TASC 49 – Normal Frequency Management Strategy

Phase 1: Performance Benchmarks

Benchmark Values for Evaluating Frequency Management Options

TRANSPOWER

Version	Date	Change
0.1	5 June 2015	Initial Draft
0.2	21 June 2015	Reviewed and Revised Draft
1.0	31 July 2015	Final version
2.0		Feedback from EA incorporated into report

	Position	Date
Prepared By:	Andrew Ward	31 July 2015
Input from:	Charles Chrystall - Statistical guidance	
Reviewed By:	Transpower SO TASC 49 Team	

IMPORTANT

Contact Details

Address: Transpower New Zealand Ltd
96 The Terrace
PO Box 1021
Wellington
New Zealand

Telephone: +64 4 495 7000

Fax: +64 4 498 2671

Email: system.operator@transpower.co.nz

Website: http://www.systemoperator.co.nz

TRANSPOWER

1 Executive Summary

1.1 Deliverables: SFK-Based Performance Benchmarks

Phase 1 has delivered on the following clause from the TASC 49 Statement of Work (SoW):

Phase 1: Develop Benchmark

3.1 Through assessment of historical data whilst operating with single frequency keeping (SFK) in the North and South islands, define a normal frequency performance benchmark to be used for comparisons of options within this SoW. A separate performance benchmark for each island along with a national performance benchmark is to be derived. These performance benchmarks are to be described in terms of normal deviations from 50 Hz.

The table below contains the requested SFK-based performance benchmarks.

Table 1: North Island and South Island Benchmarks for Frequency Management in the Normal Band

Island	**North Island (SFK, No FKC)**	**South Island (SFK, No FKC)**
Weighted Average of Monthy Standard Deviation (σ) Hz	0.05221 Hz	0.03014 Hz
Weighted Average of Monthy 3rd Order Deviation (DEV^3) Hz	0.06410 Hz	0.03841 Hz
Weighted Average of Monthy 4th Order Deviation (DEV^4) Hz	0.07543 Hz	0.04718 Hz

In Phase 2 of TASC 49 these performance benchmarks are expected to be used as follows:

1. For each short-listed option, values will be calculated for each of the three 'Deviation' performance metrics σ, DEV^3, and DEV^4 (see Table 1).
2. The 'benchmark values' for the short-listed options will be compared against the SFK benchmark values from Table 1 in order to identify the option with the best relative frequency management performance.

For details of this benchmark analysis, see the report 'TASC 49 Normal Frequency Management Strategy – Future Solution Option Analysis'.

1.2 Variations to the Statement of Work

In consultation with the Electricity Authority, the following variations to the SoW have been made:

- Three 'Deviation' benchmarks have been calculated for each island in order to mitigate one of the risks associated with a single benchmark: that the various options might all have very similar values, making the benchmark ineffective as comparison tool. The difference between them is that the higher the order of benchmark, the greater the weighting placed on larger frequency deviations from the mean.
- A national benchmark has not been calculated due to paucity of historical data needed to perform these calculations. But, the island-based benchmarks are acceptable for evaluating national short-listed options as well as island-based options.

1.3 Future Work

The following analysis has been identified as possible future work:

- Devising a benchmark for ongoing monitoring of frequency quality. An immediate action for this work would be to identify the SCADA data needed for this analysis and then to commission any addition PI data tags so that the required volumes of data can begin accumulating in Transpower's PI Data system.
- Determining if there is any functional relationship between MFK MW band size (with FKC enabled) and frequency quality.

2 PURPOSE OF TASC 49, PHASE 1

The introduction of Frequency Keeping Control (FKC), along with Multiple Frequency Keeping (MFK), has resulted in a change to the normal frequency management; some of the frequency keeping duty has moved from contracted frequency keeping providers to inherent governor response. FKC has also resulted in a change in the risk profile of the HVDC (modulation risk). As part of the Reserves and Frequency Management Programme, the objective of TASC 49 is to provide a stable frequency at the lowest long term cost to consumers.

The deliverable of TASC 49, Phase 1 was a set of North Island, South Island and national benchmarks for measuring normal frequency keeping performance. The Statement of Work (SoW) required these benchmarks to be derived using historical data recorded whilst operating with Single Frequency Keeping (SFK) in the North and South islands. That is:

> *Phase 1: Develop Benchmark*
>
> 3.1 Through assessment of historical data whilst operating with single frequency keeping (SFK) in the North and South islands, define a normal frequency performance benchmark to be used for comparisons of options within this SoW. A separate performance benchmark for each island along with a national performance benchmark is to be derived. These performance benchmarks are to be described in terms of normal deviations from 50 Hz.

The benchmarks are to be used in Phase 2 to evaluate short-listed future options for managing frequency in the normal band (49.8Hz – 50.2Hz).

The purpose of this report is to document the Phase 1 deliverable. Specifically, this report:

- documents the actual values of the benchmarks calculated from the historical SFK data (Section 3.1)
- describes why a national benchmark has not been calculated and proposes that the island-based benchmarks can be used for all short-listed options in Phase 2 (Section 3.3)
- includes some observations on the characteristics of the data and on the benchmark values (Section 3.4)
- describes the method and assumptions underpinning the benchmark calculations (Section 4)
- identifies future work arising from this analysis (Section 5)

3 The Benchmarks

3.1 The Actual Benchmark Values

Table 2: North Island and South Island Benchmarks for Frequency Management in the Normal Band

Island	**North Island (SFK, No FKC)**	**South Island (SFK, No FKC)**
Data Date Range[1]	01 Jan 2007, 00:00:00 to 31 Mar 2013, 23:59:59	01 Jan 2007, 00:00:00 to 31 Jul 2014, 23:59:59
Frequency Keeping Management Approach Used During Date Range	SFK	SFK
Weighted Average Monthly Mean (μ) Hz	50.00218 Hz	50.00219 Hz
Weighted Average of Monthy Standard Deviation (σ) Hz	0.05221 Hz	0.03014 Hz
Weighted Average of Monthy 3rd Order Deviation (DEV^3) Hz	0.06410 Hz	0.03841 Hz
Weighted Average of Monthy 4th Order Deviation (DEV^4) Hz	0.07543 Hz	0.04718 Hz

See Section 4.2 for the method used to calculate these benchmarks and Appendix 3 for the benchmark formulae.

The benchmark values were used to evaluate the performance of short-listed future options identified by TASC 49 and not for ongoing monitoring of the system frequency due to the assumptions underpinning the benchmark values. See Section 5 for comments on developing a benchmark for ongoing monitoring.

Figure 1 below illustrates the range over which the system frequency might vary 99.7% of the time if the single trader frequency keeping method were to be employed (i.e. derived from 3x Standard Deviation). A 'box and whisker' plot is used with the 'box' illustrating the expected system frequency range in the South Island. The 'whisker' illustrates the expected system frequency range in the North Island.

The probable system frequency ranges for the future short-listed options are included in the plot as examples of how the benchmarks can be used as a baseline for analysing the impact of various frequency keeping strategies. Appendix 4 contains plots for the actual deviation benchmark values.

[1] The end dates are different for the two islands (31 March 2013 and 31 July 2014). These dates are just prior to each island's transition to MFK. The extra South Island data was included to ensure that the benchmark calculations reflect the most recent frequency keeping behaviour.

The final report[2] contains conclusions from and details of that benchmark comparison analysis.

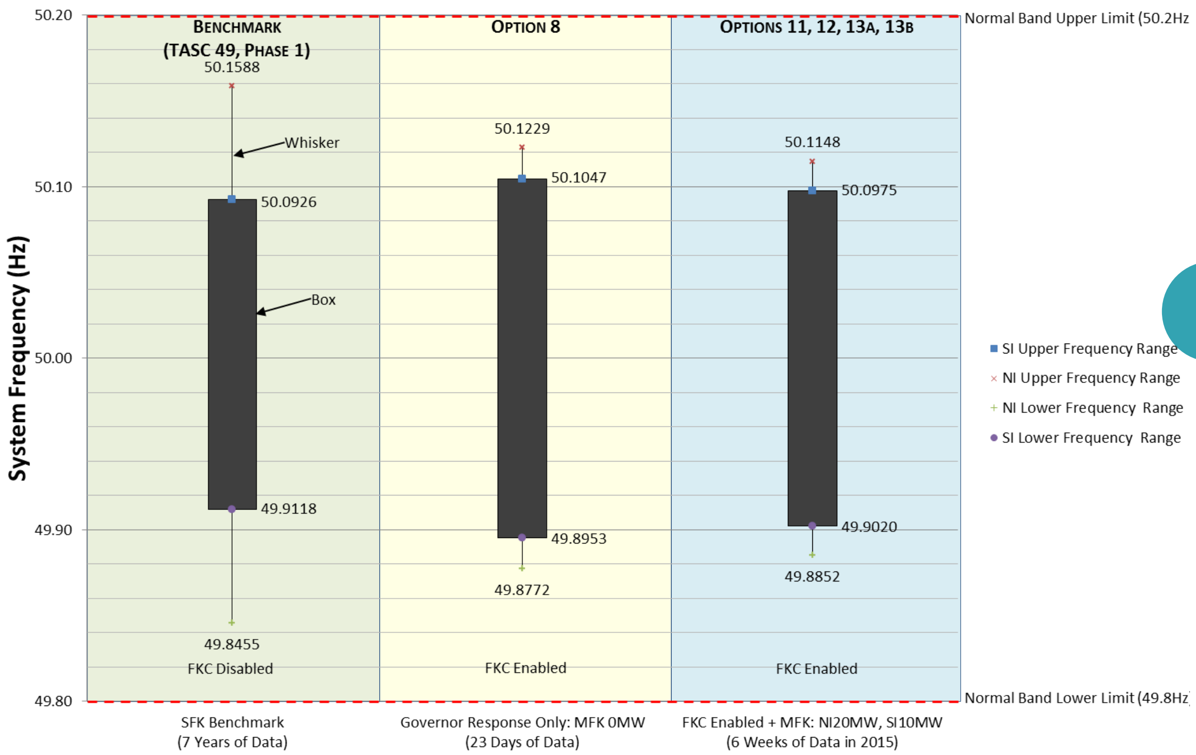

Figure 1 – Possible average variations in frequency for short-listed options during normal operation 99.7% of the time (i.e. 3x Standard Deviation).

For reference, the future options detailed in the final report are:

Option 8: Control response with Compensation

Option 11: National Market: National Frequency Keeping Selection without Co-optimisation

Option 12: National Market: National Frequency Keeping Selection with Co-optimisation

Option 13a: National Market: National Frequency Keeping Selection with Co-Optimisation; Compensation for Control Response (Hybrid -Options 12 and 8)

Option 13b: National Market: National Frequency Keeping Selection without Co-Optimisation; Compensation for Control Response (Hybrid -Options 11 and 8)

3.2 RECOMMENDED SOW VARIATION: USE THREE BENCHMARKS

Clause 3.1 of the TASC 49 SoW requires one "*separate performance benchmark for each island*". However, we recommend the use of three separate benchmarks (as shown in

[2] Ref. '*TASC49_Normal Frequency Management Strategy_Future Solution_Option Analysis.docx*'.

Table 2) for each island when comparing the relative 'quality' of frequency management to be delivered by the short-listed future options identified in TASC 49, Phase 2.

One risk with using a single benchmark is that the various options might all have very similar values, making the benchmark ineffective as comparison tool. In order to reduce this risk therefore, three deviation benchmarks with different weightings were chosen. The expectation is that at least one benchmark will result in a wide enough range of values to help identify a clear 'winner' when comparing the future options.

Furthermore, when choosing the benchmarks it was unclear as to which benchmark had the most appropriate weighting for all the processes involved, hence the decision to calculate three 'deviation' benchmarks. Usually a benchmark metric is designed or chosen based on its ability to clearly measure a specific quantity or factor. In our situation multiple power system processes require 'quality' frequency management in the normal band.

Phrased differently, how do we define 'quality of performance' when considering all the processes dependent on frequency management? Examples of dependent processes include cost of governor wear and tear, cost of reserves procured, stable frequency for machine synchronisation, operating efficiency/performance of load and generator units, the effect of FKC, etc. For each of these processes, 'quality of performance' may be defined differently with respect to larger frequency deviations from the mean. The three deviation benchmarks attempt to capture the possible differences in definitions of performance quality.

The 'Deviation' benchmarks in Table 2 are simply weighted averages of all the relative deviations from the mean frequency during a specified period. The only difference between them is the weighting given to larger deviations from the mean frequency. The higher the order of benchmark, the greater the weighting placed on larger frequency deviations from the mean. See Appendix A-3.2 for the deviation benchmark formulae.

3.3 The National Benchmark

3.3.1 National Benchmark Not Calculated

The intent of the SoW was to create a national benchmark against which to assess the change in quality of frequency management provided by each Phase 2 option that linked both islands using the HVDC FKC. However, there is currently insufficient historical data to derive a national benchmark for evaluating Phase 2 options. Below is an explanation of the process followed in order to come to this conclusion. But, see also Section 5 for comments on the future work needed to derive a national benchmark for ongoing monitoring of frequency performance.

The SoW requested that all benchmarks be calculated using historical frequency data from when the grid was operated using a single frequency keeper (SFK) in each island's AC system. From seven years' worth of historical SFK data the island-based benchmarks in Table 2 were calculated (see Section 4.2 for the calculation method).

With respect to a national benchmark using historical SFK data implies a system configuration in which the frequencies of both islands are tied together using FKC and the frequency is managed using a single national frequency keeper (i.e. only one frequency keeper, which could be located in either island with FKC maintaining the same frequency in both islands). However, historical frequency data does not exist for periods whilst operating with a national SFK provider and FKC enabled simply because the power system has never been operated using this frequency keeping configuration. Consequently, a national benchmark cannot be calculated directly from SFK data.

In the absence of historical national SFK data, the next logical choice would be to use MFK data to calculate a national MFK benchmark. But, this also would not produce a reliable benchmark. The FKC trials only provide a month of usable data, which does not average out seasonal variations and any short-term anomalistic frequency keeping behaviour that occurred during the trial.

Since it was not possible to directly derive a national benchmark, two methods of inferring a national benchmark from existing data were investigated:

1. Using island load to produce a weighted average of the island-specific variances calculated in Section 4.2, step 2.
2. Inferring a national benchmark from the island-based benchmarks using the FKC trial data during which multiple frequency keeping (MFK) was in operation.

However, neither method produced meaningful benchmarks.

The load-weighted averaging method produced national benchmark values that contradicted the observations from the MFK + FKC enabled/disabled periods during the FKC trials, and that were counterintuitive to the fact that most of the governor action comes from the South Island. See Appendix A-5.1 for the load-weighted values and for a commentary.

With regard to inferring a national benchmark from FKC trial data, the assumption in this method was that the ratio of 'frequency variance with FKC-enabled (i.e. Jan 2014)' to 'frequency variance with FKC-disabled (i.e. Nov-Dec 2014)' would be an acceptable indication of the magnitude of the cross-island governor response caused by enabling FKC. The FKC trials revealed that governor action is the primary factor influencing frequency quality in the North and South islands with FKC-enabled allowing governors to respond to frequency changes in the opposite island. See Appendix 2 for variance statistics on these data and for a commentary.

It was hoped that this ratio could be used to scale the Island-based SFK variances (calculated in Section 4.2, step 2) in order to obtain a credible national benchmark. However, initial calculations using this method did not produce meaningful results, highlighting a paucity of data needed to calculate necessary mathematical relationships. See Appendix A-5.2 for MFK-inferred values, formulae, a summary of the approach taken and comments on the additional data needed to use this method.

3.3.2 Alternative to National Benchmark

In the absence of a national benchmark the island benchmarks derived from historical SFK data can and will be used for comparing the Phase 2 options. Even though the FKC links the island frequencies together (compared with independent island frequencies during SFK periods), all Phase 2 options including national options are still expected to have different benchmark values for North and South islands based on the findings of the FKC trials performed from late 2014 to early 2015.

The MFK + FKC periods of 2014-15 show that "even with FKC on, North Island frequency still has more variation than South Island (compare the MFK + FKC enabled/disabled performance metrics in Appendix 2, Tables 3 and 4). This is expected as the frequencies are linked through the FKC control system, which will have some lag and a small dead band, so the frequencies are not exactly synchronized and a small aspect of the FKC-off trend will remain."[3] That is, when the HVDC FKC links the two AC systems, both islands have similar frequencies but are still different.

Accordingly, the SFK-derived, island-based deviation benchmarks in Table 2 can provide a reference point from which to compare the relative performance of all short-listed Phase 2 options, national or otherwise.

3.4 OBSERVATIONS ON ISLAND BENCHMARK CHARACTERISTICS

The frequency data is an interpolated time series of frequency measurements every two seconds. These 2 second frequency data points for the North and South Islands are very tightly distributed around the mean of 50.002 Hz, with weighted standard deviations of 0.05221 Hz and 0.03014 Hz respectively (see Table 2 above), which are well within the normal band of ±0.2 Hz (i.e. 49.8 to 50.2 Hz). See Appendix 1 below for graphs of the distributions.

With respect to the mean, the daily time error correction performed by the System Operator results in the mean always being 50.002 Hz. Therefore the mean is expected to be the same for all options proposed in TASC 49 Phase 2, and unusable for benchmarking; time error correction is assumed to be correctly functioning for all future options. Note: the exact cause of the 0.002 Hz offset in mean frequency has not been established, but not unreasonable to expect that the system frequency is not exactly 50Hz.

With respect to the island-based deviation benchmarks in Table 2 (columns 2 and 3), the North Island is more widely distributed than the South Island. The primary causes for this difference are: the slower type of generation used for single frequency keeping in the North Island, larger load variations than in the South Island, and much less free governor action than in the South Island.

3.5 UNSUITABLE BENCHMARK: 'PERCENT OUTSIDE NORMAL BAND'

The metric 'Percentage of Time outside the Normal Band' was investigated and found to be unsuitable as a measure of 'quality of performance' for frequency management during normal operation (i.e. for the frequency keeping ancillary service).

The frequency data points are tightly distributed around the mean and well inside the normal band. See Figures 2 and 3 below in Appendix A-1.1 for an example of tight monthly frequency distributions with very low percentages of data points outside the normal band.

The South Island's frequency distribution is almost exclusively inside the normal band. In March 2009 (i.e. the distribution plotted in Figure 2) only 90 of the South Island's 1,339,200, 2-second data points lie outside the Normal Band (i.e. 0.0067% of data points). This South Island SFK frequency behaviour is typical of most weeks across the entire dataset from 2007 to 2014 (during the week plotted in figures 5 and 6 there were only 21 data points or 0.0069%). Therefore, it is reasonable to attribute the majority of South Island excursions outside the normal band to events rather than to steady-state load changes.

---

[3] Ref. Transpower, "Frequency Keeping Control Trial Technical Review Report", June 2015, p. 52.

The North Island frequency however, typically has more data points outside the Normal Band (0.269% or 3603 data points during March 2009, and 0.232% or 702 points for the week illustrated in Figure 6). These frequency excursions are due to factors such as large load changes and lack of free governor action in addition to system events.

Therefore, the metric 'Percentage of Time outside the Normal Band' is unsuitable as a metric because it only reflects the quality of frequency keeping during normal operation in the North Island. In the South Island, given that most frequency excursions outside the Normal Band are due to events, 'Percentage Outside Normal Band' is actually a reflection of the quality of event mitigation and not a measure of frequency keeping quality during normal operation.

4 DATA PREPARATION & CALCULATIONS

4.1 DATA FILTERED TO 49.75 TO 50.25 HZ

Based on the tight distribution of frequency data points, this benchmark analysis assumed that the majority of data measurements inside the range 49.75 to 50.25 Hz are caused by frequency keeping. Accordingly, the dataset was filtered to discard frequency data points outside this range in order to minimise the influence of the following kinds of data points on the 'Deviation' benchmark values:

- Low frequency data points caused by SCADA errors, which ramp down from 50Hz to 15Hz and back again.
- Data points attributed to system events.

4.2 METHOD FOR CALCULATING THE ISLAND BENCHMARKS

The following method was used for estimating the various benchmarks in Table 2:

1. The SFK north and south island frequency data recorded during 2007-13 and 2007-14 respectively were split up into calendar months. For each island, a mean and variance was then calculated for each month.
2. For each island, the weighted average of these monthly means and variances were calculated, where each monthly mean or variance metric was weighted according to the number of data points used to calculate that monthly metric.
3. The variances were then converted to deviations, which are the values in columns 2 and 3 of the table.

5 FUTURE WORK

5.1 A BENCHMARK FOR ONGOING MONITORING OF FREQUENCY QUALITY

As stated in Section 3.1 the intended use of the benchmark values in Table 2 is for evaluating the short-listed options in Phase 2 of TASC 49. If a performance standard is to be used (and potentially included in the Code) for ongoing monitoring of system frequency quality we recommend initiating some future work that takes the following approach, which is based on discussions to date with the Electricity Authority:

1. As soon as possible, identify the SCADA data needed to calculate numerical values for these performance standard(s) and then have these PI tags commissioned as soon as practical in order to start accumulating the necessary data in PI.

   Justification: Some SCADA data relating to MFK do not have PI Data tags such as whether the system is currently operating in MFK or SFK mode, and the size of the MFK band (i.e. total MFK MW) in each island.

2. Once the final frequency keeping option is decided, design the performance standard around the specific performance monitoring requirements of that option. That is, determine the kind of performance standard(s) that would be needed to measure frequency quality once that frequency keeping option is implemented. See the notes below.

   Note 1: The current benchmarks in Table 2 measure the quality of the system frequency and do not measure the performance of individual frequency keepers. All of the short-listed Phase 2 options have requirements for measuring and assessing the performance of individual frequency keepers, which should be considered when designing a performance standard.

   Note 2: The performance standard needs to be more intuitive to understand than the standard deviations in Table 2; for example, 'Percentage of Time outside a Defined Band' such as Australia's frequency operating standard of 49.85 to 50.15 HZ, 99% of the time.

   Note 3: See Section 5.1.1 below for comments on monthly averaging versus weekly averaging.

3. Analyse relevant SCADA data to determine suitable numerical values for these standard(s). This analysis should ideally be made using data collected once the other Reserve and Frequency Management (RFM) initiatives are in place in order to capture any consequential changes in frequency keeping behaviour.

   Note 4: at minimum, one year of data captured during MFK + FKC-Enabled periods is needed in order to average out seasonal variations and variations in generator behaviour.

   Note 5: If a 'Percentage of Time outside a Defined Band' metric is used, this band would need to be tighter than the Normal Band, which, for reasons detailed in Section 3.5, is too wide to be useful as a measure of 'quality of performance' for frequency management during normal operation.

5.1.1 Monthly Averaging vs. Weekly Averaging

Data was grouped by months, with those months with less than 99% usable data discarded. Monthly data was used for this historical analysis instead of weekly data because the difference in deviations was only at the 5th decimal place.

However, weekly metrics should be considered as an option for ongoing monitoring of frequency keeping performance for the following reasons:

- This Phase 1 analysis showed that 'weekly metrics' gives finer granularity, making it easier to identify the time and causes of poor frequency management.

- Some weeks have limited or no usable frequency data due to SCADA errors. Grouping frequency data by weeks allows weeks with less than 99% usable data to be discarded without significantly impacting the frequency performance metric for the entire billing month.

5.2 A Functional Relationship Between MFK MW and Frequency Quality

The Electricity Authority posed the questions "Can we observe any functional relationship between MFK MW band size (with FKC enabled) and frequency quality? What pattern in change of quality is observable, especially below 30MW?" To date, MFK has been operated with four different MW bands:

- 75MW (NI: 50MW; SI: 25MW)
- 30MW (NI: 20MW; SI: 10MW)
- 30MW (NI: 10MW; SI: 20MW)
- 0MW

A functional relationship of this nature was described as being "useful for ongoing economic analysis."

This piece of analysis is outside the current SoW and would need to performed as future work.

6 Summary

Phase 1 has delivered three 'Deviation' benchmarks. North Island and South Island values were calculated for each of these benchmarks (see Table 2). As required by the TASC 49 SoW, the island values were calculated using historical data recorded whilst operating with Single Frequency Keeping the North and South islands. Accordingly, these benchmarks reflect the quality of frequency management using SFK.

National values however, could not be calculated. Insufficient historical data exists to infer a statistically meaningful national benchmark from the island-based SFK data or from the four weeks of MFK data (see Section 3.3 and Appendix 2). In lieu of national benchmarks, the island-based benchmarks will be used for comparing all future options. The analysis showed that they are suitable for comparing both island-based and national frequency keeping options.

Three different benchmarks were calculated rather than one (as was requested in the original SoW). One risk with using a single benchmark metric is that the various options might all have very similar 'deviation values', making the benchmark ineffective as a comparison tool. In order to reduce this risk therefore, three deviation benchmarks with different weightings were chosen. The expectation is that at least one benchmark will result in a wide enough range of values to help identify a clear 'winner' when comparing the future options. Appendix 3 documents the benchmark formulae.

Prior to calculating the various benchmarks in Table 2, the data was filtered to discard data points outside the range 49.75 to 50.25 Hz in order to minimise the influence of data affected by SCADA errors and data attributed to system events.

The intended usage of these benchmarks is to evaluate the short-listed future frequency management options identified in Phase 2 with respect to 'quality' of frequency management. For each of the three benchmark metrics a 'deviation value' will be calculated for each of the short-listed future options. These deviations will then compared with each other relative to the SFK benchmark values from Table 2 in order to rank the options with respect to 'quality'. See the Phase 2 final report[4] for the details and conclusions of the benchmark evaluation analysis.

The metric 'Percentage of Time outside the Normal Band' was investigated as a potential benchmark and found to be unsuitable as a measure of 'quality' for frequency management during normal operation. In the South Island, frequency deviations outside the normal band are almost exclusively due to events and not due to normal frequency keeping. Consequently, 'Percentage of Time' is actually a reflection of the quality of event mitigation in the South Island and not a measure of frequency keeping quality during normal operation.

This benchmark analysis has identified some future work:

- Designing and calculating benchmarks for ongoing monitoring of frequency quality and for assessing and monitoring the performance of individual frequency keepers.

  This work contains an urgent action: identifying and commissioning any new PI tags needed to calculate these ongoing benchmark values. Only once commissioned is Transpower able to begin accumulating sufficient data to perform this analysis. Approximately 1 year of data is needed.

- Analysing frequency data to determine if there is any functional relationship between the MFK MW bands and the quality of frequency.

[4] '*TASC 49 Normal Frequency Management Strategy – Future Solution Option Analysis*' report.

Appendix 1 FREQUENCY DISTRIBUTIONS

A-1.1 MONTHLY DISTRIBUTIONS

Below are the North and South Island distributions of two, one-month periods:

- March 2009
- May 2014

These two months were chosen because they have monthly standard deviations closest to the weighted average standard in the North and South Islands respectively.

The North Island monthly standard deviation (0.05223 Hz) is closest to the North Island monthly-weighted average standard deviation (0.05221 Hz) across the month of March 2009. See Figure 2. The South Island distribution (SD_{SI} = 0.02792 Hz) is included for comparison.

The South Island monthly standard deviation (0.03019 Hz) is closest to the South Island monthly-weighted average standard deviation (0.03014 Hz) across the month of May 2014. See Figure 4. A North Island distribution cannot be included for comparison because North Island SFK finished in March 2013.

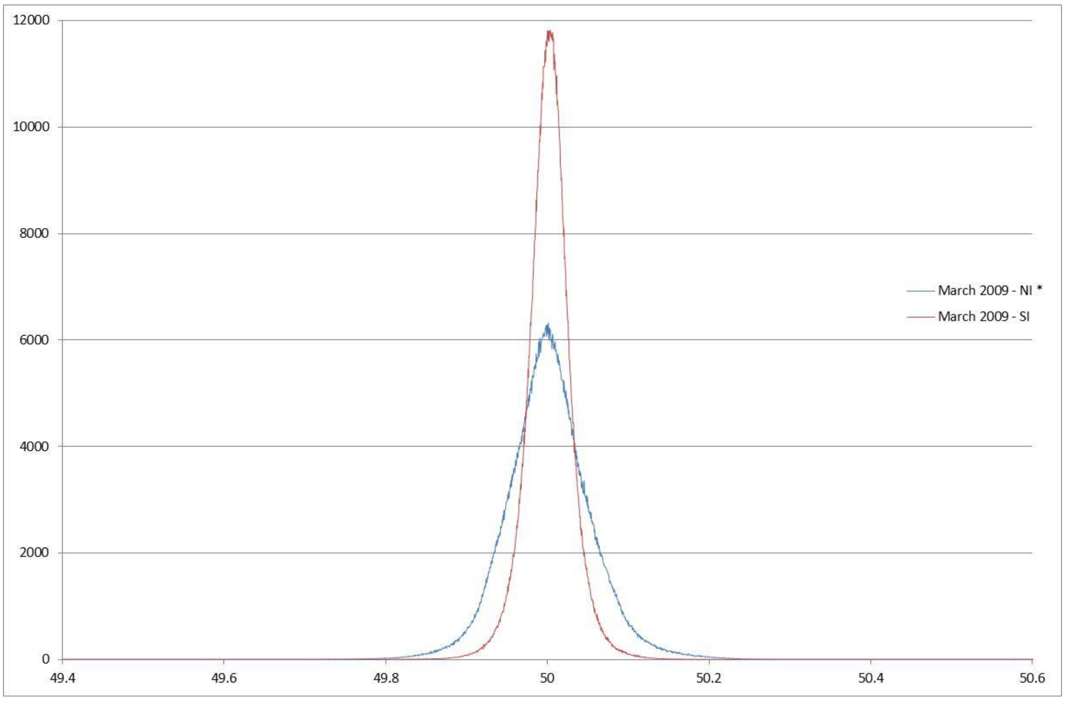

Figure 2: Distributions when the North Island monthly standard deviation (*) is closest to its weighted average standard deviation

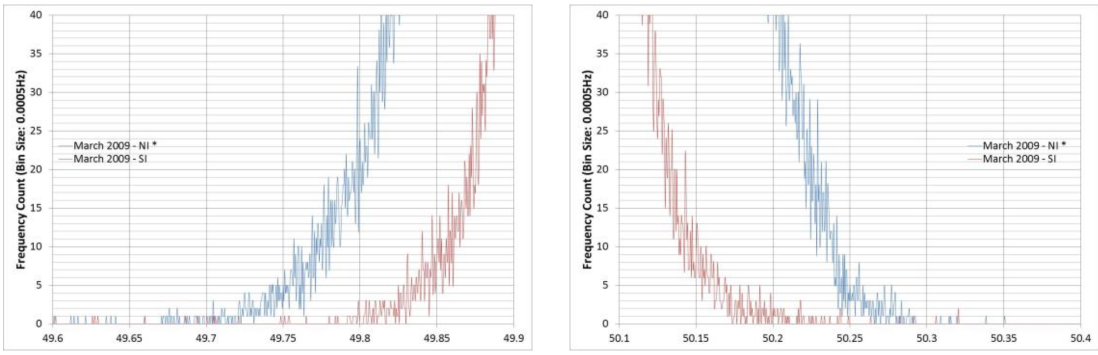

Figure 3: Zoom in on the March 2009 distributions. Frequency measurements outside the Normal Band are primarily event-driven for the South Island

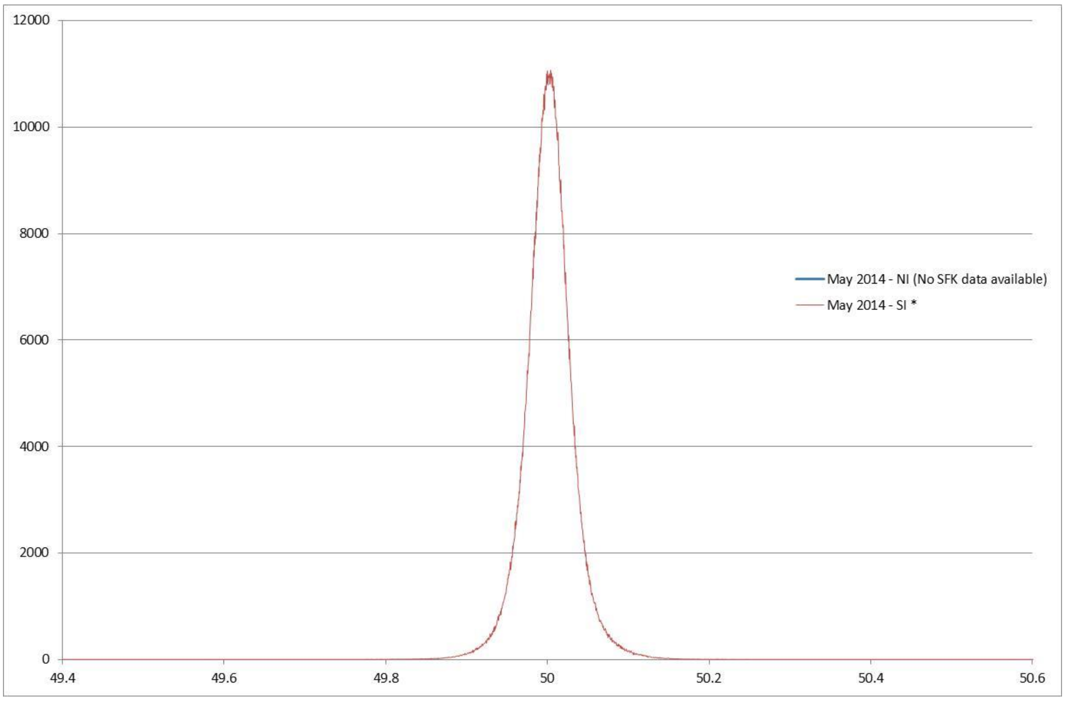

Figure 4: Distributions when the South Island monthly standard deviation (*) is closest to its weighted average standard deviation

The datasets used to plot the distributions were different to the datasets used to calculate the benchmark values. The 'Benchmark Datasets' only contain data in the range of 49.75 – 50.25 Hz in order to measure the quality of steady state, single frequency keeping behaviour, and minimise the effect of frequencies caused by SCADA errors and system events.

The datasets used to plot these distributions were chosen in order to compare the relative distribution counts of event-driven frequencies and frequencies resulting from steady state, single frequency keeping behaviour. The 'distribution graph' datasets were filtered to the range 49.4 – 50.6 Hz and counted with a bin size of 0.0005 Hz. This allows both event-driven and steady state frequencies to be counted and plotted while minimising the long distribution tails caused by erroneous SCADA data.

A-1.2 Weekly Distributions

For comparison with the monthly distributions, below are the North and South Island distributions of two, single-week periods:

- Mon. 16 – Sun. 22 August 2010
- Mon. 14 – Sun. 20 January 2013

These two weeks were chosen because they have weekly standard deviations closest to the weighted average standard in the North and South islands respectively.

The North Island weekly standard deviation (0.05222 Hz) is closest to the North Island weighted average standard deviation in Section 3.1 (0.05223 Hz) across the week of 16 – 22 August 2010 (see Figure 5). The South Island distribution (SD_{SI} = 0.03023 Hz) is included for comparison.

The South Island weekly standard deviation (0.03012 Hz) is closest to the weighted average standard deviation in Section 3.1 (0.03014 Hz) across the week of 14 – 20 January 2013 (see Figure 7). The North Island distribution (SD_{NI} = 0.05148 Hz) is included for comparison.

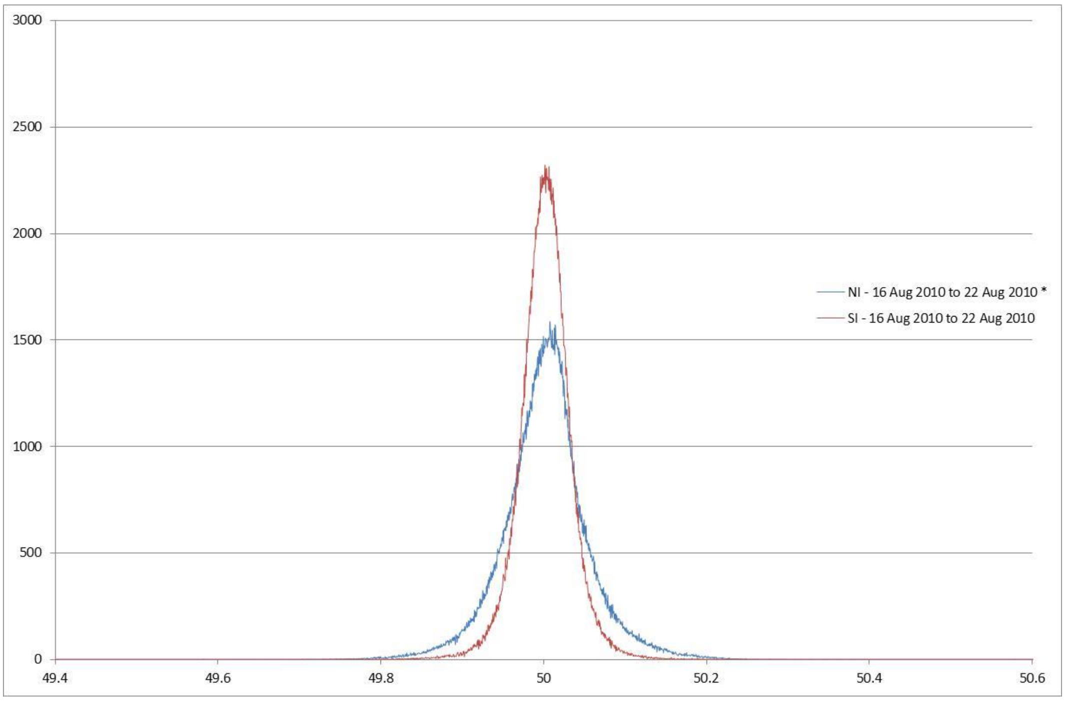

Figure 5: Distributions when the North Island weekly standard deviation (*) is closest to its weighted average standard deviation

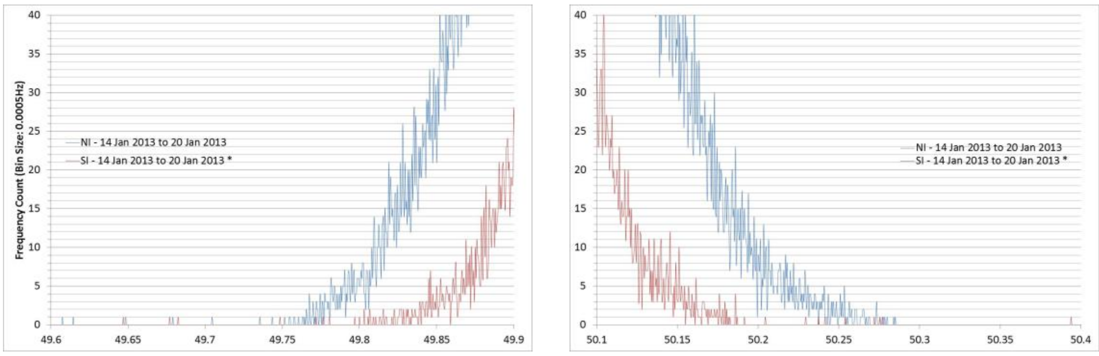

Figure 6: Zoom in of a January 2013 weekly distributions. Frequency measurements outside the Normal Band are primarily event-driven for the South Island

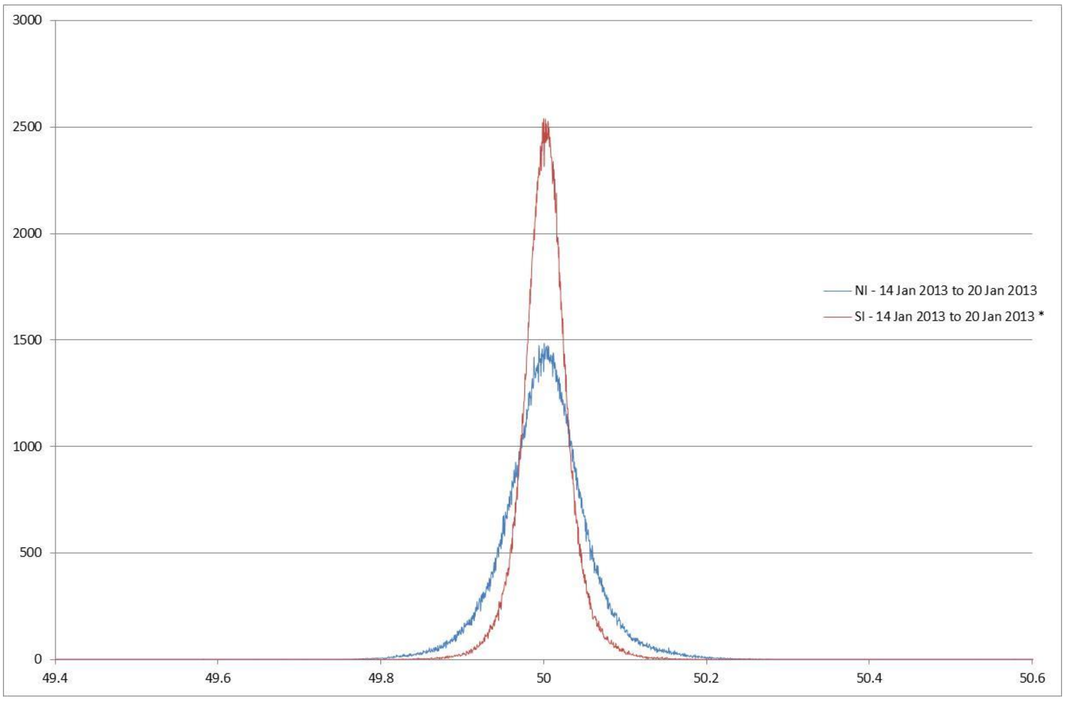

Figure 7: Distributions when the South Island weekly standard deviation (*) is closest to its weighted average standard deviation

Appendix 2 MFK + FKC ENABLED/DISABLED PERFORMANCE METRICS

The performance metrics below were calculated using data collected during the HVDC Frequency Keeping Control (FKC) trials dated 16 Nov – 15 Dec 2014 and 1st – 28th January 2015.

Table 3: MFK + FSC Only Period (i.e. FKC Disabled), 16 Nov – 15 Dec 2014

Metric	North Island	South Island	Units
Mean Frequency	50.000357	50.008269	Hz
Variance	0.004348	0.000529	Hz^2
Variance - 3rd Order	0.000501	0.000034	Hz^3
Variance - 4th Order	0.000074	0.000004	Hz^4
Standard Deviation	0.065942	0.022990	Hz
Deviation - 3rd Order	0.079431	0.032382	Hz
Deviation - 4th Order	0.092621	0.044014	Hz

Table 4: MFK + FKC Enabled, 1st – 28th January 2015

Metric	North Island	South Island	Units
Mean Frequency	50.000456	50.000098	Hz
Variance	0.001152	0.000809	Hz^2
Variance - 3rd Order	0.000077	0.000045	Hz^3
Variance - 4th Order	0.000007	0.000004	Hz^4
Standard Deviation	0.033944	0.028442	Hz
Deviation - 3rd Order	0.042469	0.035585	Hz
Deviation - 4th Order	0.050964	0.043291	Hz

A-2.1 OBSERVATIONS

Data from the trials in November-December 2014 and January 2015 with FKC disabled and enabled respectively, reveal the effect of governor response on each island's frequency. Note that Multiple Frequency Keeping (MFK) was operating during these trials.

Compare the change in each island's standard deviation from Table 3 (FKC disabled) to Table 4 (FKC enabled). The North Island frequency deviation improved dramatically (i.e. got smaller) whereas the South Island frequency deviation deteriorated (i.e. got larger), but deteriorated less than the North Island improved. That is, frequency performance was still better in the South Island with FKC enabled.

Governor response is the primary reason attributed to these changes in frequency performance. FKC 'links' the two islands together, enabling governors in each island to respond to frequency changes in the other island. Currently, the majority of fast-acting governors are in the South Island and the largest load changes are in the North Island. Enabling FKC allows the South Island governors to correct frequency deviations in the North Island resulting in the observed changes in frequency performance of each island.

Other factors such as generator inertia, and size and inertia of load do influence the frequency, but are very much secondary effects with respect to governor action.

Appendix 3 Benchmark Formulae

A-3.1 Monthly Means for North and South Islands

The mean frequency benchmark for each island is calculated as the normalised weighted average of all the individual monthly mean frequencies for that island (μ):

$$\mu = \sum_{j=1}^{k} w_j \mu_j \tag{1}$$

where w_j is the normalised weighting for each month:

$$w_j = \frac{N_j}{\sum_{j=1}^{k} N_j} \tag{2}$$

N_j is the total number of usable measurements (i.e. data points remaining once the data set has been cleansed of erroneous SCADA data), recorded during month j, and used to calculate the monthly mean (μ_j)

μ_j is the mean of all N_j frequency data points in month j:

$$\mu_j = \sum_{i=1}^{N_j} \frac{f_i}{N_j} \tag{3}$$

f_i is a frequency data point (i.e. measurement i). For these benchmark calculations, 2 second frequency data was used (i.e. a 2 sec measurement interval).

Interpretation:

1. 2 second data was obtained for the date ranges stated in Table 2.
2. This data was filtered to discard all data points outside the range 49.75 – 50.25 Hz, which were the results of SCADA errors and system events. The retained data is assumed to be measurements taken during steady state, reflecting single frequency keeping behaviour.
3. The data was grouped by month.
    a. Note, for weekly calculatings the data was grouped according to the 'ISO Week' standard (i.e. Mon – Sun, with week 1 of each year being the week containing 4 January). The number of data points (N_j) in each week (j) will be different depending on the number of data points discarded in that particular week.
4. The mean (μ_j) was calculated for each month
5. These monthly means were then averaged to obtain an average mean by multiplying all k monthly means by their normalised weightings (w_j) and then summing them.

A-3.2 Monthly Deviation Benchmarks for North and South Islands

A-3.2.1 Standard Deviation Benchmark

The standard deviation (σ) benchmark for each island is similarly derived from the normalised weighted average of all the individual monthly variances for that island (σ_j^2):

$$\sigma = \sqrt{\sum_{j=1}^{k} w_j \sigma_j^2} \qquad (4)$$

where w_j is the normalised weighting for each month described by (2).

σ_j^2 is the variance of all N_j frequency data points in month j:

$$\sigma_j^2 = \sum_{i=1}^{N_j} \frac{(f_i - \mu_j)^2}{N_j} \qquad (5)$$

The 3rd and 4th order deviation benchmarks have a similar structure.

A-3.2.2 3rd Order Deviation Benchmark

$$DEV^3 = \sqrt[3]{\sum_{j=1}^{k} w_j VAR_j^3} \qquad (6)$$

where w_j is described by (2), and:

$$VAR_j^3 = \sum_{i=1}^{N_j} \frac{(|f_i - \mu_j|)^3}{N_j} \qquad (7)$$

A-3.2.3 4th Order Deviation Benchmark

$$DEV^4 = \sqrt[4]{\sum_{j=1}^{k} w_j VAR_j^4} \qquad (8)$$

where w_j is described by (2), and:

$$VAR_j^4 = \sum_{i=1}^{N_j} \frac{(f_i - \mu_j)^4}{N_j} \qquad (9)$$

A-3.2.4 Benchmark System Frequency Range

The system frequency ranges calculated for the plot in Figure 1 use equation 10, which is derived from equations 1 and 4. A range of the mean frequency ± three standard deviations implies that there is a 99.7% probability (or that 99.7% of the time) the frequency can be expected to stay within this range. Anything beyond 99.7% of the time is statistically an outlier; e.g. an event-based frequency measurement.

$$f_{range} = \mu \pm 3\sigma \tag{10}$$

Calculation of the system frequency for the South Island:

$$f_{range} = 50.00219 \pm 3 \times 0.03014 = (49.9118\,, 50.0926)$$

Appendix 4 3RD AND 4TH ORDER DEVIATION BENCHMARKS

Below are plots for the standard deviation, 3rd order deviation and 4th order deviation benchmarks. Deviation metrics for the TASC 49 short-listed future options are included to illustrate how the benchmarks can be used as a baseline for analysing the impact of various frequency keeping strategies.

The higher the order of benchmark, the greater the weighting placed on larger frequency deviations from the mean frequency. See the future solutions report for conclusions derived from these plots.

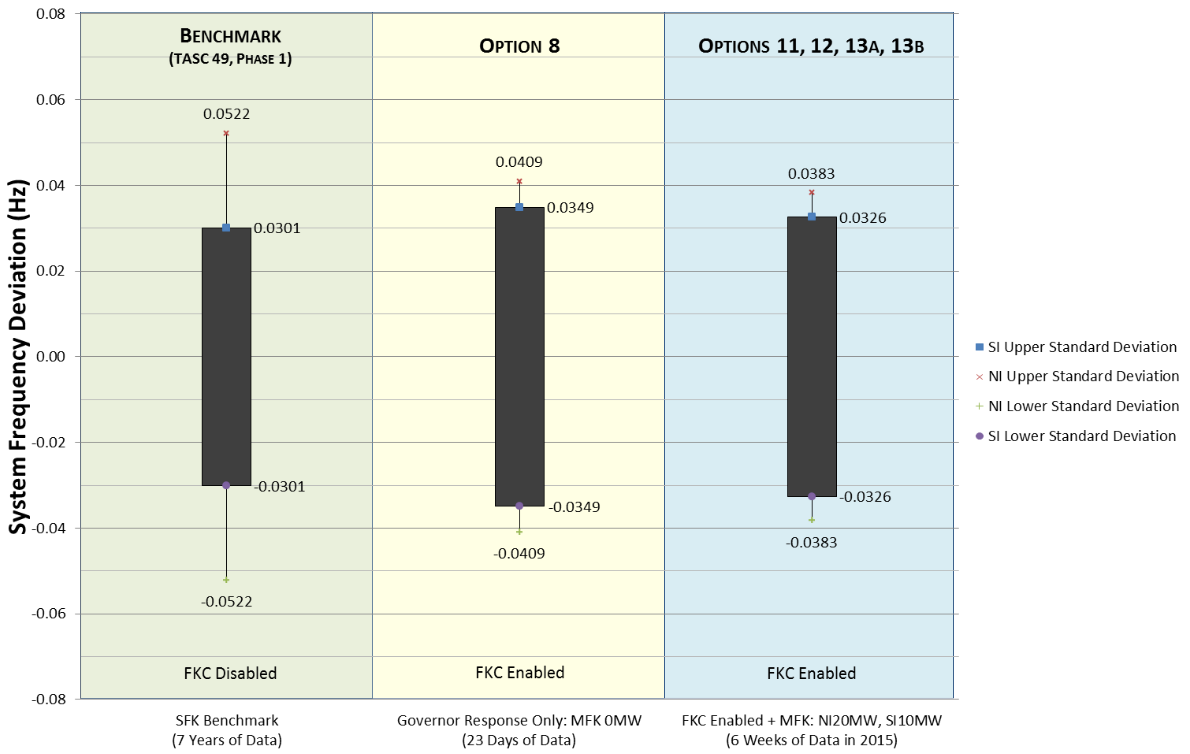

Figure 8 – Average standard deviations of North and South island frequencies for short-listed options during normal operation.

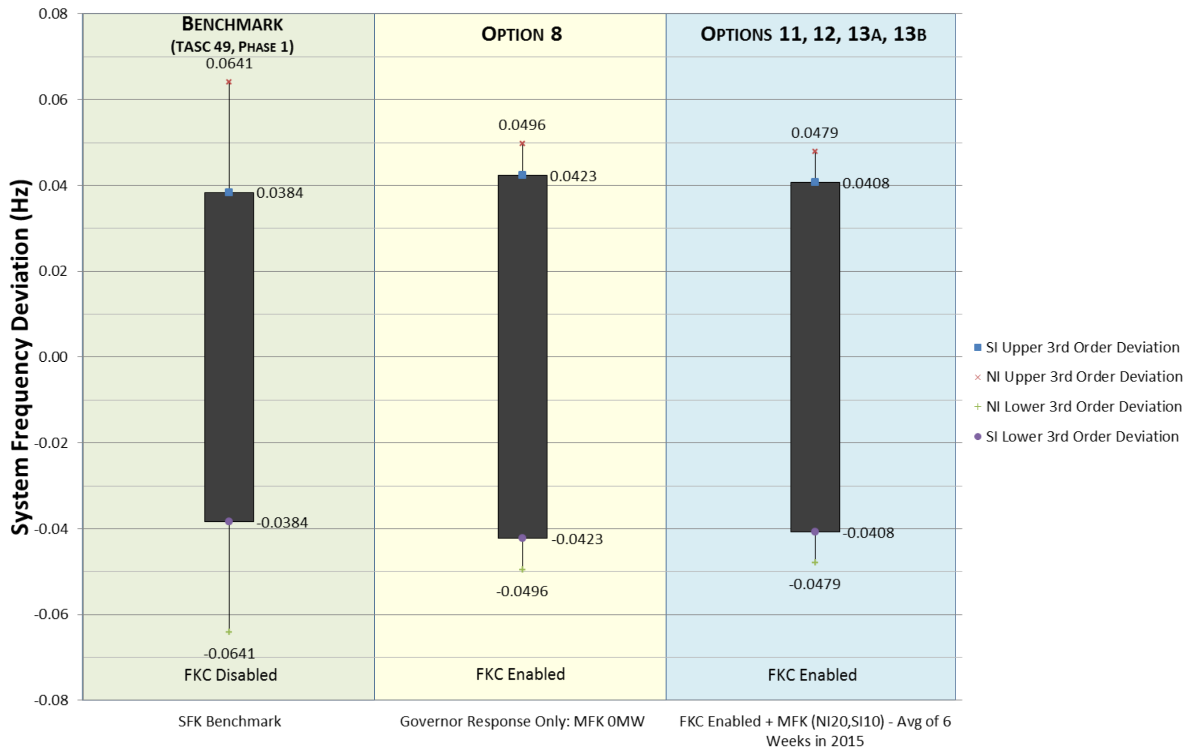

Figure 9 – Average 3rd Order deviations of North and South island frequencies for short-listed options during normal operation.

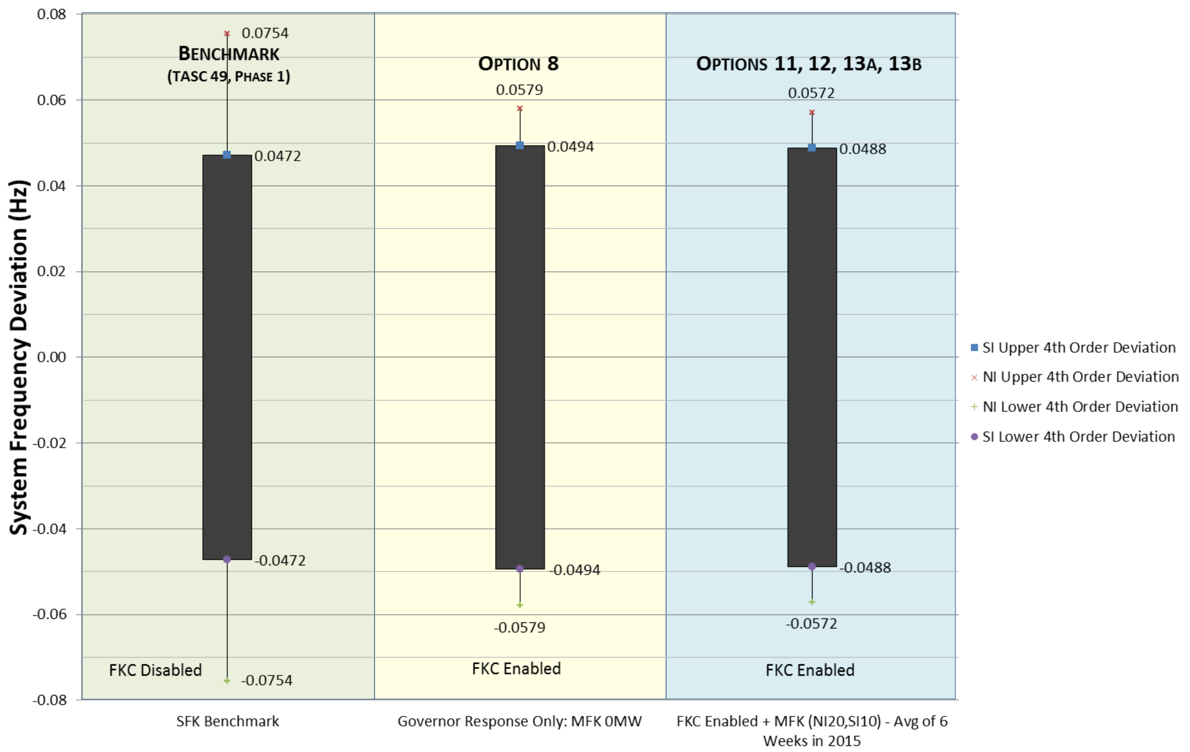

Figure 10 – Average 4th Order deviations of North and South island frequencies for short-listed options during normal operation.

Appendix 5 National Benchmark Methods Investigated

This appendix records the two methods investigated for calculating a national benchmark from historical island-based SFK data. Neither method produced meaningful benchmarks. But, for the record, they are detailed here to avoid future re-work and to explain why each method is unable to produce the national benchmark required in the TASC 49 Statement of Work.

The load-weighted average method produced results that did not align with the frequency behaviour that we observed during the FKC trials. The MFK-inferred national benchmark method concept was valid, but could not be applied due to insufficient historical data.

NOTE: The data in tables 5 and 6 is provided for illustrative purposes only and should not be quoted.

A-5.1 Load Weighted Average Method

The goal of this method was to produce national deviation benchmarks by taking the load-weighted average of the island-specific variances calculated in Section 4.2, Step 2 and then converting them to deviations. This method produced the national deviation values in Table 5 below.

Table 5: Incorrect national frequency deviation values calculated using load-weighted averaging

Island	National Load-Weighted Average (NI, SI values copied from Table 2)
Data Date Range	01 Jan 2007, 00:00:00 to 31 Mar 2013, 23:59:59
Weighted Standard Deviation (σ) Hz	0.04545 (0.05221, 0.03014)
Weighted 3rd Order Deviation (DEV^3) Hz	0.05727 (0.06410, 0.03841)
Weighted 4th Order Deviation (DEV^4) Hz	0.06873 (0.07543, 0.04718)

Data provided for illustrative purposes only

A-5.1.1 Calculation Method

1. For each month of frequency data in the data date range, each island's variance was calculated.
2. For each of these months, the total MWh for each island was calculated and then converted into a normalised weighting for each island by dividing that 'island's monthly MWh' by the 'total monthly national MWh'.

3. The island variances were then mulitplied by these monthly normalised weightings and added together in order to produce a single, monthly average frequency variance for the national power system.
4. All these 'national' monthly variances were then averaged to produce a single variance. To perform this second average, all 'national monthly variances' were weighted by the number of data points used to calculate those monthly variance, giving less importance to those variances derived for months having missing data.
5. The final 'national' variances was then converted to a standard deviation.
6. This method was repeated for the 3rd Order and 4th Order deviations.

A-5.1.2 Comments

Using island load as a weighting to create a national benchmark for measuring performance of frequency management implies that the performance is somehow strongly linked to size of load. The North Island load is larger than the South Island load. Accordingly, these load-weightings produce deviations that are between their North and South island counterparts, but weighted towards the higher North Island deviation values. The North and South island deviations from Table 2 are included in parentheses for comparison.

These load-weighted average values suggest that the performance of frequency management in the North Island would improve a little and that the performance of frequency management in the South Island would deteriorate if FKC was enabled while a national SFK provider is operating. However, the FKC periods demonstrated the opposite that frequency management would actually improve a lot in the North Island and deteriorate a little in the South Island (see Appendix 2).

Accordingly, the above values derived from load-weighted averaging have not been proposed for the national benchmark.

A-5.2 MFK-Inferred National Benchmark Method

The goal of this method was to use statistics derived from FKC trial data in order to infer a national benchmark from the SFK Island-based benchmarks in Table 2. The FKC trial data were collected during MFK periods in November-December 2014 and January 2015 with FKC disabled and enabled respectively.

These data sets showed that enabling FKC results in an improvement in North Island frequency performance and a deterioration of the South Island frequency performance (see Appendix 2 for frequency statistics and for a commentary). Governor response was the primary reason attributed to these changes in frequency performance with FKC 'linking' the two islands together, enabling governors in each island to respond to frequency changes in the other island.

This method assumed that the ratio of 'frequency variance with FKC-enabled (i.e. Jan 2014)' to 'frequency variance with FKC-disabled (i.e. Nov-Dec 2014)' is an acceptable indication of the magnitude of the cross-island governor response caused by enabling FKC. Based on this assumption, this ratio was calculated from the variances in Appendix 2 and used to scale the Island-based SFK variances (calculated in Section 4.2, step 2) in order to obtain national benchmark values.

Note: due to the small amount of MFK + FKC data a seasonally-adjusted version of this ratio was investigated.

This method produced the national values in Table 6, column 4. By using the ratio to scale the Island-based SFK variances, the national benchmark would comprise of different values for the North and South island rather than a single value. This is consistent with the observation made during the FKC trials that "even with FKC on, North Island frequency still has more variation than South Island"[5] due to lag and a small deadband in the FKC control system. Compare the MFK + FKC enabled/disabled performance metrics in Appendix 2, Tables 3 and 4.

The third value in parenthesis is a simple average of the NI and SI variances.

Table 6: Incorrect national frequency deviation values inferred from SFK data using MFK + FKC trial data

Island	**North Island (No FKC) *Copied from Table 2***	**South Island (No FKC) *Copied from Table 2***	**National MFK-Inferred (i.e. FKC Enabled): NI, SI (Average)**
Data Date Range	01 Jan 2007, 00:00:00 to 31 Mar 2013, 23:59:59	01 Jan 2007, 00:00:00 to 31 Jul 2014, 23:59:59	01 Jan 2007, 00:00:00 to 31 Mar 2013, 23:59:59
Weighted Standard Deviation (σ) Hz	0.05221 Hz	0.03014 Hz	0.02883, 0.03883 (0.03420)
Weighted 3rd Order Deviation (DEV^3) Hz	0.06410 Hz	0.03841 Hz	0.03591, 0.04337 (0.03999)
Weighted 4th Order Deviation (DEV^4) Hz	0.07543 Hz	0.04718 Hz	0.04299, 0.04735 (0.04533)

Data provided for illustrative purposes only

A-5.2.1 Calculation Method

The following steps were performed. See Section A-5.2.3 for associated formulae.

1. The variance in frequency data collected during the November-December 2014 period with MFK on and FKC disabled was calculated for each island (ref. Table 3, p 21).
2. The variance in frequency data collected during the January 2015 period with MFK on and FKC enabled was calculated for each island (ref. Table 4, p 21).
3. Graphing the monthly SFK variances of Section 4.2, step 1 reveals that they vary periodically with season, primarily with the availability of hydro which provides the majority of governor response. Therefore, before calculating the FKC-

[5] Ref. Transpower, "Frequency Keeping Control Trial Technical Review Report", June 2015, p. 52.

enabled/disabled ratio, seasonal effects were removed from those Nov/Dec-14 and Jan-15 variances using the 'Ratio to Moving Average' (RMA) method.

a. The island-based monthly SFK variances from Section 4.2, step 1 were analysed using the RMA method to obtain a seasonal index for November, December and January.

b. To minimise seasonal effects the variances from steps 1 and 2 above were divided respectively by the average of the November and December seasonal indexes and by January seasonal index.

4. For each island, the ratio of FKC-enabled/FKC-disabled was calculated using the seasonalised variances of step 3-b.

5. The island SFK variances from Section 4.2, step 2 were multiplied by the FKC enabled/disabled ratio of step 4 above to provide an estimate of the average frequency variance in each island with SFK and FKC enabled. These variances were converted to deviations and are the NI and SI values in column 4.

6. The SFK/FKC-enabled variances of step 5 were averaged and converted to the single parenthesised deviation value in column d.

This method assumes the following:

- Seasonal variations in generation inertia and hydro governor availability are the same under SFK and MFK.
- Frequency keeping behaviour due to MFK is cancelled out in the 'FKC enabled/disabled' ratio.

A-5.2.2 Comments

The values in Table 6, column 4 are not meaningful. From the FKC trials we know that the frequency deviation in the South Island will always be smaller than the North Island deviation. The values in Table 6 violate this condition.

Further investigation highlighted that the two MFK + FKC datasets used to calculate the ratio approximately represent two random variables and the ratio of two semi-normally distributed random variables is estimated using a Taylor's expansion series. It cannot be calculated simply by taking the ratio of two variances. Hence, the values in Table 6 do not align with the FKC trial statistics.

To use a Taylor's series however, mathematical relationships must be derived to reflect these predominant factors:

- The effect on frequency and governor action as a result of changing the frequency keeping regime from SFK to MFK.
- The change in governor action when changing from FKC-disabled to FKC-enabled.

Additional data is required to calculate these relationships, but unavailable as we have not undertaken trials for some combinations of states. Consequently, this method cannot be used to calculate a national benchmark.

A-5.2.3 MFK-Inferred Formulae

The non-seasonal trend in frequency variance was identified using a centred moving average with a 12-month moving window.

$$Trend_{NI} = \text{Centred-Moving-Average of all SFK North Island Monthly Variances} \quad (6)$$

$$Trend_{SI} = \text{Centred-Moving-Average of all SFK South Island Monthly Variances} \quad (7)$$

The seasonality index for each calendar month was calculated by dividing the original variance data by the trend data and then taking the average of all 'January ratios' and the average of all 'November-December ratios'. This was done for each island.

$$Seasonality\_Index_{Jan\_NI} = AVG_{n=2007}^{2013}\left(\frac{VAR_{Jan\_NI\_n}}{Trend_{NI\_Jan\_n}}\right)$$
$$Seasonality\_Index_{Sep\_NI} = AVG_{n=2007}^{2013}\left(\frac{VAR_{Sep\_NI\_n}}{Trend_{NI\_Sep\_n}}\right) \quad (8)$$

$$Seasonality\_Index_{Jan\_SI} = AVG_{n=2007}^{2014}\left(\frac{VAR_{Jan\_SI\_n}}{Trend_{SI\_Jan\_n}}\right)$$
$$Seasonality\_Index_{Sep\_SI} = AVG_{n=2007}^{2014}\left(\frac{VAR_{Sep\_NI\_n}}{Trend_{NI\_Sep\_n}}\right) \quad (9)$$

The final benchmark values were calculate using equations 11 and 12, which multiplies the island based SFK variances by the ratio of MFK variance with FKC-on and FKC-off.

$$FKC\frac{ON}{OFF}Ratio_{NI} = \frac{VAR_{NI-MFK-FKC-On\ Jan\ 2015} \times Seasonality\_Index_{Jan\_NI}}{VAR_{NI-MFK-FKC-Off\ Sep\ 2014} \times Seasonality\_Index_{Sep\_NI}}$$
$$FKC\frac{ON}{OFF}Ratio_{SI} = \frac{VAR_{SI-MFK-FKC-On\ Jan\ 2015} \times Seasonality\_Index_{Jan\_SI}}{VAR_{SI-MFK-FKC-Off\ Sep\ 2014} \times Seasonality\_Index_{Sep\_SI}} \quad (10)$$

$$VAR_{National_{NI}} = VAR_{SFK\_NI} \times FKC\frac{ON}{OFF}Ratio_{NI}$$
$$VAR_{National\_SI} = VAR_{SFK\_SI} \times FKC\frac{ON}{OFF}Ratio_{SI} \quad (11)$$

$$VAR_{National_{avg}} = \frac{(VAR_{NI} + VAR_{SI})}{2} \quad (12)$$