Very Fast FCAS Sampling Rate Analysis in Support of the Market Ancillary Services Specification (MASS) consultation

Prepared for the Australian Energy Market Operator

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May 2022

Executive Summary

To help control power system frequency with deeper penetration of asynchronous renewables, in July 2021 the Australian Energy Market Commission (AEMC) published a final determination and a final rule [1] to introduce two new market ancillary services, namely, very fast raise and very fast lower frequency control ancillary services (FCAS). Accordingly, in May 2022 the Australian Energy Market Operator (AEMO) initiated a consultation on the Market Ancillary Service Specification (MASS) [2] with regards to the development of the new “very fast FCAS” products.

AEMO has commissioned the University of Melbourne (UoM) a study to determine the implied assessment error for Very Fast FCAS when data is captured at different measurement time resolutions (e.g., from 10ms to 200ms). UoM has thus performed several studies examining a number of real-life response profiles provided by AEMO for both switched loads and devices equipped with proportional controllers.

Methodologically, the study is fundamentally based on the existing MASS methodology [2] and the foundations laid in the previous work carried out by UoM [3-5]. However, a few new specific considerations were to be made in order to address the requirements brought by a much lower assessment window (one second or half a second, as opposed to six seconds).

With regards to **switched loads**, they generally exhibit response delays associated with a combination of actual response initiation delay and the time difference between when the frequency exits the normal operating frequency band (NOFB) and when it reaches the trigger setting of the load (which may be different from the NOFB). The response delays observed for most of the switched loads studied were beyond the assessment window proposed for the very fast FCAS services. Hence, FCAS verification based on the assessment window starting at the frequency disturbance time (FDT) and ending 1 second or 0.5 seconds (depending on the case) from the FDT, proposed in the issues paper [6], was not applicable for the purpose of this study. Additionally, for a group of loads managed by an aggregator, one actual trigger setting could not be considered as the aggregator has a range of trigger settings scattered across its portfolio of switched loads. Therefore, in order to provide a meaningful analysis of the assessment error from lower sampling rates associated with switched loads, a “rolling assessment window” was adopted for these cases, whereby a most plausible starting time was identified based on the highest rate of change of the response and then parametrically assessed with respect to different shifting times. This rolling assessment window strategy was adopted for both 1s service and 0.5s service studies.

With regards to devices equipped with **proportional controllers**, four response profiles of three **batteries**, recorded in real-life contingency events, were analysed. In this case, it should be noted that the “assessment window” used to evaluate the 1s service delivery is defined in the issues paper [6] as the *1 second time interval starting from the “frequency disturbance time (FDT)”*, while the FDT is defined as the time when the local frequency is outside the normal operating frequency band (NOFB) following a frequency disturbance. Similarly, the assessment window in the 0.5s service analysis corresponds to the 0.5-second duration time interval starting from the FDT.

From the data provided and the studies performed, the following set of conclusions and recommendations are of particular note:

- In delivering the 1s service, lowering the sampling rate from 20ms to 200ms for switched loads may introduce absolute values of assessment errors of more than 8%. In comparison, by using 100ms and 50ms sampling rates, the absolute assessment error for switched responses may be limited to some 4% and 1%, respectively. For the 0.5s service, these errors almost double for 100ms and 50ms sampling rates, with magnitudes being limited to 8% and 2%, respectively. However, the absolute error for 200ms sampling rate in the 0.5s assessment windows can exceed 35%.
- Lower sampling rates introduce higher assessment errors for high-ramp switching response profiles compared to slower switching response profiles.
- For the 1s service analysis for switched responses sampled at 50ms with a response delay of 500ms or less, the absolute value of assessment error is still limited to 2%. However, for the 0.5s service, the absolute error for a switched response sampled at 50ms with 200ms delay can exceed 2%. In general, for both 1s and 0.5s assessments, initiating a response with a considerable delay in conjunction with lower sampling rates may bring about significant assessment errors for switched responses, and longer delays in the response increase the assessment errors for all sampling rates.
- For the 1s service, lowering the sampling rate to 200ms may result in an absolute assessment error of up to 8% for batteries, while this error might be limited to 4% and 1% when using 100ms and 50ms sampling rates, respectively. For the 0.5s service, the absolute assessment errors for 100ms and 50ms sampling rates are within 8% and 2%, respectively, that is, almost double compared to the 1s case. Also, the absolute error for 200ms sampling rate in the 0.5s assessment window can exceed 30%.
- Overall, for both switching and proportional controllers, the general trend of the findings in the 1s and 0.5s analyses appears to be similar for 100ms and 50ms sampling rates. That is, the absolute assessment error in the 1s analysis is generally limited to 4% and 1% for the responses sampled at 100ms and 50ms rates, respectively, while for the 0.5s service, these numbers almost double in magnitude, with similar trends in error distribution. However, for 200ms sampling rate, the absolute assessment error may be up to some 8% when delivering a 1s Very Fast FCAS, while this error may exceed 35% in delivering a 0.5s service. The relatively higher assessment error of 200ms sampling rate for the 0.5s service is due to a compounding effect of low sample granularity and uncaptured area.

Table of Contents

1 Introduction

In May 2022, the Australian Energy Market Operator (AEMO) initiated a consultation on the Market Ancillary Service Specification (MASS) with regards to the incorporation of very fast frequency control ancillary services (Very Fast FCAS). This consultation is being conducted to consider the inclusion of a very fast raise service and a very fast lower service, referred to collectively as Very Fast FCAS. In this context, two different time windows of very fast FCAS assessment are of interest: 1s service and 0.5s service.

In the first stage of this consultation, the University of Melbourne (UoM) was invited by AEMO to perform an independent analysis of the Very Fast FCAS sampling and the corresponding verification process and potential errors when considering lower sampling rates (e.g., 50ms, 100ms, 200ms) compared to the highest available sampling rates of 10/20ms. This report summarises the main findings of the study carried out for a number of anonymised profiles provided by AEMO for both switched loads and batteries equipped with proportional controllers.

Methodologically, while the study is fundamentally based on the existing MASS methodology [2] and the foundations laid in the previous work carried out by UoM, a “rolling assessment window” method was additionally introduced here to approximate the assessment errors stemming from lower sampling rates for switched loads with response delays beyond the assessment window of Very Fast FCAS. The assessment window time interval is equal to one second in the 1s service analysis and half a second in the 0.5s service analysis. This report is organised as follows:

- Section 2 elaborates on how the methodology is applied to switched loads and proportional controllers (e.g., battery energy storage systems). More specifically:
  - Section 2.1 presents the context for the study of the assessment error of very fast FCAS.
  - Section 2.2 lays out the methodological assumptions behind the studies conducted in this report.
  - Section 2.3 describes the calculation approach for switched loads, which is used to measure the performance of different sampling rates and Very Fast FCAS verification assessment. This includes the response delay for switching controllers, explained in Section 2.3.1, and then the methodology, introduced in Section 2.3.2, which is used to analyse different sampling rates considering the response delay.
  - Section 2.4 explains the methodological considerations for proportional controllers.
- Section 3 discusses the 1s service analysis results for the case studies on the assessment error. In particular:
  - Sections 3.1 and 3.2 examine the results for switched loads when considering lower sampling rates and different response delays, respectively.
  - Section 3.3 explores the results when downsampling the response of proportional controllers.
- Section 4 presents the results for switched loads and batteries considering the 0.5s service. More specifically:
  - Section 4.1 and 4.2 evaluate the results for switched loads while considering lower sampling rates and various response delays, respectively.
  - Section 4.3 explores the results of downsampling considering the response of proportional controllers.
- The conclusions and key remarks are provided in Section 5.

2 Methodology

2.1 Very Fast FCAS assessment error

FCAS providers must set up relevant facilities to continuously monitor and record their output power and the local frequency at their connection points. In the occurrence of contingency events, such profiles may be requested by AEMO to verify the provider's performance against the enablement. This verification process follows a standard methodology published by AEMO, details of which can be found in [2], which separates FCAS response from the output power profile. This verification process is used to help determine whether the participant provided the agreed amount of FCAS, assuming that the FCAS contribution derived from the verification tool is accurate. The "assessment window", which is used to evaluate the Very Fast FCAS delivery, is defined in the issues paper as the *1 second time interval starting from the "frequency disturbance time (FDT)"*. The FDT is defined as the time when the local frequency is outside the normal operating frequency band (NOFB) following a frequency disturbance.

This study aims at investigating the impact of using lower sampling rates on the Very Fast FCAS performance verification. The assessment error indicates the relative difference of the Very Fast FCAS contribution (in MW.s) when changing the sampling rate. Note that a small assessment error in the results reported here only shows that the Very Fast FCAS contribution calculated with the given settings is close to the contribution calculated with the benchmark (the response sampled at 10/20ms). Thus, for a given event, a small error shown in the results presented in this report does not necessarily indicate that the provider would have an acceptable performance in terms of Very Fast FCAS delivery as recognised by AEMO.

2.2 General methodological assumptions

In line with the existing MASS [2] and previous work [3-5], the methodological hypotheses are as follows:

- The comparison is made between the Very Fast FCAS contribution (in MW.s) of the highest available sampling rate (10/20ms) and lower sampling rates (50ms, 100ms, and 200ms),
- The trapezoid rule is implemented as the integration method,
- The assessment window is one second in the 1s service analysis and half a second in the 0.5s service analysis,
- The RoCoF-based method is used to locate the FDT,
- The highest available sampling rate (10/20ms) with the RoCoF-based method and trapezoid rule is considered as the benchmark,
- Downsampling with linear interpolation is used to derive 50ms profiles from 20ms profiles.

Furthermore, the following assumptions are considered in the studies presented in this report:

- As the response profiles analyzed do not belong to scheduled or semi-scheduled units, the observed changes in active power are considered to be solely driven by a contingency event as part of contingency FCAS provision (and hence not be, for example, the result of a dispatch target),
- The response profiles are assumed to have no inertial response capabilities,
- The compensation factors are not considered at this stage,
- Due to data availability, the "baseline" power profile before a frequency event is calculated as the average active power of the profile for any samples available before the FDT if at least 8s of the

profile is not available before FDT. Any portion (or all) of the profile available between the 20s and 8s before the FDT is used otherwise.

It is to note that the above assumptions hold for both 1s and 0.5s service analyses.

2.3 Specific considerations for switching controllers

In this report, the switching controller refers to a frequency-responsive load that changes its active power consumption as a response to the measured frequency excursions at its terminals if the system frequency enters the operating region of the load frequency setting (i.e., the system frequency goes beyond a certain frequency threshold). In the frequency response from switched controllers, there may be a certain time delay. Two factors cause the mentioned time delay: 1) there is a time interval between the FDT and the time at which the system frequency reaches the response initiation threshold of a switched load , and 2) there may be some time delays associated with internal control schemes of a switched load (i.e., response initiation delay). In the context of this report, these time delays are aggregated and referred to as the "response delay". For example, a group of loads that are managed by an aggregator (e.g., virtual power plants) may not provide an aggregate frequency response in a high-ramp step-change form due to different trigger settings allocated to each load to stagger the FCAS response or some coordination and measurement delays.

2.3.1 Response delay

For most of the switched responses provided, a considerable delay in the response is observed, yielding a response time beyond the Very Fast FCAS verification assessment window. For example, assuming a 1s service and its corresponding assessment window of one second, the frequency and active power profiles for one of the switched loads are depicted in Figure 2.1. In this figure, the lower NOFB (49.85 Hz), the frequency curve, and the active power profile are indicated as a dashed red line, and blue and orange curves, respectively. From Figure 2.1, it can be appreciated how the response initialisation for the switched load occurs with a significant delay with respect to the time that frequency crosses the NOFB. As already mentioned, this aggregate time delay may be associated with both response initiation delay and internal control delay. Therefore, the assessment window starting from FDT cannot capture this response, and the assessment window based on FDT will result in almost zero calculated Very Fast FCAS response value. This issue is observed in most available switched responses. The associated response delay made it thus implausible to conduct a standard approach, i.e., with a 1s (resp. 0.5s) assessment window starting from FDT in the 1s (resp. 0.5s) service analysis, to analyse the impact of lower sampling rates on the verification of switched loads. Therefore, a “rolling assessment window” was considered, whose details are provided in the following section.

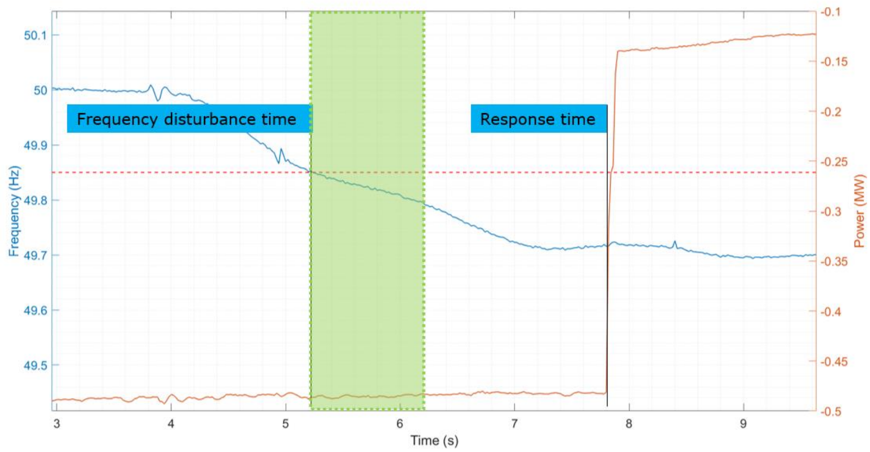

Figure 2.1. Example of frequency and active power profiles for a switched load, with relevant response delay window

2.3.2 Rolling assessment window approach

As already discussed, the delay in the response of switched loads is the aggregated time delay associated with the response initiation delay and the internal control delay. However, as these trigger settings are not available, for the purpose of analysing the impact of different sampling rates in measuring the response, the starting point of the assessment window is shifted from the FDT to a "most plausible" response time of the switched profiles. A visual representation of this new assessment, assuming one-second time window, is shown in Figure 2.2. In the context of the 0.5s service, the 0.5s assessment window would be similarly shifted towards the response time, which is not shown here to avoid repetition.

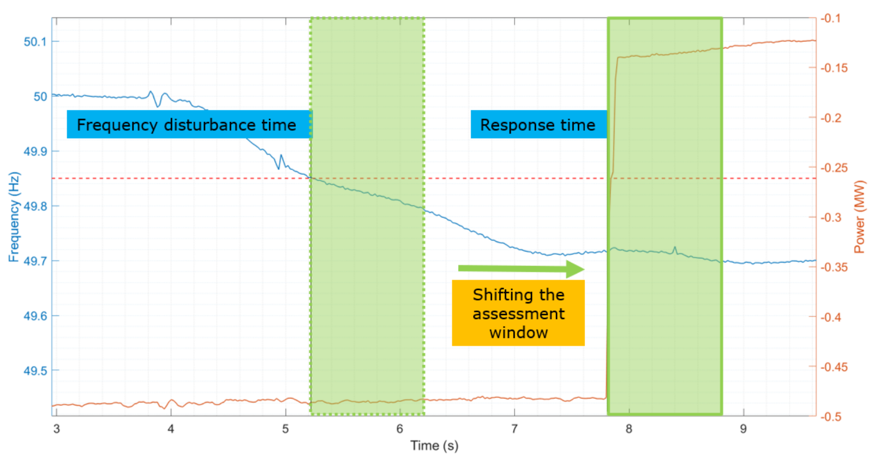

Figure 2.2. Shifting the starting point of the assessment window to the "most plausible" response time

However, again it is not straightforward to identify the most plausible response time across a range of possible response shapes and ramping values. For the purpose of sampling rate analysis carried out here[1], the proposed methodology relies on using the ***slope*** of the response to find the starting point for the

[1] This "rolling window" assessment is only considered here for a *mathematical* assessment of the impact of lower sampling rates, and not for actual Very Fast FCAS verification, for which further studies will be needed in the future.

assessment, namely, by calculating the ***highest change*** in the active power in the ***shortest amount of time after contingency***.

The starting point of the rolling assessment window is located using the highest available sampling rate and is assumed to be ***universal*** for all sampling rates. This is similar to having a reference point, such as the NOFB crossing in the actual Very Fast FCAS verification, for defining the starting point of the assessment. The highest available sampling rate will therefore also drive what is considered the response starting time. On the other hand, defining the starting point of the rolling assessment window separately for each sampling rate would inevitably introduce further errors[2].

The caveat on this process is that some parts of the response in the initialisation phase might be left out if the response initialisation was not sufficiently fast. A visual representation of such a situation is illustrated in Figure 2.3, assuming a 1s service. As shown, the proposed definition of the rolling assessment window can successfully capture most areas related to a switched response. However, as highlighted using the orange triangle, some initial parts of the response might not be covered by the rolling assessment window. The uncaptured part of the response is associated with the lower ramping during the response initialisation when the assessment starts from the highest ramp in the response.

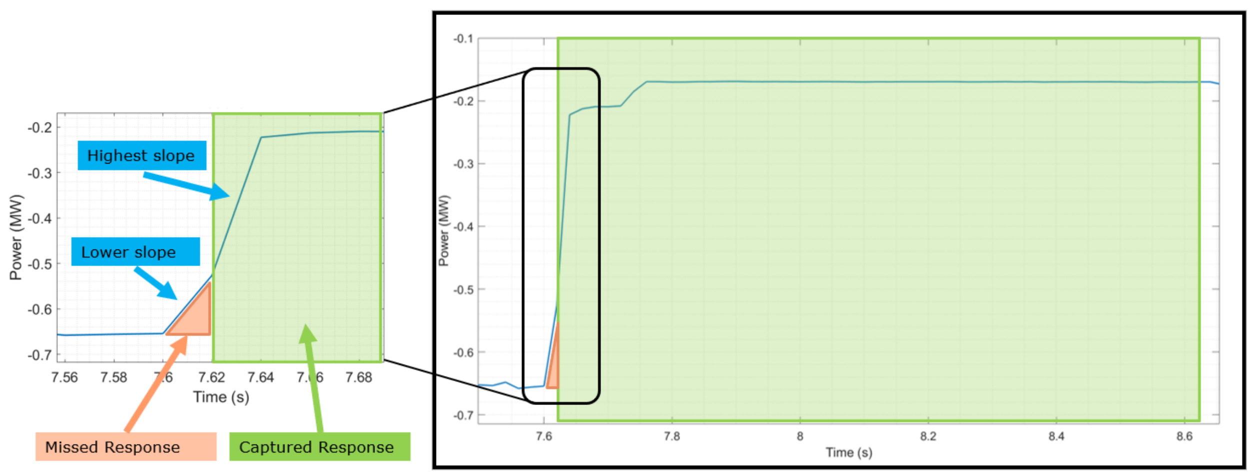

Figure 2.3. Visual representation of the rolling assessment window in capturing a switched response

Although not perfect, the proposed definition appears to be sufficiently robust for the purposes of comparing assessment errors for different sampling rates, while in practice any other methodology would be profile-dependent and therefore case-specific and thus suffer similar downsides. Note that, due to the uncaptured proportion of the response, the value for Very Fast FCAS contribution might be different from its actual value, but the relative difference of Very Fast FCAS contribution when changing the sampling rate would remain practically unchanged. Therefore, the impact of the proposed definition on the assessment of different sampling rates should be negligible.

Furthermore, the assessment based on a rolling window enables analysing the impact of **various ranges** of *response delays* on the assessment error for different sampling rates. The response delay can be considered equivalent to an offset in the starting point of the rolling assessment window. In this way, the

[2] Downsampling might change the response shape and consequently affect the starting point's detection, introducing further error due to defining a unified assessment window besides the error for different sampling rates.

rolling assessment window can be used to approximate the assessment error of switched loads stemming from lower sampling rates while also considering the impact of several possible and plausible response delay. On these premises, a parametric analysis is conducted on a wide range of values for response delay, whose detailed results and discussions are provided in Section 3.2.

It should be noted that although only the 1s service was used as an example to describe the rolling assessment window approach in the above discussions, exactly the same principles apply to the 0.5s service.

2.4 Specific considerations for proportional controllers

Droop control is the most common practice used by various technologies (e.g., batteries, gas turbines) to deliver frequency response following system frequency disturbances. The droop controller usually includes a frequency deadband setting that determines when the technology response should ideally initiate, with active power output changing proportionally to a certain frequency variation when the system frequency is beyond the deadband. It is to note that the specific frequency deadband may be different from the FDT associated with the general NOFB (e.g., 49.85 Hz for under-frequency events), which could cause challenges when verifying the very fast response from proportional responsive technologies (e.g., batteries in this report).

3 Case studies for 1s service

3.1 Downsampling for switched loads

This case study is designed to analyse the impact of different sampling rates for switched loads based on the 1s rolling assessment window defined in Section 2.3.2.

One potential impact of lower sampling rates is the possibility of failing to accurately capture the response change time, consequently resulting in a potentially significant error. Therefore, an analysis is carried out to obtain the potential *error distribution*[3] introduced by downsampling for fifteen anonymised switched response profiles provided by AEMO. These profiles correspond to responses delivered by switched loads during real frequency events.

To cater for many possible start times of lower sampling rate profiles, we study a family of response profiles obtained by shifting the first sample within the set of original samples included in the first interval of the lower sampling rate. For example, five and twenty profiles with 100ms and 200ms sampling rates are generated from every original response profile with a 20ms sampling rate, respectively. This family of response profiles will then result in a distribution of results for the assessment error that we represent by means of a boxplot. The benchmark for this study is the highest available sampling rate (20ms for switched loads), and the calculation is based on the trapezoid rule. The following results illustrate the errors comparing 50ms, 100ms, and 200ms sampling rates with the 20ms benchmark for each response profile.

Figure 3.1 – Figure 3.3 show the error distribution of 200ms, 100ms, and 50ms sampling profiles, respectively. Each figure depicts the assessment error for each profile (black points), average error value (red point), median error value (black line within the box), and minimum and maximum error values (lines at the extremities of the whiskers). As seen in Figure 3.1, considering the 200ms sampling rate for all load

[3] It should be appreciated that a lot more profiles should be analysed to reach statistically significant conclusions. On the other hand, the general trend of the findings appears to be relatively robust.

profiles introduces a considerable assessment error in the majority of the cases under consideration. The absolute value of assessment error in some profiles can exceed 8%[4] for the 200ms sampling rate. By contrasting these results with Figure 3.2, it is possible to see that the absolute value and the distribution of the assessment error decrease for 100ms compared to 200ms for all response profiles, such that the absolute value of the assessment error is limited to 4% for the analysis we conducted. For a 50ms sampling rate, there is a significant reduction in both the magnitude and the range of distribution of the error, such that the maximum absolute error for all profiles is limited to 1%.

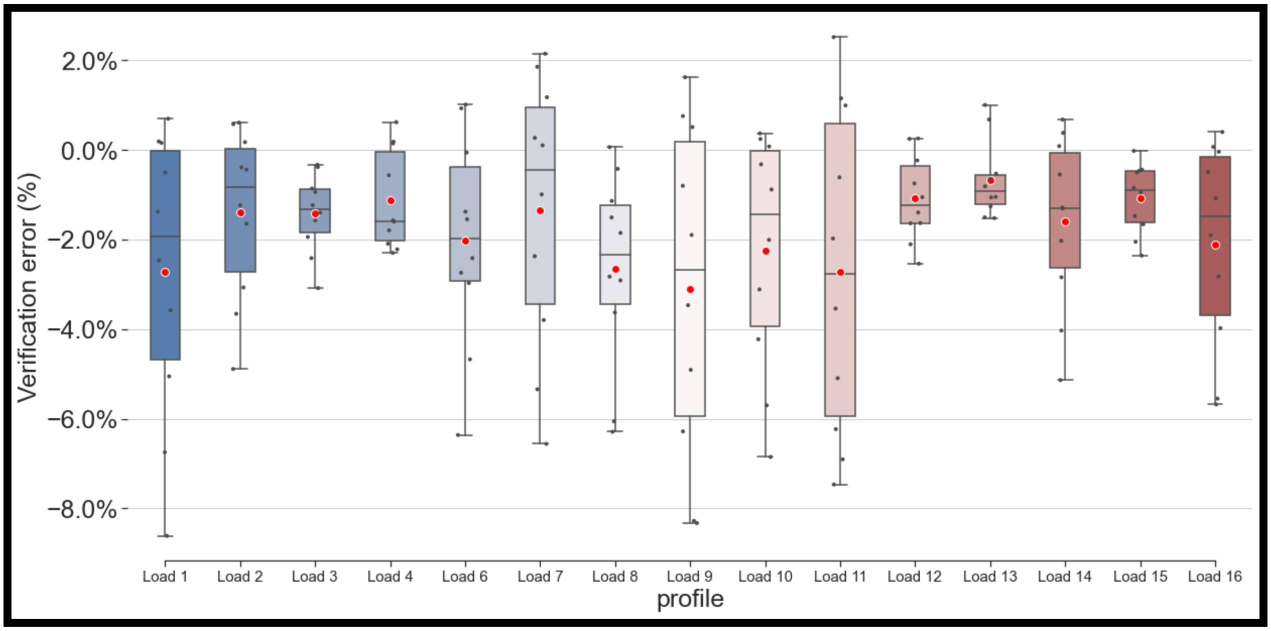

*Figure 3.1 Error distribution of **200ms** sampling rate for different switched response profiles, 1s service.*

[4] The assessment errors can be positive or negative, depending on whether the approximated area calculated for the sampled response is over-estimated or under-estimated, respectively. When reporting the results observed in each case study 'error' will refer to 'absolute error', unless otherwise specified. Therefore, for example, when referring to a higher error this will mean a higher absolute error.

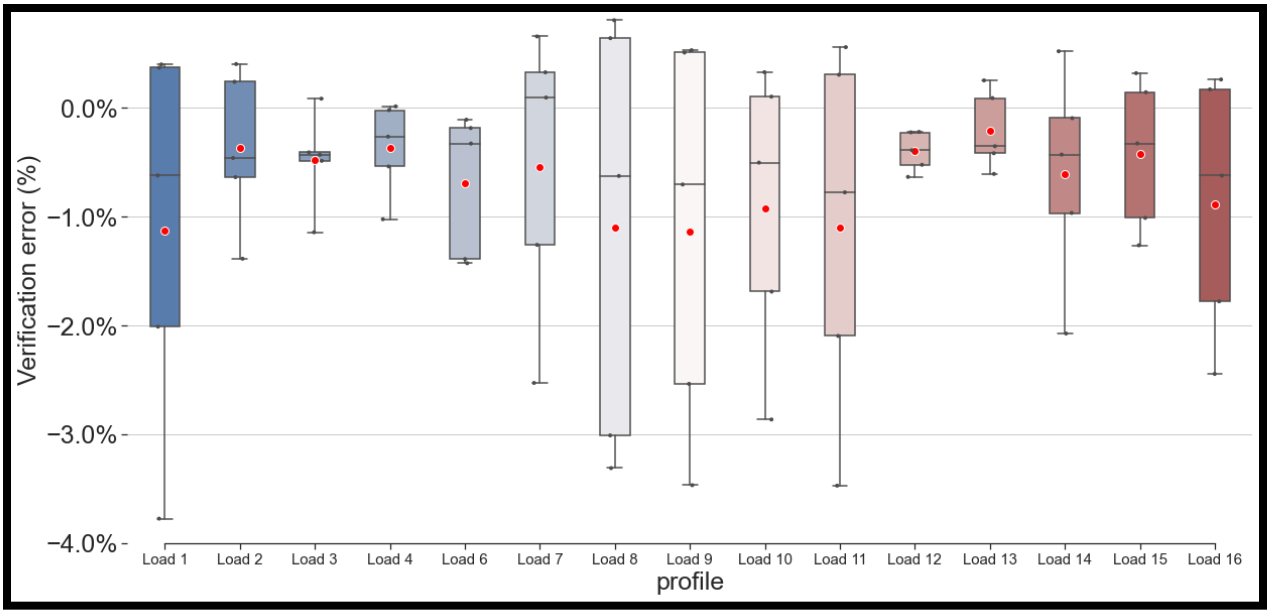

*Figure 3.2. Error distribution of **100ms** sampling rate for different switched response profiles, 1s service.*

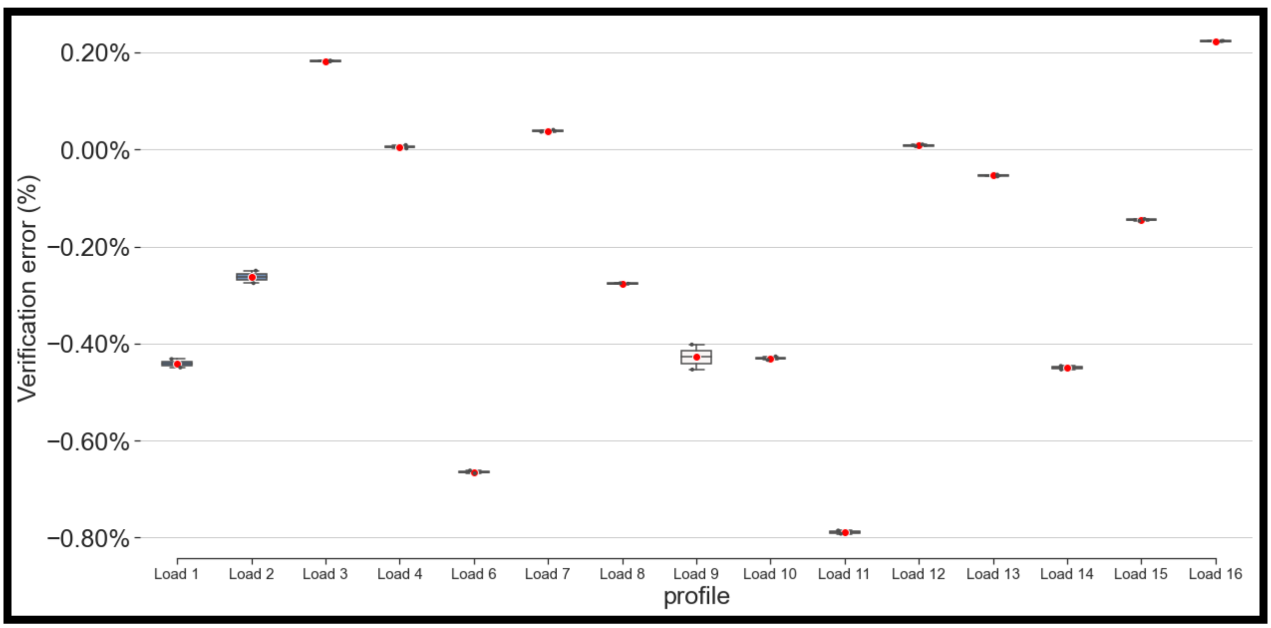

*Figure 3.3. Error distribution of **50ms** sampling rate for different switched response profiles, 1s service.*

Furthermore, there are some clear differences in the error distribution of different load profiles, such that some high-error cases can be observed across all sampling rates, while some profiles introduce lower errors for all sampling rates. To further clarify this, Figure 3.4 shows the assessment errors for each load considering different sampling rates. For instance, response profiles for loads 1, 9, and 11 are associated with higher assessment errors, which can be noted for almost all sampling rates. On the other hand, comparatively lower assessment errors can be observed for the response profiles of loads 3, 4, 12, 13 and 15. This shows that different switched profiles have different assessment errors when considering lower sampling rates. These differences originate from the specific shapes of the responses seen for switched loads. In comparing assessment errors of different load profiles, the largest absolute values are of key interest for the measurement requirements, as typical response profiles can display potentially different (and generally not known *a priori*) shapes. Therefore, it is of importance to consider the "worst" cases in terms of assessment errors[5].

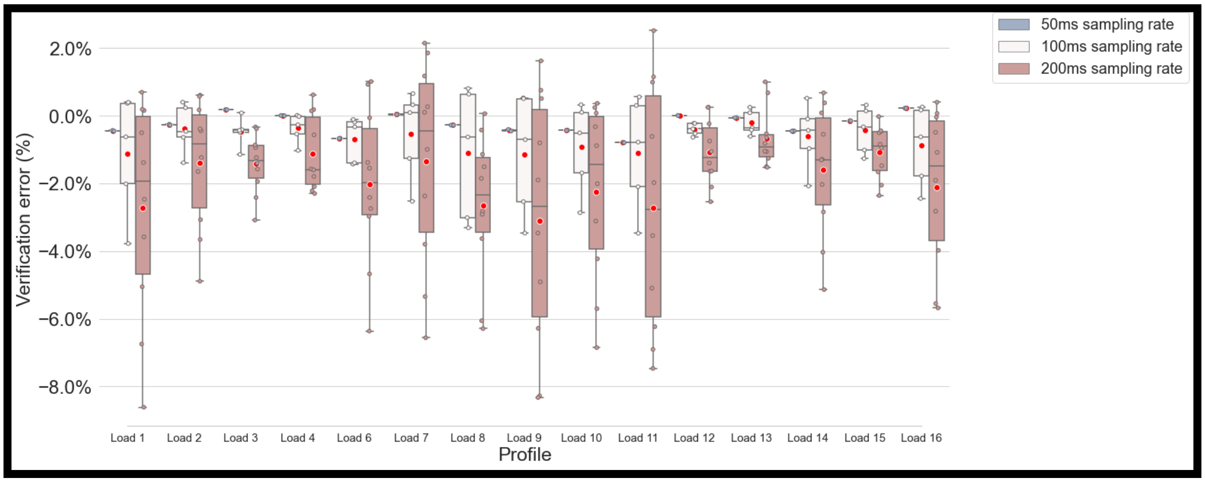

Figure 3.4. Error distribution of different sampling rates for all switched response profiles, 1s service.

To further explore the differences in the assessment errors of different load profiles, individual response shapes are examined against various sampling rates. The response shapes with different sampling rates for loads 1 and 11 are depicted in Figure 3.5. As shown, the difference in sampling rates results in different approximations of the actual profile and lower sampling rates may fail to follow actual changes in the response. For example, one sample selected when considering a 200ms sampling rate can coincide with the starting point of the response, while the following sample might fall after the step change. This can create one of the worst cases for a sampling rate of 200ms, where the available samples may fail to capture the step change of switched response. This can result in a considerable approximation of the area under the response curve and thus a higher assessment error. Therefore, relatively high errors might appear for lower sampling rates in the case of profiles that behave as high-ramp switched response.

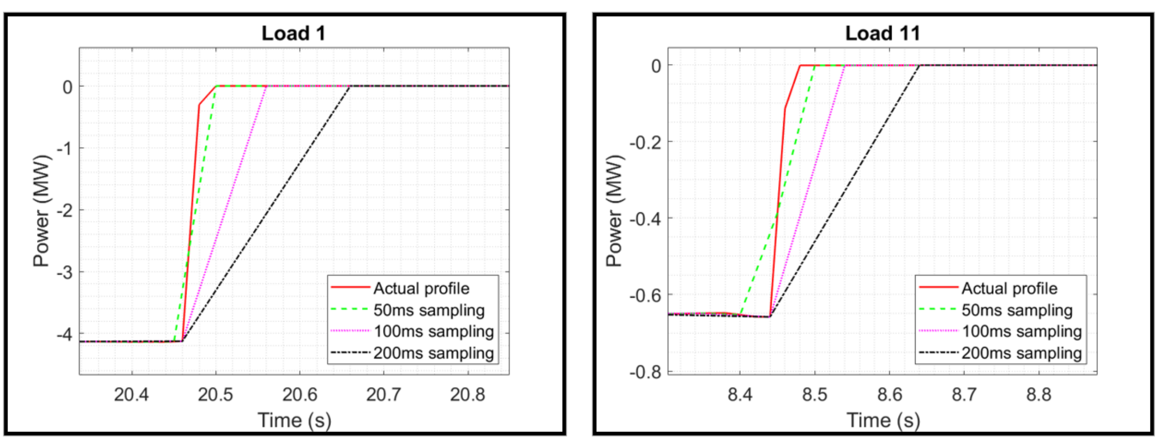

Figure 3.5. Response shape with different sampling rates for loads 1 and 11

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[5] Once again noting, though, that no statistical meaning can be attributed to these "worst cases", given the limited size of the available dataset.

Another high error case example is related to load 9. The response shapes for different sampling rates for load 9 are shown in Figure 3.6. It can be noted that the load 9 profile also has a steep change during the response initialisation, which creates difficulties for lower sampling rates in the estimation of the area for this response profile. Additionally, this response profile displays some variations in the response after initialisation that may also increase the likelihood of higher assessment errors for low sampling rates. However, based on the profiles at hand, no general conclusion can be drawn on the contribution of these variations to increasing or decreasing the assessment error.

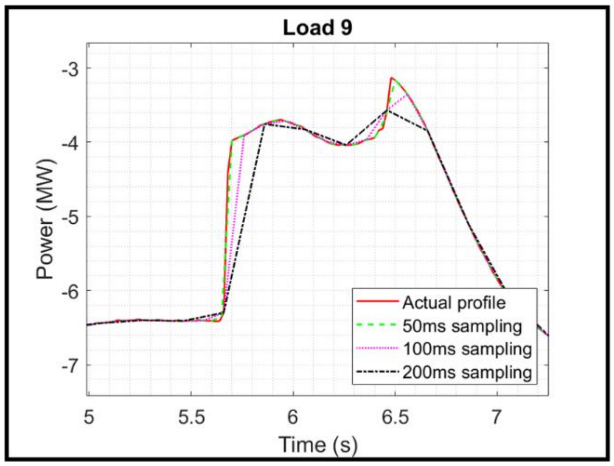

Figure 3.6. Response shape with different sampling rates for load 9

The response shapes for loads 3 and 13 (low-error cases) are shown in Figure 3.7. As can be noted, the initialisation of the response in these profiles is less pronounced than a high-ramp switched response. In these low-ramp switched responses, the initial ramping is slower, which fits better the trapezoid approximation for lower sampling rates. Also, the smaller increases in response that follow the initial ramp result in sampling approximations that may cancel each other out. These features of low-ramp switched responses can explain the lower assessment error observed for these profiles; however, again, no general conclusions can really be made for this type of response.

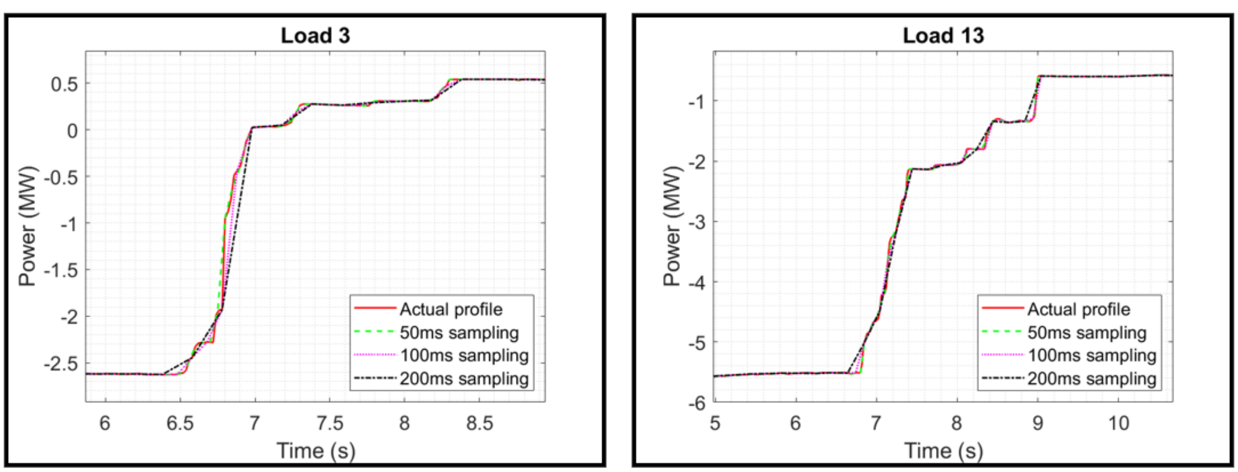

Figure 3.7. Response shape with different sampling rates for loads 3 and 13

3.2 Response delay for switched loads

As mentioned in Section 2.3, the response of the switched loads used to conduct this study displays a considerable delay from FDT, which results in some or all parts of the response being left out of the 1s assessment window. Understanding that these sources might fine-tune their controllers to participate in the Very Fast FCAS market, here we lay out a methodology to analyse the error distribution caused by low sampling rates considering different delays in the response of switched loads. The rolling assessment window method, defined in Section 2.3.2, is used to approximate the assessment error of switched loads stemming from lower sampling rates considering the impact of response delay. In the proposed methodology, the delay in the response corresponds to an offset in the starting point of the rolling assessment window. For example, when studying a 600ms delay in the response, an offset of 600ms is considered for the rolling window to start 600ms earlier than its conventional starting point (as defined in Section 2.3.2). The shifting of the rolling assessment window to imitate the impact of the delay in response is visualised in Figure 3.8. Note that, as discussed in Section 2.3.2, the shifting of the rolling assessment window is again based on the highest available sampling rate and assumed to be universal for all sampling rates.

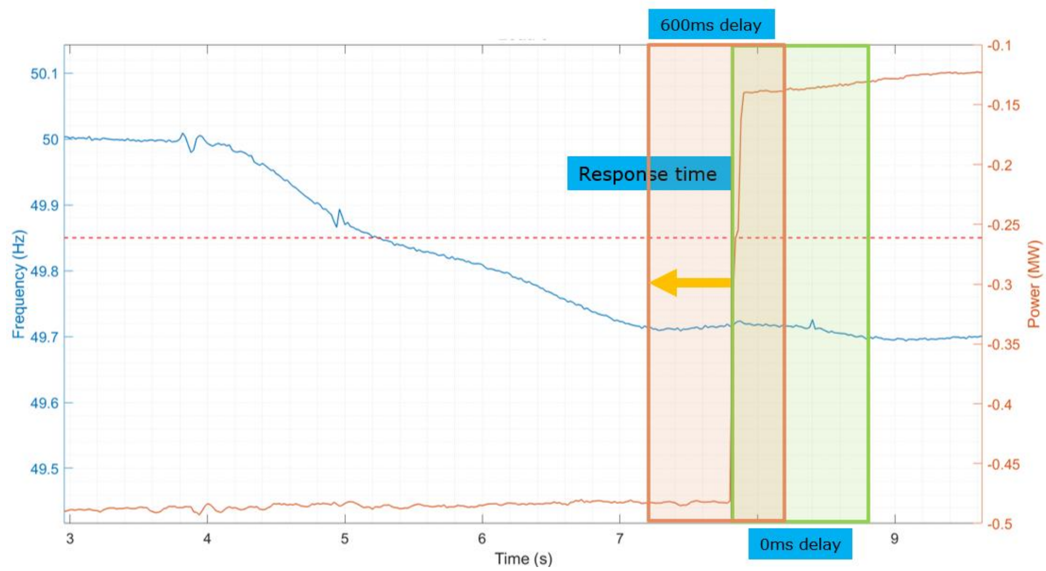

Figure 3.8. Considering a response delay of 600ms for a switched load based on the rolling assessment window

A parametric analysis is conducted on different delay values of 200ms, 400ms, 500ms, 600ms, and 800ms. Note that the case study in Section 3.1 is associated with the delay of 0ms. A comparison is then made between an ideal case with 0ms delay and the set of five predefined delay values in response profiles described before. The results for 200ms, 100ms, and 50ms sampling rates are shown in Figure 3.9 – Figure 3.11, respectively. As can be seen, the delay in response can increase the error significantly. This is consistent across all sampling rates of 200ms, 100ms, and 50ms. A very late initialisation of the response with 800ms delay in conjunction with a lower sampling rate of 200ms can increase the maximum absolute error to more than 40%. Therefore, initiating a response with a considerable delay in conjunction with a low sampling rate may bring about significant assessment errors.

The impact of response delays on the assessment error reduces when using higher sampling rates of 100ms compared to 200ms. However, the maximum absolute assessment error for a switched load with a response delay of 800ms may still exceed 15% when using a 100ms sampling rate. Using the sampling rate of 50ms reduces the maximum absolute error to under 2% for all the cases that consider a delay of 600ms or less, also displaying a generalised reduction in the distribution of the error. It is worth noting that even with a higher sampling rate of the 50ms, initiating the response in very late moments of the assessment window (800ms delay) results in a maximum absolute error that exceeds 2%, and even 3% in some cases[6].

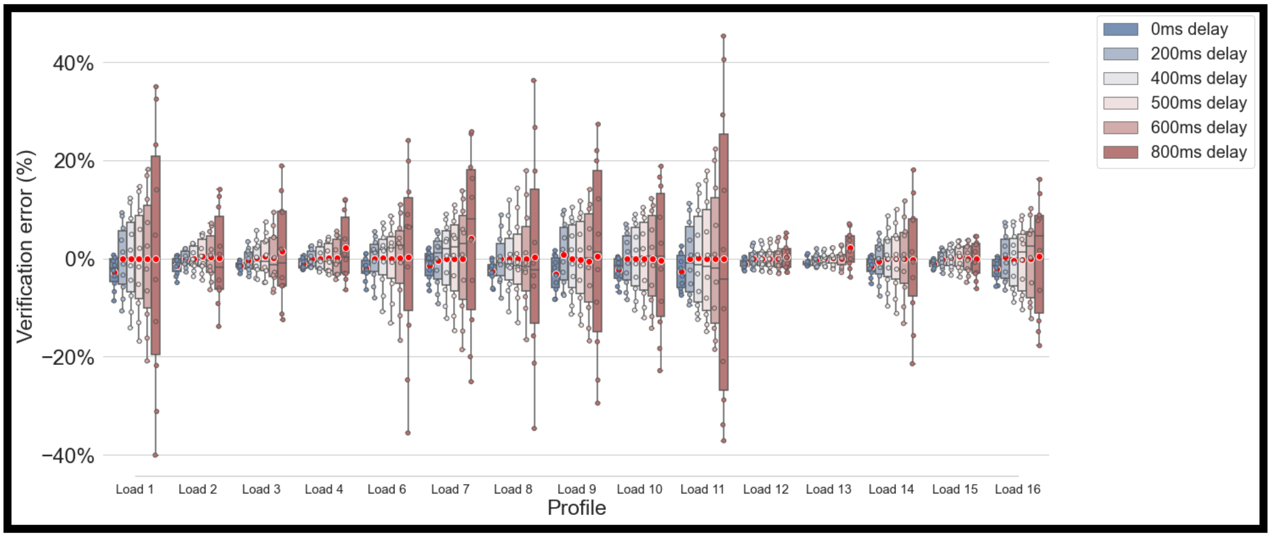

*Figure 3.9. Assessment errors for **200ms** sampling rate considering different values of delays in the response*

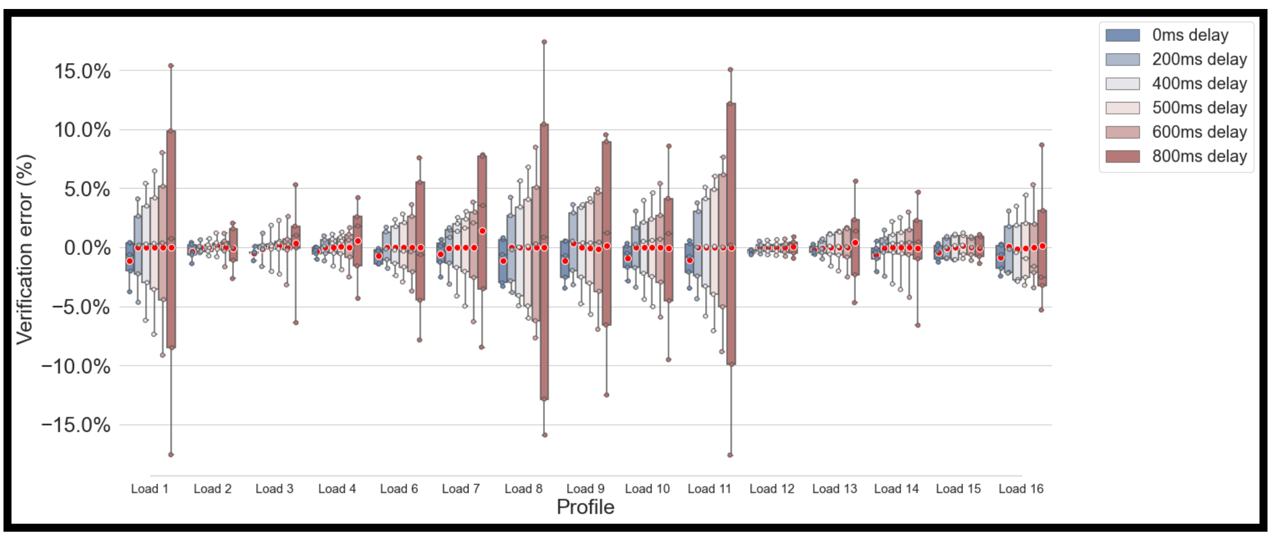

*Figure 3.10. Assessment errors for **100ms** sampling rate considering different values of delays in the response*

[6] In any case, change in sampling rate is not an effective practice to mitigate the impact of the response delay on the assessment error. In the future it might also be expected that participants be requested to deliver a very fast response within a maximum delay time.

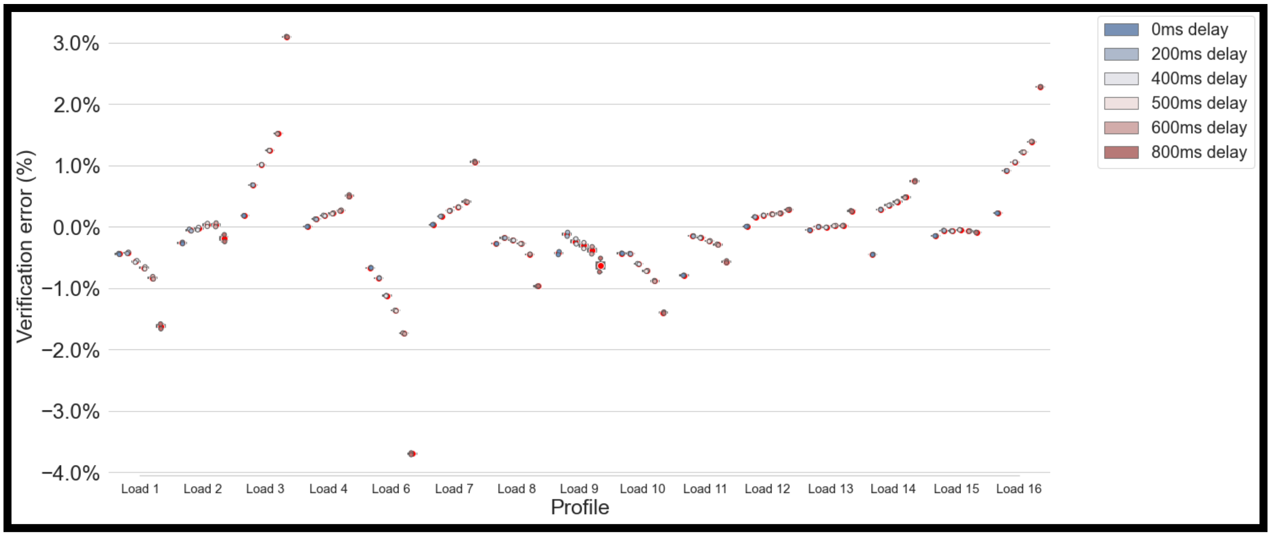

*Figure 3.11. Assessment errors for **50ms** sampling rate considering different values of delays in the response*

3.3 Downsampling for proportional controllers

This section aims at investigating the impact of lower sampling rates on the assessment error for proportional responsive technologies. The methodology applied in this section uses an assessment window based on the FDT. The analysis is based on the active power profiles of three different batteries responding to real-life events.

It should be noted that:

- The responses of these batteries can be captured within the assessment window starting from FDT;
- The highest available sampling rate is used as the benchmark to calculate the verification delivery based on the trapezoid rule in the 1s assessment window;
- The starting point is located using the RoCoF-based method;
- The highest available sampling rate is 10ms for Battery 1 and Battery 3, and 20ms for Battery 2;
- The response of battery 3 is analysed for two independent frequency events.

The results for the assessment errors of lower sampling rates for batteries are shown in Figure 3.12. These results also include the assessment errors for 20ms compared to the benchmark of 10ms for Battery 1 and Battery 3. The assessment error of 20ms for Battery 2 is zero, as the highest available sampling rate for the benchmark is also 20ms, and this result is included in Figure 3.12 for the sake of completeness.

Battery 2 has a lower benchmark sampling rate than Battery 1 and Battery 3, so when downsampling the profile of Battery 2, the rate of reduction in granularity of the samples is lower. On the hand, for Battery 1 and Battery 3, more reduction in the granularity of samples occurs comparing the lower sampling rates such as 200ms with the benchmark of 10ms. However, it can be noted that lower sampling rates introduce higher assessment errors for Battery 2. For a sampling rate of 200ms, the maximum absolute errors of Battery 1 and Battery 3 are limited to 4%, while for Battery 2, it can reach 8%. For the 50ms sampling rate, the maximum absolute assessment error for all Batteries is lower than 1%.

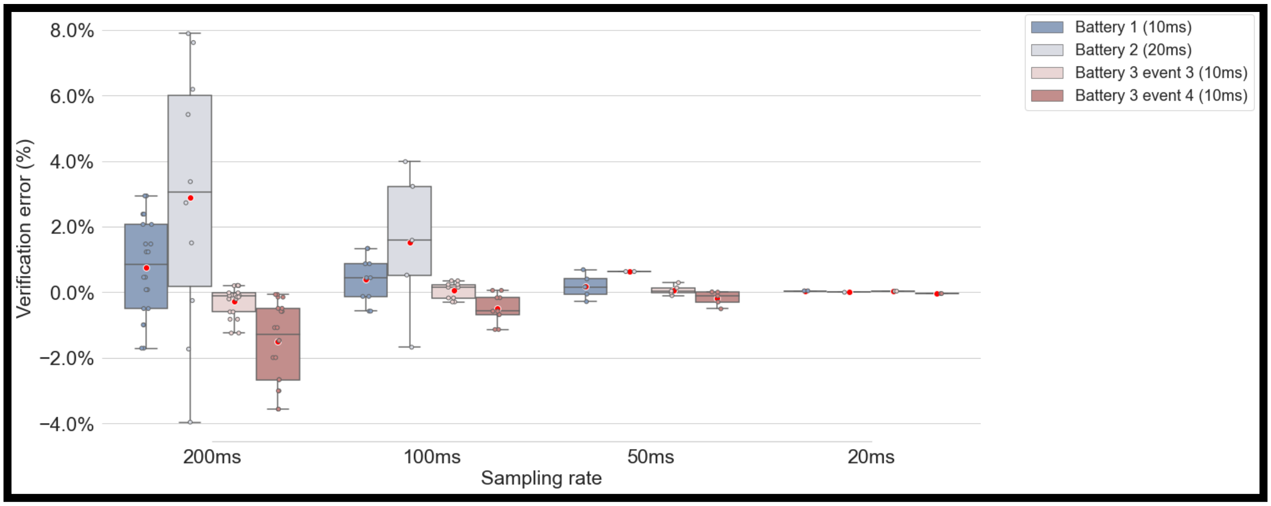

Figure 3.12. Error distribution of lower sampling rates for batteries in the assessment case based on FDT

As mentioned, Battery 2 has a lower sampling rate for the benchmark, yet it has a higher error for lower sampling rates. One of the contributing factors to the higher error for Battery 2 might be relatively fast variations in the response. With these variations in the response, it is less likely that lower sampling rates be able to follow the actual response shape, resulting in a higher likelihood of more approximations made by lower sampling rates. To further explore this, the response shape for different sampling rates of Battery 1 and Battery 2 are depicted in Figure 3.13. As shown in Figure 3.13, Battery 1 has a smooth response profile, so lower sampling rates are able to follow the response shape without introducing much approximation of the response shape. On the other hand, some variations are observed in the response profile of Battery 2 that introduce errors when using lower sampling rates to represent the trajectory of the response. These variations in the response of Battery 2 may contribute to higher assessment error for lower sampling rates.

As mentioned, more and faster variations during the response increase the likelihood of more approximations made by lower sampling rates. However, it should be noted that these approximations may not necessarily result in relatively high assessment errors. In fact, in some cases, the approximations might cancel each other out in such a way that the impact on verification error could be relatively limited. Therefore, no general numerical conclusion can be drawn when quantifying the impact of a highly variable response on the assessment error. On the other hand, as using higher sampling rates generally reduces the likelihood of approximations, better verification error performance can be expected.

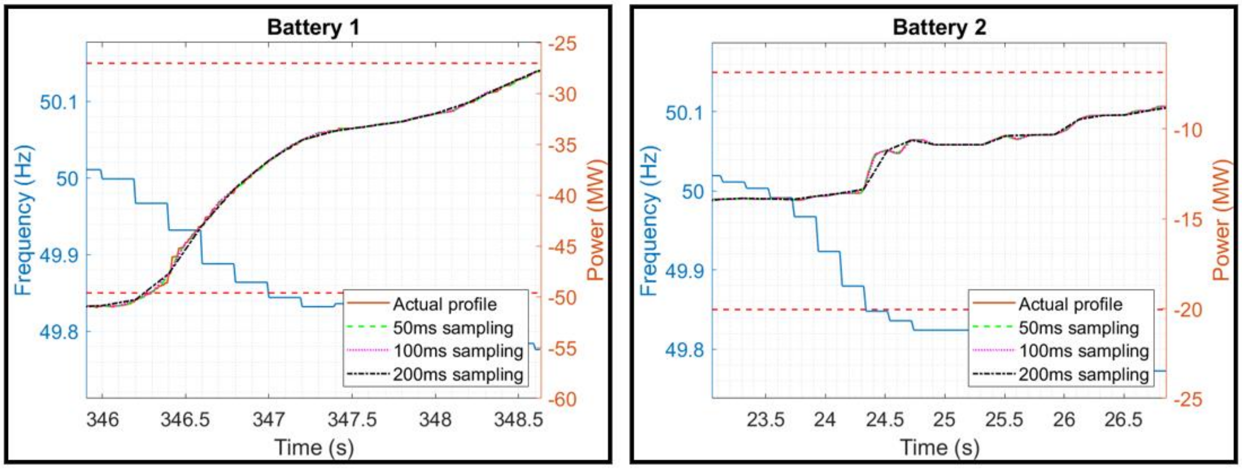

Figure 3.13. Response shape with different sampling rates for Battery 1 and Battery 2

4 Case studies for 0.5s service

In this section, we discuss the results for the 0.5s service. The methodology used to conduct the assessment is presented in Section 2, and it considers an assessment window of 0.5s.

4.1 Downsampling for switched loads

This case study aims to analyse the impact of different sampling rates for switched loads based on the rolling assessment window defined in Section 2.3.2, considering that the very fast FCAS service only involves a period of 0.5 seconds of delivery. The analysis carried out to obtain the potential *error distribution* introduced by downsampling considers the same fifteen anonymised switched response profiles provided by AEMO that were used in Section 3.1. In this case too we study a family of response profiles obtained by shifting the first sample within the set of original samples included in the first interval of the lower sampling rate. This approach yields a distribution of results for the assessment error that we represent by means of a boxplot. The benchmark for this study is the highest available sampling rate (20ms for switched loads), and the calculation is based on the trapezoid rule.

The 0.5s service is subject to the same issues as the 1s service in the sense that a lower sampling rate is likely to fail to capture the real shape of the response, thus resulting in potentially significant errors. However, and as it will be seen throughout the analysis, a shorter assessment window generally worsens the performance of lower sampling rates. In fact, as it was pointed out earlier in this report, the main source of higher approximations is associated with high-ramp switched responses, for which sparser samples can miss relatively sharp edges of the response. This behaviour persists for the 0.5s service. However, since the duration of the service is smaller, the approximations from lower sampling rates induce a larger relative error.

As seen in Figure 4.1, considering the 200ms sampling rate for all load profiles introduces a large assessment error in all the cases under consideration. The absolute value of the average error across all profiles is in the order of 25%, and its maximum absolute value in some profiles can exceed 35% for the 200ms sampling rate. These results largely exceed an absolute average error of 2% and a maximum absolute error of 8% observed for the 1s service in Figure 3.1. It is worth highlighting that the loads under consideration display a similar behaviour relative to one another when describing the error magnitude and distribution: the loads that displayed the lowest/largest errors for the 1s service also correspond to the loads with the lowest/largest errors for the 0.5s service.

If we now focus our attention on the assessment that considers a sampling rate of 100ms (see Figure 4.2) it is possible to see that the magnitude and the distribution of the assessment error decrease relative to the errors seen for 200ms, but they substantially increase compared to the errors observed for the 1s service, as seen in Figure 3.2. The maximum absolute error for the 100ms sampling rate using a 0.5s window can exceed 8%, which contrasts with the close to 4% absolute error associated with the same sampling rate for the 1s case. The analysis for 50ms sampling rate is similar (see Figure 4.3), with a maximum absolute error of almost 1.5%, which almost doubles the maximum error seen for the 1s service, as depicted in Figure 3.3.

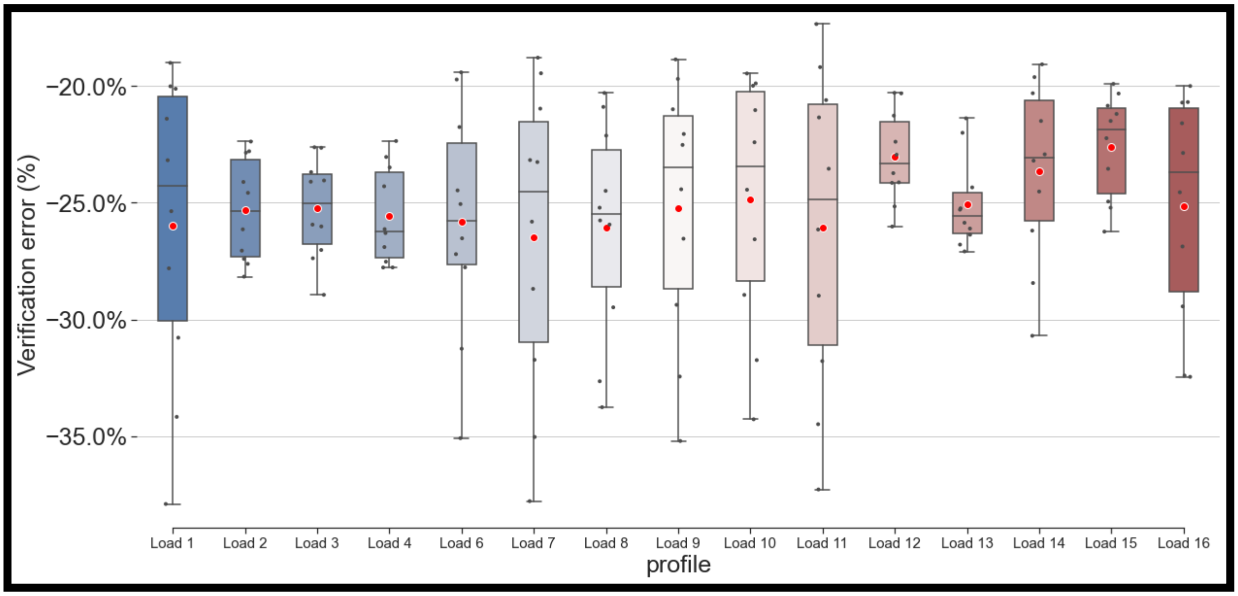

*Figure 4.1 Error distribution of **200ms** sampling rate for different switched response profiles, 0.5s service.*

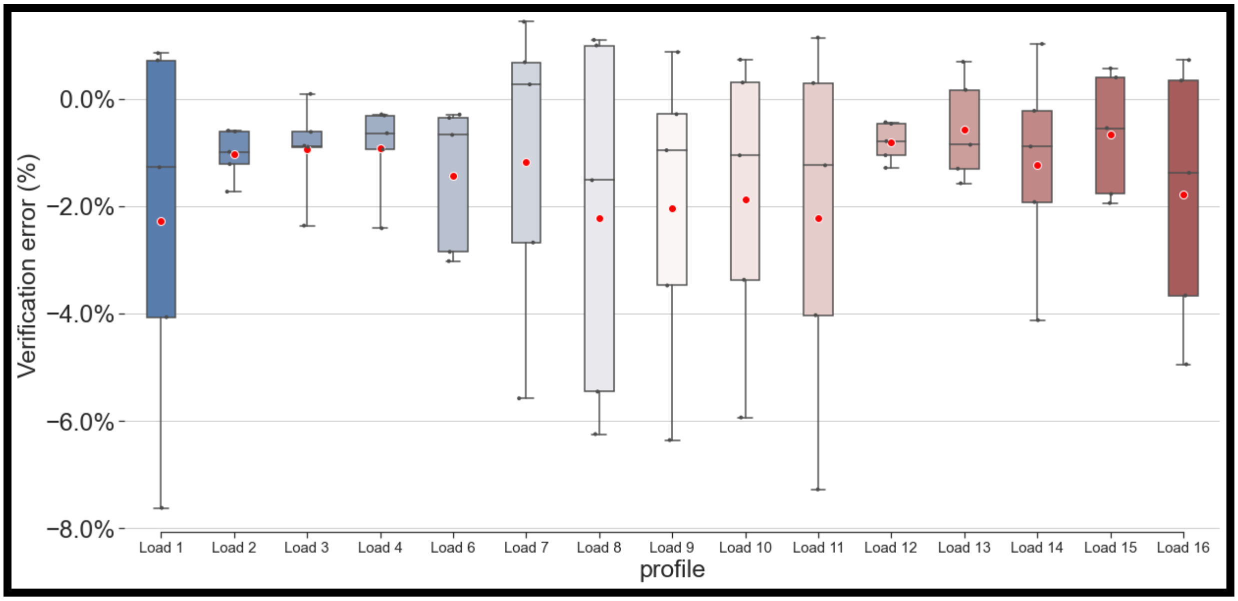

*Figure 4.2 Error distribution of **100ms** sampling rate for different switched response profiles, 0.5s service.*

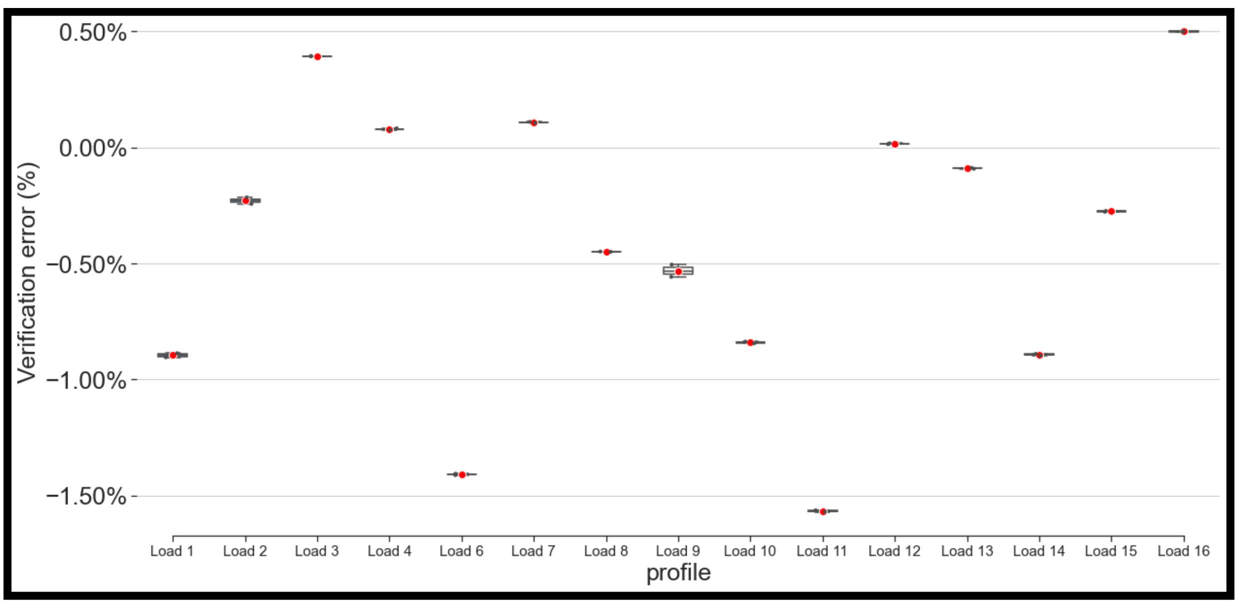

*Figure 4.3 Error distribution of **50ms** sampling rate for different switched response profiles, 0.5s service.*

It should be noted that there is a clear difference between the results for 0.5s and 1s cases when considering 200ms sampling rate. As we already discussed, the error associated with the 0.5s assessment window is naturally higher due to the reduction of the total area that is being assessed and the persistence of the error associated with the approximation of the response shape. However, for the 200ms sampling rate, this is not the only factor in play, as shown in Figure 4.4. When this figure is compared to Figure 3.4, it is evident that the error distributions associated with the 200ms case in the 0.5s analysis display a particularly large drift compared to the 1s results.

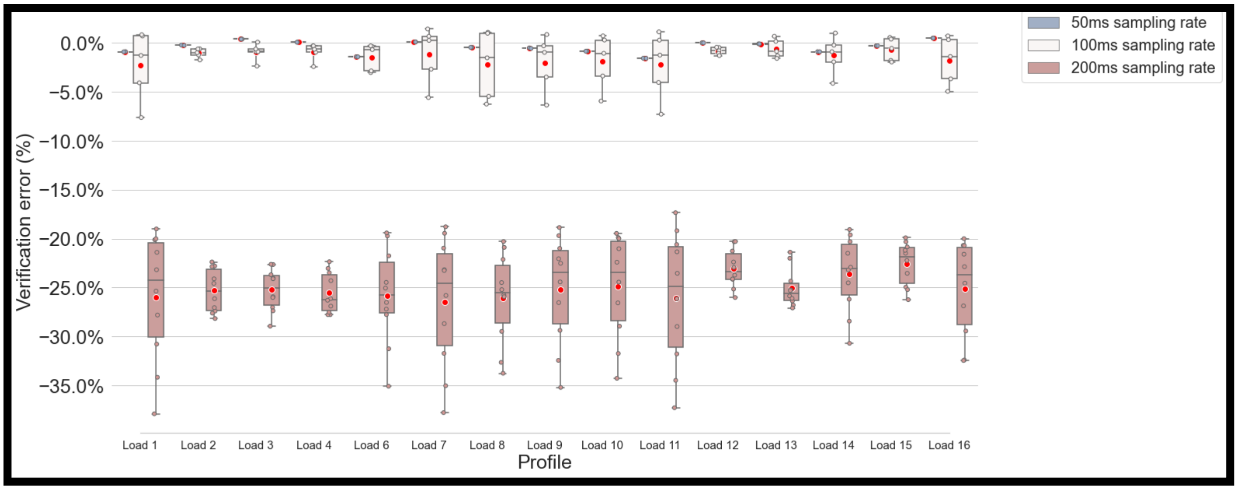

Figure 4.4 Error distribution of different sampling rates for all switched response profiles, 0.5s service.

These larger errors stem from the way samples are selected for the assessment. In the case of 200ms sampling rate, the 0.5s assessment window only enables capturing three samples, potentially leaving a fifth of the response unaccounted for. This uncaptured area naturally introduces another approximation in the area calculated as the Very Fast FCAS contribution, thereby increasing the assessment errors for 200ms sampling rate. Sampling rates of 50ms and 100ms are divisors of 500ms, which create samples that, in principle, can cover the full window of 0.5s. This issue was not experienced in the 1s assessment window, as all the sampling rates considered (50ms, 100ms and 200ms) are divisors of 1000ms.

4.2 Response delay for switched loads

As presented in Section 2.3.2 and later seen for the results introduced in Section 3.2, the response of the switched loads used to conduct this study displays a considerable delay from FDT, which leaves some or all parts of the response uncaptured by the 1s assessment window. This problem becomes even worse in the case of the 0.5s assessment window.

Recapping the methodology adopted: the response delay corresponds to an offset in the starting point of the rolling assessment window, and a parametric analysis is conducted on different delay values of 100ms, 200ms, 300ms, and 400ms. For example, when studying a 300ms delay in the response, an offset of 300ms is considered for the rolling window to start 300ms earlier than its conventional starting point (as defined in Section 2.3.2).

This study encompasses a comparison between a reference case of 0ms delay (the assumed delay value used in the study presented in Section 4.1) and the four predefined delay values in response profiles described before. Each delay is tested for the three sampling rates used across this study (200ms, 100ms, and 50ms). In the case of the assessment window of 0.5s, the response delay not only shows an increase in the error distribution spread, but also results in the maximum errors observed. This is seen across all sampling rates of 200ms, 100ms, and 50ms, as shown in Figure 4.5, Figure 4.6, and Figure 4.7, respectively. For this assessment window, a late initialisation of the response with 400ms delay and a lower sampling rate of 200ms can lead to a maximum absolute error exceeding 80%. It is to be noted that for the case of 200ms sampling rates, the error distributions are negative, which is an indication of underestimations due to the uncaptured area of the response. Furthermore, as shown in Figure 4.6, the maximum absolute assessment error with a response delay of 400ms can reach some 40% when using 100ms sampling rate. For a response sampled at 50ms with 200ms delay, the absolute error can exceed 2%.

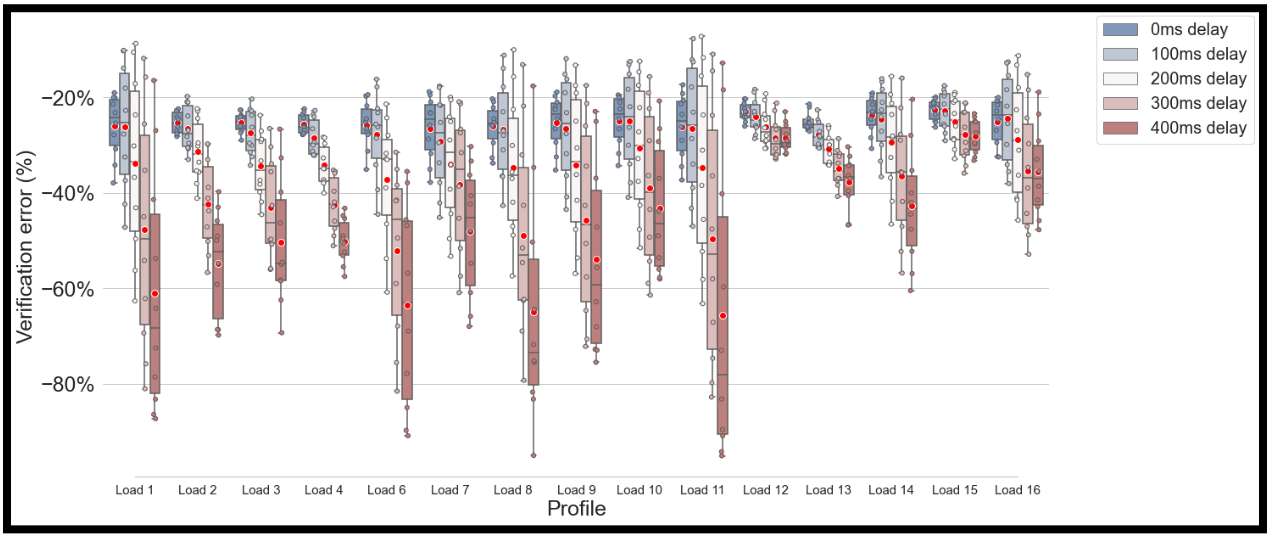

*Figure 4.5 Assessment errors for **200ms** sampling rate considering different values of delays in the response, 0.5s service*

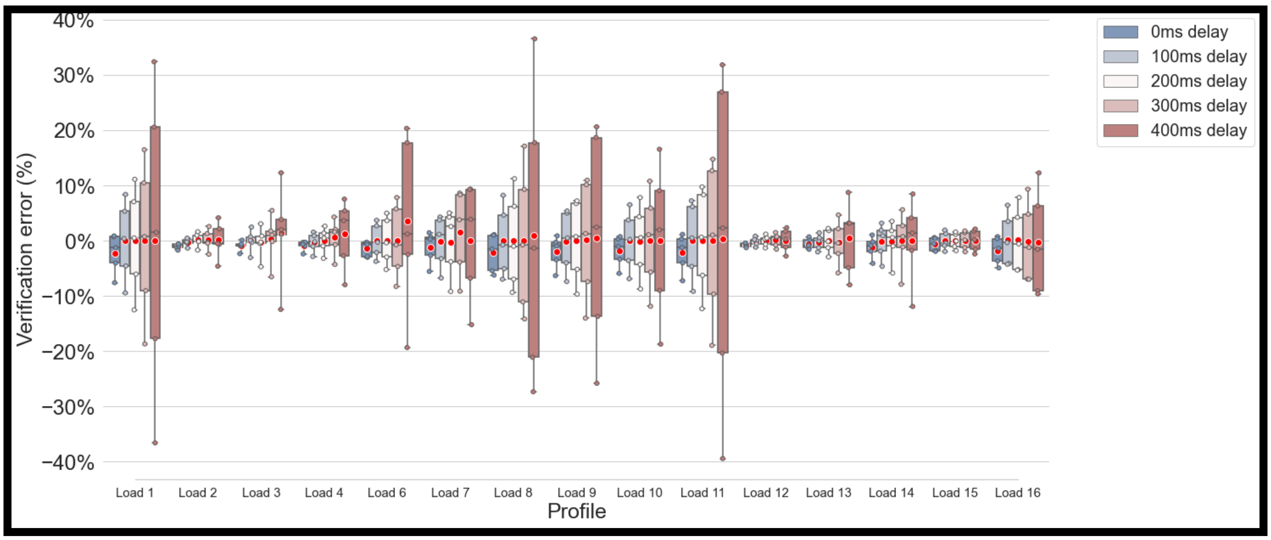

*Figure 4.6 Assessment errors for **100ms** sampling rate considering different values of delays in the response, 0.5s service*

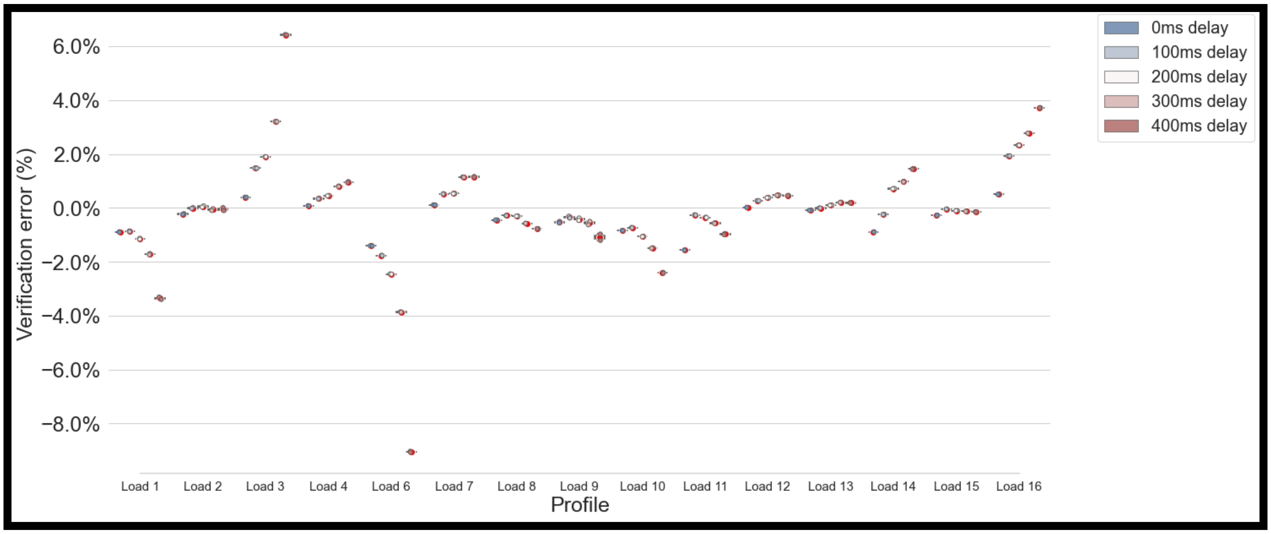

Figure 4.7. Assessment errors for ***50ms*** *sampling rate considering different values of delays in the response, 0.5s service*

4.3 Downsampling for proportional controllers

In this section, we investigate how lower sampling rates impact the assessment error for proportional responsive technologies. An assessment window based on the FDT is used in the methodology. The following analysis considers the active power profiles of three different batteries responding to real-life events.

It should be noted that:

- The batteries' responses are captured within the assessment window starting from FDT;
- In the benchmark, the highest available sampling rate is considered in order to calculate the assessment error based on the trapezoid rule in the 0.5s time window;
- The RoCoF-based method is employed to identify the starting point of the assessment;
- The highest available sampling rate is equal to 10ms for Battery 1 and Battery 3, while it is equal to 20ms for Battery 2;
- The response of battery 3 is evaluated for two different frequency events.

Figure 4.8 illustrates the assessment errors for lower sampling rates for batteries. Also, the assessment errors for 20ms are compared to the benchmark of 10ms for Battery 1 and Battery 3. The assessment error of 20ms for Battery 2 is implicitly zero since the highest available sampling rate is also equal to 20ms for the benchmark.

The results point out that the impact of downsampling on the assessment error is not intuitive. In fact, Battery 2 has a lower benchmark sampling rate than Battery 1 and Battery 3. Therefore, downsampling of the Battery 2 profile results in a lower rate of reduction in granularity of the samples. Comparing the lower sampling rates (e.g., 200ms) with the benchmark of 10ms for Battery 1 and Battery 3, there is more reduction in the granularity of samples. However, lower sampling rates result in higher assessment errors for Battery 2. For a sampling rate of 50ms, the maximum absolute assessment error for Battery 1 is around 0.91%, while for Battery 2, the absolute error can reach 1.28%. As already discussed, one of the potential contributing factors to the higher absolute error for Battery 2 might indeed be fast variations in the response. Finally, considering a 50ms sampling rate, the absolute assessment errors are less than 2% for all batteries.

Considering the results illustrated in Figure 4.8, the following observations can be made:

- The sampling rate of 200ms does not seem to be suitable for 0.5s service assessment since it can result in a high absolute error of up to 33%;
- Considering the sampling rates of 100ms and 50ms, the absolute error is limited to 8% and 2%, respectively;
- Comparing the results with the ones for the 1s service assessment (Section 3.3), the absolute error has almost doubled for 100ms and 50ms sampling rates.

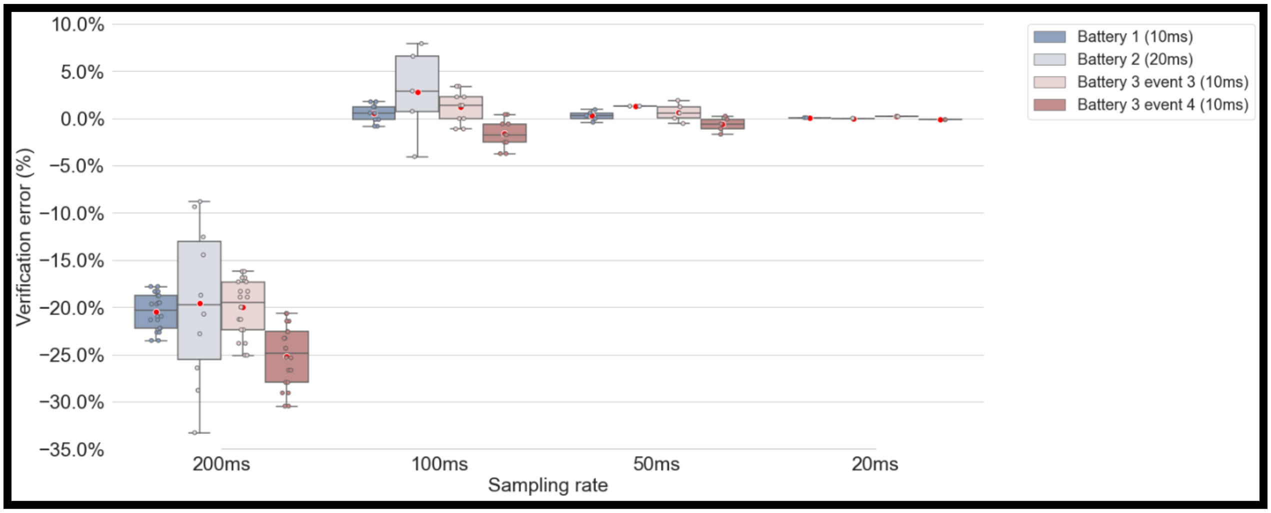

Figure 4.8 Error distribution of lower sampling rates for batteries in the assessment case based on FDT considering 0.5s service

5 Conclusion and recommendations

The effect of lower sampling rates on the Very Fast FCAS assessment error assessment was discussed in this report. The highest available sampling rate (10/20ms) was considered for the benchmark. The Very Fast FCAS delivery was calculated based on the trapezoid rule, and the RoCoF-based method was used to locate the FDT. Four case studies were designed to conduct different analyses for both switching and proportional controllers.

The results for 1s studies can be summarised as follows:

- Decreasing the sampling rate for switched loads from 20ms to 200ms can introduce absolute assessment errors of more than 8%, while by using 100ms, the absolute assessment error may be limited to 4%. By decreasing the sampling rate from 20ms to 50ms, the magnitude of the assessment error is still limited to 1%.
- Higher delays in response combined with lower sampling rates can significantly increase the assessment error for switched responses. The absolute assessment error of switched loads with a 200ms sampling rate and a very late response of 800ms can exceed 40%. On the other hand, considering the sampling rate of 50ms with a response delay of 600ms or less, the magnitude of the assessment error may still be limited to 2% for switched loads.

- In the case of the batteries equipped with proportional controllers considered in this study, the absolute assessment error can increase to 8% when using a lower sampling rate of 200ms. This error might be limited to 4% and 1% when using 100ms and 50ms sampling rates, respectively.

The results for 0.5s studies can be summarised as follows:

- Decreasing the sampling rate from 20ms to 50ms and 100ms, the absolute assessment errors are limited to 2% and 8%, respectively. However, lowering the sampling rate to 200ms could potentially introduce an absolute error exceeding 35%.
- The absolute assessment error of switched responses sampled at 200ms with a very late response of 400ms could exceed 80%. Furthermore, the absolute assessment error could go beyond 2% for switched loads considering a sampling rate of 50ms with a response delay of 200ms.
- Lowering the sampling rate for batteries to 100ms and 50ms leads to absolute assessment errors within 8% and 2%, respectively. However, downsampling to 200ms might bring about assessment errors of magnitude higher than 30%.

As key numerical results, the largest absolute value of the percentage errors across different sampling rates observed for both 1s and 0.5 services are summarised in Table 5.1 (switched loads) and Table 5.2 (proportional controllers).

Table 5.1 Largest absolute value of percentage assessment errors (relative to a 20ms sampling reference) for the switched controllers analysed

Sampling rate/ms	**0.5s service**				**1s service**			
	Delay – 0 ms	**Delay - 200 ms**	**Delay - 300 ms**	**Delay - 400 ms**	**Delay – 0 ms**	**Delay - 200 ms**	**Delay - 500 ms**	**Delay - 800 ms**
50	1.57	2.46	3.87	9.07	0.79	0.92	1.37	3.71
100	7.62	12.54	18.99	39.47	3.78	4.67	7.38	17.63
200	37.9	63.17	82.77	95.05	8.61	11.21	17.83	45.32

Table 5.2 Largest absolute value of percentage assessment errors (relative to a 20ms/10ms sampling reference)) for the proportional controllers analysed

Sampling rate/ms	**0.5s service**	**1s service**
20	0.18	0.04
50	1.89	0.69
100	7.90	3.98
200	33.28	7.88

Key remarks from the analyses performed are as follows:

- Relatively high-error cases for switched loads are associated with high-ramp switched response profiles. On the other hand, low-error cases might be associated with low-ramp switched response profiles. This trend is observed to be consistent in both 1s and 0.5s analyses. However, this remark only reflects the response profiles analysed in this study and might not necessarily be generalised to other switched loads with potentially different response profiles.

- Initiating a response with a considerable delay in conjunction with lower sampling rates may bring about significant assessment errors for switched responses.
- For switched loads, the rolling assessment window is defined independently of the frequency settings and only for the purpose of a mathematical assessment of the impact of lower sampling rates. However, more analyses based on the original assessment window (starting from FDT) and actual frequency settings are required to create more precise estimations of the actual verification errors for switched responses.
- The impact of downsampling on the assessment error is not intuitive. In other words, the granularity of samples in the assessment window may not be the main contributing factor to the assessment error when changing the sampling rate. A response profile may have a lower sampling rate for the benchmark, yet it may display a higher assessment error for lower sampling rates. This is due to the fact that other contributing factors, such as response shape, fast variations, and response delay, as per our discussions, can have a significant impact on the assessment error.
- If the rate of change of the response is higher than the sampling rate, this may escalate or shrink the assessment error introduced from lower sampling rates. That is, changes in the response occurring at a higher rate than the sampling rate can increase the likelihood of approximations from response shape made by lower sampling rates. However, the impact of these approximations on the assessment error is not intuitive. Hence, it is difficult to draw a general numerical conclusion about the impact of fast response variations on the assessment error.
- Overall, the absolute assessment error may exceed 8% in delivering 1s Very Fast FCAS when using a 200ms sampling rate for both switched and proportional controllers, while for the 0.5s case, this figure can go beyond 35%. The absolute assessment error for the 1s service is limited to 4% and 1% when lowering the sampling rate to 100ms and 50ms, respectively, while these errors almost double for the 0.5s case for both switched loads and batteries.
- The analyses conducted in this report should be further expanded to include the contribution of the compensation factor in the assessment of the actual verification error for lower sampling rates. The compensation factor is used to scale up the response profile to avoid under-valuation of the provider's performance in the verification process. This compensation factor is mainly a function of system frequency variations and a standard frequency ramp as defined in [7]. This analysis could also include a narrow deadband compensation factor that is being considered by AEMO [6] for technologies with a deadband within NOFB.
- The discussions and remarks made in this report are derived based on the data provided by AEMO for the studies conducted here. It is advisable to revisit the findings of this study in the future once higher amount of data and a wide array of response profiles are available from participants in the Very Fast FCAS market.

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