TASC 55 – Normal Frequency Management Strategy Project

MFK Refinement

TRANSPOWER

IMPORTANT

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1. EXECUTIVE SUMMARY

TASC 55 multiple frequency keeping (MFK) refinement was commissioned by the Electricity Authority (EA) to study the effects of refining the system operator's frequency keeping bands. The work followed implementation of improvements to the system operator's security assessment and management tools (SO security tools), itself following introduction of HVDC capability and control changes in 2014.

The work required completing 16 tests focused on:

1. Pre-Solve Deviation (PSD) functionality and optimising PSD settings.
2. Use of augmented (automatic PSD calculation, automatic dispatch send) dispatch with frequency keeping control (FKC) operation.
3. The effect of reducing the MFK bands, covering:
    a. 30 MW of MFK: 20 MW North Island, 10 MW South Island, FKC enabled.
    b. 20 MW of MFK: 10 MW North Island, 10 MW South Island, FKC enabled.
    c. 0 MW of MFK: FKC enabled.
    d. 25 MW of North Island MFK, 25 MW of South Island MFK, FKC disabled.

Observations were made for effects of operating with different MFK bands on time error, HVDC modulation, frequency and extent to which governors were off dispatch. Results were as follows:

1. Time Error

    Time error can be effectively managed to well within the code requirement of ±5 seconds under all test periods. MFK has a positive effect on time error control; however, with the right PSD settings time error can be effectively managed using only dispatch.

2. HVDC modulation

    Results indicate a relationship between the MFK MW band and the amount the FKC modulates the HVDC. With a higher MFK regulation band, less HVDC modulation is seen.

3. Frequency

    Comparing 30 MW MFK band to 20 MW MFK band operations, the data indicated no deterioration in frequency. Comparing 30 MW MFK band to 0 MW MFK band, the data showed an increase in standard deviation of frequency in the North Island. In all tests with FKC enabled the frequency variation was better than what had been the normal North Island frequency variation.

4. Governors off dispatch

    Considering governor off dispatch, a comparison of 30 MW and 20 MW MFK operations data showed a slight increase in governor action. Comparing 30 MW and 0 MW of MFK, a larger increase in governor action was seen.

Recommendations

1. Utilise future FKC outages for trial operation with North Island 25 MW MFK.
2. Consider further PSD enhancement.

3. If reducing the MFK bands with FKC enabled is considered for introduction in to operations, the benefits of reducing MFK should first be assessed against the impact it will have on governors off dispatch and HVDC modulation.

This report is intended for readers with a reasonable understanding of power system operation (particularly in dispatch and the frequency keeping ancillary service) and knowledge of Transpower's earlier reports on FKC and MFK operations[1].

[1] FKC Trial Report *https://www.systemoperator.co.nz/sites/default/files/bulk-upload/documents/FKC%20Trial%20Report.pdf*

FKC Technical Report *https://www.systemoperator.co.nz/sites/default/files/bulk-upload/documents/FKC%20Technical%20Report.pdf*

2. INTRODUCTION AND BACKGROUND

2.1 INTRODUCTION

2.1.1 FREQUENCY KEEPING CONTROL AND MULTIPLE FREQUENCY KEEPING

On 16th October 2014, a 6 month trial of frequency keeping control (FKC) operation was undertaken. FKC modulates the active power on the HVDC to tie the North and South Island frequencies together.

FKC was found to be beneficial to economic operation of the power system, notably by reducing the amount of frequency keeping required and hence the cost of the frequency keeping ancillary service.

Before FKC operations were introduced, frequency keeping was transitioned from a system of single frequency keeping (SFK), where one generator in each island was contracted to provide the total frequency keeping MW range, to a system of multiple frequency keeping (MFK), where multiple generators would each take a portion of the total MW. Frequency keeping behaviour with SFK was dependant on the individual frequency keeping generator, as SFK was reliant on a generator's control system. Frequency keeping behaviour with MFK is dependent on a centralised control system, which measures frequency and sends continuous frequency keeping regulation instructions to MFK participants.

When FKC was enabled it was found that significantly fewer MWs were required by MFK to fulfil the frequency keeping function. Frequency keeping bands were changed from 50 MW in the North Island and 25 MW in the South Island to 20 MW in the North Island and 10 MW in the South Island.

2.1.2 SO SECURITY TOOLS UPGRADE PROJECT

In September 2015, an upgrade to the SO security tools took place. This increased the capability of the market system tools and simplified operational procedures to maintain security while FKC and Roundpower[2] are active.

The upgrade enhanced the capability of the Pre-Solve Deviation calculation tool (PSD, see Section 2.2) to enable it to run in automatic mode whilst FKC is in operation. This capability required tuning and testing to gain operational confidence.

2.1.3 MFK REFINEMENT AND PSD TESTING

Since introduction of FKC, power system operation is being continuously optimised to adapt to this new technology. Frequency keeping has been reduced from 75 MW to 30 MW. But, could the power system be operated with even less frequency keeping service?

From October 2015 to February 2016 a series of power system tests were conducted with three purposes in mind:

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[2] An operational mode of the HVDC which allows seamless switching between north and south transfer.

1. To optimise PSD settings to give both a stable dispatch and reduce HVDC modulations and time error fluctuations.
2. To test automatic dispatch[3] with FKC operation.
3. To test operation with 30 MW of MFK, 20 MW of MFK, and 0 MW of MFK and to study power system operation under each scenario.

2.1.4 TASC 55 – MFK Refinement

As part of the Normal Frequency Management Strategy Project, Transpower was tasked by the EA with TASC 55 – MFK Refinement, to optomise the quantity of MFK purchased.

This report presents analysis of the MFK band and PSD tests, with a focus on the operational effects of using the different MFK MW bands.

2.2 PSD Inputs

A significant part of the testing focused on the variations to the PSD inputs.

Figure 1 shows the PSD interface into the Market Operator Interface (MOI)[4]. The inputs to the PSD calculation which were important to the testing periods analysed in this report were:

- Time error: the time errors for both North and South Islands were input into the calculation. Where time error exceeded the deadband in either direction, the corresponding time error correction would offset by a fixed quantity the dispatch to the island where time error had exceeded the deadband
- DC sent: the difference between the HVDC MW transfer and the HVDC dispatch was applied to offset each island's dispatch
- MFK Average Regulation Value: the average MFK regulation value in each island for the previous 5 minute dispatch periods was applied to each island dispatch.

All inputs into the PSD could have, as options, the addition of a constant offset in each island or adjustment to the coefficient for each island.

The constant offset would offset the dispatch at all times, regardless of the PSD input.

The coefficient for each island would affect the participation of the input into each island dispatch. For example, if the South Island coefficient was set to 0 for the HVDC sent input, only the North Island dispatch would be affected by HVDC being off dispatch.

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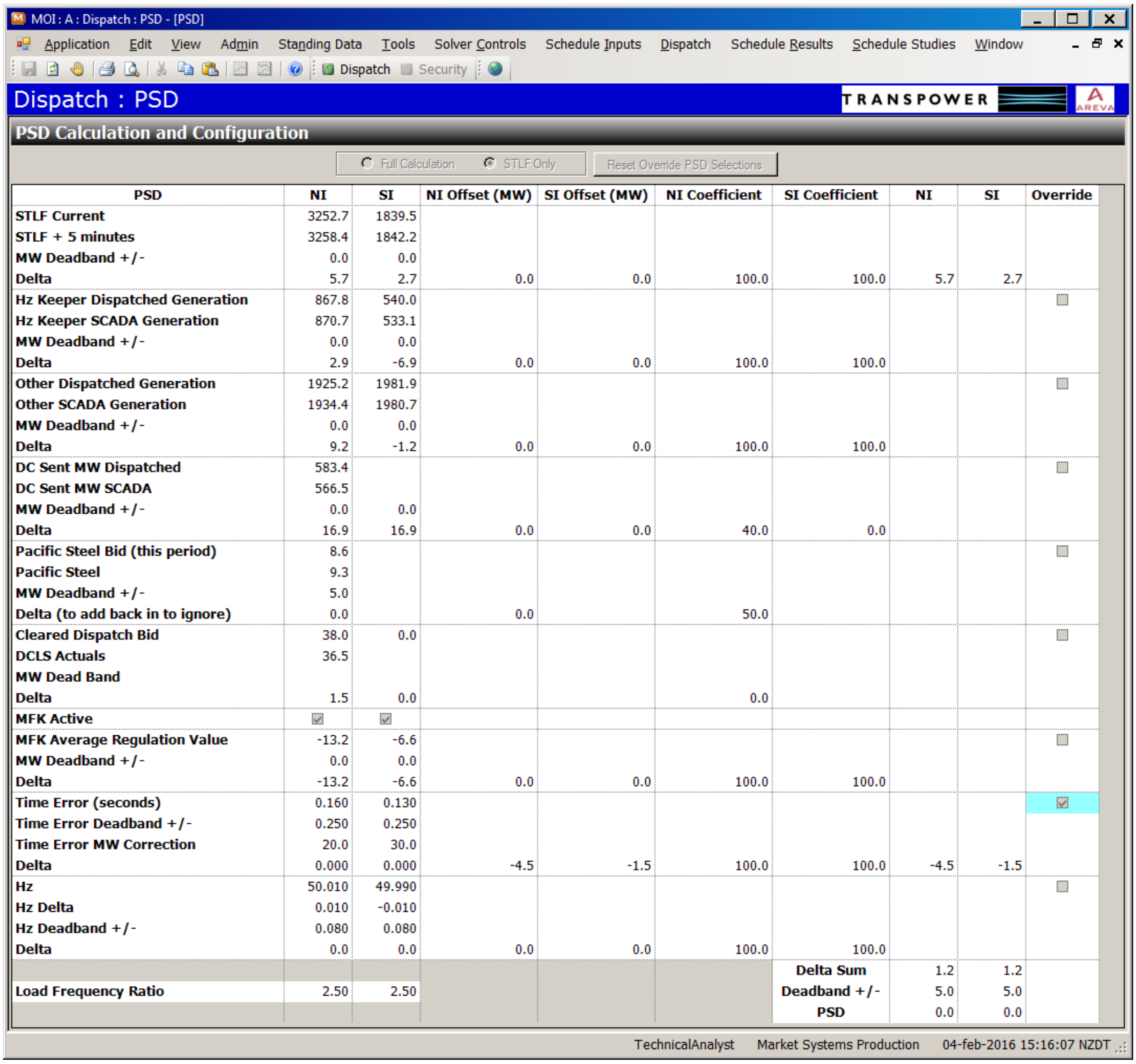
[3] Automatic dispatch refers to the action of sending a dispatch solution. It does not refer to the whole dispatch process which, amongst other things, requires creation and security checking of dispatch schedules. In the dispatch context, the term augmented dispatch refers to the dispatch process in which some, but not all, elements of the process are automated.

[4] System co-ordinators access their operational tools using the MOI.



PSD	NI	SI	NI Offset (MW)	SI Offset (MW)	NI Coefficient	SI Coefficient	NI	SI	Override
STLF Current	3252.7	1839.5							
STLF + 5 minutes	3258.4	1842.2							
MW Deadband +/-	0.0	0.0							
Delta	5.7	2.7	0.0	0.0	100.0	100.0	5.7	2.7	
Hz Keeper Dispatched Generation	867.8	540.0							☐
Hz Keeper SCADA Generation	870.7	533.1							
MW Deadband +/-	0.0	0.0							
Delta	2.9	-6.9	0.0	0.0	100.0	100.0			
Other Dispatched Generation	1925.2	1981.9							☐
Other SCADA Generation	1934.4	1980.7							
MW Deadband +/-	0.0	0.0							
Delta	9.2	-1.2	0.0	0.0	100.0	100.0			
DC Sent MW Dispatched	583.4								☐
DC Sent MW SCADA	566.5								
MW Deadband +/-	0.0	0.0							
Delta	16.9	16.9	0.0	0.0	40.0	0.0			
Pacific Steel Bid (this period)	8.6								☐
Pacific Steel	9.3								
MW Deadband +/-	5.0								
Delta (to add back in to ignore)	0.0		0.0		50.0				
Cleared Dispatch Bid	38.0	0.0							☐
DCLS Actuals	36.5								
MW Dead Band									
Delta	1.5	0.0			0.0				
MFK Active	☑	☑							
MFK Average Regulation Value	-13.2	-6.6							☐
MW Deadband +/-	0.0	0.0							
Delta	-13.2	-6.6	0.0	0.0	100.0	100.0			
Time Error (seconds)	0.160	0.130							☑
Time Error Deadband +/-	0.250	0.250							
Time Error MW Correction	20.0	30.0							
Delta	0.000	0.000	-4.5	-1.5	100.0	100.0	-4.5	-1.5	
Hz	50.010	49.990							☐
Hz Delta	0.010	-0.010							
Hz Deadband +/-	0.080	0.080							
Delta	0.0	0.0	0.0	0.0	100.0	100.0			
						Delta Sum	1.2	1.2	
Load Frequency Ratio	2.50	2.50				Deadband +/-	5.0	5.0	
						PSD	0.0	0.0	

Figure 1 PSD interface in the MOI

2.3 DISPATCH MODES

During these tests, three dispatch modes were used in the PSD tool:

1. Manual/Manual: The PSD applied to the dispatch is a manual input from the system co-ordinator and the dispatch instruction is sent manually. No tests were run exclusively in this mode. However, at times dispatch was switched to this mode if co-ordinators chose, to manage situations such as load ramps manually or for training purposes.
2. Manual/Auto: The PSD applied to the dispatch is an automatic calculation and the dispatch instruction is sent manually. The first tests were carried out in this mode.
3. Auto/Auto (Augmented): The PSD applied to the dispatch is an automatic calculation and the dispatch instruction is sent automatically. The tool has safety thresholds which if exceeded will not send a dispatch instruction automatically. After initial tests to tune PSD input settings, remaining tests were carried out in this mode. This is augmented dispatch mode.

3. TEST PERIODS

The work involved a series of weekly test periods testing different aspects of using PSD inputs, different MFK bands, and manual or augmented dispatch. The testing periods are in Table 1.

Table 1 Test periods

Test Period	Start Time	End Time	FKC	MFK		PSD Inputs
				NI	SI	
Test period 1	21/10/2015 12:00	28/10/2015 12:00	On	20	10	Time error
Test period 2	28/10/2015 12:00	4/11/2015 12:00	On	20	10	Time error DC sent
Test period 3	4/11/2015 12:00	11/11/2015 12:00	On	20	10	Time error MFK
Test period 4	11/11/2015 12:00	18/11/2015 12:00	On	20	10	Time error DC sent
Test period 5	18/11/2015 12:00	25/11/2015 12:00	On	20	10	Time error Augmented dispatch
Test period 6	26/11/2015 6:30	29/11/2015 20:30	Off	25	25	FKC off
Test period 7	2/12/2015 12:00	9/12/2015 12:00	On	20	10	Time error Augmented dispatch
Test period 8	9/12/2015 12:00	16/12/2015 12:00	On	0	0	Time error Augmented dispatch
Test period 9	13/01/2016 12:00	20/01/2016 12:00	On	20	10	Time error Augmented dispatch
Test period 10	20/01/2016 12:00	27/01/2016 12:00	On	0	0	Time error Augmented dispatch
Test period 11	27/01/2016 12:00	3/02/2016 12:00	On	10	10	Time error Augmented dispatch
Test period 12	3/02/2016 12:00	10/02/2016 12:00	On	20	10	Time error Augmented dispatch
Test period 13	10/02/2016 12:00	17/02/2016 12:00	On	0	0	Time error Augmented dispatch

Test periods 1 – 4 focused on testing time error, MFK regulation and DC sent PSD inputs. These tests were carried out with automatic PSD calculation, manual send.

From test period 5 onwards, augmented dispatch was tested, along with further testing and refining of PSD settings. Based on what was seen in test periods 1 – 4, only the Time Error PSD input was used throughout the remaining tests.

Test period 6 was carried out over a period where FKC was unavailable. Since removing FKC has a market impact this testing period was bound by outage circumstances and was only carried out for approximately two and a half days.

Test periods 8, 10 and 13 tested operation with 0 MW of MFK, relying only on governor action and dispatch to maintain frequency.

Test period 11 tested operation with 20 MW of MFK.

To compare time error, MFK regulation and HVDC modulation behavior before the testing with the upgraded SO tools started, data from July 2015 was used.

Following the first set of test periods, 3 additional test periods were undertaken in May to further study reduced MFK operation. These are given below in Table 2.

Table 2 Additional test carried out in May

Test Period	Start Time	End Time	FKC	MFK		PSD Inputs
				NI	SI	
Test period 14	11/05/2016 12:00	18/05/2016 12:00	On	15	15	Time Error
Test period 15	18/05/2016 12:00	25/05/2016 12:00	On	0	0	Time Error
Test period 16	25/05/2016 12:00	1/06/2016 12:00	On	10	10	Time Error

4. Study Methodology

This section outlines the study methodology undertaken in this analysis.

For all measures, statistical data was calculated from Plant Information (PI) data over full test periods.

4.1 Time Error

Time error data was analysed using data with 1 minute resolution.

The measures looked at were:

1. Average time error (seconds).
2. Absolute average time error (seconds).
3. Time per day spent above 0.3 seconds (minutes/day) – absolute value.
4. Time per day spend above 0.5 seconds (minutes/day) – absolute value.

With FKC enabled the two island time errors move together, with a relatively constant gradient of divergence across extended time periods. With this behavior, the variation of North and South Island time error could be analysed together, rather than separately. For all test periods where FKC was enabled, analysis was undertaken on the average of North and South Island time errors.

4.2 MFK Regulation

MFK regulation data was analysed using data with 1 minute resolution.

The total MFK regulation was calculated from a sum of regulation to all MFK active participants. This did not capture actual MFK participant generation output changes, so any variation in performance which may have been caused due to different MFK participants will not have been captured in this analysis. With the data available, analysing the MFK participant generation output changes from the MFK regulation signal was impractical.

The measures looked at for MFK regulation were:

1. Average MFK regulation (MW).
2. Absolute average MFK regulation (MW).
3. Time per day spent above 66% – absolute value:
4. Time per day spend above 93% – absolute value:
5. Cumulative distribution function with the 5th, 50th and 95th percentiles highlighted.

During the period when FKC was disabled, MFK was operated with 25 MW of MFK in each island. In the North Island this period was split between 25 MW regulation band and 30 MW regulation band. This is in Figure 2 below.

The MFK market tool finds the cheapest option to cover at least 25 MW as it was the North Island MW band setting for the test period. Depending on offers from MFK participants, the cheapest combination could exceed 25 MW. During the test period it was found that significant time was spent with 30 MW of MFK in the North Island.

Filtering the periods with 30 MW of MFK in the North Island was considered, but resulted in a loss of too much data.

Analysis was performed on the full period including periods with 25 MW North Island MFK regulation and 30 MW North Island MFK regulation. While including the periods where 30 MW MFK was procured will have had an effect on the analysis, especially when calculating time spent at the limits, it is representative of the expected behaviour with 25 MW of MFK set to be procured in the North Island.

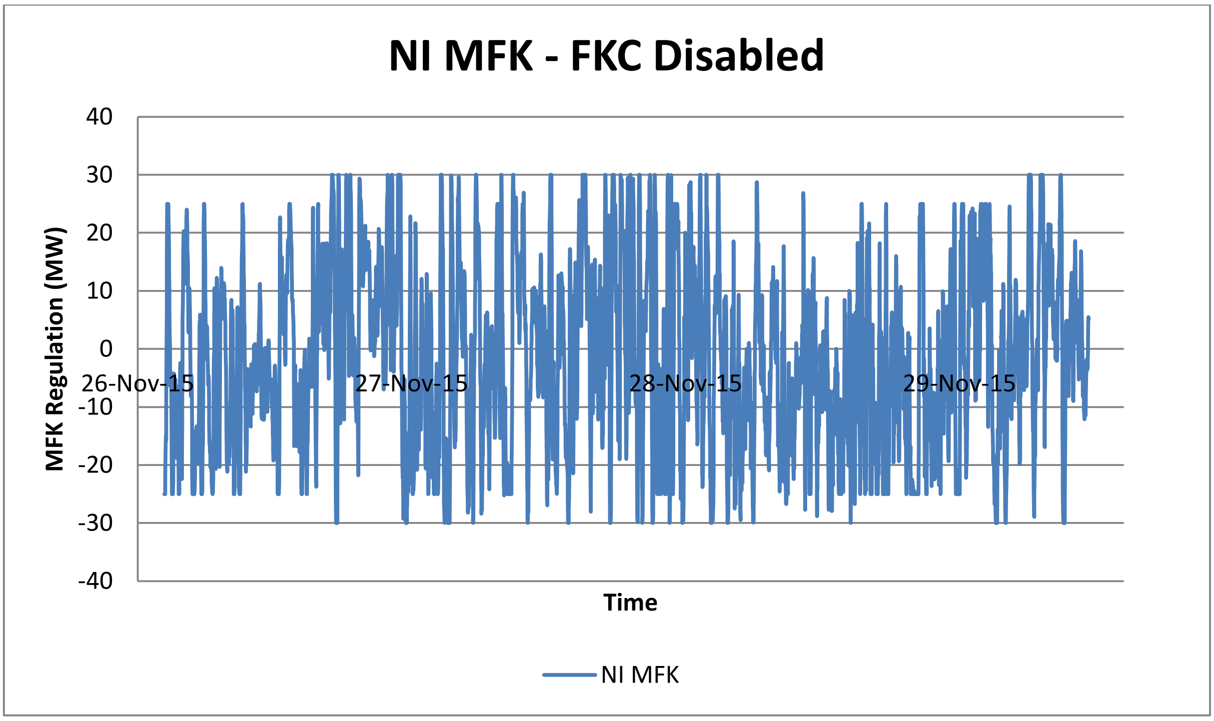


Figure 2 NI MFK with FKC disabled – test period 6

4.3 HVDC MODULATION

HVDC modulation was analysed using data with 1 minute resolution.

Data available for this analysis was:

- HVDC MW dispatch
- HVDC bipole MW transfer
- FKC modulation
- HVDC ramping status.

During periods with FKC enabled, the PI tag used for analysis was the signal for FKC modulation. This has advantages over using the HVDC dispatch and HVDC bipole transfer as the data does not need to be filtered for the HVDC ramping to meet dispatch changes.

During periods with FKC disabled, HVDC modulation was calculated using HVDC dispatch, and HVDC bipole transfer PI tags. Periods where the HVDC was ramping to meet dispatch changes were filtered out with the HVDC ramping status PI tag, which signals when the HVDC is ramping.

The measures looked at for HVDC modulation were:

1. Average HVDC modulation (MW).
2. Absolute average HVDC modulation (MW).
3. Time per day spent above 20 MW (minutes/day) – absolute value.
4. Time per day spend above 30 MW (minutes/day) – absolute value.
5. Cumulative distribution function with the 5th, 50th and 95th percentiles highlighted. This was done only for periods with FKC enabled.

HVDC dispatch data was also used to derive an indicative measure of the quantity of dispatches sent. While not all dispatches involved the HVDC, being one of the more consistently dispatched assets on the power system the HVDC dispatches could provide an indication for this analysis.

4.4 FREQUENCY

Frequency was analysed using data with 2 second resolution.

The measures used for analysis of frequency were chosen to line up with the analysis of frequency in TASC 49 Phase 1: Performance Benchmarks. This allowed easy comparison between the analysis presented here and the benchmarks provided in TASC 49.

The measures looked at for frequency variation were:

1. Mean average.
2. Standard deviation.
3. From 1 and 2: Average ± 3*Standard Deviation – this gave the upper and lower bound of values between 0.3% and 99.7%.

Transpower's TASC 49 report to the Authority provided North Island and South Island benchmarks[5] for:

1. SFK benchmark.
2. 30 MW of MFK with FKC Enabled: NI 20 MW, SI 10 MW.

[5] TASC 49 Phase 1:Performance Benchmarks, page 5

3. Governor response only: MFK 0 MW.

In addition to the TASC 49 benchmarks, the period from 15th November 2014 – 15th December 2014 was analysed to give a representation of MFK operation with FKC disabled – 50 MW North Island MFK band, 25 MW South Island MFK band. Due to the length of time over which results were analysed, the data for this period was sampled at 15 seconds, rather than 2 seconds for the other periods. This will not have significantly affected the results.

4.5 GOVERNOR OFF DISPATCH

The governor off dispatch analysis studied two of the MFK generation blocks recognised as having governors responsive to frequency deviations in the normal band.

There is no data available in PI which directly provides governor regulation signal from these generators. Therefore, calculation from other data was needed.

Data available for this analysis was:

- block dispatch values for total generation groups – this was a single station or a combination of stations
- actual active power output of individual generator units
- generator circuit breaker status
- generation block MFK regulation band.

The governor off dispatch analysis was carried out by calculating the difference between the generation block dispatch and the sum of all individual active power outputs. Analysis was undertaken using 10 second resolution data on two generation groups in the South Island.

As these generation blocks are MFK participants, the times these generation groups were actively participating in MFK would produce large governor off dispatch values. Therefore, data for those times was filtered out in the analysis.

Active power output was converted to per unit by calculating the overall MW rating based on which unit circuit breakers were currently closed.

A challenge with this analysis was filtering out the times taken to ramp to new dispatch set points. This was managed by ignoring values immediately following and preceding large dispatch changes – a larger dispatch change resulted in more data being filtered out. Ignoring values before a dispatch change accounts for the dispatch and MW output data not being completely time synchronised.

5. RESULTS AND DISCUSSION

The test periods described in Table 1 (Section 3) are grouped into the following categories defined below in Table 3.

Table 3 Test period categories used in results analysis

Category	North Island MFK	South Island MFK	Test Periods
30 MW MFK band	20 MW	10 MW	1, 2, 3, 4, 5, 7, 9, 12, 14
20 MW MFK band	10 MW	10 MW	11, 16
0 MW MFK band	0 MW	0 MW	8, 10, 13, 15
25/25 MW MFK band – FKC Disabled	25 MW	25 MW	6

5.1 TIME ERROR

Control of time error during the tests was mainly influenced by:

1. The time error PSD input settings; and
2. MFK regulation.

Time error input had a range of settings ranging from a 0.15 second deadband, 15 MW correction in each island to 0.25 second deadband and 20 MW North Island, 30 MW South Island. A permanent negative offset to the PSD was also trialed through the time error PSD input.

To compare time error behavior before the testing with the upgraded tools started, data from July 2015 was analysed for time error variation.

To compare the effect of MFK on time error control the comparison of test periods with similar PSD settings was made. Consequently, along with the total results, individual test periods with similar PSD settings were compared:

- Test Period 9 – 30 MW MFK, 0.15 second deadband, 25 MW North Island correction, 35 MW South Island correction.
- Test Period 11 – 20 MW MFK, 0.15 second deadband, 15 MW North Island correction, 25 MW South Island correction
- Test Period 10 – 0 MW MFK, 0.15 second deadband, various North and South Island MW correction.

Note: with the exception of Test Period 6 (FKC disabled), the time error was analysed as an average of North and South Island time errors.

Figure 3 shows the time error average and absolute average; Figure 4 shows the minutes / day the time error spent above 0.3 and 0.5 seconds. A table of results for all test periods is in Appendix A: Full Overall Comparison Tables.

From the average and time-above thresholds analysis the following is noted:

- Time error absolute average and time above 0.3 and 0.5 seconds / day data shows a significant improvement throughout the SO Tools testing from pre SO tools operation

- Test period 11, with 20 MW of MFK, shows a better result than with 30 MW of MFK. This is likely due to the variation seen within the 30 MW MFK results as the PSD settings were refined. Comparing test period 11 with test period 9 shows that very similar time error control has been seen with 20 MW and 30 MW of MFK
- The data indicates that with 0 MW of MFK time error control is impacted. However with the right settings in the time error PSD input good control of time error can be achieved. Test period 10, with 0 MW of MFK has an absolute average only slightly worse than test periods 9 and 11
- The Electricity Industry Participation Code (EIPC) obligations for managing time error are to keep time error within ±5 seconds. These tests have shown the PSD can be used to keep time error much tighter than that if required

The PSD settings for 0 MW of MFK were continually optimised throughout the testing. Test period 13, the final week of 0 MW MFK, was compromised due to issues with market tools for some time. Test period 14, the additional 0 MW of MFK test period carried out in May, showed good time error control.

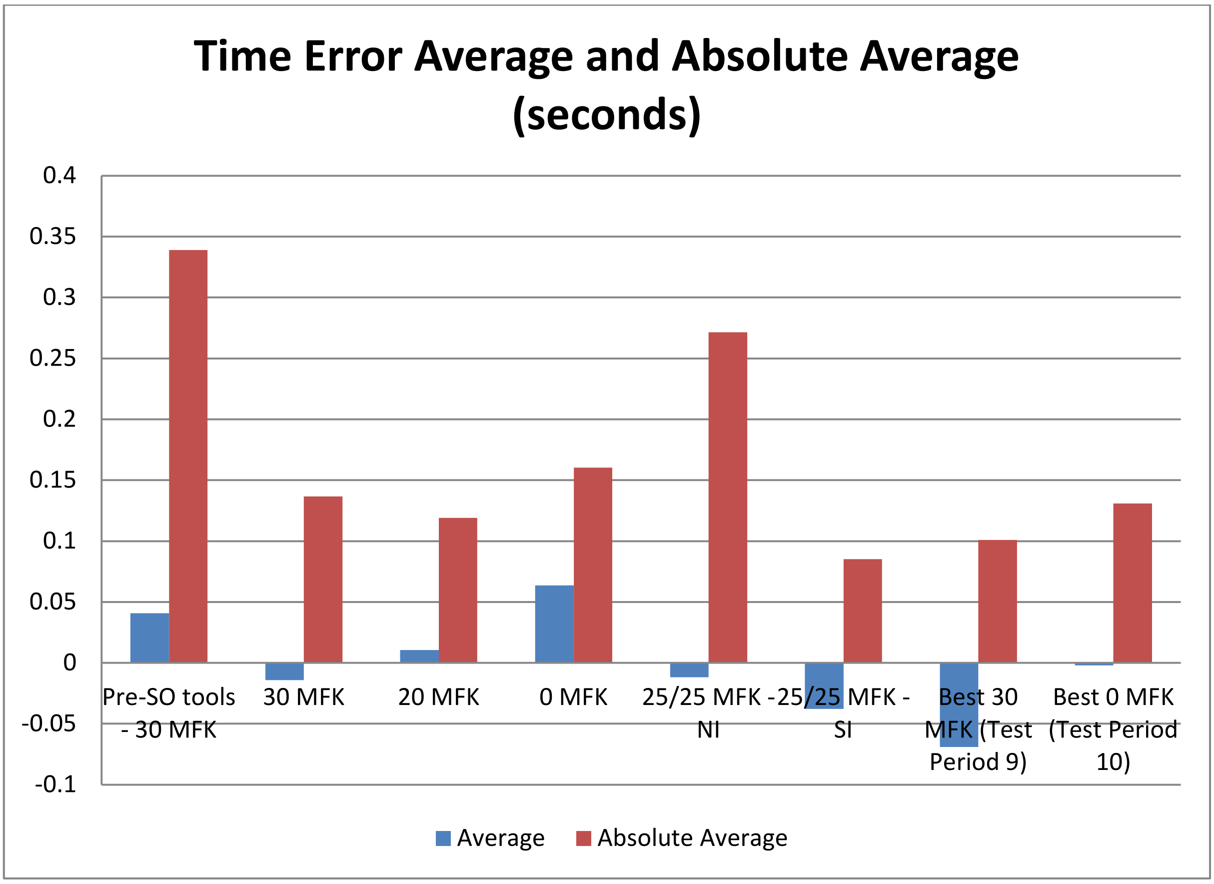


Figure 3 Time error analysis results – Average and Absolute Average

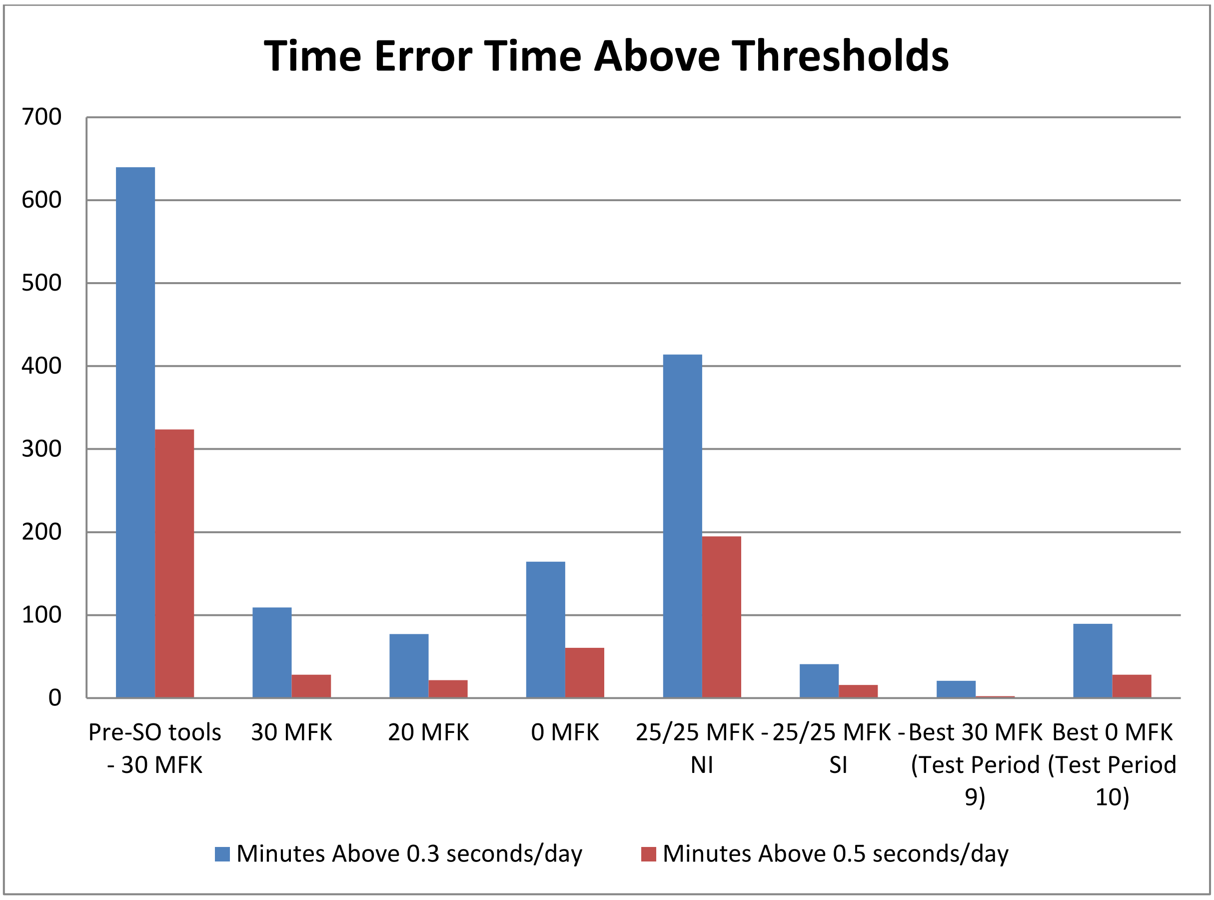


Figure 4 Time error analysis results – time above thresholds

5.1.1 FKC Disabled

With FKC disabled South Island time error was very close to 0 seconds. North Island timer error was notably higher than during other periods in the trial but was nevertheless much lower than before SO security tools operation with FKC.

5.2 MFK Regulation

Throughout the PSD testing (with the upgraded SO security tools) no patterns of improvement in or deterioration of MFK regulation were observed.

To compare MFK regulation behavior, before and after testing with the upgraded tools started, data from July 2015 was analysed for MFK regulation.

Figure 5 shows the average and absolute MFK regulation; Figure 6 gives the time above thresholds. As discussed in 4.2, the thresholds chosen for the analysis were 66.7% and 93%, resulting in different MW for the different MFK bands.

Full results are in Appendix A: Full Overall Comparison Tables.

From the analysis the following is noted:

- with 30 MW of MFK the data suggests there was less regulation during the test periods than in before the SO security tools upgrade

- comparing 30 MW of MFK with 20 MW of MFK the reduction in average regulation with 20 MW was sensible given that MFK is operating within a tighter band. When comparing 20 MW and 30 MW operation by % of the band, more time is spent at the higher end of the band when in 20 MW of MFK operation.
- throughout the test periods the average MFK regulation consistently had a negative average.

Additional tests in May showed very similar MFK usage to the original set of tests.

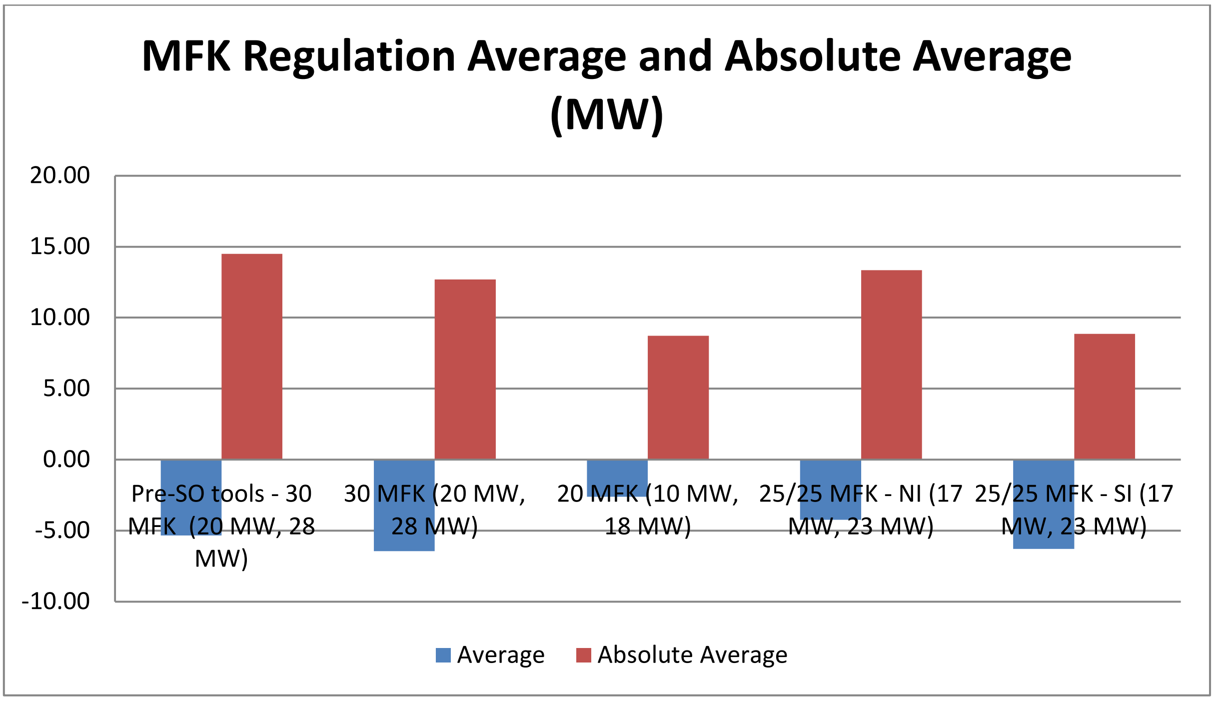


Figure 5 MFK regulation analysis results – Average and Absolute Average

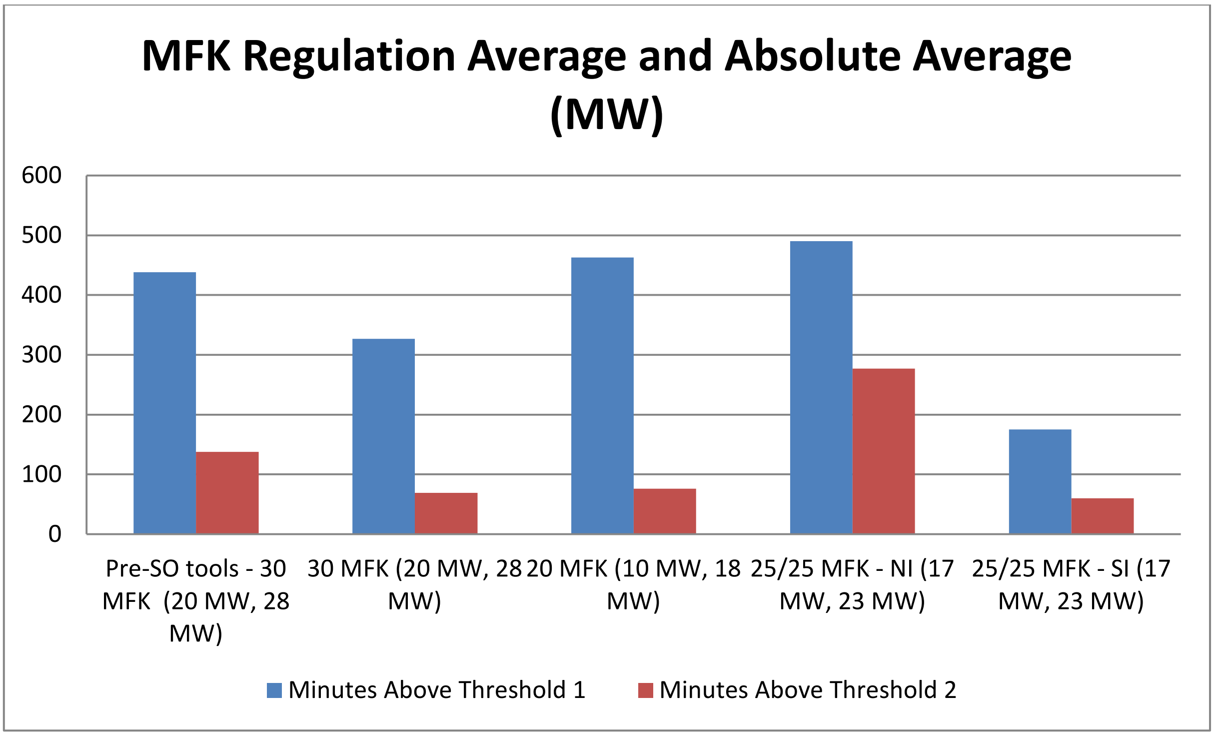


Figure 6 MFK regulation analysis results – time above thresholds 1 and 2

Figure 7 shows the cumulative distribution function for both 30 MW of MFK and 20 MW of MFK as a percentage of the MFK regulation band.

Both the 30 MW and 20 MW band data showed more activity in the negative region than in the positive region, with 5% of the time being within 1 MW of maximum negative regulation.

Table 4 MFK regulation percentile values

Frequency Keeping Configuration	5th Percentile MW / %	50th Percentile MW / %	95th Percentile MW / %	5th – 95th Percentile Range MW
30 MW MFK Band	-27.2 / -91%	-7.8 / -26%	18.9 / 63%	46.2 / 154%
20 MW MFK Band	-17.8 / -89%	-3.3 / -17%	14.8 / 74%	32.5 / 163%

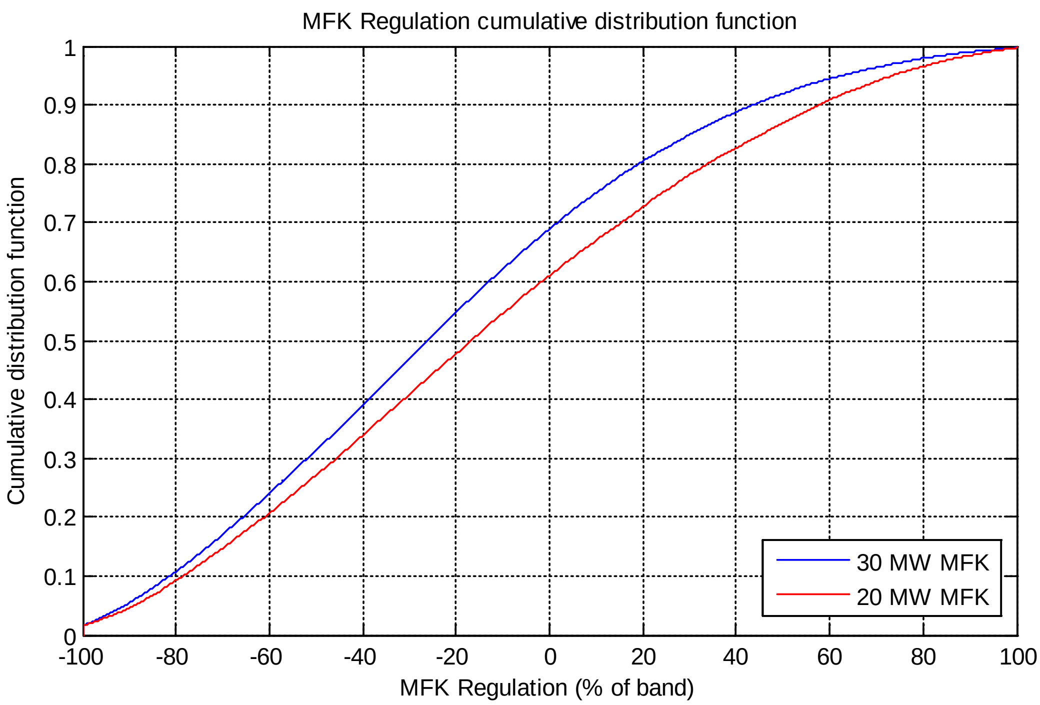


Figure 7 MFK regulation cumulative distribution function

5.2.1 FKC DISABLED

MFK operation with FKC disabled showed a much higher use of MFK in the North Island than the South Island. This is partly due to the North Island MFK band being 30 MW rather than 25 MW for about half of the review period. This is discussed further in Section 4.2.

The North Island, despite having only a 25 MW MFK band half of the time, had the same absolute average as the 30 MW MFK band data with FKC enabled. The time spent above 23.3 MW, close to the maximum of 25 MW, averaged out to about 5 times greater in the North Island than in the South Island, partly due to the North Island having 30 MW of MFK some of the time.

Figure 8 shows the cumulative distribution function for both the North and South Islands with 25 MW band. Table 5 gives percentile values for North and South Island MFK regulation.

The South Island shows more activity in the negative region, the 95th percentile being a third of the maximum 25 MW regulation limit.

The North Island is much closer to regulating evenly positive and negative.

Table 5 MFK Regulation percentile values – FKC Disabled

Frequency Keeping Configuration	5th Percentile MW / %	50th Percentile MW / %	95th Percentile MW / %	5th – 95th Percentile Range MW / %
25 MW MFK Band – North Island (FKC Disabled)	-26.8 / 107%	-1.5 / -6%	23.9 / 96%	50.7 / 202.8%
25 MW MFK Band – South Island (FKC Disabled)	-20.9 / -83%	-6.3 / -25%	8.3 / 33%	29.2 / 116.8%

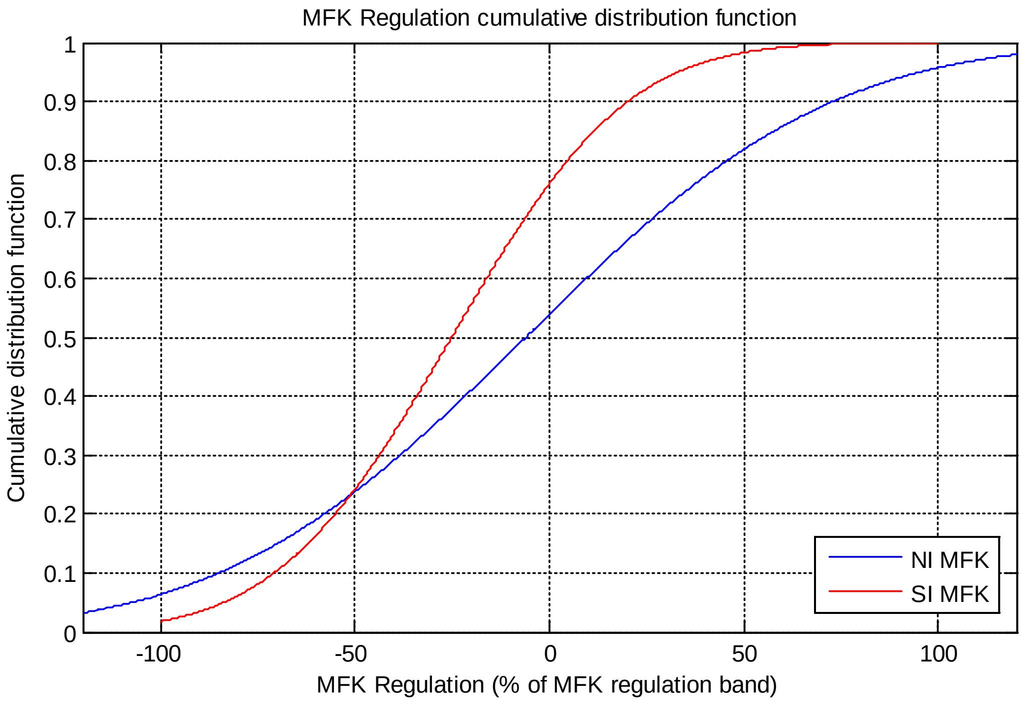


Figure 8 MFK cdf function – FKC disabled

5.3 HVDC MODULATION

HVDC modulation was impacted by the PSD settings. Test periods 2 and 4 tested the use of the DC sent PSD input to improve HVDC modulation. Results for those weeks did not reveal any major improvements to the HVDC modulation not also seen in other weeks without the DC sent PSD input.

Another strategy to reduce the HVDC modulation was to offset time error correction, i.e. instead of applying 25 MW in both the North and South Island, 30 MW was applied in the South and 20 MW in the North. This put more change of MW in the island with more reactive governors, the aim being to produce less HVDC modulation of that dispatch deviation.

To compare HVDC modulation behavior before this testing with the upgraded tools started, data from July 2015 was analysed for HVDC modulation.

Figure 9 shows the average and absolute HVDC modulation; Figure 10 gives the time above thresholds. Figure 11 shows the cumulative distribution function of the HVDC modulation under periods of 30 MW MFK, 20 MW MFK, and 0 MW MFK. Table 6 shows the 5th, 50th and 95th percentile HVDC modulation values.

From the analysis the following is noted:

- With 30 MW of MFK, the data indicated a reduction in HVDC modulation seen throughout the testing compared to pre-SO security tools operation. Test period 9 showed the least HVDC modulation.
- Comparing 30 MW of MFK with both 20 MW and 0 MW MFK bands, the data indicated a slight increase in HVDC modulation with decreased MFK bands. However, both 20 MW and 0 MW values were within the range of values seen for 30 MW MFK band, the worst being test period 5, with an absolute average of 11.9 MW, and an average of 68 minutes / day spent above 30 MW.
- Test period 8 with 0 MW MFK shows an absolute average of 12.5 MW and a daily average of 293 minutes above 20 MW / day. This is significantly worse than the periods tested with 30 MW MFK, although the data for test period 8 was significantly influenced by one particularly bad day (this may suggest that MFK has a positive impact on reducing HVDC modulation). However, given the results seen in test period 10, the tests indicate that with no MFK and the right PSD settings, the HVDC modulation can be kept on par with 30 MW MFK conditions.

Additional tests in May showed more HVDC modulation than the original tests. The tests also reinforced the relationship between less MFK and increased HVDC modulation.

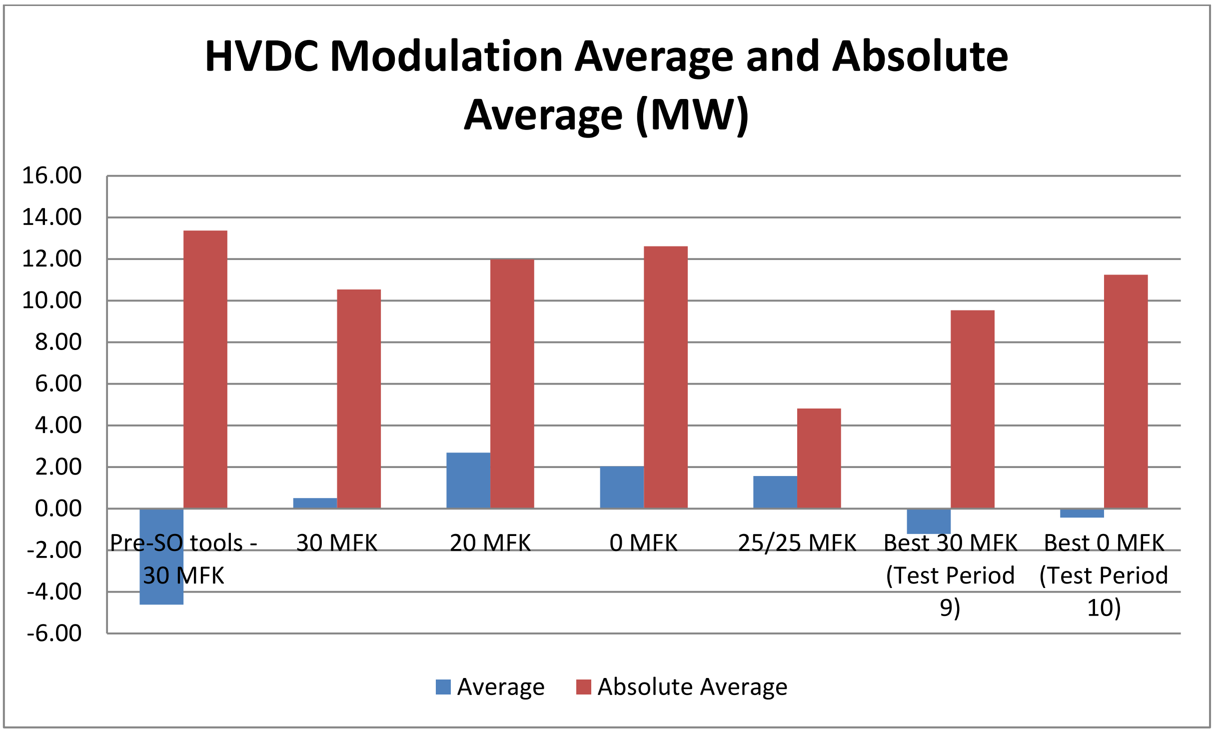


Figure 9 HVDC modulation analysis results – average and absolute average

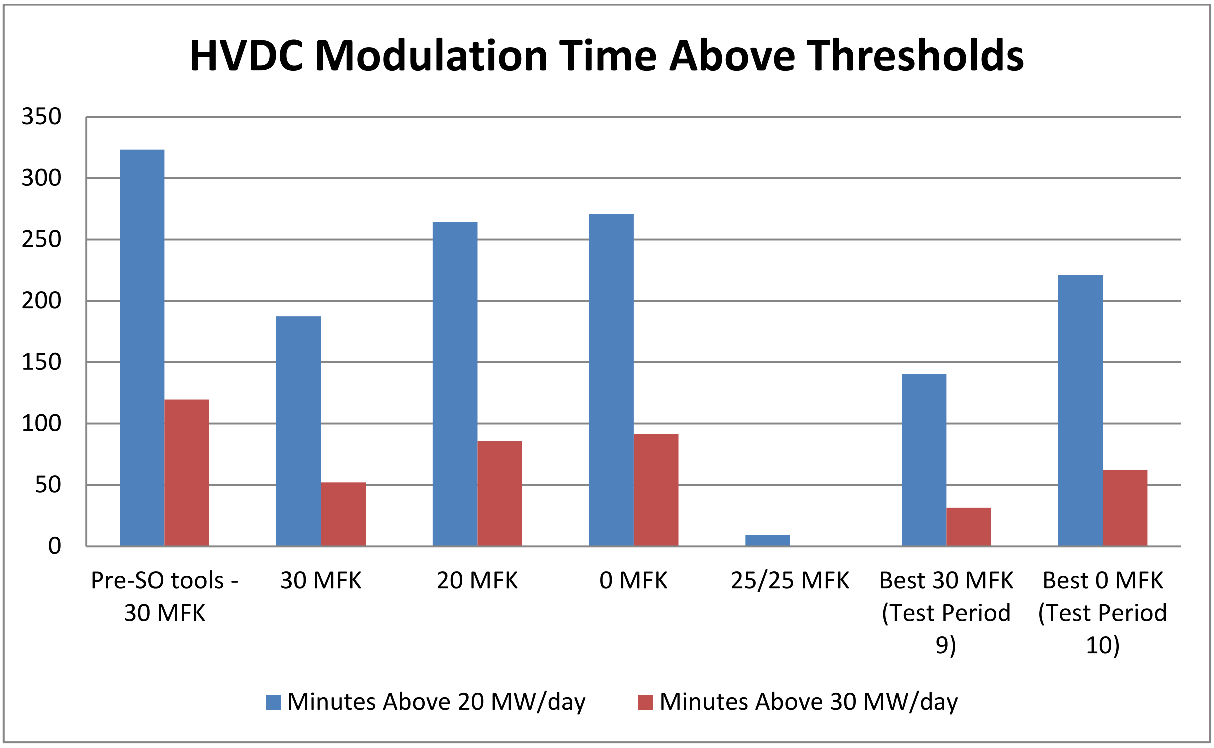


Figure 10 HVDC modulation analysis results – Time above 20 MW and 30 MW /day

The 30 MW HVDC modulation data has a 50th percentile value at almost 0 MW. The 20 MW MFK data showed a 50th percentile modulation slightly positive. A positive HVDC modulation meant additional MW from Haywards to Benmore. This indicated either the South Island having insufficient generation or the North Island having surplus generation and may be a result of a reduction of MFK in the North Island, the PSD settings used for the trial or another factor not considered in the analysis. The PSD could potentially be better tuned.

Table 6 HVDC modulation percentile values

Frequency Keeping Configuration	5th Percentile MW	50th Percentile MW	95th Percentile MW	5th – 95th Percentile Range
30 MW MFK Band	-21.15	0.30	22.92	44.07
20 MW MFK Band	-22.12	2.60	27.65	49.78
0 MW MFK Band	-22.74	1.73	27.63	50.38

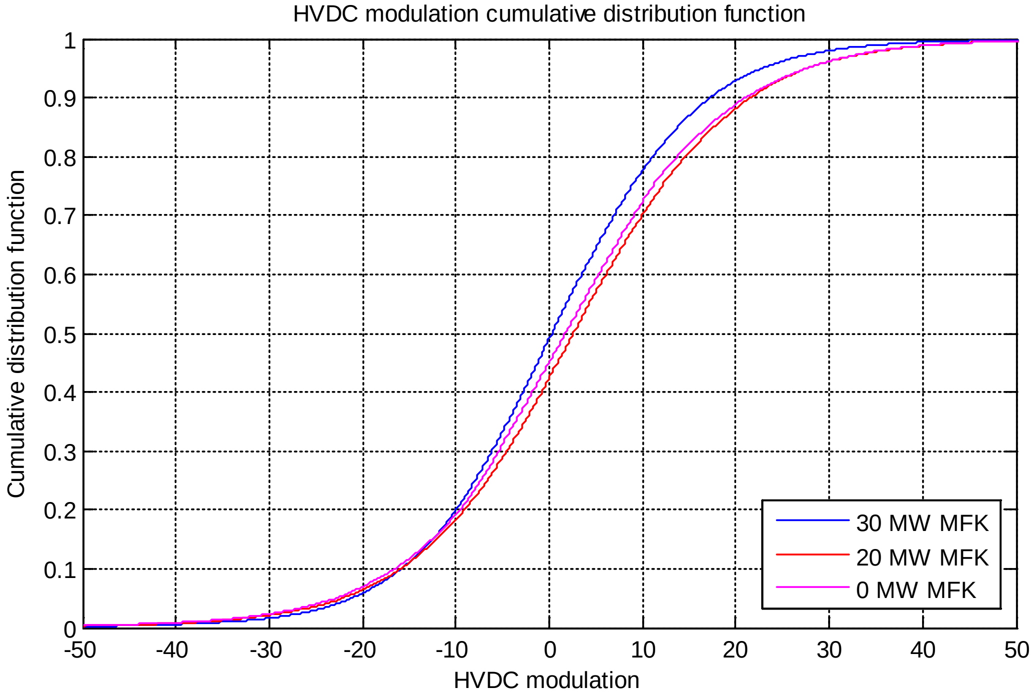


Figure 11 HVDC modulation cumulative distribution function

A full table of results is given in Appendix A.

5.5 FREQUENCY

Table 7 shows the North Island frequency standard deviations for the periods analysed. A full table of results for all test periods is in Appendix A: Full Overall Comparison Tables

Figure 12 shows the North and South Island frequency ranges for the total periods. The average frequency ± 3 standard deviations is plotted and gives the range of values between 0.3 percentile and 99.7 percentile.

From the analysis the following is noted:

- With 30 MW of MFK, the frequency standard deviations from TASC 49 analysis and during these test periods were very similar.
- With 20 MW of MFK, the South Island standard deviation was slightly lower than the figure for 30 MW of MFK. This value is within the range of values obtained for 30 MW of MFK, the lowest being test period 4 with a standard deviation of 0.0311. The data from these tests indicated there was no significant improvement or deterioration of frequency with 20 MW of MFK.
- During this testing, only one week was dedicated to testing operation with 20 MW of MFK. Although that test period produced results showing little to no deviation from operation with 30 MW, it is recommended that more testing be undertaken with 20 MW of MFK if it is being considered for normal operation.

Additional tests in May show higher frequency deviation than the original tests. The tests also reinforced the relationship between less MFK and increased frequency variation. The frequency variations seen in the tests were still within normal frequency bands and frequency ranges seen in previous operation.

Table 7 Frequency keeping configuration standard deviation values

Frequency Keeping Configuration	North Island Standard Deviation	South Island Standard Deviation
(TASC 49) SFK Benchmark	0.0522	0.0301
(TASC 49) MFK Trials with FKC Enabled: NI 20MW, SI 10MW	0.0383	0.0326
(TASC 49) Governor Response Only: MFK 0MW	0.0409	0.0349
30 MW MFK Band	0.03933	0.03369
20 MW MFK Band	0.03997	0.03428
0 MW MFK Band	0.04295	0.03642
25/25 MW MFK Band - FKC Disabled (30 MW NI Excluded)	0.0682	0.0300
25/25 MW MFK Band - FKC Disabled (30 MW NI Included)	0.0650	0.0300
50/25 MW MFK Band - FKC Disabled (15/11/14 - 15/12/14)	0.0653	0.0303

5.5.1 FKC DISABLED

Data from 15th November – 15th December 2014 with FKC disabled was analysed to provide a benchmark for 50 MW North Island and 25 MW South Island MFK operations. This analysis gave a North island frequency standard deviation significantly larger than the SFK benchmark identified in TASC 49.

South Island frequency showed less variation during test period 6 with FKC disabled, consistent with data analysed from 15th November – 15th December 2014.

With FKC disabled, North Island frequency operating with MFK had a much higher standard deviation than the South Island.

The results indicated that with a 25 MW North Island MFK band the standard deviation suffered no deterioration from with 50 MW of MFK. It was not evident if the departure of highly variable load in the current power system had a positive effect on operating the North Island with a lower MFK band.

However, if only the periods where 25 MW of MFK were contracted for the North Island are considered, the North Island frequency has a significantly higher standard deviation. Looking at Figure 12, the 0.3 to 99.7 percentile data included values outside the normal frequency range – 49.8 to 50.2 Hz.

It should be noted, though, that due to the time restrictions only 3 days of data were produced for analysis, about half of which was discarded when removing periods with 30 MW North Island MFK. To better understand operation of the North Island power system with 25 MW of MFK it is recommended to operate with 25 MW of MFK with FKC disabled in the North Island on a trial basis to establish whether satisfactory operation can be observed before being making a recommendation for FKC-disabled as normal operation.

Recommendation 1 – Utilise future FKC outages for trial operation with North Island 25 MW MFK.

The North Island frequency data for MFK operation with no FKC showed significantly more variation than the SFK benchmark provided from TASC 49. Given the upper and lower bounds of frequency (mean ± 3 standard deviations) were close to the limits of the normal frequency band, consideration could be given to operating the North Island with SFK (without MFK), when FKC is disabled.

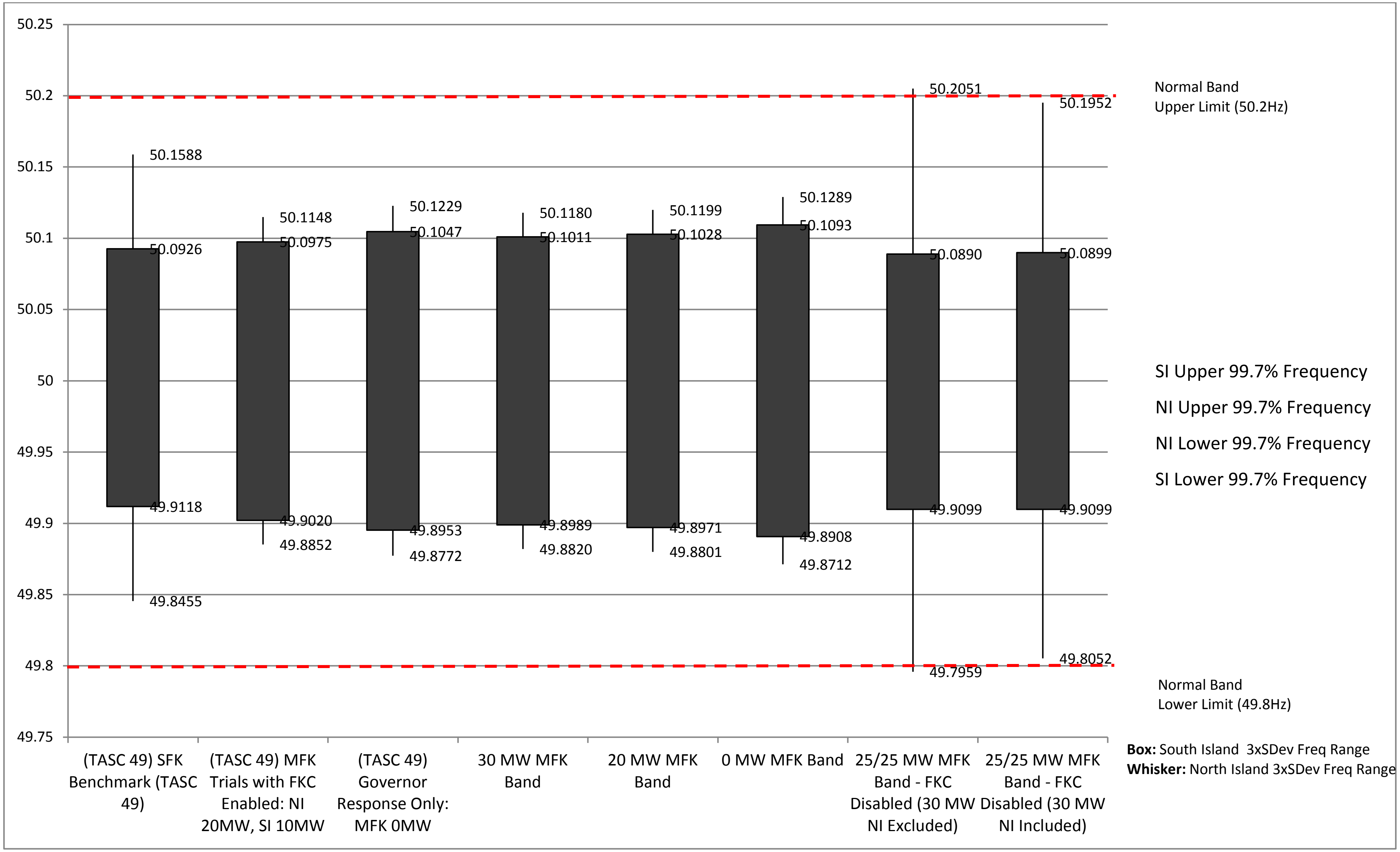


Figure 12 Frequency Comparison

5.6 GOVERNOR OFF DISPATCH

This section presents analysis of governor off dispatch during the test periods analysed. Test period 6 with FKC disabled was not analysed for governor off dispatch.

To compare governor off dispatch behavior (before the upgraded SO security tools were in operation) data from August 2015 was analysed for governors deviating from their dispatch setpoints.

Figure 13 shows the governor off dispatch standard deviation in per unit (pu) format grouped by MFK MW band.

From the standard deviation data the following is noted:

- Comparing 30 MW MFK pre-SO security tools data with similar data from after the tools upgrade an improvement was seen.
- There is a clear increase in governor off dispatch behaviour when operating with 0 MW of MFK.
- There is a marginal increase in governors off dispatch when operating with 20 MW of MFK.

Additional tests in May showed a similar trend in governor off dispatch to the original tests. The tests also reinforced the relationship between less MFK and increased governor off dispatch behaviour.

A table of results is in Appendix A: Full Overall Comparison Tables The absolute average data shows a similar trend to that seen in the standard deviation data, excepting the pre-SO security tools period which showed an absolute average much closer to 0 MW of MFK operation for Hydro Group 1.

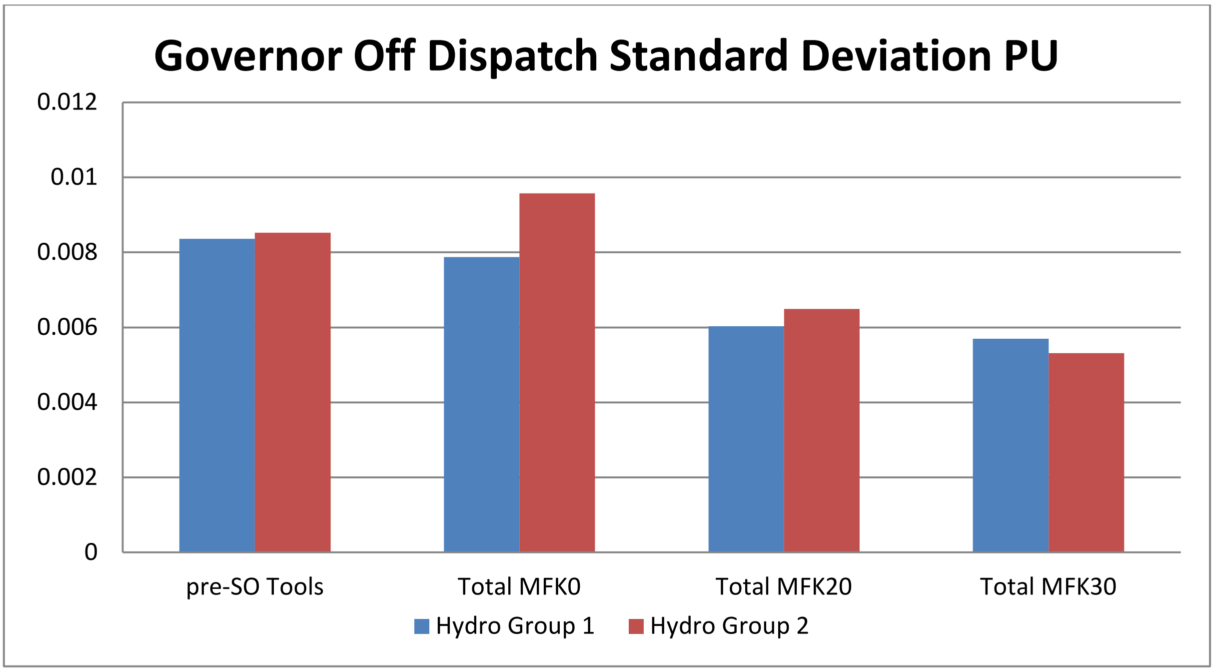


Figure 13 Governor off dispatch standard deviation pu.

6. ISSUES HIGHLIGHTED DURING TESTS

6.1 PSD NOT RESPONDING TO TIME ERROR INPUT

During test period 3 the PSD was noted to be unresponsive to the time error input. On 8th November at 16:40 the following was logged regarding time error correction:

"Time error in both islands consistently & slowly tracking more negative through entire shift with no attempt to correct it automatically. As getting close to -1 second, have manually adjusted target frequency in NI to return time error to zero. PSD & MFK settings all appear normal for the trial but response behaviour to time error does appear to have changed for the worst for unknown reasons."

This behavior appears to be an anomaly, as the time error input to the PSD was used and functioned correctly for the majority of the test periods.

6.2 GOVERNOR REGULATION CAUSING DIFFICULTY IN MANAGING CONSTRAINTS

During test period 8 (a 0 MW MFK test) increased governor action in the South Island was noted to have created difficulty managing Southland constraints. This was noted by the co-ordinator on shift and prompted intervention to the PSD settings. On 11th December, at 12:40 the following was logged regarding managing constraints due to generator units being off their dispatch setpoints:

"+20MW added to the NI PSD offset to help keep SI generators close to their set points to assist in managing Southland constraints."

Although this was noted in the 0 MW MFK test, this issue may also be experienced with 30 MW of MFK. With 30 MW of MFK, less governor regulation from dispatch was seen, though the magnitude of the governor regulation was still comparable with that seen with 0 MW of MFK. Figure 14 shows governor off dispatch swings of similar magnitude for both 0 MW and 30 MW of MFK operations.

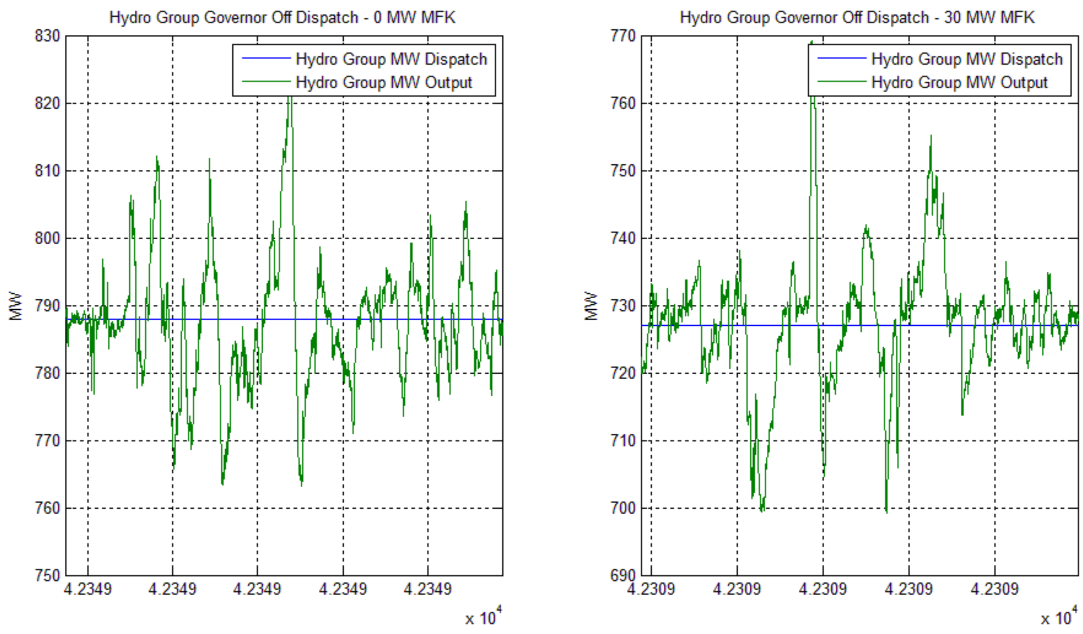


Figure 14 Governor off dispatch fluctuation example – 0 MW and 30 MW of MFK

6.3 INSUFFICIENT TIME ERROR CORRECTION IN 0 MW MFK TEST

During test period 13 with 0 MW MFK band, issues with the effectiveness of the PSD under the settings at the time were noted. Figure 15 (below) shows time error fluctuating above and below the 0.25 second threshold over a 2 hour period. The correction here was not sufficiently aggressive to move time error far enough away from the 0.25 second deadband. Therefore, when the correction was removed from the dispatch (once time error had dropped below 0.25 seconds) it quickly rose back to above 0.25 seconds.

This was noted by the co-ordinator on shift to have undesirable effects on dispatch, frequently removing then restoring 50 MW of generation to the dispatch. Figure 15 below shows this particular example (where the majority of the changes to dispatch were affecting one generation block).

However, it should be noted that this behaviour may also be experienced with 30 MW of MFK. Figure 16 below is an example of time error correction demonstrating similar saw-toothing behaviour during operation with 30 MW of MFK (seen in test period 3).

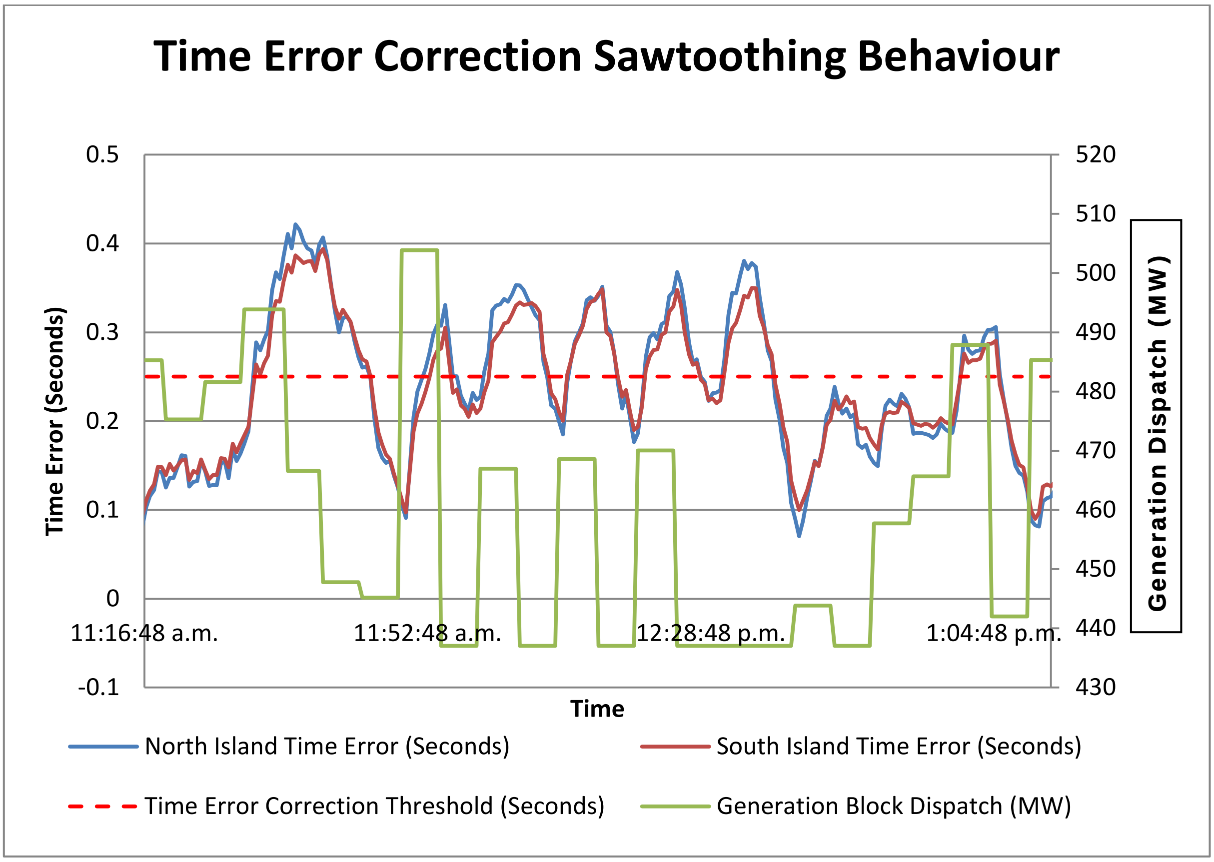


Figure 15 Time Error during saw-toothing behaviour experienced with initial test period 13 settings

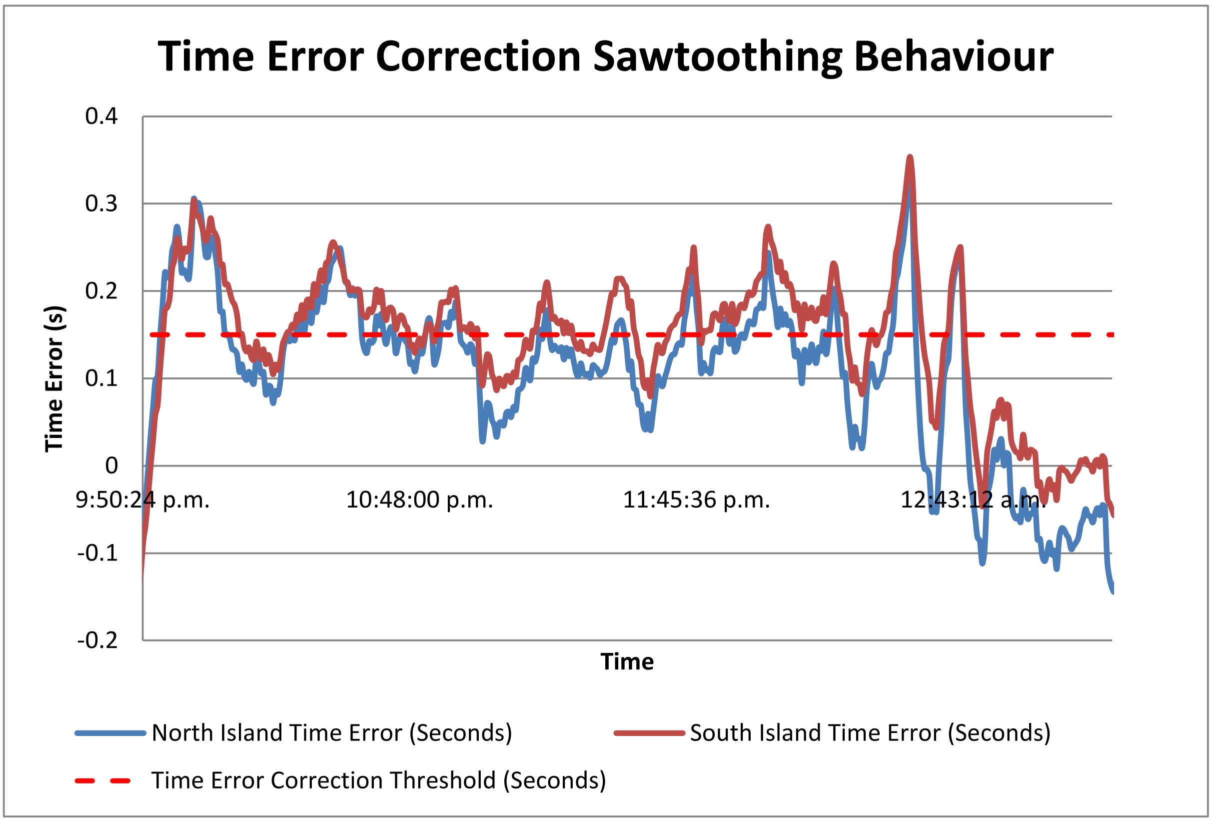


Figure 16 Saw-toothing behaviour of time error correction with 30 MW of MFK (Test Period 3)

Potentially, time error PSD calculation could be enhanced to help address the saw-toothing behavior seen on 10th February by using:

1. A proportional correction on the time error, where the MW correction applied to the PSD is proportional to the magnitude of the time error. This would mean more significant corrections are applied to higher deviations. A deadband such as used currently could be used along with the proportional correction to avoid constant PSD offsets being applied.
2. Hysteresis added to the time error correction, allowing the set value to be higher than the reset value. This would result in time error correction only being removed from the PSD when time error is well below the threshold to trigger correction.

Other PSD inputs may also be considered for enhancement aiming to reduce governor off dispatch behaviour and HVDC modulation.

Recommendation 2 – Consider further PSD enhancements.

7. RECOMMENDATIONS

Based on the analysis and experience during the testing, the following recommendations and considerations are made:

1. Utilise future FKC outages for trial operation with North Island 25 MW MFK.
2. Consider further PSD enhancement.
3. If reducing the MFK bands with FKC enabled is considered, the benefits of reducing MFK should be assessed against the impact it will have on governors off dispatch and HVDC modulation.

8. CONCLUSION

Following completion of the SO security tools project in September 2015, a series of tests were conducted to determine optimal PSD settings, test the use of augmented dispatch with FKC, and test the impact of operating with reduced MFK bands.

A total of 16 test periods were conducted, 3 of which were undertaken following identification of the need for more tests. The test periods are summarised as follows:

- 4 consisting of 30 MW of MFK, automatic PSD, manual send dispatch
- 5 consisting of 30 MW of MFK, augmented dispatch
- 4 consisting of 0 MW of MFK, augmented dispatch
- 2 consisting of 20 MW of MFK, augmented dispatch
- 1 consisting of operation with FKC disabled, 25 MW of MFK in each island.

The test periods were analysed for time error, MFK regulation, HVDC modulation, frequency variation, and governors off dispatch.

The data for 30 MW of MFK operations compared with 20 MW of MFK operations showed no indication of deterioration in performance of time error control or frequency. governors off dispatch and HVDC modulation showed a slight increase with 20 MW of MFK (though still within the range of values seen in some 30 MW MFK test periods).

The data for 30 MW of MFK operations compared with 0 MW of MFK showed an increase in frequency variation, governors off dispatch, time error control and HVDC modulation. The control of time error, although better with 30 MW of MFK, was managed to well within its limits with dispatch. The increase seen in frequency variation and time error are acceptable as they are within the range of previous acceptable operation. HVDC modulation and governors off dispatch may require investigation and consultation with industry to determine what is acceptable for normal system operation.

If reducing the MFK bands with FKC enabled is to be operationally implemented, the benefits of reducing MFK should first be assessed against the impact on governors off dispatch and HVDC modulation.

With FKC disabled the full range of test data indicated no deterioration of frequency between operation with 50 MW of MFK, and 25 MW of MFK.

However, if the periods where 30 MW of MFK rather than 25 MW of MFK was procured are removed from the analysis, the data indicated a small deterioration of frequency, placing the upper and lower bounds (0.3% - 99.7%) just outside the normal frequency band of 49.8 – 50.2 Hz. However, by removing the 30 MW MFK periods a significant amount of data is lost from an already small analysis period, reducing confidence in results drawn from the dataset.

The results of this analysis do not materially impact the recent Authority initiative to shift the MFK bands to 15 MW North Island, 15 MW South Island. The analysis of 20 MW of MFK operation did not reveal any negative effects on operation which could be attributed to the equal split of MFK between the North and South Island.

APPENDIX A: FULL OVERALL COMPARISON TABLES

Table 8 Frequency results

Test Period	Island	Standard Deviation	Average	Deviation from 50 Hz absolute average	Number of values in dataset (1 week at 2s data resolution = 302401)	Frequency Keeping Configuration
0	North Island	0.0653	50.00014	0.0508	172835	Pre-SO tools - 30 MFK
1	North Island	0.0410	49.99996	0.0314	302157	30 MFK
2	North Island	0.0411	50.00002	0.0319	302345	30 MFK
3	North Island	0.0398	49.99997	0.0307	302398	30 MFK
4	North Island	0.0366	49.99999	0.0282	302394	30 MFK
5	North Island	0.0365	49.99999	0.0281	302393	30 MFK
6	North Island	0.0682	50.00045	0.0513	133036	25/25 MFK
7	North Island	0.0373	49.99991	0.0287	302392	30 MFK
8	North Island	0.0435	50.00005	0.0330	302318	0 MFK
9	North Island	0.0374	49.99997	0.0287	200570	30 MFK
10	North Island	0.0423	50.00001	0.0327	302375	0 MFK
11	North Island	0.0382	49.99995	0.0293	302395	20 MFK
12	North Island	0.0399	49.99998	0.0308	302400	30 MFK
13	North Island	0.0399	50.00026	0.0309	180508	0 MFK
14	North Island	0.0432	50.00001	0.0334	302372	30 MFK
15	North Island	0.0448	50.00005	0.0350	302291	0 MFK
16	North Island	0.0417	49.99998	0.0321	302290	20 MFK
0	South Island	0.0303	50.00010	0.0225	172835	Pre-SO tools - 30 MFK
1	South Island	0.0354	49.99997	0.0272	302157	30 MFK
2	South Island	0.0355	50.00002	0.0276	302345	30 MFK
3	South Island	0.0335	50	0.0260	302398	30 MFK
4	South Island	0.0311	49.99998	0.0239	302394	30 MFK
5	South Island	0.0315	49.99996	0.0243	302393	30 MFK

6	South Island	0.0300	49.99989	0.0225	133036	25/25 MFK
7	South Island	0.0319	49.9999	0.0246	302392	30 MFK
8	South Island	0.0347	49.99998	0.0268	302318	0 MFK
9	South Island	0.0321	49.99997	0.0246	200570	30 MFK
10	South Island	0.0370	50.00002	0.0286	302375	0 MFK
11	South Island	0.0323	49.99995	0.0248	302395	20 MFK
12	South Island	0.0334	49.99998	0.0259	302400	30 MFK
13	South Island	0.0342	50.00020	0.0264	180508	0 MFK
14	South Island	0.0377	50.00000	0.0291	302372	30 MFK
15	South Island	0.0387	50.00003	0.0302	302291	0 MFK
16	South Island	0.0362	49.99999	0.0278	302290	20 MFK

Table 9 Time error results

Test Period	Average	Absolute Average	Minutes Above 0.3 seconds/day	Minutes Above 0.5 seconds/day	Number of values in dataset	Frequency Keeping Configuration
1	-0.007	0.131	97	22	10081	30 MFK
2	0.026	0.119	58	11	10011	30 MFK
3	-0.091	0.161	208	59	10081	30 MFK
4	0.051	0.15	163	49	10081	30 MFK
5	0.097	0.155	182	53	10081	30 MFK
6 – North Island	-0.065	0.262	408	177	10321	25/25 MFK
6 – South Island	-0.038	0.085	41	16	10321	25/25 MFK
7	-0.011	0.102	67	30	10081	30 MFK
8	0.182	0.24	346	160	9747	0 MFK
9	-0.069	0.101	21	2	10081	30 MFK
10	-0.002	0.131	90	28	10081	0 MFK
11	0.024	0.096	32	6	10081	20 MFK
12	-0.12	0.168	64	0	10081	30 MFK
13	0.026	0.151	84	22	6031	0 MFK
14	-0.003	0.142	122	27	10081	30 MFK
15	0.033	0.116	90	13	10081	0 MFK
16	-0.003	0.142	122	37	10081	20 MFK

Table 10 MFK regulation

Test Period	Average	Absolute Average	Minutes Above 66.7% MW/day	Minutes Above 93.3% MW MW/day	Number of values in dataset	Frequency Keeping Configuration
1	-6.535	13.383	367	79.714	10081	30 MFK
2	-6.43	13.142	352.857	67.857	10081	30 MFK
3	-6.764	12.686	314.286	57.571	10081	30 MFK
4	-5.619	13.406	366.286	80.143	10081	30 MFK
5	-5.619	13.406	366.286	80.143	10081	30 MFK
6 – North Island	-1.4678	12.8422	481	248	4860	25/25 MFK
6 – South Island	-6.33	8.926	188	54	4860	25/25 MFK
7	-7.545	12.805	326.143	64.000	10081	30 MFK
8					0	0 MFK
9	-5.43	12.299	301.571	63.857	10081	30 MFK
10					0	0 MFK
11	-2.960	8.681	334.571	65.000	10081	20 MFK
12	-6.588	12.358	295.429	47.571	10081	30 MFK
13					0	0 MFK
14	-6.637	12.971	332.286	67.286	10081	30 MFK
15						0 MFK
16	-2.267	8.764	348.714	67.429	10081	20 MFK

Table 11 HVDC modulation

Test Period	Average	Absolute Average	Minutes Above 20 MW/day	Minutes Above 30 MW/day	Number of values in dataset	Frequency Keeping Configuration
1	-3.637	10.32	179.571	49	10081	30 MFK
2	-0.118	9.839	160.143	46.143	10081	30 MFK
3	-1.744	10.692	199.286	51.714	10081	30 MFK
4	2.612	11.146	212.571	65.429	10081	30 MFK
5	7.337	11.881	242.429	67.857	10081	30 MFK
6	1.403	5.123	7.116	0	10321	25/25 MFK
7	1.609	10.189	165.429	44.143	10081	30 MFK
8	3.248	12.495	293.286	95	10081	0 MFK
9	-1.214	9.537	140.286	31.571	10081	30 MFK
10	-0.435	11.251	221.143	62	10081	0 MFK
11	2.749	11.101	220.286	68.714	10081	20 MFK
12	-2.499	9.885	161.143	35	10081	30 MFK
13	0.555	12.145	154.286	54.143	6031	0 MFK
14	2.230	11.350	225.286	76.714	10081	30 MFK
15	4.170	14.360	367.143	140.857	10081	0 MFK

16	2.640	12.870	307.857	103.429	10081	20 MFK

Table 12 Governor off dispatch (Hydro Group 1)

CLU	average	absolute average	standard deviation	Data points used
pre-SO Tools	0.00442	0.00728	0.00836	67453
0 MFK	0.00127	0.00617	0.00787	72329
20 MFK	0.00121	0.00459	0.00603	54617
30 MFK	0.00200	0.00457	0.00570	201897

Table 13 Governor off dispatch (Hydro Group 2)

	average	absolute average	standard deviation	data used
pre-SO Tools	-0.00035	0.00596	0.00852	106843
0 MFK (Total)	-0.00141	0.00735	0.00958	150698
20 MFK (TP11)	-0.00109	0.00469	0.00649	102799
30 MFK (Total)	-0.00047	0.00373	0.00531	417594