“Standard Tests and Requirements for Rate-of-Change of Frequency (ROCOF) Measurements in Smart Grids”

Webinar 17 May 2019

Presenters:

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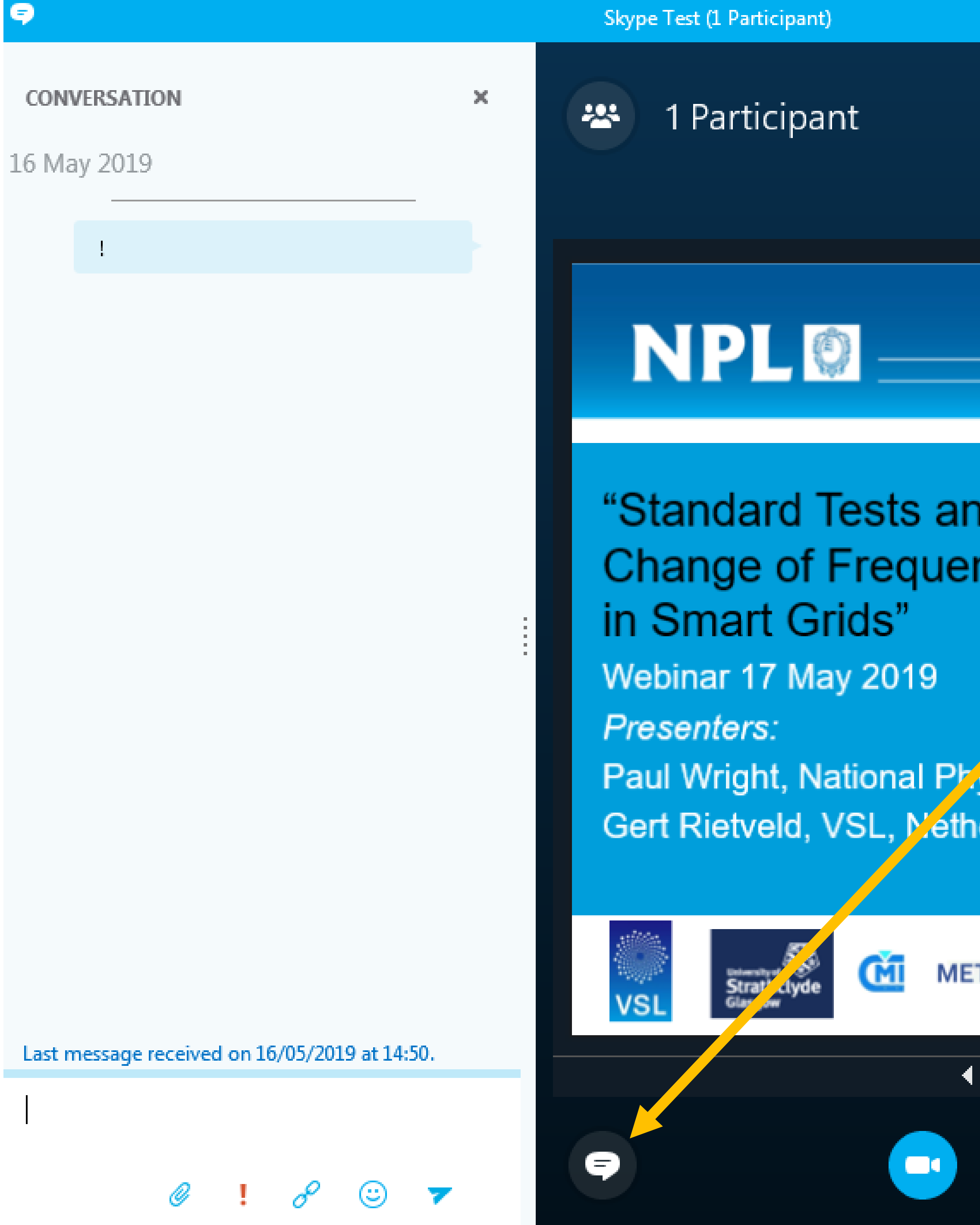
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Agenda (15h UTC until 17h UTC)

1. **Introductions** (5 mins)
2. **Background: ROCOF uses, expectations and problems** (10 min + 10 min discussion)
3. **An overview of the findings of the EU ROCOF project** (15 min + 10 min discussion)
4. **Trade-off of accuracy and latency: use-cases and waveforms** (15 min + 10 min discussion)
   ROCOF use cases derived following discussions with users, and associated library of representative test waveforms each with a target ROCOF accuracy for each case
5. **Algorithms and filter masks** (20 min + 10 min discussion)
   Filter masks for use in PMU algorithms and how they can be designed to attempt to meet the use-case requirements. This will include performance results obtained from testing the filters with the waveform library
6. **The next steps in Standardisation** (5 min + 10 min discussion)
   ROCOF is included in IEEE/IEC Standard 60255-118-1. Discussion on the state of ROCOF standardisation and how the above findings can be used to further the standards process.



RAISE HAND TO SPEAK

- There are a lot of people on the call.
- If you want to make comment or ask a question…
- Please use the comment facility!
- Click here
- and type any character (e.g. !)
- We will invite you to speak
- Requests will be taken in order.
- But we may not have time for all.
- Thanks for your cooperation!

Background: ROCOF uses, expectations and problems

Why is ROCOF important to Utilities ?

- ROCOF is used in **loss of mains relays** which protect distributed generation against disconnection from the synchronous network.
- LOM is important to protect personnel working to on networks.
- ROCOF can be used in **fast frequency response** and "**synthetic inertia**" control schemes which attempt to provide active power response to frequency changes.
- ROCOF can be a metric for **under-frequency load shedding**, where some customers allow their loads to be disconnected to protect the energy balance.

ROCOF is becoming more important to system operators as the number of distributed energy resources (DER) increases.

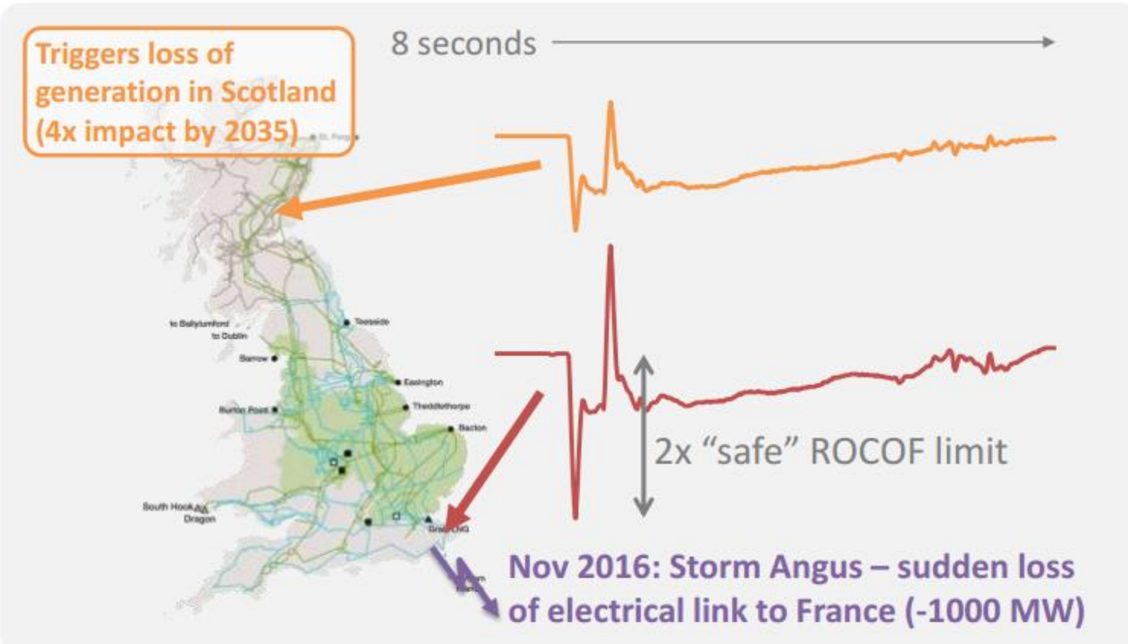
The difficulties of measuring ROCOF

The derivative and double derivative multiply PQ noise
This leads to FALSE TRIPS, faults and ultimately blackouts

ROCOF is the double differentiation of phase – differentiation amplifies noise

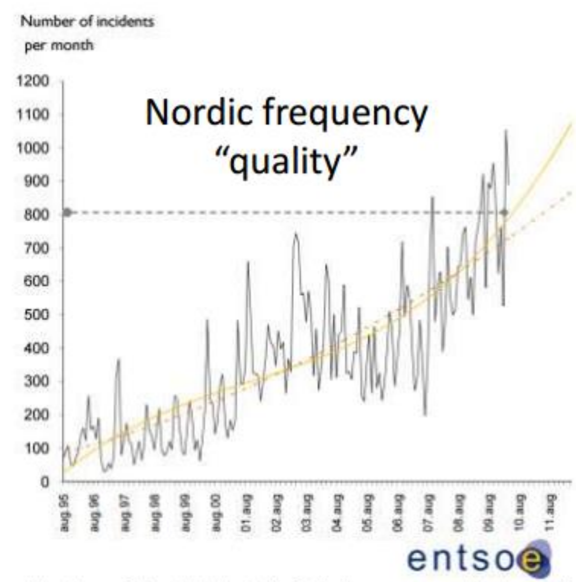
ROCOF events and false breaker trips

Unprecedented grid changes and challenges



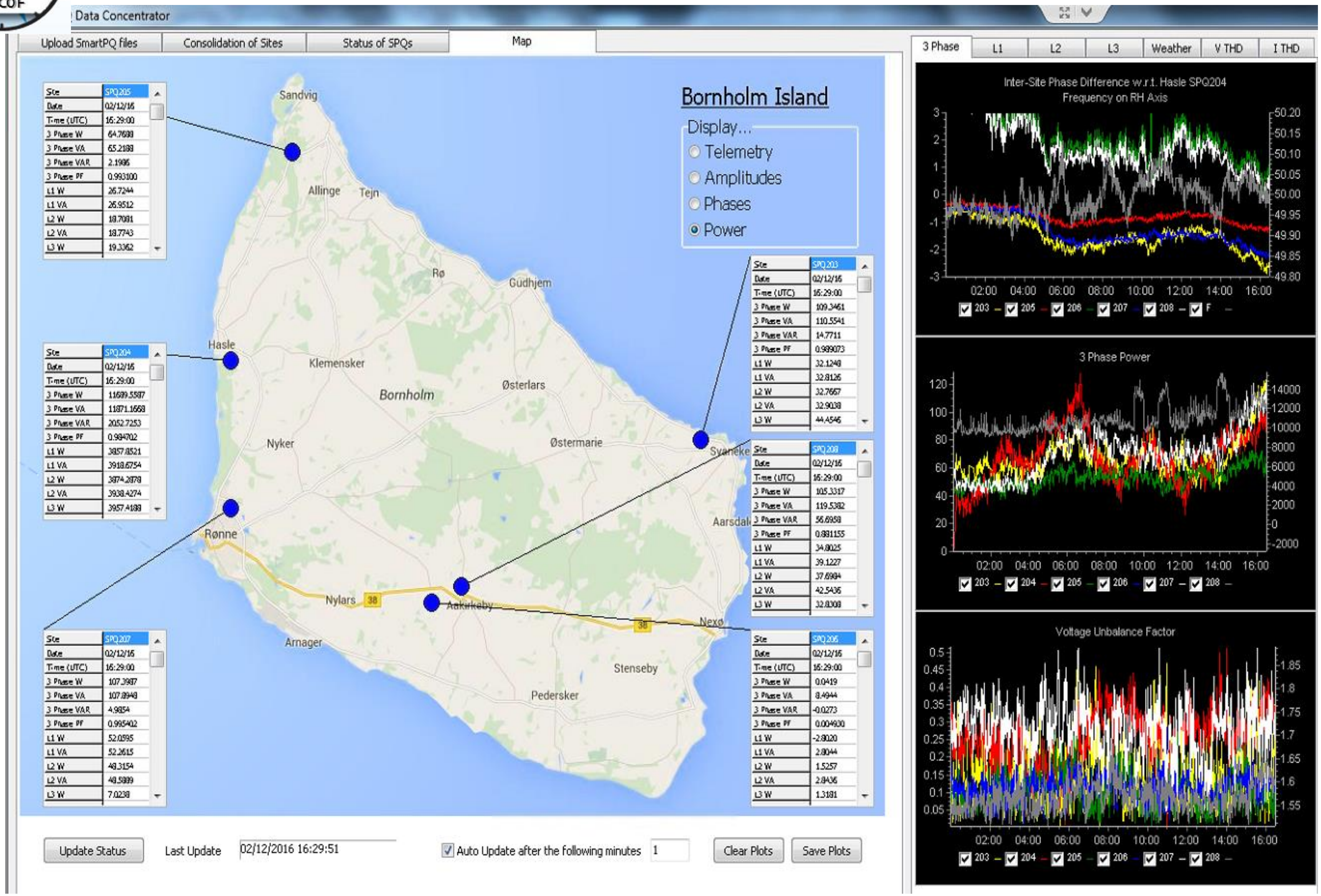
Need timely, robust measurements

2020+ grid: volatile, distributed



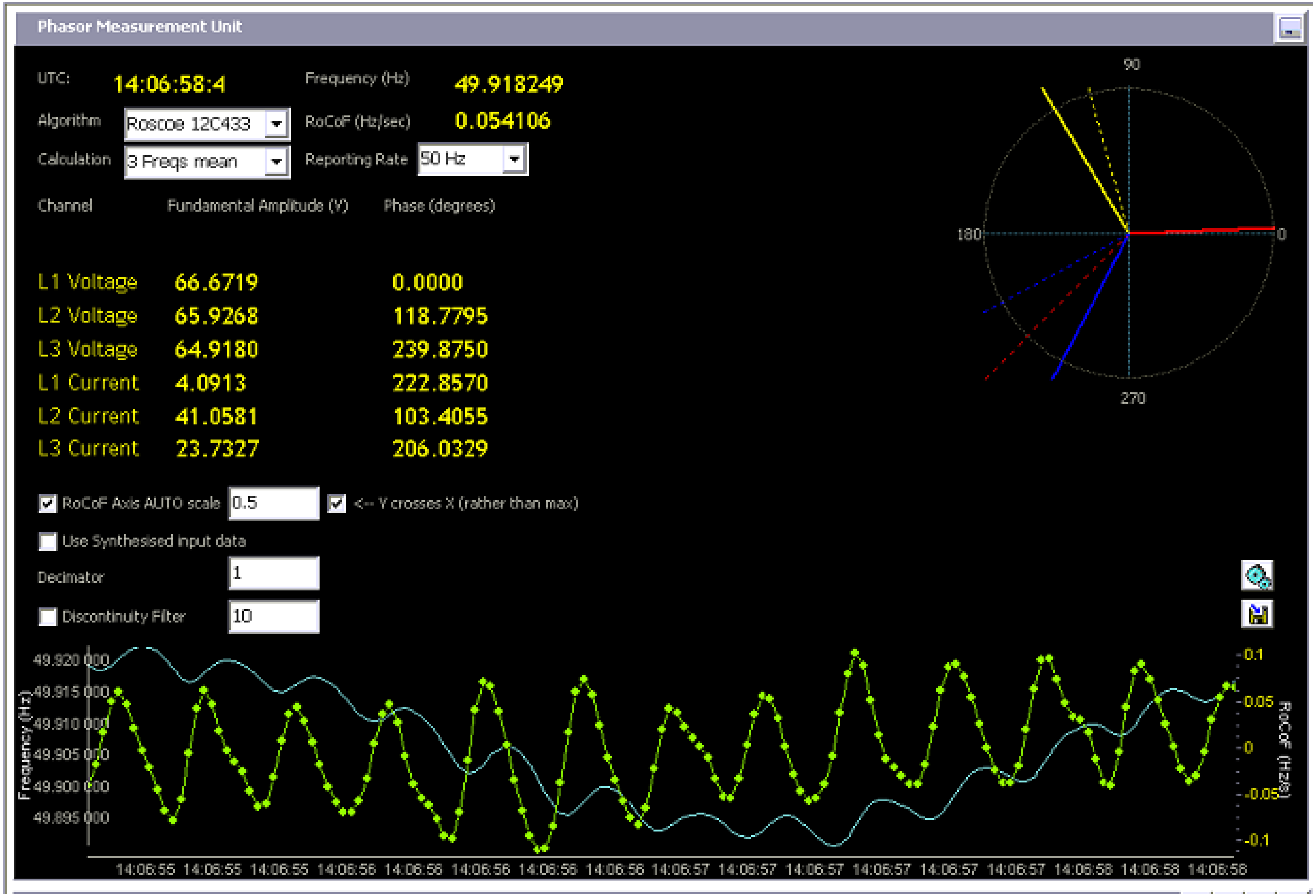
https://www.sintef.no/globalassets/project/balance-management/gardermoen/8---gjerde-statnett---lfc-and-agc---nordic-perspective.pdf

PMU campaign on Bornholm “Green Island”



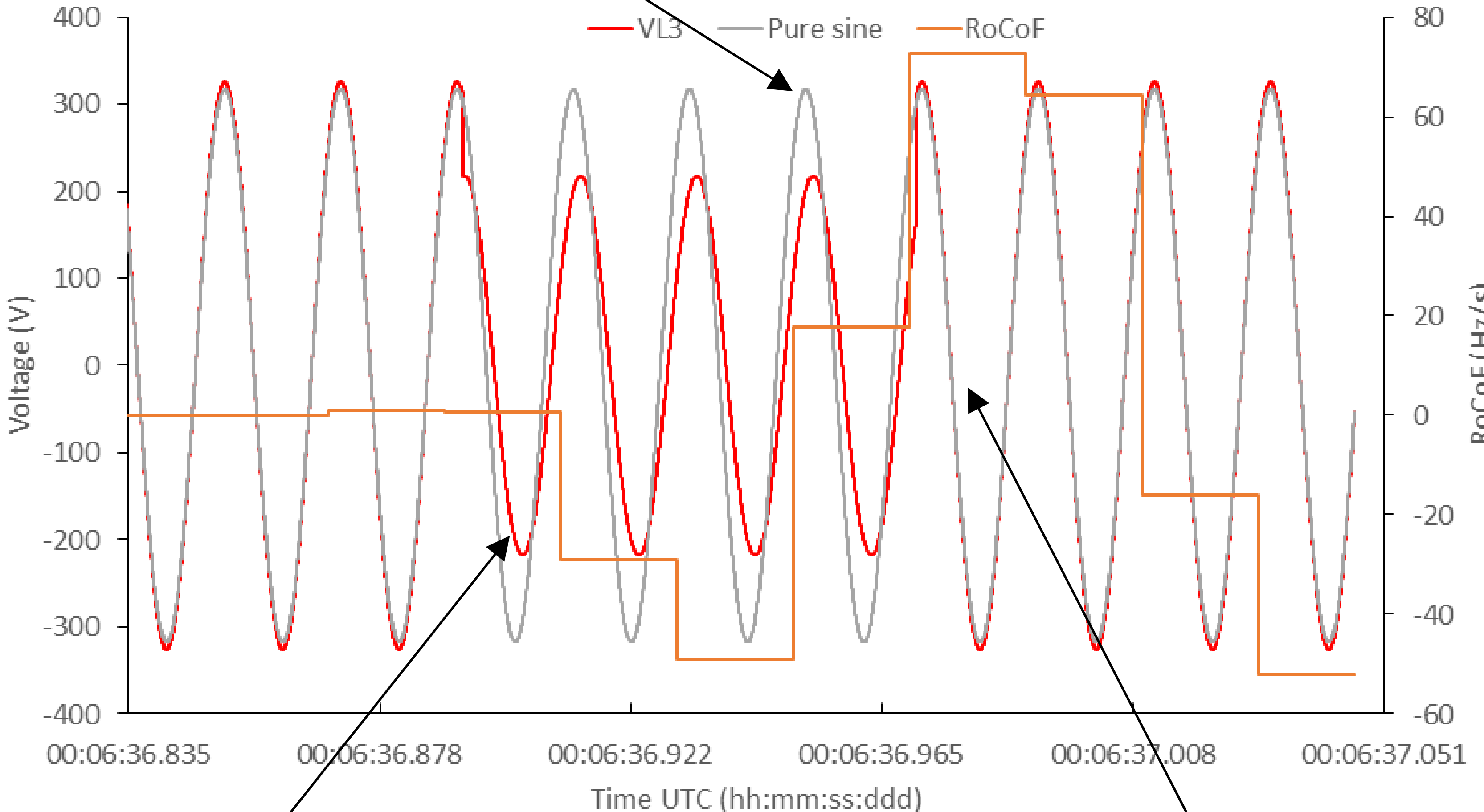
Site at Hasle at 60kV near the undersea connection to the island from mainland Sweden.

Bornholm Island – in “island mode” i.e. all Distributed Generation
09/05/19 – Using a 130 ms latency filter



Threshold trigger to capture waveforms @ RoCoF events

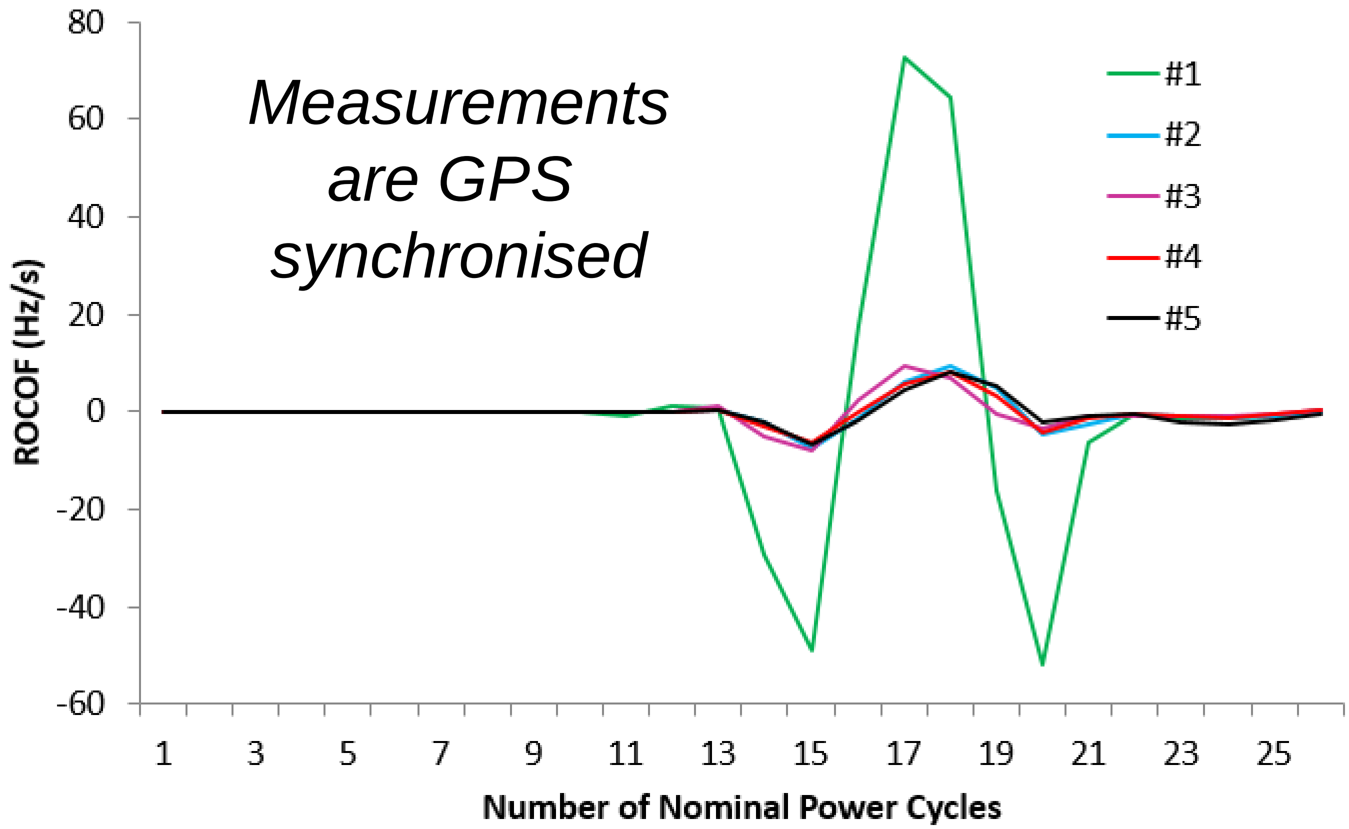
Underlying Frequency



Phase has jumped

and recovered

ROCOF at 5 sites - fault near #1



This is not a change in the underlying frequency of the power system – The double dip is characteristic of a Phase Step. Phase steps cause false LOM relay trips

The difficulties of measuring ROCOF

- In 2014 IEEE/IEC C37.118.1 relaxed many of the ROCOF test accuracy levels for PMUs as they could not be met.
- False trips have become a significant problem.
- In 2016 UK National Grid relaxed the trip level from 0.125 Hz/s to a reduced 1 Hz/s to reduce nuisance trips. Increases islanding risk by ~X100.


IEEE STANDARDS ASSOCIATION

IEEE Standard for Synchrophasor Measurements for Power Systems

IEEE Power & Energy Society

Sponsored by the
Power System Relaying Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

28 December 2011

IEEE Std C37.118.1™-2011
(Revision of
IEEE Std C37.118™-2005)

The inability to measure ROCOF reliably is undermining LOM protection

- ROCOF can also be used as a metric for **fast frequency control** and **under frequency load shedding**.
- Poor ROCOF measurement accuracy and spurious results undermine these innovative schemes.

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

An overview of the findings of the EU ROCOF project

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

What is Euramet?

- Organisation of national metrology laboratories in Europe,
- Runs metrology joint research projects (JRPs) as part of the EMPIR programme
- EMPIR funded by H2020 & National Governments (~50:50),
- JRPs also involve universities and/or industrial partners.

What is a pre-normative R&D project?

- Special JRPs dedicated to a standardisation issue.
- Aim to provide R&D to support the work of SDOs e.g.:
  - new test methods, instruments, test rigs,
  - new algorithms,
  - test protocols,
  - research the need and justification.

ROCOF Project Summary Information

- 3 Year joint research project (JRP)
  June 2016 to May 2019.
- 5 partners:
  - 4 National Government Measurement Labs,
    UK, NL, CZ, CH (NPL, VSL, CMI, METAS).
  - 1 University: University of Strathclyde, UK.
- ~50:50 EU funded/National Funded.
- EU funds from EMPIR (FP7) – Normative Project Fund.
- 4 Technical Work Packages (WP).

User expectations: Use Cases

Objective:

To evaluate the problem of ROCOF measurement in the context of actual use cases and a "wish list" of accuracy and latency requirements from an end-user point of view.

Achievements:

- Survey of ROCOF users regarding accuracy and latency expectations.
- Combined results with ENTSO-E document "Frequency Measurement Requirements and Usage".
- With reference to different user applications, proposed **three use cases**.
- Each use case has different **latency and accuracy expectations**.
- The **use case report** can be accessed here.

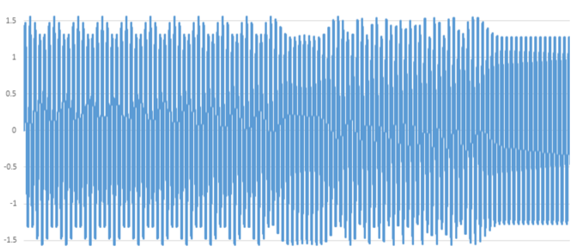
A Library of standard-test-waveforms

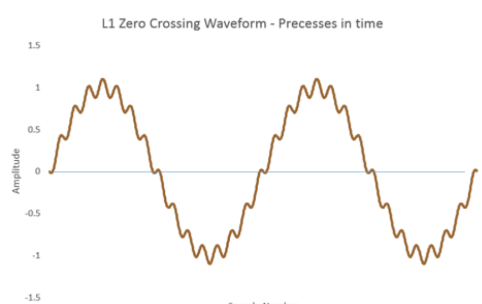
Objective:

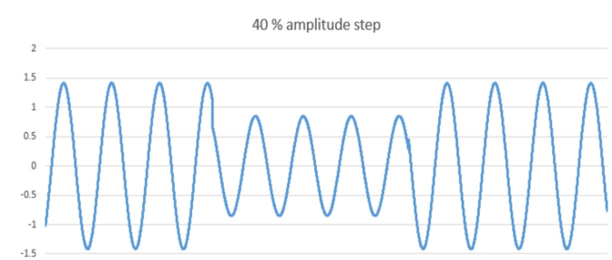
To develop a library of standard-test-waveforms representative of typical PQ events on electricity networks, including extreme events, in order to adequately test ROCOF algorithms and instrumentation containing these algorithms.

Achievements:

- Ten test waveforms for ROCOF instruments are proposed.
- These include: close-in interharmonics, amplitude & phase jumps, noise frequency ramps and unbalance.
- The library of waveforms with pseudo code to generate each signal.
- For each waveform, target accuracies are proposed for each use case.
- The table of test waveforms is given in the use-case report.







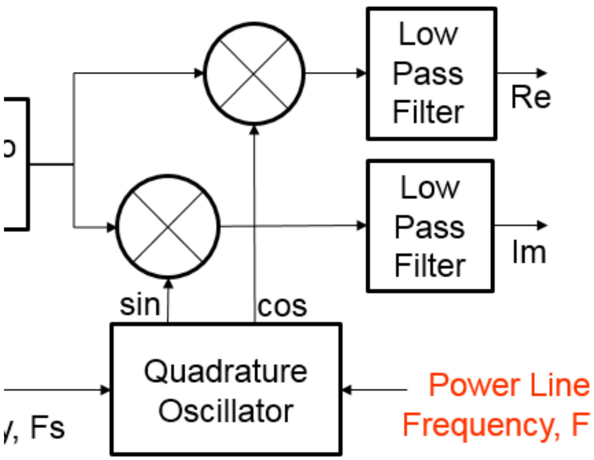
ROCOF Algorithms

Objective:

To review, develop and optimise algorithms to reliably and accurately measure ROCOF over the full range of network conditions, specifying any use cases where this is not achievable.

Achievements:

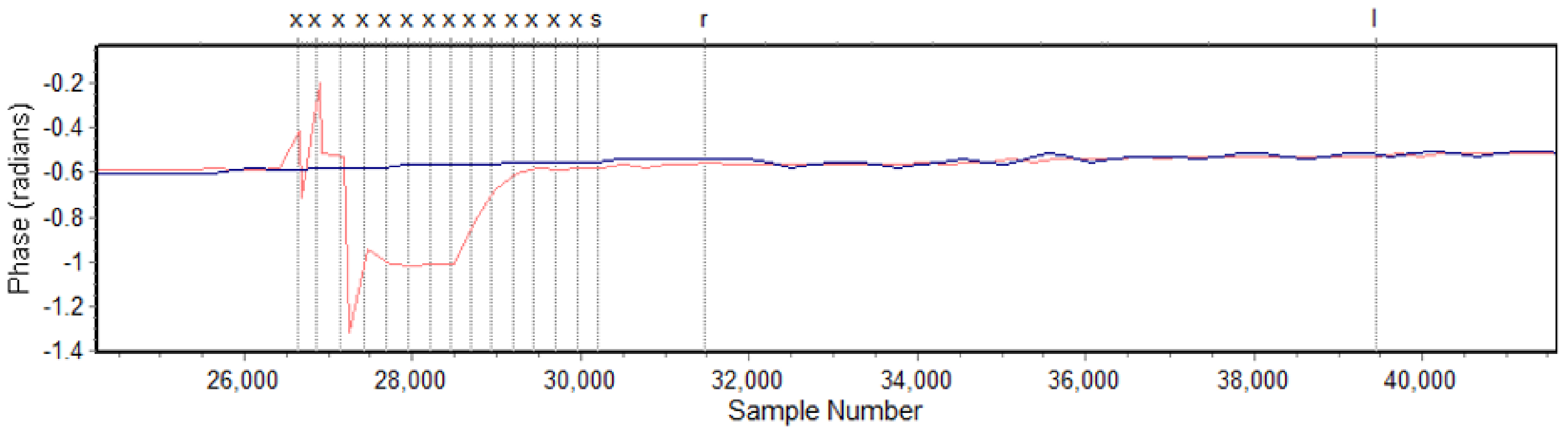
- Basis: IEEE PMU heterodyne algorithm.
- Challenge: reject poor PQ but pass power system dynamics.
- Tailor filters to use cases - maximise the filtering to available latency.
- Used a simple cascaded box-car filters architecture.
- Implemented in PMU and tested with waveforms and in networks.



ROCOF Algorithms - Phase Steps

- Phase steps are a major challenge for ROCOF measurements.
- Developed and tested a phase step ride-though method.
- Still needs to real-time implemented and tested in a network.
- Open access IEEE TIM paper here

Phase Trajectory for Bornholm Events



Correcting for the phase step in 02 Feb 2018 event.

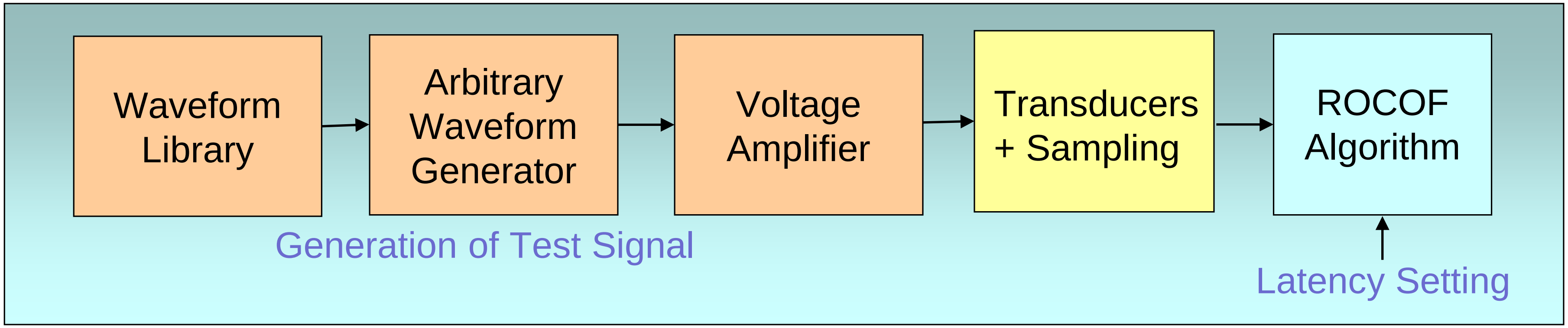
Testing ROCOF Instruments

Objective:

To implement and test selected ROCOF algorithms utilising the standard waveform library via computer simulations as well as in instrument hardware that will be tested using precisely generated electrical waveforms in the laboratory. This will lead to compliance verification protocols for ROCOF instruments.

Achievements:

- Implemented three real-time algorithms on a PMU: *Heterodyne, Roscoe, and Sine-fit.*
- Selectable latencies for each of the three use-cases.
- Applied the 10 test conditions in simulation and lab generation.
- For each waveform - compare algorithms for each use case latency.
- This demonstrates the practicality of the 10 tests.



ROCOF Instrument Reference Architecture

Objective:

To specify a reference signal processing architecture for a ROCOF instrument. To use sensitivity analysis to determine the uncertainty specification for each element of the measurement chain required to manufacture an instrument to implement the selected algorithms and be capable of compliant accuracy measurements for each of the use cases.

Achievements:

- Model architecture: **sampling part** and **processing part.**
- Incorporates*: transducers, analogue signal processing, filtering, analogue to digital convertors, digital signal processing, computational processing.*
- Noise and jitter effects of modules are analysed.
- Monte-Carlo simulations to determine the ROCOF errors caused by the measurement chain.

The trade-off of accuracy and latency: use-cases and waveforms.

The ideal ROCOF Instrument Wish List

- It can measure all modulations of the power system 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
  - Sudden jumps in phase (associated with power system 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

Survey of Users' Expectations of ROCOF Measurements

To determine users' expectations of ROCOF, a survey was undertaken:

1. Describe up to **3 of the main uses of ROCOF.**
2. What **device(s) do you use** to derive the ROCOF data.
3. Your expectation and need of the **accuracy and noise/ripple level** (in Hz/s) during normal grid conditions.
4. What is the **highest noise or error level** would still make ROCOF usable in each *use case* during abnormal conditions (high PQ).
5. What time **latency** is considered normal for the ROCOF measurement in each *use case*.
6. If a longer **latency is unavoidable**, what would the upper limit on latency be for each *use case*.
7. What level of noise, ripple or error would make ROCOF **useless** in each *use case.*
8. Are you effected by **phase steps**? How do your applications deal with them, and/or how would you propose to deal with them?
9. During **close-in full-depth faults** ROCOF is unusable – how do you deal with this?

Users' Expectations of ROCOF – ENTSO-E Study

About the same time as the survey, ENTSO-E also published their expectations for power system frequency measurements:

Table 1: Frequency Measurement Requirements

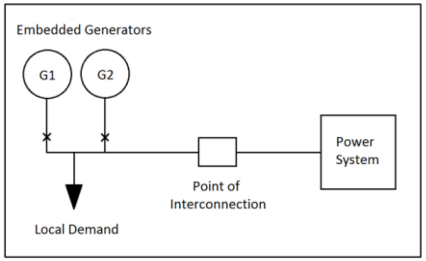
Application	Meas. Window / ms	Accuracy	Comments
Protection	90-120[3]	30 mHz	generation unit, underfrequency load shedding
Local control	100-200	10 mHz	decentralised generation control
Centralised control	500	1 mHz	centralised generation control (AGC)
LFSM	100	50 mHz	system control, system protection
RoCoF	180-240	50 mHz/s	additional protection criteria for generation or load
RoCoF	500-1000	1 mHz/s	evaluations on synchronous area level

ENTSO-E, "Frequency Measurement Requirements and Usage - Final Version 7", RG-CE System Protection & Dynamics Sub Group, 2018.
(LFSM = Limited Frequency Sensitive Mode, activated in network emergency for under or over frequency)

Survey of Users’ Expectations of ROCOF Measurements

The following uses emerged:

1. Loss of Mains (LOM) protection,
2. Under Frequency Load Shedding (UFLS),
3. Generator Frequency Response (synthetic inertia).



Summary of ROCOF Expectations for LOM Protection

User	Max Error (Hz/s)	Max Delay (ms)	Comments
DNO	0.05	100	
TSO	0.125	2500	
ENTSO-E	0.05	120	
IEEE 2011	0.01	40	No longer in force, relaxed 2014
IEEE 2014	0.4	40	Replaces above
UK DC0079 2017 (relaxed G59)	0.1	500	Accuracy of 0.1 Hz/s is assumed from 10 % of the setting value of 1 Hz/s.

Survey of Users' Expectations of ROCOF Measurements

The ENTSO-E and the user survey findings have been incorporated into **three use-cases** summarised in the table below:

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

Survey of Users' Expectations – Disturbances, PQ Issues

The survey responses, other user inputs and results from on-site measurements led to a set of waveforms for use as test conditions, A **selection of the proposed tests** are shown following:

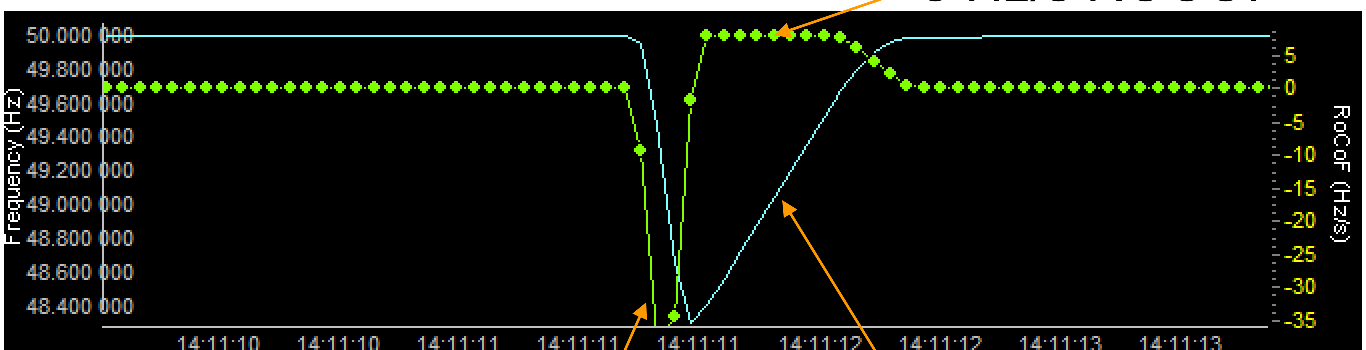
Disturbance	Existing IEC/IEEE C37.118.1	Proposed additional test	Rationale	Worst Case RFE Ripple (Hz/s)
3) Noise	No test	3 % of the fundamental white noise up to 2 kHz. (Steady state, at nominal f_0, V, I)	To account for heavy plant in the vicinity of the connection.	UC1: 1.2 UC2: 0.2 UC3: 0.1

Survey of Users' Expectations – Disturbances, PQ Issues

Disturbance	Existing IEC/IEEE C37.118.1	Proposed additional test	Rationale	Worst Case RFE Ripple (Hz/s)
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

Response from a UC1 ROCOF Instrument

8 Hz/s ROCOF

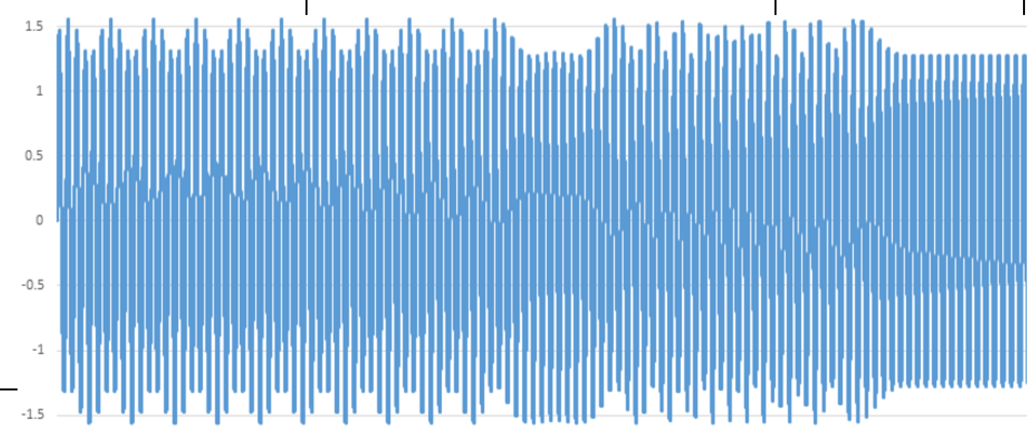


Phase Step ROCOF Response

8 Hz/s ramp in frequency

Survey of Users' Expectations – Disturbances, PQ Issues

Disturbance	Existing IEC/IEEE C37.118.1	Proposed additional test	Rationale	Worst Case RFE Ripple (Hz/s)
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 2^{nd} harmonic of the power frequency for all frequencies excluding the stop band. The stop band is defined as ±Fs/2 either side of the fundamental frequency, where Fs is the measurement update rate.	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.	5% tone UC1: N/A UC2: 0.6 UC3: 0.3 10% tone UC1: 2.5 UC2: 0.2



Time series for 90 Hz to 150 Hz sweeping interharmonic at 10% amplitude, stopping at 150Hz shown by the non-modulated part at the end of the time series. (Amplitude vs. time)

Algorithms and filter masks

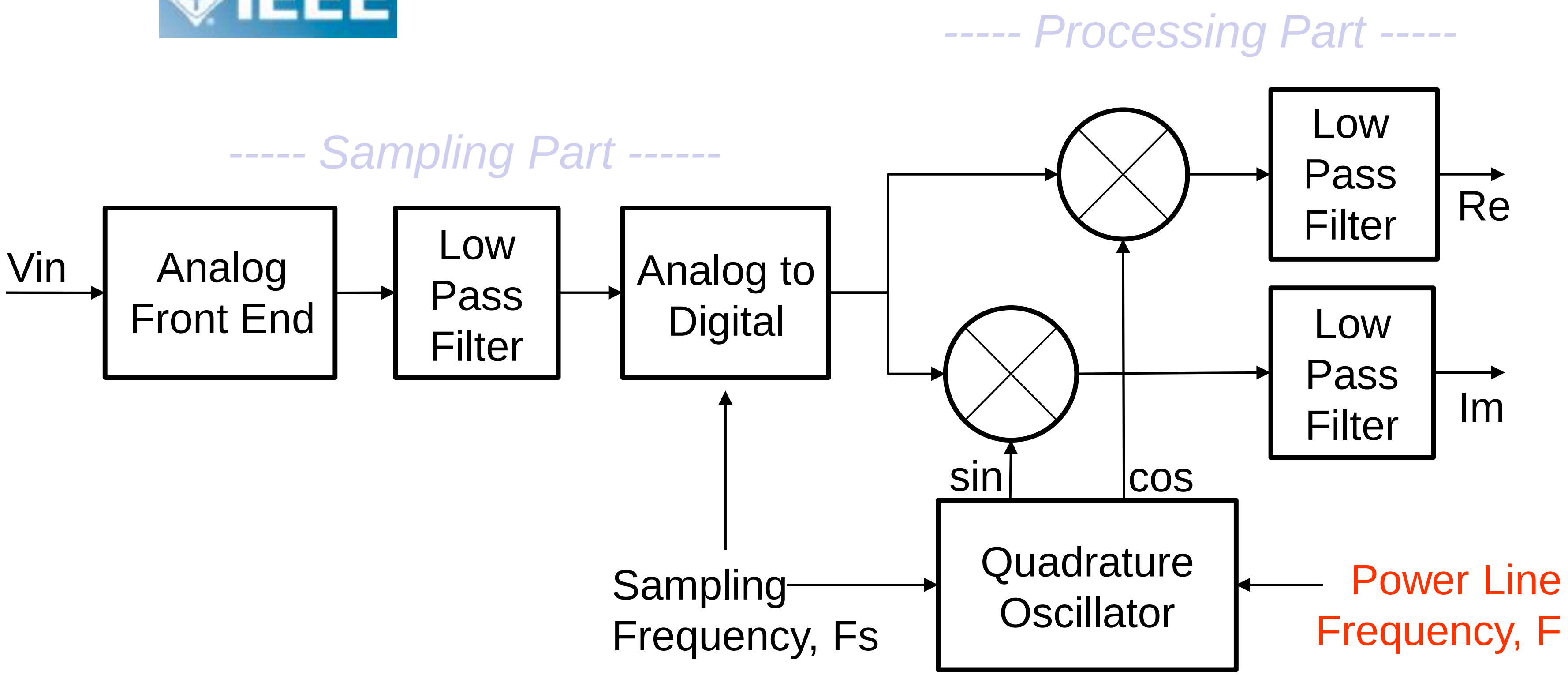
What is required on the Algorithm - Specification

- Efficient – must run in **real time** on an embedded system or similar.
- Stable – must recover after an event such a phase jump
- Low latency – minimise delay between power systems events and the availability of the results.
- Rejection of harmonics, interharmonics and flicker (particularly any interharmonics close to the power frequency).
- Reject (white) noise on the power system voltage.
- Must not attenuate frequencies close to power frequency that are associated with the power system dynamics (what we want to measure!).

Many researchers have developed algorithms…

Here we see how well we can adapt the simple/fast heterodyne to the use cases. (more complex algorithms may do a better job!)

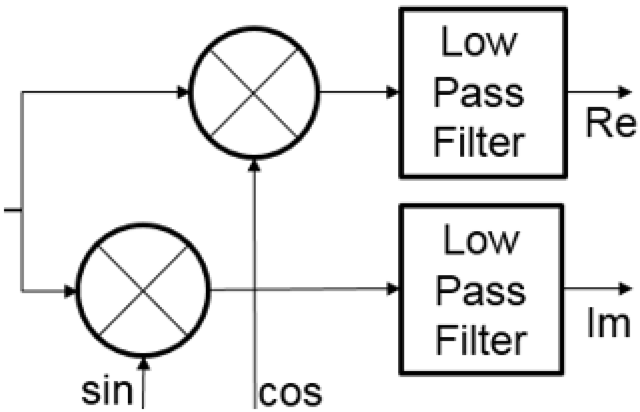
The IEEE PMU Example Implementation (1 of 3 phases)



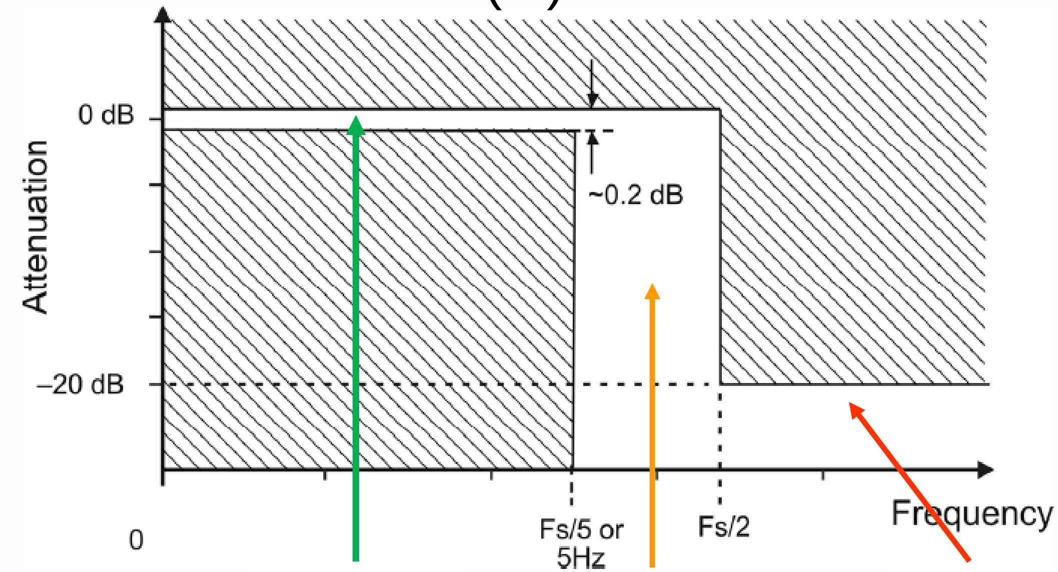
Re and Im give the phase Φ; dΦ/dt is frequency, f; df/dt is ROCOF

Heterodyne from IEEE Standard for Synchrophasor Measurements for Power Systems

Low pass Filters



C37.118 PMU(M) Low Pass Filter Mask



Pass Band

No Man's Land (undefined)

Stop Band

(Fs is the instrument reporting rate; response must be outside shading)

- Pass Band should include power system dynamics – e.g. modulation of the fundamental.
- Stop Band should attenuate unwanted PQ related frequencies (to < -20 dB).
- The response in-between is undefined and crucial to instrument performance

Low-Pass Filter Design Rules for good ROCOF meas^{t}

Pass Band: What is the maximum frequency of modulation on the fundamental voltage waveform, which needs to be measured with reasonably accuracy? (that is: within -3 dB attenuation)

The passband (f_{PB}) should include:
any power system voltage modulation frequency $\boldsymbol{f}$ (system dynamics), centred around the filter tuning frequency ($\boldsymbol{f_T}$ ~50 Hz or ~60 Hz),

Passband Rule: 3dB bandwidth

$$H(|f - f_T|) \le 10^{\left(\frac{-3}{20}\right)} \text{ for all } |f - f_T| < f_{PB}$$

Filter response centred on f_T

-3bB attenuation

The passband

The passband width f_{PB} will be assigned for each use case

Low-Pass Filter Design Rules for good ROCOF meas[t]

Stop Band: How far above the fundamental frequency should unwanted influences (i.e. bad power quality) be rejected from the result ?

Users want to reject harmonic effects…
…also interharmonics near the fundamental….
Worst-case: 10% amplitude interharmonic at 100 Hz (from EMC testing)

Stopband rule 1 RCTs
Attenuate signals of A . .0%)
for all $|f_T - f| > 40$ Hz

(the 40 Hz is *100 Hz minus 60 Hz* fundamental)

A conservative approach to allow flicker levels and interharmonics associated with broadband transients for frequencies not covered by Rule 1

Stopband rule 2: Close-in and flicker
Attenuate signals with $A = 0.05$ (5%)
for all $f_{SS} < |f - f_T| < 40$ Hz

Low-Pass Filter Design Rules for good ROCOF meas[t]

Stop Band – Noise rejection:

Users want to reject noise that will cause ROCOF errors;

- The effect of **extreme** noise observed near an iron works on the public 110 kV network at signal-to-noise ratio of 35 dB.
- Inside the iron works at 20 kV it was even more extreme, only SNR=20 dB.
- The instrument front end also introduces noise at SNR = 74 dB.

Set the requirement of the filter in-terms of the desired ROCOF error (RFE) according to the use case requirements:

Stopband rule 3: Wideband noise

2x (Three-phase RMS RFE) < $\textit{Desired Use Case RFE}_{pk}$

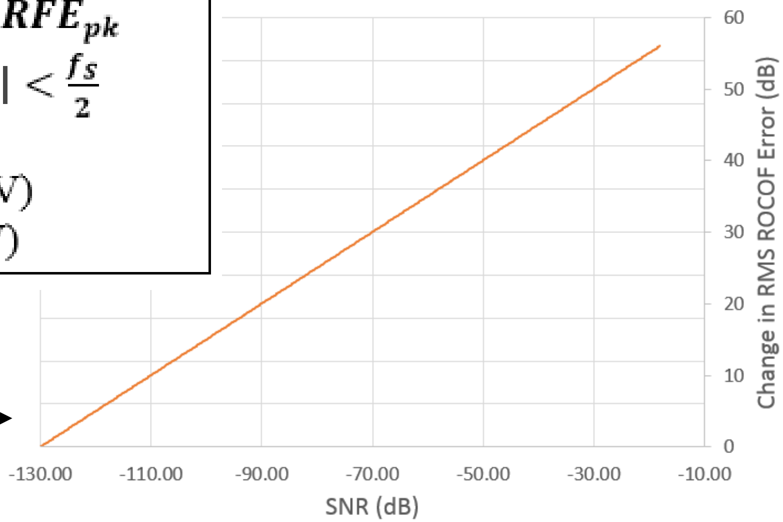
assessed across the full Nyquist range $0 < |f - f_T| < \frac{f_S}{2}$

Rule 3A : SNR 74 dB (ENOB 12)

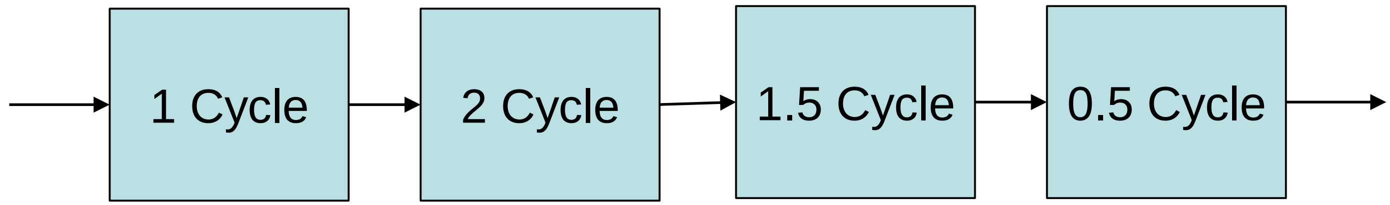
Rule 3B : SNR 35 dB (ironworks external 110 kV)

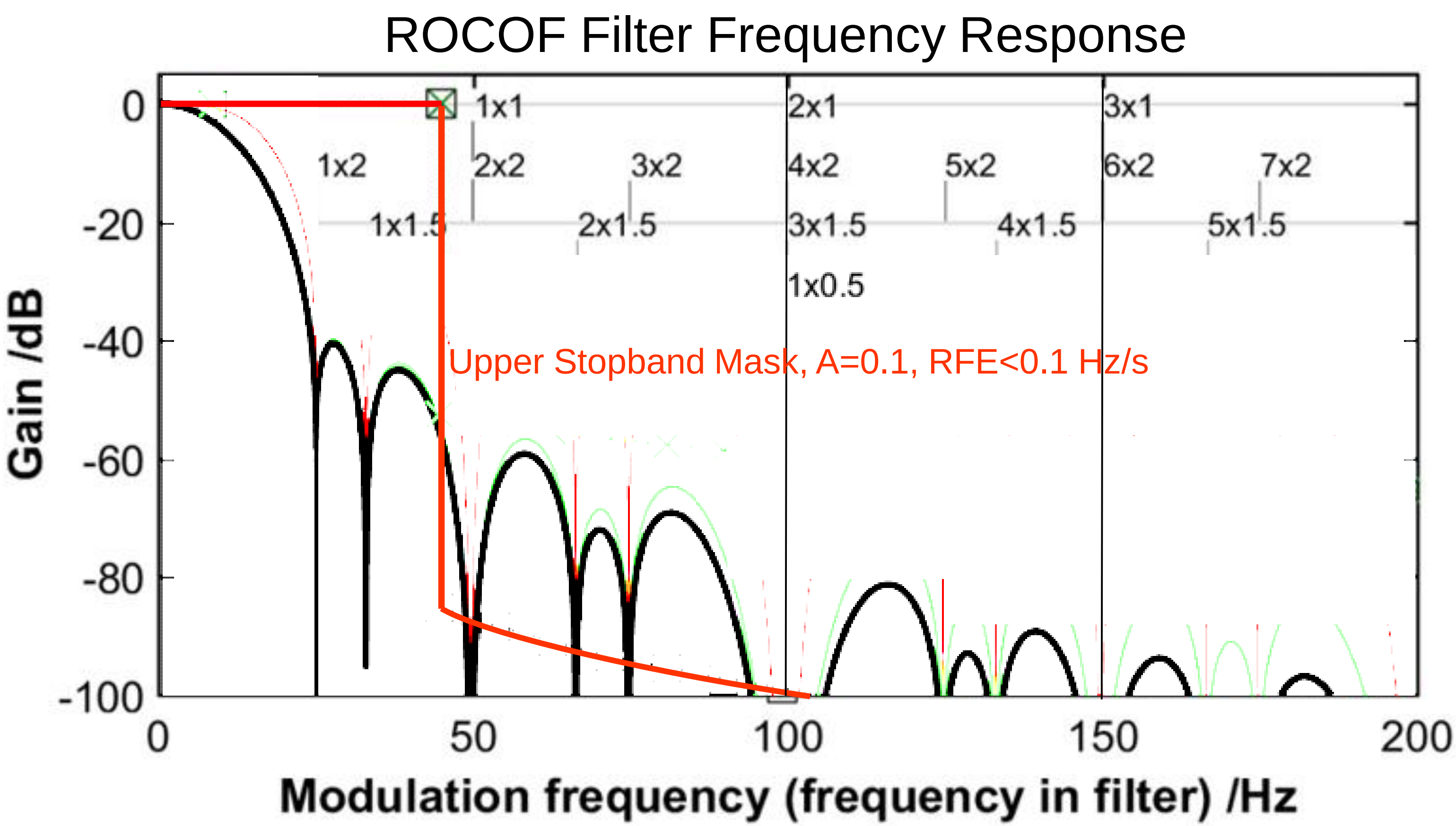
Rule 3C : SNR 20 dB (ironworks internal 20 kV)

Where R is the RMS ROCOF error related to SNR by: →



Cascaded Tuned Boxcar Filters

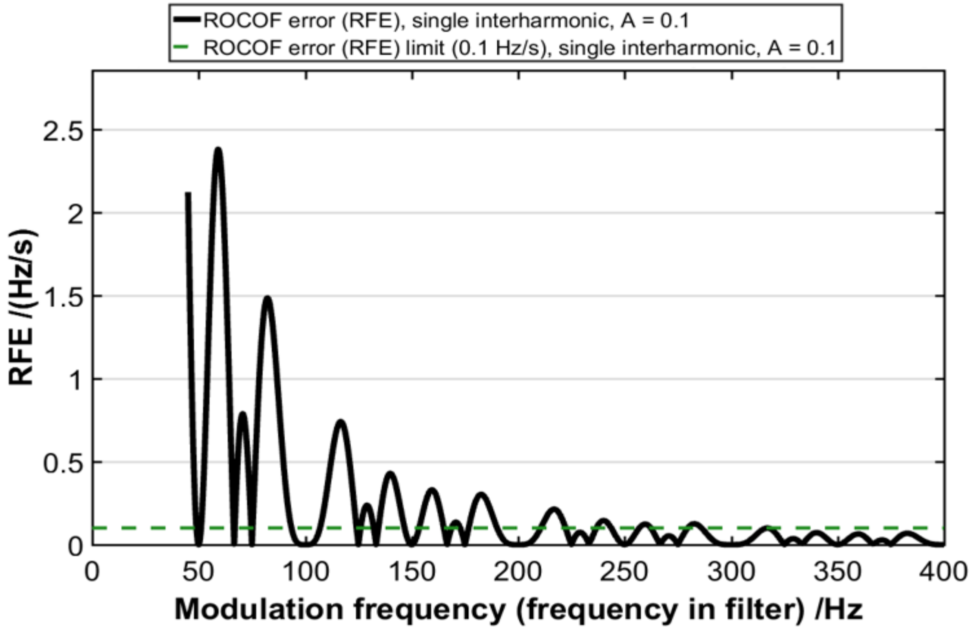




Filter Design Examples Using the rules:

A low latency filter (Synthetic Inertia, UFLS, inter-device oscillations).

- 5-cycle filter window, 50 ms latency and 100 ms window length (at 50 Hz).
- Achieves 8 Hz passband width – easily measures wanted dynamics
- But the stopband starts at 45 Hz from the fundamental – so very susceptible to close-in PQ – **Fails** stopband Rule 1
  2.4 Hz/s peak error for 10% interharmonics (see plot).



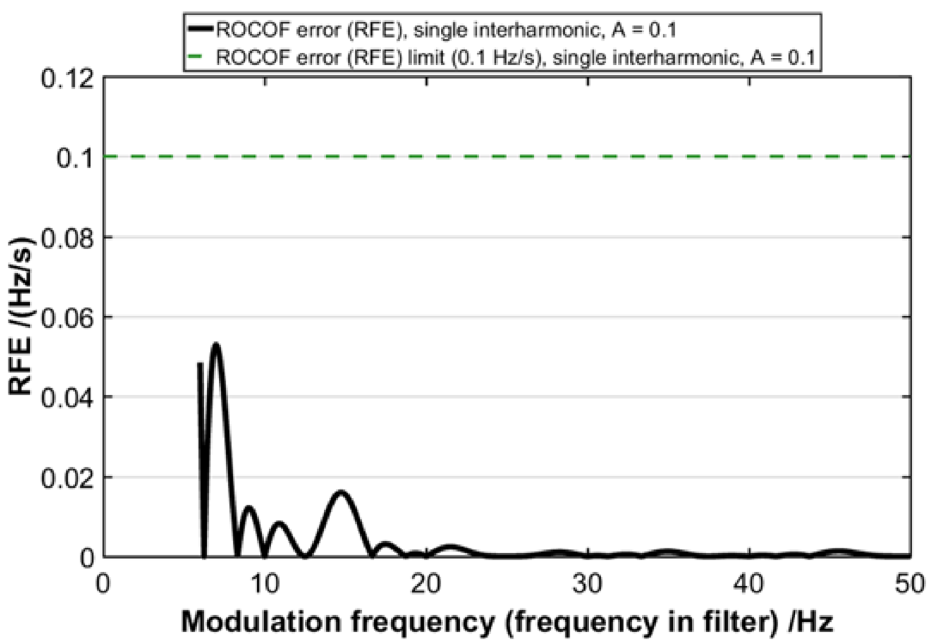
- Stopband starts above 40 Hz so automatically **fails** Rule 2 – all flicker in the passband/no mans's land.
- Very poor noise rejection
  0.32 Hz/s RFE Max Error
  Fails Rule 3

Fast filter only usable if noise & PQ is very well understood / managed.

Filter Design Examples Using the rules:

Long latency, very stable (Loss-of-mains tripping functions).

- 25-cycle filter window, 250 ms latency and 500 ms window length.
- 1.88 Hz passband width – just **Fails** Passband Rule (>2 Hz) – but long enough for most inter-area oscillations.
- Stopband starts at 6 Hz from the fundamental.
- Rule 1 **Pass**: <0.01 Hz/s peak error for 10% interharmonics.



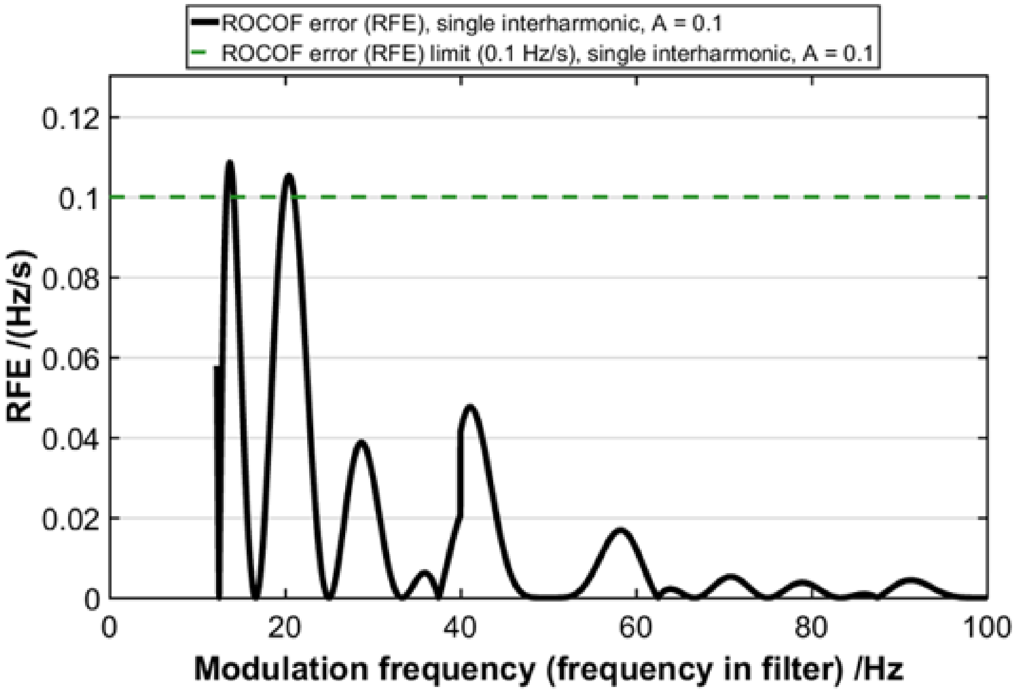
- Rule 2 **Pass**: ~0.06Hz/s RFE for 5% harmonics and flicker
- Rule 3 **Pass**: Very good noise rejection even able to achieve 0.03 Hz/s RFE inside iron works.

Excellent performance at the expense of long latency and narrow passband.

Filter Design Examples Using the rules:

Compromise Device. (*c.f.* 25 cycle – long latency; *c.f.* 10 cycle – filter too weak)

- 13-cycle filter window, 130 ms latency and 260 ms window length.
- 3.63 Hz passband width –useful width for dynamics.
- Stopband starts at 12.5 Hz from the fundamental –
- Rule 1 **Pass**: ~0.11 Hz/s peak error for 10% interharmonics



- Rule 2: **Just fails**, 0.11 Hz/s for 5% interharmonics and flicker.
- Rule 3: **Just fails**, noise rejection achieve 0.13 Hz/s RFE inside iron works. (target 0.1 Hz/s for 20 dB SNR).

Good rejection of noise and PQ influences with more acceptable latency and good passband width.

Summary: Filter Design Challenges and Trade-offs

- Low latency filters have higher stop band start frequencies.
  E.g. for 50Hz power systems:
  50ms latency filter, the stopband starts at F+25Hz (75Hz)

  But for slower filters…
  250ms latency filter, the stopband starts at F+6Hz (56Hz).

  So low latency filters will be poor for close-in PQ and noise.

- Low latency filters have wide pass band and will capture power system dynamics (& unwanted PQ),
  whereas slow filters have narrow pass bands which may miss some interarea/device oscillations.

- There is no easy answer, only compromises:
  assigning a filter to each use case allows users to select a compromise for the given application.

The next steps in Standardisation.

Summary and possible next steps in standardisation

The use case study has given a clear indication on the required ROCOF accuracy for typical applications:

- Ideally 0.01 Hz/s, preferably < 0.05 Hz/s, certainly < 0.1 Hz/s

⇒ adjust test limits in IEEE/IEC Standard 60255-118-1?

The evaluation of grid conditions 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

⇒ Consider in next IEEE/IEC Standard 60255-118-1 update?
(balance required test time versus completeness in testing)

ROCOF algorithms have been evaluated and improved

- Design criteria for ROCOF algorithms
- Series of implementations, optimised for different use cases

⇒ Achievable, realistic accuracies for proposed ROCOF test signals

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

Disturbance	Existing IEC/IEEE C37.118.1	Proposed additional test	Rationale	Worst Case RFE (Hz/s)
1) Harmonics	Single tone swept to 1 kHz. 1 % for P Class, 10 % for M Class	Harmonics number and amplitude in percent of the fundamental. Harmonic phase angles are zero. H2: 2 %; H3: 5 %; H4: 1 %; H5: 6 %; H6: 0.5 %; H7: 5 %; H8: 0.5 %; H9: 1.5 %; H10: 0.5 %; H11: 3.5 %; H12: 0.5 %; H13: 3 %.	More realistic and quicker to perform test. IEC61000-2-2 [8] refers to a tolerated THD of 8 %. As the PMU algorithm will low pass filter the signal, higher order harmonics are less challenging for the algorithm. The chosen harmonics are therefore limited to H13 to simplify the testing.	UC1: 0.02 UC2: 0.02 UC3: 0.01
2) Additional zero crossings	Similar to above, but phase is important	10 % of interharmonic at 14.01401• f_0 at an angle of 180 degrees relative to the fundamental.	To test sensitivity to multiple zero crossings. 10 % is the maximum value allowed by the power line communications standards (Meisner curve) [9]. The tone frequency is chosen to cause the variable zero crossing position to precess in time, changing the calculated "period" if the zero-crossing method were to be used.	UC1: 0.02 UC2: 0.02 UC3: 0.01
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
4) Amplitude Steps	Step change of 10 % of amplitude	40 % of amplitude dip on all phases; unbalanced test with 40 % amplitude dip on each phase in turn, with the other phases at 100 %. The dip duration should be long enough to the ROCOF to settle to the same ripple as before the dip.	More realistic short fault condition	UC1: 0.02 UC2: 0.02 UC3: 0.01
5) Phase steps (or jumps)	0.1 radian	0.3 radian The step duration should be long enough to the ROCOF to settle to the same ripple as before the step.	More realistic short fault condition	UC1: 50 UC2: 25 UC3: 5

Disturbance	Existing IEC/IEEE C37.118.1	Proposed additional test	Rationale	Worst Case RFE (Hz/s)
6) Off nominal frequency		Off nominal harmonics: propose a composite waveform as per the first entry in this table but shifting the fundamental frequency by ±2 Hz either side of the nominal power system frequency f_0.	Off-nominal frequency testing with harmonics is important, since the heterodyne mixing frequency in the PMU may cause the attenuation notches in the digital filters to misalign. IEC61000-2-2 [8] allows nominal frequency variations of ±2 Hz.	UC1: 0.02 UC2: 0.02 UC3: 0.01
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 frequency for all frequencies excluding the stop band. The stop band is defined as ±Fs/2 either side of the fundamental frequency, where Fs is the measurement update rate.	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 [9] limits.	5% tone UC1: N/A UC2: 0.6 UC3: 0.3 10% tone UC1: 2.5 UC2: 0.2 UC3: 0.01
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
9) Unbalance or phase misconnection	No tests	Repeat the noise test but with phase L1 with a phase shift of 180 degrees. See NOTE 4.	This simulates the misconnection of one of the PMU channels. This has a similar magnitude of effect as a number of serious unbalanced faults.	UC1: 2 UC2: 0.3 UC3: 0.1

ROCOF project reports and papers

Reports:

- The ROCOF use-case report gives a detailed description of the ROCOF uses cases together with the proposed test waveforms.
- A report on the specifications of a reference signal processing architecture for a ROCOF instrument, including the uncertainty specification for transducers, analogue signal processing, filtering, analogue to digital convertors, digital signal processing, computational processing.

Papers:

- Gert Rietveld, Paul Wright, and Andrew Roscoe, "*Reliable Rate of Change of Frequency (ROCOF) Measurements: Use Cases and Test Conditions*", in preparation for publication in IEEE TIM (2019)
- Andrew J. Roscoe, Kevin Johnstone, Paul S. Wright, and Gert Rietveld, "*Filter Designs for Frequency and ROCOF (Rate of Change of Frequency) Measurement Devices*", submitted for publication to IEEE TIM (2019)
- Paul S. Wright, Peter N. Davis, Kevin Johnstone, Gert Rietveld, and Andrew J. Roscoe, "*Field Measurement of Frequency and RoCoF in the Presence of Phase Steps,*" IEEE Transactions on Instrumentation and Measurement, Early access, (2018). **DOI:** 10.1109/TIM.2018.2882907
- Andrew J. Roscoe, Steven M. Blair, William Dickerson, and Gert Rietveld, "*Dealing with Front-End White Noise on Differentiated Measurements such as Frequency and ROCOF in Power Systems*,"
IEEE Transactions on Instrumentation and Measurement, **67**, No. 11, pp. 2579 – 2591 (2018).
DOI: 10.1109/TIM.2018.2822438
- Andrew J. Roscoe, Adam Dyśko, Ben Marshall, Martin Lee, Harold Kirkham, and Gert Rietveld, "*The Case for Redefinition of Frequency and ROCOF to Account for AC Power System Phase Steps*", Proceedings of the IEEE international workshop on Applied Measurements for Power Systems (AMPS), Liverpool, UK, pp. 1 – 6 (2017). **DOI:** 10.1109/AMPS.2017.8078330