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

Prepared for the Australian Energy Market Operator

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Executive Summary

The Australian Energy Market Operator (AEMO) has recently initiated a consultation to revise the Market Ancillary Service Specification (MASS). This consultation is focused on assessing the specification requirements for Distributed Energy Resources (DERs) to participate in Frequency Control Ancillary Services (FCAS) markets. The provision of FCAS from DERs has already been tested in the Virtual Power Plant (VPP) Demonstrations programme that is expected to end in June. AEMO is now exploring potential regulatory framework changes and required operational processes to ensure that DERs gain a fair access to FCAS markets. There are a few differences between the MASS and the specification used in the VPP Demonstration, particularly in terms of the sampling rate of power delivered and local frequency measures. MASS requires all providers to have 50ms or faster sampling rates, while the minimum sampling rate requirement in the VPP Demonstrations is 1s. A slower sampling rate may result in inaccurate verification of response performance and consequently affect the efficient operation of FCAS markets.

The University of Melbourne has been commissioned by AEMO to explore the impact of having a sampling rate lower than 50ms (e.g., 100ms, 200ms or 1s) for response performance verification and investigate different integrations rules in assessing the energy contribution in the fast service window. We have thus performed several studies examining 28 response profiles provided by AEMO, recorded in the FCAS registration tests and in actual contingency events. The first study analyses the relative errors of using different integration rules in calculating the energy delivered during the six second fast service window. It also computes the errors of the profiles with lower sampling rates in comparison with original 20ms/50ms ones when using the same integration rule. The second study performs a more detailed analysis to account for the error distribution when using low sampling rates (i.e., 200ms and 1s), considering the uncertainty in the assessment of the time lapse between the actual occurrence of a contingency and when the local frequency is sampled to get outside of the normal operating band.

Our studies overall suggest the following:

- The methodology that AEMO uses for FCAS validation and assessment is based on solid engineering and mathematical principles, and adjustments may be made to refine it further in light of the challenges that diverse and disperse DER providers may bring.
- The trapezoidal rule is far superior to simpler integration methods such as Riemann methods, while its performance is quite similar to other higher polynomial order methods, such as Simpson's rules and Boole's rule. This behaviour is consistent across sampling rates. Hence, it appears well suitable to be used in the standard assessment methodology.
- In terms of the energy delivery verification process, using 1s sampling rate may introduce noticeable overestimation errors relative to 20ms/50ms sampling rate. By increasing the sampling rate to 200ms, though, both the average error and the error distribution range may be reduced significantly, with a range of average errors decreasing from 15% to less than 3%.
- When using 1s sampling rate, local sampling of the time when the frequency exits the normal operating band – which is used to determine the 6s window for FCAS assessment – may create a consistent over-estimation of the energy delivered (with an average error of 15%) relative to the case of higher sampling rate (e.g., 50ms). To avoid such over-estimation, an alternative approach might be considered that deploys a "universal" rather than a local, "relative" assessment window. However, more analyses and discussion with stakeholders would be needed to understand the actual requirements for and potential value of such implementation.

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1 Introduction

AEMO launched a two-year Virtual Power Plant (VPP) Demonstration programme back in 2019. The programme aimed at exploring the feasibility of VPP participation in FCAS markets, particularly for the provision of fast raise and lower services. Two options of onsite data sampling rates (100ms and 1s) were given to the demonstration participants, with most opting for using 1s sampling rate. While the VPP Demonstration is coming to an end, AEMO has started a consultation on Market Ancillary Service Specification (MASS) to allow a proper integration of distributed energy resources (DERs) into FCAS markets. The existing MASS [1] requires that all fast service providers use at least 50ms sampling rate to record their performance, which is significantly higher than the 1s used in the VPP demos. AEMO is now exploring different options to smoothly transit from the VPP Demonstration project to business as usual while enabling FCAS participation from DERs and at the same time a level playing field assessment of their performance.

The objective of this project is to quantitatively analyse the potential errors of FCAS energy delivery measurement when using different sampling rates (i.e., 20ms, 50ms, 100ms, 200ms, and 1s) and different integration methodologies (i.e., Riemann methods, trapezoidal rule, etc.), as well as the impact of other factors (e.g., time lapse between a contingency and the first local sample) in calculating such energy delivery. The findings may then be used to inform the potential changes of MASS in the next review cycle.

2 Methodology

2.1 Numerical integration methods

In order to calculate the energy that is delivered during fast FCAS response, six numerical integration methods have been considered, including three non-polynomial options, i.e., left Riemann sum, right Riemann sum, and trapezoidal sum, and three polynomial options, i.e., Simpson's rule, Simpson's 3/8 rule, and Boole's rule. These methods are used to approximate the integral of a generic response $f(x)$ over an *assessment interval* $[0, n]$. We assume that there are $n+1$ sample points of the integrand $f(x)$ and they are equally spaced (in this case temporally), with a distance h (the sampling interval) between two successive sampling points/times equal to $x_{i+1} - x_i = h$.

Riemann sums are the simplest methods of approximating integrals by summing the areas of rectangles that are suitably defined for each subinterval. Left Riemann sum approximates the area using rectangles whose height is the function value at the left endpoint of the sampling interval, while right Riemann sum considers the right endpoint. An illustration of the two Riemann sum methodologies is shown in Figure 1. In the example, to approximate the integral between $[x_0, x_1]$, the left Riemann method calculates the area of the rectangle that has a height of $f(x_0)$, while the right Riemann sum calculates the area of the rectangle that has a height of $f(x_1)$.

$$Left\ Riemann\ sum = \sum_{i=0}^{n-1} f(x_i)$$

$$Right\ Riemann\ sum = \sum_{i=1}^{n} f(x_i)$$

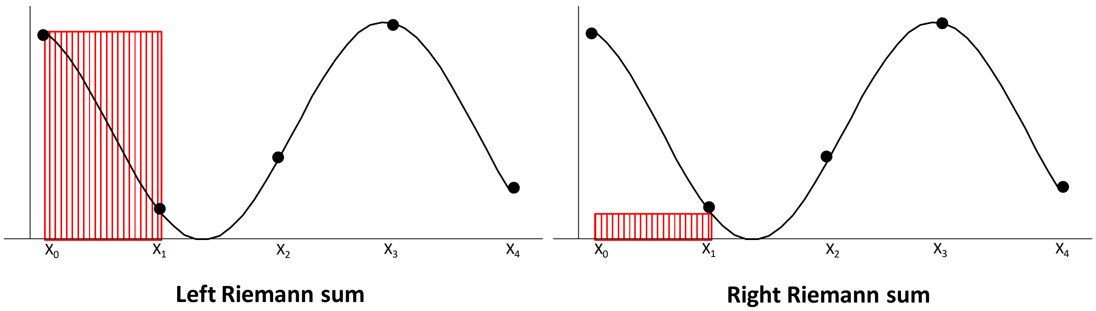

Figure 1. Illustration of left Riemann sum and right Riemann sum.

The **trapezoidal rule** approximates the integral by fitting a trapezoid into each sampling interval and then calculating the total area of the resulting trapezoids. An illustration of the trapezoidal rule is provided in Figure 2. The trapezoidal sum can be calculated as:

$$Trapezoidal\ sum = \frac{h}{2}\left[f(x_0) + 2\sum_{i=1}^{n-1} f(x_i) + f(x_n)\right]$$

Simpson's rule calculates the integral approximation by fitting a quadratic polynomial across three points of two consecutive subintervals, e.g., $\left(x_{i-1}, f(x_{i-1})\right), \left(x_i, f(x_i)\right)$ and $\left(x_{i+1}, f(x_{i+1})\right)$. An illustration of using Simpson's rule (also called Simpson's 1/3 rule) to calculate the integral between $[x_0, x_1]$ is provided in Figure 2:

$$Simpson's\ rule = \frac{h}{3}\left[f(x_0) + 4\sum_{i=1, i\in odd}^{n-1} f(x_i) + 2\sum_{i=2, i\in even}^{n-2} f(x_i) + f(x_n)\right]$$

Simpson's 3/8 rule approximates an area by fitting a cubic polynomial across four points of three consecutive subintervals, as shown in Figure 2:

$$Simpson's\ 3/8\ rule = \frac{3h}{8}\left[f(x_0) + 3\sum_{i=1,4,7,\dots}^{n-2} f(x_i) + 3\sum_{i=2,5,8,\dots}^{n-1} f(x_i) + 2\sum_{i=3,6,9,\dots}^{n-3} f(x_i) + f(x_n)\right]$$

Finally, considering four consecutive subintervals, **Boole's rule** creates a fit of a polynomial of 4th degree across the relevant five points (as shown in Figure 2).

$$Boole's\ rule = \frac{2h}{45}\left\{7[f(x_0) + f(x_n)] + 32\sum_{i=1,3,5,,\dots}^{n-1} f(x_i) + 12\sum_{i=2,6,10,\dots}^{n-2} f(x_i) + 14\sum_{i=4,8,12,,\dots}^{n-4} f(x_i)\right\}$$

The Riemann sums, trapezoidal rule, Simpson's rule, Simpson's 3/8 rule, and Boole's rule are all approximations, thus some errors occur. The error bounds of the area estimates for different methods decrease with different powers of h while the size of h decreases. The accuracy of both Riemann sums is of order $O(h)$, while the trapezoidal rule accuracy is $O(h^2)$. Both Simpson's 1/3 rule and Simpson's 3/8 rule have $O(h^4)$ accuracy, with Simpson's 3/8 rule being about twice as accurate as of the 1/3 rule. Finally, Boole's rule has an accuracy that is $O(h^5)$.

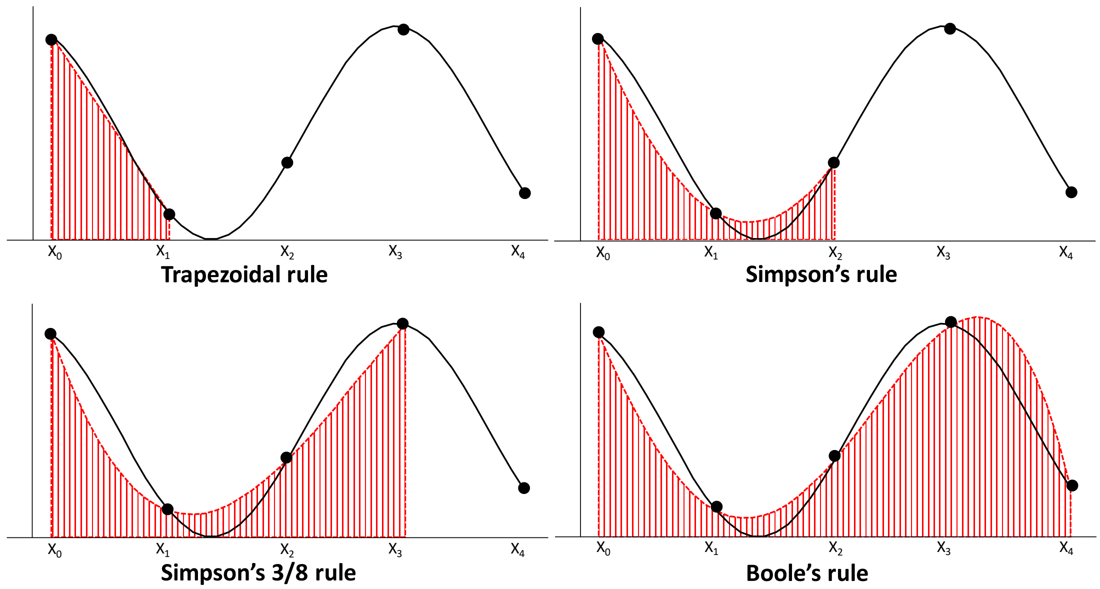

Figure 2. Illustration of trapezoidal rule, Simpson's rule, Simpson's 3/8 rule, and Boole's rule.

2.2 FCAS verification

2.2.1 Verification tool methodology

FCAS providers are required to set up relevant facilities to continuously monitor and record their output power and the local frequency at connection points. In the occurrence of contingency events, such profiles may be requested by AEMO *ex post* to verify the provider's performance against its registered capacity in the market. The verification process follows a standard methodology published by AEMO which separates FCAS response from the output power profile [2]. A flowchart that summarises this verification methodology is shown in Figure 3, with the calculation following these steps:

1) The profile firstly excludes the reference trajectory which is determined by dispatch order from the system operator if the provider is a scheduled or semi-scheduled unit.
2) Then, when relevant, the inertial response is subtracted from the profile to derive a profile called "adjusted power measurement".
3) A baseline point is calculated by taking the time-averaged value of the profile from 20 to 8 seconds before the contingency event time[1].
4) By taking the adjusted power measurement and subtracting the baseline, a basic response profile is derived.
5) A scaling factor is calculated based on the type of provider's controller (i.e., switching, variable). The basic response profile is then multiplied by this scaling factor to derive adjusted response profile.
6) The adjusted response profile is split into two parts, namely, from 0 to 6 seconds and from 6 to 60 seconds after the frequency disturbance time[2]. The minimum value of the twice average of

[1] Where the initial frequency change that led to a Frequency Disturbance is clearly apparent, by way of there being a single rapid and significant change in frequency, the starting point of that frequency change will be used as the Contingency Event Time [1].

[2] Frequency disturbance time is the time at which local Frequency crosses the normal operating frequency band (NOFB) during a Frequency Disturbance, referenced to Australian Eastern Standard Time [2].

these two profiles is used as the FCAS delivery capacity of the provider for the specific contingency event considered.

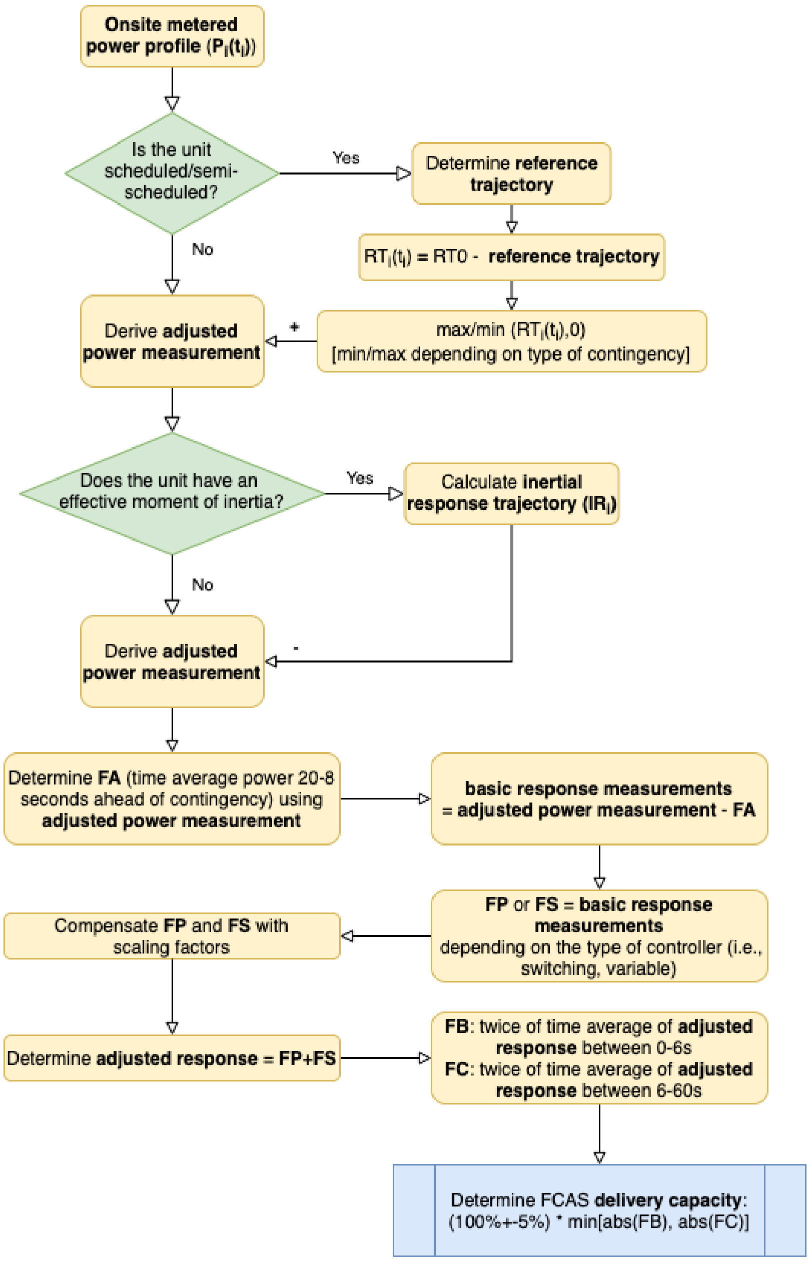

Figure 3. fast FCAS performance verification methodology (summarised from [2]*).*

In the studies performed below, the following considerations and assumptions apply:

- The response profiles analysed are from relatively small batteries and VPPs (which may include batteries) and are not considered to be scheduled or semi-scheduled units in National Electricity Market (NEM).
- Batteries and VPPs are assumed to have no inertial response capabilities.
- The scaling factors mentioned in step (5), which are used to compensate for basic response measurements, are ignored. 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 relative errors of energy contribution during FCAS response.

- Due to data availability, the baseline point described in step (3) is calculated as the average power of the profile between 3 and 0 seconds before the frequency disturbance time instead of using the profile between 20 to 8 seconds.

2.2.2 Assessment window methodology

As shown in the last two blocks of Figure 3, the FCAS delivery capacity calculation of each provider is based on twice the time-averaged response profile between 0 and 6 seconds following the frequency disturbance time. This **frequency disturbance time**, which is the start of this 6s window, is determined by the measurement of *local* frequency when it falls or rises outside the normal operating frequency band (NOFB) (i.e., +- 0.15 Hz). However, using different sampling rates for the local frequency to determine the frequency disturbance time may introduce potential ambiguity in terms of assessment of the energy actually delivered.

For example, let us assume that there are two providers at the same location and with the identical physical response – as determined by relevant resource capability, controller, inverter setting, etc. – but with different sampling rates equal to 50ms and 1s, respectively. Assuming the local frequency breached the NOFB at 3.6s, the provider with 50ms sampling rate can quickly (basically instantaneously, for the purposes of our comparison) record the frequency drop when it just crossed NOFB. In this case, the actual assessment window for the provider with 50ms sampling rate will thus essentially be the time interval 3.6-9.6s and result in a very good accuracy in terms of energy delivery assessment, as shown in Figure 4.

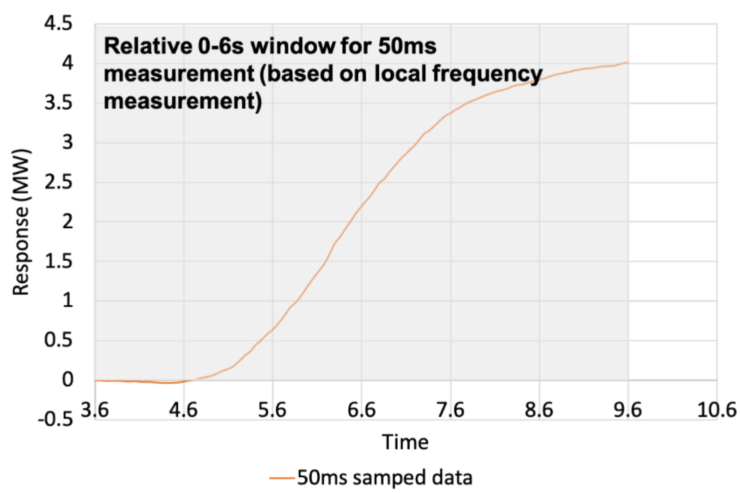

Figure 4. Response profile and relative assessment window for a provider with a sampling rate of 50ms.

For the other provider with a sampling rate of 1s, however, it might be that the sampling has just happened right before the frequency exits the NOFB. The first sampling recording the frequency being outside the NOFB might thus occur much later, up to close to 1s delay in the limit case. For example, if the sampling has occurred at 3.5s and the frequency exits the NOFB at 3.6s, the provider may only sample the frequency excursions at 4.5s. Hence, the 6s assessment window for verification purposes will be 4.5s-10.5s, as shown in Figure 5. However, we also assumed that the actual *physical* responses of the providers were exactly the same. In fact, the inverter's frequency measurement rate, based on which the actual frequency response is provided, may be much smaller (i.e., 50ms) than the sampling rate of 1s (which is used for response recording and response assessment purposes).

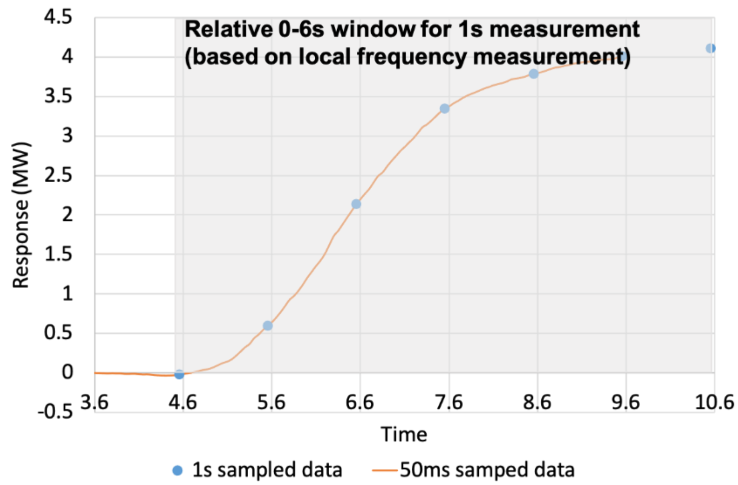

Figure 5. Response profile and relative assessment window for a provider with a sampling rate of 1s.

For the sake of clarity, we will call this 6s window determination methodology that is based on *local* frequency sampling the *"relative"* assessment window.

Figure 6 shows, for the case of the two providers of the above example (which use 50ms and 1s sampling rate, respectively), the two response profiles that would be applied to AEMO's verification tool if the relative time window is adopted. For the 1s sampling rate, this would result in a higher estimated energy contribution than what is actually provided within 6s after the local frequency crossing NOFB (taken as the actual reference time associated with the contingency occurrence). Assessing FCAS delivery based on such a *relative* time window, where the assessment window is defined based on local contingency measurement, would then lead to positive errors (over-estimation). As will be discussed more below, this happens regardless of the integration methodology uses and across all integration methodologies. This is in fact fundamentally due to the energy content difference between 50ms and 1s profiles, which is shown as the shadowed area in Figure 6.

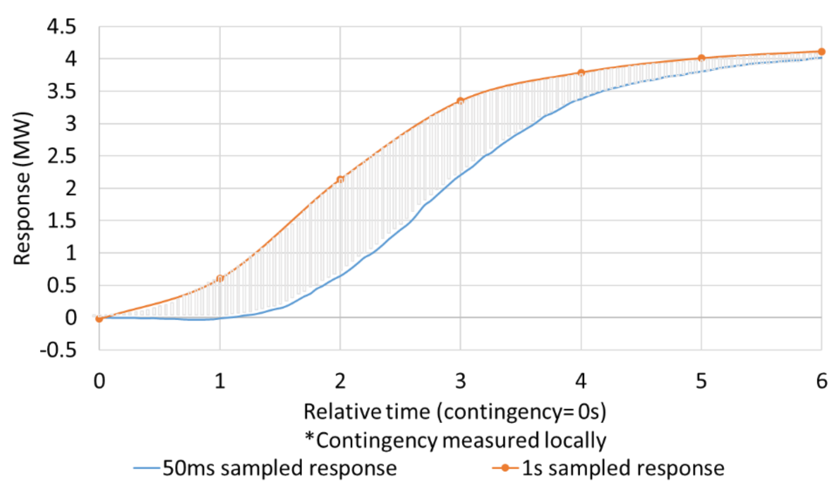

Figure 6. Response profile applied in AEMO verification tool with relative window methodology and high and low sampling rates.

In principle, another methodology to determine the assessment time window could also be considered, which we will refer to as the *"universal"* assessment window (as opposed to *relative*). This assumes that the frequency disturbance time window for all providers in each event is universally the same and does not depend on the local frequency sampling data recorded by each provider. In this case, two providers with respectively 1s and 50ms sampling rate would both be assessed across the 3.6s-9.6s window, as depicted in Figure 7, regardless of when the frequency excursion is locally recorded (namely, at 4.5s for the 1s sampling provider and right after the actual frequency excursion time for the 50ms sampling provider).

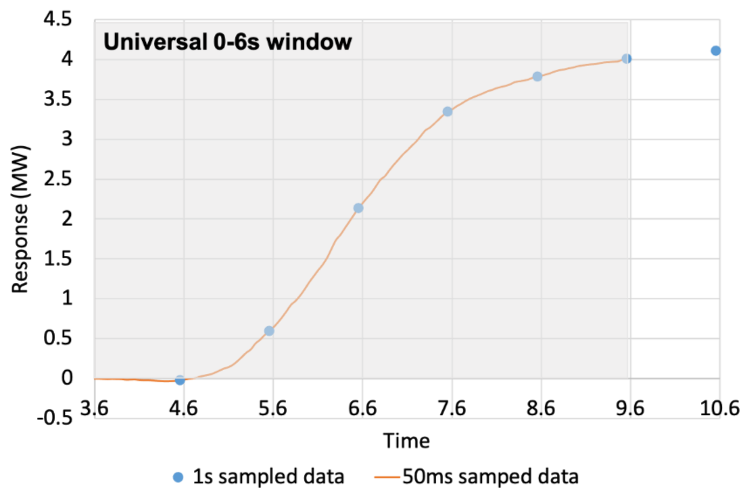

Figure 7. Response profiles and universal assessment window for two providers with a sampling rate of 1s and 50ms.

To summarise the definition of the two methodologies considered:

- **Relative window**: the start point of the assessment window is determined by the first point sampled by the provider when the local frequency crosses NOFB;
- **Universal window**: 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 each provider.

It needs to be acknowledged that the universal window method considered here is for *reference purposes*. In practice, the actual implementation of such a universal window mechanism requires further analysis to identify what procedures, requirements and possibly additional facilities would be needed to gather relevant data (e.g., to ensure timestamp synchronisation across various providers and with respect to a reference frequency disturbance identification that might be carried out by AEMO, for instance).

In the studies below, the two window assessment methodologies presented are applied to a number of real response cases in addition to the evaluation of the performance of different integration methods.

3 Case studies

In the case studies considered, four typical events and responses from two different providers are analysed:

- Registration lower FCAS response from provider 1 DUID 1;
- Event 7 raise FCAS response from provider 1 DUID 1;

- Event 7 raise FCAS response from provider 1 DUID 1, with superimposed alternate signal[3];
- Event 1 raise FCAS response from provider 2 DUID 1.

The performances of six integration methods are compared when using universal and relative windows. Furthermore, sensitive studies with different sampling rates are carried out by examining 28 response profiles across various events which are provided by AEMO.

3.1 Provider response in registration events and contingency events

The provider's responses in the registration event are shown in Figure 8 while the responses in different contingency events are shown in Figure 9-Figure 11. More specifically, the metered power output from the provider and the associated local frequency are shown from 3s before the contingency to 12s after contingency, for all four profiles.

It can be seen that provider 1 DUID 1 has a linear ramp response (see Figure 8 and Figure 10), while provider 2 DUID 1 has a step change response (see Figure 9). The response shown in Figure 11 is generated by superimposing an alternate (sinusoidal) profile to the response profile of provider 1 DUID 1 in Event 7. This sinusoidal function has a period value of 0.6s and a magnitude of 30% of the original response profile.

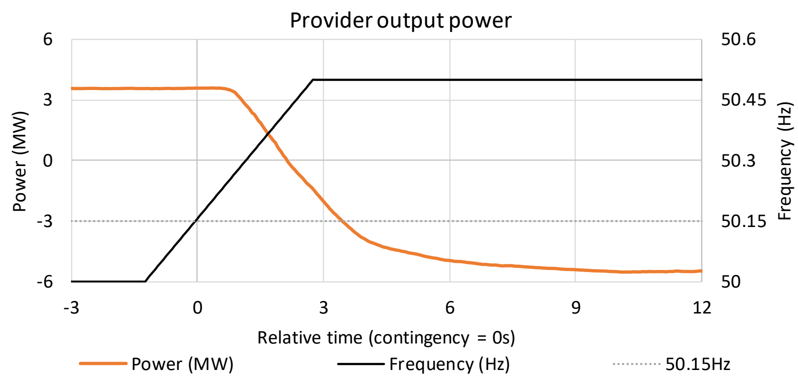

Figure 8. Registration event, Provider 1 DUID 1 lower FCAS response, 50ms sampling rate.

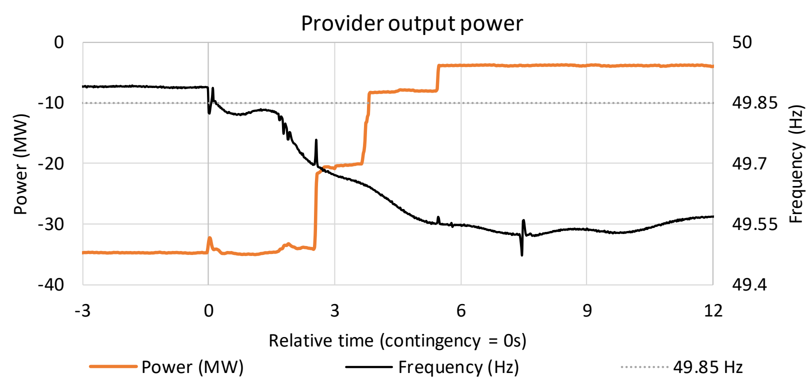

Figure 9. Event 1, Provider 2 DUID1 raise FCAS response, 20ms sampling rate.

[3] This profile was artificially created to "stress-test" the different integration methods and sampling rates against an otherwise linear response, and could correspond to responses that might be seen in less diverse aggregates of inverter-based providers.

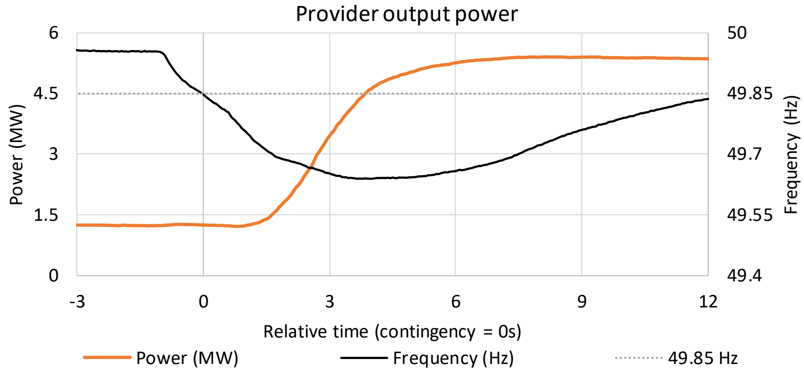

Figure 10. Event 7, provider 1 DUID 1 raise FCAS response, 50ms sampling rate.

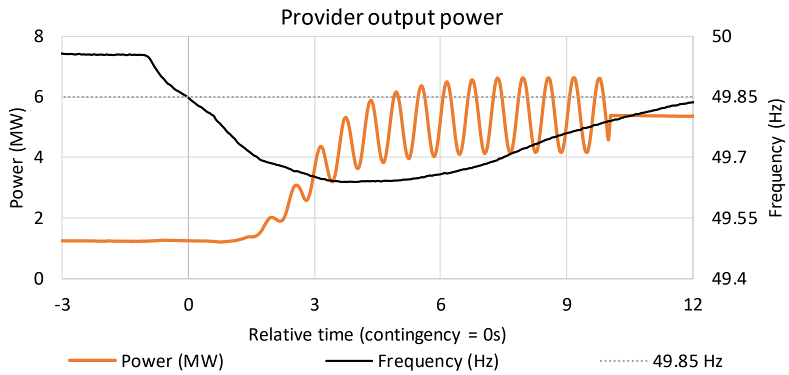

Figure 11. Event 7, provider 1 DUID 1 raise FCAS response with superimposed alternate signal, 50ms sampling rate

3.2 Sensitivity studies with integration methods

Sensitivity studies with six integration methods are carried out to assess their performance for different sampling rates. As baseline, the highest sampling rate (e.g., 50ms for provider 1 and 20ms for provider 2) is used and is calculated based on Boole's rule (that is theoretically the most accurate, particularly for small sampling intervals, as discussed above). The results of each integration method are then compared to the baseline and the resulting error is calculated as the difference between the calculated value and the baseline, in percentage of the baseline.

The comparison of six integration methods with the use of the relative assessment window is illustrated in Figure 12-Figure 15. The calculated FCAS energy delivery is measured in Megawatt-seconds (MWs) and the relevant values are shown, for different integration methods and sampling rates, on the left table of each figure. Furthermore, the errors of the calculated FCAS energy delivery compared with the baseline is shown on the right subfigure of each figure.

It can be seen that significant errors may be observed for all calculations with 1s sampling rate, for all events. This is mainly due to the assessment window approach which leads to actual different window start times for different sampling rates, as illustrated in the examples in Section 2.2.2 and with reference to Figure 6. In particular, in the case of step-change response, i.e., event 1 provider 2 raise response, the errors of the trapezoidal rule, Simpson's rule, Simpson's 3/8, and Boole's rule are significant, up to 45%, as shown in Figure 15.

Reg 1 Provider 1 Lower, 0-6s response				
MWs	50ms	100ms	200ms	1s
Left Riemann	-28.82	-28.60	-29.02	-30.64
Right Riemann	-29.25	-29.46	-30.74	-39.29
Trapezoid rule	-29.04	-29.03	-29.88	-34.97
Simpson's rule	-29.04	-29.03	-29.88	-35.15
Simpson's 3/8 rule	-29.04	-29.03	-29.88	-35.06
Boole's rule	-29.04	-29.03	-29.88	-35.15

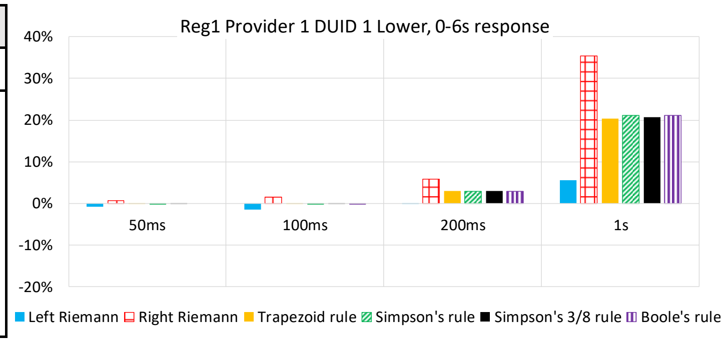

Figure 12. Comparison of different integration methods for registration event provider 1 lower FCAS response, with relative window.

Event 7 Provider 1, 0-6s response				
MWs	50ms	100ms	200ms	1s
Left Riemann	11.89	11.80	11.60	11.56
Right Riemann	12.10	12.20	12.40	15.63
Trapezoid rule	12.00	12.00	12.00	13.60
Simpson's rule	11.99	12.00	12.00	13.57
Simpson's 3/8 rule	11.99	12.00	12.00	13.51
Boole's rule	11.99	12.00	12.00	13.58

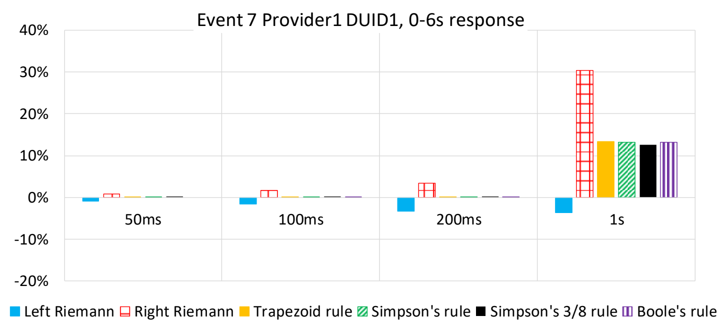

Figure 13. Comparison of different integration methods for event 7 provider 1 raise FCAS response, with relative window.

Event 7 Provider 1 oscillation profile, 0-6s response				
MWs	50ms	100ms	200ms	1s
Left Riemann	11.76	11.67	11.51	11.82
Right Riemann	11.96	12.08	12.31	14.86
Trapezoid rule	11.86	11.88	11.91	13.34
Simpson's rule	11.86	11.86	11.84	12.93
Simpson's 3/8 rule	11.86	11.86	11.83	13.71
Boole's rule	11.86	11.87	11.86	12.84

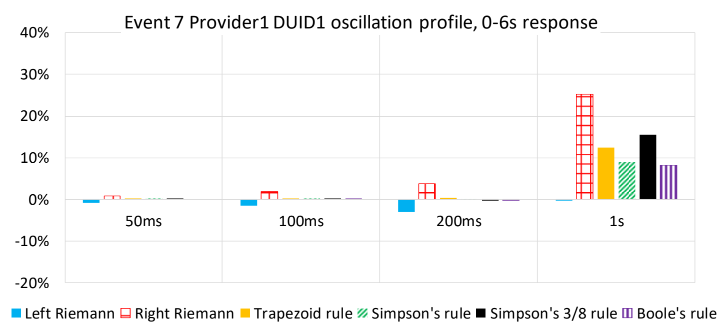

Figure 14. Comparison of different integration methods for event 7 provider 1 raise FCAS response with superimposed alternate signal, with relative window.

Event 1 Provider 2 DUID 1, 0-6s response				
MWs	50ms	100ms	200ms	1s
Left Riemann	80.00	78.66	85.52	99.40
Right Riemann	80.58	81.57	91.72	130.59
Trapezoid rule	80.29	80.11	88.62	114.99
Simpson's rule	80.31	79.96	87.75	115.91
Simpson's 3/8 rule	80.30	80.14	88.09	113.70
Boole's rule	80.32	79.89	87.51	115.93

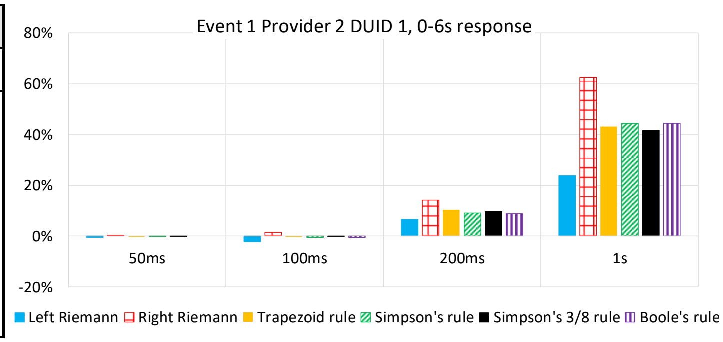

Figure 15. Comparison of different integration methods for event 1 provider 2 raise FCAS response, with relative window.

The comparison of the six integration methods with a universal assessment window is illustrated in Figure 16-Figure 19. Again, the calculated FCAS delivery (in MWs) for different integration methods and sampling rates is shown on the left of each figure, while the errors of the calculated FCAS delivery compared with the baseline are shown on the right of each figure. The error of each integration method is again calculated with respect to the baseline (Boole's rule, 20ms/50ms sampling rate). It can be seen that in all cases a decreasing sampling rate causes an increase in the error, for all integration methods. This is again because a lower sampling rate fails to capture the full behaviour of the response, and it is particularly obvious in event 7 provider 1 raise FCAS response with alternate signals (Figure 18) and event 1 provider 2 with step change responses (Figure 19). However, when the sampling rate is equal to or higher than 200ms, the errors that are obtained from the trapezoidal rule, Simpson's rule, Simpson's 3/8 rule and Boole's rule are minor for all events. Trapezoidal rule, Simpson's rule, Simpson's 3/8 rule, and Boole's rule exhibit similar performance under all cases. The performance of trapezoidal rule, Simpson's rule, Simpson's 3/8 rule and Boole's rule do also appear adequate even with 1s sampling rate, except for the response with superimposed alternate signal (Figure 11) and step-change response (Figure 9). On the other hand, the Riemann sum (left and right) methodologies exhibit the worst performance among the six integration methods and their error may be very significant for a lower sampling rate.

Reg1 Provider 1 DUID 1 Lower, 0-6s response				
MWs	50ms	100ms	200ms	1s
Left Riemann	-28.82	-28.60	-28.17	-24.75
Right Riemann	-29.25	-29.46	-29.87	-33.15
Trapezoid rule	-29.04	-29.03	-29.02	-28.95
Simpson's rule	-29.04	-29.03	-29.02	-29.12
Simpson's 3/8 rule	-29.04	-29.03	-29.02	-29.05
Boole's rule	-29.04	-29.03	-29.02	-29.12

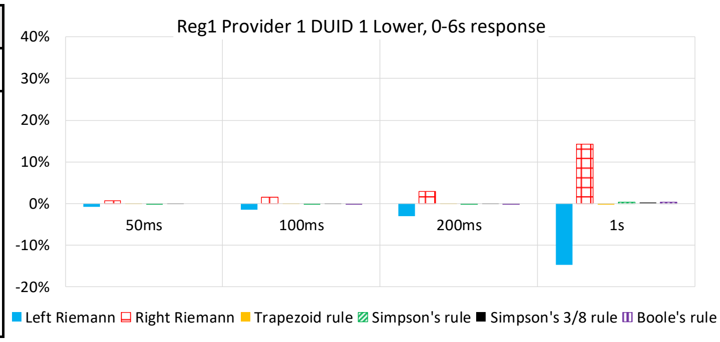

Figure 16. Comparison of different integration methods for registration event provider 1 lower FCAS response, with universal window.

Event 7 Provider1, 0-6s response				
MWs	50ms	100ms	200ms	1s
Left Riemann	11.89	11.80	11.60	9.99
Right Riemann	12.10	12.20	12.40	13.91
Trapezoid rule	12.00	12.00	12.00	11.95
Simpson's rule	11.99	12.00	12.00	11.91
Simpson's 3/8 rule	11.99	12.00	12.00	11.86
Boole's rule	11.99	12.00	12.00	11.93

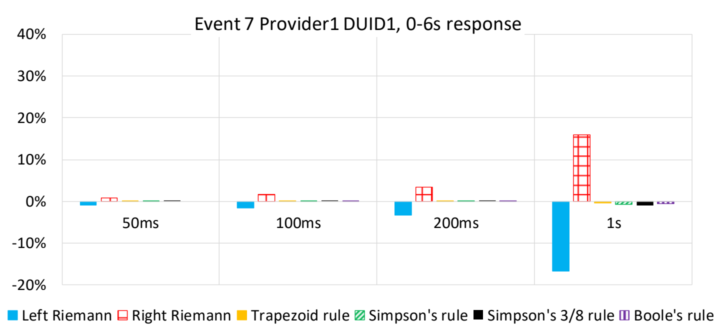

Figure 17. Comparison of different integration methods for event 7 provider 1 raise FCAS response, with universal window.

Event 7 Provider1 oscillation profile, 0-6s response				
MWs	50ms	100ms	200ms	1s
Left Riemann	11.76	11.67	11.51	10.23
Right Riemann	11.96	12.08	12.31	14.21
Trapezoid rule	11.86	11.88	11.91	12.22
Simpson's rule	11.86	11.86	11.84	11.77
Simpson's 3/8 rule	11.86	11.86	11.83	12.65
Boole's rule	11.86	11.87	11.86	12.11

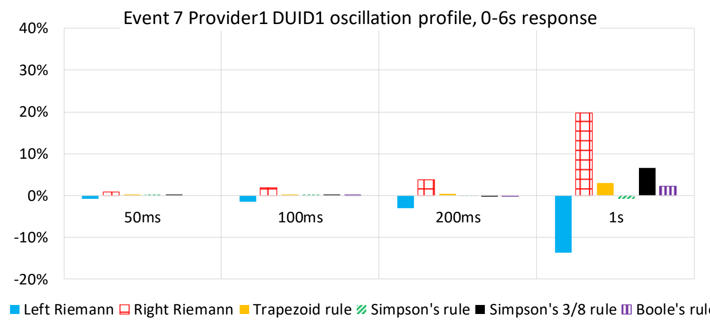

Figure 18. Comparison of different integration methods for event 7 provider 1 raise FCAS response with superimposed alternate signal, with universal window.

Event 1 Provider 2, 0-6s response				
MWs	50ms	100ms	200ms	1s
Left Riemann	80.00	78.66	76.55	71.57
Right Riemann	80.58	81.57	82.67	102.52
Trapezoid rule	80.29	80.11	79.61	87.04
Simpson's rule	80.31	79.96	80.46	87.61
Simpson's 3/8 rule	80.30	80.14	79.97	85.06
Boole's rule	80.32	79.89	80.68	87.93

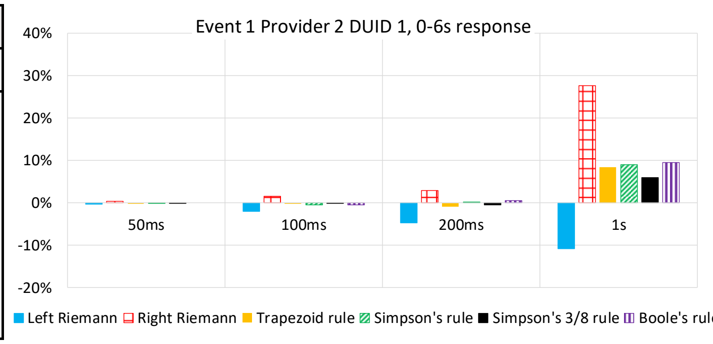

Figure 19. Comparison of different integration methods for event 1 provider 2 raise FCAS response, with universal window.

In summary, all integration rules perform uniformly across the two assessment window approaches for various events. The use of a relative window approach generally results in a positive average error (over-estimation) for the 1s sampling rate relative to higher sampling rates, and particularly relative to the 20ms/50ms faster sampling rates used as reference. This is for all integration methods starting from trapezoidal integration to higher orders, noting that Riemann methods are not suitable methods in general due to their large errors across all events. This also means that all these integration methods (excluding Riemann) perform very similarly to each other, so there does not appear any reason to use anything more complex than a trapezoid method.

3.3 Sensitivity study with low sampling rates

As seen in Section 3.2, the performance of the trapezoid and other higher order methods is quite similar. Therefore only the trapezoid method is applied in the sensitivity study of lower sampling rates. One significant impact of having a lower sampling rate is the possibility of failing to accurately capture the response change point (for instance, the step change of response from a switching controller), thus consequently resulting in a potentially large error. Therefore, here we carried out an analysis of the error distribution caused by low sampling rates, considering 28 response profiles provided by AEMO. These 28 profiles include raise/lower registration tests, similar to the ones shown in Figure 8 for illustration purposes, as well as other real events.

The naming of registration tests in the figure is composed of two letters and one number. It starts with “R” to represent the registration and the number indicates the provider id, while the last letter shows that it is either a raise (“R”) or lower (“L”) test. The naming of real events follows three numbers. The first number is the contingency event id. The second number indicates the provider id, and the third number shows the sub id of the asset linking to the provider which may be a VPP.

To cater for many possible start times of 1s sampling profiles, we study a family of response profiles obtained by shifting the profile by 20ms/50ms with respect to each other and within a 1s window. For example, there are 20 and 50 profiles with 1s sampling rate generated from every original response profile with 50ms/20ms sampling rate, respectively. Similarly, there are 4 and 10 profiles using 200ms sampling rate generated from the original 50ms/20ms ones, respectively. The baseline of each response profile is calculated using 20ms/50ms sampling profile with Boole's rules. The following results show the errors comparing 1s and 200ms sampling rates with the baseline for each response profile.

Figure 20 shows the error distribution of 1s sampling profiles when using the trapezoid method and relative assessment window. The results are visualised with boxplots, which indicate the errors for each profile (black points), average error value (red point), median error value (black line within the box), and minimum and maximum error value (lines at the extremities of the whiskers). First of all, errors are almost all positive when using relative windows, due to misalignment of the start time for window assessment. The maximum error can even exceed 50% in profile 4.2.3. Secondly, the trapezoid method does not show any significant bias.

The error distribution of 1s sampling profiles with the universal window method is depicted in Figure 21. Errors are largely evenly distributed with an average error of around 0%. The error deviation is almost negligible in the profiles of registration tests, but swings largely to over 15% in profiles 4.2.2 and 4.2.3.

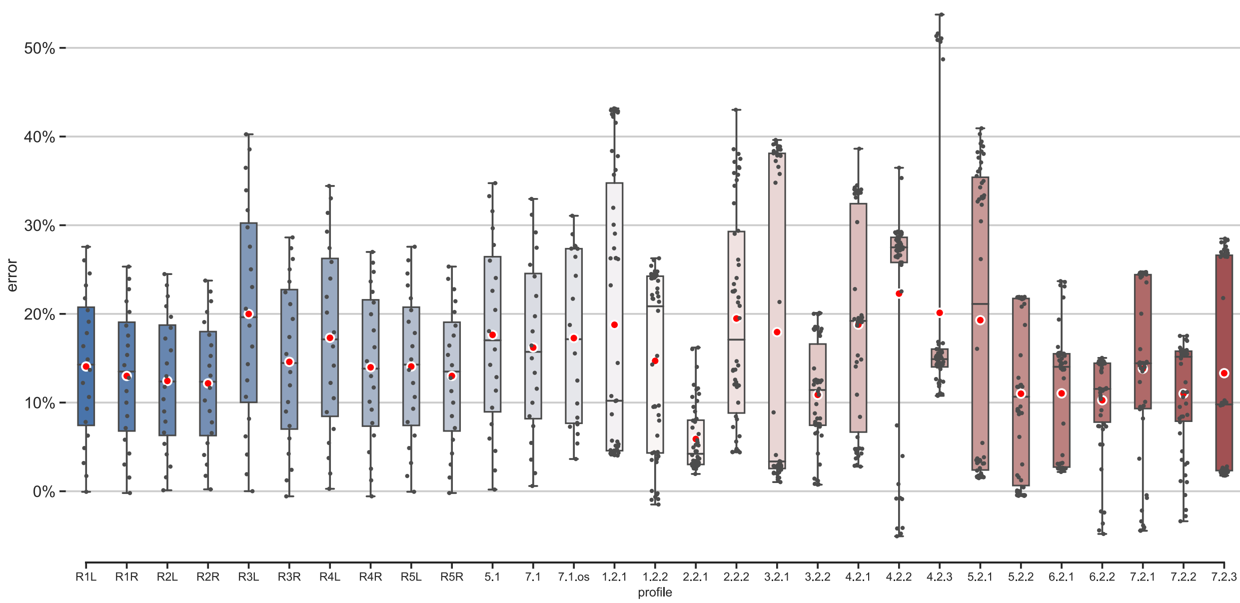

Figure 20. Error distribution of 1s sampling profiles with trapezoid method and relative window across 28 profiles.

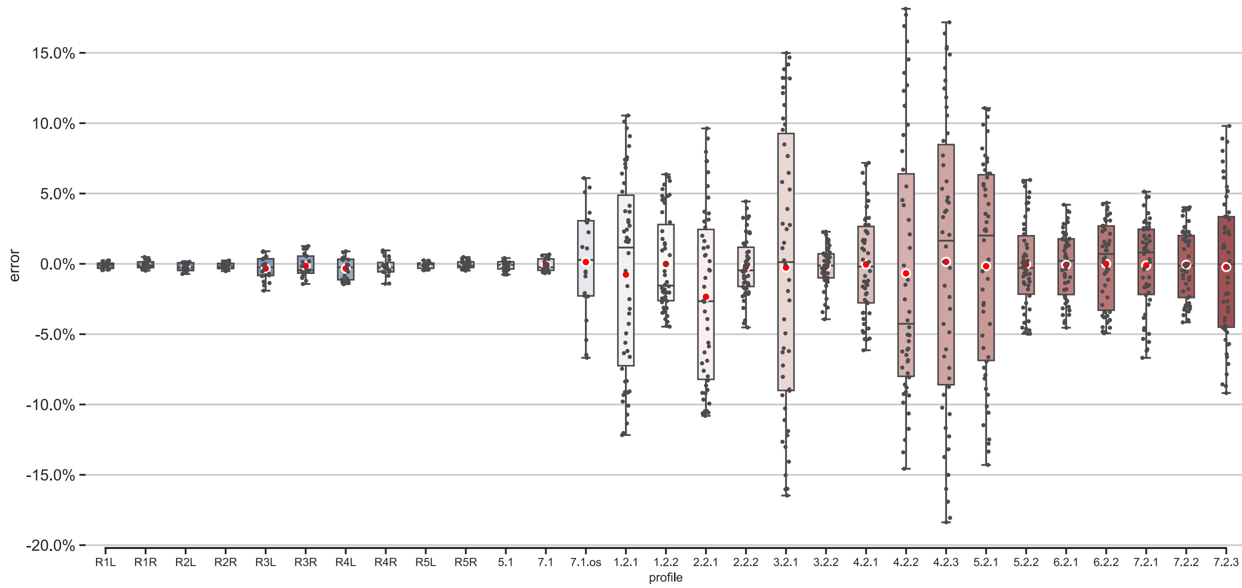

Figure 21. Error distribution of 1s sampling profiles with trapezoid method and universal window across 28 profiles.

The error distribution of 200ms sampling profiles when using trapezoidal method and relative window is shown in Figure 22. Errors are still almost all positive with relative window, but they are much smaller compared with the error distribution in 1s sampling rate. The average error of 200ms sampling profile is 2.8%, to be compared with 15% average error of 1s sampling rate profile shown in Figure 20. Applying universal window to 200ms sampling profiles would create an error distribution with an average value close to around 0%, as depicted in Figure 23. In comparison with 1s sampling case in Figure 21, the distribution of error when using universal window also narrowed from over 15% to around 3%.

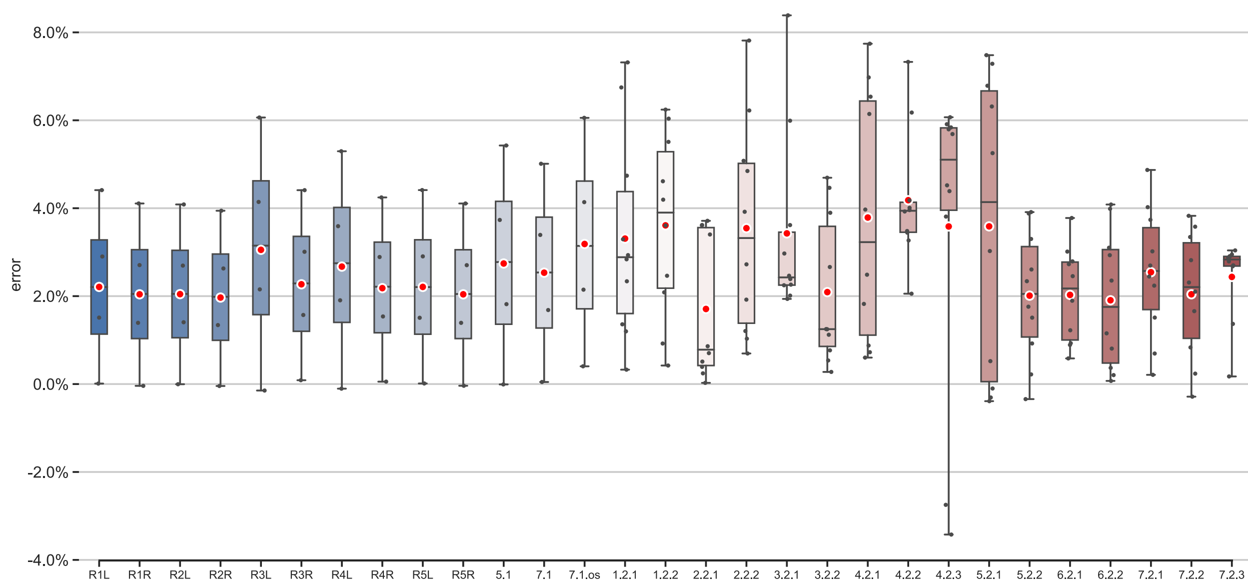

Figure 22. Error distribution of 200ms sampling profiles with trapezoid method and relative window across 28 profiles.

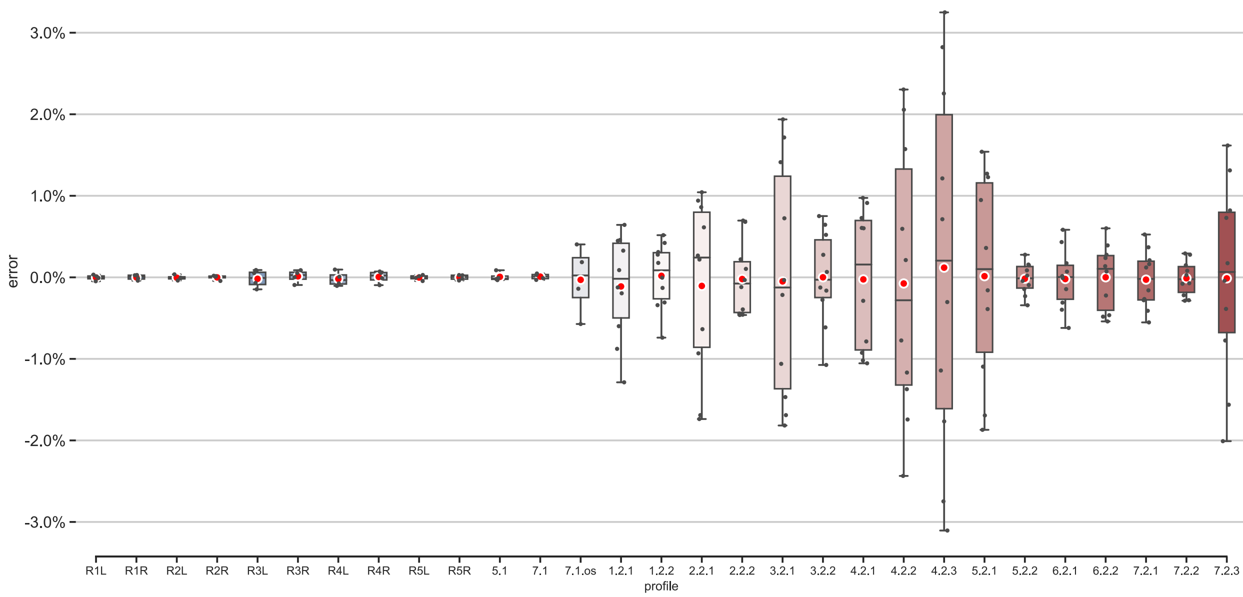

Figure 23. Error distribution of 200ms sampling profiles with trapezoid method and universal window across 28 profiles.

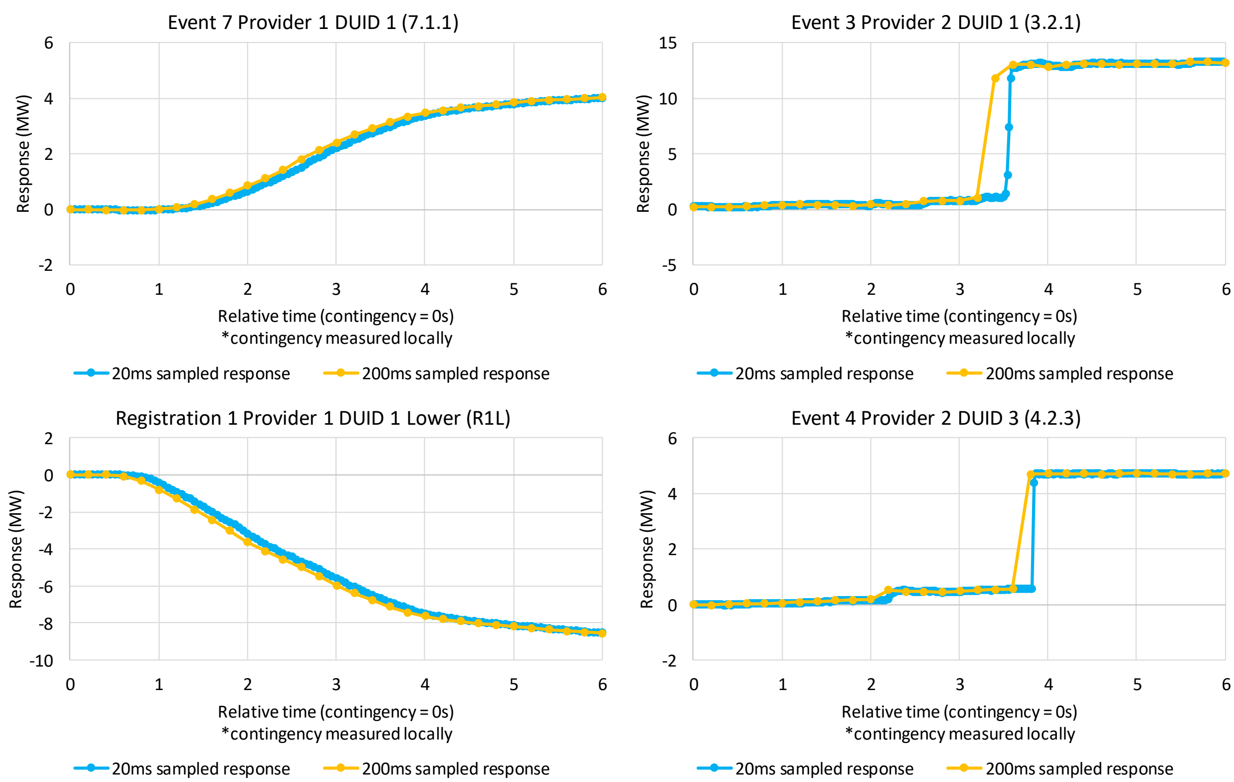

Figure 24. Response profile with 20ms and 200ms sampling rate of Profile 7.1.1 (left-upside), R1L (left-downside), 3.2.1 (right-upside), 4.2.3 (right-downside).

Furthermore, on the one hand, the error distributions in profiles 3.2.1 and 4.2.3 are wider comparing with other profiles when using the same window method. On the other hand, profiles 7.1.1 and R1L have a smaller error range when using the same window method. These response profiles are displayed in Figure

24, which can be categorised into step change (profiles 3.2.1 and 4.2.3) and linear ramping (profiles 7.1.1 and RL1).

Overall, these findings suggest that using a relative assessment window may introduce a noticeable over-estimation in the assessment of step change responses (i.e., profiles 3.2.1, 4.2.3) comparing with linear ramping responses (i.e., profiles 7.1.1, R1L).

4 Conclusion and recommendations

All integration rules performed consistently across various profiles when using the same window methodology. Overall, however, Riemann methods do not seem suitable because of their large errors across all profiles. The use of a relative window approach that uses local samples may result in a positive average error (over-estimation of the delivered energy) for both 1s and 200ms sampling rates relative to 50ms sampling rate due to the misalignment of the start point of the assessment window. However, using 200ms sampling would substantially reduce the over-estimation comparing with 1s sampling. This is for all integration methods starting from trapezoid rule to higher order. The use of a universal window approach brings an average error of around 0% for all integration methods from the trapezoid to higher order integration methods.

Some recommendations that may be extracted from our analyses are the following:

- The trapezoidal rule performs similarly to other higher polynomial order integrations rules (i.e., Simpson's, Boole's, etc.) in terms of calculating energy delivery for FCAS response, so it seems well suitable to be used in the standard methodology.
- Increasing the sampling rate from 1 second to 200ms might significantly reduce both average error and the error distribution range.
- Using a "universal" window instead of a "relative" window that relies on the local sampling of the frequency excursion could avoid a consistent over-estimation of energy delivery caused by the misalignment of the assessment window's start time, which is particularly severe for 1s sampling. However, for the events studied such over-estimation goes down to less than 3% when using 200ms instead of 1s sampling rate.

References

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

[2] Australian Energy Market Operator (AEMO), "FCAS Verification Tool User Guide," 2020.

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