# APPLICATION NOTE: POWER MEASUREMENTS ERROR

## Methodology

### Frequency Measurements (20ms)

This study uses 20ms frequency measurements in Queensland and New South Wales during the frequency disturbance that happened at 14:06 on 25th May 2021 following the loss of Callide C coal plant. These measurements were provided by the Australian Energy Market Operator (AEMO). They show that the frequency disturbance lasted about 15 seconds in QLD and 2 seconds in NSW. Therefore, the 60sec period following the Frequency Disturbance Time considered for the verification of performance for Fast Services, as per section 3.7.1. (a) (i) of the Market Ancillary Service Specification (MASS), covers the entire duration of the frequency disturbances observed in QLD and NSW on 25th May 2021.

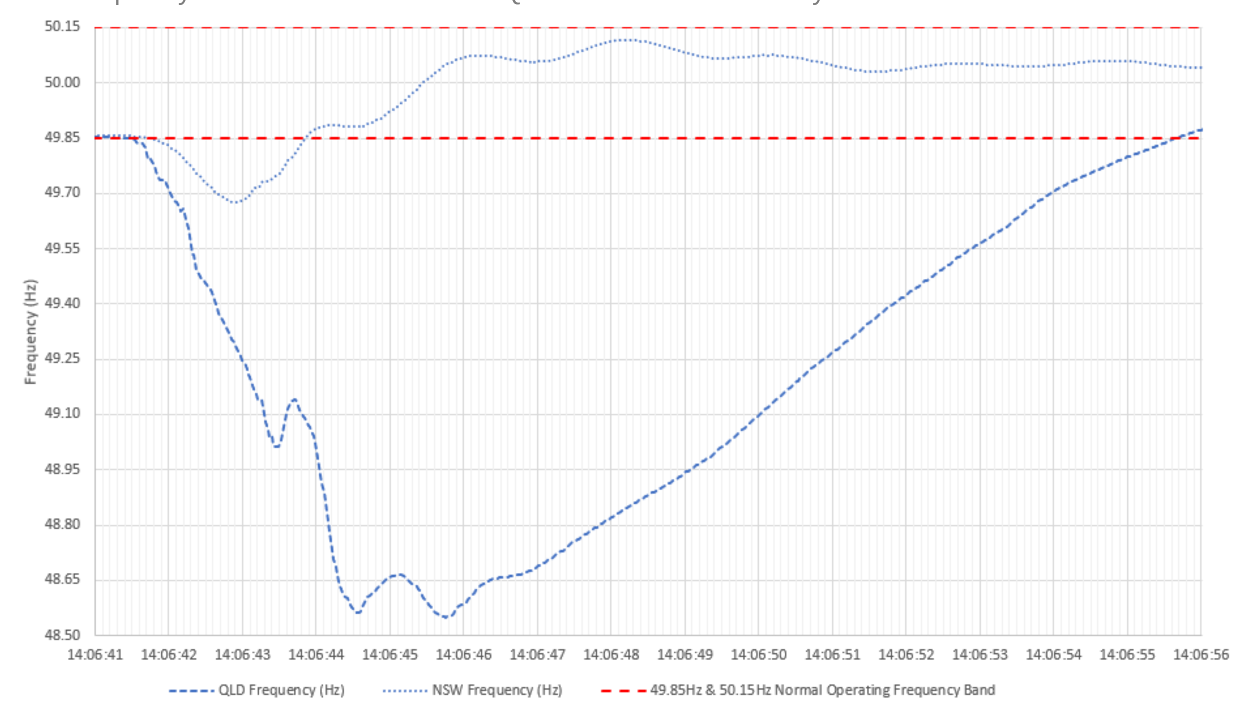


*Figure 1 - AEMO's frequency measurements in QLD and NSW during the 25 May 2021 events (20ms sampling rate)*

### Power Response (20ms)

The response from a 5kW Tesla Powerwall 2 ("Powerwall") registered under Dispatchable Unit ID (DUID) VSSEL1V1 is calculated using the 0.7% droop setting provided to this DUID by AEMO upon registration. The capability of the Powerwall to respond to a frequency deviation was demonstrated during a frequency injection test performed in a laboratory. Figure 2 shows that the Powerwall provides a proportional raise response of 5kW from 49.85Hz to 49.5Hz, and Figure 3 shows a proportional lower response of 5kW from 50.15Hz to 50.5Hz. Both responses start within less than 250ms of the frequency deviation outside of the 49.85Hz-50.15Hz Normal Operating Frequency Band (NOFB). Therefore, a 240ms response time (multiple of 20ms) between the start of the frequency deviation and the start of the power response is introduced in this study.

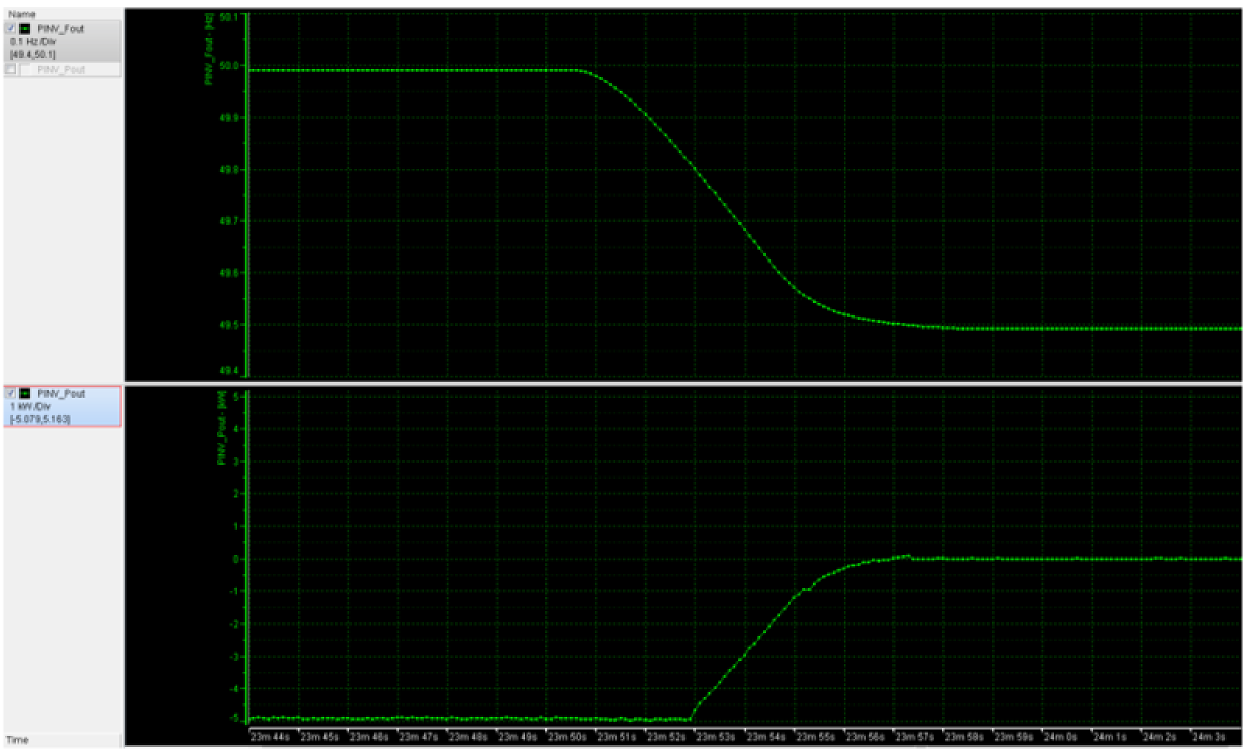


*Figure 2 - Tesla Powerwall 2 Frequency Injection Test Results: 5kW Raise Response*

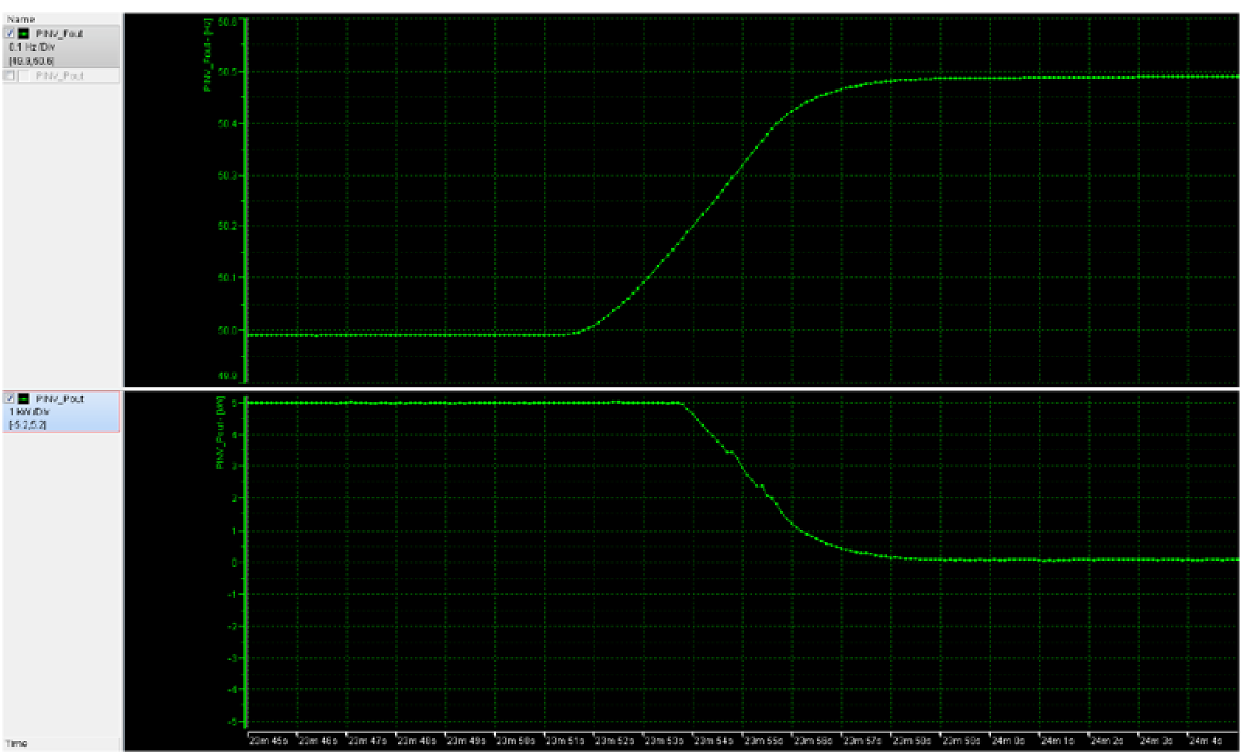


*Figure 3 - Tesla Powerwall 2 Frequency Injection Test Results: 5kW Lower Response*

The Powerwall uses open loop controls to provide contingency FCAS services, whereby the grid-tied Powerwall inverter initiates a power response as soon as it detects a frequency deviation. The Powerwall power response therefore does not depend on frequency measurements from a meter. As a result, no random variable is introduced to account for frequency measurement margin of error. However, a random variable is introduced for each site to account for a ≤2% of measurement range margin of error for power measurements ("error random variable") as allowed by the MASS. For a 5kW Powerwall, a ≤2% of measurement range margin of error corresponds to a ≤100W margin of error. The 20ms resolution power response is then calculated for 1000 Powerwalls.

## Sampling Rates (100ms, 200ms, 500ms and 1sec)

For each of the 1000 power responses, another random variable is introduced to determine when power is polled ("polling random variable"). For a given Powerwall, in the 100ms sampling rate scenario, the first polling happens randomly during one of the first five 20ms intervals, and every 100ms after that. The response of all 1000 Powerwalls is then aggregated using one of two aggregation methods:

- The truncated method adds the responses with a time stamp of 20ms, 40ms, 60ms, 80ms or 100ms under time stamp 100ms, the responses with a time stamp of 120ms, 140ms, 160ms, 180ms or 200ms under time stamp 200ms, etc…
- The rounded method adds the responses with a time stamp of 60ms, 80ms, 100ms, 120ms or 140ms under time stamp 100ms, the responses with a time stamp of 160ms, 180ms, 200ms, 220ms or 240ms under time stamp 200ms, etc…

There are three other sampling rate scenarios, which all use the same method: 200ms, 500ms and 1sec. Figure 4 illustrates the 1 sec sampling rate scenario using the truncated method at three sites without introducing a 240ms response time and the error random variable, for clarity. Polling for each site happens at random and distinct 20ms intervals within a 1000ms interval. The 1 sec power response is then calculated as the *average* of the three distinct 20ms measurements for illustration purposes – as described above, to calculate the aggregate response, these values are actually *summed*.

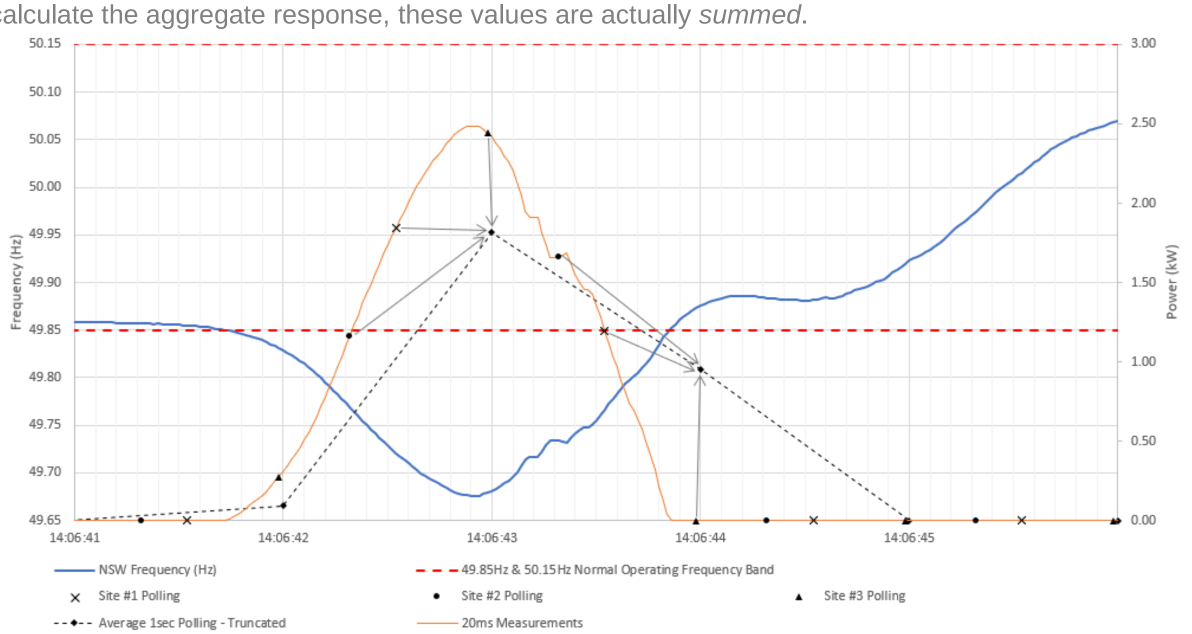


*Figure 4 - Aggregation method for three sites (random 20ms polling, 0ms response time, no error random variable, truncated)*

Figures 5 and 6 compare the *target* response – which has 0ms response time, and no error and polling random variables – to the *actual* responses with varying sampling rates for 1000 Powerwalls using the truncated method. For avoidance of doubt, the 20ms *actual* response includes the 240ms response time and the error random variable, but it cannot include the polling random variable, contrary to the 100ms, 200ms, 500ms and 1sec scenarios.

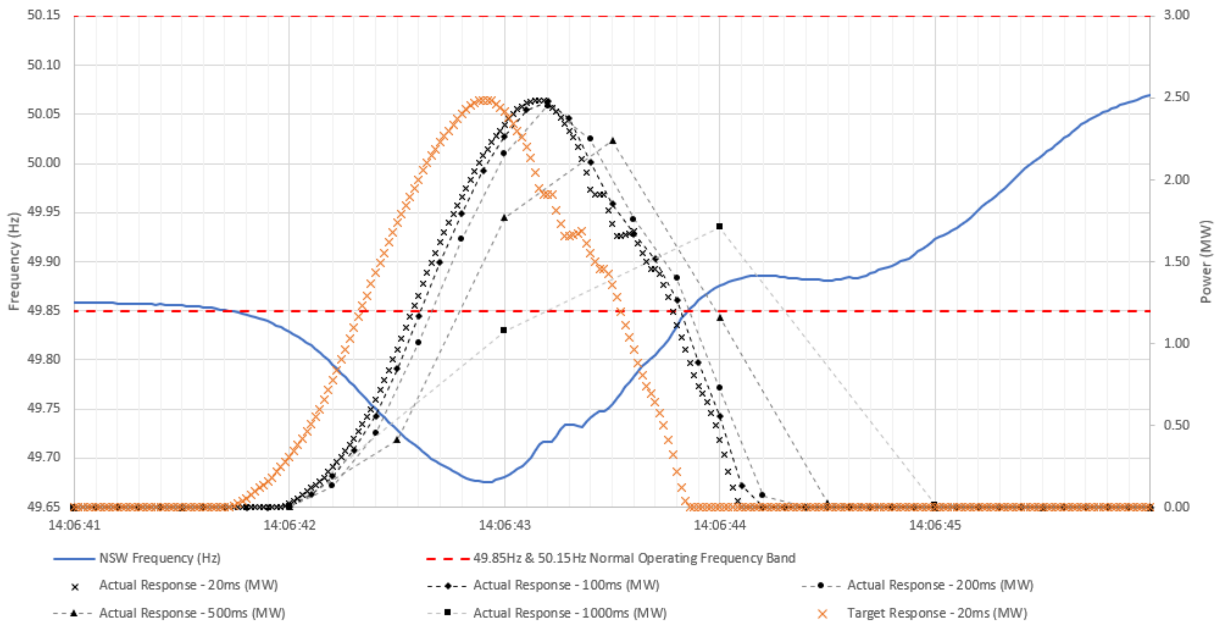


*Figure 5 - Target and actual responses of 1000 Powerwalls in NSW to the 25 May 2021 events (varying sampling rates, truncated method)*

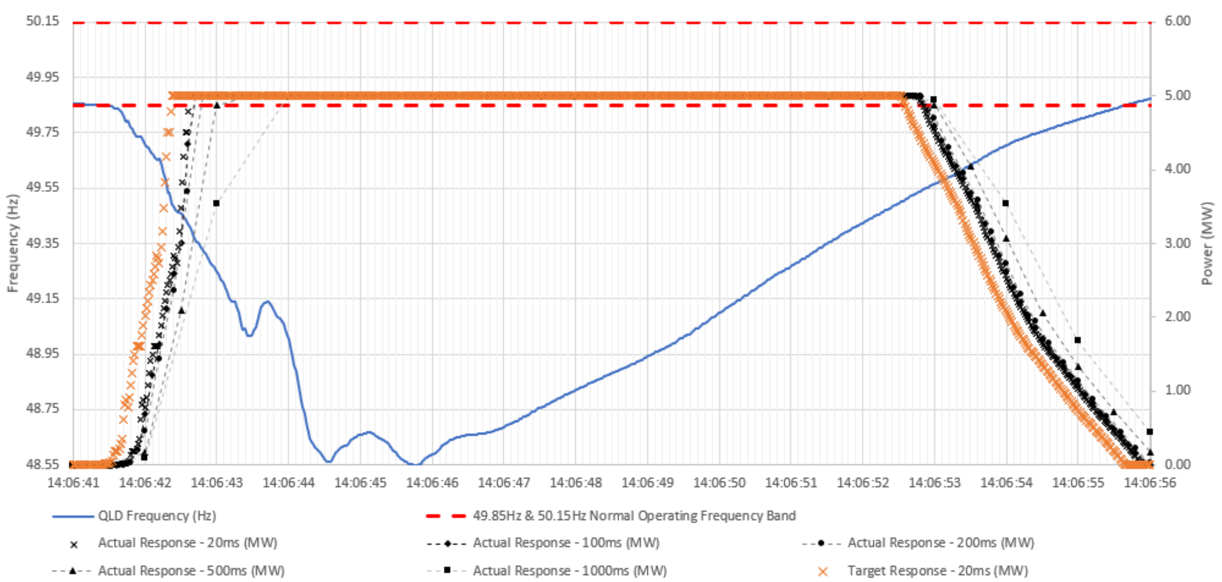


*Figure 6 - Target and actual responses of 1000 Powerwalls in QLD to the 25 May 2021 event (varying sampling rates, truncated method)*

For frequency deviations of short duration, the maximum power measured decreases as the sampling rate decreases due to the aggregation method, as illustrated in Figure 4. This is not the case for longer frequency deviations below 49.5Hz or above 50.5Hz lasting multiple sampling intervals. Indeed, QLD frequency deviation required a full 5kW response over 15 seconds, which means that there were multiple 1-second intervals during which the 5kW response of all 1000 sites could be measured.

## Evaluation Metrics

Two metrics are used to estimate the measurement error between the actual response and the target 20ms response:

- $Energy\ Error_n = \frac{\left(\sum_{i=1}^{q} Actual\ Response_i\right) / \frac{1000\text{ ms}}{Sampling\ Rate} - \left(\sum_{i=1}^{p} Target\ Response_i\right) / \frac{1000\text{ ms}}{20\ ms}}{\left(\sum_{i=1}^{p} Target\ Response_i\right) / \frac{1000\text{ ms}}{20\ ms}}$
- $Power\ Error_n = \frac{\max(Actual\ Response) - \max(Target\ Response)}{\max(Target\ Response)}$

where:

- n = number of Powerwalls (1, 10, 25, 50, 200, 500 or 1000)
- p = 750, which is the number of 20ms intervals over 15 seconds
- Sampling Rate = 20ms, 100ms, 200ms, 500ms or 1000ms
- q = 750 / (Sampling Rate / 20ms), which is the number of intervals over 15 seconds for a given Sampling Rate
- Target Response is the 20ms power response of n Powerwalls calculated using the 20ms frequency measurements and 0.7% droop settings. It does not include the 240ms response time or the error and polling random variables.
- Actual Response is the power response of n Powerwalls calculated using the sampling methodology described above. It includes the 240ms response time and the error and polling random variables, except for the 20ms scenario which cannot include the polling random variable.
- max(Target Response) is the maximum target power response over the 15 seconds interval
- max(Actual Response) is the maximum actual power response over the 15 seconds interval

The energy error formula uses the right Riemann sum method, similar to the FCAS Verification Tool, as AEMO mentions in section 4.1.2. of Amendment of the MASS – DER and General Consultation's Draft Report and Determination published in June 2021.

A 50ms sampling rate scenario is also introduced since the MASS currently requires ≤50ms sampling rate to provide Fast FCAS services. For this scenario, the 20ms frequency data is first up-sampled to 10ms using linear interpolation. It is then down-sampled to 50ms by polling the 10ms frequency data every five intervals starting with time stamp ending in 0ms. A 250ms response time (multiple of 50ms) is then introduced, along with the error random variable, but no polling random variable was introduced since this methodology uses 50ms frequency data.

## Monte Carlo Simulations

Monte Carlo simulations were run in order to assess the impact of the error and polling random variables on the energy error and power error metrics, for each of the six sampling rates and seven quantities of sites. The tables below show the average value of the absolute error in 500 different simulations for each sampling rate x site quantity scenario (that is 21,000 distinct simulations).

## Results

**Energy Error (%)**

| Method | Nb of sites | QLD 20 ms | QLD 50 ms | QLD 100 ms | QLD 200 ms | QLD 500 ms | QLD 1000 ms | NSW 20 ms | NSW 50 ms | NSW 100 ms | NSW 200 ms | NSW 500 ms | NSW 1000 ms |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Truncated | 1 | 1.01% | 1.02% | 1.01% | 0.99% | 1.03% | 1.13% | 1.04% | 0.98% | 0.98% | 1.03% | 2.11% | 5.04% |
| Truncated | 10 | 0.29% | 0.31% | 0.29% | 0.29% | 0.30% | 0.35% | 0.29% | 0.29% | 0.30% | 0.29% | 0.62% | 1.43% |
| Truncated | 25 | 0.18% | 0.19% | 0.20% | 0.19% | 0.19% | 0.21% | 0.18% | 0.18% | 0.18% | 0.19% | 0.39% | 0.88% |
| Truncated | 50 | 0.13% | 0.14% | 0.12% | 0.13% | 0.14% | 0.15% | 0.13% | 0.13% | 0.13% | 0.14% | 0.28% | 0.66% |
| Truncated | 200 | 0.07% | 0.06% | 0.07% | 0.07% | 0.07% | 0.08% | 0.06% | 0.07% | 0.07% | 0.07% | 0.14% | 0.31% |
| Truncated | 500 | 0.04% | 0.04% | 0.04% | 0.04% | 0.04% | 0.05% | 0.04% | 0.05% | 0.04% | 0.04% | 0.09% | 0.20% |
| Truncated | 1000 | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.07% | 0.14% |
| Rounded | 1 | 0.99% | 0.98% | 1.00% | 1.01% | 0.97% | 1.17% | 1.01% | 0.99% | 0.98% | 1.00% | 2.14% | 4.99% |
| Rounded | 10 | 0.31% | 0.29% | 0.27% | 0.29% | 0.30% | 0.34% | 0.29% | 0.30% | 0.30% | 0.30% | 0.63% | 1.39% |
| Rounded | 25 | 0.19% | 0.19% | 0.18% | 0.17% | 0.20% | 0.22% | 0.19% | 0.18% | 0.18% | 0.20% | 0.42% | 0.87% |
| Rounded | 50 | 0.12% | 0.13% | 0.13% | 0.13% | 0.13% | 0.14% | 0.13% | 0.13% | 0.13% | 0.13% | 0.29% | 0.61% |
| Rounded | 200 | 0.07% | 0.07% | 0.06% | 0.06% | 0.07% | 0.08% | 0.07% | 0.07% | 0.07% | 0.07% | 0.14% | 0.32% |
| Rounded | 500 | 0.04% | 0.04% | 0.04% | 0.04% | 0.04% | 0.05% | 0.04% | 0.05% | 0.04% | 0.04% | 0.09% | 0.19% |
| Rounded | 1000 | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.06% | 0.14% |

*Figure 7 - Monte Carlo simulation results for absolute value of energy error (500 simulations)*

**Power Error (%)**

| Method | Nb of sites | QLD 20 ms | QLD 50 ms | QLD 100 ms | QLD 200 ms | QLD 500 ms | QLD 1000 ms | NSW 20 ms | NSW 50 ms | NSW 100 ms | NSW 200 ms | NSW 500 ms | NSW 1000 ms |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Truncated | 1 | 1.00% | 0.99% | 1.00% | 1.06% | 1.04% | 1.04% | 0.96% | 1.01% | 0.99% | 1.51% | 5.89% | 16.83% |
| Truncated | 10 | 0.30% | 0.30% | 0.27% | 0.30% | 0.27% | 0.30% | 0.29% | 0.30% | 0.34% | 1.23% | 9.30% | 30.22% |
| Truncated | 25 | 0.18% | 0.18% | 0.19% | 0.18% | 0.18% | 0.19% | 0.18% | 0.19% | 0.24% | 1.25% | 9.21% | 30.62% |
| Truncated | 50 | 0.14% | 0.13% | 0.13% | 0.13% | 0.13% | 0.13% | 0.13% | 0.13% | 0.19% | 1.26% | 9.33% | 30.64% |
| Truncated | 200 | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.07% | 0.07% | 0.16% | 1.26% | 9.35% | 30.82% |
| Truncated | 500 | 0.04% | 0.04% | 0.04% | 0.04% | 0.04% | 0.04% | 0.04% | 0.04% | 0.16% | 1.25% | 9.35% | 30.96% |
| Truncated | 1000 | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.16% | 1.25% | 9.37% | 30.86% |
| Rounded | 1 | 0.99% | 0.98% | 0.99% | 1.01% | 1.02% | 0.99% | 0.99% | 1.00% | 1.07% | 1.42% | 5.69% | 16.44% |
| Rounded | 10 | 0.30% | 0.30% | 0.28% | 0.29% | 0.30% | 0.31% | 0.29% | 0.30% | 0.70% | 1.51% | 8.89% | 20.50% |
| Rounded | 25 | 0.19% | 0.20% | 0.19% | 0.17% | 0.19% | 0.18% | 0.19% | 0.19% | 0.75% | 1.50% | 9.07% | 20.10% |
| Rounded | 50 | 0.13% | 0.13% | 0.13% | 0.13% | 0.13% | 0.14% | 0.14% | 0.13% | 0.78% | 1.54% | 8.96% | 20.04% |
| Rounded | 200 | 0.06% | 0.07% | 0.06% | 0.06% | 0.07% | 0.07% | 0.06% | 0.07% | 0.81% | 1.55% | 8.98% | 20.12% |
| Rounded | 500 | 0.04% | 0.04% | 0.04% | 0.04% | 0.04% | 0.04% | 0.04% | 0.04% | 0.81% | 1.54% | 9.02% | 20.03% |
| Rounded | 1000 | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.03% | 0.81% | 1.54% | 8.98% | 20.03% |

*Figure 8 - Monte Carlo simulation results for absolute value of power error (500 simulations)*

The energy error is less than the 2% allowable margin of error for power measurements for all scenarios except single sites in NSW with 500ms or 1000ms sampling rates. This means that a sampling rate of 200ms or less ensures that for any number of sites, both energy and power error remain less than 2% for the QLD and NSW frequency deviations, and for the truncated and the rounded methods. A minimum of 1MW is required to register a Virtual Power Plant in the FCAS markets, i.e. no fewer than 200 Powerwalls.

The power error is less than 2% except for 500ms and 1000ms sampling rates in NSW. The power error for 1000ms sampling rate in NSW is lower for single sites than for multiple sites because:
For single sites, the power error can range:

- from +2% if a) the 1sec polling happens during the 20ms interval when the power measurement is highest (2.48kW for a 5kW Powerwall), and b) the power measurement error is +2%

- to -41% if a) the 1sec polling happens during the two 20ms intervals when the maximum value across these two intervals is the lowest (1.50kW), and b) the power measurement error is -2%
- and given the NSW frequency measurements, it is slightly more likely that the 1sec polling of a single site yields a maximum power measurement closer to 2.48kW than to 1.50kW
- as a result, the average absolute value of the power error for a single site is around 17%.

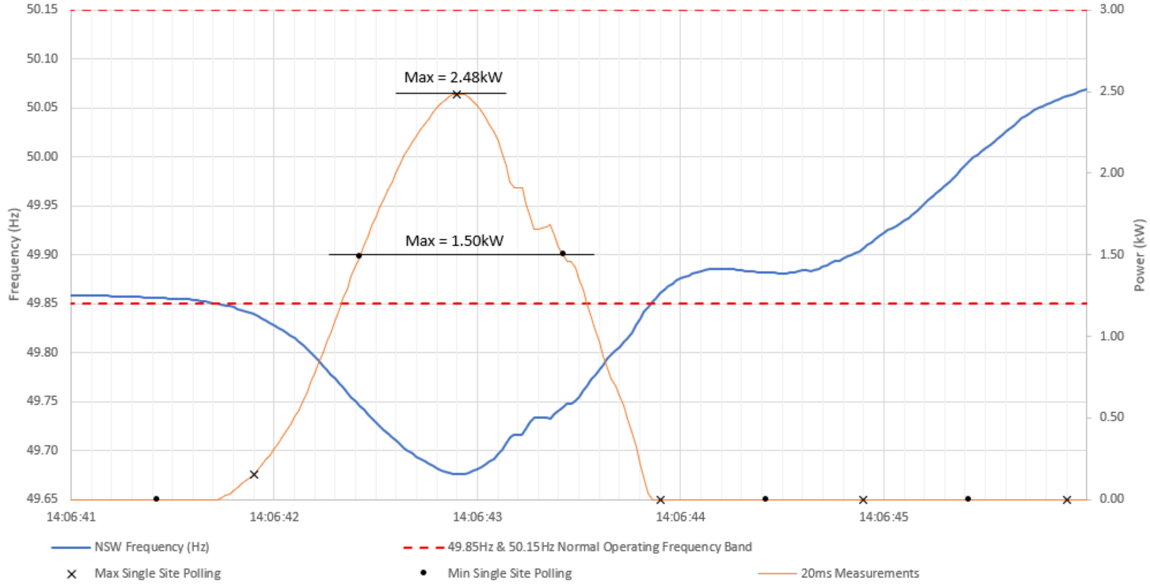


*Figure 9 - Single site power error using NSW frequency measurements (0ms response time, no error random variable)*

For multiple sites, the error depends on the average measurements across these sites, as shown in Figure 4, and varies based on the method (rounded or truncated) and the response time. With the truncated method and a 240ms response time, given that the power response starts with time stamp ending in 20ms (i.e. beginning of a 1sec interval) and lasts for two seconds, the power error is a function of the max of:

- the average of the fifty 20ms power measurements over the first 1-sec interval (1.03kW), and
- the average of the fifty 20ms power measurements over the next 1-sec interval (1.75kW)
- as a result, the average absolute value of the power error for multiple sites is around 31%.

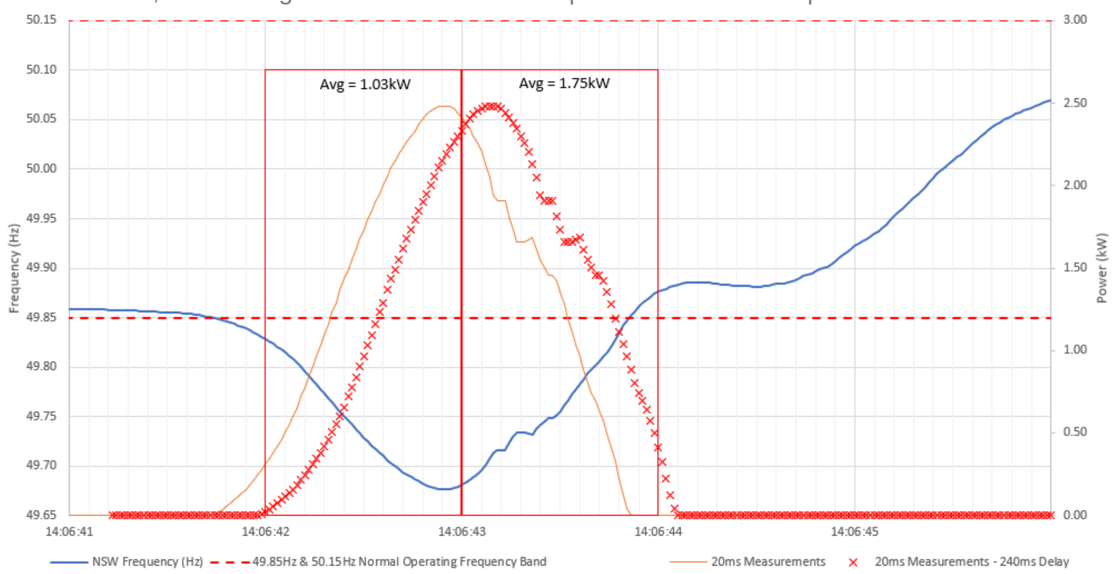


*Figure 10 - Multiple sites power error (NSW frequency, 240ms response time, no error random variable, truncated)*

Lastly, Figures 7 and 8 show that the difference between the truncated and rounded methods is negligible (<0.5%) except for power error with 1sec sampling rate scenario in NSW, as explained above.

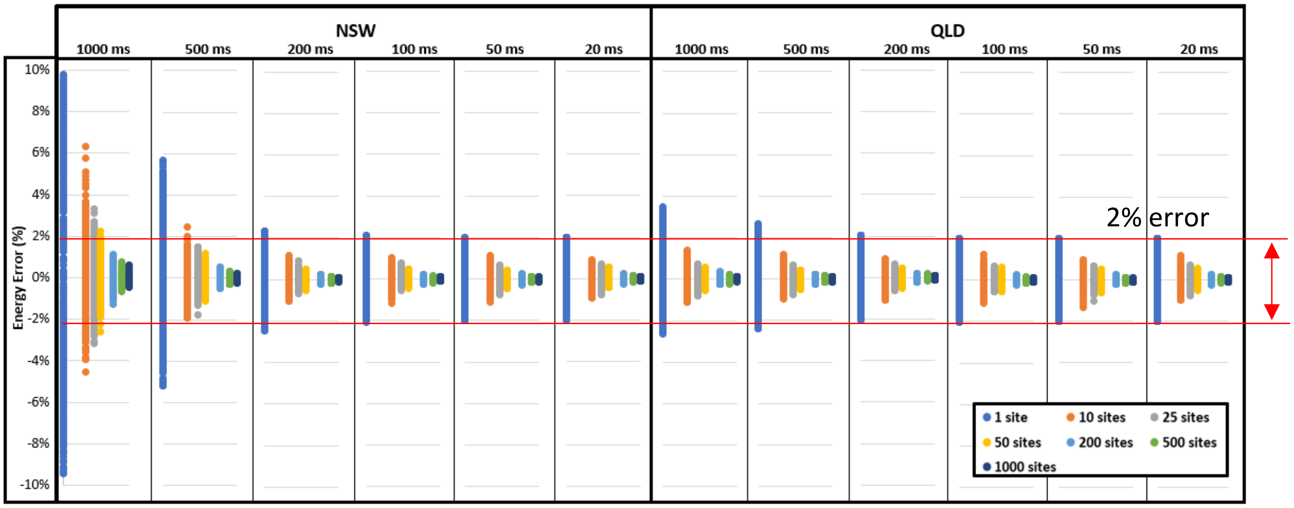


*Figure 11 - Energy error distribution of Monte Carlo simulation using rounded method (500 simulations)*

Figure 11 illustrates the energy error of the 500 Monte Carlo simulations across different sampling rates using the rounded method. As the number of sites and the sampling rate increase, the variance of the energy error reduces significantly. Interestingly, the number of sites has a larger impact on the energy error variance than the sampling rate. Indeed, with 1000 sites, the energy error calculated for each simulation stays well within +/-0.5% for any sampling rate, and with 200 sites (the minimum number of 5kW Powerwalls required to register in FCAS markets) it stays within +/-1% for any of the 500 simulations.

For comparison, in NSW, where the duration of the frequency deviation is short, the energy error for a single site is reduced from +/-10% with 1sec sampling rate to +/-2.5% with 100ms sampling rate; in QLD it is reduced from +/- 4% to +/-2%.

## 0.125Hz/sec Synthetic Frequency Disturbance

A synthetic frequency disturbance was created to estimate the energy error over the first 6 seconds of a frequency excursion (grey area in Figure 12). The frequency starts at 49.85Hz, – the lower band of the NOFB – stays there for 500ms and drops at a rate of -0.125Hz/sec – the Frequency Ramp Rate of the MASS – for 2.8sec until it reaches 49.5Hz. It was assumed that when the frequency reaches 49.5Hz, it does not recover and remains at this value. Given that the Right Riemann sum method over-estimates the energy delivered (i.e. area under the curve) for a raise service (i.e. power response with a positive slope), this can be considered as a scenario illustrating the largest expected energy error.

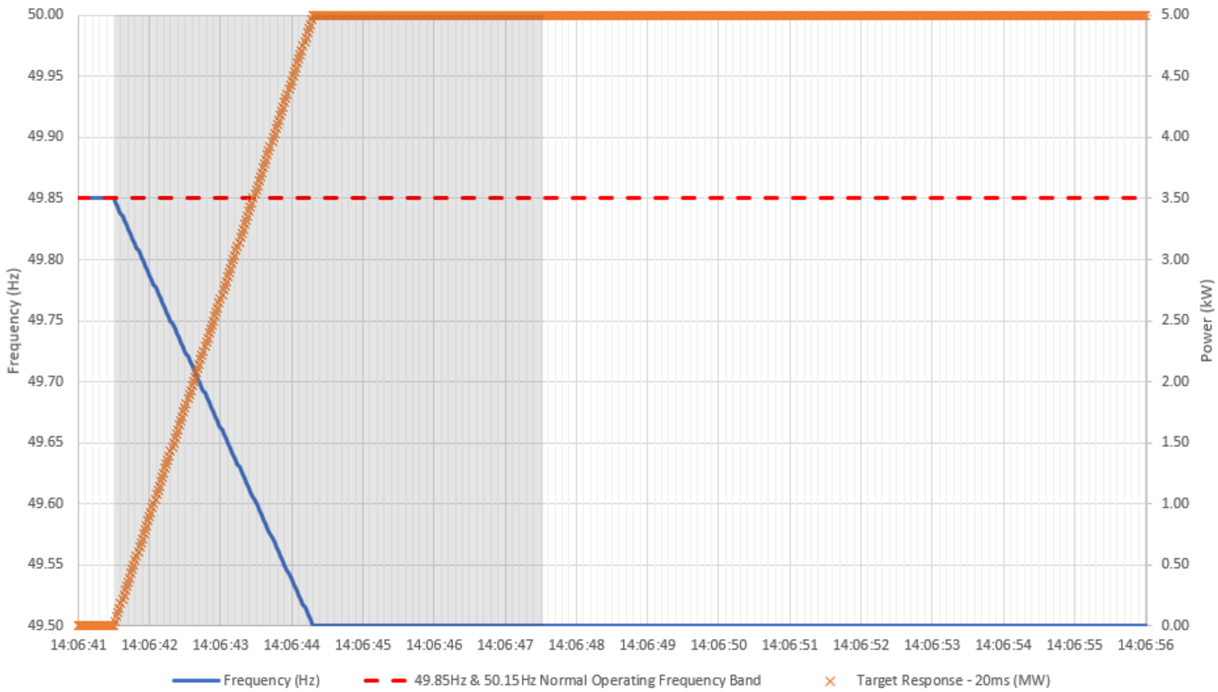


*Figure 12 – Synthetic frequency disturbance using 0.125Hz/sec Frequency Ramp Rate (20ms sampling rate)*

The same method as in the previous sections was then used to estimate the energy error, with a response time of 0ms, in order to isolate the impact of the error random variable and polling random variable as the number of sites increases. Figure 13 below captures the energy error of 500 Monte Carlo simulations for each sampling rate x site quantity scenario (21,000 distinct simulations), for both the rounded and the truncated methods. It is worth noting that the largest possible over-estimate for a single site is of the same order as the over-estimates identified by AEMO in section 4.1.2. of Amendment of the MASS – DER and General Consultation's Draft Report and Determination published in June 2021. This largest possible over-estimate error of 25% for any response time faster than one second is the result of:

- +2% power measurement error, and
- 23% maximum error from a) the random 1-sec polling happening at millisecond 480 while b) the frequency excursion starts at millisecond 500, c) the 0ms response time assumed, and d) the rounding method being used.

However, regardless of the method used, the Monte Carlo simulations show the same trends as for the NSW and QLD frequency excursions: as the number of sites and the sampling rate increase, the variance of the energy error reduces significantly, with the number of sites having a larger impact on the energy error variance than the sampling rate. As such, with 200 sites (the minimum number of 5kW Powerwalls required to register in FCAS markets) and 100ms measurements, all Monte Carlo simulations are within the ≤2% of measurement range margin of error for power measurements allowed by the MASS. And as shown on Figure 14, the average value of the absolute error for 500 Monte Carlo simulations is less than 2% for both methods with sampling rate of 200ms or faster, and for 10 sites or more.

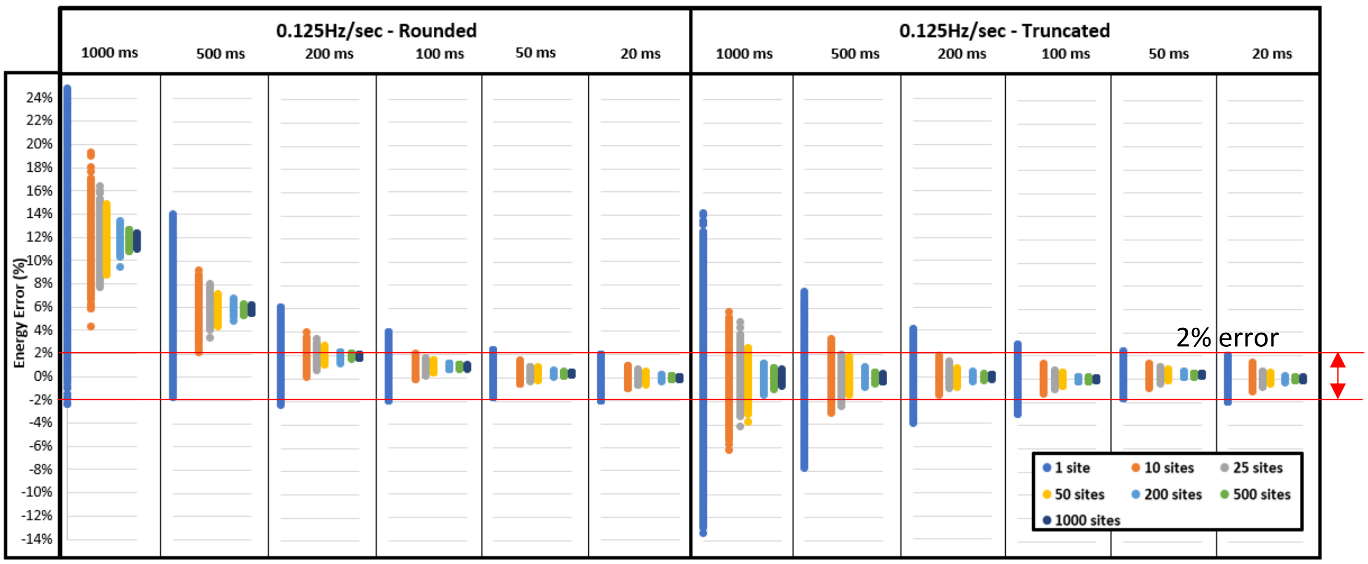


*Figure 13 - Energy error distribution of Monte Carlo simulation (500 simulations, 0ms response time)*

**Energy Error (%)** — 0.125Hz/sec

| Method | Nb of sites | Sampling rate (ms) 20 | 50 | 100 | 200 | 500 | 1000 |
|---|---|---|---|---|---|---|---|
| Truncated | 1 | 1.00% | 1.06% | 1.16% | 1.47% | 3.11% | 6.13% |
| | 10 | 0.30% | 0.42% | 0.36% | 0.46% | 0.96% | 1.65% |
| | 25 | 0.19% | 0.38% | 0.22% | 0.28% | 0.60% | 1.07% |
| | 50 | 0.13% | 0.37% | 0.15% | 0.22% | 0.40% | 0.78% |
| | 200 | 0.06% | 0.36% | 0.07% | 0.10% | 0.21% | 0.38% |
| | 500 | 0.04% | 0.36% | 0.05% | 0.07% | 0.13% | 0.24% |
| | 1000 | 0.03% | 0.37% | 0.03% | 0.05% | 0.09% | 0.18% |
| Rounded | 1 | 1.00% | 1.06% | 1.36% | 2.18% | 5.74% | 11.32% |
| | 10 | 0.30% | 0.43% | 0.99% | 1.96% | 5.89% | 11.69% |
| | 25 | 0.20% | 0.38% | 0.99% | 1.94% | 5.83% | 11.62% |
| | 50 | 0.14% | 0.36% | 0.98% | 1.95% | 5.84% | 11.68% |
| | 200 | 0.07% | 0.37% | 0.98% | 1.94% | 5.85% | 11.69% |
| | 500 | 0.04% | 0.36% | 0.97% | 1.95% | 5.83% | 11.67% |
| | 1000 | 0.03% | 0.37% | 0.97% | 1.94% | 5.84% | 11.68% |

*Figure 14 - Monte Carlo simulation results for absolute value of energy error (1000ms sampling rate, 500 simulations)*

## Conclusions

Errors of less than 0.5% are considered negligible. Errors between 0.5% and 1% are considered minimal. Errors between 1% and 2% are considered acceptable given the ≤2% of measurement range margin of error for power measurements allowed by the MASS.

### 0.125Hz/sec Synthetic Frequency Disturbance (6-sec assessment)

The synthetic frequency disturbance, which illustrates the largest expected errors, shows a significant reduction in energy error as the number of sites and the sampling rate increase. Even with the rounded method and a combination of factors leading to the largest possible over-estimates, the energy error with a 200ms sampling rate is acceptable for 10 sites and it is minimal with a 100ms sampling rate.

### 25 May 2021 Events, NSW and QLD Frequency (3-sec and 15-sec assessments)

- Energy error: For any sampling rate and both frequency deviations, the energy error is negligible for 200 sites and more. It exceeds 2% only for a single site, when sampling rate is 500ms or 1sec.
- Power error:
    - Maximum actual response is lower than maximum target response for multiple sites.
    - In QLD, where the frequency deviation exceeds +/-500mHz for multiple seconds, the power error is negligible for 10 sites or more and for any sampling rate.
    - In NSW, where the frequency deviation is only +/-350mHz for fewer than 3 seconds, the power error is minimal with 100ms measurements for 10 sites or more, and it is acceptable for 200ms measurements for any number of sites.

<table>
<tr><td>20ms...</td><td rowspan="6">...sampling rate keeps power and energy errors <0.5% for...</td><td>...10 sites and more...</td><td colspan="4" rowspan="2">...for both the QLD and NSW frequency deviations, and for both the truncated and the rounded methods.</td></tr>
<tr><td>50ms…</td><td>…10 sites or more…</td></tr>
<tr><td>100ms...</td><td>...10 sites and more...</td><td rowspan="4">...for both the QLD and NSW frequency deviations, and for both the truncated and the rounded methods...</td><td rowspan="4">...except for the power error for NSW frequency deviation where it is between...</td><td>...0.5% and 1%...</td><td>...using the rounded method.</td></tr>
<tr><td>200ms...</td><td>...10 sites and more...</td><td>...1% and 1.6%...</td><td rowspan="3">...whether the truncated method or the rounded method is used.</td></tr>
<tr><td>500ms...</td><td>...25 sites and more...</td><td>...9% and 10%...</td></tr>
<tr><td>1000ms...</td><td>...200 sites and more...</td><td>...20% and 30%...</td></tr>
</table>

## Revisions

| Revision | Date | Description | Authors |
|---|---|---|---|
| 0 | 14/07/2021 | Initial Release | Antoine Riboulon, Liam Lukey |
| 1 | 03/09/2021 | Synthetic frequency disturbance added | Antoine Riboulon, Liam Lukey |