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Measuring power grid signals in the presence of reduced system inertia

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EPFL Distributed Electrical Systems Lab

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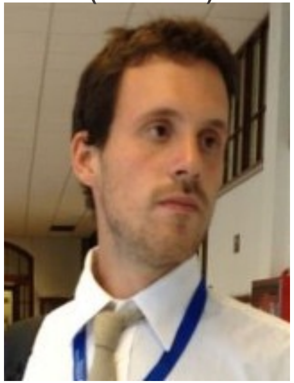

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The context

- Power systems are large, nonlinear, multi-time-scale, discrete/continuous complex systems.
- Usually analyzed for specific problems with relatively simplified models under appropriate assumptions, e.g.
  - Dynamics (electromechanical) dominated by the response of synchronous machines → use of time-varying phasors.
  - Electromagnetic transient models when time-varying phasors are not appropriate.
- The increased penetration of converter-interfaced generation (CIG) and HVDC in power systems challenges the above decomposition of power system studies into phasor-based vs electromagnetic-transient-based.
- New needs in dynamics, control and stability studies of systems with significant penetration of CIG.

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.

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The context

Event of September 28, 2016, Australia

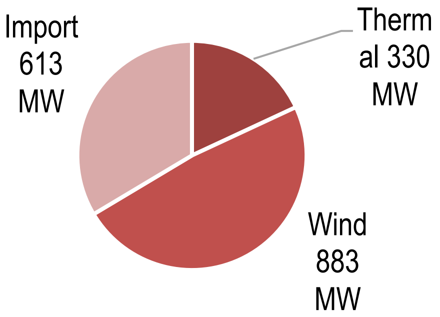
Multiple tornadoes in South Australia (SA) tripped multiple 275 kV transmission circuits, and resulted in multiple faults in quick succession.

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

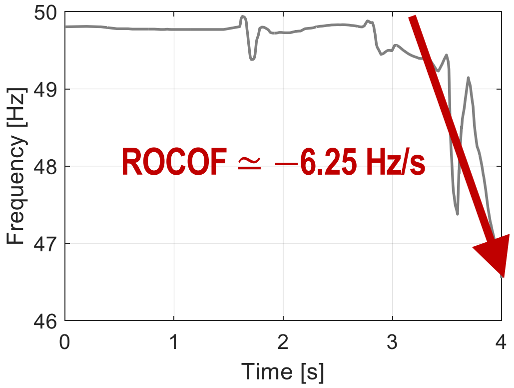
The reduction in wind farm output was compensated by an increase in power imported from Victoria. However, the import reached a level that tripped the interconnector on loss of synchronism protection.

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.

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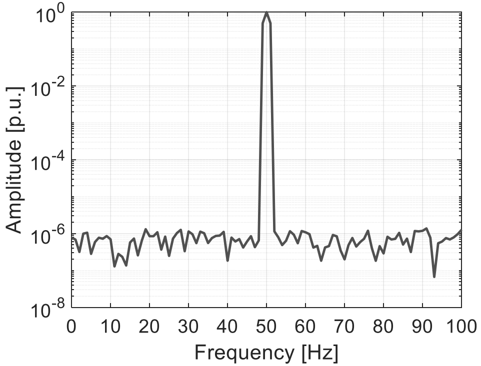
Adequacy of signal processing techniques

Steady-state

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

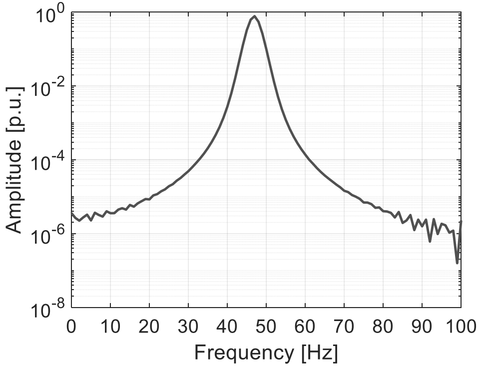


Energy of the signal in [48, 52] Hz 99.X%

Narrow-band signals: discrete spectrum with energy concentrated around a single, or finite and discrete set, of sinusoidal components.

Transient with ROCOF R=-6.25 Hz/s

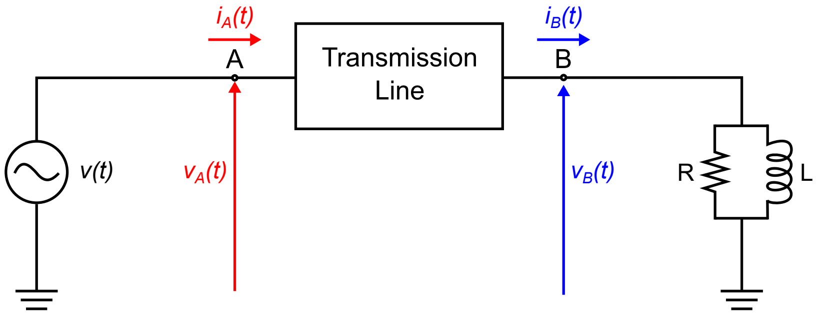
$$v(t) = A \cdot cos(2\pi(f - Rt)t)$$



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

Broad-band signal: continuous spectrum of generic bandwidth where the spectrum of the signal (and its energy) cannot be reconstructed by a finite and discrete set of sinusoidal components.

Adequacy of signal processing techniques



- Numerical experiment carried out using the EMTP-RV
- Voltage generator: 380 kV (ph-ph), generic time-dependent voltage source
- Line: 100 km frequency-dependent model
- Load: R-L parallel equivalent ➔ 400 MW, $cos\varphi$ 0.9
- $v_A(t)$ negative frequency ramp characterized by RoCoF of -5 Hz/s (starting from 50 Hz)
- $v_A(t)$ amplitude modulation characterized by 10% depth and 5 Hz modulating frequency

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.

Adequacy of signal processing techniques

- Phasor analysis based on IEC Std. 61000-4-7, sliding window of 200 ms.

$p(t) = \sum_{abc} v(t) \cdot i(t)$	True instantaneous power
for $x(t) = \{v(t), i(t)\}_{abc}$	
$\quad x(t) = x(t) + \mathcal{N}(t)$	Noise adding, SNR = 80 dB
$\quad$ **for** $t = 0 \rightarrow end, \Delta t = 200ms, \Delta f = 5Hz$	
$\quad\quad X(k) = \mathcal{F}[x(t) \cdot w(t)]$	Hanning window, $\mathcal{F} \approx$ DFT
$\quad\quad \{\tilde{f}(t), \tilde{A}(t), \tilde{\varphi}(t)\} = IpDFT[X(k)]$	Estimate of the phasor params
$\quad\quad \tilde{x}_{\mathcal{F}}(t) = \tilde{A}(t)\cos(2\pi\tilde{f}(t)\Delta t/2 + \tilde{\varphi}(t))$	Reconstruct the time-domain signal
$\quad$ **end for**	
end for	
$\tilde{p}_{\mathcal{F}}(t) = \sum_{abc} \tilde{v}_{\mathcal{F}}(t) \cdot \tilde{i}_{\mathcal{F}}(t)$	Instantaneous power of the reconstructed signals
$\Delta p_{\mathcal{F}}(t) = \tilde{p}_{\mathcal{F}}(t) - p(t)$	Power error

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.

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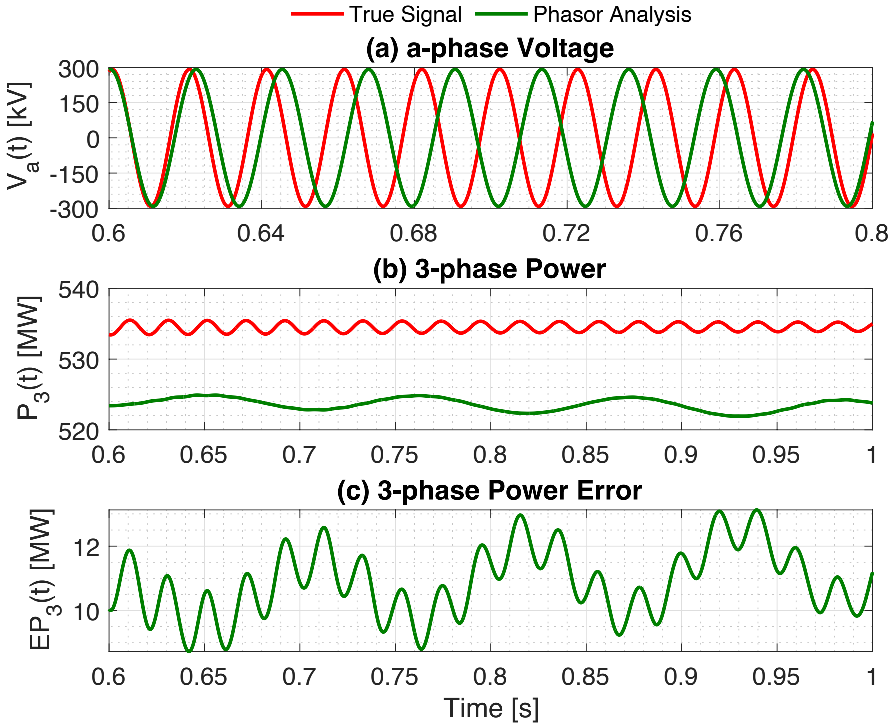
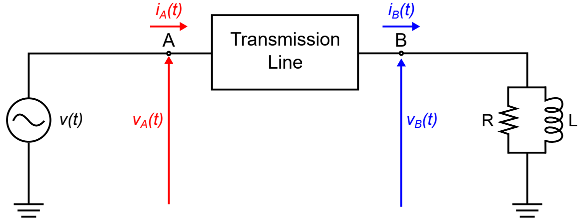
Adequacy of signal processing techniques

Frequency ramp of -5 Hz/s applied to $v_A(t)$





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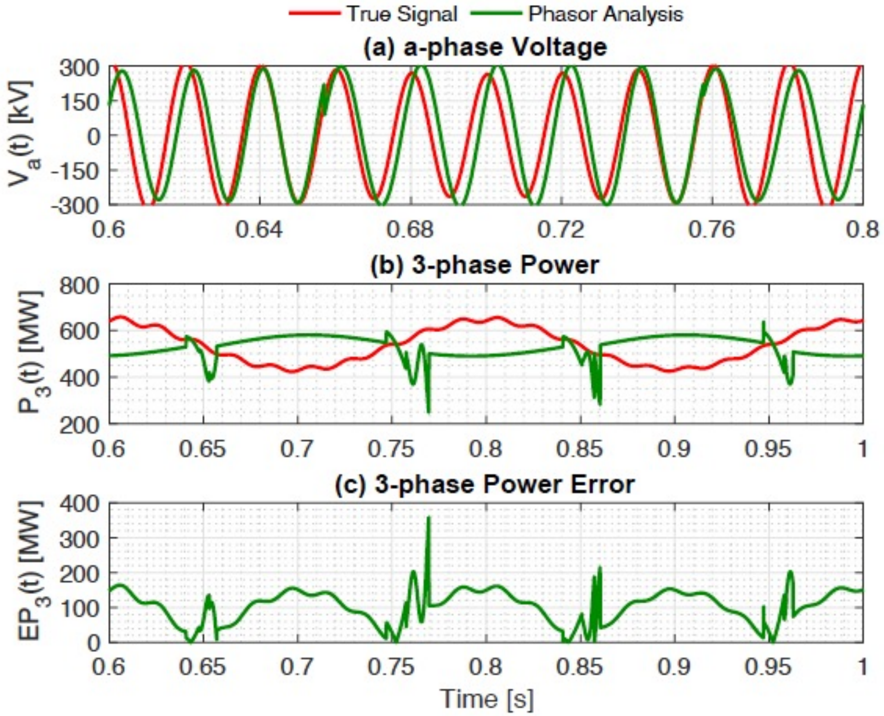
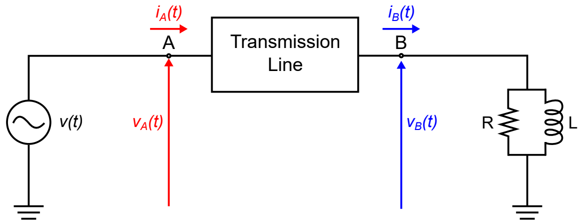
Adequacy of signal processing techniques

10% amplitude modulation with modulating frequency of 5 Hzs applied to $v_A(t)$





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Possible solutions

To overcome the **limitations of traditional phasor analysis**, two possible approaches:

- **Dynamic phasor analysis**

  Dynamic phasors have been introduced as an **extension of the phasor concept**, where **fundamental parameter time-derivatives** are included in the signal model.

  Enhanced signal models allow for more accurate reconstruction of time-varying parameters and **soften the stationarity constraint. However, it is not possible to dissociate dynamic phasor from DFT-based analysis, and they are likely to face similar model inconsistency issues.**

- **Functional basis analysis**

  information theory provides several **transformations and projection bases other than simple DFT** for the analysis of time-varying or continuous spectrum signals.

Dynamic phasors: pros & cons

- **Outperform stationary phasors** in dynamic conditions.
- Prove to be **compliant with IEEE Std requirements.**
- **Still rely on narrow-band approximations** of signals and **cannot represent** in a complete way signals characterized by a **continuous spectrum** (see comparison with Functional Basis Analysis presented next).

→NEED FOR ALTERNATIVE TRANSFORMATIONS

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

- As seen at the beginning of the tutorial, the exact modeling of 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)** may be the appropriate tool since its use results into negligible errors in the reconstruction of the spectral power transfer in case of extreme power systems transients

Power System $\xrightarrow{x(t)}$ $\mathcal{H}[x(t)]$ $\xrightarrow{\hat{x}(t)}$ Analysis Algorithm $\rightarrow$ Instantaneous Signal Parameters

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Power Systems Transients Using the HT

Given a generic time varying real signal $x(t)$, its HT is defined as:

$$\tilde{x}(t) = \mathcal{H}[x(t)] = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau}\, d\tau$$

being P the Cauchy principal value.

The real signal $x(t)$ and its HT form the so-called ***analytic signal***:

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

About the Cauchy principal value: it is used to assign a value to the integral $\int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau}\, d\tau$ which would be undefined when the denominator is null.

The Cauchy p.v. is defined according to the following rule (being $f(x)$ singular at the finite number b):

$$p.v. = \lim_{\epsilon \to 0^+} \left[\int_{a}^{b-\epsilon} f(x)dx + \int_{b+\epsilon}^{c} f(x)dx \right]$$

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HT applied to Power System Transients

- Amplitude Modulation ➔ inter-area oscillations between large system regions

$$x(t) = A\big(1 + k_a cos(2\pi f_a t)\big)cos(2\pi f_0 t + \varphi_0)$$

FT

$$\mathcal{F}[x(t)] =$$
$$= \frac{A}{2} \cdot [\delta(f - f_0)e^{j\varphi_0} + \delta(f + f_0)e^{-j\varphi_0} + \frac{k_a}{2}$$
$$\cdot \big[\delta(f - (f_0 + f_a))e^{j\varphi_0} + \delta(f + (f_0 + f_a))e^{-j\varphi_0} + \delta(f - (f_0 - f_a))e^{j\varphi_0} + \delta(f + (f_0 - f_a))e^{-j\varphi_0}\big]]$$

HT

$$\boldsymbol{\hat{x}(t) = A \cdot [\, 1 + k_a cos(2\pi f_a t)] \cdot e^{j(2\pi f_0 t + \varphi_0)}}$$

A. Derviškadić, G. Frigo and M. Paolone, "Beyond Phasors: Modeling of Power System Signals Using the Hilbert Transform," *in IEEE Transactions on Power Systems*.

HT applied to Power System Transients

- Frequency Ramp ➔ severe system collapse

$$x(t) = A\cos(2\pi f_0 t + \varphi_0 + R\pi t^2)$$

FT

$$\mathcal{F}[x(t)] = \frac{A}{2\sqrt{R}} e^{j\left[\frac{\pi(f-f_0)^2}{R} - \frac{\pi}{4} + \varphi_0\right]} + \frac{A}{2\sqrt{R}} e^{-j\left[\frac{\pi(f+f_0)^2}{R} - \frac{\pi}{4} + \varphi_0\right]}$$

HT

$$\boldsymbol{\hat{x}(t) = Ae^{j(2\pi f_0 t + \varphi_0 + R\pi t^2)}}$$

A. Derviškadić, G. Frigo and M. Paolone, "Beyond Phasors: Modeling of Power System Signals Using the Hilbert Transform," *in IEEE Transactions on Power Systems*.

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HT applied to Power System Measurements

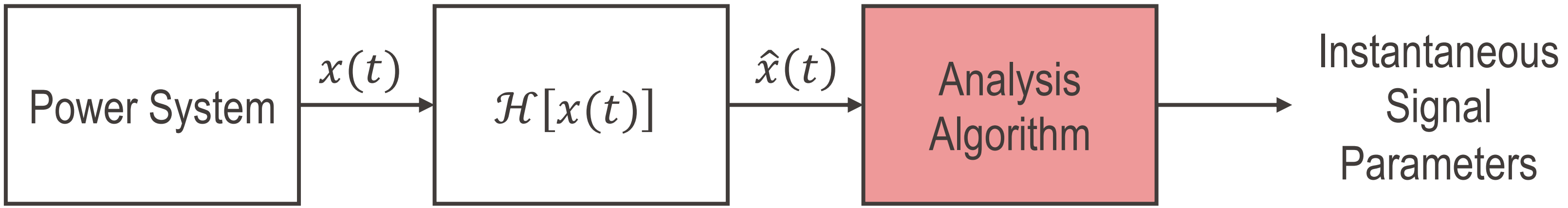
- The derived analytic signals $\hat{x}(t)$ are a **closed-form expression** of the real-valued signals $x(t)$. E.g. Frequency Ramp:

$$x(t) = A\,cos(2\pi f_0 t + \varphi_0 + 2R\pi t^2)$$

$$\hat{x}(t) = A\,e^{j(2\pi f_0 t + \varphi_0 + R\pi t^2)}$$

- The HT may provide an **exact match between the real-valued time-domain signal and its analytic representation**
- If we project the real-valued signal in $x(t)$ over a basis containing the analytic signal in $\hat{x}(t)$, we would obtain a projection coefficient that unequivocally identifies the parameters of the signal in $x(t)$.
- **How do we engineer this functional basis in order to extract signal parameters with a high level of fidelity?**

Characterization of Non-Stationary Signals



Goal:

- Extracting valid signal parameters from measured signals in power grids
- Exploit improved representation of signal dynamics using Hilbert Transform

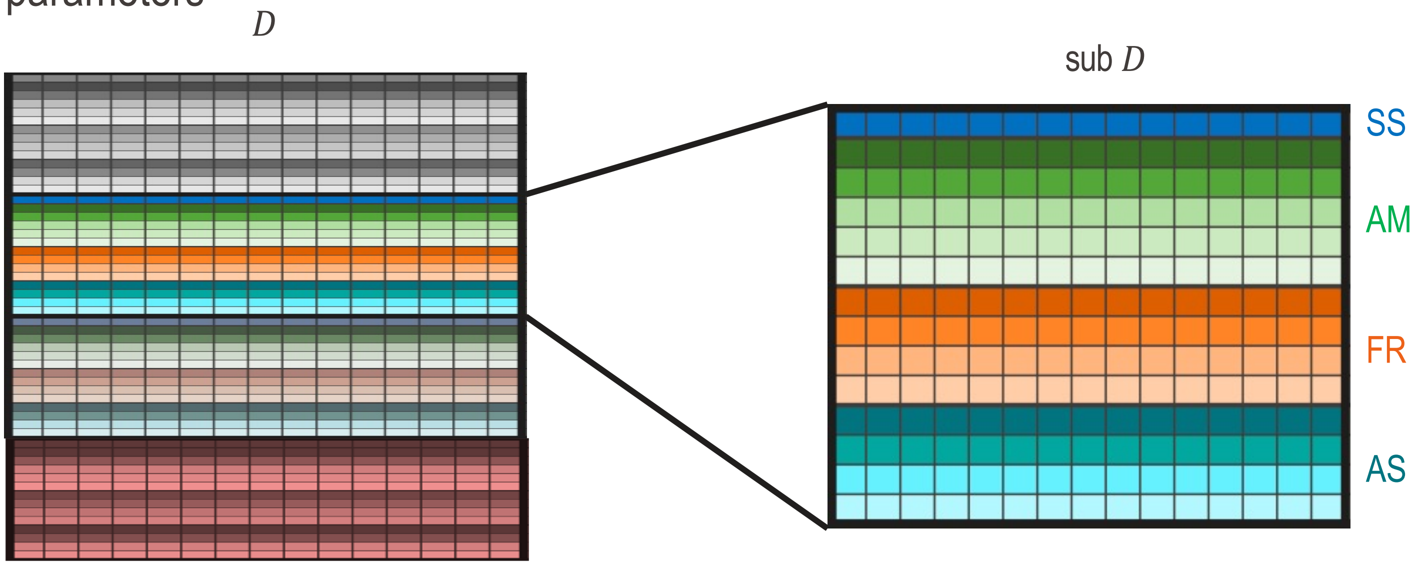
Inspired by:

- **Fourier and Wavelet analysis** which rely on bases of complex exponentials and wavelet kernels
- **Compressed Sensing** which use dictionaries of kernels to reconstruct inputs

→ Create a dictionary based on the Hilbert Transform for instantaneous signal parameter extraction

Dictionary Formulation

- Assumption that the set of possible signal dynamics in the grid is finite
  - Can be spanned by a dictionary of common dynamics (e.g., AM, FR, AS)
  - Dictionary is **user-engineered to capture dynamics of interest**
- Each atom in the dictionary represents a specific function for a defined set of parameters



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Kernel Models

$$d = DFT\left[\left(1 + g_A(t)\right) \cdot e^{j\left(2\pi f_0 t + g_\varphi(t)\right)}\right]$$

The frequency of the fundamental component is limited to a finite bandwidth between 48 and 52 Hz, for each fundamental frequency, the following vectors are included in D:

- A **steady-state (SS)** sinusoid

$$d = DFT\left[e^{j(2\pi f_0 t)}\right]$$

- A sinusoid characterized by an **Amplitude Modulation (AM)**

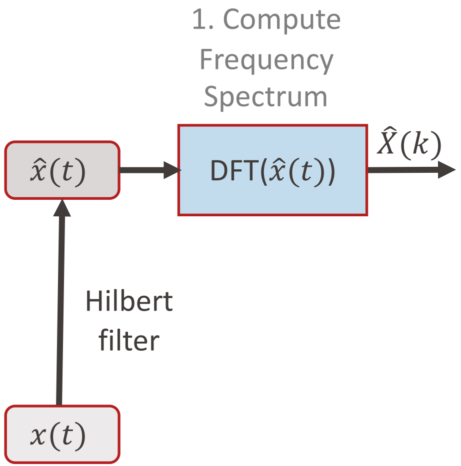
$$d = DFT\left[\left(1 + \boldsymbol{k_m \cos(2\pi f_m t +)}\right) \cdot e^{j(2\pi f_0 t)}\right]$$

k_m = 10%, f_m = [0,5] Hz, $\varphi_m = [0, 2\pi]$ rad

A. Derviškadić, G. Frigo and M. Paolone, "Beyond Phasors: Modeling of Power System Signals Using the Hilbert Transform," *in IEEE Transactions on Power Systems*.

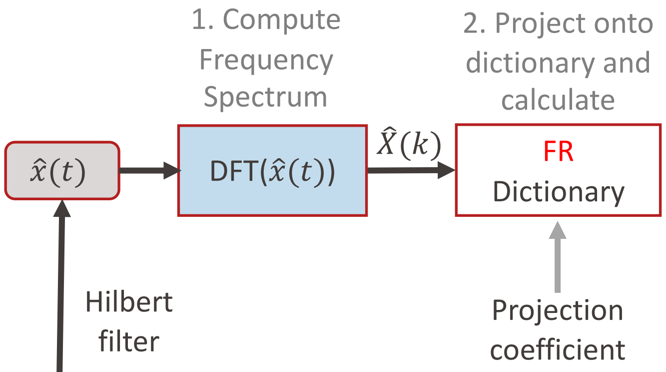
Functional Basis Analysis

- Parameter Identification



Functional Basis Analysis

- Parameter Identification



Residual: $r_{i,j} = \left\| \overbrace{\boldsymbol{d}_{i,j}^{H}\hat{X}}^{c_{i,j}}\boldsymbol{d}_{i,j} - \hat{X} \right\|_2$

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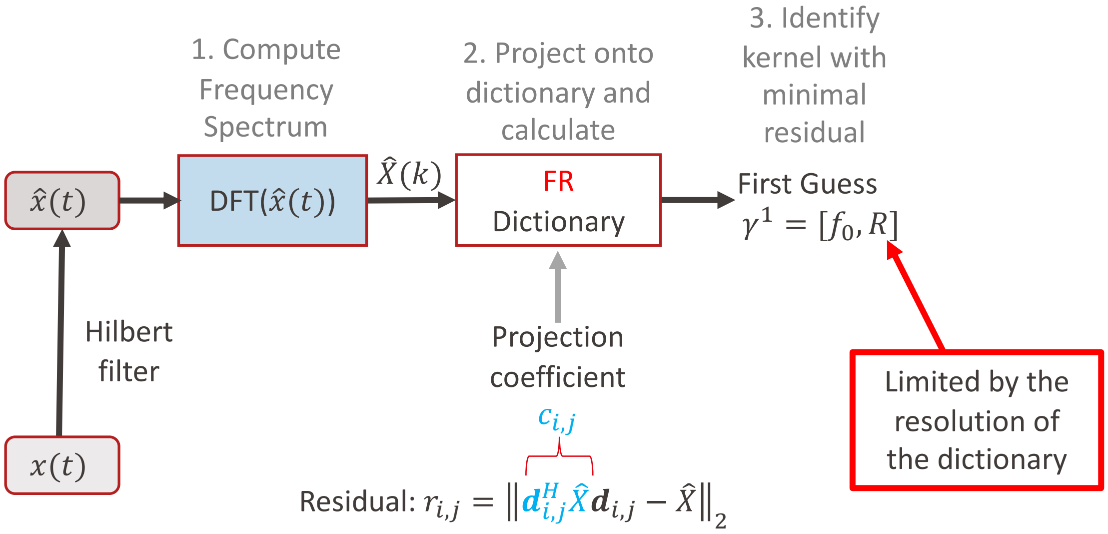
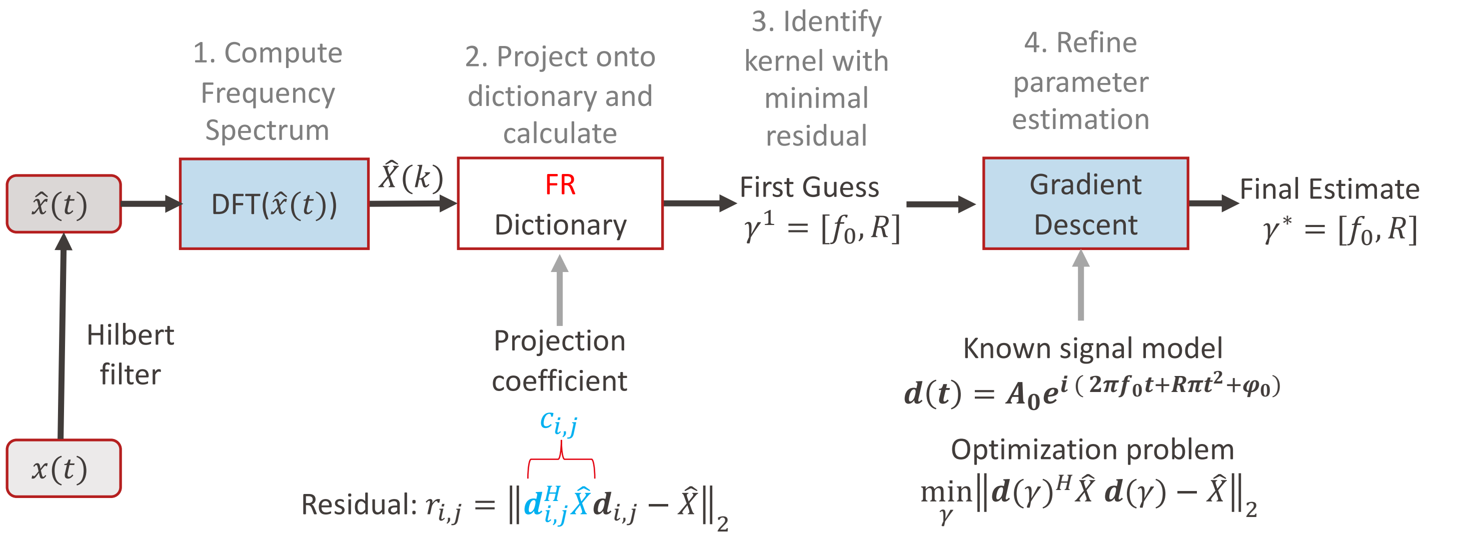
Functional Basis Analysis

- Parameter Identification



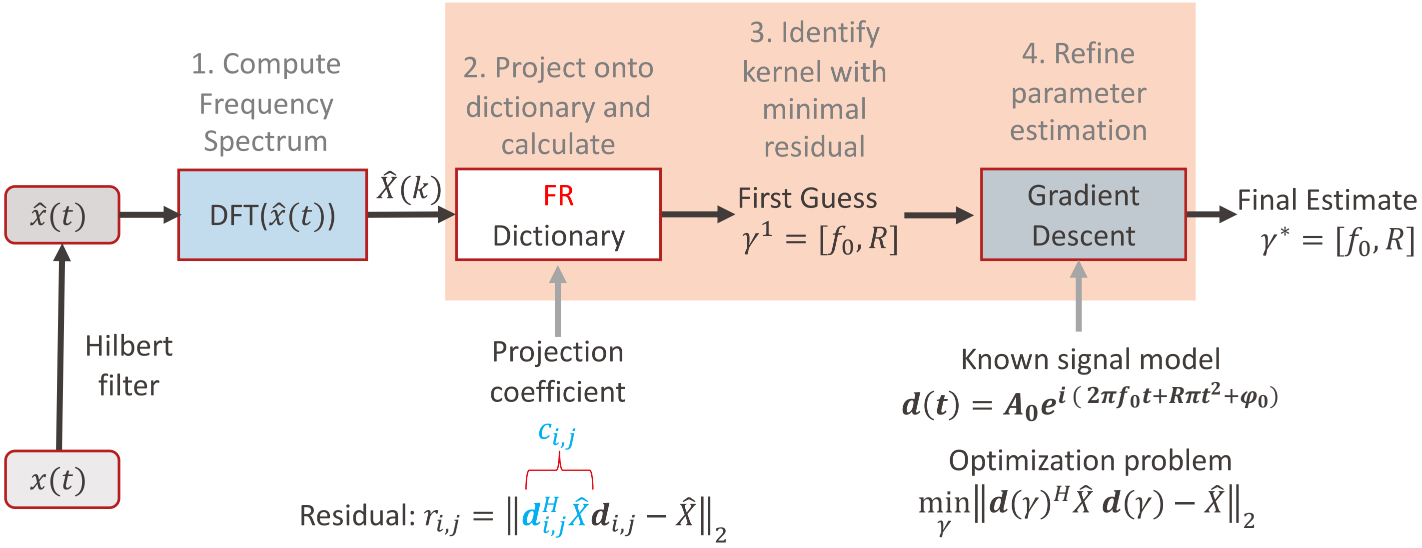
Functional Basis Analysis

- Parameter Identification



Functional Basis Analysis

- Parameter Identification



Performance Evaluation

- Comparison made between:
  1. **FBA**
  2. **Static phasor method**:
     - 2-point iterative IpDFT method (i-IpDFT) [13]
     - Han window and negative spectrum compensation
  3. **Dynamic phasor method:**
     - Compressed Sensing Taylor-Fourier Multifrequency (CSTFM) method [7]
     - 1st and 2nd order derivatives approximated
     - Corrections made to static phasor parameters (f_0, A_0, φ_0)

M. Bertocco, G. Frigo, C. Narduzzi, C. Muscas, and P. A. Pegoraro, “Compressive sensing of a Taylor-Fourier multifrequency model for synchrophasor estimation, ”IEEE Trans. on Instr. and Meas., vol. 64,no. 12, pp. 3274–3283, 2015.

A. Derviskadic, P. Romano, and M. Paolone, “Iterative-interpolated DFT for synchrophasor estimation: A single algorithm for P- and M-class compliant PMUs, ”IEEE Trans. on Instr. and Meas., vol. 67, no. 3, pp.547–558, Mar. 2018

Performance Evaluation

- Metrics:
  - **Time Domain Error (TDE):** residuals of time-domain reconstruction

$$TDE = \frac{\left\| x_{est}(t_n) - x_{ref}(t_n) \right\|_2}{\sum_{n=1}^{L} \left| x_{ref}(t_n) \right|}$$

  - **Frequency Error (FE):** comparing instantaneous frequency at the center of the window [14]

$$FE = \left| f\left(\frac{T_w}{2}\right) - f_{est}\left(\frac{T_w}{2}\right) \right|$$

  - **Parameter Error**: parameter estimation error

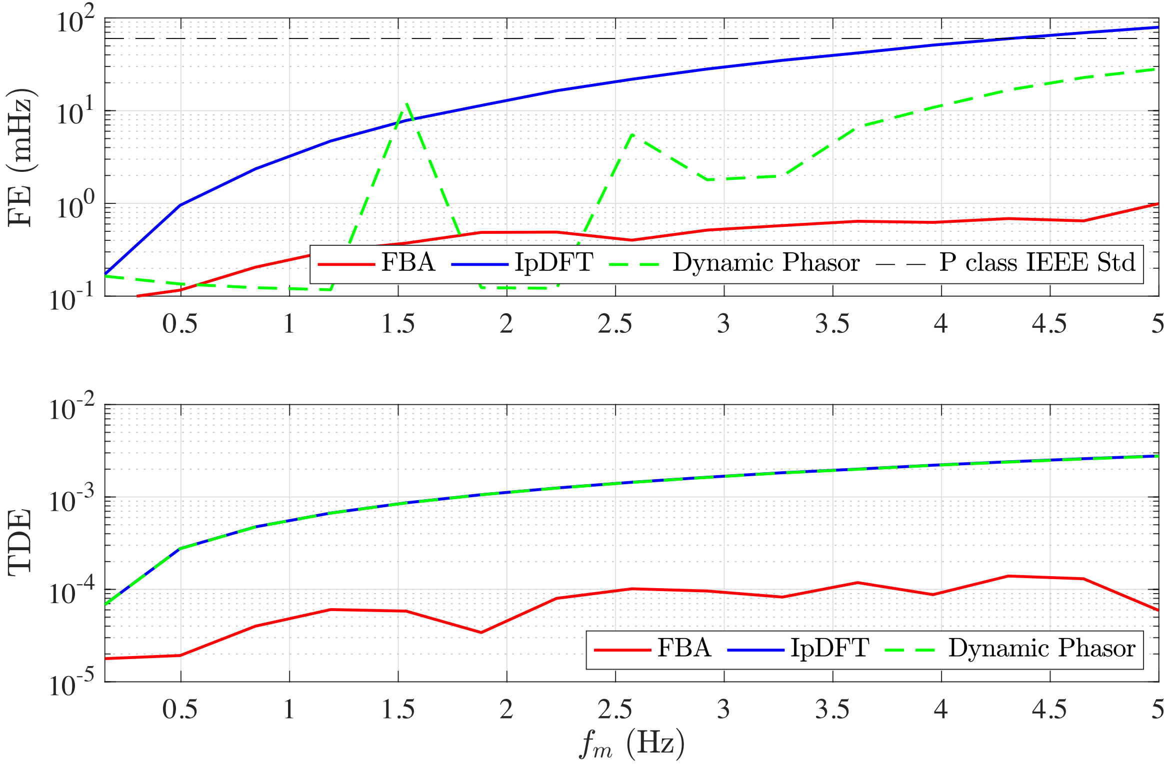
$$e.g., R\ error = |R - R_{est}|$$

- Tests:
  - Synthetic signals created for each signal dynamic case
  - 60 ms sliding window (50 fps)
  - 80 dB Guassian noise
  - Tests based on IEEE C37.118 Standard [14]

IEEE Standard for Synchrophasor Measurements for Power Systems, ”IEEE Std C37.118.1-2011 (Revision of IEEE Std C37.118-2005), pp.1–61, Dec 2011.

Amplitude Modulations

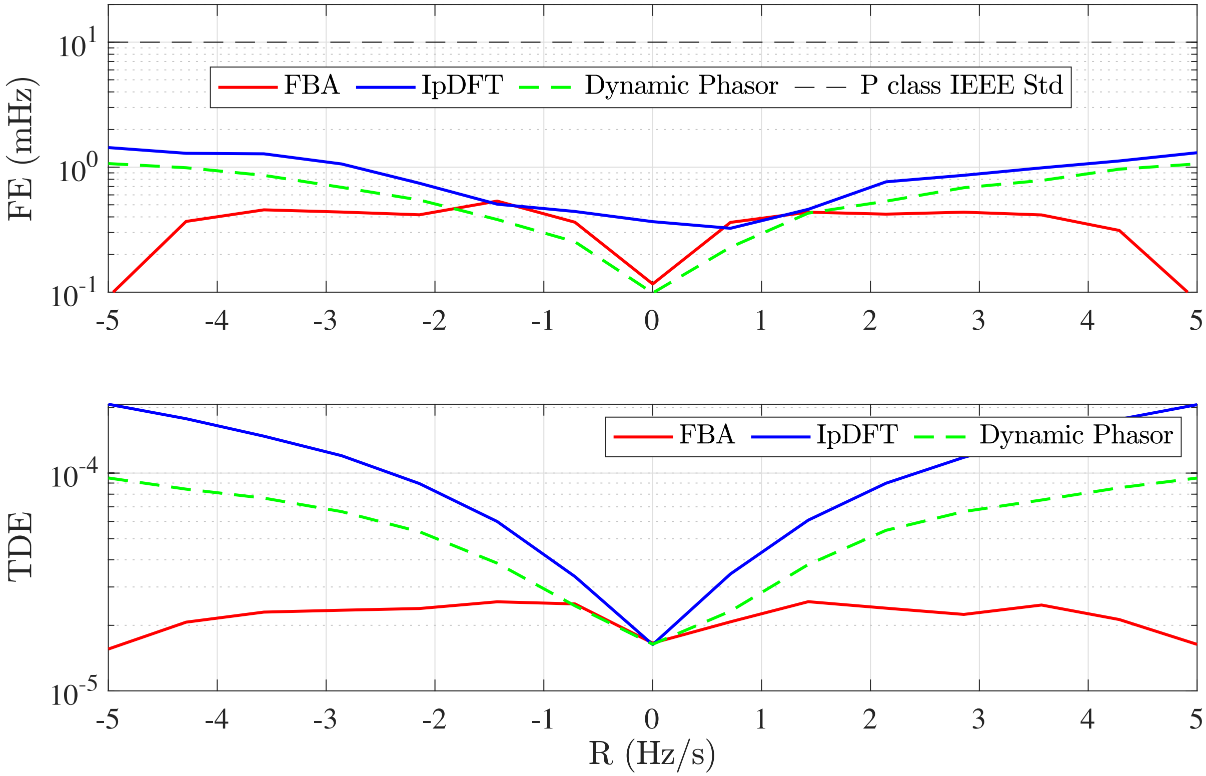
$$f_0 = 50.15\,Hz, k_m = 10\%, f_m = [0.1,5]Hz$$



A. Karpilow, A. Derviskadic, G. Frigo, M. Paolone, "Characterization of Non-Stationary Signals in Electric Grids: a Functional Dictionary Approach" (*in review). IEEE Transactions on Power Systems, 2021.*

Frequency Ramps

$$f_0 = 50.15\ Hz, R = [-5{,}5]Hz/s$$



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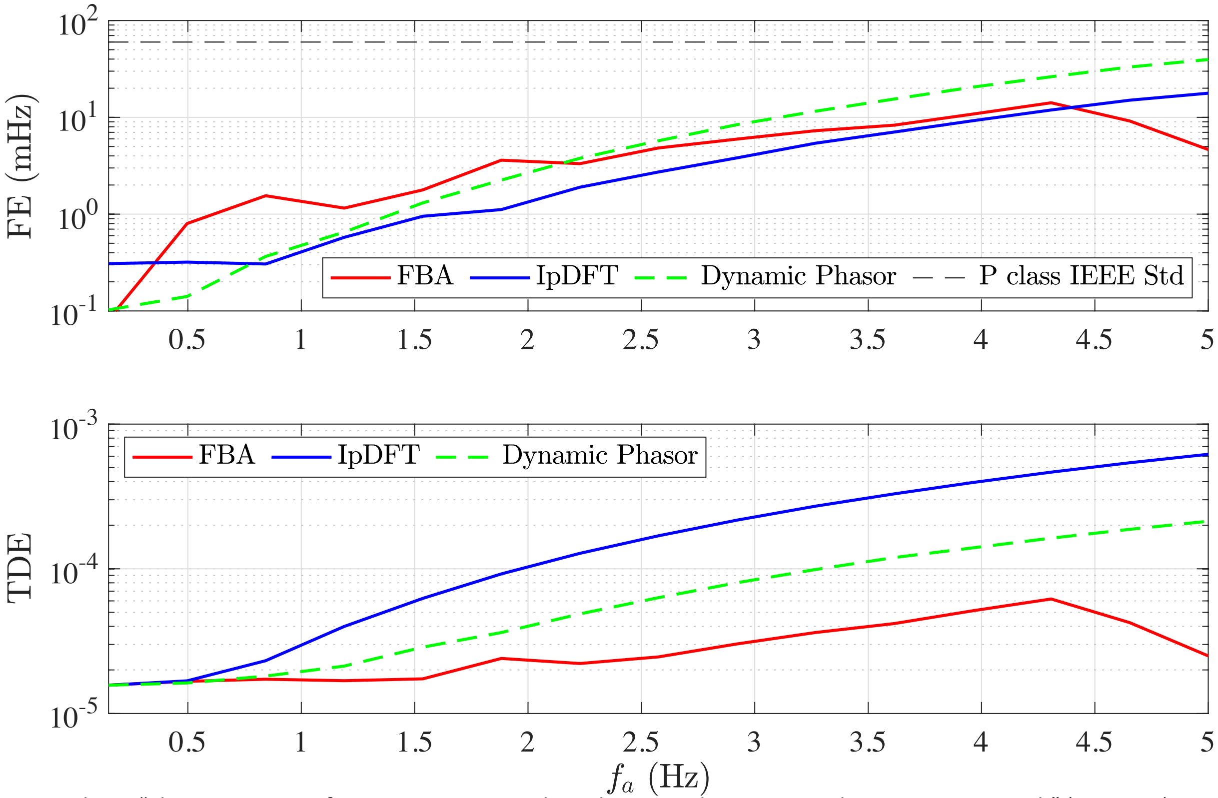
Phase Modulations

$$f_0 = 50.15\ Hz, k_a = 10\%, f_a = [0.1,5]Hz$$



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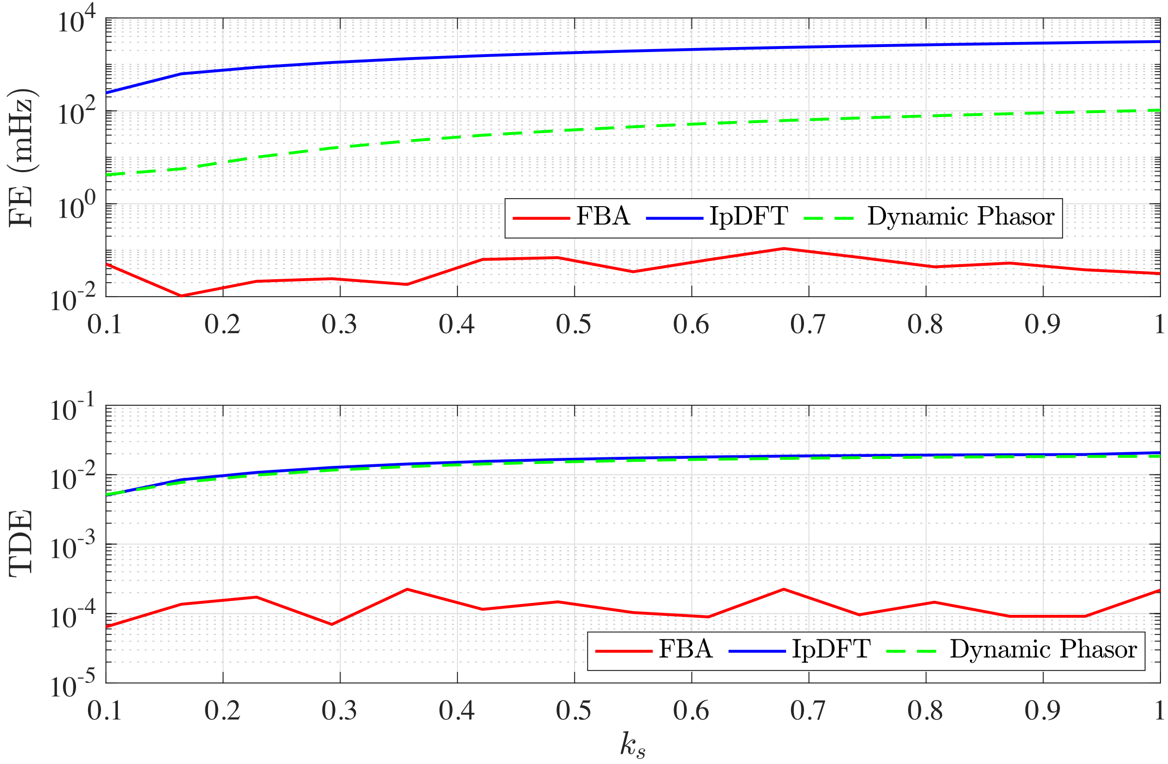
Amplitude Steps

$$f_0 = 50Hz, k_s = [10, 100]\%$$



A. Karpilow, A. Derviskadic, G. Frigo, M. Paolone, "Characterization of Non-Stationary Signals in Electric Grids: a Functional Dictionary Approach" (*in review). IEEE Transactions on Power Systems, 2021.*

Parameter Error

Dynamic	Max FE (mHz)			Max RFE (mHz/s)			Mean TDE	
	60 ms	200 ms	IEEE Limit	60 ms	200 ms	IEEE Limit	60 ms	200 ms
SS	0.1	1.6E-2	5	2	1.2	10	8.2E-06	4.5E-06
AM	0.9	0.1	60	32	6	2300	9.9E-6	5.7E-06
FR	5	4.7	10	147	222	400	1E-05	1.8E-05
PM	8	13	60	112	420	2300	1.3E-05	2.4E-05
AS	4	1.3		27	108		1.1e-03	5.2E-04
AM/FR	2	3		223	196		1.4E-05	3.7E-05
AM/PM	8	18	60	276	498	3000	1.9E-5	3.7E-05

Dynamic	Mean Parameter Error for 200 ms window							
	f_0 (mHz)	f_m (mHz)	φ_m (rad)	f_a (mHz)	φ_a (rad)	R (mHz/s)	k_s (%)	t_s (ms)
SS	0.2							
AM	0.2	3.5	0.018					
FR	5					48		
PM	14			58	0.16			
AS	1						2.6	1.5
AM/FR	4	45	0.078			30		
AM/PM	13	39	0.04	76	0.14			

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 of reduced-inertia power grids.
- Dynamic phasors outperform stationary phasors in dynamic conditions but still rely on narrow-band approximations of signals and cannot represent in a complete way signals characterized by a continuous spectrum.
- 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 and real-world signals when compared to dynamic and static phasor methods.

References

[1] M. Paolone, T. Gaunt, X. Guillaud, et al, “Fundamentals of power systems modelling in the presence of converter-interfaced generation,” Electric Power Systems Research, vol. 189, 2020.

[2] AEMO, “Review of the Black System South Australia report system event of 28 September 2016,” Australian Energy Market Operator, Tech. Rep., 2017.

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

[4] D. Petri, D. Fontanelli and D. Macii, "A Frequency-Domain Algorithm for Dynamic Synchrophasor and Frequency Estimation," in IEEE Transactions on Instrumentation and Measurement, vol. 63, no. 10, pp. 2330-2340, Oct. 2014.

[5] D. Belega, D. Fontanelli and D. Petri, "Dynamic Phasor and Frequency Measurements by an Improved Taylor Weighted Least Squares Algorithm," in IEEE Transactions on Instrumentation and Measurement, vol. 64, no. 8, pp. 2165-2178, Aug. 2015.

[6] P. Banerjee and S. C. Srivastava, "An Effective Dynamic Current Phasor Estimator for Synchrophasor Measurements," in IEEE Transactions on Instrumentation and Measurement, vol. 64, no. 3, pp. 625-637, March 2015.

[7] M. Bertocco, G. Frigo, C. Narduzzi, C. Muscas and P. A. Pegoraro, "Compressive Sensing of a Taylor-Fourier Multifrequency Model for Synchrophasor Estimation," in IEEE Transactions on Instrumentation and Measurement, vol. 64, no. 12, pp. 3274-3283, Dec. 2015.

[8] C. Narduzzi, M. Bertocco, G. Frigo and G. Giorgi, "Fast-TFM—Multifrequency Phasor Measurement for Distribution Networks," in IEEE Transactions on Instrumentation and Measurement, vol. 67, no. 8, pp. 1825-1835, Aug. 2018.

References

[9] P. Romano and M. Paolone, "Enhanced Interpolated-DFT for Synchrophasor Estimation in FPGAs: Theory, Implementation, and Validation of a PMU Prototype," in IEEE Transactions on Instrumentation and Measurement, vol. 63, no. 12, pp. 2824-2836, Dec. 2014.

[10] G. Frigo *et al*, "Definition of Accurate Reference Synchrophasors for Static and Dynamic Characterization of PMUs," in IEEE Transactions on Instrumentation and Measurement, vol. 66, no. 9, pp. 2233-2246, Sept. 2017.

[11] A. Derviškadić, G. Frigo and M. Paolone, "Beyond Phasors: Modeling of Power System Signals Using the Hilbert Transform," in IEEE Transactions on Power Systems.

[12] Mehrdad Yaghoobi, Laurent Duadet, Mike E. Davies, "Parametric Dictionary Design for Sparse Coding," IEEE Trans. on Signal Processing, vol. 57, no. 12, 2009.

[13] A. Derviskadic, P. Romano, and M. Paolone, "Iterative-interpolated DFT for synchrophasor estimation: A single algorithm for P- and M-class compliant PMUs, "IEEE Trans. on Instr. and Meas., vol. 67, no. 3, pp.547–558, Mar. 2018

[14] IEEE Standard for Synchrophasor Measurements for Power Systems, "IEEE Std C37.118.1-2011 (Revision of IEEE Std C37.118-2005), pp.1–61, Dec 2011.

[15] A. Karpilow, A. Derviskadic, G. Frigo, M. Paolone, "Characterization of Non-Stationary Signals in Electric Grids: a Functional Dictionary Approach" (*under review*). IEEE Transactions on Power Systems, 2021.

[16] A. Karpilow, A. Derviskadic, G. Frigo, M. Paolone, "Characterization of Real-World Power System Signals in Non-Stationary Conditions using a Dictionary Approach" (*accepted*). PowerTech 2021, Madrid.

[17] ENTSO-E, "Report on blackout in turkey on 31st march 2015 – final version 1.0," European Network of Transmission System Operators for Electricity, Project Group Turkey, Tech. Rep., 2015

[18] ENTSO-E, "Oscillation Event 03.12.2017," 2018.