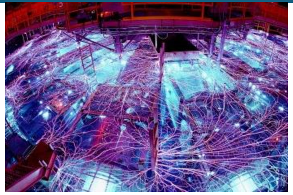
Numerical Algorithms for Estimating Frequency to Enable Synthetic Inertia



Felipe Wilches-Bernal
Sandia National Laboratories
Albuquerque, NM

NASPI (webinar)
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Project Team & Acknowledgements

- **Sandia National Laboratories**
  - Dr. Felipe Wilches-Bernal (PI)
  - Ricky Concepcion
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  - 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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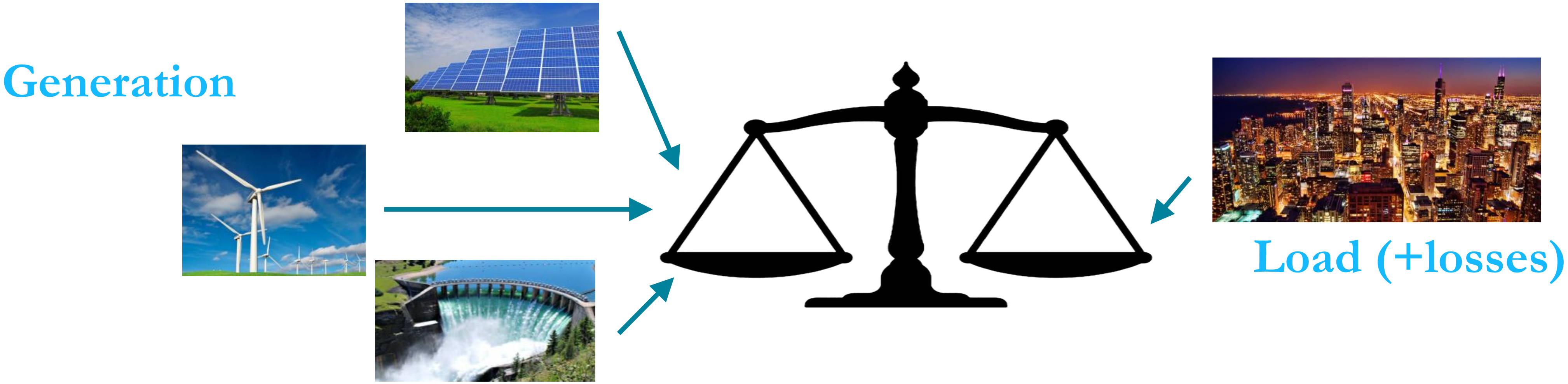
Purpose and Motivation

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

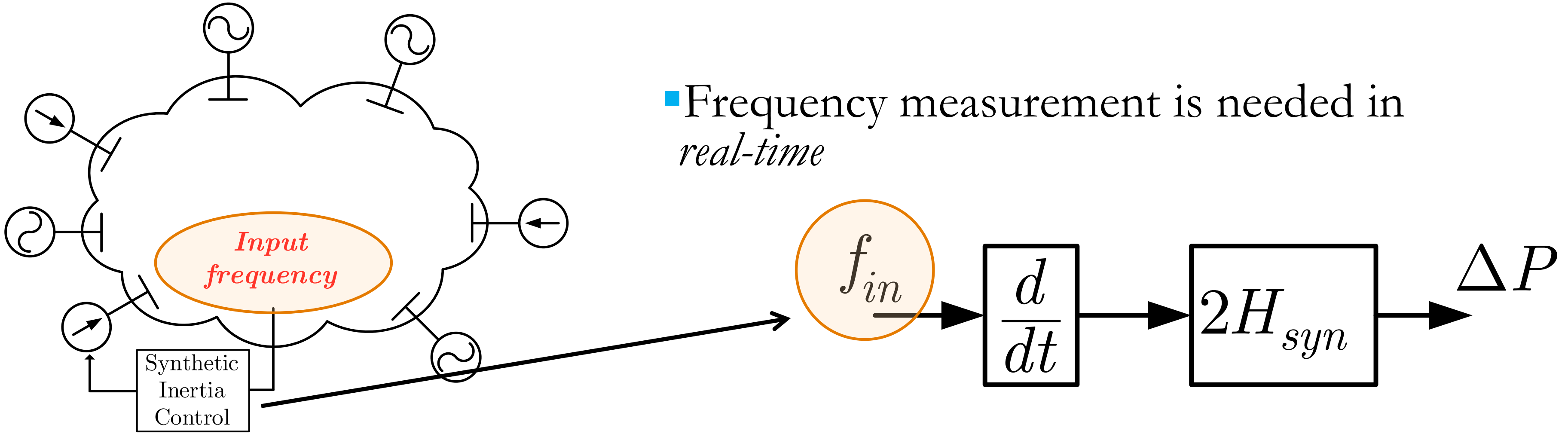


- Frequency of electrical signals (voltages and currents) in the power system is related to the velocity of rotation of machine speeds
- At the transmission level frequency there is interest of a global of system frequency as an indicator (for power imbalance events)
- The variations in frequency of 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

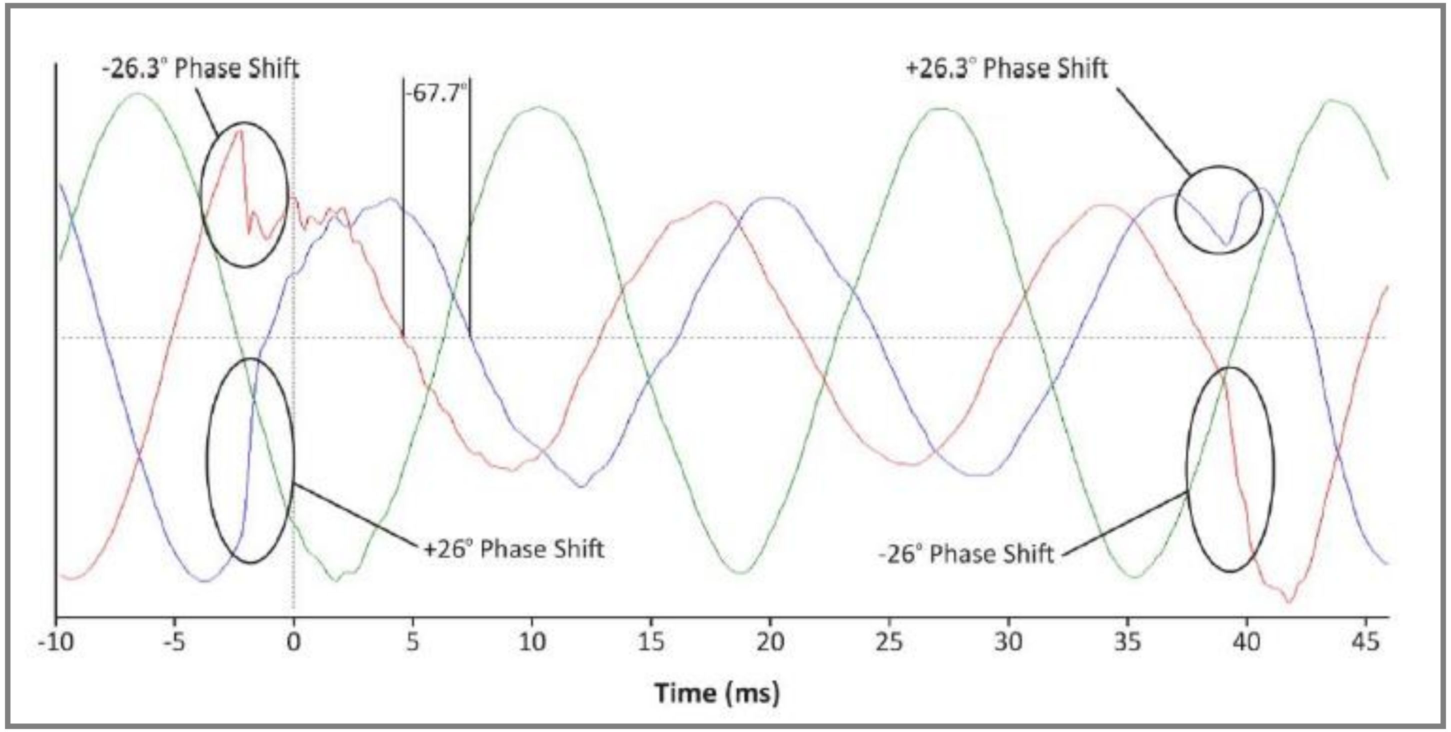
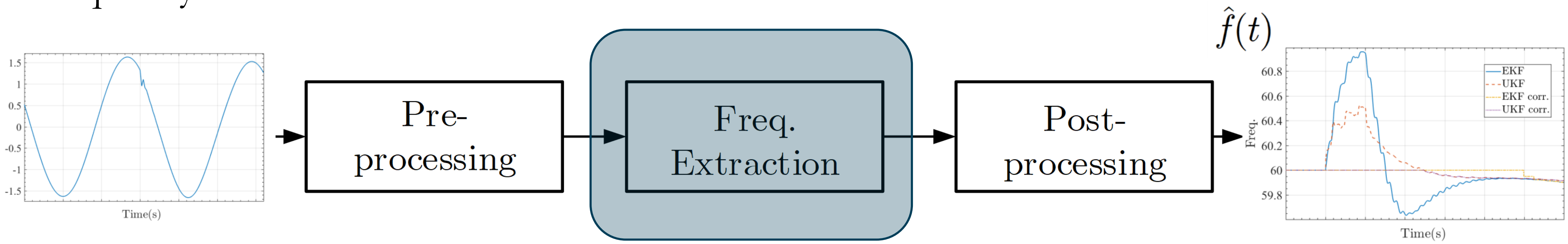


Figure from *1,200 MW Fault Induced Solar Photovoltaic Resource Interruption Disturbance Report Southern California 8/16/2016 Event*
NERC Report

Technical Approach

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



Input:
- Single phase
- Three phase
- Multisignal

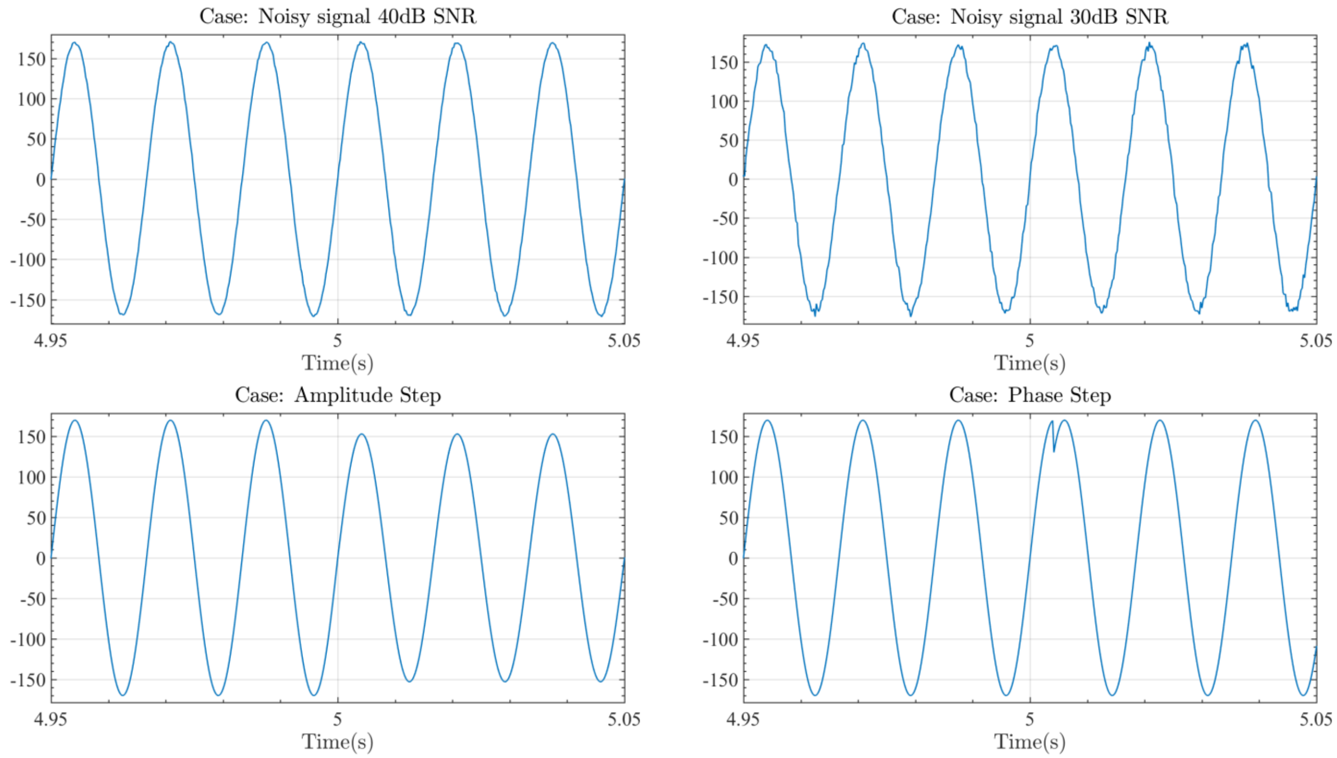
Preprocessing (optional)
Filtering to reduce noise and distortion

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

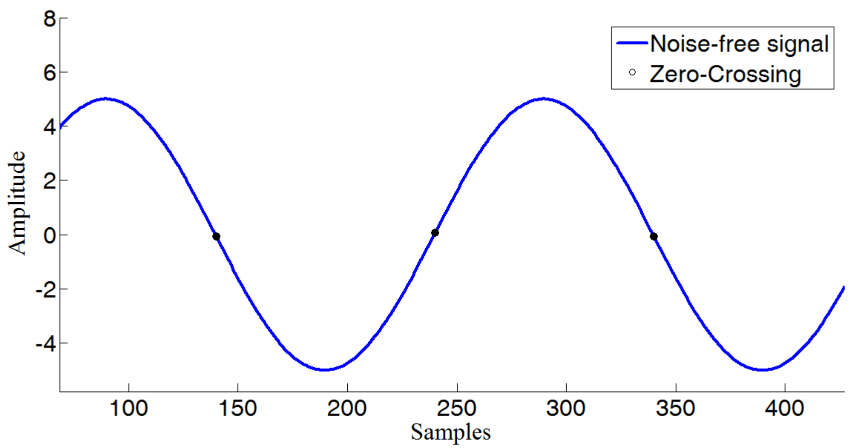
- Phenomena that corrupt input signals and affect frequency estimates can be divided into two:
  - Broad spectrum (white) noise
  - Specific disturbances/imperfections such as harmonic distortion, DC offset, imbalance, phase steps, and amplitude steps

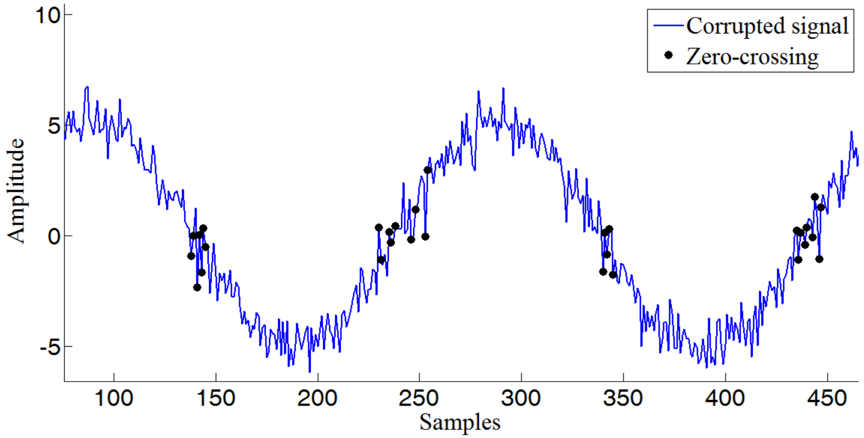


- Algorithm sensitivity to noise is unavoidably linked and traded against bandwidth (speed of response to changes in actual frequency)
  - Managing this tradeoff is called 'tuning' and an important characteristic of any algorithm is tuning difficulty

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.**

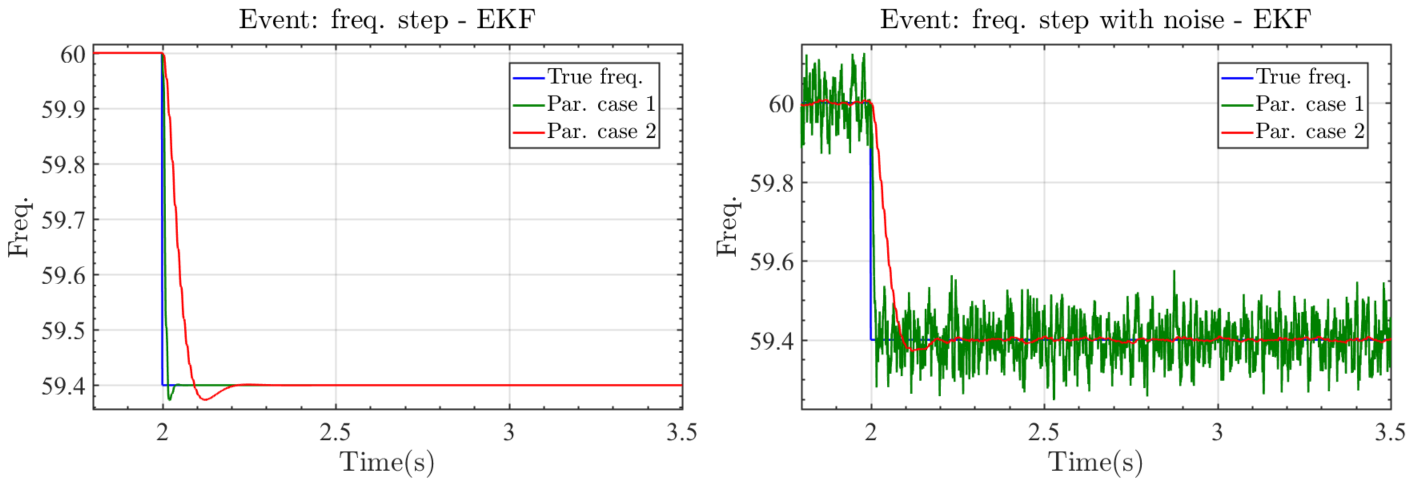
Project Objectives

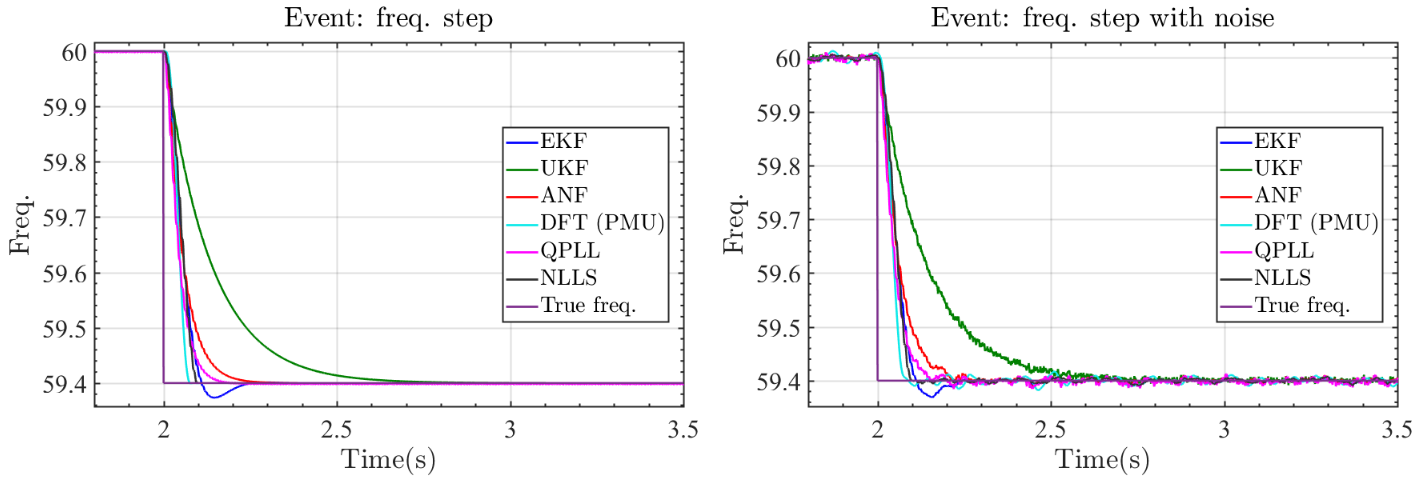
- One of the goals of the project is to study and propose methods for overcoming challenges of real-time frequency estimation
- Synthetic inertia controllers require accurate frequency estimates and fast (manage the tradeoff between sensitivity to noise and bandwidth)
- The project studied/implemented 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

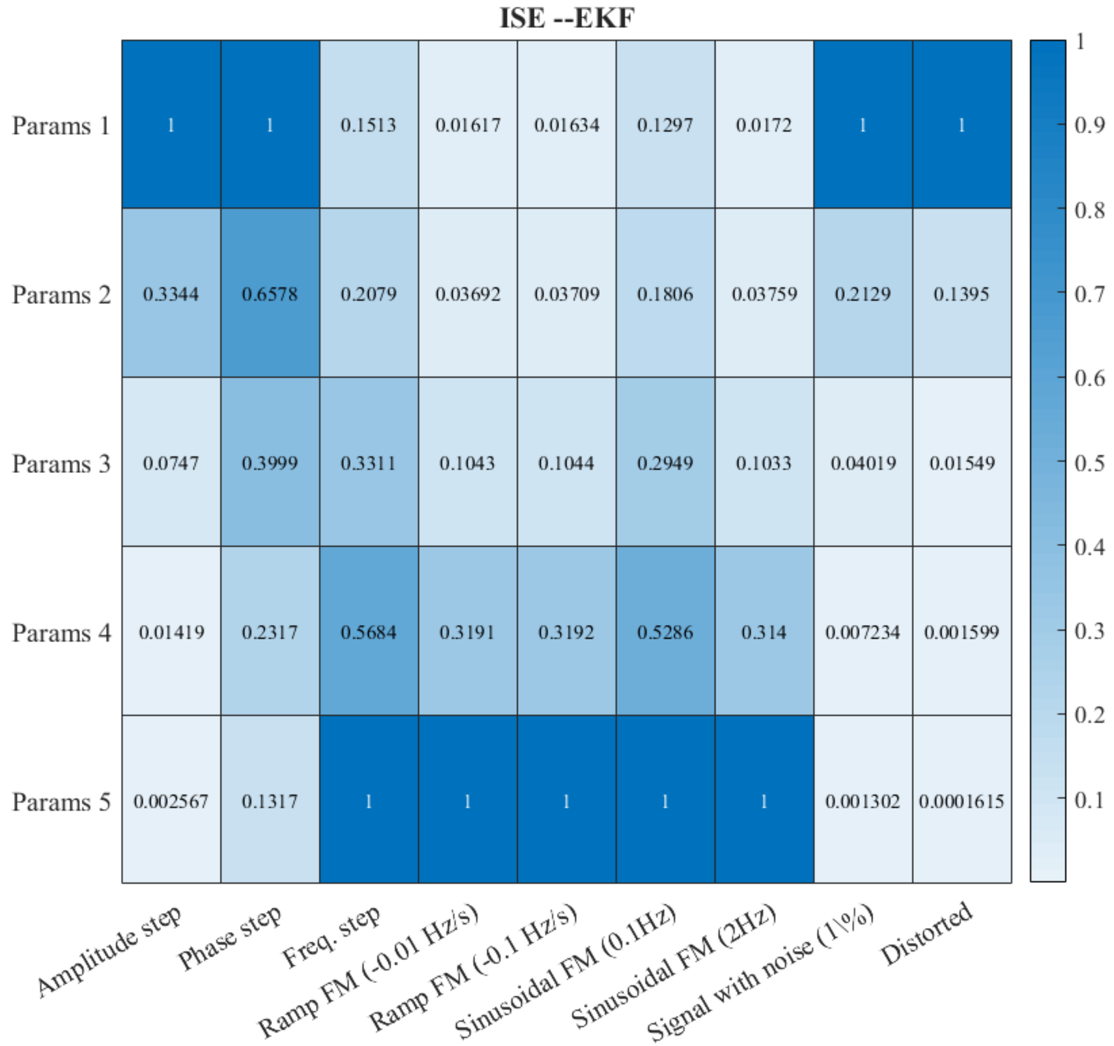
- Different metrics to determine the performance of the frequency estimation were considered

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

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

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

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



- 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*

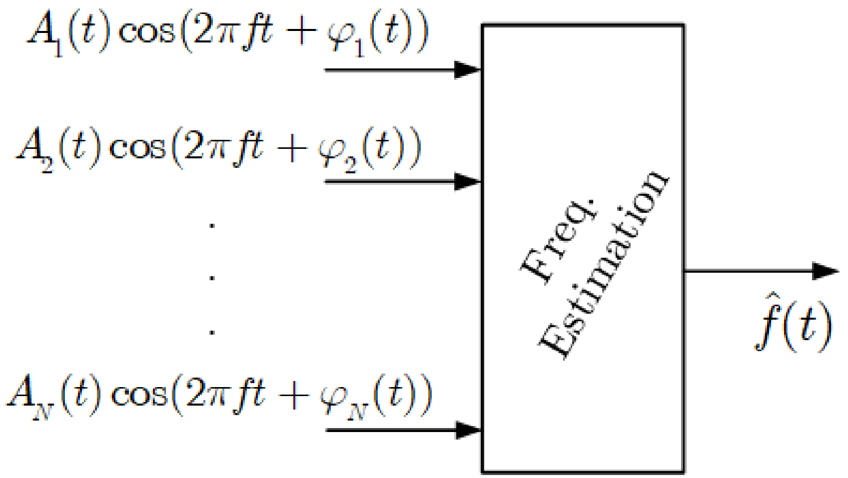
Multisignal Frequency Estimation

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

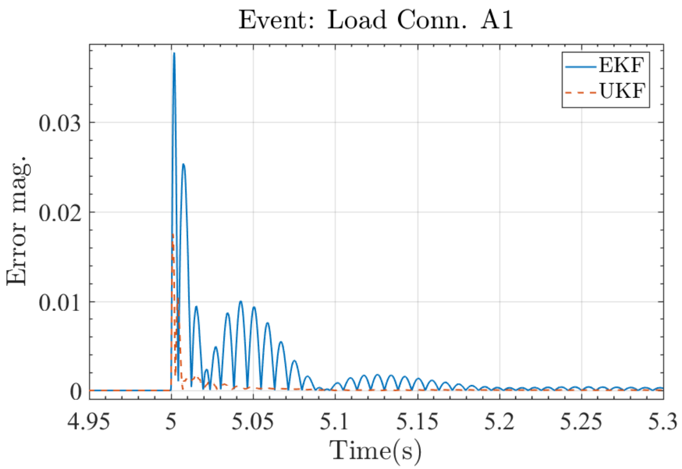
Frequency Correction

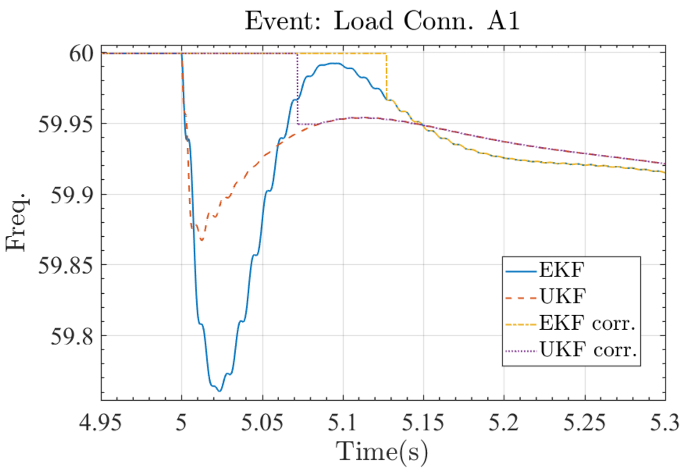
Improving the frequency estimate

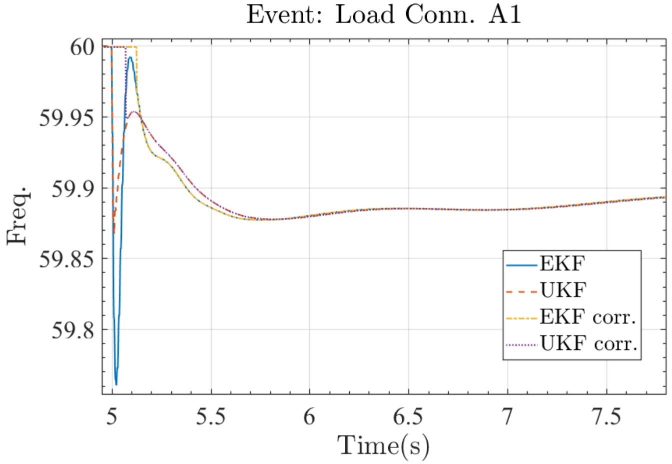
- **Correcting the frequency estimate:** based on the idea that some corruptions in the point on wave are only temporary (sometimes really fast e.g. phase jump) but their effect on the frequency estimate can linger for longer time (depending on the tuning.)

Algorithm 2: Frequency Correction Algorithm

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

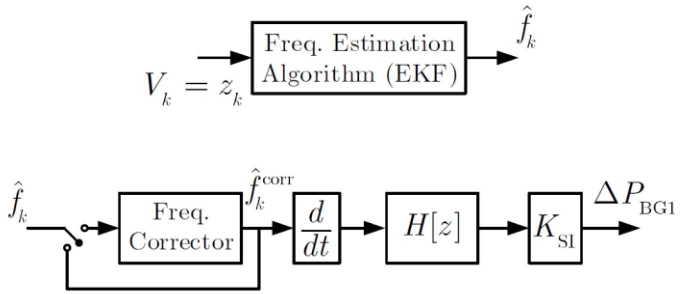




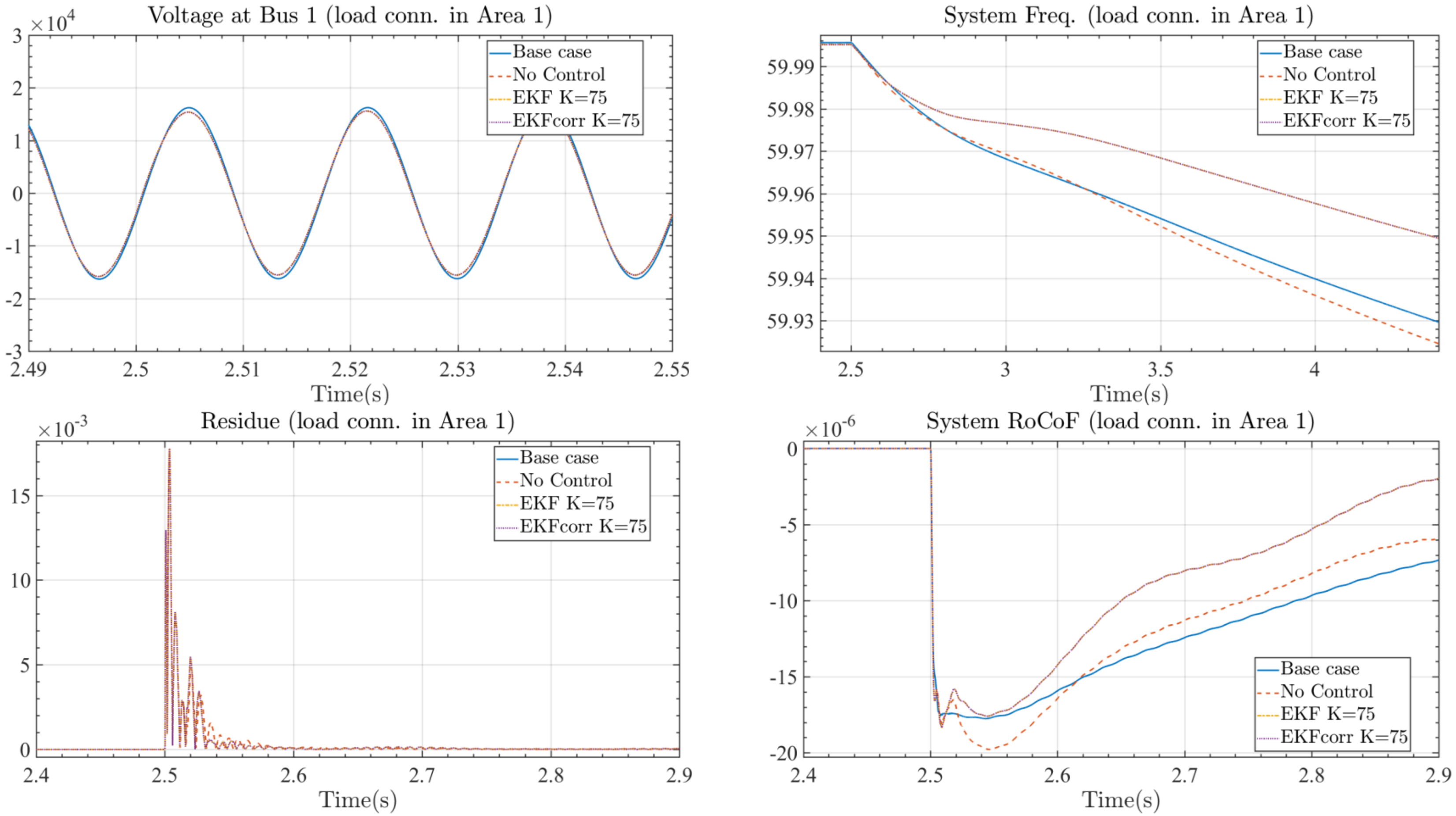


Frequency Correction in Synthetic Inertia Control

- **Synthetic inertia controller:**

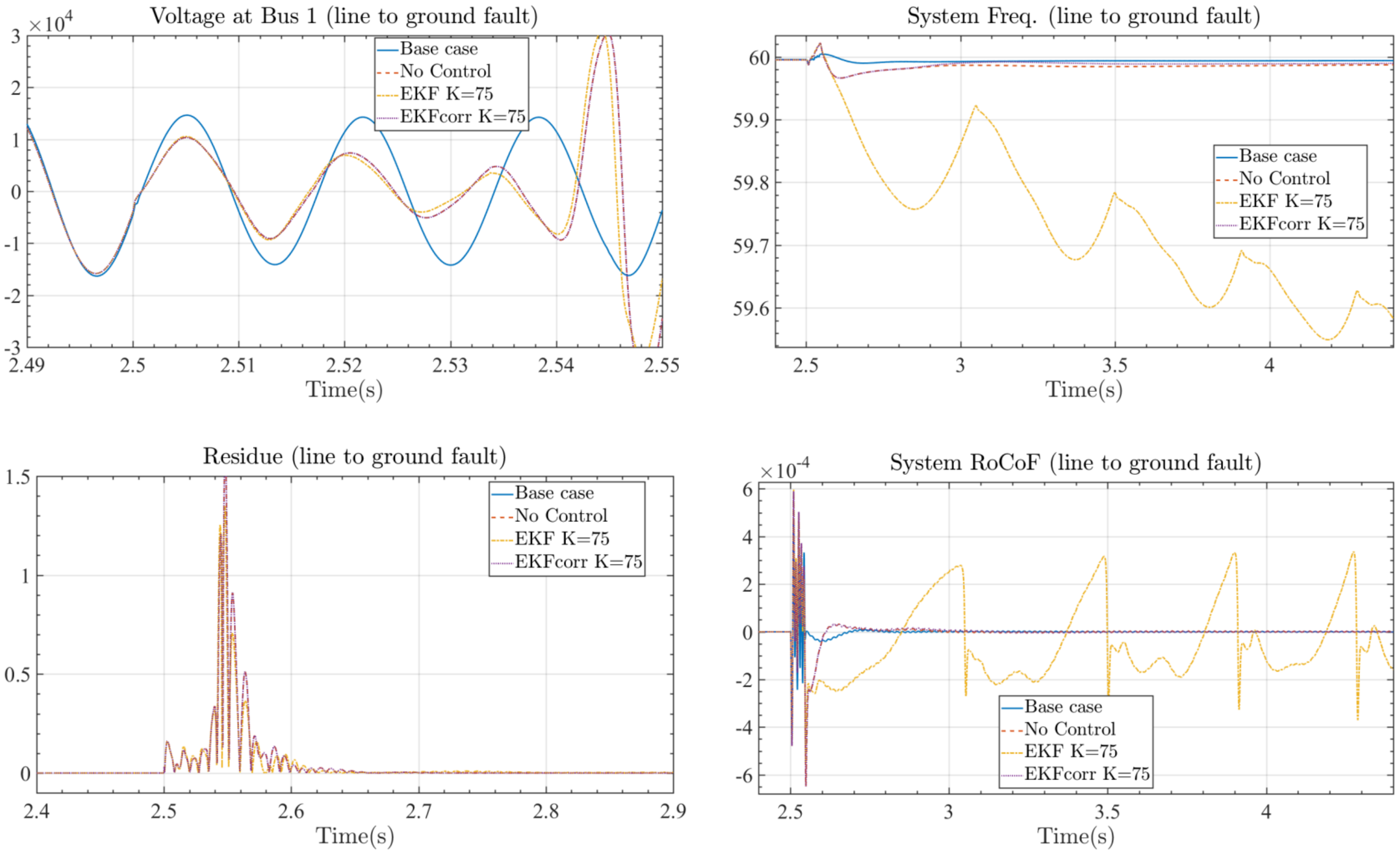


- Tested the frequency corrector for a power imbalance event (connection of 100 MW load). This type of event does not typically distort the waveforms



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

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ROCOF Measurement Challenges in Continental Europe Synchronous Area

Guglielmo Frigo, EPFL

NASPI Webinar
16/04/2020

École polytechnique fédérale de Lausanne

A TSO perspective

European Network of Transmission System Operators for Electricity (ENTSO-E)

- ENTSO-E represents 42 transmission system operators (TSOs) across Europe.

- ENTSO-E main objectives are:
  - to set up the **internal energy market** and ensure its optimal functioning;
  - to support the **European energy agenda** (e.g. renewables integration);
  - to maintain **security of supply** and support **regional cooperation**.

ENTSO-E reports at: https://www.entsoe.eu/publications/

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EU regulation framework

In April 2016, the European Commission introduced a regulation on the **requirements for grid connection of power-generating facilities** [1].

- Frequency requirement

FREQUENCY RANGE	TIME PERIOD FOR OPERATION
[47.5, 48.5] Hz	To be specified by each TSO, but **not less than 30 min**
[48.5, 49.0] Hz	To be specified by each TSO, but not less than previous range (**30 min**)
[49.0, 51.0] Hz	**Unlimited**
[51.0, 51.5] Hz	**30 min**

- ROCOF requirement

connected to the network and operating at ROCOF up to a **value specified by the TSO**, **unless** disconnection was triggered by ROCOF-based **LOM protection.**

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ROCOF withstand capability

In November 2017, ENTSO-E issued a guidance for the definition of ROCOF withstand capability and the implementation of EU regulations [2].

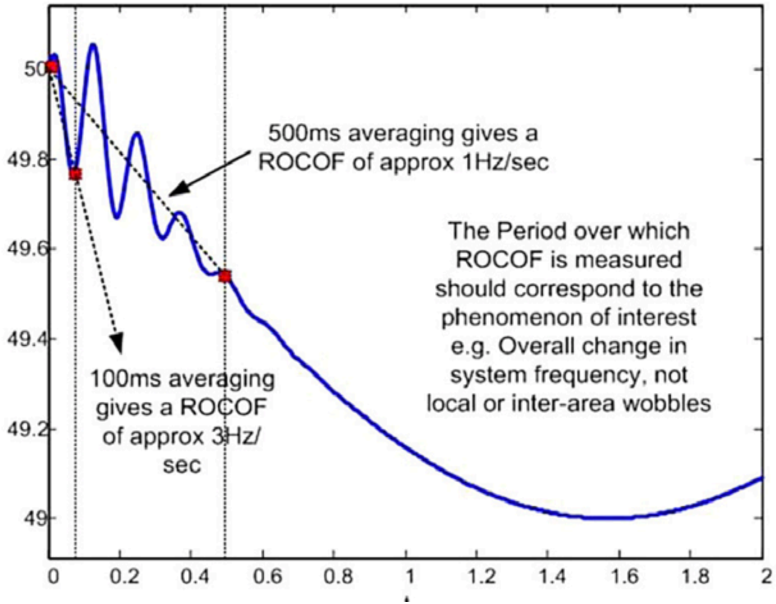
Large ROCOF **values** may occur after a severe **system contingency** (e.g. system split or loss of large generator) but power generating facilities shall remain connected to contribute to stabilize and restore the network to normal operating states.

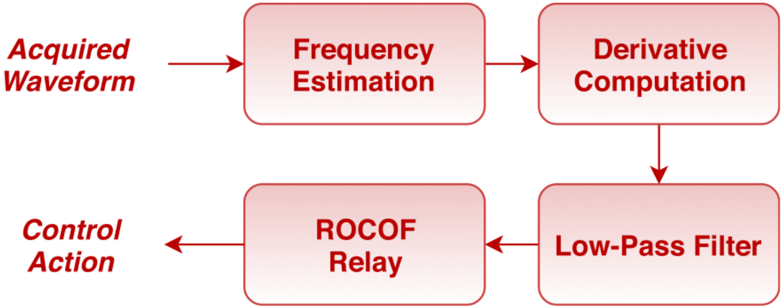
- ➔ The facilities shall **not disconnect** from the network **up to a max** ROCOF defined by the TSO based on the system characteristics.
- ➔ The **time window to measure** ROCOF has to be accordingly dimensioned, otherwise protection schemes are likely to trigger spuriously.
- ➔ The resulting ROCOF withstand capability will be an important input to calculate the essential **minimum inertia** (inherent in synchronous generators or synthetic).

ROCOF measurement

ROCOF measured values depend on the adopted time window [3].

EirGrid (Irish TSO) proposed a maximum ROCOF of 1Hz/s measured over a rolling 500 ms window, since this aligns with the time for generators to return to a “coherent state” and for wind generation post-fault.



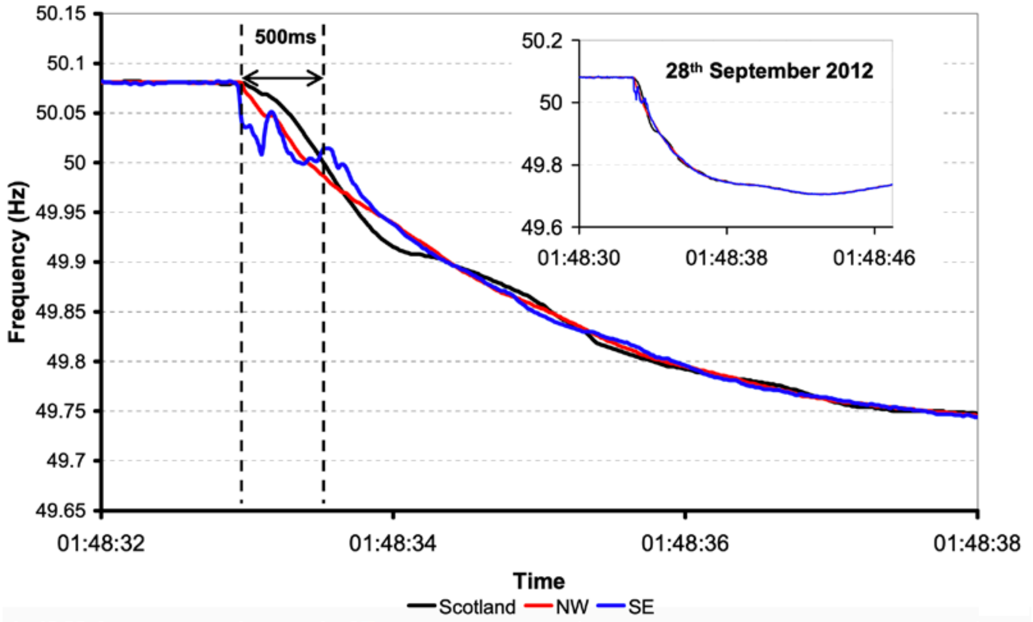


Measurement comparability

Dr. Guglielmo Frigo

Another issue to be considered is the possibility to compare ROCOF measurements coming from different nodes.

A window of 500 ms seems a suitable time window as shown by National Grid (UK TSO) frequency measurements during a 1,000 MW instantaneous infeed loss [4].



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Generator transient stability

However, ROCOF withstand capabilities of synchronous generators are sensitive to the total duration of the ROCOF event [5].

Most generators could achieve **compliance with a 1Hz/s over** a time window of **500 ms**, but their capability is significantly **reduced** when the **1Hz/s ROCOF** is sustained over **1 s**.

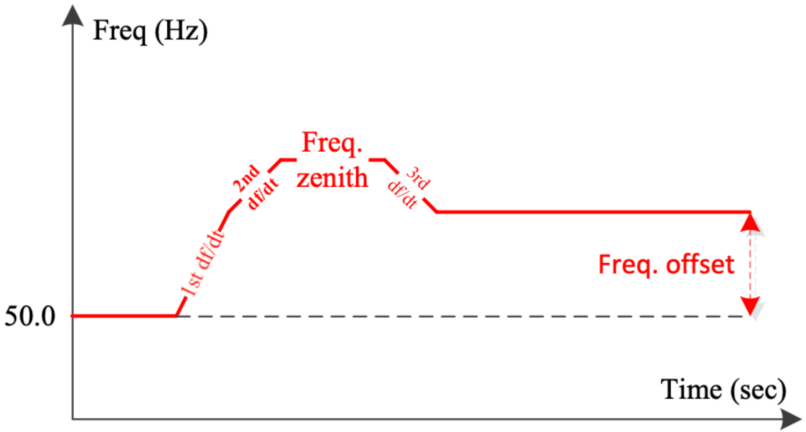
Generator Type	Unit Size (MW)	Stable during ROCOF event?		
		0.5 Hz/s	1.0 Hz/s	2.0 Hz/s
CCGT Single-shaft	400	Y	Y*	N
CCGT Dual-shaft	260	Y	Y*	N
CCGT Dual-shaft	140	Y	Y*	N
Steam Thermal (Reheat)	300	Y	Y*	N**
Steam Thermal (Once Through)	150	Y	Y*	N
Steam Thermal (Fluidised Bed peat)	150	Y	Y*	N
OCGT	50	Y	Y*	Y*
Salient-pole Hydro	30	Y	Y	Y

Y	stable operation
Y*	pole slip only for 0.93 leading power factor
N	pole slip also for 1 leading power factor or 0.85 lag
N**	no pole slip, but negative power generation

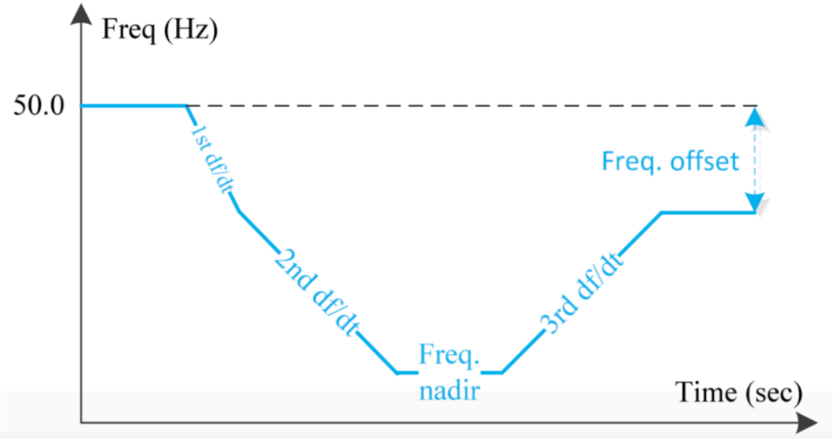
ENTSO-E proposal

The TSO may define the withstand capability requirements as a set of **frequency-vs-time profiles**, with lower and upper limits for frequency deviation in the network **before**, during and after the contingency.

Over-frequency



Under-frequency



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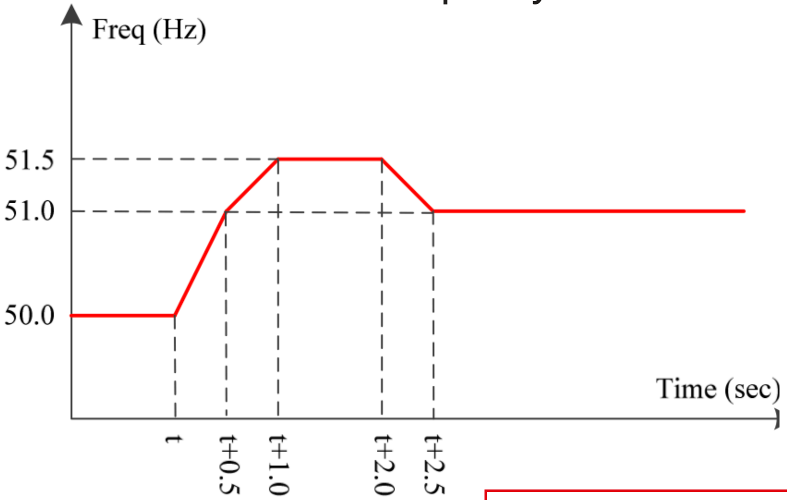
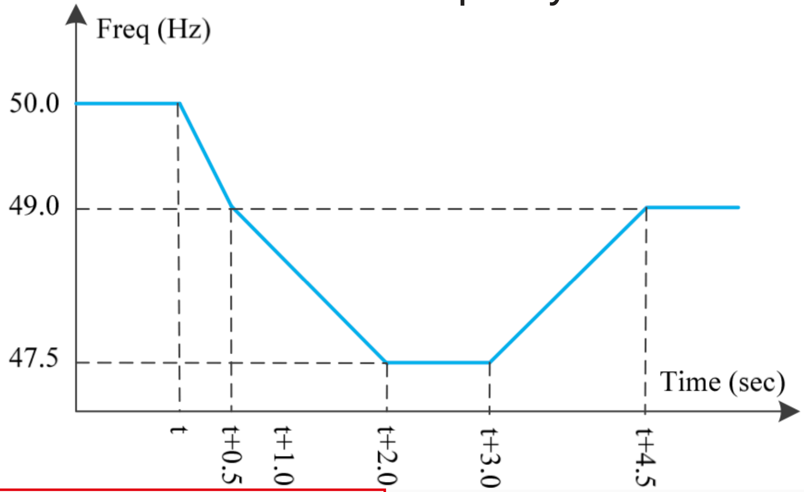


Under-frequency



max ROCOF = ±2 Hz/s over 500 ms

PMU-based solution

Common Phasor Measurement Units (PMUs) employ **shorter time windows** in order to cope with latency and response time requirements:

- P-class → around 3-4 nominal cycles (e.g. 60 ms)
- M-class → 5 or more nominal cycles (e.g. 100 ms)

with reporting rates in the order of **tens frames per second.**

➔ on such short time windows the ROCOF estimation might be subject to higher uncertainty (fluctuations, inconsistent values)

The **IEEE Std C37.118** is characterized by high variability in terms of RFE limits [6]:

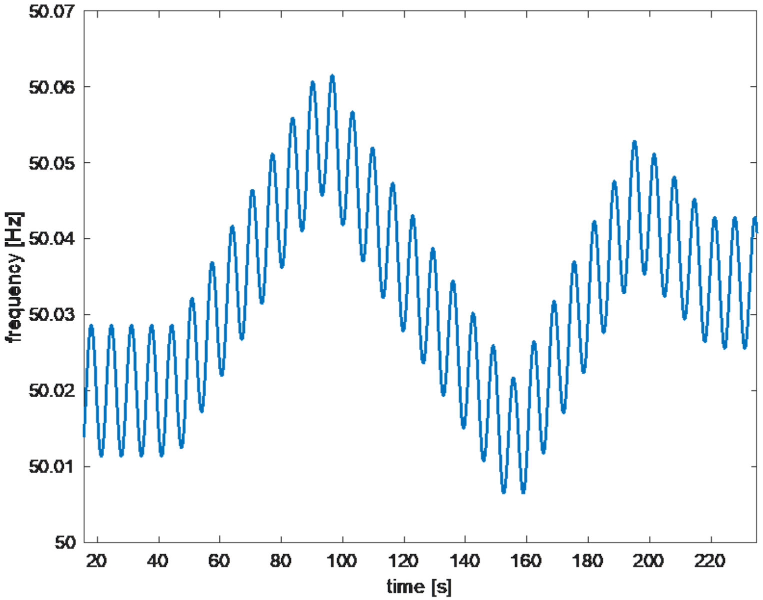
- 0.01 Hz/s in steady-state conditions,
- 6 Hz/s in the presence of harmonic distortion.

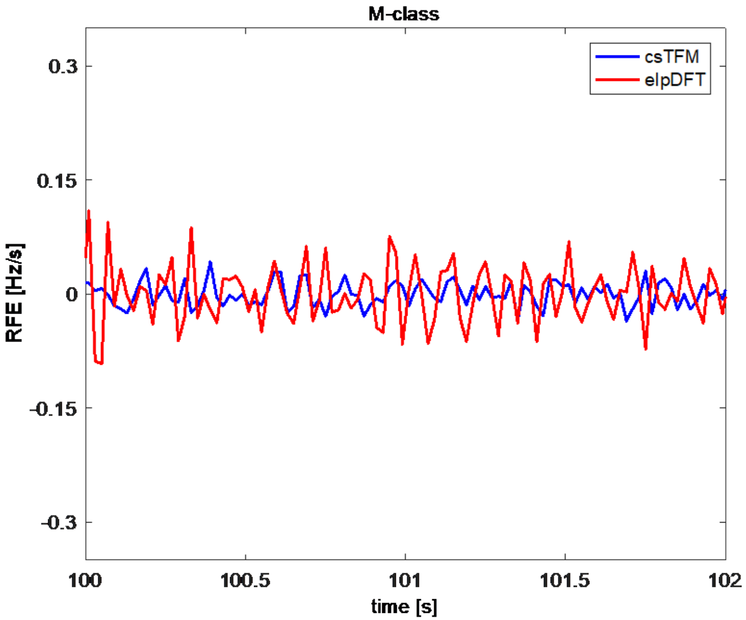
➔ **scarce reliability** of PMU-based measurements during **off-nominal conditions.**

Inter-Area Oscillation

In December 2016, an unexpected opening of a line in the French transmission network caused an inter-area oscillation in the Continental Europe electricity system.

Based on the PMU estimates in Lausanne, we derived a test waveform and characterized the RFE provided by **two different PMU-algorithms** (static vs dynamic) [7].

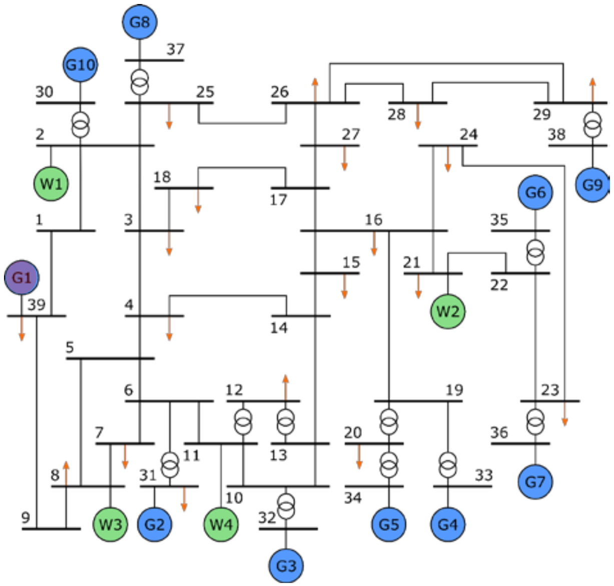


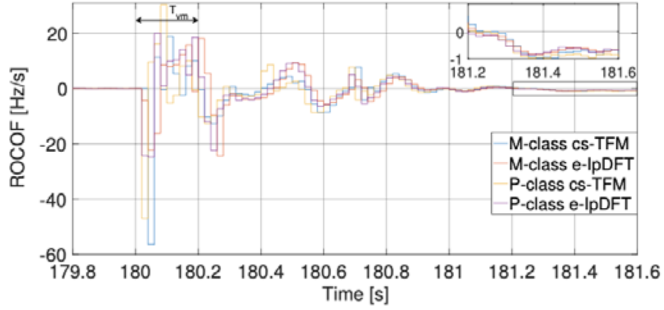


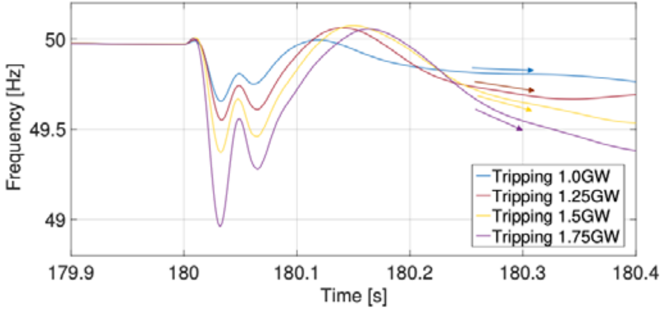
Low-Inertia scenario

In order to study the behavior of PMU-based measurements of frequency and ROCOF in a reduced-inertia scenario, we modified the **IEEE 39-Bus** standard test system by adding **4 wind farms and dynamic load profiles** [8].

A PMU is placed in each node in order to measure frequency and ROCOF.



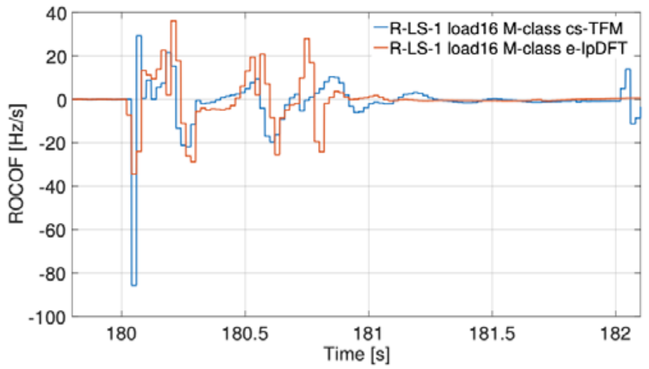


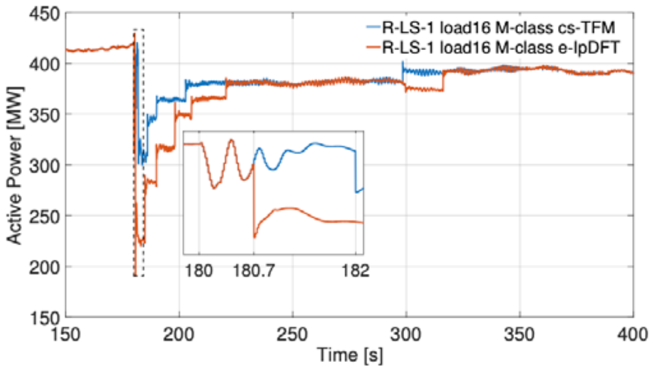


ROCOF-based Load Shedding

Under-frequency load-shedding (UFLS) scheme relying on PMU measurements.

We consider ROCOF estimates R over an interval of 500 ms, 25 estimates at 50 fps.
The load share is shed if **at least p** estimates exceed the corresponding threshold.





Load Share [%]	95	90	85	75	60
R [Hz/s]	0.3	0.4	0.6	0.7	1
p [%]	88	84	72	68	64

Conclusions

ROCOF measurements prove to be dependent on the time window and location.

- typically, rolling windows of 500 ms

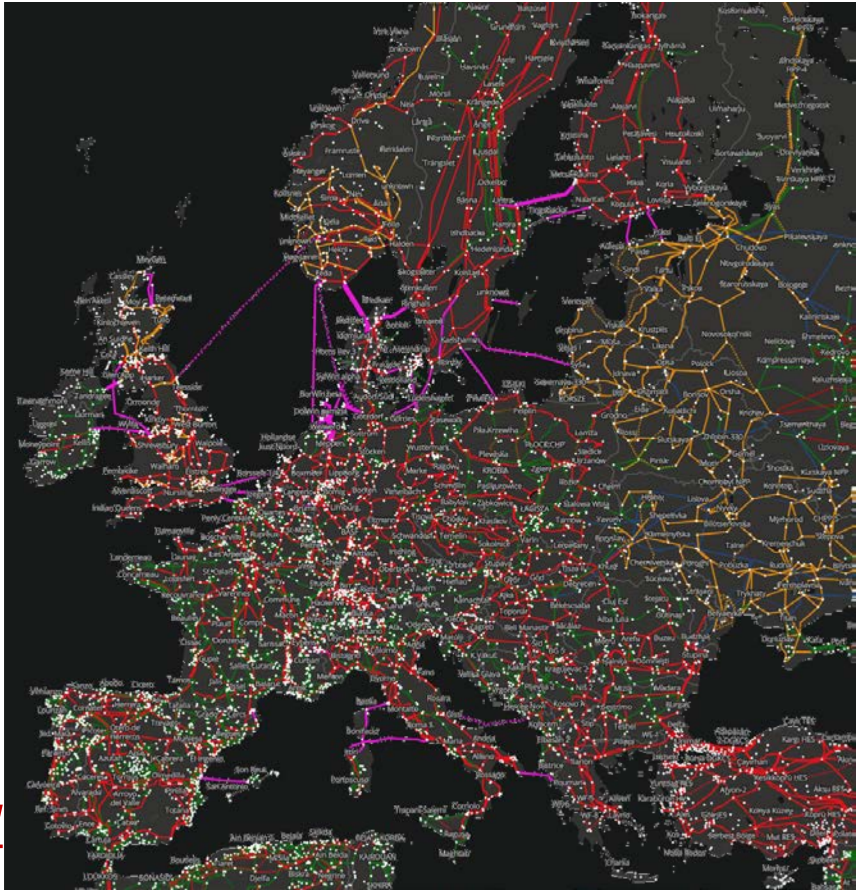
ENTSO-E guidance:

- frequency-vs-time profiles
- max withstand capability of $\pm$2 Hz/s over 500 ms

PMU-based measurements:

- shorter windows → higher uncertainty
- different estimation techniques
- positive results in inter-area oscillations and under-frequency load shedding

THANK YOU FOR THE ATTENTION



Guglielmo Frigo

guglielmo.frigo@epfl.ch

https://www.epfl.ch/labs/desl-pwrs/

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[1] Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators, http://data.europa.eu/eli/reg/2016/631/oj

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Requirements and Test Conditions for Reliable ROCOF Measurements

16 April 2020

Gert Rietveld, VSL

Paul Wright, NPL

Andrew Roscoe, Strathclyde

ROCOF – EU R&D project

Project summary information

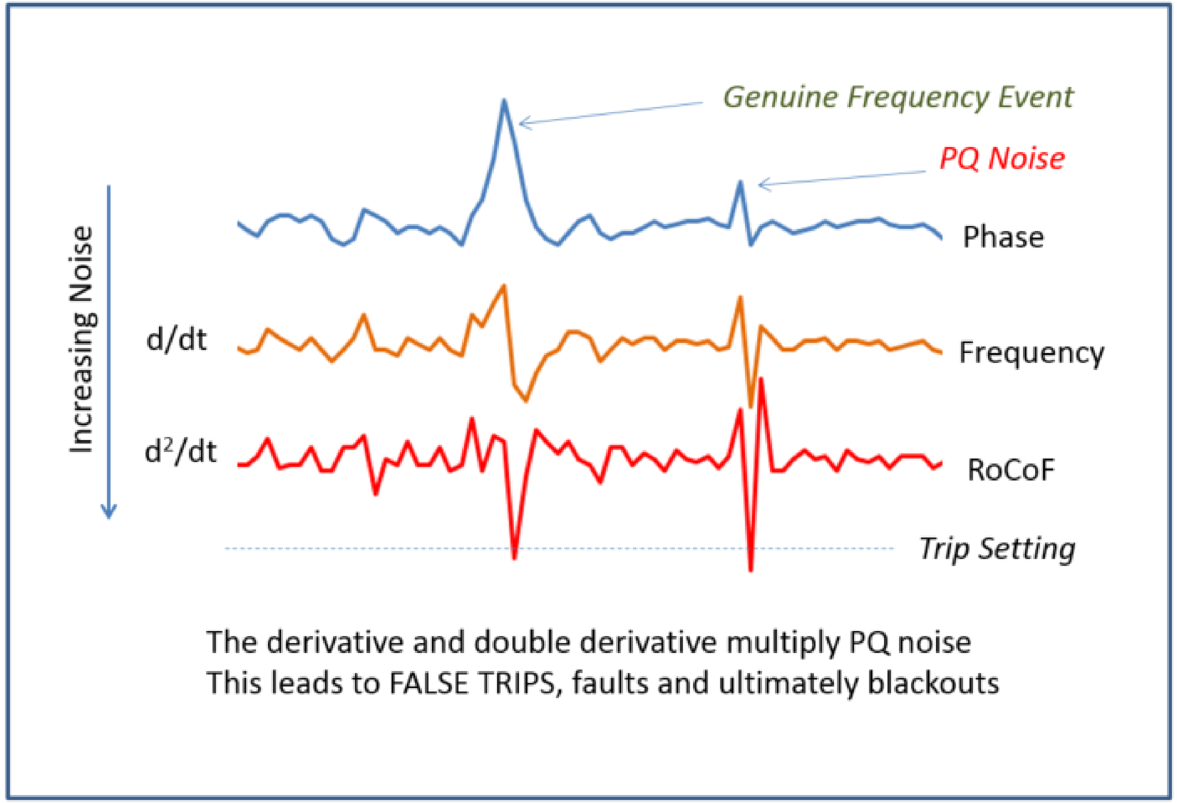
- 3 Year joint research project (JRP) - June 2016 to May 2019
- 5 partners:
  - 4 National Measurement Labs: UK, NL, CZ, CH (NPL, VSL, CMI, METAS)
  - 1 University: University of Strathclyde, UK.
- 4 Technical Work Packages: user expectations, test waveforms, algorithms, hardware

EU funds from EMPIR (FP7) – Normative Project Fund (dedicated to standardisation)

EMPIR program run by EURAMET, the organization of the national NMIs in Europe

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

The difficulties of measuring ROCOF (*project trigger*)



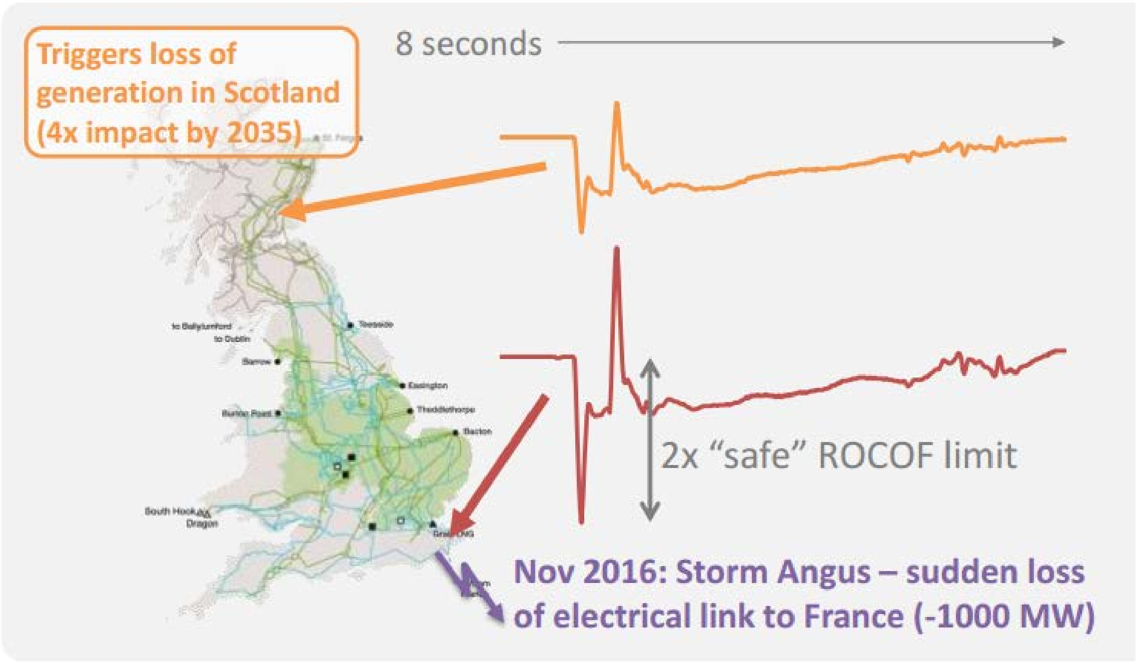
ROCOF is the double differentiation of phase – differentiation amplifies noise

In 2014 IEEE C37.118.1 relaxed many of the ROCOF test accuracy levels for PMUs as they could not be met.

The inability to measure ROCOF reliably is undermining LOM protection

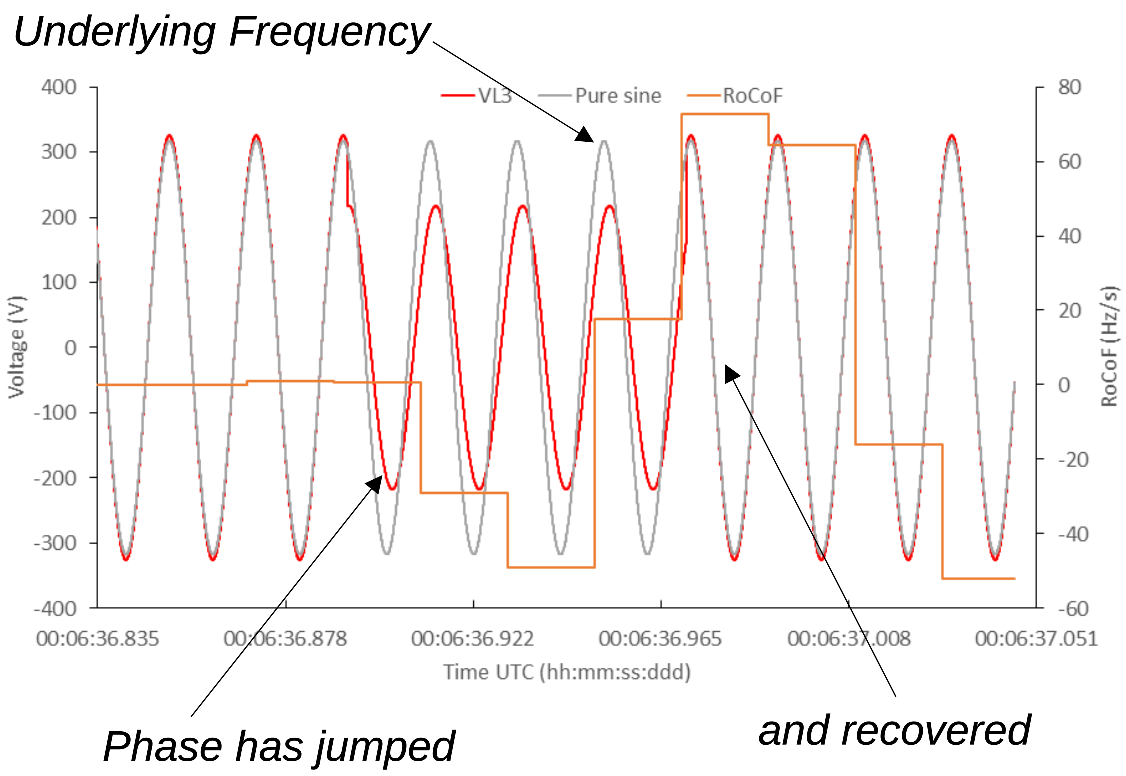
Lack of confidence in ROCOF measurements is holding back DER and advances in network balance management

ROCOF events and false breaker trips



Need timely, robust measurements

Major ROCOF event due to phase jump in island with significant RES (Bornholm)
– note the underlying frequency is stable!!



User requirements: ideal ROCOF instrument wish list

- It can measure all modulations of the grid associated with power system dynamics
- Delivers results in less than a power cycle, so it can be used as an input to protection and control systems (low latency)
- Has high accuracy and reliability…under all actual grid conditions:
  - It rejects all power quality (PQ) influences such as harmonics, interharmonics and flicker
  - It is not upset by amplitude dips/swells
  - Phase jumps (faults) do not cause errors or unstable behaviour
  - Noise on the power system voltage is rejected

The reality inequality:

Stability α 1/Latency

For low ROCOF errors, longer latencies are needed

For low latency, large ROCOF ripple and errors are expected

User requirements: use cases

Survey of users' expectations of ROCOF measurements identified three use cases:

- Loss of Mains (LOM) protection,
- Under Frequency Load Shedding
- Generator Frequency Response

Accuracy requirements are given for each use case

ENTSO-E publication of power system frequency requirements (RG-CE group, 2018)

Maximum allowed ROCOF error

Overview of requirements

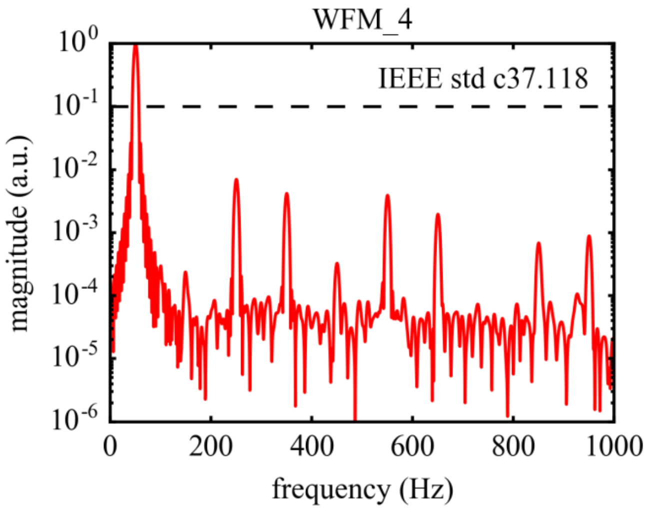
Application	Latency	Window length	Ideal peak error / ripple	Worst case peak error / ripple (limit of usability)
UC1: Active power damping and control. Fast Frequency Response (FFR) and "Synthetic Inertia". Under-frequency load shedding	50 ms (2.5 cycles)	100 ms (5 cycles)	0.02 Hz/s	0.1 Hz/s
UC2: FFR, longer, more stable measurement.	100 ms (5 cycles)	200 ms (10 cycles)	0.02 Hz/s	0.1 Hz/s
UC3: Anti-Island Detection (LOM, Loss of Mains) *"Evaluations on synchronous area level"* e.g. inter-area oscillations	250 ms (12.5 cycles)	500 ms (25 cycles)	0.01 Hz/s	0.1 Hz/s

Preferred accuracy: < 0.05 Hz/s

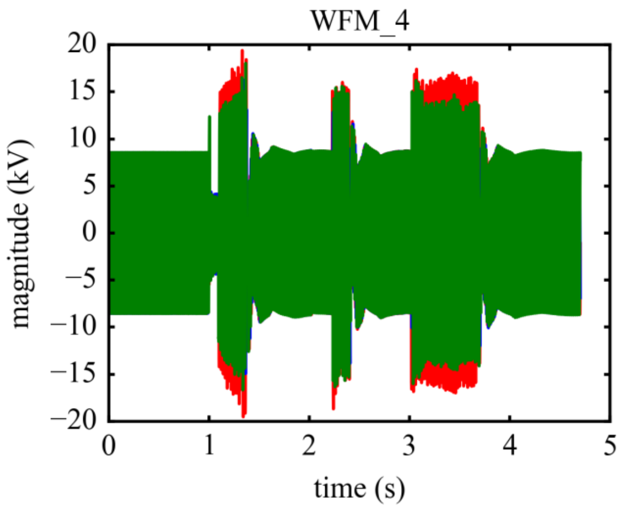
IEEE/IEC requirement: 0.01 Hz/s → 0.4 Hz/s (2014)

Testing ROCOF accuracy

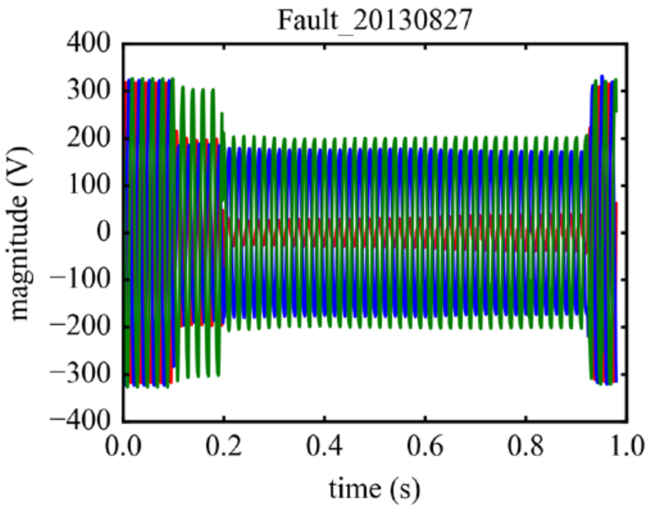
Objective: To develop a library of standard-test waveforms representative of typical PQ events on electricity networks, including extreme events, in order to adequately test ROCOF algorithms and instrumentation containing these algorithms.



Harmonics



Disturbances: dips and swells



Faults

VSL

Proposed additional ROCOF tests

Disturbance	Existing IEC/IEEE C37.118.1	Proposed additional test	Rationale	Worst Case RFE Ripple (Hz/s)
3) Noise	No test	3 % of the fundamental white noise up to 2 kHz. (Steady state, at nominal f_0, V, I)	To account for heavy plant in the vicinity of the connection.	UC1: 1.2 UC2: 0.2 UC3: 0.1
8) Joined phase step and frequency ramp	No tests	From a sinewave at f_0, an instantaneous frequency change to f_0-2 Hz. Linear ramp in frequency at 8 Hz/s back to f_0.	Realistic fault condition	UC1: 50 UC2: 25 UC3: 10
7) Close-in Interharmonics and flicker	Tests for frames per second ≥10, none for <10. A single 10 % (of the nominal voltage) amplitude frequency is swept between 10Hz and the 2nd harmonic of the power	A single 5 % amplitude tone varied from 10 Hz to 90 Hz, but excluding the stop band. For frequencies outside the stopband and >40 Hz above the fundamental, increase the tone amplitude to 10 %. Sweep to 150 Hz	Test rejection of close to the pass band interharmonics and flicker modulations. The 5 % amplitude is a conservative limit based on allowed flicker. The 10 % amplitude is a conservative rounding of the Meister Curve limits	<u>5% tone</u> UC1: N/A UC2: 0.6 UC3: 0.3 <u>10% tone</u> UC1: 0.5

No single accuracy requirement; requirement tuned to use case!

Limits based on what seems achievable with state-of-the-art algorithms

Testing ROCOF algorithms

Test signals have been tried with 3 PMU algorithms, both simulation and laboratory synthesis

- M-class PMU algorithm of the IEEE C37.118.1 standard
- Box-car filter algorithm developed by Roscoe
- Phase Sensitive Frequency Estimation (PSFE) developed by Lapuh

Noise (3% fund. to 2 kHz)

Algorithm	R_{min}	R_{max}	1σ	Latency
Standard UC1	*-1.9*	*1.7*	0.6	59 ms
Standard UC2	*-0.44*	*0.31*	0.18	138 ms
Standard UC3	*-0.04*	*0.04*	0.02	412 ms
Roscoe UC1	-0.78	1.02	0.6	50 ms
Roscoe UC2	-0.15	0.16	0.07	100 ms
Roscoe UC3	-0.02	0.03	0.01	250 ms
PSFE UC1	*-3.5*	*3.5*	1.8	50 ms
PSFE UC2	*-0.7*	*0.8*	0.3	100 ms
PSFE UC3	*-0.14*	*0.12*	0.05	250 ms

Joined phase step & frequency ramp (-2 Hz, + 8 Hz/s)

Algorithm	R min	R max	Notes
Std. UC1	*-52.6*	*11.3*	Records 8 Hz/s with V. low ripple, but 11.3 Hz/s overshoot at start. Slow recovery to 0 Hz/s at end.
Std. UC2	*-27.0*	*11.2*	Ditto.
Std. UC3	*-9.90*	*8.76*	Filters too slow to settle to 8 Hz/s.
Rosc. UC1	-37.9	7.96	Records 7.96 Hz/s (-0.04 Hz/s error) with V. low ripple, no overshoot.
Rosc. UC2	-9.6	7.99	Good response (-0.01 Hz/s error)
Rosc. UC3	-7.4	6.33	Filters too slow to settle to 8 Hz/s. Only gets to 6.33 Hz/s.
PSFE UC1	-44.6	8.1	Records 8 Hz/s with V. low ripple, slight overshoot at start.
PSFE UC2	*-32.1*	8.1	Ditto. Some instability after the phase jump.
PSFE UC3	*-11.1*	*13.9*	Unstable after phase jump, never settles to 8 Hz/s. Settles back to 0 Hz/s at the end.

Conclusions and outlook

- ROCOF is an increasingly important measurement for power systems
- Use case studies clearly indicate the required ROCOF accuracy for typical applications
  - Ideally 0.01 Hz/s, preferably < 0.05 Hz/s, certainly < 0.1 Hz/s
- The evaluation of actual grid signals has led to a series of suggested additional ROCOF test signals w.r.t. IEEE/IEC Standard 60255-118-1
  - E.g. noise, larger phase steps, joined phase step & *f*-ramp
- Test signals have been tried on 3 ROCOF algorithms

  ⇒ Achievable, realistic accuracies for proposed ROCOF test signals

More information on:
http://www.rocofmetrology.eu/
Recent paper IEEE TIM (early access):
https://ieeexplore.ieee.org/document/9057685

Reliable Rate of Change of Frequency (RoCoF) Measurements: Use Cases and Test Conditions

Gert Rietveld, *Senior Member, IEEE,* Paul S. Wright and Andrew J. Roscoe, *Senior Member, IEEE*

IEC 62786-41
DISTRIBUTED ENERGY RESOURCES CONNECTION WITH THE GRID

Part 41: Requirements for frequency measurement used to control Distributed Energy Resources (DER) and loads

Gustavo Brunello
Senior Applications Manager
GE Grid Automation

SCOPE of IEC 62786-41

- Technical specification - A work in progress, estimated 2021
- Characterizes measurement of frequency and ROCOF
- Applies to distributed energy resources and loads connected to electrical power networks, both SM and IBR.
- Defines Use Cases
- High level definition for performance tests
- Does not specify hardware, software or a method for computing frequency or rate of change frequency

Definitions

Frequency

ROCOF

Measurement range: range of input values for which the instrument maintains its measurement accuracy specification.

Operating range: extended beyond the measurement range, to ensure input values in the operating range, do not cause the instrument to enter any form of saturation mode that requires a recovery time when the input values returns into the measurement range.

Quantity	**Measurement Range**	**Operating Range**
Frequency	0.95 to 1.05 of nominal frequency	0.90 to 1.10 of nominal frequency
ROCOF	-5 Hz/s to +5 Hz/s	-10 Hz/s to +10 Hz/s

Characteristics of Freq and ROCOF

- Characteristic X
- Characteristic Y
- Characteristic Z

Examples:

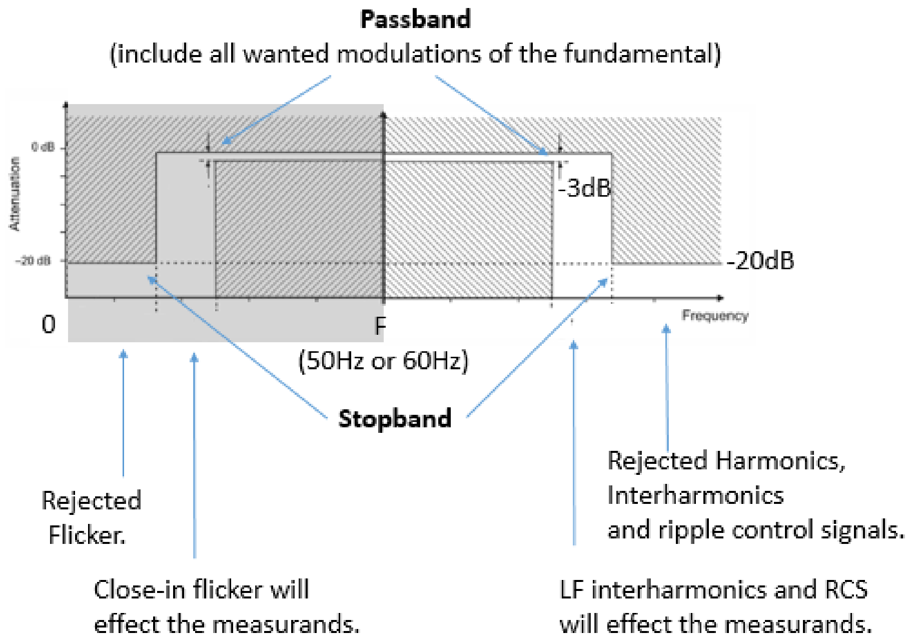
- Accuracy (steady state)
- Response and Settling Time
- Delay time
- Latency
- Frequency bandwidth
- Measurement and Operating range (f, df/dt)

Performance

- **Frequency and ROCOF**

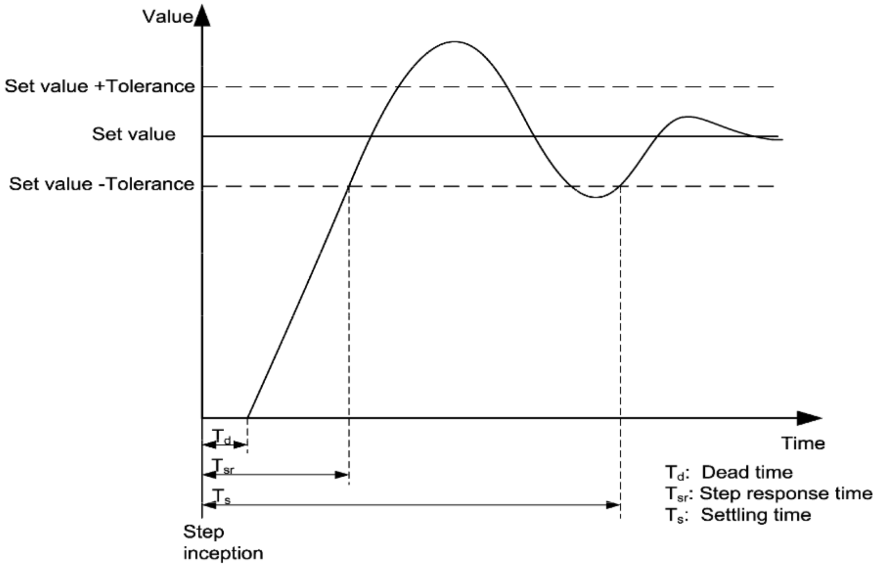
  Resolution and accuracy will be defined for each Use Case

- **Frequency bandwidth**



Measurement bandwidth mask centred on the fundamental

- **Response and Settling time for a step change**



USE CASES

Use case A:

- profile of performance: X1, Y1, Z1 …

Use case B:

- profile of performance.: X2, Y2, Z2 …

Examples:

- Synthetic inertia (time frame < 1s)
- P-f control of DERs
    - Primary reserve (time frame ≈ 1s)
    - Secondary reserve (time frame ≈ 15s)
- Loads with active power management
- Self-dispatchable loads (microgrids)

Out of scope:

Power quality, PMU, freq. protection

Identified USE CASE

- Primary reserve (conventional SM)

  Rapidly re-establishing the active power balanced immediately after an event

  Response time: 0.2s, Accuracy: 0.01Hz

- Decentralized Secondary reserve (conventional SM)

  Each power plant connected to the transmission or the distribution network performs secondary reserve.

  Response time: 0.5s, Accuracy: 0.001Hz.

- Fast response to frequency variation / “synthetic inertia”

  Typically implemented on power storage systems dedicated to power-frequency response

  Frequency: Response time: 0.1s; Accuracy: 0.05Hz

  Rocof: Response time 0.1; Accuracy 0.1 Hz/s

- Load control with active power management
- Load shedding schemes (frequency based)
- Anti-islanding detection

Recommendations for Functional Tests

- To evaluate declared characteristics (X, Y, Z…), not detailed procedure
  - Accuracy
  - Time response
- Influencing factors
  - Phase step change
  - Magnitude change
  - Harmonics
  - Inter-harmonics
  - Sub-harmonics
  - Frequency ramp
  - White noise
  - Flicker

Takeaways

An international standard that provides guidance on frequency and ROCOF measurements:

- Definitions
- Characterize Frequency and ROCOF
- Use Cases
- Performance
- Recommendations for Functional Tests