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1 Overview

This project performed the pre-normative research required to develop new IEEE/IEC/CENELEC standards for rate-of-change-of-frequency (ROCOF) measurements in electricity networks. Network frequency and changes in network frequency are key indicators of network stability and of the balance between electricity supply and demand. This balance is becoming more critical with the increased use of highly-variable renewable energy sources (RES) for electricity generation, and at the same time present ROCOF measurements are inadequate for monitoring this balance.

2 Need

The increased use of RES is essential if the EU is to meet its 2020 objective of 20 % renewable electricity generation and its further 2050 objectives of at least 50 % renewable electricity generation. Traditional carbon-based electricity generation uses massive rotating machines which provide significant inertia to the grid, able to absorb unpredictable changes in consumer demand. They also act as voltage sources, leading to an almost "perfect" power quality (PQ). By contrast, RES are connected to the network via power-electronic converters. These generally provide negligible contribution to grid inertia, and often have a strong negative contribution to PQ. PQ is further degraded by other new emerging grid components like HVDC (High Voltage DC) Links, and electric vehicle chargers, which are also converter-connected to the grid. ROCOF is required as a metric of system inertia in order for network operators to take control actions in order to maintain system stability. Poor PQ and other short-lived events on the electricity supply can cause large ROCOF errors which would lead to false control actions. It is therefore important to understand the conditions in which ROCOF needs to be measured by surveying possible network operational scenarios. Algorithms can then be selected and configured to measure ROCOF and the limitations and eventual expectations of the measurement can be understood, such that control strategies can be pursued by network operators with confidence. IEC/IEEE TC95 WG1 have therefore called for research to be carried out to address the lack of standardisation in this area.

3 Objectives

A "use case" is defined as a particular situation in the grid where a utility would like to perform a ROCOF measurement. This maybe under normal operating conditions or during an exceptional event such as the sudden disconnection of a large load or generator.

The "wish list" will define the desired specification of accuracy the measurement latency (or measurement update rate) and cost-effectiveness from an end-user point of view for the given use cases.

In order to develop a ROCOF standard, this pre-normative project addressed the following scientific and technical objectives:

1. To evaluate the problem of ROCOF measurement in the context of actual use cases and the "wish list" from an end-user point of view. 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.
2. 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.
3. 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 suitable for inclusion in a ROCOF standard (new or pre-existing).
4. To specify a reference signal processing architecture for a ROCOF instrument suitable for inclusion in a ROCOF standard. To use sensitivity analysis to determine the uncertainty specification for each element of the measurement chain (this could include: transducers, analogue signal processing, filtering, analogue to digital convertors, digital signal processing, computational processing) required to manufacture an instrument to implement the selected algorithms and be capable of compliant accuracy measurements for each of the use cases.

5. To work closely with the European and International Standards Developing Organisations, in particular CENELEC TC8X and the working-group/technical committee responsible for IEEE/IEC 60255 118-1, and the users of the standards they develop, to ensure that the outputs of the project are aligned with their needs, communicated quickly to those developing the standards, and in a form that can be incorporated into current standards and used to develop a new internationally accepted standard at the earliest opportunity.

4 Results

4.1 Objective 1

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

The measurement of ROCOF is particularly sensitive to power system disturbances and noise. As a result, relatively intensive filtering must be employed in order to deliver robust and usable data. For example, if noisy measurements are averaged, the simplest form of filtering, the availability of the data is delayed by the number of readings used in the calculation, therefore introducing a latency period.

This results in a trade-off between accuracy and latency, which in turn may give rise to a disconnect between the expectations of users and what is practically achievable.

Using a questionnaire, electricity energy utilities were asked to describe their ROCOF use cases and to give information on the specifications which they would like to see met by potential future devices, in terms of both measurement accuracy and latency.

In addition, the European network of transmission system operators for electricity (ENTSO-E) produced a report on their expectations for ROCOF and frequency measurements: "RG-CE System Protection and Dynamics Sub Group" [1]. The findings were presented in a table on "Frequency Measurement Requirements and Usage" [1] which was considered alongside the user questionnaire results.

From these sources, the three main use cases for frequency and ROCOF were identified, namely:

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

Each use case has different minimum accuracy and latency requirements which are discussed below.

Use Case 1, Loss of Mains (LOM) Protection

LOM protection is required when embedded generation (e.g. renewable generation) is used in power systems. Areas of a power network will occasionally become isolated from the wider network either deliberately for maintenance or accidently due to a fault. If the isolated "island" area contains embedded generation, any personnel working to restore power will be at serious risk from intermittent unexpected voltages. LOM (anti-islanding) relays are therefore required to disconnect local renewables when the wider network is not present. This is done by making the assumption that the wider synchronised network has a more stable frequency than an isolated small sub-network. It follows that the rate of change of frequency can be used in protection relays to detect LOM and trip-off the renewables to ensure the protection of engineering personnel.

However, due to common power system disturbances and the particular noise sensitivity of ROCOF, the variation of readings can be larger than the required trip thresholds, resulting in false tripping, for which LOM relays are notorious. These false trips are highly undesirable because they are expensive to the operator and they stress other parts of the grid when major energy sources falsely trip.

A particularly common cause of false trips is ***phase jumps*** which occur due to routine network reconfigurations, circuit breaker operations and other faults. Phase jumps are localised and give rise to changes in the measured value of local frequency and an associated ROCOF spike that will often trip a LOM relay. Distinguishing between changes in localised frequency caused by LOM and those caused by phase jumps, is perhaps the biggest challenge for LOM protection and the setting of relay trip thresholds.

Each network operator will set their own thresholds for LOM relays, taking into account natural frequency variation of their network and in particular the ROCOF that results from the loss of the largest single energy in-feed connected to their network. The sudden loss of that in-feed should clearly not falsely result in a ROCOF that causes mass tripping of renewables protected by LOM relays. As more renewables are connected to a network, the level ROCOF values which will be experienced in normal operation will also increase. So, utilities will need to review trip settings as the generation mix changes.

New regulations for LOM trip thresholds in the UK [2] reflect this problem and trip thresholds have been relaxed from 0.125 Hz/s to 1 Hz/s in an attempt to reduce cost of operator interventions to maintain the frequency variation.

Trip thresholds have an impact on the required accuracy for ROCOF when used for LOM. If a desired accuracy value of $1/10^{th}$ of the trip threshold is chosen, this gives a 0.1 Hz/s accuracy requirement for the UK's new limits. Surveys of other network operators and recommendations by ENTSO-E [1] confirm user ROCOF accuracy expectations to be close to this value.

The other side of the trade-off is latency; ROCOF protection needs to operate in under 2.5 s before the auto reclose of the circuit breakers that caused the LOM in the first place. If auto-reclosure happens before LOM tripping, the reconnected islanded network will connect out of synchronism with the wider network, potentially causing damage to network infrastructure. Any latency in ROCOF measurement eats into this 2.5 s time along with the breaker open time and tolerances.

LOM accuracy and latency requirements accounting for the needs of various sources and concludes the following specification for ROCOF for LOM:

- 0.1 Hz/s maximum error
- No greater than 250 ms measurement delay.

The ability of the ROCOF instrument to make robust and reliable measurements to this specification in the presence of phase jumps remains a major challenge.

Use Case 2, Under Frequency Load Shedding (UFLS).

UFLS devices are used as a last resort protection scheme to disconnect loads from a network to maintain the frequency within limits. These generally trip off a pre-determined amount of demand at a given under-frequency set point, thus redressing the balance between generation and demand and protecting the system frequency.

As with LOM, the spurious activation of ROCOF-based UFLS schemes can have serious implications for system stability and reliability. For example, a high ROCOF value caused by a phase jump could cause the non-coordinated triggering of de-centralised UFLS schemes, leading to a sudden wide-spread loss of load, resulting in a fast over-frequency event.

The findings suggest similar accuracy to the LOM Use Case with slightly shorter latency.

- 0.1 Hz/s maximum error
- No greater than 50 ms measurement delay.

Use Case 3, Generator Frequency Response (synthetic inertia).

Traditional generation plants provide natural inertial response to meet any short-term deficit in generation capacity to meet demand. As the proportion of generation capacity provided by renewables increases, this natural inertia is reduced, limiting the ability of the network to respond to sudden changes. “Synthetic Inertia” (SI) from wind turbines, or a similar concept from battery storage or solar PV can be used to provide some measure of reserve power for injection to the system on a short-term basis.

ROCOF measurements can be used as the control input to the synthetic inertia controller which must be able to discern a genuine ROCOF event (real power imbalance in the system) from spurious readings. This requires the use of long filtering windows of the order 500 ms to provide robust data such that there is no doubt that the synthetic inertia will operate when required to do so, while continuing normal service during spurious disturbance events.

This filtering delay unfortunately prevents extra active power response within the window latency, which in-turn delays the onset of the “inertial” response of the wind generator. The resulting response time is long after that provided by natural inertia from synchronous machines [3] .However, it will still provide response before the primary response (droop) of the synchronous machine governors, and can do so with a higher ramp-rate. Therefore, this generator response still provides a useful contribution towards arresting the initial frequency fall, both in terms of the rate of change of frequency and the depth of the frequency nadir for a loss-of-generation event.

So, in terms of ROCOF latency, a fast response is needed, where “fast” is loosely defined as at least fast enough (e.g. 100’s of ms) compared to traditional response times of synchronous machines (e.g. seconds). ENTSO-E suggests accuracies for frequency of the order of 10 mHz [2].

Tabulated Use Cases

The following table summarises industries views as surveyed in this work and the ENTSO-E findings.

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

Table 1, Proposed Use Cases

From the above table and taking into account what is practically realisable with the above latencies, it is recommended that the **accuracy requirement for ROCOF is set at 0.05 Hz/s**. This lies in between the amended requirement of 0.4 Hz/s of the 2014 IEEE C37.118.1 standard [4] and the 0.01 Hz/s level that is in the original 2011 IEEE C37.118.1 standard [5]. It therefore is concluded that the amended 2014 IEEE requirements are too much relaxed with respect to the original 2011 requirements.

Power System Events and Disturbances

Under *nominal* power system conditions, the above accuracy recommendation is readily achievable using available commercial instruments. However, the prevailing power system conditions are subject to regular disturbances and are unlikely to be *nominal* during times when the power system is stressed, the very times when ROCOF is most relevant.

Likely disturbance conditions including harmonics, noise, voltage amplitude steps, off-nominal frequency, interharmonics and phase steps. Whilst all ROCOF algorithms will be to some extent susceptible to these, it is the occurrence of phase steps (or phase jumps) that are the most challenging for ROCOF algorithms.

Phase steps occur regularly in power systems and are caused by routine events related to network management such are reconfigurations and transformer tap changes, as well as being related to short lived faults. Phase steps result in large ROCOF spikes; if the phase step is localised, that is the underlying system frequency has remained largely stable, then the ROCOF spike can be regarded as misleading.

Typically, up to (and above) 20-degree phase steps can be observed on each phase during faults/reclosures due to strikes on HV lines. The present IEEE C37.118.1 standard [4] includes testing at phase steps of 0.1 radian (5.7 degrees), which is significantly below the 20-degree phase steps occurring during bad weather events.

The ability of a ROCOF algorithm to measure changes in the underlying system frequency to the required accuracy in the required latency time, whilst rejecting localised phase jumps, is the most challenging issue in delivering the useful measurement of ROCOF. Future algorithms to reject phase jumps will most likely require added latency for decision processing.

The future testing of ROCOF instrument implementations at various window lengths (update rates) will need to use test waveforms which are representative of PQ and disturbing events. For high update rates which use short window lengths (5 cycles), achieving the above accuracy target in the presence of slowly modulated voltage (flicker) and close to fundamental interharmonics or subharmonics may not be possible to achieve.

Summary of Disturbance Levels for the Testing of ROCOF Instruments

Based on findings of site measurements, published material and knowledge of the pitfalls in digital filter implementation the following additional disturbance levels are proposed for the testing of ROCOF instruments.

The tests given in Table 2 should be used in conjunction with the user expectations given in the use-case table. Ideally from the user's point of view, the ROCOF worst case ripple for a given use case should not be exceeded in any of the tests. However, for some tests, achieving the user expectations will not be possible. One such example is the presence of phase steps which will give rise to a significant ROCOF spike unless some form of phase step correction algorithm is used.

The right-hand column in the table gives a recommended worst case RFE ripple for each of the three uses cases based on what should be achievable for the given latency constraints. The values were achieved using an algorithm with digital filters optimised to each use-case.

These target RFE can be seen as the present reality of ROCOF measurements and can be compared against the user's expectations and wishes. It remains a challenge to instrument designers to develop algorithms to reduce the target RFE in the table in order to satisfy the user's expectations.

When testing a ROCOF instrument using the tests in the following table, the peak value and standard deviation of RFE and the frequency error (FE) should be recorded as an indicator of instrument performance. This should be repeated for each reporting rate.

Disturbance	Existing IEC/IEEE C37.118.1	Proposed additional test	Rationale	Worst Case RFE Ripple (Hz/s)
1) Harmonics	Single tone swept to 2.5 kHz. 1 % for P Class, 10 % for M Class (50th harmonic in a 50 Hz system)	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 [6] 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. The precessing tone takes 1000 cycles of the 14th harmonic, so at least 1.5 seconds of measurement time is needed to include all possible crossings.	To test sensitivity to multiple zero crossings. 10 % is the maximum value allowed by the power line communications standards (Meisner curve) [7]. 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) See NOTE 1	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 step change on all phases; unbalanced test with 40 % amplitude step change on each phase in turn, with the other phases at 100 %.	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 See NOTE 2.	More realistic short fault condition	UC1: 50 UC2: 25 UC3: 5
6) Off nominal frequency		Off nominal harmonics: propose a composite waveform as per the first entry in this table but performing a linear sweep of 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. EN61000-2-2 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 See NOTE 3.	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 [7] 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

Table 2, Disturbance levels for the testing of ROCOF instruments with target worse case RFE for each use case.

Notes on the generation of test signals:

NOTE 1 - The bandlimited noise can be generated using a software pseudo-random number generator. The band limiting can be approximately achieved by updating the random values at a slower rate than the samples that are used to synthesise the testing waveform. Define the fixed update rate of the random values as *Tr,* and set this rate relative to the synthesis sampling rate to give an approximate 2 kHz bandwidth for the noise.

NOTE 2 - The phase of start point of the phase jump, relative to the zero crossing of the voltage, makes some difference to the recorded ROCOF. A repeated train of phase jumps, with the start point phase changing on each jump, will show this.

NOTE 3 - The test can be carried out using a linear chirp tone mixed with the fundamental. Three such chirps need to be used to cover the 5 % test below and above the stop band, and the 10 % test above 90 Hz. Prior to starting the chirp, the instrument should apply the fundamental and the out of band tone set at the chirp start frequency (e.g. 10 Hz) for sufficient time for the algorithm filters to settle. The chirp time is compromise between testing quickly and being able to observe the maximum ROCOF. A chirp time of 60 s is suggested.

NOTE 4 - The unbalance test is a repeat of the noise test performed with the L1 phase channel with a phase shift of 180 degrees (on some systems this might be achieved by reversing the L and N connections at the PMU signal input terminals, please check the manufacturers manual). This connection configuration will reduce the positive sequence phasor to 0.33 per unit, thus increasing its susceptibility to noise. In terms of the positive sequence phasor magnitude, this is equivalent to losing two phases during a fault, so it should be a realistic test for extreme operating conditions.

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Objective 1 was fully achieved. The problem of ROCOF measurement was evaluated in the context of actual use cases and the “wish list” of measurement requirements was compiled taking into account the point of view of end-users. Table 2 shows the library of standard-test-waveforms representative of typical PQ events on electricity networks.

4.2 Objective 2

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.

Development of measurement algorithms for ROCOF is a significant problem with the poor PQ waveforms. This is because a ROCOF measurement first requires frequency to be found using the d/dt derivative from phase, before ROCOF is itself determined via a second d/dt derivative from frequency. Any disturbances on the original phase estimate due to noise, poor PQ, transients, fault events, or instrumentation noise are vastly “amplified” by the double derivative causing spurious results.

Power system frequency and ROCOF can be measured using the method proposed in the IEEE C37.118.1 standard [5] using a quadrature multiplier heterodyne structure. The method makes use of digital filters to attempt to reject unwanted PQ events in the filter stopband, whilst passing genuine changes in frequency which should appear in the filter passband.

The rejection of harmonics by this method can be improved, by adapting the frequency of the heterodyne to attempt to match the continuously varying power system frequency. Updates to the tuning frequency are provided by the algorithm itself, so the feedback loop must be broken using two processes operating in parallel, one feeding the frequency measurement to tune the other, before reversing roles in a so-called “tick-tock” manner [8] Other workers propose a variety of techniques based on DFTs [9] , parameter fitting algorithms [10] [11] and curve fitting methods that minimise residuals [12].

Each method has its advantages for different types of PQ disturbance, but all must address the basic trade-off of the rejection of disturbance versus the latency delay of updating the results. In many cases, users of ROCOF measurements do not appreciate the potential uncertainty of the measurements under imperfect PQ, and sometimes assume that measurement is instant.

In this project, the use cases for frequency and ROCOF measurements as described in the previous section are utilised to tailor measurement algorithms to each use case, by selecting digital filter configurations to, as far as possible, satisfy user requirements. This is carried out using a number of design rules to define the filter stop band and pass band for each use case specification. Using these specifications, we then go on to use a cascaded set of boxcar (moving average) filters to achieve the desired results, which allows the successful measurement of ROCOF for each use case.

In defining the rules for the passband width of the filters, i.e. the maximum frequency of modulation on the fundamental voltage waveform, which needs to be measured with reasonably accuracy, we define a ***Passband Rule*** where the single-sided passband width where attenuation is at least 3dB at the passband edge. We also account for the required ROCOF and frequency error specifications as defined in the PMU standard [5]. This rule should ensure that the width of the passband should be sufficient to measure the power system dynamics such as inter-area oscillations, inertial changes and modulations. The stopband rules below should remove the unwanted influences that cause the ROCOF readings to be noisy and in-error.

No users, nor ENTSO-E, expressed any comments about where the stopband should start, i.e., “*what is the frequency separation from the fundamental, above which all influence quantities (i.e. bad power quality) should ideally be excluded from the measurement result, ideally with infinite filter attenuation?*” Most users understand that they want harmonic effects to be excluded from the measurement. However, the end-user understanding of interharmonics that are close to the fundamental, for example flicker, and of the effects of Ripple Control Transmitters (RCT) is much less. Flicker consists of modulations of the fundamental at frequencies which may be within the passband, in which the flicker effects will have a large impact on the ROCOF measurement. Flicker effects may also appear at modulation frequencies further from the fundamental, in which case the user would like the effect to be completely filtered out, leaving a stable measurement with zero ripple.

Perfect filtering is impossible. However, when designing the ROCOF measurement it is possible to quantify a “stopband start frequency” where any interfering voltage signal at a frequency should be attenuated enough, so that the effect of the influences is reduced to a point that the required accuracy/ripple/noise specification can be met. The required stopband performance is dependent on the exact interference that is likely to be encountered in the real world. Here we consider the work of [7] which specifies harmonic and interharmonic amplitude levels to be used in EMC immunity testing. It allows 9 % of amplitude at absolute frequencies between 100 and 500 Hz, then dropping to 1.5 % at 3 kHz; for the ***stop band rule 1*** we round this to assume a 10% level of interference.

Closer-in interference which should be attenuated in the stop band is particularly challenging for filter design. Low frequency interharmonics and flicker are in the range of frequencies close to the power system frequency. Here we make use of the IEC flicker standard [13] apply a conservative approach to close-in flicker and interharmonic effects in the stopband, defining ***stop band rule 2*** as a 5 % interharmonic limit everywhere in the stopband which is not covered by the above stop band rule 1.

Next to providing specific minimum attenuations at particular modulation frequencies, the filter must also provide an “average” attenuation across the entire stopband that is sufficient to cope with broadband white or coloured noise. Here we use a series of field measurements in an extreme environment of an iron works in Slovenia [14] to define the worst-case noise levels expected on the public power supply. For the filter design we define ***Stopband rule 3*** to specify that these noise levels should cause a peak ROCOF error no greater than twice the root mean squared ROCOF error, such that the peak errors will be statistically less than twice the RMS errors for 95 % of the time. We define the noise levels from the iron works as a signal to noise ratio (SNR) of 35 dB (***rule 3B)*** obtained on the 110 kV network of the iron works and SNR of 20 dB ***(rule 3C)*** obtained on the 20 kV network inside the iron works. ***Rule 3A*** relates to the level of noise generated by a typical ROCOF instrument internal electronics which we assess from [15] to be SNR= 74 dB.

These rules can then be used to design filters to match the use cases. In this project, box car filters were selected as [8]. As many as possible, and at least two of the boxcar filters should be actively tuned to lengths which are integer multiples of the fundamental period, to deal with all harmonics and spectral leakage of the heterodyned fundamental image. All remaining boxcar sections should have lengths of n½ fundamental periods, to further assist with odd-harmonic and spectral leakage reduction. Using this approach, a filter configuration was optimised to each use case latency and accuracy requirement and that are summarised in the following table.

It can be seen from the table that the resulting filters achieve variable degrees of success in meeting the design rule specifications. The low latency UC1 filter is particularly challenging, this 5-cycle window device will perform quite well in conditions of good power quality, or high levels of steady-state harmonics. However, any interference signal, or the presence of any significant flicker, will cause this device to have errors which far exceed the Rule 1 0.1 Hz/s threshold. The device will be resilient to background noise due to its own circuitry (Rule 3A), when the waveforms are at nominal amplitude. However, near the previously discussed ironworks, the ROCOF error will be intolerable for both Rule 3B and 3C. This device cannot even be tested against Rule *2*, for close-in flicker, since its stopband starts at above 40 Hz. So, all signals conventionally regarded as flicker, with modulation frequencies less than or equal to 45 Hz, will be either fully in the device passband, or in the “no-man’s land” between passband and stopband. The device will output complex and probably confusing measured values during any type of flicker disturbance.

The UC2 filter also fails to achieve the Rule 1, 0.1 Hz/s interference threshold although the device is much less sensitive to interference and flicker than the 5-cycle device. The stopband start frequency is still quite high at 22.5 Hz and a significant part of what would conventionally be called flicker will be partially attenuated in the “no man’s land” between the stop and pass bands, leading to ripple on the ROCOF results. However, this is a much more stable device than the 5-cycle device, offering significantly more rejection of interference signals.

The UC3 device, which uses a long window which results in high latency, is required to be very stable and provide LOM tripping functions. The device should also have a high enough passband width to allow observation of inter-area oscillations within large power systems. This is a very stable device, performing to the required interference levels in all scenarios except for during the presence of the most severe flicker and interharmonics, closer to the fundamental than interference, but outside the passband. The passband width is only 1.88 Hz (either side of the fundamental centre), which is slightly lower than target, but probably acceptable for the application.

These filters have been implemented in real time in a PMU and using this instrument the results given in the table were verified independently of the original MATLAB simulations. The filter configurations were tested on six PMUs installed on Bornholm Island in Denmark.

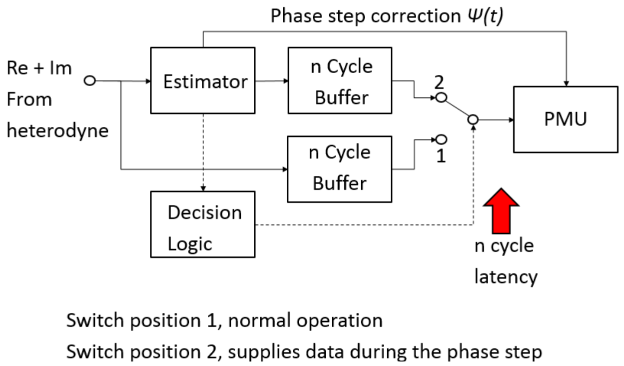
Use Case	Single-sided 3 dB passband width f_{PB}. (Target, Achieved)	Target ideal peak RFE / ripple	Target worst case peak RFE / ripple (limit of usability)	Filter configuration. Cascades of boxcars with cycle periods in {} C→P is Cartesian-to-polar conversion	Latency	Stopband start frequency f_{SS}. Multiplier f_{SS} / f_{PB}	Stopband rules 1 & 2 Peak RFE due to 5 % close-in interharmonics, or 10 % Meister curve.	Stopband rule 3 Noise/ironworks three-phase RMS RFE's 3A: SNR 74 dB 3B: SNR 35 dB 3C: SNR 20 dB
UC1 Active power damping and control. FFR and "Synthetic Inertia". Under-frequency load shedding Assessment of local inter-device oscillations	Target ≥ 5 Hz Achieved 8.25 Hz	0.02 Hz/s	0.1 Hz/s	5 cycle window length {1,2, C→P, 1½,½}	50ms (2.5 cycles)	45 Hz f_{PB} x 5.45	***Rule 1: Gross fail*** ***~2.4 Hz/s***, for a 110 Hz 10 % interference signal (60 Hz modulation in the filter). Particularly vulnerable to interference signals in the band between 110 and 140 Hz, with > 0.1 Hz/s perception possible for any RCT frequency up to around 400 Hz. ***Rule 2 cannot be applied, as f_{SS} ≥ 40 Hz***	SNR 74 dB 0.002 Hz/s RMS ***SNR 35 dB*** ***0.16 Hz/s RMS*** ***SNR 20 dB*** ***0.95 Hz/s RMS***
UC2 Active power damping and control. FFR and "Synthetic Inertia". Under-frequency load shedding Assessment of local inter-device oscillations.	Target ≥ 5 Hz Achieved 4.13 Hz	0.02 Hz/s	0.1 Hz/s	10 cycle window length {1,2, C→P, 4,3}	100ms (5 cycles)	22.5 Hz f_{PB} x 5.45	***Rule 1: Fail*** ***0.1-0.4 Hz/s***, for the lowest 100-120 Hz 10 % interference signals (40-60 Hz modulation in the filter). However, for higher-frequency interference signals, the device can be compliant with a 0.1 Hz/s RFE. Rule 2 can be applied, as f_{SS} ≤ 40 Hz. ***RFE to 0.3 Hz/s can occur in the presence of 5 % interharmonics/flicker near f_0 + f_{ss}.***	SNR 74 dB 0.0003 Hz/s RMS SNR 35 dB 0.03 Hz/s RMS ***SNR 20 dB*** ***0.17 Hz/s RMS***
UC3 Island Detection (LOM, Loss of Mains) "Evaluations on synchronous area level" e.g. inter-area oscillations	Target ≥ 2 Hz Achieved 1.88 Hz	0.01 Hz/s	0.1 Hz/s	25 cycle window length {2,4, C→P, 8,6,5}	250 ms (12½ cycles)	6.0 Hz f_{PB} x 3.19	Rule 1: Pass All potential interference signals result in RFE less than 0.01 Hz/s. Rule 2 can be applied, as f_{SS} ≤ 40 Hz. RFE to 0.06 Hz/s can occur in the presence of 5 % interharmonics/flicker near f_0 + f_{ss}.	SNR 74 dB <0.0001 Hz/s RMS SNR 35 dB 0.004 Hz/s RMS SNR 20 dB 0.024 Hz/s RMS
Compromise device	Target ≥ 3 Hz Achieved 3.63 Hz	0.01 Hz/s	0.1 Hz/s	13 cycle window length {1,2, C→P, 4,3,3}	130 ms (6½ cycles)	12.5 Hz f_{PB} x 3.63	Rule 1: Pass All potential RCT signals result in RFE less than 0.02 Hz/s. Rule 2 can be applied, as f_{SS} ≤ 40 Hz. ***RFE to 0.11 Hz/s can occur in the presence of 5 % interharmonics/flicker near f_0 + f_{ss}.***	SNR 74 dB 0.0003 Hz/s RMS SNR 35 dB 0.02 Hz/s RMS ***SNR 20 dB*** ***0.13 Hz/s RMS***

Table 3, ROCOF algorithm optimisations and performance for the combined ROCOF use cases and requirements – 50 Hz power systems. Bold italic text in the table indicates that the proposed filter fails to satisfy the design rules.

Phase Step Ride-Through Algorithm

A significant problem with ROCOF measurements is related to phase steps or phase jumps [16] . As the name suggests these are a sudden step in phase lasting perhaps a few cycles that do not represent a real change of the power system frequency. Phase steps have a number of causes including faults, lightning strikes, power and system large load switching. Whilst filter optimisation and particularly long high-latency filters reduce these effects, these highly dynamic events require an alternative approach.

A proposed scheme for phase step removal is depicted below.



Proposed scheme for phase step removal.

The algorithm uses the real (*Re*) and imaginary (*Im*) parts output from the heterodyne modulator employed in the PMU algorithm [5] shown in the upper part of **Error! Reference source not found.**, provided at the PMU sampling rate. Conventionally, these *Re* and *Im* data from each line-phase are fed to the chosen PMU algorithm which contains digital filters, positive sequence calculations and a data decimator.

When the switch in the figure is at position 1, this conventional data processing method is used as normal with the exception that the data are delayed in a first-in, first-out (FIFO) buffer by n-cycles. This n-cycle latency is added to give sufficient time to process data to decide whether a phase step has occurred. For example, the typical 4-cycle phase steps commonly seen on Bornholm should be identified and removed during this latency period.

When a suspected phase step occurs, the FIFO provides an n-cycle period in which it has to be decided whether the data is an actual valid ROCOF event or a short-lived phase step. In the case of an actual phase change (i.e. a change to the underlying phase θ(t)), the decision logic will not change the switch from position 1 and the data will continue uninterrupted and will be processed as normal.

The estimated signal is required in order to maintain an uninterrupted stream of *Re* and *Im* data to the PMU algorithm. Continuous data is essential because the PMU consists of digital filters and interrupting the data stream to the algorithm will in itself cause discontinuities resulting in ROCOF spikes.

In order to synthesise the replacement data, an estimator of the signal dynamics is required to model the underlying signal during a phase step. The replacement data estimator will run continuously, even when there are no suspected issues with the data, and is required to track the phase, amplitude and frequency of the real data. In a real power system, these parameters are all time varying and the accuracy of the estimator will ultimately determine how well the effect of the phase step can be removed from the PMU output. It should also be remembered that the estimator must run in real time and must therefore be computationally efficient. The output of the estimator is fed into an indicial n-cycle FIFO buffer to that used in switch path 1.

If the decision logic judges the data to contain a phase step, the switch is changed to position 2 to provide the estimated data to the PMU until such time as the phase step is deemed to be over. At the conclusion of the phase step, the switch is changed back to position 1 to provide the real data again.

The process of the changeover of the switch is likely to introduce discontinuities due to the differences between the real and estimated data, which in turn will give rise to erroneous ROCOF steps on the PMU. Ensuring a smooth changeover between the two step positions requires an accurate estimator whose data is in phase with the real data. Data changeover is one of the main challenges of this method and a period of estimator alignment to the real data following the end of a phase step is likely to be needed to minimise errors.

The phase step ride through algorithm was implemented and tested using data from the Bornholm power network. It was successful in reducing phase step induced errors of ~100 Hz/s to less than 5 Hz/s. Details and full results can be found at [17].

Therefore Objective 2 was fully achieved. Algorithms were reviewed, developed and optimised to reliably and accurately measure ROCOF over the full range of network conditions, and table was produced specifying the accuracy achievable for each use cases.

4.3 Objective 3

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 suitable for inclusion in a ROCOF standard (new or pre-existing).

Based on findings of site measurements, publications, and knowledge of the pitfalls in digital filter implementation, the disturbance scenarios shown in Table 2 are proposed for future testing of ROCOF instruments. The tests given in Table 2 should be used in conjunction with the specifications for the use cases given in Table 1: ideally, the ROCOF worst-case ripple of 0.1 Hz/s is not exceeded in each of the tests and accuracies of better than 0.05 Hz/s are achieved. This may not be possible to achieve in the presence of phase steps (test 5 and test 8) unless some form of phase step correction algorithm is used, e.g. [17]. In addition, for low-latency designs, test 3 and test 7 may give rise to ROCOF ripple higher than the user's desired specifications. To reflect this, the right-hand column in Table 2 gives a proposed set of worst case ROCOF errors (RFE) for each of the three uses cases based on what is deemed achievable with optimised filters for the given latency constraints.

These target RFE can be seen as the present reality of ROCOF measurements and can be compared against the user's expectations and wishes. It remains a challenge to instrument designers to develop algorithms to reduce the target RFE in the table in order to satisfy the user's expectations under all grid conditions and use cases.

When testing a ROCOF instrument using Table 2, the peak value and standard deviation of RFE and the frequency error should be recorded as an indicator of instrument performance. This should be repeated for each reporting rate.

In order to demonstrate the applicability of the tests and RFE targets proposed in Table 2, several different ROCOF algorithms were tested using both simulated and laboratory synthesised tests from this Table. In all cases, the algorithms were implemented using the description given in the associated cited publications. These implementations were made without consultation with their respective designers and as a consequence may not include any up-to-date optimisations. The window lengths and update rates were adjusted to match the latency requirement of each use case as given in Table 1.

The following three algorithms were selected and implemented for real-time processing on a digitiser system interfaced to a PC [18]: the M-class PMU algorithm of the IEEE standard [5], the box-car filter algorithm discussed in the previous section of this report, and a Phase Sensitive Frequency Estimation (PSFE) method developed by Lapuh [19].

The IEEE C37.118.1 [5] standard gives an example algorithm that uses a classic heterodyne structure with digital filters as specified for an M-Class PMU with filter coefficients calculated in accordance with Section C6 in [1]. As Table C.1 in [1] is not applicable to the faster ADC sampling rate of 20.48 kHz used in the present test instrument [11], the method described in [8] was used calculate the filter length and reference frequency. Standard reporting rates for PMUs given in [5] of 100, 50 and 25 frames per second for 50 Hz grid frequency are the closest to the use-case latencies for UC1, UC2 and UC3 respectively, which correspond to filter latencies of 59 ms, 138 ms and 412 ms respectively.

The PSFE frequency estimation algorithm uses a method of least squares three-parameter sinewave fit [19]. The frequency is estimated from the phase difference between two points in a series of sampled waveform cycles. In an iterative scheme, the new frequency estimate is then used in the sine fit algorithm to calculate an improved phase difference, which in-turn improves the frequency estimate. To accommodate iterative calculations and data collection in real-time, the algorithm has been implemented in this work using a "tick-tock" buffer scheme which update results every power system cycle. The PSFE is just one example of a possible fitting type algorithm and was selected for processing speed and due to its relatively high harmonic immunity when compared to other algorithms [11]. The PSFE method allows the frequency, phase and magnitude to be estimated. Three-phase results are achieved by the weighted average of the three frequency estimates from the individual phases, using the three magnitudes as the weights.

Each of the nine tests in Table 2 were carried out on each of the algorithms, with latencies set to match each of the three use cases in Table 1. The tests were carried out with mathematically simulated wave shapes as well as with waveforms synthesised using laboratory equipment (Arbitrary Waveform generator (ARB) and amplifiers).

Simulation method

Each of the test waveforms was programmatically generated in the same software that implements each algorithm. The simulation generates 4096 samples every 10 power system cycles (204.8 kHz sampling rate), on each of the three phases.

Laboratory Synthesis Method

Each of the test waveforms were generated using an ARB which can be loaded with a time series that represents a particular given test waveform. The ARB sampled waveform reconstruction rate was 500 kS/s. The output of the ARB is amplified from its low voltage output to the digitiser working input voltage using a laboratory voltage amplifier. This produces only a single-phase test condition.

Test Results

Results for test waveforms 1, 2, 6 of Table 2 gave results within the target errors for all algorithms and all use cases. Rather than reproducing all the results for the other test waveforms in this report, only the results of tests 3, 7 and 8 are shown below.

The results for simulation and laboratory synthesis testing were broadly similar. Therefore, for brevity only the simulation results are shown in this report. Results shown highlighted and italic exceed the target errors.

Noise Tests

Both test 3 and 9 are essentially noise tests. The results for waveform 3 are shown in Table 4.

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

Table 4, simulation results for test waveform 3 (noise) for various algorithms configured to use cases. R min and R max refer to the min. and max. ROCOF recorded values. Results in italic exceed the table ii worst case RFE recommendation for the given use case.

The 1-sigma value in Table 4 was estimated from the 63 % envelope of data on a real-time plot of ROCOF results on the instrument display.

Step Tests

Table 2, Tests 4, 5 and 8 all involve steps. Test 8 is a phase step which induces a step change in frequency by -2 Hz. The frequency then linearly ramps back to its original value at a rate of 8 Hz/s. The resulting ROCOF recording would be expected to show a negative-going spike associated with the phase step and then a period of constant 8 Hz/s ROCOF followed by a return to 0 Hz/s. The results for the various algorithms are given in Table 5. These results are also representative of the algorithm performance for tests 4 and 5.

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.

Table 5, Simulation results for test waveform 8.

Close-in interharmonics and flicker test results

The results for test waveform 7 are shown in Table 6. The results are obtained from the maximum and minimum ROCOF values seen in a given frequency sweep.

		Low	Low	High	High	150	150
Algorithm	**Fstop**	**R max**	**R min**	**R max**	**R min**	**R max**	**R min**
Std. UC1	25	*2.21*	*-2.21*	*3.29*	*-3.28*	0.06	-0.04
Std. UC2	12.5	*0.90*	*-0.90*	*0.37*	*-0.37*	0.00	0.00
Std. UC3	5	0.10	-0.08	0.11	-0.11	0.00	0.00
Rosc.UC1	45	N/A	N/A	N/A	N/A	2.34	-2.32
Rosc.UC2	22.5	0.30	-0.29	0.27	-0.27	0.17	-0.17
Rosc.UC3	6	0.05	-0.05	0.05	-0.05	0.00	0.00
PSFE UC1	40	N/A	N/A	N/A	N/A	*29.8*	*-31.3*
PSFE UC2	20	*4.79*	*-4.49*	*3.38*	*-3.34*	*2.71*	*-2.46*
PSFE UC3	8	*1.90*	*-1.33*	*1.41*	*-1.59*	*0.50*	*-0.50*

Table 6, Simulation results for test waveform 7.

Discussion of results

The test results are a useful comparison of three different algorithms and their implementation. The tests show-up some of the problems with ROCOF measurements. The noise tests in Table 4 reinforce the obvious point, that longer (and slower) filters do a better job of averaging the effect of noise. The cascaded filter design in the Roscoe algorithm has good attenuation in the stop band and does the best job of the three algorithms at rejecting the noise.

The step tests in Table 5 underline the problem of measuring ROCOF in the presence of phase steps. Here the longer and slower filters smooth-out the phase step to some extent, but all algorithms give RFE results which would be highly problematic for their potential use in grid control systems. Once the step effect has worked through the filters, the constant 8 Hz/s frequency ramp should give a ripple free value for ROCOF; in this case the faster filters settle quickly to this ramp value. For slower response filters, the algorithms do not have time to settle before the ramp has completed.

The close-in interharmonics signals for test 7 in Table 6 reveal the sensitivities of the algorithm configurations to frequency tones that are in the zone between the filter stop band and the filter pass band, where the attention is insufficient to suppress the ripple effect of the tone. In general, the scan of frequencies reveals a series of high sensitivities to various frequencies and the values reported are the worst-case error in the scanned range. For the fast filters (UC1), the 10 Hz to 90 Hz scan is not applicable (N/A) because the stopband extends across the entire scan range. The detailed filter design of the Roscoe algorithm has given the best rejection of these effects, although optimisations of the other algorithms may be possible. Indeed, the last statement reveals the potential usefulness of these tests to instrument designers who can use them as a benchmark to optimise their algorithm designs.

Application of the tests on various algorithms has confirmed the practicality of the tests as a testing protocol. It is realised that it may not be possible to achieve the desired accuracy for tests involving phase steps; low-latency PMUs may in addition fail tests with noise and interharmonics. The worst-case RFE levels given in Table 2 for different tests were selected as a compromise between ideally required and practically achievable accuracy. It will remain an item of debate whether these target ROCOF accuracy levels indeed are acceptable to industry.

In summary Objective 3 has been met. The use cases, waveforms and performance tests in Table 2 of this report have been used to tested various ROCOF algorithms as shown in Tables 4 to 6. The testing described here have been discussed with the convener of IEEE/IEC TC95 / WG1 (60255-118-1) and will provide useful input as testing protocols to the normative standards process for frequency and ROCOF measurements currently under discussion in WG1 and in IEC/CENELEC TC8 JWG12. The results will be presented at the Applied Measurements for Power Systems Conference in September 2019 and will be published in the associated IEEE proceedings.

4.4 Objective 4

To specify a reference signal processing architecture for a ROCOF instrument suitable for inclusion in a ROCOF standard. To use sensitivity analysis to determine the uncertainty specification for each element of the measurement chain (this could include: transducers, analogue signal processing, filtering, analogue to digital convertors, digital signal processing, computational processing) required to manufacture an instrument to implement the selected algorithms and be capable of compliant accuracy measurements for each of the use cases.

This reference system architecture implementation is intended as an aid to a manufacturer of a ROCOF instrument and is proposed as an informative to a ROCOF standard to demonstrate a method to implement a compliant instrument.

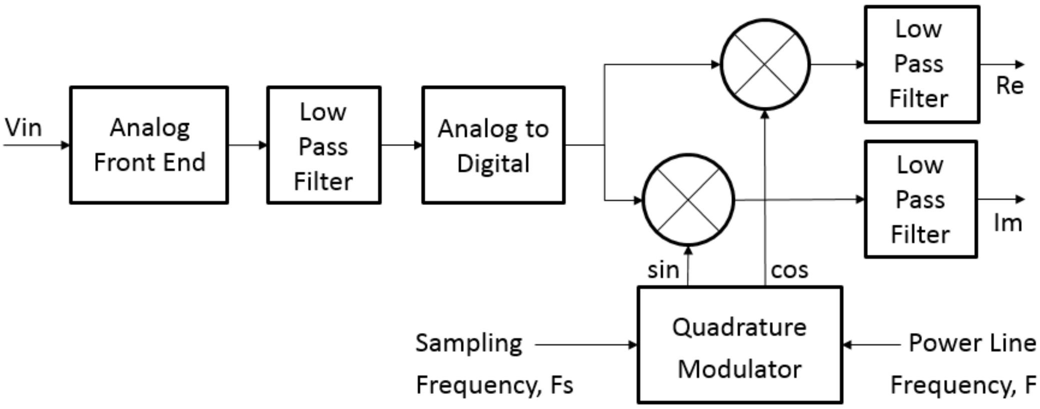
The architecture is intended to be as simple as possible for ROCOF and where appropriate, builds-on the existing IEEE C37.118.1 Annex C [5] heterodyne based example, such that existing hardware can be used to implement ROCOF. If desired, other experts can extend the reference model to cover implementations of PMUs and/or Power Quality instruments.

Other instrument architectures such as those based on phase locked loops and frequency estimators were not considered.

The proposed reference model for a ROCOF instrument is divided into a sampling part (in hardware) and a processing part (in a processor, implemented by firmware and/or software).

Each component of the architecture is considered in turn, giving some commentary on the functionality, advice on implementation requirements, and an accuracy/uncertainty recommendation to assist manufacturers in the design of a ROCOF instrument. In some cases, an uncertainty analysis is calculated using Monte-Carlo simulations in order to assess the sensitivity of the final frequency and ROCOF results to errors in the components of the architecture.

The architecture for a heterodyne based instrument [5] is shown the figure below and a summary of the components is given below.



One phase of a heterodyne based ROCOF instrument architecture.

Sampling Part

The sampling part of the ROCOF instrument contains electronic hardware as follows:

A transducer to convert the supply system voltage to low signal levels suitable for the instruments electronics

The transducer reduces the supply system voltage to low signal levels suitable for electronics. The nominal input (primary) levels to the transducers are defined by the supply system voltage. The output (secondary) signal levels are defined by the peak (not r.m.s.) working input voltage of the analogue electronics. Consideration should be given to the possibility of spikes on the supply system that could increase the secondary peaks that cause over-range and saturation in the electronics. The transducers should be able to safely withstand over voltages consistent with the fault level of the supply system.

Non-linearity’s in the transducers will distort the output signal, however if the algorithm is designed to reject steady-state harmonic distortion with high attenuation this should not be a problem for ROCOF.

Delays (time constants) will cause absolute phase errors, giving rise to different angular errors at different harmonic frequencies, in general this will distort the input signal. Notwithstanding this distortion, constant absolute phase errors have no effect of ROCOF.

The attenuation factor will change with time and temperature due to component drifts, this will have no first order effect of ROCOF.

Electric and/or magnetic coupling between poly phase transducers will give-rise to “cross-talk” coupling of the signals channels.

Transducers have negligible impact on the uncertainty of ROCOF measurement. The errors in transducer ratio, phase does not impact ROCOF measurement. Even for a 1 Hz/s linear frequency ramp and considerable 0.1 radian phase error in the signal processing chain did not cause ROCOF errors greater than 10^{-6} Hz/s. Therefore, there are no particular accuracy requirements for the specification of the transducer.

An analogue front end, possibly containing buffer amplifier and over-voltage protection

The analogue front end is signal conditioning electronics could, for example, contain an input buffer amplifier and over-voltage protection.

The input amplifier could be included to give the instrument a high input impedance so that it does not cause a loading of the transducer stage. This amplifier maybe given some gain to match the transducer output with the full range input of the analogue to digital convertor (ADC).

Overvoltage protection maybe included, for example incorporating clamping diodes such as Zener diodes or transient voltage suppression diodes. These should be specified to prevent damage to the ADC during an overvoltage fault.

The SNR contribution of the analogue front end will degrade the frequency error (FE) and ROCOF error (RE). Distortion and non-linearity will add to the harmonic content which will be supressed by the digital filters.Time delay and bandwidth are unlikely to be an issue at power frequencies. Gain drift, for example caused by the temperature coefficients of the gain resistors in the amplifier will not affect FE and RE.

A low pass “anti-aliasing” filter

The anti-aliasing filter should attenuate all frequency components (e.g. harmonics and noise) above the Nyquist frequency, i.e. above half the sampling rate (fs/2). Unfiltered or attenuated components above the Nyquist will be aliased to lower frequencies which could interfere with the wanted signal components.

Compared to a PMU or PQ analyser, the design specification for the anti-aliasing filter can be relaxed to allow the filter break point to be at a relatively low frequency. This is because a ROCOF measurement is only concerned with the power frequency fundamental and any attenuation of harmonics is to be welcomed. When ROCOF is part of a multi-parameter instrument, the requirements of other parameters will be dominant in the filter design. So, for any dedicated ROCOF instrument with 14.4 kHz sampling frequency (as recommended), a passive single pole filter with a break point at say 250 Hz is a feasible low-cost solution. Relaxed filter designs have the added benefit of reducing the group delay (latency) caused by the filter.

An analogue to digital convertor (ADC)

The maximum working scale of the ADCs should not clip the signal and should have provision for at least 15 % overvoltage (10 % plus an allowance for harmonic crest factor), preferably at least 20-30 % overvoltage is a safer margin to allow for abnormal power system behaviour.

IEC 61869-9:2016 recommends a minimum of 14.4 kS/s sampling rate for the ADC. Increasing sample rate always decreases the effect of noise on the final measurement, since the linear noise amplitude density $\sqrt{L(f)}$ scales with $1/\sqrt{f_S}$, as the noise is spread over a wider Nyquist band.

Experience shows that for these sampling rates, 12 to 13 effective number of bits (ENOB) is just about sufficient for ROCOF measurements, so a minimum of a 14 bit resolution ADC should be sufficient. Given the wealth of available relatively inexpensive chips, a 16 bit device may the most appropriate choice to guarantee the required 13 ENOB.

ROCOF algorithms are relatively insensitive to ADC linearity errors. Any linearity errors will distort the sampled waveform and cause additional harmonics which will be readily rejected by the digital filters.

Some ADC designs (e.g. delta-sigma) apply ADC dithering techniques to improve linearity, which deliberately add white noise to the analogue signal. This should be considered in context of the SNR discussions.

For a decent ADC, "aperture jitter" shouldn't be a problem, but the designer should check that it is not dominantly defining SNR which will degrade the FE and RFE results. As a rule of thumb clock jitters at 30 ns or above could cause problems.

The noise present in the signal and/or generated by the analogue front end and by the digitiser is the main contribution to the uncertainty of the ROCOF. Based on the simulations, by rule of thumb every 20 dB of noise leads to increase of uncertainty by one order of magnitude. For digitiser sampling signal with total SNR about 80 dB the uncertainty of ROCOF can be down to 0.1 %, for SNR about 100 dB the uncertainty can be down to 0.01 %.

The nonlinearity of analogue front end or ADC does not impact the uncertainty of the ROCOF.

The sampling frequency of the ADC has some impact on the uncertainty. If the sampling frequency is kept higher than 5 000 samples per second, the contribution to the uncertainty will be smaller than the contribution of noise of common digitiser.

A sampling clock (not necessarily disciplined by GPS unless PMU operation is required)

A common clock can be used to supply all ADCs in a multi-phase instrument, so that the samples are taken at the same point in time. The sampling clock will be common to all channels of a poly-phase instrument, the other components will be replicated for each channel of a poly-phase instrument.

As the clock defines the instruments unit of time, the clock accuracy is directly related to the frequency measurement accuracy. As the accuracy of even the cheapest quartz clocks is <50 ppm, it is not strictly necessary to have a GPS (or other source) conditioned clock, however accuracy can be readily assured in this way. The clock needs to be stable and have low “jitter”. The clock frequency will be set by whatever sampling frequency is required. The sampling frequency will often be derived by dividing a higher frequency clock (e.g. 10 MHz) down to the required sampling frequency. As with the ADC jitter, the effect of sampling clock jitter translates to an increase in SNR, which in turn cause the FE and RFE to degrade.

Processing Part

The processing part consists of:

A real-time arithmetic processing engine

Processing engines include digital signal processors, microprocessors, micro-controllers, and PCs (with real time data link).

The processor speed must obviously be considered and should be sufficient to carry out the required calculations for the given algorithm in real-time and dispatch the results in the chosen form. Real-time processing kernels maybe required as it is essential to maintain a constant stream of output results without variations in the update rate or variations latency of the results. The optimisation of the algorithm code for the actual hardware platform can be essential to maintain a constant stream of results.

The arithmetic processing engine will limit the size of processed number to a finite number of bits. Rounding the data to fit this finite word length will have an impact on the ROCOF results. Choice between single or double precision floating point arithmetic or fixed-point calculations will need to be considered when selecting the processor and the requirements of the given algorithm and processing speed. Experience suggests 32-bit is “enough”, but clearly 64-bit is preferable if processor supports this for real time applications.

Memory size will also be determined by the chosen algorithm and the access speed must be sufficient for the update and latency requirements of the instrument. Using the tick-tock algorithm in [4], for a 26-cycle window, tuned to the lowest frequency (say 40 Hz), at 14.4 kSa/s, 4 buffers in parallel for 2 signals, for 3 phases, gives:

3*26/40*14400*4*2=224640 values

At 32-bit, 898560 bytes

At 64 bit 1797120 bytes

So some 2 MB of storage would be required for this algorithm. The RAM needs to be fast access, since the buffer access is core to the signal processing algorithms. The organisation of the code and data storage is important to maximise execution speed; if memory locations are accessed in groups, rather than “dotted” throughout the memory space, this has a positive impact on execution speed. This makes best use of cache memory and minimises “cache misses”.

The processor will also be required to parse and dispatch the results to the communications or display stage.

Communications and time stamping to dispatch the results to other systems

The ROCOF and frequency results could be used as part of the real time control of a power system and therefore must be dispatched in a reliable and time regimented fashion. They may also be logged and time stamped for diagnostic purposes.

Extensive commentary of communications and time stamping requirements is given the C37.118.1 PMU standard [5] and these guidelines may apply to a given ROCOF application and should be considered according to the intended application of the instrument.

Latency and response time are equally important in ROCOF applications as PMUs. In the case of some ROCOF applications, it is often necessary to provide reports much more often than standard PMU reports. For example, in converter-based systems new ROCOF measurements are required at the full converter switching frequency (e.g. 2 to 4 kHz). In these applications, so long as the response time and latency are small enough, and the filtering good enough, users are generally unconcerned as to what the exact timestamp is.

A quadrature oscillator

The heterodyne operation involves the multiplication of the digitised signal with cosine and sine waveforms at the fundamental power system frequency which are digitally generated from the quadrature oscillator.

The multiplication operation takes place at the sampling frequency resulting in two outputs, a real part and an imaginary part. This is a real time continuous version of the Fourier Transform kernel. These outputs can be integrated (summed) over one power system cycle to give the Fourier coefficients.

The resulting real and imaginary parts considered as a time series is an approximate sinusoidal function at the quadrature oscillator frequency which is set to be approximately the present power system fundamental frequency. Mixing products caused by the difference of the quadrature oscillator frequency from the power system frequency (which, in general, is constantly changing) will be present in the spectrum. Harmonics and interharmonics in the incoming signal will also be present and any amplitude modulation products caused by the voltage fluctuations.

This output is digitally filtered by the next stage to remove these unwanted frequencies

Ideally, the frequency of the quadrature oscillator should match the frequency of the power system which is continuously changing. So, a tuned oscillator can be used to track the power system frequency. This tuning can be driven by a feedback of the instrument’s frequency measurement, although care will need to be taken to avoid instability in this feedback loop. Parallel path heterodyne stages can be used to afford tracking and safeguard against instability, in such “tick-tock” systems [8] whist one path provides the heterodyning output, the other path’s filters settle on the present quadrature oscillator frequency, set to the last measured frequency. Once this dormant path has settled, the paths are switched, and the newly dormant path is re-tuned to the latest frequency and is given time to settle.

The closeness of the quadrature oscillator frequency to the actual power system frequency will determine how many unwanted mixing products remain at the output from this stage. These products will cause the ROCOF result to vary and due to the nearness of the unwanted frequencies to the power system frequency, these cannot be well filtered. So good frequency matching the quadrature oscillator frequency to the actual power system frequency is highly desirable.

Digital filters

Finite impulse response filters are used select the fundamental component and reject other frequencies such as harmonics, interharmonics and modulation products.

This stage may also perform the required integration over a fundamental cycle required to complete the heterodyne operation.

Some suggestions on digital filter design were given using the design rules specified in the previous section of this report which identifies and defines the filter passband and stopband requirements in the context of the identified use cases and PQ scenarios. It then describes a filter architecture which can be added to the PMU heterodyne structure. This is based on cascaded boxcar (moving average) filters and a description is given as to how these can be applied in the context of the design rules. This gives rise to several filter cascade configurations which attempt to meet the design rules, whilst satisfying the latency constraints of each use case.

A positive sequence calculator

In general, it is required to measure ROCOF in three phase power. In such systems there may be a temptation to implement ROCOF measurement on a single phase only to save processing. However, there are advantages to implementing all three phases as this affords significant cancellation of the effect of balanced harmonics, improving the accuracy of the ROCOF measurement. The positive sequence component of the three phases can be readily calculated by the standard formula. This can then be used to calculate frequency and ROCOF.

However, as discussed above, three-phase analysis allows a further SNR benefit of $1/\sqrt{3}$ (4.77 dB) to be gained by simply averaging the three results.

The text-book symmetrical component transformation can be used to calculate the positive sequence component.

Alternatively, the three values of frequency obtained on each phase can be averaged using a magnitude weighed average of the three calculated frequencies. This average weighting is based on the phasor magnitude and has the advantage of eliminating the effect of unbalance as well as optimising the SNR as discussed above. ROCOF is then calculated from the weighted average frequency.

Phase and frequency differentiation

Frequency is calculated by differentiating the measured phase. ROCOF is measured by differentiating the frequency.

The PMU standard C37.118.1 [1] recommends that the differentiation of phase be carried out using a weighted average of the past four phase differences (see equation C3 in C37.118.1). This is intended to smooth some of the variations in this generally noisy operation. Other methods use least squares methods or filtered outputs to reduce the variation.

It is important to ensure that the phase value used is not affected by principle value wrapping at two pi radians (360 degrees). Care needs to be taken to ensure transitions across this boundary are correctly handled in the calculation. For example, some algorithms may record two phases of 179 degrees followed by 181 degrees, do the phase difference is clearly 2 degrees. However, if 181 degrees wraps to -179 degrees to maintain the angle within the principle range, then the phase difference will erroneously be recorded as 358 degrees.

An output decimator

ROCOF algorithms can provide sample-by-sample updates of results. Different applications require different update rates and the outputs are decimated to reduce the output rate of the instrument to the desired value.

Typical update rates are given in the PMU C37.118.1 standard and these may vary from once per half cycle (of the power system frequency) to once per 5 cycles as shown in Section C.7 of C37.118.1. As with any decimation process, a low-pass filter must be used to prevent aliasing. Similar filters as used as used above as “digital filters” can be used to perform decimation.

Summary

The above describes the signal processing architecture for a ROCOF instrument suitable for inclusion in a ROCOF standard. Monte-Carlo sensitivity analysis was used 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. Therefore Objective 4 on the project was met.

5 Impact

Key dissemination and engagement activities

A virtual workshop was held to obtain information from the power industry and instrument manufactures on what they considered to be problems associated with ROCOF and the required information the project would have to gather in order to deal possible scenarios. The consortium has circulated questionnaires, based on experience and information from the virtual workshop, on the impact of ROCOF on smart grids PQ stability and received feedback from industry and standards bodies. There has been extensive engagement with IEC/IEEE TC95 / WG1 (60255-118-1) and IEC TC8 JWG12.

A highly successful final project meeting Webinar was attended by 50 people, ranging from China to the west coast of the US. It included all key people we were targeting for, but also had around 20 stakeholders we had not been in contact before. To a significant part, the attendance was the result of the active promotion of the webinar by the Chair of IEC/IEEE TC95 / WG1 (60255-118-1). During the webinar, slides were presented on the projects outputs, with each part followed by discussions. The discussions appeared to be lively and focused, with to-the-point issues. All attendants stayed connected during the 2 hours the webinar lasted and we collected a series of very positive responses afterwards.

A paper on the development and field testing of new ROCOF algorithms was presented to the Conference of Precision Electromagnetic Measurements in July 2018. A further paper was given on Uncertainty of ROCOF calculated by means of Monte Carlo method. The keynote address of the Smart Grids Measurement Conference in June 2018 was made by a member of the project team and a further paper was given on uncertainties.

Impact on industrial and other user communities

This project will establish the foundations for new documentary standards that will normalise ROCOF measurements such that this metric can be used with confidence by utility companies to ensure the stable operation of renewable energy resources (RES). The research will ensure that the new standard is practical, implementable, reliable, rigorous, cost effective and defensible based on testing and analytical evidence. The outputs of the pre-normative research will be directed to the standards committees who will work on a parallel time-scale to this project, to implement a new ROCOF standard in tandem with this research.

Without this pre-normative research, any future standard would risk serious gaps, in which real-world power system scenarios could cause severe errors in ROCOF measurements, potentially leading to blackouts and asset damage. Any new standard unsupported by pre-normative research could quickly lose credibility, potentially delaying the integration of RES and the missing of EU 2050 targets.

Reliable, usable ROCOF measurements underpinned by defensible standardisation will benefit the Power-system operators, RES providers, and instrument manufactures.

Impact on the metrology and scientific communities

ROCOF is a complex measurement parameter which needs to be determined over a wide-range of real-world scenarios. This type of measurement marks a departure from the more traditional NMI activity of laboratory based measurements of single quantities at the highest accuracy. Conversely, ROCOF is a multiple input measurement industrial problem, however its solution lies with the application of the metrological principles of good definition (Objective 1 and 2), piece-wise characterisation/calibration of complex systems (Objective 3), GUM based Monte-Carlo analysis of uncertainties (Objective 4) and analysis/mitigation of non-ideal conditions (Objective 2). These activities add essential experience to the application of metrology to industrial measurements and lead to improvements in measurement capabilities to support their practical implementation. The compliance and calibration procedures developed as part of this project (Objective 4) will give rise to new measurement capabilities for ROCOF at NMIs (which have the potential to form part of CMCs) and second-tier calibration laboratories.

Impact on relevant standards

This project has been conceived to provide essential pre-normative research to enable the publication of new international standards on ROCOF. The project has been particularly connected to IEC/IEEE TC95 / WG1

(60255-118-1), IEC TC8 JWG12 where the project outputs are influencing the development of standards by both of these committees. Such research will provide a rigorous basis for practical and effective standardisation which will command the support of industry.

Such standardisation is essential to ensure that network-critical ROCOF measurements can be made reliably with instrumentation from any manufacturer. As these measurements involve particularly complex parameters and are subject many unpredictable influences, the project will provide input to future standards to define hardware, algorithms, immunity to disturbances and test conditions.

Longer-term economic, social and environmental impacts

ROCOF is vital for the safe and stable large-scale integration of renewables into the electricity grid. The use cases identified by the project target various aspects of this long-term energy landscape and the project is going on to develop new algorithms to match these use cases. Some examples of the longer term social, environmental and economic impacts include Loss of Mains (LOM) protection for maintenance personnel at serious risk from intermittent unexpected voltages; Under Frequency Load Shedding (UFLS) protection to disconnect loads from a network to maintain the frequency within limits, thus preventing serious power cuts; Generator Frequency Response (synthetic inertia) work, key to reliable and usable SI metrics which will enable stable and secure public power supply when using the very high proportion of renewables predicted in 2050 scenarios.

6 List of publications

"Dealing with Front-End White Noise on Differentiated Measurements such as Frequency and ROCOF in Power Systems", Roscoe, A.J., Blair, S.M., Dickerson, W., Rietveld, G., IEEE Transactions on Instrumentation and Measurement, 2018. DOI: 10.1109/TIM.2018.2822438.

"The Case for Redefinition of Frequency and ROCOF to Account for AC Power System Phase Steps, A. J. Roscoe, A. Dyko, B. Marshall, M. Lee, H. Kirkham, G.Rietveld, IEEE Applied Measurements for Power Systems, 2017. DOI: 10.1109/AMPS.2017.8078330

"PMU-based power system analysis of a MV distribution grid", N. Save, M. Popov, A. Jongepier, and G. Rietveld, CIRAD 2017. DOI: 10.1049/oap-cired.2017.1035

"Field Measurement of Frequency and ROCOF in the Presence of Phase Steps", P.S.Wright, P. N. Davis, K. Johnstone, G. Rietveld, and A. J. Roscoe, IEEE Transactions on Instrumentation and Measurement, 2019. DOI: 10.1109/TIM.2018.2882907.

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