Reliable Rate-of-Change-of-Frequency Measurements: Use Cases and Test Conditions

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***Abstract*— Based on user expectations and requirements, this article discusses three use cases (UCs) for measurements of power system frequency and rate-of-change-of-frequency (ROCOF) measurements, specifying accuracy and latency requirement for each UC. Furthermore, a set of realistic test conditions are proposed, extending those of the present IEC/IEEE 60255-118-1 standard, to ensure ROCOF measuring instruments are adequately tested on their suitability for reliable ROCOF measurements in power systems. Target worst case ROCOF errors (RFEs) are given for each test waveform and UC. Several published ROCOF algorithms are tested using the proposed test conditions. A selection of the test results is reported and compared against the target RFEs. The results show that the defined tests are indeed helpful in evaluating the ROCOF algorithms, and furthermore that the algorithms can be designed to meet all the requirements on RFEs for the tests proposed in this article.**

***Index Terms*— Accuracy, algorithms, frequency, frequency estimation, frequency measurement, phasor measurement units (PMUs), power system measurements, power quality (PQ), rate-of-change-of-frequency (ROCOF), synchrophasor, test conditions.**

I. INTRODUCTION

POWER system frequency and rate-of-change-of-frequency (ROCOF) are important metrics in the context of increasing levels of distributed generation; they are used as inputs to control systems for protection, power balance management, and provision of system inertia of electricity grids [1]–[4].

As with any measurand, a user would ideally wish for noise- and error-free data which are available with minimum delay (or latency). However, the measurement of frequency and ROCOF is particularly sensitive to power system disturbances and noise. Since they, respectively, are the first and second derivatives of the measured phase, any noise in the phase measurement is amplified in the frequency and ROCOF measurement [5], [6]. This can lead to erroneous control and protection actions, such as false tripping of distributed generation and false load shedding when used as inputs to power balance management schemes [7]. As a result, relatively intensive filtering must be used 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 (of half the measurement period). This results in a tradeoff between accuracy and latency, which in turn may give rise to a disconnect between the expectations of users and what is practically achievable.

ROCOF measurements are generally implemented in phasor measurement units (PMUs) [8], [9], the specification and testing of which is governed by the IEC/IEEE 60255-118-1 standard [10], [11]. Both a P-class and an M-class PMU specification are defined in this standard. Difficulties with the measurement of ROCOF led to a relaxation of the specifications for ROCOF from the initial 0.01 Hz/s [12] to the present 0.4-Hz/s accuracy requirement for the P-class PMUs, as published in an amendment to the IEEE PMU standard [13]. However, from the point of view of utilities, these accuracy relaxations are unacceptable for most applications, and there is a need to optimize the tradeoff of accuracy and latency for a range of applications and power system scenarios. Users also expect conformity testing of instruments to ensure acceptable performance in the presence of realistic power system voltage waveforms that may occur during both normal and fault conditions.

Several authors have worked on testing of PMUs under realistic power system conditions not covered by the present IEC/IEEE synchrophasor standard. These conditions include noise [5], [6], fault conditions and transients [3], [14]–[16], unbalance [17], voltage fluctuations [18], and other distorted signals [19]. Several of these conditions are particularly important for applications of PMUs in distribution grids [18], [20]. However, so far, a systematic discussion of possible new test signals for synchrophasor testing is still lacking. Furthermore, none of these studies has performed a review of the utility requirements for the actual accuracies to be achieved under these test conditions. In a previous article, we presented a "wish list" of accuracy and latency requirements for power system frequency and ROCOF measurements from an end-user point of view and performed a first exploration of possible new synchrophasor test conditions based on

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power quality (PQ) measurements in a series of medium- and low-voltage electricity grids [21].

In this article, we extend this work with the presentation of a full set of PMU test signals, extending those of the present IEC/IEEE 60255-118-1 standard, including an evaluation of the accuracies achieved by three different synchrophasor algorithms under these conditions for three different use-case (UC) scenarios. The structure of this article is as follows: Section II starts with an overview of user requirements on ROCOF accuracy and latency for three different UC scenarios identified by these users. Section III subsequently summarizes some of the realistic power system disturbances and events that occur in power systems. Based on these user requirements and realistic power system conditions, a table of testing conditions is developed in Section IV to ensure that commercial PMUs are suitable for reliable ROCOF measurements under actual power system conditions. Based on what is achievable with well-optimized algorithms, the proposed target worst case RFEs for each test condition and each UC are included in Table II of testing conditions. Section V confirms the practicality of the proposed test conditions using implementations of a selection of ROCOF algorithms and Section VI closes with conclusion.

II. USER REQUIREMENTS

To gain insight into the actual user requirements on ROCOF measurements, utilities were asked through a questionnaire to describe their ROCOF UCs 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, requirements expressed by the ENTSO-E "RG-CE System Protection and Dynamics Sub Group" in its table on "Frequency Measurement Requirements and Usage" [22] were considered. From these sources, three main UCs for frequency and ROCOF were identified, namely:

1) loss-of-mains (LOM) protection;
2) under-frequency load shedding (UFLS);
3) generator fast frequency response [e.g., "synthetic inertia (SI)"].

As discussed in the following parts of this section, each UC has different minimum accuracy and latency requirements, which we have based on the utility enquiry responses and the ENTSO-E report. We received only five replies to our questionnaire from both transmission and distribution system operators. In contacting a few utilities that did not respond, we learned the reason that the low response relates to the problem we are addressing in this article: given the existing low confidence in ROCOF measurements, utilities are not using them and also do not have detailed insight into their actual ROCOF measurement needs. Fortunately, the responses that did provide us with quantitative ROCOF measurement needs were quite consistent and in line with the ENTSO-E requirements and also in line with own understanding of ROCOF needs based on literature reviews and discussions with other utilities in the past years.

A. Loss-of-Mains Protection

LOM protection is required when embedded generation (e.g., renewable generation) is used in power systems [1], [2]. 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 assuming that the wider synchronized network has a more stable frequency than an isolated small subnetwork. It follows that the ROCOF can be used in protection relays to detect LOM and trip off the renewables to ensure protection of engineering personnel.

However, due to common power system disturbances and the particular noise sensitivity of ROCOF measurements, the variation in ROCOF 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 are phase jumps which occur due to routine network reconfigurations, circuit breaker operations, and other faults. Phase jumps are localized and give rise to the changes in the measured value of local frequency and an associated ROCOF spike that will often trip an LOM relay. Distinguishing between the changes in localized 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, considering the natural frequency variation in 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 an ROCOF value that causes mass tripping of renewables protected by LOM relays. As more renewables are connected to a network, the level of ROCOF values which will be experienced in normal operation will also increase. Therefore, utilities will need to review trip settings as the generation mix changes.

New regulations for LOM trip thresholds in the U.K. [23] reflect this problem and trip thresholds have been relaxed from 0.125 to 1 Hz/s in an attempt to reduce the 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 U.K.'s new limits. Surveys of other network operators and recommendations by ENTSO-E [22] confirm user ROCOF accuracy expectations to be close to this value.

The other side of the tradeoff is latency; ROCOF protection needs to operate in less than 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.

It is concluded that the LOM accuracy and latency requirements on ROCOF measurements, accounting for the needs of various sources, have the following specification:

1) 0.01 Hz/s preferred error and 0.1 Hz/s maximum error;
2) not greater than 250-ms measurement delay.

Similar ROCOF measurement requirements are valid for the detection of intersynchronous area oscillations in power systems. These subsynchronous oscillations are an important indicator for possibly system instability and should be measured with long latencies, such that the slow oscillations (of the order of 1 Hz) can be captured.

B. Under-Frequency Load Shedding

UFLS devices are used as a last resort protection scheme to disconnect loads from a network to maintain the frequency within limits [3], [25]. UFLS devices generally trip off a predetermined amount of demand at a given underfrequency 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 noncoordinated triggering of decentralized UFLS schemes, leading to a sudden widespread loss of load, resulting in a fast overfrequency event. The findings suggest similar accuracy to the LOM UC with slightly shorter latency:

1) 0.02 Hz/s preferred error and 0.1 Hz/s maximum error;
2) not greater than 50-ms measurement delay.

C. Generator Fast Frequency Response ("Synthetic Inertia")

Traditional generation and grid-forming plants can provide natural inertial response to meet any short-term deficit in generation capacity to meet demand. As the proportion of generation capacity provided by converter-connected devices increases, this natural inertia can be reduced, limiting the ability of the network to respond to sudden changes. "SI" from converter-connected devices using current control (nongrid-forming) control techniques 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 an SI 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 of 500 ms to provide robust data such that there is no doubt that the SI will operate when required to do so, while continuing normal service during spurious disturbance events.

This filtering delay unfortunately prevents an active power response within the window latency, which in turn delays the onset of the "inertial" response of the converter. The resulting response time is long after that provided by natural inertia from synchronous machines and grid-forming converters [24]. However, it will still provide response before the primary response (droop) of the synchronous machine governors and furthermore can do so with a higher ramp rate. Therefore, this generator response still provides a useful contribution toward arresting the initial frequency fall, both in terms of the ROCOF and the depth of the frequency nadir for a loss-of-generation event.

Therefore, in terms of ROCOF latency, a fast response is needed, where "fast" is loosely defined as at least fast enough (e.g., thousands of milliseconds) compared with traditional response times of large synchronous machine prime movers (e.g., seconds). ENTSO-E suggests accuracies for frequency of the order of 10 mHz [22].

TABLE I

OVERVIEW OF ROCOF UCs AND THEIR REQUIREMENTS ON LATENCY AND ACCURACY. IN ALL CASES, THE MAXIMUM ALLOWED PEAK ERROR/RIPPLE IS 0.1 Hz/s

Application	**Latency**	**Ideal peak error / ripple**
UC1: Active power damping and control. Under-frequency load shedding (UFLS).	50 ms (2.5 cycles)	0.02 Hz/s
UC2: Fast Frequency Response (FFR) and "Synthetic Inertia".	100 ms (5 cycles)	0.02 Hz/s
UC3: Anti-Island Detection (LOM, Loss of Mains). Inter-area oscillations.	250 ms (12.5 cycles)	0.01 Hz/s

D. Overview of Use-Case Requirements

Table I provides a summary of the industry views as surveyed in this article and the ENTSO-E findings [22] for the three identified UCs (UC1–UC3). In all UCs, the worst case peak error/ripple (i.e., the limit of usability) was deemed to be 0.1 Hz/s. Generally, the latency is half the measurement window time length (when the middle of the window is taken as the measurement instant), plus the computation time, plus the communication time. So to achieve a certain latency as specified in Table I, the window length of the ROCOF algorithm used in the ROCOF measurement device should be at most twice this latency, with the exact length depending on the type of algorithm used in the ROCOF estimation, the data processing time, and additional internal PMU delays.

The enquiry findings summarized in Table I confirm that the actual (ideal) wish of utilities concerning PMU accuracies is indeed quite close to the 0.01-Hz/s test accuracy requirements of the 2011 IEEE PMU standard [12]. However, taking into account what is practically realizable with the desired latencies, it is recommended that the general accuracy requirement for ROCOF is set at 0.05 Hz/s. This is still below the 0.1-Hz/s limit of usability set by utilities and well below the amended requirement of 0.4 Hz/s of the 2014 amendment to the IEEE C37.118.1 standard for P-class devices under steady-state conditions [13]. However, the 2014 relaxation of

ROCOF accuracy to 0.4 Hz/s is clearly above the limit of what utilities deem acceptable for useful ROCOF measurements.

III. POWER SYSTEM DISTURBANCES AND EVENTS

Under nominal power system conditions, the 0.05-Hz/s general 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 include harmonics, noise, voltage amplitude steps, off-nominal frequency, interharmonics, and phase steps.

To find relevant PQ scenarios for testing PMUs beyond those already covered by the IEC/IEEE 60255-118-1 standard [10], a series of representative waveforms were acquired from measurements in three European (50 Hz) subtransmission and distribution grids [21]. The analysis of the waveforms focused on four PQ parameters: harmonics (including interharmonics), noise, amplitude steps, and phase steps. For the harmonics, it was found that the present IEC/IEEE test levels essentially cover all harmonics levels detected in the three grids, but that actual grids always contain multiple (inter)harmonics so that it seems useful to extend synchrophasor testing with such signals. Noise is always present in the grids and synchrophasor measurement instrumentation [5], [6] and therefore certainly deserves testing, in particular because any noise in the phase measurement is strongly amplified in the ROCOF measurement. Amplitude steps in the evaluated grids occurred up to 50%, significantly larger than 10% included in the present IEC/IEEE standard.

While all the ROCOF algorithms will be to some extent susceptible to (inter)harmonics, noise, and amplitude steps, it is the occurrence of phase steps (or phase jumps) that are the most challenging for the ROCOF algorithms. The evaluation of the grid measurements revealed that phase steps regularly occur in power systems, among others caused by routine events related to network management such as reconfigurations and transformer tap changes, as well as being related to short-lived faults. The phase steps within the acquired data were as large as 20° in each phase, resulting in large ROCOF spikes. Such 20° phase steps are significantly above the 10° phase step of the present IEC/IEEE synchrophasor testing.

If the phase step is localized (the underlying system frequency has remained largely stable), then the ROCOF spike can be regarded as misleading. The ability of an ROCOF algorithm to measure the changes in the underlying system frequency to the required accuracy within the required latency time, while rejecting localized phase jumps, is the most challenging issue in delivering the useful measurement of ROCOF. Future algorithms such as [16] to reject phase jumps will most likely require added latency for decision processing.

Because each grid is different, and there certainly are significant differences between transmission, subtransmission, and distribution grids, the acquired waveforms cannot readily be generalized to ROCOF test waveforms. However, the acquired grid waveforms, combined with the existing literature on grid disturbances and knowledge of the pitfalls in digital filter implementation, provided a good basis for new ROCOF test signals as presented in Section IV.

IV. DISTURBANCE LEVELS FOR THE TESTING OF ROCOF INSTRUMENTS

To ensure compliance to the M or P PMU classes, a set of tests are defined in the IEC/IEEE synchrophasor standard [10] so that commercial vendors can ensure their instruments measure ROCOF with the accuracy requirements of the standard. In general, these tests are performed by carefully synthesizing and amplifying the test waveforms and applying them to the PMU under test. However, these tests need extension and modification to better ensure that PMUs are able to measure ROCOF and frequency under some of the more challenging grid conditions, such as poor PQ, frequency variations, and those induced during faults on power systems such as dips and phase jumps. Based on the findings of on-site measurements as summarized in Section III, publications, and knowledge of the pitfalls in digital filter implementation, the disturbance scenarios shown in Table II are proposed for future testing of ROCOF instruments. Tests 1, 2, 6, and 7 are all extensions of the (inter)harmonics testing, with, respectively, multiple harmonics, harmonics causing multiple zero-crossings, harmonics with off-nominal frequency, and tests for less than 10 frames/s reporting rates. Test 3 is a noise test, and test 9 is a combined noise/unbalance test. Test 4 is an additional amplitude step test, and finally, tests 5 and 8 concern test conditions with phase steps, inspired on actual grid conditions during faults.

The tests given in Table II should be used in conjunction with the specifications for the UCs given in Table I: 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 (tests 5 and 8) unless some form of phase step correction algorithm is used (see [16]). In addition, for low-latency designs, tests 3 and 7 may give rise to ROCOF ripple higher than the user's desired specifications. To reflect this, the right-hand column in Table II gives a proposed set of worst case RFEs for each of the three UCs based on what the authors deemed achievable with optimized filters for the given latency constraints. These target RFEs can be seen as the present reality of ROCOF measurements (i.e., what is considered achievable with present state-of-the-art algorithms) 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 Table II to satisfy the user's expectations under all grid conditions and UCs.

A. Implementation of Proposed ROCOF Tests

In actual testing of an ROCOF instrument against the tests in Table II, 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.

TABLE II

Proposed Disturbance Tests for ROCOF Measuring Instruments. The Last Column Gives a Recommended Worst Case RFE for Each of the Three UCs. The RFE Values Are Based on What Is Deemed Achievable With Optimized Filters for the Given Latency Constraints

Disturbance	**Existing IEC/IEEE C37.118.1**	**Proposed additional test**	**Rationale**	**Worst Case RFE (Hz/s)**
1) Harmonics	Single tone swept to 1 kHz. 1 % for P Class, 10 % for M Class	Harmonics number and amplitude in percent of the fundamental. Harmonic phase angles are zero. H2: 2 %; H3: 5 %; H4: 1 %; H5: 6 %; H6: 0.5 %; H7: 5 %; H8: 0.5 %; H9: 1.5 %; H10: 0.5 %; H11: 3.5 %; H12: 0.5 %; H13: 3 %.	More realistic and quicker to perform test. IEC61000-2-2 [26] refers to a tolerated THD of 8 %. As the PMU algorithm will low pass filter the signal, higher order harmonics are less challenging for the algorithm. The chosen harmonics are therefore limited to H13 to simplify the testing.	UC1: 0.02 UC2: 0.02 UC3: 0.01
2) Additional zero crossings	Similar to above, but phase is important	10 % of interharmonic at 14.01401• f_0 at an angle of 180 degrees relative to the fundamental.	To test sensitivity to multiple zero crossings. 10 % is the maximum value allowed by the power line communications standards (Meisner curve) [27]. The tone frequency is chosen to cause the variable zero crossing position to precess in time, changing the calculated "period" if a zero-crossing method were used.	UC1: 0.02 UC2: 0.02 UC3: 0.01
3) Noise	No test	white noise with 3 % amplitude of the fundamental, bandlimited (-3 dB) to 2 kHz. (Steady state, at nominal f_0, V, I).	To account for heavy plant in the vicinity of the connection. The noise level is based on levels measured in the vicinity of an ironworks.	UC1: 1.2 UC2: 0.2 UC3: 0.1
4) Amplitude Steps	Step change of 10 % of amplitude	40 % of amplitude dip on all phases; unbalanced test with 40 % amplitude dip on each phase in turn, with the other phases at 100 %. The dip duration should be long enough to the ROCOF to settle to the same ripple as before the dip.	More realistic short fault condition	UC1: 0.02 UC2: 0.02 UC3: 0.01
5) Phase steps (or jumps)	π / 18 radian (10°)	0.3 radian (17°) The step duration should be long enough to the ROCOF to settle to the same ripple as before the step.	More realistic short fault condition	UC1: 50 UC2: 25 UC3: 5
6) Harmonics with off-nominal frequency	No tests	Off nominal harmonics: composite waveform as per the first entry in this table but shifting the fundamental frequency by ±2 Hz either side of the nominal power system frequency f_0.	Off-nominal frequency testing with harmonics is important, since the heterodyne mixing frequency in the PMU may cause the attenuation notches in the digital filters to misalign. IEC61000-2-2 [26] allows nominal frequency variations of ±2 Hz.	UC1: 0.02 UC2: 0.02 UC3: 0.01
7) Close-in Interharmonics and flicker	Tests for ≥ 10 frames per second (FPS), none for <10 FPS. A single 10 % (of the nominal voltage) amplitude frequency is swept between 10 Hz and the 2nd harmonic of the power frequency for all frequencies excluding the stop band.	A single 5 % amplitude tone varied from 10 Hz to 90 Hz, but excluding the stop band. For frequencies outside the stopband and >40 Hz above the fundamental, increase the tone amplitude to 10 %. Sweep to 150 Hz.	Test rejection of close to the pass band interharmonics and flicker modulations. The 5 % amplitude is a conservative limit based on allowed flicker. The 10 % amplitude is a conservative rounding of the Meister Curve [27] 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 sinewave at f_0, an instantaneous frequency change to f_0-2 Hz (which effectively corresponds to a phase step), followed by linear frequency ramp at 8 Hz/s back to f_0.	Simplistic simulation of a fault condition causing a sudden loss of frequency, followed by a fast frequency recovery to nominal.	UC1: 50 UC2: 25 UC3: 10
9) Unbalance or phase misconnection	No tests	Repeat the noise test but with phase L1 having a phase shift of 180 degrees.	Simulates misconnection of one of the PMU channels or significant grid unbalance [17], with the additional effect of increased sensitivity to noise.	UC1: 2 UC2: 0.3 UC3: 0.1

The “stopband” referred to in test 7 in Table II is related to the digital filters used by the PMU algorithm. The filter used is aligned at the fundamental or actual power system frequency and has a passband of a few hertz either side with the stopband starting at $\pm F_s/2$, with F_s being the measurement update rate [10]. This allows the PMU to measure interarea oscillations in the power system (see Fig C5 in [12]). However, the unwanted effects of harmonics, interharmonics, and amplitude modulations will cause the frequency measurements to ripple and the filter must attenuate these effects within its stopband.

In test 2, the $14.01401 f_0$ tone frequency is chosen to cause the variable zero-crossing position to precess in time, changing the calculated “period” if a zero-crossing method was used. This choice of noninteger harmonic frequency with H14 as a basis is somewhat arbitrary other than wanting to ensure that the “carrier” is well within the PMU stopband. Other lower or higher frequency noninteger harmonic frequencies could have been chosen to induce a moving signal.

In test 3, the bandlimited white noise can be generated using a software pseudo-random number generator. This can be conveniently implemented as shown in [34, Sec. III] where the bandlimiting can be approximately achieved by updating the random values at a slower rate than the samples that are used to synthesize the testing waveform. This is achieved by defining a fixed update rate of the random values as T_r and setting 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 $\sin(x)/x$ spectrum of the sampled noise then is $0.4T_r$. To achieve 2-kHz band limited noise, a 50-Hz synthesizing signal generator should have the random noise values updated $2000/(50 \times 0.4) = 100$ times per generated cycle. The output of the synthesizing signal generator will be amplified to give the working voltage (230 or 110 V) of the ROCOF measuring instrument. The bandwidth of this amplifier should be sufficient to generate the 2-kHz noise.

For the phase step test 5, the phase of the starting 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 [34], will show this. The difference in the ROCOF peak is less than 1% on the trials looked at in simulation.

When testing close-in interharmonics and flicker, test 7 can be carried out using a linear chirp tone [28] mixed with the fundamental as shown in [34]. Three such chirps need to be used to cover the 5% test below and above the stopband, 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) to allow for sufficient time for the algorithm filters to settle. The instrument may record an 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 a compromise between testing quickly and being able to observe the maximum ROCOF. A chirp time of 60 s is suggested.

The unbalance test in test 9 is a repeat of the noise test performed with the L1 phase channel with a phase shift of 180° (on some systems this might be achieved by reversing the live and neutral connections at the PMU signal input terminals). 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 that combine a large grid unbalance with significant noise.

A detailed description of all the proposed test waveforms, including pseudo-code and waveform graphs, is available to facilitate future testing of other algorithms [34].

V. TESTING PMU ALGORITHMS WITH PROPOSED TEST WAVEFORMS

To demonstrate the applicability of the tests and RFE targets proposed in Table II, different ROCOF algorithms were tested using both simulated and laboratory synthesized tests from Table II. In all cases, the algorithms were implemented using the description given in the associated cited publications. These implementations were reconstructed without consultation with their respective designers (including [30] and [31], despite the coauthorship of this article) and as a consequence may not include any up-to-date optimizations. The window lengths and update rates were adjusted to match the latency requirement of each UC as given in Table I.

A. Algorithms Selected for Testing

The following three algorithms were selected and implemented for real-time processing on a digitizer system interfaced to a PC [29]: the M-class PMU algorithm of the IEEE standard [10], the boxcar filter algorithm developed by Roscoe *et al.* [30], and a phase-sensitive frequency estimation (PSFE) method developed by Lapuh [32].

1) IEEE Standard M-Class PMU Algorithm: The IEC/IEEE synchrophasor 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 D7 in [10]. As Table D.1 in [10] is not applicable (N/A) to the faster analog-to-digital-converter (ADC) sampling rate of 20.48 kHz used in the present test instrument [29], the method described in [30] was used to calculate the filter length and reference frequency. Standard reporting rates for PMUs given in [10] of 100, 50, and 25 frames/s for 50-Hz grid frequency are the closest to the UC latencies for UC1, UC2, and UC3, respectively, which correspond to filter latencies of 59, 138, and 412 ms, respectively.

2) Roscoe Boxcar Filter Algorithms: The Roscoe boxcar filter algorithm [30] is based on the standard IEC/IEEE algorithm but uses adaptive tuning of the heterodyne mixing frequency to dynamically match the changing power system frequency, f_0. To facilitate the frequency adaption, a dual calculation process and “tick–tock” scheme is used, with the “tick” process supplying real-time ROCOF readings, while the “tock” process allowing filters to settle. Once “tock” has settled, the processes swap, tuning the recently reset (former “tick,” now “tock”) process to the latest estimate of f_0, after which it must settle for one full filter length T before it can be used, and the processes again can be swapped. A series of cascaded boxcar filters, used in the algorithm, can be readily configured to the latency of each UC [31].

3) Phase-Sensitive Frequency Estimation (PSFE): The PSFE frequency estimation algorithm uses a method of least-squares three-parameter sinewave fit [32]. 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 updates the 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 with other algorithms [33]. 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.

B. Algorithm Testing Methods

Each of the nine tests given in Table II was carried out on each of the three selected algorithms, with latencies set to match each of the three UCs in Table I. The tests were carried out with mathematically simulated wave shapes and with waveforms synthesized using laboratory equipment using an arbitrary waveform generator (ARB) and amplifiers.

1) Simulation Method: In the simulation test method, each of the test waveforms was programmatically generated by the same software that implements each algorithm. The simulation generates 4096 samples every ten power system cycles (204.8-kHz sampling rate), on each of the three phases.

2) Laboratory Synthesis Method: In the laboratory test method, each of the test waveforms was generated using an ARB and amplifiers. The ARB 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 digitizer working input voltage using a laboratory voltage amplifier. This produces only a single-phase test condition.

C. Test Results

The results for test waveforms 1, 2, and 6 of Table II gave results within the target errors for all algorithms and all UCs. The results of tests 3, 7, and 8 are shown in detail below, together with discussion of the test 4 and 5 results. The results for simulation and laboratory synthesis testing were equal within 10% of the RFE value, with the best agreement being equal results within the recording resolution of 0.01 Hz/s. Therefore, for brevity, only the simulation results are shown in this article. The results shown italic exceed the target errors given in Table II.

1) Noise Tests: Both tests 3 and 9 are essentially noise tests. The results for waveform 3 are shown in Table III, and the maximum, minimum, and standard deviation of the RFE errors are given in Table III.

TABLE III

Simulation Results for Test Waveform 3 (White Noise) for Various Algorithms Configured to UCs. R_{min} and R_{max} Refer to the Minimum and Maximum ROCOF Recorded Values in Hz/s, Respectively. Results in Italic Exceed Table II Worst Case RFE Recommendation for the Given UC

Algorithm	**R_{min}**	**R_{max}**	**1σ**	**Latency**
Standard UC1	*-2.1*	*1.5*	0.5	59 ms
Standard UC2	*-0.41*	*0.28*	0.13	138 ms
Standard UC3	-0.04	0.05	0.02	412 ms
Roscoe UC1	-0.83	1.01	0.4	50 ms
Roscoe UC2	-0.17	0.17	0.07	100 ms
Roscoe UC3	-0.03	0.03	0.01	250 ms
PSFE UC1	*-3.6*	*3.8*	1.5	50 ms
PSFE UC2	*-0.7*	*0.7*	0.3	100 ms
PSFE UC3	*-0.12*	*0.13*	0.04	250 ms

2) Step Tests: 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 back to 0 Hz/s. The results for various algorithms are given in Table IV. As in Table III, R_{min} and R_{max} refer to the minimum and maximum ROCOF recorded values during the test, respectively, and the results in italic exceed Table II worst case RFE recommendation for the given UC. These results are also representative of the algorithm performance for tests 4 and 5.

3) Close-In Interharmonics and Flicker Test Results: The results for test waveform 7 are shown in Table V. The results are obtained from the maximum and minimum ROCOF values seen in a given frequency sweep. F_{stop} in Table V refers to the frequency at the beginning of the algorithm filter stopband, which is configured in each algorithm to best meet the window width (latency) requirements of each UC. The stopband of the filter is a concept familiar to PMU manufacturers and can be seen diagrammatically in Fig. C5 in the PMU standard [12]. Any frequency components within the stopband are deemed adequately attenuated and will not unduly influence the ROCOF result. Conversely, any unwanted frequency components in the filter passband (e.g., poor PQ) will affect the ROCOF results. The F_{stop} value is used to define the range of frequency sweeps in test 7. For example, in 50-Hz systems, if F_{stop} is 12.5 Hz, the "low" test uses a 5% amplitude tone swept from 10 to 37.5 Hz (50–12.5) and a "high" test from 62.5 Hz (50 + 12.5) to 90 Hz. The "150" refers to the part of the test that uses a 10% amplitude tone up to 150 Hz. For the fast filters (UC1), the 10–90 Hz scan is N/A because the stopband extends across the entire scan range.

4) Discussion: The test results are a useful comparison of three different algorithms and their implementations for the

TABLE IV

SIMULATION RESULTS FOR TEST WAVEFORM 8 (NEGATIVE PHASE STEP, FOLLOWED BY A +8 HZ/S FREQUENCY RAMP) FOR VARIOUS ALGORITHMS CONFIGURED TO UCS. $R_{\min}$ AND $R_{\max}$ REFER TO THE MINIMUM AND MAXIMUM ROCOF RECORDED VALUES IN HZ/S, RESPECTIVELY. ALGORITHM LATENCIES ARE THE SAME AS THOSE GIVEN IN TABLE III

Algorithm	**$R_{\min}$**	**$R_{\max}$**	**Notes**
Std. UC1	*-52.6*	11.3	Records 8 Hz/s with very 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 very 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 very 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 V

SIMULATION RESULTS FOR TEST WAVEFORM 7. $R_{\min}$ AND $R_{\max}$ REFER TO THE MINIMUM AND MAXIMUM ROCOF RECORDED VALUES, RESPECTIVELY. FOR EXPLANATION OF "F_{stop}," "LOW," "HIGH," AND 150, SEE TEXT

		Low	**Low**	**High**	**High**	**150**	**150**
Algorithm	**F_{stop}**	**$R_{\max}$**	**$R_{\min}$**	**$R_{\max}$**	**$R_{\min}$**	**$R_{\max}$**	**$R_{\min}$**
Std. UC1	25	N/A	N/A	N/A	N/A	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*

three different UCs. Because the harmonics tests 1, 2, and 6 are passed successfully by all algorithms in all UCs, they do not seem to add significantly to the existing tests of the IEC/IEEE synchrophasor standard.

The other tests show some of the typical problems with ROCOF measurements. The results of noise test 4 in Table III 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 stopband and does the best job of the three algorithms at rejecting noise.

The step test 8 results in Table IV 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 very significant RFE values. Even though the Roscoe algorithms meet the requirements set in Table II, the measured ROCOF peaks still would be problematic for their potential use in grid control systems: the present limits in Table II are a compromise between ideally required accuracy and what is practically realizable. Using an exclusion interval around the step, similar to what is already done in the frequency ramp test of the IEC/IEEE standard, helps have more algorithms pass the phase step test, but does not result in better behavior during grid events. Once the phase 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 (i.e., within 250 ms).

The close-in interharmonics signals for test 7 in Table V reveal the sensitivities of the algorithm configurations to frequency tones that are in the zone between the filter stopband and the filter passband, where the attenuation 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. The detailed filter design of the Roscoe algorithm has given the best rejection of these effects, although further optimizations of the other algorithms may be possible leading to better test results. Indeed, this last statement reveals the potential usefulness of these tests to instrument designers who can use them as a benchmark to optimize their algorithm designs.

VI. CONCLUSION

Based on user expectations (collected through an enquiry) and recent ENTSO-E information, this article presents three general UCs for ROCOF and frequency measurements in power systems. The three UCs all show that reliable and accurate ROCOF measurements are important to make the correct grid control decisions. Depending on the UC, latency requirements are between 50 ms for fast frequency response applications and 250 ms for anti-islanding and LOM detection. The general accuracy requirement for ROCOF for all UCs is set to better than 0.05 Hz/s. This is below the 0.1-Hz/s limit of usability set by utilities for their protection applications and lies in between the amended requirement of 0.4 Hz/s of the 2014 amendment to the IEEE C37.118.1 standard for P-class devices under steady-state conditions [13] and the 0.01-Hz/s level that is in the earlier 2011 IEEE C37.118.1 standard [12]. It is therefore concluded that the amended 2014 IEEE requirements, still used in the 2018 IEC/IEEE update of the standard [10], are too much relaxed with respect to the earlier 2011 requirements.

The basic 0.05-Hz/s RFE requirement sets a challenge to instrument designers to optimize the filters for PMU/ROCOF instruments for each of various UCs and achieve the desired accuracies and latencies. Based on a literature study and actual measurements in distribution grids, nine tests are proposed, in addition to the existing IEC/IEEE synchrophasor testing, which can be used to verify whether the proposed solution meets the performance requirements under various realistic power system conditions. Per test, individual accuracy limits are proposed for each of the three UCs. These worst case RFE limits reflect the state-of-the-art in synchrophasor algorithm development and are a compromise between ideally required and practically achievable accuracy.

The practicality of the proposed tests is proven through application on various algorithms, with different implementations tuned to the three UCs. At least one of the tested algorithms is able to meet all the proposed test requirements for all UCs. Some of the proposed additional harmonics tests are passed by all algorithms and therefore do not seem to add much to the IEC/IEEE synchrophasor tests. However, the tests with noise and large amplitude and phase steps certainly seem useful additions. Phase steps are a particular challenge for all algorithms. This is not surprising because the concept of phase and frequency is ill-defined or even N/A under these circumstances [35] and may need redefinition [36]. Special fault-ride-through algorithms might be needed to tackle this challenging situation [16].

The UCs and performance tests presented in this article hopefully provide useful input to the normative standards process for frequency and ROCOF measurements under discussion in the joint IEC/IEEE synchrophasor working group and in IEC TC8 JWG12. These committees should in particular discuss what target ROCOF accuracy levels are acceptable to industry. Given the limited response to our user enquiry, it would be very useful to have further input and confirmation from utilities on whether the ROCOF accuracy levels proposed in this article indeed meet their needs, or whether they need further refinement.

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