Automatic Under-Frequency Load Shedding (AUFLS) Technical Report

August 2010

SYSTEM OPERATOR

Keeping the energy flowing

TRANSPOWER

Transpower New Zealand Ltd The National Grid

	Position	**Date**
Prepared By:	System Operator	6 August 2010
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This report and the appendices are available to download from the System Operator website at http://www.systemoperator.co.nz/n3210,254.html.

TABLE OF CONTENTS

1 Executive Summary

Automatic Under-Frequency Load Shedding (AUFLS) is the New Zealand power system's last-resort safety net to prevent power system collapse and blackout following large, rare system events.

New Zealand's AUFLS scheme is made up of a minimum of two 16% blocks in each island. This means that a minimum of 32% of customer demand can be automatically disconnected in two stages to seek to restore stability to the power system. The current AUFLS arrangements are largely based on historical practice and are in need of an end-to-end review.

The System Operator recognises that the nature of the power system has changed significantly over the last five years and in response is conducting a number of reviews around our security policies. In addition to a wide range of equity and policy issues with the existing AUFLS scheme, there are also new technical concerns about whether there will be sufficient AUFLS to cover large system events given the number of changes to the power system since the AUFLS system was last reviewed and the impending commissioning of HVDC pole 3.

Following on from the review of our credible event management policies, the System Operator has launched a review of the AUFLS system from a technical, economic and policy perspective. The purpose of the review is to:

1. Inform the industry and stakeholders of the effectiveness of the current AUFLS arrangements
2. Enable a wider discussion to be held to determine the benefits, risk and opportunities for New Zealand with regard to AUFLS and other methods of under-frequency management
3. Inform the AUFLS exemption process
4. List the options available for moving forward.

As the AUFLS arrangements are a key aspect of the tools to manage system security, it is important that the findings from the AUFLS review are well understood and discussed. The purpose of this review is to enable this discussion, noting that any changes to the mandated AUFLS arrangements would have to be made by the Regulator.

This report presents the findings and conclusions from the AUFLS technical review.

The results show that the System Operator's tools will ensure that there is sufficient reserve generation and demand available to be disconnected to prevent system collapse from large defined risks, such as the sudden disconnection of HVDC bi-pole, at all times. This is likely to require limiting the transfer on the HVDC link to below its maximum capability under certain system conditions to ensure power system security.

However, the overall design of the AUFLS scheme provides the System Operator with insufficient confidence that the current AUFLS scheme will be effective to prevent the system from collapsing from large risks that are not currently identified. The studies have also shown that significant over-voltage issues are likely to occur following AUFLS operation which have the potential to collapse the system.

The System Operator has identified a number of options to address these issues. The following options will be presented and discussed with industry at the upcoming System Operator workshops in August 2010:

- *Improve the performance of the existing AUFLS scheme*

  Significant improvements can be made to the existing AUFLS scheme by modifying the number and size of the AUFLS blocks and their activation mechanisms and settings. When reviewing the design of the AUFLS scheme, the total size, speed of the response and the make up of the blocks are key considerations that need to be viewed as a total package to produce the best outcomes.

- *Review the products provided in the instantaneous reserves market*

  The technical studies have revealed that system collapse can occur in less than 4 seconds following a very large event. This highlights the need for investigation of new products and markets, such as a 3 second instantaneous reserves market, to ensure that there are sufficient fast-acting measures (reserves) available on the system to ensure power system security.

- *Move toward a coordinated over-voltage protection scheme*

  The System Operator will address the over-voltage issues in the North Island as a matter of priority. The potential options and appropriate course of actions to address this issue will be discussed and coordinated with the Grid Owner and the industry.

The System Operator recognises that the options will need to be subjected to further economic assessment as it is important to achieve the right balance between the instantaneous reserves market (a $33.8 million[1] market) and the mandated AUFLS scheme to ensure power system security in an efficient manner that best meets New Zealand's needs.

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[1] $33.8 million was spent on instantaneous reserves from July 2009 to June 2010.

2 Glossary

AC — Alternating Current

An electric current that reverses directions at regular intervals. In New Zealand's electricity system this occurs 50 times a second. See *frequency*.

AUFLS — Automatic Under-Frequency Load Shedding

Automatic shedding of electrical load when the frequency falls below preset frequency levels as specified in the EGRs.

AVR — Automatic Voltage Regulator

A device that continuously monitors the voltage at a voltage regulating point on the system (generator, condenser, transformer etc.) and automatically initiates corrective action to maintain that voltage within pre-set limits.

Bi-pole

Both poles of the HVDC link are commonly referred to as the bi-pole. See *HVDC*.

Blackstart

In the event of a blackout the first generating station required to initiate the system restoration process must do so without relying on the external energy sources which would normally be available from the system. Self-starting without external energy sources is known as a 'blackstart'.

Busbar

A busbar, or bus, is a common electrical connection between multiple electrical devices.

CCGT — Combined Cycle Gas Turbine

A type of generation where a gas turbine generator generates electricity and the waste heat is used to make steam to generate additional electricity via a steam turbine.

Examples of CCGT plant on the New Zealand power system include Otahuhu B, Stratford Power Ltd, and Huntly unit 5.

CE — Contingent Event

Events that could happen relatively frequently or cause a severe enough impact on the power system to justify incorporating pre-event mitigating measures into the scheduling and dispatch processes. Examples of such measures are instantaneous reserves or security constraints.

DC — Direct Current

An electric current that does not reverse and flows in only one direction. See *HVDC*.

ECE Extended Contingent Event

Events that may have a severe impact on the power system but the likelihood of them occurring is too low to justify implementing any mitigating measures in planning time. In such cases, reliance may be placed on demand shedding (AUFLS) to avoid power system collapse.

EGRs Electricity Governance Rules and Regulations

The Electricity Governance Rules and Regulations 2003.

Frequency

The frequency at which alternating current is transmitted from a power plant to the end user. Frequency is measured in Hertz (Hz). In most parts of the world, including New Zealand, the frequency is 50 Hz. In the Americas it is typically 60 Hz.

GXP Grid Exit Point

A point of connection where electricity may flow out of the grid

HVDC High Voltage Direct Current

A high-voltage direct current (HVDC) link connects the power systems of New Zealand's North and South Islands. These cables are commonly referred to as the Cook Strait Cable or the HVDC.

The HVDC is made up of two poles known as Pole 1 and Pole 2. Transpower is carrying out a project to replace Pole 1 with a new pole (to be known as Pole 3) by 2012.

Hz Hertz

See *frequency*.

IL Interruptible Load

Demand which, by commercial arrangement between the System Operator and a provider, may be disconnected without prior warning for the purposes of maintaining grid security. IL is a type of instantaneous reserve.

IR Instantaneous Reserves

Generation and interruptible load which are able to counter a contingent event, the response being fast enough to limit the fall in frequency to within the limits set out in part C of the EGRs. Instantaneous reserve comes in the form of interruptible load, partly loaded spinning reserve and tail water depressed reserve.

Note: There are two classes of instantaneous reserve:
1. Fast instantaneous reserve, being fast enough to limit the fall in frequency; and
2. Sustained instantaneous reserve, being able to assist in the recovery of frequency to 50 Hz.

Load

Another term for electricity demand (consumption of electrical energy).

Mvar — Megavolt-ampere Reactive

Reactive power is measured in volt-amperes reactive (var). A megavolt-ampere reactive (Mvar, pronounced megavar) is equal to one million var.

MW — Megawatt

A watt is a unit for measuring electric energy. One megawatt is equal to one million watts.

Nordel

Nordel was founded in 1963 for cooperation between the Transmission System Operators of Denmark, Finland, Norway, Sweden and Iceland. Nordel merged with the European Network of Transmission System Operators for Electricity (ENTSO-E) in July 2009.

PLSR — Partly Loaded Spinning Reserve

This is a form of instantaneous reserve. PLSR is spare capacity held in reserve on a generating unit, but not operating at full output, which is able to provide instantaneous reserve following a drop in system frequency.

PJM — Pennsylvania New Jersey Maryland Interconnection

The PJM Interconnection is a regional transmission organisation that coordinates wholesale electricity operation in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia.

Pole

See *HVDC*

SPS — Special Protection Scheme

Equipment provided for detecting faults or abnormal conditions in power systems and initiating remedial action.

SVC — Static Var Compensator

An electrical device for providing fast-acting reactive power on high-voltage electricity transmission networks. It regulates voltage and stabilises the system.

Trip

To release a lever or set free a mechanism.

In this report *trip* is used in reference to:

1. System events - the sudden disconnection of a large amount of generation e.g. tripping of multiple generation units or tripping of the HVDC.
2. AUFLS – the operation of the AUFLS scheme.

3. Interruptible load – the operation of the IL scheme

TWDR **Tail Water Depressed Reserve**

This is a form of instantaneous reserve provided by hydro generators. TWDR is generating capacity on a motoring hydro generation unit with no water flowing through the turbine that is available to provide instantaneous reserve following a drop in system frequency.

UCTE **Union for the Coordination of Transmission of Electricity**

Before merging to the European Network of Transmission System Operators for Electricity (ENTSO-E) in July 2009, UCTE represented 29 transmission system operators of 24 countries operating the 50 Hz synchronous grid of Continental Europe.

Voltage

The flow of electrical charge is known as electrical current. The force that is applied to the electrons to make them flow is known as voltage. As an analogy, consider water flowing through a pipe: the current is the rate of water flow, and the voltage is equivalent to the pressure that is applied to make the water flow through the pipe.

Voltage is measured in volts (V) or kilovolts (kV). One kilovolt is equal to one thousand volts.

3 Introduction

3.1 Background and Purpose

AUFLS is the acronym for Automatic Under-Frequency Load Shedding.

This describes the set of relays in New Zealand which automatically trip blocks of load following a severe under-frequency event to seek to restore the system frequency.

These relays are used as a last resort to attempt to prevent the collapse of the system from under-frequency following an extended contingent event or other undefined events which have the potential to cause a system blackout.

The AUFLS obligations are set out in Part C Schedule C3 Technical Code B of the Electricity Governance Rules (EGRs). Distributors[2] in the North Island and grid owners in the South Island are required to provide a minimum of 2 x 16% blocks of AUFLS as described in tables 3-1 and 3-2 below:

Table 3-1 AUFLS settings for North Island

	Block 1 – North Island	Block 2 – North Island
Trip Frequency (Hz)	47.8	47.8
Time Delay (sec)	0.4	15
2nd Trip Frequency (Hz)	-	47.5
Time Delay (sec)	-	0.4

Table 3-2 AUFLS settings for South Island

	Block 1 – South Island	Block 2 – South Island
Trip Frequency (Hz)	47.5	47.5
Time Delay (sec)	0.4	15
2nd Trip Frequency (Hz)	-	45.5
Time Delay (sec)	-	0.4

The current arrangements are largely based on historical practice and it is our understanding that no real cost-benefit analysis or consideration of equity issues was taken into account when the obligations were rolled into the EGRs. As such, the existing AUFLS obligations were intended to be an interim measure until the wider issues and long term initiatives raised by industry groups could be addressed.

The wider policy and equity issues have remained unaddressed while new technical concerns have been raised about whether there is sufficient AUFLS to cover an extended contingent event given the number of changes to the power system since AUFLS was first introduced. Recent changes include the commissioning of more CCGT (Huntly unit 5) and geothermal (Kawerau geothermal, Nga Awa Purua) generation in the North Island as well as an increase in wind technology in both islands. Reliance on AUFLS will also increase with the upcoming commissioning of HVDC pole 3 in 2012.

The System Operator has commenced a review of the AUFLS system. The purpose of this review is to:

1. Inform the industry and stakeholders of the effectiveness of the current AUFLS arrangements

[2] For the purpose of Part C obligations this includes consumers connected directly to the grid, also known as 'direct connects'

2. Enable a wider discussion to be held to determine the benefits, risks and opportunities for New Zealand with regard to AUFLS and other methods of under-frequency management.
3. Inform the AUFLS exemption process
4. List the options available for moving forward

This report provides a comparison of international AUFLS settings and requirements against New Zealand's standards. In addition, this report highlights a number of key observations following a literature review of the use of AUFLS in international under-frequency events.

This report also sets out a summary of the findings from the technical studies of the AUFLS scheme. It identifies the system events that were studied and details the performance of the existing AUFLS scheme and a number of alternative AUFLS schemes against each event. The studies assume that AUFLS providers deliver exactly 2 x 16% blocks of AUFLS at each grid exit point, except where the provider has an AUFLS exemption or is known not to provide an AUFLS response. However, as load patterns vary throughout the day and year, it is likely that the quantity of AUFLS provided also varies throughout the day and year. To gain a better picture of the quantity of AUFLS available, the System Operator is currently undertaking analysis to determine the quantity of AULFS provided at each grid exit point for different periods throughout the year[3].

Finally, this report presents a number of options for further analysis and discussion with the industry, and sets out the next steps for the AUFLS review. This report does not extend to providing economic analysis of the various options to address the technical issues identified in this report. Given that industry participants will wish to comment on some of the proposed solutions that will be done in a later report.

[3] Profiles are being created for summer weekdays, summer weekends, winter weekdays and winter weekends.

3.2 What is AUFLS and why do we have it?

3.2.1 An introduction to reserve management concepts and AUFLS

Power supply must be carefully balanced with demand in order to keep our power system stable. When power supply is balanced with demand the system frequency is 50 Hz.

It is important that the frequency remains close to 50 Hz for operational, security and quality of supply reasons. For example, many industrial processes rely on the frequency staying close to 50 Hz. Generators are also only capable of operating within a certain frequency range. This range varies between generation types.

When there is an imbalance in supply and demand, the system frequency moves away from 50 Hz. Excess demand will cause the frequency to drop (known as under-frequency). Excess supply will cause the frequency to rise (known as over-frequency).

The sudden disconnection of a large generating unit is a typical example of a system event that will cause the system frequency to drop below 50 Hz. The balance can be restored by either increasing supply (generation) or decreasing demand (commonly referred to as load).

In New Zealand we procure reserves to ensure that the frequency does not drop below 48 Hz in certain types of events (known as contingent events, see section 3.2.2). This means that we have a combination of fast-response backup generation and demand that can be shed quickly (known as interruptible load)[4] to ensure that the frequency does not drop below 48 Hz and is quickly restored to 50 Hz. Typical examples of contingent events are the loss of a generating unit or the loss of one of the poles of the HVDC link.

For even larger and rarer system events, the frequency has potential to drop below 48 Hz. When this happens, we have another layer of demand shedding known as automatic under-frequency load shedding[5] (AUFLS). AUFLS is physical equipment, or a set of relays, which are attached to selected circuits that provide direct connections to customers. AUFLS relays are designed to physically disconnect customers once the system frequency drops below a pre-set level. AUFLS is made up of two 16% demand blocks in each island. This means that we can shed a minimum of 32% of demand in two stages to stop the frequency from falling below the minimum frequency standards of 47 Hz and 45 Hz in the North Island and South Island respectively. AUFLS is used to recover the system from an extended contingent event (which is currently defined as the loss of the entire HVDC link, see section 3.2.2) and other rare events such as the loss of multiple generating units or other undefined events.

AUFLS is the last response that we have available to correct the power system from collapse on under-frequency. If the AUFLS response is insufficient to correct the imbalance, the frequency will continue to fall below the levels that generators can continue to safely operate. At 47 Hz, combined cycle gas turbines and wind generators will typically disconnect which further exacerbates the situation. All generation will disconnect below 45 Hz. This continual disconnection of supply is known as cascade failure. Eventually the imbalance between supply and demand will be so severe that supply is lost is to the entire island. This is more commonly known as a blackout.

As the consequences of a blackout are severe, the System Operator's security planning is to mitigate wherever possible, and with the assets made available, the opportunity for a blackout to occur.

[4] Interruptible load, or IL, is automatically shed within 1 second of the frequency reaching 49.2 Hz. Interruptible load is typically made up of ripple control (hot water heating) and industrial processes.

[5] While they are both forms of load shedding, there are some key differences to note between IL and AUFLS. IL is dispatched as reserves but may not always be available. AUFLS is not dispatched but must always be available.

3.2.2 Contingent Events and Extended Contingent Events: What is the difference?

Contingent events (CE) and extended contingent events (ECE) are defined in the System Operator's Policy Statement (Part C Schedule C4).

Contingent events are events that happen regularly enough[6] that it is important that we have sufficient reserves available to restore the system frequency to 50 Hz without impacting on end-users[7]. The System Operator procures sufficient instantaneous reserves to prevent the system frequency from falling below 48 Hz following a contingent event. The System Operator's Reserve Management Tool (RMT) and Scheduling Pricing and Dispatch (SPD) tools ensure that sufficient reserve is procured to meet the risk in a least cost manner.

Extended contingent events are events that occur much less frequently, and because of this, it is not cost efficient to procure sufficient reserves to cover an ECE. As well as instantaneous reserves, the System Operator also relies on AUFLS to cover the risk of an ECE. The System Operator's tools (RMT and SPD) will ensure that there is sufficient reserve procured taking into account the amount of AUFLS available to prevent the system frequency from falling below 47 Hz and 45 Hz for the North and South Islands respectively following an ECE. There is a significant impact on customers following an ECE, but this is justified given the infrequency of such events.

	Contingent Event (CE)	**Extended Contingent Event (ECE)**
Minimum frequency limit	· 48 Hz	· 47 Hz (North Island) · 45 Hz (South Island)
Examples of risk	· Single generation unit tripping · Single HVDC pole tripping	· HVDC bi-pole tripping
Risk mitigation measure	· Procure instantaneous reserves (IR)	· Procure instantaneous reserves, and · Rely on AUFLS
Customer impact	Nil to minimal	Moderate to significant 16 – 32 % of customer demand shed

3.2.2 Social consequences of a blackout

In the event that the power system experiences a major disturbance and there is insufficient AUFLS to cover an event resulting in cascade failure, a blackstart would be required to start the restoration process of the power system. This is a complex process and could take from a minimum of 12 hours up to possibly several days to achieve full restoration of the system.

A loss of electricity over an extended period of time would have both significant and wide-ranging social and economic impacts on the end-user. The impact of an extended outage needs to be carefully considered when reviewing the current AUFLS system.

[6] As at April 2010, we have had an average of 14 such events a year over the last 3 years

[7] Except for those end-users who have a contract to provide interruptible load. These end-users are paid for this service through the IR market.

3.3 A Brief History of AUFLS in New Zealand

Significant changes to the power system

AUFLS was first installed in New Zealand with the introduction of the HVDC link in 1965. As the new HVDC link would impose a significant change to the way in which the power system would be run, British consultants Preece Cardew and Ryder (PCR) were contracted to advise on the operational aspects of the link. One of the concerns was to prevent blackout should both poles trip.

PCR recommended a simple two stage load shedding system together with their trip frequencies and block sizes. The original scheme was for 2 x 20% AUFLS blocks to cover the loss of the original HVDC bi-pole which had a capacity of 600 MW. Block one was set to trip instantaneously at 47.5 Hz, and block two was set to trip instantaneously at 45.5 Hz or 15 seconds after the first block should the frequency remain below 47.5 Hz. These settings would allow the system to maintain a minimum frequency standard of 45 Hz.

AUFLS was only implemented in the North Island given that was the direction in which the link was expected to operate. Although the scheme was designed and introduced with the HVDC in mind, AUFLS would activate irrespective of the source of disturbance once the frequency had dropped below the set frequency for the pre-set duration. The AUFLS scheme would cover for either the loss of the HVDC link or the largest North Island generating unit.

The 1980s saw the introduction and development of a number of models to predict the appropriate level of spinning reserve required to cover either the tripping of a Huntly unit or a HVDC pole. However, the AUFLS scheme remained unchanged during this time.

The HVDC link was significantly upgraded in 1993 with the introduction of pole 2. As the link rating doubled from 600 MW to 1200 MW, a new load shedding scheme was implemented to complement the existing AUFLS scheme as well as enhance the robustness and stability of the power system in the North Island. The Fast Response Emergency Dumper, or FRED, allowed for fast load shedding following the tripping of the HVDC link. FRED was armed once HVDC north flow exceeded 300 MW and could dump approximately 400 MW in 0.5 seconds. FRED was designed to cover a single pole tripping, while AUFLS would cover a bi-pole tripping.

The early 1990s also saw most of the AUFLS relays move from grid exit points to zone substation level to allow for better load shedding control.

The advent of the electricity market in 1996 saw the introduction of a formal market for energy and reserves, including interruptible load. As a result, the FRED scheme disappeared shortly after the introduction of the market.

New generation technology and frequency standards

The emergence of large Combined Cycle Gas Turbine (CCGT) plant into New Zealand's North Island power system in the late 1990s established a need to review the existing frequency standards. Thermal generators, particularly CCGTs, face material plant damage at frequencies below 47 Hz. The existing minimum standard of 45 Hz was considered prohibitive in allowing new large scale CCGTs to connect to the system.

An industry formed group, the Frequency Standards Working Group (FSWG), was put together in 2000 and tasked with reviewing New Zealand's frequency standards given the current technology.

The FSWG came up with an immediate solution as well as a longer term solution. The immediate solution was to be implemented as soon as possible with a view that the longer term solution should be incorporated into the new industry rulebook[8].

The immediate solution recommended by the FSWG was to raise the minimum frequency from 45 Hz to 47 Hz. This would be achieved by:

- Modifying the minimum frequency standard in the North Island from 45 Hz to 47 Hz. The South Island standard was to remain at 45 Hz unless the economic benefits justified a change in the South Island.
- Requiring distributors (which includes direct connects) to provide 2 x 20% AUFLS blocks. Block 1 was to operate at 47.8 Hz after 0.2 seconds, and block 2 was to operate at 47.5 Hz after 0.2 seconds or after 15 seconds if the frequency remains at or below 47.8 Hz.
- Modifying generator under-frequency technical performance requirements to align with the AUFLS adjustments (e.g. continuous operation above 47.5 Hz; 120 seconds at 47.5 Hz and 0.1 seconds at 47 Hz).

The FSWG also recommended that exemptions from AUFLS obligations be granted where a provider could satisfy that the cost of providing the facility (or its equivalent) was greater than the expected cost of the second AUFLS block.

The details of the immediate solution were clarified and modified following submissions from the industry as follows:

- Distributors and direct connects are to provide 2 x 16% AUFLS blocks at all times[9].
- AUFLS Block 1 is to operate at 47.8 Hz after 0.4 seconds, and block 2 is to operate at 47.5 Hz after 0.4 seconds or after 15 seconds if the frequency remains at or below 47.8 Hz[10].
- Clarification that AUFLS blocks must be exclusive of any contracted Interruptible Load.

Further studies conducted by Transpower revealed that:

- The minimum frequency standard should remain at 45 Hz in the South Island.

  Preliminary studies were completed analysing the quantity of IR that would be required if the South Island minimum frequency standard was raised to 47 Hz. These studies showed that at some particular demand levels the IR required might be almost three times as much as required for the current (45 Hz) standard. For this reason, it was considered imprudent to change the South Island frequency standards without full industry consultation and further technical analysis. While it was recommended that the South Island standards remained unchanged, this did not preclude them being modified

[8] The Electricity Governance Rules and Regulations

[9] The requirement for 2 x 20% AUFLS blocks *at all times* was considered to be unachievable by many participants. Distributors were previously required to provide 2 x 20% blocks, which was generally interpreted as either a percentage of *peak* load or an *average* estimate of the load available for shedding. In response to industry feedback, the FSWG recommended a change to 2 x 16% blocks to *all connected parties* including the directly connected loads. Historically, directly connected customers were not included in the AUFLS solution. Analysis by Transpower indicated that a move from 2 x 20% from distributors to 2 x 16% from all connected parties would not alter the current security risk.

[10] Assuming 170ms for circuit breaker operating and relay decision making time, the original requirement of 200ms AUFLS operation time left only a 30ms margin. There was concern that this may not be enough to stabilise the AUFLS relays against mal-operation for close-in feeder faults at 50 Hz. Anecdotal evidence from the installation of AUFLS relays in 1992 suggests that some spurious trippings did occur, and it was found that a 200ms time delay tended to stabilise the relays and thus eliminate spurious tripping.

in the future, especially if different types of generating plant were to be connected in the South Island.

- AUFLS should be extended into the South Island.

  This would allow for increased HVDC south flow during a dry year scenario (as experienced in winter 2001). Procuring IR to cover for a rare event such as the ECE was considered to be economically inefficient. As well as increasing security of supply to the South Island, cost benefit analysis revealed the net national benefit of installing AUFLS in the South Island to be over $500,000 a year.

In general, stakeholders were supportive of the FSWG's immediate solution. As a result, the Grid Security Committee formally requested Transpower to implement the FSWG's immediate solution.

The immediate solution was incorporated into Transpower's Common Quality Obligations from 1 April 2002. Most North Island direct connects applied for and were granted exemptions from providing AUFLS.

The FSWG also recommended a long term solution which had mixed support from the industry. The long term solution recommended changes to the new rulebook when it became operational, including changes to load shedding accountabilities, the introduction of an emergency reserve market and new generator under frequency performance obligations. It was also recommended that a third AUFLS block be investigated in addition to the two currently in the rules. A further block would avoid total system failure should non-compliance of connected plant or failure to provide the full automatic under-frequency load shedding block sizes occur during an event.

It is also important to note that the FSWG's work did not extend to considering whether the changes in the immediate solution were optimal with regard to cost and security. For example, are the relationships between the AUFLS blocks (including settings, size and number of blocks) and the minimum frequency limits for single contingency under-frequency events optimal? The FSWG recommended that further work be undertaken in this regard.

Moving toward an industry rulebook

The Frequency Development Working Group (FDWG) was established by the Grid Security Committee to assess common quality development needs in relation to frequency quality and related arrangements. It assessed a wide range of development initiatives, including the proposal to introduce AUFLS in the South Island.

By mid 2003, Transpower had installed AUFLS in the South Island at the GXP level following a recommendation from the FDWG. Although AUFLS installation at GXPs allowed for flexibility in load control and provided Transpower with the ability to monitor feeder load, it was recognised that:

- The system could not provide finer load discrimination. Installation of the load shedding relays further down in the chain in the zone substations might be able to better discriminate loads depending on their social or economic value. Distributors are better placed to make the right decisions on feeders to be tripped given the required demand blocks and the type of demand to be tripped.
- From a legal and policy perspective, it is better for obligations to fall on the same parties across both islands.

Feedback from South Island participants indicated a preference for Transpower to install and maintain AUFLS relays at the grid substations on their behalf. While Transpower was responsible for installing and maintaining the relays, it remained the responsibility of distributors to ensure that there was adequate load to meet the 2 x 16% load shedding requirement at all times.

While the FDWG's recommendation to install AUFLS in the South Island went ahead, its other recommendations[11] were put on hold when the Electricity Commission and the EGR framework were established.

The birth of the Electricity Governance Rules (EGRs) in 2004 saw Transpower's Common Quality Obligations rolled into the EGRs, including the existing AUFLS obligations. Since 2004, exemptions from the AUFLS obligations have been granted to:

- Norske Skog Tasman Ltd
- Northpower Ltd
- Winstone International Pulp and Paper
- Toll NZ Ltd
- Pan Pac Forest Products, and
- New Zealand Steel

Under the current rules, an exemption from AUFLS will be granted if the applicant can satisfy the Electricity Commission that the direct financial impact of providing AUFLS would exceed the expected interruption costs for each kilowatt interrupted. Approximately 400-500 MW of load is currently exempted from AUFLS.

It has since become apparent that the rules and process for granting AUFLS exemptions are unclear. The rules provide no guidance as to what should be included in an assessment of 'direct financial impact'[12].

Furthermore, all end-users benefit from the provision of AUFLS, including those participants who are exempt from providing it. Inequities are also introduced through other means such as:

- Participants behind an AUFLS feeder are excluded from providing IL, but those who are not can participate freely in the IL market.
- Differences in the size and make up of distributor networks mean that some end-users may or may not be exempt from AUFLS purely by virtue of which network they are connected to.

Concerns have also been raised about the potential for the total AUFLS base to erode over time with the granting of each exemption. In practice, AUFLS exemptions are made up for by procuring more IR when the ECE is binding. This relies on there being sufficient IR offered to cover such a scenario.

To date, the long term development initiatives identified by FSWG and FDWG with respect to AUFLS have not all been addressed. AUFLS requirements have not been reviewed or modified since the FSWG's immediate solution was adopted. A number of attempts (in 2004, 2005 and 2009) have been made to review the AUFLS exemptions process, but the technical requirement for 2 x 16% blocks has not been revisited.

[11] Other recommendations included assessing whether the CE target frequency should be raised to provide greater discrimination between CE and ECE events and progressing toward a national reserves market.

[12] For example, should this include the opportunity cost of not being able to participate in the IL market?

4 Literature Review

4.1 An International Comparison of AUFLS Schemes

It is acknowledged that AUFLS schemes between power systems cannot be directly compared as each power system is unique, has different reserve management schemes and operates to different frequency standards. However, the System Operator undertook a study of international AUFLS schemes to:

- Gain an understanding of what AUFLS schemes are used for internationally and what is technically possible
- Inform the risks chosen to be studied in this report, and
- Inform the alternative schemes that were studied in this report.

The literature review concluded that, in general, New Zealand as compared to the other power systems studied:

- Sheds less AUFLS as a total percentage of load
- Has less AUFLS blocks
- Has larger AUFLS block sizes, and
- Trips AUFLS at much lower frequencies.

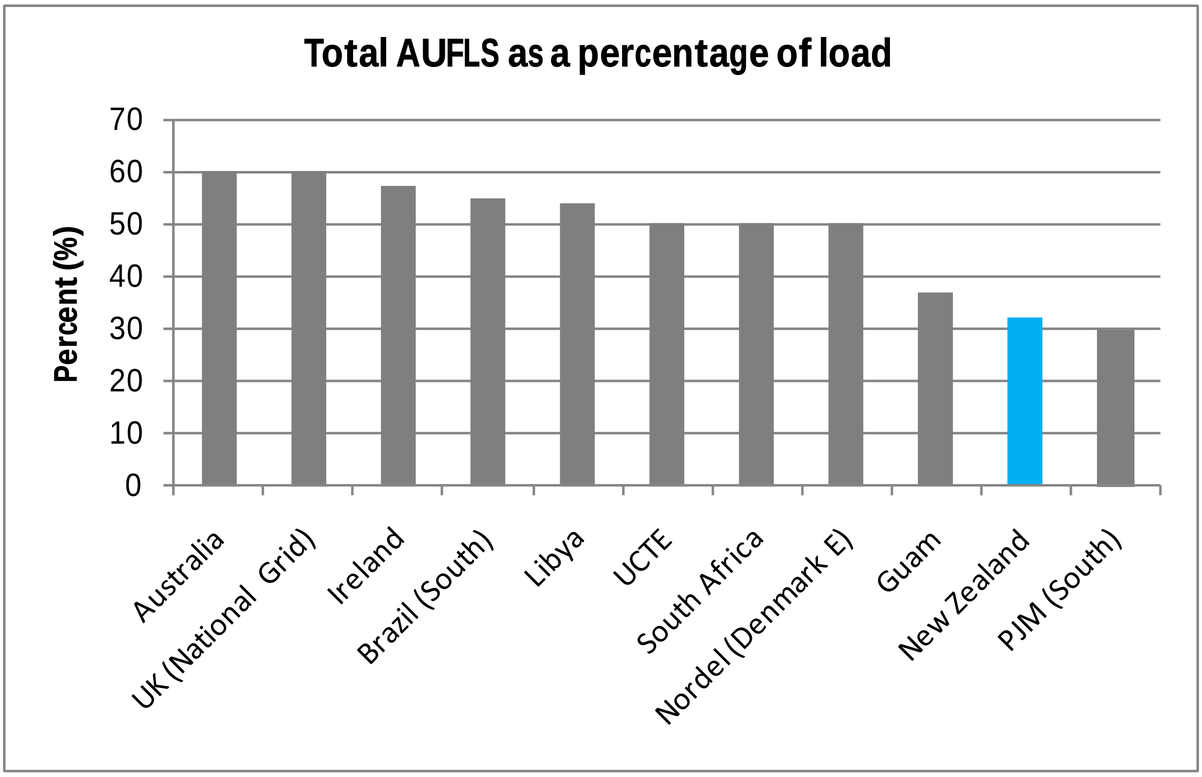
Of the international power systems studied, it is noted that the United Kingdom, the Union for the Coordination of Transmission of Electricity (UCTE), Brazil, Nordel and Pennsylvania New Jersey Maryland Interconnection (PJM) have a different AUFLS regime for each of their regions. For these systems, AUFLS information for a selected region is shown and indicated on the charts where relevant.

4.1.1 *Total AUFLS as a percentage of load*

Figure 4-1 provides a comparison of the total AUFLS shed in New Zealand against ten other power systems.

Generally speaking, one of the key factors to ensuring the system remains intact after an AUFLS event is to shed sufficient load to match the size of the disturbance. Shedding more AUFLS effectively covers the system against a larger range of risks including high impact low probability events. See sections 6.2 and 7.4 for the results of the studies on the effect of increasing the total AUFLS percentage on the New Zealand power system.

Figure 4-1



In New Zealand a total of 32% of system load is shed as AUFLS. This is quite low in comparison with the other countries studied.

4.1.2 *Size and number of AUFLS blocks*

Figures 4-2 and 4-3 provide a comparison of the total number of AUFLS blocks in each power system and the average size of each block. Note that information on the number and size of AUFLS blocks in Australia is omitted from figures 4-2 and 4-3. This is because the total amount of AUFLS required from each customer and the trip frequency range is specified in Australia's Electricity Rules, but not the number and size of the blocks. This is set by each responsible Transmission Network Service Provider.

The effect of more, smaller blocks allow for better matching of the load shed to the size of the disturbance which reduces the potential for over-frequency and over-voltage from excessive load shedding. This is demonstrated in sections 6.3 and 7.3 of this report.

Figure 4-2

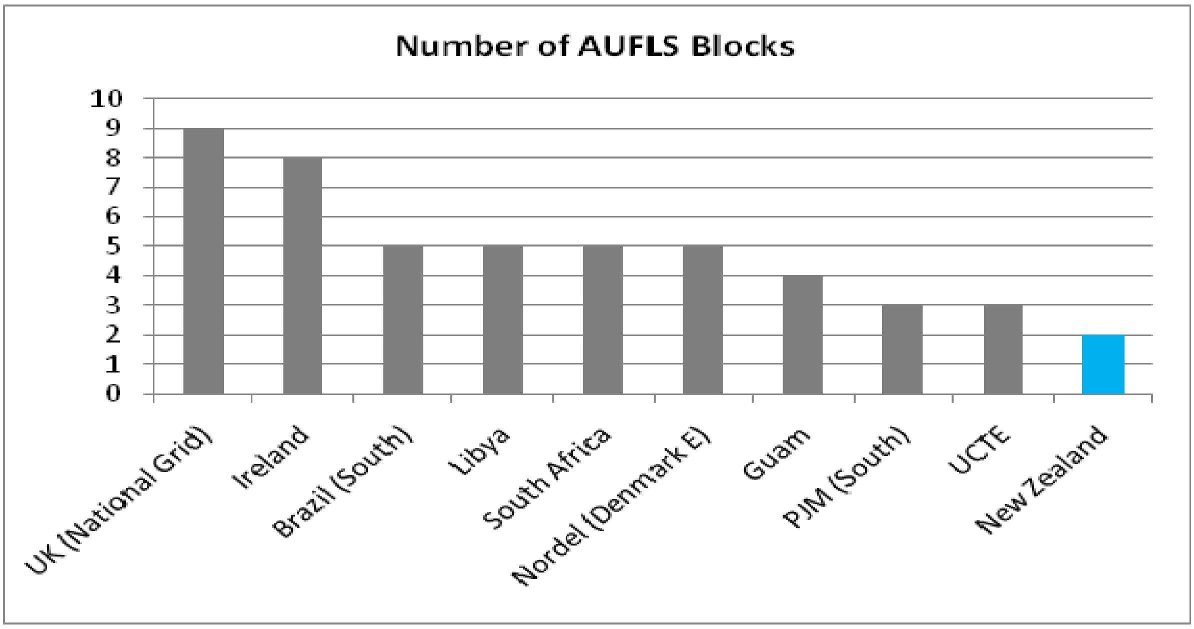
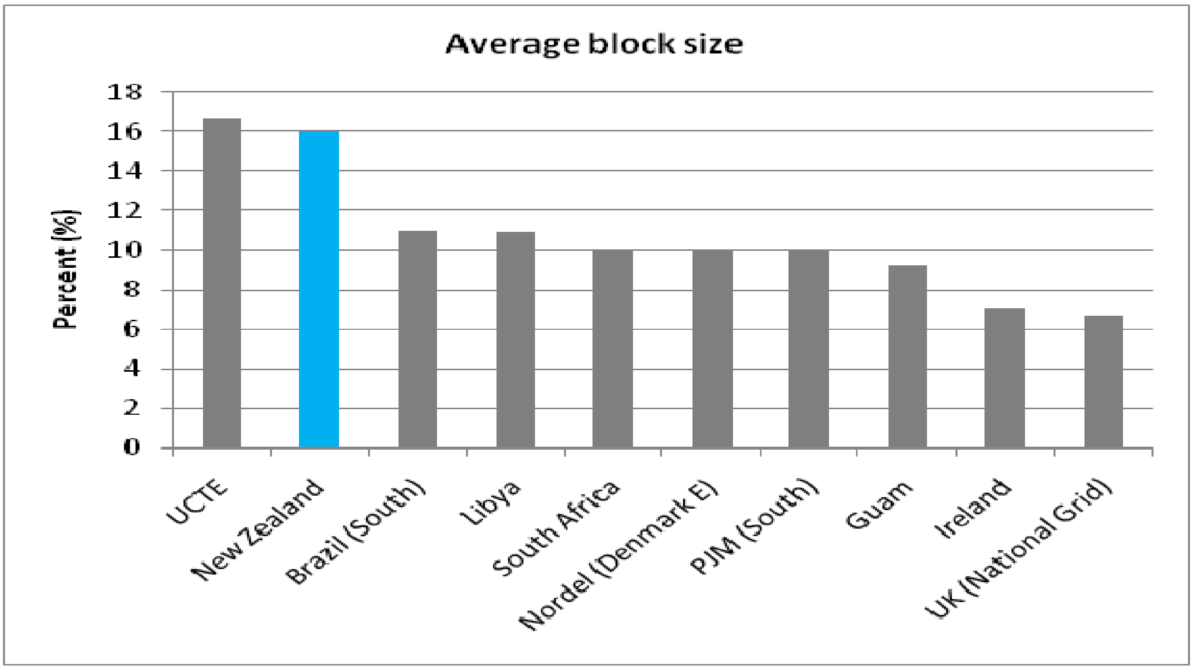


Figure 4-3



New Zealand has fewer blocks than all countries studied and our blocks are also on average much larger in size.

The block number, sizes and total percentage for New Zealand's AUFLS scheme are based on the original AUFLS scheme which was designed for a bi-pole tripping, and these have not been significantly modified since. See section 3.3 for more information on the history of AUFLS in New Zealand.

4.1.3 *AUFLS trip frequencies*

Figure 4-4 shows the trip frequencies for the first and last AUFLS block on each of the power systems studied. Information on the trip settings for intermediate blocks has been omitted for simplicity. Note that PJM, Guam and Brazil have a nominal frequency base of 60 Hz, i.e. they run a 60 Hz system. The other countries shown have a nominal base of 50 Hz.

Higher trip settings allow for greater speed of AUFLS response. As other countries initiate load shedding earlier (closer to nominal system frequency) they have a wider frequency range over which they can shed load before the system frequency reaches minimum levels for safe operation of generators, motors and other electrical devices. They also have more time than the New Zealand system does for generator Automatic Voltage Regulators (AVRs) to respond, allowing more load to be shed without the danger of over-voltage.

Figure 4-4

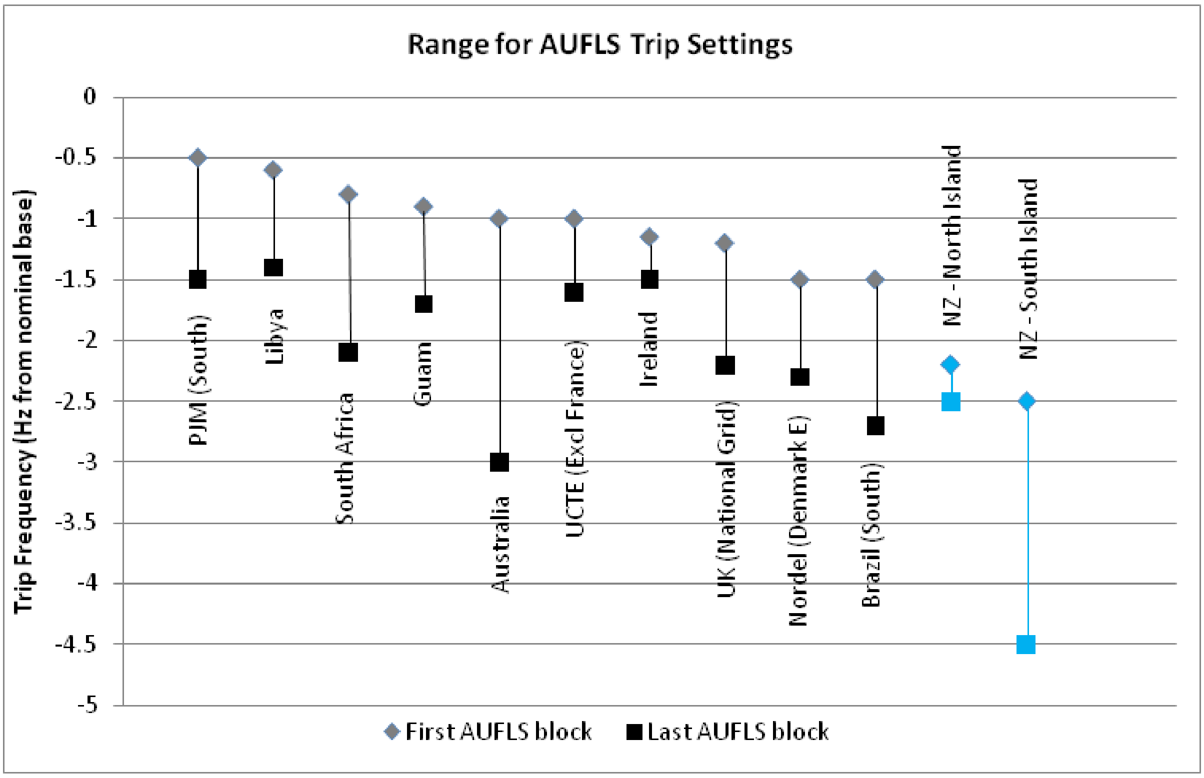


Figure 4-4 can be interpreted as follows:

PJM's first AUFLS block operates once the frequency has moved 0.5 Hz from nominal frequency (60Hz), or at 59.5 Hz. PJM's last block operates at 1.5 Hz from nominal, or at 58.5 Hz. This means that PJM's AUFLS response is fast and operates within a range of 1 Hz.

The key observations that can be made from figure 4-4 are as follows:

- New Zealand's first AUFLS block is set to trip after the last block for most of the other countries.

The AUFLS block 1 settings of 47.8 Hz in the North Island and 47.5 Hz in the South Island are quite low in comparison with other countries. South Africa initiates voluntary load shedding at 49.2 Hz with mandatory load shedding at 48.8 Hz, followed by Australia and UCTE at 49 Hz. The United Kingdom's automatic load shedding starts at 48.8 Hz.

- The North Island AUFLS scheme particularly has a very small range for operation (the blocks are set 0.3 Hz apart).

The reasons for New Zealand's lower frequency settings are mainly historic. The North Island used to have a frequency range of 45 to 55 Hz which had to change when more non compliant plant was built. Additionally the low target of 48 Hz for a Contingent Event (CE) allows for less reserve to be scheduled. This has resulted in a very narrow range for our AUFLS to operate as the minimum frequency for an Extended Contingent Event (ECE) is 47 Hz in the North Island.

It is difficult to draw direct comparisons between power systems as the trip settings will vary depending on:

- The size of the power system. Generally speaking, overseas systems are much larger and have greater inertia than ours, and are thus more resilient to the causes of under-frequency events.
- The make up and generation mix of the power system.
- The size of the risk and whether each system covers a defined risk. Of all the systems studied, New Zealand's system is the only system which has an AUFLS scheme designed to cover a specific risk (e.g. a bi-pole tripping). Other systems do not define the risk that AUFLS is intended to cover.

The speed of AUFLS response is critical for successful recovery of the system. See sections 6.4, 6.5 and 7.2 for the results of the studies on the effect of increasing the speed of the AUFLS response on the New Zealand power system.

A more detailed discussion of the reserve and automatic under-frequency load shedding policies in the countries shown in this section has been included in Appendix A.

4.2 The Use of AUFLS during Under-Frequency Events

Ideally, recent AUFLS events on the New Zealand power system would have been studied to gain an understanding of the effectiveness of the scheme and determine what the critical factors were to the success (or otherwise) of the AUFLS operation.

However, the last time there was a widespread tripping of AUFLS was nearly 15 years ago. The most recent events of a widespread tripping of AUFLS were[13]:

- *3 March 1996* - AUFLS tripped following an HVDC bi-pole tripping
- *9 March 1993* – AUFLS tripped following an HVDC bi-pole tripping.
- *6 February 1987* – AUFLS tripped following a generator circuit breaker failure at Whakamaru.
- *1 June 1984* – Otahuhu-Whakamaru circuit fault triggered both manual and automatic load shedding.

This demonstrates that AUFLS operates for a wide range of events.

In light of having no recent New Zealand AUFLS events, the System Operator studied two recent events where AUFLS was triggered internationally. Each event and the key information gained is described briefly below. A detailed description of the events and the automatic load shedding that occurred is available in Appendix B.

4.2.1 *UCTE Event on 4 November 2006*

UCTE stands for Union for the Coordination of Transmission of Electricity. Before merging to the European Network of Transmission System Operators for Electricity (ENTSO-E) in July 2009, UCTE represented 29 transmission system operators of 24 countries operating the 50 Hz synchronous grid of Continental Europe.

Pre-event

Prior to the event UCTE generation was 274,100 MW including approximately 15,000 MW of wind generation (or approximately 5.5% of total generation).

Event details

This event occurred because the outage of two 380 kV Conneforde-Diele circuits was brought forward, leaving insufficient time for additional contingency studies which would have taken into account any changed system conditions prior to the rescheduled outage. There were also several transmission lines out for maintenance at the time.

When these two circuits were switched out other circuits started overloading. This overloading was compounded by “remedial” operator action and resulted in cascade tripping of circuits. Over the space of 31 minutes UCTE split into 3 areas.

Extensive load shedding occurred in the Western area. The initial imbalance of 9000 MW (approximately 5% of total generation in the Western area) and subsequent under-frequency tripping of generators resulted in a total of 18,600 MW of load and pumps being shed. The Western area under-frequency situation was compounded by the tripping of distributed generators[14] and resulted in more load being shed than would have been necessary for the

[13] There may have been other events that were not identified. Transpower’s records:

a) Generally code interruptions against the initiating cause (such as equipment failure) rather than load shedding
b) Do not distinguish between automatic or manual load shedding.

While this report lists recent examples of AUFLS operation there is no guarantee that this is a complete list of events in the last 30 years. There are also likely to have been localised trippings of AUFLS.

[14] Also known as embedded generators.

initial imbalance. Distributed generators are not controlled by the system operators and have less stringent under-frequency operational requirements than generators connected to the main grid.

The North-East area experienced high over frequency with a generation surplus of 10,000 MW (approx 17% of total generation). Their main issue was the uncontrolled restarting of wind generation. The South-East area had a generation deficit of approximately 770 MW (approximately 2.6% of total generation) and had enough reserve to avoid any load shedding during this event.

Post-event findings

The use and speed of under frequency load shedding relays in the Western area allowed the bulk of the area load to remain connected and prevent the total collapse of this area. This would not have been possible without the use of automatic load shedding relays. The Western and North-Eastern areas both experienced additional problems from generation which had less stringent connection requirements than grid connected generators.

4.2.2 *Victoria, Australia Event on 16 January 2007*

Australia has a 50Hz system. In Australia, all loads greater than 10 MW must provide a minimum of 60% automatic under-frequency load shedding to be used in manageable steps from 49 Hz to 47 Hz.

Pre-event

Prior to the event the combined import into Victoria from New South Wales (NSW) and South Australia (SA) was about 1990 MW, together with an additional 500 MW from Tasmania (TAS).

Event details

This event was triggered by the loss of the second Dederang (DDTS) to South Morang (SMTS) 330 kV Lines. The entire network remained in a stable condition following the loss of the first DDTS-SMTS 330 kV line due to smoke from nearby bush fires. When the second DDTS-SMTS 330 kV line tripped, system frequency and system voltages began to show signs of instability. This eventually led to separation from NSW and South Australia. After the event, import from NSW was in the order of 490 MW together with 500 MW from TAS (i.e. loss of 1500 MW or 60% of total import).

There was rapid frequency decline to 48.6 Hz which resulted in the operation of the automatic load shedding scheme to maintain system stability and power supply to the maximum number of customers possible. Approximately 2,200 MW of load was shed.

The entire event, from loss of the second DDTS-SMTS 330 kV line to automatic load shedding until the frequency stabilised, lasted approximately 12 seconds. This stabilisation of system frequency was only possible through the speed of the automatic under frequency load shedding relays.

Post-event findings

The Victorian Energy Networks Corporation (VENCorp) considered that the performance of the transmission network protection, control and automatic load shedding schemes prior to, during and following the event was found to be satisfactory and generally in accordance with the design, except for the operation of some capacitor banks and non-tripping of load that was not on the AUFLS scheme due to sub transmission changes which had not been communicated to the Demand Reduction Committee (DRM).

The time to restore the network and customer load was satisfactory, but VENCorp noted that established procedures to assist in restoration can improve restoration times for targeted priority loads.

As a consequence of this event, VENCorp would also consider the frequency of actual separation events and their impact on planning criteria; and investigate the viability of control schemes to avoid voltage collapse during contingency events.

4.3 Key Observations from Literature Review

- New Zealand's AUFLS settings starting at 47.8 Hz in the North Island are much lower compared to all the other countries studied. The EGR requirement to maintain frequency above 47 Hz in the North Island leaves us with a very small frequency range (1 Hz) for AUFLS operation.
- New Zealand has only 2 blocks of AUFLS whereas other countries have 5 to 7 blocks. Having more and smaller blocks allows better "matching" of load shedding to the initial contingency loss, and reduces the potential for over-frequency and over-voltage from excessive load shedding.
- The small frequency range for AUFLS operation in the North Island (0.3 Hz) combined with the fewer and larger sized blocks makes discrimination between blocks very difficult to achieve and can reduce the effectiveness of AUFLS.
- Both international events studied in this report were due to system splits caused by line trippings. This illustrates that AUFLS operates for a range of events, not just large risks.
- Problems were exacerbated in the UCTE event by tripping of distributed (embedded) generation and uncontrolled starting of wind generation.
- The use and speed of under frequency load shedding relays in the UCTE and Victoria events allowed the bulk of the load to remain connected and prevent the total collapse of the transmission network. This would not have been possible without the use of automatic load shedding relays.

5 Technical Studies – Methodology and Assumptions

This section sets out the methodology that was followed and the key assumptions made when conducting the AUFLS technical studies.

The objective of the technical review is to understand the effectiveness of the existing AUFLS scheme and to identify alternative options to the current scheme where appropriate.

This means identifying a number of risks to study and determining for each risk:

- Whether there is currently enough AUFLS to cover the risk,
- Whether the system response (in terms of frequency, voltage, line loading and generator response) is acceptable, and
- Whether there is an alternative scheme which may provide for a better system response.

The studies also set out to:

- Review the use of capacitors and line switching in relation to AUFLS events,
- Review the operation and stability of automatic control systems in relation to an AUFLS event,
- Identify whether known risks such as an ECE can be managed in other ways (AUFLS versus Special Protection Schemes), and
- Estimate the time needed to restore AUFLS.

5.1 Events to be studied

Worst case scenarios were chosen as events to study i.e. events which will result in the most significant frequency drop rather than the most likely events. Studying the most extreme cases helps to:

a) Provide a comparison against the risks that currently rely on AUFLS.

b) Provide information on the absolute limitations of the system.

The following events were identified as risks to study:

1. **Loss of the HVDC bi-pole**

   This is an obvious risk to study for both the North and South Islands as a bi-pole tripping is currently defined as an extended contingent event (ECE) in the System Operator's Policy Statement. AUFLS is identified as a key measure for covering an ECE.

2. **Loss of the entire Huntly station including units 5 and 6**

   There are many possible generation tripping scenarios. However, the most extreme cases for each island were chosen as events to study. In the case of the North Island, this is the tripping of all of Huntly station.

   In the studies, the capacity of the bi-pole is 1200[15] MW, while the capacity of Huntly station is 1400 MW. As these risks are similar in size, studying them provides a useful comparison against the different effects on the system.

   A tripping of all of Huntly station is also bigger than other generation tripping scenarios such as multiple CCGT trippings. Studying a tripping of Huntly station provides better information on the absolute limitations of the system and also eliminates the need to study other, smaller events.

3. **Loss of a Manapouri busbar**

   For the South Island, the most extreme generation tripping scenario is the loss of a Manapouri busbar. This would result in the tripping of three Manapouri units[16].

   The loss of a Manapouri busbar is also greater than the loss of other South Island stations such as Ohau A. From 1 October 2010, the loss of a 220 kV busbar (such as a Manapouri busbar) will be defined as an extended contingent event in the System Operator's Policy Statement.

4. **Electrical System Splits**

   The review of international AUFLS events (see section 4.2) revealed that AUFLS commonly operates following a system split. For this reason a number of system splits on the New Zealand power system were studied focusing on large regional islands. The following islands were studied:

a) Loss of both 220 kV circuits into Redclyffe.

   This has the effect of islanding Hawkes Bay.

b) Loss of the Atiamuri-Whakamaru circuit and the Ohakuri–Wairakei circuit (assuming one to be on outage and the normal system split is in place on the Kinleith-Tarukenga circuits).

   This has the effect of islanding the Bay of Plenty.

c) Loss of the Whakamaru bus.

   This has the effect of splitting the North Island into two electrical systems.

[15] This is the capacity of the bi-pole post pole 3 commissioning. See section 5.3.1.
[16] Each Manapouri unit has a capacity of 121.5 MW.

d) Loss of both Coleridge-Hororata circuits and the Atarau-Reefton Inangahua circuit.

   This has the effect of islanding the West Coast.

e) Loss of both Clyde-Twizel circuits and consequential trip of the Naseby-Roxburgh circuit.

   This has the effect of creating a system split north of Clyde.

f) Loss of the two 220 kV circuits into Waitaki.

   This has the effect of creating an island of Studholme, Waitaki, Blackpoint and Oamaru.

It was decided not to study the following risks:

- Events that do not rely on AUFLS e.g. contingent events or other events that would not lead to sufficient generation loss to trigger AUFLS as these are covered through the procurement of instantaneous reserves.
- Multiple CCGT trippings (two or more). While of interest, this would not lead to as much generation loss as all of Huntly station.
- Loss of Huntly units 1-4. Again, this would not lead to as much generation loss as all of Huntly station.
- Loss of Manapouri station (all 7 units). The loss of the entire Manapouri station has previously been studied by the System Operator. These studies resulted in non-convergence due to the large magnitude of the generation loss, i.e. unacceptable frequency conditions caused the system to collapse in these studies.
- Events resulting in the islanding of Cobb, Tekapo A or Mangahao. As we know that these islands can be successfully created (they have occurred in reality) there is no need to study them. Note that in the case of Mangahao, the use of AUFLS was required to maintain system stability.
- System splits that would result in small, fragmented islands, e.g. islanding of Waipouri and Karapiro. The focus of the studies is large, regional islands, not small, single bus islands.
- System splits where the system response is of a similar nature to a system split already studied. For example, the loss of the two Clyde Roxburgh circuits is similar to the loss of two Clyde Twizel circuits. Where islands or system splits of a similar nature can be formed, then only one has been studied.
- Two AUFLS events. Whilst extremely unlikely events have been selected to study, this study does not include two such extremely unlikely events occurring almost simultaneously.

5.2 Scenarios to be studied

This section sets out the range of load and generation scenarios that were studied for the North and South Islands. The scenarios were chosen to represent a diverse range of system conditions where AUFLS operation might occur.

5.2.1 *North Island Scenarios*

Table 5-1 shows the load and generation scenarios studied for the North Island. These represent the worst cases of under-frequency excursions under the conditions of light, medium and heavy loads. Appendix C.2 lists the system data for these scenarios.

As worst case scenarios were chosen as events to study, it was decided not to study any load or generation scenarios that would not produce as severe a system response as the ones identified below.

Table 5-1 North Island scenarios studied

Scenario	Description	Load (MW)	Generation (MW)	HVDC North Flow (MW)	CE (MW)	IL (MW)	Risk (MW)	Risk
1	Winter peak case with high HVDC north flow	4511	3611	1200	500	470	1200	HVDC bi-pole
2	Winter peak case with little HVDC north flow	4511	4505	200	400	260	1400	Huntly plant
3	Mid load case with high HVDC north flow	3000	2000	1200	500	400	1200	HVDC bi-pole
4	Mid load case with medium HVDC north flow	3000	2500	600	380	130	1000	Huntly plant
5	Mid load case with no HVDC flow	3000	3100	0	400	161.5	1150	Huntly plant
6	Very light load with no HVDC flow	1811	1870	0	210	0	750	Huntly plant

Points to note about table 5-1:

- Total generation (North Island generation plus HVDC North transfer) is greater than the North Island load. This is due to transmission losses.
- The amount of interruptible load available was determined by first identifying the contingent event for each scenario (i.e. identifying whether the largest contingent event is a tripping of a single HVDC pole or the largest generating unit) and then determining what level of generator reserve and IL was required to manage the frequency to 48 Hz for that risk.
- The difference between the contingent event (CE) value and the interruptible load (IL) value shown in the table above is the amount of generator reserve available on the system.

For each of the 6 scenarios, dynamic studies were performed by tripping either the HVDC bi-pole or Huntly units 1 to 6 for each of the following schemes:

- Scheme 1: Operation of the current AUFLS scheme – 2 x 16% AUFLS blocks
- Scheme 2: New AUFLS scheme – 2 x 25% AUFLS blocks
- Scheme 3: New AUFLS scheme – 4 x 10% AUFLS blocks
- Scheme 4: New AUFLS scheme – 4 x 8% AUFLS blocks with df/dt acceleration

- Scheme 5: New AUFLS scheme – 4 x 10% AUFLS blocks with increased CE target of 48.5 Hz

5.2.2 *South Island Scenarios*

Table 5-2 shows the load and generation scenarios studied for the South Island. The worst case scenarios studied were the cases when the system is lightly loaded with either no HVDC transfer or the HVDC bi-pole transferring maximum south and at peak load with no HVDC bi-pole transfer. Appendix D provides more detail on the system data for these scenarios.

Table 5-2 South Island Scenarios studied

Scenario	Description	Load (MW)	Generation (MW)	HVDC South Flow (MW)	CE (MW)	Risk (MW)	Risk
1	Low load (Christmas trough) case with medium HVDC south flow	1004	624	400	100	400	HVDC bi-pole
2	Low load (Christmas trough) case with no HVDC flow	1004	1034	0	110	225	Manapouri busbar
3	Winter trough case	1541	892	660	110	660	HVDC bi-pole
4	Winter trough case with high HVDC south flow	1541	865	800	110	800	HVDC bi-pole
5	Winter trough case with no HVDC flow	1541	1561	0	105	315	Manapouri busbar
6	Winter peak case with no HVDC flow	2178	2256	0	120	360	Manapouri busbar

For each of the six scenarios above, dynamic studies were performed by tripping either the HVDC bi-pole or 3 Manapouri units for each of the following schemes:

- Scheme 1: Operation of the current AUFLS scheme (2 x 16% AUFLS blocks) and where necessary, the effects of additional reserves.
- Scheme 2: New AUFLS scheme – 2 x 16% AUFLS blocks with df/dt acceleration
- Scheme 3: New AUFLS scheme – 4 x 8% AUFLS blocks
- Scheme 4: New AUFLS scheme – 4 x 12% AUFLS blocks

5.3 AUFLS Schemes to be Studied

This section sets out details of the settings of the AUFLS schemes studied for the North and South Islands. Note that Fset is the frequency trip setting for the AUFLS relays. Td is the total time from under-frequency reached to final clearance by the circuit breaker. See sections 6 and 7 for a more detailed discussion of each of the schemes studied.

5.3.1 *North Island AUFLS Schemes*

Table 5-3 Settings for North Island scheme 1 – existing AUFLS scheme (2 x16% blocks)

Name	Block size (%)	Fset1 (Hz)	Td1 (s)	Fset2 (Hz)	Td2 (s)
Block 1	16	47.8	0.4	-	-
Block 2	16	47.5	0.4	47.8	15

Table 5-4 Settings for North Island scheme 2 - AUFLS with 2 x 25% blocks

Name	Block size (%)	Fset1 (Hz)	Td1 (s)	Fset2 (Hz)	Td2 (s)
Block 1	25	47.8	0.4	-	-
Block 2	25	47.5	0.4	47.8	15

Table 5-5 Settings for North Island scheme 3 – AUFLS with 4 x 10% blocks

Name	Block size (%)	Fset1 (Hz)	Td1 (s)	Fset2 (Hz)	Td2 (s)
Block 1	10	47.8	0.4	-	-
Block 2	10	47.7	0.4	47.8	15
Block 3	10	47.6	0.4	47.7	15
Block 4	10	47.5	0.4	47.6	15

Table 5-6 Settings for North Island scheme 4 – AUFLS with 4 x 8% blocks and df/dt acceleration

Name	Df/dt elements			Under Frequency elements		Block size (%)
	df/dt (Hz/s)	df/dt pickup (Hz)	Td (s)	Freq (Hz)	Td (s)	
Block 1	-1	49.5	0.4	47.8	0.4	8
Block 2	-1.25	49.5	0.4	47.7	0.4	8
Block 3	-1.5	49.5	0.4	47.6	0.4	8
Block 4	-1.75	49.5	0.4	47.5	0.4	8

Some important points to note about scheme 4:

- Under-frequency elements have been retained in case the scheme fails to trigger on df/dt. See section 6.4 for more detail.
- The df/dt settings have been chosen to allow the under-frequency elements time to operate before 47 Hz if any of the AUFLS blocks fail to trigger on df/dt elements[17].

[17] As an example, suppose a system disturbance of 32% generation deficiency and the initial rate of frequency fall following this event is -1.5 Hz/s. Due to the "leakage" by the df/dt elements, the 2nd and 3rd AUFLS

- The df/dt pickup setting of 49.5 Hz is a safety setting to ensure that AUFLS will not incorrectly operate when the frequency is above 49.5 Hz. This safety setting is not an optimised number.

Table 5-7 Settings for North Island AUFLS scheme 5 – AUFLS with 4 x 10% blocks and contingent event (CE) target frequency raised to 48.5 Hz

Name	**Block size (%)**	**Fset1 (Hz)**	**Td1 (s)**	**Fset2 (Hz)**	**Td2 (s)**
Block 1	10	48.4	0.4	-	-
Block 2	10	48.1	0.4	48.4	15
Block 3	10	47.8	0.4	48.1	15
Block 4	10	47.5	0.4	47.8	15

5.3.2 *South Island AUFLS Schemes*

Table 5-8 Settings for South Island scheme 1 - existing AUFLS scheme (2 x 16% blocks)

Block	Block size (%)	Fset1 (Hz)	Td1 (s)	Fset2 (Hz)	Td2 (s)
1	16	47.5	0.4	-	-
2	16	45.5	0.4	47.5	15

Table 5-9 Settings for South Island scheme 2 - AUFLS with df/dt acceleration (2 x 16% blocks)

Block	Df/dt elements			Under Frequency elements		Block size (%)
	df/dt (Hz/s)	df/dt pickup (Hz)	Td (s)	Freq (Hz)	Td (s)	
1	-1.5	49	0.2	47.5	0.4	16
2	-2	49	0.2	45.5	0.4	16

blocks did not operate. Upon the successful df/dt element operation by the 1st AUFLS block, the rate of frequency fall is slowed to -1.125 Hz/s, which is within the speed limit of the under-frequency elements of the remaining AUFLS blocks.

Table 5-10 Settings for South Island scheme 3 - AUFLS with 4 x 8 % blocks

Block	Block size (%)	Fset1 (Hz)	Td1 (s)	Fset2 (Hz)	Td2 (s)
1	8	47.5	0.4	-	-
2	8	47	0.4	-	-
3	8	46.5	0.4	-	-
4	8	45.5	0.4	-	-

Table 5-11 Settings for South Island scheme 4 – AUFLS with 4 x 12 % blocks

Block	Block size (%)	Fset1 (Hz)	Td1 (s)	Fset2 (Hz)	Td2 (s)
1	12	47.5	0.4	-	-
2	12	47	0.4	-	-
3	12	46.5	0.4	-	-
4	12	45.5	0.4	-	-

5.4 Assumptions

The studies were conducted using the DigSilent modelling tool. This section sets out the assumptions that were applied to the model.

5.4.1 *Grid*

Assumption 1 **- The HVDC has a capacity of 1200 MW.**

In the studies of this report, the Transpower base grid is used with modifications to reflect post pole 3 commissioning. In particular the AC filters at Haywards are changed, but the model does not include the Haywards Statcom. Appendix C.1 shows the single line diagram of the North Island grid studied in this report. A single line diagram of the South Island grid studied in this report can be found in Figure 1 of Appendix D.

The amount of HVDC transfer is modelled as the amount received at Haywards and Benmore for the North Island and South Island studies respectively.

Assumption 2 **– The HVDC does not respond to system frequency or voltage deviations.**

The HVDC is modelled as constant negative load and therefore does not respond to system frequency or voltage deviations in our model.

Assumption 3 **- All AUFLS relays operate at 400ms (not before).**

400ms is the total clearance time from protection trigger to circuit breaker clearance. 400ms is the EGR requirement for AUFLS response. This means that there is a 400ms delay between the time that the frequency drops below the AUFLS trigger frequency to when the breakers open to disconnect the load.

Assumption 4 **- All AUFLS providers deliver exactly the amount of AUFLS specified by the scheme (e.g. 2 x 16%) at each GXP except where the provider has an exemption (see tables below).**

It is known that the total AUFLS available at each GXP is not exactly equal to a set percentage (e.g. 32%) at all times. As load patterns vary throughout the day and year, it is to be expected that the total AUFLS available at each GXP will also vary. AUFLS providers may need to over provide (over-arm) to ensure that the total load connected to an AUFLS feeder meets the minimum requirement at all times. The System Operator is undertaking analysis to determine the level of AUFLS provided at each GXP for different periods throughout the year[18]. Until this analysis is complete, it is prudent to assume that no more or less than the amount of AUFLS specified by each of the schemes studied is provided at each GXP.

Table 5-12 lists the loads that were excluded from the North Island studies and their corresponding MW for the different scenarios studied in this report. These exemptions are excluded from the load base used for normalisation in the studies of this report.

[18] Profiles are being created for summer weekdays, summer weekends, winter weekdays and winter weekends.

Table 5-12 List of North Island loads exempted from AUFLS obligation

Exempted Party	Scenario / Area Name	1 (MW)	2 (MW)	3 (MW)	4 (MW)	5 (MW)	6 (MW)
Northpower	Bream Bay	40.52	40.52	32.13	32.13	32.13	36.3
NZ Steel	Glenbrook	128.12	128.12	149.23	149.23	149.23	100.08
Norske Skog	Kawerau	120.72	120.72	151.13	151.13	151.13	104.94
Carter Holt Harvey[19]	Kinleith	87.83	87.83	85.84	85.84	85.84	68.66
Winstone	Tangiwai	38.46	38.46	38.17	38.17	38.17	31.53
Pan Pac	Whirinaki	45.79	45.79	50.59	50.59	50.59	69.4
	TOTAL	**461.44**	**461.44**	**507.09**	**507.09**	**507.09**	**410.91**

Table 5-13 lists the load that was excluded from the South Island studies and the corresponding MW for the different scenarios studied in this report.

Table 5-13 List of South Island loads that do not provide AUFLS

Exempted Party	Scenario / Area Name	1 (MW)	2 (MW)	3 (MW)	4 (MW)	5 (MW)	6 (MW)
N/A	Tiwai	450	450	620	620	620	620

It is noted that Rio Tinto does not provide an AUFLS response at Tiwai nor does Transpower hold an exemption from providing AUFLS at the Tiwai grid exit point.

5.4.2 *Interruptible Load*

***Assumption 5* – The amount of IL modelled in the studies is sufficient to ensure that the frequency does not fall below 48 Hz for a contingent event.**

See section 5.2.1 for more detail. Appendix C.3 provides the frequency plots for the 6 scenarios with calibrated IL. Note that no IL is modelled in the South Island studies as no IL is currently offered in the South Island.

***Assumption 6* – All IL relays operate at 1 second (not before).**

1 second is the total clearance time from protection trigger to circuit breaker clearance. Note that 1 second is the EGR requirement for IL response. In reality, IL relays may operate faster than one second.

5.4.3 *Load Modelling*

***Assumption 7* – Load follows a constant impedance load model.**

The type of load model used in the DigSilent case affects the percentage of load dropped after operation of the AUFLS relays.

Because adequate data is not available to use a dynamic load model, the studies use a constant impedance load model. Using a constant impedance load model is standard practice in the absence of a dynamic load model.

[19] Carter Holt Harvey is party to an AUFLS exemption held by Norske Skog Tasman.

Generally speaking, the off take of the remaining connected loads after load shed following an event is dependent on the voltage. As the voltage rises, the effective amount of load shed reduces. The magnitude of this voltage effect depends on the load model used.

5.4.4 *Generation Modelling*

***Assumption 8* – Generators trip on over and under-frequency.**

The protection trip settings specified in each generator's Asset Capability Statement was used to determine whether each generator would trip on over or under-frequency in the studies. Note that for the North Island studies, Otahuhu B (OTC) was not running.

5.5 Other Study Parameters

The following system parameters were used in determining whether the system response for each of the scenarios studied was acceptable.

5.5.1 *Frequency*

The acceptable frequency limits were determined from the EGRs:

Table 5-14 Frequency limits for the North and South Islands

	North Island	*South Island*
High Limit (Hz)	52	55
Low Limit (Hz)	47	45

Approximately 24% of North Island generation has under-frequency protection armed at 47 Hz. It is therefore concluded that operation of the North Island system below 47 Hz must be avoided at all times if the system is to remain intact.

Hydro generators make up almost all of the South Island generation. Most of the South Island generation has under-frequency protection armed at 45 Hz.

5.5.2 *Voltage*

The acceptable voltage limits were determined from the EGRs:

Table 5-15 Voltage limits for the North and South Islands

Voltage (kV)	*Lower Limit (kV)*	*Upper Limit (kV)*
220	198	242
110	99	121
66	62.7	69.3
50	47.5	52.5

A number of locations are the subject of an arrangement whereby they are able to operate to larger voltages post event.

5.5.3 *System Stability Conditions*

The requirement for system integrity following AUFLS operation in the studies is that the average system frequency response is well damped. The connected machines should maintain synchronism and any oscillation modes should also be damped.

The other requirement is that post event frequency settles satisfactorily and does not lead to significant tripping of plant for high and/or low frequency. Whilst good models of governors, automatic voltage regulators, power system stabilisers, and wind farms are available this is not true of special protection schemes, reactive power controllers and station / block controllers. The effect that system conditions will have on these devices has not been considered in detail.

5.5.4 *Line loading*

It was decided to operate to the loading specified by the grid owner for operation. Whilst consideration could be given to other limits such as protection it was determined that this would extend the investigation beyond its scope.

6 North Island Results

This section sets out the results of the North Island studies against the 6 scenarios described in table 5-1.

For each of the 6 scenarios, dynamic studies were performed by tripping either the HVDC bi-pole or Huntly units 1 to 6 for each of the following schemes:

- Scheme 1: Operation of the current AUFLS scheme – 2 x 16% AUFLS blocks
- Scheme 2: New AUFLS scheme – 2 x 25% AUFLS blocks
- Scheme 3: New AUFLS scheme – 4 x 10% AUFLS blocks
- Scheme 4: New AUFLS scheme – 4 x 8% AUFLS blocks with df/dt acceleration
- Scheme 5: New AUFLS scheme – 4 x 10% AUFLS blocks with increased CE target of 48.5 Hz

A performance summary table, chart of frequency traces and detailed discussion is provided for each scheme and scenario in each section below.

6.1 The existing AUFLS scheme and its performance

The technical studies first considered the effectiveness of the current AUFLS scheme in the North Island against the 6 scenarios described in table 5-1.

Detailed plots of system frequencies, load, generation and system voltages can be found in Appendix C.4.1.

Performance Summary Table

Table 6-1 provides a summary of the performance of the existing scheme against the 6 scenarios presented in table 5-1.

Table 6-1 Performance summary of existing AUFLS scheme against 6 scenarios in Table 5-1

Scenario	Risk	Disturbance (%)	Total Load shed (%)	IL @ freq (%; Hz)	Initial df/dt (Hz/s)	Min Freq (Hz)	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Generators tripped	Summary
1	Bi-pole	30	43.6	11.6; 47.6	-1.75	47.09	51.8	47.33	47.11	Under-frequency: Te Rapa co-gen Over-frequency: Tararua Wind Farm Central, Tararua Wind Farm South	System remained intact and within EGR frequency limits. Windfarms tripped on over-frequency protection
2	Huntly	34	38.4	6.4; 47.6	-1.57	System Collapse		47.27	47	System Collapse	System collapse. Insufficient load shed
3	Bi-pole	48	48	16; 47.08	-2.23	System Collapse		47.08	46.92	System Collapse	System collapse. Insufficient load shed
4	Huntly	40	37.2	5.2; 47.58	-1.59	System Collapse		47.3	47.05	System Collapse	System collapse. Insufficient load shed
5	Huntly	46	38.5	6.5; 47.57	-1.55	System Collapse		47.25	47.07	System Collapse	System collapse. Insufficient load shed
6	Huntly	54	32	0; -	-2.3	System Collapse		46.97	46.77	System Collapse	System collapse. Insufficient load shed

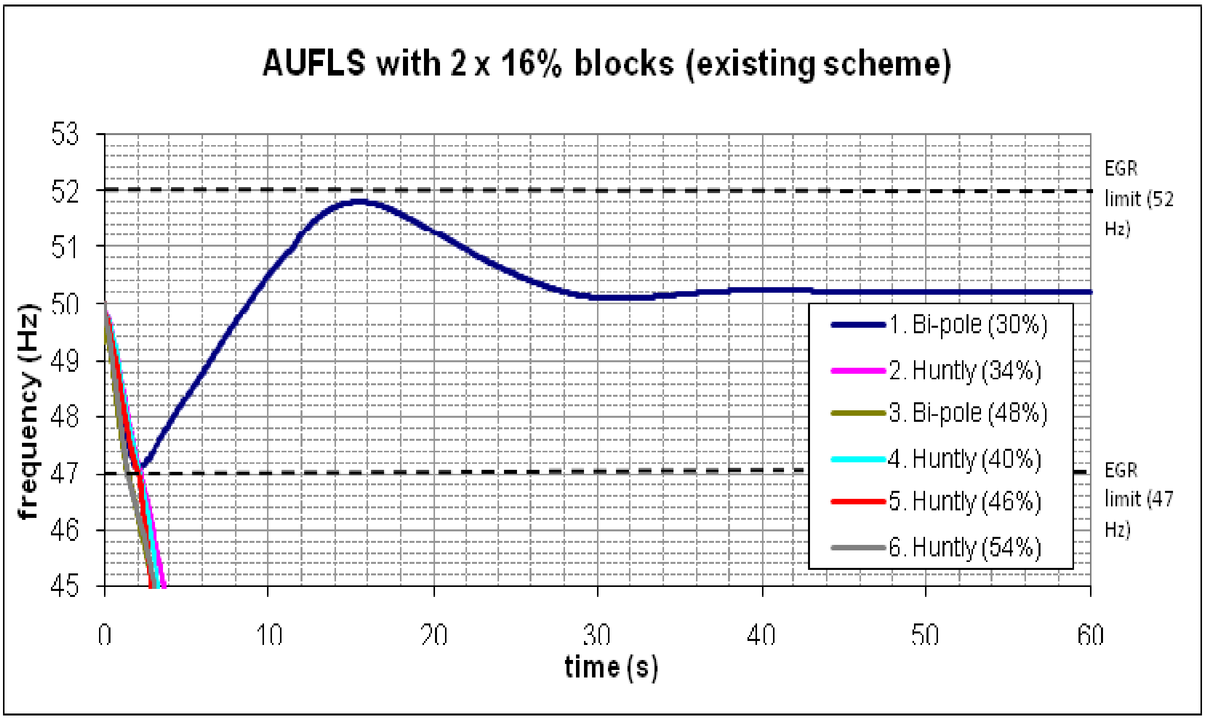
The column annotation for table 6-2 and for the other performance summary tables in section 6 is provided below for clarity:

Scenario:	Number of the scenario studied as in table 5-1.
Risk:	The risk. See table 5-1 for a more detailed description of the load and generation conditions.
Total Load Shed:	Total load shed. This is the sum of the AUFLS and interruptible load.
Disturbance:	Magnitude of the generation loss (from the initial event) as percentage of the load base.
IL @ freq:	Magnitude of IL as percentage of the load base; average system frequency at which the IL operated.
Initial df/dt:	The average initial rate of system frequency change.
Min freq:	Minimum average system frequency between 0 to 60 seconds after the first event.
Max freq:	Maximum average system frequency between 0 to 60 seconds after the first event.
Freq @ 1st block:	The average system frequency at which the 1st AUFLS block operated.
Freq @ 2nd block	The average system frequency at which the 2nd AUFLS block operated.
Generators tripped:	Sequential tripping of generators on under or over-frequency protection within 60 seconds of the initial event/generation loss.
Summary:	Summary of results.

Frequency Traces

Figure 6-1 shows the system frequency for each of the 6 scenarios studied against the existing AUFLS scheme (2 x 16%). The legend shows the scenario number, risk name and the magnitude of the disturbance.

Figure 6-1 Frequency plot for 6 scenarios with existing (2 x 16%) AUFLS scheme



Discussion

The studies have concluded that two key factors to ensure that the system remains intact are making sure that:

1. Sufficient load is shed to match the MW imbalance, and
2. The load is shed fast enough before generators trip on under-frequency protection.

Accordingly, under all but one scenario the North Island system will collapse on the basis of the existing AUFLS scheme. Detailed commentary of each scenario is set out below.

In respect of scenario 1, the system survived and remained within the EGR frequency limits as the total load shed (AUFLS + IL = 43.6%) was greater than the disturbance (30%). Windfarms tripped on over-frequency protection (51.1Hz). For this scenario, the AUFLS response was adequate in both size and speed.

For scenario 2, the system theoretically should have survived as the total load shed (38%) was greater than the disturbance (34%). However, the voltage effect of the load model resulted in a reduction in the effective load shed. I.e. a 10% rise in the voltage resulted in a 20% reduction in the load shed. This means that there was effectively only 30.4% load shed.

While the voltage would have eventually been reduced by either AVRs on synchronous machines or capacitors over-voltage protection this did not occur as the second AUFLS block operated at 47 Hz. Because the response of the block was too slow, a number of generators tripped on under-frequency protection which lead to system collapse.

For scenarios 3 to 6 the system collapses simply due to the fact that insufficient load is shed compared to the size of the disturbance (MW imbalance).

6.2 The effect of increasing the total quantity of AUFLS

The performance of the existing scheme (as set out in section 6.1) illustrates the need to shed sufficient MW to match the MW imbalance. The next step was to study the effect of increasing the total percentage of load shed and determine whether this would improve the system response. The international literature review also revealed that other systems shed much larger percentages of load compared to New Zealand.

Analysis was undertaken to determine the highest percentage of total load (IL and AUFLS) that can be shed without causing significant over-voltage issues on the system (see section 6.6 for more detail). It was determined that approximately 55% of load can be shed. If more than 55% is shed then more sophisticated over-voltage correction mechanisms are needed on the system. We currently do not have any e.g. line switching.

This section summarises the performance of a 2 x 25% AUFLS scheme. Note that it was decided to study a 50% AUFLS scheme as the total load shed also needs to take into account IL.

Detailed plots of system frequencies, load MW, generation MW and system voltages can be found in Appendix C.4.2.

Performance Summary Table

Table 6-4 provides a summary of the performance of a 2 x 25% AUFLS scheme against the 6 scenarios presented in Table 5-1.

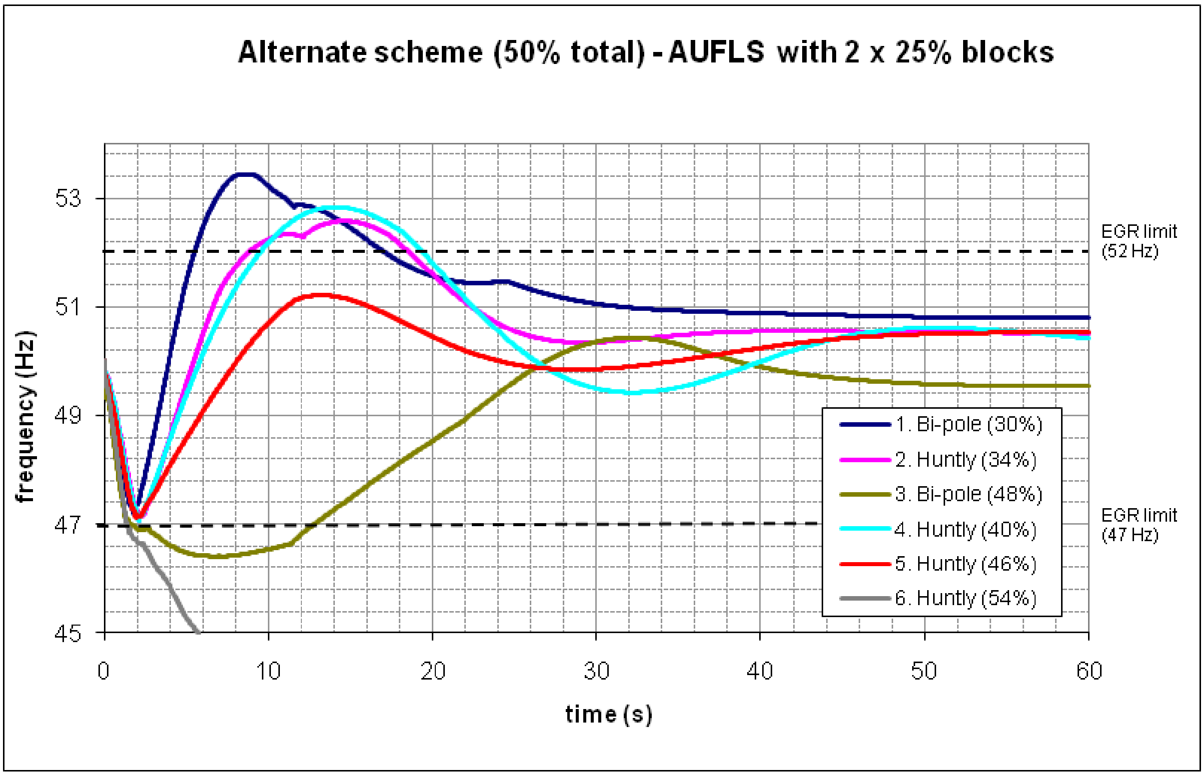
Table 6-2 Performance summary of 2 x 25% (50%) AUFLS scheme

Scenario	Risk	Disturbance (%)	Total Load shed (%)	IL @ freq (%; Hz)	Initial df/dt (Hz/s)	Min Freq (Hz)	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Generators tripped	Summary
1	Bi-pole	30	61.6	11.6; 47.6	-1.75	47.2	53.44	47.33	47.2	Under-frequency: Te Rapa co-gen Over-frequency: Te Apiti Wind Farm, Kawerau Geothermal, Glenbrook, Poihipi, Tararua Wind Farm Central, Tararua Wind Farm South	System remained intact but over-shedding resulted in over-frequency of 53.4 Hz. As this is well above the EGR limit of 52 Hz, this cannot be considered an acceptable system response. System remained intact due to the generation mix.
2	Huntly	34	56.4	6.4; 47.6	-1.57	47.05	52.58	47.27	47.08	Under-frequency: Glenbrook, Te Rapa co-gen Over-frequency: Tararua Wind Farm Central, Poihipi, Tararua Wind Farm South, Te Apiti Wind Farm	System remained intact but over-shedding resulted in over-frequency of 52.58 Hz
3	Bi-pole	48	66	16; 47.08	-2.23	46.41	50.42	47.08	46.97	Under-frequency: Mokai, Wairakei, Ohaaki, Patea, Stratford Power Ltd Over-frequency: -	System remained intact but was very close to system collapse as 2nd AUFLS block operated below 47 Hz. This cannot be considered a successful system response.
4	Huntly	40	55.2	5.2; 47.58	-1.59	47.05	52.84	47.33	47.12	Under-frequency: Te Rapa co-gen Over-frequency: -	System remained intact but over-shedding resulted in over-frequency of 52.84 Hz
5	Huntly	46	56.5	6.5; 47.57	-1.55	47.11	51.21	47.25	47.13	Under-frequency: Te Rapa co-gen Over-frequency: Tararua Wind Farm South, Tararua Wind Farm Central.	System remained intact. Frequency maintained within EGR limits.
6	Huntly	54	50	0; -	-2.3	System Collapse		46.95	46.85	System Collapse	System collapse. Insufficient load shed.

Frequency Trace

Figure 6-2 shows the system frequency for each of the 6 scenarios studied using a 2 x 25% AUFLS scheme.

Figure 6-2 Frequency plot for 6 scenarios with 50% (2 x 25%) AUFLS scheme



Discussion

Based on an increase of AUFLS to 2 x 25% blocks, only one scenario collapses. However, only one of the six scenarios is acceptable as the remaining scenarios came very close to collapse on under-frequency or experienced significant over-frequency.

The following conclusions can be reached for each scenario:

Increasing the block size from 16% to 25% has resulted in a higher minimum and maximum frequency for scenario 1. This is expected as more load is shed with AUFLS block 1 (which tripped at 47.33 Hz in both cases). However, while the maximum frequency is maintained within the EGR limit of 52 Hz for the current (32%) scheme, increasing the total AUFLS size to 50% has resulted in the maximum frequency reaching 53.44 Hz. This high over-frequency is due to over-shedding of load (30% disturbance vs. 66.6% load shed).

As a consequence, geothermal generation, gas turbines and windfarms tripped on over-frequency in this scenario. While this did not cause the system to collapse, it should be noted that Otahuhu B (OTC) is not generating in this scenario. Had there been a different generation mix (i.e. OTC was on), the CCGT would have tripped at 52 Hz[20] which may have caused the frequency to drop below 50 Hz a second time, only without any AUFLS available. As this scenario resulted in the uncontrolled tripping of generation which had the potential to cause system collapse, this scenario cannot be considered an acceptable system response.

In respect of scenarios 2 and 4, the system remained intact. However, the EGR maximum frequency limit of 52 Hz was breached.

[20] OTC has two over-frequency protection trip settings: 20 seconds @ 51.5 Hz and 0.12 seconds @ 52 Hz.

Scenario 3 survived as sufficient load was shed to prevent system collapse (48% disturbance versus 66% load shed). However, a key point to note is that the second AUFLS block tripped at 46.97 Hz. As a significant amount of generation is armed to trip below 47 Hz, this scenario was very close to system collapse. Because the 2nd AUFLS block operated below 47 Hz, this cannot be considered a successful system response. While sufficient load was shed, the speed of the AUFLS response was simply too slow.

For scenario 5, the system remained intact and the frequency remained within EGR limits.

Finally, for scenario 6 insufficient load was shed compared to the disturbance (54% disturbance versus 50% load shed). This resulted in system collapse.

While studies of a 50% AUFLS scheme resulted in 5 out of 6 scenarios being saved from system collapse, the use of AUFLS was inefficient as all of the scenarios resulted in significant over-shedding and subsequent high frequency (except for scenario 6). This is particularly evident in scenario 1 where the frequency peaks at 53.44 Hz.

These scenarios demonstrate that simply increasing the total quantity of AUFLS may not produce an acceptable system response. There is still the risk of system collapse following significant over-frequency or over-voltage. An important point to note is that better matching of the total load shed to the magnitude of the imbalance will lead to a better and more efficient system response. Over-voltage issues are discussed in more detail in section 6.6.

6.3 The effect of increasing the number of blocks

Section 6.2 concluded that over-shedding is inefficient and can lead to a risk of system collapse if the magnitude of the over-shedding is significant.

One approach to better match the total load shed to the total generation loss is to increase the number of AUFLS blocks i.e. more blocks but smaller in size. The review of international practice also revealed that other systems have more than two AUFLS blocks, and most blocks are 10% or less in size.

This section summarises the performance of a 4 x 10% scheme. This scheme was chosen as:

- A total of 40% provides a reference point against the other studies. Studying a 40% scheme will demonstrate whether there is much difference in system response between a 32% scheme (as set out in section 6.1) and a 50% scheme (as set out in section 6.2).
- There is a trade-off between the number of blocks and the speed of the response. More blocks take more time to operate in total. A 4 x 10% block scheme is comparable with the number and size of blocks used internationally but also does not compromise too much speed through the number of blocks.

Detailed plots for system frequencies, load MW, generation MW and system voltages can be found in Appendix C.4.3.

Performance Summary Table

Table 6-3 provides a summary of the performance of a 4 x 10% AUFLS scheme against the 6 scenarios presented in table 5-1.

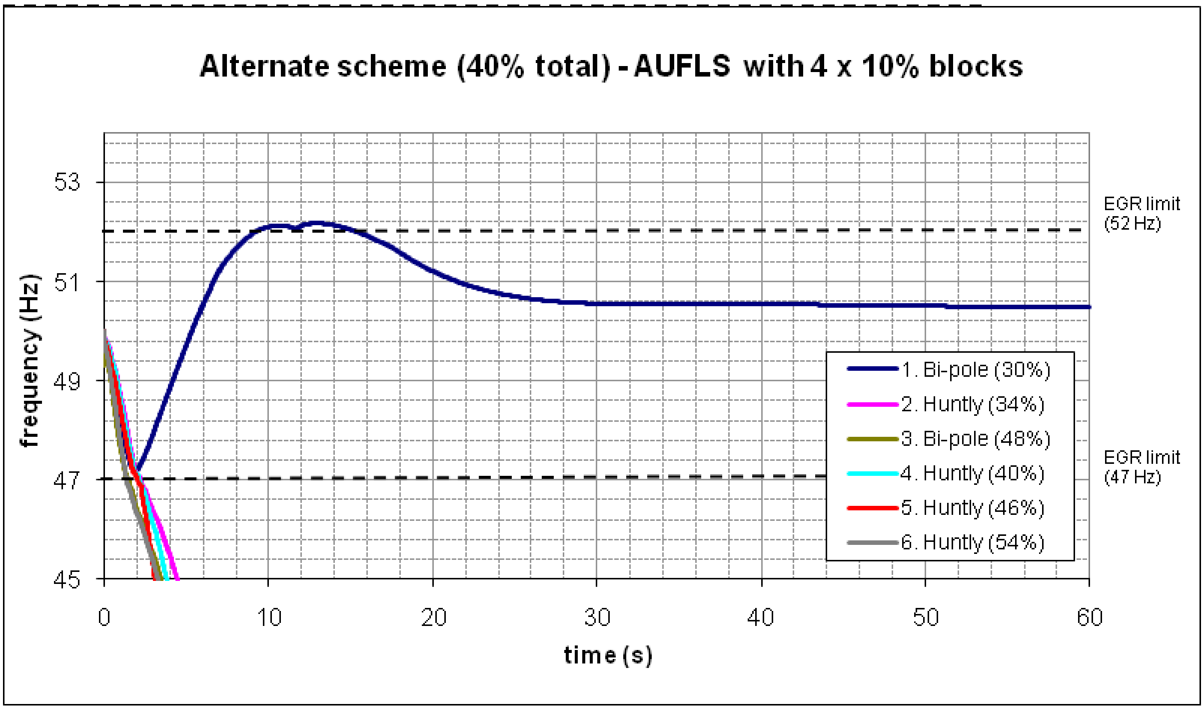
Table 6-3 Performance summary of 4 x 10% (40%) AUFLS scheme

Scenario	Risk	Disturbance (%)	Total load shed (%)	IL @ freq (%; Hz)	Initial df/dt (Hz/s)	Min Freq (Hz)	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Freq @ 3rd block (Hz)	Freq @ 4th block (Hz)	Tripped Generators	Summary
1	Bi-pole	30	51.6	11.6; 47.6	-1.75	47.18	52.18	47.3	47.25	47.2	47.18	Under-frequency: Te Rapa co-gen Over-frequency: Tararua Wind Farm South, Te Apiti Wind Farm , Tararua Wind Farm Central, Poihipi	Over-shedding resulted in over-frequency and breach of upper frequency limit. Only 3 AUFLS blocks should have operated, but the 4th block operated as the speed of the first 3 blocks was too slow.
2	Huntly	34	46.4	6.4; 47.6	-1.57	System Collapse		47.28	47.18	47.10	47.04	System Collapse	System collapse. Voltage effect reduced the effective amount of load shed.
3	Bi-pole	48	56	16; 47.08	-2.23	System Collapse		47.1	47	46.9	46.9	System Collapse	System collapse. Rate of frequency fall is so fast that AUFLS block 1 operates before IL. Blocks 3 and 4 operated below 47 Hz – too late to save the system.
4	Huntly	40	45.2	5.2; 47.58	-1.59	System Collapse		47.2	47.12	47.1	47.07	System Collapse	System collapse. Voltage effect reduced the effective amount of load shed.
5	Huntly	46	46.5	6.5; 47.57	-1.55	System Collapse		47.2	47.17	47.14	47.1	System Collapse	System collapse. Voltage effect reduced the effective amount of load shed.
6	Huntly	54	40	0; -	-2.3	System Collapse		46.96	46.91	46.87	46.85	System Collapse	System collapse. Insufficient load shed.

Frequency Trace

Figure 6-3 shows the system frequency for each of the 6 scenarios studied using a 4 x 10% AUFLS scheme.

Figure 6-3 Frequency plot for 6 scenarios with 40% (4 x10%) AUFLS scheme



Discussion

Based on a change to 4 x 10% AUFLS blocks, none of the scenarios have an acceptable system response. Five out of six scenarios collapse and scenario 1 breaches the upper EGR frequency limit. Detailed commentary of each scenario is set out below.

The system remains intact in scenario 1 as sufficient load is shed (51.6%) compared with the disturbance (30%). However, in this scenario all 4 blocks tripped when 3 blocks would have been sufficient (41.6%). The fourth block operated unnecessarily as by the time the 3rd block had operated, the frequency had already dipped below the trip setting for the 4th AUFLS block (47.5 Hz). Because the rate of fall in frequency was so fast, all 4 AUFLS blocks operated. This resulted in over-shedding and a maximum frequency of 52.18 Hz. This maximum frequency is higher than with the 32% AUFLS scheme (maximum was 51.8 Hz) but lower than with the 50% AUFLS scheme (53.44 Hz). This result is expected.

In respect of scenarios 2, 4 and 5 the total load shed is close to the magnitude of the disturbance. However, the voltage effect reduces the effective amount of load shed. While the system may have recovered following a reduction in the voltage, the 4th AUFLS block operated too close to the 47 Hz limit. At this stage, generators would have tripped on under-frequency protection before the voltage regulation could take action.

The system should have remained intact for scenario 3 as the total load shed (56%) exceeded the disturbance (48%). However, in this scenario the rate of frequency fall is so fast that AUFLS block 1 operates before IL. Blocks 3 and 4 operated below 47 Hz which is too late to save the system from collapse.

For scenario 6 insufficient load was shed compared to the disturbance (54% disturbance versus 40% load shed). This resulted in system collapse.

It can therefore be concluded that for a 4 x10% scheme:

- From a system frequency perspective, there is no significant difference in performance to the existing AUFLS scheme of 2 × 16 % blocks, as scenarios 2-6 experience system collapse in both schemes.
- Because the blocks are so close together (only 0.1 Hz apart), for most large frequency excursions it is likely that all AUFLS blocks will operate leading to over-shedding.
- The only way that discrimination between the AUFLS blocks can be achieved is if the rate of frequency decay is slower than -0.25 Hz/s. This was not the case in any of the scenarios studied. It is also unlikely to be the case in reality as a slow rate of decay will occur when the magnitude of the loss is small and the system inertia is heavy. These system conditions are very unlikely following large system events greater than or equal to an ECE in magnitude.
- An obvious benefit of the four block scheme would be when a CE has failed to be corrected by market reserves and the system frequency falls to 47.8 Hz. The load shed following the 1st AUFLS trigger would be reduced to 10 % instead of 16 % in the existing scheme.
- More blocks are not helpful if the speed of the response from each block is too slow.

Adding more blocks alone will not reduce the risk of over-shedding. As mentioned in section 6.1 and as demonstrated in scenarios 1 to 5 of the 4 x 10% scheme, speed of the AUFLS response is critical to preventing the system from collapsing.

6.4 The effect of incorporating frequency rate of change (df/dt) elements

Section 6.3 illustrated the importance of speed of the AUFLS response in preventing system collapse. One way to improve the speed of the response is to change the trigger mechanism for the AUFLS blocks.

The existing AUFLS scheme (and the schemes studied in sections 6.2 and 6.3) uses under-frequency elements to trigger the AUFLS blocks. Simply put, this means that AUFLS will trip once the frequency has dropped below a set frequency for a set period of time.

Another way to trigger AUFLS is to use frequency rate of change elements. Also known as df/dt elements, this means that AUFLS will trip once the frequency rate of fall has reached a certain speed. A benefit of a df/dt scheme is that it will allow AUFLS to be triggered at frequencies higher than the 48 Hz CE target frequency.

This section summarises the performance of a 4 x 8% df/dt scheme. This scheme was chosen as a 4 x 8% scheme (32% total) provides an interesting comparison against the existing 2 x 16% scheme (also 32% total). It will help determine whether any improvements can be gained from increasing the speed of the response and the number of blocks while keeping the total AUFLS quantity constant.

While the scheme is designed to study the effect of triggering AUFLS using df/dt elements, the under-frequency settings from the 4 x 10% scheme were retained as a back-up. Under-frequency settings need to be retained in case the scheme fails to trigger on df/dt. This could happen as:

- Measurement errors and power system oscillation can introduce errors with the triggering of df/dt elements. The settings in table 5-6 allow for errors of up to 20%.
- Df/dt elements may fail to completely arrest the fall in frequency. For example, looking at table 5-6, assume that an event causes the frequency to fall at an initial rate of -1.2 Hz per second. This will cause AUFLS block one to trigger. While the response from block one may be sufficient to slow the decay in frequency, it may not be sufficient to completely arrest the decay in frequency. Therefore it is possible that the frequency may continue to fall (e.g. at a rate of -0.6 Hz/s) without triggering further AUFLS blocks that would aid in recovering the system.

Detailed plots for system frequencies, load MW, generation MW and system voltages can be found in Appendix C.4.4.

Performance Summary Table

Table 6-4 provides a summary of the performance of a 4 x 8% AUFLS scheme with df/dt elements against the 6 scenarios presented in table 5-1.

Table 6-4 Performance summary of 4 x 8% (32%) AUFLS scheme with df/dt acceleration

Scenario	Risk	Disturbance (%)	Total Load Shed (%)	IL @ freq (%; Hz)	Initial df/dt (Hz/s)	Min Freq (Hz)	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Freq @ 3rd block (Hz)	Freq @ 4th block (Hz)	Tripped Generators	Summary
1	Bi-pole	30	43.6	11.6; 48.36	-1.75	48.34	51.46	49.14	49.07	49.03	49	Under-frequency: - Over-frequency: -	System frequency maintained within EGR limits. Minimum frequency is much higher than the existing (2 x16%) scheme even though total load shed is the same.
2	Huntly	34	38.4	6.4; 48.04	-1.57	47.32	50.05	49.18	49.16	48.84	47.39	Under-frequency: Te Rapa Co-gen, Glenbrook Over-frequency: -	System frequency maintained within EGR limits. Last AUFLS block operated on under-frequency setting rather than the df/dt setting.
3	Bi-pole	48	48	16; 48	-2.23	47.87	50.69	49.13	49.08	49	48.94	Under-frequency: - Over-frequency: -	System frequency maintained within EGR limits. All AUFLS blocks operated on df/dt. Governor response helped with system recovery.
4	Huntly	40	37.2	5.2; 48.02	-1.59	47.29	50.69	49.2	48.15	48.82	48.6*	Under-frequency: Te Rapa co-gen Over-frequency: -	System frequency maintained within EGR limits. All AUFLS blocks operated on df/dt. Governor response helped with system recovery.
5	Huntly	46	38.5	6.5; 47.98	-1.55	System Collapse		49.11	49.11	49.11	48.6*	System Collapse	System collapse. Insufficient load shed.
6	Huntly	54	32	0;	-2.3	System Collapse		48.86	48.86	48.86	48.86	System Collapse	System collapse. Insufficient load shed.

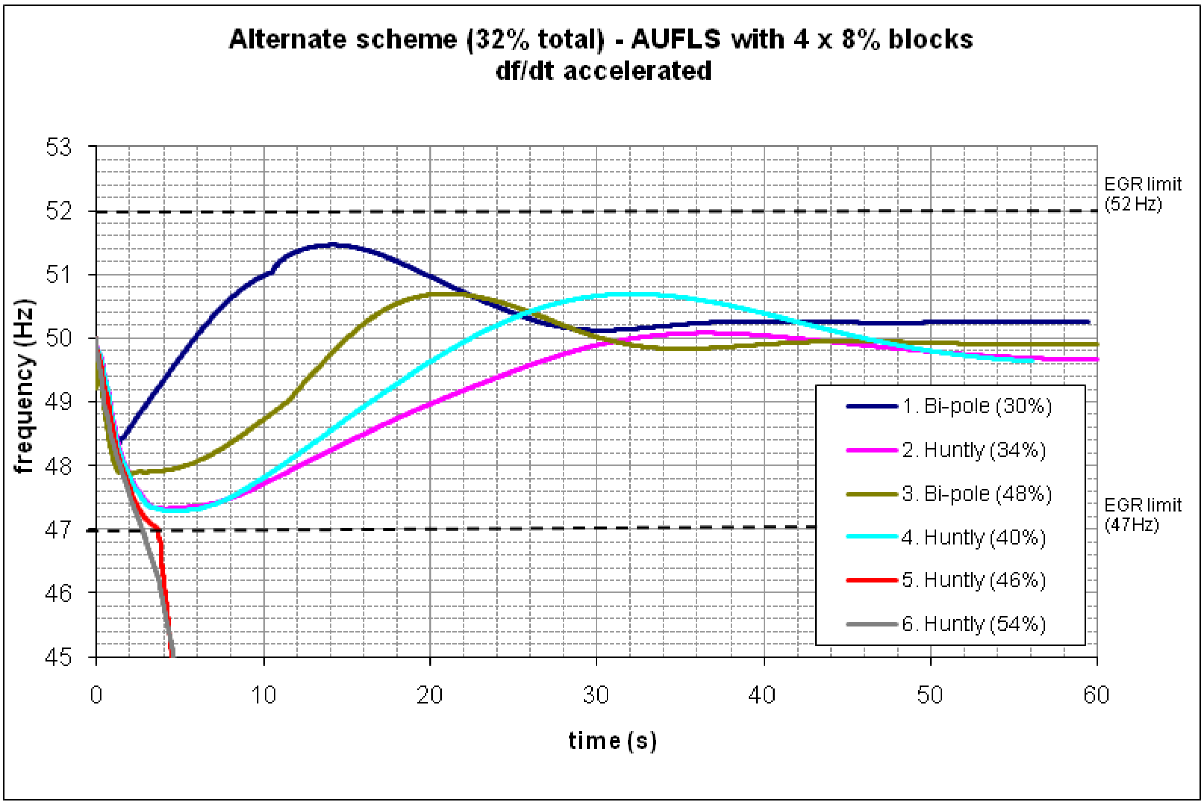
* Only partial number of loads tripped on df/dt element and the remaining tripped on under-frequency elements.

Note that AUFLS blocks which operate below 48 Hz are triggered by the under-frequency element, not df/dt elements.

Frequency Trace

Figure 6-4 shows the system frequency for each of the 6 scenarios studied using a 4 x 8% AUFLS scheme with df/dt settings.

Figure 6-4 Frequency plot for 6 scenarios with 32% (4 x 8%) AUFLS scheme with df/dt acceleration



Discussion

Based on a 32% AUFLS scheme of 4 x 8% blocks with df/dt settings, only two out of six scenarios collapses. While the scheme performs better than the schemes studied in sections 6.1 – 6.3, it is still reliant on using the current under-frequency trigger mechanism. An AUFLS scheme with df/dt settings needs more investigation in terms of:

a) Capability of existing relays, and
b) Optimisation of all of the numbers and settings.

The following conclusions can be reached for each scenario:

In respect of scenario 1, the same amount of load is shed as with the existing (2 x 16%) scheme. However, note that the minimum frequency is only 48.34 Hz with df/dt (this is within the CE limit of 48 Hz) and the maximum frequency is also with the EGR limits. IL operation (at 48.36 Hz) causes a sharp swing in frequency back toward 50 Hz.

The system remains intact for scenario 2 and the frequency remains within the EGR limits. In this case, the frequency dropped quite low (47.32 Hz) compared with the first scenario, as the fourth AUFLS block operated on the back up setting, and not on df/dt. This illustrates the need to keep the existing settings as once the frequency rate has slowed to a certain speed, df/dt will not operate.

For scenario 3 the system remains intact and the frequency remains within the EGR limits. Note that even though the disturbance is much larger than scenario 2, the minimum frequency is higher (47.87 Hz). The key difference between this scenario and scenario 2 is that the last AUFLS block operated on df/dt (i.e. operated at a much higher frequency of 48.94 Hz). This illustrates that the minimum frequency under a df/dt scheme does not entirely depend on the magnitude of the disturbance. Rather, it depends on the combination of the rate of frequency decay and the magnitude of the disturbance.

The system remains intact for scenario 4 and the frequency remains within the EGR limits.

Finally, for scenarios 5 and 6 the system collapses simply due to the fact that insufficient load is shed compared to the size of the disturbance (MW imbalance).

It can therefore be concluded that:

- For scenarios 1-4, there are significant improvements in the system frequencies where the minimum system frequency remains above 47 Hz and below 52 Hz. A direct consequence of this is that only one generator sequentially tripped after the first event.
- Compared with existing 2 x 16% scheme, although the total load shed is the same, the performance is much better (1 vs. 4 successful scenarios) as the faster AUFLS response also allows for governor response to help recover the system. This is particularly the case for scenarios 3 and 4.
- Compared with the 4 x 10% scheme (see section 6.3), scenarios 2, 3 and 4 survive as fast AUFLS response prevents the system frequency from falling below 47 Hz even though less load is shed.
- A df/dt scheme allows us to maintain discrimination against a CE but trigger AUFLS at a much higher frequency. In all of these scenarios, AUFLS block 1 operates before IL.
- Fast AUFLS operation has 2 benefits. It diminishes the voltage effect and allows for greater response from governors (see table 6-5 below).

The benefit from the turbine response depends on:

1. The speed of the fall in frequency. If the frequency falls too fast then generators will not have time to respond.
2. The speed of the turbine response. The faster they can respond then the more benefit they can provide to the system.

Table 6-5 illustrates the potential turbine responses that can be considered if turbines respond within 6s and 3s.

Table 6-5 Some empirical performance indices for df/dt accelerated AUFLS

	Turbine Response (6s)			**Turbine Response (3s)**		
Initial df/dt (Hz/s)	F_final (Hz)	df/dt final (Hz/s)	Reserve from Governor	F_final (Hz)	df/dt final (Hz/s)	Reserve from Governor
-1.2	47.32	-0.075	6.25%	47.32	-0.253	21.05%
-1.5	47.24	-0.057	3.78%	47.23	-0.174	11.58%
-1.8	47.23	-0.055	3.07%	47.21	-0.169	9.37%
-2.1	47.27	-0.077	3.66%	47.21	-0.254	12.11%

The column annotation for table 6-5 is provided below for clarity:

Turbine Response	The speed at which turbines fully respond after the event (3 seconds / 6 seconds)
Initial df/dt (Hz/s)	The initial rate of frequency change. The four initial rates of fall shown are chosen to allow for errors of up to 20% on the triggering of df/dt elements.
F_final (Hz)	This is the estimated frequency at which the 4^{th} (final) AUFLS block operated.
Df/dt final (Hz/s)	The estimated rate of frequency change after the 4^{th} (final) AUFLS block has operated.
Reserve from Governor	Reserve from the governor (generator). See the example below for an explanation of how to interpret these values.

Table 6-5 should be read as follows:

Say the initial rate of frequency change (df/dt) following a disturbance is -1.5 Hz/s. If turbines respond within 6 seconds, then the system frequency should not breach 47 Hz for a loss of 33.26%[21] generation. If turbines respond within 3 seconds, then the system frequency should not breach 47 Hz for a loss of 36.19%[22] generation.

Generally, the faster the turbine response, the less response (MW) required from load shedding through IL and AUFLS.

AUFLS relays with df/dt settings must also retain under-frequency settings (see scenario 2 where the scheme still relies on under-frequency settings). For scenarios where the scheme operates on under-frequency settings, there is still room for optimisation as there is little discrimination between the blocks on under-frequency settings in scheme studied.

Generally, while this scheme shows better results than the existing AUFLS scheme, it needs more investigation in terms of:

1. Capability of existing relays
2. Optimisation of all numbers and settings.

[21] (4x8%)/(1-3.78%) = 33.26%
[22] (4x8%)/(1-11.58%) = 36.19%

6.5 The effect of increasing the contingent event target frequency

Section 6.4 investigated the effect of improving the speed of the AUFLS response by using df/dt elements. Another method to improve the speed of the AUFLS response is to trigger AUFLS at a higher frequency setting.

The current EGR standards require the System Operator to maintain the frequency to 48 Hz for a contingent event (CE) and to 47 Hz for an extended contingent event in the North Island. As AUFLS is not intended to operate for a contingent event, this means that there is only a 1 Hz range for AUFLS operation in the North Island.

If the CE target frequency is increased to 48.5 Hz, the under-frequency settings in the AUFLS relay can be set at higher frequencies. The benefit of this is two-fold: the setting distance between each AUFLS block is increased (hence reducing the risk of over-shedding) and AUFLS can start to operate earlier, and further from the frequency limit of 47 Hz.

A 4 x 10% AUFLS scheme with a CE target frequency of 48.5 Hz was studied to:

- Determine whether triggering AUFLS at higher frequencies than the current settings will improve the overall performance.
- Provide a comparison against the 4 x 10% scheme studied in section 6.3 and determine whether speed of the AUFLS response makes a significant difference.

Note that assumption 6 was modified for this scheme (see section 5.4.3). This scheme assumes that all interruptible load relays operate at 0.5 of a second. If the 1 second operation time for IL is retained, it is highly likely that the reserves procured for a contingent event will be insufficient to prevent the frequency from falling below 48.5 Hz under peak load conditions[23].

Detailed plots for system frequencies, load MW, generation MW and system voltages can be found in Appendix C.4.5.

[23] To illustrate this, consider a frequency initial rate of fall of 1 Hz per second following a contingent event. If IL triggers at 49.2 Hz this allows only 0.7 seconds [(48.5 Hz – 49.2 Hz) / -1 Hz/s = 0.7s] for IL to operate before the new CE minimum frequency of 48.5 Hz is reached. Generator turbines will not be able to respond within this short time period and therefore will not be able to assist in recovery of the system frequency. The operation time for IL therefore needs to be reduced in order to prevent the frequency from falling below 48.5 Hz.

Performance Summary Table

Table 6-6 provides a summary of the performance of a 4 x 10% AUFLS scheme with the CE target frequency increased to 48.5 Hz against the 6 scenarios presented in table 5-1.

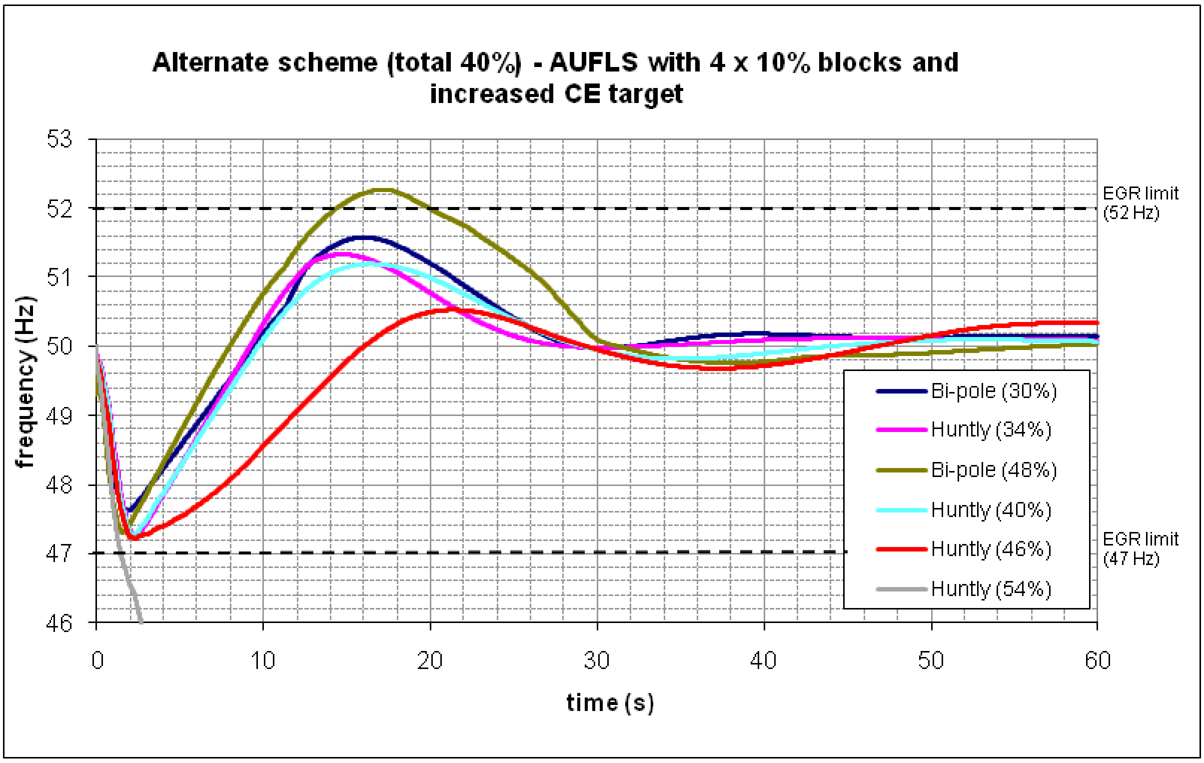
Table 6-6 Summary table for 4 blocks of AUFLS with CE target frequency increased to 48.5Hz.

Scenario	Risk	Disturbance (%)	Total Load Shed (%)	IL @ freq (%; Hz)	Initial df/dt (Hz/s)	Min Freq (Hz)	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Freq @ 3rd block (Hz)	Freq @ 4th block (Hz)	Tripped Generators	Summary
1	Bi-pole	30	41.6	11.6; 48.25	-1.75	47.61	51.57	47.9	47.74	47.6	No operation	Under-frequency: Te Rapa co-gen Over-frequency: Tararua Wind Farm South, Tararua Wind Farm Central	System remained intact and within EGR frequency limits. Windfarms tripped on over frequency protection. 4th AUFLS block did not operate due to successful discrimination between the blocks.
2	Huntly	34	46.4	6.4; 48.41	-1.57	47.25	51.33	47.72	47.59	47.4	47.25	Under-frequency: Te Rapa co-gen, Glenbrook Over-frequency: Tararua Wind Farm South, Tararua Wind Farm Central	System remained intact and within EGR frequency limits. Windfarms tripped on over frequency protection
3	Bi-pole	48	56	16; 48.04	-2.23	47.29	52.27	47.7	47.56	47.36	47.3	Under-frequency: Te Rapa co-gen Over-frequency: Poihipi	System remained intact but over-shedding resulted in over-frequency.
4	Huntly	40	45.2	5.2; 48.28	-1.59	47.24	51.19	47.72	47.56	47.4	47.25	Under-frequency: Te Rapa co-gen Over-frequency: -	System remained intact and within EGR frequency limits.
5	Huntly	46	46.5	6.5; 48.34	-1.55	47.21	50.53	47.74	47.53	47.4	47.25	Under-frequency: Te Rapa co-gen Over-frequency: -	System remained intact and within EGR frequency limits.
6	Huntly	54	40	0;	-2.3	System Collapse		47.48	47.24	47.04	46.91	System Collapse	System collapse. Insufficient load shed.

Frequency Trace

Figure 6-5 shows the system frequency for each of the 6 scenarios studied using a 4 x 10% AUFLS scheme and with an increased contingent event target of 48.5 Hz.

Figure 6-5 Frequency plot for 6 scenarios with 40% (4 x10%) AUFLS scheme and an increased CE target



Discussion

Only one scenario collapses in the studies of a 4 x 10% AUFLS scheme with an increased contingent event target of 48.5 Hz. The system remains intact and within the EGR frequency limits for four of the remaining five scenarios.

The following conclusions can be reached for each scenario:

The system remains intact and within the EGR frequency limits for scenario 1. Unlike the study of scenario 1 under the 50% scheme (see section 6.2) and the 40% scheme (see section 6.3) there is no over-shedding. The fourth AUFLS block did not trip as adequate discrimination between the blocks allowed the system to recover. In this scenario 41.6% of load was shed to cover for a 30% disturbance. This was the only scheme studied that achieved discrimination between the AUFLS blocks.

In respect of scenarios 2 and 4, the system remains intact and within the EGR frequency limits.

For scenario 3 the system remained intact, however, the EGR maximum frequency limit of 52 Hz was breached.

The quantity of load shed (46.5%) in scenario 5 is just enough to match the disturbance (46%). this scenario survived as the speed of the AUFLS response gave governors time to respond and allowed more time for AVRs to regulate the system voltage which also reduced the voltage effect. Note that this scenario failed when studying a 40% scheme with the existing CE target frequency (see section 6.3).

Finally, for scenario 6 the system collapsed as insufficient load was shed to match the disturbance.

The following conclusions can be made:

- Increasing the distance between the trip settings of the AUFLS blocks reduces the risk of over-shedding. This is evident in scenario 1 where the last AUFLS block did not operate. Of all the North Island schemes studied, this is the only example where all AUFLS blocks did not operate.
- In scenarios 2-5, because the load is shed at higher frequencies than the existing settings, early triggering of AUFLS reduced the rate of the fall in system frequency enough to:
    1. Allow turbines to respond to the fall in frequency and provide generator reserves and,
    2. Allow AVRs more time to react to voltage rises following load shedding and reduce the voltage effect.
- While this scheme produced the best system response of all the schemes studied, this scheme needs more investigation in terms of:
    1. The capability of the existing IL relays and whether they are able to operate within 0.5 seconds. This would also require an EGR rule change.
    2. The impact on the energy and reserves market.

6.6 The effect of load shedding on system voltage

Analysis was undertaken to establish the lower limit of load at which the system can operate without breaching its voltage limit (refer to section 5.4.2 for the EGR limits). This was done by using the scenario with the lowest load in table 5-1[24] and shedding load in increments until 1.1 pu steady-state voltage was reached on any busbar in the system after 20 seconds.

Without considering automatic line switching, the lower load limit is found to be around 1100 MW. This was confirmed by studying two events: the loss of Huntly station (750 MW) and the loss of the HVDC bi-pole (800 MW).

The voltage plots for these two studies are shown in Figure 6-6 to 6-9. For the first 5 seconds after the event, the busbar voltages are significantly different between the two events due to the different dynamics occurring on the system. However, as time progresses, the steady-state voltages settle just below 1.1pu for both contingencies.

In the very lightly loaded North Island grid, all system capacitors, except the harmonic filters required for the Albany SVC and the HVDC link, are not needed and are therefore switched out of service.

In the case of the HVDC bi-pole contingency, the filters at Haywards are assumed to be automatically switched out 1 second after the bi-pole converters are blocked by the control system[25].

For cases other than the very light load scenario, because there would be various system capacitors switched in during normal operation, it is possible that the voltages at some bus-bars may exceed 1.1pu after under-frequency load shedding has occurred.

These over-voltages, however, should be adequately corrected by switching out the connected capacitors. Appendix C.2 Table 3 lists the over-voltage protection settings assumed for various reactive shunts in the North Island grid. Note that these settings are based on a crude assumption that if a capacitor unit is commissioned after the year 2000 and a modern numerical protection relay is available, the capacitor has over-voltage protection with a standard definite time setting of 1.1pu at 10 s delays.

The voltage dynamics for all the six scenarios under various load shedding schemes has been included in Appendix C.4. The voltage plots clearly show that, with the assumed over-voltage protections on the reactive plants, there are cases where the 1.1pu steady-state limit is breached.

These over-voltages can be further corrected by incorporating over-voltage protection on the remaining connected capacitors. Grading of the over-voltage protections, however, can be complicated. A possible form of protection trigger may be with system frequency assisted over-voltage elements.

[24] Scenario 6 in table 5-1

[25] The AC filters at Haywards needed to be tripped within 0-2s after the HVDC bi-pole block. Otherwise, although the existing condensers are able to regulate Haywards voltages for the loss of HVDC bi-pole, the sequential operation by AUFLS will push the system beyond its capability. In some of the scenarios studied, it has been found that if the Haywards filters are left switched in, Haywards voltages rise very quickly following AUFLS operation and some North Island generators may pole-slip.

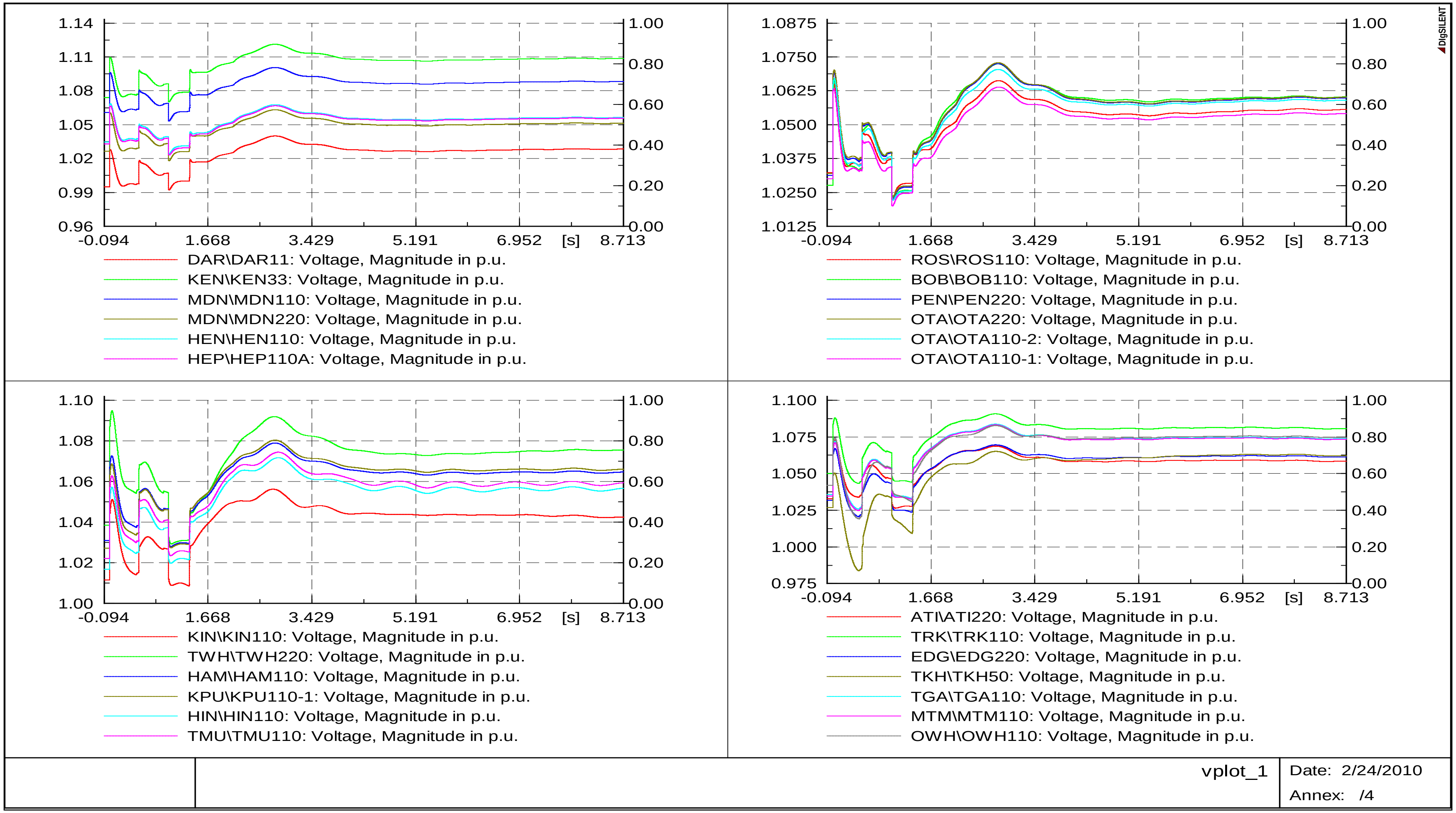


Figure 6-6 Upper North Island voltage plots for 750 MW load shed from a 1800 MW base load (HVDC bi-pole tripping of 800 MW).

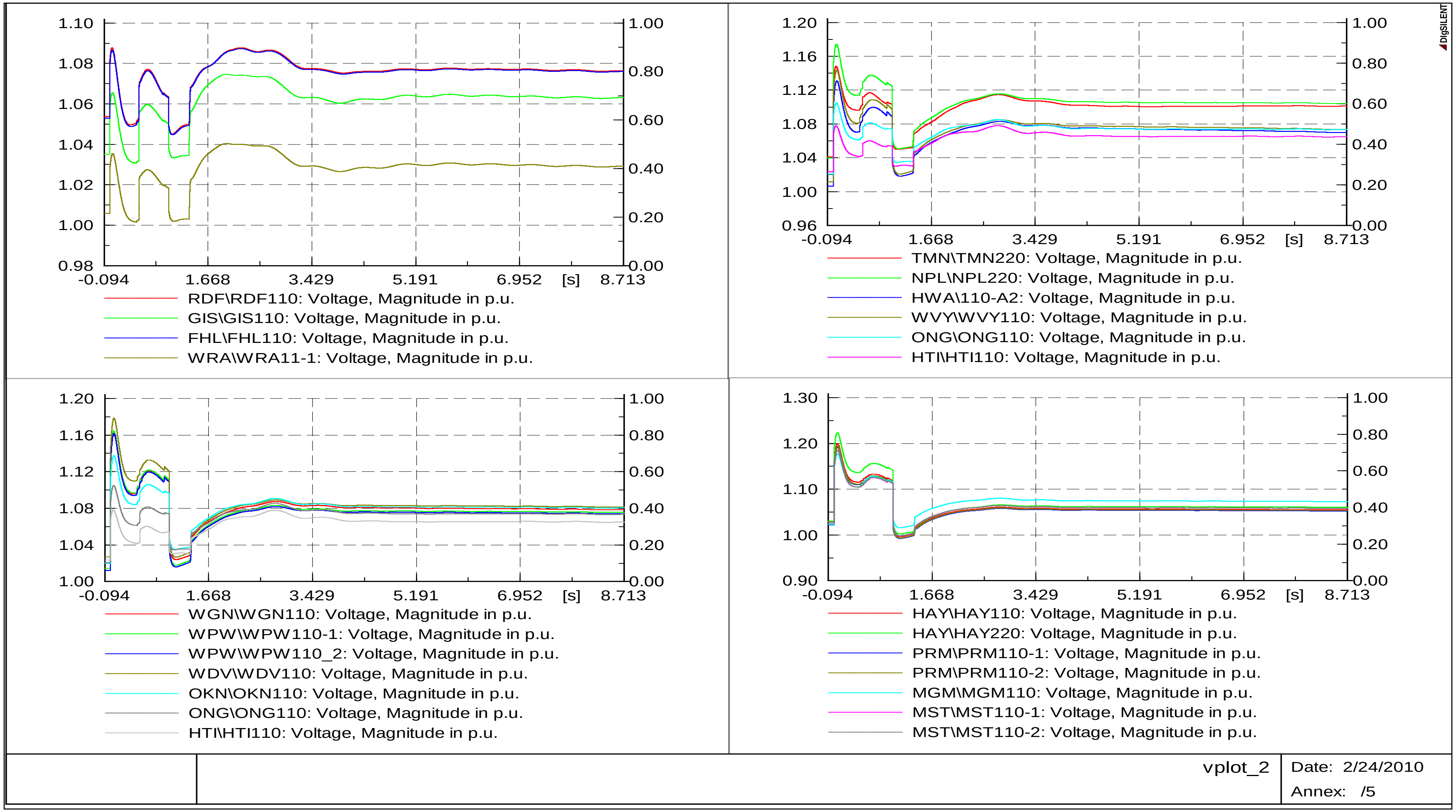


Figure 6-7 Lower North Island voltage plots for 750 MW load shed from a 1800 MW base load (DC bi-pole tripping of 800 MW).

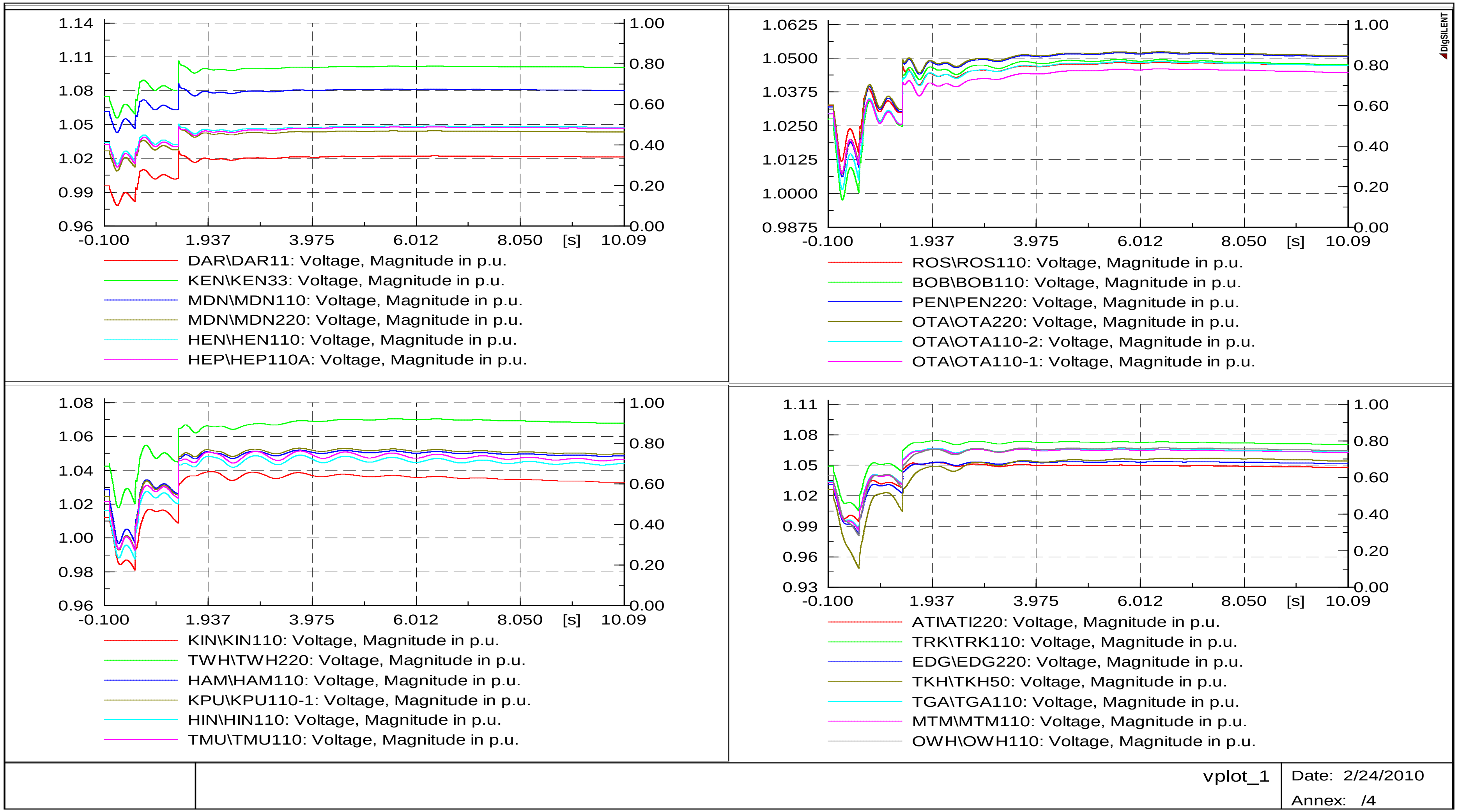


Figure 6-8 Upper North Island voltage plots for 800 MW load shed from a 1800 MW base load (HLY station tripping of 750 MW).

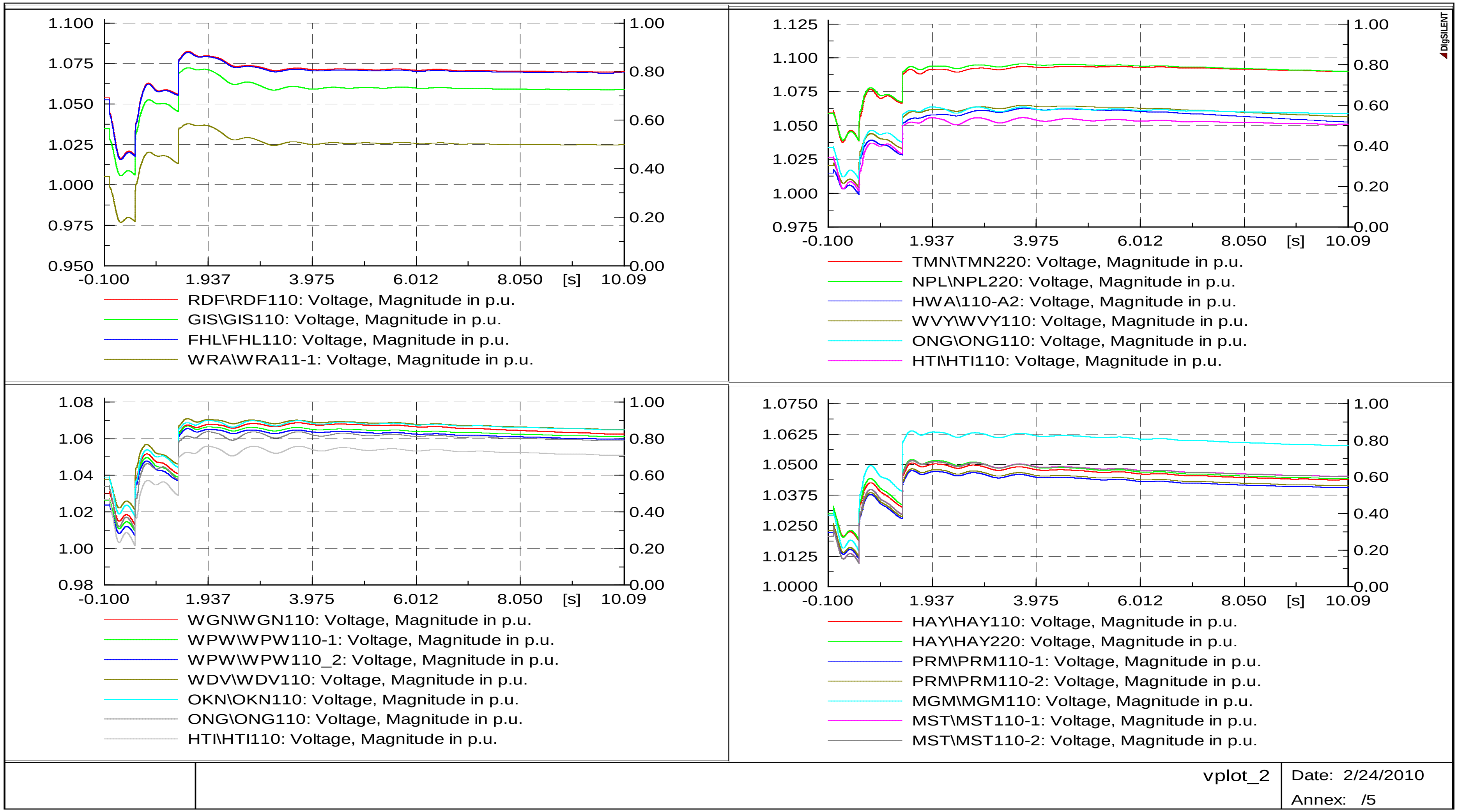


Figure 6-9 Lower North Island voltage plots for 800 MW load shed from a 1800 MW base load (HLY station tripping of 750 MW).

6.7 The influence of load dynamics

In this report, all the loads have been modelled as constant impedance loads. In particular, other than for scenarios 1, 3 and 6, it is not possible to attain a converged electromagnetic solution post event with a constant power load model since the Mvar loss following the loss of entire Huntly station is so great that voltage collapse will occur.

For the scenarios with loss of Huntly station, the system voltage will first fall due to the loss of Mvar injection provided by the Huntly generators and then increase following load shedding. Because a constant impedance load model is assumed, these variations in system voltages correspond to a natural reduction and increment of MW off-take from the grid respectively.

From the MW balancing perspective, the initial reduction of MW off-take will slow the initial rate of system frequency decay and the latter increment will reduce the effective load shed performed by AUFLS.

For the scenarios with the loss of the HVDC bi-pole, the system voltage will first increase following the loss of Mvar off-take by the HVDC converters. However, this increment is quickly corrected by the synchronous condensers at Haywards.

Depending on the speed of AUFLS, if it operates before the 1 s tripping delay assumed for the Haywards filters, the system voltage may rise then fall again when the filters at Haywards are tripped off.

For both the contingencies studied, the final system voltages tend to be higher after the load shed by AUFLS. This increment in system voltage will correspond to a reduction in effective load shed. In some extreme cases, up to 30 % reduction is observed (70% effective).

The constant impedance model is quite inert to system frequency deviations.

6.8 North Island Results – Summary and Conclusions

6.8.1 Summary of North Island results

The results from the AUFLS schemes studied for the North Island are summarised in table 6-7:

Table 6-7 Summary table for results of the North Island studies

Scheme Studied	Summary of North Island Results
Existing scheme 2 x 16%	· Five out of six scenarios collapse. · AUFLS is insufficient in either quantity, speed of response, or both for the scenarios studied.
2 x 25%	· This scheme studied the effect of increasing the total quantity of AUFLS. · One out of six scenarios collapse but three result in significant over-frequency due to over-shedding. · Over-shedding is inefficient and can lead to risk of system collapse if the magnitude of the over-shedding is significant.
4 x 10%	· This scheme studied the effect of increasing the number of blocks and decreasing the block size in order to reduce the potential for over-shedding. · Five out of six scenarios collapse. · Adding more blocks alone does not reduce the risk of over-shedding if the blocks are set to trip too close together. · The speed of the AUFLS response is too slow to prevent collapse in most of the scenarios studied.
4 x 8% with df/dt elements	· This scheme studied the effect of increasing the speed of the AUFLS response by triggering AUFLS on the rate of change in frequency. · Two out of six scenarios collapse. · Using df/dt triggers allows AUFLS to operate before 48 Hz and gives generator turbines and AVRs time to respond and help recover the system. · This scheme demonstrates that the system response can be improved without increasing the total quantity of AUFLS. · Df/dt schemes need more investigation in terms of capability of relays and optimisation of settings.
4 x 10% with CE target of 48.5 Hz	· This scheme studied the effect of increasing the speed of the AUFLS response by triggering AUFLS at a higher frequency (using the existing trigger mechanism). · One out of six scenarios collapse. · The higher trip settings allow generator turbines and AVRs time to respond to help recover the system. · This scheme produces the best results of the schemes studied as it accounts for the total quantity of the AUFLS response, the number and size of blocks and the speed of the response. · This scheme needs more investigation in terms of capability of IL relays and also the impact on the energy and reserves market.

6.8.2 Conclusions from the North Island studies

The North Island currently has a 32% AUFLS scheme made up of two large 16% blocks that are set to trip close together and at relatively low frequencies of 47.8 Hz and 47.5 Hz.

The existing AUFLS scheme is sufficient to prevent system collapse following an HVDC bi-pole tripping at a North transfer level of 1200 MW when there is high North Island load of around 4500 MW or more (scenario 1). Under these conditions, high levels of North Island generation (other than HVDC) are required to meet North Island demand. High levels of generation help the system to recover (i.e. the system inertia is heavy) and also reduces the magnitude of an HVDC tripping in terms of percentage of generation lost.

While the studies show that the system does not survive following an HVDC bi-pole tripping under other load and generation scenarios, it is important to note that a bi-pole tripping is defined as an extended contingent event (ECE). This means that the System Operator’s tools will ensure that extra reserve is procured and/or the HVDC transfer is limited to prevent system collapse following an HVDC bi-pole tripping under all load and generation scenarios.

However, the overall design of the scheme provides the System Operator with low confidence that the current AUFLS scheme will be effective to prevent the system from collapsing from large risks that are not currently defined as an ECE.

The following conclusions can be made about the existing North Island AUFLS scheme:

1. **The trip settings for the North Island AUFLS blocks are too close together.**

   The AUFLS blocks are currently set only 0.3 Hz apart. Because the rate of frequency fall is very fast for large system events (over 2 Hz per second in some of the scenarios studied) this means that both blocks will trip even when only one block is required. Over-shedding is inefficient as too many customers are disconnected unnecessarily and it may also cause significant over-frequency and over-voltage problems which can also lead to system collapse. The large size of each block also increases the potential for over-shedding to occur.

   Figure 6-10 demonstrates that under the existing settings, AUFLS block 1 will trigger and operate before AUFLS block 2 is triggered when the frequency rate of fall is 0.5 Hz per second. While our reserve management system is designed to respond to frequency falls of this speed (i.e within 6 seconds), the studies demonstrate that the frequency fall is much faster following very large events such as an ECE.

   In the scenarios studied, the frequency rate of fall is between 1.55 and 2.3 Hz per second. At these speeds, the EGR frequency limit of 47 Hz is reached in 2 seconds or less after the event. Figure 6-11 demonstrates that under the existing settings, AUFLS block 2 may trigger before AUFLS block 1 has operated when the frequency rate of fall is 1.5 Hz per second.

2. **The second AUFLS block is set to trip too close to 47 Hz for a time delay of 0.4 seconds.**

   In many of the scenarios studied, while sufficient AUFLS is shed to recover the system, the system collapses due to late AUFLS operation. In particular, the second AUFLS block is set to trip too close to 47 Hz. For events where the initial rate of frequency fall is greater than 2 Hz per second, the frequency has already fallen below 47 Hz by the time the second AUFLS block operates. This is illustrated in Figure 6-11. As 24% of North Island generation is armed to trip at 47 Hz, it is important that AUFLS triggers and operates before the frequency has breached this limit.

3. **Over-voltage issues occur post-event.**

   Most North Island capacitors are switched in under peak load conditions. When significant load shedding occurs following AUFLS operation, there is the potential for over-voltage issues to occur. These over-voltage issues have the potential to collapse the system. While capacitors will switch out on unit protection, a need to move beyond unit protection and toward systematic protection has been identified.

4. **Generator reserves provide less value than IL and AUFLS following an extended contingent event**

   The rapid speed of the frequency fall in the events studied show that generator reserves provide less value to the system than AUFLS and IL following an extended contingent event

   The studies also show that it is possible in extreme cases for AUFLS block 1 to operate at the same time as or even before IL. Given the relatively slow operating time of 1 second, procuring large amounts of IL to cover an ECE may not be as effective as expected when the frequency rate of fall is very fast. As shown in the studies of an AUFLS scheme with an increased contingent event target of 48.5 Hz, there is benefit to be gained by reducing the IL response time from 1 second to 0.5 of a second.

5. **A bi-pole tripping (ECE) is more likely to become the binding risk post pole 3 commissioning**

   The HVDC will be able to transfer up to 1200 MW post pole 3 commissioning. However, given the current AUFLS scheme, it is likely that the System Operator's tools will need to procure more reserve and/or limit the HVDC transfer to ensure that there are sufficient reserves and AUFLS to cover a bi-pole tripping.

To demonstrate the conclusions above, consider figures 6-10 and 6-11. Figures 6-10 and 6-11 illustrate the frequency at which generator reserves (PLSR and TWD), interruptible load and AUFLS blocks 1 and 2 trigger, and the time it takes for each to respond. The frequency at which each responds will depend on the rate of frequency fall. Although the rate of frequency fall is not constant following an event, a constant rate of frequency fall is shown in figures 6-10 and 6-11 for simplicity.

Figure 6-10

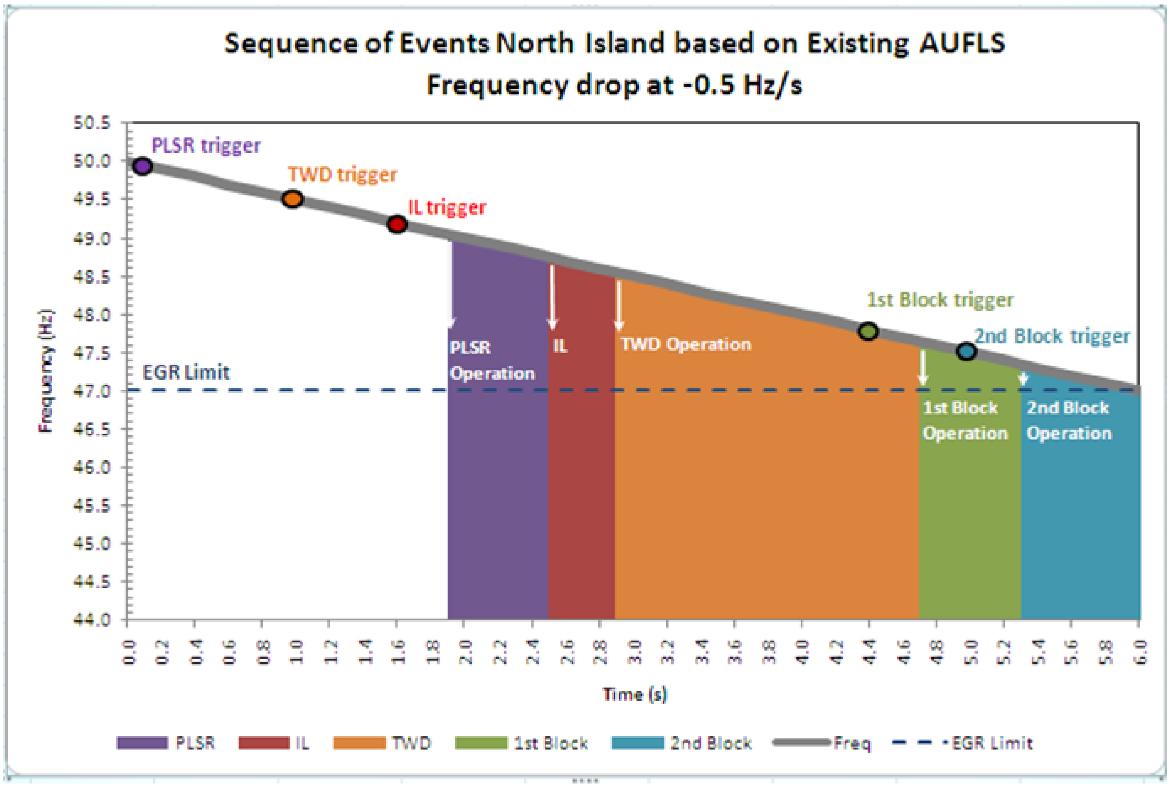


Figure 6-10 can be interpreted as follows:

The grey slope shows the rate of frequency fall. In this example, the rate of frequency fall is -0.5 Hz/s. -0.5 Hz/s means that it takes 2 seconds for the frequency to fall 1 Hz, or 0.2s for the frequency to fall 0.1 Hz. At this rate, the frequency reaches 47 Hz in 6 seconds after the event. The existing reserve management scheme is designed around a frequency rate of fall of this speed.

The trigger points are shown as points on the slope, and the coloured area below the slope shows the point (time and frequency) at which a response is provided.

Under a constant frequency rate of change of -0.5 Hz per second, the following sequence of events occurs:

- PLSR triggers just below 50 Hz
- TWD triggers at a range of frequencies between 49.5 – 49 Hz.
- IL triggers at 49.2 Hz (1.6s after the event)
- PLSR responds between 49 Hz and 48.5 Hz (within 2 – 3 seconds from trigger)
- TWD responds between 48.5 Hz and 47 Hz (within 2-4 seconds from trigger)
- IL operates at 48.7 Hz (2.6s after the event – IL takes 1s to operate)
- AUFLS block 1 triggers at 47.8 Hz (4.4 s after the event)
- AUFLS block 1 operates at 47.6 Hz (4.8 s after the event – AUFLS takes 0.4s to operate)

- AUFLS block 2 triggers at 47.5 Hz (5 s after the event)
- AUFLS block 2 operates at 47.3 Hz (5.4 s after the event).

Figure 6-11

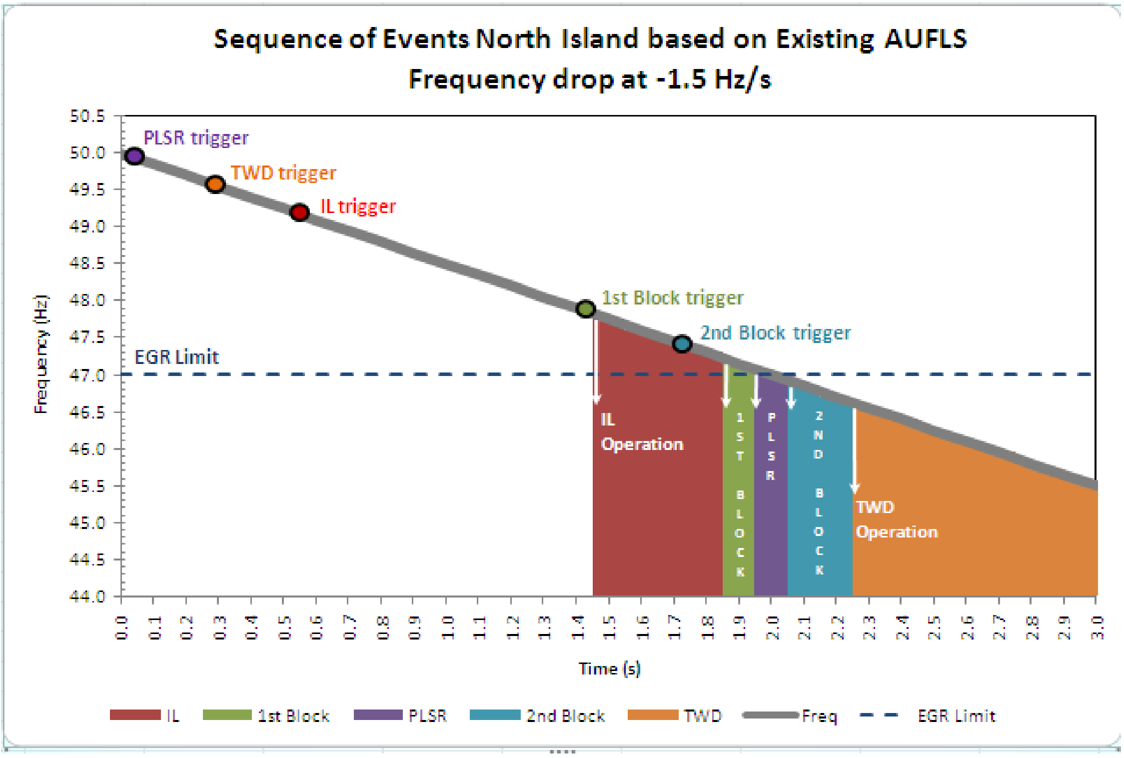


Figure 6-11 can be interpreted as follows:

The grey slope shows the rate of frequency fall. In this example, the rate of frequency fall is -1.5 Hz/s. -1.5 Hz/s means that it takes 0.67 seconds for the frequency to fall 1 Hz, or 0.067s for the frequency to fall 0.1 Hz. At this rate, the frequency reaches 47 Hz in 2 seconds after the event. This rate of fall in frequency was observed in the studies of the existing North Island AUFLS scheme.

Under a constant frequency rate of change of -1.5 Hz per second, the following sequence of events occurs:

- PLSR triggers just below 50 Hz
- TWD triggers at a range of frequencies between 49.5 – 49 Hz
- IL triggers at 49.2 Hz (0.54 s after the event)
- AUFLS block 1 triggers at 47.8 Hz (1.47 s after the event)
- IL operates at 47.7 Hz (1.54 s after the event – IL takes 1s to operate)
- AUFLS block 2 triggers at 47.5 Hz (1.67 s after the event)
- AUFLS block 1 operates at 47.2 Hz (1.87 s after the event – AUFLS takes 0.4s to operate)
- PLSR responds between 47 Hz and 45.5 Hz (within 2 – 3 seconds from trigger)
- AUFLS block 2 operates at 46.9 Hz (2.07 s after the event – this is below the 47 Hz limit).
- TWD responds between 46.5 Hz and 43 Hz (within 2 – 4 seconds from trigger)

This diagram demonstrates that for the rate of frequency fall after an extended contingent event or other large event:

- The AUFLS blocks in the North Island are set to trip too close together
- AUFLS block 2 in the North Island is set to trip is too close to 47 Hz
- IL is slow to respond relative to AUFLS but is fast to respond relative to generator reserves (PLSR and TWD). While there will not be a constant rate of frequency change following an event (i.e. the speed of fall will slow following IL and AUFLS response), this diagram does illustrate that TWD is relatively slow to operate.

6.8.3 Options and Next Steps

The System Operator has identified the following options to address the key issues identified from the North Island studies:

Option 1: Improve the performance of the existing AUFLS scheme in North Island.

Significant gains can be had by better controlling the AUFLS that is currently available. Modifying the number and size of the existing AUFLS blocks and the trip mechanisms and settings for these blocks can significantly improve the performance of the existing AUFLS scheme and produce better outcomes for New Zealand.

When reviewing the existing scheme, there are a number of key considerations that should be taken into account, namely:

- Total size of AUFLS response (percentage of total load shed) is important
- The number and size of the AUFLS blocks (more blocks, smaller in size) can reduce the potential for over-frequency and over-voltage problems.
- The speed of the response is critical.

Each of the points above cannot be considered in isolation, and a combination will provide for the scheme with the best response.

The System Operator will be holding workshops with the industry in August 2010 to discuss the option of modifying the existing AUFLS scheme.

Option 2: Address the over-voltage issues

As mentioned above, a need to move beyond unit protection and toward schematic system protection has been identified. The System Operator will address this issue as a matter of priority and coordinate any action.

The System Operator is also currently testing the Christchurch reactive power control (RPC) under an AUFLS scenario to ensure that it will not contribute to any over-voltage problems.

Option 3: Review the products provided in the North Island reserves market.

The findings of the review illustrate that the existing reserve products do not interact well with AUFLS. These findings demonstrate a need for a review of the reserves market and for an investigation of new reserve products or other markets such as a 3 second reserves market.

The System Operator will be holding workshops with the industry in August 2010 to discuss this option

6.8.4 *North Island Results - Questions and Answers*

Will increasing the total quantity (percentage) of AUFLS improve the existing scheme?

Increasing the total quantity of AUFLS will help system recovery following large events, including rare undefined events, but introduces the problem of over-shedding if the size of the AUFLS blocks are too large.

Over-shedding is undesirable from a system perspective as it will cause the system frequency to rise above 50 Hz. If the frequency rises too high, generators will start to disconnect which increases the risk of system collapse.

Over-shedding is also undesirable from a customer perspective as it means that too many customers are disconnected unnecessarily

Increasing the total quantity of AUFLS without carefully reviewing other parameters (such as the size and number of blocks and their trip settings) has the potential to increase the risk of system collapse on over-frequency.

Will removing North Island AUFLS exemptions improve the existing scheme?

Removing North Island AUFLS exemptions will have the effect of increasing the total quantity (size) of AUFLS. This will not necessarily improve the performance of the AUFLS scheme if other factors are not modified (see above).

Will adding more blocks remove the risk of over-shedding?

Adding more blocks can reduce the potential for over-shedding to occur but does not address the issues of system collapse following insufficient quantity or speed of AUFLS.

Importantly, the potential for over-shedding is only reduced if the additional blocks are set far enough apart. If they are set too close together (as with the current North Island scheme), it is likely that a number of blocks will operate unnecessarily causing too much load to be shed. Adding more blocks without carefully reviewing other parameters (such as trip setting and block size) will not produce results significantly different from the current scheme.

Is it possible for AUFLS to operate faster than 400 milliseconds?

Yes, but the current AUFLS relays are relatively old technology. An operation time of faster than 400 milliseconds given the current technology can lead to more instances of AUFLS triggering unnecessarily (circuit breaker misoperation).

Is it possible for IL to operate faster than 1 second?

Yes, many IL relays do operate faster than 1 second. However, a 1 second IL operation time is the EGR requirement and would require a rule change to be modified. While faster IL has benefits (gives generators more time to respond), tightening the standard may also prevent some providers from participating in the IL market.

7 South Island Results

This section sets out the results of the South Island studies against the 6 scenarios described in table 5-2.

For each of the 6 scenarios, dynamic studies were performed by tripping either the HVDC bi-pole or 3 Manapouri units for each of the following schemes:

- Scheme 1: Operation of the current AUFLS scheme (2 x 16% AUFLS blocks) and where necessary, the effects of additional reserves.
- Scheme 2: New AUFLS scheme – 2 x 16% AUFLS blocks with df/dt acceleration
- Scheme 3: New AUFLS scheme – 4 x 8% AUFLS blocks
- Scheme 4: New AUFLS scheme – 4 x 12% AUFLS blocks and where necessary, the effects of additional reserves

For each scheme, the effect of including an AUFLS response at the Tiwai grid exit point has also been studied.

A performance summary table, chart of frequency traces and detailed discussion is provided for each scheme and scenario in each section below.

7.1 The existing AUFLS scheme and its performance

The technical studies first considered the effectiveness of the current AUFLS scheme in the South Island against the 6 scenarios described in table 5-2. As noted in section 5.4.2, an AUFLS response is not currently provided at the Tiwai grid exit point. This section sets out the details of the existing scheme with and without an AUFLS response at the Tiwai grid exit point. It also sets out the results of the existing scheme after adding extra reserve to prevent the system frequency from falling below 45 Hz.

7.1.1 *The existing scheme*

This section summarises the performance of the existing AUFLS scheme in the South Island against the 6 scenarios described in table 5-2. Detailed load and generation plots can be found in Appendix D Figures 1-6 and the voltage plots can be found in Appendix D Figures 7-12.

Performance Summary Table

Table 7-1 provides a summary of the performance of the existing South Island AUFLS scheme against the 6 scenarios presented in Table 5-2.

Table 7-1 Performance summary of existing AUFLS scheme against 6 scenarios in table 5-2

Scenario	Risk	Disturbance (%)	Initial df/dt (Hz/s)	Min Freq (Hz)	Time to min freq	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Generators tripped on under-frequency	Summary
1	Bi-pole	72.2	-2.4	43.86	4.771s	49.8	46.61	44.74	White Hill Windfarm	System remained intact but minimum frequency of 43.86 Hz is well below the EGR limit of 45 Hz. AUFLS block 2 operates below 45 Hz.
2	Manapouri busbar	40.6	-1.05	46.48	4.573s	50.1	47.02	-	White Hill Windfarm	System remained intact and within EGR frequency limits. 2nd AUFLS block did not trip.
3	Bi-pole	71.7	-3.6	System Collapse			45.8	44.16	System Collapse	System collapse. Insufficient load shed
4	Bi-pole	86.9	-4.5	System Collapse			45.38	43.75	System Collapse	System collapse. Insufficient load shed
5	Manapouri busbar	34.2	-1.6	45.91	7.73s	52.76	47.03	47.3	White Hill Windfarm	System remained intact and within EGR frequency limits. Frequency remained below 47.5Hz for longer than 15s thus the 2nd AUFLS block tripped resulting in over-frequency
6	Manapouri busbar	23.1	-1.56	47.2	3.04s	50.78	46.89	-	-	System remained intact and within the EGR frequency limits. 2nd AUFLS block did not trip

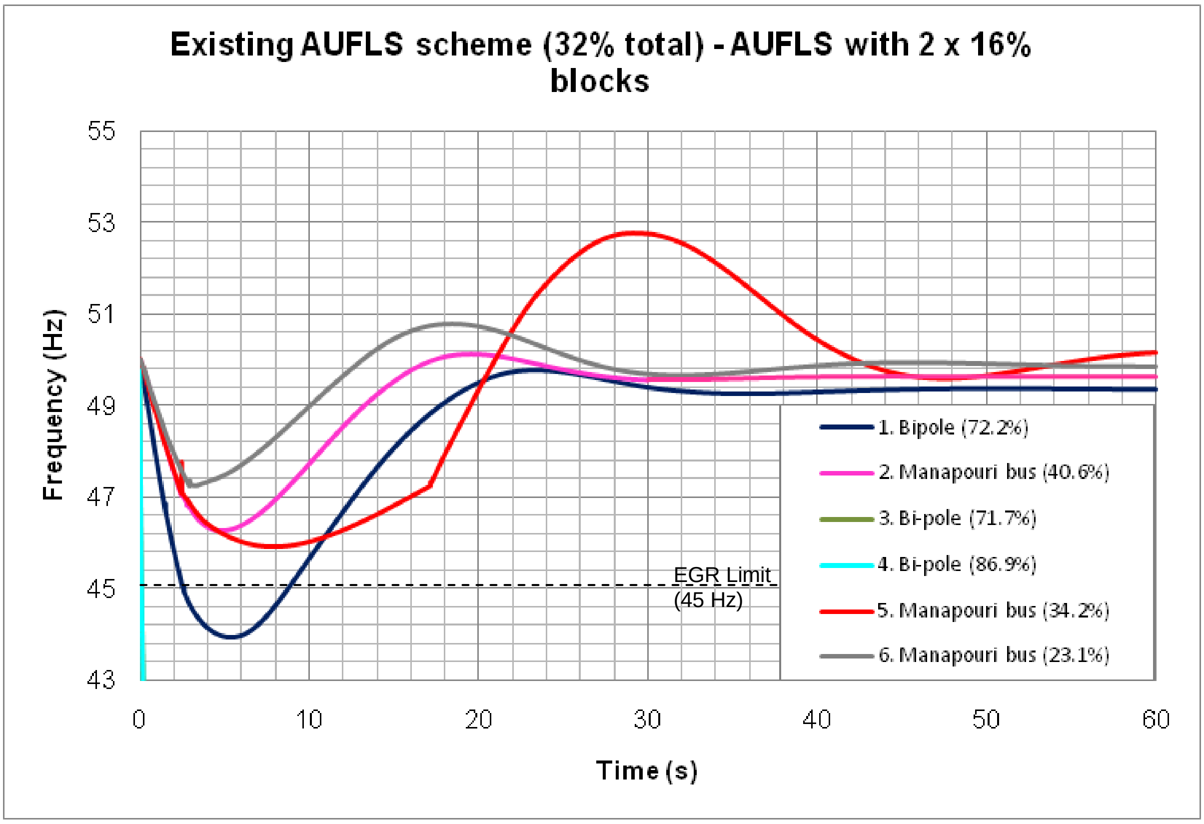
The column annotation for table 7-1 and for the other performance summary tables in section 7 is provided below for clarity:

Scenario:	**Number of the scenario studied as in table 5-2.**
Risk:	The risk. See table 5-2 for a more detailed description of the load and generation conditions.
Disturbance:	Magnitude of the generation loss (from the initial event) as percentage of the load base. The load base is the total island load less the load at any GXP where an AUFLS response is not provided (i.e. the load at the Tiwai GXP is subtracted from the total island load).
Initial df/dt:	The average initial rate of system frequency change.
Min freq:	Minimum average system frequency between 0 to 60 seconds after the first event.
Time to min freq	The average time taken to reach the minimum frequency.
Max freq:	Maximum average system frequency between 0s-60s after the first event.
Freq @ 1st block:	The average system frequency at which the 1st AUFLS block operated.
Freq @ 2nd block	The average system frequency at which the 2nd AUFLS block operated.
Generators tripped on under-frequency:	Sequential tripping of generators on under-frequency protection within 60 seconds of the initial event / generation loss.
Summary:	Summary of results.

Frequency Traces

Figure 7-1 shows the system frequency for each of the 6 scenarios studied against the existing AUFLS scheme (2 x16%). The legend shows the scenario number, risk name and the magnitude of the disturbance.

Figure 7-1 Frequency plot 6 scenario with for existing (2 x16%) AUFLS scheme



Discussion

Studies of the existing AUFLS scheme show that the South Island system collapses or comes close to collapse for all three bi-pole events studied. The system remains intact and within the EGR frequency limits for the remaining three scenarios. Detailed commentary of each scenario is set out below.

The operation of the current AUFLS scheme under scenario 1 results in a minimum frequency of 43.86 Hz. While the total load shed (32%) is less than the size of the disturbance (72.2%), the initial rate of frequency change (-2.4 Hz/s) is such that generators (governors) have time to respond and help recover the system. However, because the minimum EGR frequency limit of 45 Hz is breached and AUFLS block 2 operates below 45 Hz, this scenario came very close to system collapse and cannot be considered an acceptable system response.

The system remains intact for scenario 2 and within the EGR frequency limits. While the disturbance is 40.6% in size, only the first AUFLS block tripped. This is sufficient to recover the system as the lower initial rate of frequency change (-1.05Hz/s) allows enough time for the governors to respond.

In respect of scenarios 3 and 4, the system collapses as the amount of load shed is significantly less than the amount of generation lost. The speed of the fall in frequency is so fast that governors do not have time to respond.

For scenario 5, the maximum frequency exceeds 52 Hz which is permitted in the South Island. The frequency exceeding 52 Hz is a result of over-shedding which is caused by the 2nd AUFLS block tripping at 19 seconds. The 2nd AUFLS block does not trip because the frequency reached 45.5 Hz, but because the frequency stayed at 47.5 Hz for longer than 15 seconds (see the existing AUFLS settings in table 5-8). For scenario 5, having smaller blocks instead of two big blocks would remedy the over-shedding problem.

The existing AUFLS scheme produces an acceptable response for scenario 6 as the system remains intact and within the EGR frequency limits. The existing AUFLS scheme is sufficient in both size and speed for scenario 6.

7.1.2 *The effect of procuring more instantaneous reserves to cover the risk*

While the current AUFLS arrangements do not produce an acceptable system response for the bi-pole tripping scenarios studied (scenarios 1, 3, and 4), the System Operator's tools (RMT and SPD) will ensure that sufficient reserve is procured to ensure that the system frequency does not drop below 45 Hz following a bi-pole tripping. The effect of adding extra reserve for these scenarios was studied. The load and generation plots can be found in Appendix D Figures 13-15 and the voltage plots can be found in Appendix D Figures 16-18.

Performance Summary Table

Table 7-2 provides a summary of the performance of the existing scheme including sufficient reserve procured to ensure that the frequency does not drop below 45 Hz following the bi-pole tripping events presented in table 5-2.

Table 7-2 Performance summary of existing AUFLS scheme with additional reserves

Scenario	Risk	Disturbance (%)	Initial df/dt (Hz/s)	Additional generation capacity (units) added	Min Freq (Hz)	Time to min freq	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Generators tripped on under frequency
1	Bi-pole (400 MW)	72.2	-2.4	1 Manapouri 1 Clyde	45.14	4.1s	49.7	46.76	45.19	White Hill Windfarm
3	Bi-pole (660 MW)	71.7	-3.36	4 Manapouri 3 Clyde 1 Aviemore	45.07	3.9s	49.7	46.67	45.14	White Hill Windfarm
4	Bi-pole (800 MW)	86.9	-4.17	4 Manapouri 3 Clyde 3 Aviemore 3 Ohau A 3 Ohau B	45.04	3.9s	49.5	46.65	45.16	White Hill Windfarm

Frequency Traces

Figures 7-2 to 7-4 show the system frequency for each of the 3 scenarios studied against the existing AUFLS scheme (2 x 16%) with additional reserves procured. Note that fmin is the minimum frequency and tmin is the time taken to reach the minimum frequency.

Figure 7-2 Frequency plot for scenario 1 with additional reserve

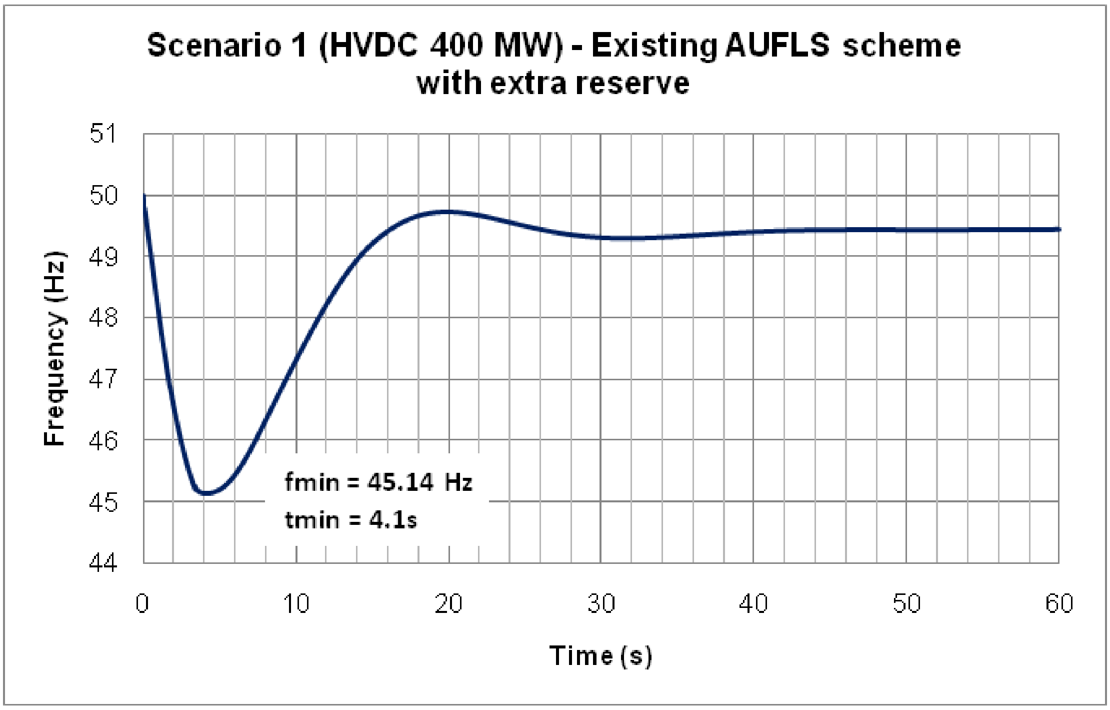


Figure 7-3 Frequency plot for scenario 3 with additional reserve

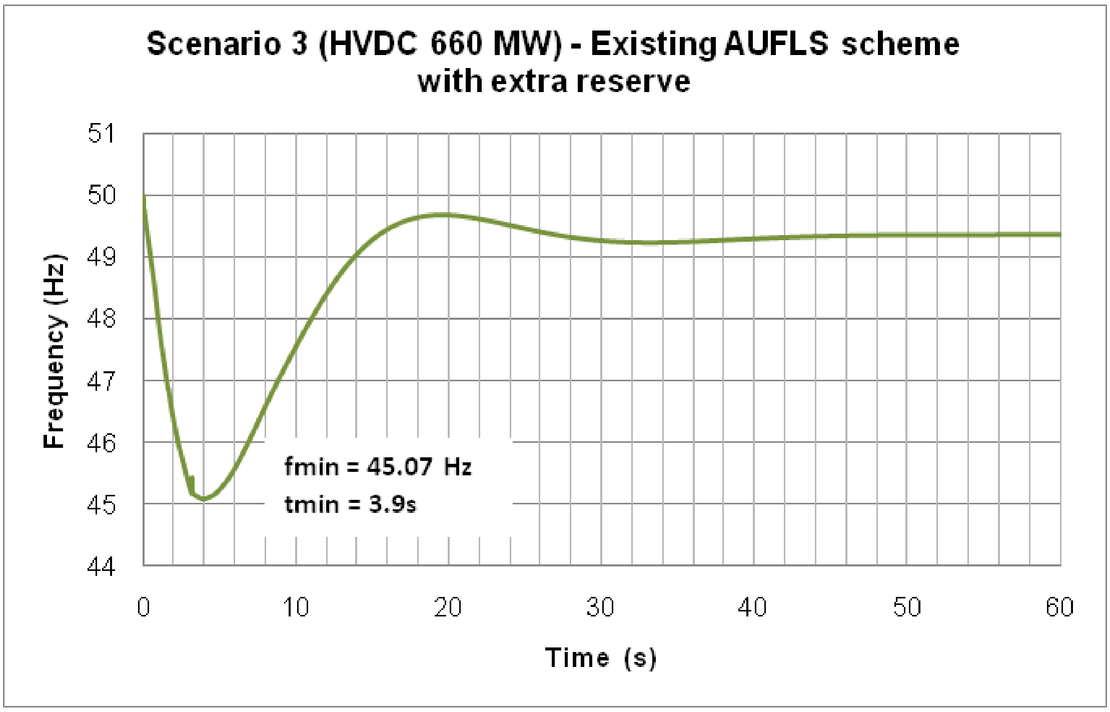
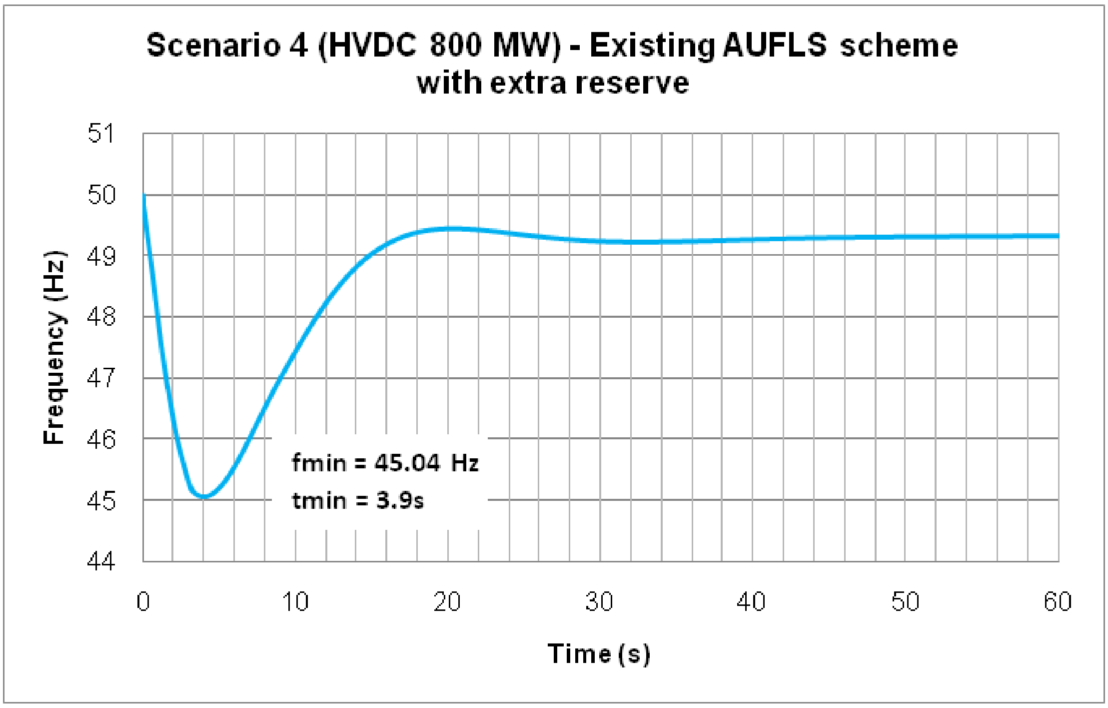


Figure 7-4 Frequency plot for scenario 4 with additional reserve



Discussion

While the system remains intact and within the EGR frequency limits for all 3 scenarios with additional reserves procured, the following conclusions can be made:

- A significant amount of generation capacity needs to be added to the system to ensure that there is sufficient reserve (and AUFLS) available to prevent the system from collapsing. This reserve needs to be in the form of partly loaded spinning reserve (PLSR), not tail water depressed (TWD) reserve as TWD is simply too slow to respond. In the examples above, minimum frequency is reached in around 4 seconds. TWD is triggered at a range of frequencies between 49.5 Hz to 49 Hz and will operate within 2 to 4 seconds. PLSR is triggered just below 50 Hz and will operate within 2 to 3 seconds.
- Almost all large generation units need to be running in the South Island to ensure that there is sufficient partly loaded spinning reserve available to cover a bi-pole tripping when the HVDC is transferring 800 MW or more from North to South under mid load conditions.
- Adding extra units on partly loaded mode is inefficient from a water management perspective. While high HVDC south transfer levels are likely to be required when the South Island lakes are low, running all South Island units in PLSR mode will use water rather than conserve it.

7.1.3 *The effect of including an AUFLS response at the Tiwai GXP*

Currently, no AUFLS response is provided at the Tiwai grid exit point. As the load at Tiwai makes up a significant proportion of the South Island load, the effect of including an AUFLS response at Tiwai was studied to determine whether this would produce a better system response for the scenarios presented in table 5-2. The load and generation plots can be found in Appendix D Figures 19-24 and the voltage plots can be found in Appendix D Figures 25-30.

Performance Summary Table

Table 7-3 provides a summary of the performance of the existing South Island AUFLS scheme with an AUFLS response included at the Tiwai grid exit point against the 6 scenarios presented in Table 5-2. Note that the size of the disturbance is significantly reduced for each scenario[26].

Table 7-3 Performance summary of existing AUFLS scheme with AUFLS response included at Tiwai GXP

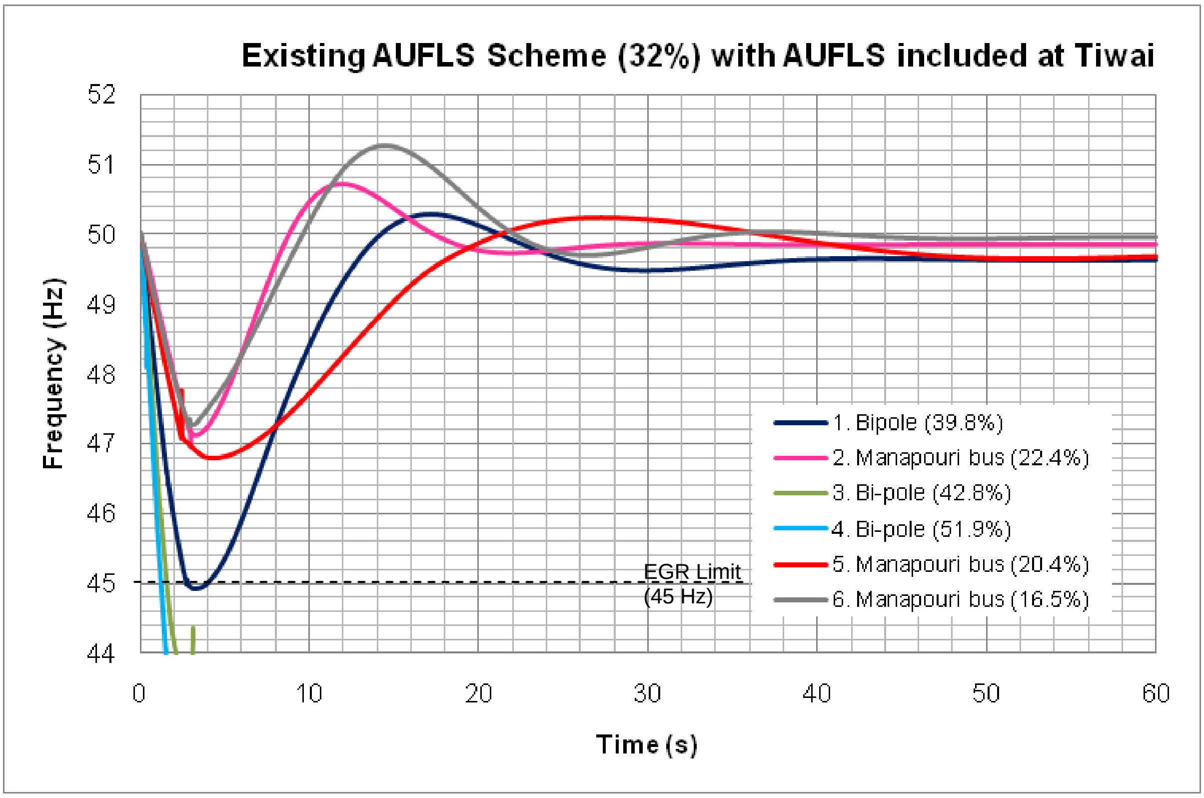
Scenario	Risk	Disturbance (%)	Initial df/dt (Hz/s)	Min Freq (Hz)	Time to min freq	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Generators tripped on under frequency	Summary
1	Bi-pole	39.8	-2.4	44.9	3.2s	50.3	46.58	45.04	White Hill Windfarm	System remained intact but minimum frequency of 44.9 Hz is just below the EGR limit of 45 Hz.
2	Manapouri busbar	22.4	-1.05	47.12	3.2s	50.7	47.15	-	-	System remained intact and within EGR frequency limits. 2nd AUFLS block did not trip.
3	Bi-pole	42.8	-3.6	System Collapse			46.05	44.03	System Collapse	System collapse. Insufficient load shed
4	Bi-pole	51.9	-4.5	System Collapse			45.33	44.58	System Collapse	System collapse. Insufficient load shed
5	Manapouri busbar	20.4	-1.6	46.78	4.3s	50.24	47.05	-	White Hill Windfarm	System remained intact and within EGR frequency limits. 2nd AUFLS block did not trip.
6	Manapouri busbar	16.5	-1.56	47.23	2.9s	51.3	47.22	-	-	System remained intact and within EGR frequency limits. 2nd AUFLS block did not trip.

[26] For example, the disturbance for scenario 1 without AUFLS at Tiwai is 400/(1004-450) = 72.2%. With an AUFLS response at Tiwai the disturbance is 400/1004 = 39.8%

Frequency Traces

Figure 7-5 shows the system frequency for each of the 6 scenarios studied against the existing AUFLS scheme (2 x 16%) with an AUFLS response included at the Tiwai grid exit point.

Figure 7-5 Frequency plot for 6 scenarios with existing (2 x 16%) AUFLS scheme and including an AUFLS response at Tiwai grid exit point



Discussion

Studies of the existing AUFLS scheme with an AUFLS response included at the Tiwai grid exit point show that the South Island system collapses for only two out of the three bi-pole events studied. The system remains intact and within the EGR frequency limits for the remaining three scenarios. Detailed commentary of each scenario is set out below.

For scenario 1, while the system does not collapse, the total quantity of AUFLS is insufficient to prevent the system frequency from falling below 45 Hz. However, the minimum frequency (44.9 Hz) is higher than the results for scenario 1 without an AUFLS response a Tiwai (43.86 Hz). This is expected, as providing an AUFLS response at Tiwai effectively increases the total quantity of AUFLS.

In respect of scenario 2, because the frequency remains above 47 Hz, the White Hill windfarm does not disconnect on under-frequency protection.

As with the studies of the current AUFLS scheme without an AUFLS response at Tiwai, scenarios 3 and 4 result in system collapse since the disturbance is greater than the amount of load shed by AUFLS.

With regard to scenario 5, the over-shedding problem observed in the studies without a response at Tiwai is avoided. This is because the system recovers faster.

Finally, the results for scenario 6 are very similar for the existing AUFLS scheme with and without an AUFLS response at Tiwai. The system remains intact and within the EGR frequency limits for both cases.

7.1.4 *The effect of including an AUFLS response at the Tiwai GXP and procuring extra reserves.*

The effect of adding extra reserve to prevent the system frequency from falling below 45 Hz for the bi-pole tripping scenarios was studied to provide a comparison against the existing scheme with additional reserve but without an AUFLS response at Tiwai. The load and generation plots can be found in Appendix D Figures 31-33 and the voltage plots can be found in Appendix D Figures 34-36.

Performance Summary Table

Table 7-4 provides a summary of the performance of the existing scheme with extra reserve procured and an AUFLS response at the Tiwai GXP against the three bi-pole scenarios in table 5-2.

Table 7-4 Performance summary of existing AUFLS scheme with Tiwai included and with additional reserve

Scenario	Risk	Disturbance (%)	Initial df/dt (Hz/s)	Additional generation capacity (units) added	Min Freq (Hz)	Time to min freq	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Generators tripped on under frequency
1	Bi-pole	39.8	-2.4	1 Manapouri	45.24	3.1s	50.3	46.66	45.23	White Hill Windfarm
3	Bi-pole	42.8	-3.36	4 Manapouri 2 Clyde	45.14	2.9	50.1	46.6	45.15	White Hill Windfarm
4	Bi-pole	51.9	-4.17	4 Manapouri 3 Clyde 3 Ohau A 1 Aviemore	45.07	3.2s	49.7	46.53	45.11	White Hill Windfarm

Frequency Traces

Figures 7-6 to 7-9 show the system frequency for each of the 3 scenarios studied against the existing AUFLS scheme (2 x 16%) with additional reserves procured and an AUFLS response at Tiwai.

Figure 7-6 Frequency plot for scenario 1 withTiwai included & extra reserve

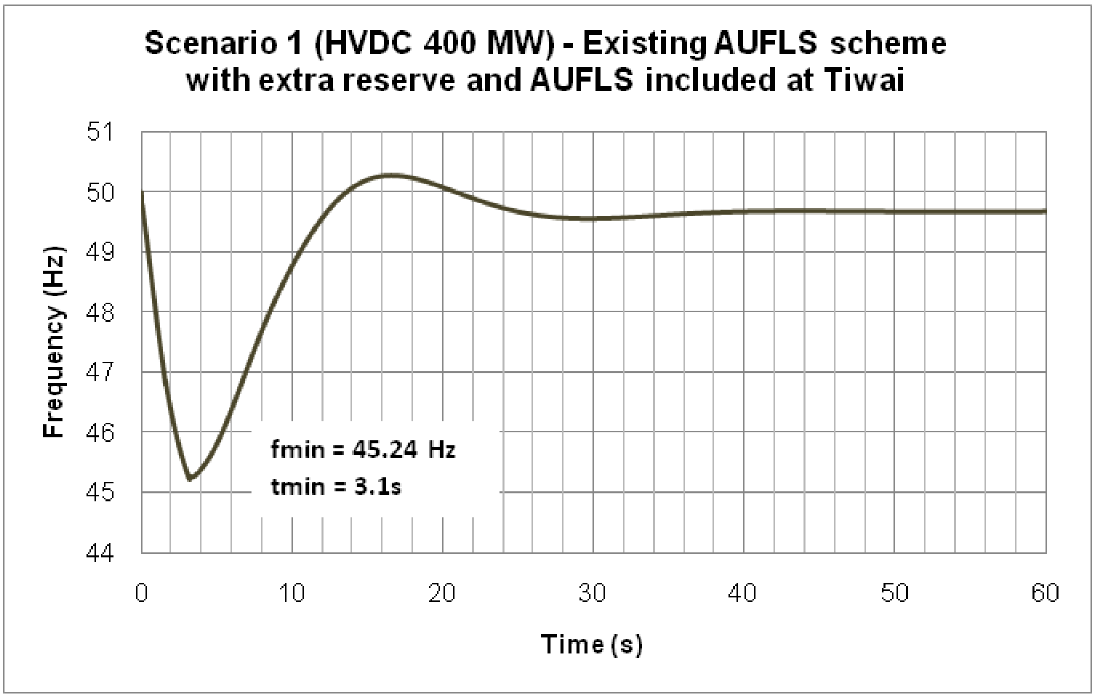


Figure 7-7 Frequency plot for scenario 3 withTiwai included & extra reserve

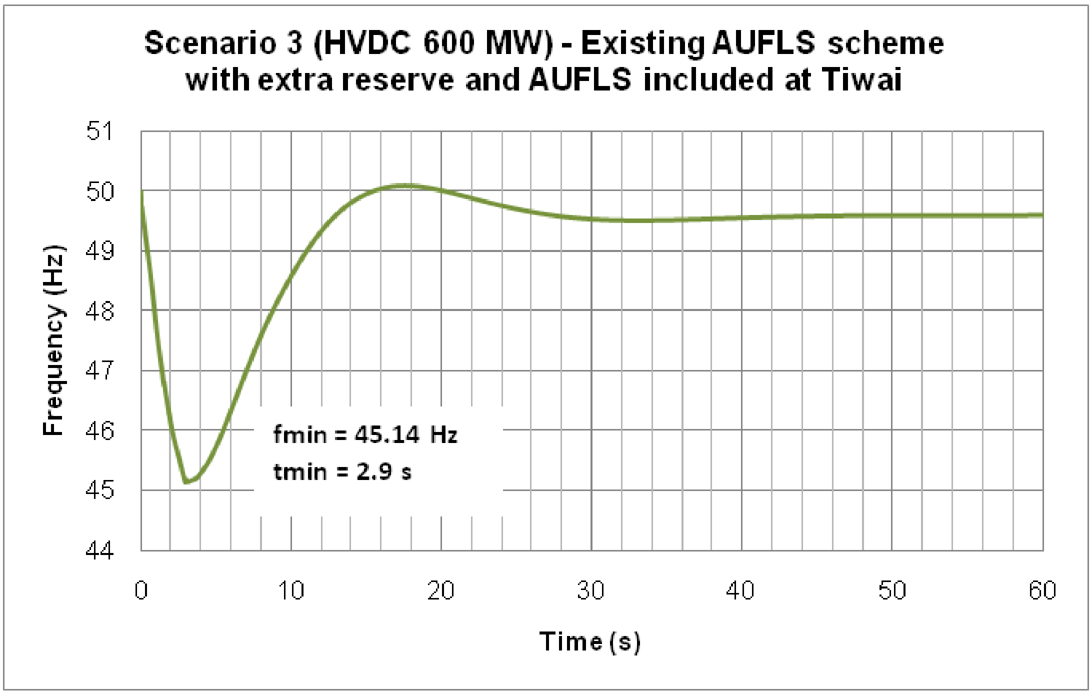
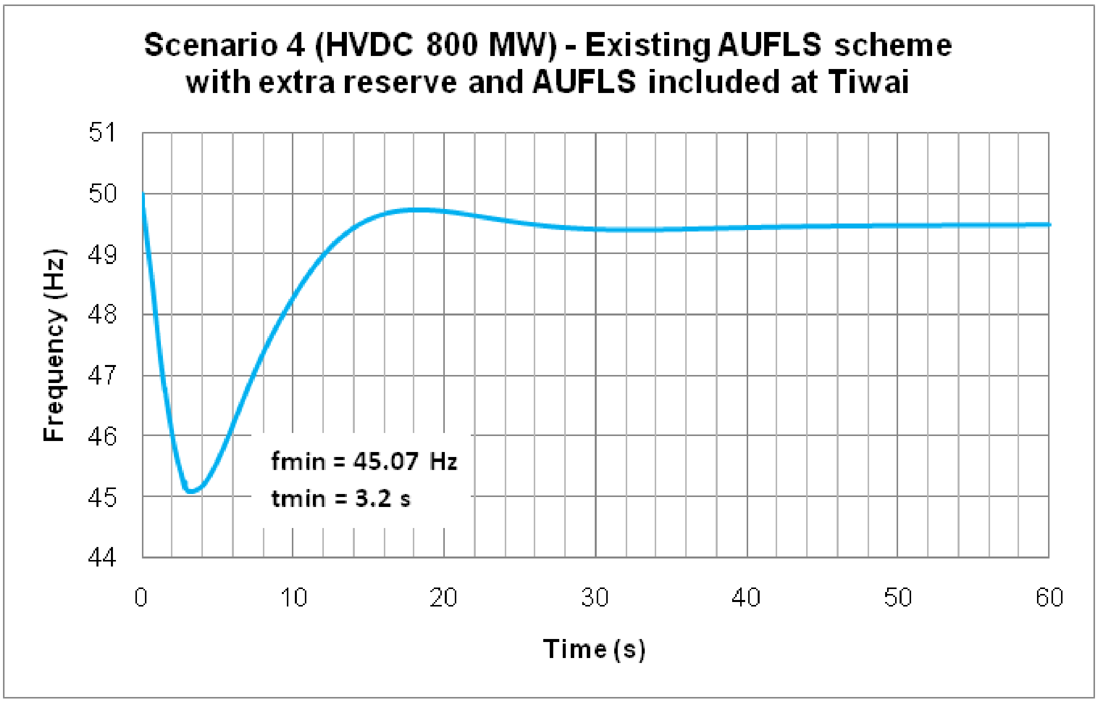


Figure 7-8 Frequency plot for scenario 4 withTiwai included & extra reserve



Discussion

While the system remains intact and within the EGR frequency limits for all 3 scenarios with additional reserves procured and an AUFLS response at Tiwai, the following conclusions can be made:

- Less additional reserve would be required to prevent the system frequency from falling below 45 Hz following a bi-pole tripping.
- While less reserve is required, the amount is still significant

7.2 The effect of incorporating frequency rate of change (df/dt) elements

The results from the North Island studies and the international review of AUFLS events illustrate the importance of speed of the AUFLS response in preventing system collapse. One way to improve the speed of the AUFLS response is to change the trigger mechanism for the AUFLS blocks to trigger on the frequency rate of change (df/dt). See section 6.4 for a more detailed discussion of df/dt elements.

This section summarises the performance of the existing scheme (2 x 16% blocks) but modified to trigger on df/dt elements. This scheme was studied to determine whether increasing the speed of response can improve the overall system response by allowing generators (governors) time to respond.

7.2.1 *The effect of df/dt acceleration*

This section summarises the performance of a 2 x 16% AUFLS scheme with df/dt acceleration against the 6 scenarios described in table 5-2. Detailed load and generation plots can be found in Appendix D Figures 37-42 and the voltage plots can be found in Appendix D Figures 43-48.

Performance Summary Table

Table 7-5 provides a summary of the performance of a 2 x 16% AUFLS scheme with df/dt acceleration against the 6 scenarios presented in Table 5-2.

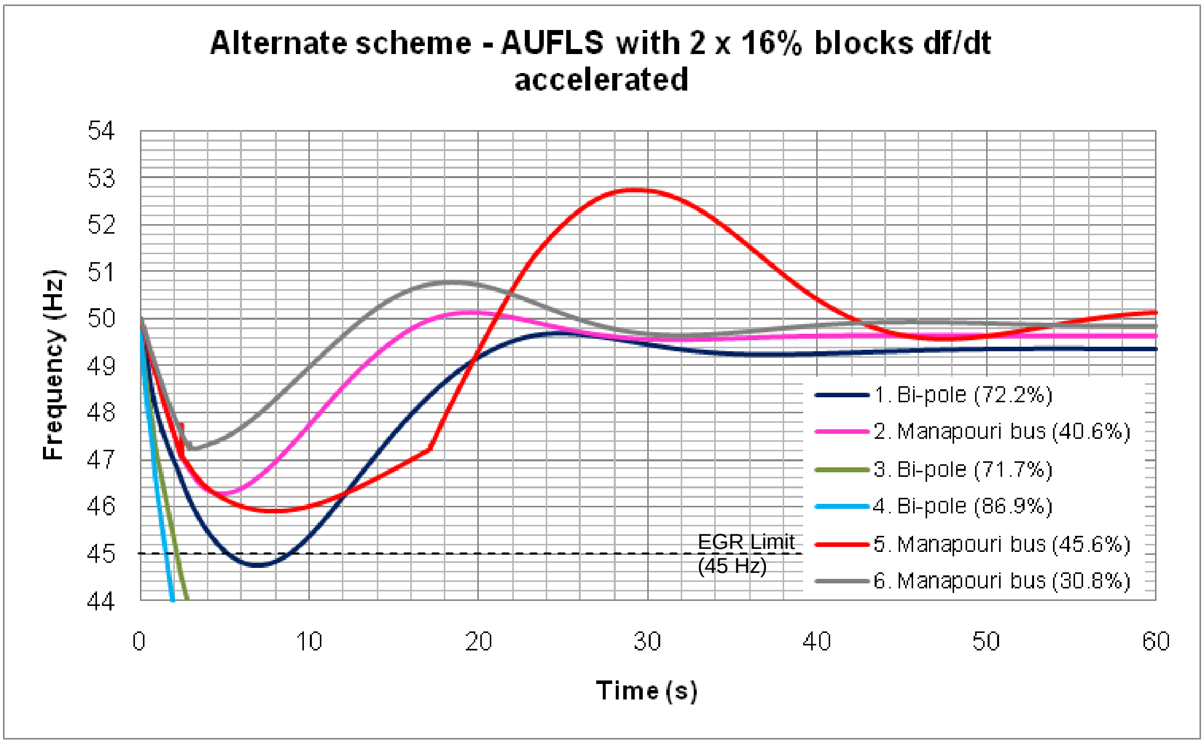
Table 7-5 Performance summary of operation of 2 x 16% AUFLS scheme with df/dt acceleration

Scenario	Risk	Disturbance (%)	Initial df/dt (Hz/s)	Min Freq (Hz)	Time to min freq	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Generators tripped on under frequency	Summary
1	Bi-pole	72.2	-2.4	44.74	6.9s	49.67	48.16	48.16	White Hill Windfarm	System remained intact but minimum frequency of 44.74 Hz is below the EGR limit of 45 Hz. Minimum frequency is higher than under the existing scheme (43.86 Hz)
2	Manapouri busbar	40.6	-1.05	46.27	4.7s	50.13	47.01	-	White Hill Windfarm	System remained intact and within EGR frequency limits. 2nd AUFLS block did not trip. Scheme did not operate on df/dt due to speed of frequency fall. Results are the same as the existing scheme.
3	Bi-pole	71.7	-3.6	System Collapse			47.81	47.81	System Collapse	System collapse. Scheme operates on df/dt triggers, but insufficient load shed
4	Bi-pole	86.9	-4.5	System Collapse			47.54	47.54	System Collapse	System collapse. Scheme operates on df/dt triggers, but insufficient load shed
5	Manapouri busbar	45.6	-1.6	45.91	7.8s	52.76	47.03	47.3	White Hill Windfarm	System remained intact and within EGR frequency limits. Frequency remained at 47.5Hz for longer than 15s thus the 2nd AUFLS block tripped which resulted in over frequency. Scheme did not operate on df/dt despite rate of frequency fall due to errors in the df/dt triggering. Results are the same as the existing scheme
6	Manapouri busbar	30.8	-1.56	47.2	3.04 s	50.78	46.89	-	-	System remained intact and within EGR frequency limits. 2nd AUFLS block did not trip. Scheme does not operate on df/dt.

Frequency Traces

Figure 7- shows the system frequency for each of the 6 scenarios studied against a 2 x 16% AUFLS scheme with df/dt triggers.

Figure 7-9 Frequency plots for AUFLS scheme with df/dt acceleration



Discussion

Studies of a 2 x 16% AUFLS scheme with df/dt triggers show that AUFLS operates on df/dt for only half of the scenarios studied. For the scenarios where AUFLS triggers successfully on df/dt, the system response is improved for only one of the scenarios studied. Detailed commentary of each scenario is provided below.

For scenario 1, the minimum frequency (44.74 Hz) is higher than under the existing scheme (43.86 Hz) as AUFLS is triggered at a higher frequency which allows generators (governors) more time to respond before the system reaches minimum frequency. Although the results are an improvement on the performance of the existing scheme, the frequency still breaches the EGR minimum frequency limit of 45 Hz.

With respect to scenarios 2, 5 and 6, the results are the same as the existing scheme as AUFLS fails to trigger on df/dt elements for these scenarios. The results from these scenarios show that under the conditions studied, the existing AUFLS settings are still required as backup. AUFLS did not trigger on the df/dt settings for these scenarios due to the rate of frequency fall or due to measurement errors with the df/dt elements. See section 6.4 for a more detailed discussion.

The system still collapses under scenarios 3 and 4 due to insufficient quantity of load shed to match the size of the disturbance.

The results from this scheme show that changing the speed of the AUFLS response via df/dt triggers without changing any other variables such as total size or the number of blocks does not produce significantly better results than the existing scheme.

7.2.2 *The effect of a df/dt scheme and including an AUFLS response at the Tiwai GXP*

The effect of including an AUFLS response at Tiwai was studied to determine whether this can improve the performance of the 2 x16% scheme with df/dt acceleration against the six scenarios presented in table 5-2.

Load and generation plots can be found in Appendix D Figures 49-54 and the voltage plots can be found in Appendix D Figures 55-60.

Performance Summary Table

Table 7-6 provides a summary of the performance of a 2 x 16% AUFLS scheme with df/dt acceleration and with an AUFLS response included at the Tiwai GXP against the 6 scenarios presented in Table 5-2

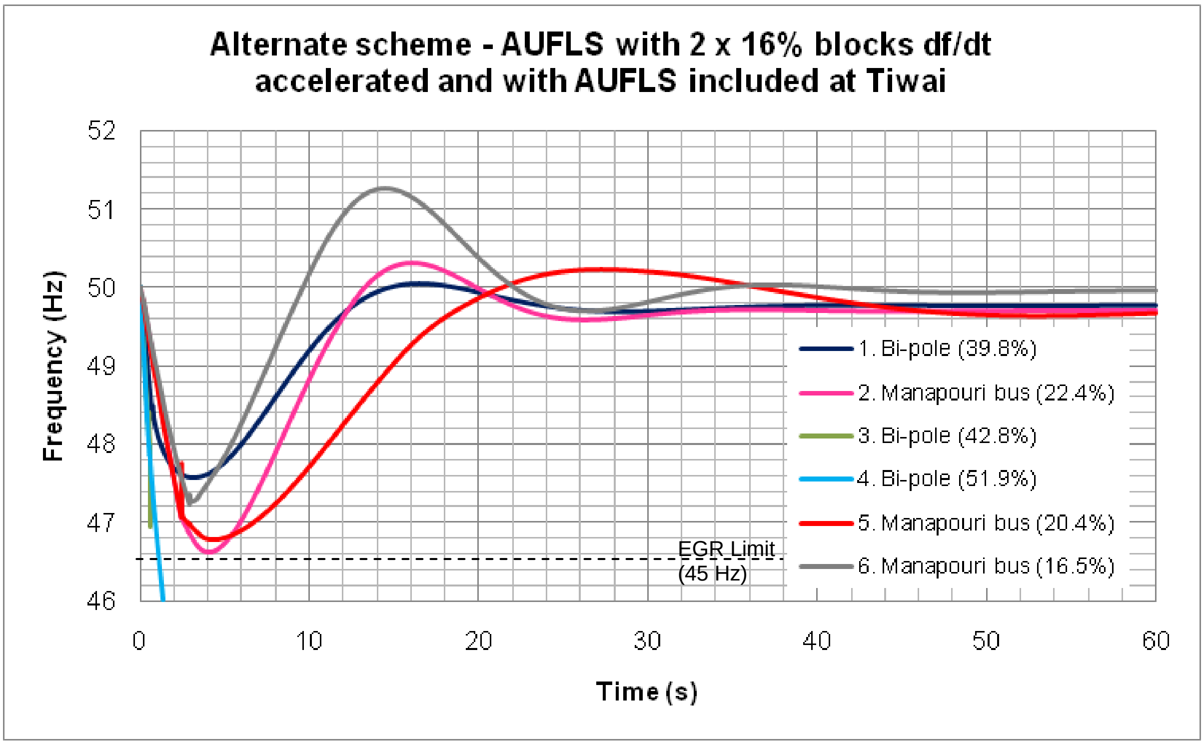
Table 7-6 Performance summary of 2 x 16% AUFLS scheme with df/dt acceleration and a response at Tiwai

Scenario	Risk	Disturbance (%)	Initial df/dt (Hz/s)	Min Freq (Hz)	Time to min freq	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Generators tripped on under frequency	Summary
1	Bi-pole	39.8	-2.4	47.6	3s	50.04	48.27	48.27	-	System remained intact and within EGR frequency limits. Produces much better response than without AUFLS at Tiwai. Minimum frequency is only 47.6 Hz.
2	Manapouri busbar	22.4	-1.05	46.6	4.1s	50.32	47.02	-	White Hill Windfarm	System remained intact and within EGR frequency limits. 2nd AUFLS block did not trip. Scheme does not operate on df/dt. Minimum frequency (46.6 Hz) is slightly higher than without AUFLS at Tiwai (46.27 Hz).
3	Bi-pole	42.8	-3.6	System Collapse			48.03	48.03	System Collapse	System collapse. Scheme operates on df/dt triggers, but insufficient load shed
4	Bi-pole	51.9	-4.5	System Collapse			47.81	47.81	System Collapse	System collapse. Scheme operates on df/dt triggers, but insufficient load shed
5	Manapouri busbar	20.4	-1.6	46.78	4.3s	50.24	47.05	-	White Hill Windfarm	System remained intact and within EGR frequency limits. Scheme does not operate on df/dt but only 1 AUFLS blocks trips (both trip without AUFLS at Tiwai). Produces same result as existing scheme with AUFLS included at Tiwai.
6	Manapouri busbar	16.5	-1.56	47.22	2.95s	51.25	47.22	-	-	System remained intact and within EGR frequency limits. 2nd AUFLS block did not trip. Scheme does not operate on df/dt.. Produces same result as existing scheme with AUFLS included at TWI.

Frequency Traces

Figure 7- shows the system frequency for each of the 6 scenarios studied against a 2 x 16% AUFLS scheme with df/dt triggers and an AUFLS response included at the Tiwai grid exit point.

Figure 7-10 Frequency plots for AUFLS scheme with df/dt acceleration



Discussion

Including an AUFLS response at the Tiwai GXP produces a much better result for scenario 1 under a 2 x 16% df/dt accelerated AUFLS scheme than without AUFLS at Tiwai. Including an AUFLS response at Tiwai effectively increases the total quantity of AUFLS. A consequence of this for scenario 1 is that it allows governors more time to respond and as a result, the minimum frequency of 47.6 Hz is well above the EGR minimum frequency limit of 45 Hz.

However, the scheme does not produce significantly different results for the remaining scenarios.

Since AUFLS with df/dt acceleration with AUFLS at the Tiwai GXP included provided better results than the existing AUFLS scheme for scenario 1, it may be worthwhile to explore the scheme a bit further but the HVDC transfer would have to be limited under scenarios 3 and 4 in order to prevent system collapse for these scenarios under this scheme.

7.3 The effect of increasing the number of blocks

The results from the North Island studies concluded that over-shedding is inefficient and can lead to a risk of system collapse if the magnitude of the over-shedding is significant. The review of international practice also revealed that other systems have more than two AUFLS blocks, and most are 10% or less in size.

This section summarises the performance of a 4 x 8% AUFLS scheme. This scheme was studied to determine whether increasing the number of blocks can improve the overall system response, especially for scenario 5, by better matching the quantity of load shed to the size of the disturbance.

7.3.1 *The effect of more, smaller blocks*

This section summarises the performance of a 4 x 8% AUFLS scheme against the 6 scenarios described in table 5-2. The load and generation plots can be found in Appendix D Figures 61-66 and the voltage plots can be found in Appendix D Figures 67-72.

Performance Summary Table

Table 7-7 provides a summary of the performance of a 4 x 8% AUFLS scheme against the 6 scenarios presented in Table 5-2

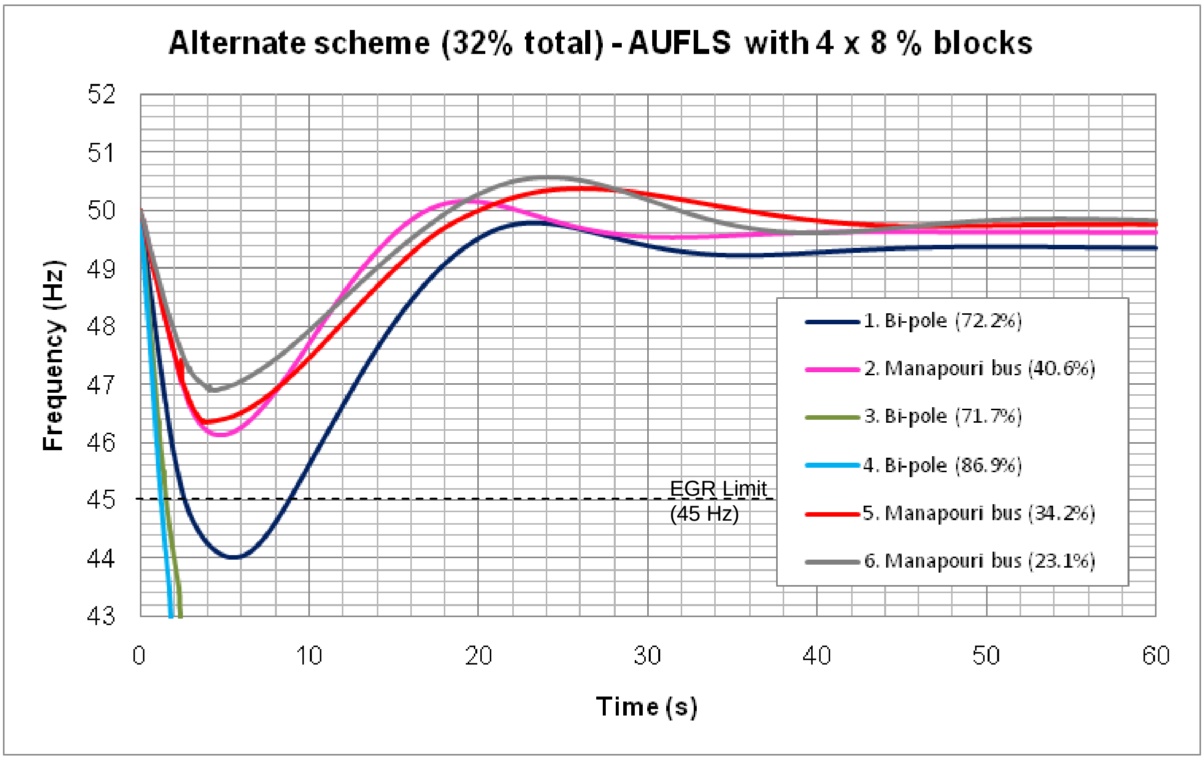
Table 7-7Details of operation of AUFLS scheme with 4 x 8 % blocks

Scenario	Risk	Disturbance (%)	Initial df/dt (Hz/s)	Min Freq (Hz)	Time to min freq	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Freq @ 3rd block (Hz)	Freq @ 4th block (Hz)	Generators tripped on under frequency	Summary
1	Bi-pole	72.2	-2.4	44.0	5.3s	49.8	46.46	46.02	45.64	44.95	White Hill	System remained intact but minimum frequency of 44 Hz is below the EGR limit of 45 Hz. 4th AUFLS block tripped below 45Hz. Results are better than the existing scheme but worse than df/dt scheme studied.
2	Manapouri busbar	40.6	-1.05	46.3 2	3.7s	50.5	46.98	46.59	46.32	-	White Hill	System remained intact and within EGR frequency limits. 3 blocks (24%) of AUFLS tripped. This scheme performs worse than existing scheme as more load is shed and the minimum frequency is lower.
3	Bi-pole	71.7	-3.6	System Collapse			45.84	45.41	45.03	44.30	System Collapse	System collapse. Insufficient load shed
4	Bi-pole	86.9	-4.5	System Collapse			45.42	44.99	44.59	43.85	System Collapse	System collapse. Insufficient load shed
5	Manapouri busbar	34.2	-1.6	46.3 5	3.7	50.38	47.0	46.62	46.34	-	White Hill	System remained intact and within EGR frequency limits. Only 3 AUFLS blocks trip. This scheme performs better than the existing scheme as less load is shed and the minimum frequency is higher. Maximum frequency is lower as there is no over-shedding.
6	Manapouri busbar	23.1	-1.56	46.8 9	4.03 s	50.57	47.18	46.88	-	-	White Hill	System remained intact and within EGR frequency limits. 2 blocks of AUFLS tripped. Same amount of load shed as existing scheme, but minimum frequency is lower. This is because less load is shed at 47.5 Hz.

Frequency Trace

Figure 7-11 shows the system frequency for each of the 6 scenarios studied against a 4 x 8% AUFLS scheme.

Figure 7-11 Frequency plots for AUFLS scheme with 4 x 8 % blocks



Discussion

This scheme provides mixed results when compared to the existing AUFLS scheme. While scenarios 3 and 4 still collapse there are some slight differences in the performance of the other scenarios, but not sufficient to conclude that a 4 x 8% scheme will produce an overall better system response. Detailed commentary of each scenario is provided below.

Since the same amount of load is shed as with the existing AUFLS scheme, scenarios 3 and 4 resulted in system collapse as the amount of load shed (32%) is less than the amount of generation lost.

For scenarios 2 and 6 under a 4 x 8% scheme, these scenarios have a lower minimum frequency than under the existing scheme, and more load is shed for scenario 2 where 24% is shed rather than 16% under the existing scheme.

In respect of scenarios 1 and 5, however, the system response is improved under a 4 x 8% scheme, particularly for scenario 5 where over-shedding is avoided due to only 3 AUFLS blocks tripping (24%). While the same amount of load is shed (32%) for scenario 1, the minimum frequency is slightly higher than under the existing scheme, but is still 1 Hz below the EGR minimum frequency limit of 45 Hz.

Since this scheme is only adequate for scenarios 2, 5 and 6 and does not provide significantly better performance than the existing AUFLS scheme, the results demonstrate that modifying the number and size of AUFLS blocks without taking into account other variables (such as total size or the speed of the AUFLS response) will not produce better results than the existing scheme.

7.3.2 *The effect of more blocks and including an AUFLS response at the Tiwai GXP*

The effect of including an AUFLS response at Tiwai was studied to determine whether this can improve the performance of a 4 x 8% scheme against the six scenarios presented in table 5-2.

The load and generation plots can be found in Appendix D Figures 73-78 and the voltage plots can be found in Appendix D Figures 79-84.

Performance Summary Table

Table 7-8 provides a summary of the performance of the 4 x 8% scheme with an AUFLS response included at the Tiwai GXP against the 6 scenarios presented in Table 5-2

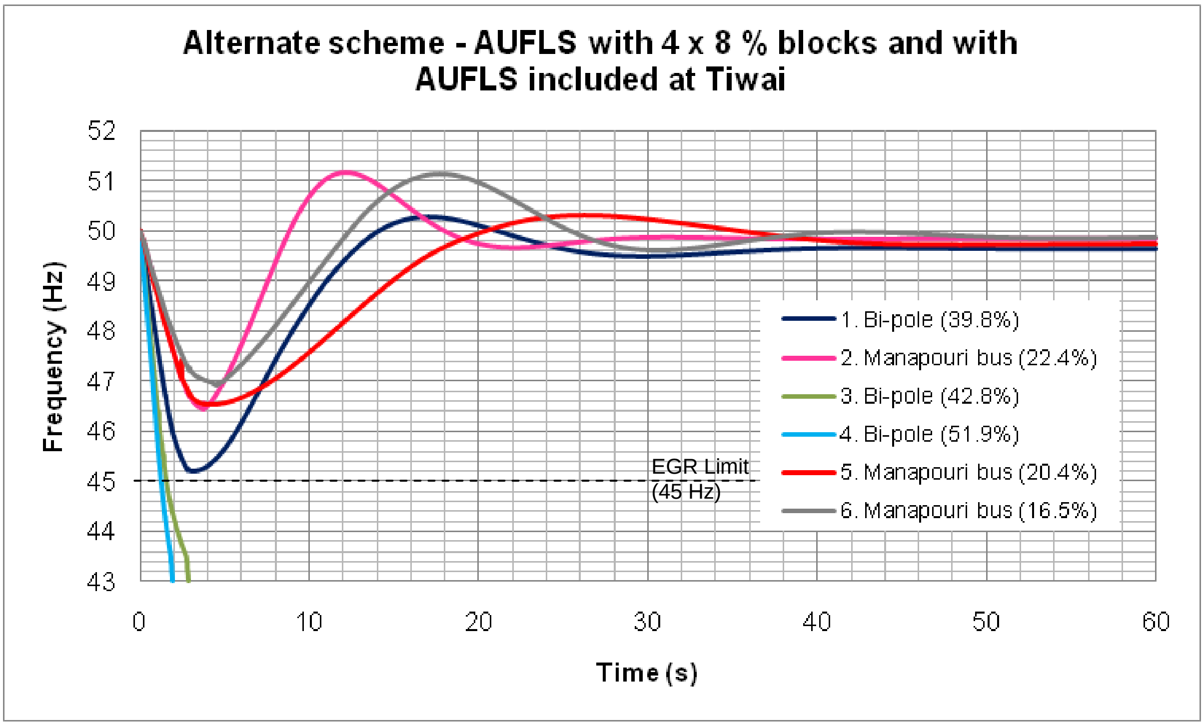
Table 7-8 Performance summary of 4 x 8% AUFLS scheme with df/dt acceleration and a response at Tiwai

Scenario	Risk	Disturbance (%)	Initial df/dt (Hz/s)	Min Freq (Hz)	Time to min freq	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Freq @ 3rd block (Hz)	Freq @ 4th block (Hz)	Generators tripped on under frequency	Summary
1	Bi-pole	39.8	-2.4	45.19	3.14s	50.28	46.48	46.08	45.76	45.22	White Hill Windfarm	System remained intact and within EGR frequency limits.
2	Manapouri busbar	22.4	-1.05	46.43	3.74s	51.16	46.99	46.63	46.45	-	White Hill Windfarm	System remained intact and within EGR frequency limits. 3 blocks (24%) of AUFLS tripped.
3	Bi-pole	42.8	-3.6	System Collapse			45.85	45.43	45.09	44.48	System Collapse	System collapse. Insufficient load shed
4	Bi-pole	51.9	-4.5	System Collapse			45.43	45.02	44.65	44.01	System Collapse	System collapse. Insufficient load shed
5	Manapouri busbar	20.4	-1.6	46.55	4.1s	50.32	47.02	46.69	-	-	White Hill Windfarm	System remained intact and within EGR frequency limits. 2 AUFLS blocks trip.
6	Manapouri busbar	16.5	-1.56	46.94	4.4s	51.2	47.18	46.95	-	-	White Hill Windfarm	System remained intact and within EGR frequency limits. 2 blocks of AUFLS tripped.

Frequency Traces

Figure 7- shows the system frequency for each of the 6 scenarios studied against a 4 x 8% AUFLS scheme with an AUFLS response included at the Tiwai grid exit point.

Figure 7-12 Frequency plots for AUFLS with 4 x 8 % blocks and AUFLS included at Tiwai



Discussion

Overall, a 4 x 8% AUFLS scheme with an AUFLS response at Tiwai performs slightly better than a 4 x 8% scheme without an AUFLS response at Tiwai, but much the same as the existing scheme (2 x 16%) with an AUFLS response at Tiwai. Detailed commentary of each scenario is provided below.

Compared to the existing AUFLS scheme with Tiwai included, the same amount of load is shed in scenarios 1, 5 and 6 and 3 blocks (24%) are shed in scenario 5 compared to 16% with the existing AUFLS scheme with Tiwai included.

Scenarios 3 and 4 resulted in system collapse as before due to the amount of load shed (32 %) being less than the amount of generation lost.

This scheme does not provide significantly better performance than the existing AUFLS scheme. Since this scheme is only adequate for scenarios 1, 2, 5 and 6 and since it would require a considerable amount of additional reserve to cover scenarios 3 and 4, the results show that increasing the number of AUFLS blocks while keeping other variables (such as the total quantity of AUFLS and the speed of the response) the same will not produce better results than the existing scheme.

The results from sections 7.1 to 7.2 also show that a block size of 16% does not result in significant over-frequency issues for the scenarios studied. The highest frequency in the scenarios and schemes studied is 52.76 Hz (scenario 5 under the existing scheme). While 52.76 Hz is high, this is well within the EGR frequency limit of 55 Hz for the South Island.

7.4 The effect of increasing the total quantity of AUFLS

The results of the AUFLS schemes studied in sections 7.1 to 7.3 illustrate the importance of the size of the AUFLS response in the South Island. While including an AUFLS response at the Tiwai grid exit point improves the response of all the schemes studied, the results also show that an AUFLS scheme of greater than 32% is needed. Analysis also determined that up to approximately 50% of load can be shed in the South Island without causing significant over-voltage issues.

7.4.1 *The effect of increasing the number of blocks and the total quantity of AUFLS*

This section summarises the performance of a 4 x 12% AUFLS scheme against the 6 scenarios described in table 5-2. The load and generation plots can be found in Appendix D Figures 85-90 and the voltage plots can be found in Appendix D Figures 91-96.

Performance Summary Table

Table 7-9 provides a summary of the performance of a 4 x 12% AUFLS scheme against the 6 scenarios presented in Table 5-2.

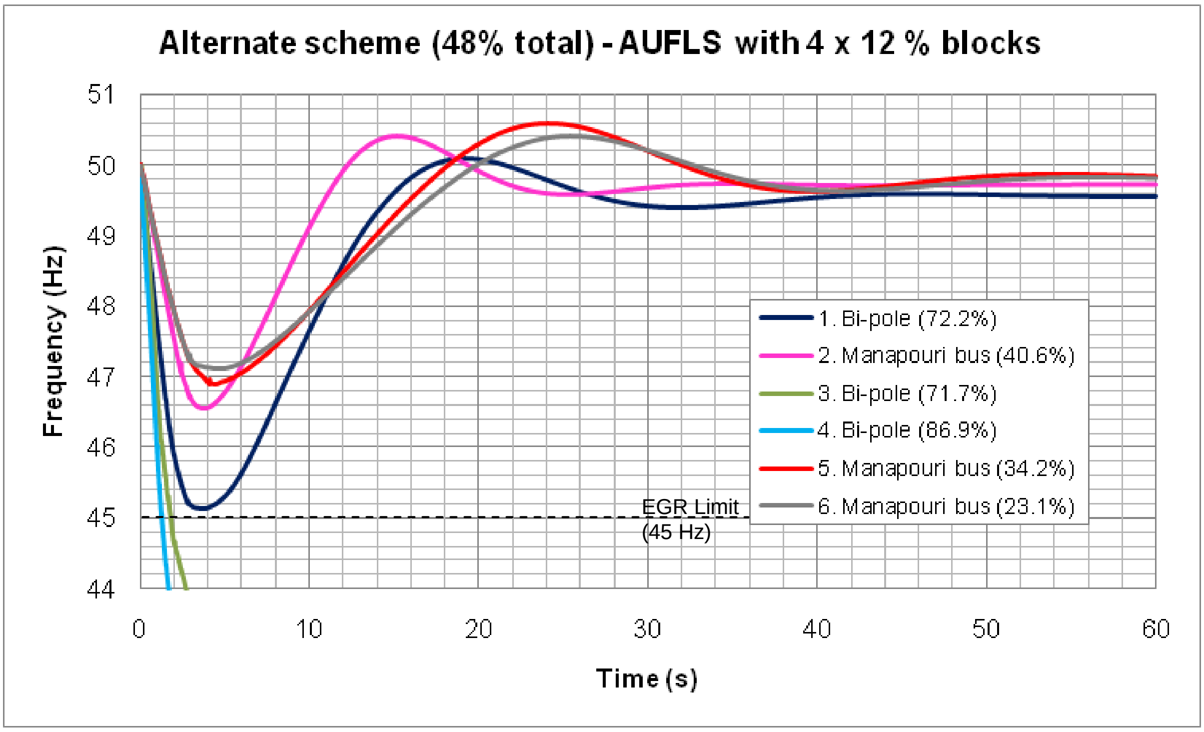
Table 7-9 Details of operation of AUFLS scheme with 4 x 12 % blocks

Scenario	Risk	Disturbance (%)	Initial df/dt (Hz/s)	Min Freq (Hz)	Time to min freq	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Freq @ 3rd block (Hz)	Freq @ 4th block (Hz)	Generators tripped on under frequency	Summary
1	Bi-pole	72.2	-2.4	45.13	3.4s	50.1	46.48	46.09	45.78	45.19	White Hill Windfarm	System remained intact and within EGR frequency limits. All blocks tripped (48%). Minimum frequency of 45.13 Hz is much better than the minimum frequency produced under the existing scheme (43.86 Hz)
2	Manapouri busbar	40.6	-1.05	46.56	3.7s	50.4	46.99	46.68	-	-	White Hill Windfarm	System remained intact and within EGR frequency limits. Only 2 AUFLS blocks (24%) tripped. This is more than the existing scheme where only 1 AUFLS block tripped (16%)
3	Bi-pole	71.7	-3.6	System Collapse			45.78	45.38	45.07	44.56	System Collapse	System collapse. Insufficient load shed.
4	Bi-pole	86.9	-4.5	System Collapse			45.44	45.05	44.7	44.11	System Collapse	System collapse. Insufficient load shed.
5	Manapouri busbar	34.2	-1.6	46.6	3.9s	50.3	47.02	46.7	-	-	White Hill Windfarm	System remained intact and within EGR frequency limits. Only 2 AUFLS blocks (24%) tripped compared with 32% under the existing scheme. No over-shedding.
6	Manapouri busbar	23.1	-1.56	47.12	4.1s	50.4	47.19	-	-	-	-	System remained intact and within EGR frequency limits. Only 1 AUFLS block (12%) tripped. Results are better than the existing scheme as less load tripped in total.

Frequency Trace

Figure 7- shows the system frequency for each of the 6 scenarios studied against a 4 x 12% AUFLS scheme.

Figure 7-13 Frequency plots for AUFLS scheme with 4 x 12 % blocks



Discussion

A 4 x 12% AUFLS scheme performs the best of all the schemes studied without an AUFLS response at Tiwai. Although two scenarios still collapse under this scheme, the frequency recovers before the 45 Hz limit is reached for the remaining scenarios and over-shedding is also avoided. Detailed commentary of each scenario is set out below.

In respect of scenario 1, all four AUFLS blocks tripped. As 48% of load is shed, the frequency is maintained within the EGR limit of 45 Hz. This is the only scheme studied (when not taking into account an AUFLS response at Tiwai or extra reserves) that manages to keep the frequency above 45 Hz for scenario 1.

When compared with the existing scheme, scenarios 5 and 6 also perform better under a 4 x 12%. Less load is tripped for these scenarios, and over-shedding is also avoided for scenario 5. The maximum frequency in scenario 5 reaches 50.3 Hz under the 4 x 12% scheme compared with 52.76 Hz under the existing (2 x 16%) scheme.

The system remained intact and within the EGR frequency limits for scenario 2.

However, scenarios 3 and 4 result in system collapse as 48% AUFLS is still insufficient to counter the amount of generation lost.

This scheme overall performs better than the existing AUFLS scheme and the AUFLS scheme with 4 x 8 % blocks since it secures the South Island system for four of the six scenarios studied. Having more load available to be shed by AUFLS together with having more blocks available would be advantageous especially during high HVDC south transfer and having more blocks would prevent over-shedding. Running the HVDC as high as simulated in scenarios 3 and 4 should be given special consideration before implementation since quick analysis showed that more than 80 % load will have to be shed under scenario 4 in order to cover the loss of the HVDC bi-pole under this scenario.

7.4.2 *The effect of procuring more instantaneous reserves to cover the risk*

While a 4 x 12% AUFLS scheme is insufficient to prevent scenarios 3 and 4 from collapse, this problem can be addressed by either procuring additional reserve under high HVDC transfer scenarios or by not allowing the HVDC to run this high. The effect of adding extra reserve for scenarios 3 and 4 under a 4 x 12% AUFLS scheme was studied.

The load and generation plots can be found in Appendix D Figures 97-98 and the voltage plots can be found in Appendix D Figures 99-100.

Performance Summary Table

The effects of adding extra reserve for scenarios 3 and 4 were studied and details of the results are shown in Table 7-10.

Table 7-10 Details of operation of AUFLS scheme with 4 x 12 % blocks for scenarios 3 & 4 with extra reserve

Scenario	Risk	Disturbance (%)	Initial df/dt (Hz/s)	Additional generation capacity (units) added	Min Freq (Hz)	Time to min freq	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Freq @ 3rd block (Hz)	Freq @ 4th block (Hz)	Generators tripped on under frequency
3	Bi-pole (660 MW)	71.7	-3.36	3 Manapouri 2 Clyde	45.20	3.2s	50.1	46.46	46.08	45.78	45.24	White Hill Windfarm
4	Bi-pole (800 MW)	86.9	-4.17	4 Manapouri 3 Clyde 3 Ohau A	45.12	3.5s	49.7	46.5	46.09	45.77	45.2	White Hill Windfarm

Frequency Trace

Figure 7-2 and

Figure 7-4 show the system frequency for scenarios 3 and 4 against a 4 x 12% AUFLS scheme with additional reserves procured.

Figure 7-14 Frequency plot for scenario 3 with additional reserve

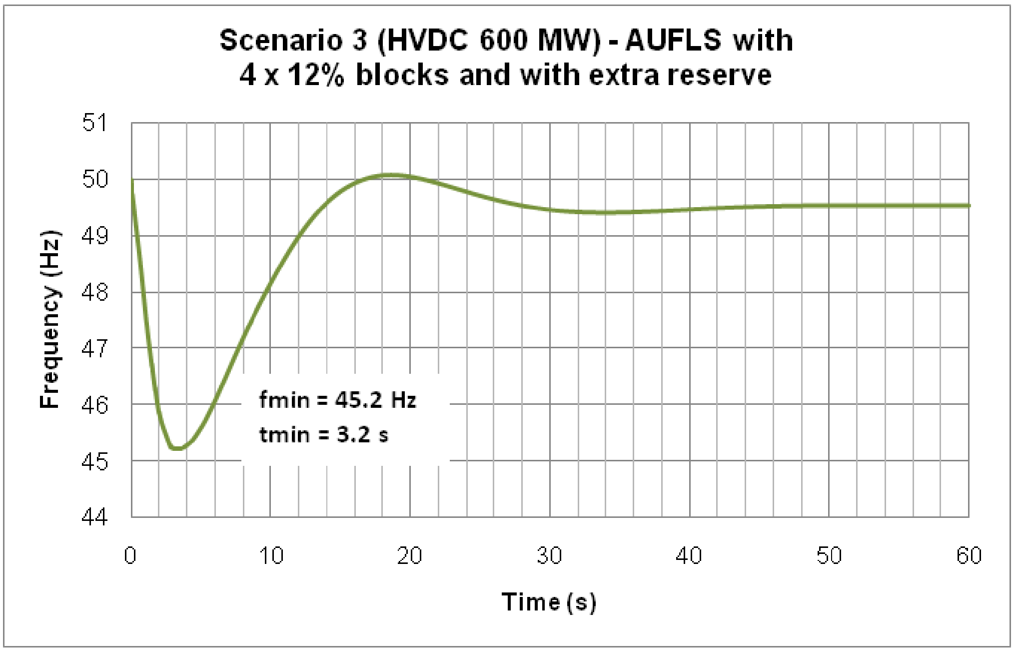
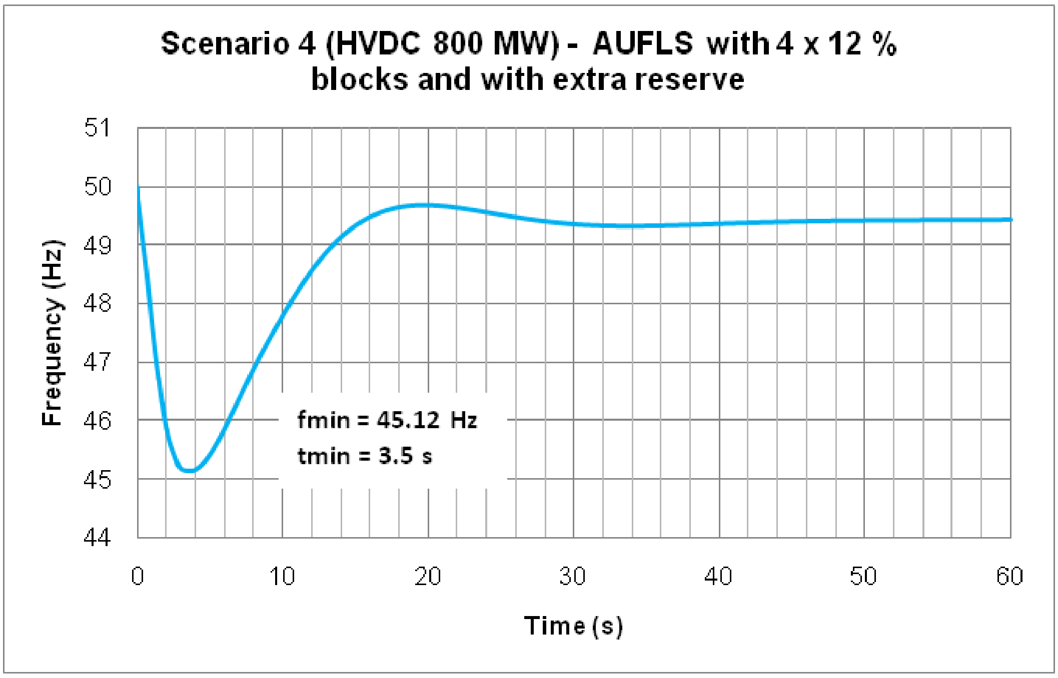


Figure 7-15 Frequency plot for scenario 4 with additional reserve



Discussion

While the system remains intact and within the EGR frequency limits for both scenarios with additional reserves procured, the following conclusions can be made:

- A significant amount of generation capacity needs to be added to the system to ensure that there is sufficient reserve (and AUFLS) available to prevent the system from collapsing, although less reserve is required than under the existing 2 x 16% AUFLS scheme.
- Additional reserves need to be in the form of partly loaded spinning reserve (PLSR), not tail water depressed (TWD) reserve as TWD is simply too slow to respond. In the examples above, minimum frequency is reached in 3.5 seconds or less. TWD is triggered at a range of frequencies between 49.5 Hz to 49 Hz and will operate within 2 to 4 seconds. PLSR is triggered just below 50 Hz and will operate within 2 to 3 seconds.
- Adding extra units on partly loaded mode is inefficient from a water management perspective. While high HVDC south transfer levels are likely to be required when the South Island lakes are low, running all South Island units in PLSR mode will use water rather than conserve it.

7.4.3 *The effect of increasing the total quantity of AUFLS and including an AUFLS response at the Tiwai GXP*

The effect of including an AUFLS response at Tiwai was studied to determine whether this can improve the performance of the 4 x12% scheme with against the six scenarios presented in table 5-2.

The load and generation plots can be found in Appendix D Figures 101-106 and the voltage plots can be found in Appendix D Figures 107-112.

Performance Summary Table

Table 7-11 provides a summary of the performance of a 4 x 12% AUFLS scheme with an AUFLS response included at the Tiwai GXP against the 6 scenarios presented in Table 5-2

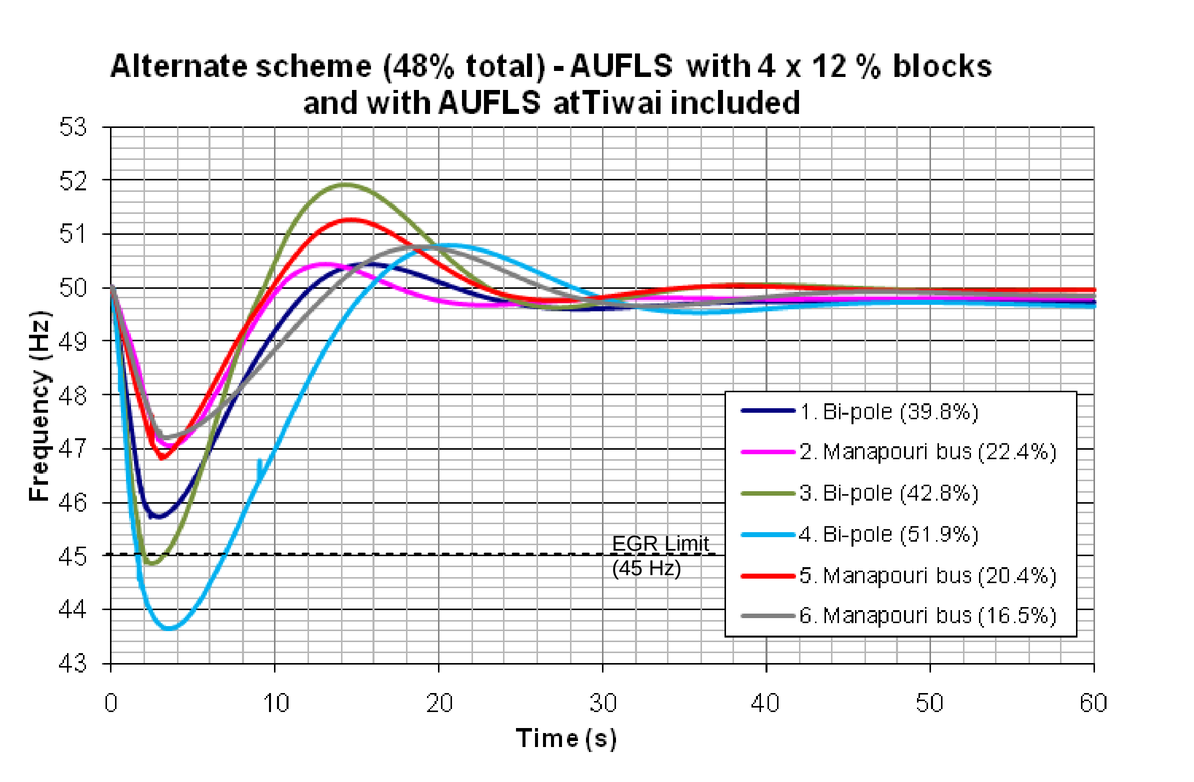
Table 7-11 Details of operation of AUFLS with 4 x 12 % blocks with Tiwai included

Scenario	Risk	Disturbance (%)	Initial df/dt (Hz/s)	Min Freq (Hz)	Time to min freq	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Freq @ 3rd block (Hz)	Freq @ 4th block (Hz)	Generators tripped on under frequency	Summary
1	Bi-pole	39.8	-2.4	45.73	2.7s	50.4	46.59	46.14	45.93	-	White Hill Windfarm	System remains intact and within EGR frequency limits. Only 3 AUFLS blocks (36%) trips compared with 4 blocks without AUFLS at Tiwai.
2	Manapouri busbar	22.4	-1.05	47.06	3.4s	50.4	47.16	-	-	-	None	System remains intact and within EGR frequency limits. Only 1 AUFLS block (12%) trips compared with 2 blocks without AUFLS at Tiwai.
3	Bi-pole	42.8	-3.6	44.9	1.9s	51.9	46.07	45.51	45.2	44.96	White Hill Windfarm	System remains intact but the minimum frequency is below 45 Hz. AUFLS block 4 trips below 45 Hz.
4	Bi-pole	51.9	-4.5	43.63	2.7s	50.8	45.68	45.12	44.66	44.24	White Hill Windfarm	System remains intact but the minimum frequency is over 1 Hz below the EGR limit of 45 Hz. AUFLS blocks 3 and 4 trip below 45 Hz.
5	Manapouri busbar	20.4	-1.6	46.81	2.98s	51.3	47.03	46.82	-	-	White Hill Windfarm	System remains intact and within the EGR frequency limits. Maximum frequency is 1 Hz higher than without an AUFLS response at Tiwai.
6	Manapouri busbar	16.5	-1.56	47.18	3.3s	50.7	47.2	-	-	-	-	System remains intact and within EGR frequency limits. Only 1 AUFLS block (12%) trips compared with 2 blocks (24%) without AUFLS at Tiwai.

Frequency Trace

Figure 7- shows the system frequency for each of the 6 scenarios studied against a 4 x 12% AUFLS scheme with an AUFLS response included at the Tiwai grid exit point.

Figure 7-16 Frequency plots for AUFLS scheme with df/dt acceleration



Discussion

A 4 x 12% AUFLS scheme with an AUFLS response included at the Tiwai grid exit point results in the system remaining intact for all scenarios, although the minimum frequency for scenarios 3 and 4 is below the EGR limit of 45 Hz. Detailed commentary of each scenario is provided below.

Including an AUFLS response at the Tiwai GXP results in less AUFLS blocks tripping for scenarios 1, 2 and 6 when compared with a 4 x 12% scheme without an AUFLS response at Tiwai. This is because including an AUFLS response at the Tiwai GXP effectively increases the total amount of AUFLS.

In respect of scenario 5, the system remains intact and within the EGR frequency limits.

For scenarios 3 and 4 the minimum EGR frequency limit of 45 Hz is breached. In these scenarios, AUFLS blocks 3 and 4 operate below 45 Hz. Moving the trip frequency for blocks 3 and 4 to trigger at a higher frequency (further from 45 Hz) may improve the system response and help to maintain the frequency within the EGR limits. Procurement of additional reserve is another possible solution.

7.4.4 *The effect of including an AUFLS response at the Tiwai GXP and procuring extra reserves.*

While a 4 x 12% AUFLS scheme with an AUFLS response at the Tïwai GXP does not prevent scenarios 3 and 4 from breaching the EGR minimum frequency limit of 45 Hz, the problem can be addressed by either procuring additional reserve under high HVDC transfer scenarios or by not allowing the HVDC to run this high. The effect of adding extra reserve for scenarios 3 and 4 under a 4 x 12% AUFLS scheme with AUFLS included at Tiwai was studied.

The load and generation plots can be found in Appendix D Figures 113-114 and the voltage plots can be found in Appendix D Figures 115-116.

Performance Summary Table

The effects of adding extra reserve for scenarios 3 and 4 were studied and details of the results are shown in Table 7-12.

Table 7-12 Details of operation of AUFLS with 4 x 12 % blocks for scenarios 3 & 4 with Tiwai included & extra reserve

Scenario	Disturbance (%)	Initial df/dt (Hz/s)	Additional generation capacity added	Min Freq (Hz)	Time to min freq	Max Freq (Hz)	Freq @ 1st block (Hz)	Freq @ 2nd block (Hz)	Freq @ 3rd block (Hz)	Freq @ 4th block (Hz)	Generators tripped on under frequency
3	42.8	-3.36	1 CYD	45.07	1.9s	51.8	46.00	45.64	45.43	45.11	White Hill windfarm
4	51.9	-4.17	3 MAN 2 CYD	45.17	2.3s	50.7	46.2	45.8	45.58	45.16	White Hill windfarm

Frequency Traces

Figure 7-2 and

Figure 7-4 show the system frequency for scenarios 3 and 4 against a 4 x 12% AUFLS scheme with additional reserves procured and an AUFLS response included at Tiwai.

Figure 7-17 Frequency plot for scenario 3 with Tiwai included & extra reserve

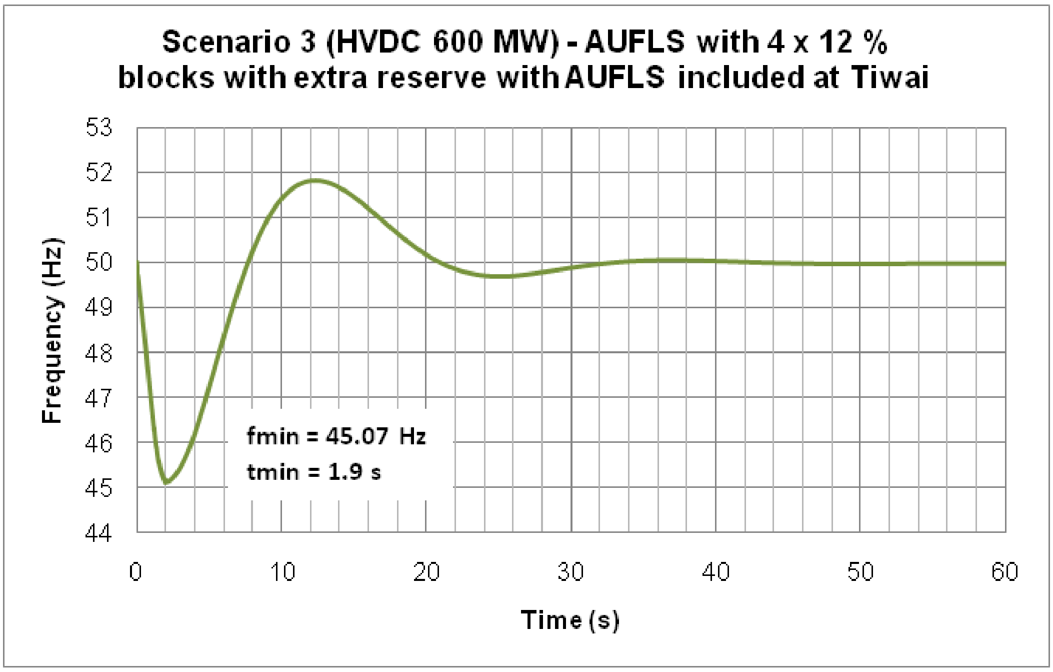
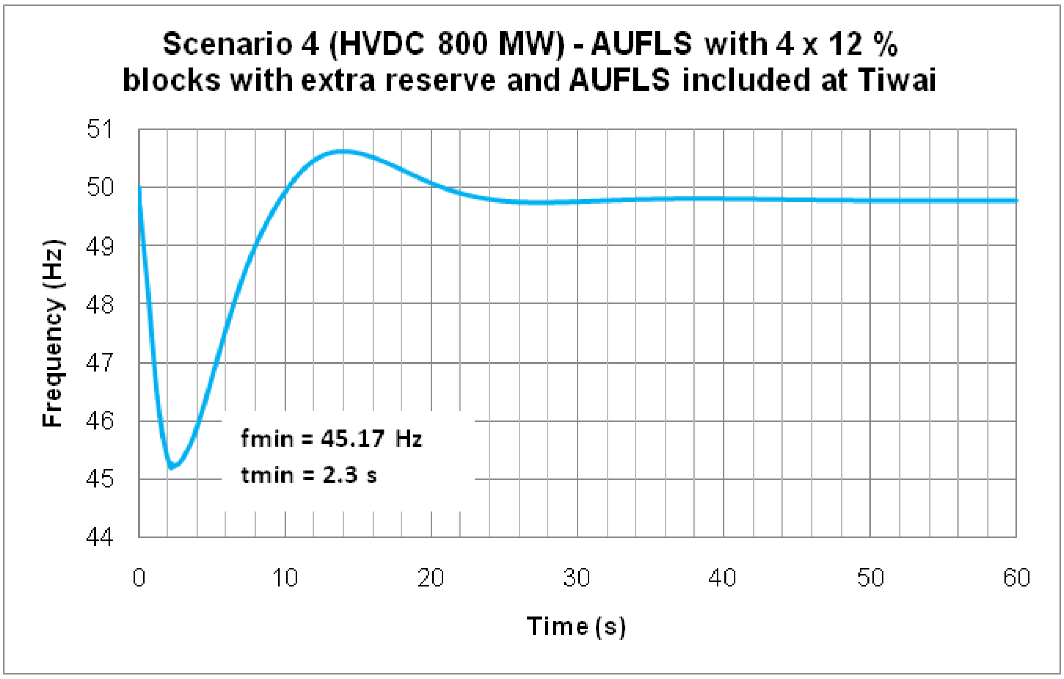


Figure 7-18 Frequency plot for scenario 3 with Tiwai included & extra reserve



Discussion

The results show that significantly less reserve is required to cover scenarios 3 and 4 if Tiwai were included in a 4 x 12% AUFLS scheme.

7.5 The effect of load shedding on system voltage

In the very lightly loaded South Island grid, all system capacitors except the Kikiwa STATCOM and Islington SVC, are not needed and are therefore switched out of service.

The maximum steady-state voltages recorded for each of the scenarios studied under each of the different schemes are shown in Table 7-1.

Table 7-1 Summary of maximum steady-state voltages under the different schemes

Scenario	Biggest risk	Maximum steady-state voltage (pu)											
		Existing AUFLS	Existing AUFLS with extra reserve (pu)	Existing AUFLS with Tiwai included (pu)	Existing AUFLS with Tiwai included & extra reserve (pu)	AUFLS with df/dt acceleration (pu)	AUFLS with df/dt acceleration with Tiwai included (pu)	AUFLS with 4 x 8 % blocks (pu)	AUFLS with 4 x 8 % blocks with Tiwai included (pu)	AUFLS with 4 x 12 % blocks (pu)	AUFLS with 4 x 12 % blocks with extra reserve	AUFLS with 4 x 12 % blocks with Tiwai included (pu)	AUFLS with 4 x 12 % blocks with Tiwai included & extra reserve (pu)
1	HVDC – 400 MW	1.065	1.06	1.082**	1.082**	1.06	1.088**	1.062	1.082**	1.065	-	1.082**	-
2	3 MAN units (225 MW)	1.055	-	1.052	-	1.051	1.05	1.053	1.06	1.053	-	1.051	-
3	HVDC – 660 MW	system collapse	1.052	system collapse	1.078	system collapse					1.063	1.1**	1.1**
4	HVDC – 800 MW	system collapse	1.055	system collapse	1.075	system collapse					1.06	1.1**	1.082**
5	3 MAN units (315 MW)	1.05	-	1.06	-	1.051	1.058	1.052	1.052	1.06	-	1.06	-
6	3 MAN units (360 MW)	1.075	-	1.075	-	1.075	1.075	1.08*	1.078	1.078*	-	1.075	-

*The maximum voltages occurred in the upper South Island

**The maximum voltages occurred in the lower South Island

Cases where the maximum steady-state voltages exceed 1.08 pu is of concern since it is uncertain whether certain customers' equipment are able to handle such high voltages. All the voltages shown in table 7-1 are within the EGR steady state limits and are therefore acceptable. The high voltages in the lower South Island could, however, be addressed be possibly tripping some of the filters at Tiwai.

7.6 South Island Results – Summary and Conclusions

7.6.1 Summary of South Island results

The results from the AUFLS schemes studied for the South Island are summarised in table 7-14:

Table 7-14 Summary table for results from the South Island studies

Scheme Studied	Summary of South Island Results
Existing scheme 2 x 16%	· 3 out of 6 scenarios collapse or are very close to collapse. AUFLS is insufficient in size for the collapsed (bi-pole tripping) scenarios. · Over-shedding results in high frequency for one scenario studied, although the frequency is within the EGR limits. · Including an AUFLS response at Tiwai results in better (higher) minimum frequencies for the scenarios that do not collapse. · A significant amount of additional partly loaded spinning reserve (PLSR) is required to keep the system from collapsing for the bi-pole tripping scenarios. Procuring large quantities of PLSR is inefficient from a water management perspective.
2 x 16% with df/dt	· 2 out of 6 scenarios collapse · 3 of the scenarios studied do not trigger on df/dt (i.e. they trigger on the existing settings). · This scheme does not provide significantly different or better results than the existing scheme except for scenario 1 when an AUFLS response is included at the Tiwai GXP. · Increasing the speed of the AUFLS response without modifying other variables (such as total size or number of blocks) does not improve the performance of the existing scheme.
4 x 8%	· 2 out of 6 scenarios collapse · The results of this scheme are mixed in comparison with the existing scheme. 2 scenarios studied perform worse under this scheme, but the problem of over-shedding is avoided for scenario 5. · This scheme illustrates that the total quantity of AUFLS is a key issue for the South Island. Increasing the number of blocks does not improve the performance of the existing scheme if the total quantity of AUFLS remains the same.
4 x 12%	· 2 out of 6 scenarios collapse. These scenarios collapse as the disturbance to the system is greater than 70%. · With an AUFLS response included at Tiwai, no scenarios collapse although the EGR minimum frequency limit of 45 Hz is breached for 2 scenarios. · This is the best performing scheme as more load is available to be shed by AUFLS (48%) and smaller blocks reduce the potential for over-shedding. · Extra reserve is still required under this scheme to keep the frequency within the EGR limits for 2 of the scenarios, but far less is required than any of the other schemes studied.

7.6.2 Conclusions from the South Island studies

The South Island currently has a 32% AUFLS scheme made up of two large 16% blocks that are set to trip at 47.5 Hz and 45.5 Hz. There is also no AUFLS response currently provided at the Tiwai grid exit point.

The existing AUFLS scheme is sufficient to prevent system collapse following a Manapouri busbar tripping. While the studies show that the system does not survive or comes very close to collapse following an HVDC bi-pole tripping, it is important to note that a bi-pole tripping is defined as an extended contingent event (ECE). This means that the System Operator's tools will ensure that extra reserve is procured and/or the HVDC transfer is limited to prevent system collapse following an HVDC bi-pole tripping under all load and generation scenarios.

The following conclusions can be made about the South Island AUFLS scheme:

1. **The total quantity of AUFLS in the South Island is low compared to the size of the disturbance from an HVDC bi-pole tripping.**

   Post pole 3 commissioning the HVDC will have a capacity of 1200 MW, although it is not anticipated that the HVDC will run up to 1200 MW in south transfer. This report studied HVDC south flow of up to 800 MW. However, when compared with average South Island demand of around 1600 MW, it is clear that the percentage of generation lost from an HVDC bi-pole tripping is much larger in magnitude for the South Island than it is for the North Island. This is compounded by the fact that an AUFLS response is not provided at the Tiwai grid exit point[27].

   Although the System Operator's tools will ensure there are sufficient reserves procured to cover a bi-pole tripping, increasing the total quantity of AUFLS in the South Island and including an AUFLS response at Tiwai will considerably decrease the amount of extra reserve required to cover these HVDC transfer scenarios. See point 2 below for more detail.

   It should also be noted that while increasing the number of AUFLS blocks will allow for better control of the load shedding and reduce the potential for over-shedding, there is no real benefit to be gained by increasing the number of blocks in the South island if the total quantity of AUFLS (32%) remains the same.

2. **The second AUFLS block is set to trip too close to 45 Hz for a time delay of 0.4 seconds.**

   Studies of a 4 x 12% AUFLS scheme with an AUFLS response included at Tiwai showed that the system remained intact following the bi-pole tripping scenarios studied (scenarios 3 and 4), but the minimum frequency limit of 45 Hz was breached. Moving the bottom frequency range of AUFLS in the South Island a bit further from 45 Hz would improve the minimum frequency under scenarios 3 and 4 and should be further investigated.

3. **A bi-pole tripping (ECE) is more likely to become the binding risk post pole 3 commissioning**

   The HVDC will be able to transfer up to 1200 MW post pole 3 commissioning. However, given the current AUFLS scheme, it is likely that the System Operator's tools will need to procure a significant amount of reserve and limit the HVDC transfer to 800 MW or less to ensure that there are sufficient reserves and AUFLS to cover a bi-pole tripping.

   Furthermore, the additional reserve procured will need to be partly loaded spinning reserve (PLSR), not TWD. Almost all large generation units will need to be running in the South Island to ensure that there is sufficient PLSR (and AUFLS) available

[27] The load at Tiwai is typically between 400 MW to 600 MW.

to cover a bi-pole tripping when the HVDC is transferring 800 MW South under mid load conditions. Adding extra units on PLSR mode is inefficient from a water management perspective. While high HVDC south transfer levels are likely to be required when the South Island lakes are low (dry year scenario), running all South Island units on PLSR will use water rather than conserve it.

4. **Generator reserves provide less value than IL and AUFLS following an extended contingent event**

The studies show that generator reserves, particularly tail water depressed reserve (TWD), provide less value to the system than AUFLS and IL following an extended contingent event because of the speed of the frequency fall. This is illustrated in Figure 7-20.

It is clear from the results that TWD of less value for the South Island following an ECE since for almost all the scenarios studied, under each of the different AUFLS schemes, the minimum frequency was reached well before 6 seconds. In many of the scenarios, the time taken to reach minimum frequency is less than 4 seconds. TWD is triggered at a range of frequencies between 49.5 Hz – 49 Hz and will operate within 2 to 4 seconds.

The studies also highlight the need for interruptible load in the South Island, as IL provides a much faster response than generator reserves.

These findings demonstrate a need for further investigation into a 3 second reserves market.

To demonstrate the conclusions above, consider figures 7-19 and 7-20. Figures 7-19 and 7-20 illustrate the frequency at which generator reserves (PLSR and TWD), and AUFLS blocks 1 and 2 trigger, and the time it takes for each to respond. The frequency at which each responds will depend on the rate of frequency fall. Although the rate of frequency fall is not constant following an event, a constant rate of frequency fall is shown in figures 7-19 and 7-20 for simplicity. Note that interruptible load is not currently offered in the South Island.

Figure 7-19

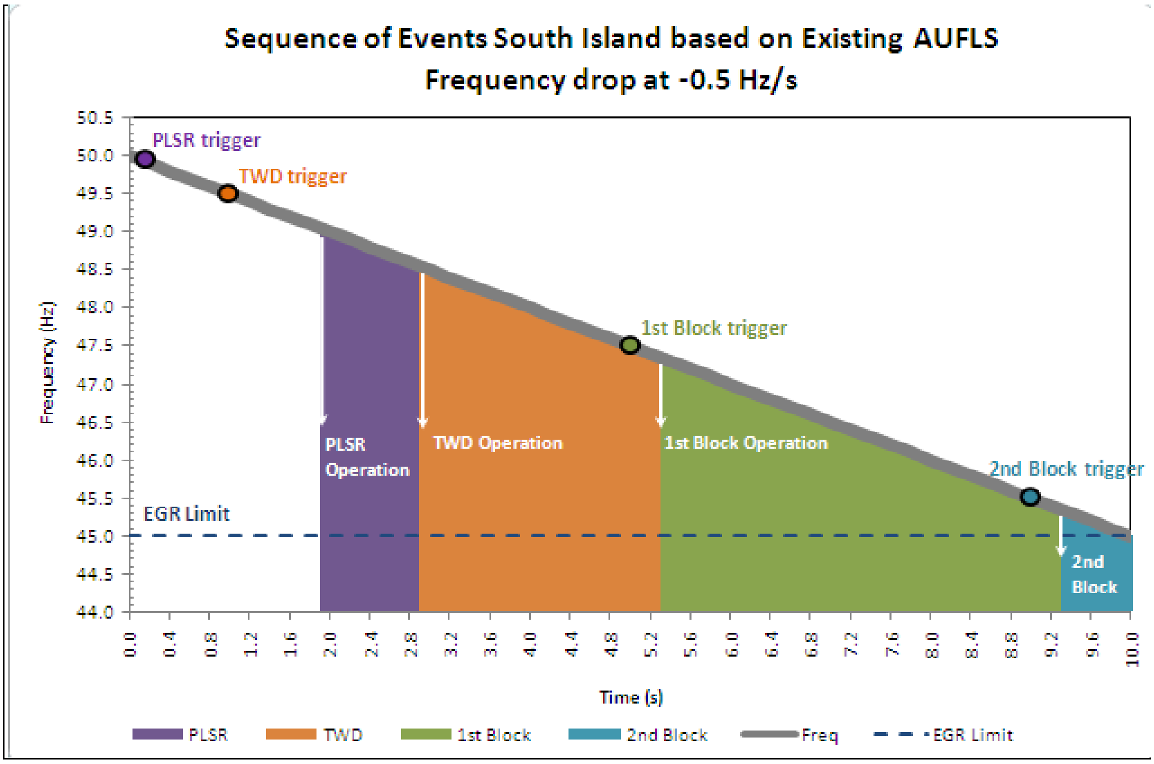


Figure 7-19 can be interpreted as follows:

The grey slope shows the rate of frequency fall. In this example, the rate of frequency fall is -0.5 Hz/s. -0.5 Hz/s means that it takes 2 seconds for the frequency to fall 1 Hz, or 0.2s for the frequency to fall 0.1 Hz. At this rate, the frequency reaches 47 Hz in 6 seconds after the event. The existing reserve management scheme is designed around a frequency rate of fall of this speed.

Under a constant frequency rate of change of -0.5 Hz per second, the following sequence of events occurs:

- PLSR triggers just below 50 Hz
- TWD triggers at a range of frequencies between 49.5 – 49 Hz.
- PLSR responds between 49 Hz and 48.5 Hz (within 2 – 3 seconds from trigger)
- TWD responds between 48.5 Hz and 47 Hz (within 2 - 4 seconds from trigger)
- AUFLS block 1 triggers at 47.5 Hz (5 s after the event)
- AUFLS block 1 operates at 47.3 Hz (5.4 s after the event – AUFLS takes 0.4s to operate)
- AUFLS block 2 triggers at 45.5 Hz (9 s after the event)
- AUFLS block 2 operates at 45.3 Hz (9.4 s after the event).

Figure 7-20

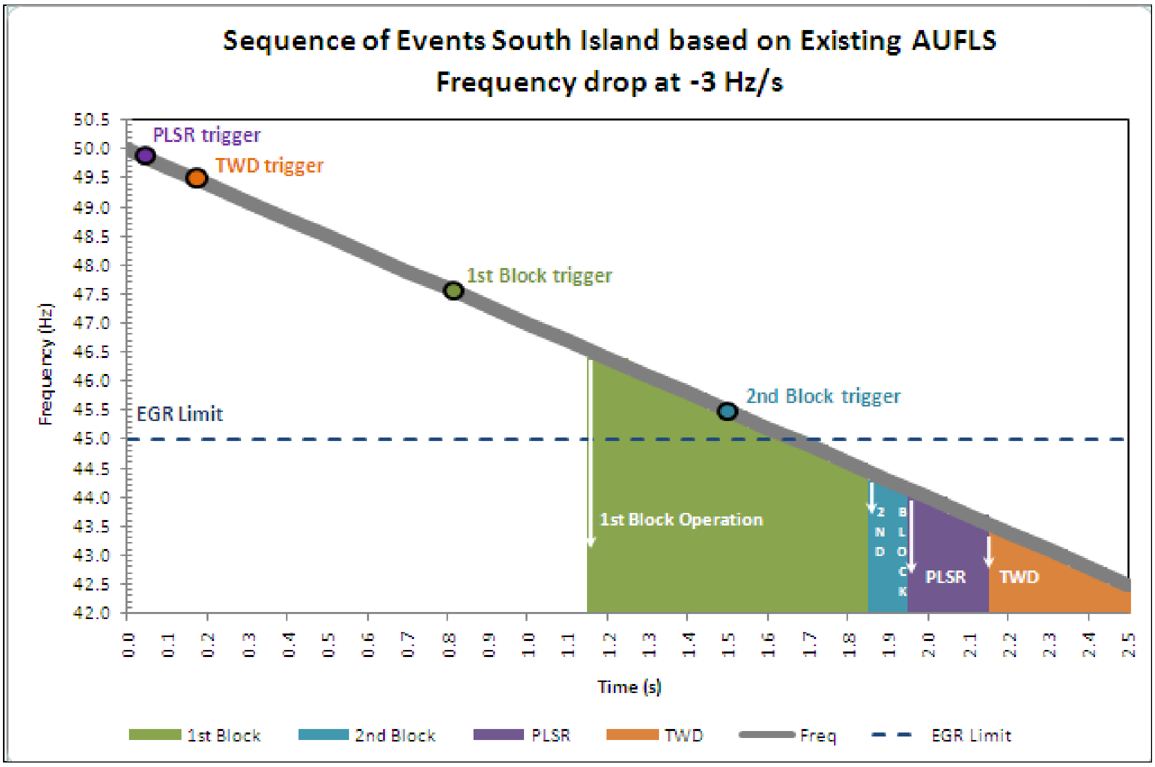


Figure 7-20 can be interpreted as follows:

The grey slope shows the rate of frequency fall. In this example, the rate of frequency fall is -3 Hz/s. -3Hz/s means that it takes 0.33 seconds for the frequency to fall 1 Hz, or 0.033s for the frequency to fall 0.1 Hz. At this rate, the frequency reaches 45 Hz in 1.65 seconds after the event. This rate of fall in frequency was observed in the studies of the existing South Island AUFLS scheme.

Under a constant frequency rate of change of -3 Hz per second, the following sequence of events occurs:

- PLSR triggers just below 50 Hz
- TWD triggers at a range of frequencies between 49.5 – 49 Hz
- AUFLS block 1 triggers at 47.5 Hz (0.83 s after the event)
- AUFLS block 1 operates at 46.3 Hz (1.23 s after the event – AUFLS takes 0.4s to operate)
- AUFLS block 2 triggers at 45.5 Hz (1.5 s after the event)
- AUFLS block 2 operates at 44.3 Hz (1.9 s after the event – this is below the 45 Hz limit).
- PLSR responds between 44 Hz and 41 Hz (within 2 – 3 seconds from trigger)
- TWD responds between 43.5 Hz and 37 Hz (within 2 – 4 seconds from trigger)

This diagram demonstrates that for the rate of frequency fall after an extended contingent event or other large event:

- AUFLS block 2 in the South Island is set to trip is too close to 45 Hz

- TWD does not provide a MW response for rates of frequency fall of this speed. While there will not be a constant rate of frequency change following an event (i.e. the speed of fall will slow following AUFLS response), this diagram does illustrate that TWD is slow to operate.

7.6.3 Options and Next Steps

The System Operator has identified the following options to address the key issues identified form the South Island studies:

Option 1: Improve the performance of the existing AUFLS scheme in the South Island.

Significant gains can be had by better controlling the AUFLS that is currently available. Modifying the number and size of the existing AUFLS blocks and the trip mechanisms and settings for these blocks can significantly improve the performance of the existing AUFLS scheme and produce better outcomes for New Zealand.

- When reviewing the existing scheme, there are a number of key considerations that should be taken into account, namely:
- Size of AUFLS response (percentage of total load shed) is important, particularly in the South Island.
- The number and size of the AUFLS blocks (more blocks, smaller in size) can reduce the potential for over-frequency and over-voltage problems.
- Speed of the response is critical.

Each of the points above cannot be considered in isolation, and a combination will provide for the scheme with the best response.

The System Operator will be holding workshops with the industry in August 2010 to discuss the option of modifying the existing AUFLS scheme.

Option 2: Review the products provided in the South Island reserves market.

The findings of the review illustrate that the existing reserve products do not interact well with AUFLS. The studies also highlight the need for interruptible load in the South Island, as IL provides a much faster response than generator reserves. These findings demonstrate a need for a review of the reserves market and for an investigation of new reserve products or other markets such as a 3 second reserves market.

The System Operator will be holding workshops with the industry in August 2010 to discuss this option.

7.6.4 *South Island Results - Questions and Answers*

Do we need an AUFLS response at the Tiwai GXP?

The System Operator will ensure that sufficient reserves are procured to cover an extended contingent event regardless of whether an AUFLS response is provided at Tiwai or not. However, it should be noted that including an AUFLS response at Tiwai will result in less reserve needing to be procured when the ECE is the binding risk, and will potentially allow the HVDC to operate to higher transfer levels in South mode.

Procuring large amounts of PLSR reserve is inefficient, especially during dry year scenarios.

We have run the HVDC in south transfer mode of up to 600 MW in the past. Does this mean that we were not covered for a risk of this size in the past?

Sufficient reserve was procured under these scenarios to ensure that a bi-pole tripping at 600 MW was covered. However, it should be noted that during winter 2008 IL was offered in the South Island to enable HVDC south flow of this magnitude.

8 Other Results

This section sets out the conclusions from other aspects of AUFLS that were reviewed as part of this report. This section summarises the results of the studies of electrical system splits, and provides comment on:

- The use special protection schemes to cover for an extended contingent event
- The use of line switching to manage voltages, and
- Restoring load following an AUFLS tripping

8.1 Electrical System Splits

This section sets out the results of the studies of electrical system splits identified in section 5.1.

8.1.1*Hawkes Bay*

On a number of occasions the two 220 kV circuits from Wairakei into the Hawkes Bay region have been lost. This has mostly occurred during winter storms due to snow loading overnight. Often the lines will not be returned to service for a number of days.

There is a significant amount of generation in the Hawkes Bay region at the Tuai generation scheme (156 MW) and Whirinaki (153 MW). The Whirinaki generation plant is a dry year / peaking plant and does not run often. The black start capability at Tuai has been removed. The peak load in the area is approximately 312 MW.

It is possible for a successful island to form if sufficient generation is connected. The results are shown in Appendix E Figures 1-2.

All generation except one Whirinaki unit needs to be connected and AUFLS must successfully operate in order for an island to be sustained following the loss of the two 220 kV circuits from Wairakei. For all generation scenarios the success of electrical islanding is entirely dependent on the number of machines synchronised in the Hawkes Bay region.

If an island is successfully created then synchronising the Whirinaki generation will allow supply to be maintained and AUFLS restored within this electrical island until the lines can be restored.

However, as an alternative, various Special Protection Schemes (SPS) were considered. Consideration was given to an SPS to shed load on tripping of specific circuit/s or perhaps using the ability of the Tuai Generation to operate to below 47 Hz[28] to automatically trip further load. The latter would require a rule change but may be a viable option.

A very simple but yet robust[29]scheme would be to island Tuai generation with a small amount of load. The detection of a low frequency (maybe 46.5 Hz) would open all the circuits at Tuai except the Wairoa circuits. Controlled grid restoration from Tuai could then be carried out. The advantage of this scheme is that generation does not have to be dispatched outside of merit order to ensure an island is formed, as there will always be three machines running for resource consent reasons. A graph showing the frequency from such an SPS is shown in Appendix E Figure 3.

Consideration could be given to a scheme that if it saw sufficient generation from Tuai, both the Wairoa and the Gisborne load would remain connected.

8.1.2*Bay of Plenty*

There are two 220 kV circuits into the Bay of Plenty region (Whakamaru-Atiamuri and Ohakuri-Wairakei) and two 110 kV circuits (through Kinleith). When one 220 kV circuit is taken out of service for planned maintenance the two 110 kV circuits are removed from service to prevent overload for a contingent event.

The loss of both 220 kV circuits was investigated and it was assumed that the 110 kV circuits would either trip on overload or were already out of service.

The ability of the region to sustain an electrical island relies on there being sufficient generation. Some scenarios were assisted by the use of AUFLS to achieve islanding.

[28] Because Tuai is a hydro generation scheme, these generators will remain connected to the grid below the EGR limit of 47 Hz.

[29] A key requirement for special protection schemes

One particular issue of concern is the post event over-voltage and it is suggested that under-frequency acceleration is applied to the over-voltage capacitors at Mount Maunganui and Tauranga to prevent pole slip and system collapse post event.

The frequency and voltage plots for this study can be found in Appendix E Figures 4-5.

8.1.3 *Loss of Whakamaru Bus*

This tripping was designed to simulate a split of the North Island into two electrical systems. It was assumed that on loss of the Whakamaru bus the two circuits North from Stratford would trip on overload.

In most cases, however, the loss of the Whakamaru bus actually causes so many other power system issues such as line overloading and various types of voltage stability issues that did not occur in the other islanding simulations. Only with high Huntly generation was it possible for the northern electrical island to be formed.

The frequency and voltage plots for this study can be found in Appendix E Figures 6-7.

8.1.4 *Split North of Clyde.*

The two Clyde Twizel circuits are physically located on the same set of transmission towers.

With the loss of both these circuits, if significant power is being transferred between the areas, it is likely that the Naseby Roxburgh circuit will trip and two electrical systems will be formed.

This was found to be the case and the results are shown in Appendix E Figures 8-9.

8.1.5 *Coleridge Island*

When one of the Coleridge Hororata 66 kV circuits is taken out of service for maintenance, a split is put in on the west coast so that for the loss of Atarua Inangahua, the remaining Coleridge Hororata circuit does not trip on overload.

This will either lead to Coleridge forming a separate electrical system or to the loss of supply. AUFLS can extend the range of generation scenarios where a successful island is formed. As in all islanding cases sufficient generation must initially be connected.

Frequency and voltage plots for this study can be found in Appendix E Figures 10-11.

8.1.6 *Waitaki Island*

If the two 220 kV circuits into Waitaki are lost, an electrical island comprising the Waitaki generation and the load at Studholme, Waitaki, Black point and Oamaru can be formed. This assumes the Studholme split is in place.

This island has a high probability of forming due to the Waitaki generators usually having to generate to meet the minimum flow obligations.

AUFLS would obviously extend the number of occasions when islanding would be successful.

Frequency and voltage plots for this study can be found in Appendix E Figures 12-13.

8.1.7 *Conclusions from Studies of System Splits*

The results show that AUFLS can help to form successful islands following a system split under certain load and generation conditions. Consideration should be given to special protection schemes, such as the one identified in section 8.1.1 for the Hawkes Bay, where it can assist in creating the correct load and generation conditions to ensure that an island is successfully formed.

Although not considered in detail in this report, regional requirements for AUFLS should be considered when assessing an application for an AUFLS exemption. For example, too many AUFLS exemptions in a particular region may reduce the likelihood of an island successfully forming in the region following a system split.

Furthermore, it was noted that for certain events, AUFLS tripped before IL due to the very fast rate of fall in frequency. It would seem additionally prudent to have AUFLS connected to IL relays to increase the chances of a successful island forming. From a voltage perspective it does not matter whether the load is AUFLS or IL, the time until pole slip occurs is usually about 30 seconds compared to the second or so difference in triggering time of IL and AUFLS.

While system splits can lead to the loss of busbars or substations that could lead to more onerous system conditions, these scenarios were not studied as it is known that the current AUFLS scheme is not sufficient to cover these scenarios.

8.2 The use of Special Protection Schemes to cover for an ECE

In some overseas power systems, special protection schemes (SPS) are used rather than AUFLS to cover against large **defined** risks. AUFLS is typically used in overseas power systems to provide a safety net against large, undefined risks.

When the risk is defined, it is possible to design a scheme to specifically address any system issues that may result from the event.

For example, a special protection scheme could be set up to trip a targeted load such as the lower North Island following a HVDC bi-pole tripping when in north transfer. A SPS such as this would operate faster than AUFLS, and trip load that is closer to the source of the disturbance. This may have the result of the frequency not dropping as low as under the existing AUFLS scheme and would remove the need to shed load across the entire island[30] for a bi-pole tripping.

An SPS could also be used for electrical islands when a region is split electrically from the rest of the country such as the Hawkes Bay islanding scenario discussed in section 8.1.1.

However, it is important to note that an SPS designed for an extended contingent event such as a bi-pole tripping would not remove the requirement for an AUFLS scheme. As power grid operation can be unpredictable it is generally considered that an SPS should complement AUFLS i.e. it is prudent to have both.

AUFLS may still be required to:

- cover other undefined events such as multiple CCGT trippings,
- assist in creating a successful electrical island following a system split (as discussed in section 8.1), and
- provide a backstop to any existing SPS where the load conditions are insufficient to cover the risk.

[30] Although all of the load in the targeted region would be shed.

8.3 The use of line switching to control voltages

A number of actions can be taken to control high voltages following an AUFLS event. These include:

- Switching out capacitors,
- Relying on machines to absorb the reactive power, and
- Switching out lines.

The studies in this report use switching of capacitors to maintain voltages at manageable levels and do not consider line switching.

Line switching is used by Transpower at certain times of the day to control high voltages, but not as part of an AUFLS scheme. In some overseas power systems, automatic line switching is used as part of an AUFLS scheme to help control the voltage post event.

This is not considered to be a valid solution for the New Zealand power system as automatic switching of lines is not prudent when there is uncertainty on the cause of the event. Automatic switching of certain lines (depending on the event) can exacerbate problems on the system rather than help the system to recover.

8.4 Restoring load following an AUFLS tripping

Load restoration time after an AUFLS event depends heavily on the availability of transmission assets and generation.

Practical restoration time following an AUFLS event is likely to be between 90 minutes to up to 4 hours *provided transmission assets and generation are available to restore the system*. Given the variables that may exist at the time of an AUFLS event, it is important to note that the restoration times provided are informed estimates based on experience of power system events such as:

- **30 October 2009** - A container-moving vehicle struck one circuit of the Otahuhu-Henderson 220 kV lines 30 minutes after the other circuit had been taken out of service for essential maintenance. This resulted in supply being lost to half of Auckland and the whole of Northland, or approximately 560 MW.

  Restoration of supply to customers began at approximately 8:20am at Bream Bay when the 220 kV circuits to the north were re-energised, and progressed steadily to approximately 11:00am when supply at Kaikohe was restored. Shortly after this time the load was essentially back to normal at all affected points of service.

- **12 June 2006** – A major fault involving two 220 kV transmission lines and three sections of 110 kV busbar occurred at Otahuhu substation resulting in the loss of supply to much of Auckland, or approximately 850 MW. Full restoration of load took approximately 8 hours.

Generally speaking, the System Operator can restore the system as fast as the distributors can connect the load, *provided there is the transmission capacity and the generation available* to support the load.

9 Next Steps

The System Operator will be engaging with industry participants to ensure that the findings from this technical paper are well understood and we invite industry comment. The System Operator will also raise and discuss the options presented in this report at the next round of System Operator workshops in August 2010.

Depending on the feedback received from industry participants, further analysis that could be conducted includes economic and policy analysis in the following areas:

- the impact on the energy and reserves market given the increased likelihood of a bi-pole tripping becoming the binding risk post pole 3 commissioning.
- the cost of treating an extended contingent event as a contingent event (i.e. what is the cost of not having AUFLS?)
- the cost and consequences of an AUFLS event compared with a blackout event
- the risks and incentives for various parties to provide AUFLS
- whether any class of participant should be exempt from providing AUFLS and the appropriate process to grant such exemptions
- the viability of a primary and/or secondary market for AUFLS (such as equivalence arrangements).
- the quantity of AUFLS provided at each grid exit point for different periods throughout the year.

The System Operator will be conducting further technical work in the following areas:

- Coordinate any actions required to address the potential over-voltage issues in the North Island.

  This includes an audit of over-voltage protection on reactive devices to ensure that they trip for 1.1 pu voltage.
- The technical performance and reliability of df/dt relays
- Assessing the viability of a special protection scheme to facilitate the electrical islanding of the Tuai generation scheme/Hawkes Bay.
- Dynamic models (frequency and voltage dependency) of loads in the New Zealand Power system

  There is a need to develop a better understanding of load dynamics following an AUFLS event. This is especially needed from the aspects of; (a) the natural MW damping provided by the load as the system frequency falls and, (b) the load dependencies on the busbar voltages