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Strategies and limitations for the detection of sub-synchronous oscillations in power systems

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Abstract. Sub-synchronous oscillations pose a significant challenge in modern power systems, particularly in networks with high penetration of power electronic converters. While phasor measurement units (PMUs) are generally used for grid monitoring, their ability to detect sub-synchronous oscillations is being challenged. This paper discusses PMU limitations in measuring sub-synchronous oscillations, introducing a novel algorithm to detect their occurrence by leveraging PMU phasor data and rate-of-change-of-frequency analysis to trigger high-resolution voltage waveform recordings. This approach enables direct comparison between PMU-reported events and raw waveform data, which paves the way to analysing discrepancies and limitations in PMU-based detection.

Key words. Measurement techniques, power grids, phasor measurement units, oscillations, power quality.

1. Introduction

As nations accelerate efforts to reach net-zero carbon emissions, the energy sector is undergoing profound technological change, primarily driven by the rapid electrification of various sectors. Renewable energy sources such as wind and solar are replacing traditional fossil fuel-based power generation at an unprecedented pace, while sectors like transportation, heating, and industrial processes are shifting toward electricity as their primary energy source. At the same time power grids are adapting to accommodate these changes, by integrating a growing number of distributed energy resources, managing bidirectional energy flows and energy storage systems.

One of the most significant trends shaping modern power systems is the increasing reliance on power converters – advanced electronic devices that enable the connection of renewable energy sources and new types of electrical loads, such as electric vehicle charging stations, to the grid. The shift toward inverter-based resources (IBRs) and, more in general, grids dominated by power converters, introduces new complex electrical disturbances that can impact electromagnetic compatibility and power quality. A particularly concerning issue is sub-synchronous oscillations (SSOs), which results from interactions between power converters and can lead to instability, potentially threatening the overall reliability and security of power systems [1].

This paper discusses the issue of detecting SSOs in power systems and some of the measurement aspects related to this challenge, emphasising on the requirements for their accurate detection, presenting a trigger mechanism for the early detection of SSOs from existing measurement instrumentation, and limitations to measurement strategies based on phasor measurement units (PMUs).

2. Sub-synchronous oscillations

A. Description of the phenomenon

SSOs are a type of electrical instability which occurs in power systems when components interact at frequencies below the system's nominal frequency, typically 50 Hz or 60 Hz. These oscillations arise from the dynamic interactions between generators, transmission lines, and power electronics, particularly in systems with high levels of renewable energy and power converters. SSOs can be classified in three main types, torsional interactions, electrical interactions and power electronic interactions. Torsional and electrical interactions are mostly related to resonances in the grid and to synchronous resources and electro-mechanical machines. Power electronic interactions occur between IBRs, flexible AC transmission systems, and power converter controls [2]. While traditionally the main concerns have been around electrical and torsional interactions, with the increasing integration of power converters in modern grids, converter-driven SSOs have become a growing concern, as they can negatively interact with resonances that amplify oscillations, potentially leading to instability. These oscillations can cause excessive stress on power system components, leading to equipment damage, grid disruptions, or even large-scale blackouts if not properly mitigated [16].

Recent cases of SSOs have been reported in the literature, primarily in power systems with a significant presence of IBRs (and at the same time advanced monitoring capabilities). This includes regions such as Texas (USA), China, Australia and Great Britain. The study presented in [3] provides a comprehensive overview of various real-world SSO incidents that have emerged in recent years within power networks heavily reliant on power-electronic technologies.

Since electrical and torsional SSOs started appearing before the introduction of power electronics in power systems, most of the standards and practices were developed without considering the presence of converters in the grid. However, as power systems transition towards a higher share of renewables and electronic-based components, detecting and mitigating SSOs requires new strategies and new standardised methods of analysis systems [1].

B. Importance of measurement

Mitigating the risk of SSOs involves two key aspects. The first is operational management, where grid operators are increasingly recognising the need for high-quality situational awareness and robust monitoring capabilities, both of which depend on a reliable measurement infrastructure. Effective real-time monitoring plays a crucial role in detecting and assessing SSOs, helping operators respond swiftly to potential threats. The second aspect relates to system planning. Operators are placing greater emphasis on developing advanced modelling techniques, with electromagnetic transient (EMT) models gaining traction due to their superior accuracy in capturing complex phenomena such as SSOs and control interactions. However, as models becomes more sophisticated, they require greater validation using accurate real-world measurement data. It is only when the model has been validated that it can be used to inform critical decision making in a reliable manner. Furthermore, given that SSOs can lead to grid instability, both early detection and predictive capabilities can provide valuable foresight for system operators, enabling proactive interventions.

Finally, a thorough characterisation of SSOs holds significant value for post-mortem analysis, such as in cases where grid disturbances have led to major system failures or incidents that can generate disturbances in power systems, including catastrophic events like the one reported in [4].

3. Literature review of detection methods

A grid measurement infrastructure should integrate instrumentation and data processing techniques capable of promptly identifying the onset of SSOs and effectively characterising their dynamic behaviour. Traditional SCADA systems, which are widely deployed for power system monitoring, are inherently limited by their timescales, making them unsuitable for detecting SSOs, which occur at sub-second timescales. In contrast, PMUs have gained prominence due to their ability to perform high-resolution, time-synchronised measurements, which provide the ability to see how power systems are operating over a wide area. Consequently, PMUs –being the only wide area monitoring tool installed– are being used to detect SSOs, with many system operators viewing them as a viable solution. However, PMUs present inherent limitations, as it was shown in [5]. Their hardware and associated algorithms are optimised to analyse the power line frequency only (i.e. 50 Hz or 60 Hz), intentionally rejecting spectral content far away from the fundamental. Additionally, the reporting rates of PMUs are constrained, limiting their ability to capture high-frequency oscillatory modes with sufficient precision. The studies in [6] [7] show examples of a misleading identification of an SSO frequency and of an interaction of two distinct modes generating undetected aliasing because of the PMU limitations. Finally, it must be noted that fault recorders can provide high-resolution data for capturing SSOs more accurately. However, these devices require significant computational resources and are typically not designed for real-time analysis, making them unsuitable for online SSO detection.

C. Current practices

A significant portion of the literature relies on PMU data for SSO analysis, including operational incident reports from the National Energy System Operator (NESO) in the UK [2] and the Australian Energy Market Operator (AEMO) [8]. Recent detection methods see the use of a wide-area measurement system (WAMS) that measures the variations in the synchro-phasors measured by PMUs using a discrete Fourier transform (DFT). This has been used to detect SSOs in [9], where the GPS-synchronised timestamps allow for analysis on the development and propagation of SSOs [9]. The measurement of syncro-phasors has been further refined in [10], with the use of Hann filter interpolation, combined with DFT analysis, with the objective of reducing spectrum leakage and achieving higher accuracy in SSO parameter identification, especially the amplitude. This however increases the necessary time window to detect an SSO to 10 s reducing its suitability as an online SSO detection method [10]. An alternative currently being explored are machine learning detection methods such as the one proposed in [11]. However, the low number of recorded and measured SSOs leads to most of a model's training to be conducted where a large proportion of the training data is without SSOs or on the benchmark simulations defined in [12]. To mitigate this effect, a transfer learning algorithm was suggested in [13]. Due to the limitations in the measurements of real SSO events discussed further below, incorrect parameters limit the applicability of transfer learning algorithms and lead to the proposal of a model free method in [13]. Overall, the lack of an accurate real time detection and measurement method for SSOs creates a risk for the further implementation of more renewable energy sources, with the AEMO stating, "weak grid associated stability challenges are viewed as the most significant challenges to higher IBR penetrations" [3].

4. Limitations in Measurements of SSOs

PMUs have been proven able to detect SSOs to a certain extent. However, some of their inherent limitations might raise concerns, especially when it comes to characterise SSOs [6]. Two of their largest limitations are their relatively low reporting rates and their onboard filters.

A. Reporting rates

Table I shows the reporting rates in frames-per-second of IEEE-compliant PMUs for different system frequencies, with only some going as high as 100 fps (or 120 fps), but with most already-deployed PMUs reporting at 50 fps (60 fps).

Table I. - Standard PMU reporting rates [14].

System freq. (Hz)	50 Hz				60 Hz						
Report. rates (fps)	10	25	50	100	10	12	15	20	30	60	120

Due to the Nyquist theorem, frequency oscillatory modes can only be captured up to half of the reporting rate i.e., up to 25 Hz in most cases. Therefore, only a proportion of PMUs can observe oscillations up to the synchronous frequency posing questions to their suitability to detect and characterise SSO events. This can also lead to large aliasing effects that when measured have returned incorrect SSO characteristics [6]. Additionally, as highlighted in [10] many PMUs algorithms rely on a fixed frequency and window length to calculate the synchro-phasors. As a result, measuring a non-integer number of power cycles will cause spectral leakage, leading which has been shown to lead inaccuracies in SSO characteristics measured.

B. Filtering

To comply with the IEC/IEEE 60255-118-1 standard, PMUs are required to feature analogue and digital filters to reduce the effect of aliasing of the PMU measurement [14]. For M class, PMUs digital filters must be contained within the unshaded region shown in Figure 1.

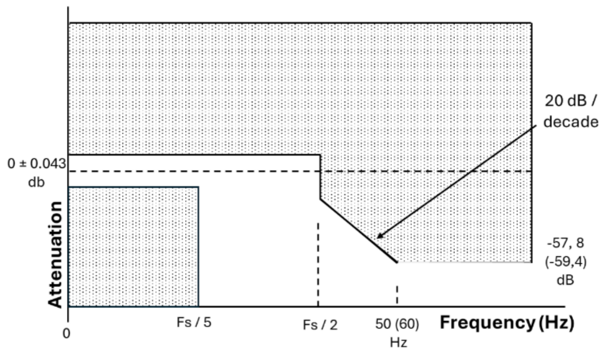


Figure 1. Filter mask that all M class PMU digital filters must be compliant with [14].

The filter mask shows that the current standards allow for variety of attenuation responses between frequencies of Fs/5 and 50 Hz in the anti-aliasing filters. This means the measured characteristics of the SSOs will differ dependent on the filtering strategy of each PMU algorithms used.

Given that the filtering strategies and frequency response of PMU algorithms is often unknown, the following work details an experimental analysis into the frequency response characteristics of various PMU algorithms. The objective is to evaluate the algorithms' performance in accurately capturing and processing SSO signals, specifically focusing on the out-of-band signal rejection i.e., the attenuation that the filtering stages introduce to frequencies outside the nominal system frequency. To achieve this, artificial waveforms y_i containing a known single-tone sinusoidal SSO superposed to a 50 Hz signal were generated according to:

$$y_i = A\cos(2\pi f_0 t) + 0.1\,A\cos(2\pi f_{SSO} t) \qquad (1)$$

Where t represents the time, the first term is an ideal fundamental signal at f_0 = 50 Hz and amplitude A, and the second term is the superposed SSO with frequency f_{SSO}. Note that the amplitude of the SSO is 10 % of the fundamental signal. Waveforms y_i were used as input to six different PMU algorithms and the outputs were analysed. By varying f_{SSO} from 1 Hz to 65 Hz, a frequency sweep was performed, providing a characterisation of the frequency response of the algorithms.

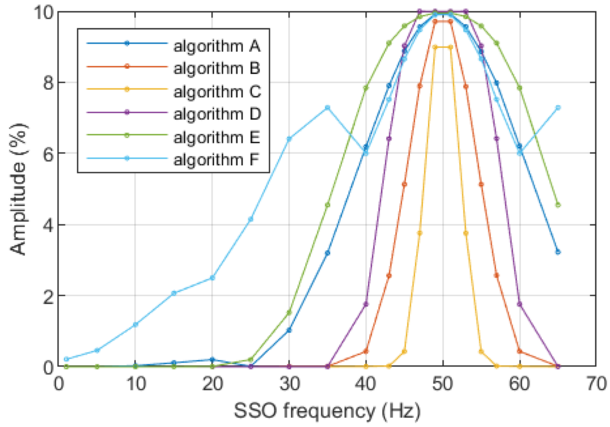


Figure 2. Frequency response of six different PMU algorithms to a frequency sweep of single-tone SSOs.

Figure 2 shows the measured output amplitude of the SSO tone, at varying values of frequency. It can be seen that all the tested algorithms aim at providing an unattenuated response when the tone is very close to the nominal system frequency at 50 Hz. However, as the SSO frequency moves away from the 50 Hz the amplitude gets attenuated, in some cases very abruptly (e.g. algorithms B and C). It must be noted that the algorithms with the most aggressive attenuation tend to provide better results in estimating the systems frequency, especially under distorted grid conditions. This is a design choice to improve PMU estimations at 50 Hz. The results therefore reveal a distinct trade-off: algorithms with better accuracy frequency estimation exhibit superior out-of-band rejection, and a higher suppression of the SSO components. This analysis suggests that conventional PMUs are not optimised for SSO measurement, necessitating careful interpretation of PMU-derived SSO data.

The limitations discussed above will return inaccuracies in the SSO characteristics measured which are crucial in effective SSO mitigation strategies. This in turn could lead to preventable economic and physical damage to the grid. It also raises a question of whether some SSO events would be potentially overlooked due to high attenuation in the sub synchronous frequency range.

5. Detection algorithm for SSOs

A comparative measurement approach can provide an effective way to evaluate practical limitations of SSO detection using PMUs. This involves the simultaneous and synchronised recording of SSOs at a single location using both a PMU and an advanced waveform recorder, used as a reference. A custom-designed instrument capable of high sampling-rate voltage and current waveform digitization, as well as real-time PMU calculations via onboard algorithms, allows for parallel computations from a single acquisition. However, given the unpredictable nature of SSOs, continuous high-speed waveform recording is impractical due to the resulting large data volume. Therefore, it is necessary to be able to detect when a SSO is happening to trigger the recording of samples. This mechanism enables continuous PMU phasor and frequency calculations, with the capture of both phasor data and raw voltage waveforms upon SSO detection. This section details the development of an SSO detector based on PMU frequency measurements.

A. Detector description

As discussed in Section 3, SSOs can and are typically observed as oscillations in PMU frequency measurements. This can be seen in Figure 3 which shows an SSO observed in frequency data measured with a PMU in Australia and obtained from [15].

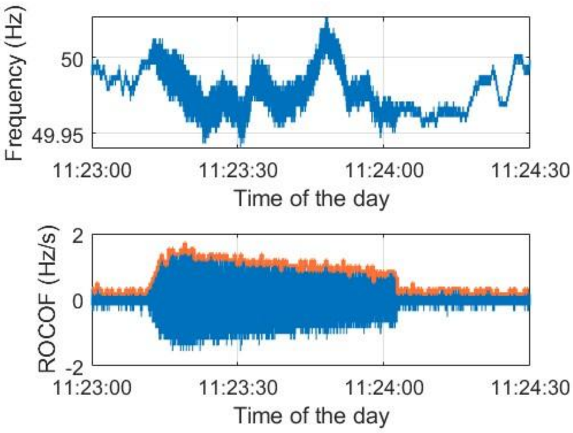


Figure 3. System frequency measured by a PMU during an SSO (top) taken from [15] and calculated ROCOF with corresponding envelope (bottom).

The figure also shows the calculated rate-of-change-of-frequency (ROCOF) which, being the derivative of frequency, exhibits a near-zero baseline under stable frequency conditions. However, the onset of an SSO induces rapid fluctuations in ROCOF's absolute value, making it a sensitive indicator for SSO detection. Consequently, an SSO can be detected when the ROCOF surpasses a predefined threshold for a sustained duration. The initial step in the detection process involves the calculation of the ROCOF at time n, R_n, defined by:

$$R_n = \frac{f_n - f_{n-1}}{T} \qquad (2)$$

Where f_n is the frequency value at time n, and T is the time resolution i.e. the inverse of the PMU reporting rate, typically 50 fps or 100 fps, corresponding to 20 ms or 10 ms, respectively. Subsequently, the envelope of the ROCOF signal is determined. Given the oscillatory nature of SSOs, the positive and negative envelope amplitudes are expected to be symmetrical. Therefore, the detection algorithm considers only the positive envelope. The envelope is derived by applying non-overlapping, contiguous windows of 25 ROCOF readings, equivalent to 500 ms at a 50 fps reporting rate. Within each window, the maximum ROCOF value defines the envelope point, resulting in an envelope with a 500 ms time step. This envelope facilitates the threshold-based SSO detection. Upon exceeding the threshold, a potential SSO event is flagged, and a counter tracks the number of consecutive samples exceeding the threshold. If a minimum duration criterion is met, the instrument is triggered to store raw voltage waveforms. Otherwise, the event is classified as noise, and the waveforms are discarded. The minimum duration is specified as a predefined number of samples, e.g., 5 samples corresponding to 2.5 seconds. The storage protocol captures 5 seconds of pre-event waveforms, the entire SSO duration, and an additional 5 seconds post-event. Figure 4 provides a detailed view of the ROCOF envelope and the detection threshold, with the green line indicating the identified SSO event.

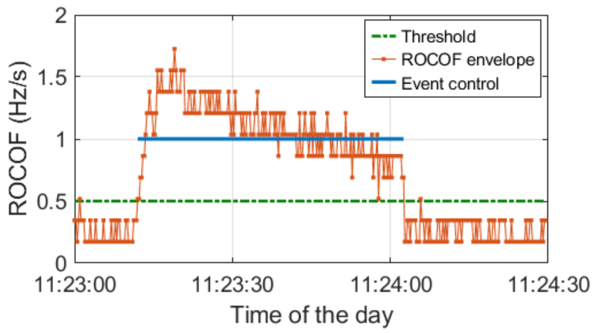
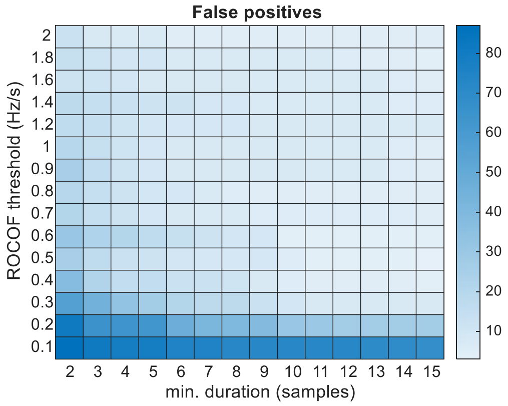


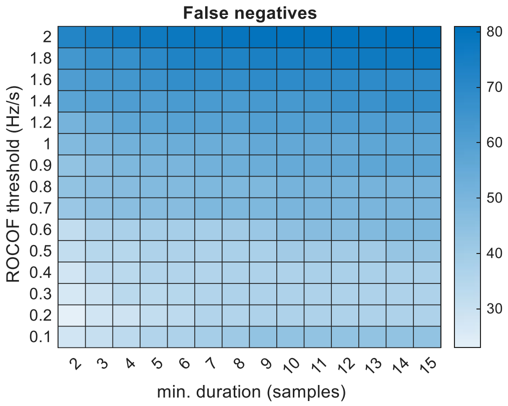
Figure 4. Detail of the ROCOF envelope from the event in Figure 3, with the selected threshold and the control signal identifying the SSO event.

B. Choice of detector parameters

The detector's performance is governed by two parameters: the ROCOF envelope threshold (in Hz/s) and the minimum event duration (in samples) required for SSO classification. The parameter selection is critical to minimise false triggers while avoiding missing events. Optimal parameter values are ultimately application dependant and influenced by the objective of the detection (e.g. post-mortem studies or early warning) as well as by grid conditions. In this work, to determine suitable parameters, a database of 184 PMU-recorded SSO events was utilized, comprising measurements from system operators in GB and publicly available data from [15]. Due to the diverse recording locations, the dataset includes few files with no evidence of the SSO events. The optimization of the parameters employed two criteria. False negatives i.e., instances where an SSO is not detected in a file containing an SSO, were minimized. False positives i.e., instances where multiple SSOs are detected in a single file, were also minimized. By cross-referencing these two indicators, optimal parameter values were determined. Figure 5 illustrates heatmaps depicting the optimization results. The heatmaps present the detection performance across a range of threshold values and minimum event durations.



(a)



(b)

Figure 5. Heatmaps illustrating the number of false positive (a) and false negative (b) detections of SSOs, in counts.

The heatmaps in Figure 5 (a) and (b) exhibit opposing trends, indicating an optimal parameter region within a threshold range of 0.3 Hz/s to 0.6 Hz/s and a minimum duration range of 8 to 13 samples. Based on these results, the following parameters were selected:

- Threshold = 0.5 Hz/s
- Minimum duration = 10 samples, corresponding to 5 s

The detection algorithm has been tested for its functionality on examples of SSOs, artificially created as well as measured on the grid. Examples of results are presented in the remaining of this section. Figure 6 and Figure 7 show the examples of the application of the detection algorithm to two synthetic SSOs. In both cases, a 20 Hz oscillation is superposed to a pure 50 Hz signal starting and finishing at defined instants in time, the first one (Figure 6) with a rectangular modulation and the second one (Figure 7) with a gaussian modulation. The synthetic test waveforms have then been processed by a PMU emulator with a reporting rate of 100 fps, and then analysed with the detection algorithm. It is possible to observe how, in the case of the gaussian modulation, the PMU algorithm produces a frequency measurement with a complex pattern. All synthetic tests are purely for the purpose of validation as the frequency oscillations are artificially large, generating significantly high ROCOF values with in particular Figure 7 showing frequency variations almost outside of statutory limits. Figure 8 and Figure 9, instead, are two examples of real instances of SSOs measured with PMUs in Australia and taken from [15], where it is again possible to see that

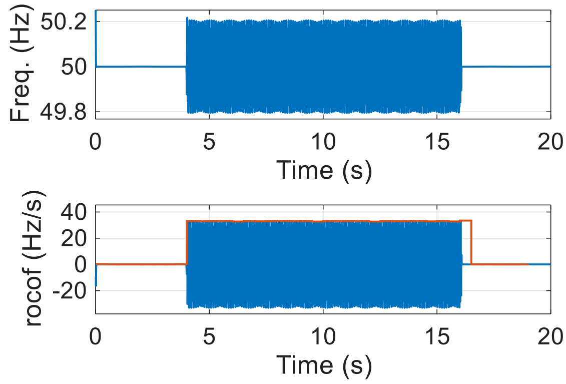


Figure 6. Top: frequency calculated by a PMU during a synthetic SSO localised in time, with 2 % amplitude and a rectangular modulation. Bottom: ROCOF and envelope.

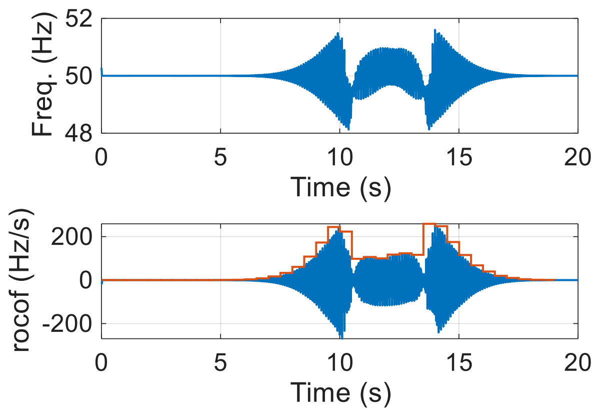


Figure 7. Top: frequency calculated by a PMU during a synthetic SSO localised in time, with 10 % amplitude and a gaussian modulation. Bottom: ROCOF and envelope.

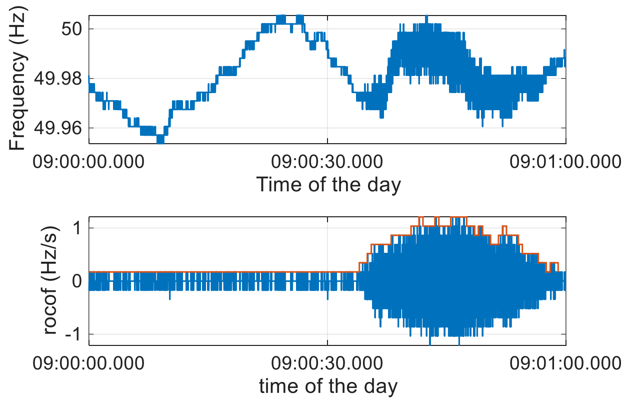


Figure 8. Top: Frequency measured by a PMU during a real SSO in Australia [15]. Bottom: ROCOF and envelope.

the ROCOF envelope is effectively obtained, and the event trespasses the threshold, identifying the onset of the SSO. In summary, the application of the detection algorithm to both artificially generated and real-world SSO events, as demonstrated in Figure 6 through Figure 9, confirms the practical applicability of the proposed detection algorithm for detecting the occurrence of sub-synchronous oscillations in power systems using PMU data. This can therefore pave the way to the acquisition of more valuable SSO data from PMUs, in parallel with high-resolution voltage waveforms that can serve to fully identify the limitations of PMUs in SSO detection and at the same time provide a better characterisation of this phenomenon.

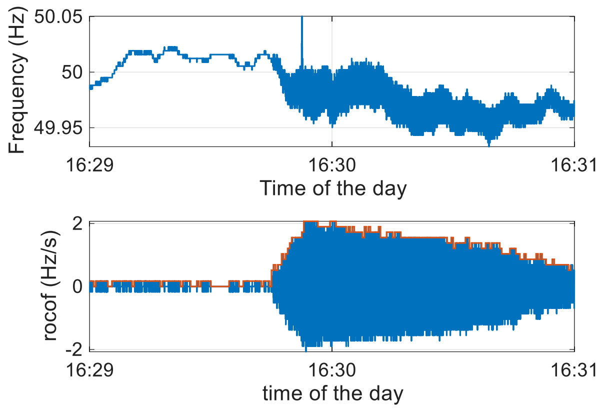


Figure 9. Top: Frequency measured by a PMU during a real SSO in Australia [15]. Bottom: ROCOF and envelope.

6. Conclusions and future work

While the need for enhanced SSO monitoring in power systems is clear, system operators currently rely predominantly on existing PMUs for SSO measurement. After analysing the limitations of conventional PMU-based SSO measurement, this paper proposes an SSO event-triggering algorithm, based on the detection of frequency modulation and oscillatory behaviour of ROCOF values obtained from PMU estimations of system frequency. This has the objective of enabling the simultaneous capture of both PMU data and raw voltage waveforms during SSO events, allowing for a full understanding of the practical limits of the capability of PMUs for SSO detection, and subsequent characterisation of events. The detection algorithm has been defined starting from a large dataset of SSOs measured on the transmission grid, and has then been tested to ensure its validity, using both real and synthetic test signals. It's also been shown that the validity and the robustness of the method is dependent on the choice of the parameters and those are influenced by grid conditions e.g. noise levels or existing disturbance, requiring care in the choice of the parameters.

Future research will involve deploying the developed algorithm on dedicated advanced waveform recorders strategically placed within the power grid. This will enable the capture and detailed analysis of real SSO events with high sampling rates and appropriate measurement bandwidth, essential to improve situational awareness and event characterisation.

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