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A New Method of Identifying Grid Parameters From Disturbance Events

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UCSD Phasor Measurement System

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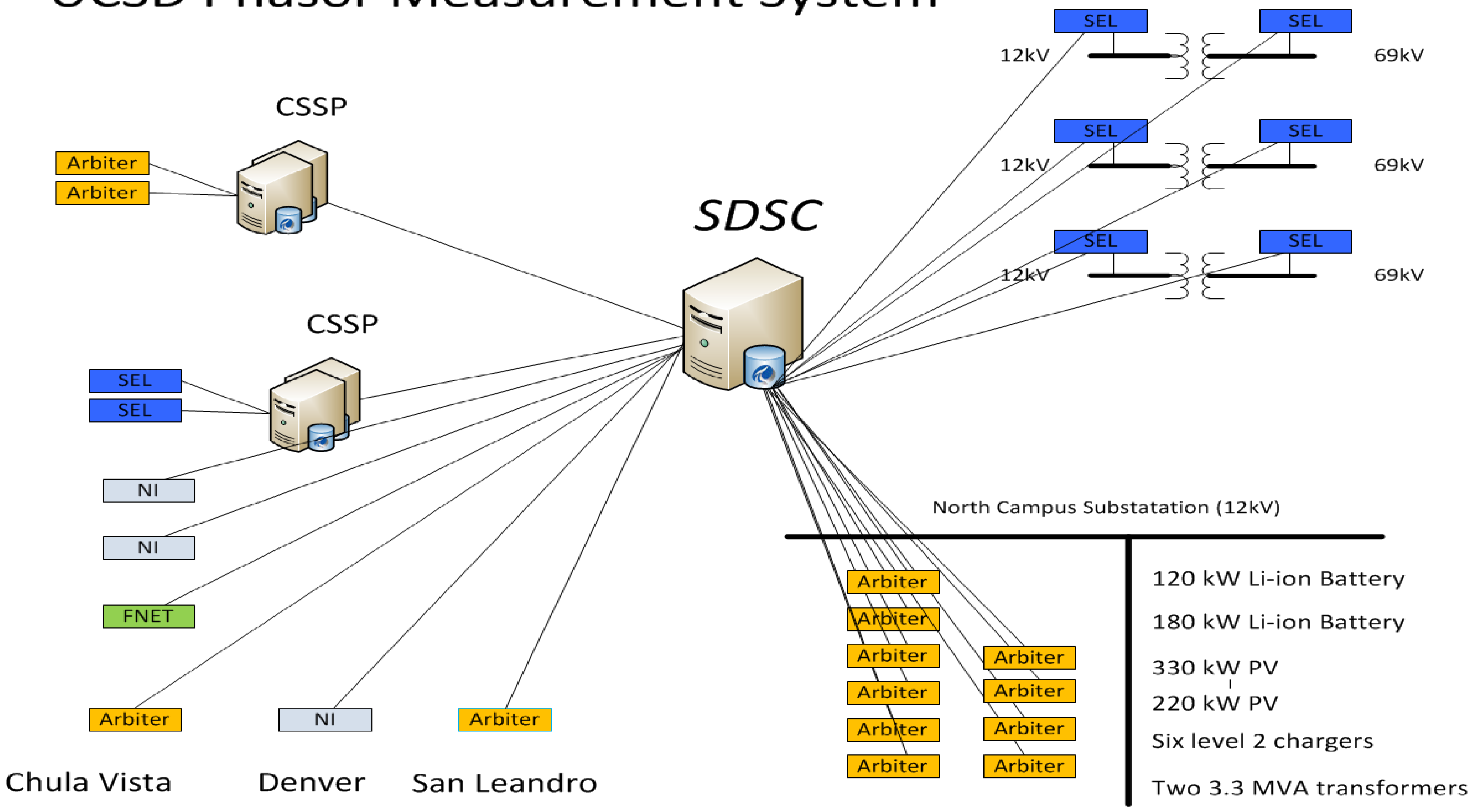
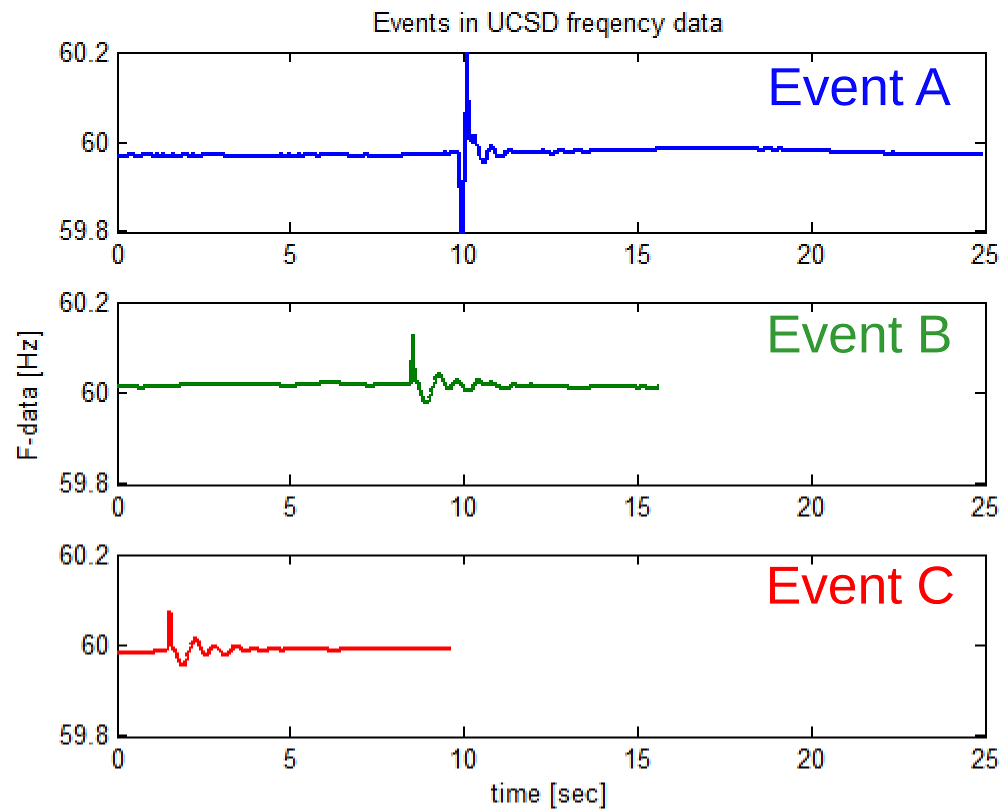


Typical Events

Typical events/oscillations we currently measure in the UCSD microgrid:

- How do we detect these events?
- How can we quantify these events?
- What do these events tell us about our (micro)grid?



Main contribution

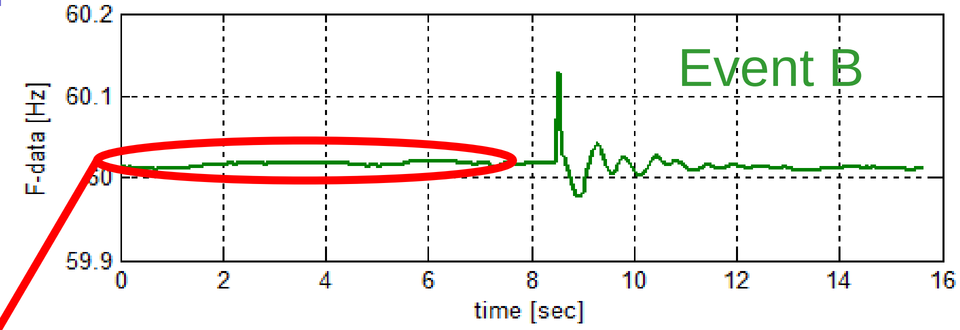
- Automatically detect when a disturbance/transient event occurs
- Automatically estimate Frequency, Damping and Dynamic Model from disturbance event.

Main Features:

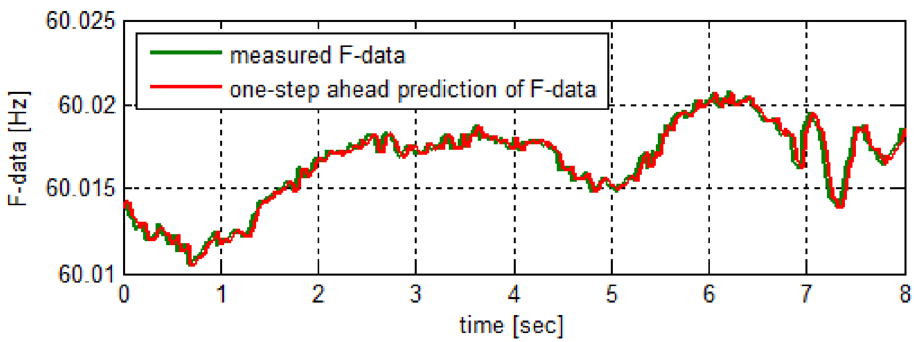
- Automatically detect:
  - Predict ambient Frequency signal "one-sample" ahead
  - Observe when prediction deviates for event detection
- Automatically estimate:
  - # of modes of oscillations in measured disturbance
  - Estimate frequency and damping of the modes
  - Put results in dynamic mode
- All done in real-time!

Illustration of Main contribution

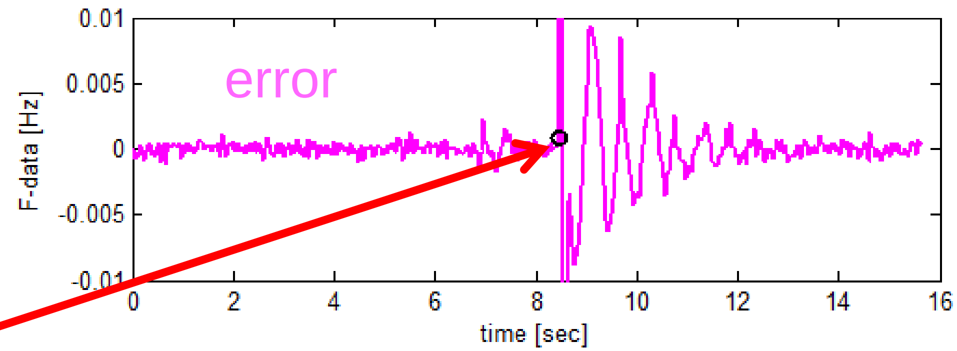
For illustration: Frequency oscillation on UCSD microgrid (event B)



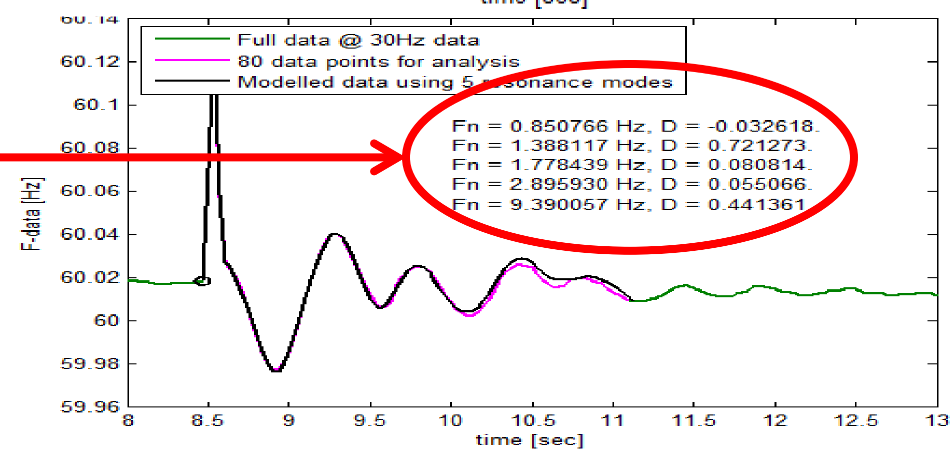
- Predict "one-step ahead" ambient



Frequency and track error:



- Detect beginning of event
- Estimate frequency & damping of oscillations via a new Realization Algorithm



Outline of Remainder

- Prediction of ambient Frequency signal
  - Autoregressive Model
  - Estimation and Error Threshold
- Analysis of events via Realization Algorithm
  - State Space Model
  - Singular Value Decomposition of Hankel matrix
  - Effective rank via Threshold
- Illustration of Method
  - Chief Joseph Brake Insertion
  - UCSD Micro grid data
- Summary

Prediction of Ambient Frequency Signal

- In ambient situation we may assume:
  - Fluctuations in Frequency signal $F(k)$ is due to "random noise" on grid
  - $F(k)$ can be modeled as a "filtered white noise"

$$F(k) = H(q)e(k)$$

  where $H(q)$ is an unknown filter and $e(k)$ is a white noise.

- Possible approximation for filter $H(q)$: AutoRegressive (AR)

$$F(k) = e(k) - a_1F(k-1) - a_2F(k-2) - \cdots - a_nF(k-n)$$

  where $F(k)$ depends on a linear combination in the past, so

$$H(q,\theta) = \frac{1}{1 + a_1q^{-1} + a_2q^{-1} + \cdots + a_nq^{-n}}$$

  where $\theta = [a_1 \quad a_2 \quad \cdots \quad a_n]$.

- Simply estimate θ from data and use AR model to predict!

Prediction of Ambient Frequency Signal

- For estimation of θ one can see that

$$e(k,\theta) = F(k) - \theta\varphi(k),$$
$$\varphi(k) = [F(k-1) \quad F(k-2) \quad \cdots \quad F(k-n)]$$

- Estimation of θ can be formulated as a (Recursive) Least Squares problem with a unique solution.

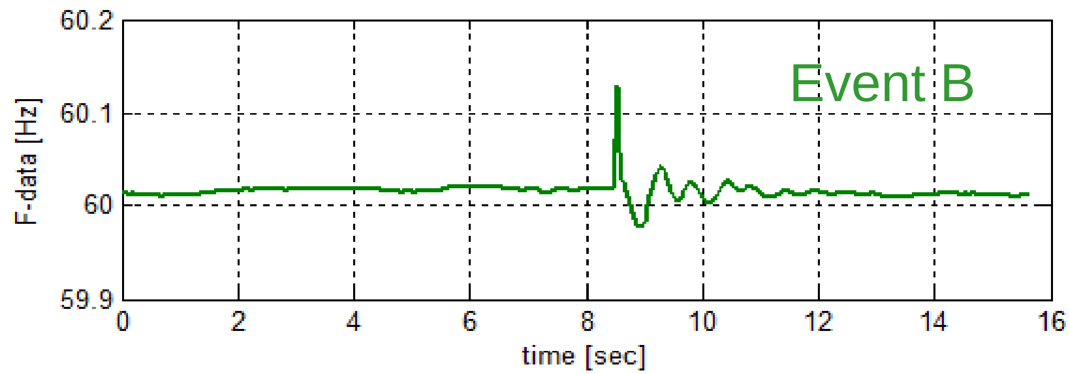
- Resulting "one-step ahead" prediction of $F(k)$ is simply given by

$$F(k) = -a_1F(k-1) - a_2F(k-2) - \cdots - a_nF(k-n)$$

- Variance of the error $e(k,\theta)$ can be used to formulate a threshold

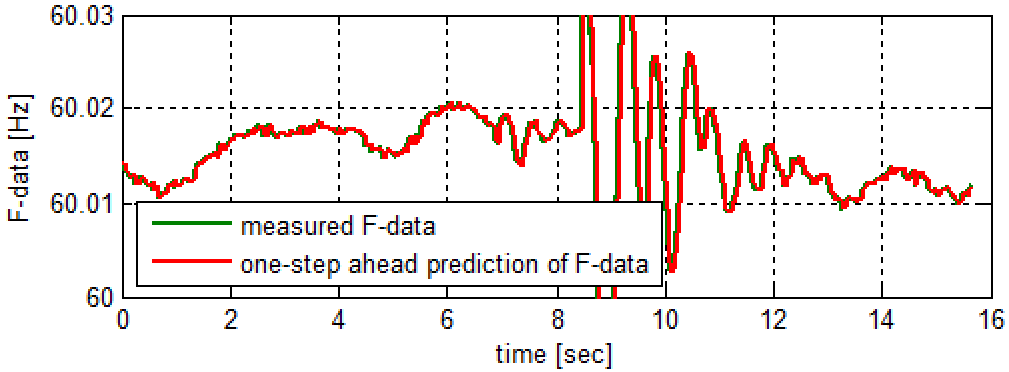
Prediction of Ambient Frequency Signal

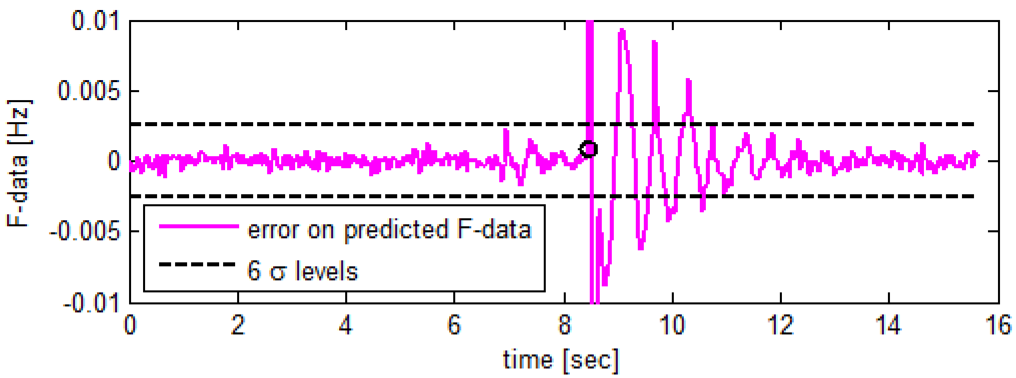
- Illustration: Frequency oscillation on UCSD microgrid (event B)



Model used:

$$F(k) = 0.9715F(k-1) + 0.0285F(k-2)$$





Observations:

- Excellent prediction for ambient frequency data!
- Immediate detection of event based on 6σ level of prediction error…
- Begin of event detected

Approach:

- Assume observed event in frequency F(t) is due to a deterministic system

$$x(k+1) = Ax(k) + Bd(k)$$
$$F(k) = Cx(k)$$

Discrete-time model

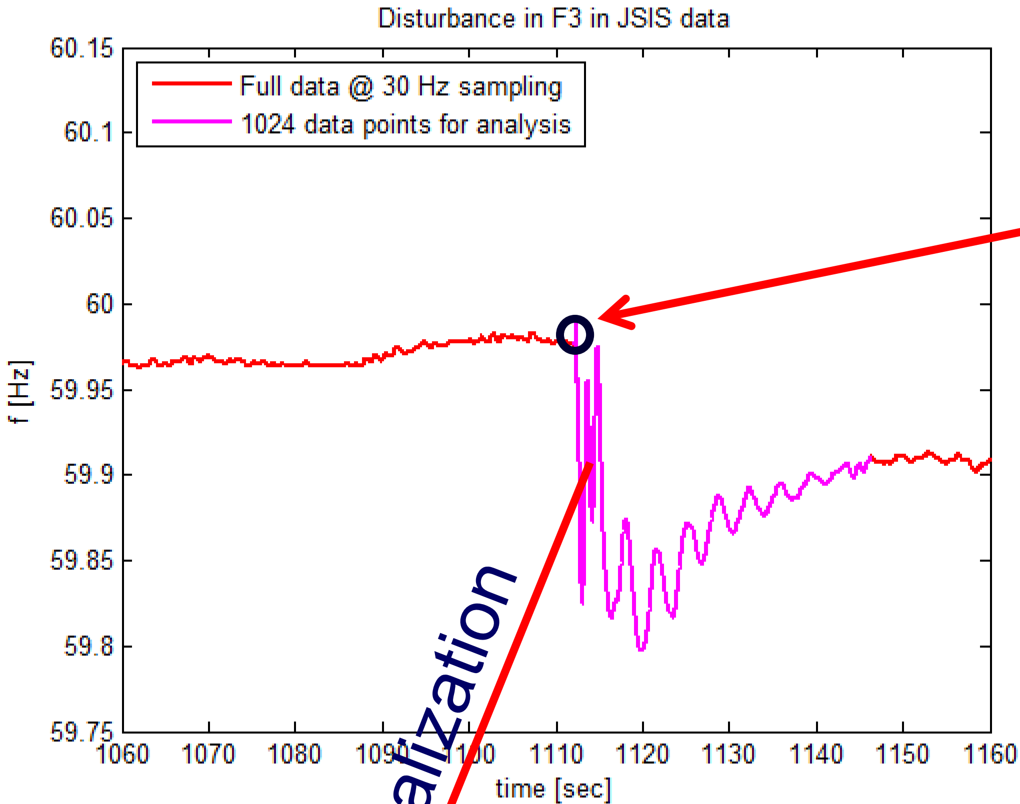
where (unknown) input d(t) can be \`impulse' or \`step' or \`known shape'

- Store a finite number of data points of F(t) in a special data matrix **H**
- Inspect rank of (null projection on) **H**: determines # modes
- Compute matrices A, B and C via Realization Algorithm.
- Extension of Ho-Kalman, Kung algorithm. Miller, de Callafon (2010)

End Result:

- Dynamic model (state space model) can be used for
  - Simulation: simulate the disturbance data
  - Analysis: Compute resonance modes and damping (from eigenvalues of A)

Analysis of Events - Realization Algorithm



detect beginning of event

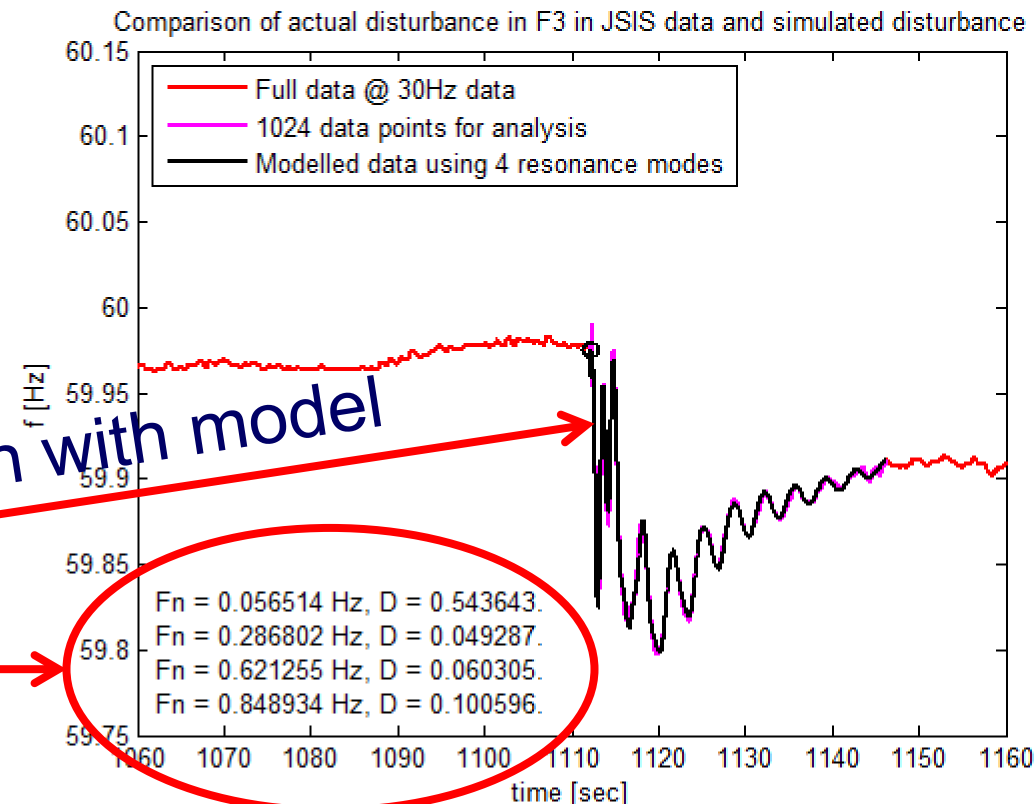
realization

simulation with model

analysis

$$x(t+1) = Ax(t) + Bd(t)$$

$$F(t) = Cx(t)$$



Realization Algorithm – Hankel matrix

FACT

- Let $F(k)$ be generated by dynamic system

$$x(k+1) = Ax(k) + Bd(k)$$

$$F(k) = Cx(k)$$

where $d(k)$ is an impulse starting at index $k=0$ and $A = n \times n$ matrix, then the matrix

$$H = \begin{bmatrix} F(1) & F(2) & \cdots & F(m) \\ F(2) & F(3) & \cdots & F(m+1) \\ \vdots & \ddots & \ddots & \vdots \\ F(m) & F(m+1) & \cdots & F(2m-1) \end{bmatrix}$$

with $m > n$ has $rank(H) = n$. Result dates back to Ho, Kalman (1966)

- Can be generalized to step event or multiple events for $d(k)$

Realization Algorithm – Hankel matrix

IMPLICATIONS

We can use a matrix $H = \begin{bmatrix} F(1) & F(2) & \cdots & F(m) \\ F(2) & F(3) & \cdots & F(m+1) \\ \vdots & \ddots & \ddots & \vdots \\ F(m) & F(m+1) & \cdots & F(2m-1) \end{bmatrix}$ to:

- Determine the order n of a dynamic system that could have generated the measured disturbance $F(k)$.
- Each oscillation (resonance) requires 2 orders
- Find a decomposition

$$H = H_1 H_2 \quad \text{where} \quad H_1 = m \times n, \quad H_2 = n \times m$$

are respectively full column/row rank.

Realization Algorithm – Hankel matrix

IMPLICATIONS

We can use the matrix $\vec{H} = \begin{bmatrix} F(2) & F(3) & \cdots & F(m+1) \\ F(3) & F(4) & \cdots & F(m+2) \\ \vdots & \ddots & \ddots & \vdots \\ F(m+1) & F(m+2) & \cdots & F(2m) \end{bmatrix}$

and the decomposition

$$H = H_1 H_2$$

to compute state matrix A via $A = H_1^* \vec{H} H_2^*$ (left/right inverses)

- Computation of state matrix A is just a linear algebra problem.
- These just shifted matrices – moving window possible.
- Eigenvalues of state matrix A contains frequency and damping of resonance modes.
- Matrices H_1 and H_2 can be used to extract C and B.

Realization Algorithm – SVD

To find a dynamic model we just need:

1. Store H and $\vec{H}$
2. Determine rank of H
3. Compute decomposition $H = H_1 H_2 \quad H_1 = m \times n, \quad H_2 = n \times m$

Computation procedure that combines step 2 and 3: Singular Value Decomposition (SVD):

$$H = \begin{bmatrix} U_1 & U_2 \end{bmatrix} \begin{bmatrix} \Sigma_1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_1^T \\ V_2^T \end{bmatrix}, \quad \Sigma_1 = \mathrm{diag}(\sigma_1, \sigma_2, \cdots, \sigma_n), \quad \sigma_j > 0$$

- We find $rank(H) = n = \#$ non-zero singular values
- We find decomposition $H_1 = U_1 \Sigma_1^{1/2}, \quad H_2 = \Sigma_1^{1/2} V_1^T$

Realization Algorithm – SVD

- SVD can be computed by a numerically stable algorithm
- HOWEVER, SVD of Hankel matrix H will only be (ideally)

$$H = \begin{bmatrix} U_1 & U_2 \end{bmatrix} \begin{bmatrix} \Sigma_1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_1^T \\ V_2^T \end{bmatrix}, \quad \Sigma_1 = \mathrm{diag}(\sigma_1, \sigma_2, \cdots, \sigma_n), \quad \sigma_j > 0$$

  if there is NO noise on measurements $F(t)$
- In general:

$$H = \begin{bmatrix} U_1 & U_2 \end{bmatrix} \begin{bmatrix} \Sigma_1 & 0 \\ 0 & \Sigma_2 \end{bmatrix} \begin{bmatrix} V_1^T \\ V_2^T \end{bmatrix}$$

$$\Sigma_1 = \mathrm{diag}(\sigma_1, \cdots, \sigma_n)$$

$$\Sigma_2 = \mathrm{diag}(\sigma_{n+1}, \cdots, \sigma_m)$$

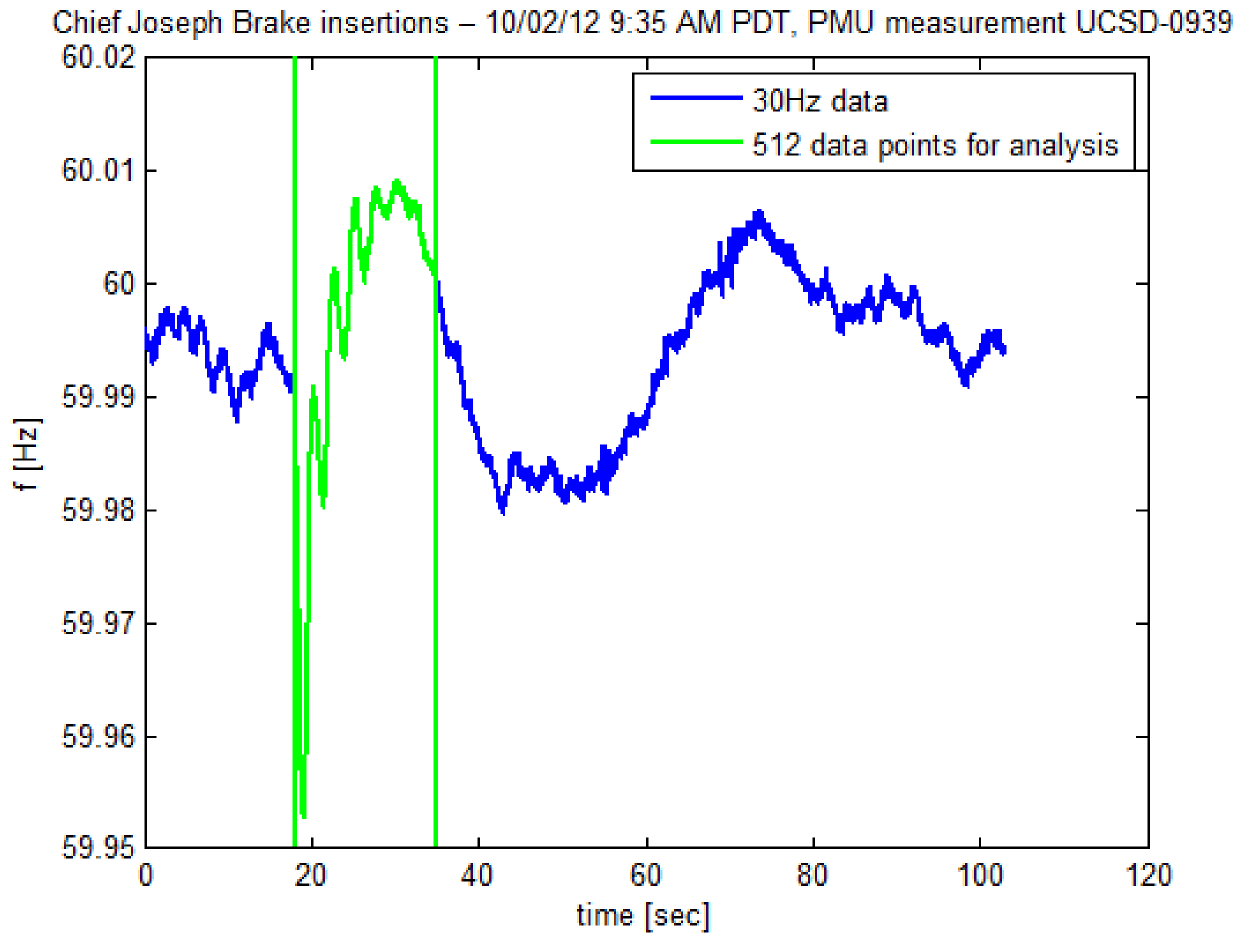
$$\sigma_{n+1} << \sigma_n$$

- SOLUTION: decide on effective rank via threshold.

Illustration of Method – Chief Joseph BI

- October 2, 2012: two test probes were injected into the WECC grid
- Frequency and angle measurements @ 30Hz from PMU located at UCSD

- Assume disturbance d(t) is impulse
- Only use 512 data points (17.2sec, green line)
- Only use single frequency measurement for transient analysis

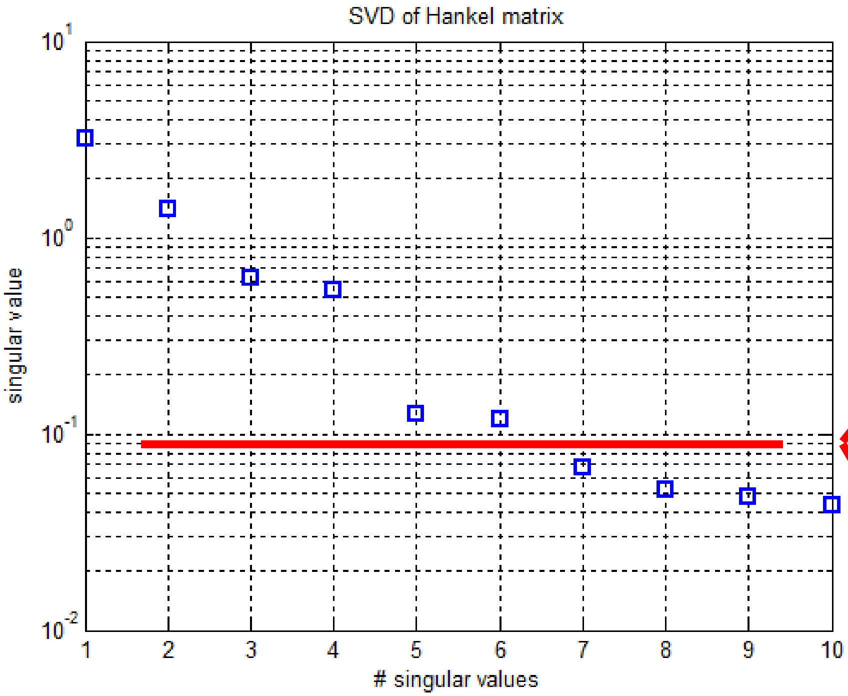


Main Question:

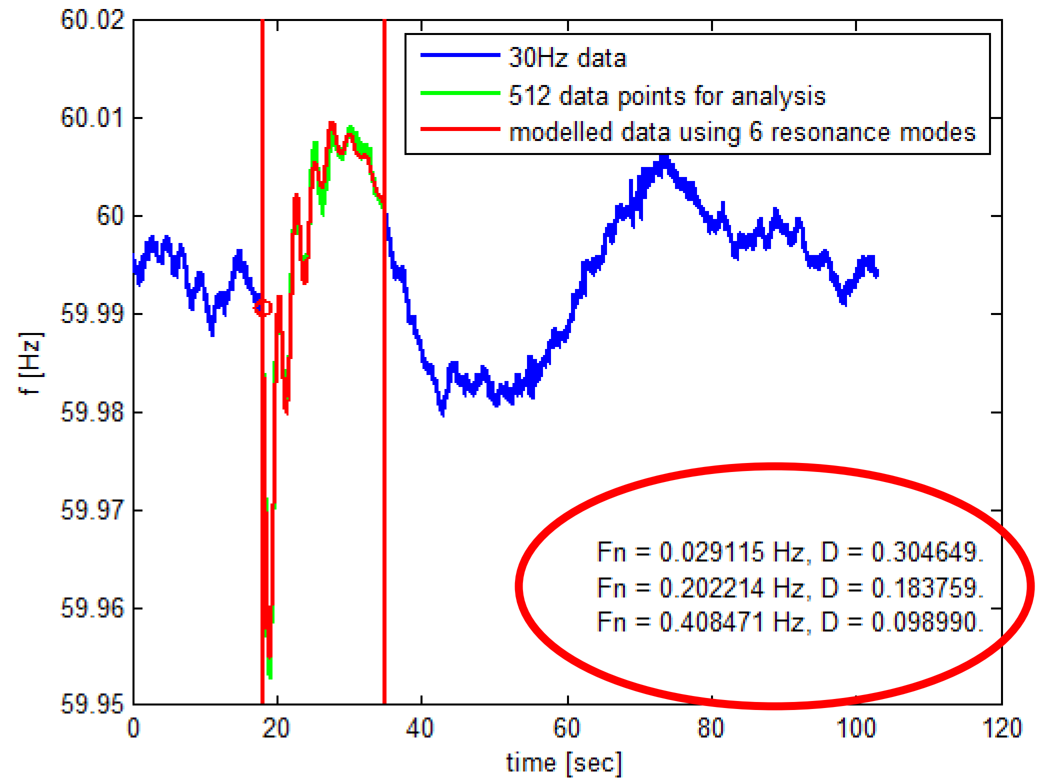
How many oscillations and what are their freq/damping?

Illustration of Method – Chief Joseph BI

SVD of data matrix (Hankel matrix)



Time Domain Validation of Model



Frequency Domain Validation of Model

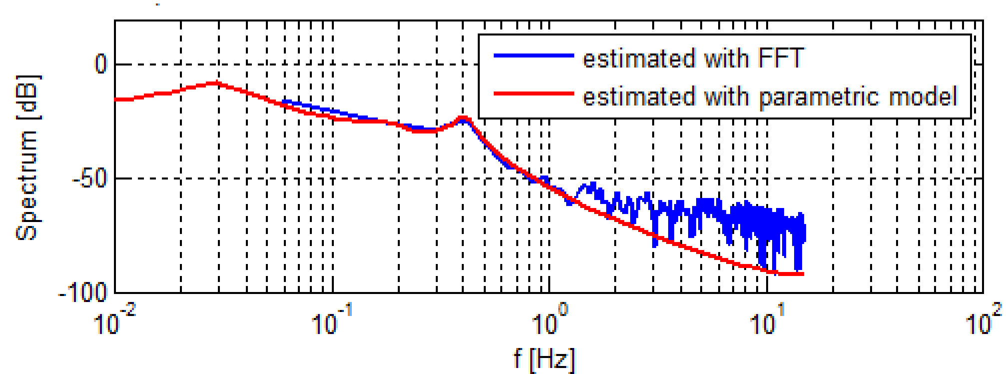
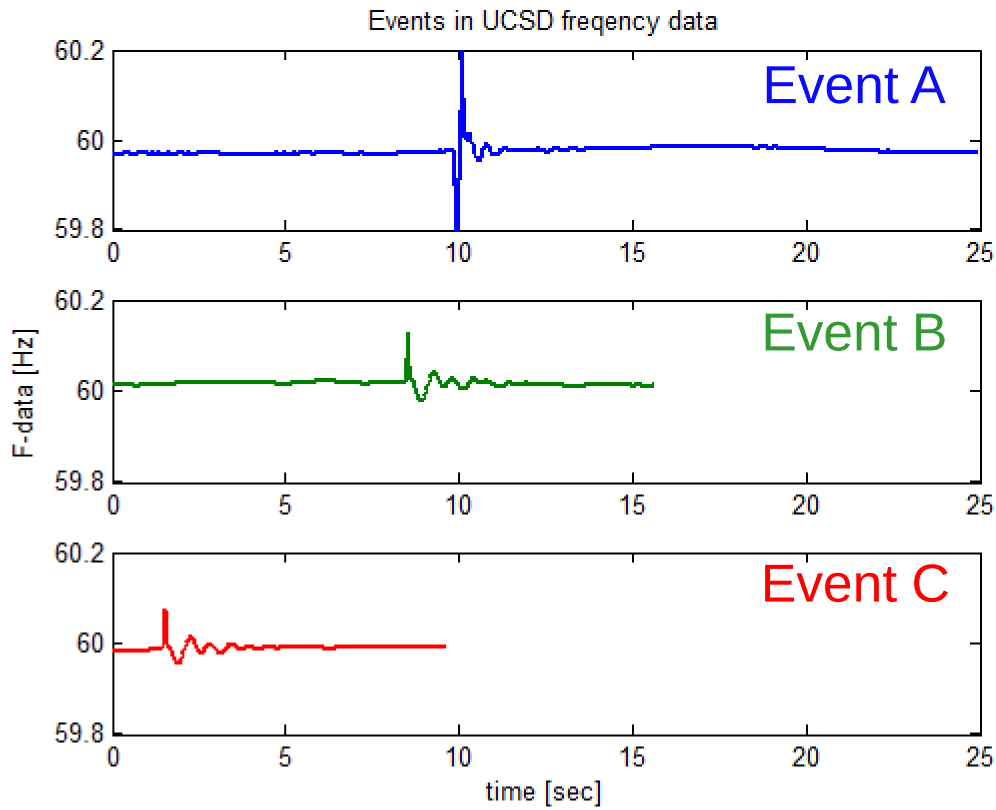


Illustration of Method – UCSD MG

- November 7, 2012: three minor disturbances on UCSD MigroGrid
- Frequency and angle measurements @ 30Hz from PMU located at UCSD

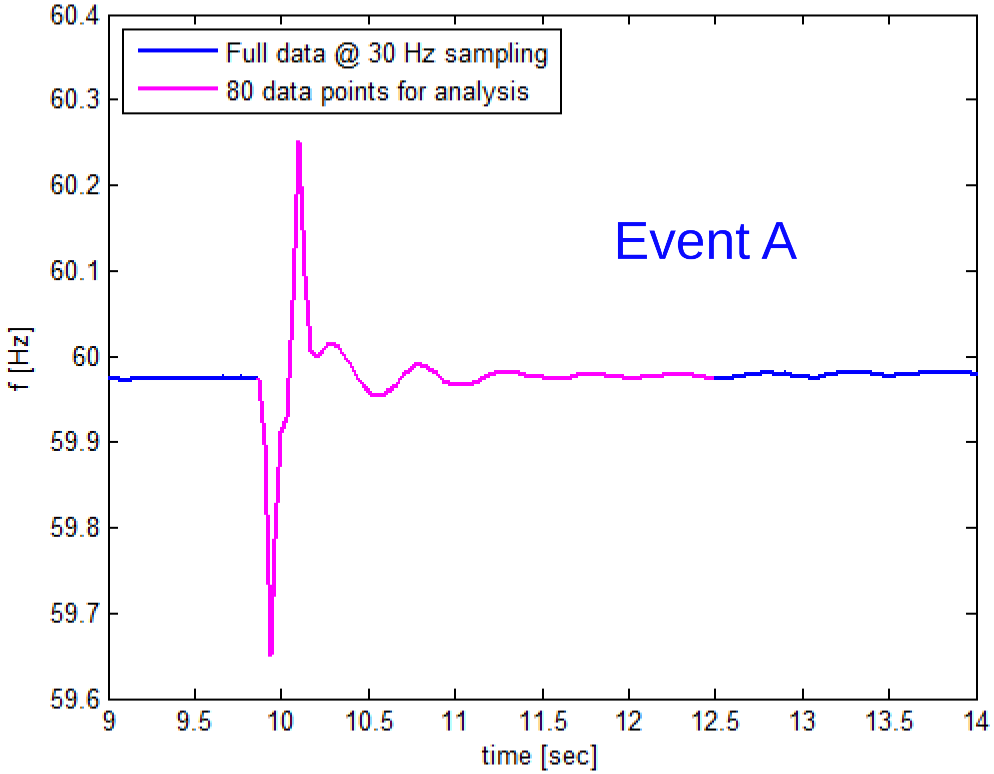


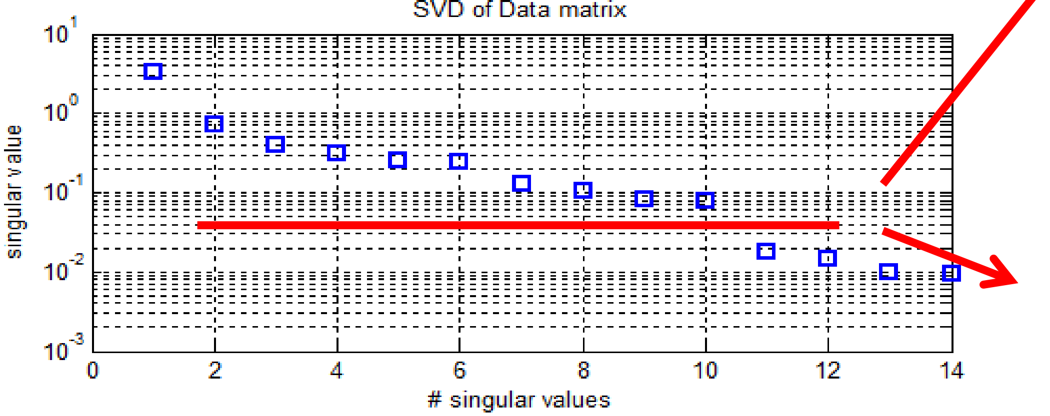
- Assume in each case disturbance d(t) is step
- Only use 80 data points (2.7sec) for analysis
- Choose a particular event, use only single frequency measurement for transient analysis

Main Question:

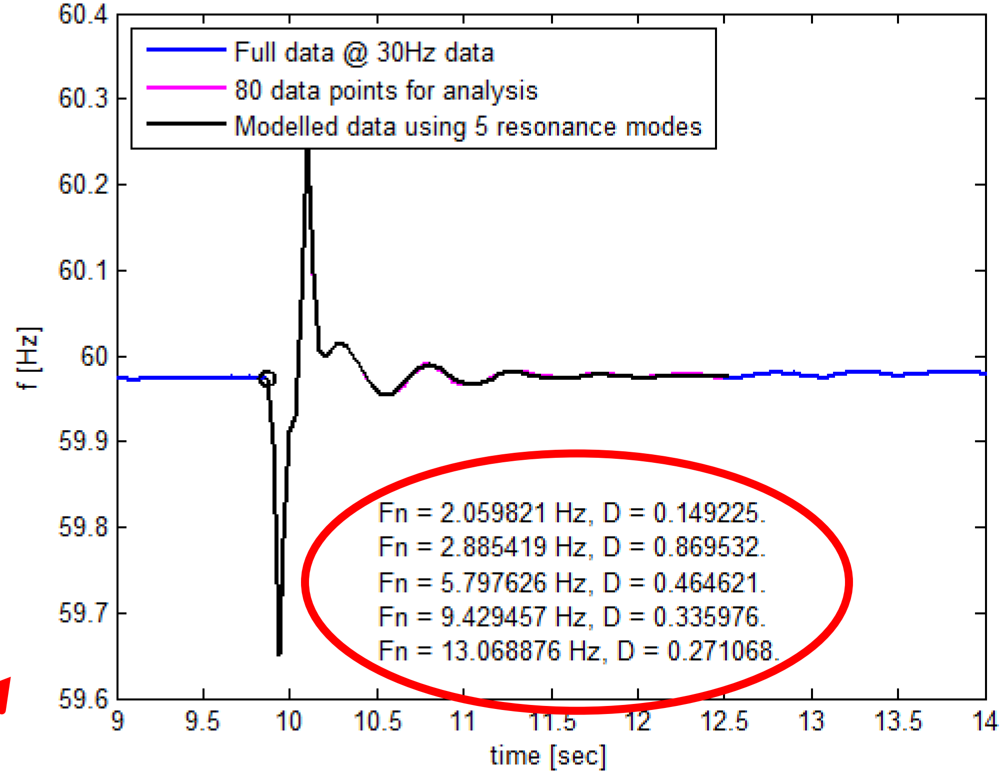
How many oscillations and what are their freq/damping?

Illustration of Method – UCSD MG





Time Domain Validation of Model



Frequency Domain Validation of Model

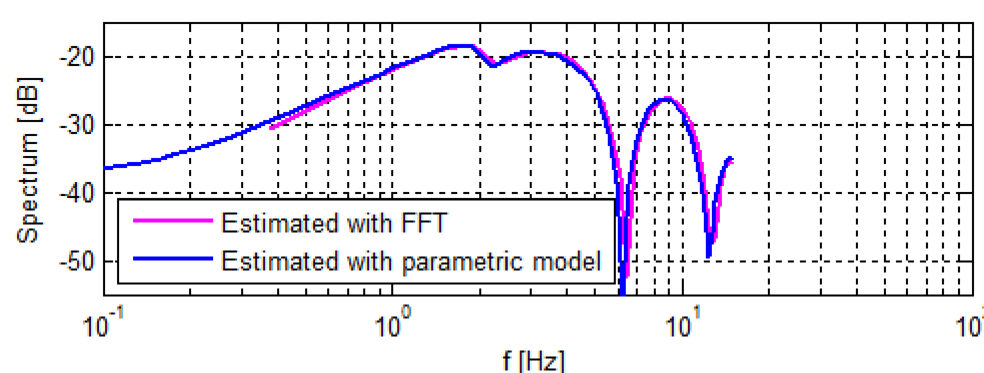


Illustration of Method – UCSD MG

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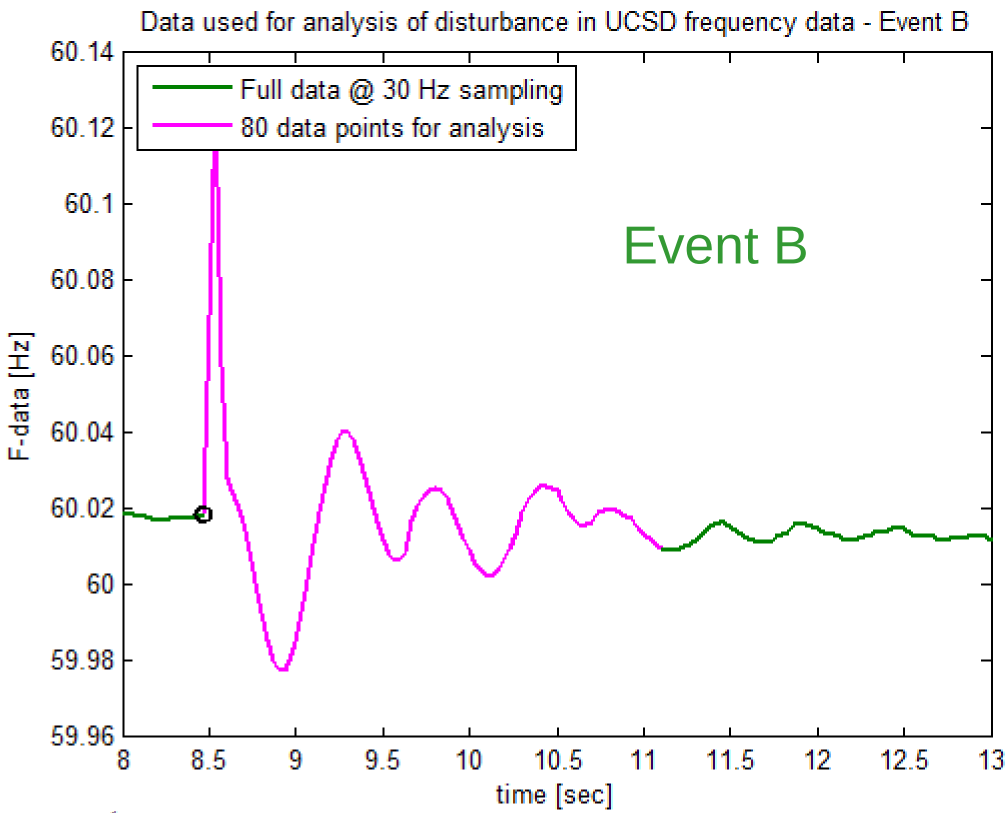

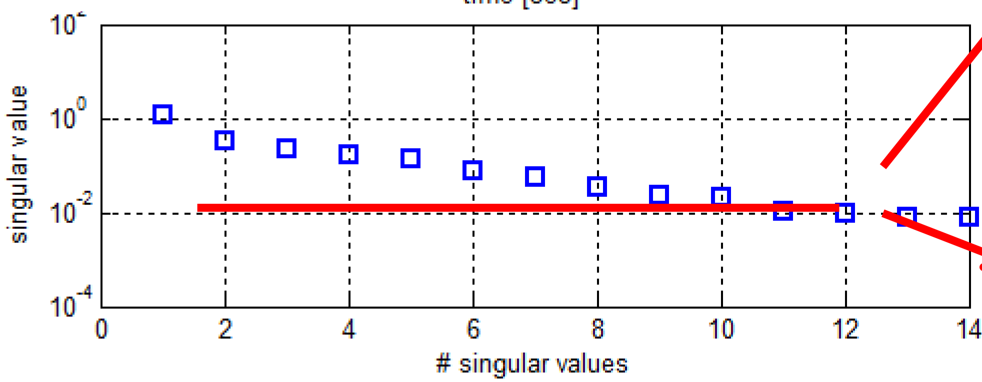

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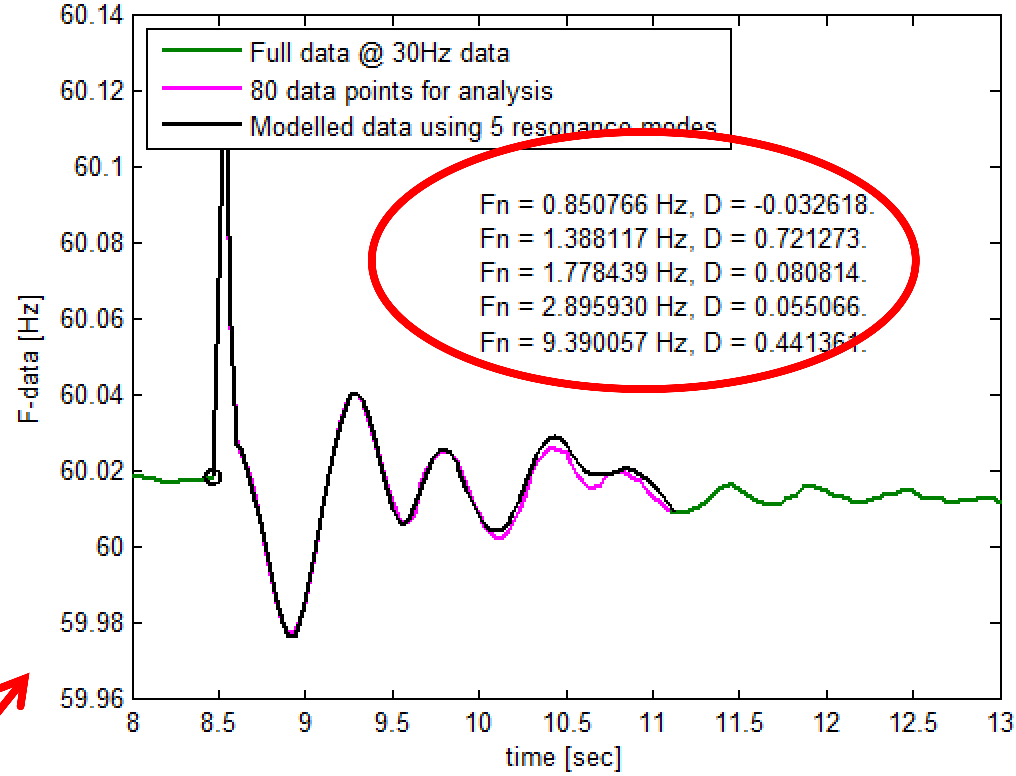

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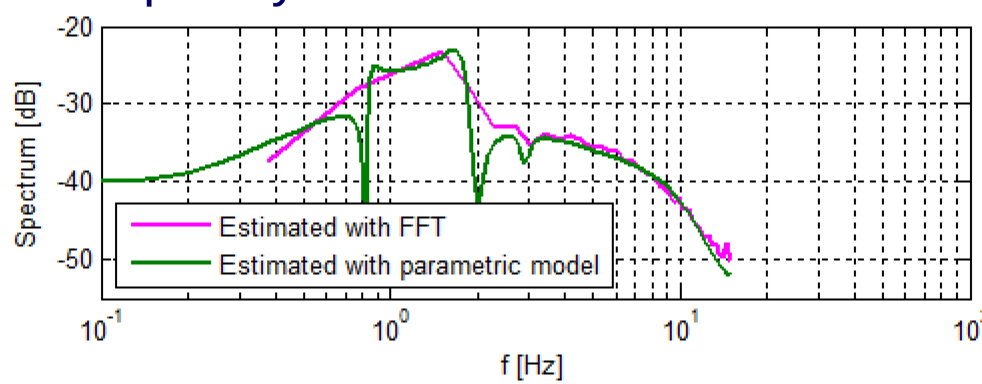
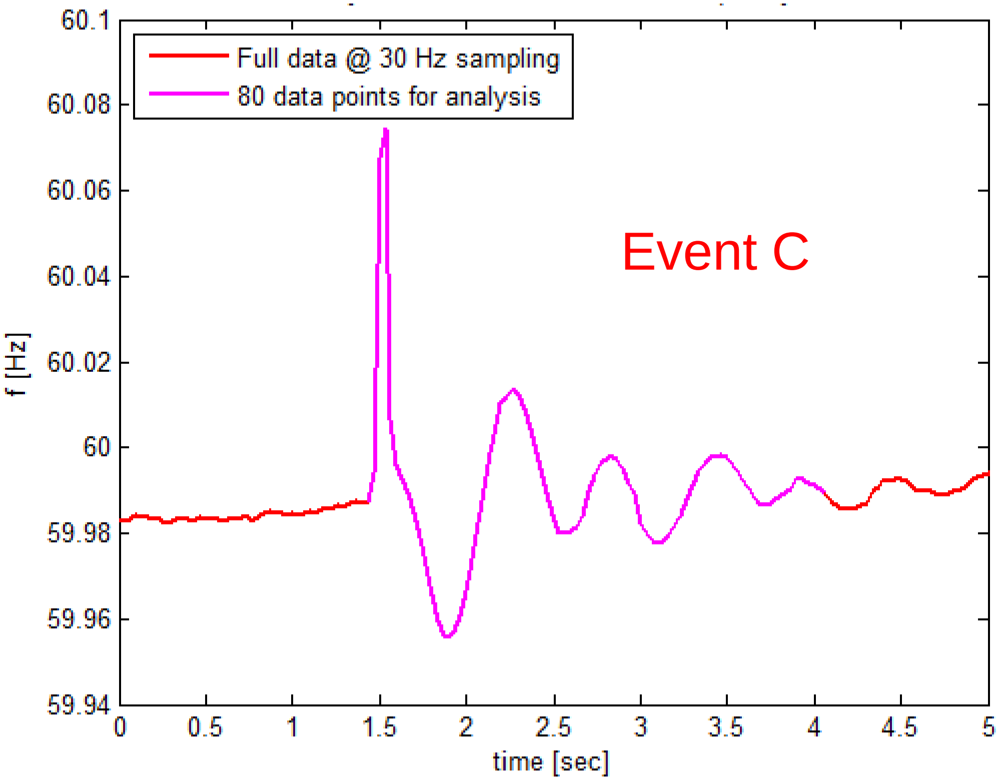
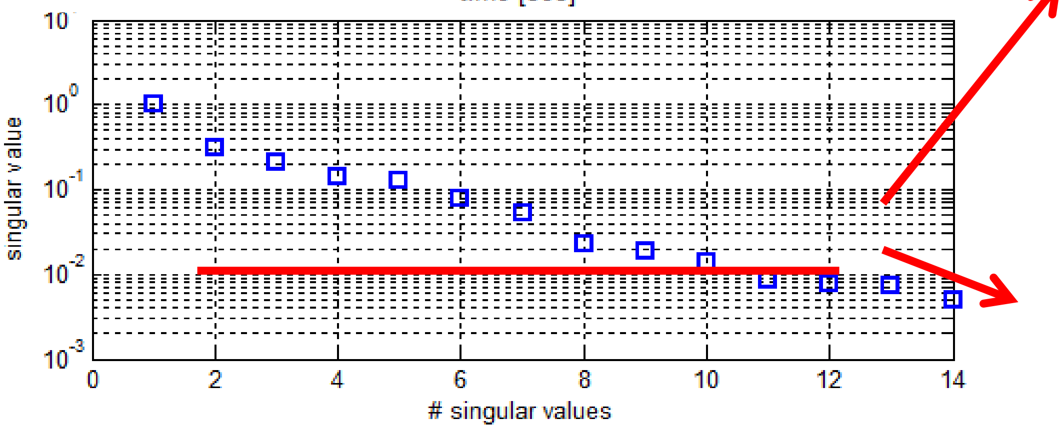


Illustration of Method – UCSD MG





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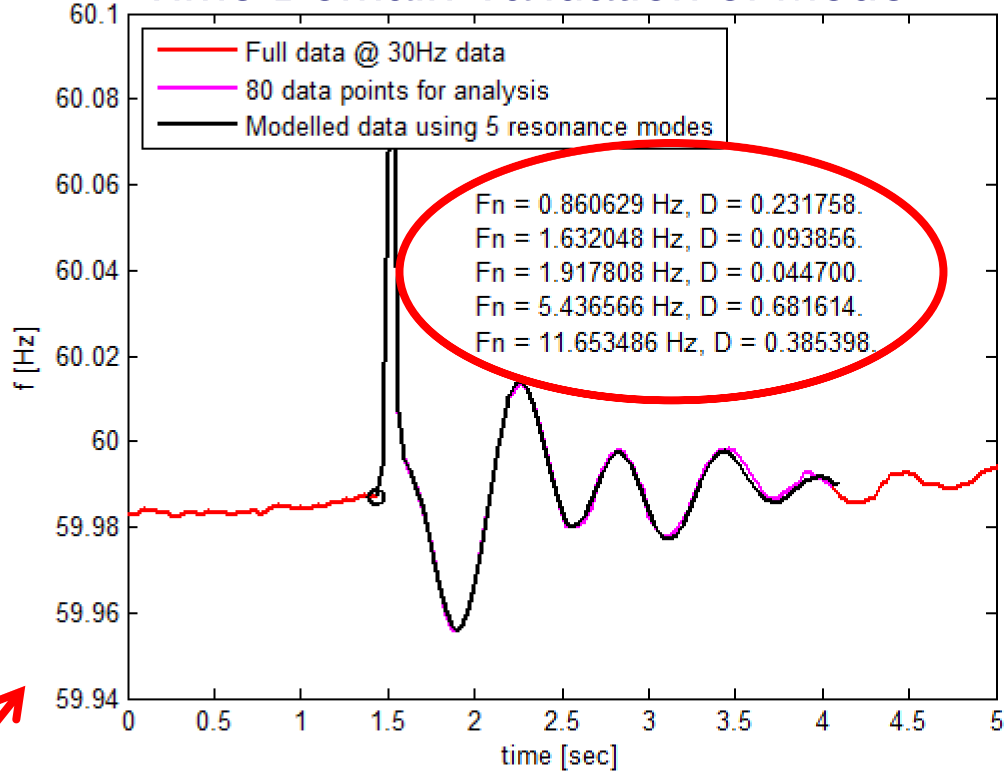

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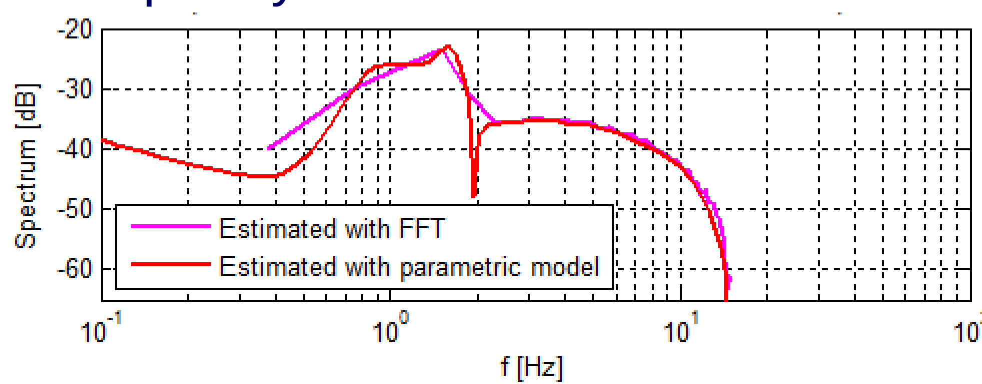

Summary

- System ID tools for Electric Grid Monitoring and Dynamic Modeling!
- Access to data of PMU's linked to PI's OSIsoft provides access to data
- New identification algorithms:
  - AR model for ambient frequency data modeling and detection of events
  - Identification of dynamic effects in data via Realization Algorithm
  - Uses only numerical stable algorithms for data analysis
  - Automatic: detection of event, order, frequency and damping
  - Can be implemented in moving window
- Dynamic models can be used for control design to mitigate effects