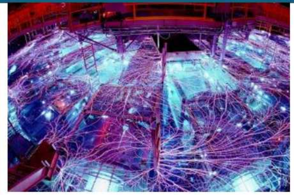
SAND2020-5751C

Numerical Algorithms for Estimating Frequency to Enable Synthetic Inertia



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Albuquerque, NM

NASPI (webinar)
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Project Team & Acknowledgements

- **Sandia National Laboratories**
  - Dr. Felipe Wilches-Bernal (PI)
  - Ricky Concepcion
  - Dr. David Schoenwald
  - Dr. Ray Byrne
  - Hill Balliet (intern 2019)
  - Jamie Budai (intern 2018)
- **Montana Technological University**
  - Prof. Josh Wold (co-PI)
  - Patrick Cotes (intern 2018)
  - Prof. Daniel J. Trudnowski

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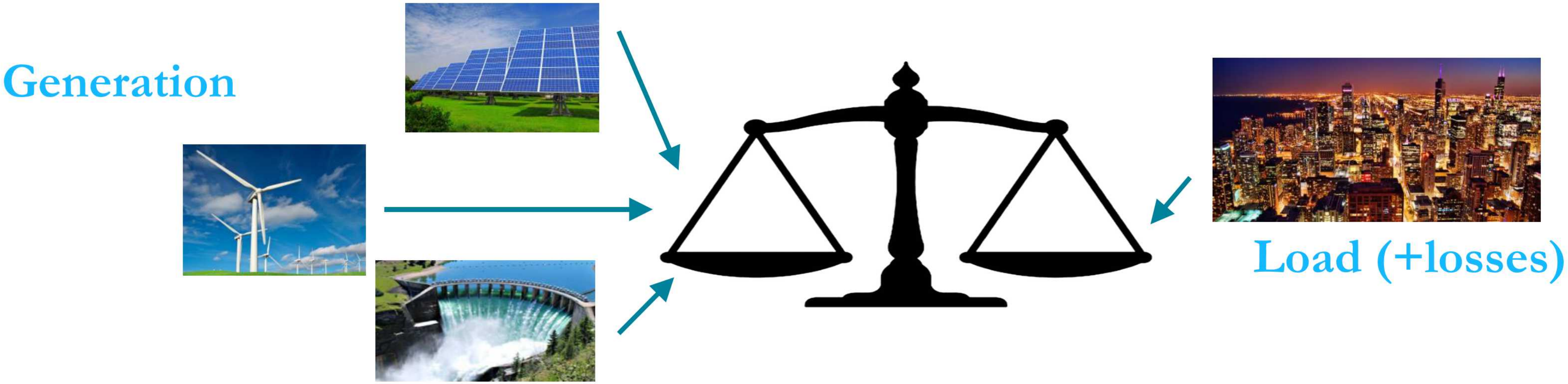
Purpose and Motivation

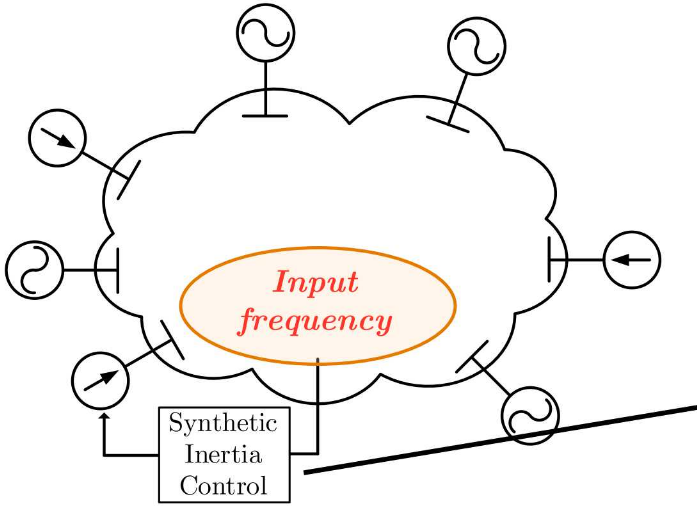
- Why is frequency important in power systems?
- Frequency is a key indicator of network stability and the balance between generation and load (plus losses)



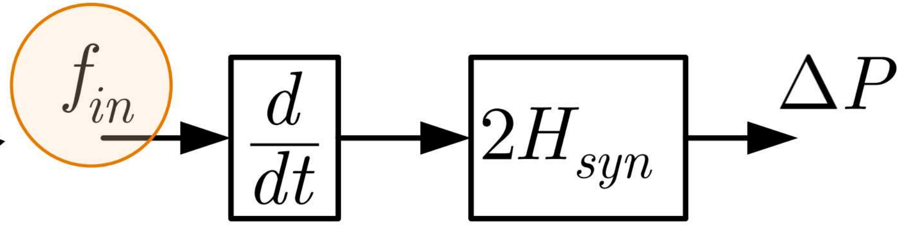
- Frequency of electrical signals (voltages and currents) in the power system is related to the velocity of rotation of machine speeds
- At the transmission level frequency there is interest of a global of system frequency as an indicator (for power imbalance events)
- The variations in frequency of certain aggregated regions are also important to determine inter-area oscillations

Purpose and Motivation

- At the distribution level frequency is important for DERs (grid following) to determine what frequency they should lock to and to determine potential faults in the system and activate control actions.
- As the power system evolves to accommodate larger contributions of converter-interfaced generation (CIG) the need for *cleaner* frequency measurements increases. Larger CIG contribution causes the following problems:
  - Distortion in waveforms
  - **Reduction in inertia (focus of this project)**
- **Solution:** make CIG responsive to frequency variations



- Frequency measurement is needed in *real-time*



Purpose and Motivation

- Frequency in power systems cannot be measured directly and it is instead *estimated* from power system signals (voltages and currents). Frequency estimation is becoming a challenge at moments where the need for it is greater.
- Figure below shows an example of an event where estimating frequency is challenging

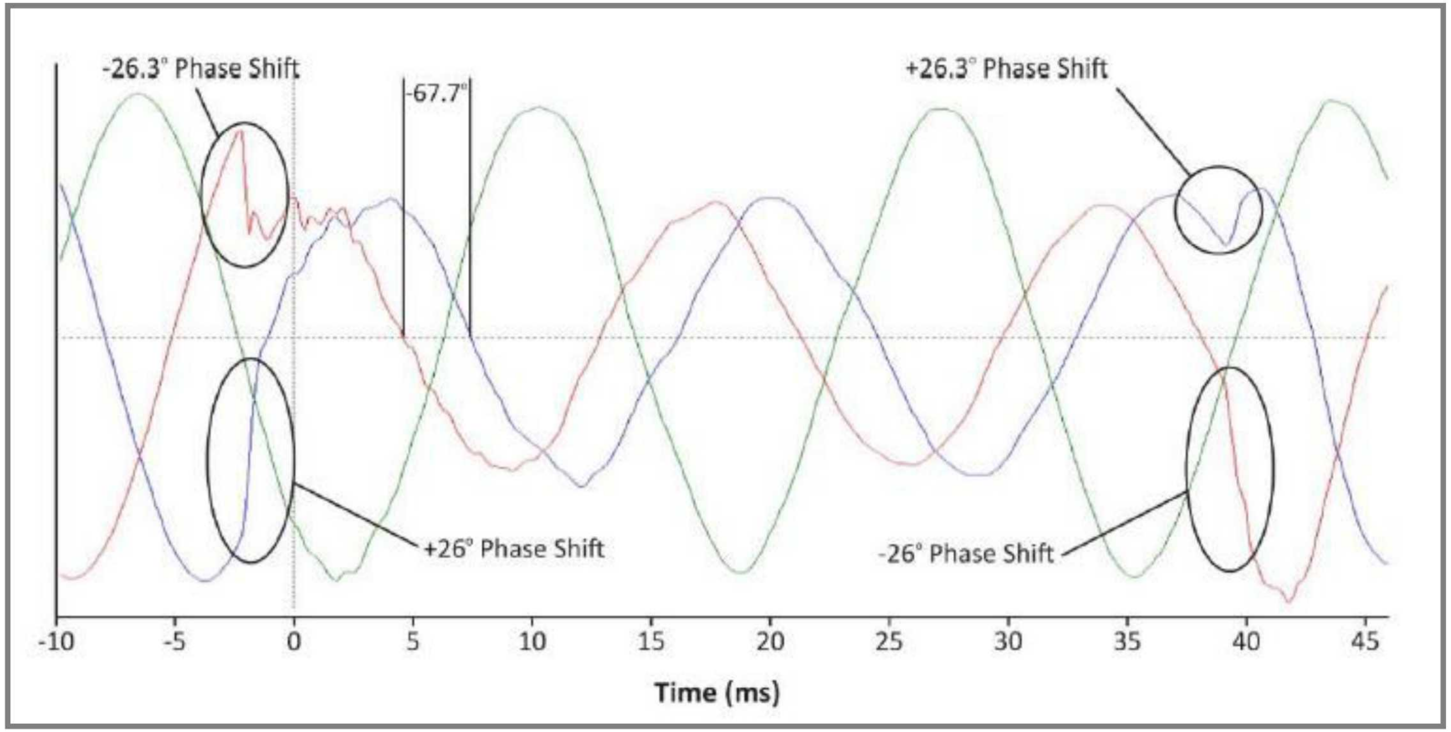
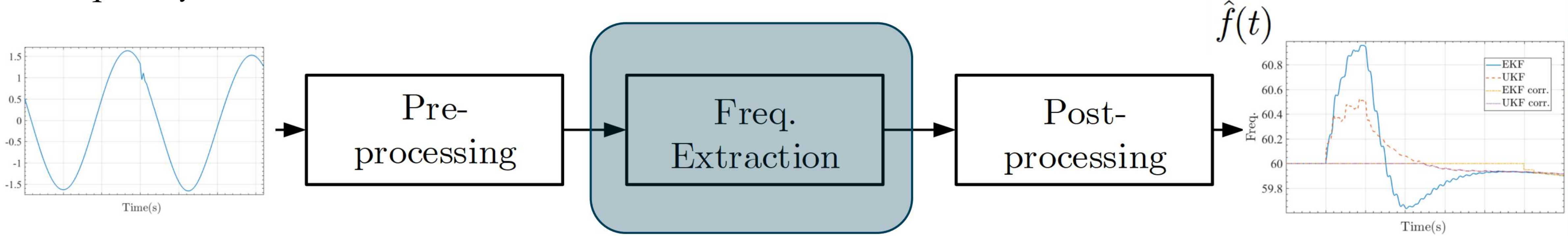


Figure from *1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report Southern California 8/16/2016 Event*
NERC Report

Technical Approach

- Our approach takes *raw* sinusoidal waveforms (point on wave -POW-) to estimate their frequency



Input:
- Single phase
- Three phase
- Multisignal

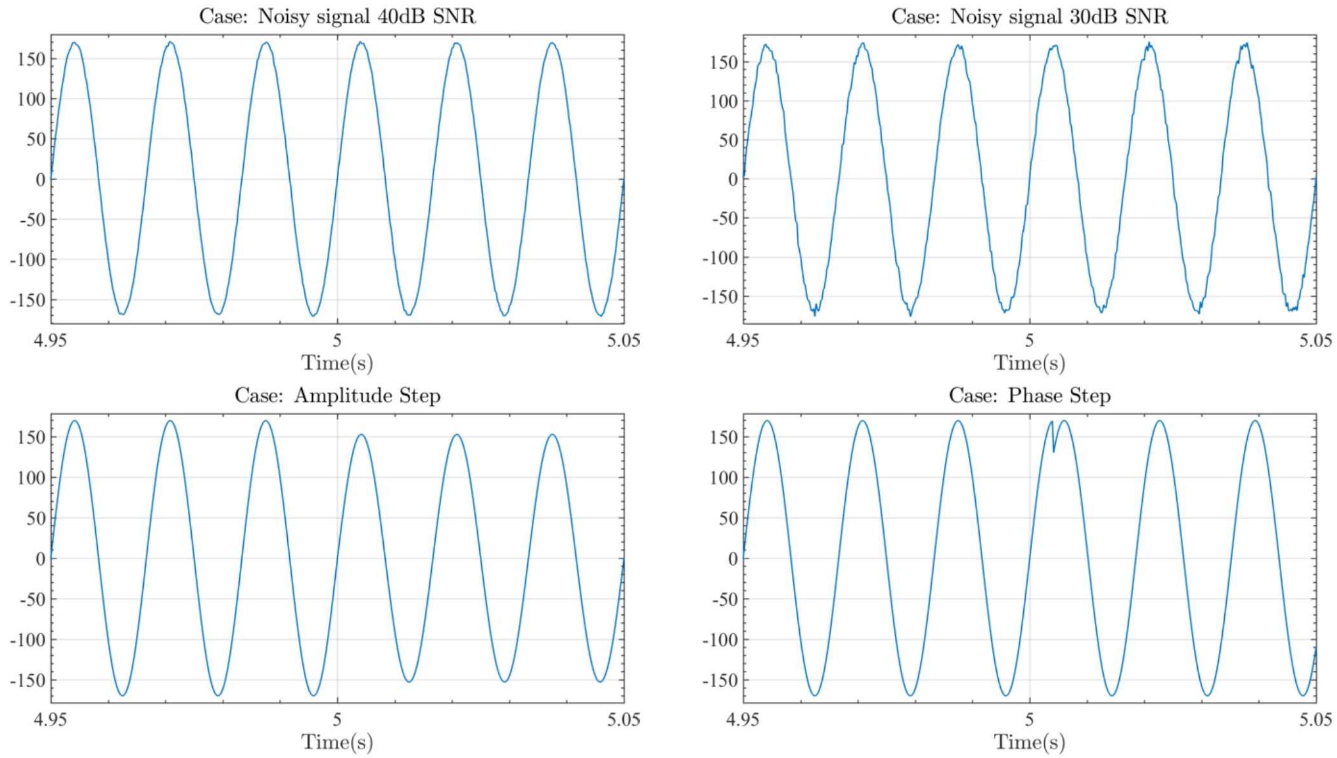
Preprocessing (optional)
Filtering to reduce noise and distortion

Estimation algorithms
- Discrete Fourier transform (DFT) based
- Kalman Filter (KF) based
- Phase-locked loop (PLL) based
- Adaptive Notch Filter (ANF)
- Least squares based

Postprocessing (optional)
Filtering to reduce noise
Correction of faulty estimates

Challenges in Frequency Estimation

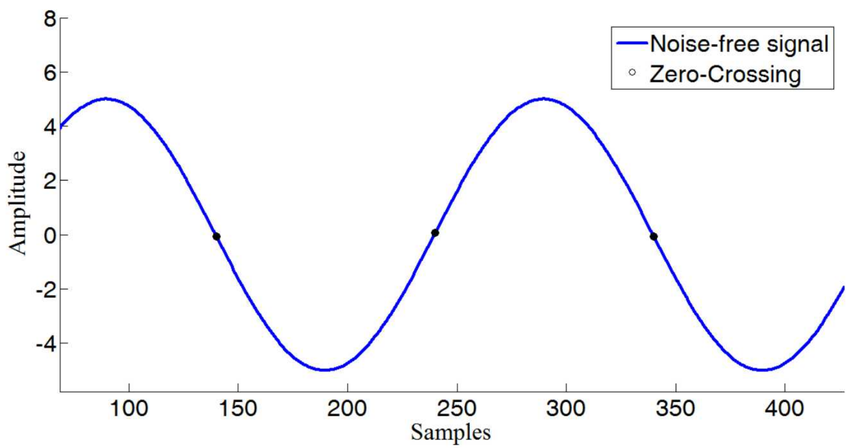
- Phenomena that corrupt input signals and affect frequency estimates can be divided into two:
  - Broad spectrum (white) noise
  - Specific disturbances/imperfections such as harmonic distortion, DC offset, imbalance, phase steps, and amplitude steps

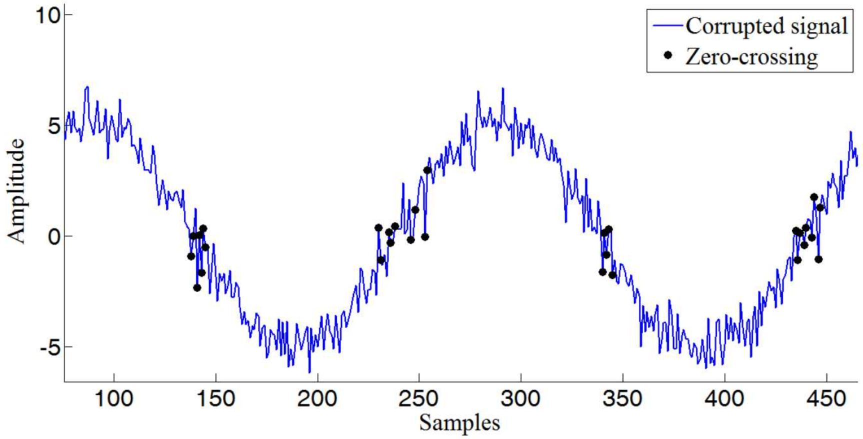


- Algorithm sensitivity to noise is unavoidably linked and traded against bandwidth (speed of response to changes in actual frequency)
  - Managing this tradeoff is called 'tuning' and an important characteristic of any algorithm is tuning difficulty

Challenges in Frequency Estimation

- Zero crossing is an intuitive and crude method for frequency estimation (in *real-time*) and was used for early generations of inverter technology
- It is however prone to errors for signals distorted with harmonics and/or high noise levels
- Also prone to errors for events such as phase steps





Figures taken from: Mendonça, T. R., Pinto, M. F., & Duque, C. A. (2014, December). *Least squares optimization of zero crossing technique for frequency estimation of power system grid distorted sinusoidal signals*. In 2014 11th IEEE/IAS International Conference on Industry Applications (pp. 1-6). IEEE.

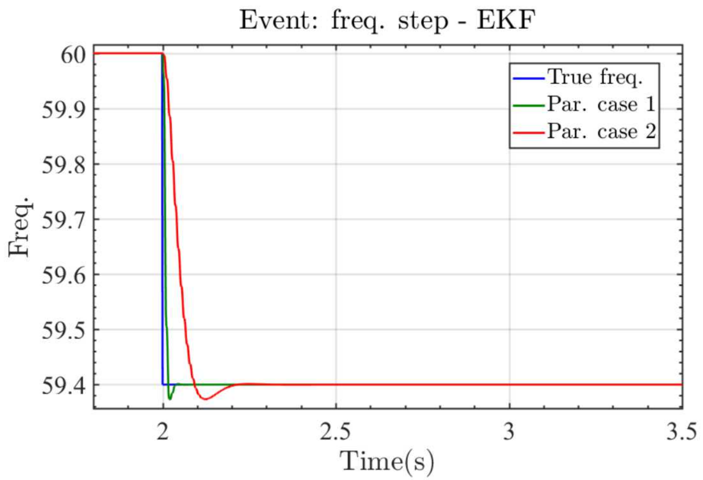
Project Objectives

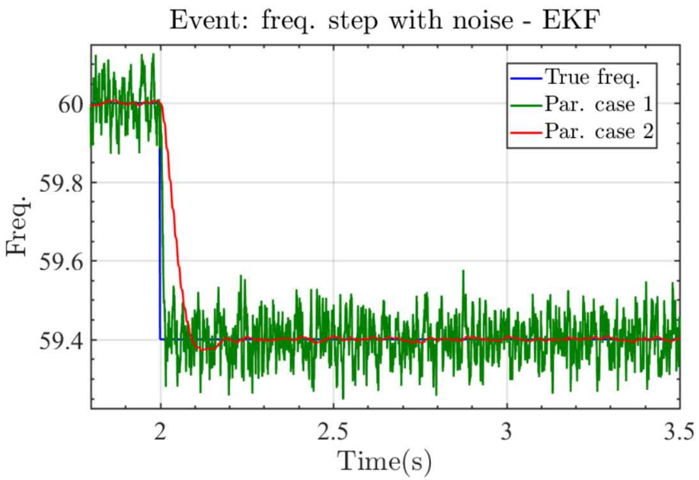
- One of the goals of the project is to study and propose methods for overcoming challenges of real-time frequency estimation
- Synthetic inertia controllers require accurate frequency estimates and fast (manage the tradeoff between sensitivity to noise and bandwidth)
- The project studied/implemented several families of algorithms to study they advantages and disadvantages
- The model and specifics of certain families of algorithms can help improve the frequency estimate
  - Some algorithm families have an inherent measure of the reliability of the estimate
  - Some algorithm families can accommodate multiple input signals

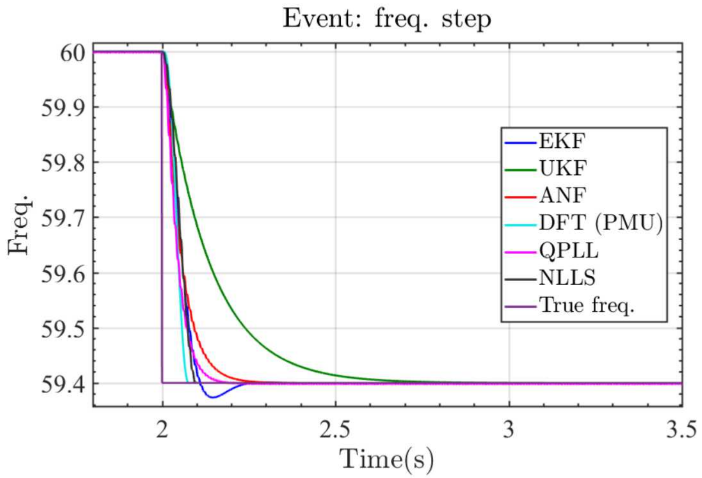
Algorithm Tuning

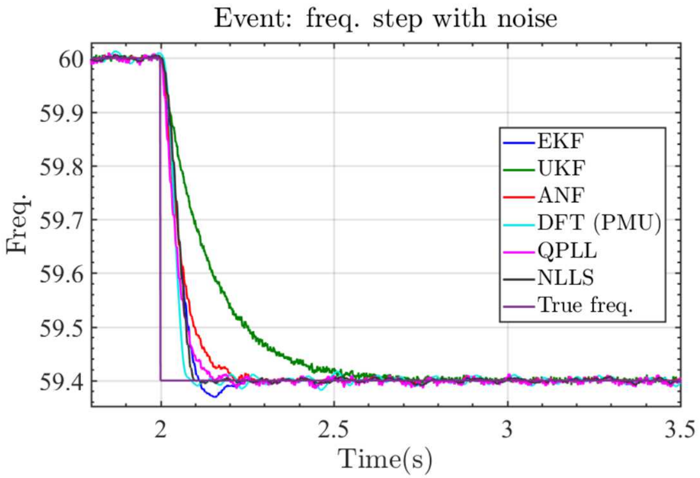
- Multiple frequency estimation approaches were tested against a database of synthetic waveforms exhibiting different types of corruption

- Tradeoff of sensitivity to noise vs bandwidth for the Extended Kalman Filter. Parameter adjusting can completely change the response of the filter









- Tradeoff of sensitivity to noise vs bandwidth for the different frequency estimation algorithms. **Tuning the parameters can make them behave similarly**

Algorithm Tuning

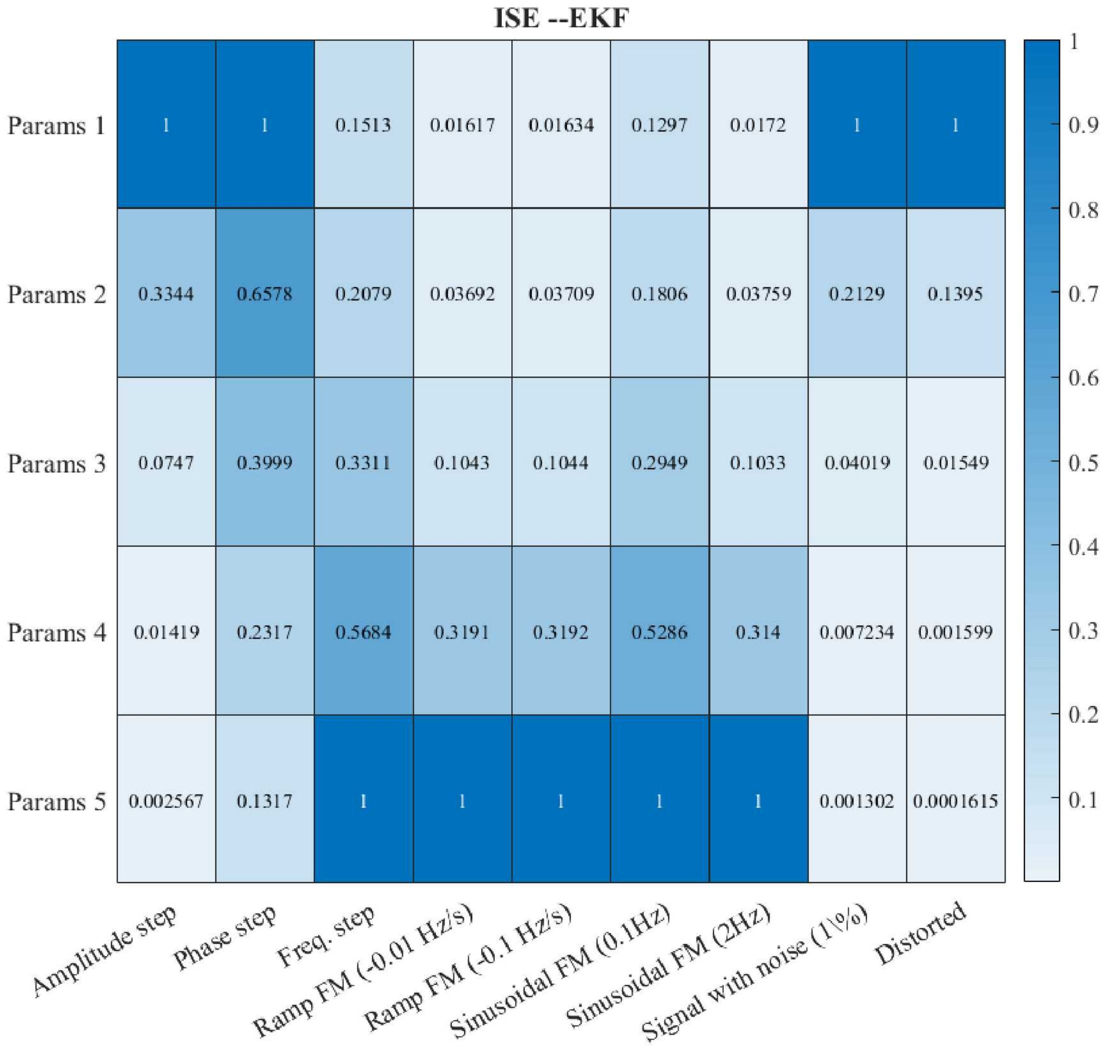
- Different metrics to determine the performance of the frequency estimation were considered

$$f_{\text{err}}(t) = \hat{f}(t) - f_{\text{true}}(t)$$

$$\text{IAE} = \int_0^\infty |f_{\text{err}}(t)| dt$$

$$\text{ISE} = \int_0^\infty f_{\text{err}}^2(t) dt$$

$$||f_{\text{err}}||_\infty = \max_t |f_{\text{err}}|$$



- Other signal dependent metrics were also considered (e.g. settling time when the signal is freq. step).

NLLS Freq. Estimation

Improving the frequency estimate

- User selects a signal model and an iterative, numerical procedure finds the model parameters that best fit a window of the measured signal
- Simplest model

$$\hat{y}_k = A\cos(2\pi f t_k) + B\sin(2\pi f t_k)$$

- Cost function

$$V(\theta) = \sum_{k=1}^{N} (y_k - \hat{y}_k(\theta))^2$$

- Easily scales up to add harmonics, offset; more complicated but possible for phase and amplitude jumps

- **Advantages**
  - User can easily add *any* feature to the model to reduce its impact on the frequency estimate
  - Easy to tune for noise/bandwidth tradeoff
  - Includes a natural measure of the estimate reliability (norm of residual vector) that can be used for control decisions
- **Disadvantages**
  - Heavy computational burden
  - Understudied, complicated
    - Iterative nature of solution makes performance difficult to predict theoretically
    - We are working on overcoming this disadvantage

J. Wold and F. Wilches-Bernal, "Nonlinear Least Squares for Power System Frequency Estimation" work submitted to the *IEEE Transactions on Power Systems journal*

Multisignal Frequency Estimation

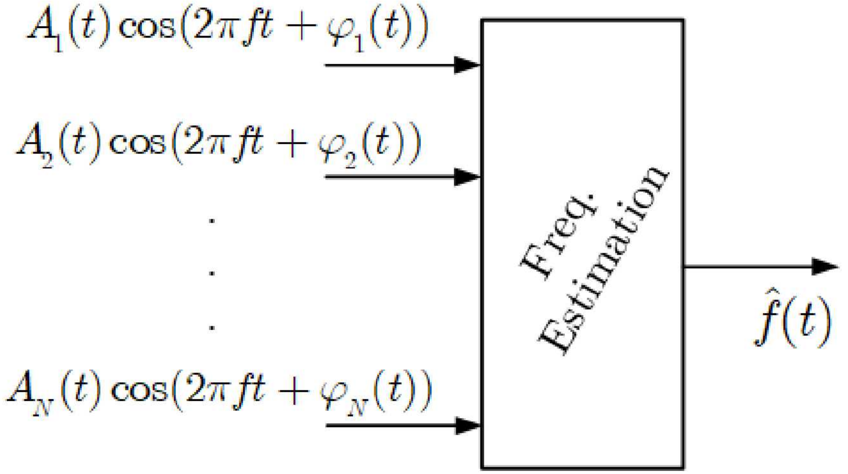
Improving the frequency estimate

- This research has studied approaches that consider multiple inputs (N-signals)
- Model: input is a vector of dimension N

$$\mathbf{z}(t) = \begin{bmatrix} A_1(t)\cos(\omega t + \phi_1(t)) \\ A_2(t)\cos(\omega t + \phi_2(t)) \\ \vdots \\ A_N(t)\cos(\omega t + \phi_N(t)) \end{bmatrix}$$

- The 3-phase case is a special case where N=3 (doesn't make use of Clarke transform or positive sequence)
- It is *immune* to phase imbalances and phase losses.
- Suitable for some frequency estimation algorithms like Kalman Filter and Nonlinear least squares

- Based on the idea that frequency information is redundant in the system (present in many signals, e.g. voltages and currents). It has an inherent noise reduction advantage over single signal (one phase) approaches



- Empirical results have shown that the multisignal approach is much faster than using single sequential single signal and then averaging

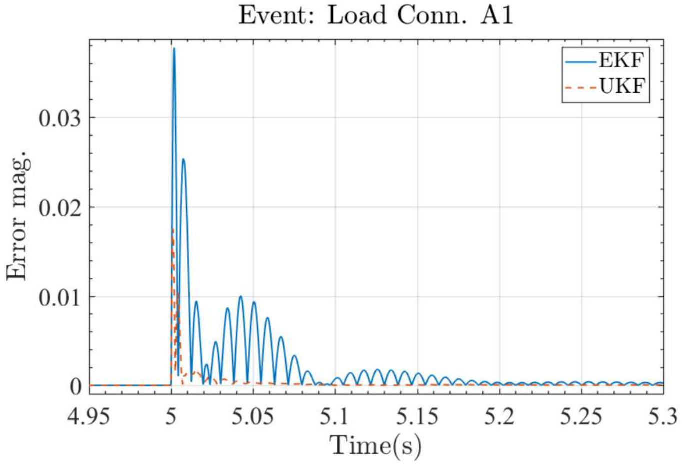
Frequency Correction

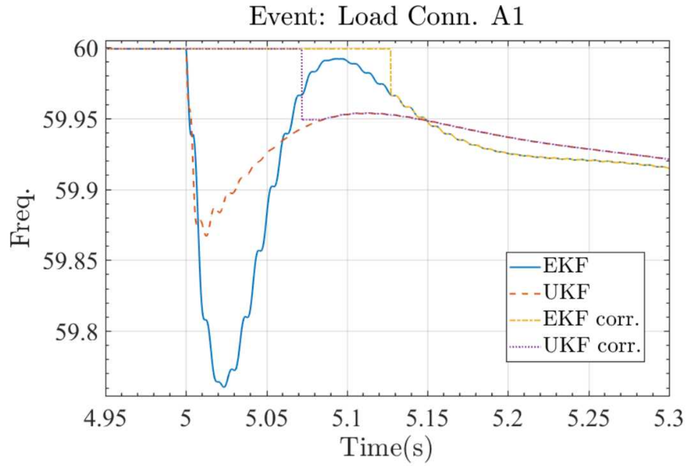
Improving the frequency estimate

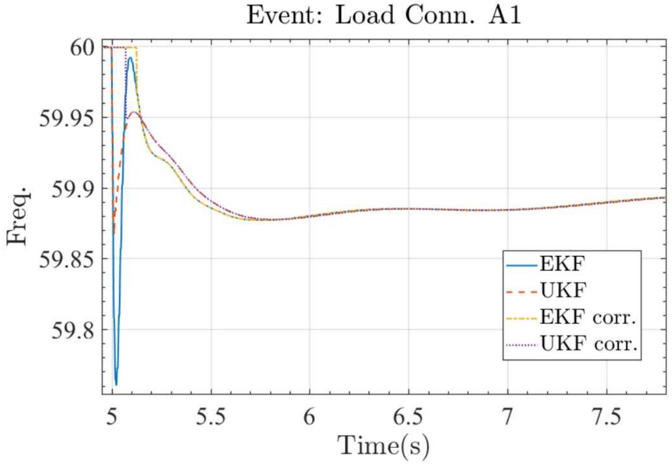
- **Correcting the frequency estimate:** based on the idea that some corruptions in the point on wave are only temporary (sometimes really fast e.g. phase jump) but their effect on the frequency estimate can linger for longer time (depending on the tuning.)

Algorithm 2: Frequency Correction Algorithm

if $|e_k| < \epsilon$ **and** $\neg F_{\mathrm{tH}}$ **and** $\neg F_{\mathrm{ramp}}$ **then**
  $\hat{f}_k^{\mathrm{corr}} \leftarrow \hat{f}_k$
else if $|e_k| < \epsilon$ **and** F_{tH} **and** F_{ramp} **then**
  if $t_{\mathrm{cont,k}} > t_{\mathrm{hold}}$ **then**
    $F_{\mathrm{tH}} \leftarrow$ False
  end
  $\hat{f}_k^{\mathrm{corr}} \leftarrow \hat{f}_{\mathrm{prev}}$
  $t_{\mathrm{cont,k}} = t_{\mathrm{cont,k-1}} + T_s$
else if $|e_k| < \epsilon$ **and** $\neg F_{\mathrm{tH}}$ **and** F_{ramp} **then**
  $\Delta \hat{f}_k = \hat{f}_k - \hat{f}_{k-1}^{\mathrm{corr}}$
  if $|\Delta \hat{f}_k| > R_{\mathrm{fmax}}$ **then**
    $\Delta \hat{f}_k \leftarrow \mathrm{sgn}(\Delta \hat{f}_k) R_{\mathrm{fmax}}$
  else
    $F_{\mathrm{ramp}} \leftarrow$ False
  end
  $\hat{f}_k^{\mathrm{corr}} \leftarrow \hat{f}_{k-1}^{\mathrm{corr}} + \Delta \hat{f}_k$
else if $|e_k| > \epsilon$ **then**
  $\hat{f}_k^{\mathrm{corr}} = \hat{f}_{\mathrm{prev}}$
  Reset time: $t_{\mathrm{cont,k}} \leftarrow 0$
  $F_{\mathrm{tH}} \leftarrow$ True
  $F_{\mathrm{ramp}} \leftarrow$ True
end

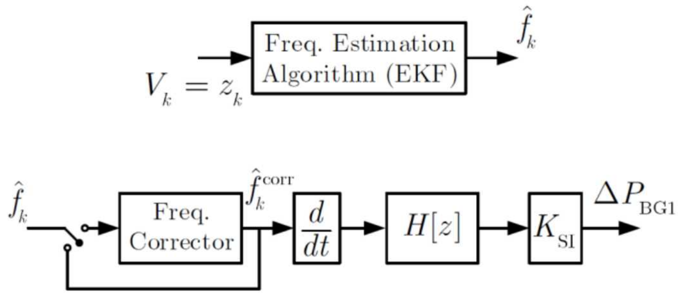




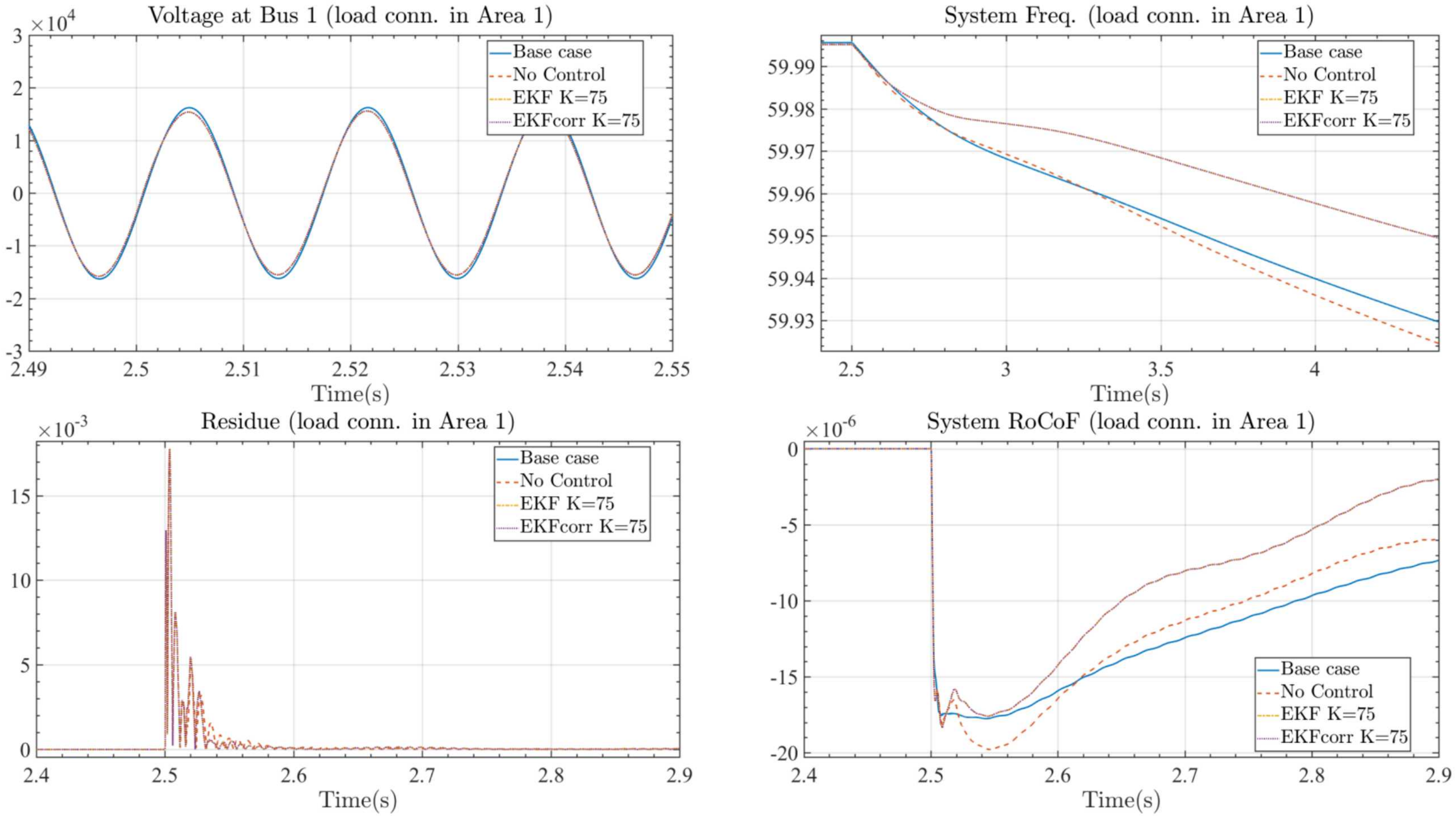


Frequency Correction in Synthetic Inertia Control

- **Synthetic inertia controller:**

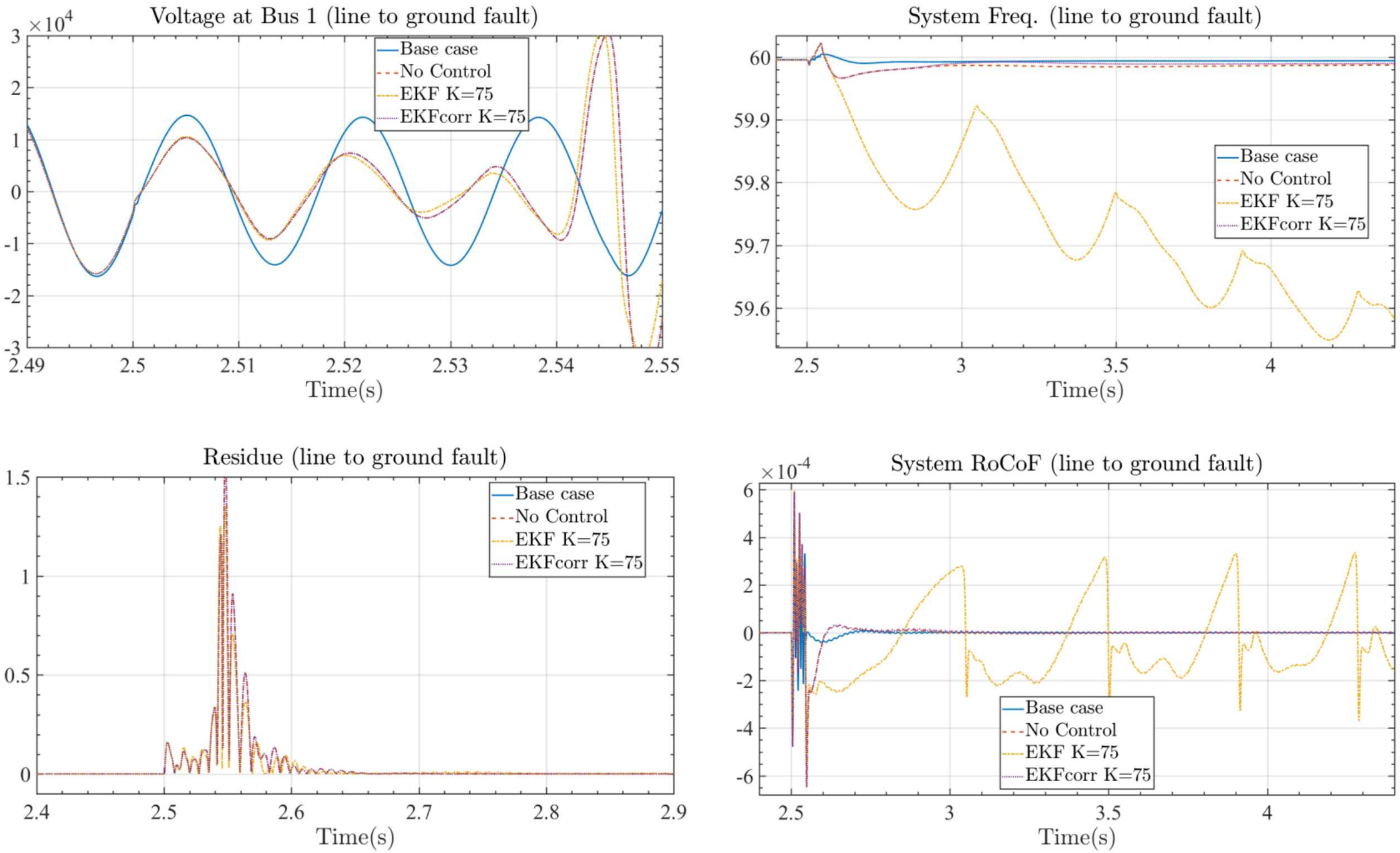


- Tested the frequency corrector for a power imbalance event (connection of 100 MW load). This type of event does not typically distort the waveforms



Frequency Correction in Synthetic Inertia Control

- Results of the frequency corrector for a line to ground fault event. This type of disturbance does distort the power system signals nearby



Conclusions

- Integration of converter interfaced generation is affecting the power quality of power system waveforms and the primary frequency regulation of the system ➔ Estimating frequency is becoming a more challenging task
- There are multiple ways of estimating frequency in power systems and because the approaches are tunable, similar results can be achieved with them
- All approaches have a tradeoff between noise rejection and bandwidth, tuning to manage the tradeoff varies across algorithms
- Including multiple signals can help mitigate this trade-off
- Certain disturbances (phase steps) cause large estimation errors for all algorithms, and heavier filtering is not an acceptable remedy in real-time control applications
- Post processing in the form of frequency correction is a promising approach for generating cleaner signals to perform control actions