Fast FCAS Sampling Verification in Support of Market Ancillary Services Specification (MASS) consultation

- Phase 2

Prepared for the Australian Energy Market Operator

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Executive Summary

The Australian Energy Market Operator (AEMO) launched a general consultation on the amendment of the Market Ancillary Service Specification (MASS) [1] and one of the main focuses is to adjust the MASS so that Distributed Energy Resources (DER) can participate in Frequency Control Ancillary Services (FCAS) markets in a fair and transparent way. Successful trials have already been held in AEMO's VPP Demonstrations programme which shows the feasibility of using VPPs to provide FCAS response. However, there are differences between the technical requirements used in the VPP Demonstrations programme and the ones in the MASS. Therefore, this consultation is seeking to resolve such differences by running technical assessments, discussing with relevant stakeholders, and eventually updating the MASS.

The consultation has already gone through two stages. During the second stage of the consultation, the University of Melbourne (UoM) was commissioned by AEMO to explore the impact of using sampling rates lower than 50ms (current requirement in the MASS) on FCAS performance verification, and investigate different integration rules when assessing FCAS contribution. The conclusion of the first report indicates that 1s sampling rate (used in VPP Demonstrations programme) may introduce significant verification error and overestimate in FCAS contributions, and that a trapezoid rule performs better than the Riemann methods currently used in the MASS. Additionally, UoM found that the so-called "relative window" method used in the MASS, which was designed for 50ms sampling, is not suitable for low sampling rates. This is because there are significant verification errors potentially introduced by the misalignment of the start point of the six-second assessment window when using lower sampling rates. A theoretical method called "universal window" was proposed by UoM to address this misalignment issue. In this report, we refer to the starting time of six-second Fast FCAS assessment window as *frequency disturbance time*, which is used in AEMO's FCAS verification tool.

The third stage of the consultation is ongoing and UoM was commissioned by AEMO to explore a wide range of factors affecting the verification error and establish a methodology to identify potential oscillatory responses. UoM has identified seven key factors of relevance for the requested analysis, namely, power measurement errors, sampling rates, frequency disturbance time, inertial response, compensation factor, site aggregation, and integration rules.

Six case studies have been defined and relevant FCAS response profiles from both DER and synchronous generators have been analysed:

1. The first case study evaluates the verification error of synchronous generators' response profiles when using lower sampling rates;
2. The second case study analyses the calculation of compensation factor and the impact of replacing smoothed frequency with actual frequency in the calculation of compensation factor for variable controllers in the verification process;
3. The third case study assesses the verification error introduced by five different assessment window methods (including the "relative window" and "universal window" methods discussed and introduced in the first report);
4. The fourth case study investigates the site aggregation effect when using NMI-level data instead of aggregated response to evaluate the verification error, when using lower sampling rates;
5. The fifth case study examines the potential additional verification error if the allowance of power measurement error is relaxed from 2% to 4%;

6. The last case study aims to test the effectiveness of the proposed methodology for oscillatory response detection and indicates the minimum sampling rate requirements in order to identify such oscillatory responses.

The results of our studies translate into the following set of recommendations:

- Adjustments need to be made to the FCAS verification tool so that one *unified* tool can be built to accurately capture the performance of both DER and synchronous generators in FCAS delivery.
- The novel “RoCoF-based” method proposed by UoM in this report has a similar performance as the “universal window” method and is superior to other “relative window” methods proposed by different stakeholders when determining frequency disturbance time.
- Lower the sampling rate of synchronous generators’ response may introduce significant errors, which are in the range of $\pm$5% for 100ms case and may further increase to between -20% and +10% at 200ms. Therefore, a 50ms sampling rate requirement should be maintained when recording the synchronous generator’s response for FCAS verification purposes.
- By removing the frequency smoothing process when calculating the compensation factor for variable controllers in the FCAS verification process, additional verification errors that are caused by lower sampling rates could be eliminated. However, the most suitable changes to accurately calculate the compensation factor need further consideration, as the compensation factor’s purpose is to scale up the response profile to prevent the verification tool from under-evaluating the FCAS provider’s performance. For instance, FCAS providers with variable controller typically follow droop control to proportionally respond to frequency deviation; so, if frequency nadir is higher than 49.5 Hz (i.e., in a less severe contingency), the original FCAS contributions (in MW.s) may be relatively small. Without considering the compensation factor, in the FCAS verification tool such FCAS contributions would be converted to a value that is smaller than the FCAS enablement.
- When the response profiles of a fleet distributed across multiple sites are sampled at a lower rate (e.g., 100ms, 200ms), using NMI-level data instead of aggregated response reduces the verification error. However, the reduction of the error is rather small when the aggregation sites number is above 200.
- Relaxing the power measurement error from 2% to 4% may introduce significant verification error. The magnitude of such errors depends on the allocation of the provider’s active power output for Fast FCAS response and other market services.
- 1s sampling rate is not suitable for detecting oscillatory behaviour of Fast FCAS response. The proposed oscillatory response identification methodology could be further improved by running tests on a range of response profiles and consulting stakeholders’ advice on key parameters, such as the oscillation threshold (50% at present).

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1 Introduction and recap

The Australian Energy Market Operator (AEMO) has initiated a consultation of reviewing Market Ancillary Service Specification (MASS) of National Electricity Market (NEM) [1] in January 2021. The focus of this round of consultation is to make necessary adjustments on MASS, so that distributed energy resources (DER) will gain fair and transparent market access opportunities when providing Frequency Control Ancillary Services (FCAS).

The trial of DER participating in FCAS market started in 2019 in AEMO's Virtual Power Plant (VPP) Demonstrations programme, which has been concluded recently. Then, the latest MASS consultation is aimed at looking into the technical configurations of DER used in VPP Demonstrations programme and propose potential changes needed to enable a smooth transition towards the formal inclusion of DER in FCAS market without compromising system security and economic efficiency of the FCAS market.

In the second stage of this consultation, the University of Melbourne (UoM) was invited by AEMO to perform an independent analysis on the Fast FCAS sampling and verification process in June [2]. The results of the analysis indicated the potential verification errors brought by **different integration rules** (e.g., Left and Right Riemann, trapezoid and Simpson's, etc.), **lower sampling rates** (e.g., 100ms, 200ms and 1s). Additionally, the report discussed the findings on the **verification error associated with the existing "relative window" method**. In the verification tool guide, the six-second window of Fast FCAS only starts from the first recorded point after the normal operating frequency band (NOFB) (i.e., 50Hz +/- 0.15 Hz) is breached. Therefore, using low sampling rates (e.g., 1s) might significantly shift the six-second assessment window without capturing the initial ramping process of the response. Therefore, an overestimation of the response contribution was observed in the results of the first report.

To minimise the verification error introduced by the relative window method, a theoretical method was proposed in the report and was referred to as "**universal window"** (as opposed to *relative*). The "universal window" method assumes that the NOFB is crossed simultaneously for all providers in each event and such time can be determined without relying on the local frequency sampling data recorded by each provider (and therefore is not affected by low sampling rates). The report put a caveat on the "universal window" method as more discussion was needed to identify how to adopt the "universal window" in practice.

Following the publication of the draft determination along with UoM's report, various stakeholders have been widely discussing potential alternatives to the relative window method. Based on feedback from AEMO to UoM, stakeholders have proposed other two methods called "*midpoint"* and "*average"* (which will be referred as "*twin points*" in this report) to reduce the overestimation effect brought by the relative window method. The effectiveness of these two alternative methods will be demonstrated in this report.

In the third stage of the MASS consultation, UoM has performed further analyses to address various points raised by different stakeholders and AEMO. Notably, UoM has proposed a new method, which is called "Rate of Change of Frequency (RoCoF)"-based method, to replace the existing relative window method (which will be called "first recorded method" in this report).

The content of this report is instrumental to provide answer to the following questions raised by AEMO:

1. *What is the most accurate method to determine the frequency disturbance time for Fast FCAS assessment window?*

2. *How does the measurement of inertial response and compensation factor change with lower sampling rates (e.g., 100ms, 200ms, 1s) when comparing with 50ms?*
3. *How to identify oscillatory behaviour of response and what sampling rates are needed to detect such oscillatory response?*
4. *Will verification error be lower if NMIs data is used to calculate response contribution instead of the aggregated response? Does the error decrease as the number of NMIs increases?*
5. *What is the possible difference in the calculated Fast FCAS capacity delivered (from the Verification tool) if the allowable error for the measurement of power expanded from 2% in MASS to 4%?*

2 Methodology

2.1 FCAS response verification process

The methodology used in the FCAS verification tool was summarised as a flowchart in the first report [2], which is redrafted here in Figure 2.1. The analysis performed in the first report focused on aggregated response profiles of DER. In that case, some assumptions were made when performing the analysis:

- *Reference trajectory,* which is calculated in steps (i)-(iii) of Figure 2.1, is not considered, assuming that the VPPs in the examples are not classified as scheduled or semi-scheduled units.
- VPPs have no *inertial response* capability, therefore the inertial response in step (iv) does not need to be calculated.
- The *baseline point (*written as *FA)* described in step (v) is calculated as the average power of the profile between 3s and 0s before the frequency disturbance time, instead of using the profile between 20s to 8s due to limited data availability.
- The *compensation factors* mentioned in steps (viii) and (ix) of Figure 2.1, which are used to scale basic response measurements, are neglected. This is because the response profiles with different lower sampling rates (i.e., 100ms, 200ms and 1s, etc.) are derived from the original profiles with high sampling rates (i.e., 20ms, 50ms). Therefore, a uniform scaling up/down of all response profiles with different sampling rates would not change the verification errors.

In the latest round of consultation, AEMO commissioned UoM to expand the scope of the independent analysis by also considering response profiles from synchronous generators, such as the one shown in Figure 2.2. One of the objectives of this expanded analysis is to determine the verification error of the synchronous generators' response when lower sampling rates (e.g., 100ms, 200ms) applied. The results of such analysis can be used to inform the possibility of relaxing the existing 50ms sampling rate requirement for all market participants instead of just DER.

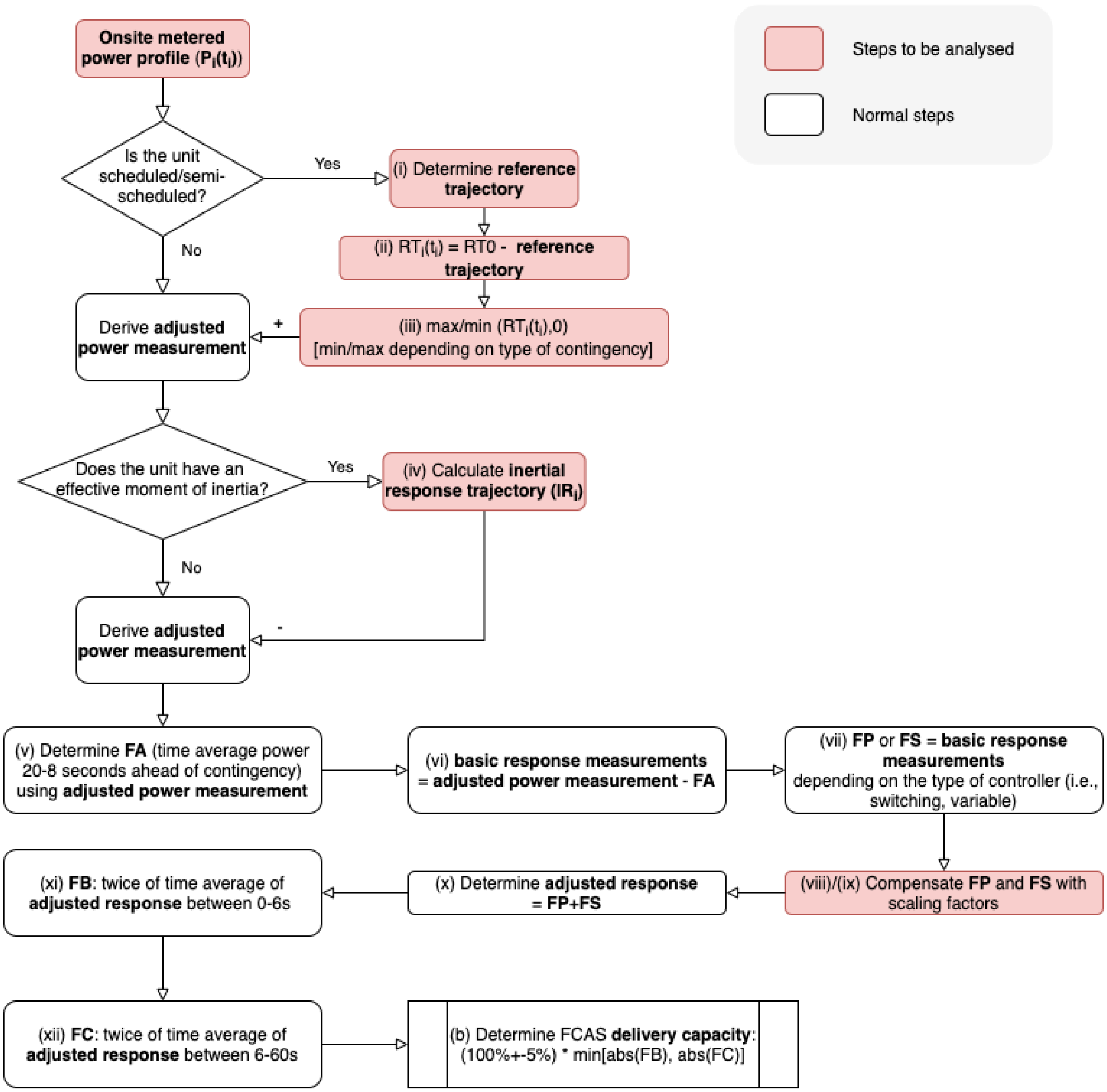

Figure 2.1. Fast FCAS performance verification methodology (redrafted from [2])

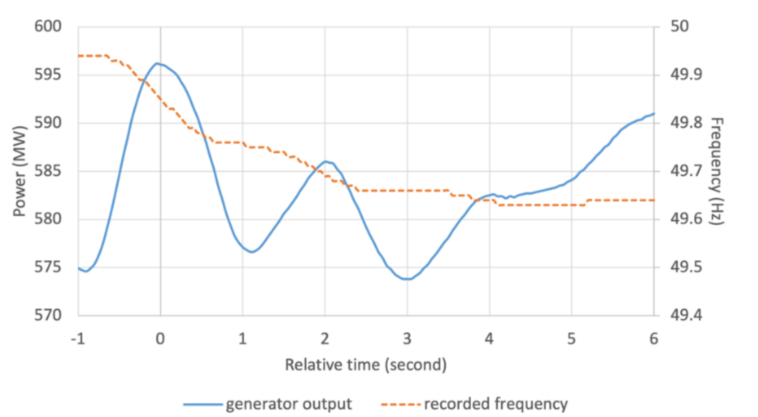

Figure 2.2. Synchronous generator's output profile and recorded frequency profile sampled at 50ms

In this analysis, the scope will cover few steps (highlighted as red blocks in Figure 2.1). Some of these steps were not considered in the first report since the analysis was solely focusing on VPPs. Figure 2.3 shows seven factors related to verification error in Fast FCAS provision. The impact of three of them on the verification error were analysed in the first report; these are *sampled response profiles* considering low sampling rate, *frequency disturbance time*, and *integration rules,* as shown in Figure 2.3. The impact of six out of seven factors will be evaluated in this report. The conclusion of the first report indicated the superiority of using the trapezoid rule to calculate the contribution of Fast FCAS response. Therefore, no further study on the integration rules will be carried out in this report and the trapezoid rule is applied to replace Riemann method used in steps (xi) and (xii) of the FCAS verification tool.

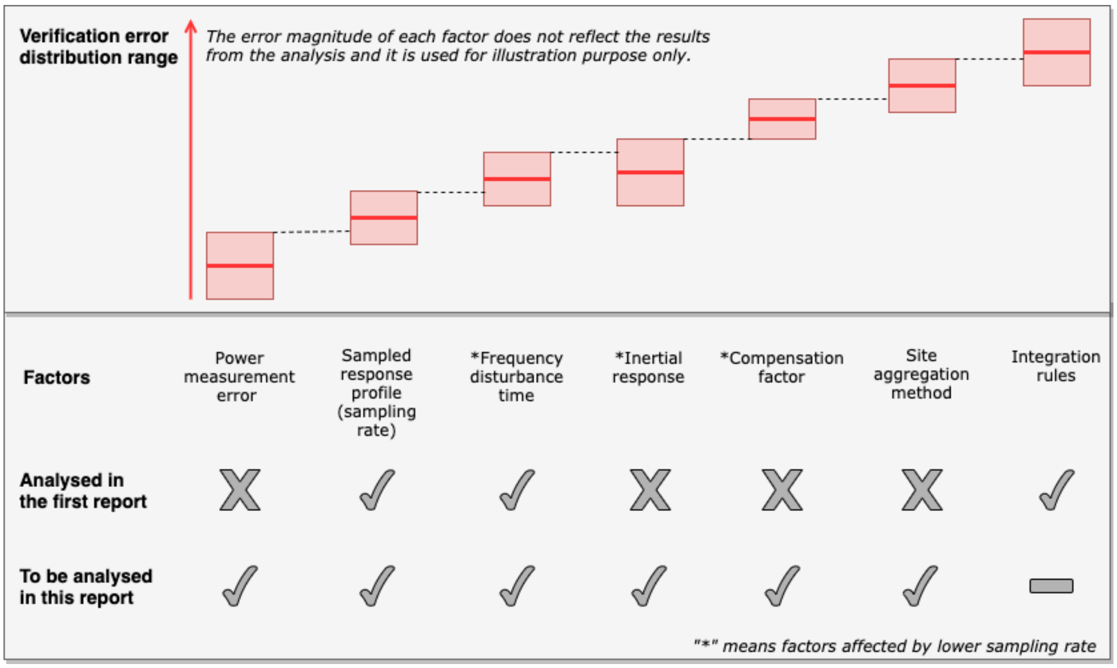

Figure 2.3. Key factors determining the verification error analysed in first UoM report (refer to [2]) and to be analysed in this report

In the following sections, section 2.1.1 explains the calculation approach for the metric "*verification error*", which is used to measure the performance of different sampling rates and FCAS verification configurations proposed in this report. Then, the methodology to model *power measurement error* is introduced in 2.1.2. Profiles with lower sampling rates (e.g., 100ms, 200ms, 1s) are directly extracted from the metered 20/50ms (power and frequency) profiles. Five different methods which are used to determine frequency disturbance time are in 2.1.3. The calculation of synchronous generators' inertial response and of the compensation factor is described in 2.1.4. The aggregation method to move from national metering identifiers (NMIs) metering data to fleet response profile is finally illustrated in section 2.2. The methodology of identifying oscillatory response behaviours and the minimum requirement of sampling rate for identifying such oscillatory behaviours are introduced in section 2.3.

2.1.1 Verification error

Verification error is used to measure the performance of potential verification configurations. Such metric indicates the relative difference of FCAS contribution when changing the underlying assumptions of the verification, for example, lowering sampling rate (i.e., from 50ms to 100ms-1s), using different methods of defining assessment window, applying different integration rules (e.g., left/right Riemann, trapezoid, etc.), and considering power measurement error (i.e., 2% allowance defined in the MASS). **As a rule of thumb, when calculating the verification error, the benchmark is the FCAS contribution (in MW.s) using 20ms/50ms response with "universal window" method and trapezoid rule for integration.** Other settings (e.g., inertial response and compensation factor consideration, power measurement error, etc.) for benchmark and sensitivity studies will be specified in the tables presented at the beginning of each case study in section 3.

In AEMO's FCAS verification tool [2], the FCAS contribution is compared with the enablement that is agreed by the Ancillary Service Market Participants, while in the VPP Demonstrations programme, the FCAS contribution is compared with the target response [3]. Such comparisons are used to define whether the participant provided the agreed amount of Fast FCAS, assuming that the FCAS contribution derived from the verification tool is accurate. In this report, different configurations of the verification process are tested to improve the tool's accuracy, particularly when using lower sampling rates and resulting low granularity of data. Note that a small verification error in the results reported here only shows that the Fast FCAS contribution calculated with the given settings (e.g., sampling rate, frequency disturbance time assessment method) is close to the contribution calculated with the response sampled at 20/50ms, assuming that the 20/50ms response with "universal window" method is the benchmark. **Thus, for a given event, a small error shown in the results of this report does not necessarily indicate that the provider would have an acceptable performance in terms of FCAS delivery as recognised by AEMO**.

2.1.2 Power measurement errors

As indicated in MASS 6.0, "*Measurements of power flow must have a measurement range appropriate to the Ancillary Service Facility, error of less than or equal to 2% of the measurement range, and resolution of less than or equal to 0.2% of the measurement range.*"

Therefore, the measurement error is imposed on metering power flow data. To analyse the impact of the measurement error on FCAS verification, we impose random errors on the power flow data which have a normal distribution with mean value μ and standard deviation σ. An example of the normal distribution probability density function is shown in Figure 2.4, where the area under the curve of the normal distribution between two values represents probabilities between these two values. For example, given a dataset with a normal distribution $N(\mu, \sigma^2)$ (as shown in Figure 2.4), the probability for a random data from such a dataset to be between $\mu - \sigma$ and $\mu + \sigma$ is 68.2%, which equals to the dark blue area in Figure 2.4. For a normal distribution, roughly 99.7% of the data is within 3 standard deviations of the average, i.e., from $\mu - 3\sigma$ to $\mu + 3\sigma$. Thus, the error allowance (i.e., 2% as indicated in the MASS) is assumed to be equal to 3σ, while $\mu = 0$.

The process of creating potential metering profiles featuring 2% measurement error is as follows:

- Random errors are generated with normal distribution function $e_{2\%} = N(\mu, \sigma^2)$, with a mean value of 0, and standard deviation $\sigma = 0.67\%$.
- The original response profile is applied with the random errors, that is, $\tilde{p} = (1 + e_{2\%})p_{ori}$. Here p_{ori} represents the original response while $\tilde{p}$ represents the metered response with a maximum 2% error. For example, if the error e is 1% and the original profile p_{ori} is 100 MW, the response with measurement error $\tilde{p}$ is 101 MW.

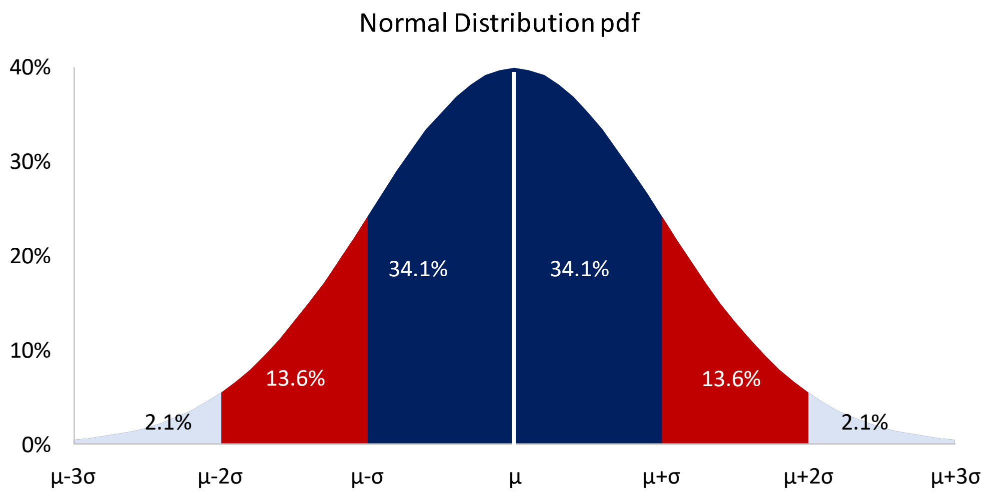

Figure 2.4. Normal distribution probability density function, with mean value μ and standard deviation σ.

In order to analyse the additional verification error that is introduced by moving from 2% measurement error to 4% measurement error, metering profiles featuring 4% measurement error are introduced. The response with 4% measurement error $e_{4\%}$ is obtained using the original response profile applying the random errors which are doubled from the random errors that are generated for 2% measurement error profiles, i.e., $e_{4\%} = 2e_{2\%}$. An example of the original profile, metering data for 2% measurement profile, and metering data for 4% measurement profile is shown in Figure 2.5.

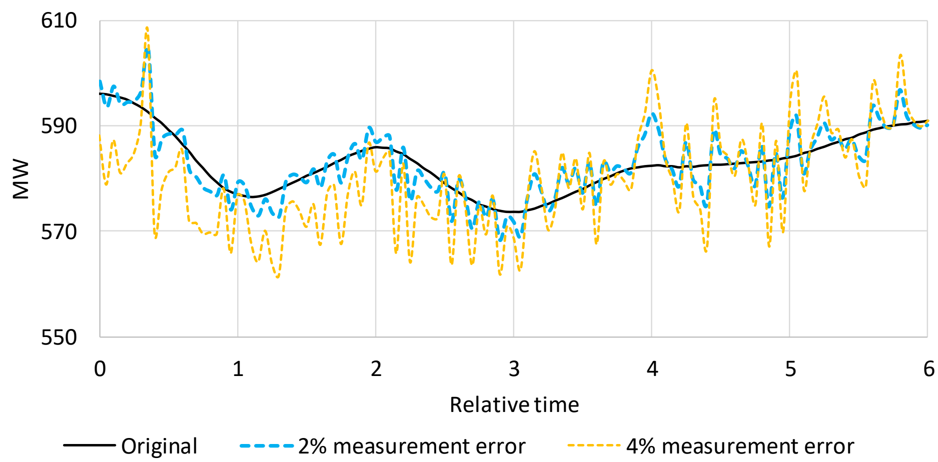

Figure 2.5. Example of original response profile, response profile with 2% measurement error, and response profile with 4% measurement error.

Once the response profiles with 2% and 4% measurement error are obtained, the FCAS delivery is verified following the steps illustrated in Figure 2.1. The verification error introduced by moving from 2% to 4% measurement error allowance is calculated as the differences between the FCAS contribution considering 2% measurement error and 4% measurement error, divided by the FCAS contribution of the original profile.

2.1.3 Frequency disturbance time

The assessment window refers to the six-second time interval which is used to evaluate the performance of Fast FCAS market participants in contingency events. In the MASS and verification tool guide, the initial point of the six-second window corresponds to the first time point when the locally metered frequency breaches the normal operating frequency band (NOFB): this is called *frequency disturbance time* in the FCAS verification tool guide [4]. The existing method was named as "*relative window"* in the first report. As seen in the results of the first report, applying the relative window method can cause significant overestimation (i.e., over 50% in certain cases) of response contribution when providers use a low sampling rate (e.g., 1s). Therefore, a theoretical method was proposed in the first report, namely the "*universal window" method*. The "universal window" method relies on 20/50ms data to determine the frequency disturbance time regardless of the provider's sampling rate and thus it has extremely low latency when detecting NOFB breaching. As seen in the first report, the "universal window" method almost eliminated the overestimation issue caused by the relative window when using low sampling rates, as most verification error distributions have a mean value of 0% in this case.

However, as mentioned above the implementation of the "universal window" requires high-resolution frequency data, while the availability of such data may be limited. Therefore, more practical methods are needed to utilise the low sampling-rate frequency data to optimally determine the frequency disturbance time. There are three methods presented below in addition to the "relative window" and "universal window" methods. Among them, the "*twin points average"* and "*midpoint"* methods that were proposed by different stakeholders. In this report, UoM also proposes a method to determine the frequency disturbance time that calculates the rate of change of frequency following contingency. The frequency curve of a response profile with 1s sampling rate is presented in Figure 2.6, which is used to illustrate the difference between the five methods when estimating the frequency disturbance time.

- **"Universal window" method**: Assumes that a universal frequency disturbance time can be defined for all providers in each event and does not rely on the local frequency data sampled by providers. The corresponding frequency disturbance time is 5s in Figure 2.6, which is used for illustrative purposes.
- **"Relative window" methods**: All other four methods are called "relative window" because they rely on local frequency data:
    - **"First recorded point" method**: Uses the first recorded point which crossed the NOFB. The corresponding frequency disturbance time is 5.55s in Figure 2.6.
    - **"Twin points average" method**: Calculates the Fast FCAS response contribution area separately using the first recorded point which crossed NOFB and the previously recorded point, and then takes the average value of the two area sizes. These two points are 4.55s and 5.55s in Figure 2.6.
    - **"Midpoint" method**: Calculates the average time between the first recorded point which crossed NOFB and the previously recorded point. The corresponding frequency disturbance time is 5.05s in Figure 2.6.
    - **"RoCoF-based" method**: Takes the frequency data of the first recorded point which crossed the NOFB and the previous recorded point and use linear interpolation of the two frequency points to estimate the time of the frequency crossing NOFB. The corresponding frequency disturbance time is 5.18s in Figure 2.6.

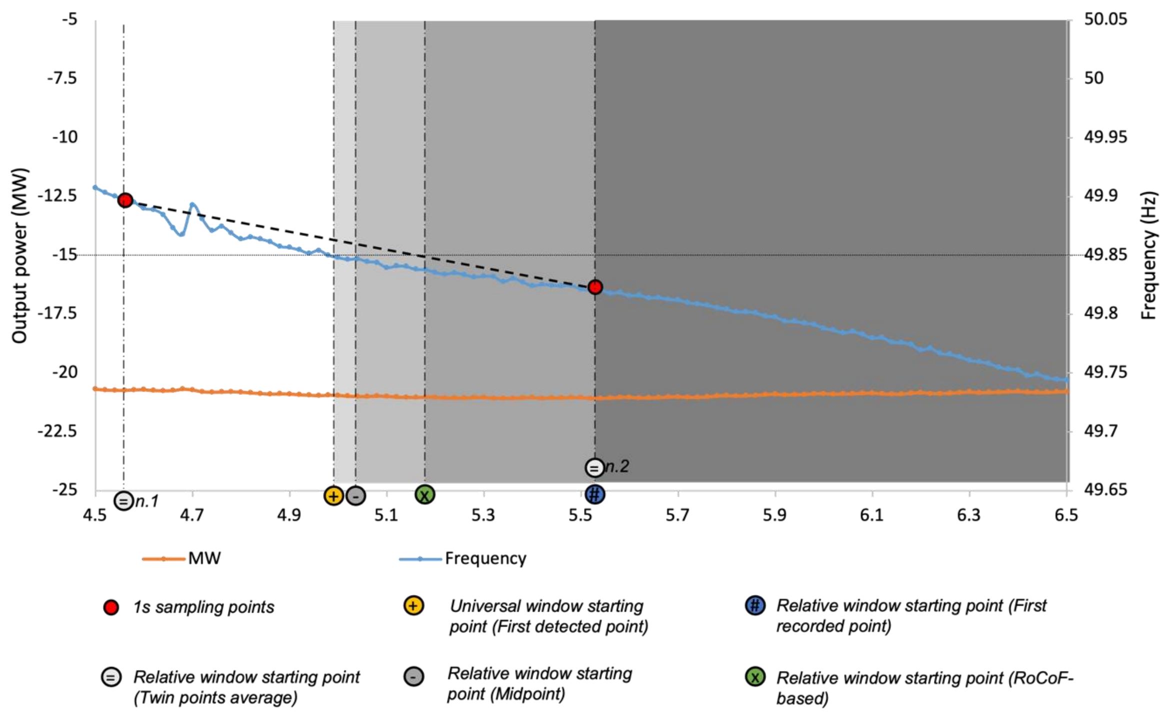

Figure 2.6. Starting points of "relative window" and "universal window" methods of Fast FCAS response provider with 1s sampling rate in a Raise event

2.1.4 Inertial response adjustment and compensation factor

The *inertial response* is a physical property of synchronous machines. Their more or less large rotating mass speeds up or slows down to overcome the imbalance between system demand and supply, and while doing this they contribute to the system energy balance, for example by injecting energy in the case of an under-frequency event. However, this *natural* increase/decrease of the power output of synchronous generators is not accounted for as part of the contribution to FCAS response and needs to be excluded from the response profile when AEMO performs Fast FCAS verification.

Compensation factor is defined to adjust the response profile when the recorded local frequency has breached the NOFB but not substantially deviated from the NOFB. For example, if the recorded frequency only varies between 49.85 and 49.5 Hz following a contingency. In this case, response providers with variable controllers may not ramp up to FCAS enablement within the assessment window, as their droop control settings only allow a proportional response against frequency deviation. If such response is not compensated in the verification tool, the result of the tool could suggest that the provider underperformed as it made insufficient FCAS contribution against FCAS enablement. For response providers with switching controllers, such compensation factor is usually 1, as its "step-change" response is not frequency-sensitive after the frequency disturbance time and should be activated immediately.

It is important to investigate the calculation of the two components above when assessing the response profile, because the existing verification tool methodology involves the process of smoothing the recorded frequency curve when calculating both inertial response and compensation factor. Such "smoothing" process may result in different response profiles used in the verification tool when lower sampling rates (e.g., 100ms, 200ms, 1s) are applied.

2.1.4.1 Inertial response calculation

The inertial response calculation corresponds to step (iv) in the FCAS verification methodology as illustrated in Figure 2.1. The inertial response IR_i is calculated as follows:

$$IR_i = 4 \cdot \pi^2 \cdot I \cdot f_i^{local} \cdot \frac{df}{dt_i} \qquad (1)$$

Where I is the effective moment of inertia of the ancillary service generating unit or ancillary service load as agreed between AEMO and the relevant Market Participant. f_i^{local} is the measured local frequency at time t_i. df/dt_i is the rate of change of offset smoothed local frequency at time t_i, which is calculated by:

$$\frac{df}{dt_i} = \frac{2f_{i+2}^{offset-smoothed} + f_{i+1}^{offset-smoothed} - f_{i-1}^{offset-smoothed} - 2f_{i-2}^{offset-smoothed}}{5t_{i+1} - 5t_{i-1}} \qquad (2)$$

$f_i^{offset-smoothed}$ is the offset smoothed local frequency at time t_i, which is calculated based on smoothed local frequency $f_i^{smoothed}$:

$$f_i^{offset-smoothed} = f_{i+9}^{smoothed} \qquad (3)$$

$$f_i^{smoothed} = 0.9 \cdot f_{i-1}^{smoothed} + 0.1 \cdot f_i^{local} \qquad (4)$$

2.1.4.2 Compensation factor calculation

The compensation factor is calculated for variable controllers and switching controllers, which corresponds to steps (viii) and (ix) in FCAS verification methodology, respectively, as illustrated in Figure 2.1 [4].

The compensation factor for a ***variable controller*** is calculated as follows:

$$\min\left(\max\left(1, \frac{ABS\left(f_{raise\ DB} - f_i^{resp\ rate}\right)}{ABS\left(f_{raise\ DB} - f_i^{offset-smoothed}\right)}\right), 3\right) G \text{ if } f_i^{local} \text{ less than 50Hz} \qquad (5)$$

$$\min\left(\max\left(1, \frac{ABS\left(f_{lower\ DB} - f_t^{resp\ rate}\right)}{ABS\left(f_{lower\ DB} - f_i^{offset-smoothed}\right)}\right), 3\right) G \text{ if } f_i^{local} \text{ greater than 50Hz} \qquad (6)$$

$f_{raise\ DB}$ is the raise frequency of the controller's frequency dead-band, while $f_{lower\ DB}$ is the lower frequency of the controller's frequency dead-band. $f_i^{resp\ rate}$ is the reference frequency which is calculated as follows:

$$f_i^{resp\ rate} = 49.85 - i * frequency\ ramp\ rate \text{ for } 0 \le i \le frequency\ reference\ time \text{ and if } f_{local} \text{ less than 50Hz} \qquad (7)$$

$$f_i^{resp\ rate} = raise\ reference\ frequency \text{ for } i > frequency \text{ and if } f_{local} \text{ less than 50Hz} \qquad (8)$$

$$f_i^{resp\ rate} = 50.15 + i * frequency\ ramp\ rate \text{ for } 0 \le i \le frequency\ reference\ time \text{ and if } f_{local} \text{ greater than 50Hz} \qquad (9)$$

$$f_i^{resp\ rate} = raise\ reference\ frequency \text{ for } i > frequency \text{ and if } f_{local} \text{ greater than 50Hz} \quad (10)$$

Moreover, the "boost" parameter G is calculated as $G = T_{reg}/T_{act}$, with T_{reg} being the maximum capacity corresponding to the relevant registered FCAS trapezium and T_{act} being the maximum capacity corresponding to the maximum availability of the trapezium that is appropriate for the measured maximum rate of change of frequency that occurred.

The compensation factor for a ***switching controller*** is calculated as follows:

$$\max(1, ((6 - frequency\ setting\ time))/(6 - t_{initiate} + t_{step})) \quad (11)$$

where $t_{initiate}$ is the time after the event when the local frequency measurement reaches the relevant frequency setting, and t_{step} is equal to the time interval between the power flow measurements during the first 6s after the frequency disturbance time.

2.1.4.3 Alternative method to calculate the compensation factor for a variable controller

The current methodology for calculating the compensation factor for variable controllers are designed for high-speed sampling data, i.e., 50ms and 20ms data, where the offset smoothed local frequency $f_i^{offset-smoothed}$ is used (see (5)-(6)). However, this formula may not work as well with a lower sampling rate, as it will create major deviations between the smoothed frequency and local measured frequency. In this case, we introduce an alternative way to calculate the compensation factor for variable controllers using the locally measured frequency rather than the offset smoothed local frequency:

$$\min\left(\max\left(1, \frac{ABS\left(f_{raise\ DB} - f_i^{resp\ rate}\right)}{ABS\left(f_{raise\ DB} - f_i^{local}\right)}\right), 3\right) G \text{ if } f_i^{local} \text{ less than 50Hz} \quad (12)$$

$$\min\left(\max\left(1, \frac{ABS\left(f_{lower\ DB} - f_t^{resp\ rate}\right)}{ABS\left(f_{lower\ DB} - f_i^{local}\right)}\right), 3\right) G \text{ if } f_i^{local} \text{ greater than 50Hz} \quad (13)$$

To further demonstrate the potential issue of using the offset smoothed local frequency to calculate the compensation factor with low sampling rate data, an example is illustrated in Figure 2.7. As shown in Figure 2.7, when using 50ms data the offset smoothed local frequency can be seen as a good representation of the local frequency with a smoothed curve. Hence, using either the local frequency or the offset smoothed local frequency to calculate the compensation factor only leads to minor differences in the adjusted response. However, when the sampling rate is changed from 50ms to 200ms, the gap between the offset smoothed local frequency and the local frequency may be substantial, which leads to differences in compensation factor and the adjusted response. It can also be seen that when using 200ms data, the offset smoothed local frequency can no longer represent the local frequency, which may create a large error in the verification process.

In Section 3.2 we will perform more analyses on the impact of directly using the local frequency as opposed to a smoothing frequency curve. However, it is worth pointing out here that such analysis solely focuses on determining the variation of a verification error. In fact, as mentioned at the beginning of 2.1.4, the compensation factor is used to scale up/down the response profile of a Fast FCAS provider with variable controller in less severe contingency events, so that the verification tool will not over/under-evaluate the response performance. The effectiveness and accuracy of using actual local frequency instead of smoothed frequency in such scaling process will not be discussed in this report, as it is out of the scope of this project.

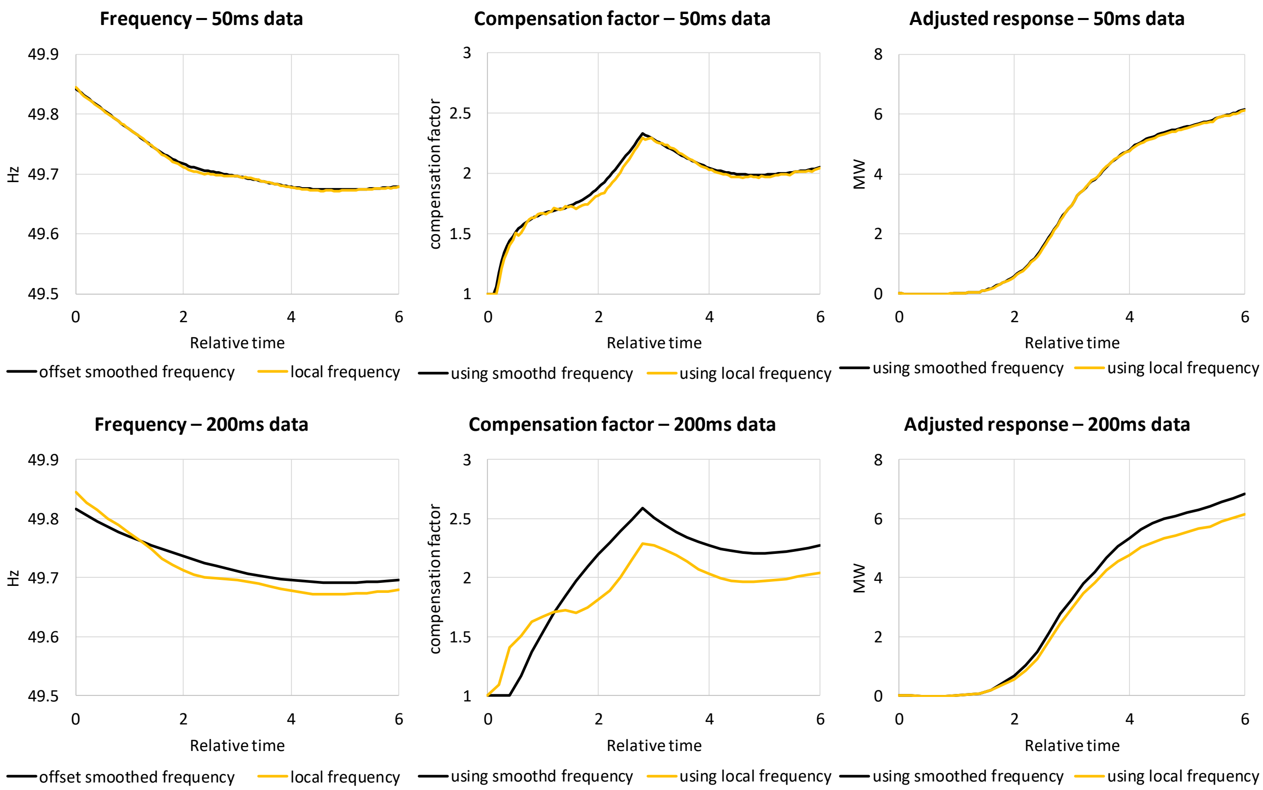

Figure 2.7. Example of using smoothed frequency and local frequency to calculate the compensation factor.

2.1.5 VPP Demonstrations programme FCAS verification

In AEMO's VPP Demonstrations programme, in addition to verifying the FCAS contribution using AEMO's verification tool, the response profile is also examined on a temporal basis against the frequency signal, using the following steps:

i) Determine a baseline, which is the average power measurement over the last 5s before a frequency excursion;
ii) Determine the FCAS response, which is the change in active power after the frequency disturbance time compared to the baseline determined above;
iii) Verify the FCAS response relative to the target response based on the droop-control settings at every sampling point.

It can be therefore seen that this represents a slightly different approach relative to the steps that are presented in Figure 2.1. More specifically, instead of imposing the compensation factor, FCAS delivery is directly verified with respect to the target response.

2.2 Site aggregation

In the VPP Demonstrations programme, AEMO verifies the performance of VPP based on the aggregated response to deliver contingency FCAS during a frequency disturbance. Moreover, the FCAS response is required to be measured at every FCAS response measurement point[1] at the relevant sites. The VPP is required to provide aggregated response which is an aggregation of the responses of the individual sites. The clock associated with individual meters at the relevant site may record slightly different times. To correct this, the VPP is required to align the data for each meter to the actual time that the Frequency Disturbance was detected, i.e., the time that the measured frequency fell outside the NOFB.

This report will analyse an alternative way for FCAS verification for VPP, i.e., using individual NMI data to verify FCAS delivery and then aggregating the calculated FCAS delivery for individual NMIs. The following steps are therefore proposed:

- Retrieve site response profiles of individual NMIs with different sampling rates, i.e., 100ms, 200ms, and 1s;
- Calculate FCAS contribution of individual NMIs using the methodology illustrated in Figure 2.1;
- Calculate FCAS contribution of the VPP by summing up the FCAS contribution of individual NMIs;
- Calculate benchmark FCAS contribution of the VPP:
    - Retrieve site response profiles of individual NMIs with 20ms/50ms sampling rate.
    - Generate the aggregated response by summing up the response from individual NMIs, after aligning NMIs data based on the actual frequency disturbance time.
- Calculate FCAS contribution of the aggregated response, using the methodology illustrated in Figure 2.1.Compare the aggregated FCAS contribution with the benchmark FCAS contribution.

In order to analyse the impact of different numbers of sites on the verification error, different levels of aggregation are tested, e.g., 1/10/25/50/200/500 sites.

2.3 Oscillatory behaviour identification

Due to network disturbances and other voltage and stability issues, the power output of an FCAS provider may oscillate, which could potentially reduce its response contribution and affect system security due to insufficient response provision. Therefore, it is necessary to establish a methodology to identify such oscillatory behaviour so that a formal definition of oscillatory response could be created and discussed with relevant stakeholders.

Let us assume that an oscillatory response can be interpreted as a raise FCAS response with superimposed alternate signal, as calculated in (14). Here: t is relative time after frequency disturbance time, T is the period of the oscillatory behaviour, b is the response ramping speed assuming a variable controller is, and k is the oscillatory magnitude (relative to b).

$$s(t) = b \cdot t \cdot \left(1 + k \sin\left(t \cdot \frac{2\pi}{T}\right)\right) \tag{14}$$

According to Nyquist–Shannon sampling theorem, *if a function s(t) contains no frequencies higher than B Hz, it is completely determined by giving its ordinates at a series of points spaced $1/(2B)$ seconds apart*. This means that for a sinusoidal signal with 1s period, the minimum sampling rate needs to be 0.5s to reconstruct the sinusoidal signal. However, Shannon's formula applies to a signal not limited in time, while

[1] FCAS measurement points vary according to the configuration of the controllable devices behind the connect point. The details can be found in "VPP Demonstrations FCAS Specification", AEMO: https://aemo.com.au/-/media/Files/Electricity/NEM/DER/2019/VPP-Demonstrations/VPP-Demonstrations-FCAS-Specification

the FCAS response in question lasts no more than 6s, therefore a higher sampling rate is needed for signal reconstruction.

An example is shown in Figure 2.8 which displays responses with 1s (left) and 0.25s (right) oscillatory period. The discrete sampling points with different rates (e.g., 100ms, 200ms, 1s) are also shown in Figure 2.8. It can be noticed that 1s sampling rate cannot capture the oscillatory behaviour when the period of the signal is equal or lower than 1s, as suggested by Nyquist–Shannon sampling theorem.

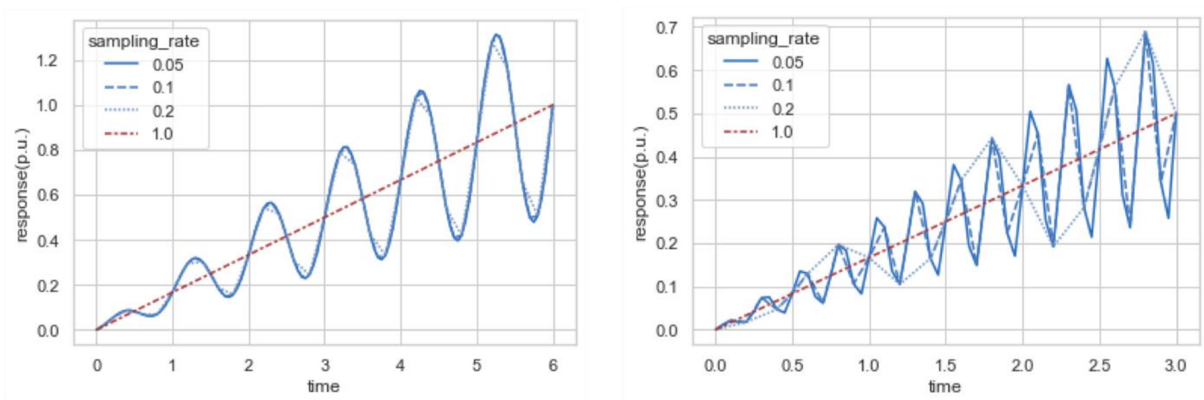

Figure 2.8. Discrete points of different sampling rates (e.g., 100ms, 200ms, 1s) on an 50ms response with 1s oscillatory period (left) and 0.25s oscillatory period (right)

In order to detect the magnitude of a sinusoidal signal, then, at least three sample points are needed within a half cycle oscillation. The proposed methodology of identifying oscillatory response is shown in Figure 2.9 and explained as follows:

- Sets of three response sample points are selected, with the interval (i) between adjacent points within a same set being required to be equal. These sets of points are used to detect a potential oscillatory response with a range of periods (e.g., 0.2s-3.2s).
- Within each three-points set sampled above, the response magnitudes of the first and the third points (LF_T, LE_T) should have similar values (i.e., +-10%), otherwise the ramping process of a switching controller might be misidentified as oscillatory response.
- The expected response of the middle point ($LM_{\_T}$) within each set can be calculated by using linear interpolation of the response of initial and end points.

$$LM_{\_T} = \frac{(LF_T + LE_T)}{2} \tag{15}$$

- For raise FCAS, only a downward oscillation is analysed, which is $LM_T < LM_{\_T}$.
- For lower FCAS, only an upward oscillation is analysed, which is $LM_T > LM_{\_T}$.
- To measure the response oscillation level, a specific metric "*oscillation ratio*" (os_ratio) is proposed, as calculated in (16) below. Notice that the denominator in (16) takes the maximum value of the expected response magnitude ($LM_{\_T}$) and 25% of the maximum response across six-second assessment window. The reason of setting this denominator is considering that at the initial stage of the ramping process the expected response may be very small, so minor oscillation may result in a large value of os_{ratio}.

$$os_{ratio} = abs\left(\frac{(LM_T - LM_{\_T})}{max[abs(LM_{\_T}),\ abs(P_N \times 25\%)]}\right) \tag{16}$$

- Finally, if the oscillation ratio of any given sets is higher than 50%, the profile will be considered as an oscillatory response. The 50% threshold is an initial proposal that could be revised later following consultations, if needed.

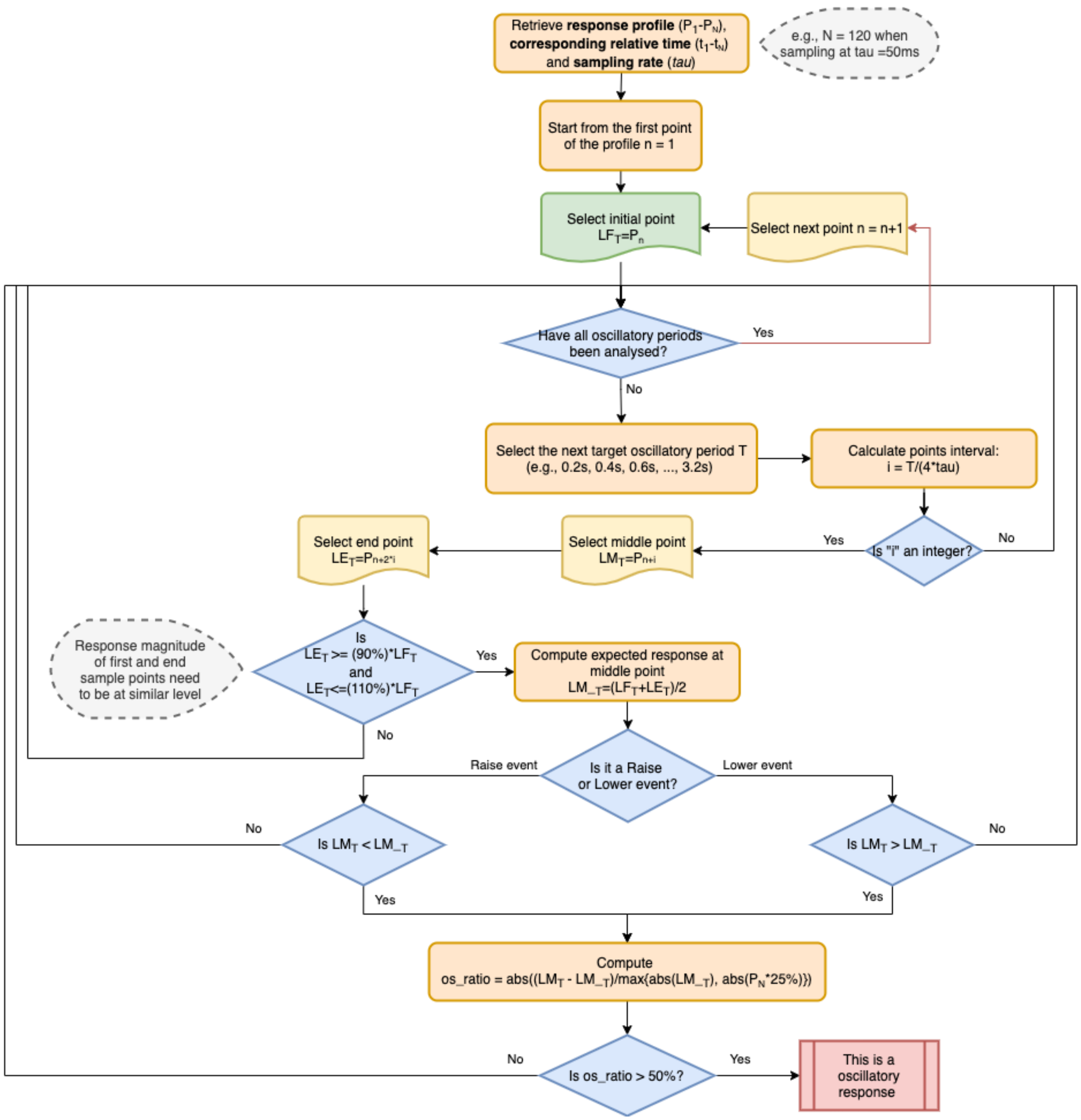

Figure 2.9. Methodology to identify an oscillatory response profile

3 Case studies

3.1 Inertial response adjustment

In order to demonstrate the impact of sampling rate on the inertial response for synchronous generators, five synchronous generators (namely, Unit A, B, C, D, and E) with oscillatory response are analysed according to the FCAS verification process that is illustrated in Figure 2.1. For this case study, the settings of seven factors related to verification error calculation are displayed in Table 3.1. The sensitivity study is focused on the sampling rates and assessment window methods. Note that 1s sampling rate is not considered here as profiles with 1s sampling rate do not have sufficient data points to calculate the offset smoothed local frequency $f_i^{offset-smoothed}$ which requires 10 data points (see equation (3)). Hence, the compensation factor and inertial response cannot be calculated.

Table 3.1. Settings of seven factors related to verification error calculation in benchmark and sensitivity study

	Power measurement error	Sampling rate	Site aggregation	Integration rule
Benchmark	Not considered	• 50ms	N/A	• Trapezoid
Sensitivity study	Not considered	• 100ms • 200ms	N/A	• Trapezoid
	Inertial response	**Compensation factor**	**Frequency disturbance time**	
Benchmark	• Use smoothed local frequency	• Use smoothed local frequency	• "Universal window" method	
Sensitivity study	• Use smoothed local frequency	• Use smoothed local frequency	• "Universal window" method • "First recorded point" method • "Twin points average" method • "Midpoint" method • "RoCoF-based" method	

Using Unit D as an example, the calculated smoothed frequency $f_i^{smoothed}$, df/dt, inertial response IR_i, adjusted generation, compensation factor, and adjusted response during a raise event are illustrated in Figure 3.1. As shown in Figure 3.1, lowering the sampling rate from 50ms to 100ms or 200ms can substantially change the smoothed frequency. According to equation (3), the smoothed frequency at time i mainly depends on the smoothed frequency at time $i-1$ as well as the local measured frequency at time i. This potentially leads to higher smoothed frequency when lower the sampling rate for a raise event. The differences in the smoothed frequency lead to deviations in df/dt and inertial response under different sampling rates, with inertial response being smoother for lower frequency sampling rates such as 100ms and 200ms as opposed to 50ms. That is, a lower sampling rate may result in an underestimation of the inertial response component. The inertial response has a further impact on the adjusted generation, which is the sum of the original power measurement and inertial response. On the other hand, the calculated compensation rates are also different under different sampling rates, as they link to the smoothed frequency (see equation (3)-(6)). Overall, in the presented case, the differences in the adjusted response of synchronous generator when using different sampling rates are between 10% to 30%.

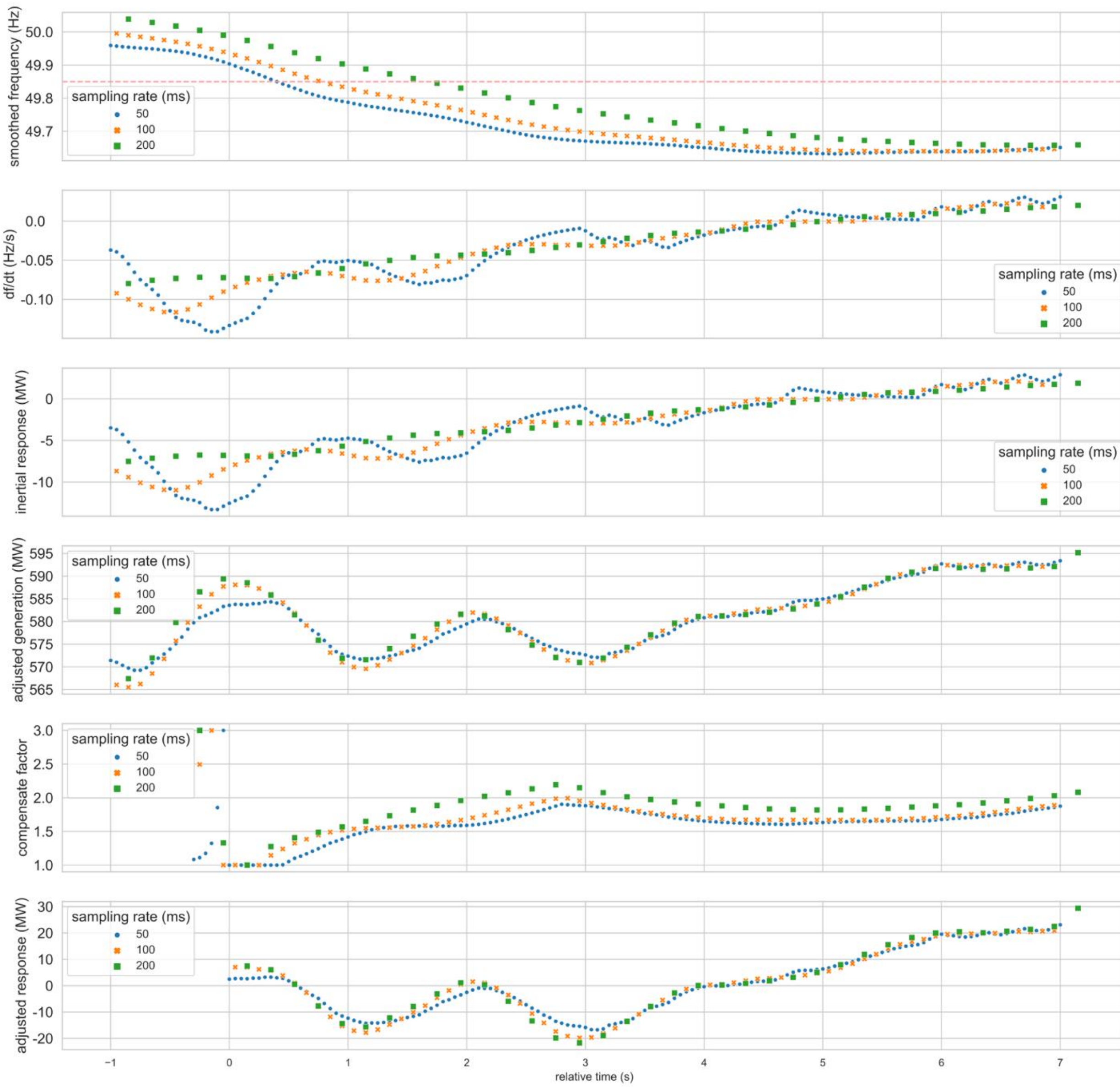

Figure 3.1. Smoothed frequency, df/dt, inertial response, adjusted generation, compensation factor and adjusted response for sampling rates of 50ms, 100ms, and 200ms.

The verification errors for Unit A-E using different assessment window methods with 100ms and 200ms sampling rates are illustrated in Figure 3.2 and Figure 3.3, respectively. It can be seen that lowering the sampling rate substantially increases the verification error. The average verification error is in the range of -30% to +10% when using a 200ms sampling rate and -5% to +5% when using a 100ms sampling rate. The errors mainly come from the calculation of the inertial response and compensation factor for variable controllers, as illustrated in Figure 3.1. Moreover, the results also show that there is no systematic over-estimation or under-estimation when using different assessment window methods with lower sampling rates, but they are rather case-dependent.

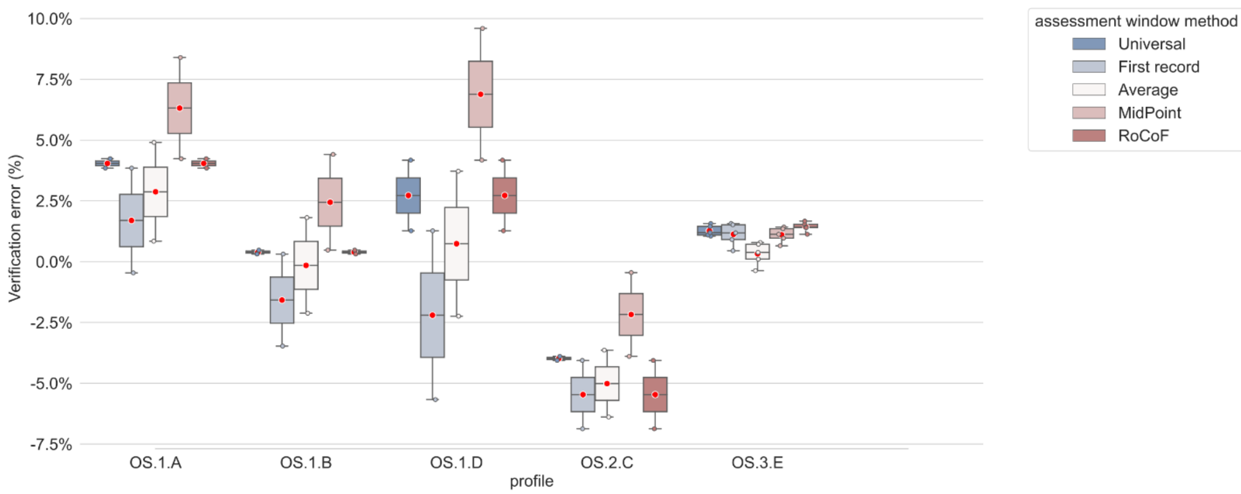

*Figure 3.2. Verification error of five oscillatory response profiles from synchronous generators, sampling at **100ms** and using five different assessment window methods and trapezoidal rule*

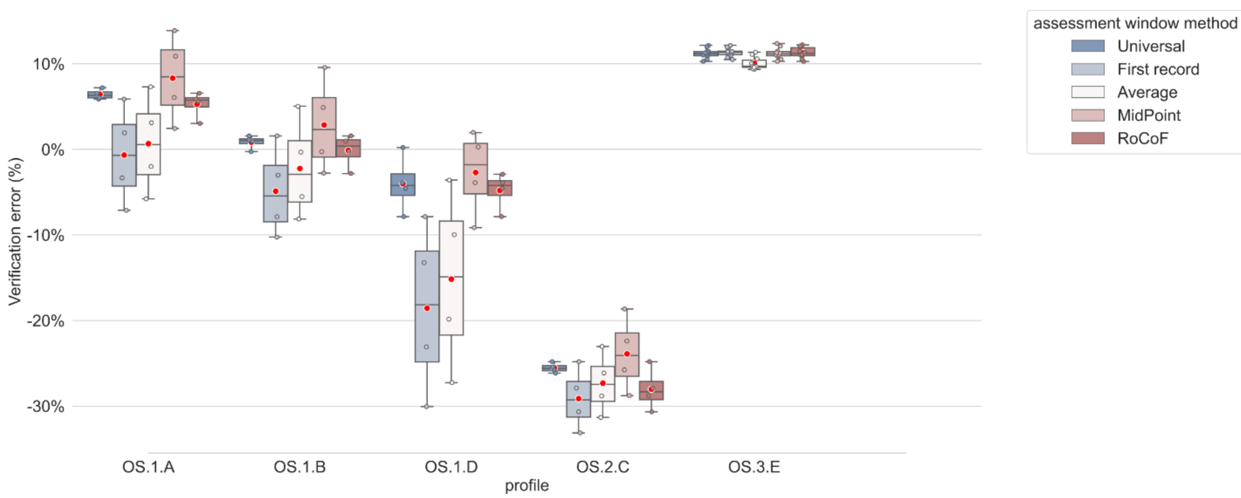

*Figure 3.3. Verification error of five oscillatory response profiles from synchronous generators, sampling at **200ms** and using five different assessment window methods and trapezoidal rule*

3.2 Compensation factor calculation

As mentioned in section 2.1.4.3, compensation factors can be calculated with *actual local frequency* instead of *offset smoothed local frequency*. In this case study, we discuss the FCAS contribution and verification error when using different methods to calculate compensation factor. Table 3.2 shows the settings of the key seven factors used in this case study, and the combination of three compensation factor methods, three sampling rates and two assessment window methods are analysed.

Table 3.2. Settings of seven factors related to verification error calculation in benchmark and sensitivity study

	Power measurement error	Sampling rate	Site aggregation	Integration rule
Benchmark	Not considered	• 50ms	N/A	• Trapezoid
Sensitivity study	Not considered	• 100ms • 200ms • 1s (for DER only)	N/A	• Trapezoid
	Inertial response	Compensation factor	Frequency disturbance time	
Benchmark	• Use smoothed local frequency	• Not considered • Use smoothed local frequency • Use local frequency	• "Universal window" method	
Sensitivity study	• Use smoothed local frequency	• Not considered • Use smoothed local frequency • Use local frequency	• "Universal window" method • "First recorded point" method	

In Table 3.2, all three compensation factor calculation methods have been considered in the benchmark. This is because the benchmark (i.e., 50ms response profile) and sensitivity study should use the same compensation factor calculation approach so that there is no additional verification error introduced by mixing the methods. For example, Figure 3.4 depicted the FCAS contributions of a synchronous generator when using different sampling rates and compensation factor calculation methods. In case study 3.1, both inertial response and compensation factor are calculated with smoothed frequency curve, as highlighted in Figure 3.4.

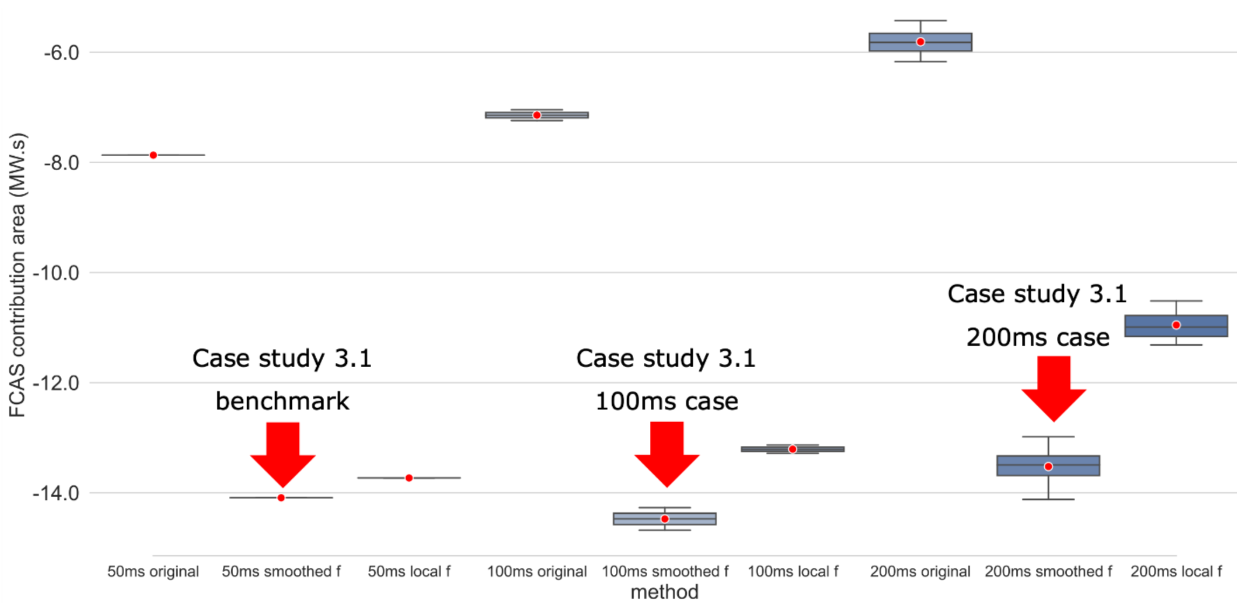

*Figure 3.4. Fast FCAS contribution of a synchronous generator response profile sampled at 50/100/200ms with "**universal window**" and three compensation factor calculation methods*

The FCAS contribution of a VPP with variable controllers using the "universal window" method is shown in Figure 3.5. The results used to calculate the verification error for the first report are highlighted in Figure 3.5: the compensation factors are fixed to 1 in these cases, and the verification error is solely induced by lower sampling rates. If the compensation factor is calculated following the verification tool methodology, the FCAS contribution is substantially higher (i.e., raising from 12 MW.s to 20.6 MW.s when using 50ms sampling rate). Additionally, using actual local frequency instead of smoothed frequency results in a lower FCAS contribution for this response profile, as depicted in Figure 3.5. Furthermore, if the smoothed frequency is used, the FCAS contribution will rise from 20.6 MW.s at 50ms to 23.6 MW.s at 200ms, which would result in 14.5% verification error. On the other hand, if the actual local frequency is used, the FCAS contribution does not change with a lower sampling rate, which maintains at 20.5 MW.s across all three sampling rate cases. **It can thus be concluded that a lower sampling rate results in a higher compensation factor in the verification process when using smoothed frequency curve for compensation factor calculation of DER response: this scales up the FCAS contribution and eventually results in a positive verification error.**

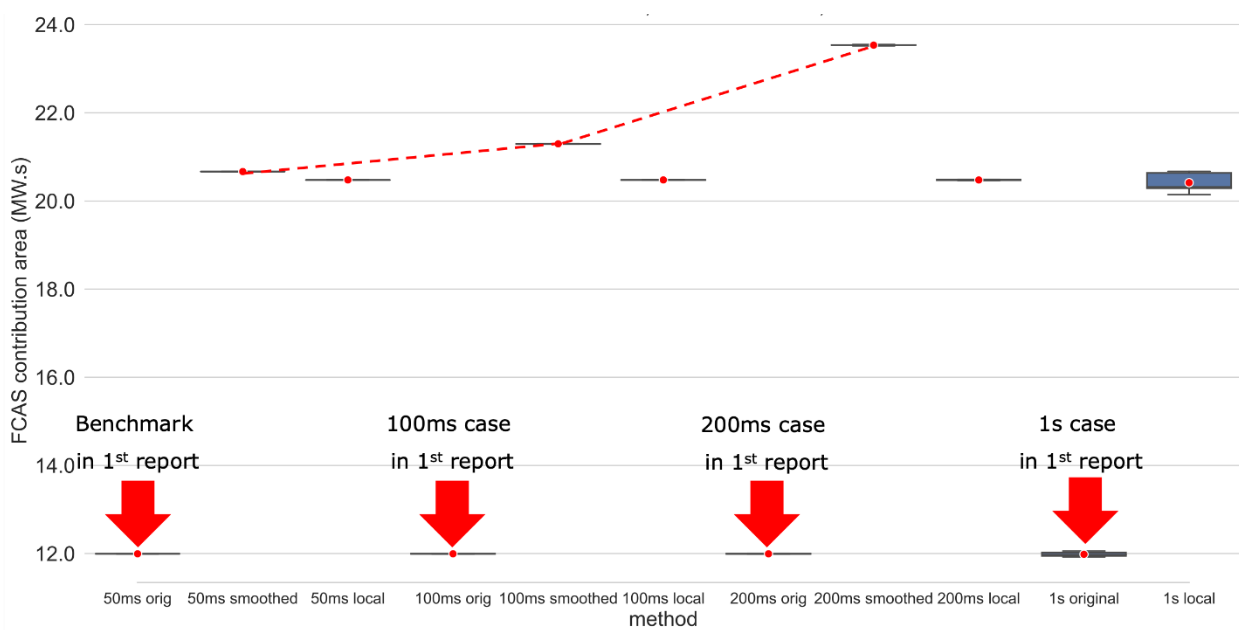

*Figure 3.5. Fast FCAS contribution of a DER response profile sampled at 50ms/100ms/200ms/1s with "**universal window**" and three compensation factor calculation methods*

Figure 3.6 shows the FCAS contribution of the same VPP but using the first recorded point method instead of the "universal window" method. The contribution increases when using lower sampling rates in both smoothed and actual local frequency cases. The contributions increase in the smoothed frequency cases when using a lower sampling rate is caused by the compounded effect of delayed assessment window (due to relative window method) and higher compensation factor (due to smoothed curve).

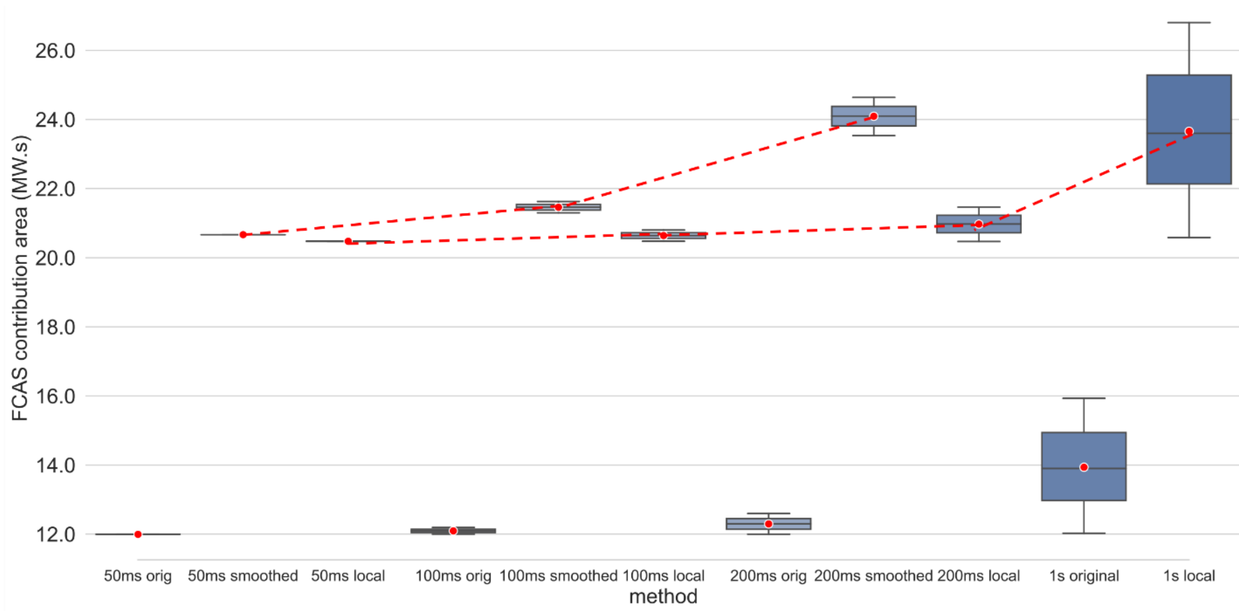

*Figure 3.6. Fast FCAS contribution of a DER response profile sampled at 50ms/100ms/200ms/1s with **"first recorded point" method** and three compensation factor calculation methods*

3.3 FCAS assessment window methods

As mentioned in section 2.1.3, five methods are proposed to determine the frequency disturbance time. Table 3.3 displays the settings of the seven key factors used in this case study. Only two factors are selected to create different combinations for sensitivity study, which are sampling rate and assessment window method. The benchmark used in this case study corresponds to the FCAS contribution calculated with the "universal window" method and using local frequency when calculating compensation factor.

Table 3.3. Settings of seven factors related to verification error calculation in benchmark and sensitivity studies

	Power measurement error	Sampling rate	Site aggregation	Integration rule
Benchmark	Not considered	• 50ms	N/A	• Trapezoid
Sensitivity study	Not considered	• 100ms • 200ms • 1s (for DER only)	N/A	• Trapezoid
	Inertial response	Compensation factor	Frequency disturbance time	
Benchmark	• Use smoothed local frequency	• Use local frequency	• "Universal window" method	
Sensitivity study	• Use smoothed local frequency	• Use local frequency	• "Universal window" method • "First recorded point" method • "Twin points average" method • "Midpoint" method • "RoCoF-based" method	

The verification errors of four different profiles with five assessment window methods when using a 200ms sampling rate are depicted in Figure 3.7. Profile 3.2.1 is the aggregated response profile of a VPP with switching controllers. Profile 7.1 is from a VPP with variable controllers. The rest two are response profiles of synchronous generators.

As seen in Figure 3.7, among five assessment window methods, applying “universal window” results the smallest verification error distribution range across all four profiles. The first recorded point method has the worst performance with large error distribution ranges and high average errors (i.e., -15% in OS.1.B). The average errors in the cases with the “twin point average” or “midpoint” methods have similar values compared with the “universal window” case. However, these two methods have a much larger error distribution range than the “universal window”. The “RoCoF-based” method achieves a very similar performance compared with the “universal window” when it comes to both average error and distribution range of the error.

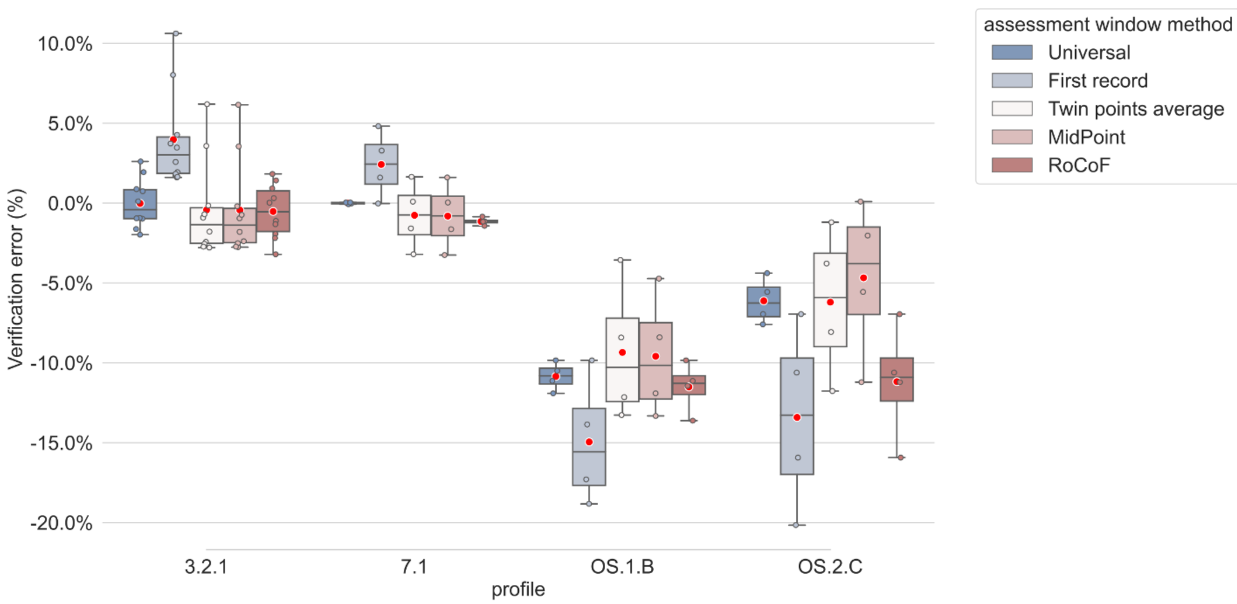

*Figure 3.7. Verification error of four representative response profiles sampling at **200ms** and using five different assessment window methods and trapezoidal rule*

Further analysis was carried out to provide insights into why the “RoCoF-based” method is able to outperform the other three relative window methods (e.g., “first recorded point”, “twin points average”, and “midpoint”) in terms of minimising the verification error. Figure 3.8 shows the difference in frequency disturbance time when using four relative window methods compared with the “universal window” method. As seen in Figure 3.8, the “RoCoF-based” method has the smallest distribution of time difference values, confirming its higher accuracy in determining the frequency disturbance time without relying on high-resolution frequency data (i.e., 50ms).

To demonstrate the superior performance of the “RoCoF-based” method, the verification error of 24 profiles with all five assessment window methods and three different sampling rates are shown in Figure 6.1 - Figure 6.15, which are reported in Appendix A.

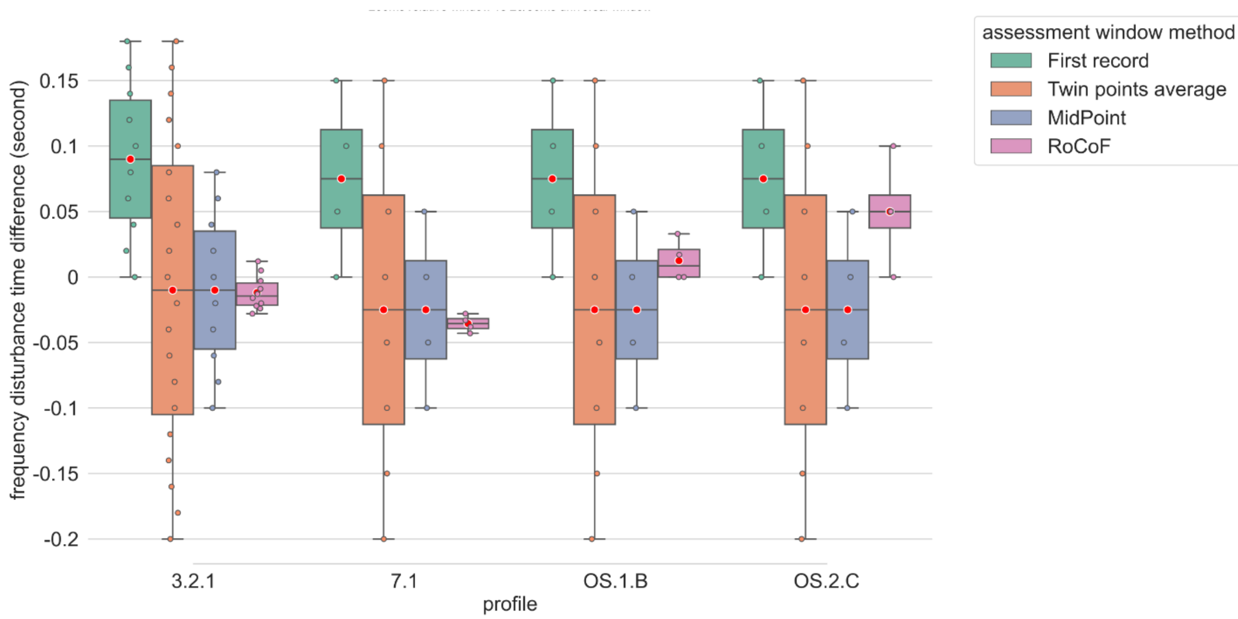

Figure 3.8. Time difference between frequency disturbance time determined by "universal window" method and other four relative window methods when assessing four representative response profiles sampling at ***200ms***

3.4 Site aggregation

This case study aims to analyse the alternative method for verifying FCAS contribution of a VPP with lower sampling rates (i.e., 100ms, 200ms, 1s). For this case study, the settings of seven factors related to verification error calculation are displayed in Table 3.4.

Table 3.4. Settings of seven factors related to verification error calculation in benchmark and sensitivity study

	Power measurement error	Sampling rate	Site aggregation	Integration rule
Benchmark	Not considered	• 50ms	Considered	• Trapezoid
Sensitivity study	Not considered	• 100ms • 200ms • 1s	Considered	• Trapezoid
	Inertial response	**Compensation factor**	**Frequency disturbance time**	
Benchmark	N/A	Not considered	• "Universal window" method	
Sensitivity study	N/A	Not considered	• "Universal window" method • "First recorded point" method • "RoCoF-based" method	

The proposed method verifies FCAS contribution for individual NMIs and then sums up the FCAS contributions for individual NMIs, which is then compared to the benchmark, i.e., the FCAS contribution that is calculated based on 20ms/50ms data. The data that is used in this study is provided by AEMO. More specifically, the response from 1000 sites for two events, i.e., NSW event and QLD event, with different sampling rate, i.e., 50ms, 100ms, 200ms, and 1s, are used in the analysis. This case study takes the approach that is used in AEMO VPP Demonstrations programme, that is, instead of imposing the compensation factor, the FCAS response is directly compared with the target response. In this case, the verification errors are only caused by the number of sites within the VPP and sampling rates, which are separated from the errors introduced by the compensation factor due to lower sampling rates, as discussed in section 3.2. The aggregated response and measured frequency for the NSW and QLD events are illustrated in Figure 3.9 and Figure 3.10, respectively. Moreover, a sensitivity study was carried out for different aggregation levels, i.e., 1 site, 10 sites, 25 sites, 50 sites, 200 sites, 500 sites, and 1000 sites. Monte Carlo simulations were run in order to randomly choose the desired number of sites from 1000 sites.

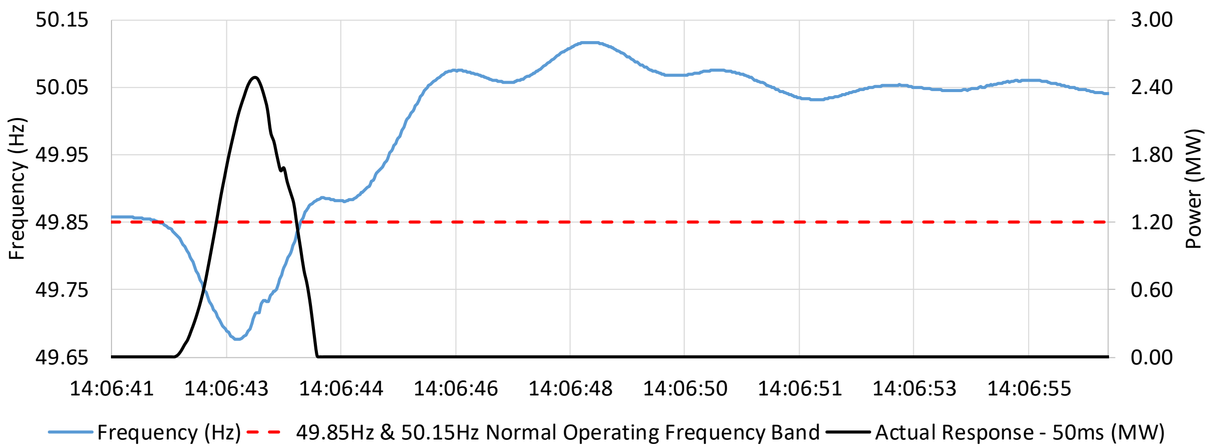

Figure 3.9. Aggregated response of 1000 sites and frequency measurement for NSW event.

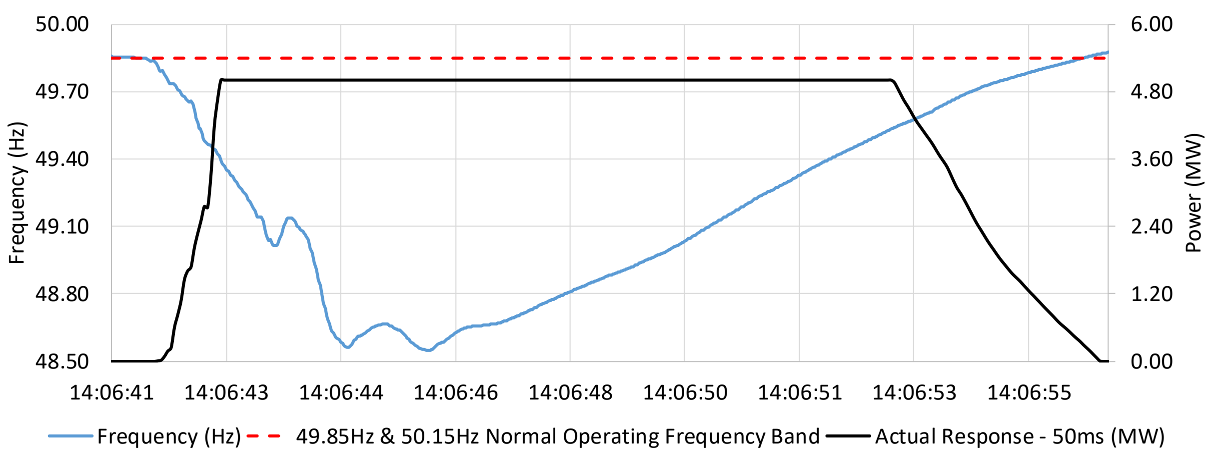

Figure 3.10. Aggregated response of 1000 sites and frequency measurement for QLD event.

The verification errors without applying the compensation factor for the NSW event and QLD event with 500 Monte Carlo simulations are shown in Figure 3.11-Figure 3.13 and Figure 3.14-Figure 3.16, respectively. The numerical values of the verification error distributions of all cases presented in Figure 3.11-Figure 3.16 are shown in Table 7.1-Table 7.6 of Appendix B. It can be seen that the distributions of verification error are almost the same for 100ms and 200ms sampling rates, when using the "universal window" method (see Figure 3.11 and Figure 3.14). Using 1s sampling rate leads to a much larger distribution of error, especially when the number of sites is small, i.e., 1 site, 10 sites, and 25 sites. Moreover, increasing the number of sites will substantially improve (reduce) the verification error. For example, when the VPP aggregates 200 sites, the error distribution range is less than +/- 1% when using 100ms and 200ms sampling rates and "universal window" method.

When adopting relative window methods, i.e., "first recorded point" and "RoCoF-based" methods, the average error for 1s sampling rate for the NSW event is -10%. The under-estimation of NSW event with 1s sampling rate is because the response only occurs for 3s within the first six-second window (see Figure 3.9). Thus, the relative window will replace the effective response at the beginning of the six-second window with a void response at the end of the six-second window.

Similarly to the results that are observed for the "universal window" method, increasing the number of sites leads to smaller verification error distribution ranges when using the "RoCoF-based" method and the "first-record point" method. The reduction is minor when the number of sites is above 200 sites as the distribution of verification error is relatively small. It is worth noting that the "RoCoF-based" method has a very similar performance compared to the "universal window" method, while the "first recorded point" method leads to the worst results among all the three methods that are compared. This is particularly obvious when using 1s sampling rate. For example, for 200 sites, the verification error ranges between −12.5% and -7.4% for the NSW event and between 6.6% and 8.4% for the QLD event when using "first recorded point" method. For the "universal window" method, the verification errors only range between -3.2% and -0.2% for the NSW event, and -1.1% to 0.3% for the QLD event. For the "RoCoF-based" method, the verification errors range between -1.4% and 1.3% for the NSW event, and between -1.2% and 0.4% for the QLD event.

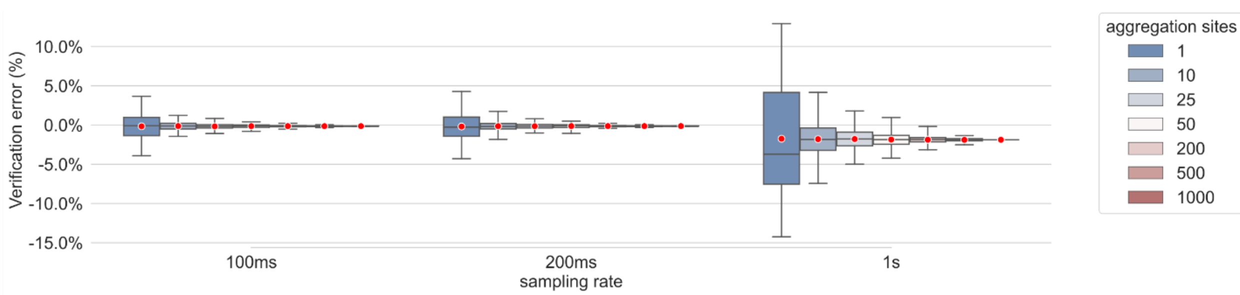

*Figure 3.11. Verification error (without compensation response) of different aggregation levels under different sampling rates, using "**universal window**" method and trapezoidal rule, for NSW event*

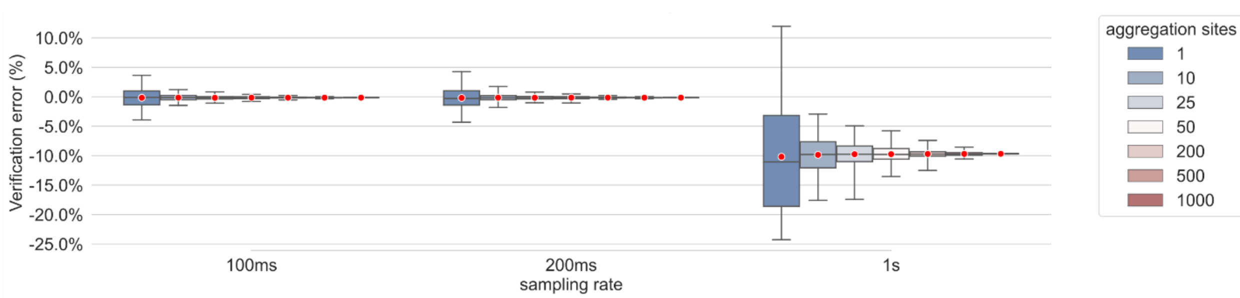

*Figure 3.12. Verification error (without compensation response) of different aggregation levels under different sampling rates, using "**first recorded point**" method and trapezoidal rule, for NSW event*

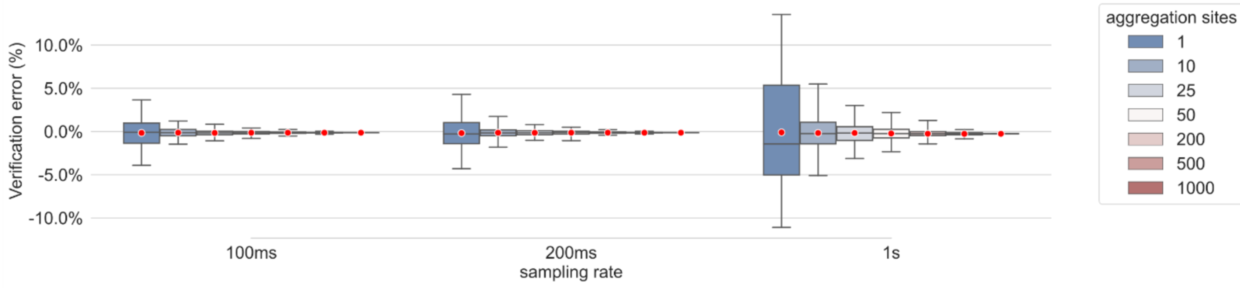

*Figure 3.13. Verification error (without compensation response) of different aggregation levels under different sampling rates, using **"RoCoF-based"** method and trapezoidal rule, for NSW event*

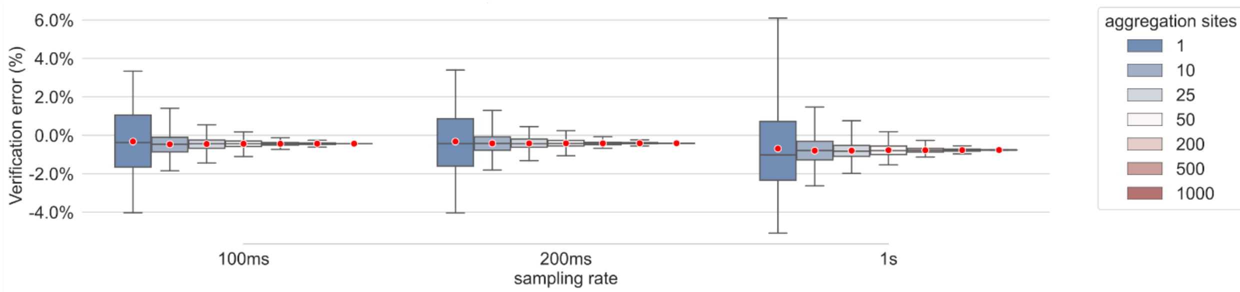

*Figure 3.14. Verification error (without compensation response) of different aggregation levels under different sampling rates, using "**universal window**" method and trapezoidal rule, for QLD event*

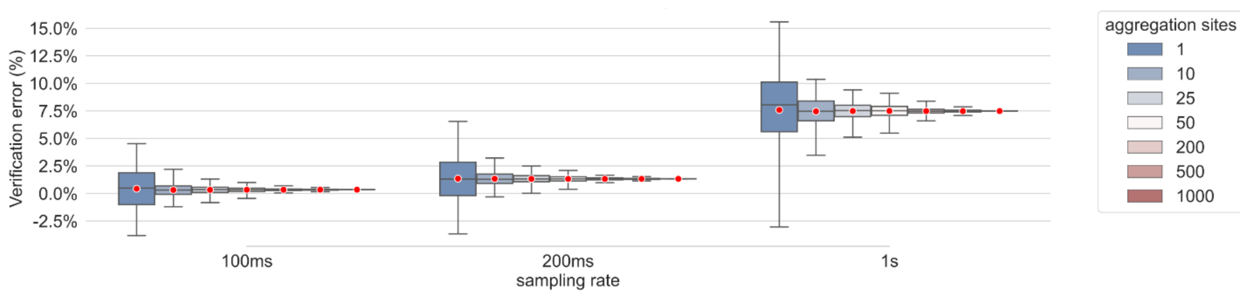

*Figure 3.15. Verification error (without compensation response) of different aggregation levels under different sampling rates, using "**first recorded point**" method and trapezoidal rule, for QLD event*

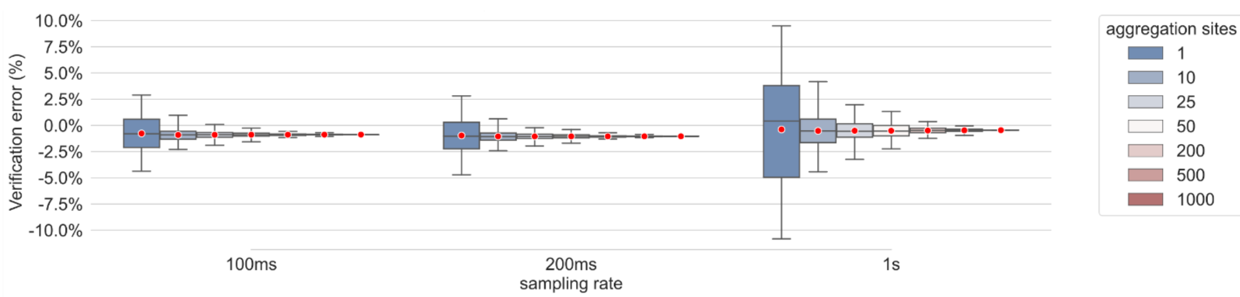

*Figure 3.16. Verification error (without compensation response) of different aggregation levels under different sampling rates, using "**RoCoF-based**" method and trapezoidal rule, for QLD event*

3.5 Measurement error

This case study aims to demonstrate the verification error that may be introduced from relaxing the allowed 2% measurement error to 4%. The set-ups for the seven factors that are considered for the verification errors are shown in Table 3.5. Random errors are generated using the methodology that is presented in section 2.1.2, while 2000 Monte Carlo simulations are carried out to generate different metering profiles with random errors. The verification error when the measurement error tolerance increases from 2% to 4% is also calculated.

Table 3.5. Settings of seven factors related to verification error calculation in benchmark and sensitivity studies

	Power measurement error	Sampling rate	Site aggregation	Integration rule
Benchmark	+/-2%	• 50ms	N/A	• Trapezoid
Sensitivity study	+/-4%	• 50ms	N/A	• Trapezoid
	Inertial response	**Compensation factor**	**Frequency disturbance time**	
Benchmark	• Use smoothed local frequency	• Use smoothed local frequency	• "Universal window" method	
Sensitivity study	• Use smoothed local frequency	• Use smoothed local frequency	• "Universal window" method	

The distribution of verification errors when allowing 4% measurement error compared to 2% measurement error from 2000 Monte Carlo simulations is illustrated in Figure 3.17, while the upper band and lower band of the verification error is shown in Table 3.6. More specifically, events 7.1.1 and 3.2.1 refer to the FCAS response from DER, while events OS.1.A, OS.1.B, OS.2.C and OS.1.D refer to the FCAS response from synchronous generators. It can be seen that for event 7.1.1 and 3.2.1, the verification error is relatively small, i.e., between -0.7% to 0.7%. For generator A-D, moving from allowing 2% to 4% measurement error introduces very substantial verification error, which can vary from -95% to 70%. This large error is because the synchronous generators mainly participate in the energy market, while only a small proportion of their capacity partakes in Fast FCAS. In all five events, the generators have large power output baselines, therefore a 2% error can be relatively substantial when compared to relatively small frequency response outputs. As an example, for event OS.1.A, generator A has a baseline around 600MW pre-event, while the maximum response within the 60s after frequency excursion is only 20MW. In this case, an 2% error can deviate from the actual response by 14MW, which will have a major impact on the response. On the contrary, for event 7.1.1 and 3.2.1, the specific DER uses the majority of its capacity to participate in Fast FCAS market. For example, for event 7.1.1, the VPP is operated at -28MW pre-event, while the maximum FCAS response is 22MW. An additional 2% error leads to a maximum deviation of 0.56MW from the actual response, which is relatively small.

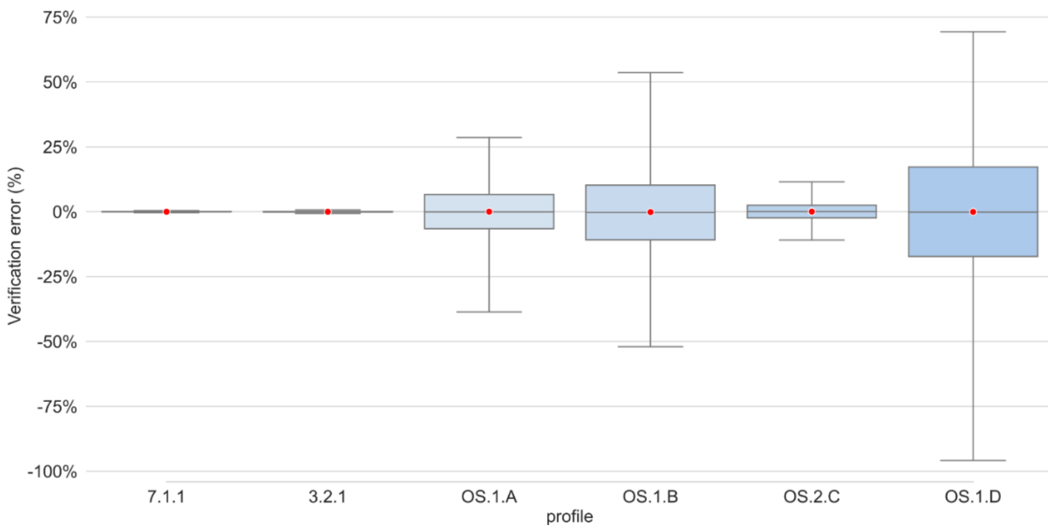

Figure 3.17. Verification error comparing 2% measurement error allowance and 4% measurement error allowance

Table 3.6. Upper band and lower band of additional verification error caused by moving from 2% measurement error allowance to 4% measurement error allowance

	7.1.1	3.2.1	OS.1.A	OS.1.B	OS.2.C	OS.1.D
Upper band of additional verification error	0.4%	0.7%	28.6%	53.6%	11.5%	69.4%
Lower band of additional verification error	-0.4%	-0.7%	-38.6%	-52.0%	-10.9%	-95.8%

In order to further investigate the reasons behind the results on verification errors, the ratio of maximum response to baseline for every event is analysed and illustrated in Figure 3.18. It can be seen that for the DER the maximum response is close to or higher than the baseline. It is worth noting that the maximum ratio is 100% in the figure for presentation purposes; however, many of the events from the DER have a much higher maximum response to baseline ratio. On the other hand, for the synchronous generator, the ratio of response to baseline is only around 3% to 7%. From the results, it can be concluded that the verification error that is introduced by increasing the measurement error allowance to 4% will highly depend on the provider's output allocation between Fast FCAS and other services and market participation (e.g., energy market).

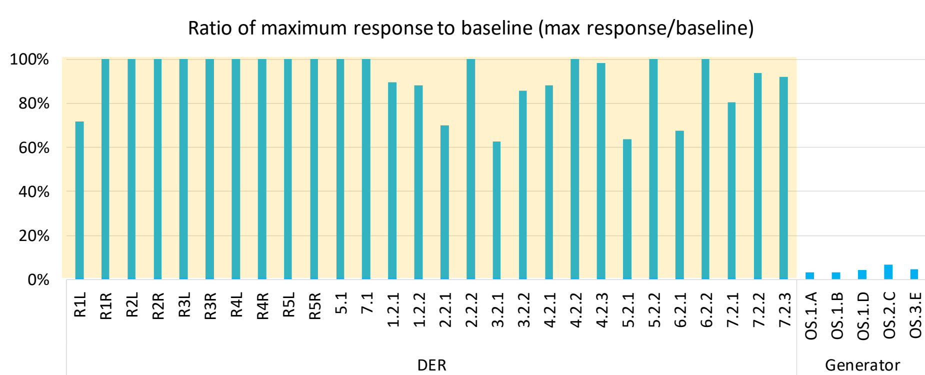

Figure 3.18. Ratios of maximum response to baseline for all events

3.6 Oscillatory response verification

The last case study is about demonstrating the effectiveness of the methodology proposed in 2.3 which identifies the oscillatory behaviour of response profile. As mentioned in section 2.3, the assessment is only performed on the adjusted response profile, which considered compensation factor and inertial response. Table 3.7 shows the setting of the seven key factors related to the calculation of FCAS contribution. Only different sampling rates are considered to evaluate the effectiveness of the methodology when assessing profiles with lower sampling rates. 1s sampling rate are not tested in this case study. This is because the periods of the oscillatory response profiles provided by AEMO are in the range 1s to 3s and, following the principle of selecting at least three sampled points (e.g., 0ms, 250ms, 500ms) in a half oscillation cycle (e.g., 0.5s), 250ms would be the minimum sampling rate requirement, as discussed in section 2.3.

Table 3.7. Settings of seven factors related to response profile calculation in benchmark

	Power measurement error	Sampling rate	Site aggregation	Integration rule
Benchmark	0%	• 50ms • 100ms • 200ms	N/A	• Trapezoid
	Inertial response	**Compensation factor**	**Frequency disturbance time**	
Benchmark	• Use smoothed local frequency	• Use smoothed local frequency	• “Universal window” method	

The oscillation ratios of five response profiles sampled at three different rates (e.g., 50ms, 100ms, 200ms) are shown in Table 3.8. The ratios are all above 50%, which can be successfully identified by the proposed methodology. For the profile OS.1.D, the oscillation ratios are extremely high, which exceeds 400%. The adjusted response of this profile is shown in Figure 3.19. If the sampled middle point is around 1.2s or 3s, and the first and last points of the three points set are at {0.6s, 1.8s} or {2s, 4s}, the expected middle response will be relatively small, which results in a high oscillation ratio value.

Table 3.8. Oscillation ratios of five oscillatory response profiles from synchronous generators

	OS.1.A	OS.1.B	OS.1.D	OS.2.C	OS.3.E
50ms	200%	158%	403%	242%	93%
100ms	221%	148%	498%	301%	105%
200ms	185%	131%	534%	281%	114%

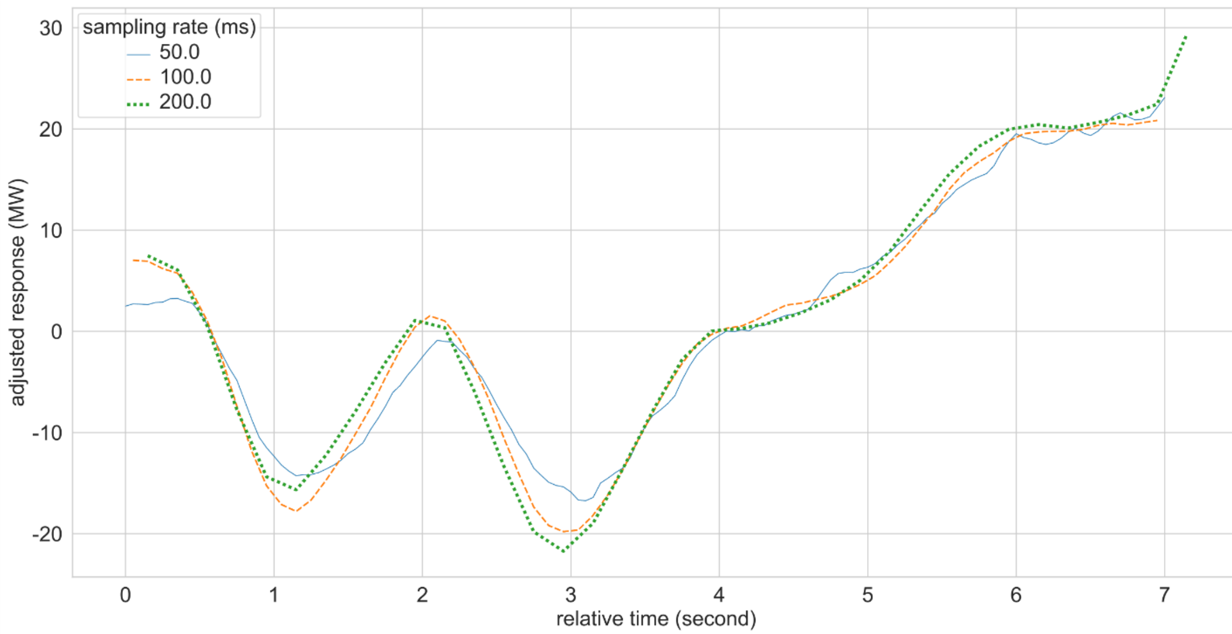

Figure 3.19. Adjusted response profiles of a synchronous generator when sampled at 50ms, 100ms and 200ms

4 Conclusion and recommendations

The effect of six out of seven key factors impacting on the verification error assessment was discussed in this report. For the other key factor, that is, the integration method, the trapezoid method was already the superior based on the conclusions and evidence provided in UoM's first report [2]. The results of six case studies are discussed as follows:

1) With regards to the method to determine the frequency disturbance time of the six-second FCAS assessment window, the "*RoCoF-based*" method exhibits a performance that is on a par with the "*universal window*": this significantly reduces the potential verification error introduced by misalignment of the start point of the assessment window.
2) Concerning the response profiles of synchronous generators, using lower sampling rate may bring a verification error that may be caused by three factors that somehow compound with each other, namely, fewer sampling points on the response profile, and consequently inaccurate estimation of inertial response and compensation factor. The compound effect of these factors results in $\pm$5% verification errors at 100ms and [-20%, 10%] at 200ms when the "*RoCoF-based*" method is used.
3) When calculating the compensation factor for variable controllers, removing the frequency smoothing process from the verification tool methodology can reduce the additional verification error introduced by lower sampling rates. This is because using smoothed frequency curves with low granularity data may result in a higher compensation factor.
4) Using individual NMI-level data instead of aggregated response profiles can substantially reduce the verification error, and such reduction is inversely proportional to the number of sites being aggregated. The gain on verification error reduction is minor (i.e., $\pm$1%) when the number of sites is above 200. Moreover, the increase in verification error is minor when moving from 100ms to 200ms sampling rate at the same aggregation level. Note that this conclusion is fully derived from

the analysis of the data provided by AEMO; studies with more diverse data may be needed to demonstrate the benefits of using NMI-level response profiles for FCAS verification.

5) Increasing the power measurement error allowance from 2% to 4% may introduce substantial verification error. However, the magnitude of such error is closely linked to the ratio between the provider's MW output used for Fast FCAS service and the MW output to provide other services or simply participate in the energy market, with smaller ratios potentially resulting in higher verification errors.
6) 1s sampling rate is not suitable for capturing oscillatory responses, as the periods of the oscillatory response provided by AEMO are in the range 1s to 3s, which requires a minimum sampling rate of 250ms (considering three sampling points per half cycle). The proposed methodology to identify an oscillatory response works well with the given profiles provided by AEMO when using 100ms and 200ms sampling rates. On the other hand, further discussion may be required as to the suitability of specific values initially used for numerical assessment, such as a 50% oscillation ratio threshold.

Key recommendations from the analysis performed are as follows:

- The first recorded point method should be replaced with the "*RoCoF-based*" method when determining the initial starting time for the six-second Fast FCAS assessment window.
- Using lower sampling rates (e.g., 200ms) for response profiles of synchronous generators might introduce significant verification errors; therefore, the current 50ms sampling rate should be maintained to properly record the FCAS response from synchronous generators.
- Using actual local frequency instead of smoothed frequency to calculate compensation factor for DER response might avoid additional verification error introduced by lower sampling rates. However, more studies are needed to justify the appropriateness of using actual frequency in the existing calculation method of compensation factor when the aim is to properly scale up the response profile to avoid under-valuation of the provider's performance in the verification process.
- When verifying the response of a fleet distributed across multiple sites, if the trapezoid rule and RoCoF-based method are used, using NMI-level data with 200ms sampling rate can achieve a relatively good performance, for example, in the range [-1.3%, 0.2%] for the 200 sites with response equal to a maximum of 5kW FCAS enablement per site analysed in this report. It is worth noting, though, that this recommendation is derived based on the data provided by AEMO for the studies conducted here, and further studies would be required to be able to provide more definite recommendations.
- Relaxing the power measurement error from 2% to 4% might introduce significant verification error depending on the ratios of active power output allocation between FCAS response and other services.
- 1s sampling rate cannot be used for detecting oscillatory behaviour of FCAS response because the periods of the oscillatory responses that were analysed within the set provided by AEMO are much smaller than 4s (considering that four sampling points within one cycle are needed for oscillation detection), and are generally expected to be like this for all typical Fast FCAS responses of interest. The proposed oscillatory response identification methodology should be further refined with the support of stakeholders' feedback on the numerical values that should be used for key parameters, e.g., the oscillation threshold (currently set at 50%).

5 References

[1] Australian Energy Market Operator (AEMO), “Market Ancillary Service Specification v6.0,” 2020.

[2] P. Mancarella, L. Zhang, and H. Wang, “Fast FCAS Sampling Verification in Support of Market Ancillary Services Specification (MASS) consultation,” Melbourne, 2021.

[3] Australian Energy Market Operator (AEMO), “AEMO Virtual Power Plant Demonstrations Knowledge Sharing Report #2.” 2020.

[4] Australian Energy Market Operator (AEMO), “FCAS Verification Tool User Guide,” 2020.

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6 Appendix A: Verification errors of five assessment window methods

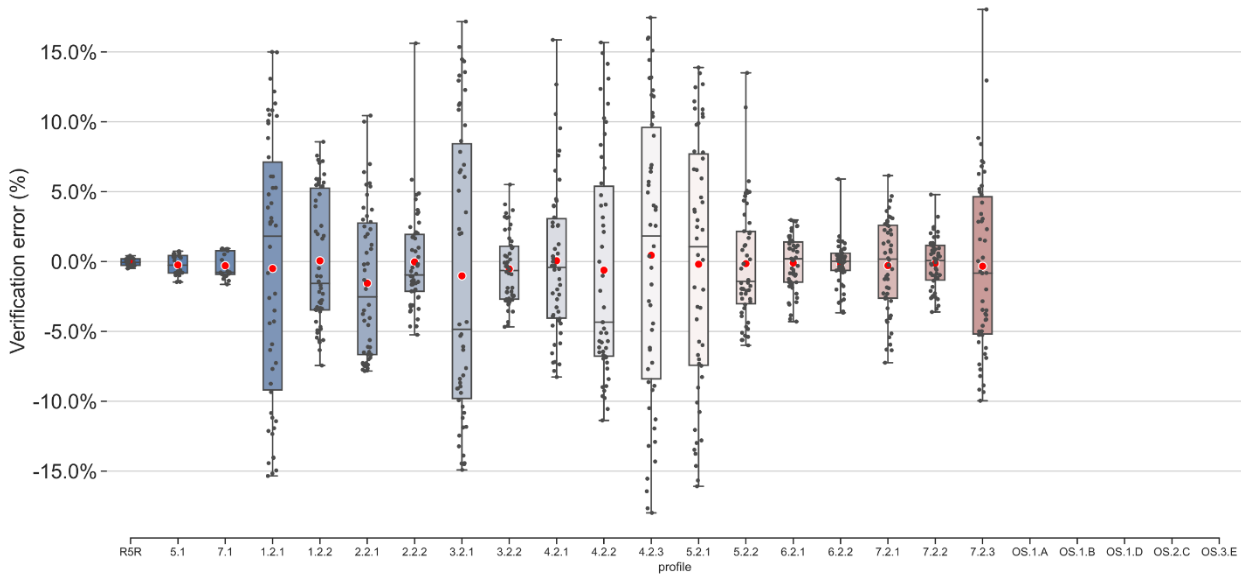

*Figure 6.1. Verification error of 30 profiles sampling at **1s** using **"universal window"** method and trapezoidal rule*

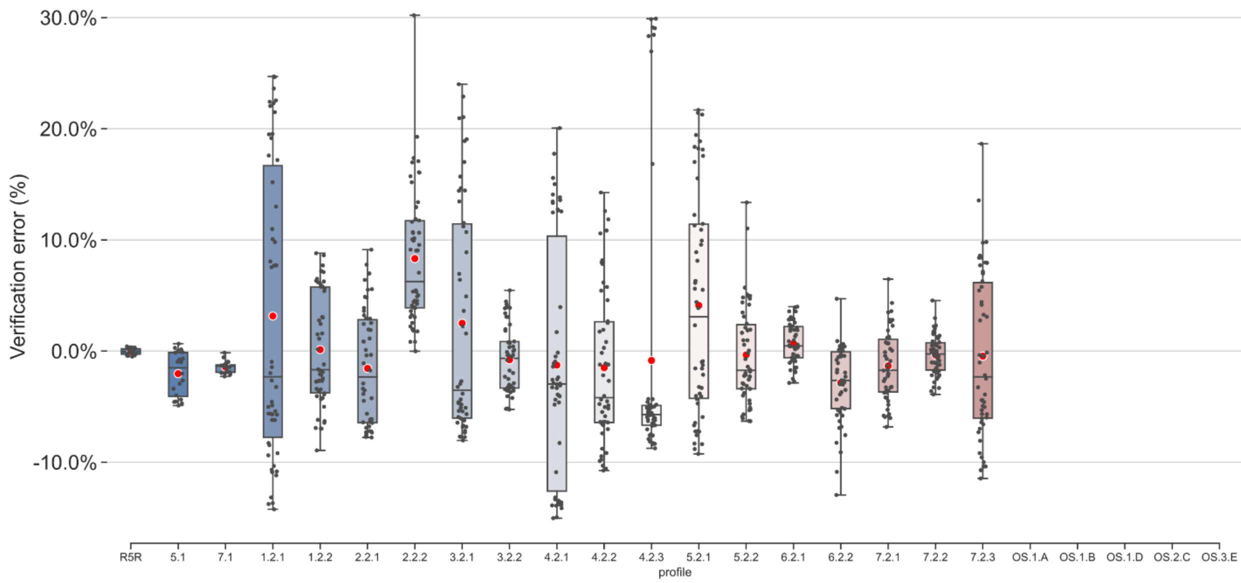

*Figure 6.2. Verification error of 30 profiles sampling at **1s** using **relative window "RoCoF-based"** method and trapezoidal rule*

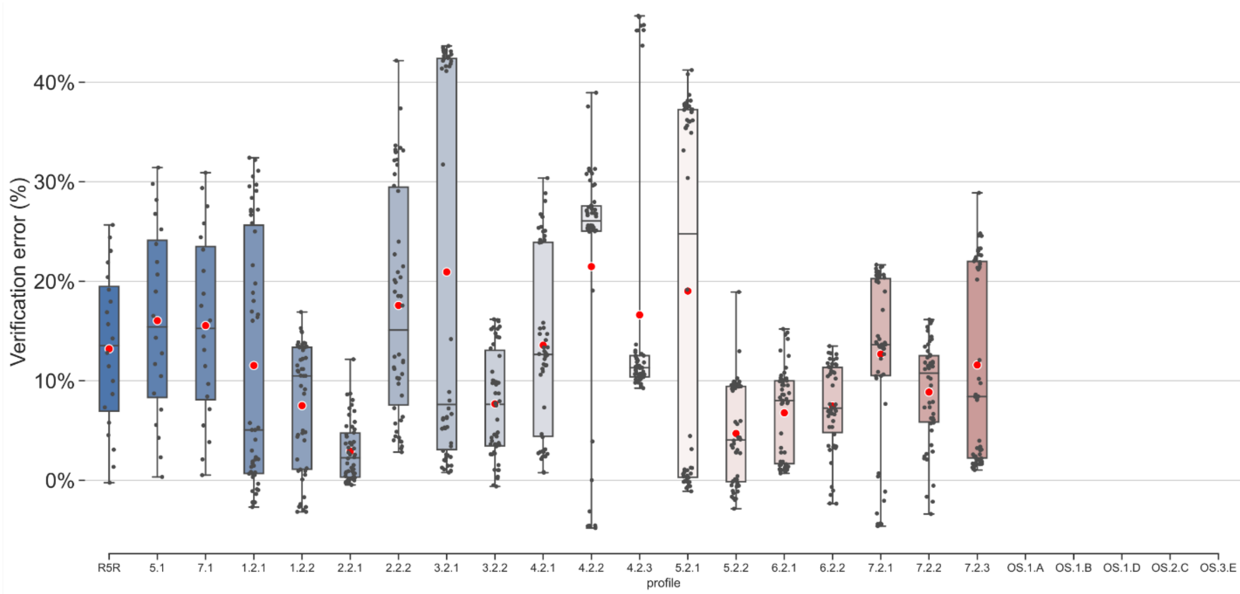

*Figure 6.3. Verification error of 30 profiles sampling at **1s** using **relative window "first recorded point"** method and trapezoidal rule*

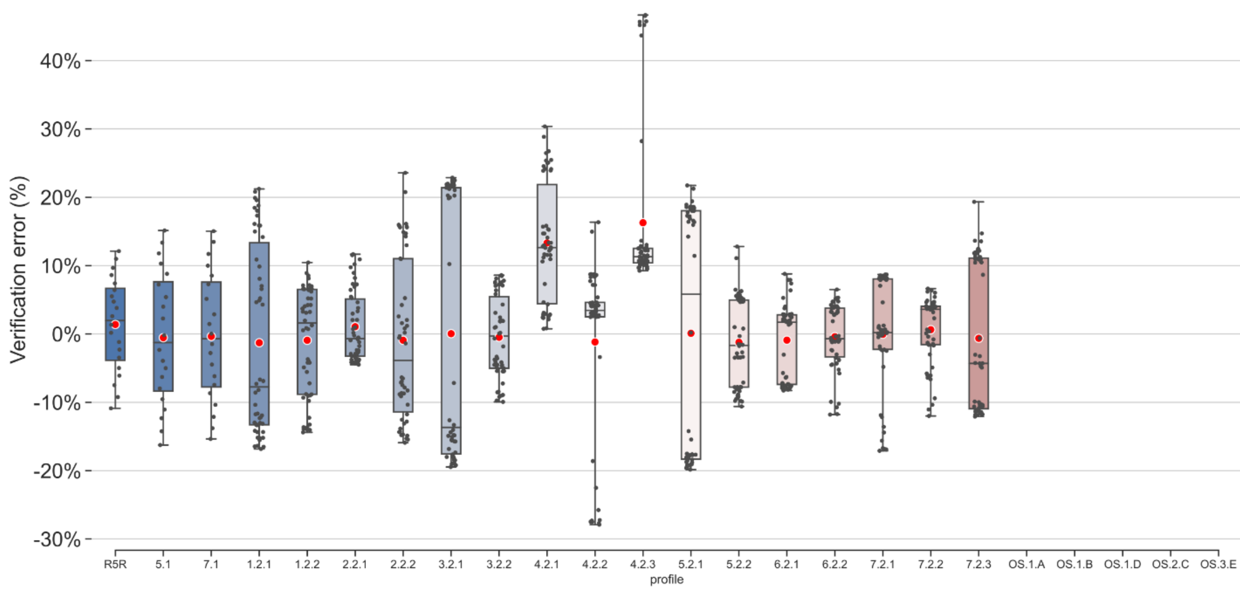

*Figure 6.4. Verification error of 30 profiles sampling at **1s** using **relative window "twin points"** method and trapezoidal rule*

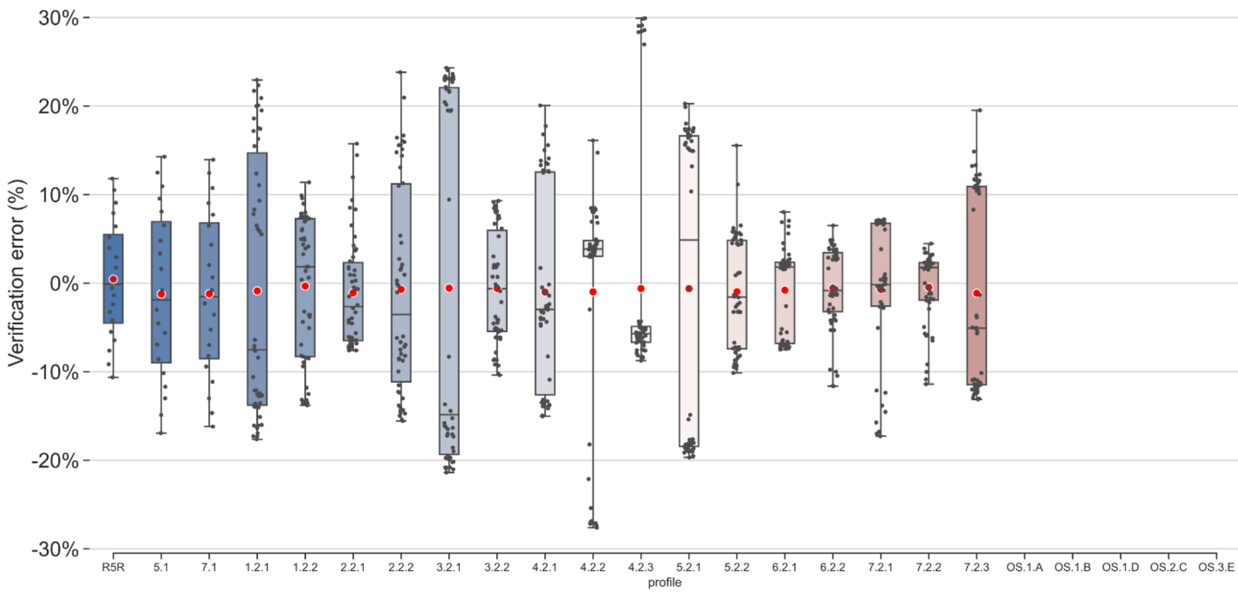

*Figure 6.5. Verification error of 30 profiles sampling at **1s** using **relative window "midpoint"** method and trapezoidal rule*

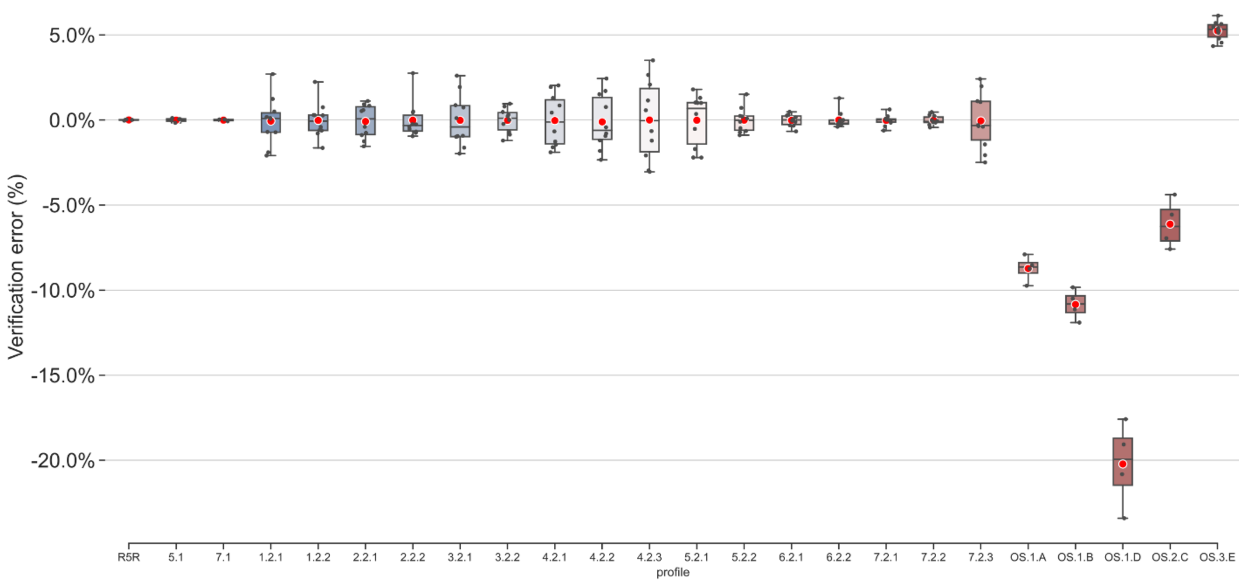

*Figure 6.6. Verification error of 30 profiles sampling at **200ms** using "**universal window"** method and trapezoidal rule*

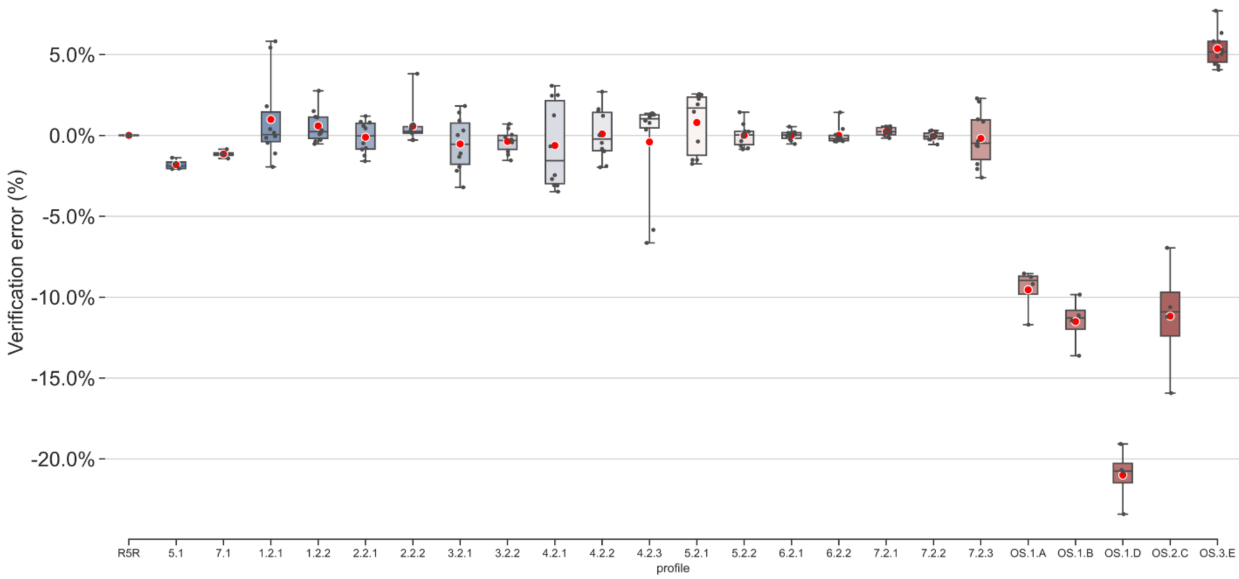

*Figure 6.7. Verification error of 30 profiles sampling at **200ms** using **relative window "RoCoF-based"** method and trapezoidal rule*

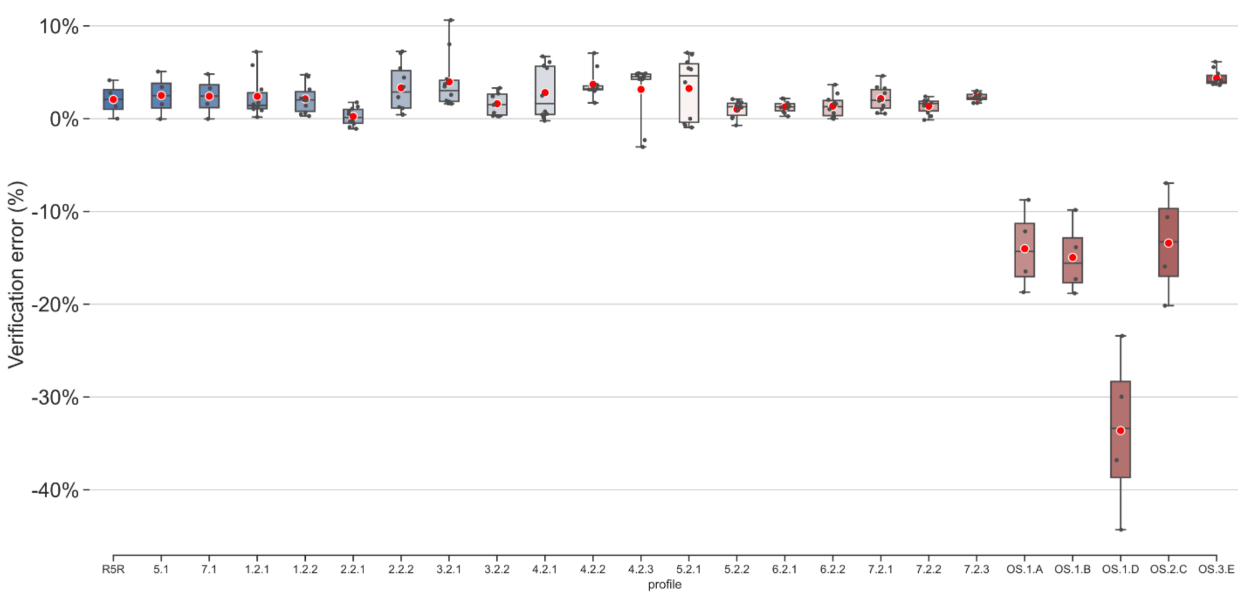

*Figure 6.8. Verification error of 30 profiles sampling at **200ms** using **relative window "first recorded point"** method and trapezoidal rule*

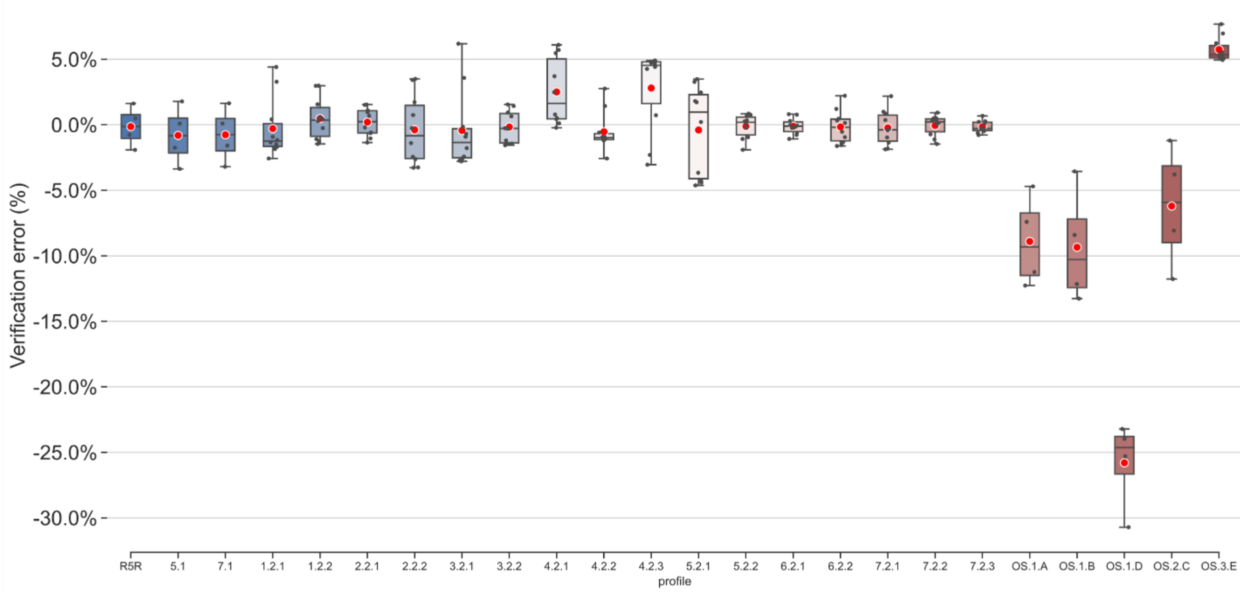

*Figure 6.9. Verification error of 30 profiles sampling at **200ms** using **relative window "twin points"** method and trapezoidal rule*

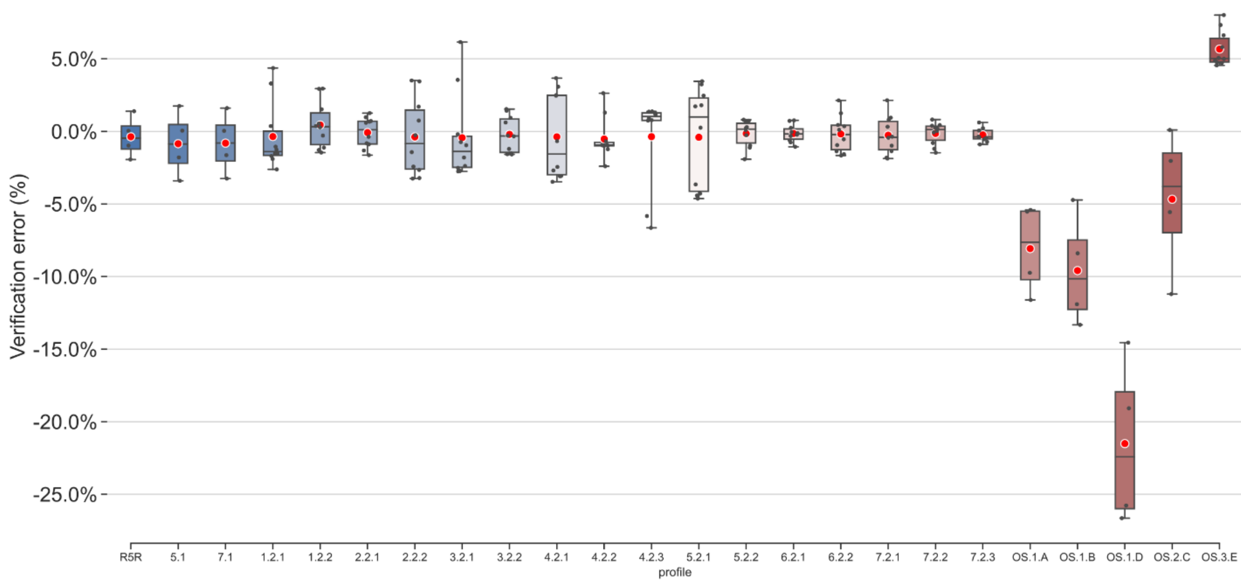

*Figure 6.10. Verification error of 30 profiles sampling at **200ms** using **relative window "midpoint"** method and trapezoidal rule*

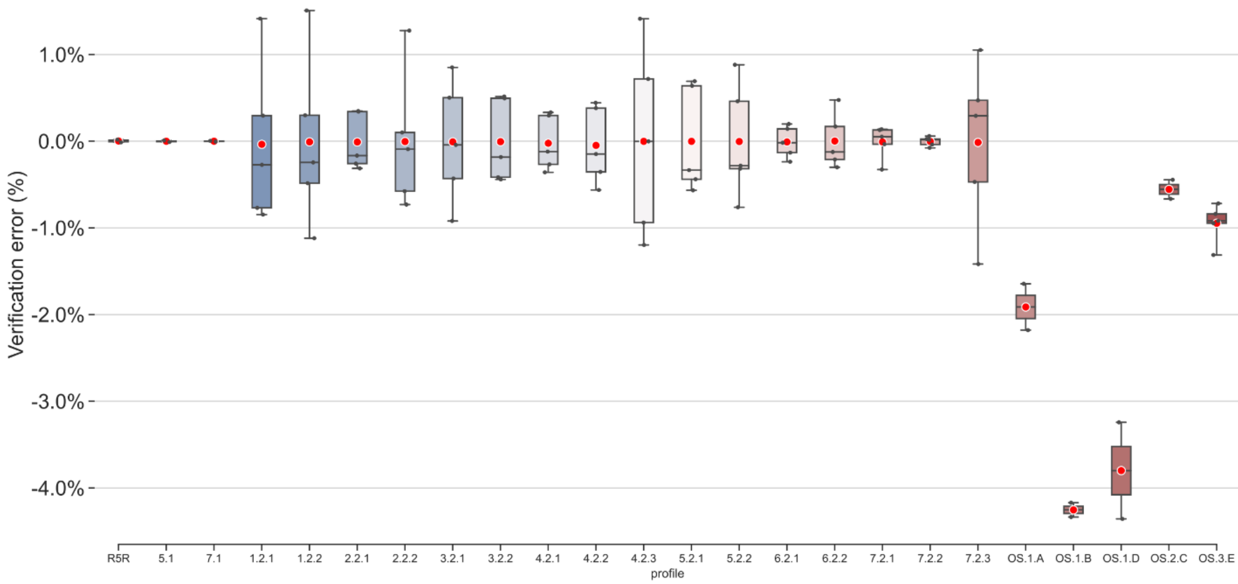

*Figure 6.11. Verification error of 30 profiles sampling at **100ms** using "**universal window"** method and trapezoidal rule*

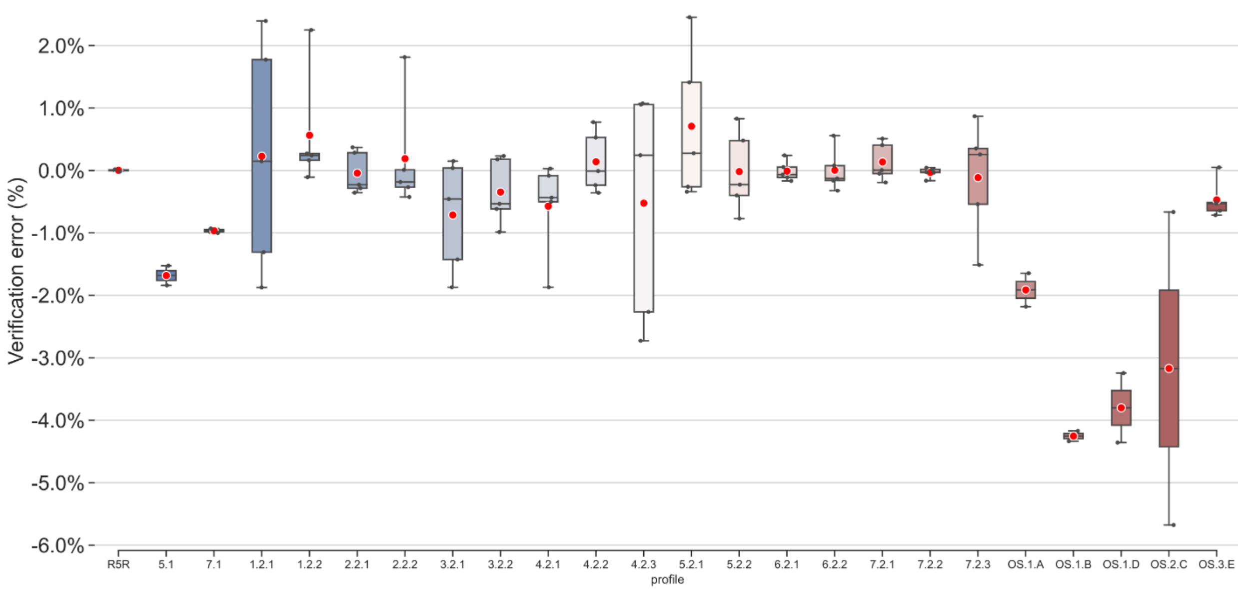

*Figure 6.12. Verification error of 30 profiles sampling at **100ms** using **relative window "RoCoF-based"** method and trapezoidal rule*

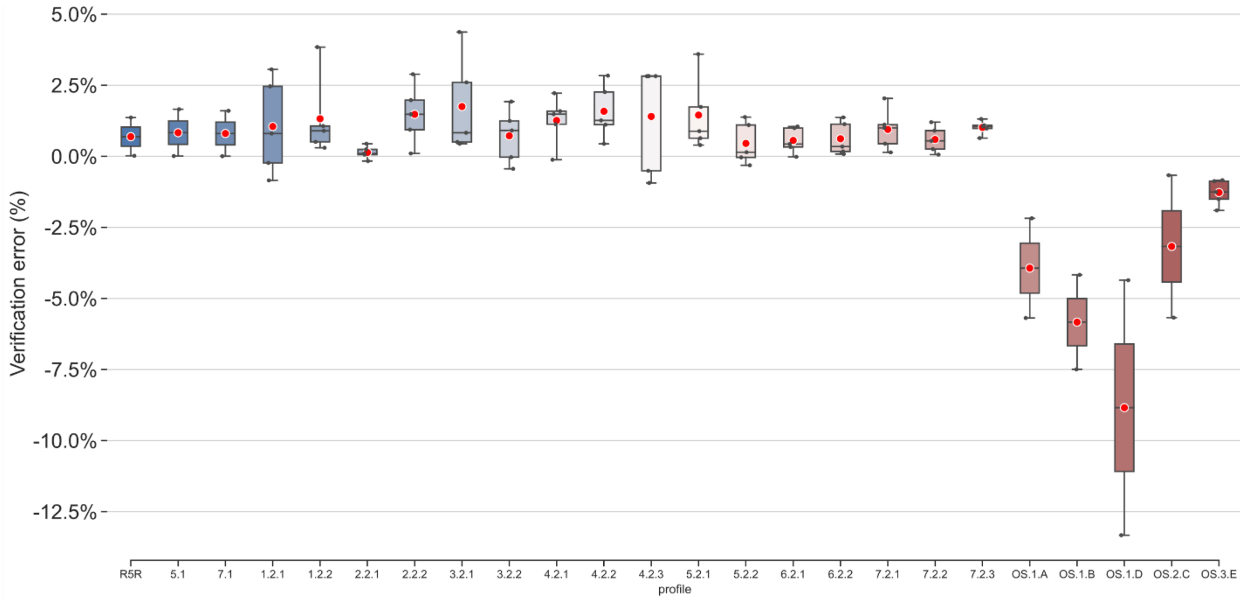

*Figure 6.13. Verification error of 30 profiles sampling at **100ms** using **relative window "first recorded point"** method and trapezoidal rule*

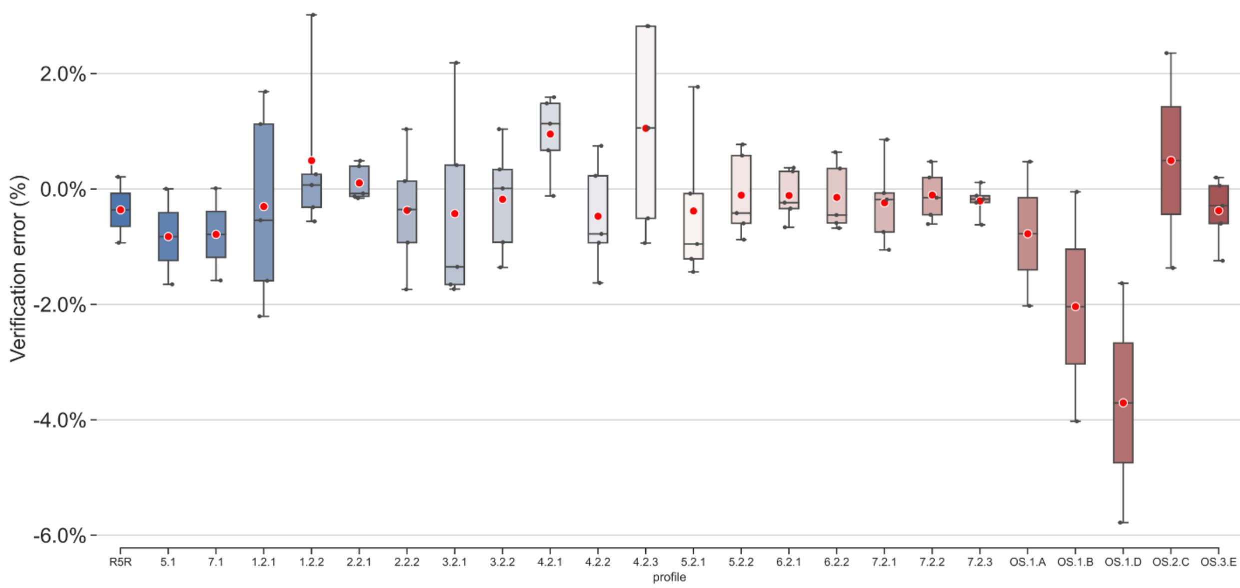

*Figure 6.14. Verification error of 30 profiles sampling at **100ms** using **relative window "twin points"** method and trapezoidal rule*

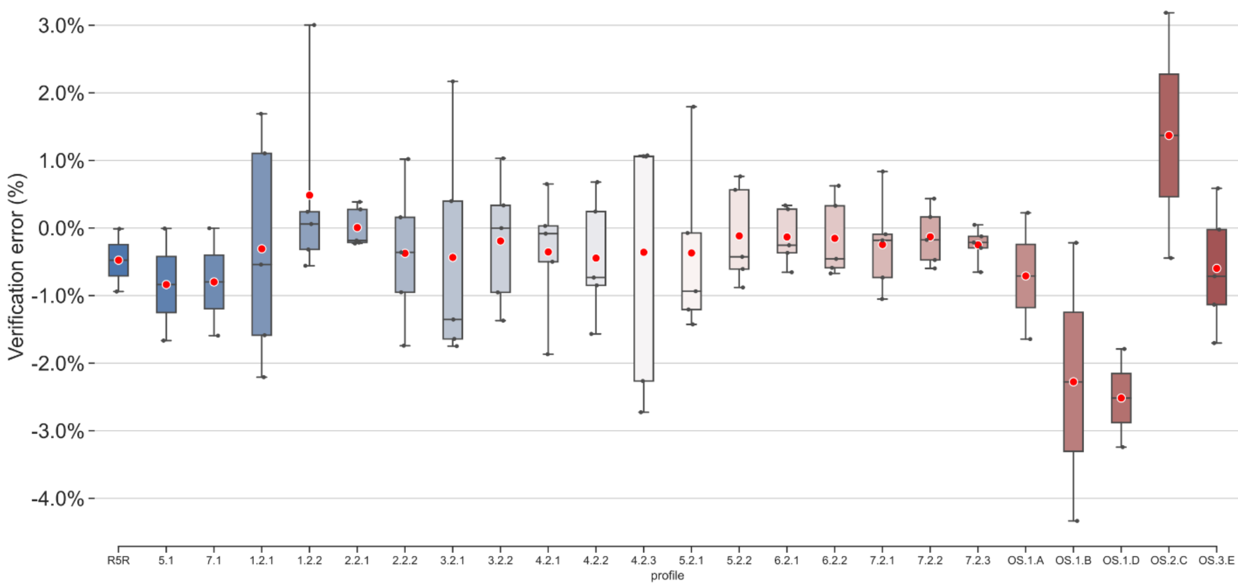

*Figure 6.15. Verification error of 30 profiles sampling at **100ms** using **relative window "midpoint"** method and trapezoidal rule*

7 Appendix B: Verification errors of site aggregation

Table 7.1. Maximum and minimum verification errors for different aggregation level and sampling rates with "universal window" method, NSW event.

No. of sites	100ms		200ms		1s	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	-3.9%	3.7%	-4.3%	4.3%	-14.2%	12.9%
10	-1.5%	1.2%	-1.8%	1.7%	-7.4%	4.2%
25	-1.1%	0.8%	-1.0%	0.8%	-5.0%	1.8%
50	-0.8%	0.4%	-1.1%	0.5%	-4.2%	1.0%
200	**-0.5%**	**0.2%**	**-0.4%**	**0.2%**	**-3.2%**	**-0.2%**
500	-0.3%	0.0%	-0.3%	0.0%	-2.5%	-1.3%
1000	-0.1%	-0.1%	-0.1%	-0.1%	-1.9%	-1.9%

Table 7.2. Maximum and minimum verification errors for different aggregation level and sampling rates with "first recorded point window" method, NSW event.

No. of sites	100ms		200ms		1s	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	-3.9%	3.7%	-4.3%	4.3%	-24.3%	12.0%
10	-1.5%	1.2%	-1.8%	1.7%	-17.6%	-2.9%
25	-1.1%	0.8%	-1.0%	0.8%	-17.4%	-4.9%
50	-0.8%	0.4%	-1.1%	0.5%	-13.5%	-5.8%
200	**-0.5%**	**0.2%**	**-0.4%**	**0.2%**	**-12.5%**	**-7.4%**
500	-0.3%	0.0%	-0.3%	0.0%	-10.6%	-8.5%
1000	-0.1%	-0.1%	-0.1%	-0.1%	-9.7%	-9.7%

Table 7.3. Maximum and minimum verification errors for different aggregation level and sampling rates with "RoCoF-based" method, NSW event.

No. of sites	100ms		200ms		1s	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	-3.9%	3.7%	-4.3%	4.3%	-11.1%	13.5%
10	-1.5%	1.2%	-1.8%	1.7%	-5.1%	5.5%
25	-1.1%	0.8%	-1.0%	0.8%	-3.1%	3.0%
50	-0.8%	0.4%	-1.1%	0.5%	-2.3%	2.2%
200	**-0.5%**	**0.2%**	**-0.4%**	**0.2%**	**-1.4%**	**1.3%**
500	-0.3%	0.0%	-0.3%	0.0%	-0.9%	0.2%
1000	-0.1%	-0.1%	-0.1%	-0.1%	-0.3%	-0.3%

Table 7.4. Maximum and minimum verification errors for different aggregation level and sampling rates with "universal window" method, QLD event.

No. of sites	100ms		200ms		1s	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	-4.0%	3.3%	-4.0%	3.4%	-5.1%	6.1%
10	-1.8%	1.4%	-1.8%	1.3%	-2.6%	1.5%
25	-1.4%	0.5%	-1.3%	0.5%	-2.0%	0.8%
50	-1.1%	0.2%	-1.1%	0.2%	-1.5%	0.2%
200	**-0.7%**	**-0.1%**	**-0.7%**	**-0.1%**	**-1.1%**	**-0.3%**
500	-0.6%	-0.3%	-0.6%	-0.2%	-1.0%	-0.5%
1000	-0.4%	-0.4%	-0.4%	-0.4%	-0.8%	-0.8%

Table 7.5. Maximum and minimum verification errors for different aggregation level and sampling rates with "first recorded point window" method, QLD event.

No. of sites	100ms		200ms		1s	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	-3.8%	4.5%	-3.7%	6.5%	-3.0%	15.6%
10	-1.2%	2.2%	-0.3%	3.2%	3.5%	10.4%
25	-0.8%	1.3%	0.0%	2.5%	5.1%	9.4%
50	-0.4%	1.0%	0.4%	2.1%	5.5%	9.1%
200	**0.1%**	**0.7%**	**1.0%**	**1.7%**	**6.6%**	**8.4%**
500	0.2%	0.5%	1.1%	1.5%	7.1%	7.9%
1000	0.3%	0.3%	1.3%	1.3%	7.5%	7.5%

Table 7.6. Maximum and minimum verification errors for different aggregation level and sampling rates with "RoCoF-based" method, QLD event.

No. of sites	100ms		200ms		1s	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	-4.4%	2.9%	-4.7%	2.8%	-10.8%	9.5%
10	-2.3%	1.0%	-2.4%	0.6%	-4.4%	4.2%
25	-1.9%	0.1%	-2.0%	-0.2%	-3.2%	2.0%
50	-1.6%	-0.3%	-1.7%	-0.4%	-2.2%	1.3%
200	**-1.2%**	**-0.6%**	**-1.3%**	**-0.7%**	**-1.2%**	**0.4%**
500	-1.1%	-0.7%	-1.2%	-0.9%	-1.0%	-0.1%
1000	-0.9%	-0.9%	-1.0%	-1.0%	-0.5%	-0.5%