WAIKATO AND UPPER NORTH ISLAND VOLTAGE MANAGEMENT

ATTACHMENT B: POWER SYSTEMS ANALYSIS REPORT

Transpower New Zealand Limited

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Keeping the energy flowing

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Table of Contents

Glossary

AOVCS	Automated over-voltage capacitor switching scheme. A protection-based scheme to rapidly switch capacitors post fault.
Capex IM	Transpower Capital Expenditure Input Methodology Determination, New Zealand Commerce Commission[1].
Code	Electricity Industry Participation Code 2010.
Demand management	The use of demand reduction pre- and/or post-fault.
Dynamic reactive device	Dynamic reactive devices can provide reactive power in a few milliseconds. Common examples are static var compensators (SVCs), static synchronous compensators (STATCOMs) and synchronous condensers. All are capable of rapid dynamic response.
Grid Reliability Standards	The grid reliability standards (GRS) are a set of standards against which the reliability performance of the existing grid (or future developments to it) can be assessed as defined in the Code (schedule 12.2).
Immediate investment horizon	The period from 2023 until the end of 2024 which is the subject of our Major Capex Project application with the Commerce Commission.
Long-list consultation	Transpower's consultation document entitled Waikato and Upper North Island Voltage Management Long List Consultation July 2016.
N-1	A security standard that ensures with all facilities in service Transpower's transmission system remains in a satisfactory state following a single contingent event (e.g. a circuit outage).
N-G-1	A security standard that ensures with a generator out of service Transpower's transmission system remains in a satisfactory state following a single contingent event (e.g. a circuit outage). The 'G' in N-G-1 can also be a proxy for transmission equipment contingencies with similar severity as 'G'.
Prudent demand forecast	Our prudent demand forecast is equal to the 90th percentile (P90) of our demand forecast distribution.
PU	Per-unit voltage is the expression of system voltage as fractions of a defined base voltage (e.g. 110 kV, 220 kV).
Rankine	A type of coal/gas generator owned and operated by Genesis Energy at Huntly.
Short-list consultation	Transpower's consultation document entitled Waikato and Upper North Island Voltage Management Short List Consultation June 2019.
STATCOM	A static synchronous compensator is a device that provides fast reactive power compensation.
SVC	A static var compensator is a device that provides fast reactive power compensation.
TOV	Transient over-voltage.
Transpower	Transpower New Zealand Limited, owner and operator of New Zealand's high-voltage electricity network (the national grid).

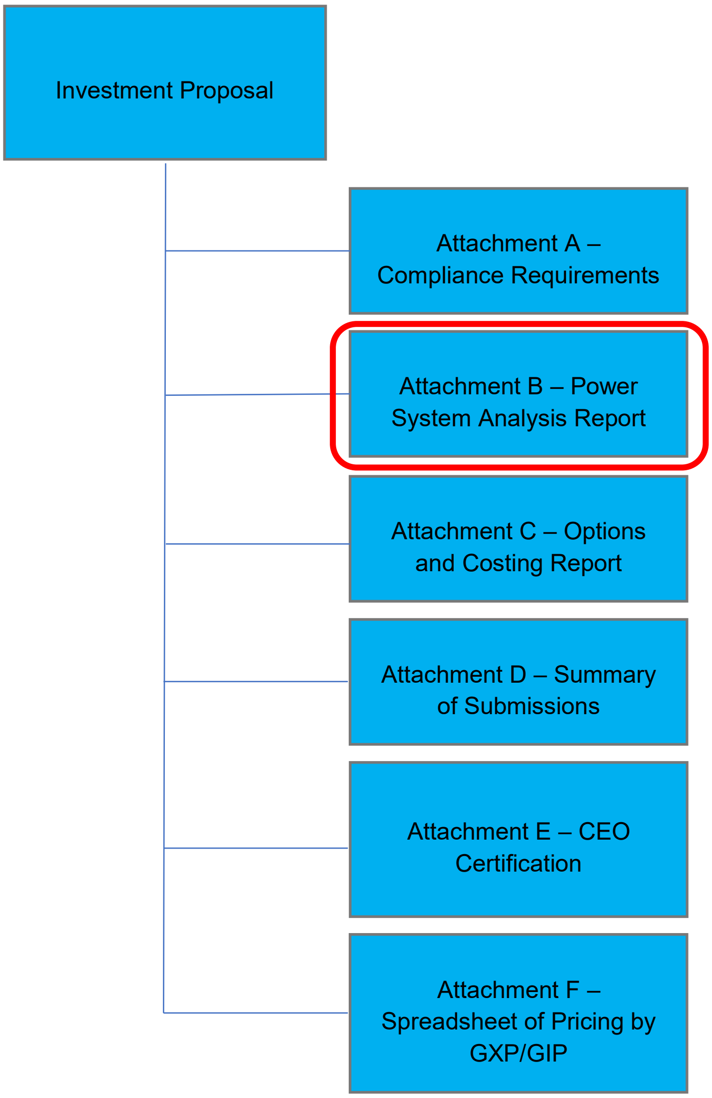
[1] See http://www.comcom.govt.nz/regulated-industries/electricity/electricity-transmission/

TSR	A thyristor switched reactor can absorb varying amounts of reactive power to address over-voltage conditions.
Voltage sensitive load	Electrical load that is sensitive to fluctuations in the supplied voltage. Such loads include inductive motors (e.g. industrial motors) that will react following a fault impacting system voltage recovery.
WUNI	Waikato and Upper North Island.
WUNIVM	Waikato and Upper North Island Voltage Management.

1 Introduction

This document is the Power Systems Analysis report for the Waikato and Upper North Island Voltage Management (WUNIVM) Investigation Major Capex Proposal application.

This document describes the power systems analysis performed to identify the WUNIVM need, components we considered for this project, and how these components were evaluated to determine our short-list. It is one of the supporting attachments for our main report (‘Waikato and Upper North Island Voltage Management Major Capex Proposal’) and should be read in conjunction with the main report.



1.1 Purpose

The purpose of this report is to:

- provide the engineering need for the WUINVM investigation
- explain the power systems analysis and assumptions used to develop short-list options.

1.2 Document structure

This report forms part of the Waikato and Upper North Island Voltage Management Investigation Major Capex Proposal (MCP) application and should be read in conjunction with the main report.

This document explains the technical analysis used to assess the need and determine possible development paths to address that need.

- Section 2 introduces the basic concepts of voltage stability which is the underlying technical reason that this analysis is required.
- Section 3 describes the technical assumptions used to ensure a consistent and repeatable analysis was performed.
- Section 4 illustrates the need which was found when applying those assumptions from Section 3.
- Section 5 presents our short-listed component building blocks which were used to prepare short-list options.
- Section 6 presents the results of options analysis which address the need described in Section 4.
- The attached appendices provide load forecast data, the technical criteria used in this analysis, simulation results, notes on the post-fault demand management scheme, and thermal constraints.

2 Voltage stability concepts

Voltage stability is essential to maintain acceptable voltages across all buses under normal conditions and after the power system has been subjected to a disturbance (such as a generator or circuit outage).

Under normal operating conditions the voltage of the power system is stable; however, when a contingency occurs the power system may lose its operational equilibrium. Voltage can become unstable resulting in a progressive and uncontrollable decline (under-voltage issue) or rise (over-voltage issue) in voltage.

Should voltage instability exist post-contingency, the power system may undergo voltage collapse, resulting in a partial or total blackout of the power system.

Voltage stability in the WUNI region is comprised of inter-related under- and over-voltage issues. If either of these voltage excursions occur, then additional load could be lost.

Furthermore, for over-voltage excursions, damage could occur to power system equipment exacerbating the problem, with the strong possibility of cascade failure as a result.

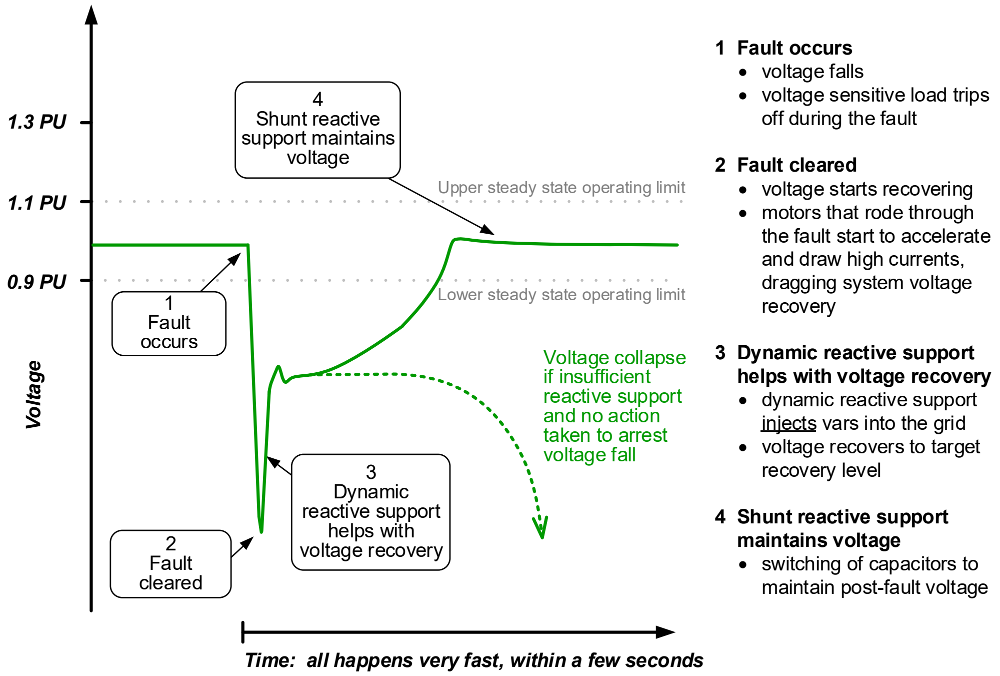
2.1 Under-voltage issues

An under-voltage issue can occur under two different scenarios.

1. A transient voltage recovery issue occurs when a dip in the voltage, due to a fault, takes too long to recover back to acceptable levels, as dictated by ride-through criteria (see Appendix 2). A contributing factor to this slow recovery are induction motors, which take time to reaccelerate following a voltage disturbance. When a motor is reaccelerating it draws high current, exacerbating the voltage recovery. If the voltage does not recover in a timely manner, protection devices can operate to disconnect load and /or generation, with the strong possibility of cascade failure of the transmission network. This can all occur in less than ten seconds.
2. A long-term voltage collapse takes longer to develop than a transient voltage recovery issue. In this scenario a fault occurs, resulting in a transmission circuit, transformer, generating unit or shunt reactive device disconnecting. The voltage recovers adequately in the transient timeframe; however, the network remains weakened and the voltage does not return to its pre-fault level. With dynamic reactive power devices operating at their capacitive maximum, the voltage begins to drop again. This happens in an unpredictable timeframe – anywhere from seconds to many minutes – however ultimately leading to a voltage collapse to zero. Before the voltage reaches zero, protection devices will operate causing load, circuits and /or generation to disconnect, possibly leading to a cascade failure.

This investigation identified the potential for under-voltage issues in the WUNI region prior to 2025. The phenomenon of an under-voltage event is illustrated in Figure 1.

Figure 1: Under-voltage example



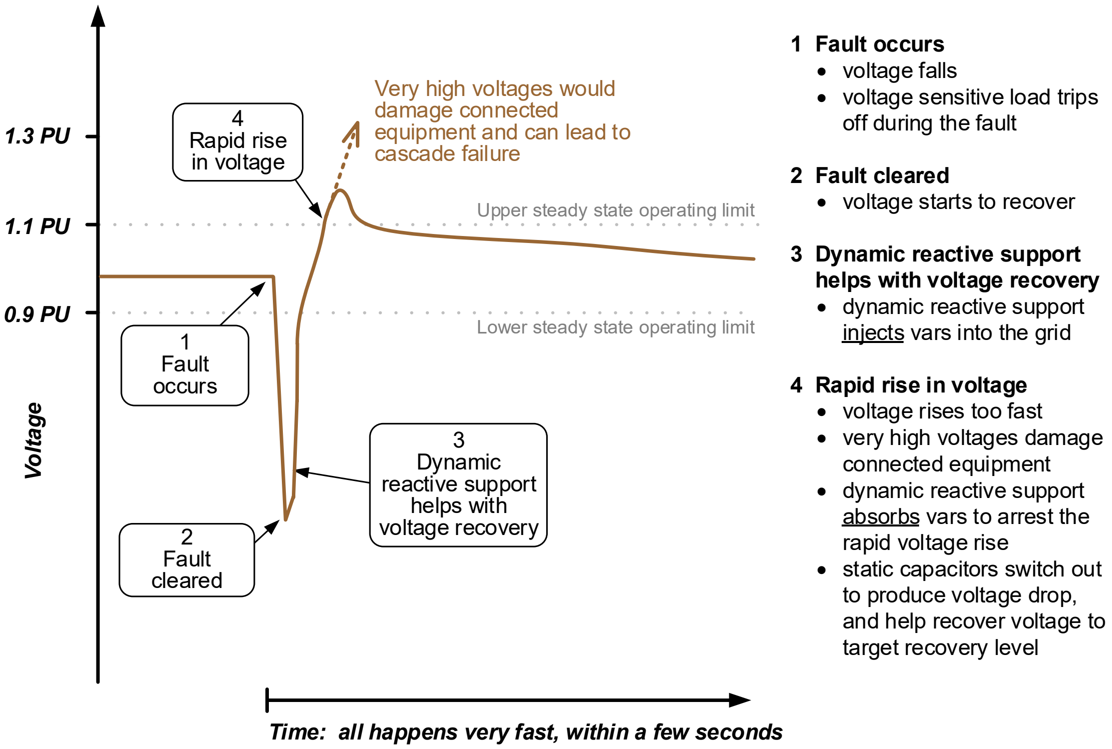
2.2 Over-voltage issues

As with under-voltage, over-voltage issues can occur under two scenarios.

1. Transient over-voltage issues occur when a dip in the voltage due to a fault results in a large proportion of voltage sensitive load disconnecting. When the fault clears, the voltage very quickly recovers above the initial steady state voltage and above acceptable levels as dictated by ride-through criteria (see Appendix 2). Excessive over-voltage can cause damage, both to transmission and connected equipment. Protection devices will try to prevent this happening by disconnecting transmission equipment, generation and /or load, which could lead to a cascade failure of the transmission network. This can all occur in less than ten seconds.
2. Steady-state over-voltage issues occur during periods of very light load. During these periods, long transmission circuits and cables are typically lightly loaded, which causes them to produce reactive power raising the network voltage. Additionally, cables and power factor correction measures within distribution networks often result in injection of reactive power to the transmission network, further exacerbating the issue.

The phenomenon of an over-voltage event is illustrated in Figure 2.

Figure 2: Over-voltage example



The Upper North Island (UNI) region is heavily compensated with 1050 Mvar of shunt capacitors and a total dynamic reactive support of +240/-228 Mvar from an SVC and three STATCOMs. The Waikato region will also have an additional 250 Mvar of shunt capacitors installed by 2020 to strengthen the transfer capability of the core grid into the WUNI region. This high compensation level can lead to the transient over-voltage issues described above.

Steady-state over-voltage issues are a known issue in the transmission network. Dynamic reactive devices that can assist with transient issues can also provide support for steady-state over-voltage issues, but as relatively expensive plant. It is transient rather than steady-state issues that drive the need for dynamic reactive devices, and our studies have focused on quantifying that.

3 Modelling assumptions and criteria

This section outlines the:

- assumptions used in the analysis to identify needs and options to address those needs.
- performance criteria applied to the analysis to quantify the timing and magnitude of the issues and effectiveness of solutions.
- methodology used to establish WUNI load limits and select appropriate solutions.

3.1 Modelling assumptions

Several modelling assumptions were used in our power system analysis to prepare short-list options.

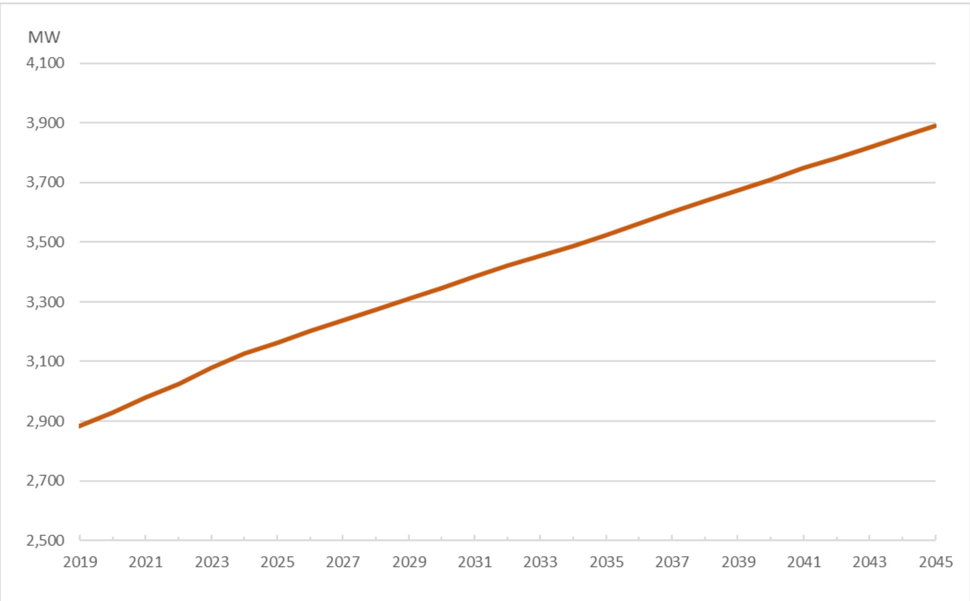
These included the demand forecast, generation, network model, dynamic load model, fault type and reactive support assumptions.

3.1.1 Demand forecast

Our power systems analysis used Transpower's 2018 demand forecast (unless otherwise stated) to determine the need and prepare the short-list of options. We used the winter prudent peak load forecast for Northland, Auckland and Waikato (WUNI) as one region[2]. Due to the extensive effort and time required to perform our power system analysis, we did not re-run our analysis using a 2019 forecast. Instead, to ensure the latest forecast was reflected in our proposal, we revised our investment timings using the 2019 forecast based on the limits derived from the 2018 forecast (described in Section 6.4).

Figure 3 shows the prudent (P90) peak demand forecast for the WUNI region until 2045. A summary of the demand forecast for each grid exit point is presented in Appendix 1.

Figure 3: WUNI region winter peak – 2018 forecast



As we focused primarily on WUNI voltage stability issues, load outside of the WUNI region is kept constant at 2023 forecast levels throughout this analysis. Transmission capacity in the lower North Island is assumed to develop as required to meet demand and generation increases in that region. This is a standard modelling technique used for grid planning purposes.

2 See www.transpower.co.nz/about-us/our-purpose-values-and-people/planning-inputs.

3.1.2 Generation assumptions

Existing generation

Our analysis is reliant on all existing generation in the Northland, Auckland and Waikato being available for dispatch and operating reliably during peak load system conditions. Maximum generation dispatch in this study is based on historical output during winter peak periods (e.g. Waikato hydro scheme, Ngawha). For intermittent generation a conservative maximum generation output is assumed due to their non-continuous and non-dispatchable output.

The assumed breakdown of generation in the WUNI area is shown below in Table 1.

Table 1: Existing and committed WUNI generation

WUNI Generation	Region	Capacity	Maximum grid injection in study	Maximum reactive range (+ve capacitive range, -ve inductive range)
Glenbrook (cogeneration)	UNI	112 MW	65 MW	+63/-31 Mvar
Ngawha (geothermal)	UNI	28 MW	25 MW	+24/-16 Mvar
Ngawha expansion[1]	UNI	27 MW	25 MW	+12/-8 Mvar
Huntly (thermal) Rankine[2] Unit 5 Unit 6	Waikato	500 MW 400 MW 50 MW	0 MW 400 MW 40 MW	0 Mvar +202/-133 Mvar +38/-18 Mvar
Waikato hydro scheme[3] Karapiro Arapuni (North)	 Waikato Waikato	1060 MW 96 MW 117 MW	880 MW 90 MW 90 MW	+466/-475 Mvar +45/-22 Mvar +44/-46 Mvar
Te Rapa (cogeneration)	Waikato	44 MW	40 MW	7 Mvar
Te Uku (wind)	Waikato	64 MW	13 MW[4]	0 Mvar

[1] Scheduled for commissioning in mid-2021.

[2] The analysis assumes that all Huntly Rankine units will be retired by the end of 2022.

[3] Not all generation from the Waikato hydro scheme falls within the WUNI region – only Karapiro and Arapuni North.

[4] Wind generation contribution throughout the whole North Island during peak period is assumed 20% of its installed capacity.

Embedded generation in the WUNI region that is not listed in Table 1 is accounted in the load forecast applied in this study.

Future generation assumptions

The Ngawha expansion project in Table 1 is the only future WUNI region generation included in this analysis. We are not aware of any new significant committed[3] generation projects within the WUNI region during the forecast period[4].

The commitment of additional generation at Huntly or north could defer the need for transmission investment to support voltage stability in the WUNI region. How we will approach any such market generation commitments is described in our main report.

Slack generation assumptions

Slack generation is used to balance the load and generation in the modelling. For the purposes of assessing transmission and non-transmission solutions, modelled slack generation and HVDC transfer was used to supply the deficit needed due to the lack of committed generation in the North Island. The additional slack generation required by the study was modelled at Wairakei.

3.1.3 Network model

The network model used is based upon the 2016 DigSilent Power Factory master case produced by Transpower (NIPS version 1.3.5c).

Modelled Projects

Future transmission projects, both planned and committed, are considered as modelled projects. Table 2 provides a list of known modelled and committed projects as of October 2018 that were used in this study.

Table 2: Modelled projects

Type	Development	Timing	Modelling details
Committed	New Hangatiki supply transformer	2019	Install a new 110/33 kV, 30 MVA supply transformer at Hangatiki.
Committed	New Hamilton shunt capacitors	2020	Install 2x 50 Mvar shunt capacitors at Hamilton 110 kV bus.
Committed	New Ohinewai shunt capacitors	2020	Install 2x 75 Mvar shunt capacitors at Ohinewai 220 kV bus.
Committed	Automatic over-voltage capacitor switching scheme	2022	A protection-based capacitor switching scheme to help control the over-voltage issue.
Modelled	New Te Awamutu shunt capacitors	2020	Install 2x 15 Mvar shunt capacitors at Te Awamutu 110 kV bus.

[3] Committed as defined in Section D9 of the Commerce Commission's Transpower Capital Expenditure Input Methodology Determination ('Capex IM'), 1 June 2018.

[4] In response to our short-list consultation, Mercury advised us of a committed capacity expansion of the Karapiro hydro generation station from 96 MW to 112.5 MW. This relatively minor capacity expansion will not materially change the power system analysis output. It is included in our economic analysis.

Type	Development	Timing	Modelling details
Modelled	Junction Road generation[1]	2020	2x 50 MW of CCGT connected to the Carrington Street–Stratford A line.
Modelled	New Bombay 220/110 kV interconnection	2022 (phase 1) 2029 (phase 2)	Phase 1: a new Bombay 220/110 kV interconnecting transformer. Phase 2: 2nd Bombay 220/110 kV interconnecting transformer. Decommission Bombay–Hamilton 1 and 2. Terminate Arapuni–Bombay 1 at Hamilton and decommission the section to Bombay. Supply Wiri from Otahuhu and dismantle the section between Bombay and Wiri Tee. Operate Otahuhu–Penrose 2 as normally closed.
Modelled	Otahuhu–T2 and T4 replacement	2023	Replace with one 250 MVA transformer.
Modelled	Penrose–T10 replacement	2023	Replace with one 250 MVA transformer.
Existing	Penrose reactor	As needed	Switch in as required to avoid thermal overloading.
Modelled	Pakuranga–Penrose 3 reactor	As needed	Modelled as required to avoid thermal overloading.
Modelled	All supply transformers in the WUNI region	As needed	Add an additional supply transformer to avoid thermal overloading under N-1.
Modelled	Otahuhu–Whakamaru 1 and 2	Assumed in 2033	Replace with simplex zebra at 75ºC when the existing conductor reaches the end of its useful life.
Modelled	Brownhill–Otahuhu cable	As needed	A new 220 kV bus at Brownhill and new 220 kV cable connection between Brownhill and Otahuhu. Modelled as loading of the Brownhill-Pakuranga cable reaches 91% pre-contingency [2].
Modelled	Ohinewai bussing	As needed	Bus Otahuhu–Whakamaru 1 and 2 at Ohinewai. Duplex southern section with Zebra at 75 ºC and disconnect northern section. Modelled as required to avoid thermal overloading.
Modelled	Ohinewai tee	As needed	The two Pakuranga–Brownhill–Whakamaru circuits are connected in a tee configuration into the Ohinewai substation. Modelled as an alternative to the Brownhill–Otahuhu cable.
Modelled	Reconductoring of: 1. Atiamuri–Ohakuri 1 2. Ohakuri–Wairakei 1 3. Atiamuri–Whamakaru 1	As needed	Replace with duplex goat at 75 ºC. Modelled as required to avoid thermal overloading.

[1] Junction Road generation is now committed and under construction at the time of writing this report.

[2] This pre-contingency loading gives post-contingency transient thermal rating of 126% for the first 30 minutes and 120% for a subsequent 30 minutes. We consider the loading on these cables can be managed operationally within this timeframe.

3.1.4 Load modelling

Analysis of voltage stability in the WUNI region requires knowledge of the make-up of voltage sensitive load in the region. The following sections describe the load model used in the analysis and proportions of load in the WUNI region.

Load model

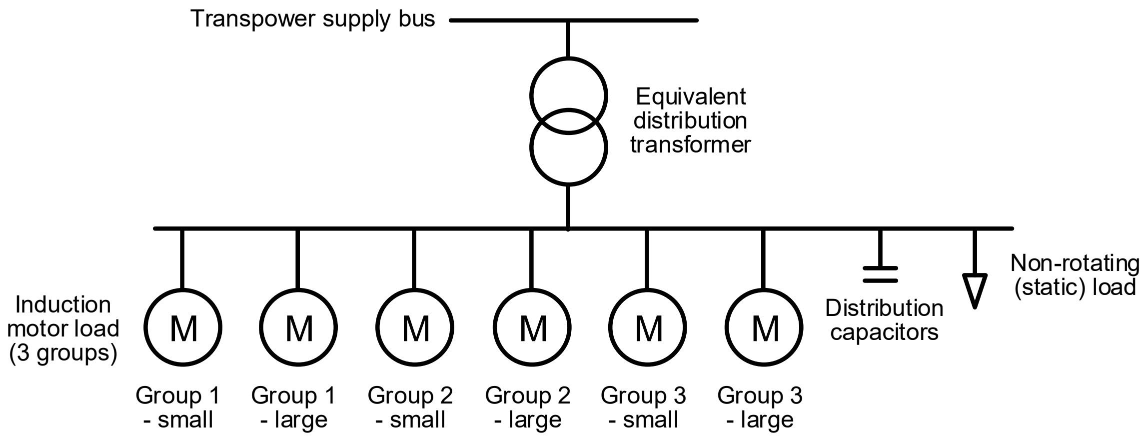
For this study we categorised loads based on an assumed load model shown in Figure 4.

The load model consists of:

- Induction motor load – these motors are split into three protection groups (Group 1, 2 and 3). Each group is further subdivided into groups based on motor sizes (large and small).
- Group 1 motors – these motors are connected with electromagnetic contactors. These contactors may open, and a proportion of motors will stay open when subjected to a two-phase-to-ground fault. We also assume that 50% of power factor correction capacitors will trip due to the contactors opening.
- Group 2 and 3 motors – these motors are assumed to remain connected during and immediately after the fault. They have over-voltage and over-current protection but only Group 3 motors have under-voltage protection. These motors are assumed to trip if:
    - the motor current is greater than 6 times the rated current (6 pu) for more than 3 seconds or greater than 3 times the rated current (3 pu) for more than 8 seconds.
    - the voltage at the motor terminals is below 0.8 pu after 4 seconds or below 0.9 pu after 60 seconds.
    - the voltage at the motor terminals is above 1.3 pu.
    - the voltage at the motor terminals is above 1.1 pu for more than 2 seconds.

- Static 'non-rotating' load – assumed to stay connected during faults. The load characteristic is commonly called PIQZ which the real power (P) has a constant current characteristic and reactive power (Q) has a constant impedance characteristic.
- Known distribution capacitors – distribution capacitor banks are needed to support voltage in the distribution network and meet distribution companies' power factor obligations. Known distribution capacitors are explicitly modelled.
- Distribution network – the distribution network represents the impedance of transformers and circuits in the distribution networks. They are modelled as a transformer between the grid exit point and the load. A network impedance of 10% is assumed (where the load MW demand is the MVA base) for the UNI and an average of 7% is assumed for the Waikato.

Figure 4: Load model, modelled at each grid exit point in WUNI region



Sensitivity to motor load assumptions

The percentage of induction motors (Group 1) that disconnect (and remain disconnected) from contactor action during a severe fault has a significant impact on voltage recovery. If too few motors disconnect then the system can experience low voltages and/or voltage collapse. If a high percentage of motors disconnect then the system may experience transient over-voltages which may damage equipment and lead to cascade failure.

There is uncertainty in the percentage of motor load across days and seasons, and future changes with additional load growth. Furthermore, there is uncertainty in the amount of Group 1 motors that will trip following a fault.

Given our uncertainty of the connected motor loads and their fault ride through capability, we consider a range between 25% (under-voltage) and 80% (over-voltage) of Group 1 motor load tripping in our analysis.

WUNI load proportions

Given the importance of voltage sensitive load and its impact on post-fault voltage stability, a motor load data survey was carried out for the Upper North Island by Sinclair Knight Merz (SKM) in 2013 and for the Waikato by Jacobs in 2017. The surveys were done for the peak winter period and extreme summer period[5], and the findings of the former form a basis for this analysis.

The WUNI load models use the surveyed motor load data, with the average composition summarised in Table 3.

[5] High motor load period during summer due to irrigation and/or air conditioning load.

Table 3: Summary of the average winter peak load composition for Upper North Island and Waikato regions (regional coincident peak load)

Region	Static	Induction motors					
		Group 1		Group 2		Group 3	
		Large	Small	Large	Small	Large	Small
Upper North Island	59.6%	5.1%	14.5%	1.2%	11.8%	2.2%	5.6%
Waikato	35.3%	6.2%	31.5%	1.4%	16.6%	2.7%	6.3%

Our analysis assumed these motor load percentages do not change over the duration of the study[6].

3.1.5 Reactive support assumptions

The configuration and operation of our reactive power support is a key assumption. Table 4 and Table 5 list the assumed dynamic and static reactive support available in the WUNI region.

Table 4: Existing dynamic reactive support

WUNI dynamic reactive support	Continuous capacity (+ve capacitive range, -ve inductive range)	Maximum pre-contingency operating point used in the studies
Albany SVC	+100/-100 Mvar	±30 Mvar
Penrose STATCOM	+60/-60 Mvar	±20 Mvar
Marsden STATCOM	+80/-68 Mvar	±25 Mvar
Total dynamic support	**+240/-228 Mvar**	**±75 Mvar**

Table 5: Existing and committed static reactive support

WUNI capacitor	Voltage (kV)	Reactive power (Mvar)	Mvar operation
Albany C1 C2	 110 220	 50 100	 50 100
Henderson C1	220	75	75
Hepburn Road C11, C12, C13	110	3x 50	150
Otahuhu C29, C30, C31 C11, C12	 220 110	 3x 100 2x 50	 300 100
Penrose C1 C11, C12, C13, C14	 220 110	 75 4x 50	 75 200
Ohinewai*	220	2x 75	150
Hamilton*	110	2x 50	100
Te Awamutu**	110	2x 15	30
Total static support		**1330**	**1330**

6 Refer to Section 4.3 in Attachment D for our discussion of future changes to voltage sensitive load.

WUNI capacitor	Voltage (kV)	Reactive power (Mvar)	Mvar operation
* Committed new shunt capacitors in the Waikato region. Refer to Table 1 for the commissioning dates.			
** This is a modelled project.			

Pre-contingency, the dynamic reactive devices at Albany, Marsden, and Penrose are assumed to be operating within maximum pre-contingency dispatch as per Table 4, giving sufficient margin for reacting to transient events. In practice this dispatch level is achieved by switching in sufficient or all shunt capacitors in the WUNI region, and/or changing voltage set points on buses which these devices are controlling. We assume the shunt capacitors in the Waikato region are always on in our studies.

3.1.6 Dynamic fault assumptions

The power system dynamic fault recovery behaviour is tested by applying a permanent two-phase to ground fault at the end of a circuit, applied at 1 second of the simulation with the faulted circuit disconnected (tripped) after 100 milliseconds.

Our analysis considers only a fault on the 220 kV network between Whakamaru and Auckland along with Huntly unit 5 and Albany SVC.

3.1.7 Thermal constraint assumptions

When building a development plan based on addressing voltage stability limits, we perform no specific analysis into thermal transmission issues. Limits are acknowledged by the following assumed overload limits on transmission equipment:

- cables – preload of 91% of cable limit. This pre-contingency loading gives post-contingency transient thermal rating of 126% for the 30 minutes and 120% for a subsequent 30 minutes. Transpower considers the loading on these cables can be managed operationally within this timeframe.
- circuits inside of WUNI region - 100% of winter rating.
- circuits outside of WUNI region - 130% of winter rating[7].

3.2 Analysis criteria

The section explains the key criteria that were applied in this analysis.

[7] Refers to transmission circuits south of Whakamaru and Arapuni South bus. These circuits are outside WUNI area so “moderate” overloads up to 130% do not materially affect the WUNI area are not considered further. However, above 130% the reactive power consumption and lower voltages due to higher overloads will begin to materially impact on voltage stability within the WUNI area. This assumption makes modelling and analysis of the voltage issues within the WUNI area more manageable.

3.2.1 Voltage performance criteria

For steady-state voltage analysis, the voltage criteria require:

- 220 kV and 110 kV buses, voltage is maintained between 0.9 pu and 1.1 pu for both normal operating conditions and for a contingent event, and
- 66 kV and 33 kV buses, voltage is maintained between 0.95 pu and 1.05 pu for both normal operating conditions and for a contingent event.

For long-term voltage stability analysis, a 5%[8] margin to the nose point is imposed.

For dynamic voltage recovery analysis, the voltage recovery criteria by which adequate voltage performance is judged are described in Appendix 2.

The overriding criteria is that the power system remains stable during and following a fault. In addition, to ensure the power system does not recover too slowly or stabilise at an unacceptable voltage, the voltage recovery trajectory must also be within the following criteria.

For major[9] (220 kV and 110 kV) buses with no generators connected[10] the recovery criteria are:

- Voltage must be greater than 0.5 pu following a single credible contingency event which removes an item of equipment from service without a transmission system short circuit fault. For modelling purposes, all load is assumed to stay connected during and following the event.
- Voltage must recover to above 0.8 pu in less than 4 seconds and above 0.9 pu in less than 60 seconds following a credible contingency event.
- Voltage overshoot must be limited to below 1.3 pu. This criterion is extended to include other low voltage buses.
- Voltage overshoot must not be above 1.1 pu for more than 2 seconds.

For generator buses[11] the recovery criteria follow the generator voltage fault ride through criteria in the Code. If only a single generator is connected to the bus and the fault is the loss of this single generator, then the criteria for a bus with no generators connected applies. The generator fault ride through criteria is shown in Appendix 2.

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[8] As with all power system modelling, load models, and the power system model are likely to contain a degree of error. To mitigate the effects of these errors, a 5% margin is maintained between the modelled voltage stability limit and the operating point.

[9] The major buses for the WUNI investigation refer to all 220 kV and 110 kV buses in the WUNI region.

[10] Buses with no generators connected includes buses with synchronous condensers or other dynamic reactive devices connected.

[11] Generator buses refers to Glenbrook 33 kV, Huntly 220 kV, Karapiro 110 kV and Arapuni 110 kV.

3.2.2 Security criteria

The Code dictates that for core-grid assets N-1 security is required. However, when economically justified we can apply a higher level of security.

Following the retirement of the last two remaining Huntly Rankine units, Huntly unit 5 is identified as both the single largest and highest risk contingency. To quantify the economic costs and benefits of the transmission system when that generator is unavailable, we also assessed N-G-1 security. This denotes an outage of the generator and the loss of another element (whether generator, circuit, or reactive device) in our analysis.

In addition, we identified and tested a third security criterion that provides partial N-G-1 security. In this criterion, the contingencies that have the lowest probability of occurring are covered by a post-fault demand management scheme (i.e. N-1 security), and primary plant is used to cover the more probable N-G-1 contingencies. This standard is referred to as N-G-(OTA-WKM). This approach is explained in more detail in Section 5.1.

3.3 Methodology

The purpose of this section is to explain the process that was followed to calculate load limits to define the need and the effectiveness of possible options.

An iterative approach was taken to prepare each short-list option. The methodology includes Power-Voltage (PV) analysis, dynamic analysis and review of thermal limits to incorporate the required building blocks to ensure voltage stability for the planning horizon out to 2045.

3.3.1 Dynamic voltage recovery analysis

Dynamic analysis is performed to find the dynamic voltage stability limits both for under- and over-voltage events.

The dynamic analysis starts at 95% of the nose point. A two-phase to ground fault is applied at the end of a circuit. The faulted circuit disconnected (tripped) after 100 milliseconds. If the voltage and current recovery falls outside the performance envelopes (voltage recovery and/or generator fault ride through envelopes), the WUNI load is reduced until the voltage recovery just passes the permissible recovery envelope. This sets the dynamic load limit for the WUNI region.

Some motor load will not ride through a fault, due to the low voltage the fault produces. The proportion of motor load that will trip in this analysis is according to motor load models explained in Section 3.1.4.

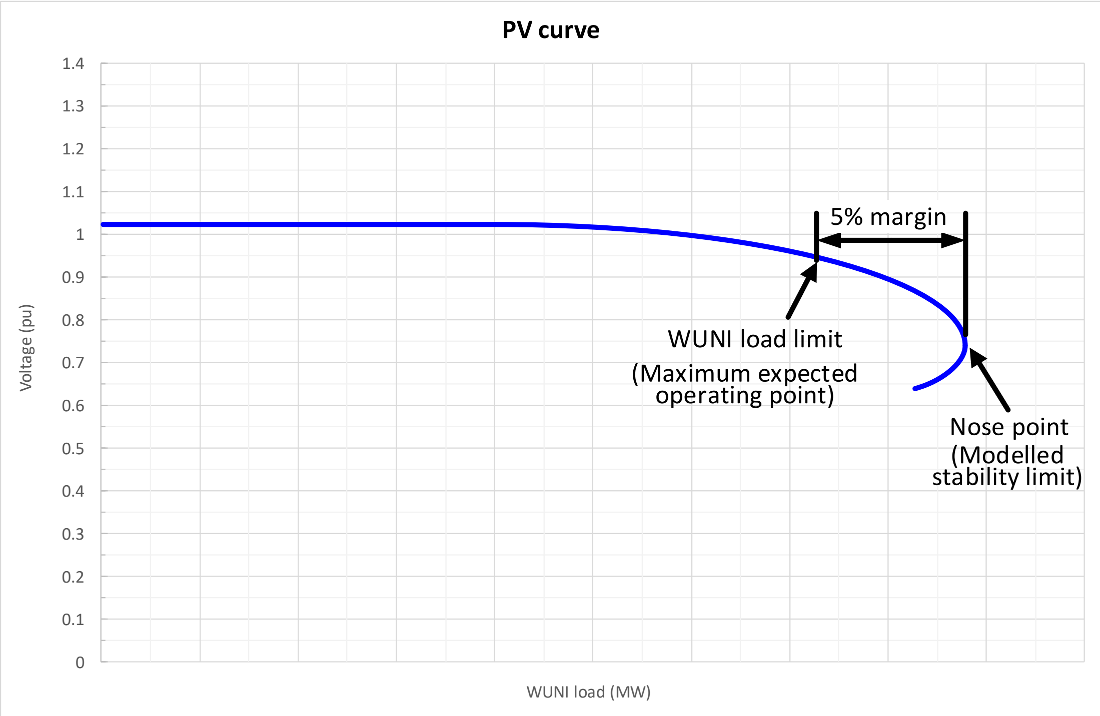
3.3.2 Long term voltage stability analysis

PV analysis is conducted to find the relationship between transmitted power and receiving voltage. PV curves are obtained through load flow analysis. The winter 2023 load year is used as the base for the study as it is the need date following the assumed retirement of the remaining Huntly Rankine units.

For PV analysis, the WUNI load is increased in steps while monitoring voltage levels at buses across the WUNI region. The characteristics of a PV curve (also illustrated in Figure 5) are:

- near the 'nose' of the PV curve, voltage drops rapidly with a small increase in power transfer.
- the PV nose point is the maximum power transfer into a region and the load at PV nose sets the voltage stability limit.
- operation at or near the voltage stability limit risks a widespread voltage collapse. A satisfactory operating condition is ensured by allowing a sufficient power margin. A margin of 5% from the nose point is applied throughout the investigation.

Figure 5: PV curve



3.3.3 Thermal limit analysis

Load flow contingency analysis is used to identify if there are any thermal issues on the network. However, there is no specific optimisation analysis into thermal issues as these issues are outside of the scope of this investigation. Earlier thermal studies undertaken by Transpower are used to identify possible modelled projects to address future thermal issues. If thermal limits bind ahead of voltage stability limits, a modelled project is included in the short-list option.

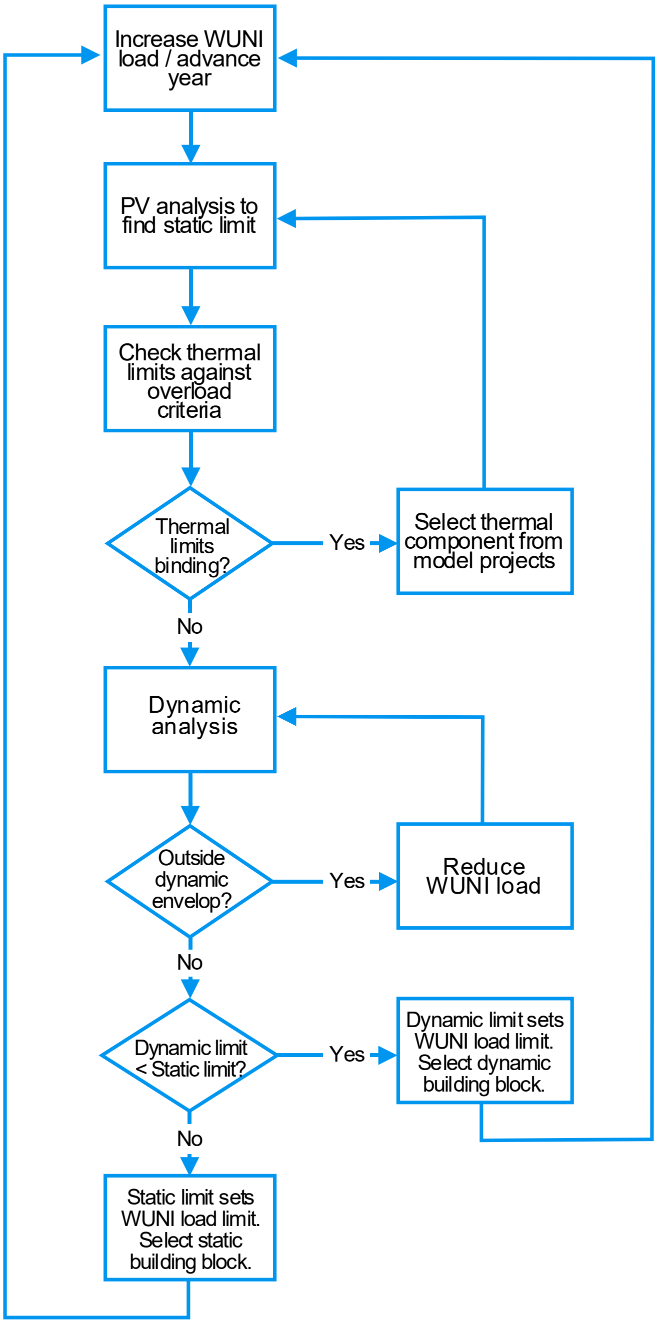
Short-term mitigation measures, when applicable, i.e. conductor short-term ratings (15-minute off load time), thermal special protection scheme may be used to address any thermal issues arises in the immediate planning horizon. A detailed investigation on longer-term solutions to address thermal issues will be carried out as a separate investigation.

3.3.4 Process to determine voltage limits

The methodology for calculating the voltage stability limits used to produce a short-list option is as follows, also illustrated in Figure 6:

- Starting from the base case, conduct PV analysis to find a PV load limit for transfer into the WUNI region.
- Check to identify thermally overloaded equipment: if found additional capacity is introduced from pre-defined modelled projects that were prepared as part of earlier thermal studies and recalculate PV limit.
- Conduct dynamic analysis at 95% of the PV 'nose' point. If the voltage recovery is:
    1. within the permissible voltage recovery envelope, dynamic simulation stops here. In this case, the PV load limit sets the static load limit for the WUNI region.
    2. outside the permissible voltage recovery envelope for 25% and 80% motor load assumptions, reduce WUNI load by 20 MW steps until the voltage recovery is within the permissible recovery envelope. This sets the dynamic load limit for the WUNI region.
- The voltage stability limit in the WUNI region is set by the lesser of (1) or (2). This limit sets the base case limit for a short-list option.
- When a new building block component is added to a short-list option (see Section 3.3.5 below), this analysis cycle is restarted to determine a new WUNI voltage stability load limit.

Figure 6: Short-list option methodology



Note:

- If voltage recovery falls within envelope but is slow and close to recovery boundary, dynamic equipment is selected.
- Pre-fault voltage plane will influence whether dynamic equipment is required instead of static equipment (to control the voltage).
- Non dynamic equipment is preferred investment due to cost.

3.3.5 Component selection methodology

When a WUNI load limit is identified, a new component is added to the short-list option to relieve the constraint and extend the development horizon further into the future.

The analysis required to prepare and validate a short-list option is extensive. To mitigate the upfront analysis required for this investigation we selected a small number of short-list options covering a broad range of possible components. The preferred transmission option was then optimised and studied further exploring sensitivities.

The type of component selected is based primarily on the voltage stability (PV limit) or voltage recovery (dynamic limit) criteria that is setting the WUNI voltage stability limit:

- If a PV limit, a static plant building block is selected to be included in the short-list option which will relieve the voltage stability limit. Shunt capacitors have the lowest build cost, so are selected first if no dynamic voltage recovery issues exist. However, if the voltage recovery is close to the voltage recovery envelope boundary, dynamic plant is also added to the short-list option. They are also selected when the dynamic reactive devices reach their pre-contingency production limit.
- If a dynamic limit (including over-voltage dynamic limits), a dynamic plant building block is selected to be included in the short-list option. Pre-fault voltage levels also influence whether dynamic plant is selected. Dynamic plant will be selected when the pre-contingency voltage plane in the WUNI region is high.

Note: Other devices (e.g. series capacitors, circuit reconductoring) also increase the voltage stability limit by reducing the circuit's impedance. These devices may also be selected to address thermal limits as a modelled project and may provide secondary benefits including reducing transmission losses.

Once a building block type has been selected, the location must then be chosen to:

- ensure that it adequately manages voltage recovery (for dynamic devices).
- ensure that it will raise the WUNI load limit.
- allow sufficient lead time to build the component before the need date.
- minimize major site-specific constraints (including major civil works and environmental restrictions).

Following the addition of the component to a short-list option, a new voltage stability limit is found following the method described in Section 3.3.4.

4 Identifying the system need

The purpose of this section is to describe the system needs that were identified using the assumptions outlined in Section 2.

In addition to the voltage stability need, we also analysed thermal constraints in the WUNI region. The results of this analysis are shown in Appendix 7.

4.1 Under-voltage

Our analysis identified that without the addition of reactive device or generation capacity into the WUNI region, the load will exceed the voltage stability limits (at prudent demand levels) from winter 2023 if Huntly unit 5 is on outage.

Figure 7 below shows the N-G-1 and N-1 WUNI load limits plotted along with the 2018 prudent winter demand forecast from 2020 to 2026, post the retirement of the Huntly Rankine units[12].

Figure 7: Existing WUNI load limits for different contingencies under N-G-1 and N-1 compared to 2018 prudent forecast

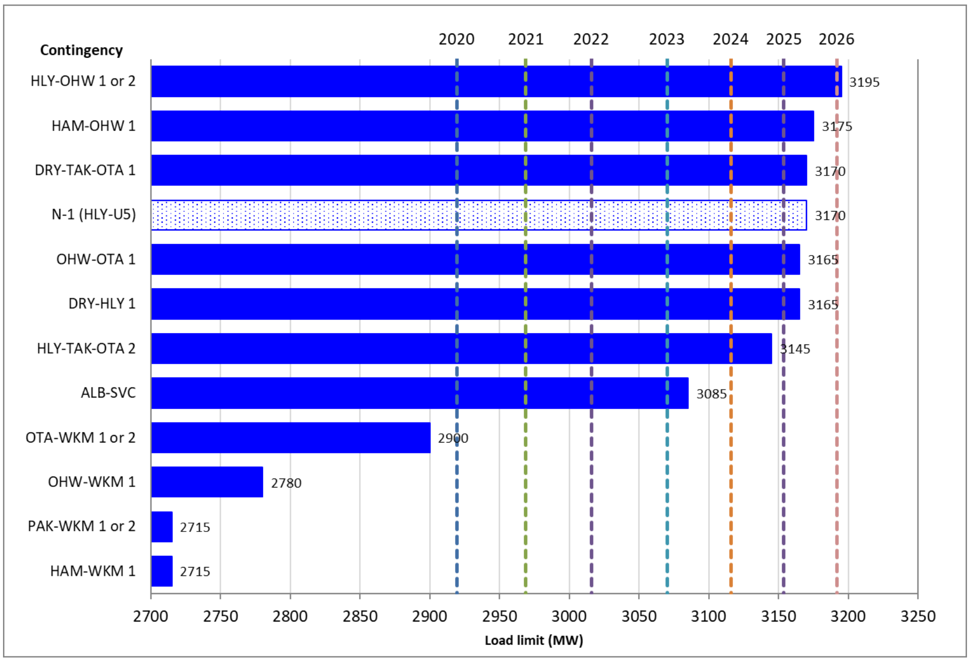


Figure 7 shows the:

- worst case faults under N-G-1 are 220 kV Hamilton–Whakamaru circuit or a 220 kV Pakuranga–Whakamaru circuit.
- N-G-1 WUNI load limit is 2715 MW, which is below the forecast 2020 load.
- worst case N-1 fault is Huntly unit 5.
- N-1 WUNI load limit is 3170 MW, which is forecast to be exceeded in 2026.

4.2 Over-voltage

Our analysis identifies that from winter 2023 over-voltage issues will require the addition of voltage support to manage the worst transient over-voltage (TOV) faults, which are on the 220 kV Huntly–Ohinewai, Hamilton–Whakamaru or Hamilton–Ohinewai circuits.

Table 6 summarises the impact of the Group 1 motor load tripping assumption on the transmission networks capability to meet voltage recovery (in particular the TOV) under N-1 and N-G-1 criteria in winter 2023. Detailed simulation results are shown in Appendix 4.

[12] See Appendix 3 for site abbreviations.

Table 6: 2023 TOV issues

Voltage recovery criteria for TOV under N-G-1	Percentage (%) of Group 1 motor load tripping	
	50%	80%
N-1		
Voltage overshoot <1.3 pu	Pass	Fail
Fault ride through curve	Fail	Fail
Voltage overshoot not above 1.1 pu for 2 seconds	Pass	Fail
N-G-1		
Voltage overshoot <1.3 pu	Pass	Fail
Fault ride through curve	Fail	Fail
Voltage overshoot not above 1.1 pu for 2 seconds	Fail	Fail

Our analysis shows without new voltage support investment to manage TOV issues, the WUNI load limit for:

- Huntly unit 5 in service pre-contingency is 2890 MW
- Huntly unit 5 not in-service pre-contingency is 2680 MW.

Therefore, investment is required by winter 2023 to increase the amount of dynamic reactive power absorption capacity and reduce the reactive power injected by shunt capacitors in the WUNI region.

5 The short-list

The short-list options comprise a combination of components that provide voltage stability throughout the future horizon to 2045 (based on the 2018 prudent forecast). This section provides key engineering details of the short-list component building blocks used in the short-list options. The short-listed components are described in more detail in Section 3 of the Options and Costing report.

5.1 Short-listed components

Shunt capacitors

Static reactive support is modelled using shunt capacitors to provide a representation of the necessary static voltage response. Shunt capacitors help prevent a slow voltage collapse by supporting the voltage level. Post-fault, shunt capacitors can also be switched to assist with dynamic response and provide static support once the voltage has stabilised.

Additional shunt capacitors are expected to be required in future to ensure static voltage limits remain in line with demand and generation growth in the WUNI region. The shunt capacitors are modelled connected at transmission voltage buses and are added to short-list options in 75 Mvar blocks.

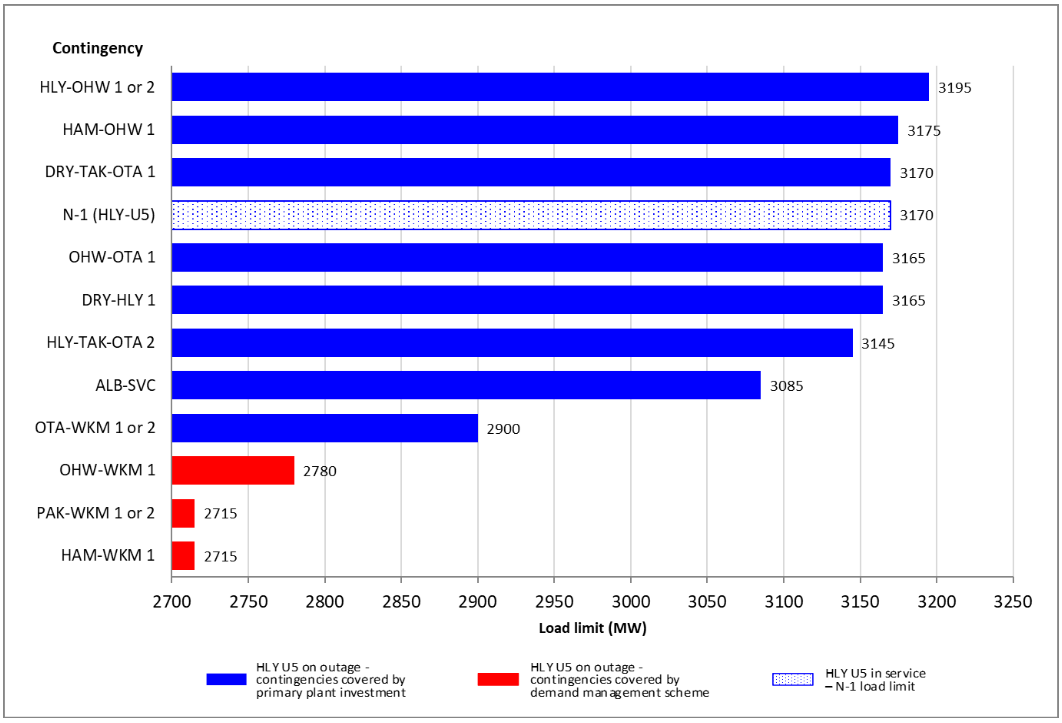
Post-fault demand management scheme

A post-fault demand management scheme enables N-G-1 security to be maintained while requiring lower investment requirements similar to N-1 security during an under-voltage event. The scheme will be armed if there is a single critical contingency (or outage) and WUNI load reaches the identified load limit; and triggered if a second of the selected critical contingencies occurs. The result is a reduction of WUNI demand, ensuring voltage stability is maintained post-contingency. The reduction of load also helps with relieving circuit loading. Figure 8 illustrates which contingencies are proposed to be covered by the demand management scheme. The contingencies covered by a load management scheme must be limited to those with a load limit below the N-1 load limit (3170 MW), based on the deterministic arm of the Grid Reliability Standards.

In parallel, to identify the contingencies with the lowest load limits, a review of circuit fault rates was performed. This review identified the Otahuhu–Whakamaru (OTA-WKM) 1 and 2 circuits have the highest risk of fault of major circuits in the WUNI region. Given this higher probability, we consider it would not be good electricity industry practice to manage these contingencies with a post-fault demand management scheme.

Refer to Appendix 6 for notes on the demand management scheme component.

Figure 8: Under-voltage event, the contingencies covered by primary plant investment and demand management scheme



By covering the hardest to manage contingencies that have a low frequency of tripping, a demand management scheme can provide a level of grid security similar to N-G-1 with a significantly lower level of primary plant investment.

Dynamic reactive devices

Dynamic reactive support is modelled using SVCs to provide a representation of the necessary dynamic response. SVCs are used as a building block providing dynamic support to raise the dynamic voltage stability limit. Although SVCs have different characteristics to other dynamic reactive support devices, they provide a suitable substitute for the purposes of an initial investigation for their capability in providing both continuous capacitive and inductive range. All SVC building blocks are modelled connected at transmission voltage buses and are added to short-list options in ±150 Mvar blocks.

Series capacitors

Series capacitors reduce the electrical length of transmission circuits to obtain the desired load division among parallel circuits and/or to improve system stability. Series capacitors on the Brownhill–Whakamaru circuits have been previously modelled as part of the earlier North Island Grid Upgrade investigation. For the purpose of preparing short-list options, the series capacitors are used for improving the dynamic voltage stability in the WUNI region by:

- improving dynamic system response, raising WUNI load limit.
- reducing transmission losses during high transfers.
- diverting power flow on heavily loaded circuits to the higher capacity Brownhill–Whakamaru circuits.

This investigation has assumed 45% compensation on the series capacitors[13].

Non-transmission solutions (NTS)

Reactive devices may be available as NTSs that we could contract for through a voltage support grid support contract (GSC)[14]. Large quantities of pre-fault demand management are another possible form of NTS.

NTSs do not have to be equivalent to transmission solutions but can defer or reduce the need for transmission solutions. We have not specifically analysed NTS in our power system modelling – instead, we model NTS as being provided by pre-fault demand management, quantified in our economic modelling in the Options and Costing report.

5.2 Modelled transmission components

Modelled projects are committed projects and future new assets or changes to existing assets that are outside of our immediate investment horizon.

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[13] 45% series compensation was established taking into consideration the balancing of voltage and thermal constraints (220 kV Brownhill–Pakuranga cables connected in series with the compensated circuits), wide area protection, sub-synchronous interactions and possible future grid configurations.

[14] Information on the design features of Transpower's grid support contracts (GSCs) is available at www.transpower.co.nz/grid-support-contracts.

The committed projects are included in all our short-list options as modelled projects. They were identified in the WUNIVM investigation but will be delivered under different work programmes rather than through the WUNIVM MCP. These projects are:

- 250 Mvar of shunt reactive support in the Waikato region to levelise the voltage profile across the transmission system. They help minimise reactive power exchange between regions, hence increase the capability of transferring active power into the WUNI region. These shunt capacitors will be installed at Ohinewai 220 kV and Hamilton 110 kV buses with an expected commissioning date of 2020.
- Automatic over-voltage capacitor switching scheme (AOVCS). A protection based automated over-voltage capacitor switching scheme to help control the over-voltage observed in our studies. This scheme:
  - is used alongside dynamic devices such as SVCs.
  - is intended to provide greater levels of reactive power reduction with significantly reduced investment cost.
  - would enable existing and future shunt capacitors in the WUNI region to be used to respond to transient over-voltage conditions.
  - would activate within a few hundred milliseconds and be aware of the real-time status of capacitors to ensure that the correct number of capacitors are switched in a controlled manner should voltages exceed their setpoints.

  Such a scheme does not replace the need for dynamic reactive devices but can reduce the need for such devices. The scheme will be installed in the WUNI region with an expected commissioning date of 2022.

The other modelled projects include shunt capacitors and SVCs as representation of static and dynamic reactive support component to increase voltage stability limit outside the immediate investment horizon (2023-2024). Modelled projects are also used to alleviate thermal issues (see Section 3.1.3 for more information).

6 Options analysis

The purpose of this section is to present the analysis and development of short-list options.

6.1 Changes since the short list consultation

We have made a number of changes to the ‘identify and assess options’ step of the option assessment approach process[15] since the short list consultation in June 2019.

- We undertook additional analysis to derive load limits associated with the over-voltage risk. This allowed us to include the over-voltage risk in our calculation of unserved energy costs (described in the Options and costing report).

[15] The process involves four key stages of investigation designed to systematically identify the best short-list option. Refer to Options and Costing report for more information.

- We added options to our short list to better show how each option delivers different voltage stability limits and therefore benefits to New Zealand electricity consumers.
- We removed option 6 from the short list[16] – the components in this option have a significantly greater cost than other options as demonstrated in the short list consultation. We excluded them as the analysis would provide little benefit.

6.2 Meeting the need in winter 2023

Following the Rankine units' retirement at the end of 2022, with no investment the power system would not be able to meet the forecast load from winter 2023 (based on the 2018 forecast). The WUNI area load is limited by the dynamic voltage stability limit. Table 7 shows the WUNI stability limit for each component assessed. The development path in each short-list option is built up starting with these components.

Table 7: WUNI load limit

Component	WUNI load limit (MW)	Binding*	Contingency	2023 voltage stability (pass/fail)
Investment timing: N-1				
Post Rankine retirement, no investment	2890 MW	TOV	HAM-WKM 1	Fail
First ±150 Mvar SVC at Otahuhu 220 kV	3020 MW	TOV	OTA SVC	Fail
First ±150 Mvar SVC at Hamilton 110 kV	3190 MW	TOV	HAM-OHW 1	Pass
Series capacitor 45%	3020 MW	TOV	HLY-OHW 1 or 2	Fail
Two SVCs (Otahuhu and Hamilton)	3295 MW	TOV	OTA SVC	Pass
Investment timing: N-G-1				
Post Rankine retirement, no investment	2680 MW	TOV	HAM-WKM 1	Fail
First ±150 Mvar SVC at Otahuhu 220 kV	2835 MW	UV	PAK-WKM 1 or 2	Fail
First ±150 Mvar SVC at Hamilton 110 kV	2835 MW	UV	PAK-WKM 1 or 2	Fail
Series capacitor 45%	2825 MW	UV	PAK-WKM 1 or 2	Fail
Two SVCs (Otahuhu and Hamilton)	2985 MW	UV	PAK-WKM 1 or 2	Fail
Investment timing: N-G-(OTA-WKM)				
Post Rankine retirement, no investment	2680 MW	TOV	HAM-WKM 1	Fail
First ±150 Mvar SVC at Otahuhu 220 kV	2840 MW	TOV	OTA SVC	Fail
First ±150 Mvar SVC at Hamilton 110 kV	2980 MW	TOV	HAM-OHW 1	Fail
Series capacitor 45%	2910 MW	TOV	HAM-WKM 1	Fail
Two SVCs (Otahuhu and Hamilton)	3105 MW	TOV	OTA SVC	Pass

* PV = static limit, UV = under-voltage dynamic limit, TOV = Transient over-voltage dynamic limit

[16] Option 6 used TSRs and series capacitors instead of SVCs to manage voltage stability during the immediate investment horizon providing the same benefits as SVCs at significantly greater cost.

Analysis shows that the reactive power requirement need cannot be met by a single component to alleviate both N-G-1 under-voltage and TOV issues. We need to invest in either:

- Two SVCs and a demand management scheme, or
- Two SVCs and series capacitors.

The combination of components above are required to maintain voltage stability once the Rankine units retire and as demand grows in the WUNI region.

Under N-1, analysis shows an SVC is still required to alleviate TOV issue even if Huntly unit 5 is in service pre-contingency.

Appendix 5 shows simulation results with one SVC and two SVCs under N-1 and N-G-1 to meet winter 2023 load.

6.3 Short-list options

This section details the short-list options prepared out to 2045. For a more detailed explanation of each option, please refer to the Options and Costing report.

6.3.1 Option 1 – Non-transmission solution (NTS)

Under this option, the combined under- and over-voltage need will be met by pre-fault demand management as a non-transmission solution.

6.3.2 Option 2 – N-G-1 with demand management

In this option, two SVCs and a post-fault demand management scheme are used to manage voltage stability in the WUNI region. The timing of component build is based on the N-G-(OTA-WKM) voltage stability limit. A post-fault demand management scheme is deployed to manage a few of the more severe and low probability faults during under-voltage events, meeting the N-G-1 standard with post-fault demand management.

This option includes the addition of series capacitors in 2024 and Ohinewai tee development in 2030 as modelled projects, to further increase the voltage stability and thermal limit in the WUNI region. The Ohinewai tee development helps to uplift the voltage stability limit by creating a more meshed 220 kV network between Whakamaru and Auckland. It also relieves the loading on the Brownhill–Pakuranga cables which are connected in series with the series compensated circuits. Thereafter, SVCs and/or shunt capacitors are built as required to meet the voltage stability need. Table 8 shows the list of components up to 2045.

Table 8: Option 2 (N-G-1 with demand management) – list of components

Option 2	WUNI load limit (MW)	Binding	Need date
Two ±150 Mvar SVCs Demand management scheme	3105	Dynamic	2023
Series capacitors on 220 kV Brownhill–Whakamaru circuits with 45% compensation	3355	Dynamic	2024
Ohinewai tee*	3485	Dynamic/ Thermal	2030
±150 Mvar SVC 150 Mvar capacitor banks	3595	Dynamic/ Static	2035
±150 Mvar SVC 150 Mvar capacitor banks	3735	Dynamic/ Static	2038
±150 Mvar SVC 150 Mvar capacitor banks	3885	Dynamic/ Static	2042
* Ohinewai tee results in reconductoring the Otahuhu–Whakamaru 1 and 2 with modern equivalent conductor when they reach the end of their useful life, assumed to be in 2033.			

6.3.3 Option 3 – N-1

The investment timing is based on the N-1 standard. In addition to the firm N-1 security provided by primary plant, we utilize the post-fault demand management scheme to cover a subset of specific, long-duration N-G-1 contingencies outages that could occur on the grid (e.g. Huntly unit 5, or a Brownhill–Pakuranga cable outage). We consider it prudent to guard against these long-duration contingencies even in options such as this that do not cover other N-G-1 contingencies, and therefore only provide firm N-1 security.

The addition of series capacitors is deferred to 2029 compared to option 2, because of the use of the lower security standard in this option. The Ohinewai tee reconfiguration will be built to relieve thermal constraints on Brownhill–Pakuranga cables initially, and to assist with voltage stability. SVCs and/or shunt capacitors are built as required to meet the voltage stability need every three to five years. Table 9 shows the list of components up to 2045.

Table 9: Option 3 (N-1) – list of components

Option 3	WUNI load limit (MW)	Binding	Need date
Demand management scheme One ±150 Mvar SVC	3190	Dynamic	2023
One ±150 Mvar SVCs	3295	Dynamic	2026
Series capacitors on 220 kV Brownhill–Whakamaru circuits with 45% compensation*	3485	Dynamic/ Static	2029
±150 Mvar SVC 150 Mvar capacitor banks	3650	Dynamic	2035
±150 Mvar SVC 150 Mvar capacitor banks	3790	Dynamic/ Static	2039
Ohinewai Tee**	3855	Thermal	2040

Option 3	WUNI load limit (MW)	Binding	Need date
±150 Mvar SVC 150 Mvar capacitor banks	4010	Dynamic/ Static	2045

* Reconductor Otahuhu–Whakamaru 1 and 2 with modern equivalent conductor when they reach the end of their useful life, assumed to be in 2033.

** Existing Brownhill–Pakuranga cable will reach 91% loading pre-contingency.

6.3.4 Option 4 – N-G-1

This option uses primary plant to cover the N-G-1 standard – with no use of a post-fault demand management scheme. Compared to option 2, in addition to the two SVCs needed in 2023, series compensation on the 220 kV Brownhill–Whakamaru circuits is also required to manage N-G-1 standard as soon as the Rankine units retire. Maintaining the N-G-1 standard without a post-fault demand management scheme requires approximately 300 Mvar reactive support every two to three years. Table 10 shows the list of components up to 2045.

Table 10: Option 4 (N-G-1) – list of components

Option 4	WUNI load limit (MW)	Binding	Need date
Two ±150 Mvar SVCs Series capacitors on 220 kV Brownhill–Whakamaru circuits with 45% compensation	3075	Dynamic	2023
±150 Mvar SVC	3200	Dynamic	2024
150 Mvar capacitor banks	3265	Static	2027
±150 Mvar SVC 75 Mvar capacitor banks	3415	Dynamic/ Static	2029
Ohinewai tee*	3420	Thermal/ Dynamic	2030
±150 Mvar SVC 150 Mvar capacitor banks	3485	Dynamic/ Static	2033
±150 Mvar SVC 150 Mvar capacitor banks	3605	Dynamic/ Static	2035
±150 Mvar SVC 150 Mvar capacitor banks	3675	Dynamic/ Static	2038
±150 Mvar SVC 150 Mvar capacitor banks	3785	Dynamic/ Static	2040
±150 Mvar SVC 150 Mvar capacitor banks	3860	Dynamic/ Static	2043
±150 Mvar SVC 150 Mvar capacitor banks	4000	Dynamic/ Static	2045

* Ohinewai tee results in reconductoring the Otahuhu–Whakamaru 1 and 2 with modern equivalent conductor when they reach the end of their useful life, assumed to be in 2033.

6.3.5 Option 5 – N-1 without series capacitors

Similar to option 3, this option explores the deployment of dynamic reactive devices rather than series capacitors to meet voltage stability need. The addition of series capacitors in 2029 in option 3 is replaced with an SVC in this option. The investment timing is based on the N-1 standard. This option uses the post-fault demand management scheme, the same context as in option 3.

The Ohinewai bussing reconfiguration is needed by 2031 to relieve the thermal constraints on some 220 kV circuits[17]. 300 Mvar reactive support is required in 2035 and additional SVCs and/or shunt capacitors are required every four years. Table 11 shows the list of components up to 2045.

Table 11: Option 5 (N-1 without series capacitors) – list of components

Option 5	WUNI load limit (MW)	Binding	Need date
One ±150 Mvar SVC Demand management scheme	3190	Dynamic	2023
±150 Mvar SVC	3295	Dynamic	2026
±150 Mvar SVC	3355	Static	2029
150 Mvar capacitor banks Ohinewai bussing*	3500	Dynamic/ Thermal	2031
±150 Mvar SVC 150 Mvar capacitor banks	3590	Dynamic/ Static	2035
±150 Mvar SVC 150 Mvar capacitor banks	3735	Dynamic/ Static	2037
±150 Mvar SVC 150 Mvar capacitor banks	3860	Dynamic/ Static	2041
±150 Mvar SVC 150 Mvar capacitor banks	4010	Dynamic/ Static	2045
* Ohinewai bussing results in the section from Ohinewai to Otahuhu of the Otahuhu–Whakamaru 1 and 2 being disconnected when they reach the end of their useful life, assumed to be in 2033.			

6.4 Short-list options based on 2019 forecast

The power system analysis to determine the need and prepare the short-list options have been carried out using Transpower's 2018 demand forecast. In July 2019, the Ministry of Business, Innovation and Employment published its Electricity Demand and Generation Scenarios (EDGS), which we have incorporated into our latest 2019 demand forecast. Due to the extensive effort and time required to perform our power system analysis, we have not rerun our analysis using the 2019 forecast. Instead, we used the voltage stability limits from our studies, aligned to our 2019 EDGS prudent forecast to determine component timings within our immediate investment horizon (2023-2024 inclusive). These component timings

[17] Overloading of Hamilton–Whakamaru 1, Ohinewai–Whakamaru 1 and Otahuhu–Whakamaru 1 and 2 circuits for major 220 kV contingencies.

are used to form the short-list options and in our economic analysis, described in the Options and Costing report. This new forecast is higher than the 2018 forecast, in part due to actual growth in historical peak demand in the region. Therefore, applying the new forecast has led to earlier need dates for components.

Table 12 summarises the timing of short-list options using the 2019 forecast in our immediate investment horizon (2023 and 2024). In addition to the five short-list options presented in this report, we have added two options (do-nothing, and option 6) to our short-list that do not provide N-1 security during the immediate investment horizon. We included these to demonstrate the economic benefits of the other options.

Table 12: Short-list options within our immediate investment horizon with 2019 forecast

	2023	2024
Defer investment until the end of 2028 (N)		
Option 1 - NTS (N-G-1)	• Pre-fault demand management as NTS	
Option 2 (N-G-1 with demand management)	• Two ±150 Mvar SVCs • Post-fault demand management scheme • Series capacitors on 220 kV Brownhill–Whakamaru circuits with 45% compensation	
Option 3 (N-1)	• Two ±150 Mvar SVCs • Post-fault demand management scheme	• Series capacitors on 220 kV Brownhill–Whakamaru circuits with 45% compensation
Option 4 (N-G-1)	• Three ±150 Mvar SVCs • Series capacitors on 220 kV Brownhill–Whakamaru circuits with 45% compensation • 150 Mvar shunt capacitors	• ±150 Mvar SVC • 75 Mvar shunt capacitors
Option 5 (N-1)	• Two ±150 Mvar SVC • Post-fault demand management scheme	• ±150 Mvar SVC • 150 Mvar shunt capacitors
Option 6 (N)	• Two ±150 Mvar SVC • Post-fault demand management scheme	

Appendix 1 Contributions to WUNI prudent peak load and forecast power factor

Table A1-1 shows estimated load in each region of interest at time of the WUNI prudent peak forecast.

Table A1-1: 10-year region's forecast load at the time of WUNI prudent peak (2018 demand forecast)

Region	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Northland	282	288	292	297	302	307	311	315	319	323
Auckland	2054	2089	2122	2156	2193	2225	2249	2275	2298	2323
Waikato	546	553	565	573	585	594	604	612	622	629
Upper North Island	2337	2377	2414	2453	2496	2532	2560	2590	2617	2646
Upper North Island + Waikato (WUNI)	**2883**	**2930**	**2979**	**3026**	**3081**	**3126**	**3164**	**3202**	**3239**	**3275**

Table A1-2 shows load and power factor at each grid exit point at the time of the prudent forecast WUNI peak.

Table A1-2: 10-year forecast load and power factor at each grid exit point at time of prudent WUNI peak (2018 demand forecast)

Grid exit point	Power factor	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Northland											
Bream Bay	0.976	60	59	59	59	60	60	61	61	62	62
Kaikohe	1.000	67	77	79	83	84	85	86	86	87	87
Maungatapere	0.996	107	105	105	106	108	110	112	114	116	118
Maungaturoto	1.000	16	16	16	16	17	17	17	17	18	18
Wellsford	1.000	32	32	33	34	34	35	36	37	37	38
Auckland											
Albany 33 kV	0.996	147	148	149	150	151	152	152	155	155	156
Wairau Road	0.944	133	134	136	137	139	140	141	141	142	143
Bombay 33 kV	0.999	15	16	0	0	0	0	0	0	0	0
Bombay 110 kV	0.999	59	64	85	91	96	102	106	110	114	118
Glenbrook 33 kV	0.984	27	28	29	30	30	31	32	32	32	33
Glenbrook - NZ Steel	0.930	85	85	85	85	85	85	85	85	85	85
Henderson	0.999	137	141	146	152	159	165	170	176	179	184
Hepburn Road	1.000	148	149	150	152	153	154	155	155	156	157

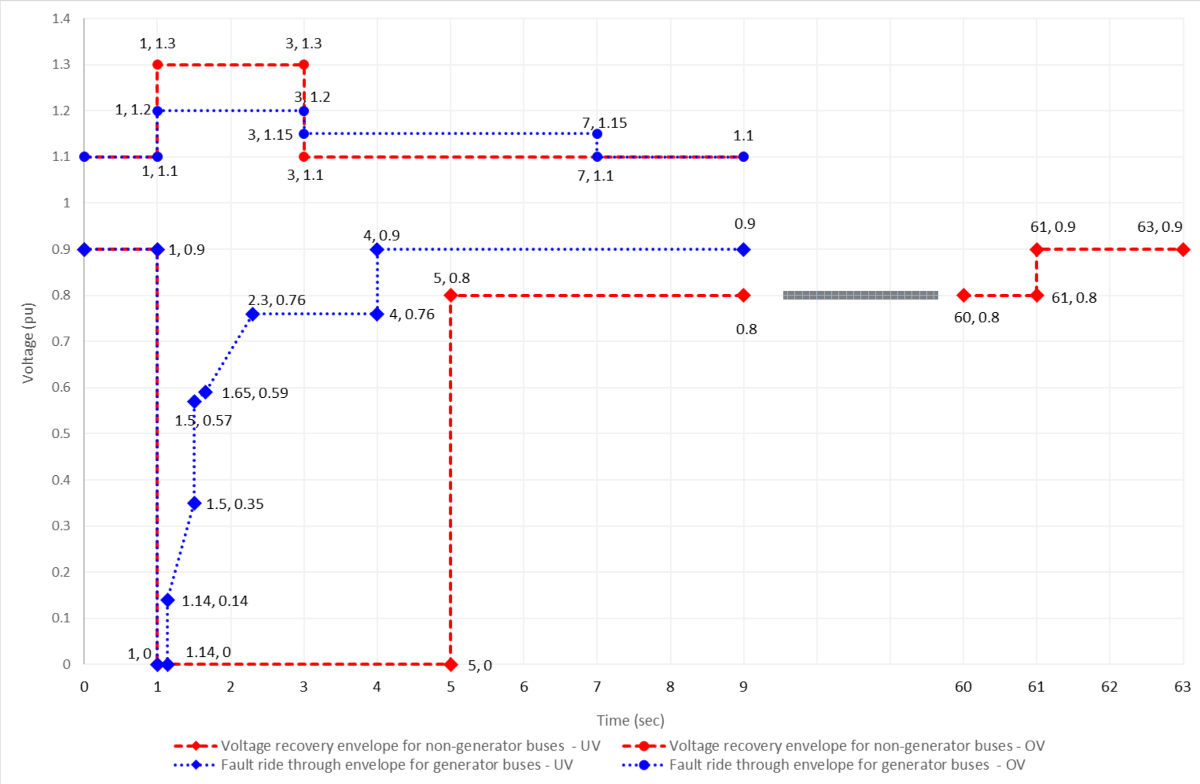
Grid exit point	Power factor	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Hobson Street	0.974	83	85	87	89	92	94	95	96	97	98
Mangere 33 kV	0.990	114	116	119	123	125	127	128	129	130	131
Mangere 110 kV	0.986	11	11	11	11	11	11	11	11	11	11
Mt Roskill 22 kV	0.989	111	112	113	115	116	117	117	118	119	120
Mt Roskill 110 kV	1.000	54	54	55	50	50	51	51	51	51	51
Otahuhu	0.991	64	64	64	65	66	66	66	66	66	67
Pakuranga	0.994	163	164	165	167	168	169	170	171	171	172
Penrose 22 kV	0.984	32	33	33	33	34	35	35	35	35	36
Penrose 25 kV	0.998	2	2	2	2	2	2	2	2	2	2
Penrose 33 kV	0.990	284	288	292	296	299	301	304	306	308	310
Penrose 110 kV – Liverpool Street	0.974	83	86	88	90	92	94	95	97	98	99
Silverdale	1.000	87	88	90	92	94	95	96	97	98	99
Southdown 25 kV	0.998	2	2	2	2	2	2	2	2	2	2
Takanini	0.995	125	127	128	131	133	134	136	137	139	141
Wiri	0.988	90	93	94	94	97	99	101	103	105	107

Waikato											
Cambridge	0.993	37	39	40	41	42	43	45	46	47	48
Hamilton 11 kV	0.998	26	26	27	27	28	28	28	28	29	30
Hamilton 33 kV	1.000	120	120	121	122	124	125	127	128	130	131
Hamilton NZR	0.831	1	1	1	1	1	1	1	1	1	1
Hangatiki	0.925	32	33	35	36	37	37	38	39	39	40
Hinuera	0.992	40	41	41	42	40	41	42	43	44	45
Huntly	1.000	24	25	25	25	25	25	26	27	27	27
Kopu	1.000	43	43	43	44	45	46	47	48	48	49
Piako	0.994	31	31	31	34	35	35	36	36	37	38
Te Awamutu	0.988	33	34	37	37	38	38	39	39	40	40
Te Kowhai	0.994	91	92	94	96	99	101	102	103	104	105
Waihou	1.000	35	35	35	36	36	37	37	37	38	38
Waikino	1.000	33	33	34	34	35	35	36	37	37	38

Appendix 2 Voltage recovery criteria

Transpower's transient voltage recovery criteria are derived from the requirements set out in the Electricity Industry Participation Code (Code) reliability standard for the New Zealand Power Transmission System. For generator buses the recovery criteria follow the generator voltage fault ride through criteria in the Code[18]. The voltage recovery criteria are shown in Figure A2-1.

Figure A2-1: Voltage recovery criteria



Note that for the under-voltage criteria the fault occurs at time 1 second, and the graph is discontinuous between 9 and 60 seconds, so – for example – the 61 second line represents 60 seconds after the fault.

Note that the over-voltage criteria apply from the point at which the voltage is above 1.1 pu. This is illustrated at 1 second in the graph but could be at a different time.

[18] Section 8.25A of the Code.

Appendix 3 Substation abbreviations

ALB	Albany
ARI	Arapuni
BHL	Brownhill
BOB	Bombay
BRB	Bream Bay
CBG	Cambridge
DRY	Drury
GLN	Glenbrook
HAM	Hamilton
HEN	Henderson
HEP	Hepburn Road
HIN	Hinuera
HLY	Huntly
HOB	Hobson Street
HPI	Huapai
HTI	Hangatiki
KOE	Kaikohe
KPO	Karapiro
KPU	Kopu
LST	Liverpool Street
MDN	Marsden

MNG	Mangere
MPE	Maungatapere
MTO	Maungaturoto
OHW	Ohinewai
OTA	Otahuhu
PAK	Pakuranga
PAO	Piako
PEN	Penrose
ROS	Mount Roskill
SVL	Silverdale
SWN	Southdown
TAK	Takanini
TMU	Te Awamutu
TWH	Te Kowhai
WEL	Wellsford
WHU	Waihou
WIR	Wiri
WKM	Whakamaru
WKO	Waikino
WRD	Wairau Road

Appendix 4 Simulation results – System need in winter 2023

A4.1 N-1 transient voltage recovery need

Figure A4-1 shows the first two seconds of the voltage response to a fault on the 220 kV Hamilton–Whakamaru circuit with 50% Group 1 motor tripping in winter 2023.

Figure A4-1: Tripping of 50% Group 1 motor load, contingency: 220 kV Hamilton–Whakamaru circuit

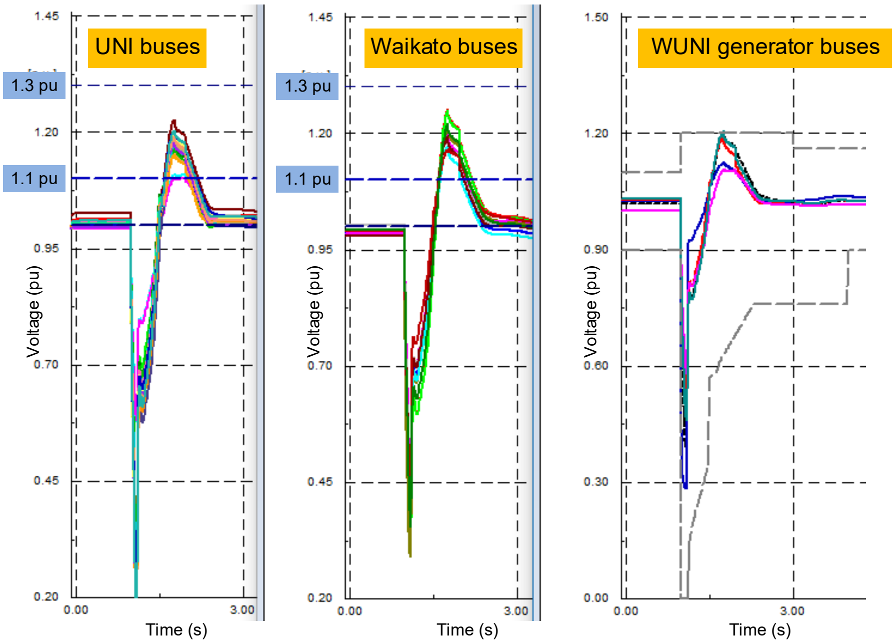


Figure A4-1 shows that:

- bus voltages exceed 1.1 pu within 350 ms after the fault clears.
- bus voltages do not exceed 1.3 pu, which passes our criteria.
- generator bus voltages exceed 1.2 pu, which fails our criteria.
- bus voltages return to 1.1 pu within 2 seconds, which passes our criteria.

Figure A4-2 shows the first two seconds of the voltage response to a fault on the 220 kV Hamilton–Whakamaru circuit with 80% Group 1 motor tripping in winter 2023.

Figure A4-2: Tripping of 80% Group 1 motor load, contingency: 220 kV Hamilton–Whakamaru circuit

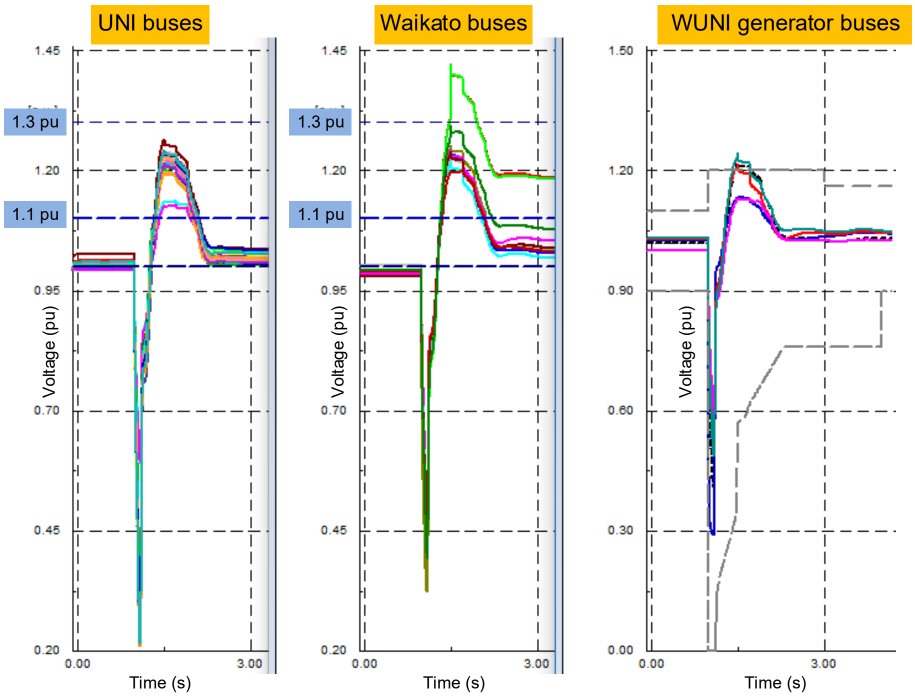


Figure A4-2 shows that:

- bus voltages exceed 1.1 pu within 250 ms after the fault clears.
- several bus voltages in the Waikato exceed 1.3 pu, which fails our criteria.
- generator bus voltages exceed 1.2 pu, which fails our criteria.
- several bus voltages do not return to 1.1 pu within 2 seconds, which fails our criteria.

A4.2 N-G-1 transient voltage recovery need

Figure A4-3 shows the first two seconds of the voltage response to a fault on the 220 kV Huntly–Ohinewai circuit with 50% Group 1 motor tripping in winter 2023 when Huntly unit 5 is on outage.

Figure A4-3: Tripping of 50% Group 1 motor load, contingency: 220 kV Huntly–Ohinewai circuit

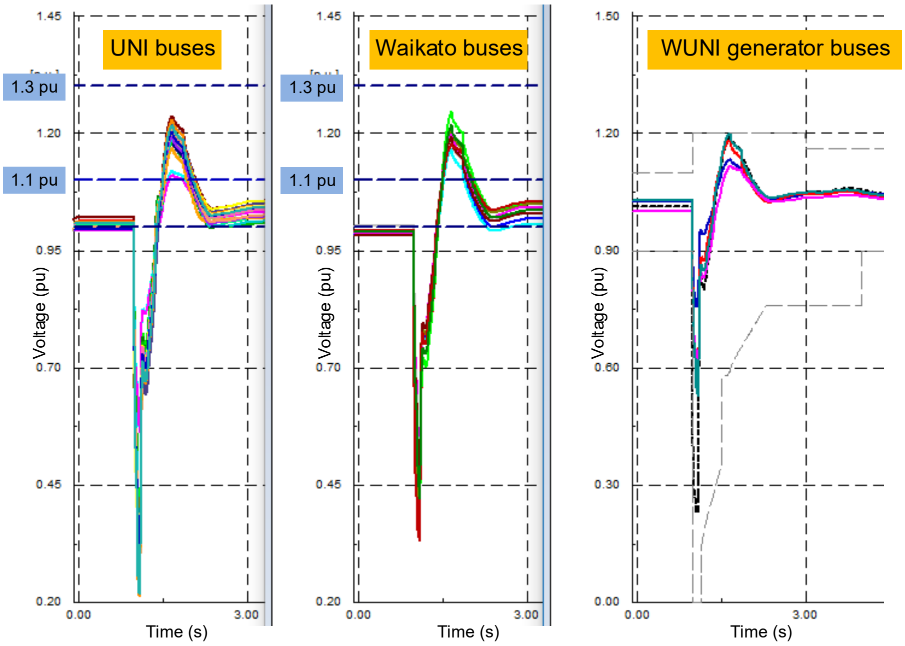


Figure A4-3 shows that:

- bus voltages exceed 1.1 pu within 300 ms after the fault clears.
- bus voltages do not exceed 1.3 pu, which passes our criteria.
- generator bus voltages exceed 1.2 pu, which fails our criteria.
- bus voltages return to 1.1 pu within 2 seconds, which passes our criteria.

Figure A4-4 shows the first two seconds of the voltage response to a fault on the 220 kV Hamilton–Whakamaru circuit with 80% Group 1 motor tripping in winter 2023 when Huntly unit 5 is on outage.

Figure A4-4: Tripping of 80% Group 1 motor load, contingency: 220 kV Hamilton–Whakamaru circuit

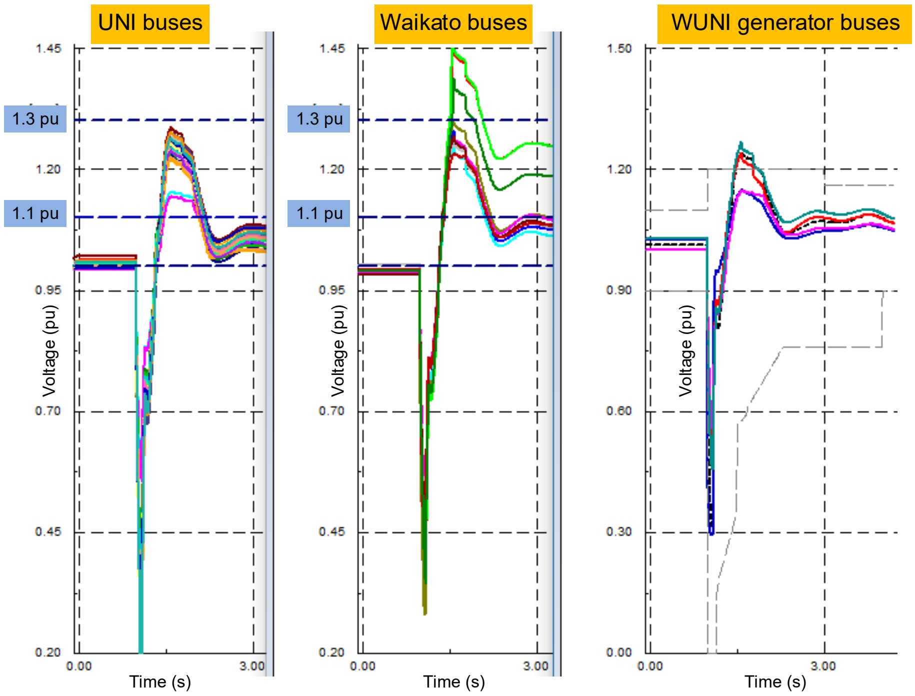


Figure A4-4 shows that:

- bus voltages exceed 1.1 pu within 200 ms after the fault clears.
- several bus voltages in the Waikato exceed 1.3 pu, which fails our criteria.
- all generator bus voltages exceed 1.2 pu, which fails our criteria.
- some bus voltages in the Waikato do not return to 1.1 pu within 2 seconds, which fails our criteria.

Appendix 5 Simulation results – Option analysis

This section shows the winter 2023 simulation results with one SVC only (either at Otahuhu or Hamilton) and two SVCs (one at Otahuhu and one at Hamilton). The SVC is rated at ±150 Mvar, connected at 220 kV bus at Otahuhu and 110 kV bus at Hamilton.

A5.1 N-1 option analysis

Under N-1, the WUNI voltage stability is limited by TOV in winter 2023. Option analysis were carried for an SVC at either Otahuhu or Hamilton for 50% and 80% Group 1 motor tripping. Results showed that:

- one SVC at either Hamilton or Otahuhu is sufficient to mitigate TOV issue for 50% Group 1 motor tripping
- an SVC at Hamilton is required to mitigate the TOV issue for 80% Group 1 motor tripping.

Figure A5-1 and Figure A5-2 show the first two seconds of the voltage response with one new SVC at Otahuhu and one new SVC at Hamilton for 80% group 1 motor tripping.

Figure A5-1: One SVC at Otahuhu, contingency: Otahuhu SVC

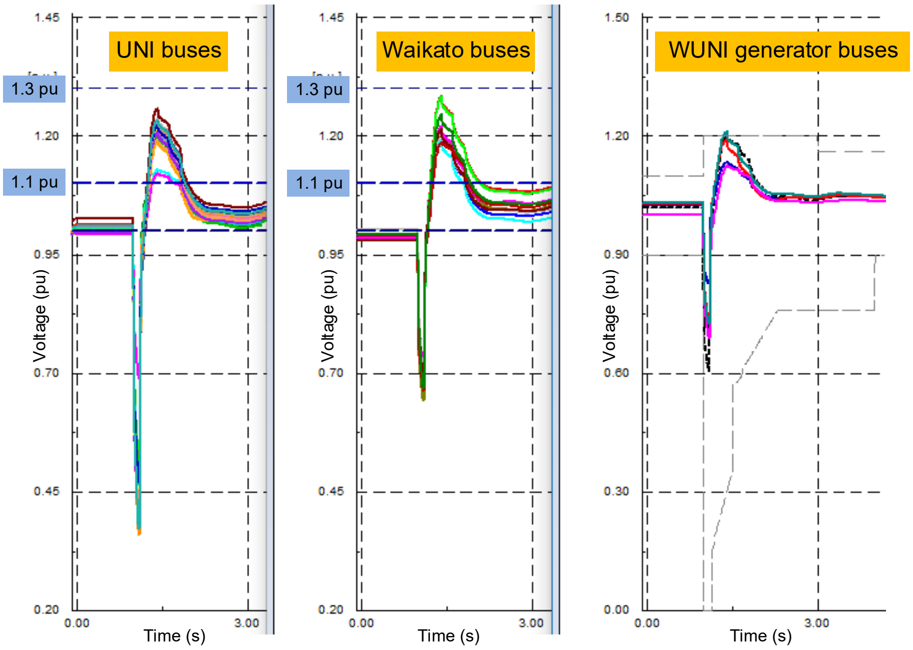


Figure A5-1 shows that:

- bus voltages exceed 1.1 pu within 250 ms after the fault clears.
- bus voltages do not exceed 1.3 pu, which passes our criteria.
- generator bus voltages exceed 1.2 pu, which fails our criteria.

Figure A5-2: One SVC at Hamilton, contingency: 220 kV Hamilton–Ohinewai 1 circuit

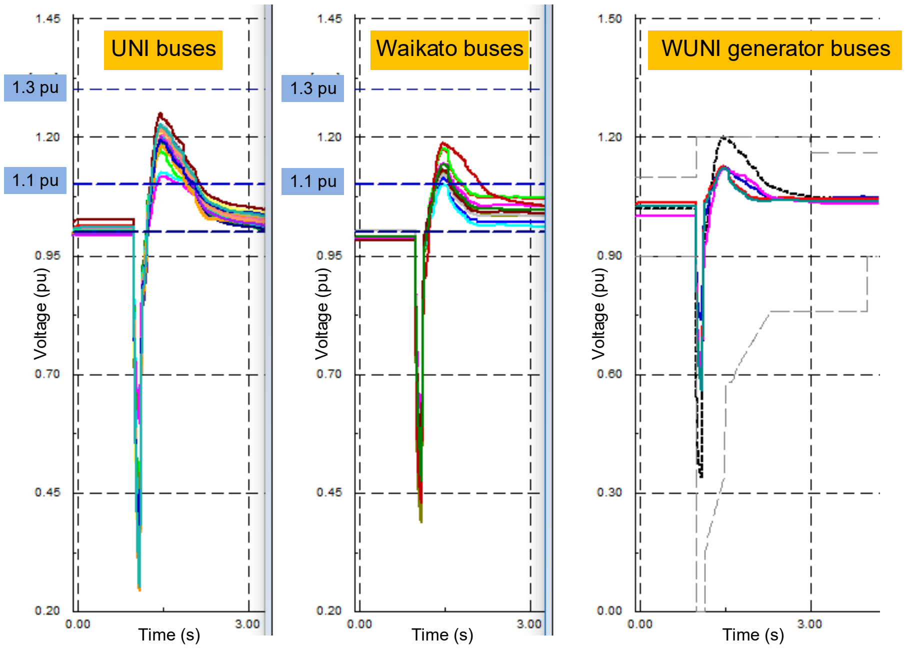


Figure A5-2 shows that:

- bus voltages exceed 1.1 pu within 250 ms after the fault clears.
- bus voltages do not exceed 1.3 pu, which passes our criteria.
- generator bus voltages do not exceed 1.2 pu, which passes our criteria.

A5.2 N-G-1 option analysis

Under-voltage

Analysis shows one SVC is not enough to meet 2023 winter peak load under N-G-1 (based on the 2018 forecast).

Figure A5-3 and Figure A5-4 illustrate the results of the first five seconds of an N-G-1 under-voltage event for one new SVC installed at Otahuhu and at Hamilton respectively. The fault is on the 220 kV Otahuhu–Whakamaru[19] circuit when Huntly unit 5 is on outage.

[19] As discussed in Section 3.2.2, N-G-(OTA-WKM) set the minimum standard covered by primary plant investment where a demand management scheme is employed to manage N-G-1 security.

Figure A5-3: One SVC at Otahuhu, contingency: 220 kV Otahuhu–Whakamaru circuit

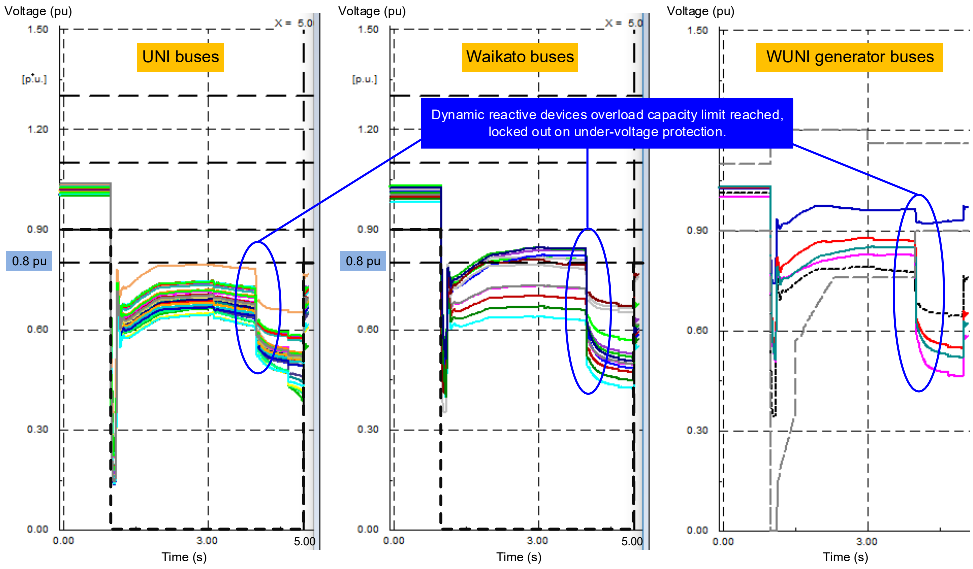


Figure A5-3 shows that:

- all bus voltages do not recover above 0.8 pu within 4 seconds, which fails our criteria.
- all generator bus voltages do not recover above 0.76 pu within 1.3 seconds, which fails our criteria.
- dynamic reactive devices locked out by under-voltage protection.

Figure A5-4: One SVC at Hamilton, contingency: 220 kV Otahuhu–Whakamaru circuit

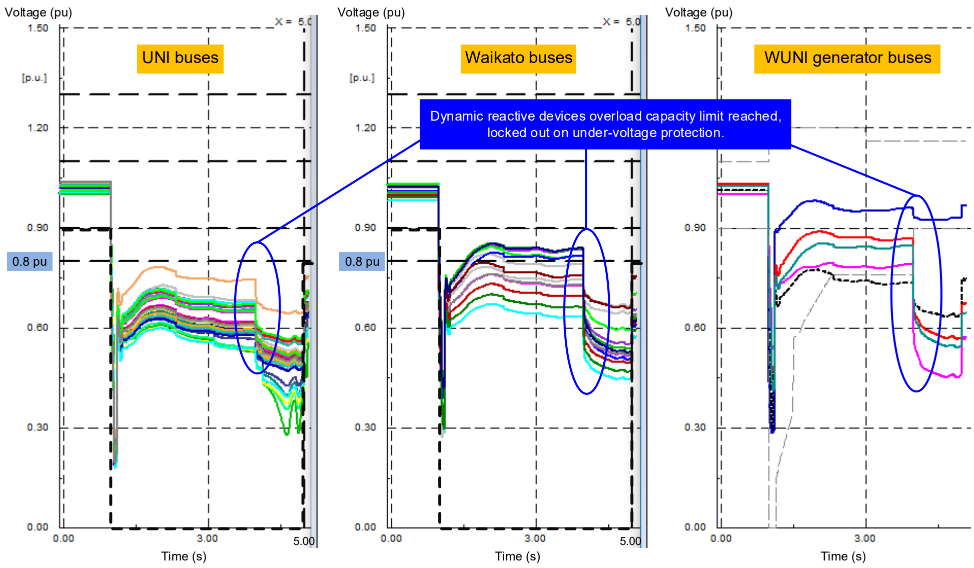


Figure A5-4 shows that:

- all bus voltages do not recover above 0.8 pu within 4 seconds, which fails our criteria.
- all generator bus voltages do not recover above 0.76 pu within 1.3 seconds, which fails our criteria.
- dynamic reactive devices locked out by under-voltage protection.

These results illustrate that one SVC is not sufficient to meet the N-G-1 under-voltage recovery criteria.

The same analysis was performed with two new SVCs, one at Otahuhu and one at Hamilton. Figure A5-5 shows a five second simulation based on 2023 winter peak load, a fault on the 220 kV Otahuhu–Whakamaru when Huntly unit 5 on outage.

Figure A5-5: One SVC at Otahuhu and one SVC at Hamilton, contingency: 220 kV Otahuhu–Whakamaru circuit

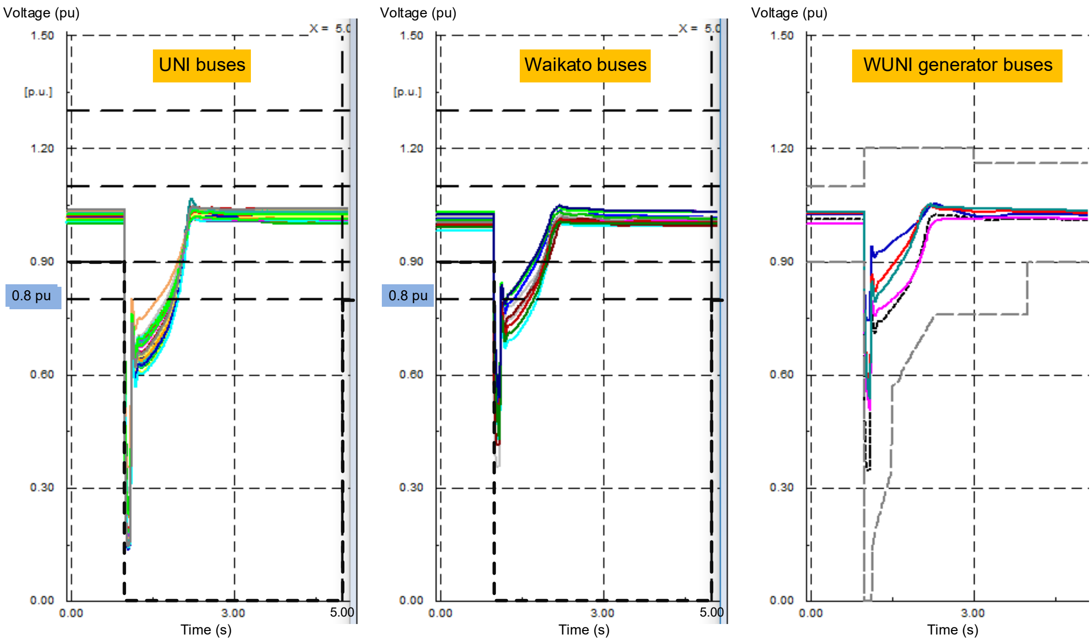


Figure A5-5 shows that:

- all bus voltages recover above 0.8 pu within 4 seconds, which passes our criteria.
- all generator bus voltages recover above 0.9 pu within 3 seconds, which passes our criteria.

Over-voltage

Option analysis were carried out for one SVC at Otahuhu and one SVC at Hamilton for 50% and 80% Group 1 motor tripping when Huntly unit 5 on outage. Results showed that one SVC at either Hamilton or Otahuhu is sufficient to mitigate TOV issue for 50% Group 1 motor. Two SVCs, one at Otahuhu and on at Hamilton are required to mitigate TOV issue from winter 2023 peak load under N-G-1 with 80% Group 1 motor tripping.

This section shows the TOV simulation results for winter 2023 with 80% Group 1 motor tripping. Figure A5-6 and Figure A5-7 shows the first two seconds of the voltage response with one new SVC at Otahuhu and one new SVC at Hamilton, respectively for 80% Group 1 motor tripping when Huntly unit 5 on outage.

Figure A5-6: one SVC at Otahuhu, contingency: Otahuhu SVC

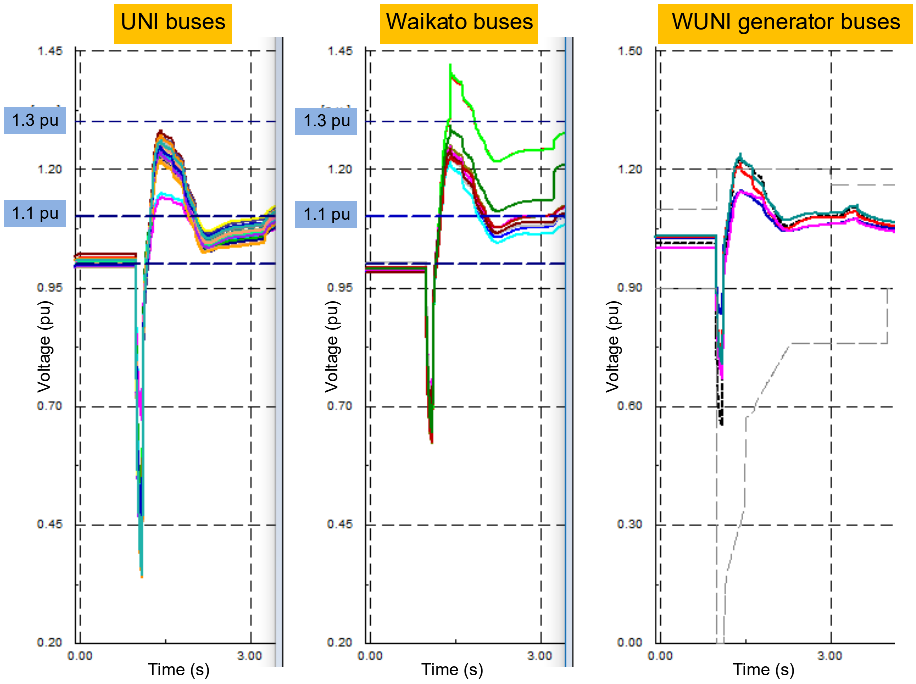


Figure A5-6 shows that:

- bus voltages exceed 1.1 pu within 200 ms after the fault clears.
- several bus voltages in the Waikato exceed 1.3 pu, which fails our criteria.
- generator bus voltages exceed 1.2 pu, which fails our criteria.

Figure A5-7: one SVC at Hamilton, contingency: 220 kV Hamilton–Ohinewai circuit

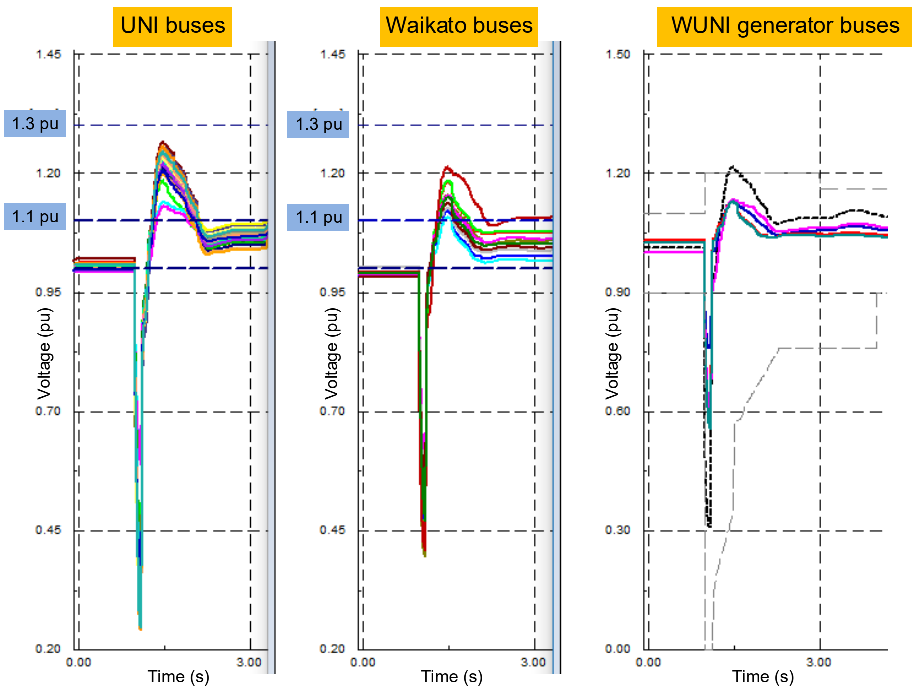


Figure A5-7 shows that:

- bus voltages exceed 1.1 pu within 200 ms after the fault clears.
- bus voltages do not exceed 1.3 pu, which passes our criteria.
- generator bus voltages exceed 1.2 pu, which fails our criteria.

These results illustrate that one SVC is not sufficient to meet the 80% Group 1 motor tripping criteria.

The same analysis was performed with two new SVCs, one at Otahuhu and one at Hamilton. Figure A5-8 and Figure A5-9 show the first two seconds of the response with 2023 winter peak load, a fault on the Otahuhu SVC and 220 kV Hamilton–Ohinewai circuit when Huntly unit 5 on outage.

Figure A5-8: One SVC at Otahuhu and one SVC at Hamilton, contingency: Otahuhu SVC

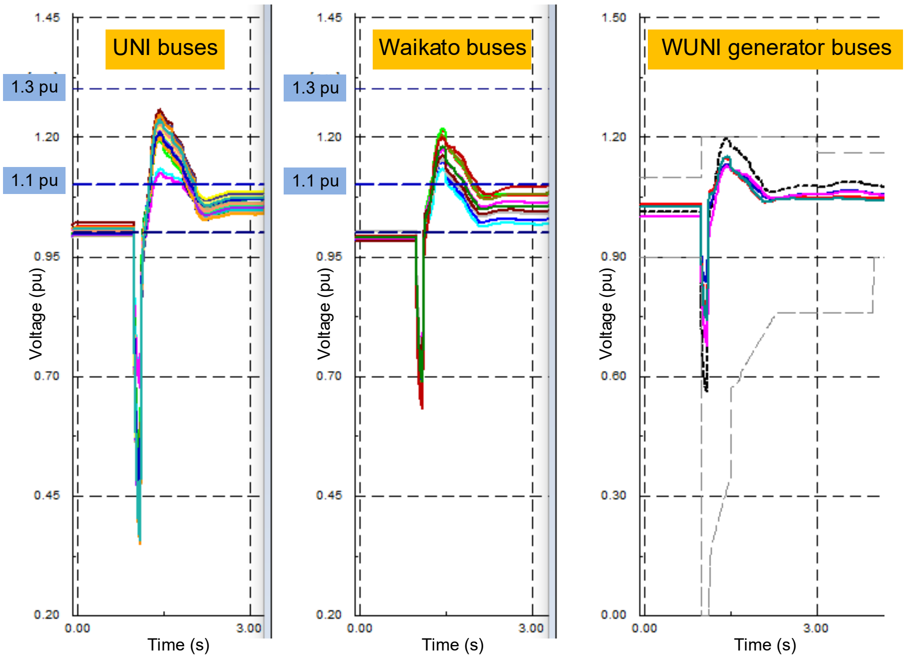


Figure A5-8 shows that:

- bus voltages exceed 1.1 pu within 250 ms after the fault clears.
- bus voltages do not exceed 1.3 pu, which passes our criteria.
- all generator bus voltages do not exceed 1.2 pu, which passes our criteria.

Figure A5-9: One SVC at Otahuhu and one SVC at Hamilton, contingency: 220 kV Hamilton–Ohinewai circuit

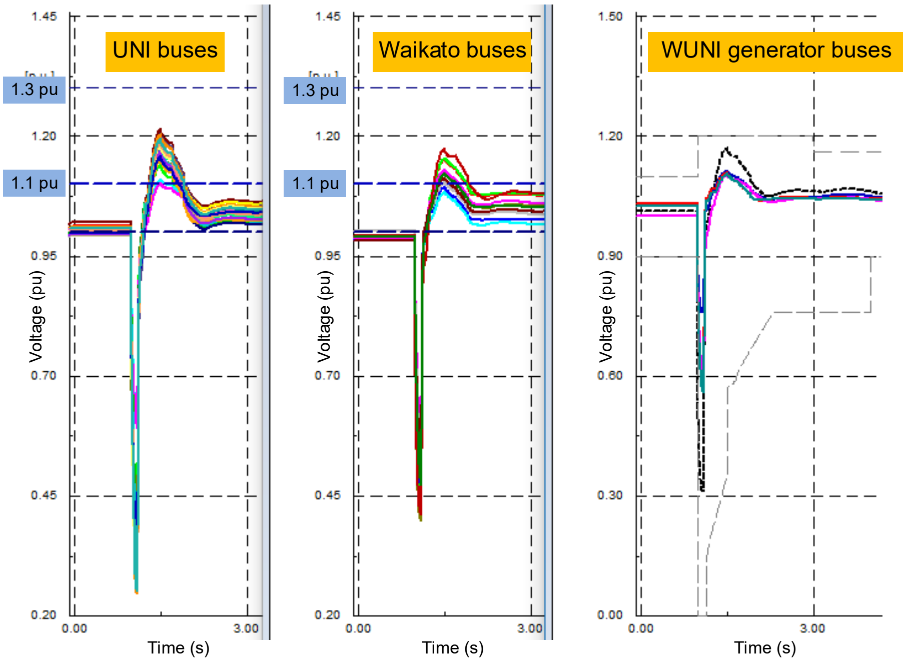


Figure A5-9 shows that:

- bus voltages exceed 1.1 pu within 250 ms after the fault clears.
- bus voltages do not exceed 1.3 pu, which passes our criteria.
- all generator bus voltages do not exceed 1.2 pu, which passes our criteria.

This analysis confirms that two SVCs is required in winter 2023 to manage voltage stability issues in the WUNI region.

Appendix 6 Post-fault demand management scheme

This appendix provides brief notes on the post-fault demand management scheme.

A6.1 International context

Internationally, some jurisdictions accept fast acting wide-area automatic schemes and tripping large blocks of load for managing very infrequent events that have a large impact (such as the post-fault demand management scheme as part of this MCP). They can be an appropriate component of the power system where the alternatives are either high cost investment in primary plant or pre-contingency load restrictions.

However, each scheme is different because each power system is different, with each scheme designed specifically for the issue being addressed.

A6.2 WUNIVM context

A6.2.1 Technical comparison to international practice

The post-fault demand management scheme proposed as part of the MCP monitors the system condition at the 220 kV busbar of several substations and, if a majority detect voltage collapse, sends signals to trip most or all load at other substation(s). Detecting voltage collapse is done by measuring the change in voltage magnitude over a short period of time (voltage signature).

The way we need to detect the voltage signature appears to be new in terms of international practice. This specific aspect of the post-fault demand management scheme will require particular care in designing the logic for how the scheme will operate and the design and installation of its hardware. The other aspects of the scheme (monitoring and control action over several dispersed sites) are more common practice.

Tripping large blocks of load protects the power system, preventing a collapse of the power system resulting in all load being lost. To be effective, the tripping of load must be fast, and the amount of load tripped must be large, such as one or more grid exit points or multiple zone substations.

A6.2.2 Alternatives to scheme

Following the retirement of the Rankine units, Huntly unit 5 will be the only major dispatchable generator in the WUNI region. Therefore, we assessed both N-1 (with Huntly unit 5 assumed to be operating) and N-G-1 voltage stability limits (where Huntly unit 5 is the “G” and is assumed to not be operating due to a forced outage or because it is out of merit order in the wholesale electricity market).

Applying the international context to WUNIVM, a wide-area automatic scheme that trips large blocks of load could be appropriate for situations such as a forced outage of Huntly unit

5 for repair to cover the risk of a circuit trip during this time. The alternatives to mitigate the voltage stability risk are either:

- investments in primary equipment such as additional dynamic reactive plant, with a significant increase in capital cost
- extensive pre-contingency load restrictions, at a significant cost to consumers.

We undertook a risk-based, economic assessment of these alternatives which determined the scheme has a significantly lower economic cost. The use of a risk-based trade-off such as this is consistent with international practice.

In addition to a forced outage of Huntly unit 5, it is possible the unit could be available but not operating due to it being out of merit order. Our market modelling indicates Huntly unit 5 is expected to be operating during winter peak periods when the N-G-1 voltage stability limits are forecast to be exceeded. This is supported by recent experience in the market. However, if Huntly unit 5 is not operating in this situation there would be a risk of voltage collapse following a fault. This risk could be mitigated by either:

- constraining Huntly unit 5 out of merit order through the application of a voltage stability constraint in the wholesale electricity market
- arming the post-fault demand management scheme
- managing demand pre-contingency.

The system operator would determine the appropriate mitigation in accordance with the Security Policy section of the system operator's Policy Statement. This mitigation may change over time as market conditions evolve or during specific situations such as during maintenance outages.

A6.3 "Fast" and "long term" voltage collapse

There are two system phenomena relevant to the post-fault demand management scheme to manage the risk of voltage collapse, "fast" voltage collapse and "long-term" voltage collapse.

Fast voltage collapse occurs within several seconds. It has a clear voltage signature that can reliably detect when load must be tripped to avoid the risk of voltage collapse with a very low risk of operating for other faults. Load tripping must be fast and significant to be effective in preventing voltage collapse.

Long-term voltage collapse can develop in periods of several tens of seconds to minutes. The system voltages appear normal or close to normal until the moment of total voltage collapse, which is near instantaneous. When in a long-term voltage collapse condition, normal automatic and manual control actions such as transformer tap changing or switching in capacitors to restore voltage actually worsen the voltage collapse condition. That is, the power system behaves in the opposite direction to normal. This makes detection particularly challenging.

The voltage signature that indicates the power system is very likely to be in a long-term voltage collapse condition is clear, but we believe it is very difficult to determine precisely when voltage collapse will occur. Therefore, load tripping must occur when a possible but not definite long-term voltage collapse condition is detected. It cannot be delayed until just before the point of the voltage collapsing to zero or during the voltage collapse. The load shedding must be fast but could be roughly granular tripping large blocks of load, with about 0.5 seconds between tripping each large load block.

To ensure the scheme will prevent a wide-area voltage collapse, it is critical the scheme always operates when needed. However, it is also important the scheme does not trip load unnecessarily, where possible. In balancing these requirements, the fast and long-term parts of the scheme are "biased" towards preventing voltage collapse. This means when it is borderline if the system is in voltage collapse or not, enough load will be tripped fast enough to prevent voltage collapse rather than a "wait and see" or "incremental load tripping" approach, which carries a high risk of not preventing voltage collapse.

A6.4 Some technical parameters

In terms of power system analysis, the nose point voltage may be above 1.0 pu. This is an expected characteristic of our power system with about 1330 Mvar of capacitors in an area supplying approximately 3000 MW of load.

Figure A6-1 shows the steady-state PV curve for the worst contingency considered, the outage of Huntly unit 5 followed by a fault on one Pakuranga–Whakamaru circuit. The power system can only operate stably on the upper part of the PV curve in the steady state.

Figure A6-1: Steady-state voltage stability curves

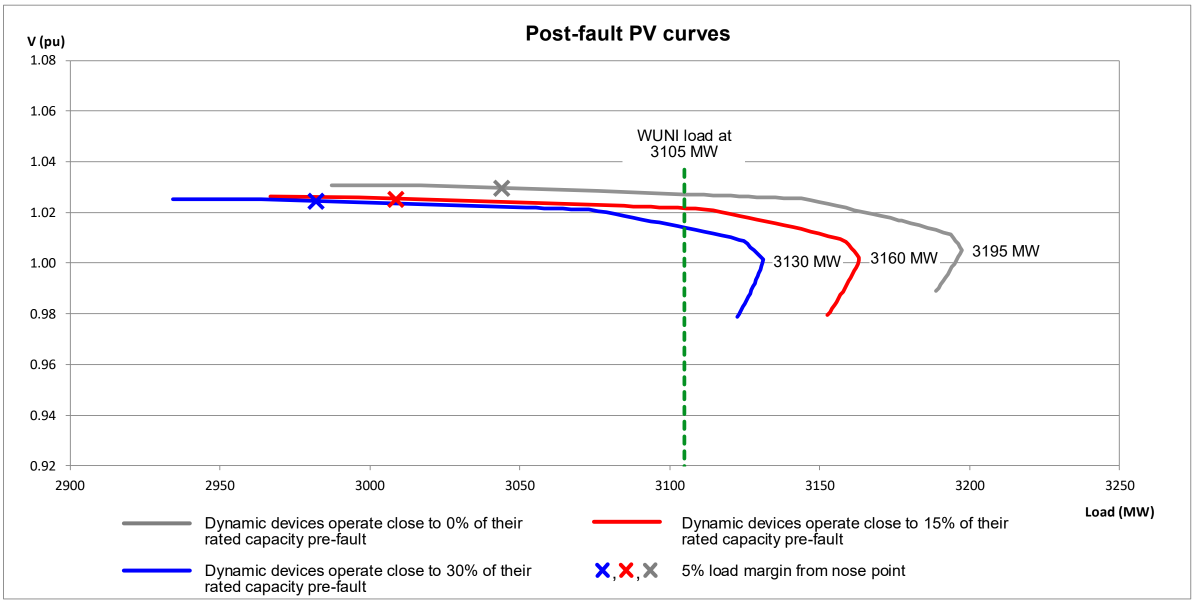


Figure A6-1 shows the steady-state PV curves with WUNI area dynamic devices operating at different levels of pre-fault reactive power contribution. In all three examples, the steady-state stability load limits are more than the WUNI load limit at 3105 MW (see Table 7). Therefore, the power system is operating within the stable zone but closer to the stability limit than a traditional 5% load margin. The analysis demonstrates our power system should not experience long term voltage collapse.

The post-fault demand management scheme focuses on managing voltage stability from fast voltage collapse. However, given the proximity to the stability limits, the scheme includes a long-term component to ensure that an unexpected capacitor configuration can be managed.

Appendix 7 Transmission thermal constraints

Our analysis identified that from winter 2023 (without Rankine units), some transmission circuits will overload (at prudent demand levels) if Huntly unit 5 is on outage. Table A7-1 shows the transmission circuit loading in 2023. There is no thermal overloading issue in 2023 if Huntly unit 5 is in service pre-contingency.

Table A7-1: 2023 transmission thermal issues under N-G-1

Contingency	Overloaded circuits	% Overload
Hamilton–Whakamaru 1	Otahuhu–Whakamaru 1 and 2 Ohinewai–Whakamaru 1	102% 100%
Ohinewai–Whakamaru 1	Hamilton–Whakamaru 1 Otahuhu–Whakamaru 1 and 2	105% 100%
Pakuranga–Whakamaru 1 or 2	Otahuhu–Whakamaru 1 and 2	100%

Our analysis indicates the WUNI load limits for these thermal contingencies are:

- 2990 MW for Ohinewai–Whakamaru 1 contingency
- 3040 MW for Hamilton–Whakamaru 1 contingency

Some short-term mitigation measures can be used to resolve thermal overload issue arises under N-G-1. These include operating the circuits to within their short-term ratings (15-minute off load time) or demand management. Some longer-term options discussed in this report include series compensation on the Brownhill–Whakamaru circuits and Ohinewai bussing development.