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A Method for Correcting Frequency and RoCoF Estimates of Power System Signals with Phase Steps

Felipe Wilches-Bernal
Sandia National Laboratories
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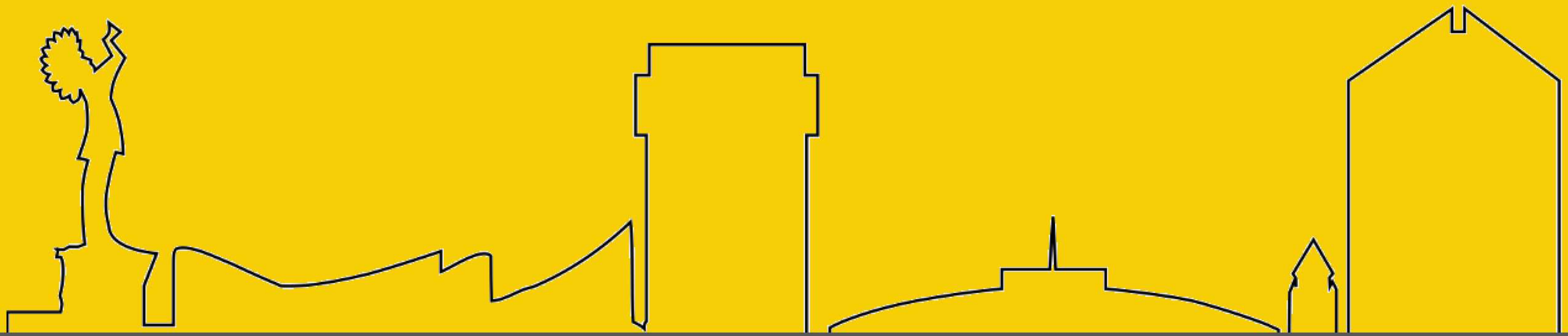


51st North American Power Symposium

Project Team

Sandia National Laboratories

- Felipe Wilches-Bernal
- Ricky Concepcion
- Hill Balliet (intern 2019)
- Jamie Budai (intern 2018)

Montana Tech

- Prof. Josh Wold
- Patrick Cotes (intern 2018)

Introduction and Motivation

- The increase of converter interfaced generation both at the transmission and distribution levels is creating unprecedented challenges to the grid operation
- Frequency is a key indicator of the balance between generation and consumption (and network stability). Electrical frequency is related to mechanical frequency (rotational speed of electrical generators)
- In certain critical occasions determining frequency from electrical waveforms is particularly challenging

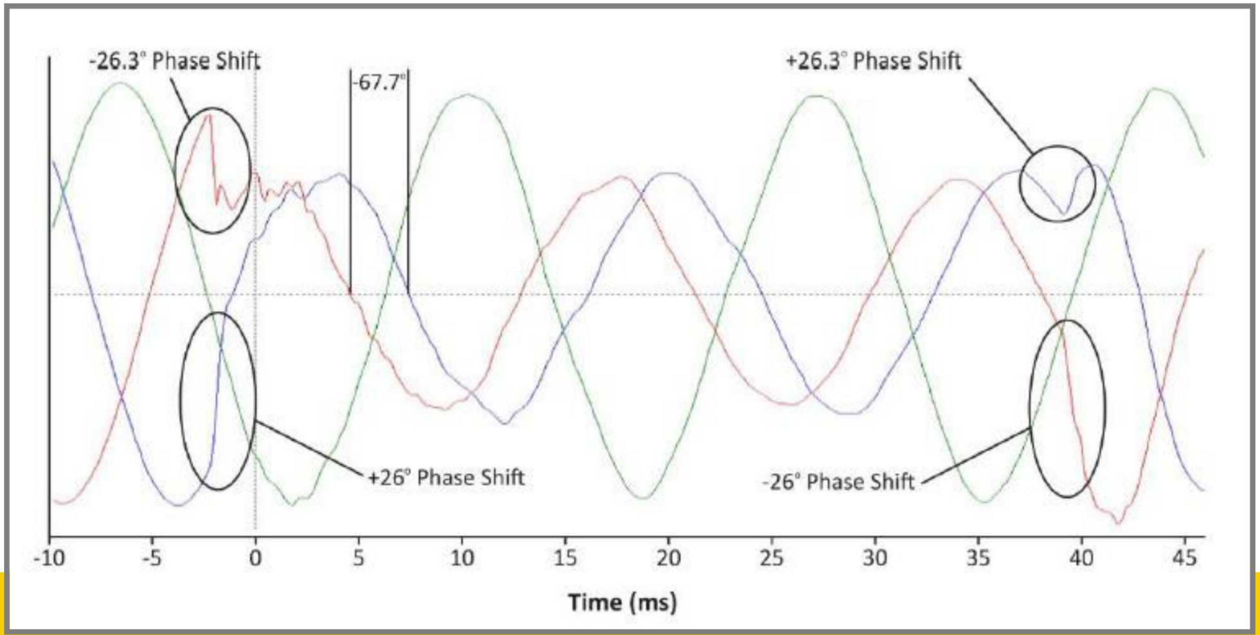


Figure from *1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report*
Southern California 8/16/2016 Event
NERC Report

Introduction and Motivation

- Phase steps are a type of frequency distortion that is very hard to deal with. It can cause problems to control equipment.
- The evolving grid requires fast but correct frequency and rate of change of frequency estimates (at all times!)
- Applications where accurate estimates are needed:
  - Synthetic inertia controllers
  - Under frequency load shedding (UFLS)
  - Loss of mains protection
- Proposed solution: **correct** frequency estimates (philosophy better to not act than to act wrongfully)

Signal Model

- A power systems signal (voltage or current) can be written as

$$z(t) = A(t)\cos(\omega t + \phi(t)) \xrightarrow[t_k = kT_s]{\text{sampling}} z_k = A\cos(\omega t_k + \phi(t_k)) \quad k = 1, \dots, N$$

$$\xrightarrow{\text{Euler's equation}} \quad z_k = \frac{A}{2}\left(e^{j(\omega t_k + \phi(t_k))} + e^{-j(\omega t_k + \phi(t_k))}\right)$$

Defining:

$$x_{1,k} = e^{j\omega T_s} \qquad x_{3,k} = e^{-j\omega T_s}$$

$$x_{2,k} = Ae^{j(\omega k T_s + \phi(t_k))} \qquad x_{4,k} = Ae^{-j(\omega k T_s + \phi(t_k))}$$

Recursive relationship

$$\mathbf{x}_k = \begin{bmatrix} x_{1,k+1} \\ x_{2,k+1} \\ x_{3,k+1} \\ x_{4,k+1} \end{bmatrix} = \begin{bmatrix} x_{1,k} \\ x_{2,k} \cdot x_{1,k} \\ x_{3,k} \\ x_{4,k} \cdot x_{3,k} \end{bmatrix}$$

- The recursive relationship can be written as

$$\mathbf{x}_{k+1} = \mathbf{f}(\mathbf{x}_k) \qquad z_k = \begin{bmatrix} 0 & \frac{1}{2} & 0 & \frac{1}{2} \end{bmatrix} \mathbf{x}_k$$

Kalman Filter Modeling

- For a nonlinear system of the form:

Process (system) $\mathbf{x}_{k+1} = \mathbf{f}(\mathbf{x}_k) + \mathbf{w}_k$

Measurement (observation) $\mathbf{z}_k = \mathbf{h}(\mathbf{x}_k) + \nu_k$

Equations of the form of the model presented above

- With process and measurement noise as

$$E[w_k] = 0 \quad E[w_k w_k^\top] = \mathbf{Q}_k \quad E[w_k w_j^\top] = 0 \text{ for } k \neq j$$

$$E[v_k] = 0 \quad E[v_k v_k^\top] = \mathbf{R}_k \quad E[v_k v_j^\top] = 0 \text{ for } k \neq j$$

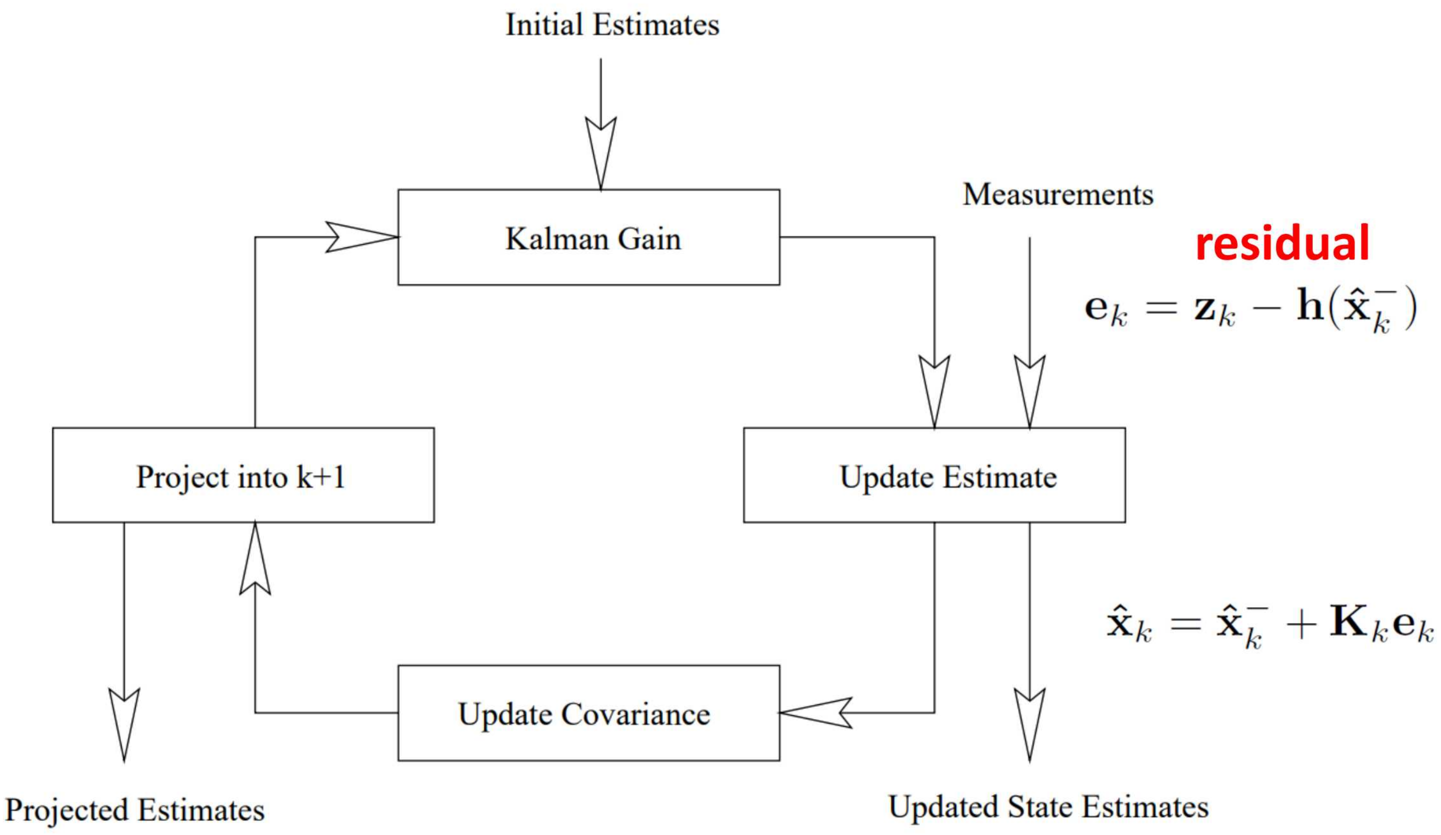
$$E[w_k v_j^\top] = 0 \text{ for all } k \text{ for all } j$$

- Kalman filter is an estimation technique (initially proposed for linear systems).
- Used for tracking and data prediction
- Works really well when the model match reality

Kalman Filter Modeling

- In this work 2 adaptations for nonlinear systems were used:
  - **Extended Kalman Filter (EKF).** Uses linearization of the state and measurement equations
  - **Unscented Kalman Filter (UKF).** Uses statistical linearization via the unscented transform

- Recursive form of Kalman Filters



Correction of Freq. Estimates

- Frequency and RoCoF are estimated as

$$\hat{f}_k = \frac{f_s}{2\pi} \cos^{-1}\left(\frac{x_{1,k} + x_{3,k}}{2}\right) \qquad \widehat{\text{RoCoF}}_k = \frac{\hat{f}_k - \hat{f}_{k-1}}{T_s}$$

Recall frequency is at the first and third states of the model

- Algorithm to correct the estimates:

Algorithm: Frequency Correction Algorithm

if $e_k < \epsilon$ **and** HoldFlag is False **then**
  $\hat{f}_k^{\text{corr}} = \hat{f}_k$
else if $e_k < \epsilon$ and HoldFlag is True **then**
  if $t_{\text{cont,k}} < t_{\text{hold}}$ **then**
    HoldFlag $\leftarrow$ False
  end
  $\hat{f}_k^{\text{corr}} = \hat{f}_{\text{avg}}$
  $t_{\text{cont,k}} = t_{\text{cont,k}-1} + T_s$
else if $e_k > \epsilon$ **then**
  $\hat{f}_k^{\text{corr}} = \hat{f}_{\text{avg}}$
  Reset time: $t_{\text{cont,k}} = 0$
  HoldFlag $\leftarrow$ True
end

Correcting of Freq. Estimates

- Frequency correction algorithm tested with signals with phase steps type of signals which are modeled as

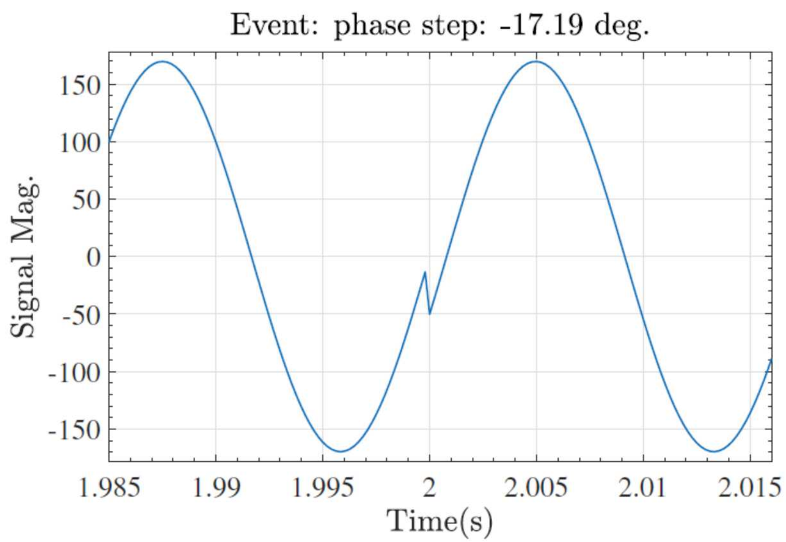
$$s(t) = A\cos(\omega t + \phi_H(t)) \quad \text{with} \quad \phi_H(t) = \begin{cases} \phi_{\text{step}}, & \text{if } t > t_{\text{step}} \\ 0, & \text{otherwise} \end{cases}$$

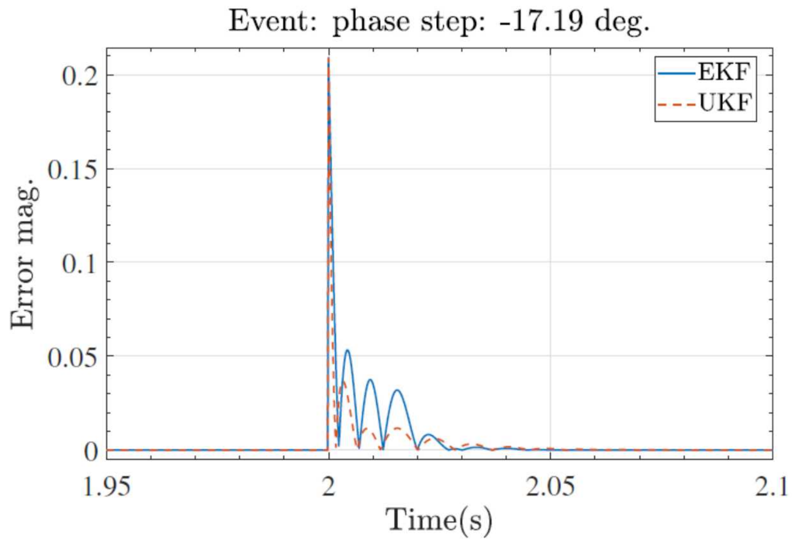
- Phase steps occurred at different points within a waveform.
- The phase step considered where of $\phi_{\text{step}} = -0.3$
- The parameters for the frequency estimation algorithm are:

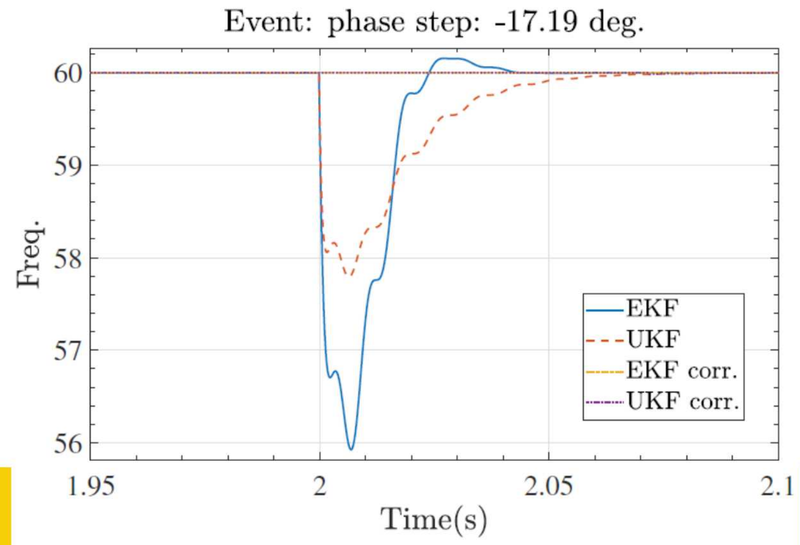
$$\epsilon = 0.018 \qquad t_{\text{hold}} = 50 \text{ ms}$$

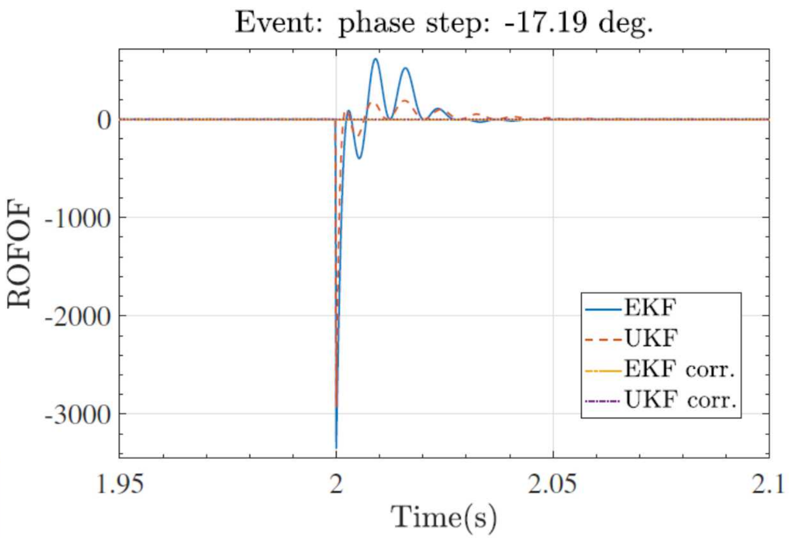
Correcting of Freq. Estimates

- Phase steps occurs when the sinusoidal wave is passing through zero (0 deg)



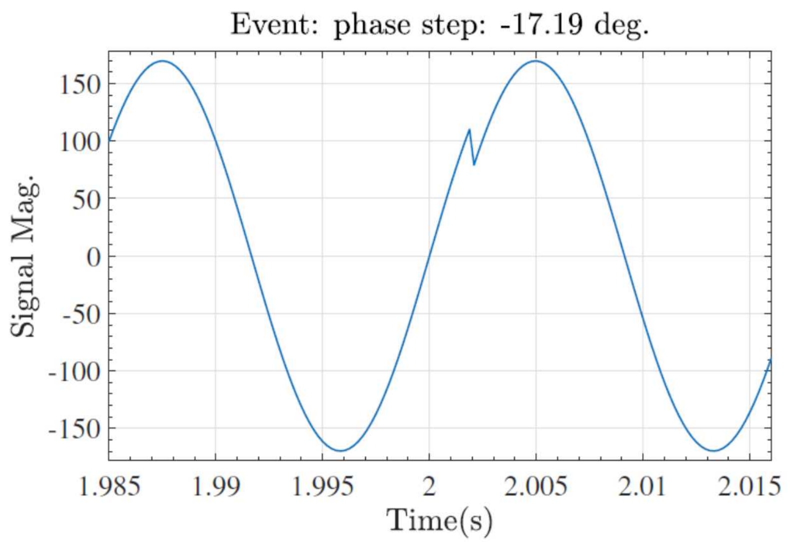


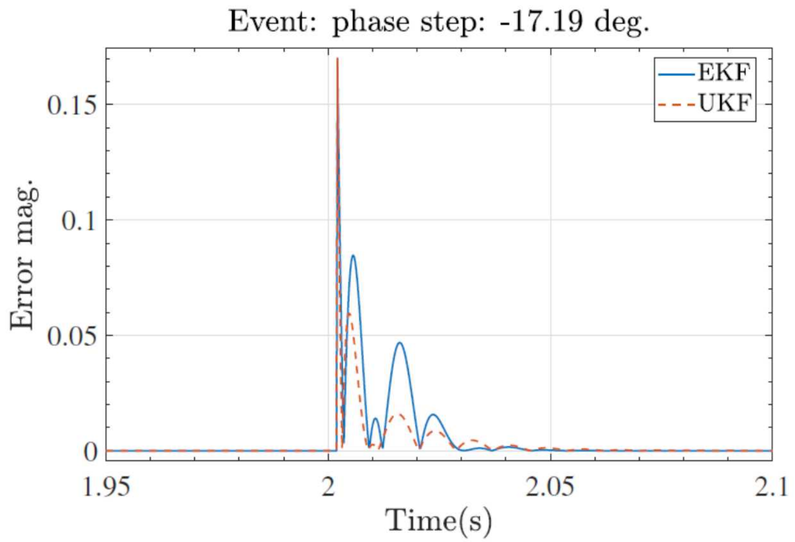


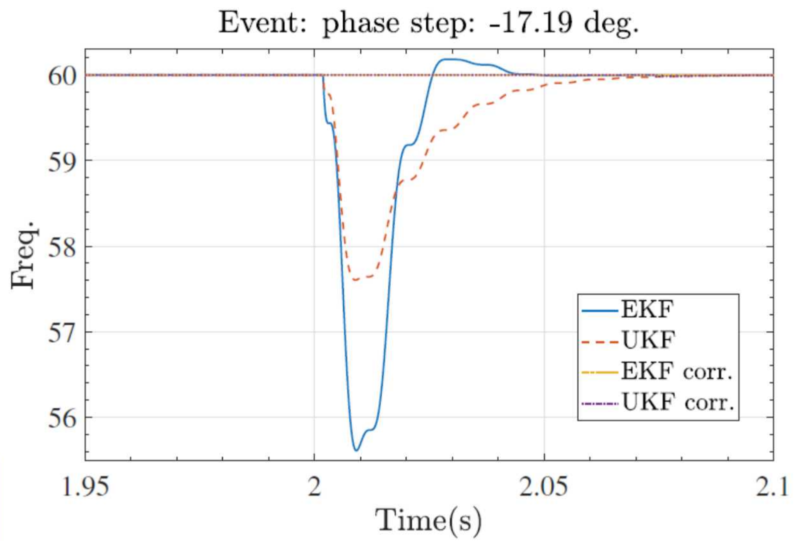


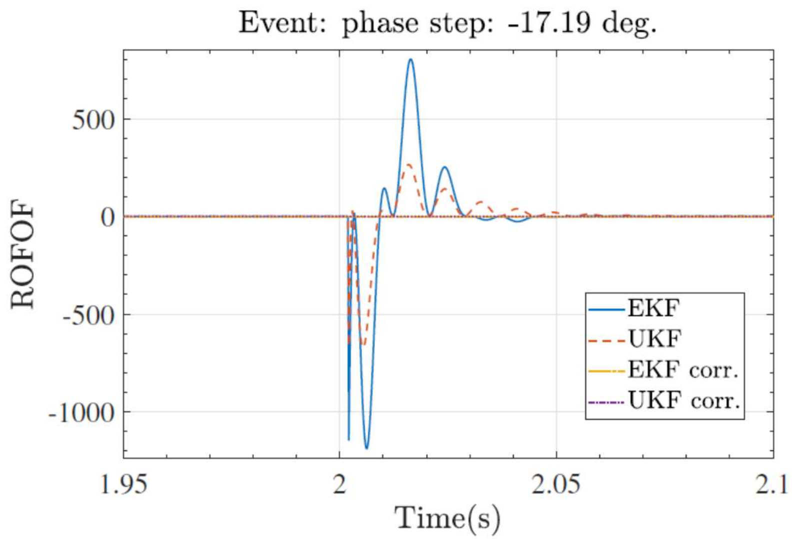
Correcting of Freq. Estimates

- Phase steps occurs at 45 degrees.



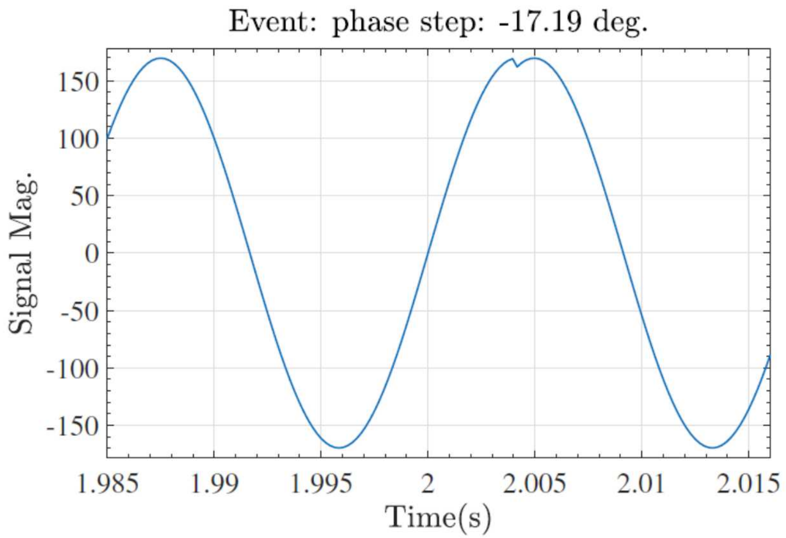


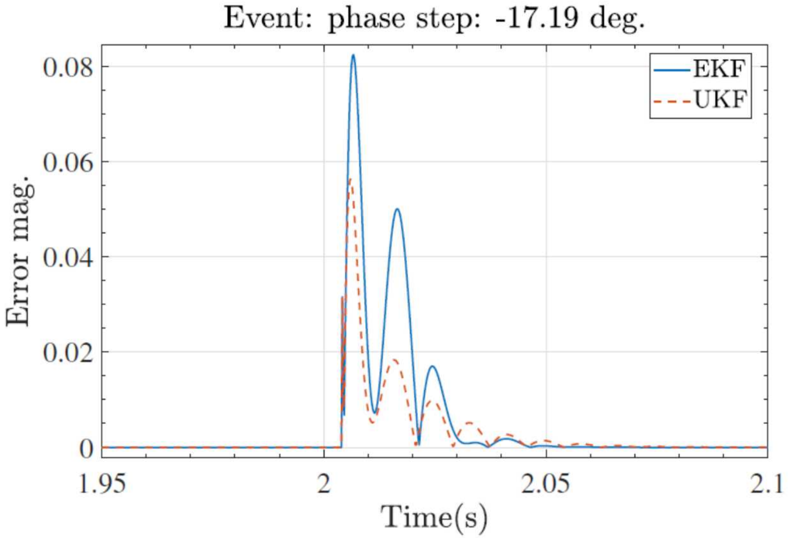


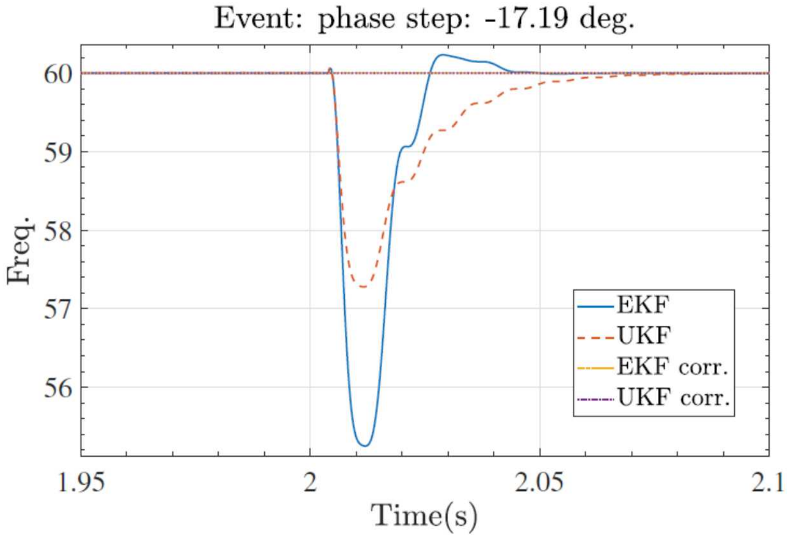


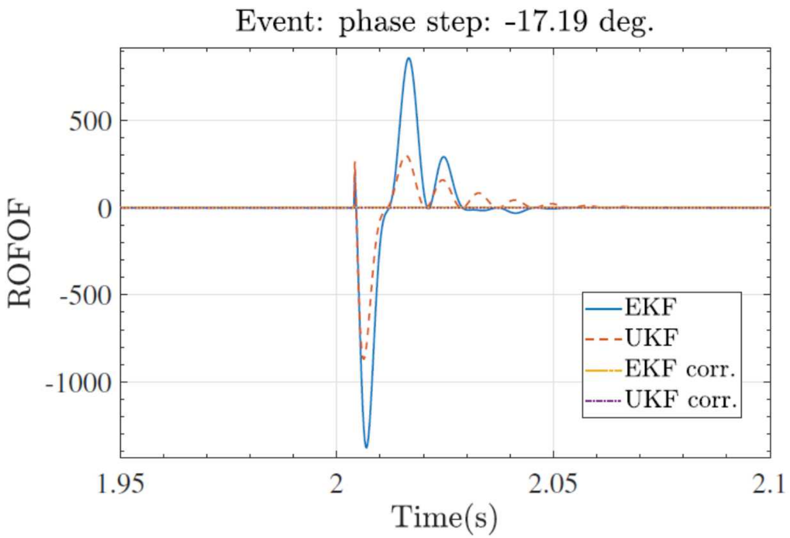
Correcting of Freq. Estimates

- Phase steps occurs when the sinusoidal reaches it maximum (90 deg)



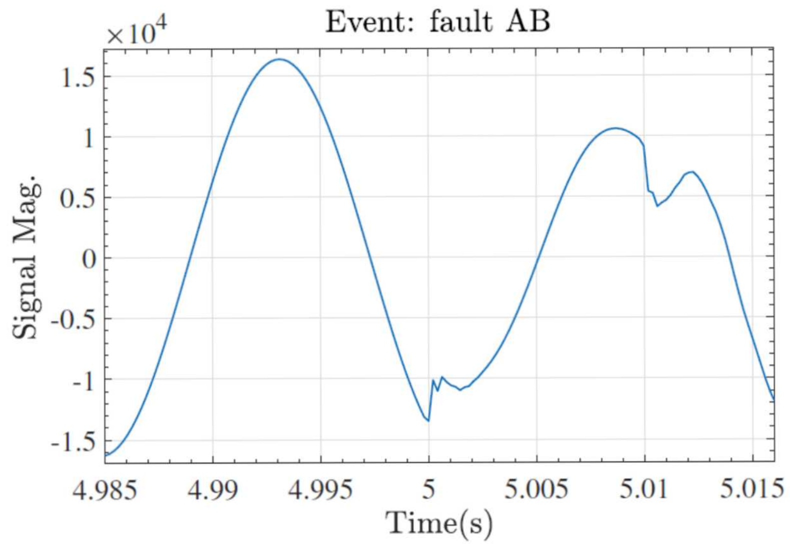


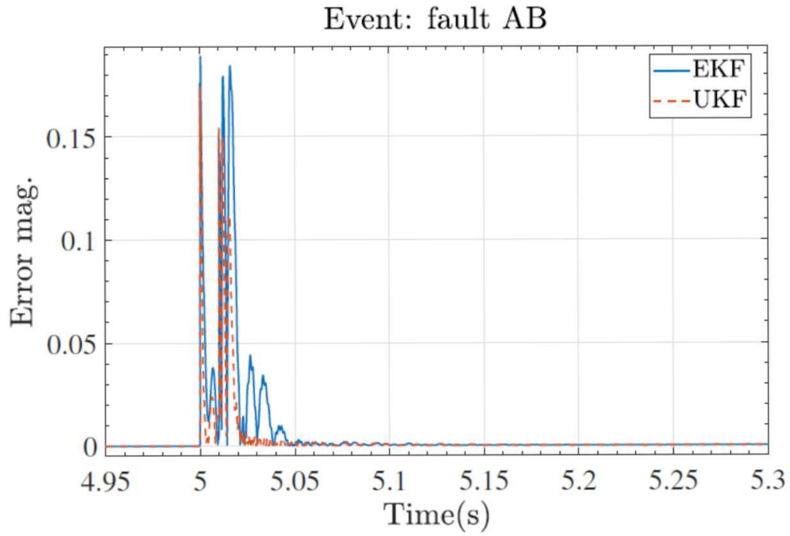


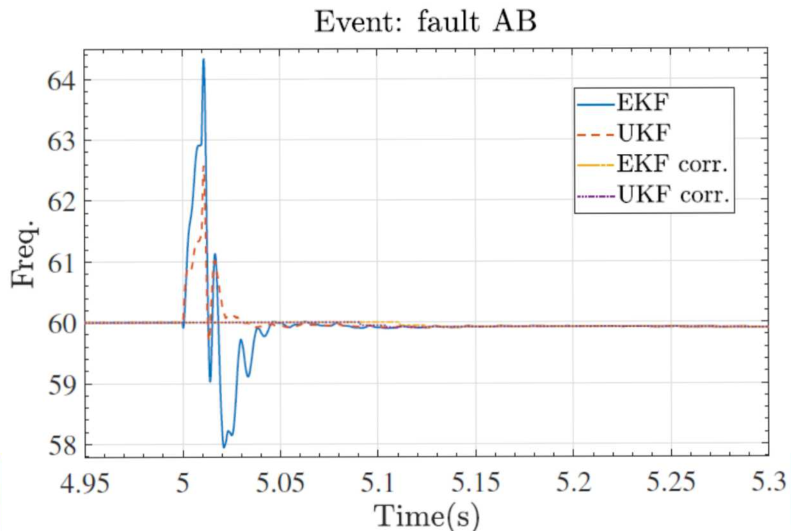


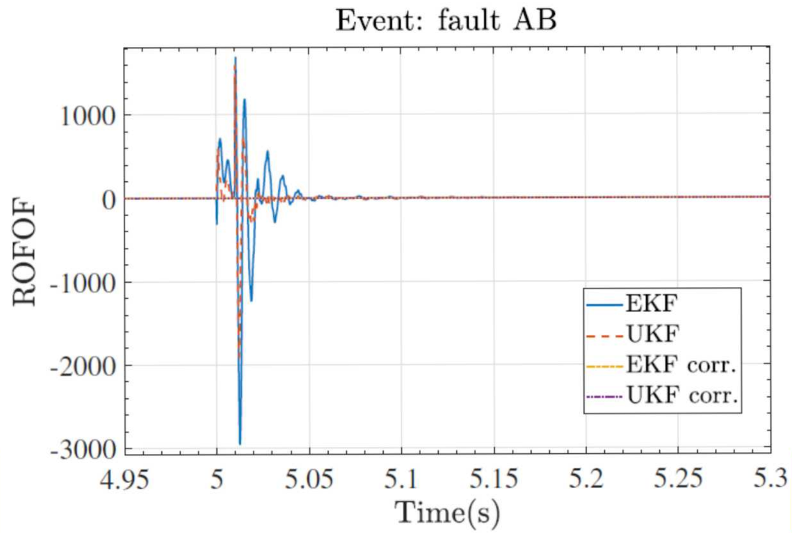
Correcting of Freq. Estimates

- Simulated data. Event: line to line fault that lasted 10ms









Conclusions and Future Work

- Phase steps heavily affect frequency estimates for Kalman Filter type of frequency estimation algorithms
- Residual of Kalman filter increases when the frequency estimate doesn't match the observation (reality); this is a fact of all Kalman filter approaches
- Correcting frequency estimates is possible and *easy* using the residual of the Kalman filter
- Future work will include adding noise and harmonics to the signals as well as considering the three-phases

Acknowledgment

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Thank you!

Contact:
Felipe Wilches-Bernal
phone: (505) 845-8292
email: fwilche@sandia.gov

Questions?