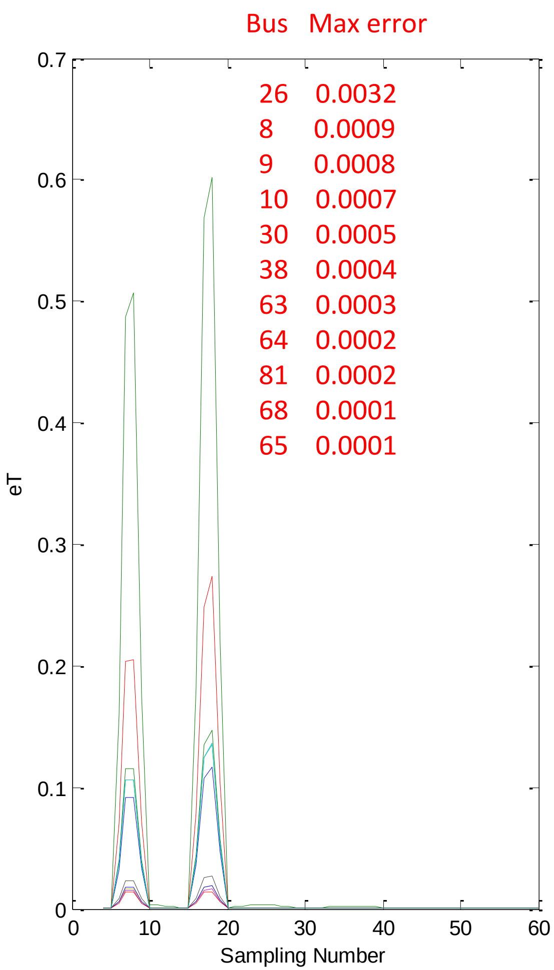




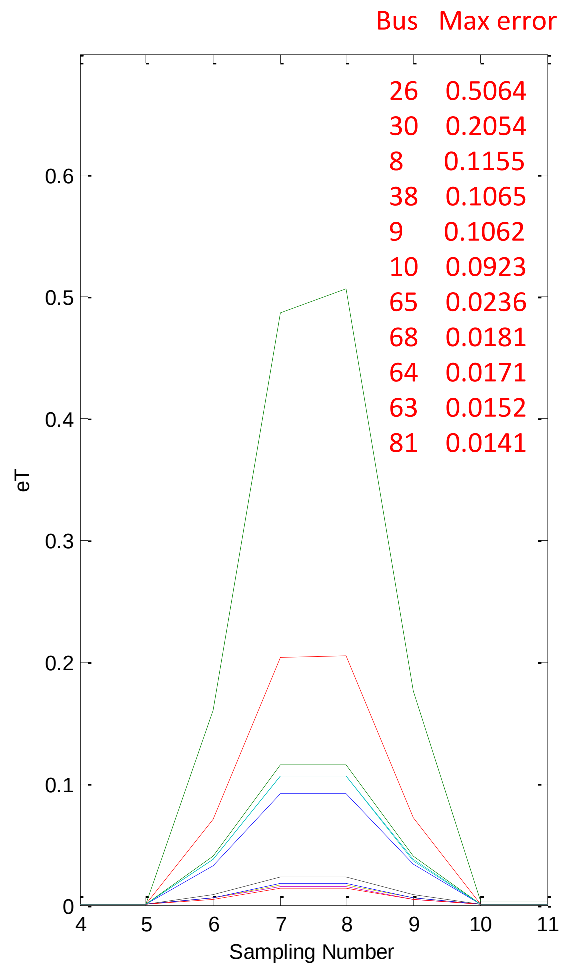




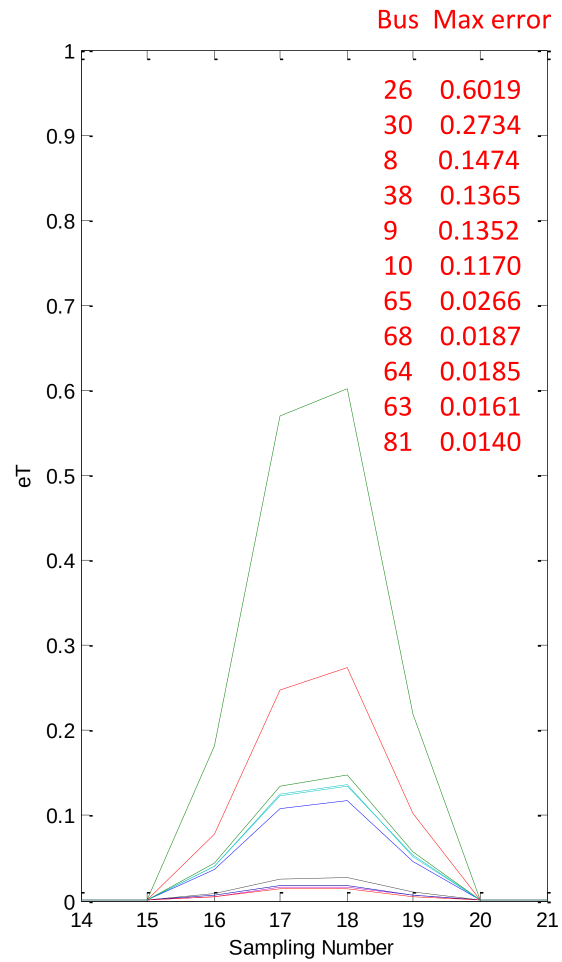
Error in quadratic fit for 345 kV One Phase to Ground Fault on Line 26-30 with Unsuccessful HSR

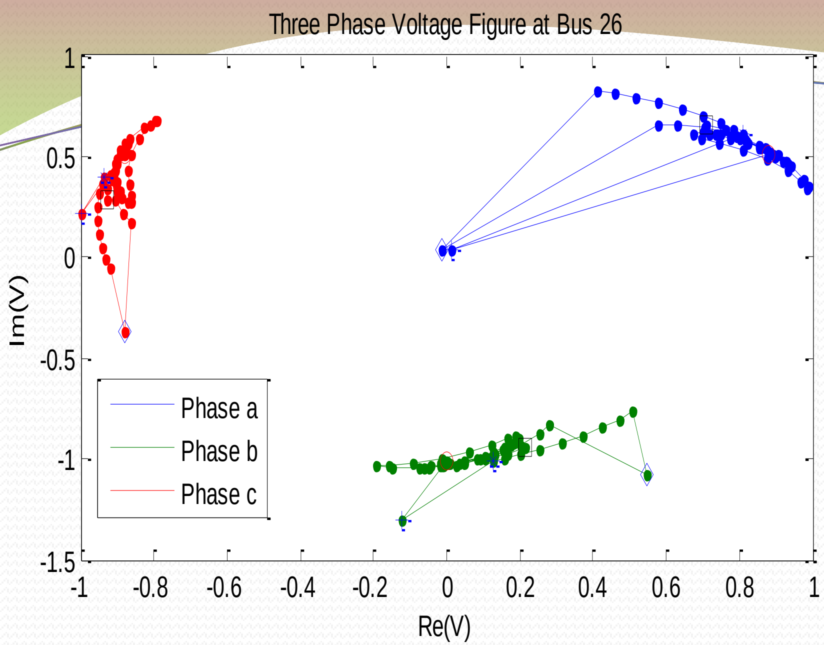


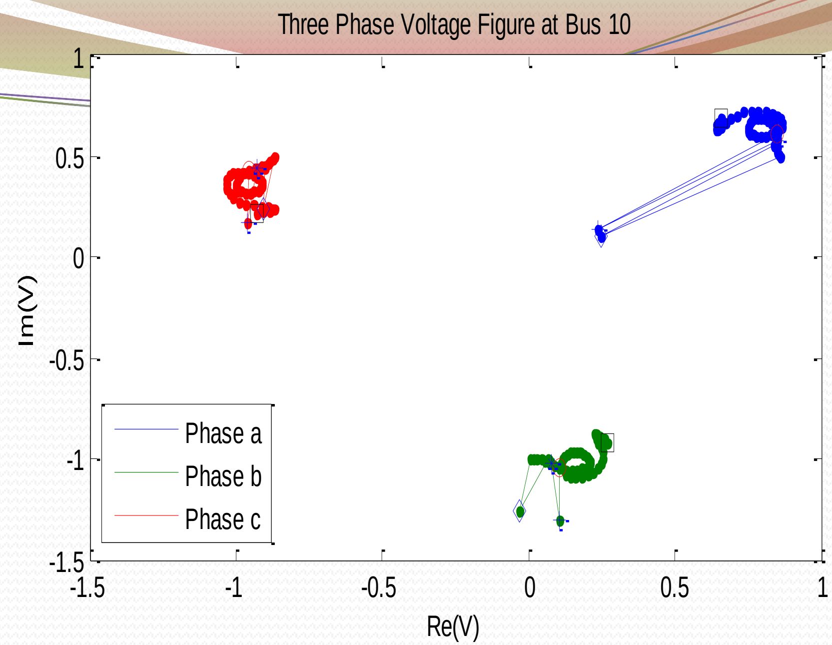
First fault

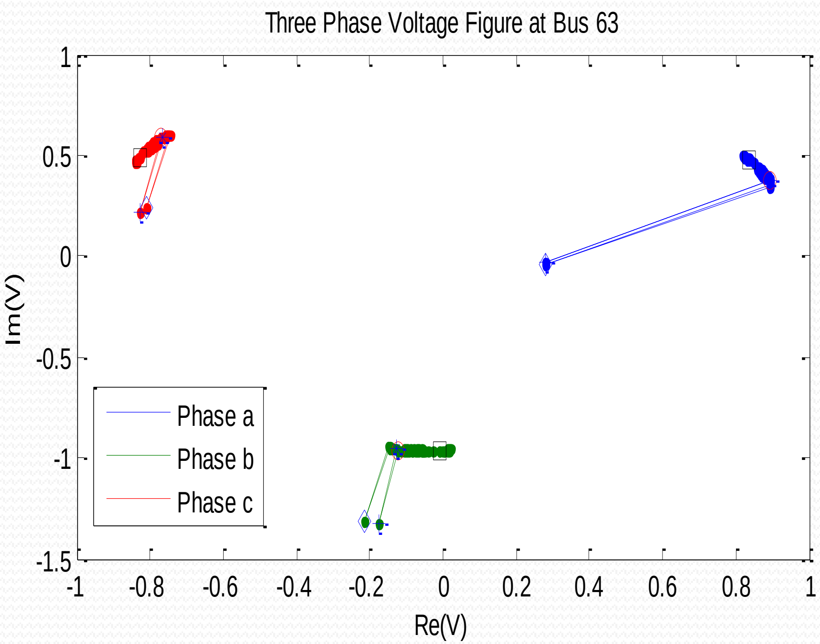


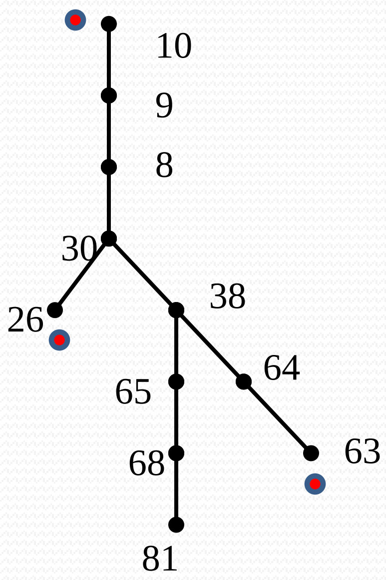
Reclose into fault











Three phase voltages (what the operator will see) on three buses for an a-ground fault on the line from 26-30

Waves and inter-area oscillations

- The connection was first made 30 years ago* but has been recast in the light of new results on waves.
- Using an *equivalent* eigenvalue model for aggregated models of continuum power systems the connection between mode shapes and eignevalues has been demonstrated**

- *R.L. Cresap and J. Hauer, “Emergence of a New Swing mode in the Western Power System” IEEE Trans PAS, vol. PAS-101, no. 4, pp 2037-2045 Apr 1981
- **A Chakrabortty and T.R. Khan, “ Modeling and Analysis of Oscillations in Complex Power System Networks”, Proceedings of the IEEE PES General Meeting 2011
- ^name, title,

Yet another connection

- The term used in "zero refection" controllers, $\dfrac{\partial \theta(x,t)}{\partial x}$
- For a traveling wave $\theta(x,t)=\alpha(x-kt)$ is

$$\frac{\partial \theta(x,t)}{\partial x} = \alpha'(x-kt) = -\left[\frac{1}{k}\right]\frac{\partial \theta(x,t)}{\partial t} = -\left[\frac{1}{k}\right]\omega(x,t)$$

- And feedback of local frequency is used to damp inter-area oscillations

Conclusion

- As the number of PMUs increase we will continue to observe things that will need explanation. Particularly as the time interval between measurements decreases our preconceived ideas will be tested.
- We might learn something.

- Thank You,
- Questions?