The Functional Basis Analysis for the Parametric Reconstruction of Synchronised Waveforms in Power Systems

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Panel: Synchro-Waveforms Data Analytics and Data-Driven Applications

Contributors

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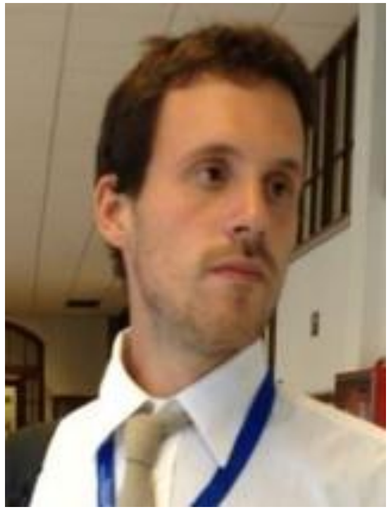


Dr. Asja Derviškadić
(Swissgrid)

Context

Event of September 28, 2016, Australia

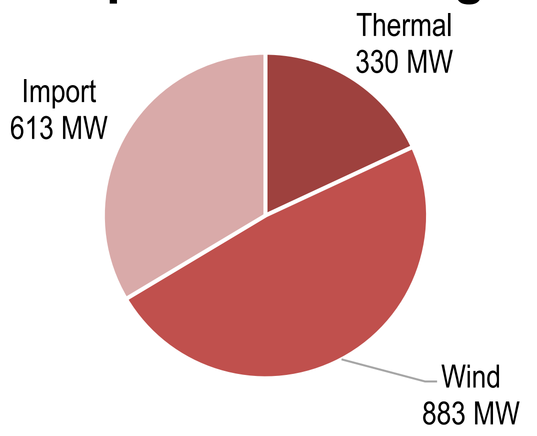
Multiple tornadoes in South Australia (SA) tripped multiple 275 kV transmission circuits and resulted in multiple faults in quick succession.

The series of voltage dips from the faults triggered protection on several wind farms to runback about 456 MW of wind generation.

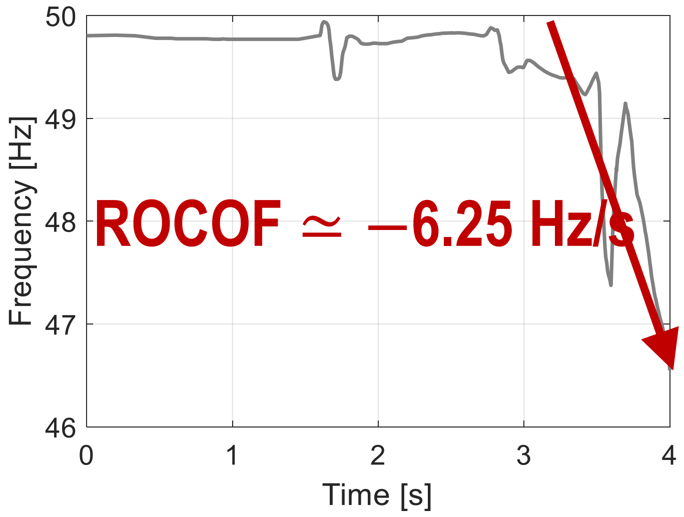
The reduction in wind farm output was compensated by an increase in power imported from Victoria. However, the import reached a level that tripped the interconnector on loss of synchronism protection.

The loss of power infeed from the wind farms and import from Victoria resulted in the frequency falling so fast that load shedding schemes were unable to stop the fall, resulting in a blackout.

SA pre-black-out generation mix



System frequency



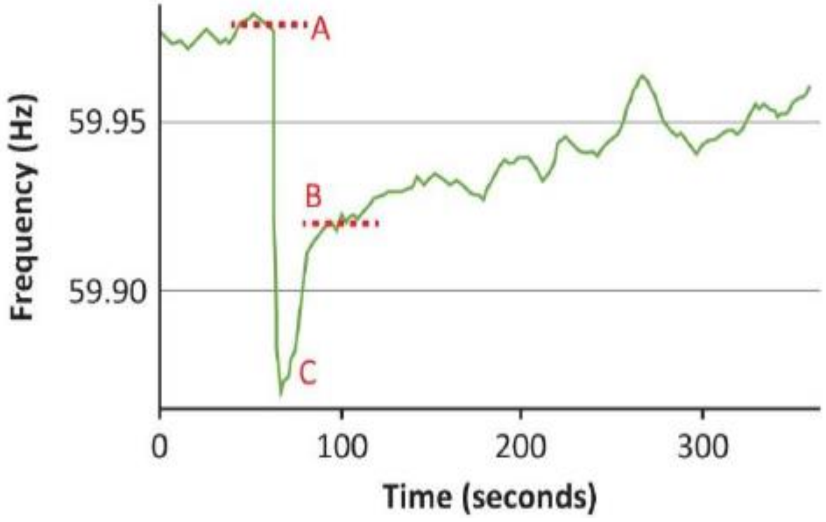
AEMO, "Review of the Black System South Australia report system event of 28 September 2016," Australian Energy Market Operator, Tech. Rep., 2017.

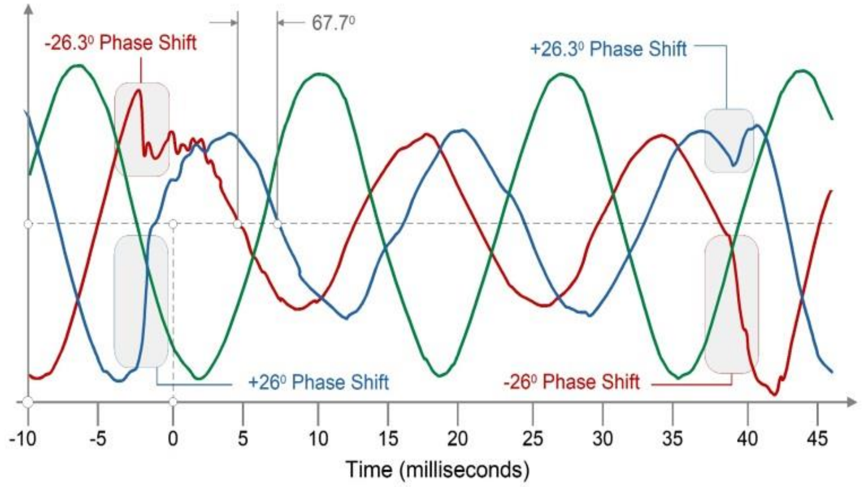
Context

Event of August 16, 2016, California

A fault induced a total of 1’178 MW of PV power interruption.

- The majority of inverters trip instantaneously based on frequency measurements obtained from PLLs; it was determined that these inverters are susceptible to erroneous tripping due to frequency changes; this response accounted for 700 MW of the lost generation.
- A number of inverters that tripped were configured to cease current injection if the voltage goes above 1.1 pu or below 0.9 pu; the inverters were returned to pre-disturbance level at a slow ramp rate; this response accounted for about 450 MW of lost generation.

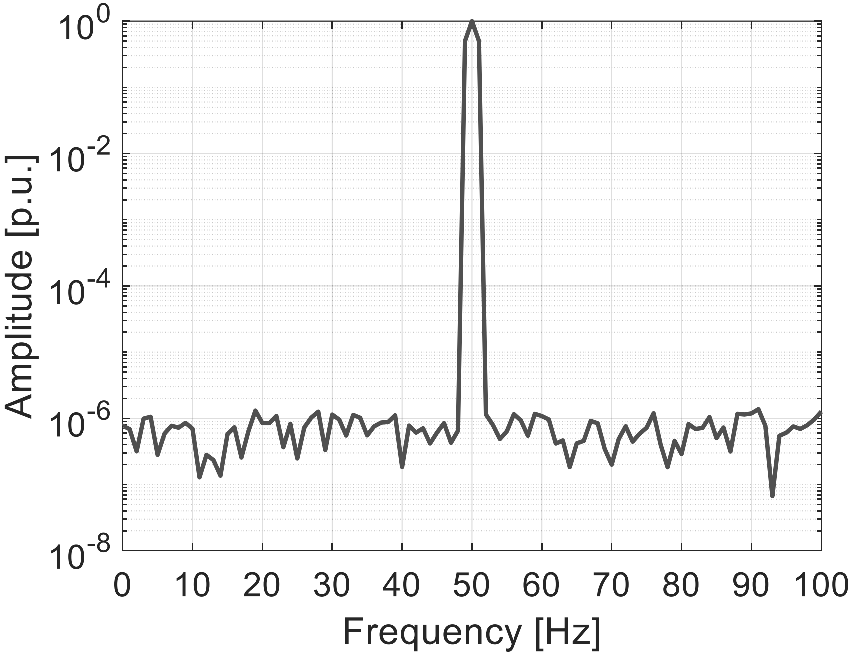




NERC, "1,200 MW fault induced solar photovoltaic resource interruption disturbance report," NERC, Atlanta, GA, 2017.

Adequacy of signal processing techniques

$$v(t) = A \cdot cos(2\pi f t)$$

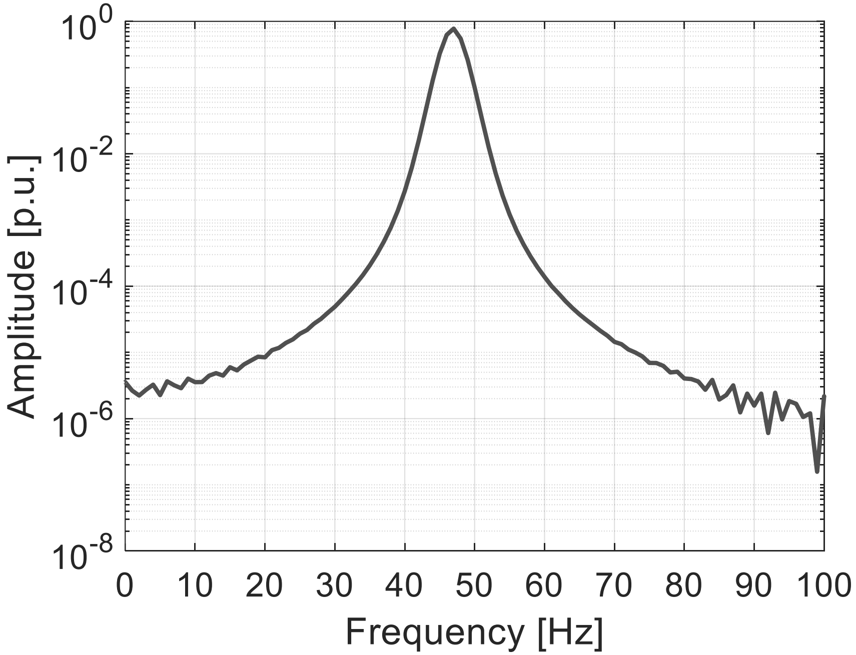


Energy of the signal in [48, 52] Hz 99.X%

➔ **Narrow-band signal**

Transient with ROCOF R=-6.25 Hz/s

$$v(t) = A \cdot cos(2\pi(f + Rt)t)$$



Energy of the signal in [48, 52] Hz 32%

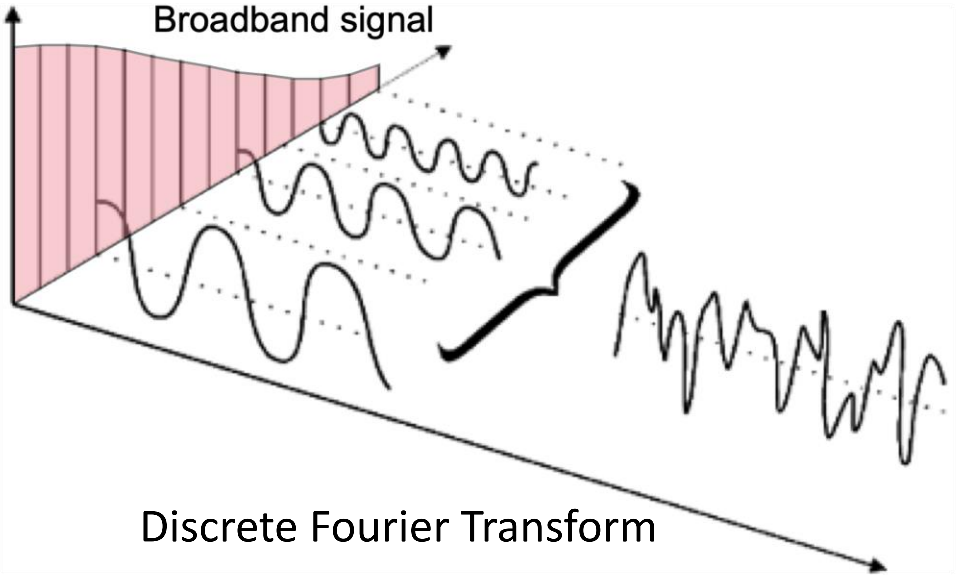
➔ **Broad-band signal**

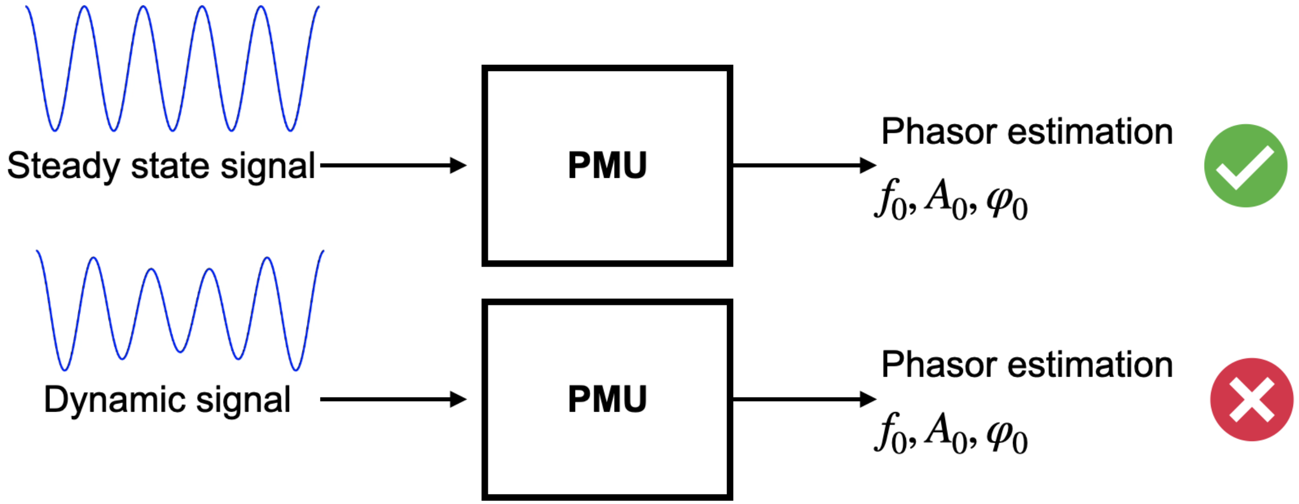
M. Paolone et al., “Fundamentals of Power Systems Modelling in the Presence of Converter-Interfaced Generation (invited paper),” in *2020 Power Systems Computation Conference (PSCC)*, Porto 2020.

Broadband Signal Analysis

Phasor limitations

- Real-world signal dynamics exhibit continuous and broadband spectra.
- Narrowband phasor estimation can yield high errors.





Incorrect model

↓

Incorrect parameters

↓

Inappropriate control actions!

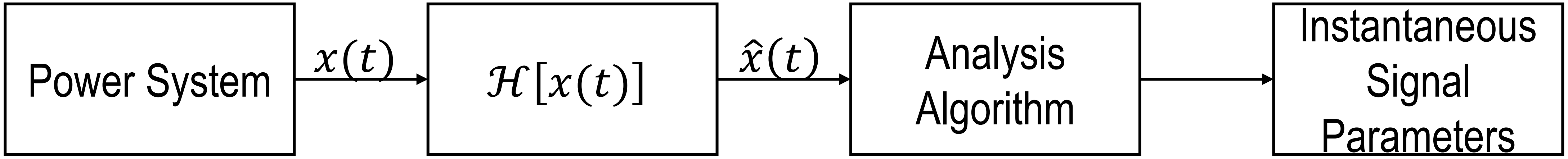
M. Paolone et al., “Fundamentals of Power Systems Modelling in the Presence of Converter-Interfaced Generation (invited paper),” in *2020 Power Systems Computation Conference (PSCC)*, Porto 2020.

Analysis of Broad-Band Signals in Reduced-Inertia Power Systems Using the Hilbert Transform (HT)

As seen, the exact modeling of voltage/current signals in inertia-less power systems may require the use of more sophisticated representations other than phasors.

> ***Proposal:*** *Can we project on a **different functional basis** not based on sinusoids that enables us to reconstruct the whole spectrum and, therefore, capable to **model the power transfer on the whole spectrum**?*

The **Hilbert Transform (HT) and analytic signals** may be the appropriate tools since allows for a seamless parametrization of the generic transients of voltage/current signals.



A. Derviškadić, G. Frigo and M. Paolone, "Beyond Phasors: Modeling of Power System Signals Using the Hilbert Transform," in IEEE Transactions on Power Systems, vol. 35, no. 4, pp. 2971-2980, July 2020.

A. Karpilow, A. Derviškadić, G. Frigo and M. Paolone, "Characterization of Non-Stationary Signals in Electric Grids: A Functional Dictionary Approach," in IEEE Transactions on Power Systems, vol. 37, no. 2, pp. 1126-1138, March 2022.

Broadband Signal Analysis

Hilbert Transform

General dynamic signal model:

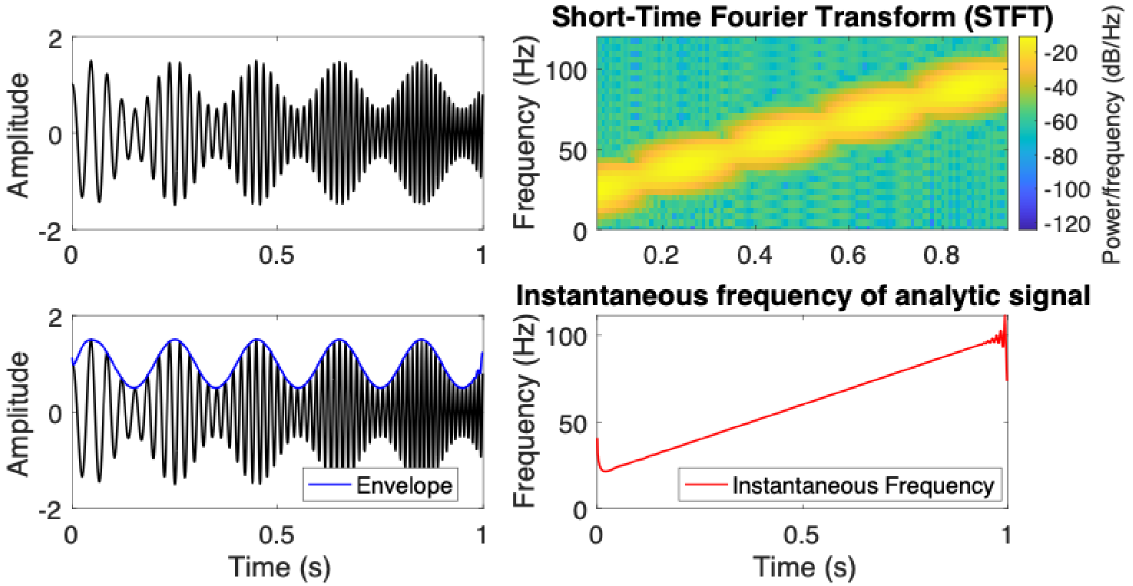
$$x(t) = \left(1 + g_A(t)\right)\cos\left(2\pi f_0 t + g_\phi(t)\right)$$

Amplitude variation — Phase variation

Through the Hilbert transform ($\mathcal{H}$), we may define the analytic signal:

$$\tilde{x}(t) = x(t) + j \cdot \mathcal{H}[x(t)]$$

$$\tilde{x}(t) = \left(1 + g_A(t)\right)e^{j(2\pi f_0 t + g_\phi(t))}$$



Comparison of STFT and analytic signal for waveform with amplitude modulation (5 Hz, 50%) and a frequency ramp (80 Hz/s)

Functional Basis Analysis (FBA): apply user-engineered dictionaries of common signal dynamics to characterize broadband waveforms

A. Karpilow, A. Derviškadić, G. Frigo and M. Paolone, "Characterization of Non-Stationary Signals in Electric Grids: A Functional Dictionary Approach," in IEEE Transactions on Power Systems, vol. 37, no. 2, pp. 1126-1138, March 2022.

Broadband Signal Analysis

Analytic signal: obs

Bedrosian's theorem:

$$\mathcal{H}[y(t)x(t)] = y(t)\mathcal{H}[x(t)]$$

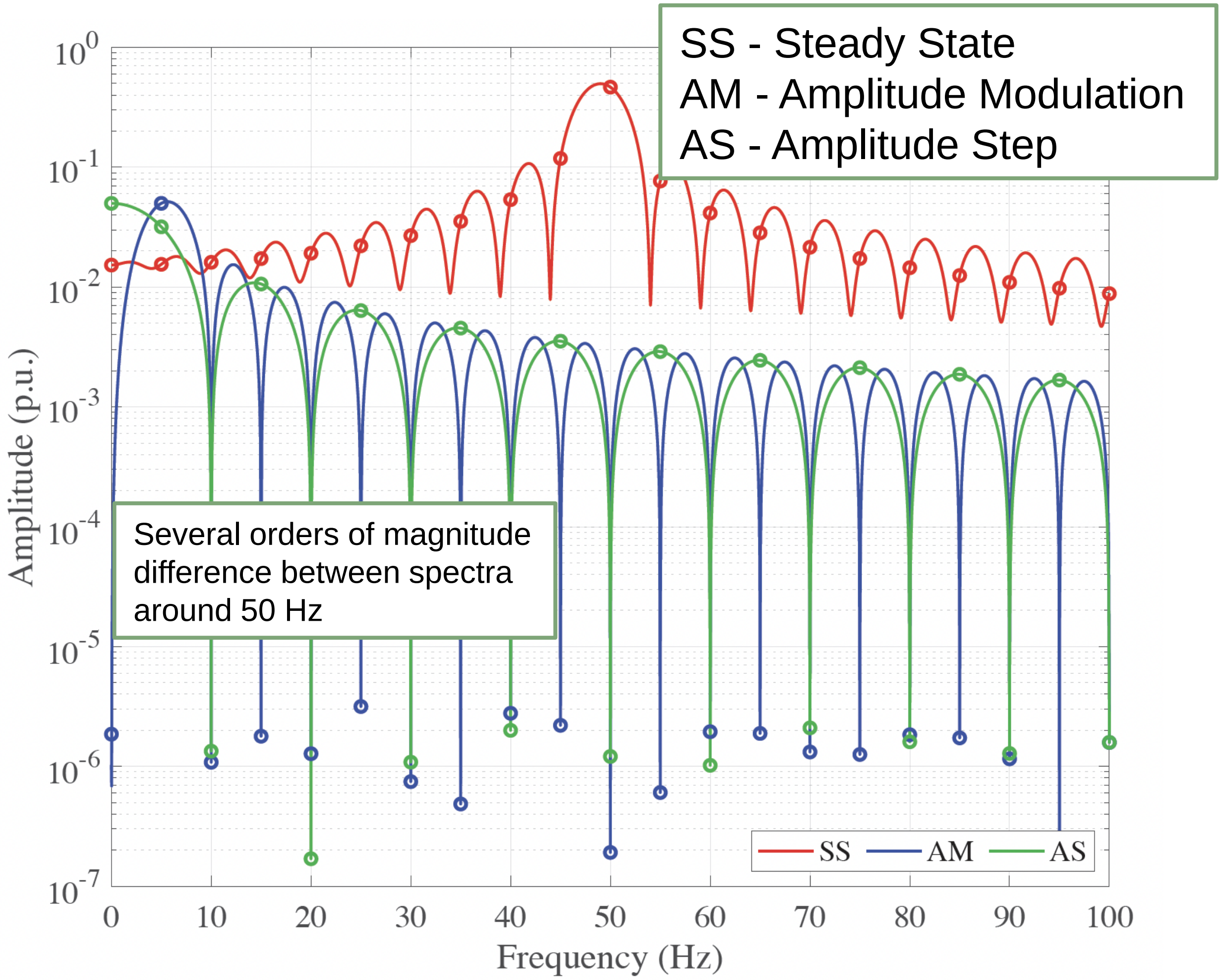
If $x(t)$ and $y(t)$ have non-overlapping spectrum and $y(t)$ is the lower frequency signal.

$$x(t) = (1 + g_A(t))\cos(2\pi f_0 t + g_\phi(t)$$

$$\downarrow$$

$$\tilde{x}(t) = (1 + g_A(t))e^{j(2\pi f_0 t + g_\phi(t))}$$

Holds for slow amplitude and phase modulations but violated for steps.



DFT of SS ($f_0 = 50\ Hz$), AM ($f_{AM} = 5\ Hz$) and AS ($t_{AS} = \frac{T_w}{2}$, $a_{AS} = 0.1\ p.u.$). 200 ms window and Fs = 10 kHz

Functional Basis Analysis

Envelope Analysis: $x_A(t) = |\tilde{x}(t)|$

Amplitude Modulation:

$$x_{AM}(t) = A_0(1 + a_{AM}\sin(2\pi f_{AM} t) + \varphi_{AM})$$
$$\equiv$$
$$x_{AM}(t) = \gamma_0 + \gamma_1 \sin(2\pi f_{AM} t) + \gamma_2 \cos(2\pi f_{AM} t)$$

Least Squares & Golden Section Search (GSS/LS_{AM})

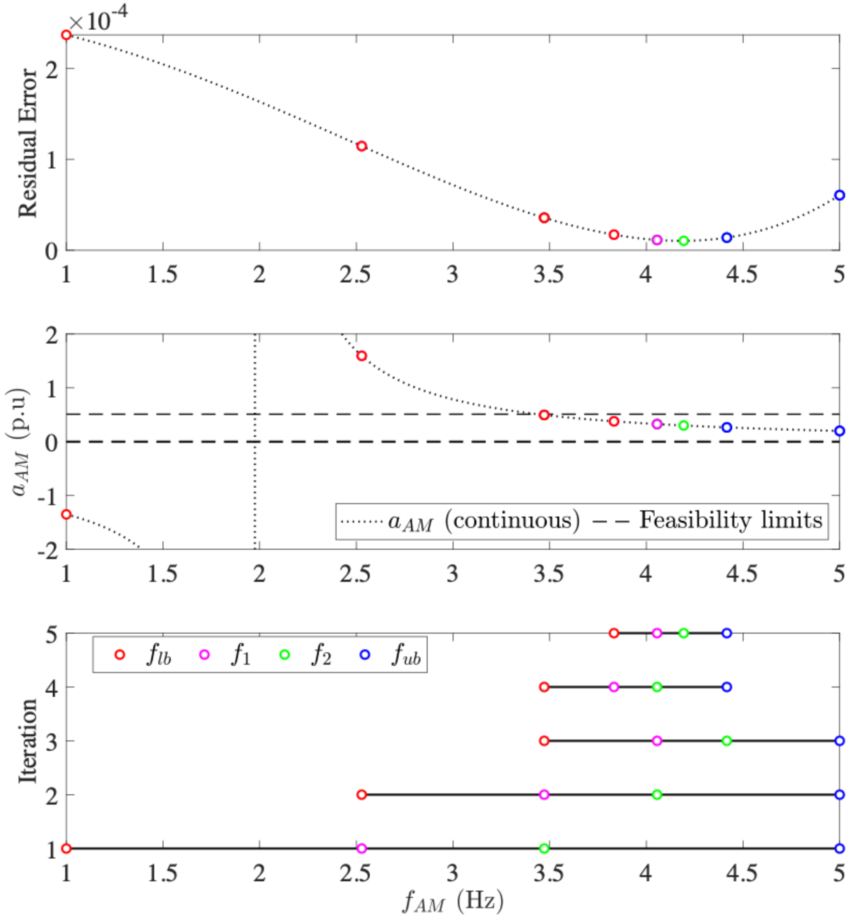
$$\min_{\boldsymbol{\gamma}} \left|\left|\boldsymbol{D}_{AM}(f_{AM})\boldsymbol{\gamma} - \boldsymbol{x}_A\right|\right|_2$$

$$\boldsymbol{\gamma} = [\gamma_0 \quad \gamma_1 \quad \gamma_2]^T, \boldsymbol{x}_A = [x_A(t_0) \quad \dots \quad x_A(t_{N-1})]^T$$

$$\boldsymbol{D}_{AM}(f_{AM}) = \begin{bmatrix} 1 & \sin(2\pi f_{AM} t_0) & \cos(2\pi f_{AM} t_0) \\ \vdots & \vdots & \vdots \\ 1 & \sin(2\pi f_{AM} t_{L-1}) & \cos(2\pi f_{AM} t_{L-1}) \end{bmatrix}$$

$$\gamma^*(f_{AM}) = \left(\boldsymbol{D}_{AM}^T(f_{AM})\boldsymbol{D}_{AM}(f_{AM})\right)^{-1} \boldsymbol{D}_{AM}(f_{AM})^T \boldsymbol{x}_A$$

Golden Section Search (GSS) for optimal f_{AM}



Objective Function

Feasibility Check
$0 < a_{AM} \leq 0.5,$
$A_0 > 0$

GSS Iterations

Functional Basis Analysis

Argument Analysis: $x_\varphi(t) = \angle\tilde{x}(t)$

Phase Modulation:

$$x_{PM}(t) = \varphi_0 + 2\pi f_0 t + a_{PM}\sin(2\pi f_{AM} t + \varphi_{PM}))$$

$$\equiv$$

$$x_{PM}(t) = \nu_0 + \nu_1 t + \nu_2 \sin(2\pi f_{PM} t) + \nu_3 \cos(2\pi f_{PM} t)$$

Least Squares & Golden Section Search: GSS/LS_{PM}

$$\min_{\boldsymbol{\gamma}} \left|\left|\boldsymbol{D}_{PM}(f_{PM})\boldsymbol{\nu} - \boldsymbol{x}_\varphi\right|\right|_2$$

$$\boldsymbol{\gamma} = [\nu_0 \quad \nu_1 \quad \nu_2 \quad \nu_3]^T, \boldsymbol{x}_\varphi = [x_\varphi(t_0) \quad \dots \quad x_\varphi(t_{L-1})]^T$$

$$\boldsymbol{D}_{PM}(f_{PM}) = \begin{bmatrix} 1 & \sin(2\pi f_{PM} t_0) & \cos(2\pi f_{PM} t_0) \\ \vdots & \vdots & \vdots \\ 1 & \sin(2\pi f_{PM} t_{L-1}) & \cos(2\pi f_{PM} t_{L-1}) \end{bmatrix}$$

$$\boldsymbol{\nu}^*(f_{PM}) = \left(\boldsymbol{D}_{PM}^T(f_{PM})\boldsymbol{D}_{PM}(f_{PM})\right)^{-1}\boldsymbol{D}_{PM}(f_{PM})^T\boldsymbol{x}_{\boldsymbol{\varphi}}$$

Frequency Ramp:

$$x_{FR}(t) = \varphi_0 + 2\pi f_0 t + R\pi t^2$$

$$\equiv$$

$$x_{FR}(t) = \beta_0 + \beta_1 t + \beta_2 \mathrm{t}^2$$

Least Squares: LS_{FR}

$$\min_{\boldsymbol{\gamma}} \left|\left|\boldsymbol{D}_{FR}\boldsymbol{\beta} - \boldsymbol{x}_\varphi\right|\right|_2$$

$$\boldsymbol{\beta} = [\beta_0 \quad \beta_1 \quad \beta_2 \quad]^T$$

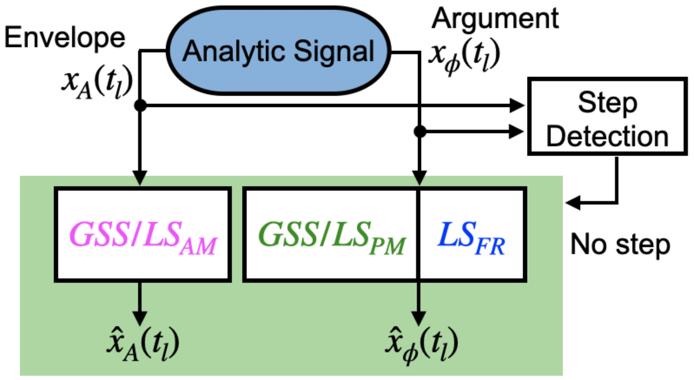
$$\boldsymbol{D}_{FR} = \begin{bmatrix} 1 & t_0 & t_0^2 \\ \vdots & \vdots & \vdots \\ 1 & t_{L-1} & t_{L-1}^2 \end{bmatrix}$$

$$\boldsymbol{\beta}^* = (\boldsymbol{D}_{FR}^T\boldsymbol{D}_{FR})^{-1}\boldsymbol{D}_{FR}^T\boldsymbol{x}_{\boldsymbol{\varphi}}$$

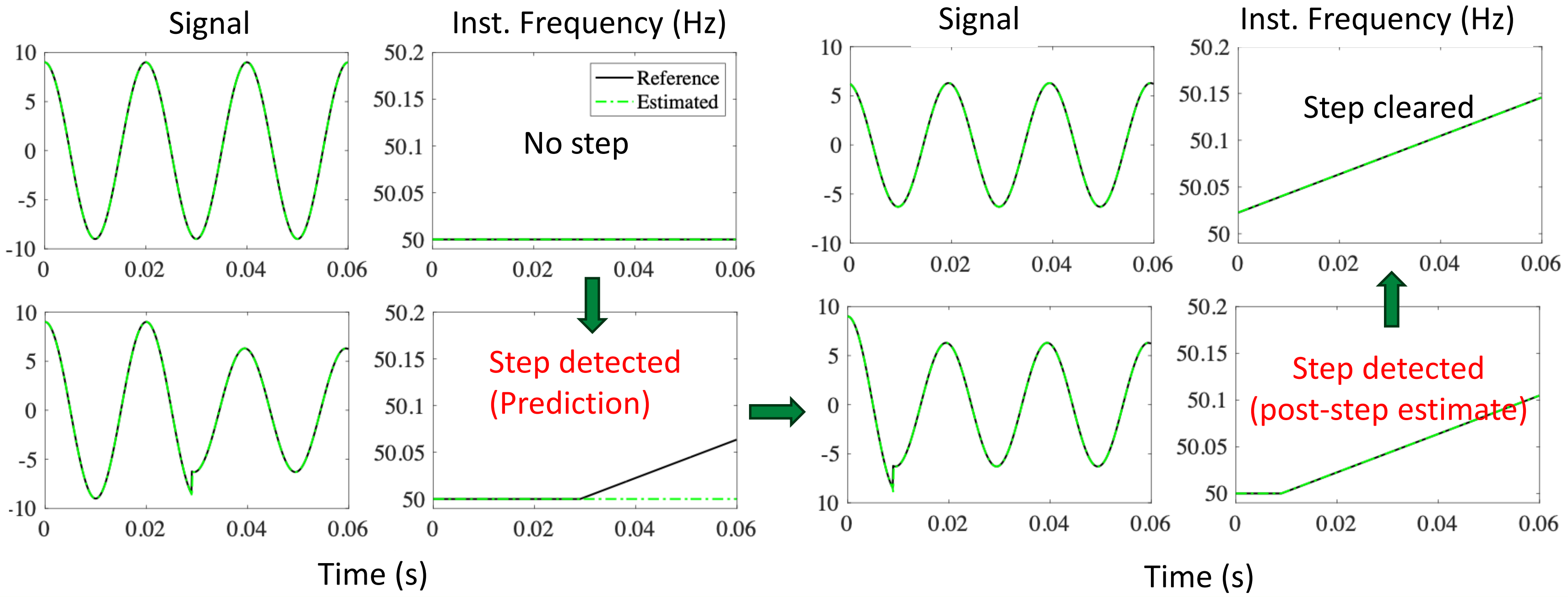
Functional Basis Analysis

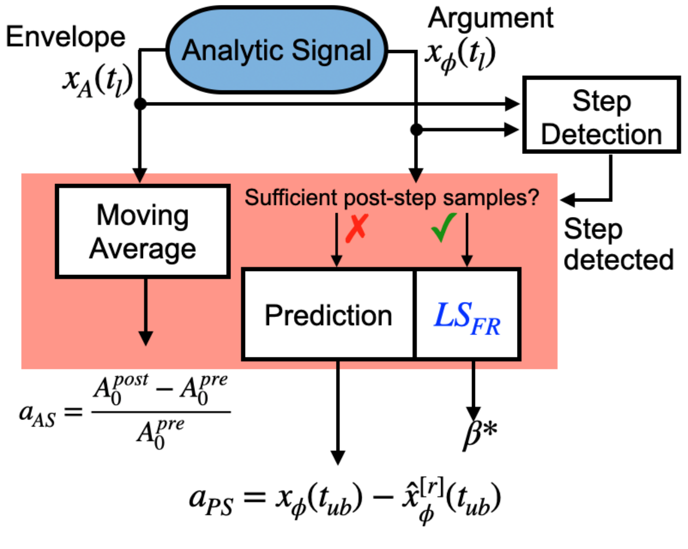
Step Detection

- Thresholds on differential envelope and argument:
  - Amplitude Step: $\Delta x_A(t_l) = x_A(t_l) - x_A(t_{l-1}) \rightarrow |\Delta x_A(t_l) - \Delta \bar{x}_A| > \epsilon_{\Delta A}$
  - Phase Step: $\Delta x_\varphi(t_l) = x_\varphi(t_l) - x_\varphi(t_{l-1}) \rightarrow |\Delta x_\varphi(t_l) - \Delta \bar{x}_\varphi| > \epsilon_{\Delta\varphi}$
- Pre- and post-step states are estimated separately.



FBA when no step is detected





FBA when a step is detected

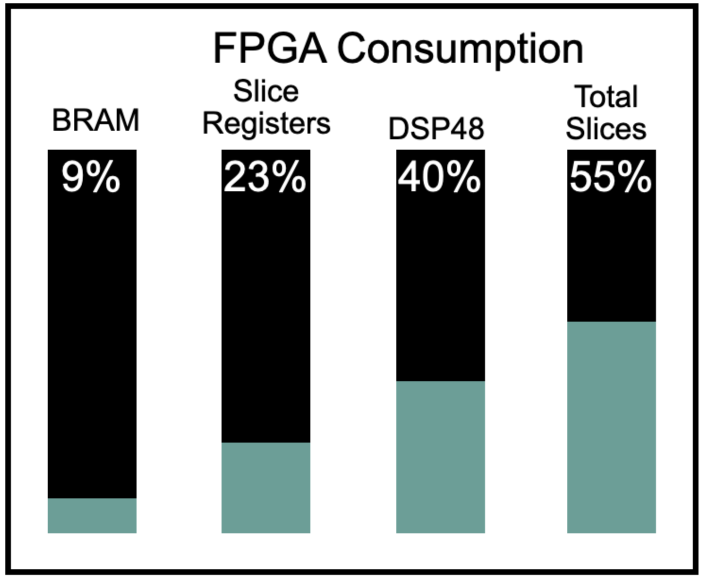
Functional Basis Analysis

Embedded Systems Deployment

- FIR Hilbert filter: low complexity, high performance, high group delay
- Recursive formulation of FR estimation
- Projected to support at least 4 more channels
- Total latency within M Class requirements

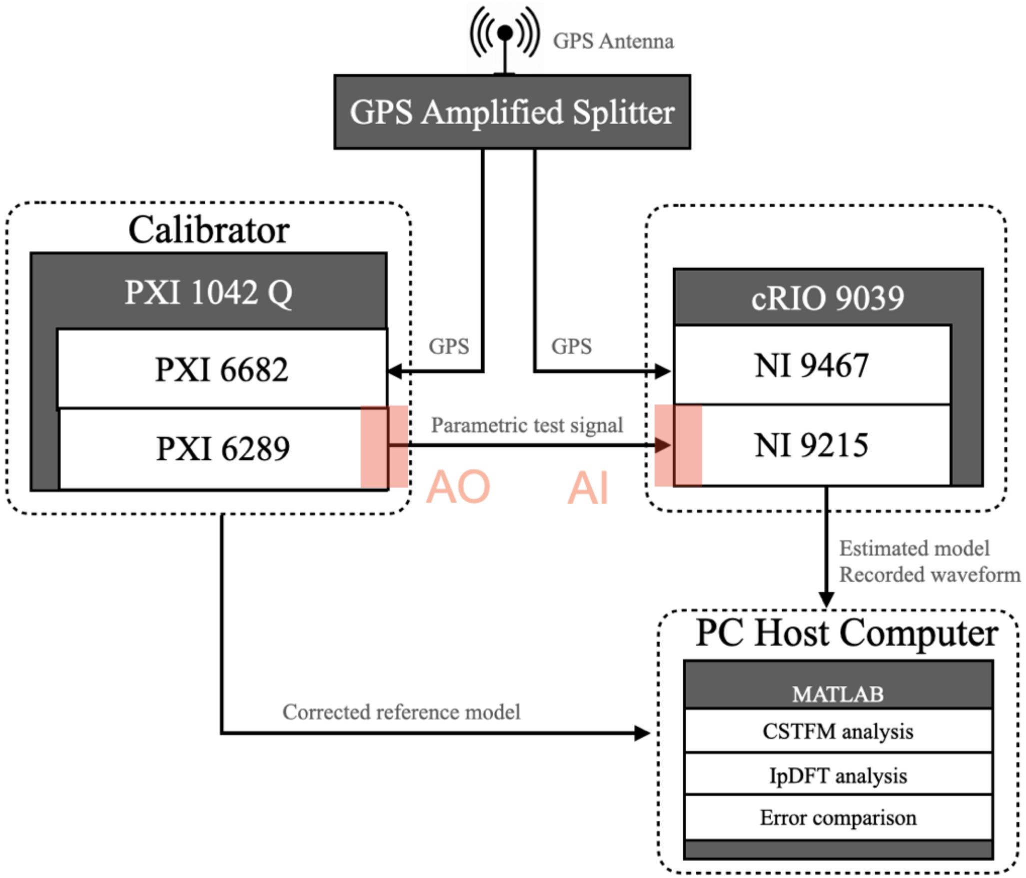
Computation Time	Filter Group Delay	Timestamp delay	Total Latency
0.3 ms	39.9 ms	60 ms/2	70.2 ms

NI cRIO 9039

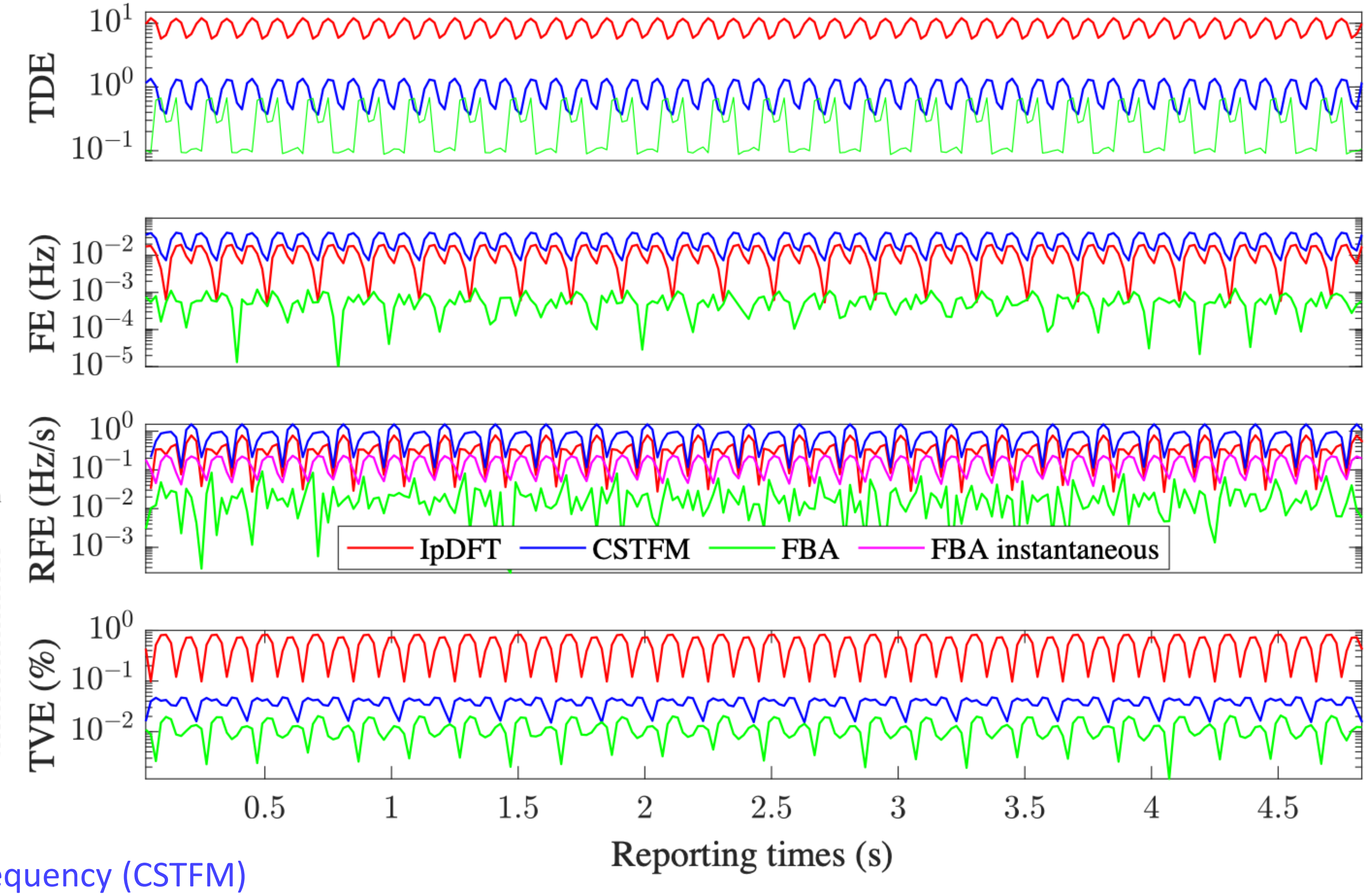


Functional Basis Analysis

Validation



Amplitude and Phase Modulation Test



Static phasor – 3pt, Hann window, iterative IpDFT

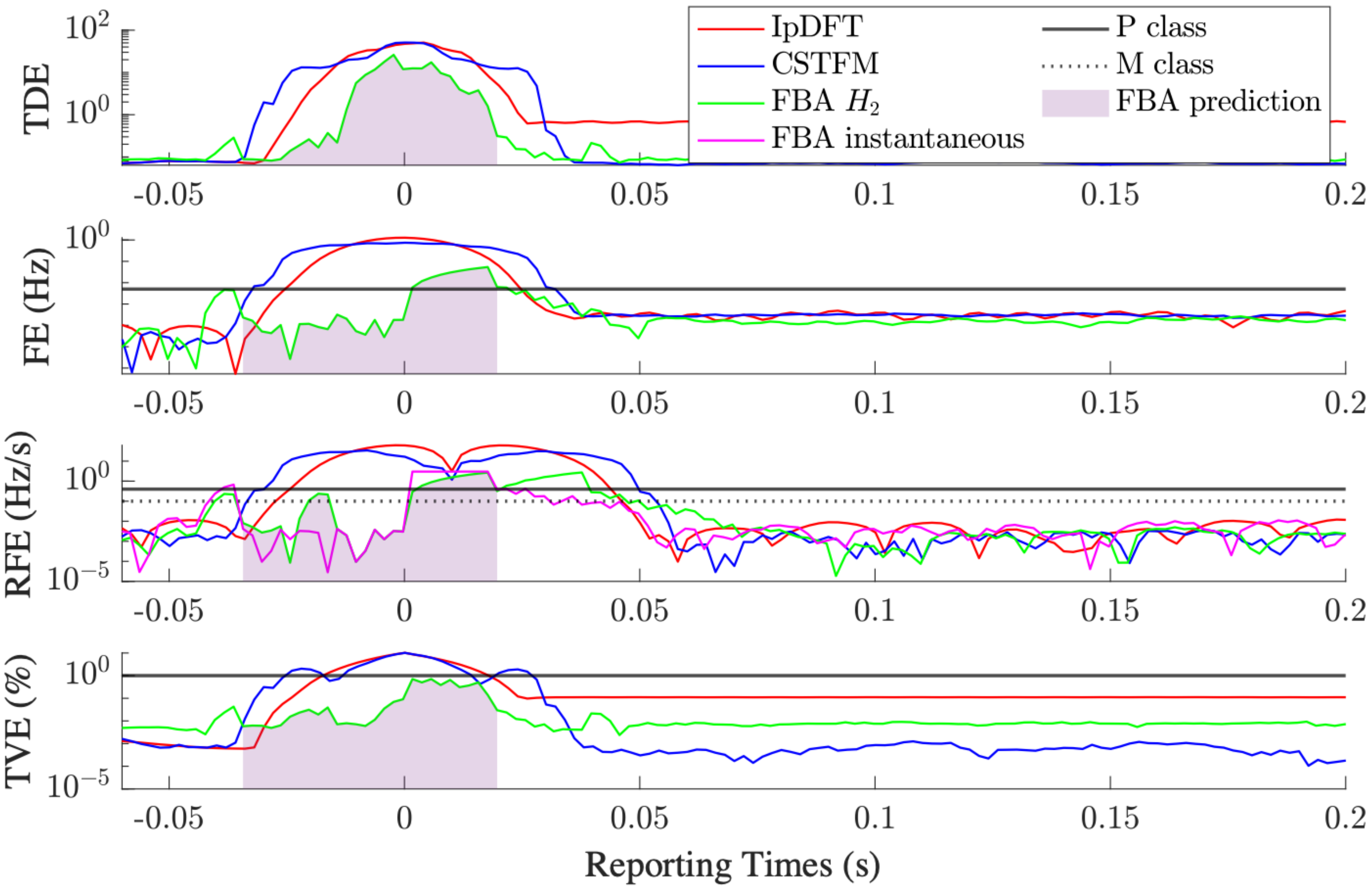
Dynamic phasor – Compressed Sensing Taylor Fourier Multifrequency (CSTFM)

Functional Basis Analysis

Validation

- The FBA detects step and provides interim prediction (shaded)
- A post-step estimation of the instantaneous frequency variation is provided by FBA before the static/dynamic phasor methods can recover

Amplitude/Phase Step Followed by a Frequency Ramp (3 Hz/s)



Conclusions

- Recent events in low-inertia power systems have shown how the use of phasors may lead to large approximations when modelling signals of electrical quantities in reduced-inertia power grids.
- The HT, integrated with the analytical signal representation, may be the appropriate tool for modelling broad-band signals associated to inertia-less power system dynamics.
- The presentation has shown how the functional basis analysis (FBA) allows for the extraction of signal parameters and the identification of common dynamics.
- The FBA method demonstrated improved performance for common signal dynamics when compared to static and dynamic phasor representations.
- The FBA can be used for the compression of time-domain signals and considered as an alternative to point-on-wave data stream.