15NRM04 ROCOF

Evaluation report on the problem of ROCOF measurement in the context of actual use cases and the "wish list" of accuracy and latency from an end-user point of view.

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TABLE OF CONTENTS

Executive Summary

Introduction and Aim

Power system frequency and rate of change of frequency (ROCOF) are increasingly important metrics for system control, protection and load management. As with any measurands (measured quantities), a user would ideally wish for noise and error free data which is available with minimum delay (or latency). However, the measurement of frequency and 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.

The aim of this report is to determine a "wish list" of accuracy and latency requirements for ROCOF from an end-user point of view. As frequency and ROCOF are useful for different purposes in power systems, accuracy and latency requirements maybe different for different ***use case*** scenarios.

Use Cases

From discussions, responses from network operators and other published documents, 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 [19] 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 1/10th 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 [18] 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.

The relevant section of this report tabulates the 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-centralized 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 [10]. 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 [18].

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 of proposed use cases

From the above table and other findings in the report, 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 [17] and the 0.01 Hz/s level that is in the original 2011 IEEE C37.118.1 standard [16]. 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.

The relevant section of this report examines the 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 [16] 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 the following table 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 [21] 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) [22]. 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 [22] 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

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.

It can be shown that the -3 dB point of the sinx/x spectrum of the sampled noise is 0.4•*Tr*. To achieve 2 kHz band limited noise, a 50 Hz synthesising signal generator should have the random noise values updated 2000/(50•0.4)= 100 times per generated cycle. This should give an approximate 2 kHz band width white noise.

The output of the synthesising signal generator will be amplified to give the working voltage (230 V or 110 V). The bandwidth of this amplifier should be sufficient to generate the 2 kHz 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. The difference in the ROCOF peak is less than 1 % on the trials looked at in simulation.

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 instrument may record a ROCOF change when the chirp stops, so there needs to be a suitable idle period between the chirp tests. Alternatively, stop the test and restart with the next chirp. 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.

1 Introduction

This document is intended to provide the basic descriptions of the concepts of Inertia and Rate-of-Change-of-Frequency (ROCOF) and the real-world use cases which are under specific investigation in this project. The specific use cases have been identified through consultation with project partners and end users. It describes the theoretical background of the most widely found ROCOF-related use cases and the problems faced with respect to each use case as a result of inaccurate or otherwise insufficient measurement of frequency, and therefore ROCOF, in their applications.

2 Background

2.1 Inertia

In order to maintain a desirable and constant electrical frequency within the system, it is imperative that balance is maintained between instantaneous generation and demand on a second-by-second basis. Any imbalance between generation and demand manifests itself in changes in frequency; when there is a deficit of generation with respect to demand the frequency will fall and when there is a surplus of generation with respect to demand the frequency will rise.

Inertia is a useful physical property in electrical networks as it acts to slow down dynamic behaviour and thus allows controllers, both automatic and manual, more time to successfully steer the system towards a stable and balanced state in the event of a fault or generation/demand imbalance. Inertia is an inherent property of synchronous generators and motors due to the direct coupling between their mechanical and electrical systems. When the electrical frequency falls, this direct coupling with the synchronous rotor (through electromagnetic synchronizing forces) causes the rotor speed to slow. Through conservation of energy, the corresponding reduction in kinetic energy within the machine rotor is therefore served to the power system as electrical energy during the period of slowing. The effect of this is to act to dampen, or slow down, the dynamics of the system as the “inertial response” exports or absorbs active power to counteract the short-term imbalances between generation and demand.

Many of the world’s power systems are due to become more and more dominated by non-synchronous generation in the form of wind power, solar PV or other converter-interfaced generation in the coming years. This steady reduction in the inherent inertia within the power system is cause for concern for system operators, since the speed (and therefore the controllability) of system dynamic behaviour will alter significantly and will require new methods of control in order to maintain present-day levels of system security and operability. This is a particularly acute problem in smaller, isolated power systems, where the largest possible loss of infeed (contingency) is proportionally large with respect to the overall demand in the system.

System operators are charged with ensuring that the largest anticipated loss of generation (and therefore largest instantaneous generation/demand imbalance) does not result in excessively large excursions in system frequency from its nominal value. Not only the magnitude of the frequency excursion should be limited, care must also be taken as well to ensure that the rate of change of frequency (ROCOF) does not exceed a certain value. It is this anticipated value of ROCOF for a given generation imbalance which is expected to rise in the coming years. The increasing levels of ROCOF means that operational and statutory frequency limits will be breached with more regularity since traditional droop control will become less able to arrest the frequency drop before these limits are reached.

Figure 1 shows projections by National Grid (the GB system operator) [1] of the annual distribution of total system inertia (in GVA.s) expected over the next decade. As can be seen from the figure, there will be a dramatic tendency for a growing part of the year to have a very low amount of synchronous inertia connected to the power system. This means that over a growing number of hours through the year there will be a high risk of system insecurity to possible loss-of-infeed events if there are no mitigation measures undertaken to address the erosion of system inertia.

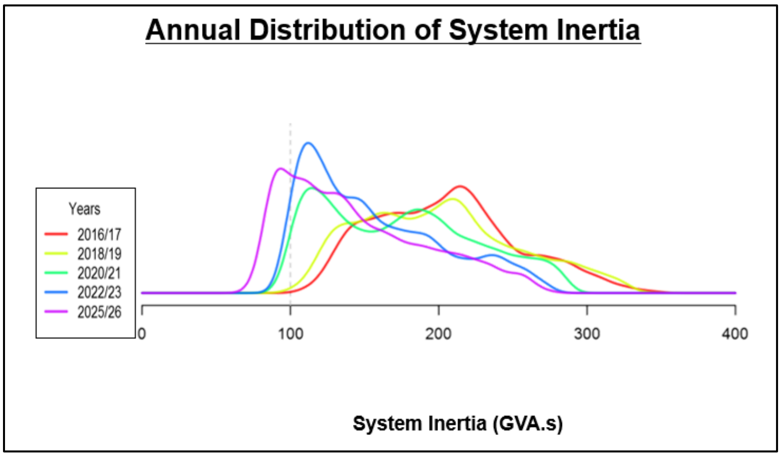

Figure 1: Projected probability density function of GB system inertia over an annual cycle [1]

2.2 Rate-Of-Change-of-Frequency

The instantaneous imbalance between the total amount of power generated and the total amount of power consumed in a power system leads to deviation in the electrical system frequency from its nominal value. This is a result of the injection or absorption of kinetic energy of the synchronous machine rotors; if the system demand is larger than the supply, energy is extracted from the spinning rotors, causing them to slow down to maintain the power balance in the short term. Conversely, an abundance of generated power manifests itself in the acceleration of the synchronous machine rotors. As these rotor speeds change, the frequency of the induced voltage waveforms in the machine stator windings also change in direct proportion. Therefore, the measured frequency of the voltage waveform detected in the power system can be used a reasonable proxy for generation/load power imbalance in real time.

The system frequency is continually changing due to normal generation/load fluctuations, and as discussed previously, the instantaneous amount of inertia available in the system dictates the initial speed at which the frequency will deviate for a given amount of power imbalance. High inertia leads to a slower drift in frequency, and low inertia leads to a faster drift from a steady-state condition. The rate of change of frequency referred to here is that occurring in the brief time window between the imbalance event taking place and the application of active power reserves (either governor-controlled primary response or fast acting active power injection from other sources, such as batteries, which seek to restore active power balance in the system).

A challenge faced by power system operators is being able to have confidence in their measurements of the ROCOF during system imbalance events. The accurate measurement of frequency and ROCOF are important in power systems as they are routinely used as input signals to control and protection systems. For example, inaccurate measurements and calculations of these measurands can lead to spurious activations of protection systems, which can result in greater frequency management problems due to generators needlessly disconnecting from the grid. It is therefore essential that operators can have confidence in their equipment to react appropriately to unexpected system events and a key way to ensure that is by having robust standards for the measurement and calculation of frequency and its derivative.

Several technologies such as measuring the angular velocity of the rotating voltage phasor, Discrete Fourier Transform (DFT) analyses and voltage zero crossing are conventionally available for frequency and ROCOF measurements. However, the majority of existing advanced digital meters (e.g. PMUs) measure ROCOF using DFT-based algorithms mainly due to the fast reporting rate that can be achieved. In particular, the majority of these DFT-based algorithms approximate ROCOF as a difference quotient. The frequency difference is averaged over a certain time frame (T_w).

$$ROCOF = \frac{\Delta f}{T_w}$$

As a consequence, ROCOF values are related to the window over which they are measured. Thus, a ROCOF value calculated using a measuring window of 1 ms, could be far greater (or smaller) than a value calculated using 100 ms or 500 ms as the relevant time frame, as illustrated in Figure 2.

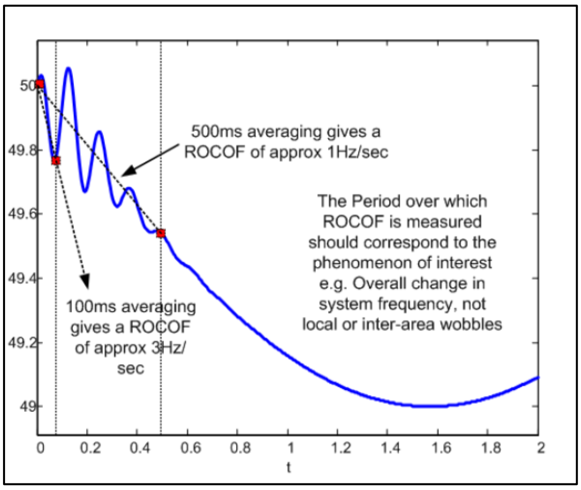

Figure 2: Effect of measurement window time on ROCOF value derived from a frequency signal.

However, whereas short measuring windows give more information on the instantaneous ROCOF value, they are much more sensitive to noise. ROCOF algorithms may have measurement windows in terms of time, or be set at a certain number of cycles of the voltage waveform. UK Engineering Recommendation G59/3-1 suggests that the use of cycles is not appropriate and should not be used [2]. The amount of noise in the measured frequency signal is an important factor, but it can be mitigated by using longer averaging windows. Unfortunately, the longer averaging translates directly into latency in the final control signal. A balance must then be struck between accuracy and latency [3].

Currently, system operators have two options for minimizing the high initial ROCOF experienced by the system during a single imbalance event. Firstly, they can ensure that a minimum amount of synchronous generation is connected and therefore provides the necessary inertia to maintain acceptable ROCOF values for all expected imbalance events. Secondly, they can plan their network such that the largest single potential loss of generation (infeed) is sufficiently small that it does not cause excessive ROCOF in the system.

The occurrence of high ROCOF levels is more prevalent in small, island networks. The relationship between the size of the interconnected grid and the largest loss of infeed determines that the smaller the network, the larger the expected ROCOF when a similar sized imbalance occurs. Therefore, it is smaller island networks, such as GB or Ireland which will be the first (larger) power systems to experience problems with ROCOF as they transition to high renewables and low inertia future scenarios. However, smaller power systems such as Shetland, and French-possessed islands in the Mediterranean have already seen ROCOF values as high as 5 Hz/s, and with frequency nadirs as low as 46 Hz (French island experience) and 42.5 Hz (anecdotal verbal evidence from Shetland).

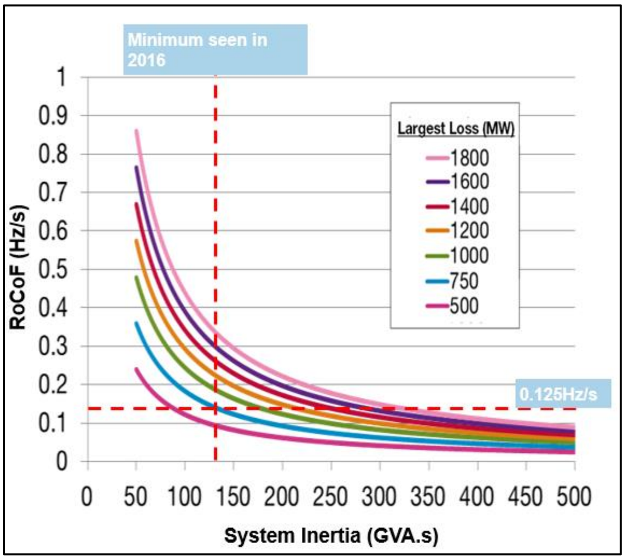

Figure 3: ROCOF experienced in GB for a range of inertia and loss of infeed events [1]

Figure 3 shows the sensitivity of ROCOF in the GB power system to the amount of system inertia online, for increasing loss-of-infeed events. It shows that for the present-day (2018) loss-of-infeed limit (1800 MW), and the minimum level of inertia already experienced in 2016, that there is a risk of ROCOF values of around 0.35 Hz/s. This exceeds the present-day ROCOF-based loss-of-mains protection settings for distributed generation. A presentation [1] given by Fiona Williams (National Grid Technical Policy) explains that the ROCOF withstand limit for generation units must be raised to over 0.5 Hz/s (measured over 500 ms) by 2025.

Owing to the lack of standardisation that this project is beginning to address, it has been noted in [4] that there is potential for two or more distributed generators connected in the same location to react differently to the same event, even with the same “settings”, due to slight differences in the ROCOF algorithms used in their respective protection devices.

3 Initial Project Questionnaire

Project industrial partners and interested parties were given questionnaires in order to elicit their opinions and experiences of rate-of-change-of-frequency related use cases in practice. The users were asked to describe their ROCOF use cases, and give information on the specifications which they would like to see met by potential future devices/algorithms, in terms of both measurement accuracy and latency (see Appendix A). The responses were variable in their quality and usefulness, however between the responses there were three stand-out use cases for ROCOF which were identified for further investigation in this project.

The most prominent use case identified by the users was that of “Loss of Mains” detection for distribution-connected generation. The use of such protection systems has caused problems for system owners and operators over the years, as spurious tripping of generation frequency occurs when islanding has not actually occurred. This leads to needless further problems of balancing in the system and frequency instability as a result.

A second use case identified in the questionnaire responses is that of Under-Frequency Load Shedding (UFLS). This is a last-resort technique used by power systems operators to maintain a sufficient balance between generation and load under extreme contingencies. By tripping selected portions of demand in the event of a large generation deficit, it is possible to keep system frequency within limits when otherwise these limits would be violated. ROCOF can be used as an input signal to the relevant controllers, allowing load shedding to be performed faster than simply waiting for certain frequency levels to be reached, and can therefore be more effective in arresting the frequency drop.

In the third use case, the use of ROCOF measurements as a control input to advanced frequency control systems, such as “Synthetic Inertia” was highlighted. In these cases, the perceived value of ROCOF can be used as a control input to a system which will deliver fast active power response to mitigate fast frequency drifts from nominal in the immediate wake of an imbalance event. By utilising ROCOF, rather than the absolute value of frequency, as a trigger for the injection of active power, such systems can be an effective method of arresting the frequency within operational limits (in a similar manner to that described for UFLS above).

A basic description of each of these three use cases for investigation is given in the following chapters.

4 Use Case 1: Loss-of-Mains Protection

A key factor in distribution system protection is the ability to identify when a disconnection has occurred between the bulk power system and the distribution system. Due to the growth in distribution-level renewable energy systems (RES), in the event where a section of distribution system has become electrically isolated from the transmission system it is increasingly likely that the distribution system will remain energised by the RES. This causes an unsafe condition for workers to attempt to diagnose and repair the fault condition.

Loss-of-mains (LOM) detection is incorporated into the protection systems of RES in order to avoid such unsafe situations. The protection is based on the principle that it is likely that the isolated section of network will be operating in an unbalanced condition, i.e. instantaneous generation and load do not match. Therefore, when the network section has been isolated from the bulk power system, there will be an instantaneous and rapid change in the frequency experienced in the isolated network. The rate of change of the frequency experienced in this part of the network will generally exceed values typically experienced while the power system is intact. The RES are therefore commonly equipped with protection systems that measure ROCOF and, when its value exceeds a pre-set threshold, are programmed to disconnect the RES from the network. This guarantees that the RES does not contribute power to the isolated part of the network – de-energising the lines and allowing workers to fix the faulted section of network.

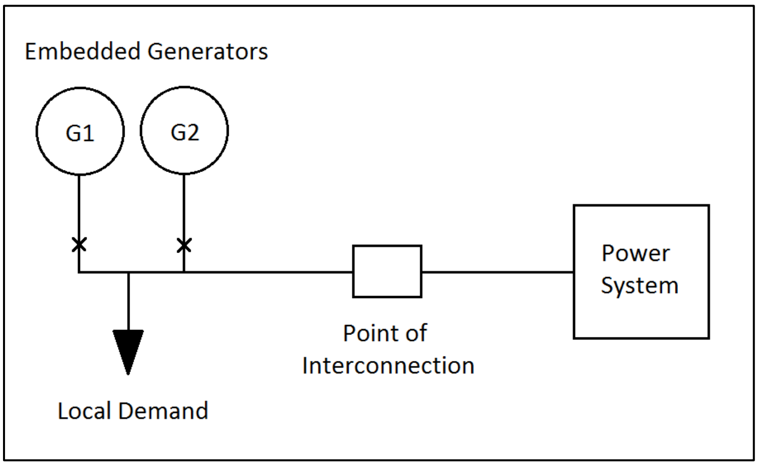

Figure 4: Typical configuration of distributed RES

4.1 Performance requirements: Sensitivity/Dependability

An ideal ROCOF-based loss-of-mains protection should be sensitive to truly problematic events during the full range of possible load and generation scenarios for a given power system (i.e. it should be capable of discerning a genuine LOM event from some other phenomena when the system is operating in a highly loaded or lightly loaded scenario). The most challenging scenario for loss-of-mains detection is when the demand closely follows the generation both in terms of active and reactive power. During such balanced conditions, the islanded local portion of the network might experience near-nominal frequency for a short period and the loss-of-mains protection will not activate as a direct result of the initial islanding. However, due to the islanding the local frequency will then be more sensitive to imbalance and it is likely that further imbalances in the electrical island will lead to high ROCOF and therefore generation tripping offline.

As the RES penetration increases and the total system inertia tends to decrease, the ROCOF values which will be experienced in normal operation will also increase. There is therefore a risk that formerly benign network events will cause disconnections of large amounts of distribution-connected RES due to overly-sensitive LOM protection systems in future. Such nuisance tripping may lead to larger problems such as cascading disconnections of generation through under-frequency protection systems.

4.2 Performance requirements: Stability/Security

The effectiveness of the LOM protection is therefore heavily dependent on the method employed for ROCOF measurement. Large discrepancies in the relay behaviour can be found between ROCOF relay manufacturers – even when the relays have the same settings. This is down to the differences in the algorithms used by the relays to give ROCOF measurements.

The system operator can mitigate against spurious tripping of LOM protection by ensuring that an adequate amount of inertia is always connected to the system (therefore slowing down the ROCOF for a given event), or ensuring that the largest loss of power infeed from a single event is kept below the level at which the ROCOF is excessive.

As an example of unwanted (though correctly triggered based on the perceived ROCOF) anti-islanding protection tripping, the May 2008 incident in GB is informative. In this event, an unexpected power imbalance of 1510 MW due to two unrelated generator trips caused ROCOF-based anti-islanding protection to trip and therefore a further loss of around 130 MW of wind and embedded generation occurred. Clearly this action only served to deepen the frequency drop and caused further problems. It is therefore imperative to ensure that anti-islanding protection only triggers in cases of genuine loss-of-mains and not where the perceived ROCOF is a result of a generation loss.

4.3 Selection of ROCOF setting in LOM protection

The selection of an appropriate setting for Loss-of-Mains protection depends on the individual characteristics of the power system into which the protection is installed. In a large interconnected grid, where the largest credible loss of power infeed (single generator or interconnector to another power system) is small in comparison to the size of the power system, a very low ROCOF will be expected due to the high inertia of the system. Conversely, in a smaller island power system such as that of Great Britain or Ireland, the same magnitude of loss-of-infeed will produce a much higher ROCOF in the system. It follows that when an excessive ROCOF is detected by LOM protection in larger power systems, it is highly likely that there has been a genuine LOM event and the protection is triggered. However, in smaller networks, particularly where the natural inertia of the system is being steadily eroded through the increased penetration of renewable energy sources, it is becoming increasingly likely that high ROCOF will be detected for normal system events which are not loss-of-mains events.

For successful Loss-of-Mains detection and relaying operation, it is imperative that normal/credible system faults such as the largest loss-of-infeed does not exceed the ROCOF threshold setting of the protection systems. Any such spurious tripping will lead to an even larger mismatch between the generation online and the demand and possible cascading failure of the power system and ultimately complete collapse of the grid frequency. It is therefore desirable that the ROCOF setting for LOM protection in a power system is above the level of ROCOF experienced during such faults. However, a ROCOF setting which is excessively above this level may lead to the LOM detection being unable to determine genuine loss-of-mains events, where the generating unit (and surrounding low-voltage network) has become electrically islanded from the bulk power system.

Therefore, it is the responsibility of the relevant transmission system operator (TSO) to set a ROCOF threshold which is unique to their power system and takes into consideration the inertia of the system, the largest loss-of-infeed and the corresponding ROCOF which is expected under the range of credible system operating conditions. The TSO is then responsible for communicating this threshold value to the distribution system operators (DSO) who in turn ensure that the distribution-connected generators comply with these settings in any loss-of-mains protection devices they operate. A "Regional based" anti-islanding protection scheme, described in [5], is also possible. In this case, the ROCOF threshold value is not fixed across the whole power system and instead an algorithm determines the best ROCOF setting for anti-islanding protection systems on a regional basis.

In the UK, previous to 2016, the prescribed LOM ROCOF setting was 0.125 Hz/s, however there was a proposal made in 2014 which would raise this to 0.5 Hz/s for all existing synchronous generators, 1 Hz/s for all non-synchronous generation and then 1 Hz/s for all new synchronous generation from 1 July 2016 onwards [6].

According a UK DNO [7], two methods for the detection of loss of mains, based on frequency measurements have historically been considered suitable, thought they both suffer from nuisance tripping during faults. For all its difficulties, ROCOF protection has been believed to be the best compromise, though Vector Shift (VS) protection can be very effective when used with asynchronous generating units.

4.4 Phase Shift (Vector Shift)

It has been identified in the industry that present-day ROCOF relays which are installed on distributed renewable energy resources can be susceptible to spurious tripping as a result of normal, otherwise innocuous, switching events and faults within the network. This behaviour can occur even when the event is located some large distance away from the ROCOF relay through the network.

This is due to the frequency measurement and resulting ROCOF calculation algorithms' correct perception of a step change in the phase angle, even when the underlying average system frequency is stable, as a loss-of-mains event. There may be situations where a high enough instantaneous ROCOF signal is perceived in order to trip the relay, even though the ROCOF signal has only been perceived for a very short duration of time and the underlying frequency is therefore stable.

The most common type of relay for loss-of-mains detection is the "Vector Shift" (VS) type relay. This works by monitoring the voltage waveform for shifts in the voltage angle and reacting to shifts which are perceived to be above a certain threshold value in degrees between two zero-crossings of the waveform. This type of relay can therefore react very quickly to an event but is susceptible to the sort of spurious tripping described above.

As an example, in May 2016 a large amount of embedded generation was lost in the south west of England following a fault. This was not due to ROCOF-based protection as the system ROCOF did not come close to the then limit of 0.125 Hz/s [5], nor was it due directly to low voltage as the dip in voltage was not long enough to cause an under-voltage trip. Investigations showed that a number of the sites had tripped due to operation of vector shift protection. Further work carried out by National Grid suggested that VS of up to 60 degrees might be seen for three phase short circuit faults on 400 kV transmission circuits and that in some circumstances these VS events are replicated on lower voltage networks with substantially the same magnitude of VS [14].

In response to the short comings of VS based LOM protection, the UK regulator has prohibited the use of VS in its DC0079 modification to the UK G59 grid code [19].

4.5 User Accuracy and latency expectations

User's requirements reflect their expectations, rather than the state-of-the-art capabilities of ROCOF instrumentation which for certain dynamic signals fall far short of these expectations.

Two utilities have indicated accuracy and latency expectations of ROCOF for the use case of LOM. A DNO, stated these as follows:

- <u>Expected noise / ripple on ROCOF (due to unwanted influences)</u>: There is very little consistency between the response from different relays when the input is representative of a real fault and even under idealised ROCOF events created by an injection test set there can still be wide variations in response. As a result, the joint Distribution and Grid code working group looking at issues with ROCOF relays required a ROCOF of 1Hz/s with a 500ms delay to be used in order to ensure stability of generators during events which caused a widespread disturbance to the frequency of the GB network. Accuracy and Noise levels need to be established but are not so important as consistency of operation between relays of different manufacturers.
- <u>Highest useable error / noise on ROCOF (due to unwanted influences)</u>: Error < 0.05 Hz/s, noise < 0.02 Hz/s (0.01 Hz/s), speed of response to a change in ROCOF < 80 ms.

- Unacceptable error / noise on ROCOF (due to unwanted influences): Error > 0.1 Hz/s, noise > 0.1 Hz/s
- Normal latency: 60 ms
- Maximum latency: 100 ms

A TSO, stated these as follows:

- Expected noise / ripple: The figures below are worst case based on the current are based on 10 % margin of error worst case for 0.1 Hz/s trip level however this could be averaged over seconds. Accuracy: 0.01 Hz/s, noise: 0.01 Hz/s
- Highest useable error / noise on ROCOF (due to unwanted influences): Error: 0.125 Hz/s, noise: 0.125 Hz/s
- Unacceptable error / noise on ROCOF (due to unwanted influences): Error > 0.125 Hz/s, noise > 0.125 Hz/s. These figures could result in false tripping while the system is perfectly stable. Less would be required if any instability on the system is detected. Note there are probably time delay associated with the trip which might filter / prevent some false tripping.
- Normal latency: According to G59 ROCOF protection may have to operate in under 2.5 s to prevent auto reclose from re-establishing an out of sync connection. Any latency in measurement eats into this time along with the breaker open time and tolerances.
- Maximum latency: see previous answer

The highest useable error in the ROCOF measurement for these two utilities of approximately 0.1 Hz/s is below the level of the present, 2014, amended IEEE requirements [17] for protection class (P class) PMUs of 0.4 Hz/s, and well above the original, 2011, IEEE requirements [6] for protection class (P class) PMUs of 0.01 Hz/s. So, from the point of view of these utilities, the amended 2014 IEEE ROCOF requirements are not meeting their requirements – they are too much relaxed with respect to the initial 2011 requirements. This initial 2011 IEEE ROCOF requirement of typically 0.01 Hz/s is much closer to the desired accuracy of the utilities of better than 0.05 Hz/s.

Concerning the latency expectation: the present maximum allowed PMU reporting latency for a P-class PMU is 2 / F_s, with F_s the reporting rate [17]. For a reporting rate of 50 readings/s, the allowed reporting latency thus is 40 ms and for a reporting rate of 25 readings/s, the allowed reporting latency is 80 ms. So only for reporting rates of 50 readings/s the IEEE requirements is sufficient to meet the DNO expectation mentioned above although the TSO can tolerate 2.5 s latency.

4.6 ENTSO-E Recommendations

In common with this document, the report from ENTSO-E RG-CE System Protection & Dynamics Sub Group published in January 2018 [18] discusses the trade of frequency measurement accuracy and window lengths for a number of use cases. The ENTSO-E report specifies window lengths, whereas in the user survey responses are given as latencies. The latency is (for a symmetric filter/window) half the window length. In the case of ROCOF measurements, it is suggested that “for an accurate ROCOF calculation experience has shown that a sliding window over approximatively five consecutive measurements gives robust results which in the case of 100 ms time resolution results in 0.5 seconds time required before a reliable ROCOF value can be available”.

The ENTSO-E recommendations for ROCOF for “additional protection criteria for generation or load”, is an accuracy of 0.05 Hz/s which is consistent with the two utilities surveyed above. In terms of latency, ENTSO-E recommends a measurement window length of between 180 ms and 240 ms, i.e. latencies ranging from 90 ms to 120 ms consistent with the perceived needs of UK utilities.

4.7 *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 See [19] (relaxed G59)	0.1	500	Accuracy of 0.1 Hz/s is assumed from 10 % of the setting value of 1 Hz/s.

Although the DNO and ENTSO-E argue for ~100 ms latency, a logical argument is provided by the TSO where the total LOM relay operational time must be less than the reclosure time of other protection relays, i.e. <2.5 s. With this in mind, latency could probably really be 250 ms (window length 500 ms) to 500 ms (window length 1000 ms) to provide a realistic chance of meeting the accuracy requirements by giving a more stable measurement.

A proposed measurement with a 500 ms window should be appropriate to meet the tasks of both LOM and the monitoring of large inter-area oscillations, with oscillation frequencies up to ~2 Hz. The latter is consistent with ENTSO-E requirement of 500 ms to 1000 ms measurement windows for the "evaluation of synchronous area level" [18].

From the above table a pragmatic ROCOF LOM specification of:

- **0.1 Hz/s maximum error**
- **No greater than 250 ms measurement delay (500 ms window).**

The ability of the ROCOF instrument to make robust and reliable measurements to this specification in the presence of phase jumps, other noise or power quality disturbances remains a major challenge. As phase jumps and switching events are associated with power system faults, one solution may be to use detection methods to ride-through fault conditions.

5 Use Case 2: Under-Frequency Load Shedding (UFLS)

The continuous adjustment of generation set points to match demand on a second-by-second basis in power systems can often fail when an unexpected event happens. The loss of a generator or tie line providing power to the network is an event that may not be predictable, but plans can be put in place to ensure that such an event does not cause variations in frequency which fall outside of allowable bounds. The last resort in such measures is Under-Frequency Load Shedding (UFLS) [13]. These protection schemes are commonly configured to trip off a pre-determined amount of demand at a given under-frequency set point, thus partially or fully restoring the balance between generation and demand and ensuring that frequency is contained within the acceptable boundaries stipulated by the network operator.

As well as traditional load shedding based entirely on the frequency deviation from nominal, UFLS devices have also been developed and used that include logic based on the rate-of-change of system frequency [8]. Such schemes allow the load-shedding protection to engage long before the frequency limits are breeched, based on high measured ROCOF magnitudes and can therefore be useful in the event of large disturbances during times of low inertia which, without the ROCOF-based logic, could result in unacceptable deviations in system frequency outside of normal bounds. By initiating load shedding before this point, further tripping of generation which would occur at the outer envelope of acceptable frequency can be avoided and thus the integrity of the power system is maintained with minimal impact on overall system operation. From the perceived ROCOF value, an estimate can be made of the severity of the disturbance and whether frequency limits are likely to be breached. The control logic can then use this information to provide tripping. This is known as a “slope estimation” method [9].

Just as is the case for ROCOF-based loss-of-mains (anti-islanding) protection, the spurious activation (or failure) of ROCOF-based UFLS schemes could also cause potential problems for system operation. In a situation where a high short-term ROCOF value is perceived, when a genuine large imbalance event has not occurred (such as a short term dynamic event or unmitigated frequency measurement noise), the triggering of UFLS schemes would be a highly undesirable outcome and could cause wide-spread effects in the system as devices act to halt the fast over-frequency event which results from the loss of load. The de-centralized nature of UFLS schemes could mean that if a high number of individual ROCOF-based UFLS devices spuriously detect an unacceptable ROCOF there could be a significant loss of load at one time. Therefore, the development of robust standards for ROCOF measurement for this application will be of great benefit in ensuring the successful use of UFLS schemes and system stability in the future power system.

A DNO commented on the accuracy and latency required for this use case:

- Expected noise / ripple: We would prefer that the devices we used could determine the difference between the ROCOF caused by the load - generation imbalance and those short-term effects caused by the reactive power flowing into the fault. We would also prefer that the output was a digital signal representing the value of ROCOF so that it could be fed into a device which would know the capacity of still operating generating units and the head room that each had to respond and allow the device to determine the optimum amount of load shedding and allow it to take place as soon as possible so as to stabilise the network frequency sufficiently quickly that embedded generators ROCOF protection did not operate and make the situation worse.
- Highest useable error / noise: Error < 0.05 Hz/s, noise < 0.02 Hz/s (0.10 Hz/s), speed of response to a change in ROCOF < 40ms.
- Unacceptable error / noise: Error > 0.1 Hz/s, noise > 0.1 Hz/s
- Normal latency: 40 ms
- Maximum latency: 60 ms

These accuracy requirements are similar to those stated for the LOM use case, but there is an increase of the latency requirements. The 40 ms normal latency corresponds to the IEEE latency requirement for a P-class PMU with 50 readings/s reporting rate [17].

5.1 ENTSO-E Recommendations

In the ENTSO-E report [18], requirements are stated in terms of frequency measurement rather than ROCOF. The accuracy requirements are stated as 0.03 Hz with a measurement window length of 90 ms to 120 ms (latency 45 ms to 60 ms) which includes the relay operation time. The ENTSO-E delay requirements are similar to the UK utilities once protection equipment operate time is taken into account.

6 Use Case 3: Generator Frequency Response (Synthetic Inertia)

In a similar, but complimentary way to the under-frequency load shedding, the ROCOF signal can be used as a control input to determine the primary frequency response from generating units. This can take the form of “Synthetic Inertia” from wind turbines, or a similar concept from battery storage or solar PV. In either case, in order for this to be useful, the resource must have some measure of possible reserve power available for injection to the system on a short-term basis. This can be accomplished by having the resource dispatched at a power output below the rating of the unit. In the case of synthetic inertia control of wind power plants, the extra power required in the primary period following a frequency disturbance can be obtained by temporarily slowing down the turbine rotor in order to extract kinetic energy to make up the extra power, which can be “paid back” to the rotor at a period after the primary response has been successfully used. This power payback can cause the full recovery of frequency to its nominal value to be delayed, and there is therefore a trade-off between the contribution to arresting the initial frequency drop and the overall time to full frequency recovery following a loss of generation event, for example.

The control input to the synthetic inertia controller may be the frequency measurements at the point of coupling to the power system. The synthetic inertia controller will then perform the necessary calculation of ROCOF based on these measurements and the ROCOF algorithm settings set by the generator owner. This makes the accurate measurement of frequency an important factor in the accurate assessment of ROCOF, and therefore the inertial response will be directly reliant on the quality of the frequency measurement for successful operation. The control logic must be able to discern a genuine ROCOF event (real power imbalance in the system) from other issues, such as excessive noise in the frequency measurement, or switching events in the system which cause the frequency measurement to be inaccurate. There should be no doubt that the synthetic inertia will operate when required to do so, while continuing normal service during other events.

A problem arises here, as the standard technique for discriminating a real ROCOF event from other phenomena is to measure the frequency over a relatively long-time window (e.g. 500 ms) to ensure that there is a genuine reduction in the overall frequency. This calculation delay ensures that there can be no extra active power response within a time window of at least the measurement time. This puts the onset of the “inertial” response of the wind generator at a post-event time window that is long after that provided by natural inertia from synchronous machines [10]. 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, synthetic inertia 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. When providing such a measurement, it is difficult to discriminate between the response of the system and the synthetic contribution. This suggests some kind of continuous feedback control rather than a bang-bang solution.

No specific accuracy and latency requirements were received from utilities for this particular use case.

The term “fast response to frequency variations” may be preferred to “synthetic inertia”. Where “fast” is loosely defined fast enough (e.g. 100’s of ms) compared to traditional response times of synchronous machines (e.g. seconds).

6.1 ENTSO-E Recommendations

In the ENTSO-E report [18] does not give explicit requirements for ROCOF, only stating “synthetic inertia will need a fast measurement”. For “decentralised generation control” (not necessarily synthetic inertia) it suggests a frequency accuracy of 0.01 Hz, measured with a 100 to 200 ms window (latency 50 ms to 100 ms).

6.2 Additional Fast Frequency Response Requirements

New requirements for active power damping and control, FFR (Fast Frequency Response) and “Synthetic Inertia” have been added by the authors, which did not appear in the original survey, nor the ENTSO-E report [18]. These are emerging requirements in the UK and EU, requiring faster active-power response to frequency changes than are traditionally provided through existing ancillary service mechanisms. Such FFR techniques are being explored, for example, in the UK EFCC project [20]. The general consensus among emerging FFR applications is that the response needs be within 500 ms, preferably less. Accounting for prime-move and other response delays, this requires measurements of ROCOF (and frequency) to occur within just a fraction of 500 ms, perhaps a 50 ms to 100 ms latency, 100 ms to 200 ms window length.

A proposed measurement with a 200 ms window (100 ms latency) is an alternative to the 5-cycle window for active-power damping and control, FFR, and “synthetic inertia” actions, where a higher latency can be accepted. The benefits of the latency extension will allow much better filtering of influence quantities, i.e. more stable measurement under poor power quality.

7 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

8 PQ Scenarios and Events

The present standardisation of ROCOF measurements is limited to the PMU standard IEC/IEEE C37.118.1 [16], which notably relaxes the ROCOF compliance requirements during certain tests, and limits certain test conditions to “nominal frequency only”. Unintentionally, IEC/IEEE C37.118.1 is the only standard which regulates power-system ROCOF assessment, but it contains many loopholes for ROCOF assessment in real-world PQ conditions.

In order to find PQ scenarios beyond the IEEE C37.118.1 standard, in the following we analyse some representative waveforms acquired at the level of sub-transmission and distribution grids. In particular, waveforms have been captured on the Dutch LiveLab grid [11], the Danish Bornholm island grid [12] and a low voltage grid in the area of the city of Glasgow. For the ROCOF point of view, we consider only voltage waveforms as they present better power quality compared to current waveforms. In the subsequent sections of this chapter, the issues of harmonics, noise, amplitude steps and phase steps are discussed respectively.

8.1 PQ - Harmonics

LiveLab Distribution Network

Figure 5 shows two representative voltage waveforms captured on the 10 kV LiveLab grid. This grid contains a large-scale penetration of decentralized generation units which are responsible for poor power quality.

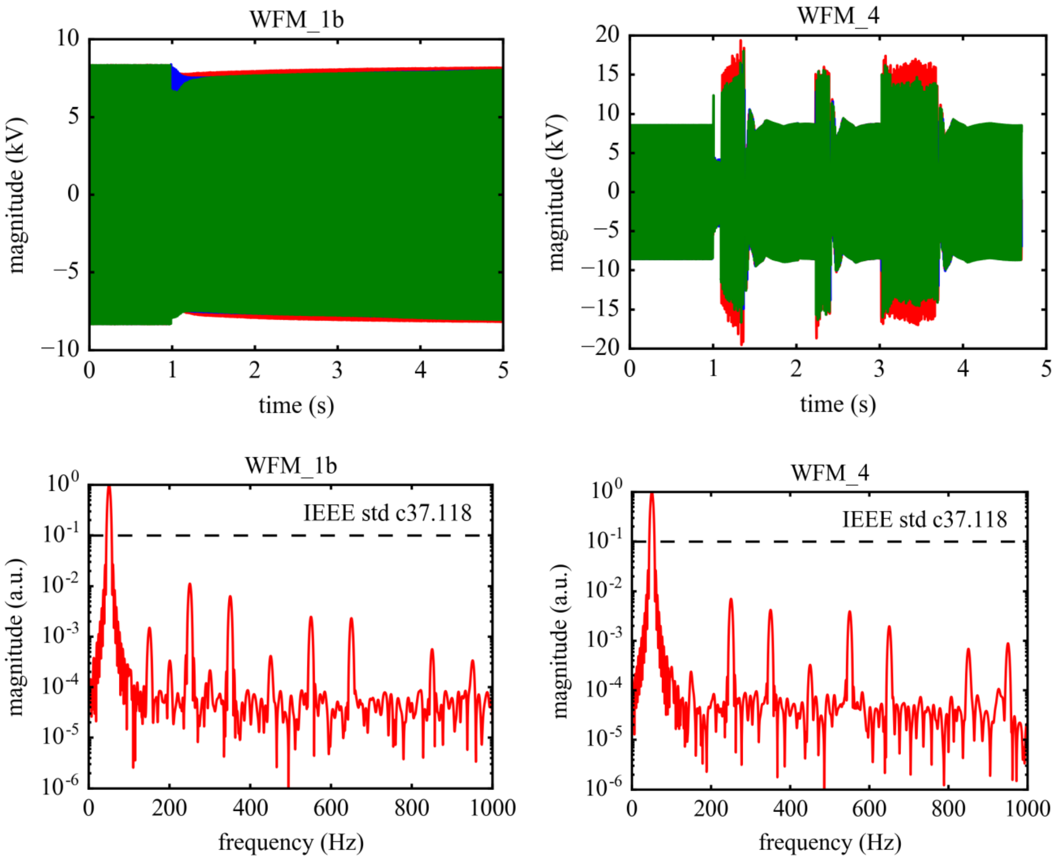

Figure 5: Two 3-phase voltage waveforms (top) captured at the LiveLab 10 kV grid and their respective Fourier spectra (bottom)

The two waveforms present two different moments in time with the effects of a transient starting after 1 s in each case. We define the steady-state condition as the time before the transient occurs. The bottom part of Figure 5 reports the relative spectrums of both waveforms respectively during the pre-transient steady-state conditions. In both cases, the magnitude of the harmonics is below the limit imposed by the IEC/IEEE C37.118.1 standard, i.e. 10% of the fundamental component (dashed lines in the bottom part of Figure 5). The tests of the IEC/IEEE C37.118.1 standard only considers a single harmonic or out-of-band harmonic added to the fundamental component, whereas the grid signals clearly show the presence of multiple harmonics next to the fundamental component.

Bornholm Island Sub-Transmission Network

Figure 6 shows two typical voltage waveforms acquired from the 60 kV sub-transmission grid of Bornholm Island. The waveforms have been acquired with a 24 bits digitizer and a sampling frequency of 20480 S/s. As in the case of the LiveLab waveforms, the harmonic contribution level is very well below the limit of the IEC/IEEE C37.118.1 standard tests.

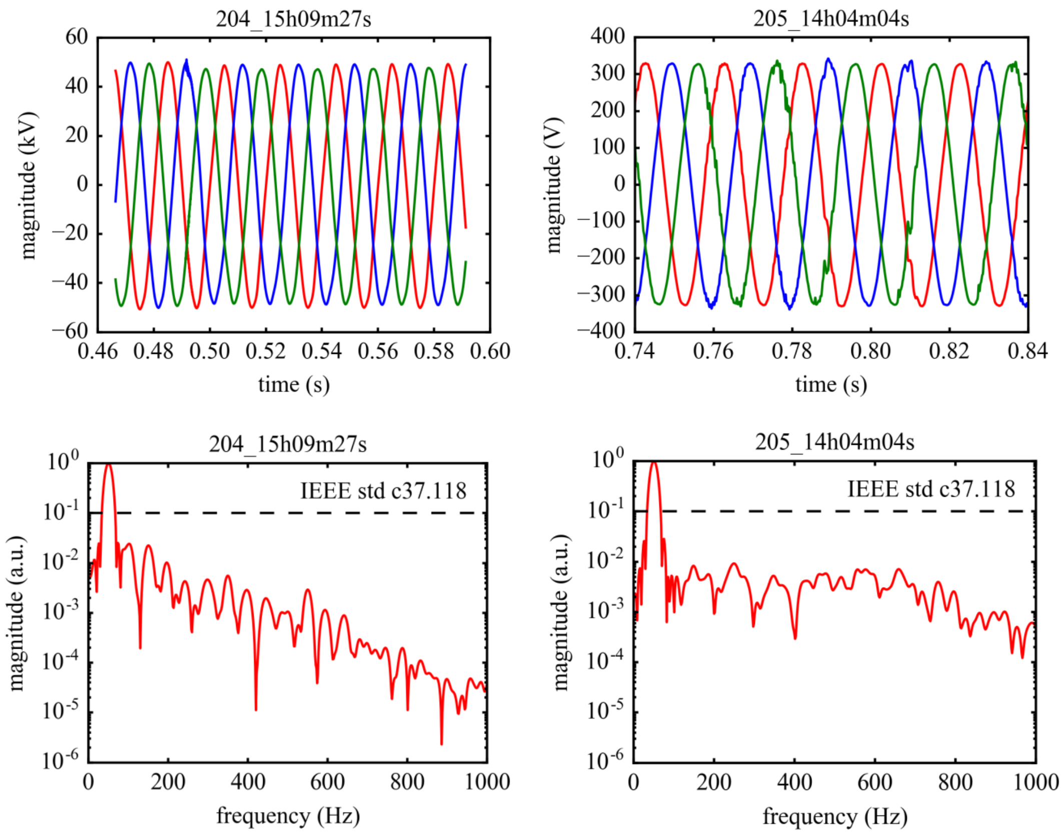

Figure 6: Two typical 3-phase voltage waveforms (top) captured at the Bornholm distribution grid and their respective Fourier spectra (bottom)

Glasgow Grid

Figure 7 shows the effect of an unbalanced fault on the distribution grid of Glasgow city. The transient occurs after circa 100 ms, and the normal operating conditions were restored after 900 ms. Considering the waveforms before the transient occurs leads to the spectrum of the right-hand side of Figure 7. As in the case of the LiveLab and Bornholm waveforms, the harmonic components are well below the limit indicated by the IEC/IEEE C37.118.1.

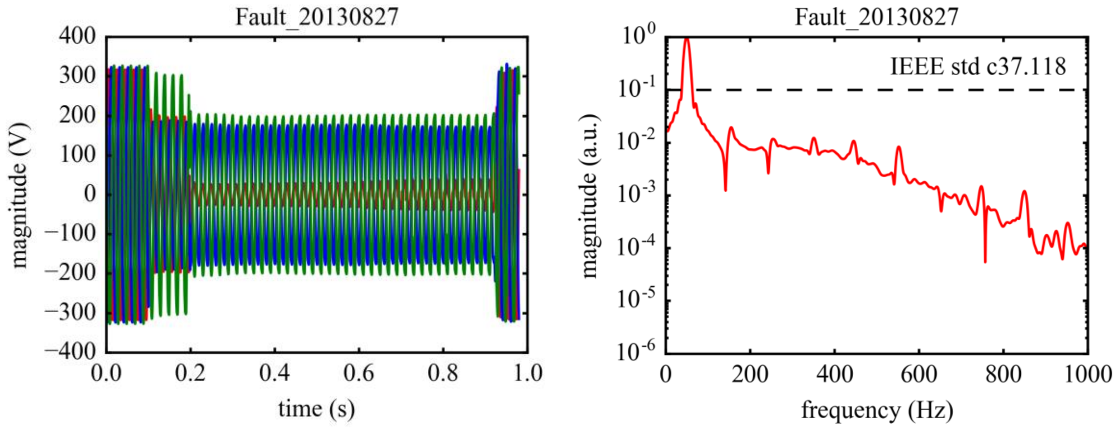

Figure 7: 3-phase voltage waveform (left) captured during a fault on the Glasgow distribution grid and its Fourier spectrum (right)

Discussion

In all three cases studied, the harmonic components in the grid signals are well below the limits set by the IEC/IEEE C37.118.1 standard. So, in this aspect the standard very well covers the actual grid conditions. However, the testing according to the IEC/IEEE C37.118.1 standard only considers testing for a single harmonic at a time, whereas in practice there are always multiple harmonics present in electricity grids. A useful additional test thus could be a signal with multiple harmonics, for example odd harmonics up to 1 kHz, with equal magnitude and the total harmonic content (THD) of 10 % (that is: the limit of the IEC/IEEE C37.118.1 standard for single harmonic component testing).

It important that even harmonics are not forgotten, even though they are generally small in magnitude in power systems, Algorithms that employ zero crossing detection are particularly susceptible to even harmonics and recommended ROCOF testing should include some small 2nd harmonic tones at several phase angles.

8.2 Noise

In a recent paper [3], several project partners have evaluated the effect of PMU front-end noise on ROCOF measurements. In addition to this noise originating in PMU, there is noise in the actual grid signals as well. The signals shown in section 7.1 have been analysed on their noise levels. In all cases, the noise in a 1-kHz bandwidth was less than 1 %.

However, measurements in the vicinity of large disturbing plant are likely to cause high noise environments, which although deemed extreme still form part of the public supply network. For example, recent data capture in an iron works in Slovenia [21], shows noise at some 10 % of the fundamental with approximately constant amplitude noise across the 2 KHz spectrum (the upper measured limit).

Since ROCOF is the second derivative of the phase of the waveforms, it is very sensitive to noise. It therefore seems useful to test ROCOF algorithms on their actual sensitivity to noise. The present IEEE standards [16, 17] do not yet include such testing.

It is common for network operators to position protection and control equipment close to the point of common coupling where noise and distortion levels would be expected to be lower. This gives rise to a pragmatic suggestion for the noise levels at which ROCOF instrument would be expected comply should be set to **3 % of the fundamental white noise up to 2 kHz**. Higher frequencies will be present in practice, but even if not attenuated by various transformers, the ROCOF filter design should be quite safely in the stopband at higher frequencies.

8.3 Amplitude steps

The IEEE C37.118.1 standard includes testing of PMU measurement accuracies for amplitude steps of 10 % [16]. However, during e.g. faults the amplitude steps are significantly larger, as demonstrated in Fig. 5 and 7, where the amplitude variations are of the order of 50 %. In general, the voltages in distribution grids will change more than in transmission grids, especially when significant RES are connected. If utilities indeed would like to have accurate ROCOF measurements during these circumstances, ROCOF algorithms should be tested on larger amplitude steps than the 10 % included in the present IEEE C37.118.1 standard [16]. ROCOF algorithms should also consider unbalanced faults which in some cases would appear as amplitude steps (and probably phase steps) on one or two of the three phases.

8.4 Phase steps

One major issue that has been identified by two of the major respondents to the survey is that of phase steps in the network. Specifically, both DNOs and TSOs have been noticing that phase steps cause significant problems for both Loss-of-Mains protection systems (via nuisance tripping) and frequency response (through inappropriate responses).

Phase steps are a natural phenomenon within power networks. Even in an infinite-inertia system, which has an “infinite bus” at some point, phase steps occur. They occur due to load steps, switching actions, or generator connections/disconnections. Even if the “underlying” network frequency remains constant, the phase change across an inductive transmission line or transformer is roughly proportional to the active power flowing through it. Therefore, even when system inertia is large or infinite, local phase steps occur when power-transfer steps occur, and these occur during many scenarios. The result is that a transient ROCOF “double blip” with alternating positive and negative peaks is perceived, via the equations in section 2.2, and their implementations in real relays and measurement systems, which sample the electrical voltages.

Phase steps also occur during faults (both balanced and unbalanced), sometimes due to hard faults directly, sometimes due to switching to alternative circuits as a result of trips, and sometimes due to transient faults like lightning strikes and lines touching during storms, which cause trip-and-reclose events. These latter events can occur in their 10’s and 100’s, in quick succession, during bad weather events. A TSO has provided us with several useful datasets containing such events during the early part of our project. 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 [16] includes testing at phase steps of 0.1 radian, that is 5.7 degrees. Similar to the situation of the amplitude steps, this is significantly below the 20-degree phase steps occurring during bad weather events.

The phase step, and the perceived time-limited “blips” and ”double blips” in frequency and ROCOF, cause large transient inputs to any protection or control system which is using those measurands. These “blips” are in addition to any genuine change in “underlying” system frequency. The magnitude of the “blips” can be reduced by using longer time windows for the measurements, but this spreads the effect out over time. Figure 8 shows how a 20-degree phase step results in a ±20 Hz/s “double blip” on the ROCOF perception when measured using an 11 cycle window. This swamps any “genuine” event which would be expected to be in the < 1 Hz/s range in the UK network. It clearly demonstrates the problem with defining ROCOF as it is, in section 2.2, and then blindly interpreting ROCOF as a direct measure of system-wide active power imbalance.

This entire issue is described in much more technical detail, with examples, in the recent paper generated by our project [15]. In that paper, we propose to attempt to address this problem by defining an alternative measurand for frequency, which deviates from the traditional definition given in section 2.2, and allows phase steps to be dealt with differently. The proposed technique requires phase steps to be detected in real time, and discriminated/separated from the measurement process, to reveal a more “underlying” system frequency and ROCOF determination. This is not simply a matter of filtering, it requires intelligent analysis of the signal (in real time, not “in hindsight”), and a decision, probably based on thresholds, of whether a specific phase trajectory relates to a phase step, or a rapid phase deviation to so a “genuine” ROCOF event.

Attempts to realise a practical implementation of the above concept has become a major part of the project objectives for the 2nd half of the project. Such algorithms will most likely require some additional latency in which to process data and make a correction decision.

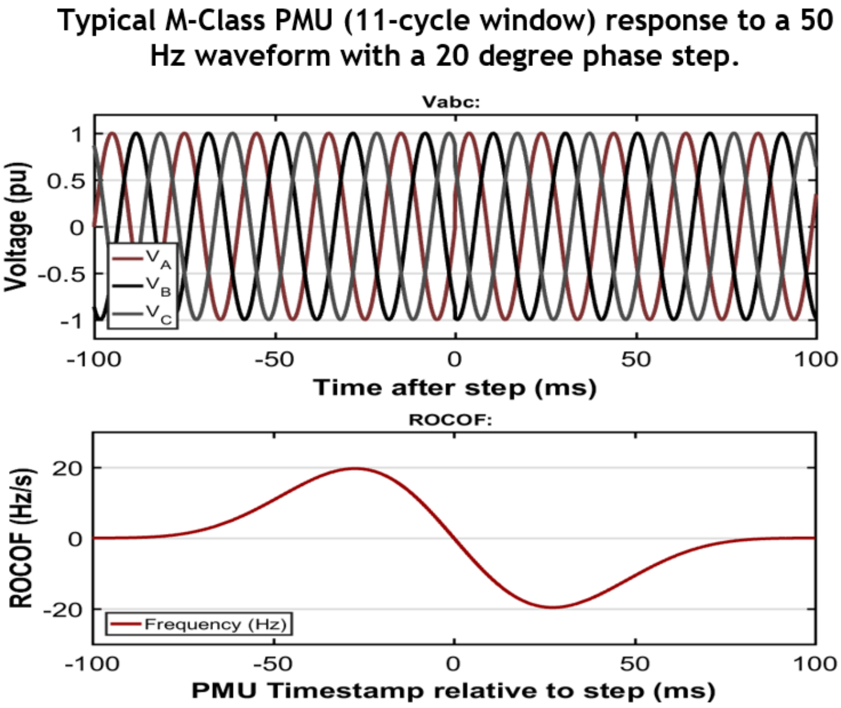

Figure 8: Waveform (top) containing a 20-degree phase step at t = 0 sec and its ROCOF perception (bottom)

8.5 Off-Nominal Frequency

The normal variation of the power system frequency will cause the heterodyne mixing frequency to misalign with the attenuation notches associated with the digital filters employed in the ROCOF instrument. Under these circumstances harmonics will not be so well supressed, leading to variations and errors in frequency and ROCOF measurements. Some PMU algorithms use an adaptive frequencies tracking method so that the heterodyne mixing frequency remains close to the power system frequency in an attempt to maximise filter performance.

8.6 Interharmonics and Flicker

Ripple control and other power line communications systems also intentionally inject interharmonics signals on to a power network.

Amplitude steps were considered in the section above, however smoother, slower voltage amplitude variation or modulation (flicker) is a common feature of the regulation of the power system. For example, if the amplitude variation were a perfect sinusoid repeating over 2 seconds, this would give rise to side-bands 0.5 Hz either side of the power system frequency. It follows that these amplitude modulations give rise to interharmonics.

As described in the previous section, many ROCOF instrument designs employ digital filters which are designed to reject the power line frequency and the harmonics which result from the heterodyne mixing process, however the effect of interharmonics or out of band frequencies, particularly those close to the power line frequency will fall within the passband of the digital filters and cause variations and errors in frequency and ROCOF measurements.

For short window lengths (5 cycles) ROCOF instrument implementations, achieving target ripple of the order 0.05 Hz/s in the presence of slowly modulated voltage (flicker) and close to fundamental interharmonics or subharmonics may not be possible to achieve.

8.7 Proposed Disturbance Tests for 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 the following table 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 [21] 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) [22]. 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 [22] 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

9 Discussion and Conclusion

An enquiry made amongst utilities and PMU experts has revealed three clear use cases where reliable, accurate ROCOF measurements are important:

- Loss of Mains protection (LOM)
- Under-Frequency Load Shedding (UFLS)
- Generator Frequency Response determination (GFR)

The three cases have in common that reliable and accurate ROCOF measurement is important to make the correct grid control decisions, e.g. to disconnect renewable generation (LOM) or loads (UFLS), or to ensure the optimal RES generator support to grid stability (GFR).

For the first two use cases two utilities have provided statements on the required accuracy and latency. The required accuracy of better than 0.05 Hz/s (certainly better than 0.1 Hz/s) lies in between the amended requirement of 0.4 Hz/s of the 2014 IEEE C37.118.1 standard [17] and the 0.01 Hz/s level that is in the original 2011 IEEE C37.118.1 standard [17]. It therefore is concluded that the amended 2014 IEEE requirements [17] are too much relaxed with respect to the original 2011 requirements [16], underlining the importance of the present project aiming to provide the basis for better ROCOF measurement and testing.

An analysis has been performed on the values of several power quality parameters for distribution grids and during events, like faults, occurring in the grid. The analysis focussed on four PQ parameters: harmonics, noise, amplitude steps and phase steps.

The 10 % test level of harmonic testing in the present IEEE PMU standard [16, 17] seems to cover quite well the situation in actual European electricity networks analysed in the project, where the actual harmonics generally are of the order of a few % at most. However, real field voltage signals characterized by poor PQ clearly present multiple harmonics added to the fundamental, whereas in the current IEEE PMU standard only a single tone is added to the fundamental one. Therefore, the analysis suggests that a more complex test signal where multiple harmonics are added to the fundamental component might be useful for ROCOF testing purposes. This for example could be a fundamental sine wave with odd harmonics up to 1 kHz of equal magnitude and a total harmonic distortion (THD) of 10 % - the limit of the IEEE PMU standard for single harmonic component testing.

ROCOF is the second derivative of the waveform phase (see section 2.2), making its measurement very sensitive to noise. Therefore, it is considered useful to test PMUs on their sensitivity to noise in their ROCOF measurements. It is noted that the present IEEE standards [16, 17] do not yet include such testing, possibly because typical noise levels electricity networks are relatively low. We indeed find low noise levels in the waveforms captured in distribution grids, typically below 1 %. Still, given the large sensitivity of ROCOF measurements to noise, PMUs should be tested to ensure that noise has no significant influence on their ROCOF measurement values. It seems sensible to add tests with a selection of test waveforms from the present IEEE PMU standard, with a few percent noise added.

Grid inertia in transmission networks is reduced due to the replacement of conventional power plants with RES, and is generally lower in distribution grids than in transmission grids. This results in larger magnitude and phase changes than before during grid events, such as faults or sudden loss of mains. The cases given by utilities to the project partners indeed have larger magnitude and phase steps than presently included in the IEEE PMU test standard: amplitude variations can be as large as 50 % and a recent grid event shared with the project team showed a phase step of 20 degrees, whereas the IEEE PMU testing is limited to an amplitude step of 10 % and a phase step of 5.7 degrees (0.1 radian). It therefore is suggested to extend the IEEE PMU testing with 5 times larger amplitude and phase steps.

In the second part of the project, the exact waveforms and test levels of the suggested additional tests with respect to the IEEE PMU standard will be determined.

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Appendix A: Stakeholder Questionnaire

ROCOF (Rate of Change of Frequency): Use cases and requirements

Viewpoints from industry, stakeholders, and the metrology/research community

We have just started a 3-year project, funded by the European Union under EMPIR, to investigate the Metrology of ROCOF (Rate of Change of Frequency) within electrical power systems. This project will perform the pre-normative research required to develop new IEEE/IEC/CENELEC standards for ROCOF measurements[1]. This brief questionnaire asks for your views on the uses of ROCOF measurements, their required/expected accuracy and latency to successfully fulfil those uses, and scenarios/events such as poor power quality or faults which need to be accounted for.

Our project is being carried out by a small number of European NMIs (National Measurement Institutes) and 1 University, and has a number of industrial stakeholders and supporters.

We need clear messages on the real-world use cases of ROCOF measurements, so that appropriate standards can be written to govern them, and suitable tests developed which support those standards. Even if you do not or cannot fill in all the sections, we value whatever input you feel able to give. Use the extra freeform sheets if you need more space. You can scan/email the questionnaire back to *andrew.j.roscoe@strath.ac.uk* or post it to the address given at the end.

Name :	Company : Email:	Use case 1	Use case 2
1) Please describe up to **3 of the main uses of ROCOF** within your company or products. e.g. Anti-Islanding or LOM detection, Other alarm thresholds, Monitoring/Visualisation, Generator control/damping, etc.			
2) What **device(s) do you use** to derive the ROCOF data? Please clarify whether you directly use a device ROCOF output, or whether (and how) you post-process frequency data in your own applications, to deduce ROCOF.			
3) What is your expectation and need of the **accuracy and noise/ripple level** (in Hz/s) of the ROCOF measurement for each case, during normal operation? (good power quality of the grid)		Accuracy: Hz/s Noise: Hz/s	Accuracy: Hz/s Noise: Hz/s

[1] http://msu.euramet.org/pre_norm_2015/SRTs/SRT-n12.pdf

	Use case 1	Use case 2
4) During poor power quality (high levels of harmonics, inter-harmonics, flicker, unbalance, and high ROCOF), what is the highest noise or error level on the measurement which would still make it usable in each use case?	Error: Hz/s Noise: Hz/s	Error: Hz/s Noise: Hz/s
5) What time **latency** is considered normal for the ROCOF measurement in each use case? You may express this in seconds or cycles. The **latency** is the time delay between the centre of the measurement window and the time that the measurement becomes available for use in your application. Generally, **latency** is half the measurement window time length, plus the computation time, plus the communication time.		
6) If a longer **latency** was technically required to achieve the target accuracy, what would the upper limit on latency be, to remain effective in each use case?		
7) What level of noise, ripple or error on the ROCOF measurement would make it **useless** in each use case?	Error: Hz/s Noise: Hz/s	Error: Hz/s Noise: Hz/s
8) Distant faults, load-switching and tap-change events etc. can produce a ROCOF measurement with a (potentially large) positive deviation, then a negative deviation (or vice-versa). For example with a 10-cycle window (5 cycle latency) **a 10° phase step can easily result in a ± 10Hz/s perceived swing**. The swing magnitude is proportionate to the phase step size, inversely proportional to the window length (and latency), and also depends on filter shape. **Does this issue presently affect you? How do your applications deal with this, and/or how would you propose to deal with this?**		
9) During **close-in full-depth faults** the ROCOF measurement can become even more "spurious". **How do your applications deal with this, and/or how would you propose to deal with this?**		
10) Do you have suitable sampled datasets (or characterisations) of difficult power-quality, switching or fault-related incidents which you could share with the project, to be used as test cases for ROCOF measurement?		

Do you want to keep updated on the project progress? YES / NO

Any other comments concerning your use of ROCOF measurements? Please use the following extension sheets.

Thank you for your time! Paul Wright (NPL), Gert Rietveld (VSL), Andrew Roscoe (Strathclyde), Martin Šíra (CMI), Jean-Pierre Braun (METAS)

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