

Data quality and delivery

Synchro-phasor Data Conditioning and Validation

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Project objective

- **Premise:** Each synchrophasors measurement, whether used for state estimation, control, or alarms, can be subjected to the same preprocessing as the linear estimator that was demonstrated in Aug'13 by Dominion Virginia Power. The proposed solution is in general a low cost solution. The open PDC is open source and freely distributed and Dominion already possesses a fully functional linear estimator in the openPDC platform. Even if a state estimator is not desired, the linear estimator can be thought of as part of the data conditioning algorithm in that it detects bad data, finds the best estimate, and increases the observability of the network.
- **Deliverable** C# openPDC software, recommendation, and functional specifications
- Dominion has put the linear estimator in the Grid Solutions open source applications library maintained by **GPA (Grid Protection Alliance)**



How does this work?

- A phasor only - three phase- state estimator has been installed on the Dominion Virginia Power 500kV system as part of a DOE demonstration project DE-0E0000118 led by Virginia Tech.
- By summer of 2013 a total of more than 600 measurements from twenty one 500kv stations, five 230kv stations, and one 115kv station will give an estimate at a rate of 30 times a second of the three phase complex voltages on the 500kV network. Both bus voltage and line currents are measured and communicated through a SONET network to the Control Center in Richmond. There is a PDC in each substation and a PDC in the control center. The application software was implemented in C# on an openPDC platform in the Dominion Control Center

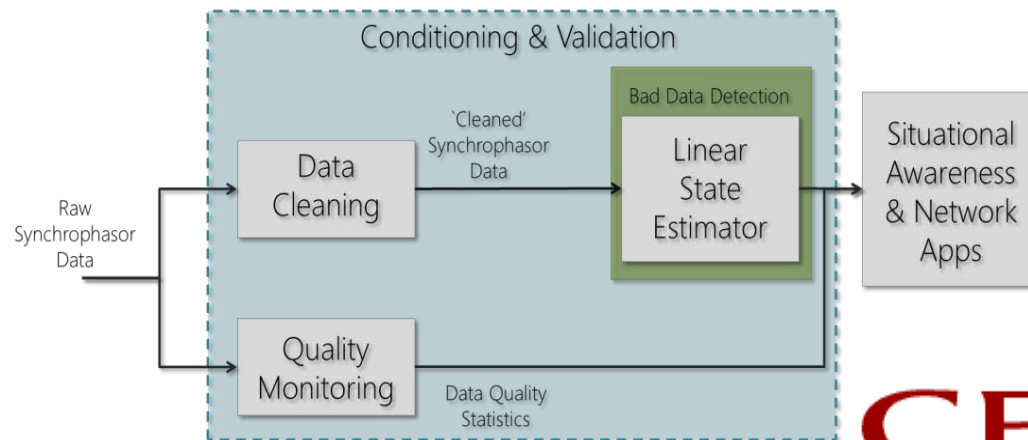


Topology changes

In complex (or rectangular) form the measurements are linear functions of the complex bus voltages.

$$z = Hx, \quad \hat{x} = Mz$$

Where M is fixed and only changes as the network topology changes. The tripping of a line whose current is in the measurement set can be detected by the time tagged breaker status from the dual use line-relay/PMU or treated as missing data. Either way a front end is a required component of the estimator.



Major technical accomplishments that will be completed this year

brief task statement list

Task

1. Prototype Development Recommendations on synchrophasor infrastructure
2. Commissioning process
3. Algorithms for online determination of Signal to Noise Ratio (SNR) of the PMU data
4. Recommendations for the central PDC architecture design and the ESOC architecture design (ESOC) Emergency System Operation Center
5. Optimized PMU placement scheme



Major technical accomplishments that will be completed this year—stage in RD&D cycle

Task list continued

6 Provide algorithms for:

- a) Loss of data from one or several PMUs
 - b) Loss of signals in a PMU
 - c) Stale (non-refreshing) data
 - d) Inconsistent data, data rates and latencies
 - e) Off-sets in signal magnitude and phase
 - f) Corrupted and drifting signals in a PMU
 - g) Corrupted and drifting time reference in one or several PMUs
 - h) Combination of several issues described above
 - i) Combination of several issues described above
 - j) The failure of the topology processor and/or bad/incomplete topology information
- j) A recommendation but implementation is not part of the proposed work.



Deliverables and schedule for activities to be completed under FY13 funding

Task 1	Task Name	Deliverables (please name the reports and clarify other deliverables)	Planned Start Date	Actual Start Date	Planned End Date	Actual End Date
1.1	Prototype Development Recommendations on synchrophasor infrastructure	Report #1	4/13	4/13	9/13	Complete Progress report sent on 09/16/2013 Final Progress report on 10/11/13
1.2	Commissioning process	Report #2	4/13	4/13	9/13	Complete Progress report sent on 09/016/2013 Final Progress report on 10/11/13
1.3	Signal to Noise Ratio(SNR) of the PMU data	Report #3	5/13		10/13	Complete Progress report sent on 10/11/13
1.4	Recommendations for the central design PDC architecture design and the ESOC architecture	Report #4	5/13		10/13	Complete Progress report sent on 10/11/13
1.5	Optimized PMU placement scheme	Report #5	9/13		2/14	
1.6	Algorithms	Report #6	4/13	4/13	11/13	
2A.	Demonstration at Dominion	Report #7	9/13		4/14	

Highlights of the progress reports

Matlab scripts and C# code for adaptors that run on Open PDC.

25 page Matlab Script for PMU Data Validation Walkthrough



Prototype Development & Recommendations on Synchrophasor Infrastructure

- Most of Dominion's initial synchrophasor substations are critical infrastructure substations because they are part of the bulk electric system (BES). Therefore the digital relays inside these houses are Critical Cyber Assets (CCAs). Any of these CCA relays that were used as PMUs meant that the synchrophasor data reported from these relays/PMUs was critical information. Therefore, any phasor data concentrator (PDC) had to meet the necessary CIP requirements. The decision was made to make any stand-alone PMUs CCAs. A single PDC system could therefore collect all synchrophasor data from stand-alone PMUs and dual-use PMUs. Making all PMUs CCAs meant that the synchrophasor data was CIP compliant, allowing Dominion's System Operations Center to use the data for real-time operations and control actions. This setup synchrophasors to play a major role in helping Dominion personnel operate the grid.
- The synchrophasor system became independent from the substation SCADA/EMS system allowing the synchrophasor system to be a back-up to the SCADA/EMS system in the event of equipment failures.



Commissioning Process

- Part of the commissioning process for PMUs in Dominion's system includes an analysis of the synchrophasor data before the PMU device goes live with the System Operations Center. An automated script that generates a report and several plots based on the perceived quality of the data. Automating the process is beneficial for a number of reasons including portability and process efficiencies.
- Before the PMU device stream is connected to the SOC, a sample set of data is downloaded from the substation PDC at full resolution. It is contained in a *.csv file with the column headers denoting the signal. The data validation script checks the downloaded data against several criteria
- **Status Word -**
- **Frequency -**
- **Rate of Change of Frequency**
- **Voltage Magnitude**
- **Current Magnitude.**

Voltage & Current - Phase Sequence



Signal-to-Noise Ratio (SNR) of the PMU Data

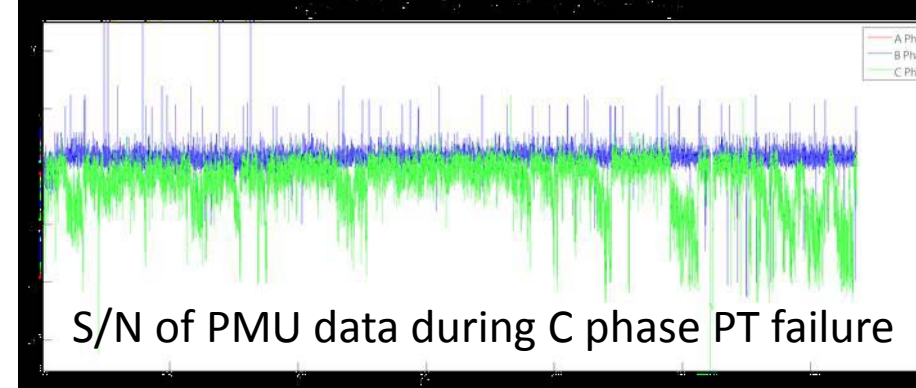
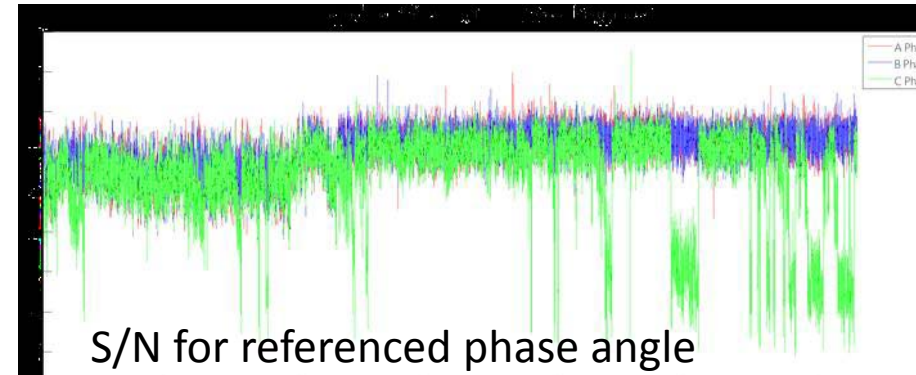
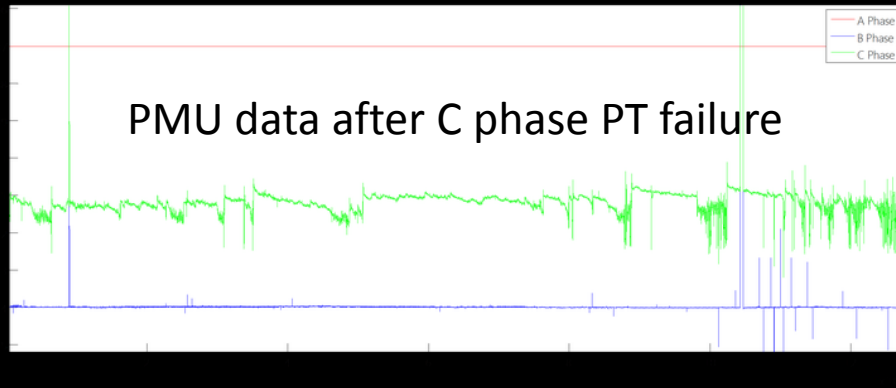
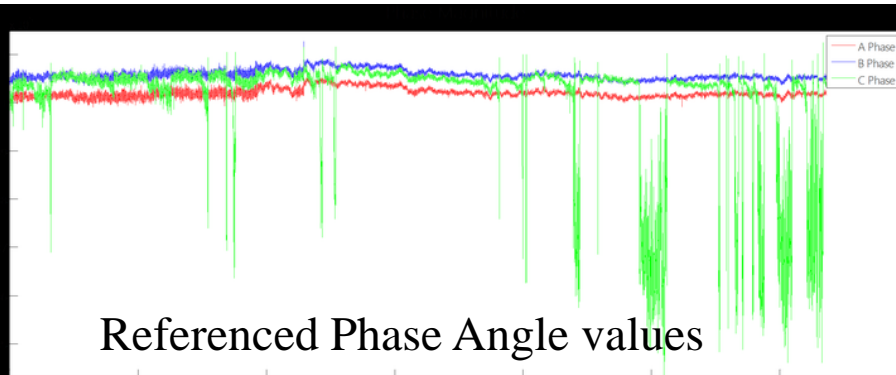
- An additional way to measure data quality of a signal is through the signal-to-noise ratio. This aspect of the project falls under data validation as it allows for quantifying the quality of an individual signal, and with alerts, provides a mechanism for mitigating data quality problems, regardless of their root cause. This aspect of the project can also be considered data conditioning in that the same alert can be an indication to downstream algorithms of when to ignore low quality data that other mechanisms can't detect.

$$SNR_{DC(db)} = 10 \log \frac{mean}{std}$$

- Initial studies were performed for proof-of-concept in Matlab using three phase PMU data provided by Dominion Virginia Power using a case of a C phase PT failure. The algorithms were then implemented in a production environment by translation to C# as an adapter than runs inside a host openPDC. Testing occurred inside Dominion Virginia Power's central PDC architecture



Example of S/N



Recommendations for the Central PDC Architecture and ESOC Architecture Design

- Dominion's experience with a recent large scale deployment of synchrophasors across their EHV network has spoken to the importance of a solid central PDC architecture design. A good design is instrumental not only for desired functionality but for security, usability, scalability, and high availability. This task report summarizes the learnings of Dominion Virginia Power during this process and includes recommendations for considerations of others going through similar deployment strategies.



Recommendations for the Central PDC Architecture and ESOC Architecture Design

The first synchrophasor deployments across the nation have been managed in many cases by the research and development groups of electric utilities and other transmission owners and operators. A production implementation was not considered from project inception and therefore, widespread adoption of the technology in the operating room has not followed. The design of proper IT infrastructure, mostly in the form of a multi-noded central PDC architecture, is paramount to a successful integration of synchrophasor technology into the daily operations.



Detecting bad data and network switching (at 30 samples a sec)

If $x(n)$ is a complex 500kV voltage or current

$$\begin{bmatrix} \hat{x}(n) \\ x(n-1) \\ x(n-2) \end{bmatrix} = \begin{bmatrix} 3 & -3 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x(n-1) \\ x(n-2) \\ x(n-3) \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} w(n) \quad z(n+3) = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x(n+3) \\ x(n+2) \\ x(n+1) \end{bmatrix} + r(n+3)$$

w ($\sigma_w=10^{-5}$) and r ($\sigma_r=10^{-3}$) random, white, and independent, can predict the state and the next measurement and form the observation residual. To make a state equation add and subtract

$$\begin{bmatrix} \hat{x}(n) \\ x(n-1) \\ x(n-2) \end{bmatrix} = \begin{bmatrix} 3 & -3 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \hat{x}(n-1) \\ x(n-2) \\ x(n-3) \end{bmatrix} + \begin{bmatrix} 3 \\ 1 \\ 0 \end{bmatrix} [x(n-1) - \hat{x}(n-1)]$$

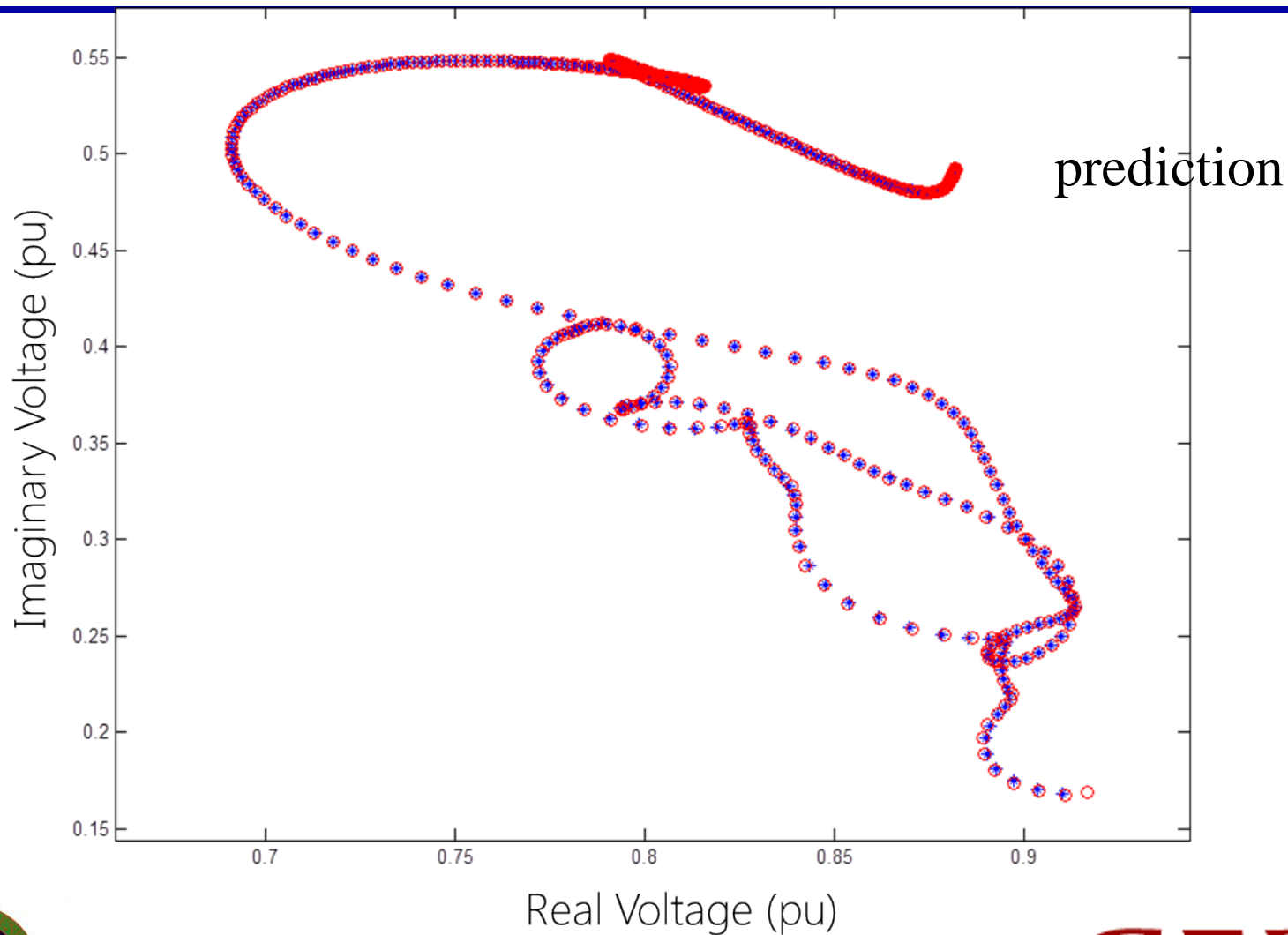
Observation residual

The added term is the “Kalman gain” multiplying the observation residual. This is the steady state Kalman gain for all covariance in w if the covariance of r is zero. For $\sigma_w=10^{-1}$, $\sigma_v=10^{-2}$ $K=[2.8793 \ 0.9915 \ 0.0244]^T$ In general K depends on the ratio of the two covariances

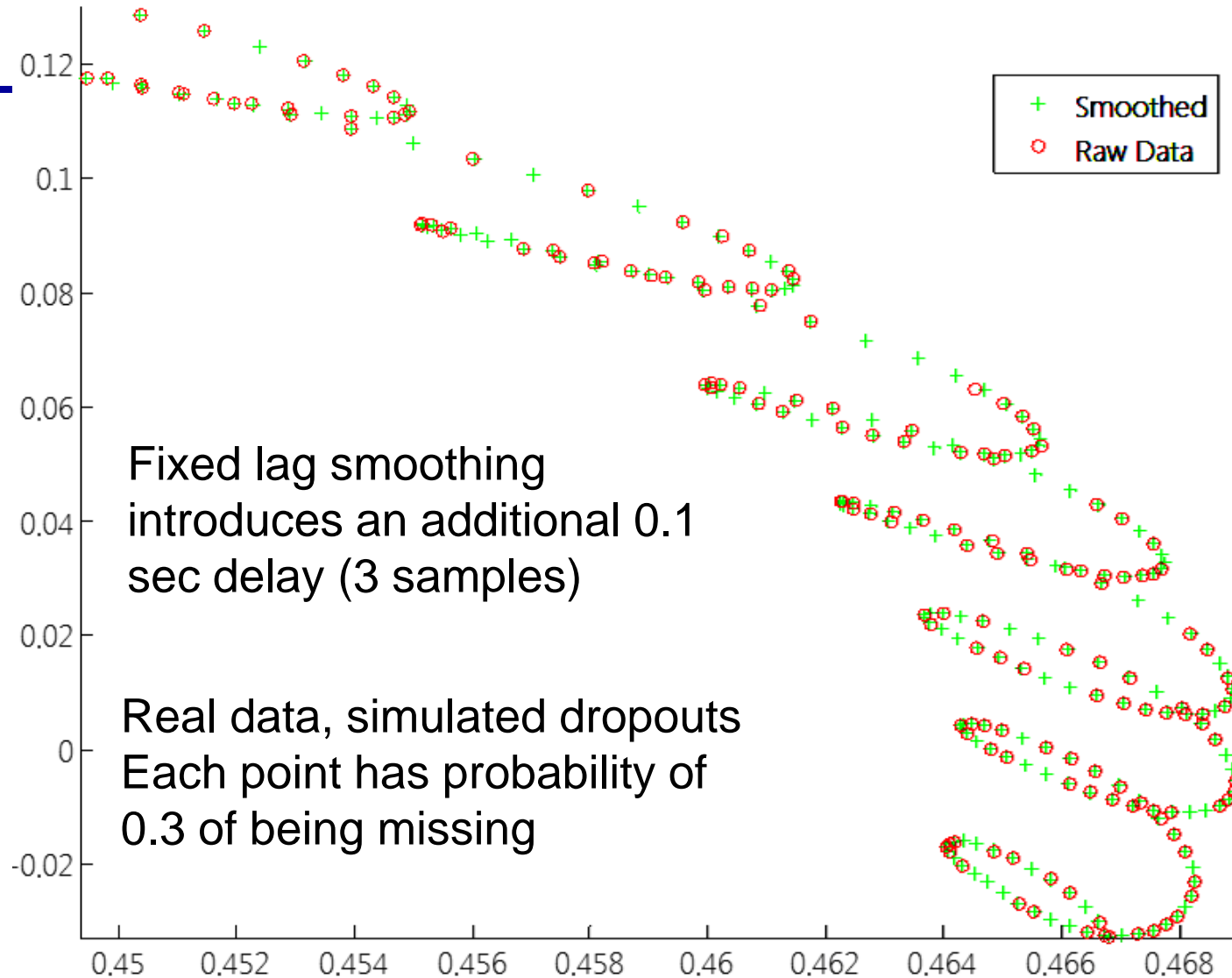


field data measurements + and estimate o formed by the last 3 values of this voltage using a Kalman Filter based on model on slide 15

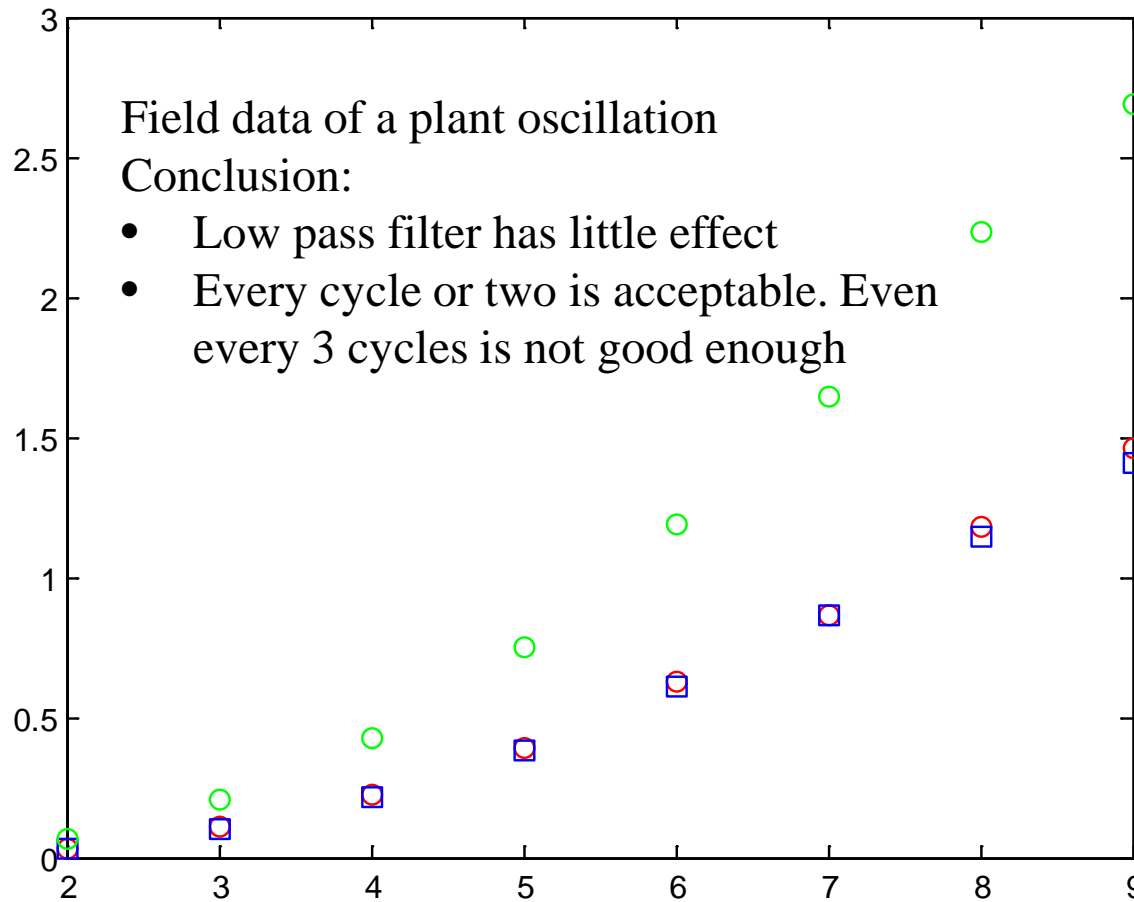
Complex Voltage Trajectory During Loss of Excitation



Oscillation, Complex Voltage, 30% Dropouts



Changing sampling rates



○ rms error in $[1 -3 \ 3 -1]$

□ rms error in $[1 -3 \ 3 -1]$ after anti-aliasing filter

○ $\max(\text{abs}([1 -3 \ 3 -1]))$

Number of 60 periods between samples

