Upper North Island Dynamic Reactive Support Investment Proposal: Attachment A – Technical Assessment of Options

20 May 2010

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Executive summary

Purpose of this document

This report documents the power system analysis for Transpower's UNI Grid Upgrade Plans for reactive support.

Purpose of the analysis

The purpose of the analysis is to compare the development options for UNI dynamic support to secure transient voltage stability in the UNI.

Development plan summary

Both N-1 and N-G-1 development plans were constructed. A summary of the development plans is outlined below.

Table 1: N-1 Development plans

Development Plan	Description
DP1	STATCOMs are built at UNI GXPs as needed
DP2	The Penrose 33kV bus is split and additional and/or replacement 220/33kV transformers are installed at Penrose. STATCOMs are built as needed.
DP3	Four of the Otahuhu synchronous condensers are contracted until the end of 2015. The remaining Otahuhu synchronous condenser is retained as back up for the other four. STATCOMs are built at UNI GXPs as needed.
DP4	Four of the Otahuhu Synchronous condensers are contracted until the end of 2012, the remaining condenser is retained as back up for the other four. From the start of 2013 to the end of 2015 two Otahuhu condensers are contracted, a third condenser is retained for back up. STATCOMs are built at UNI GXPs as needed.
DP5	Marsden condenser is contracted on a 15 year grid support contract. The Marsden exciter is replaced with a new static exciter. STATCOMs are built at UNI GXPs as needed.
DP5a	Marsden condenser is contracted on a 5 year grid support contract. The Marsden exciter is not replaced. STATCOMs are built at UNI GXPs as needed.
DP5b	Marsden condenser is contracted on a 5 year grid support contract. Marsden exciter is upgraded. STATCOMs are built at UNI GXPs as needed.
DP6	Marsden condenser is contracted on a 15 year grid support contract. Four of the Otahuhu synchronous condensers are contracted until the end of 2015. The remaining OTA condenser is retained as back up for the other four. STATCOMs are built at UNI GXPs as needed.
DP6c	Marsden condenser is contracted on a 5 year grid support contract. The Marsden exciter is not replaced. Four of the OTA condensers are contracted until the end of 2015. The remaining OTA condenser is retained as back up for the other four. STATCOMs are built at UNI GXPs as needed
DP6d	Marsden condenser is contracted on a 5 year grid support contract. The Marsden exciter is upgraded. Four of the OTA condensers are contracted until the end of 2015. The remaining OTA condenser is retained as back up for the other four. STATCOMs are built at UNI GXPs as needed.
DP7	SVCs and STATCOMs are built at UNI GXPs as needed.
DP8	Northland wind farm is built in 2015, and STATCOMs are built at UNI GXPs as needed.
DP9a	Rodney generation is built in 2017, and STATCOMs are built at UNI GXPs as needed.
DP15	Rodney generation is built in 2017, OTA condensers are contracted from 2013 to 2015, and STATCOMs are built at UNI GXPs as needed.
DP16	Otahuhu generation is built in 2015, OTA condensers are contracted from 2013 to 2015, and STATCOMs are built at UNI GXPs as needed.
DP17	Otahuhu generation is built in 2015, and STATCOMs are built at UNI GXPs as needed.
DP10	Distribution network STATCOMs are built in the UNI in 2014 and STATCOMs are built at UNI

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Development Plan	Description
	GXPs as needed.
DP12	Series capacitors are built in 2015, STATCOMs are built at UNI GXPs as needed.
DP14	Four of the Otahuhu synchronous condensers are contracted until the end of 2012, the remaining OTA condenser is retained as back up for the other four. From the start of 2013 to the end of 2015 2 OTA condensers are contracted, a third condenser is retained for back up. Series capacitors are built in 2015, STATCOMs are built at UNI GXPs as needed.

Table 2: N-G-1 Development plans

Development Plan reference	Description
DP11	STATCOMs are built at UNI GXPs as needed, but at a N-G-1 security standard

Although the development plans span over 20 years, the most significant developments are those that occur in the first 6 years. Tables 3 to 5 show the first 6 years of each development plan.

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Table 3: Development Plan Summaries, DP1 to DP6

		DP1 **N-1**	**DP2** **N-1**	**DP3** **N-1**	**DP4** **N-1**
Year	**Summer Load**	**STATCOMs**	**PENROSE TF**	**5 year OTA Contract**	**OTA 5 year contract 4 out of 5 for 2 years, 2 out of 3 for 3 years**
2010	1920				
2011	1985	2 year, 4 out of 5, OTA contract started	2 year, 4 out of 5, OTA contract begun	5 year, 4 out of 5, OTA contract begun	2 year, 4 out of 5, OTA contract started
2012	2048	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract		Last year of 4 out of 5 OTA contract
2013	2097	PEN33 +/- 40 Mvar	Build new 220/33 TFs at PEN, and split 33kV buses		3 year, 2 out of 3, OTA contract started
2014	2152	MPE33 +/- 40 Mvar	MPE33 +/- 40 Mvar		PEN33 +/- 40 Mvar
2015	2215	PEN33 +/- 40 Mvar	HEP33 +/- 40 Mvar	Last year of 4 out of 5 OTA contract PEN33 +/- 40 Mvar	Last year, 2 out of 3, OTA contract started

		DP5 **N-1**	**DP5a** **N-1**	**DP5b** **N-1**	**DP6** **N-1**
Year	**Summer Load**	**OTA 5 year contract 4 out of 5 for 2 years, 2 out of 3 for 3 years**	**MDN 5 year contract, old exciter**	**MDN 5 year contract, new exciter**	**OTA 5 year and MDN 15 year**
2010	1920				
2011	1985	2 year, 4 out of 5, OTA contract begun 15 year MDN contract begun	2 year, 4 out of 5, OTA contract begun 5 year MDN contract begun with old exciter	2 year, 4 out of 5, OTA contract begun 5 year MDN contract begun with old exciter	5 year, 4 out of 5, OTA contract begun 15 year MDN contract begun
2012	2048	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract	
2013	2097		PEN33 +/- 40 Mvar STATCOM		
2014	2152	PEN33 +/- 40 Mvar		PEN33 +/- 40 Mvar	
2015	2215		PEN33 +/- 40 Mvar Last year of MDN contract	Last year of MDN contract	Last year of 4 out of 5 OTA contract

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Table 4: Development Plan Summaries, DP6c to DP17

		DP6c	DP6d	DP7	DP8
		N-1	N-1	N-1	N-1
Year	**Summer Load (MW)**	**OTA 5 year, MDN 5 year contract, old exciter**	**OTA 5 year, MDN 5 year contract, new exciter**	**SVCs and STATCOMs**	**Pouto wind farm**
2010	1920				
2011	1985	2 year, 4 out of 5, OTA contract begun 5 year MDN contract begun with old exciter	2 year, 4 out of 5, OTA contract begun 5 year MDN contract begun with old exciter	2 year, 4 out of 5, OTA contract begun	2 year, 4 out of 5, OTA contract begun
2012	2048	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract
2013	2097	3 year, 2 out of 3, OTA contract started	3 year, 2 out of 3, OTA contract started	PEN33 +/- 40 Mvar	PEN33 +/- 40 Mvar
2014	2152	PEN33 +/- 40 Mvar		MPE110 +150/-75 Mvar SVC	MPE33 +/- 40 Mvar
2015	2215	Last year, 2 out of 3, OTA contract started Last year of MDN contract	Last year, 2 out of 3, OTA contract started Last year of MDN contract		Pouto wind-farm stage 1, 250MW.

		DP9a	DP15	DP16	DP17
		N-1	N-1	N-1	N-1
Year	**Summer Load (MW)**	**Rodney generation in 2017 with STATCOMs**	**Rodney generation in 2017 with OTA condensers**	**Otahuhu generation in 2015 with OTA condensers**	**Otahuhu generation in 2015 with STATCOMs**
2010	1920			PEN33 +/- 40 Mvar	
2011	1985	2 year, 4 out of 5, OTA contract begun	2 year, 4 out of 5, OTA contract started	2 year, 4 out of 5, OTA contract started	2 year, 4 out of 5, OTA contract started
2012	2048	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract
2013	2097	PEN33 +/- 40 Mvar	3 year, 2 out of 3, OTA contract started	3 year, 2 out of 3, OTA contract	PEN33 +/- 40 Mvar
2014	2152	MPE33 +/- 40 Mvar	PEN33 +/- 40 Mvar		MPE33 +/- 40 Mvar
2015	2215	PEN33 +/- 40 Mvar	Last year, 2 out of 3, OTA condenser	Last year, 2 out of 3, OTA condenser 400 MW Otahuhu	400 MW Otahuhu

Table 5: Development plan summaries, DP10 to DP14

		DP10 N-1	DP11 N-G-1	DP12 N-1	DP14 N-1
Year	**Summer Load (MW)**	**Distribution STATCOMs**	**N-G-1 STATCOMs**	**Series caps from 2015**	**OTA 5 year contract 4 out of 5 for 2 years, 2 out of 3 for 3 years** **Series capacitors when needed**
2010	1920		PEN33 +/- 40 Mvar		
2011	1985	2 year, 4 out of 5, OTA contract started	2 year, 4 out of 5, OTA contract begun PEN33 +/- 40 Mvar OTA110 +/- 40 Mvar MPE33 +/- 40 Mvar	2 year, 4 out of 5, OTA contract started	2 year, 4 out of 5, OTA contract started
2012	2048	Last year of 4 out of 5 OTA contract		Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract
2013	2097	PEN33 +/- 40 Mvar		PEN33 +/- 40 Mvar	3 year, 2 out of 3, OTA contract started
2014	2152	ALB 11kV 8MVAR STATCOM BRB 33kV 8MVAR OTA_T4 11kV 8MVAR HEN 11kV 8MVAR LST_110/PEN 11kV 8MVAR MPE33kV 8MVAR		MPE33 +/- 40 Mvar	PEN33 +/- 40 Mvar
2015	2215	PEN33 +/- 40 Mvar	MNG33 +/- 40 Mvar	Series caps on NIGU circuits	Last year, 2 out of 3, OTA contract started

1 Introduction

1.1 Upper North Island

The Upper North Island covers the geographical area north of Huntly, including Bombay, Glenbrook, Takanini, Auckland, and the North Isthmus. Voltage stability within this area is influenced by:

- generation in Auckland and Huntly
- the transmission network supplying the Upper North Island area, including the transmission network south of Auckland
- the composition of the area’s load (in particular the quantity of induction motor load connected).

A geographical map of the 220kV and 110kV Auckland and Northland network is shown in Figure 1. Network schematics are shown in Figure 2 for Northland and Figure 3 for Auckland.

Figure 1: Upper North Island 220 kV and 110 kV network

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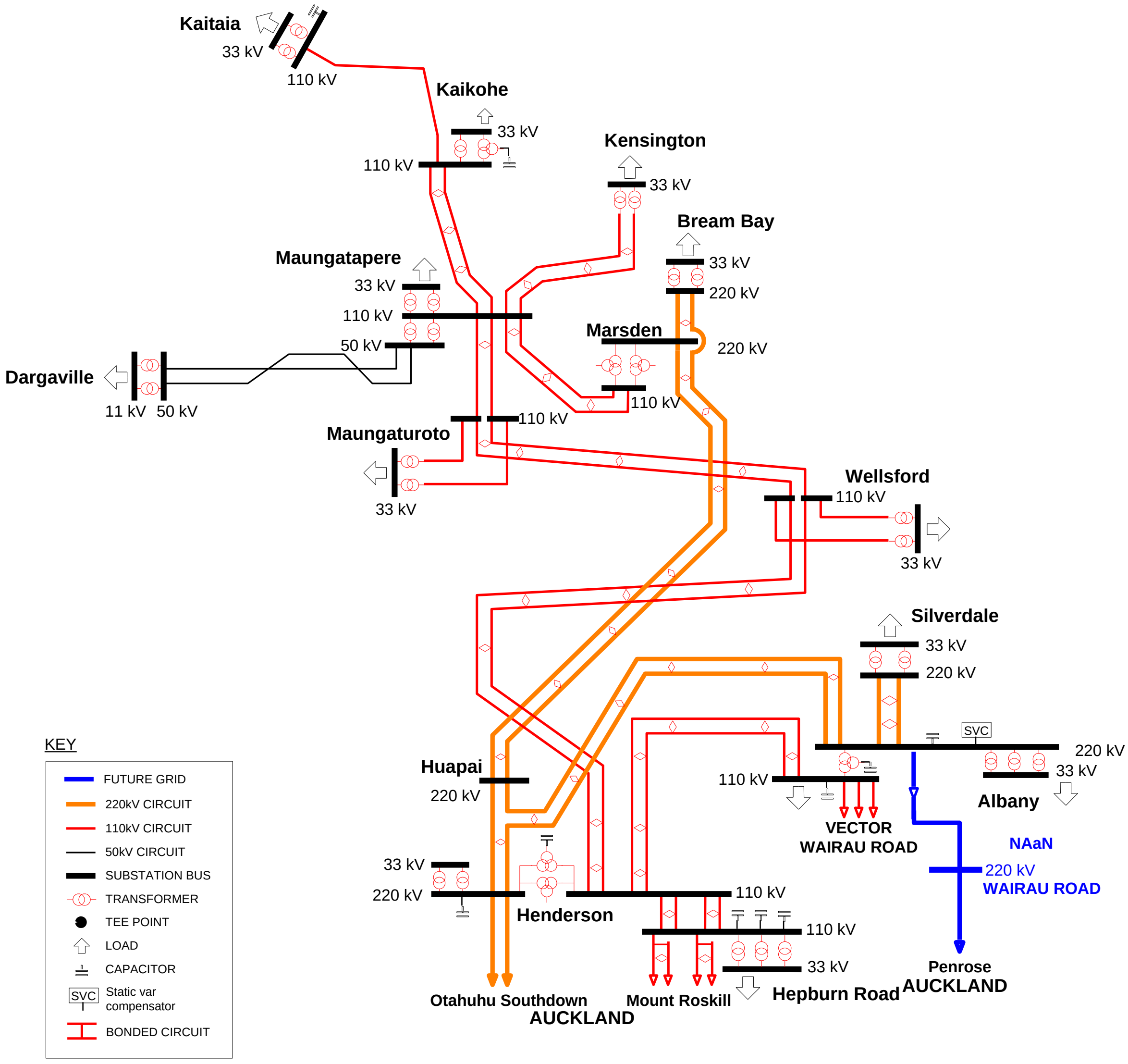

Figure 2: Northland 220 kV and 110 kV schematic

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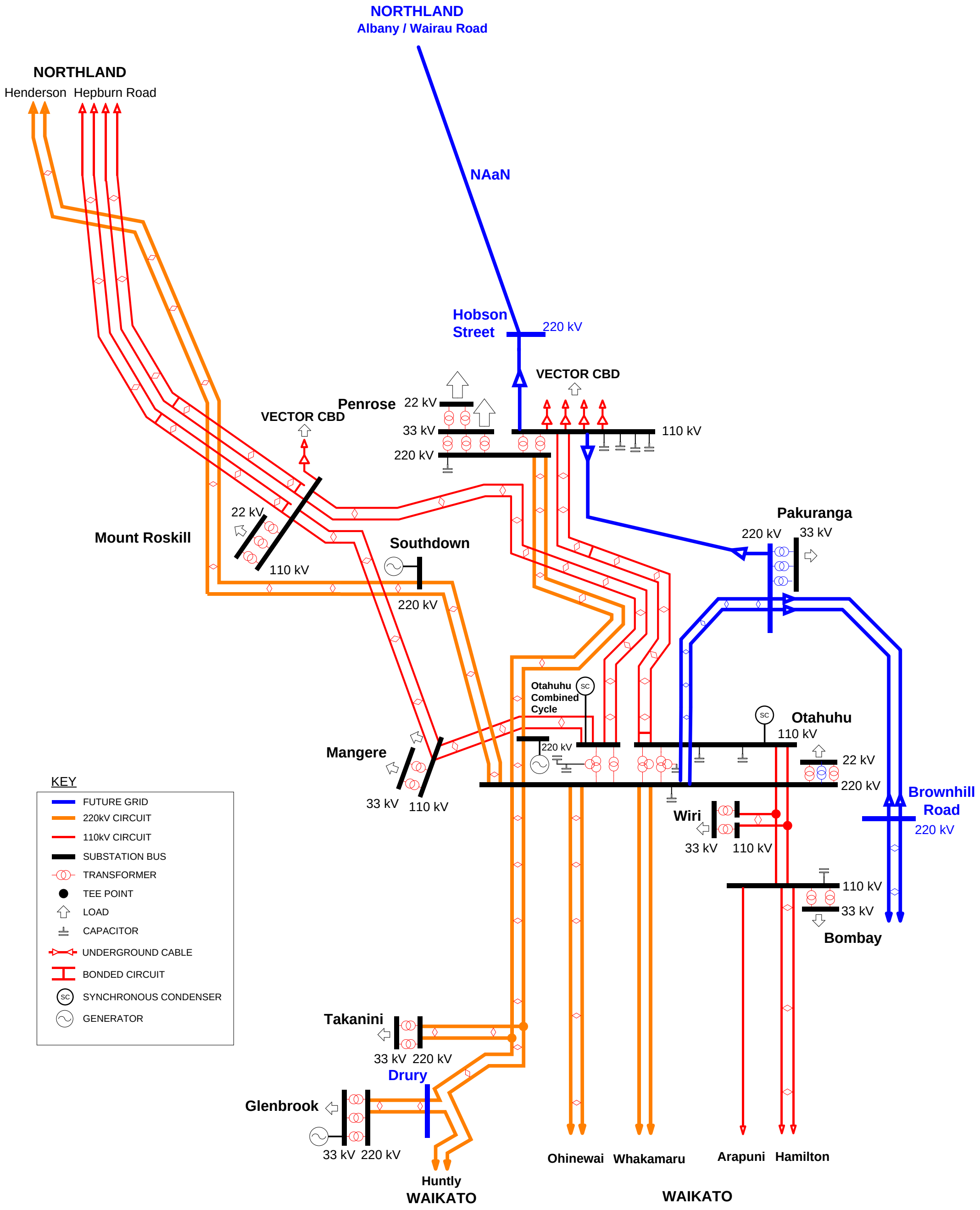

Figure 3: Auckland 220 kV and 110 kV schematic

1.2 Need for additional dynamic reactive support in the Upper North Island

The Upper North Island contains a significant proportion of induction motor load. The behaviour of this load during and following faults influences the regional transmission voltage. During a severe fault motors could stall. The stalled motors draw reaccelerating currents which delays the recovery of the post fault voltage.

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Transpower has identified that the period where voltage recovery is most at risk is the late summer period between mid-January and mid-March. In this period the greatest amount of motor load is connected.

In previous studies, (Transpower July 2009) Transpower has identified that there is a risk in the late summer period that voltage may recover unacceptably following a fault.

1.3 Development options

The tables below summarises a set of nineteen development plans to provide acceptable N-1 voltage performance to the UNI region, and one development plan to provide acceptable N-G-1 voltage performance. The development options consider a wide range of transmission and non transmission solutions to meet the need for reactive support.

Table 1-1: N-1 Development plans

Development Plan Reference	Description
DP1	STATCOMs are built at UNI GXPs as needed
DP2	The Penrose 33kV bus is split and additional and/or replacement 220/33kV transformers are installed at Penrose. STATCOMs are built as needed.
DP3	Four of the Otahuhu synchronous condensers are contracted until the end of 2015. The remaining Otahuhu synchronous condenser is retained as back up for the other four. STATCOMs are built at UNI GXPs as needed.
DP4	Four of the Otahuhu Synchronous condensers are contracted until the end of 2012, the remaining condenser is retained as back up for the other four. From the start of 2013 to the end of 2015 two Otahuhu condensers are contracted, a third condenser is retained for back up. STATCOMs are built at UNI GXPs as needed.
DP5	Marsden condenser is contracted on a 15 year grid support contract. The Marsden exciter is upgraded with a new static exciter. STATCOMs are built at UNI GXPs as needed.
DP5a	Marsden condenser is contracted on a 5 year grid support contract. The existing Marsden exciter is employed. STATCOMs are built at UNI GXPs as needed.
DP5b	Marsden condenser is contracted on a 5 year grid support contract. Marsden exciter is upgraded. STATCOMs are built at UNI GXPs as needed.
DP6	Marsden condenser is contracted on a 15 year grid support contract. Four of the Otahuhu synchronous condensers are contracted until the end of 2015. The remaining OTA condenser is retained as back up for the other four. STATCOMs are built at UNI GXPs as needed.
DP6c	Marsden condenser is contracted on a 5 year grid support contract. The existing Marsden exciter is employed. Four of the OTA condensers are contracted until the end of 2015. The remaining OTA condenser is retained as back up for the other four. STATCOMs are built at UNI GXPs as needed
DP6d	Marsden condenser is contracted on a 5 year grid support contract. The Marsden exciter is upgraded. Four of the OTA condensers are contracted until the end of 2015. The remaining OTA condenser is retained as back up for the other four. STATCOMs are built at UNI GXPs as needed.
DP7	SVCs and STATCOMs are built at UNI GXPs as needed.
DP8	Northland wind farm is built in 2015, and STATCOMs are built at UNI GXPs as needed.
DP9a	Rodney generation is built in 2017, and STATCOMs are built at UNI GXPs as needed.
DP15	Rodney generation is built in 2017, OTA condensers are contracted from 2013 to 2015, and STATCOMs are built at UNI GXPs as needed.
DP16	Otahuhu generation is built in 2015, two OTA condensers (with a third as backup) are contracted from 2013 to 2015, and STATCOMs are built at UNI GXPs as needed.
DP17	Otahuhu generation is built in 2015, and STATCOMs are built at UNI GXPs as needed.
DP10	Distribution network STATCOMs are built in the UNI in 2014 and STATCOMs are built at UNI GXPs as needed.
DP12	Series capacitors are built in 2015, STATCOMs are built at UNI GXPs as needed.

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DP14	Four of the Otahuhu synchronous condensers are contracted until the end of 2012, the remaining OTA condenser is retained as back-up for the other four. From the start of 2013 to the end of 2015, 2 OTA condensers are contracted, a third condenser is retained for back up. Series capacitors are built in 2015, STATCOMs are built at UNI GXPs as needed.

Table 1-2: N-G-1 Development plans

Development Plan reference	Description
DP11	STATCOMs are built at UNI GXPs as needed, but at a N-G-1 security standard

1.4 Outline of document

In this report:

- Section 2 summarises the modelling assumptions used in the power system analysis
- Section 3 gives the planning guidelines and performance criteria
- Section 4 gives 20 year development plans to ensure sufficient Upper North Island reactive support
- Section 5 discusses the sensitivity to load model assumptions.

Appendix A demonstrates how the voltage performance criteria are applied.

Appendix B lists the common abbreviations used in the report.

Appendix C lists abbreviated substation names.

Appendix D gives an overview of SVC and STATCOM technology.

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2 Modelling assumptions

This section gives the assumptions used in the power system analysis including:

- demand forecast
- dynamic load model
- existing UNI generation
- existing UNI reactive support
- supply and interconnector transformer upgrades
- other grid developments
- STATCOM and SVC characteristics.

2.1 Demand forecast

The analysis used the 2009 APR demand forecast, customized with two special diversities. The diversities are special in that they are for the combined Northland and Auckland peak. This compares to typically diversities which are determined for each regionally peak separately, or for an entire island. The two special diversities are when:

- the combined Northland and Auckland region is at its winter peak.
- the same region is at its peak during mid January and mid March – this diversity is called the “extreme summer” peak.

This extreme summer peak is when the worse voltage performance is predicted to occur.

Table 2-1 lists the yearly demand forecast for the two special diversities used in this analysis.

Table 2-1: Demand forecast of the UNI

Year	Winter (MW)	Extreme Summer (MW)
2010	2438	1920
2011	2520	1985
2012	2601	2048
2013	2660	2097
2014	2730	2152
2015	2809	2215
2016	2881	2272
2017	2955	2332
2018	3030	2391
2019	3106	2453
2020	3183	2514
2021	3251	2568
2022	3320	2623
2023	3389	2678
2024	3458	2733
2025	3528	2789
2026	3595	2842
2027	3662	2895
2028	3729	2949
2029	3796	3002

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2.2 Dynamic load model

Crucial to a dynamic study for transient analysis is the load model. The load model determines how the load reacts to faults and dips in voltages. In the studies documented in this report the load model is based on the motor load data surveyed by SKM in 2004. The survey is summarized in (Transpower July 2009).

The load model consists of:

- induction motor load
- static “non rotating” load
- known distribution capacitors

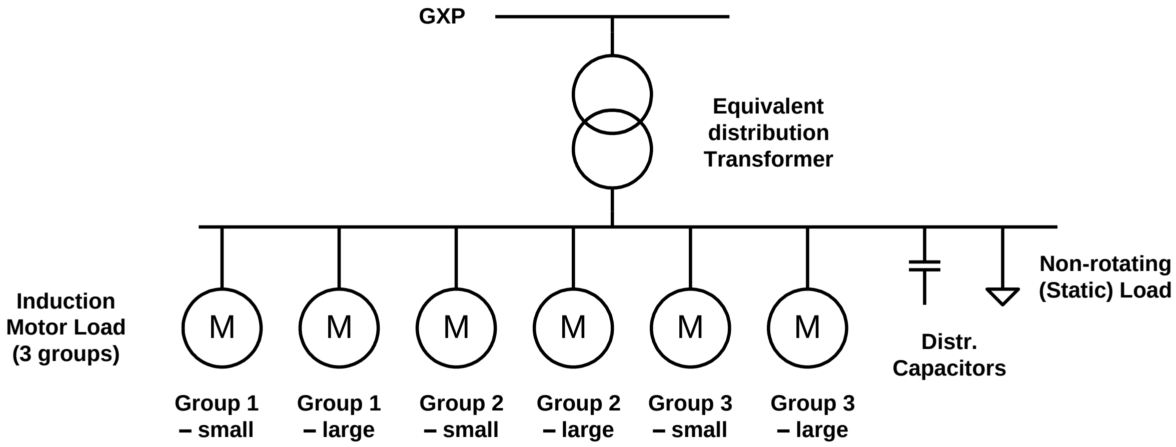

Figure 4: Load model, modelled at each UNI GXP

Each part of the load model is discussed in turn.

2.2.1 Induction motors

The induction motors are split into three different protection groups (groups one, two and three). Each group is further subdivided into groups based on motor sizes (large and small) as shown in Figure 4.

The motors of group one are connected with electromagnetic contactors. These contactors may open and stay open when the motors are subjected to low voltage conditions. This is modelled by assuming that some of group one Upper North Island motor loads will trip during a nearby under voltage fault. In the power system simulations the amount of group one motors that trip is varied between 25% and 50%. The remaining group two and group three motor loads are assumed to either remain connected, or reconnect shortly after the fault.

The group two and group three motors have a combination of over-voltage and over-current protection. The transient voltage performance criteria are designed to avoid tripping of these motors (refer section 3).

The parameters assumed for the large and small motors (single cage) are given below in Table 2-2 (Taylor 1994). The mechanical load torque is assumed to be proportional to the speed squared for both large and small motors.

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Table 2-2: Electrical parameters of motors

Electrical Parameters	Small Motor	Large motor
Rs (pu)	0.079	0.013
Xs (pu)	0.12	0.067
Xm (pu)	3.2	3.8
Rr (pu)	0.052	0.009
Xr (pu)	0.12	0.17
H (sec)	0.28	1.5
Load Factor	0.6	0.8

Other motor types, such as DC motors, and synchronous motors have been not found to be present in large numbers. Due to their comparative rarity their effect will be minimal and are not included in the studies.

2.2.2 Static load

The static load is assumed to stay connected during the fault. It is modelled as having the following voltage dependent characteristics;

- real power, P, has a constant current characteristic
- reactive power, Q, has a constant impedance characteristic

This characteristic is commonly called PIQZ.

2.2.3 Distribution capacitor banks

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.

2.2.4 Distribution network

The distribution network is modelled as a transformer between the GXP and the load. A network impedance of 8% is assumed (where the load MW demand is the MVA base).

2.2.5 Load model composition

The composition of each GXP is that found by SKM in their 2004 motor load survey. The load composition was surveyed in the peak winter period and the extreme summer period. The load composition for the entire Upper North Island is summarized in Table 2-3.

It is notable that the percentage of induction motor loads is higher in summer than in winter.

Table 2-3: Upper North Island Load Composition Summary

Period	Static	Induction motors					
		Group One		Group Two		Group Three	
		Large	Small	Large	Small	Large	Small
Winter GXP average	61.7%	3.8%	11.8%	0.9%	13.1%	1.7%	7.0%
Extreme Summer GXP average	35.9%	6.5%	20.4%	1.5%	20.3%	2.9%	12.5%

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2.3 Existing UNI generation

The assumed dispatch of the installed generation in the region is shown in Table 2-4

Table 2-4: Dispatch of installed generation

UNI Generation	Dispatch
Otahuhu B	370 MW
Southdown	179 MW
Glenbrook	75 MW
Ngawha	22 MW
Total	646MW

All UNI generators are dispatched at power factor of 1.0 pre-contingency.

Huntly Generation

Although not in the UNI region, the generators at Huntly significantly affect the voltage in the UNI. The assumptions for generation at Huntly are as follows;

- In winter all generation at Huntly is dispatched
- In summer conditions G3, G5 and G6 are at full output. To limit the temperature rise in the Waikato River G4 and G2 are run back to 125 MW. G1 is out of service
- Huntly generators are dispatch at a combined capacitive output of 280Mvars pre-contingency.

These summer assumptions are in line with those used by the System Operator in their Security Forecast (System operator 2008).

New generation is assumed installed south of Whakamaru to meet the UNI load growth.

2.4 Existing UNI reactive support

Dynamic

The current and committed UNI dynamic reactive support is listed in Table 2-5. Otahuhu A is owned by Contact-Energy and is currently contracted through Part C of the EGRs (Electricity Commission May 2010) to operate until December 2010. Several development options that follow investigate the effect of a new contract with Contact Energy to operate Otahuhu A for another 5 years.

Table 2-5: Dynamic reactive support

UNI dynamic Reactive Support	Capacity Mvar (+ve capacitive range, -ve inductive range)	
Otahuhu A (until Dec 2010)	Otahuhu G1,G2	+51/-29 each
	Otahuhu G4,G5,G6	+33/-29 each
Albany SVC	+100/-100	

Static

The static reactive support that is assumed to be installed in the analysis is listed below. There are presently 11kV banks installed at Henderson, Otahuhu, and Albany. However these 11 kV capacitors are due for decommissioning in the near future and therefore are not considered in the analysis.

Table 2-6: Static support

Capacitor	Voltage (kV)	Reactive (Mvar)
PEN_C1	220	75
ALB_C1	110	50
HEN_C1	220	75
KOE_C1,C2,C3,C4	11	20
OTA_C11	110	50
OTA_C12	110	50
HEP_C11	110	50
HEP_C12	110	50
PEN_C11	110	50
PEN_C12	110	50
ALB_C2	220	100
BOB_C11	110	50
KTA_C1, binary cap	33	24
HEP_C13	110	50
PEN_C13	110	50
PEN_C14	110	50
OTA (2 by 100Mvar banks, due before winter 2010)	220	200
Total Static Support		1044

2.5 Voltage profile

In each forecast year in both summer and winter capacitors are switched pre-contingency to maintain the pre-contingency voltage profile of Table 2-7.

Table 2-7: Voltage profile maintained in the UNI for summer

Bus-bar	Voltage set point
HEN110	1.020
HEN220	1.020
MPE110	1.020
OTA220	1.020
OTA_110_2	1.021
OTA_110_1	1.016
WKM220	1.045

As the load increases it draws increased amounts of reactive power, which requires increased amount of capacitors to be switched in to maintain the voltage profile. If the profile cannot be achieved with the existing capacitors, additional capacitors are installed.

2.6 Other grid developments

The following grid developments and timings are assumed:

- The NIGU line will run from Whakamaru to Pakuranga through a combination of overhead lines and cables; it assumed to be in service in 2012

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- In the previous NIGU analysis, series capacitors were installed in 2021 as a modelled project to force power down the high capacity NIGU circuits, and away from the lower capacity parallel 220kV lines (Transpower October 2006). Using the latest winter load forecast (Table 2-1), the series capacitors are now timed to be in service by 2025
- The NAaN cable will provide a third 220kV route into North Auckland and Northland; it is assumed to be in service in 2014. The NAaN project also includes a new GXP at Hobson Street and Wairau Road. The load at Wairau is currently supplied from Albany, whilst the load at Hobson Street will transfer from load feed from the 110kV Penrose to Vector's Liverpool Street, and Quay Street substations
- The Drury switching station is in service
- The Mount Roskill to Hepburn Road 110 kV split is closed.

2.7 Supply and interconnector transformer upgrades

As the load increase additional supply transformers and interconnectors will be constructed to meet these loads. Additional transformers will reduce the impedance between load and the rest of the network which helps aid voltage recovering. The following method has been used to predict these transformer upgrades.

- Between 2009 and 2019 the transformer upgrades indicative in the 2009 APR will be commissioned.
- In each year of the load forecast beyond 2019 if the loading on a group of transformers exceeds 125% of the N-1 capacity of the group, then an additional transformer equal to the capacity of the group's largest transformer at that GXP should be installed.

From this method the following transformer upgrades are assumed in the analysis.

Table 2-8: Transformer upgrade schedule

Year	Justification for upgrade	Substation	Rating (MVA)	Voltage (KV)
2011	APR	Penrose Interconnector	250	220/110
2014	APR	Otahuhu	50	220/22
2019	Load growth	Dargaville	15	50/11
	Load growth	Marsden Interconnector	141	220/110
	Load growth	Maungatapere	30	110/33
	Load growth	Kaitaia	20	110/33
	Load growth	Wiri	50	110/33
	Load growth	Kensington	50	110/33
	Load growth	Penrose	160	220/33
2021	Load growth	Mangere	120	110/33
	Load growth	Henderson Interconnector	200	220/110
2025	Load growth	Penrose	160	220/33
2027	Load growth	Maungatapere	10	110/50
2029	Load growth	Otahuhu Interconnector	250	220/110

2.8 STATCOM and SVC characteristics

STATCOMs and SVCs are power electronic devices that can supply dynamic reactive power to the AC system.

In the development plans that follow, a standard STATCOM rating is assumed. The STATCOM has an output range from +40 Mvar capacitive to -40 Mvar inductive at nominal voltage. In addition it is assumed that the STATCOM has a 2 second overload capacity of

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+/-100Mvar at rated voltage. The increased output capability for short durations provides significant reactive support during voltage dips to reaccelerate stalled motors and enable voltage to recover.

A standard SVC rating of +150 Mvar capacitive to -75 Mvar inductive at nominal voltage is assumed. In the development plans that follow it is assumed that SVC is connected at either 110 kV or 220 kV busses.

Pre-contingency the STATCOMs and SVCs are dispatched at 0 Mvars so that the devices maintain reserves to respond to system events.

Appendix D has more discussion on STATCOM and SVC characteristics.

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3 Planning requirements and performance criteria

This section details the planning requirements and performance criteria which are used to assess the various development options. In each year of the development plans these criteria are applied to the results of UNI network simulations. If the performance at UNI GXPs breaches the performance criteria additional reactive support is installed until the criteria are passed.

The following sections describe the transient voltage performance criteria, the justification for the criteria and provide examples of applying the criteria.

3.1 Transient voltage performance criteria

Voltage stability studies identify the maximum transfer capability of the network where the connected load can be supplied with a satisfactory system performance. This performance is assessed both during the transient period following a disturbance and in the final steady state.

3.1.1 New Zealand Governance rules for voltage performance

Although the system steady state voltage performance criteria are well defined in the New Zealand Electricity Governance Rules (Electricity Commission May 2010), there is no clear definition for satisfactory transient voltage performance criteria. Transpower has accordingly developed a set of criteria for assessing transient voltage performance.

3.1.2 Transpower's transient voltage performance criteria

Transpower's transient voltage criteria are derived from the fundamental requirements set out in the EGR reliability standard for the New Zealand Power Transmission System. The main requirements are:

- to avoid unnecessary loss of load following n-1 events
- to avoid power system cascade failure
- to avoid voltage collapse (both total and partial blackout).

The key transient voltage performance criteria used in Transpower's grid planning are as follows:

- Voltage must be greater than 0.5 pu following an N-1 event which removes an item of equipment from service without a transmission system short circuit fault
- Voltage must recover to above 0.8 pu in less than 4 seconds following an N-1 event with a three phase fault
- Motor current must not be greater than 6 times the rated current (6 pu) for more than 3 seconds and not be greater than 3 times the rated current (3 pu) for more than 8 seconds
- Voltage overshoot must be limited to below 1.3 pu
- Voltage overshoot must not be above 1.1 pu for more than 0.9 seconds.

These criteria are also within Transpower's Transmission Code (Transpower December 2009).

Appendix A gives illustrative examples of how the above criteria are applied.

3.1.3 Justification for the criteria

The justification for each of the performance criteria is given below.

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Voltage must not dip below 0.5 p.u. following an N-1 event without a short circuit fault

This criterion is to avoid the unnecessary loss of load following an N-1 event without a short circuit fault. Motors with contractors will be disconnected by contractor drop off if voltage is lower than a threshold value. Research has found that the threshold value is between 0.62 p.u. and 0.43 p.u. By maintaining the voltage limit above 0.5 p.u., most of the motors with contactors will remain connected.

Voltage must recover to above 0.8 p.u. in less than 4 seconds following a N-1 event with a three phase fault

Many large motors are equipped with under voltage protection with a pick up around 0.8 p.u. and time delay of 4-5 seconds. By applying this criterion the tripping of these large motors can be avoided. This criterion also reduces the risks of cascade tripping of generators due to low voltage, and tripping of capacitors due to over voltage.

Motor current must not be greater than 6 times the rated current (6pu) for more than 3 seconds and not be greater than 3 times the rated current (3 pu) for more than 8 seconds.

This criterion avoids tripping motors with typical over-current protection. Group 2 and Group 3 motors typically have this protection and it is these motors that the criteria to designed to avoid tripping.

Voltage overshoot must be limited to below 1.3 pu and must not be above 1.1 pu for more than 0.9 seconds.

The criterion is based on the power frequency over voltage limit given in the Australian National Electricity Rules (NER) (Australian Energy Market Commission March 2010)

The voltage overshoot is mainly due to the drop-off of contactor type motors, high level of capacitor compensation, and the slow response of generator excitation systems. In an area with large amount of contactor type motors and high level of compensation by capacitors, the over voltage could be very high. It may trigger the over voltage protection of some components, such as capacitor banks and even the connected generators. In extreme cases it may damage equipment.

3.2 Planning requirements

In addition to the transient voltage performance criteria, the following requirements are also made when undertaking the analysis:

- load is increased by 5% of the forecasted load, to maintain a margin between the stability limit and the predicted load level
- uncertainty in the amount of load that will trip because of contactor action is modelled by tripping between 25% and 50% of the expected group one contactor connected motors
- the worst expected fault type is a solid three phase fault cleared in the main 220 kV backup protection time of 120ms.

3.3 Critical faults

A detailed analysis was performed to determine the most onerous event for both an N-1 system and an N-G-1 system.

3.3.1 N-1 fault

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The most onerous N-1 event is a solid three phase fault (duration 120msec) applied at the Otahuhu 220 kV bus and is cleared by removing the Otahuhu B CCGT generator. A solid three phase fault at Otahuhu will depress the voltage in the study region close to zero and hence ensure tripping of group one motors by their under-voltage contactors. Additionally, the loss of this large generator will both; increase loading on the transmission system supplying the UNI, and result in the loss of a large source of dynamic reactive Mvars.

3.3.2 N-G-1 fault

The most onerous N-G-1 event is a 120ms three phase 220kV fault at Otahuhu which is cleared with the loss of the HLY-OTA-TAK-2 circuit. Contact Energy's Otahuhu B CCGT is assumed to be out of service pre-contingency. When series capacitors are placed on the new Whakamaru to Brownhill NIGU circuits, the loss of one of these circuits becomes the worse contingency.

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4 Development plans

The following sections provide a description of the strategy behind each development plan. Twenty plans in total are given. These plans include a range of options to meet the voltage stability need:

- Synchronous condensers (offered as Voltage Support-Grid Support Contracts (VS-GSC))
- Low impedance transformers
- STATCOMs
- SVCs
- Series capacitors

The development plan simulations are run in each year from 2009 to 2019, and every second year from 2021 to 2029 for the extreme summer scenario. The plans include new static capacitor banks required to meet the pre-contingency steady state voltage profile requirements for extreme summer scenario.

An economic analysis is then applied to the development plans (in a separate report) to determine which development path is the least cost.

For reference purposes, development plans with new local generation at Rodney, Otahuhu, and in Northland are included.

4.1 Otahuhu A synchronous condensers

In constructing the development plans it was found that there was only one option to meet the voltage stability criteria before construction of the new line in 2012. This option is to contract four of the five of Contact Energy's Otahuhu A synchronous condensers. Other options, such as building new STATCOMs, are not feasible in a short timeframe. To ensure voltage stability before the construction of the new line, four out of five Otahuhu A synchronous condensers are assumed on line until the end of 2012 in all development plans.

4.2 Development plans

4.2.1 DP1: STATCOMs

In this development plan STATCOMs are built at UNI GXPs; typically the STATCOM is built on the low voltage bus of the supply transformer close to the load. Usually the site chosen for each STATCOM is the bus where the voltage criteria are most heavily breached. A STATCOM at the low voltage bus is at an optimal position as it is electrically close to the breaching load.

Table 4-9, column 1, summarises this development plan.

4.2.2 DP2: Penrose transformers and bus splitting

Historically in the Upper North Island high impedance transformers have been placed in parallel to supply load. This has been done to both ensure N-1 reliability whilst also maintaining the fault level on the L.V. buses to avoid overloading the distribution network's protection equipment.

Unfortunately, during a heavy fault the motor load behind these transformers draws reaccelerating current which is drawn across the transformer impedance. This causes a voltage drop which help maintain the depressed L.V. voltage. By reducing the impedance between the H.V. network and the L.V. distribution network transient voltage performance can be improved.

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The 33kV GXP at Penrose is the largest GXP in the UNI and is supplied via three high impedance transformers from the Penrose 220kV bus. As discussed, by reducing the impedance between the 220kV and 33kV buses better voltage performance can be gained. Unfortunately, reducing the impedance increases the 33kV fault levels. However, this can be avoided by splitting the 33kV bus into two. Figure 5 shows Transpower's proposal for reducing the supply impedance to the 33kV bus, and splitting the bus to reduce fault levels.

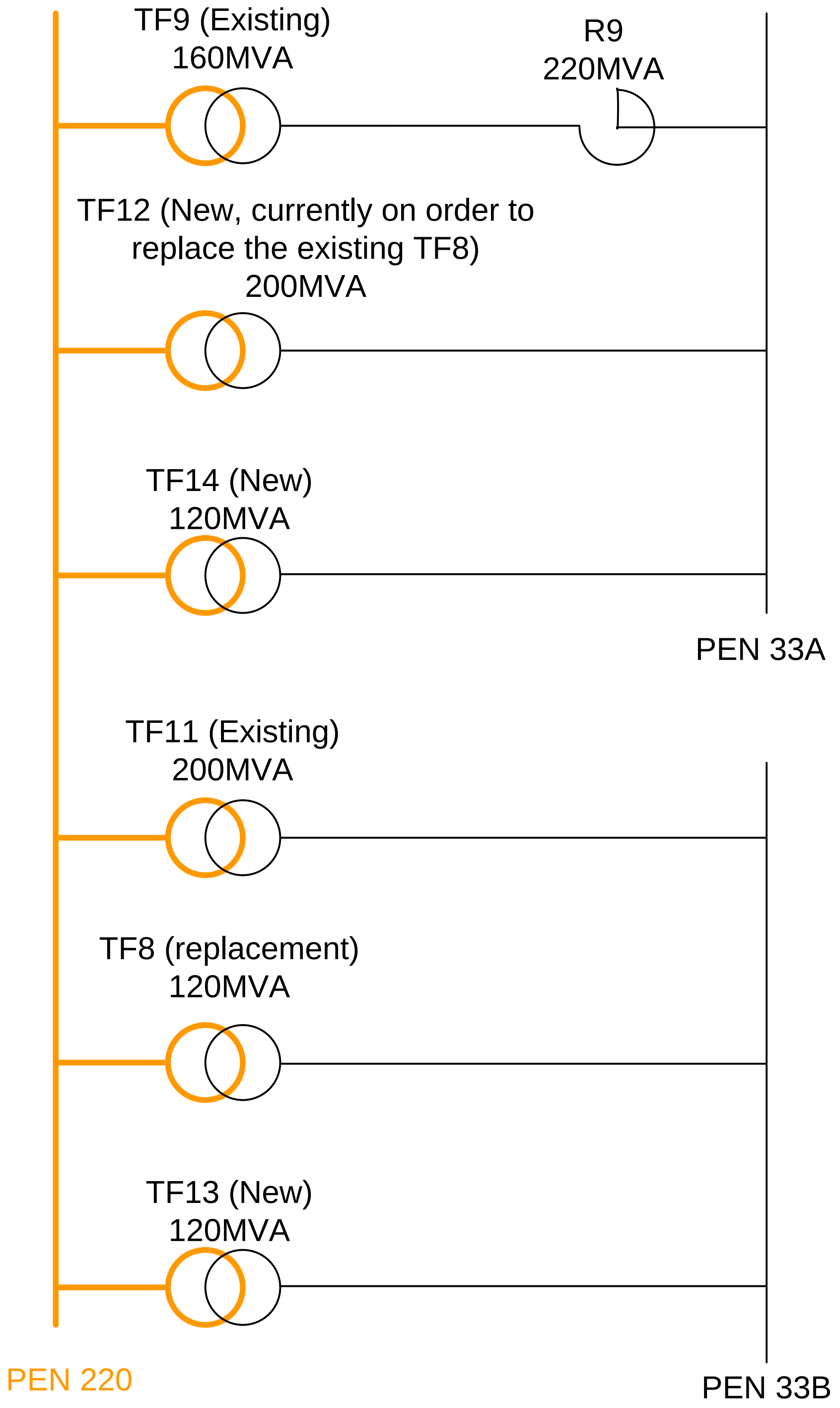

Figure 5: Suggested Penrose reconfiguration

Once the effect of reducing the Penrose 33kV supply transformer impedance is exhausted, STATCOMs are built to meet the need.

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Table 4-9, column 2, summarises this development plan.

4.2.3 DP3: Otahuhu four condensers

There are currently five synchronous machines which can be run as condensers at the now retired Otahuhu A power station. These machines are owned by Contact Energy and are contracted to the system operator until December 2010. From this date, Contact has indicated they are prepared to enter into a GSC with Transpower for a 5 year period.

Development plan DP3 includes this GSC from 2011 to the end of 2015. To ensuring a sufficient reliability, the GSC only guarantees that 4 synchronous condensers are connected at any one time. In addition to the condensers STATCOMs are built as required.

Table 4-9, column 3, summarises this development plan.

4.2.4 DP4: Otahuhu two condensers

This plan is variation to DP3. However, from the start of 2013 to the end of 2015 only two machines are contracted on, a third is retained as backup for these two machines. The three machines used are OTA_G4, G5 and G6. In addition to the condensers, STATCOMs are built as required.

Table 4-10, column 1, summarises this development option.

4.2.5 DP5: MDN condenser – 15 year plan, enhanced exciter

Mighty River Power has a synchronous machine at Marsden. This machine has in the past been used as a synchronous condenser, and was once connected to one of the now decommissioned Marsden A steam turbines. The machine has been offered by MRP using a grid support contract for a period of 15 years, the contract includes:

- reconnecting the machine with a dedicated unit transformer connected at 220 kV
- upgrading and replacing protection system including the connecting circuit breaker
- upgrading the exciter with a new static exciter.

Development plan DP5 includes this GSC from 2011 to 2025. In addition to the condenser, STATCOMs are built as required.

Table 4-10, column 2, summarises this development option.

4.2.6 DP5a: MDN condenser – 5 year plan, existing exciter

This development plan is similar to DP5, except the Marsden condenser is contracted for only 5 years, and the Marsden exciter is not upgraded. Not upgrading the exciter will mean the machine will have less performance, but it could be economic as contracting Marsden will be cheaper as the cost of paying for a new exciter will be removed from the contract cost.

Development plan DP5a includes this GSC from 2011 to 2015. In addition to the condenser, STATCOMs are built as required.

Table 4-10, column 3, summarises this development option.

4.2.7 DP5b: MDN condenser – 5 year plan, enhanced exciter

This development plan is similar 5 year Marsden condenser contract development plan DP5a. However in this plan Marsden exciter is upgraded.

Development plan DP5b includes this GSC from 2011 to 2015. In addition to the condenser, STATCOMs are built as required.

Table 4-11, column 1, summarises this development plan.

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4.2.8 DP6: MDN and OTA condensers

Development plan DP6 includes both the OTA 4 machine GSC contract from 2011 to the end of 2015 and the Marsden GSC from 2011 to 2025. In addition to the condensers, STATCOMs are built as required.

Table 4-11, column 2, summarises this development plan.

4.2.9 DP6c: MDN 5 years with existing exciter, and OTA condensers

This development plan is similar to DP6, except the Marsden condenser is contracted for only 5 years, and the Marsden exciter is not upgraded.

Development plan DP6c includes both the OTA 4 machine GSC contract from 2011 to the end of 2015 and the Marsden GSC from 2011 to 2015. In addition to the condensers, STATCOMs are built as required.

Table 4-11, column 3, summarises this development plan.

4.2.10 DP6d: MDN 5 years with enhanced exciter, and OTA condensers

This development plan is similar to DP6c, except the Marsden exciter is upgraded.

Development plan DP6c includes both the OTA 4 machine GSC contract from 2011 to the end of 2015 and the Marsden GSC from 2011 to 2015. In addition to the condensers, STATCOMs are built as required.

Table 4-12, column 1, summarises this development plan.

4.2.11 DP7: SVCs and STATCOMs

In this development plan SVCs and STATCOMs are built at UNI GXPs. The approach of this plan is to use SVCs to maintain the voltage at the HV bus. Whilst developing this plan it became clear that it was extremely difficult to maintain the voltage at some loads using this strategy. To give this strategy a fair chance STATCOMs are built at those LV buses where voltage performance is very poor. In this plan a standard SVC size is assumed, the size of this SVC is -75Mvar (inductive)/+150Mvar (capacitive).

Table 4-12, column 2, summarises this development plan.

4.2.12 DP8: Northland wind farm

Meridian Energy has indicated that they may build a 500MW wind farm in Northland on the Pouto Peninsula. This wind farm will significantly aid voltage performance in the Upper North Island. This project is indicative of the effect of new generation in this region on voltage performance.

No firm dates have been established when this wind farm will be built. It is assumed in the analysis that the wind farm will be built in two 250MW stages; the first stage is assumed to be built in 2015 and the second in 2021.

In this development plan the following power system assumptions are made about the wind farm.

- Pouto wind farm is connected to Transpower network via a 220kV 50km double circuit line. This new line is connected with double-T connections to the HPI-BRB-1 and MDN-HPI-1 circuits at a location 30km south of the Marsden substation

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- Even when not generating, the wind farm is likely to be capable of generating reactive power for voltage support. In the analysis, each stage of the wind farm is modelled as a 250MVA STATCOM, with no overload capacity, and no MW output. Each stage is connected to the new double circuit line via a 250MVA 10% impedance transformer.

Table 4-12, column 3, summarises this development plan.

4.2.13 DP9a: Rodney Generation in 2017 with STATCOMs

Genesis energy has indicated they may build a gas fired power station in the Rodney district. In a Genesis submission (Genesis Energy 2008) for resource consent application to the Auckland Regional and Rodney District Council consent for new CCGTs.

No firm dates have been established when these CCGTs will be built, if at all. In this case it is assumed that a 400 MW CCGT will be built in 2017. Similar to DP1, STATCOMs are built in 2013, 2014 and 2015.

In this development plan the following modelling assumptions are made about the CCGT:

- The CCGT is located north of the Huapai substation on the Kaipara Coast Highway. It is assumed that the power station will inject power into both circuits of the HEN_MDN_A line at a point 15 km North of Huapai
- The CCGTs has same characteristics as the Huntly E3P generator.

Table 4-13, column 1, summarises this development plan.

4.2.14 DP15: Rodney Generation in 2017 with OTA condensers

In this plan it is assumed that the Otahuhu condensers (2 of 3 units) are contracted from 2013 to 2015 and a STATCOM is built at Penrose in 2014. A 400 MW CCGT generator is assumed in 2015.

Table 4-13, column 2, summarises this development plan.

4.2.15 DP16: New Otahuhu generation in 2015 with STATCOMs

In this plan it is assumed that STATCOMs are built in 2013, 2014 and a new 400 MW CCGT generator is connected at Otahuhu 220 kV bus in 2015. The CCGT is assumed to have similar characteristics as the existing Huntly E3P generator.

Table 4-13, column 3, summarises this development plan.

4.2.16 DP17: New Otahuhu generation in 2015 with OTA condensers

In this plan it is assumed that the Otahuhu condensers (2 of 3 units) are contracted from 2013 to 2015 and a STATCOM is built at Penrose in 2014. A 400 MW Rodney generator is assumed in 2017 (as described for DP9a).

Table 4-13, column 1, summarises this development plan.

4.2.17 DP10: Distribution network STATCOMs

In this development plan a set of smaller distributed STATCOMs are placed in the UNI network. Some of these devices are placed at Transpower substations and others are assumed to be placed in lines company networks. The six distributed +/- 8Mvar STATCOMs are built in 2014.

The locations of the distributed STATCOMs are:

- ALB 11kV +/-8MVAR
- BRB 33kV +/-8MVAR
- OTA_T4 11kV +/-8MVAR

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- HEN 11kV +/-8MVAR
- LST_110/PEN 11kV +/-8MVAR
- MPE33kV +/-8MVAR

In addition to the distributed STATCOMs, +/-40MAR are placed at PEN33 when voltage support at this bus is needed.

Once the effect of the distributed STATCOMs are exhausted, +/-40 Mvar STATCOMs are built as required.

Table 4-13, column 3, summarises this development plan.

4.2.18 DP12: Series Capacitors in 2015

The North Island Grid Upgrade requires series capacitors to be placed on the new Brownhill to Whakamaru circuits to force power down these high capacity circuits, and away from the lower capacity parallel 220kV lines (Transpower October 2006). Using the updated winter load forecast (Table 2-1), the series capacitors must be in service by 2025. However, voltage stability could be improved if the installation date of the series capacitors is advanced.

In this development plan, series capacitors are placed in service in 2015. Before this date STATCOMs are built as needed. Additionally, when the effect of series capacitors is exhausted, STATCOMs are again built as needed.

Table 4-14, column 1, summarises this development plan.

4.2.19 DP14: Series Capacitors and Otahuhu condensers

This plan is combination of DP4 and DP12. From 2011 to 2012 four machines are contracted at Otahuhu. From the start of 2013 to the end of 2015 only two machines are contracted on, a third is retained as backup for these two machines. The three machines used are OTA_G4, G5 and G6. Additionally, from 2015 the series capacitors are placed in service on the Brownhill to Whakamaru lines as required. Once the effect of series capacitors is exhausted, STATCOMs are built to meet as needed.

Table 4-14, column 2, summarises this development plan.

4.2.20 DP11: N-G-1 STATCOMs

The following contains a description of the N-G-1 development plan. In this development plan STATCOMs are built at UNI GXPs; typically the STATCOM is built on the low voltage bus of the supply transformer. The site chosen for each STATCOM is the bus where the voltage criteria are most heavily breached. This development plan is similar to DP1, but at an N-G-1 reliability level.

Table 4-14, column 3, summarises this development plan.

4.3 Development plans

The development plans showing details from 2010 to 2029 are summarised in Table 4-9 to Table 4-15 below.

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Table 4-9: Development Plan Summary, Plans 1 to 3

		DP1	DP2	DP3
		N-1	**N-1**	**N-1**
Forecast Year	**Summer Load (MW)**	**STATCOMs**	**Penrose TF**	**5 year OTA Contract**
2010	1920			
2011	1985	2 year, 4 out of 5, OTA contract started	2 year, 4 out of 5, OTA contract begun	5 year, 4 out of 5, OTA contract begun
2012	2048	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract	
2013	2097	PEN33 +/- 40 Mvar	Build new 220/33 TFs at PEN, and split 33kV buses	
2014	2152	MPE33 +/- 40 Mvar	MPE33 +/- 40 Mvar	
2015	2215	PEN33 +/- 40 Mvar	HEP33 +/- 40 Mvar	Last year of 4 out of 5 OTA contract PEN33 +/- 40 Mvar
2016	2272			PEN33 +/- 40 Mvar MPE33 +/- 40 Mvar
2017	2332	HEP33 +/- 40 Mvar	PEN33 +/- 40 Mvar	HEP33 +/- 40 Mvar
2018	2391	MNG33 +/- 40 Mvar	MNG33 +/- 40 Mvar	MNG33 +/- 40 Mvar
2019	2453	GLN33/2 +/- 40 Mvar	GLN33/2 +/- 40 Mvar	GLN33/2 +/- 40 Mvar
2021	2568	PEN33 +/- 40 Mvar	MDN11 +/- 40 Mvar	PEN33 +/- 40 Mvar
2023	2678	MDN11 +/- 40 Mvar	WRU33 +/- 40 Mvar ROS22 +/- 40 Mvar	MDN11 +/- 40 Mvar
2025	2789	Series capacitor on NIGU circuits	Series capacitor on NIGU circuits	Series capacitor on NIGU circuits
2027	2895	MNG33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110	OTA110 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110	MNG33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110
2029	3002	OTA110 +/- 40 Mvar 100Mvar Caps at OTA220	PEN33 +/- 40 Mvar 100Mvar Caps at OTA220	OTA110 +/- 40 Mvar 100Mvar Caps at OTA220

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Table 4-10: Development Plan Summary, Plans 4 to 5a

		DP4 **N-1**	**DP5** **N-1**	**DP5a** **N-1**
Forecast Year	**Summer Load (MW)**	**OTA 5 year contract 4 out of 5 for 2 years, 2 out of 3 for 3 years**	**MDN 15 year contract**	**MDN 5 year contract, existing exciter**
2010	1920			
2011	1985	2 year, 4 out of 5, OTA contract started	2 year, 4 out of 5, OTA contract begun 15 year MDN contract begun	2 year, 4 out of 5, OTA contract begun 5 year MDN contract begun with old exciter
2012	2048	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract
2013	2097	3 year, 2 out of 3, OTA contract started		PEN33 +/- 40 Mvar
2014	2152	PEN33 +/- 40 Mvar	PEN33 +/- 40 Mvar	
2015	2215	Last year, 2 out of 3, OTA contract started		PEN33 +/- 40 Mvar Last year of MDN contract
2016	2272	PEN33 +/- 40 Mvar MPE33 +/- 40 Mvar	PEN33 +/- 40 Mvar	MPE33 +/- 40 Mvar
2017	2332	HEP33 +/- 40 Mvar		HEP33 +/- 40 Mvar
2018	2391	MNG33 +/- 40 Mvar	PEN33 +/- 40 Mvar	MNG33 +/- 40 Mvar
2019	2453	GLN33/2 +/- 40 Mvar	GLN33/2 +/- 40 Mvar	GLN33/2 +/- 40 Mvar
2021	2568	PEN33 +/- 40 Mvar	MPE33 +/- 40 Mvar	PEN33 +/- 40 Mvar
2023	2678	MDN11 +/- 40 Mvar	MNG33 +/- 40 Mvar HEP33 +/- 40 Mvar	MDN11 +/- 40 Mvar
2025	2789	Series capacitor on NIGU circuits	Series capacitor on NIGU circuits MDN33 +/- 40 Mvar	Series capacitor on NIGU circuits
2026			Last year of MDN contract	
2027	2895	MNG33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110	MNG33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110	MNG33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110
2029	3002	OTA110 +/- 40 Mvar 100Mvar Caps at OTA220	OTA110 +/- 40 Mvar 100Mvar Caps at OTA220	OTA110 +/- 40 Mvar 100Mvar Caps at OTA220

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Table 4-11: Development Plan Summary, Plans 5b to 6c

		DP5b **N-1**	**DP6** **N-1**	**DP6c** **N-1**
Forecast Year	**Summer Load (MW)**	**MDN 5 year contract, enhanced exciter**	**OTA 5 year and MDN 15 year**	**OTA 5 year, MDN 5 year contract, existing exciter**
2010	1920			
2011	1985	2 year, 4 out of 5, OTA contract begun 5 year MDN contract begun with existing exciter	5 year, 4 out of 5, OTA contract begun 15 year MDN contract begun	2 year, 4 out of 5, OTA contract begun 5 year MDN contract begun with existing exciter
2012	2048	Last year of 4 out of 5 OTA contract		Last year of 4 out of 5 OTA contract
2013	2097			2 year, 2 out of 3, OTA contract started
2014	2152	PEN33 +/- 40 Mvar		PEN33 +/- 40 Mvar
2015	2215	Last year of MDN contract	Last year of 4 out of 5 OTA contract	Last year, 2 out of 3, OTA contract started Last year of MDN contract
2016	2272	PEN33 +/- 40 Mvar MPE33 +/- 40 Mvar	2 by PEN33 +/- 40 Mvar	PEN33 +/- 40 Mvar MPE33 +/- 40 Mvar
2017	2332	HEP33 +/- 40 Mvar		HEP33 +/- 40 Mvar
2018	2391	MNG33 +/- 40 Mvar	PEN33 +/- 40 Mvar	MNG33 +/- 40 Mvar
2019	2453	GLN33/2 +/- 40 Mvar	GLN33/2 +/- 40 Mvar	GLN33/2 +/- 40 Mvar
2021	2568	PEN33 +/- 40 Mvar	MPE33 +/- 40 Mvar	PEN33 +/- 40 Mvar
2023	2678	MDN11 +/- 40 Mvar	MNG33 +/- 40 Mvar HEP33 +/- 40 Mvar	MDN11 +/- 40 Mvar
2025	2789	Series capacitor on NIGU circuits	Series capacitor on NIGU circuits MDN11 +/- 40 Mvar STATCOM	Series capacitor on NIGU circuits
2026			Last year of MDN contract	
2027	2895	MNG33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110	MNG33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110	MNG33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110
2029	3002	OTA110 +/- 40 Mvar 100Mvar Caps at OTA220	OTA110 +/- 40 Mvar 100Mvar Caps at OTA220	OTA110 +/- 40 Mvar 100Mvar Caps at OTA220

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Table 4-12: Development Plan Summary, Plans 6d to 8

Forecast Year	Summer Load (MW)	DP6d N-1	DP7 N-1	DP8 N-1
		OTA 5 year, MDN 5 year contract, enhanced exciter	SVCs and STATCOMs	Pouto wind farm
2010	1920			
2011	1985	2 year, 4 out of 5, OTA contract begun 5 year MDN contract begun with enhanced exciter	2 year, 4 out of 5, OTA contract begun	2 year, 4 out of 5, OTA contract begun
2012	2048	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract
2013	2097	2 year, 2 out of 3, OTA contract started	PEN33 +/- 40 Mvar	PEN33 +/- 40 Mvar
2014	2152		MPE110 +150/-75 Mvar SVC	MPE33 +/- 40 Mvar
2015	2215	Last year, 2 out of 3, OTA contract started Last year of MDN contract		Pouto wind-farm stage 1, 250MW.
2016	2272	2 by PEN33 +/- 40 Mvar MPE33 +/- 40 Mvar	PEN33 +/- 40 Mvar	
2017	2332	HEP33 +/- 40 Mvar	OTA220 +150/-75 Mvar SVC	PEN33 +/- 40 Mvar
2018	2391	MNG33 +/- 40 Mvar		
2019	2453	GLN33/2 +/- 40 Mvar	ROS110 +150/-75 Mvar SVC	
2021	2568	PEN33 +/- 40 Mvar	PEN110 +150/-75 Mvar SVC	Pouto wind-farm stage 2, 250MW.
2023	2678	MDN11 +/- 40 Mvar	HEP110 +150/-75 Mvar SVC OTA110 +150/-75 Mvar SVC	PEN33 +/- 40 Mvar GLN33/2 +/- 40 Mvar
2025	2789	Series capacitor on NIGU circuits	Series capacitor on NIGU circuits	Series capacitor on NIGU circuits
2027	2895	MNG33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110	PEN33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110	PEN33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110
2029	3002	OTA110 +/- 40 Mvar 100Mvar Caps at OTA220	MPE33 +/- 40 Mvar 100Mvar Caps at OTA220	OTA33 +/- 40 Mvar 100Mvar Caps at OTA220

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Table 4-13: Development Plan Summary, Plans 9a, 10, and 15

		DP9a **N-1**	**DP15** **N-1**	**DP10** **N-1**
Forecast Year	**Summer Load (MW)**	**Rodney generation in 2017 with STATCOMs**	**Rodney generation with OTA condensers**	**Distribution network STATCOMs**
2010	1920			
2011	1985	2 year, 4 out of 5, OTA contract begun	2 year, 4 out of 5, OTA contract begun	2 year, 4 out of 5, OTA contract started
2012	2048	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract
2013	2097	PEN33 +/- 40 Mvar	3 year, 2 out of 3, OTA contract started	PEN33 +/- 40 Mvar
2014	2152	MPE33 +/- 40 Mvar	PEN33 +/- 40 Mvar	ALB 11kV +/-8MVAR STATCOM BRB 33kV 8MVAR OTA_T4 11kV 8MVAR HEN 11kV 8MVAR LST_110/PEN 11kV 8MVAR MPE33kV 8MVAR
2015	2215	PEN33 +/- 40 Mvar	Last year, 2 out of 3, OTA contract	PEN33 +/- 40 Mvar
2016	2272		PEN33 +/- 40 Mvar MPE33 +/- 40 Mvar	
2017	2332	400 MW generator at Rodney	400 MW generator at Rodney	HEP33 +/- 40 Mvar
2018	2391			MNG33 +/- 40 Mvar
2019	2453			GLN33/2 +/- 40 Mvar
2021	2568			PEN33 +/- 40 Mvar
2023	2678	GLN33 +/- 40 Mvar	GLN33 +/- 40 Mvar	MDN11 +/- 40 Mvar
2025	2789	Series capacitor on NIGU circuits	Series capacitor on NIGU circuits	Series capacitor on NIGU circuits
2027	2895	50 Mvar Caps at OTA110	50 Mvar Caps at OTA110	MNG33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110
2029	3002	HEP33+/- 40 Mvar 50 Mvar caps at HEN110 75 Mvar caps at HEN220	HEP33+/- 40 Mvar 50 Mvar caps at HEN110 75 Mvar caps at HEN220	OTA110 +/- 40 Mvar 100Mvar Caps at OTA220

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Table 4-14: Development Plan Summary, Plans 11, 12 and 14

		DP11 N-G-1	DP12 N-1	DP14 N-1
Forecast Year	**Summer Load (MW)**	**N-G-1 STATCOMs**	**Series caps in 2015**	**OTA 5 year contract 4 out of 5 for 2 years, 2 out of 3 for 3 years** **Series capacitors in 2016**
2010	1920	PEN33 +/- 40 Mvar		
2011	1985	2 year, 4 out of 5, OTA contract begun PEN33 +/- 40 Mvar OTA110 +/- 40 Mvar MPE33 +/- 40 Mvar	2 year, 4 out of 5, OTA contract started	2 year, 4 out of 5, OTA contract started
2012	2048		Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract
2013	2097		PEN33 +/- 40 Mvar	2 year, 2 out of 3, OTA contract started
2014	2152		MPE33 +/- 40 Mvar	PEN33 +/- 40 Mvar
2015	2215	MNG33 +/- 40 Mvar	Series caps on NIGU circuits	Last year, 2 out of 3, OTA contract started
2016	2272	GLN33 +/- 40 Mvar	MPE33 +/- 40 Mvar	Series caps on NIGU circuits MPE33 +/- 40 Mvar
2017	2332	PEN33 +/- 40 Mvar	PEN33 +/- 40 Mvar	PEN33 +/- 40 Mvar
2018	2391			
2019	2453			
2021	2568	MDN11 +/- 40 Mvar TAK33 +/- 40 Mvar	PEN33 +/- 40 Mvar GLN33/2 +/- 40 Mvar	PEN33 +/- 40 Mvar GLN33/2 +/- 40 Mvar
2023	2678	ROS22 +/- 40 Mvar MPE33 +/- 40 Mvar	MNG33 +/- 40 Mvar	MNG33 +/- 40 Mvar
2025	2789	Series caps on NIGU circuits MNG33 +/- 40 Mvar	MDN11 +/- 40 Mvar	MDN11 +/- 40 Mvar
2027	2895	MDN11 +/- 40 Mvar PEN33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110	HEP33 +/- 40 Mvar MNG33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110	HEP33 +/- 40 Mvar MNG33 +/- 40 Mvar 100Mvar Caps at HEN220 50Mvar Caps at MPE110
2029	3002	HEP33 +/- 40 Mvar ALB33 +/- 40 Mvar 100Mvar Caps at OTA220	OTA110 +/- 40 Mvar 100Mvar Caps at OTA220	OTA110 +/- 40 Mvar 100Mvar Caps at OTA220

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Table 4-15: Development Plan Summary, Plans 16, and 17

		DP16 N-1	DP17 N-1
Forecast Year	**Summer Load (MW)**	**Otahuhu generation in 2015 with OTA condensers**	**Otahuhu generation in 2015 with STATCOMs**
2010	1920		
2011	1985	2 year, 4 out of 5, OTA contract begun	2 year, 4 out of 5, OTA contract begun
2012	2048	Last year of 4 out of 5 OTA contract	Last year of 4 out of 5 OTA contract
2013	2097	3 year, 2 out of 3, OTA contract started	PEN33 +/- 40 Mvar
2014	2152	PEN33 +/- 40 Mvar	MPE33 +/- 40 Mvar
2015	2215	Last year, 2 out of 3, OTA contract 400 MW generator at Otahuhu	400 MW generator at Otahuhu
2016	2272		
2017	2332		
2018	2391	MPE33 +/- 40 Mvar	
2019	2453		
2021	2568	PEN33 +/- 40 Mvar	PEN33 +/- 40 Mvar
2023	2678	GLN33 +/- 40 Mvar PEN33 +/- 40 Mvar	GLN33 +/- 40 Mvar PEN33 +/- 40 Mvar
2025	2789	Series capacitor on NIGU circuits	Series capacitor on NIGU circuits
2027	2895	50 Mvar Caps at OTA110	50 Mvar Caps at OTA110
2029	3002	HEP33+/- 40 Mvar MDN11+/- 40 Mvar 50 Mvar caps at HEN110 75 Mvar caps at HEN220	HEP33+/- 40 Mvar MDN11+/- 40 Mvar 50 Mvar caps at HEN110 75 Mvar caps at HEN220

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5 Sensitivity to load assumptions

For illustration purposes the sensitivity to the load assumptions is demonstrated.

The sections below discuss the following sensitivities:

- Percentage of group 1 motors that disconnect during the fault
- Seasonal load changes (winter, summer, extreme summer)
- Amount of large motors.

5.1 Percentage of group 1 motors that disconnect

The percentage of induction motors that disconnect (and stay disconnected) from contactor action during a severe disturbance has a significant impact on the need for investment in dynamic reactive support. If too few motors disconnect then the system can experience low voltages and / or voltage collapse. If a high percentage disconnects then the system may experience high transient over voltages which may damage equipment and is hence also undesirable.

A sensitivity analysis for years 2012 was performed with 90% group 1 motors disconnecting during the fault. If 90% of the group 1 motors disconnect then this leads to over voltages that can be effectively mitigated by installing additional dynamic reactive compensation.

To mitigate the over-voltage in year 2012 for 90% group 1 induction motors, an additional 125 Mvar of dynamic inductive support is required. Additional inductive reactive compensation is also required in subsequent years but is not further quantified here. Therefore if the 90% criteria were applied this would require significant additional investment to that already proposed.

5.2 Seasonal changes

The plans are developed in section 4 are for the mid January to mid February extreme summer scenario which previous studies show is the worst case for transient voltage stability.

The analysis has also been checked for the full summer and winter peaks to confirm that the extreme summer case considered is the most onerous and that there will be enough dynamic reactive plant.

5.2.1 Full summer period

The full summer period goes from the 20th of October to 15th of May. The load peaks in early May and is typically due to a cold-snap. Whilst this peak is higher than the extreme summer peak, it is a less onerous scenario because:

- Huntly generation is unlikely to be restricted due to Waikato river heating limitations
- the load is expected to have less refrigeration and air conditioning motor load connected, and more resistive heating static load connected.

The motor load survey did not consider the load composition during the regular summer peak. For the regular summer period it is assumed that the percentage of motor loads is the average of the extreme summer and winter percentages.

5.2.2 Comparison between seasons

The system recovery for the winter peak, the early May summer peak, and the extreme summer scenarios was investigated. In all scenarios the recovery complies with the performance criteria, e.g. the motor currents are not greater than 3 p.u. for more than 8

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seconds. Additionally, the extreme summer period was found to be the most onerous in terms voltage recovery.

5.3 Large motor percentage

The number of large induction motors (motors > 150 kW) have a significant impact on voltage recovery. After a voltage dip, the large motors draw reactive current for longer than small motors. This tends to depress voltages for longer which slows the recovery.

Figure 6 shows the impact of large motor percentage. An increase in large motor percentage by 20% (keeping the overall % of motors the same) delays the system recovery and would therefore require more dynamic reactive support. If the percentage of large motors is reduced then the recovery after the fault would be faster and hence there would be more margin until the next investment is required.

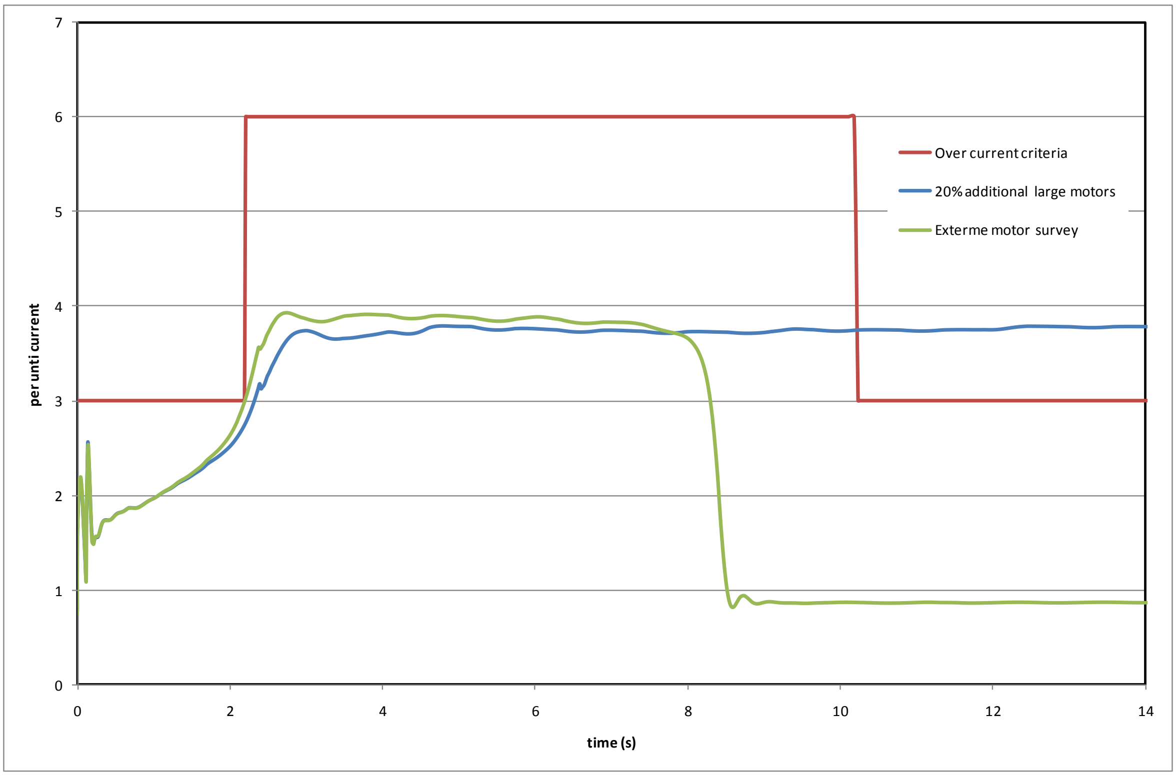

Figure 6: Effect of additional large motors

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Appendix A Application of voltage performance criteria

The following figures illustrate how to determine from the simulations if the voltage and load current recovery is satisfactory and meets the voltage stability criteria. In each figure the criteria are assessed at one GXP, in the development plans the criteria are assessed at all UNI GXPs. All of the criteria (both load voltage and motor current) must be passed for the system recovery to be judged acceptable. If one of the criteria fails then investments are necessary to improve performance. In the Upper North Island the critical criterion is generally the motor current recovery criteria.

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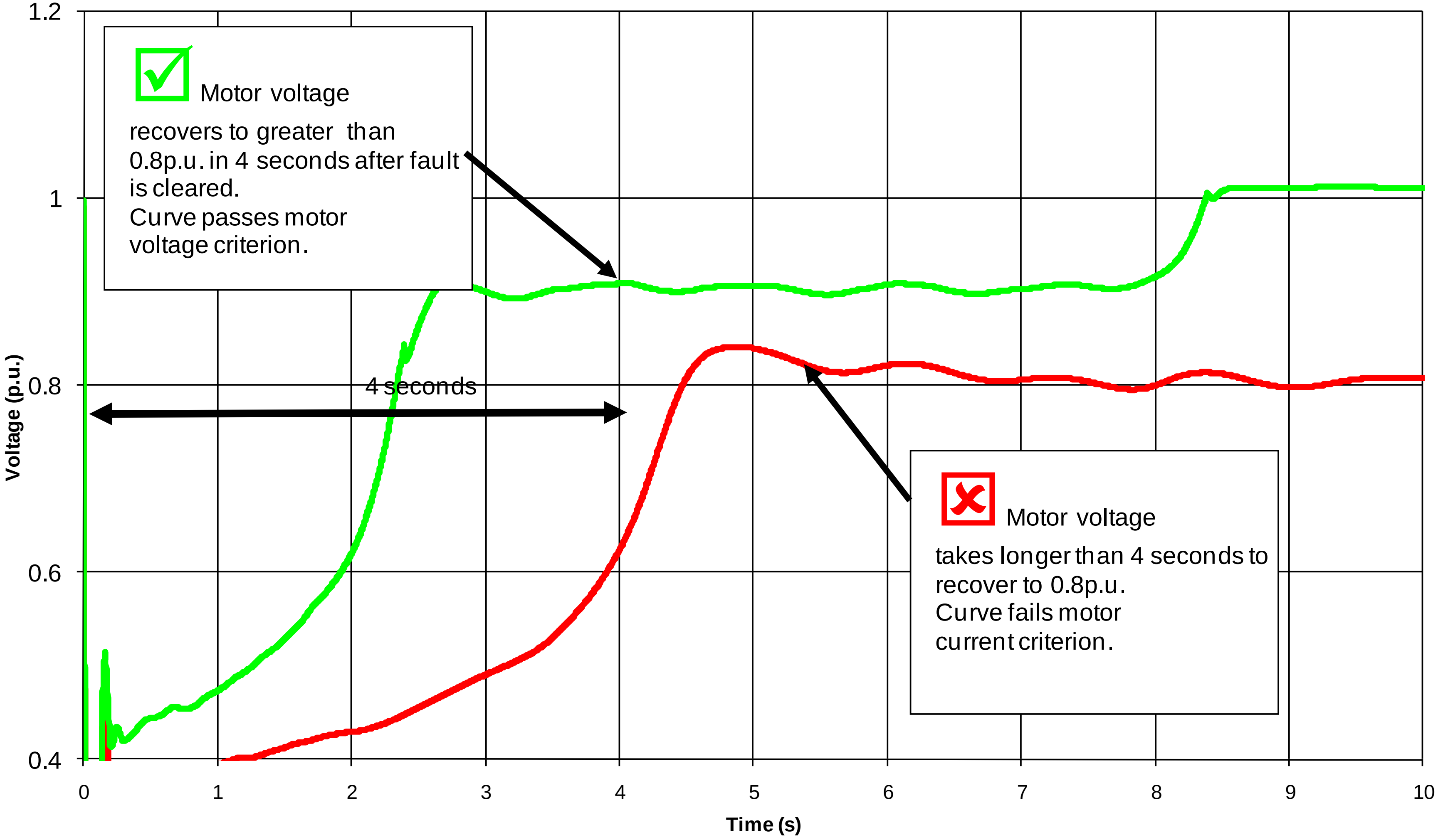

☑ Motor voltage recovers to greater than 0.8p.u. in 4 seconds after fault is cleared.
Curve passes motor voltage criterion.

☒ Motor voltage takes longer than 4 seconds to recover to 0.8p.u.
Curve fails motor current criterion.

Figure A-1: Example of application of under-voltage criterion

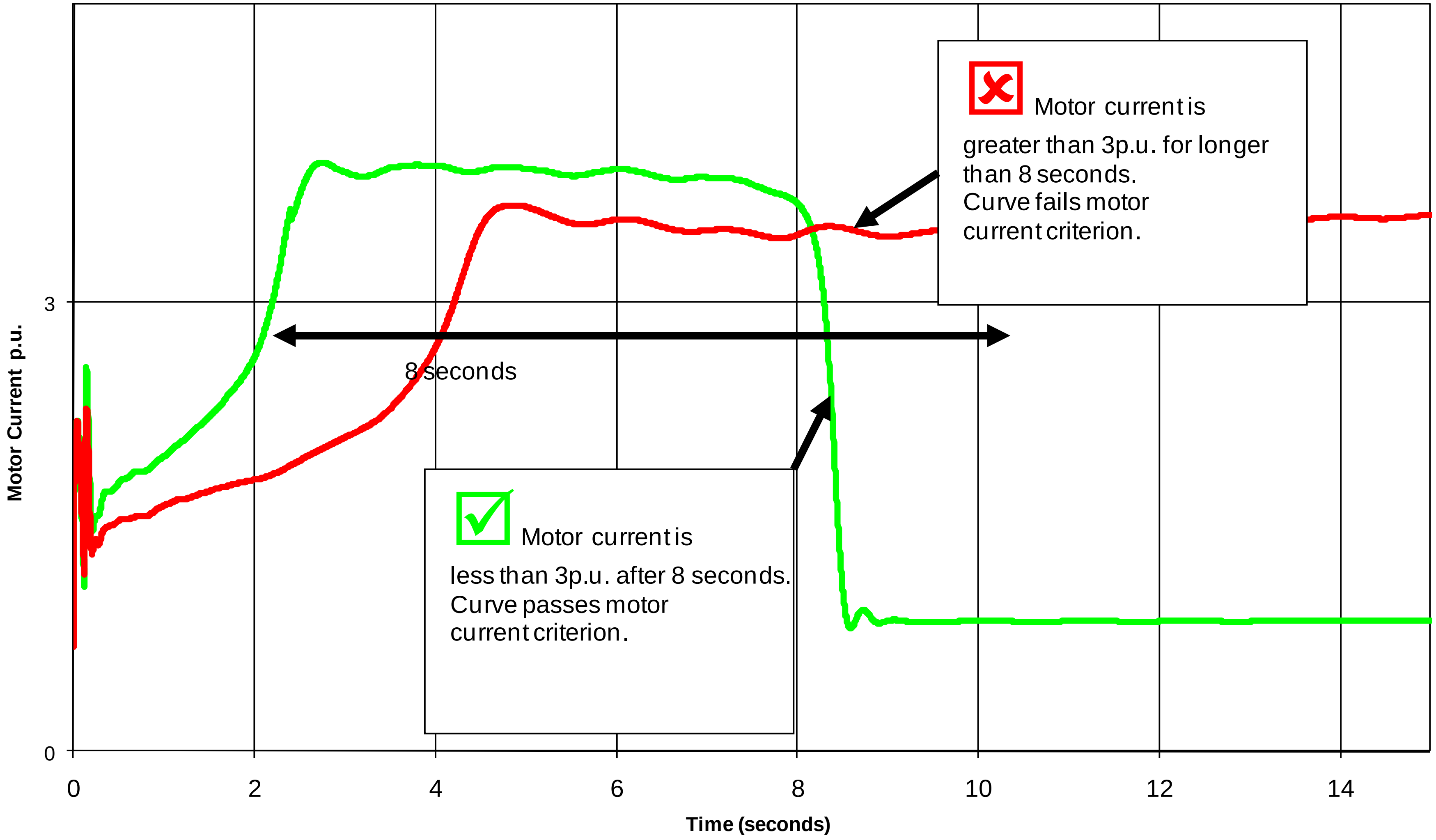

Figure A-2: Example of application of over-current criterion

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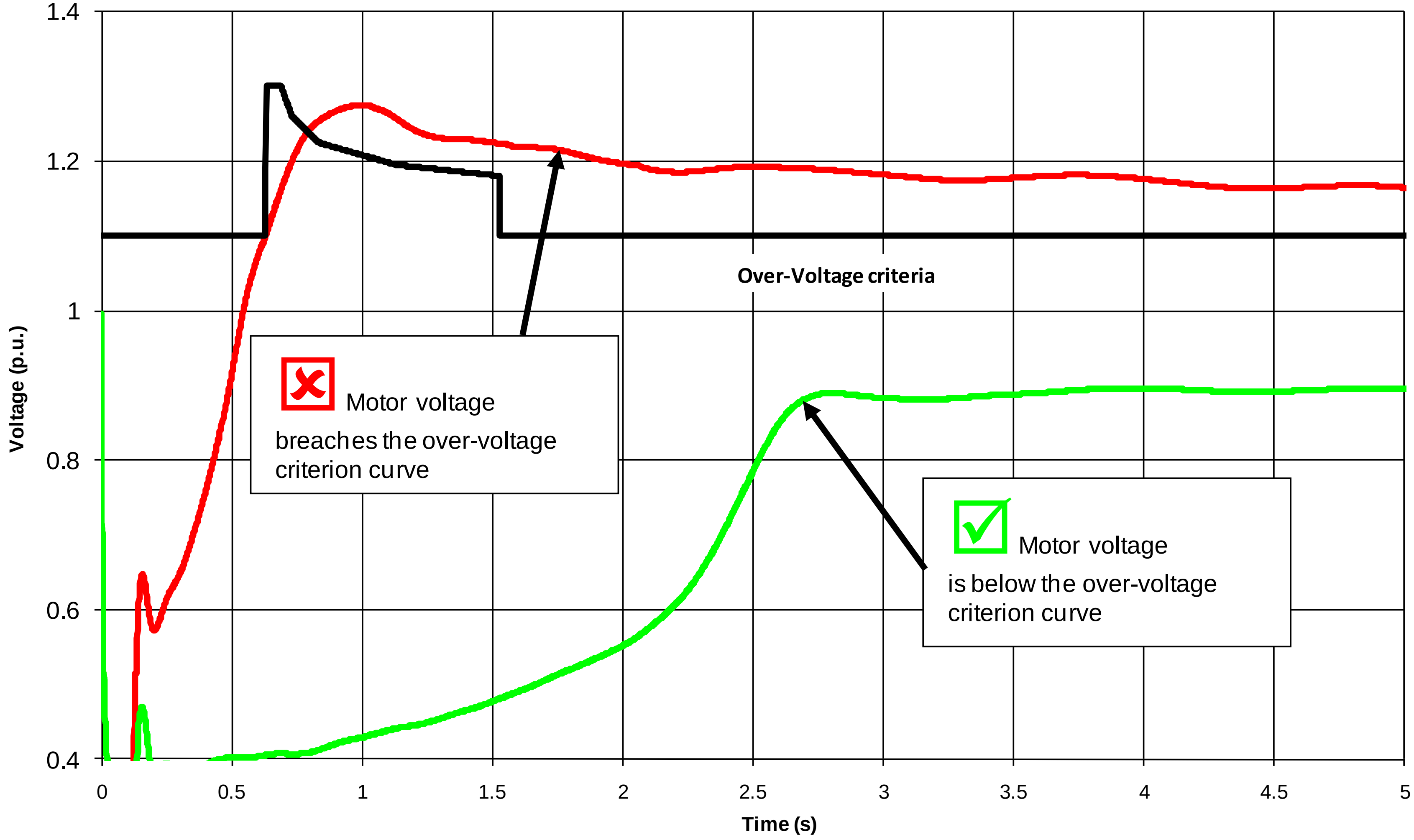

Figure A-3: Over-voltage criterion

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Appendix B Abbreviations

APR	Annual Planning Report
CCGT	Combined Cycle Gas Turbine
DP	Development Plan
EGR	Electricity Governance Regulations
GSC	Grid Support Contract
GXP	Grid Exit Point
HV	High voltage
LV	Low voltage
MRP	Mighty River Power
NAaN	North Auckland and Northland
NIGU	North Island Grid Upgrade – Whakamaru to Brownhill transmission line
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
TF	Transformer
UNI	Upper North Island

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Appendix C Substation names

ALB	Albany
BOB	Bombay
BRB	Bream bay
BRH	Brown Hill
DAR	Dargaville
DRY	Drury
GLN	Glenbrook
HOB	Hobson Street (future sub)
HEN	Henderson
HEP	Hepburn Road
HLY	Huntly
HPI	Huapai
KEN	Kensington
KOE	Kaikohe
KTA	Kaitaia
LST	Liverpool street (Vector)
MDN	Marsden
MNG	Mangere
MPE	Maungatapere
MTO	Maungaturoto
OHW	Ohinewai
OTA	Otahuhu
PAK	Pakuranga
PEN	Penrose
QUAY	Quay Street (Vector)
ROS	Mount Roskill
SVL	Silverdale
TAK	Takanini
WEL	Wellsford
WIR	Wiri
WKM	Whakamaru
WRU	Wairau Road (Vector, future Transpower)

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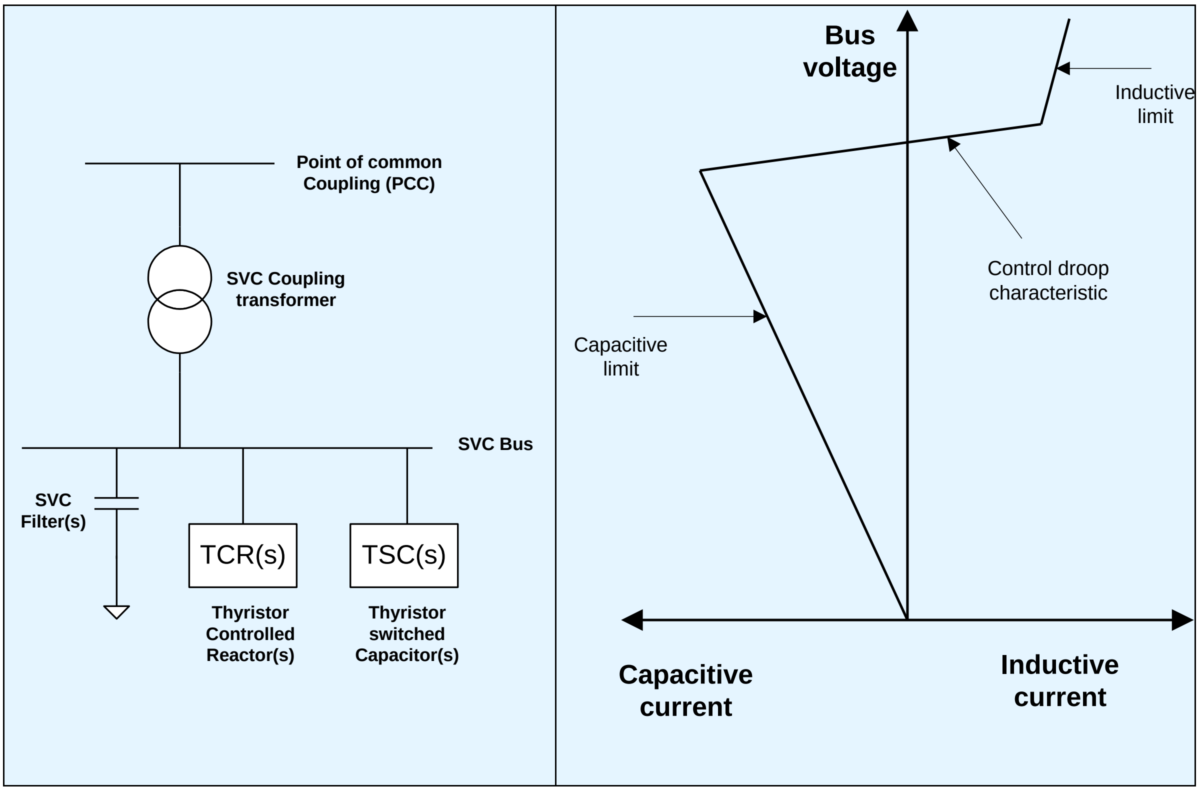
Appendix D SVC and STATCOM characteristics

D.1 Static Var Compensators (SVC)

The SVC is a line to line commutating converter and has found wide application around the world for voltage regulation and dynamic support.

Figure D-1 shows a typical SVC arrangement. Figure 6(b) shows a typical SVC characteristic. SVCs present variable shunt impedance to the network to control the Mvars delivered to the system. Therefore under limiting conditions (where they present their smallest inductive or capacitive impedance to the network) their current output will vary linearly with voltage.

For extreme under voltage scenarios their maximum reactive power output drops as a function of bus voltage squared. On the other hand for over-voltage scenarios SVCs inductive output capability increases as a function of bus voltage squared.



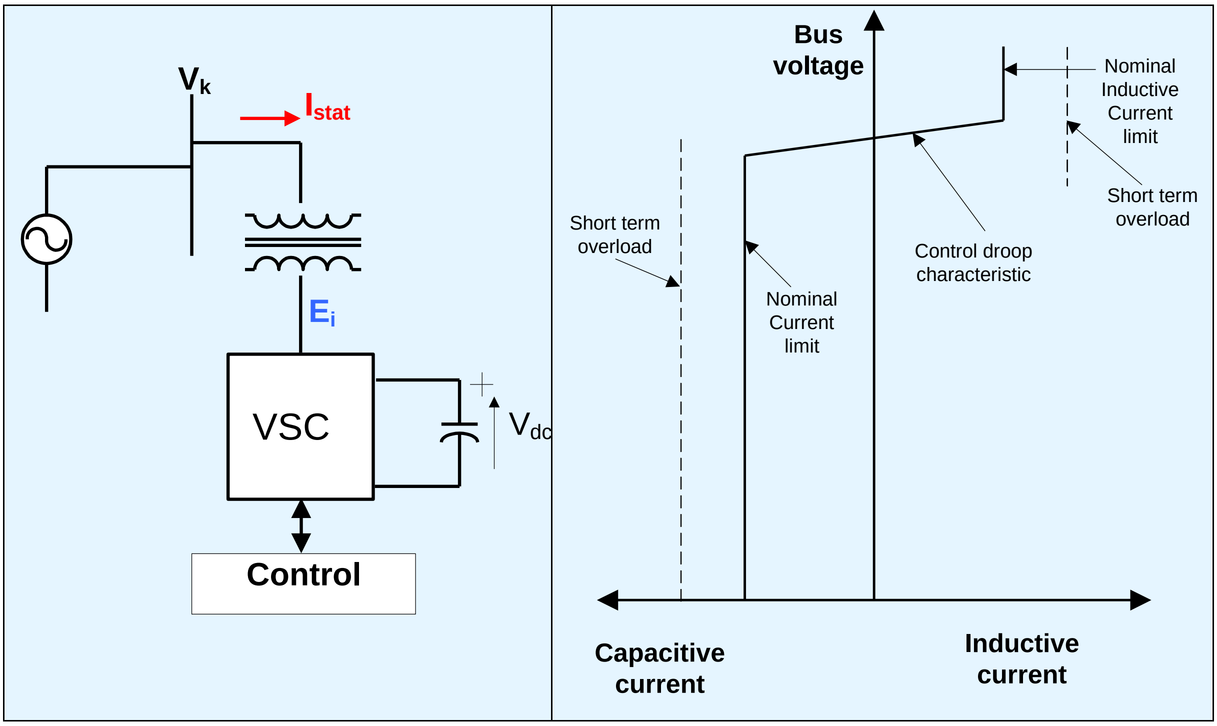
(a) SVC arrangement with coupling transformer, TCRs, TSCs and fixed filters

(b) SVC characteristic, at limits the current output varies in proportion to voltage

Figure D-1: Typical SVC arrangement and characteristics

D.2 STATCOMs

STATCOMs are voltage source converters. Figure D-2 shows a schematic and characteristic for a typical STATCOM. The maximum current output of the device is generally limited by the current rating of the power electronics (and not the bus voltage). Therefore STATCOMs can deliver constant reactive current even if the bus voltage is low as is illustrated by its characteristic in (b).



(a) STATCOM schematic (b) Characteristics

Figure D-2: typical STATCOM arrangement and output characteristics

The STATCOM synthesises (i.e. generates) an AC voltage which is synchronised with the network voltage, typically through an inductive impedance (e.g. a transformer). By changing its internally generated voltage magnitude (E_i) relative to the AC system voltage (V_k), the STATCOM can source or supply reactive current (I_{stat}) to the system. In this manner the STATCOM regulates its bus voltage.

STATCOMs generally have a symmetrical control range, i.e. the maximum inductive current is same as maximum capacitive current. The STATCOM delivers constant current even as the bus voltage reduces and hence provides better support for low voltage conditions. Some STATCOMs can also deliver extra current for short periods of time, i.e. short term overload.

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