TRANSPOWER

Part 8 Review: GXP Reactive Power Flow Assessment

This document contains the System Operator's analysis of reactive power flow through Transpower Grid Exit Points (GXPs). It aims to recommend appropriate technical requirements for managing reactive power flowing through the GXPs.

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Executive Summary

This report presents the System Operator's analysis of reactive power flow through Transpower's Grid Exit Points (GXPs) to determine suitable technical requirements for managing reactive power flow. The study was conducted as part of the Electricity Authority's Future Security and Resilience (FSR) project.

With the uptake of Distributed Energy Resources (DERs) and electrification, power system dynamics are changing. We are already observing two-way power flows through GXPs and changes in voltage profiles across distribution and transmission networks.

Traditionally, the System Operator maintained grid voltage through balancing reactive generation and demand, but the changing landscape means that voltage management is becoming more complex. This report therefore aims to present technical requirements to support a more responsive approach to managing reactive power flowing through GXPs.

Findings

The System Operator analysed a year's worth of data from GXPs across Aotearoa New Zealand. For the purposes of our study, we divided the country's substations into four different behaviour 'types' related to active and reactive power flow. We studied three criteria that could be used to monitor and regulate reactive power flowing through GXPs: power factor, absolute reactive power, and a hybrid arrangement. The hybrid arrangement combines power factor and reactive power limits to compensate for each of their drawbacks.

The study found that 66% of substations violated a 0.95 power factor limit, exceeding this limit during 17% of trading periods on average. In contrast, 40% of substations violated a 0.9 power factor limit, with limit violations during around 8% of trading periods. A small percentage of substations violated absolute reactive power limits.

The 0.95 power factor criterion and the hybrid power factor/absolute reactive power limit criterion each generally offer more significant voltage management gains compared to the 0.9 power factor criterion.

Under the third assessment criterion, applying a reasonably high electricity demand threshold for transitioning between a power factor limit and an absolute reactive power limit was found to reduce the probability of stations violating the criterion. Setting the transition point at 20-40% of maximum active power demand at the station yielded the most favourable outcome.

Recommendation

Based on this study, we recommend the use of a hybrid criterion to monitor and regulate reactive power flowing through GXPs, comprising a combination of a **0.95 power factor limit and an absolute reactive power limit, with a transition point between these two when demand at the substation is at 30% of maximum active power demand at the substation**. Of the three criteria assessed, this criterion best balances voltage profile and reactive power requirements at a substation. This criterion promotes power system stability by allowing for a relaxation of reactive power flow limits when distribution networks and/or the grid are lightly loaded, while also ensuring a constrained voltage profile during significant loading.

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Abbreviations

Abbreviation	Explanation
AOPO	Asset Owner Performance Obligation
Code	The Electricity Industry Participation Code 2010
CQTG	Common Quality Technical Group
FSR	Future Security and Resilience
GXP	Grid Exit Point
MW	Megawatt
PF	Power Factor
PPO	Principal Performance Obligations
PV	Photovoltaic
STATCOM	STATic synchronous COMpensator
SVC	Static Var Compensator
TP	30-minute trading period

1 Introduction

1.1 Purpose

This report examines reactive power flows between New Zealand's transmission network (the grid) and distribution networks, and potential criteria to monitor and regulate such reactive power flows as part of helping manage grid voltage. The work supports the Electricity Authority's Future Security and Resilience (FSR) project, in particular work on reviewing common quality requirements in Part 8 of the Electricity Industry Participation Code 2010 (Code).

The Authority published an issues paper titled "Future Security and Resilience – Review of common quality requirements in Part 8 of the Code"[1] in April 2023 which identified three voltage-related common quality issues. Subsequently, the Authority published a set of short-listed options to mitigate these issues in a consultation paper published in June 2024.[2] This study report is part of follow-on work on the appropriate technical requirements or criteria to manage reactive power flowing through GXPs.

1.2 Voltage management in the New Zealand power system

The New Zealand power system encompasses two islands, connected by an HVDC link. The instantaneous peak demand of 7157 MW was registered on 9 August 2021. North Island power system serves the island demand with power generated from a mixture of fuel sources, namely hydro, wind, geothermal, gas and coal. The South Island serves the island demnad with generation from hydro mainly, but with increasing wind and solar. Most of the time, excess hydro generation from the South Island is exported through the HVDC link to meet demand in the North Island.

Most of the North Island's current generation capacity is installed in the central North Island, Stratford regions, Huntly thermal power station and the large wind farms in the Wellington region. Most generation supplies demand in the three major load centres: Auckland, Wellington, Christchurch and Tiwai.

The System Operator manages the power system to maintain frequency within a set levels. The system operator also maintains voltage within set levels generally through adjusting reactive power outputs from generating units or reactive power compensation devices.

Reactive power demand is high during peak demand periods and the grid and distribution networks consume reactive power when delivering active power from remote generation to demand (primarily on distribution networks). Reactive power is needed to avoid low voltages in the grid and distribution network when electricity demand is high.

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[1] Link to Electricity Authority Issues Paper: Part 8 common quality requirements | Our consultations | Our projects | Electricity Authority (ea.govt.nz)

[2] Link to Electricity Authority consultation paper on voltage options: Part 8 common quality requirements l Our consultations l Our projects l Paper 2 - Addressing larger voltage deviations in New Zealand's power system.

When demand for active power (real) is low, the grid and distribution network are lightly loaded. Under this condition, the network produces reactive power, which results in high system voltage. If unmanaged, thishigh system voltage can cause equipment to fail or equipment insulation to deteriorate, leading to cascade failure.

The nature of the New Zealand power system - where generation is often remote from demand - creates challenges for voltage management. Now changes on the power system are driving new challenges for voltage managements.

Typically, Electrical power travels from Grid via Grid Exit Points (GXPs) to distribution networks or large industrial users to serve the demand connected there. Traditionally, demand was 'passive' and inflexible, consuming both active and reactive power delivered via the GXPs. With more distributed generation connected to distribution networks, the System Operator has observed more occasions where reactive power flows *into* the grid from a distribution network. This might also be due to distribution networks installing more underground cables which can influence reactive power through GXPs, especially during lightly load periods. With increased electrification, demand and distributed resources are becoming more flexible so that there are also opportunities for active and reactive power to be managed.

As the System Operator does not have visibility into the distribution network, they cannot easily coordinate with the distribution network operator to regulate the flow of reactive power through the GXPs. This can lead to inefficient use of grid and distribution assets.

1.3 How system voltage is managed currently

The System Operator maintains grid voltages within the Code requirements by balancing reactive generation and demand. The Code requires grid voltage to be managed with a maximum voltage range of:

a) +/-10% across assets that operate at 110 kV or 220 kV, and
b) +/-5% across assets that operate at 50 kV or 66 kV.

To regulate the grid voltage within the stated limits, the System Operator uses generating units to manage reactive power flows and other reactive power compensation devices connected directly to the grid. Generating units must provide a minimum net reactive power between 50% (exporting) and 33% (importing) of the maximum continuous MW output power.

The backbone of New Zealand's transmission grid is formed by high capacity, high voltage transmission lines and cables.

The long high-voltage transmission system means the System Operator has a significant challenge to manage voltage within the Code limits for all operating conditions. The system behaves like an inductor, absorbing reactive power when the network delivers high electrical power to load centres. We have taken various operational measures to manage low voltage and voltage stability, all to ensure we operate the system securely.

When there is a trough in load demand, the low levels of power transported through the transmission system make the network capacitive. This lightly loaded network produces reactive power, which inevitably increases system voltage.

To manage transmission system voltages, the System Operator employs measures such as:

- dispatching generators to absorb or produce reactive power
- utilising SVC/STATCOM to regulate voltages
- adjusting tap transformers
- switching on/off capacitor banks and reactors
- switching out lightly loaded transmission circuits

As System Operator, we must also manage voltage after events to maintain grid operability and stability. We manage voltage risk based on the appropriate risk class and apply suitable mitigation measures to avoid power system events from causing voltage to exceed the statutory limits.

1.3.1 Management of under-voltage

The System Operator maintains the system voltage above the lower statutory limit to prevent damage to equipment connected to the power system and to avoid malfunction of the protection system.

Generally, under-voltage conditions arise when system load is high and reactive power reserve is scarce. Heavily loaded transmission circuits absorb reactive power, causing lower voltage at the receiving bus. To manage under-voltage, we typically first schedule additional reactive power at the receiving bus to maintain voltage within the statutory limits. If a local reactive power source is not available, we use more distant reactive power sources to increase the overall area voltage profile, thus supporting the voltage at the receiving bus to lift it to the statutory limit. However, the latter option is less effective and increases system losses.

During normal operating conditions and following a contingency, the System Operator uses discrete shunt devices such as capacitor banks and reactors to maintain steady state voltage within statutory limits. Conversely, we use generation units, SVCs and STATCOMs to provide both steady state and dynamic voltage control.

If we exhaust all of the above options, we can deploy other more extreme measures such as grid reconfiguration or load management.

1.3.2 Management of over-voltage

High voltage increases the risk of insulator failure, causes incorrect operation of electrical equipment and can be a danger to human life. The System Operator manages high voltage conditions by switching off excess capacitor banks in the system and using generation and other devices, such as SVCs and STACOMs, that regulate dynamic reactive power to absorb excess reactive power.

These devices provide steady state regulation as well as manage post-event voltage. To enable post-event regulation, the System Operator operates the devices at a predetermined level to offer fast reactive power regulating reserve. This provides automatic post-event regulation to maintain system voltages below the limit. The current operation policy requires that the dynamic reactive power regulating devices should not import more than 25% of their rated capability.

If all options fail to maintain the dynamic reactive power reserve, the System Operator will remove one or more highly capacitive (lightly loaded) circuits from service. This reduces the overall reactive power available in the power system. Since connected circuits are also lightly loaded, the measure should not result in reduced system security.

During low load, we have certain operational procedures in place to manage voltages, including:

- switching capacitors/reactors
- lowering the voltage set points of generation to absorb reactive power
- lowering the voltage set points on dynamic reactive plants (synchronous condensers, SVCs and STATCOMs)
- switching out transmission lines to reduce reactive power production in the power system.

We have identified the following circuits as effective at reducing voltages for specific regions (see in the System Operator's PR-DP-235 Manage Grid and Supply Voltage document for more information):

Table 1: Circuits effective at reducing voltages for specific regions

Area of New Zealand	Identified Circuit
Upper North Island	Pakuranga-Whakamaru-1 and -2 220 kV circuits Pakuranga-Penrose-3 220 kV circuit
Central North Island	Huntly Stratford-1 220 kV circuit Brunswick-Stratford 1, 2 or 3 220 kV circuit
Upper South Island	Islington-Kikiwa-1 220 kV circuit Islington-Livingston-1 220 kV circuit Ashburton-Islington-1 220 kV circuit

1.3.3 Managing voltage stability

It is important to maintain voltage stability to ensure that power system voltage remains stable under normal system conditions. We must also prevent voltages from becoming unstable after a fault or disturbance and leading to progressive and uncontrollable voltage decline.

The System Operator uses online voltage stability assessment software, which relies on static analysis for voltage security assessment and transfer limit computations based on voltage security criteria and contingencies. We conduct this assessment every trading period to determine the transfer limit for predefined transmission corridors. We apply a 5% stability margin to provide an operational safety margin.

1.3.4 Voltage profile across the power system

Generally, the System Operator keeps the GXP voltage slightly higher at the transmission network to force reactive power to flow into the distribution network, thereby maintaining a healthy level of voltage all the way to the demand connection points. Distribution networks may have other reactive power compensation devices and transformers to boost the voltage where necessary.

DERs generate electricity physically closer to the demand source. Electrical power flowing through the local circuits leaves major parts of the distribution and transmission network lightly loaded. Those lightly loaded circuits will generate reactive power, forcing the voltage to increase.

Additionally, underground cables typically have a higher capacitance due to their construction – because the conductors are insulated and surrounded by dielectric materials. When an AC voltage applies to a capacitive element, it generates reactive power. Since underground cables are more capacitive than overhead lines when lightly loaded, they generate more reactive power.

When there are many DERs like rooftop solar PV installed in the distribution network, the local generation supplies the demand, leaving the distribution and transmission networks lightly loaded. Reactive power generated in the lightly loaded networks will flow to meet the reactive demand and into lower voltage points. Without managing this production, the voltage level across the transmission and distribution network will increase.

1.4 The increasing challenges of managing voltage

With the increased uptake of DERs and shifts in distribution network characteristics, the power system is changing. The System Operator anticipates that this would lead to:

- changes in voltage profiles across the distribution and transmission network due to changes in reactive power demand.
- two-way power flow through the GXPs if DERs exceed the demand

In addition, the installation of more cables in the distribution network than overhead lines – as a safer and more aesthetically pleasing option – makes the distribution network more capacitive. As a result, in some instances, the reactive power supply can exceed the demand, causing reactive power to flow back into the transmission network.

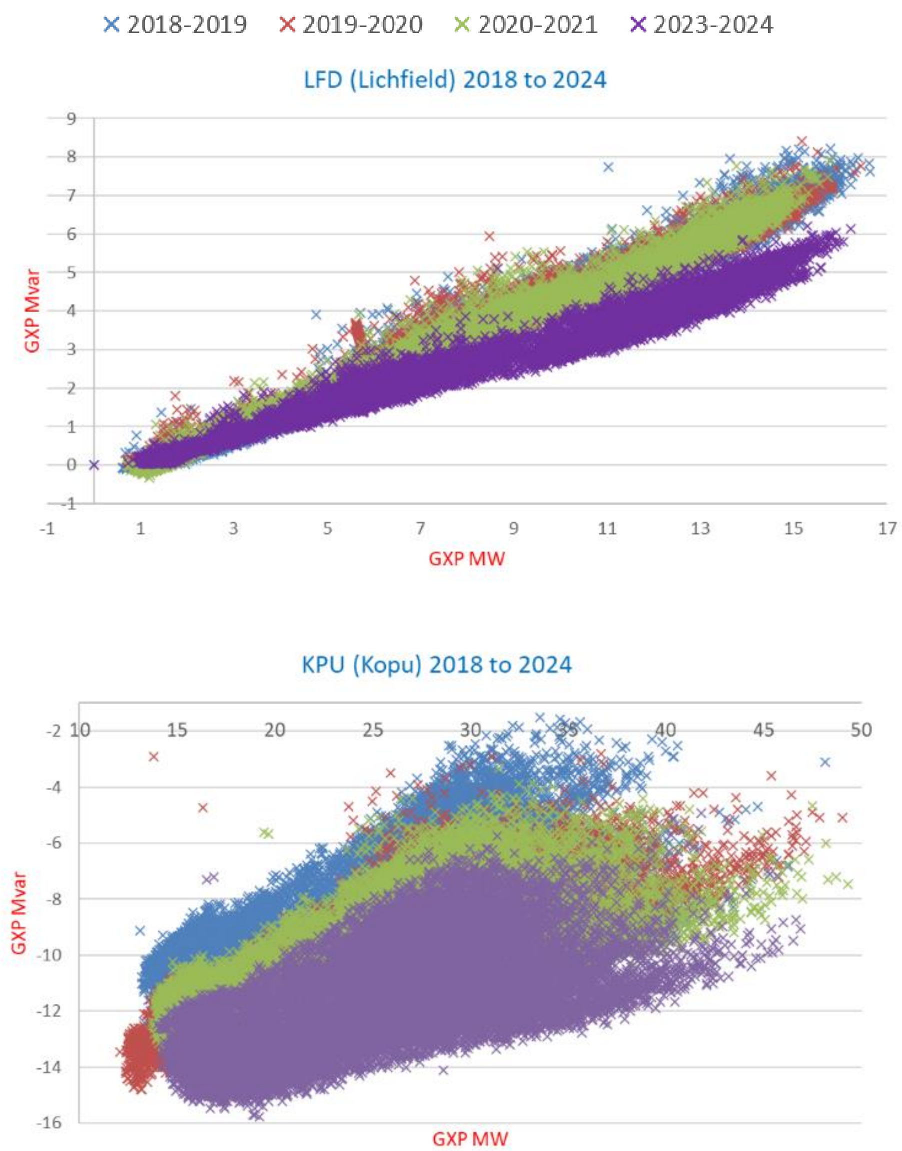
1.4.1 Changing reactive power demand

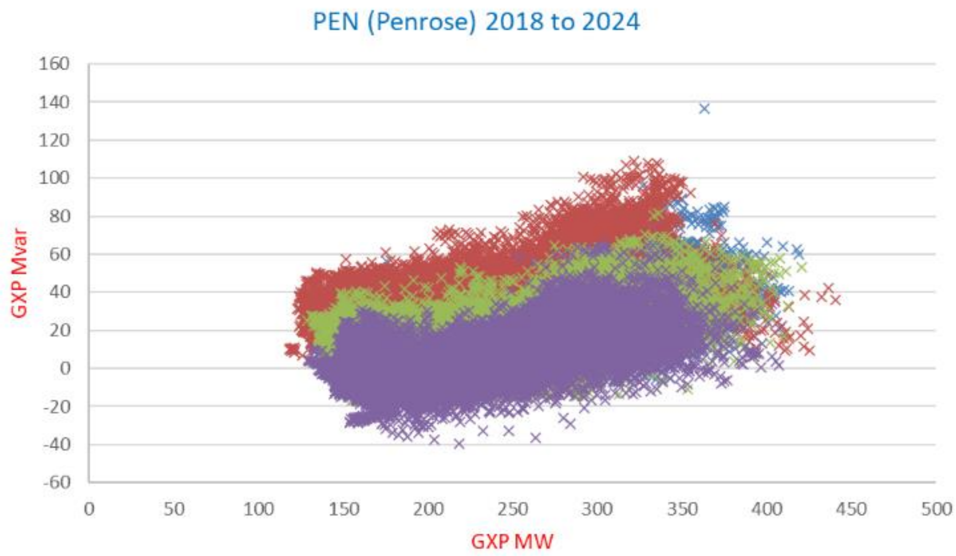
An initial analysis of GXPs indicates we are already seeing reactive power flow changes in New Zealand.

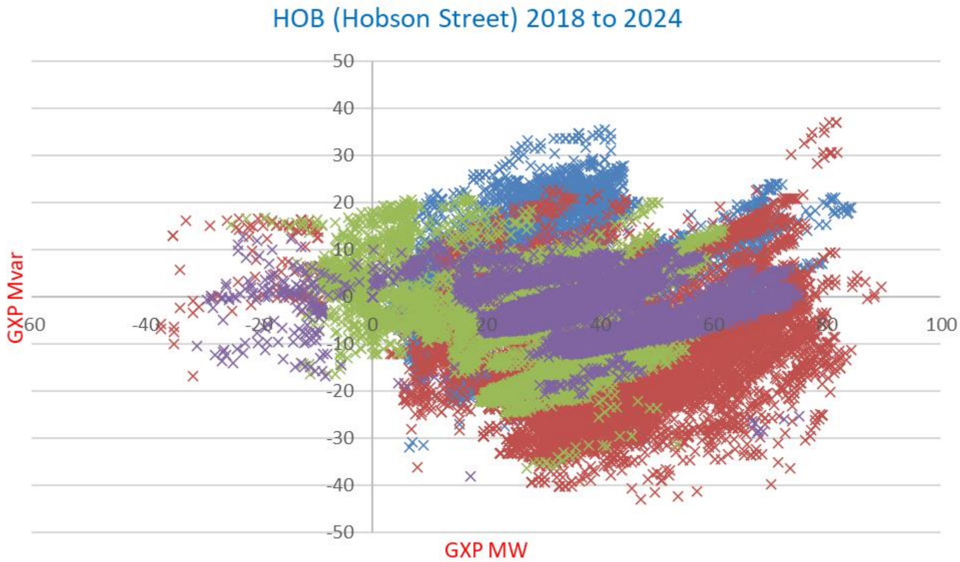
We conducted an analysis on example GXPs over a six-year period. With most of the GXPs we analysed, we observed a shift towards greater reactive power export. The results are shown below. The four graphs represent four broad types of GXPs which are described in more detail in section 3. We can draw three conclusions from the trends in these graphs:

- The distribution network is becoming more capacitive through importing less or exporting more reactive power from the transmission network.
- The active power demand appears to drop, potentially signifying an uptake of distributed generation within the distribution network.
- Compared to previous years, some stations now seem to better regulate demand and supply of distribution network reactive power; the reactive power plots showed a much narrower spread recently (shown in 'Type 4' in the fourth chart).

Figure 1: Historical view of active and reactive power through GXPs







1.4.2 Two-way power flow through the GXPs

The accelerated growth in DERs and an increase in demand due to electrification have created new challenges for designing and operating the future power system. In New Zealand, peak demand occurs during winter evenings, requiring the electrical network to have sufficient capacity to meet this demand. During trough periods, most electrical circuits are lightly loaded, generating reactive power and causing high voltage in the network.

An increased uptake in solar photovoltaic (PV) renewable energy resources is exacerbating the situation. High solar PV generation in summer midday will likely lead to loaded circuits in certain parts of the network close to the location of the solar PV generation. If solar PV generation within a distribution network is higher than demand, it can cause active power to flow out of the GXP into the transmission network. By contrast, in a low uptake solar PV scenario, the distribution network can be lightly loaded, generating enough reactive power to flow into the transmission network.

1.4.3 The impacts of rooftop solar PV on voltage regulation capability

An increase in PV generation will displace grid-connected synchronous generation, thereby changing the mix of generation and the pattern of power flowing through the transmission system. This will result in significant changes to the way Transpower plans and operates the power system.

Historically, synchronous generators connected at the transmission level have provided the system services required to reliably operate the power system. To manage transmission voltage, synchronous generation provides fault current and both static and dynamic reactive power support. These system services are an integral part of reliable power system operation, helping to keep voltage within stable limits.

The displacement of synchronous generation can reduce and ultimately remove important system services that help manage transmission voltage. A high PV penetration scenario poses a deficiency in reactive power regulating devices across the transmission system, and coupled with high voltages, managing transmission voltages may require extreme measures. These might include switching out transmission circuits and reducing PV generation.

The reduction in the system services mentioned above would have two major impacts:

- A reduction in short circuit current that synchronous generation contributes to the transmission system may make voltages more susceptible to system disturbances like circuit or capacitor bank switching.
- A reduction in online synchronous generation would reduce the system's ability to regulate voltage overall, especially during at midday when PV generation is at its maximum.

2 High-level study approach

The Authority and the Common Quality Technical Group (CQTG) requested this study to determine the appropriate level of reactive power flow. We approached this study as follows:

Stage 1: Analyse reactive power flowing through all Transpower GXPs. This task extracts the MW and Mvar data at 30-minute (trading period) intervals for each GXP for the past year to:

a. calculate the power factor for each trading period (TP),
b. determine the direction of reactive power flow (whether it is single directional or bi-directional),
c. determine how many TPs the GXP exceeded the power factor of 0.9 or 0.95, and
d. determine an appropriate technical criterion for managing reactive power flow through the GXP.

Stage 2: Determine the criteria to manage reactive power flowing through GXPs. This task establishes the magnitude of reactive power that needs to be managed if the technical criterion is imposed. The study considers factors such as:

- light and peak demand periods
- minimum power factor
- the direction of the reactive power flow.

Stage 3: Investigate the effects of managing transmission voltages or voltage stability when the System Operator controls reactive power to shift the GXP power factor within appropriate limits. This task assesses the impact of managing reactive power flow through the GXP. The study team selected trading periods from the analysis carried out in Stage 2 to determine if there are benefits to this approach to reactive power management.

3 Station characteristics

There are approximately 226 GXPs in New Zealand's transmission network, and some substations have multiple GXPs. In this analysis, we grouped all the GXPs within substations under one station and called it the substation import and export. This allows us to examine the overall active and reactive power flowing into or out of the distribution network, as well as the effects of this power flow on managing the transmission network voltage.

We extracted active and reactive power data for each GXP to analyse the electrical power flowing through the GXPs. We used one data point per 30 minute trading period from 1 September 2023 to 1 September 2024, giving us data over four calendar seasons. We also used this to calculate the power factor.

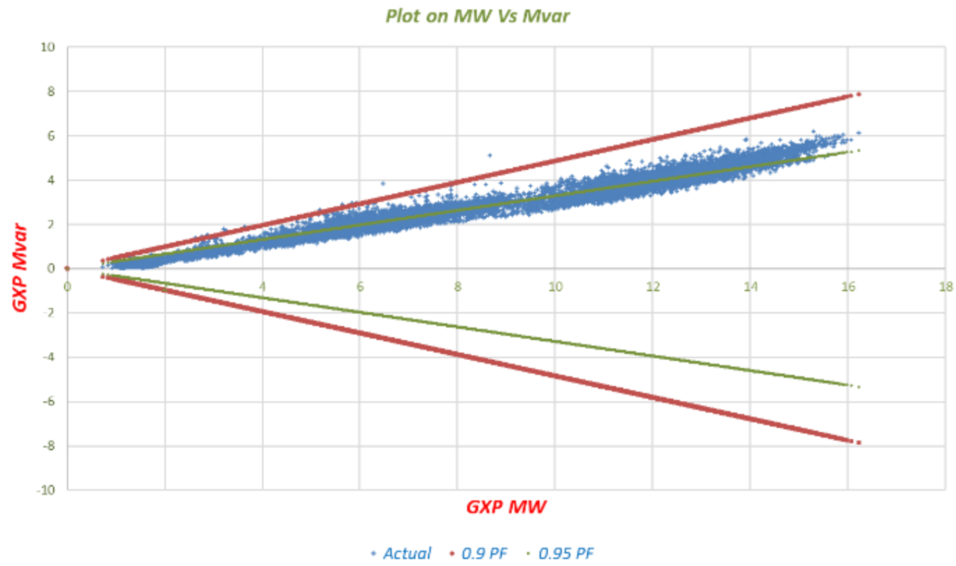
The analysis revealed the four types of behaviour that we have summarised in Table 2 below. Refer to Figure 2 for illustrated graphs representing each.

Table 2: Observed behaviour patterns of four substation groupings

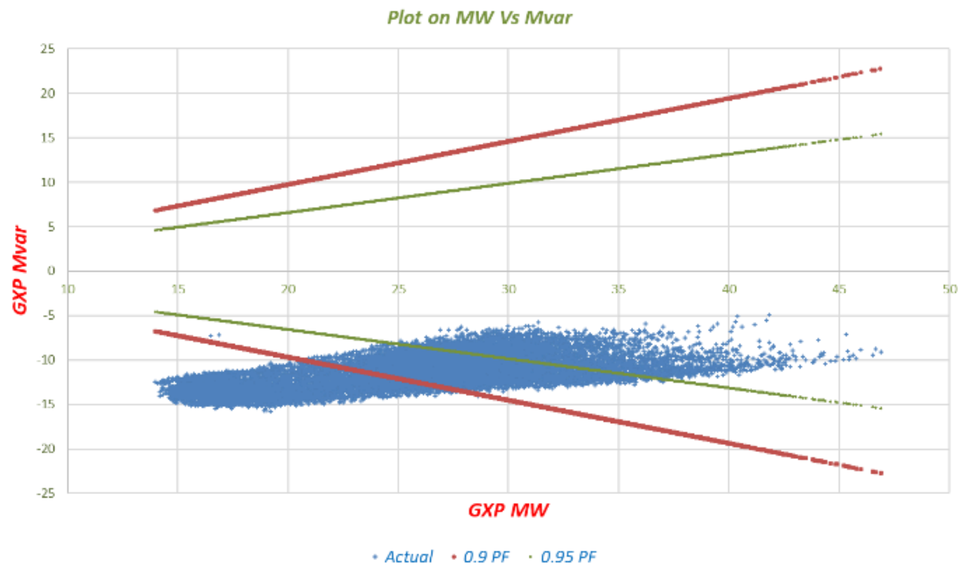
	Active and reactive power flow	Number of substations	Observed Patterns
Type 1	Active and reactive power flowing into the station	11	These resembled an inductive distribution network that imported reactive power from the transmission network.
Type 2	Active power flowing into and reactive power flowing out of the station	11	These represented a highly capacitive distribution network with reactive power flowing out of the distribution network into the transmission network.
Type 3	Active flowing into and reactive power flowing into or out of the station	92	These drew active power from the transmission network and either imported or exported reactive from the transmission network depending on the demand within the distribution network.
Type 4	Active power and reactive flowing into or out of the station	14	These house enough embedded generation or DERs to occasionally export active power, as well as import and export reactive power to the transmission network based on distribution network demand.

Figure 2: GXP active and reactive power behaviour

Type 1 Substation

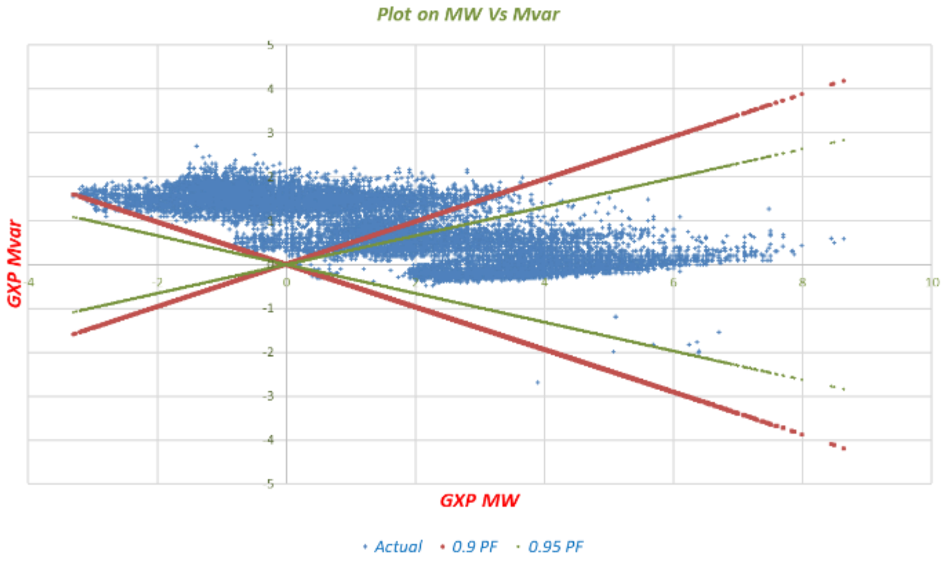


Type 2 Substation



Type 3 Substation

Type 4 Substation



4 Assessment criteria

Reactive power flowing through a GXP will affect the voltage profile across transmission and distribution networks. Managing reactive power flow allows the system operator, grid owners and distributors to manage the network voltage and better utilise asset capacity. Find below a discussion of three criteria that we can use to monitor and regulate reactive power flowing through the GXP.

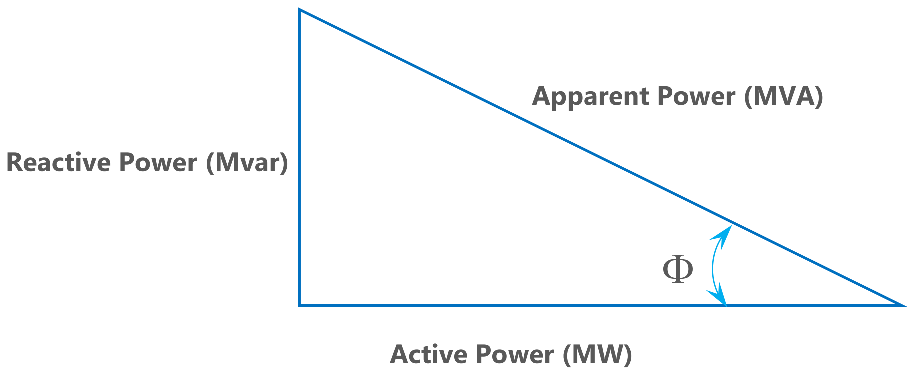
4.1 Power factor criteria

Power factor (PF) is the ratio of active power (MW) to apparent power (MVA). Active power is the electrical power that performs useful work, while apparent power is the total electrical power delivered in a circuit. We generally use power factor to measure the efficiency of electricity use.

A power factor of 1 implies that all apparent power is active power. A lower power factor means that more electrical power is needed to deliver the same amount of useful power (real power), which means an increase in consumers' electricity costs.

Figure 3 below demonstrates the relationship between active power, reactive power and power factor. By applying the formula below, we can calculate reactive power requirements if power factor and active power are given.

Figure 3: Relationship of active, reactive and apparent power

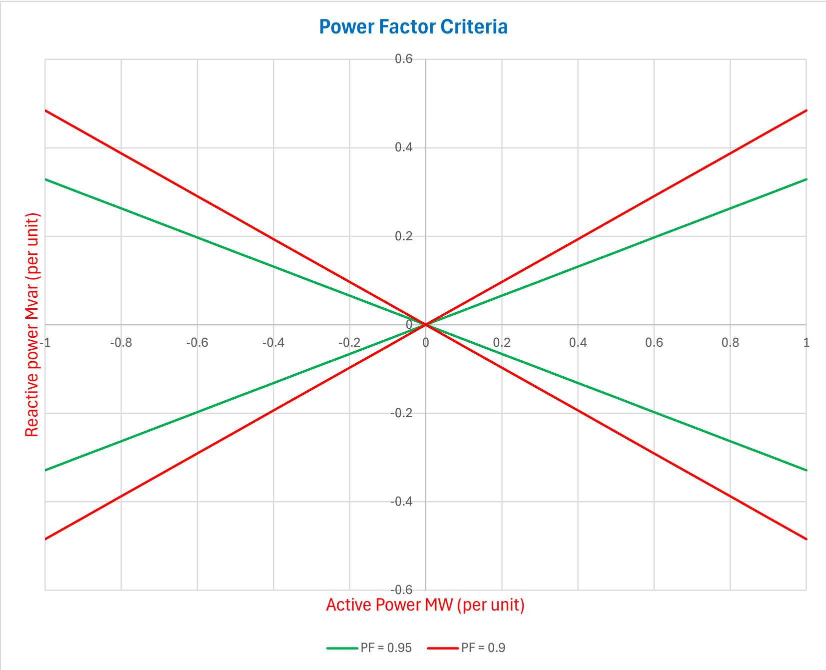


$$Power\ Factor = \frac{Active\ power}{Apparent\ power} \quad \text{Equation 1a}$$

$$Reactive\ power = \sqrt{(Apparent\ power)^2} - (Active\ power)^2 \quad \text{Equation 2b}$$

As shown in figure 4 below, the power factor criteria will generate reactive power limits depending on the active power flow and the power factor threshold we wish to apply. The higher the active power demand, the more reactive power that the GXP can import from or export to the transmission network.

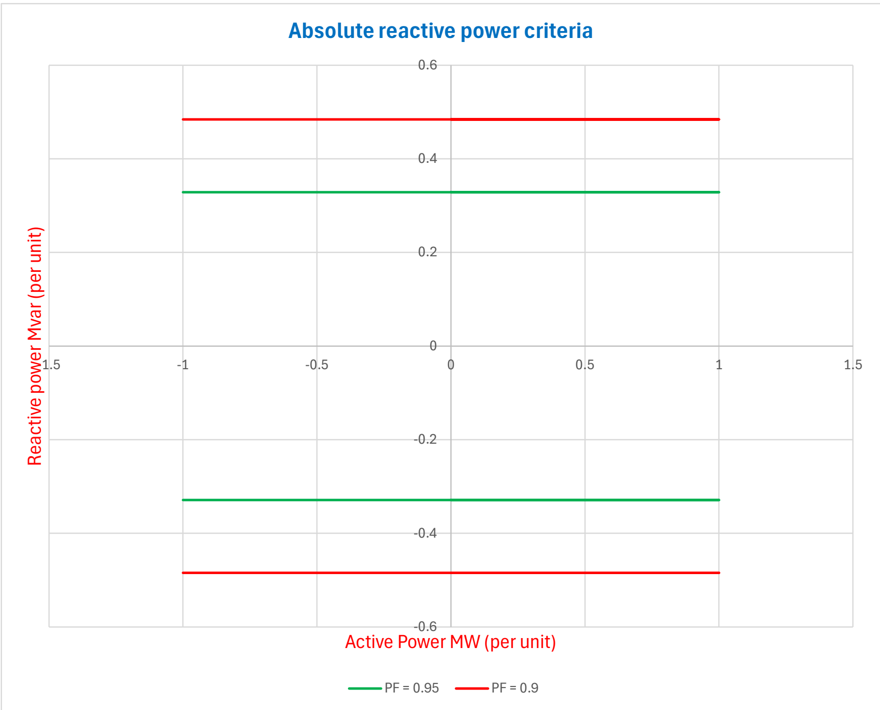
Figure 4: 0.9 and 0.95 power factor limit



4.2 Absolute reactive power criteria

We determine the absolute reactive power requirement based on maximum demand. As seen in figure 5 below, a GXP drawing a maximum demand of 100 MW can draw maximum reactive power of approximately 33 Mvar if the power factor is set at 0.95. The reactive power requirement applies to all active power conditions.

Figure 5: 0.9 and 0.95 reactive power limit



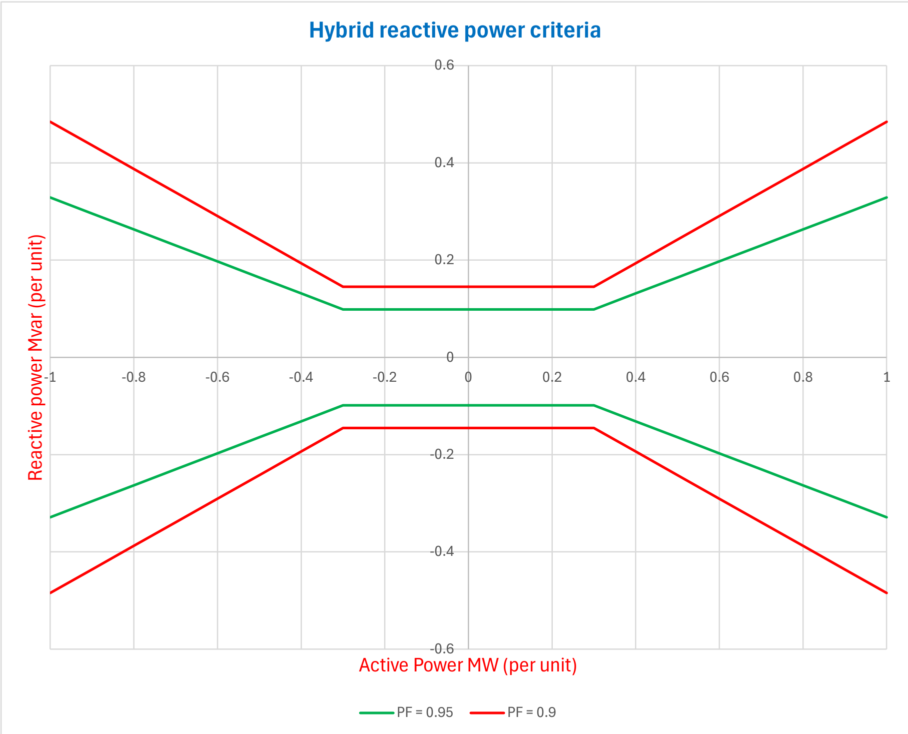
4.3 Hybrid reactive power criteria

Both criteria described above have some major drawbacks. With lower active power demand, power factor criteria are too stringent, limiting the flow of reactive power. This may require additional investment to install additional reactive power compensation devices and need more real time control during low demand periods.

Moreover, absolute reactive power criteria appear more lenient during low demand conditions, allowing more reactive power to flow through the GXP. This does not address the current challenge of managing excessive reactive power flowing into the transmission network during low demand periods. Lowering the reactive power requirements would worsen the situation during high demand periods and may require distributors to install additional reactive power compensation devices in their network to meet the reactive power demand.

A hybrid reactive power criteria that combines the previous criteria together could be a solution to address the shortcomings of the power factor and absolute reactive power criteria above. We can apply the power factor criteria in high demand conditions and the absolute reactive power criteria during low demand. **Error! Reference source not found.** Figure 6 shows the hybrid reactive power criteria concept. In the section below, we discuss at which point the power factor criteria should transition to the absolute reactive power criteria.

Figure 6: 0.9 and 0.95 Hybrid reactive power limit



4.4 Comparisons with criteria imposed by other jurisdictions

Variations of these type of criteria are used in overseas jurisdictions. A brief overview of approaches used in Australia, North America and Europe are given below.

4.4.1 Australia Electricity Market Operator (AEMO)

According to Clause S5.3.5 of the National Electricity Rules (NER), network users and distribution networks connected to another transmission networks must maintain power factor at the connection point to within the permissible ranges showed in Table 3 below. These requirements apply if the load is greater than or equal to 30% of the maximum demand.

Table 3: AEMO's Power Factor Maintenance Permissible Ranges

Supply voltage (nominal)	Power factor range
>400 kV	0.98 lagging to unity
250 kV – 400 kV	0.96 lagging to unity
50 kV – 250 kV	0.95 lagging to unity
1 kV – 50 kV	0.90 lagging to leading

The clause allows variation if the load is less than 30% of the maximum demand. In that case, the Network Services Provider may accept a power factor outside the range if this does not violate system standards. AEMO may also permit a lower power factor if this will not harm power system security or reduce intra-regional or inter-regional power transfer capability.

4.4.2 North America Reliability Council (NERC)

North America Reliability Council (NERC) have defined their reactive power requirements to ensure reliable planning and operation of the whole power system. However, they encouraged different regions to have additional requirements to address their own reactive power needs.

The transmission and distribution network planners performed joint studies to determine a set of mutually agreed minimum and maximum load power factors that would assure that the system can be planned and operated efficiently and reliably. This approach ensured that adequate reactive power support would be installed on both transmission and distribution networks to manage system voltage adequately.

The load power factor does not need to be exactly power factor unity and can range from 0.95 to as high as 0.998. For example, PJM (the Pennsylvania-New Jersey-Maryland Interconnection) set a minimum power factor of 0.97 lagging in their planning studies. California ISO (Independent System Operator) imposed power factor requirements of 0.97 lagging and 0.99 leading to maintain reactive power flow at their grid interface points.

4.4.3 Europe Network of Transmission System Operator for Electricity

The European system operator required the transmission-connected distribution network operator to maintain a power factor greater than 0.9 of their maximum import capability for import and to 0.9 of their maximum export capability in export, except in situations where either technical or financial benefits exist.

The system operator also requires transmission-connected distribution networks to ensure that they do not export reactive power (at nominal voltage) at the connection point. This applies when the active power flow is less than 25% of the maximum import capability.

5 Assessment of substation behaviours

The nature of the distribution network and the type of demand that the network serves will determine the active and reactive power flowing through the GXP. For example:

- A rural network with a long overhead circuit may appear to be more inductive than urban areas with more cables in the network.
- If a capacitor bank is installed to compensate the distribution network, it will appear capacitive.
- DERs and rooftop solar PV can affect electrical power flowing through GXP by exporting active and reactive power into the transmission network if the local generation exceeds the demand.

We analysed the past year of data for all substations against the criteria mentioned in the previous section. Tables 4-6 below provide an overview of the stations that we analysed, and the subsequent sections provide the assessment summary for each grid zone. In this analysis, we use the term "pitch" to refer to the shape of the data, highlighting the relationship between loading and reactive power. A steep pitch infers a large change in reactive power as loading increases, while a flat pitch shows little change.

5.1 Station assessment overview

The analysis determines the number of trading periods when the reactive power flowing across the GXP violates the assessment criteria set up in the above sections. For the hybrid criteria, we also assess the impact of changing the point where the power factor requirement transitions to the absolute reactive power requirement. Our analyses allow us to make the following observations:

- 66% of substations (85 out of 128) violated the 0.95 power factor criteria. On average, substations exceeded the 0.95 power factor limit during 17% of the trading periods.
- 40% of substations (51) violated the 0.9 power factor criteria. On average, stations exceeded the 0.9 power factor limit during 8% of the trading periods.
- 13% of substations (16) violated the 0.95 absolute reactive power limit. On average, substations exceeded the 0.95 reactive power limit during 2% of the trading periods.
- 2% of substations (3) violated the 0.9 reactive power limit. On average, stations exceeded the 0.95 reactive power limit during 0.3% of the trading periods.
- Applying the hybrid criteria at a very high transition point (90 percent of the maximum demand) reduces the probability of the stations violating the criteria. Conversely, decreasing the transition point increases the probability of exceeding the limits. We conclude that setting the transition point at 20-40% is most logical, as further decreasing it will not significantly increase the probability of exceeding the limits.

Table 4: Assessment results using power factor and absolute reactive power criteria

	PF Limit of 0.95	PF Limit of 0.90	Q Limit 0.95	Q Limit 0.90
GXPs > 1% affected TPs	85	51	16	3
% of GXPs > 1% affected TPs	66	40	13	2
% TPs affected (average of all GXPs)	17.76	8.13	2.26	0.26

Table 5: Assessment results using 0.90 PF hybrid reactive power criteria

	10%	20%	30%	40%	50%	60%	70%	80%	90%
GXPs > 1% affected TPs	50	48	40	29	21	14	9	6	3
% of GXPs > 1% affected TPs	39	38	31	23	16	11	7	5	2
% TPs affected (average of all GXPs)	7.57	7.17	5.97	4.19	3.00	2.08	1.43	0.92	0.45

Table 6: Assessment results using 0.95 PF hybrid reactive power criteria

	10%	20%	30%	40%	50%	60%	70%	80%	90%
GXPs > 1% affected TPs	85	82	72	64	48	39	30	23	19
% of GXPs > 1% affected TPs	66	64	56	50	38	30	23	18	15
% TPs affected (average of all GXPs)	17.2	16.7	15.7	12.9	9.8	7.3	5.5	4.2	3.1

5.2 Grid zone overviews

See below our observations of substation behaviours for each grid zone. We have included Tables 7 and 8 breaking down the results for Grid Zone 1; see the appendix for such tables connected to the other grid zones.

5.2.1 Grid Zone 1

The analysis observed the following behaviours within Grid Zone 1:

- Nine stations in Grid Zone 1 predominantly export reactive power to the transmission network during light demand periods.
- There are no type 1 stations in Grid Zone 1, two type 2 stations, eight type 3 stations and one type 4 station.
- Ten stations violated the 0.95 PF limit, of which WEL (Wellsford) performed the worst with nearly 50% of the trading periods violating the limit.
- By increasing the limit to 0.9 PF, the number of trading periods that violated the limit reduced. WEL registered 28% of trading periods where the export of reactive power exceeded the limit.
- No stations violated the limit if we applied the absolute reactive power limit.
- All stations in Grid Zone 1 performed similarly when applying the 0.9 hybrid rule with the transition point at 30% as compared to the 0.9 PF rule. Limit violations reduced when raising the hybrid transition point to 40% and 50%.
- The majority of Grid Zone 1 stations exhibited a gradual upward pitch, with two GXPs remaining relatively flat (KOE and SWN).

Table 7: GXP type, quantity of reactive power imported/exported and assessment results

GXP	Type	Export %TP- Import %TP	PF Limits		Q Limits		Hybrid 0.9 PF			Hybrid 0.95 PF		
		Exporting / Importing	0.95	0.9	0.95	0.9	30%	40%	50%	30%	40%	50%
HEP	3		1.1	-	-	-	-	-	-	0.0	-	-
ALB	3		-	-	-	-	-	-	-	-	-	-
HEN	3		7.2	-	-	-	-	-	-	0.4	-	-
BRB	3		9.9	0.2	-	-	0.2	0.0	-	9.9	9.7	2.8
KOE	3		0.2	0.0	-	-	-	-	-	0.0	-	-
MPE	3		0.7	0.0	-	-	-	-	-	0.6	0.1	-
MTO	3		18.9	5.4	-	-	5.4	1.9	-	18.9	18.2	10.9
SVL	2		26.4	3.7	-	-	0.3	-	-	26.4	15.4	-
SWN	4		25.8	19.4	-	-	-	-	-	-	-	-
WEL	2		49.3	28.3	-	-	28.3	26.5	16.9	49.3	49.3	48.5
WRD	3		45.2	22.4	-	-	21.1	12.5	7.6	45.1	38.8	25.9

5.2.2 Grid Zone 2

The analysis observed the following behaviours for Grid Zone 2:

- Six stations in Grid Zone 2 predominantly export reactive power to the transmission network during light demand periods.
- There are no type 1 stations in Grid Zone 2, one type 2 station, eight type 3 stations and one type 4 station.
- Seven stations violated the 0.95 PF limit. ROS (Mount Roskill) station performed the worst with nearly 34% of trading periods violating the limit.
- Four stations violated 0.9 PF limit, ROS registering nearly 18% of trading periods that exceeded the limit.
- No stations markedly violated the limits when we applied the absolute reactive power limit.
- All stations in Grid Zone 2 performed similarly to the 0.9 PF rule when applying the 0.9 hybrid rule with a transition point at 30%. Raising the transition points to 40% and 50% reduced the number of violating trading periods to negligible levels.
- Similarly, all stations in Grid Zone 2 performed comparably to the 0.95 PF rule when applying the 0.95 hybrid rule with a transition point at 30%. Raising the transition point to 40% reduced the number of trading periods which violated the hybrid rule, while only a single station (ROS) had notable violations at the 50% transition point.
- The majority of Grid Zone 2 stations exhibited a gradual upward pitch, with PEN (Penrose) station remaining relatively flat.

Table 8: GXP Data Grid Zone 2

GXP	Type	Export %TP-Import %TP	PF Limits		Q Limits		Hybrid 0.9 PF			Hybrid 0.95 PF		
		Exporting Importing	0.95	0.9	0.95	0.9	30%	40%	50%	30%	40%	50%
GLN	3		0.7	0.0	-	-	0.0	0.0	-	0.7	0.7	0.6
BOB	3		22.8	4.0	-	-	3.1	0.0	-	22.8	18.1	0.7
MNG	3		1.8	-	-	-	-	-	-	1.8	1.8	-
OTA	3		-	-	-	-	-	-	-	-	-	-
PAK	3		3.3	-	-	-	-	-	-	2.8	-	-
PEN	3		-	-	-	-	-	-	-	-	-	-
ROS	2		33.6	-	-	-	17.7	0.1	-	33.6	32.5	5.0
WIR	3		-	-	-	-	-	-	-	-	-	-
TAK	3		2.3	-	-	-	-	-	-	0.9	-	-
HOB	4		2.8	-	-	0.0	0.3	0.2	0.2	1.7	1.2	0.6

5.2.3 Grid Zone 3

The analysis observed the following behaviours for Grid Zone 3:

- Nine stations in Grid Zone 3 predominantly export reactive power to the transmission network during light demand periods. The largest station in grid zone 3, HAM (Hamilton) station, exports reactive power for 99% of trading periods.
- There are two type 1 stations in grid zone 3, three type 2 stations, eight type 3 stations and one type 4 station.
- 13 stations violated the 0.95 PF limit; of these, ARI (Arapuni) station performed the worst with more than 96% of trading periods violating the limit.
- 12 stations violated the 0.9 PF limit, with ARI station registering nearly 83% of trading periods that exceeded the limit.
- Five stations violated the 0.95 absolute reactive power limit, while one station violated the 0.9 absolute reactive power limit.
- With the exception of ONG (Ongarue) station, all stations in Grid Zone 3 performed similarly to the 0.9 PF rule when applying the 0.9 hybrid rule with a transition point at 30%. ONG violated limits for 48% of trading periods when we applied the 0.9 PF rule, while only violating 36% of trading periods under the 0.9 hybrid rule with the transition point at 30%.
- When raising the 0.9 hybrid rule transition point to 40% and 50%, we observed a fall in ONG station trading period violations, whereas the remaining stations were unchanged from their values using the 0.9 hybrid rule with the transition point at 30%.
- Similarly, all stations in Grid Zone 3 except for ONG station performed comparably to the 0.95 PF rule when applying the 0.95 hybrid rule with a transition point at 30%. Raising the transition point to 40% reduced the number of trading periods which violated the hybrid rule, while the 50% transition point further reduced violations.
- The majority of Grid Zone 3 stations exhibited a gradual upward pitch, with three stations – HIN (Hinuera), ARI and WHU (Waihou) – exhibiting a steeper pitch.

Table 9: GXP Data Grid Zone 3

GXP	Type	Export %TP-Import %TP	PF Limits		Q Limits		Hybrid 0.9 PF			Hybrid 0.95 PF		
		Exporting / Importing	0.95	0.9	0.95	0.9	30%	40%	50%	30%	40%	50%
HLY	3		26.4	-	-	-	9.6	-	-	26.4	26.3	17.2
HIN	3		2.3	-	-	-	0.0	0.0	-	0.1	0.1	0.1
HAM	3		14.8	-	-	-	-	-	-	14.8	1.3	-
CBG	3		-	-	-	-	-	-	-	-	-	-
ARI	2		96.1	-	-	-	82.3	82.3	79.7	95.6	95.6	95.6
KIN	1		91.3	-	-	-	4.3	4.2	2.9	91.3	90.7	90.3
KPU	2		77.5	-	-	-	37.3	37.3	35.6	77.5	77.5	77.5
PAO	3		4.7	-	-	-	0.4	-	-	4.7	4.7	2.4
TMU	3		0.0	-	-	-	-	-	-	-	-	-
TWH	3		4.7	-	-	0.0	0.2	0.0	0.0	4.7	3.0	0.0
WHU	3		6.3	-	-	-	1.1	-	-	6.3	3.5	-
WKO	2		4.2	-	-	-	0.0	-	-	4.2	2.7	0.0
HTI	1		20.9	-	-	-	2.5	2.4	2.2	20.0	19.0	17.2
ONG	4		52.7	-	-	-	35.6	10.2	0.5	43.6	39.3	26.6

5.2.4 Grid Zone 4

The analysis observed the following behaviours for Grid Zone 4:

- Seven stations in Grid Zone 4 predominantly export reactive power to the transmission network during light demand periods.
- In Grid Zone 4, there are two type 1 stations, one type 2 station, ten type 3 stations and two type 4 stations.
- 12 stations violated the 0.95 PF limit; among these, ANI (Aniwhenua) station performed the worst with nearly 91% of trading periods violating the limit.

- Ten stations violated 0.9 PF limit, with MAT (Matahina) station performing the worst with nearly 63% of the station trading periods violating the limit.
- Four stations violated the limit when we applied the 0.95 absolute reactive power limit; one station violated the 0.9 absolute reactive power limit.
- When applying the 0.9 hybrid rule with the transition point at 30%, four stations violated the limits. When raising the transition points to 40% or 50%, these four stations all reduced the amounts by which they violated those limits.
- Eleven stations violated limits when applying the 0.95 hybrid rule with the transition point at 30%. Eight stations violated the limits when raising the transition point to 40%, and six stations violated the limits when raising the transition point to 50%.

Table 10: GXP Data Grid Zone 4

GXP	Type	Export %TP-Import %TP	PF Limits		Q Limits		Hybrid 0.9 PF			Hybrid 0.95 PF		
		Exporting / Importing	0.95	0.9	0.95	0.9	30%	40%	50%	30%	40%	50%
EDG	3		1.5	-	-	-	0.3	0.2	0.0	1.5	1.4	1.0
ANI	4		90.5	-	-	0.0	48.0	28.3	14.8	80.7	65.4	44.5
KAW	3		15.5	-	-	1.9	6.6	6.4	5.9	15.4	15.2	14.7
KMO	2		15.9	-	-	-	-	-	-	13.8	-	-
LFD	1		33.5	-	-	-	0.1	0.0	0.0	32.7	27.9	20.2
MAT	4		90.5	-	-	0.0	48.2	28.3	14.9	80.6	65.5	44.5
MTM	3		-	-	-	-	-	-	-	-	-	-
OWH	2		13.0	-	-	-	-	-	-	12.6	-	-
ROT	3		0.1	-	-	-	-	-	-	0.1	-	-
TGA	3		3.7	-	-	-	-	-	-	3.6	0.1	-
TMI	3		25.3	-	-	-	8.4	-	-	25.3	17.6	0.4
TRK	3		16.1	-	-	-	-	-	-	16.0	2.1	-
WAI	3		0.0	-	-	-	-	-	-	-	-	-
WPW	3		-	-	-	-	-	-	-	-	-	-
WRK	1		6.4	-	-	-	0.5	0.3	0.1	5.4	3.7	2.4

5.2.5 Grid Zone 5

The analysis observed the following behaviours for Grid Zone 5:

- Three stations in Grid Zone 5 predominantly export reactive power to the transmission network during light demand periods.
- There are five type 3 stations in Grid Zone 5, and no stations of any of the other three types.
- Three stations violated the 0.95 PF limit; among these, WHI (Whirinaki) station performed the worst with approximately 41% of trading periods violating the limit.
- Two stations violated the 0.9 PF limit, with WHI station registering nearly 30% of trading periods exceeding the limit.
- No stations violated the limit markedly when we applied the absolute reactive power limit.
- When applying the 0.9 hybrid rule with a transition point at 30%, all stations in Grid Zone 5, except for WHI station, performed similarly to the 0.9 PF rule. WHI exceeded limits for 30% of trading periods when we applied the 0.9 PF rule, whereas applying the 0.9 hybrid rule with the transition point at 30%, resulting in violating limits for 3% of trading periods. Raising the transition points to 40% and 50% reduced the number of violated trading period to negligible levels for all stations.
- Similarly, when we applied the 0.95 hybrid rule with the transition point at 30%, all stations in Grid Zone 5 except for WHI station, performed comparably to the 0.95 PF rule. WHI exceeded limits for 41% of trading periods when we applied the 0.9 PF rule, while applying the 0.95 hybrid rule with the transition point at 30% resulted in it exceeding limits for 5% of trading periods. Raising the transition point to 40% gave similar results to the 30% transition point limit, whereas raising the transition point to 50% reduced the number of violated trading periods substantially.
- The four largest stations in Grid Zone 5 exhibited a gradual upward sloping pitch, while WHI station exhibited scattered data points with no obvious pitch.

Table 11: GXP Data Grid Zone 5

GXP	Type	Export %TP-Import %TP	PF Limits		Q Limits		Hybrid 0.9 PF			Hybrid 0.95 PF		
		Exporting / Importing	0.95	0.9	0.95	0.9	30%	40%	50%	30%	40%	50%
FHL	3		-	-	-	-	-	-	-	-	-	-
RDF	3		0.0	-	-	-	-	-	-	-	-	-
TUI	3		28.7	-	-	-	4.9	0.3	0.2	28.7	28.5	9.0
WHI	3		41.4	-	-	-	2.6	1.4	0.7	5.4	4.4	3.1
WTU	3		-	-	-	-	-	-	-	-	-	-

5.2.6 Grid Zone 6

The analysis observed the following behaviours for Grid Zone 6:

- Two stations in Grid Zone 6 predominantly export reactive power to the transmission network during light demand periods.
- In Grid Zone 6, there are three type 1 stations, no type 2 stations, six type 3 stations and no type 4 stations.
- Eight stations violated the 0.95 PF limit, with KPI (Kapuni) station performing the worst with nearly 87% of trading periods violating the limit.
- Five stations violated 0.9 PF limit, with KPI station registering nearly 30% of the trading periods exceeding the limit.
- Four stations violated the limit when we applied the 0.95 absolute reactive power limit, while two stations violated the 0.9 absolute reactive power limit.
- When applying the 0.9 hybrid rule with the transition point at 30%, all stations in Grid Zone 6 performed similarly to the 0.9 PF rule. We observed no notable change in limit violations when raising the transition points to 40% and 50% compared to 30% transition point.
- Similarly, when applying the 0.95 hybrid rule with the transition point at 30%, all stations in Grid Zone 6 performed comparably to the 0.95 PF rule. Again, we saw no notable change in limit violations when raising the transition points to 40% and 50% compared to 30% transition point.
- The majority of Grid Zone 6 stations exhibited a gradual upward pitch.

Table 12: GXP Data Grid Zone 6

GXP	Type	Export %TP-Import %TP	PF Limits		Q Limits		Hybrid 0.9 PF			Hybrid 0.95 PF		
		Exporting / Importing	0.95	0.9	0.95	0.9	30%	40%	50%	30%	40%	50%
HUI	3		7.4	-	-	-	0.7	0.0	0.0	6.2	5.7	3.7
HWA	3		-	-	-	-	0.0	0.0	0.0	0.0	0.0	0.0
CST	3		0.1	-	-	-	0.0	0.0	0.0	0.0	0.0	0.0
BRK	3		0.0	-	-	-	0.0	0.0	0.0	0.0	0.0	0.0
MNI	1		2.6	-	-	-	0.0	0.0	0.0	2.6	2.6	2.6
KPI	3		86.9	-	-	9.5	29.2	29.2	29.1	86.9	86.8	86.7
OPK	3		11.9	-	-	-	0.0	0.0	0.0	11.9	11.9	11.9
SFD	1		3.1	-	-	-	0.0	0.0	0.0	3.2	3.2	3.2
WVY	1		26.1	-	-	0.0	0.1	0.1	0.1	26.1	25.7	25.1

5.2.7 Grid Zone 7

The analysis observed the following behaviours for Grid Zone 7:

- Two stations in Grid Zone 7 predominantly export reactive power to the transmission network during light demand periods.
- In Grid Zone 7, there are no type 1 stations, no type 2 stations, eight type 3 stations and three type 4 stations. The type 4 stations in Grid Zone 7 exhibited a minimal reverse power flow of less than 1% of trading periods.
- Eight stations violated the 0.95 PF limit, with NPK (National Park) station performing the worst with nearly 34% of trading periods violating the limit.
- Six stations violated 0.9 PF limit, among which NPK registered nearly 35% of trading periods exceeding the limit.
- No stations in Grid Zone 7 markedly violated limits when we applied the absolute reactive power limit.
- When applying the 0.9 hybrid rule with transition points at 30%, 40% and 50%, no stations markedly violated limits.
- When applying the 0.95 hybrid rule with a 30% transition point, NPK station violated limits for 58% of trading periods, while TNG (Tangiwai) station violated limits for 2% of trading periods. Raising the transition point to 40% reduced NPK station violations to 9%. There were no significant violations when we raised the transition point to 50%.
- Four stations in Grid Zone 7 exhibited a flat pitch, while the remaining stations exhibited an upward pitch.

Table 13: GXP Data Grid Zone 7

GXP	Type	Export %TP-Import %TP	PF Limits		Q Limits		Hybrid 0.9 PF			Hybrid 0.95 PF		
		■ Exporting ■ Importing	0.95	0.9	0.95	0.9	30%	40%	50%	30%	40%	50%
DVK	3		-	-	-	-	-	-	-	-	-	-
LTN	3		0.0	-	-	-	0.0	0.0	-	0.0	0.0	0.0
MHO	3		0.1	-	-	-	-	-	-	0.1	0.1	0.1
MTN	3		0.0	-	-	-	-	-	-	0.0	0.0	0.0
MTR	3		-	-	-	-	-	-	-	-	-	-
NPK	4		60.5	-	-	-	0.0	-	-	58.3	8.6	-
TKU	4		5.1	-	-	-	0.0	-	-	0.3	0.1	0.0
TNG	4		15.4	-	-	0.0	0.7	0.4	0.2	2.2	1.5	1.0
WGN	3		-	-	-	-	-	-	-	-	-	-
OKN	3		0.0	-	-	-	-	-	-	-	-	-
BPE	3		0.3	-	-	0.1	0.2	0.1	0.1	0.3	0.3	0.2

5.2.8 Grid Zone 8

The analysis observed the following behaviours for Grid Zone 8:

- Ten stations in Grid Zone 8 predominantly export reactive power to the transmission network during light demand periods.
- Grid Zone 8 is composed of no type 1 stations, two type 2 stations, ten type 3 stations and no type 4 stations.
- Eight stations violated the 0.95 PF limit, with WIL (Wilton) station performing the worst with 22% of trading periods violating the limit.
- Four stations violated 0.9 PF limit; WIL registered nearly 5% of trading periods exceeding the limit.
- No stations markedly violated limits when we applied the absolute reactive power rule.
- No stations violated limits if we applied the 0.9 hybrid rule with transition points at 30%, 40% and 50%.
- Two stations markedly violated limits when we applied the 0.95 hybrid rule with the transition point set to 30%. There were no notable violations when the transition point was raised to 40% and 50%.
- All stations in Grid Zone 8 exhibited a gradual upward pitch.

Table 14: GXP Data Grid Zone 8

GXP	Type	Export %TP-Import %TP (Exporting / Importing)	PF Limits 0.95	PF Limits 0.9	Q Limits 0.95	Q Limits 0.9	Hybrid 0.9 PF 30%	Hybrid 0.9 PF 40%	Hybrid 0.9 PF 50%	Hybrid 0.95 PF 30%	Hybrid 0.95 PF 40%	Hybrid 0.95 PF 50%
HAY	3		-	-	-	-	-	-	-	-	-	-
GFD	3		0.2	-	-	-	-	-	-	-	-	-
CPK	3		-	-	-	-	-	-	-	-	-	-
KWA	3		-	-	-	-	-	-	-	-	-	-
MGM	3		0.0	-	-	-	-	-	-	-	-	-
MLG	2		3.8	-	-	-	-	-	-	0.6	-	-
MST	3		-	-	-	-	-	-	-	-	-	-
PNI	3		10.2	-	-	-	-	-	-	0.0	0.0	0.0
PRM	3		19.1	-	-	-	-	-	-	19.0	-	-
TKR	3		9.5	-	-	-	-	-	-	-	-	-
UHT	2		17.4	-	-	-	-	-	-	17.4	0.5	-
WIL	3		22.4	-	-	-	3.7	0.0	0.0	21.9	16.9	0.5

5.2.9 Grid Zone 9

The analysis observed the following behaviours for Grid Zone 9:

- Six stations in Grid Zone 9 predominantly export reactive power to the transmission network during light demand periods.
- There are no type 1 or 2 stations in Grid Zone 9, but there are five type 3 stations and three type 4 stations.
- Seven stations violated the 0.95 PF limit, with KIK (Kikiwa) station performing the worst with nearly 52% of trading periods violating the limit.
- Six stations violated 0.9 PF limit, with MCH (Murchison) station performing the worst with nearly 35% of trading periods violating the limit.
- No stations in Grid Zone 9 violated the limit when we applied the 0.95 absolute reactive power limit. However, MCH violated the 0.9 absolute reactive power limit for nearly 18% of trading periods.

- When applying the 0.9 hybrid rule with transition point at 30%, most stations in Grid Zone 9 performed similarly to the 0.9 PF rule. However, two stations exhibited a decrease in limit violations when comparing 0.9 PF rule to the 0.9 hybrid rule with a transition point at 30%. As we increased the transition point to 40% and 50%, the stations in Grid Zone 9 showed a reduction in the number of trading periods which violated limits.
- Similarly, two stations exhibited a notable decrease in limit violations when comparing the 0.95 PF rule performance to the 0.95 hybrid rule with the transition point at 30%. Conversely, the remaining stations exhibited no change in violations. We observed that three stations reduced their limit violations as we increased the transition point to 40% and 50%, while the remaining stations exhibited no change in violations.

Table 15: GXP Data Grid Zone 9

GXP	Type	Export %TP-Import %TP	PF Limits		Q Limits		Hybrid 0.9 PF			Hybrid 0.95 PF		
		Exporting / Importing	0.95	0.9	0.95	0.9	30%	40%	50%	30%	40%	50%
DOB	4		41.2	-	-	-	2.5	1.0	0.1	9.8	6.6	3.4
CUL	3		27.8	-	-	-	13.4	1.7	-	13.4	1.7	-
BLN	3		0.0	-	-	-	-	-	-	0.0	0.0	-
KIK	3		51.8	-	-	-	26.3	18.6	1.8	51.8	51.5	42.6
MCH	4		47.7	-	-	-	34.4	34.2	31.7	47.7	47.4	46.4
RFN	3		3.4	-	-	-	1.2	1.1	0.4	3.3	3.2	3.1
ROB	4		50.5	-	-	-	24.6	13.6	1.1	47.0	41.4	29.2
STK	3		-	-	-	-	-	-	-	-	-	-

5.2.10 Grid Zone 10

The analysis observed the following behaviours for Grid Zone 10:

- Four stations in Grid Zone 10 predominantly export reactive power to the transmission network during light demand periods.
- There are no type 1 stations in Grid Zone 10, one type 2 station, five type 3 stations and no type 4 stations.
- Five stations violated the 0.95 PF limit; among these, ASY (Ashley) station performed the worst with nearly 62% of trading periods violating the limit.
- Five stations violated 0.9 PF limit, with WPR (Waipara) station performing the worst with limit violations in nearly 19% of the trading periods.
- When applying the 0.9 hybrid rule with transition point at 30%, most stations in Grid Zone 10 performed similarly to the 0.9 PF rule, except WPR which reduced its violations from 19% to 3%, when comparing the 0.9 PF rule to the 0.9 hybrid rule with a transition point at 30%. All stations in Grid Zone 10 exhibited a reduction in limit violations when we raised the transition points to 40% and 50%.
- Similarly, when applying the 0.95 hybrid rule with transition point at 30%, most stations in Grid Zone 10 performed similarly to the 0.95 PF rule. We saw reduced limit violations for two stations when comparing the 0.95 PF rule to the 0.95 hybrid rule with the transition point at 30%. Most stations exhibited a reduction in limit violations when increasing the transition point to 40% and 50%.

Table 16: GXP Data Grid Zone 10

GXP	Type	Export %TP-Import %TP	PF Limits		Q Limits		Hybrid 0.9 PF			Hybrid 0.95 PF		
		Exporting / Importing	0.95	0.9	0.95	0.9	30%	40%	50%	30%	40%	50%
ISL	2		24.4	-	-	-	4.4	1.0	-	24.4	24.4	16.8
ASY	3		61.7	-	-	-	5.2	4.8	3.7	61.2	58.0	51.0
KAI	3		-	-	-	-	-	-	-	-	-	-
SBK	3		5.7	-	-	-	-	-	-	5.6	4.0	-
WPR	3		30.2	-	-	-	3.1	0.1	-	21.9	8.3	2.3
NWD	3		4.9	-	-	-	-	-	-	0.0	0.0	0.0

5.2.11 Grid Zone 11

The analysis observed the following behaviours for Grid Zone 11:

- Three stations in Grid Zone 11 predominantly export reactive power to the transmission network during light demand periods.
- There are no type 1 stations in Grid Zone 11, two type 2 stations, three type 3 stations and one type 4 station.
- Five stations violated the 0.95 PF limit, with BRY (Bromley) station performing the worst with limit violations in nearly 62% of the trading periods.
- Five stations violated 0.9 PF limit, with BRY registering nearly 25% of trading periods exceeding the limit.
- When we applied the 0.95 absolute reactive power limit, ABY (Albury) station violated the limits for nearly 7% of trading periods. No stations violated limits when we applied the 0.9 absolute reactive power limit.
- When applying the 0.9 hybrid rule with the transition point at 30%, most stations in Grid Zone 11 performed similarly to the 0.9 PF rule. ASB (Ashburton) station exhibited a reduction from 23% to 17% limit violations when comparing the 0.9 PF rule to the 0.9 hybrid rule with the transition point at 30%. All stations exhibited a reduction in limit violations as we increased the 0.9 hybrid transition point to 40% and 50%.
- When applying the 0.95 hybrid rule with the transition point at 30%, most stations in Grid Zone 11 performed similarly to the 0.95 PF rule. TMK (Temuka) station exhibited a reduction from 8% to 1% limit violations when comparing the 0.95 PF rule to 0.95 hybrid rule with the transition point at 30%. All stations exhibited a reduction in limit violations as we increased the 0.95 hybrid transition point to 40% and 50%.
- Most Grid Zone 11 stations exhibited an upward pitch.

Table 17: GXP Data Grid Zone 11

GXP	Type	Export %TP-Import %TP	PF Limits		Q Limits		Hybrid 0.9 PF			Hybrid 0.95 PF		
		Exporting / Importing	0.95	0.9	0.95	0.9	30%	40%	50%	30%	40%	50%
ABY	4		18.2	-	-	0.1	11.2	10.7	9.8	17.9	17.6	17.0
ASB	3		40.6	-	-	-	16.6	-	-	40.2	26.6	1.5
BRY	2		61.6	-	-	-	24.2	19.7	2.2	61.0	59.6	51.2
TIM	3		-	-	-	-	-	-	-	-	-	-
TKA	2		17.3	-	-	-	0.2	-	-	17.2	8.0	-
TMK	3		7.7	-	-	-	-	-	-	0.9	-	-

5.2.12 Grid Zone 12

The analysis observed the following behaviours for Grid Zone 12:

- One station in Grid Zone 12 predominantly exports reactive power to the transmission network during light demand periods.
- There is one type 1 station in Grid Zone 12, no type 2 stations, two type 3 stations and one type 4 station.
- Three stations violated the 0.95 PF limit, with KUM (Kumara) performing the worst with 71% of trading periods violating the limit.
- Three stations violated 0.9 PF limit; KUM station registered limit violations in nearly 65% of trading periods.
- No stations markedly violated limits when we applied either the 0.95 or 0.9 absolute reactive power limit.
- KUM and HKK (Hokitika) stations violated the 0.9 hybrid rule by 24% and 7% respectively when we set the transition point to 30%. As we raised transition point to 40% and 50%, limit violations decreased in number.
- KUM and HKK stations also violated the 0.95 hybrid rule by 54% and 40% respectively when we set the transition point to 30%. As we increased the transition point to 40% and 50%, limit violations decreased in number.

Table 18: GXP Data Grid Zone 12

GXP	Type	Export %TP-Import %TP	PF Limits		Q Limits		Hybrid 0.9 PF			Hybrid 0.95 PF		
		Exporting / Importing	0.95	0.9	0.95	0.9	30%	40%	50%	30%	40%	50%
HKK	3		40.2	-	-	-	7.2	6.4	2.9	39.6	38.1	35.9
GYM	3		-	-	-	-	-	-	-	-	-	-
KBY	1		8.4	-	-	-	-	-	-	-	-	-
KUM	4		71.0	-	-	0.0	24.0	6.7	0.9	53.8	32.8	15.3

5.2.13 Grid Zone 13

The analysis observed the following behaviours for Grid Zone 13:

- Three stations in Grid Zone 13 predominantly export reactive power to the transmission network during light demand periods.
- There are no type 1 stations in Grid Zone 13, one type 2 station, six type 3 stations and no type 4 stations.
- Six stations violated the 0.95 PF limit, with TWZ (Twizel) station performing the worst with 37% of the trading periods violating the limit.
- Five stations violated 0.9 PF limit, with FKN (Frankton) station performing the worst with 8% of trading periods violating the limit.
- No stations in Grid Zone 13 markedly violated the limits when we applied either the 0.95 or the 0.9 absolute reactive power limit.
- CML (Cromwell) and TWZ are the only two stations that markedly violate limits when applying the 0.9 hybrid rule with the transition point at 30%. Both reduced limit violations when we raised the transition point to 40% and 50%.
- When applying the 0.95 hybrid rule with transition point at 30%, all stations in Grid Zone 13 performed similarly to the 0.95 PF rule. As we raised the transition point to 40% and 50%, the limit violations reduced.
- Most Grid Zone 13 stations exhibited a reasonably steep upward pitch.

Table 19: GXP Data Grid Zone 13

GXP	Type	Export %TP-Import %TP	PF Limits		Q Limits		Hybrid 0.9 PF			Hybrid 0.95 PF		
		Exporting / Importing	0.95	0.9	0.95	0.9	30%	40%	50%	30%	40%	50%
FKN	2		18.8	-	-	-	-	-	-	18.8	-	-
CML	3		19.6	-	-	-	4.4	-	-	19.4	14.0	3.0
BPD	3		2.4	-	-	-	-	-	-	2.2	2.2	2.2
NSY	3		0.9	-	-	-	0.3	0.3	0.3	0.9	0.6	0.4
OAM	3		-	-	-	-	-	-	-	-	-	-
STU	3		1.7	-	-	-	-	-	-	0.2	-	-
TWZ	3		37.5	-	-	-	6.4	2.1	-	37.5	37.5	31.9

5.2.14 Grid Zone 14

The analysis observed the following behaviours for Grid Zone 14:

- Three stations in Grid Zone 14 predominantly export reactive power to the transmission network during light demand periods.
- There are two type 1 stations in Grid Zone 14, no type 2 stations, seven type 3 stations and no type 4 stations.
- Seven stations violated the 0.95 PF limit; BDE (Brydone) performed the worst with 98% of trading periods violating the limit.
- Four stations violated 0.9 PF limit, with BDE registering nearly 87% of trading periods exceeding the limit.
- Three stations violated the limit when we applied the 0.95 absolute reactive power limit, while only one station (BDE) markedly violated limits with 0.9 absolute reactive power limit.
- When applying the 0.9 hybrid rule with the transition point at 30%, all stations in Grid Zone 14 performed similarly to the 0.9 PF rule. Raising the transition points to 40% and 50% reduced the number of trading periods with limit violations.
- Similarly, when applying the 0.95 hybrid rule with the transition point at 30%, all stations in Grid Zone 14 performed comparably to the 0.95 PF rule. Raising the transition points to 40% and 50% reduced the number of trading periods with limit violations.

Table 20: GXP Data Grid Zone 14

GXP	Type	Export %TP-Import %TP	PF Limits		Q Limits		Hybrid 0.9 PF			Hybrid 0.95 PF		
		Exporting / Importing	0.95	0.9	0.95	0.9	30%	40%	50%	30%	40%	50%
HWB	3		48.9	-	-	-	24.1	21.2	3.1	48.9	48.4	43.7
INV	3		-	-	-	-	-	-	-	-	-	-
EDN	3		1.8	-	-	-	-	-	-	1.8	1.8	1.8
CYD	3		-	-	-	-	-	-	-	-	-	-
BAL	3		0.6	-	-	-	0.0	0.0	0.0	0.6	0.6	0.4
BDE	1		98.2	-	-	22.0	95.8	94.9	93.8	96.4	96.0	95.5
NMA	3		48.4	-	-	0.0	28.7	23.6	18.6	47.0	41.3	34.0
SDN	3		8.9	-	-	-	-	-	-	8.7	0.1	-
TWI	1		13.1	-	-	-	-	-	-	13.1	13.1	13.1

6 The effects of managing reactive power flow

6.1 Study methodology

After identifying appropriate criteria and assessing the behaviour of substations, the System Operator undertook a study to determine the impact on the voltage profile and reactive power requirements. We fixed the reactive power injected or absorbed by generators to "base case" values, then applied each criterion and documented the bus voltages and reactive power values.

Below is a comparison between the base case voltage/reactive power values, and those acquired as we applied each criterion. The primary goal of the study was to highlight the benefits that each criterion could offer the voltage profile in the transmission network, and to quantify the expected impact on generators. The ideal result would have been an improved voltage profile and minimum impact on generators. We identified two regions as pertinent to the voltage profile study: the upper North Island (Grid Zones 1, 2 and 3) and the upper South Island (Grid Zones 9, 10 and 12).

6.2 Voltage characteristics

Voltage characteristics can indicate how beneficial each criterion will be in ensuring voltage stability in the transmission and distribution systems. **Error! Reference source not found.** Figure 7 to Figure 9 below show the results of applying the criteria to the upper North Island (Grid Zone 1, 2 and 3), where the change in voltage is converted to a "percentage gained" value using the following equation:

$$-\left(\frac{Criterion\ bus\ voltage\ \ - Base\ voltage}{Base\ voltage}\right) \times 100$$

We can break the results down into two distinct categories:

1) The first category groups the 0.9 power factor limit and the hybrid limits which, above the transition point, use 0.9 power factor.
2) The second category includes the 0.95 power factor and associated hybrid limits.

The general shape of the two categories is similar, with the pure power factor limit delivering the largest voltage gained, followed by an exponential (with a negative coefficient) decrease as the hybrid transition points are increased. This implies that we could relax the power factor rule during light loading, with a similar result to the pure power factor criterion. In the case of the upper North Island, as the transition point moves above 40%, there is little benefit to the voltage profile, while the 30% has almost the same benefit as the pure power factor.

As expected, category one gains are much lower than category two, with the pure 0.9 power factor limit approximately equal to the 40% 0.95 hybrid limit. As voltage profile results are comparable, MVAr requirements should inform the selection of category one criteria and 0.95 hybrid limit with a transition point of 40% and above.

It is worth noting that the results of the 50% hybrid 0.9 power factor values were negative. Observing the active and reactive station power curves in the appendix provides justification for this. Reactive power exporting is prevalent at lighter loading (low MW), so the criteria with high transition points do not control it much. The 50% hybrid 0.9 power factor leads voltage to rise in the system, resulting in a negative "% voltage gained" value, thereby ruling it out as a beneficial criterion.

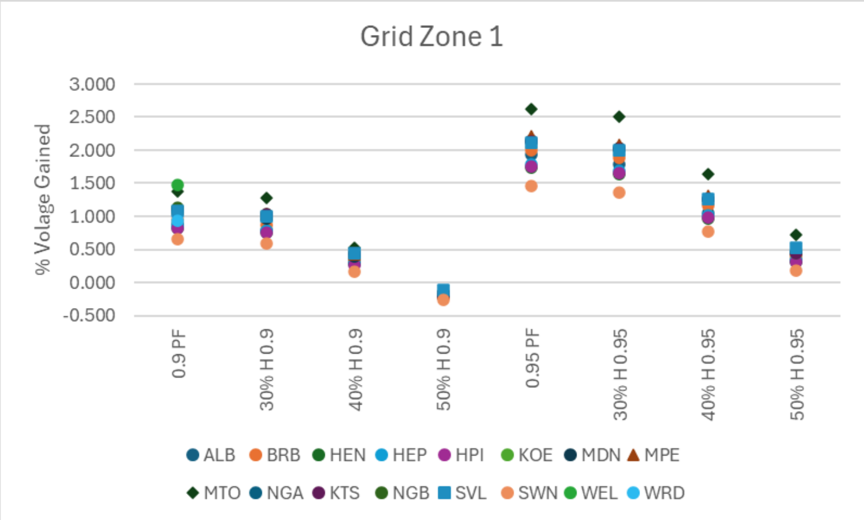


Figure 7: Bus reduction vs criteria in Grid Zone 1

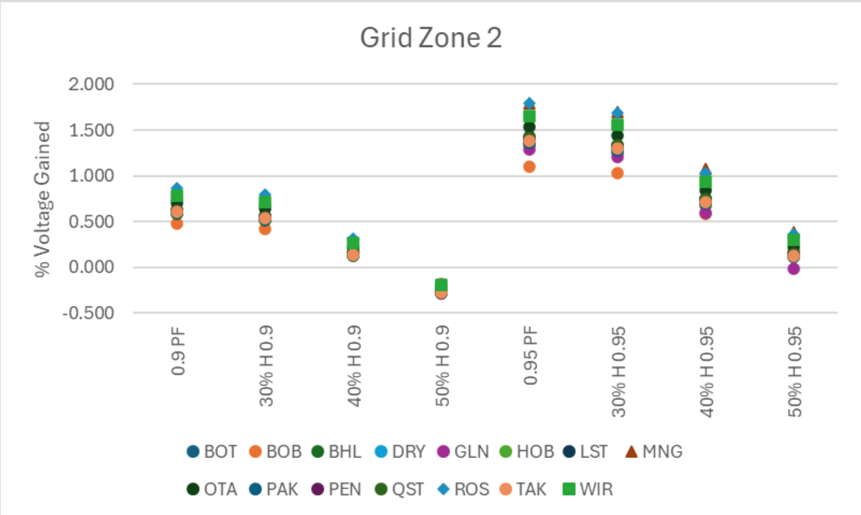


Figure 8: Bus reduction vs criteria in Grid Zone 2

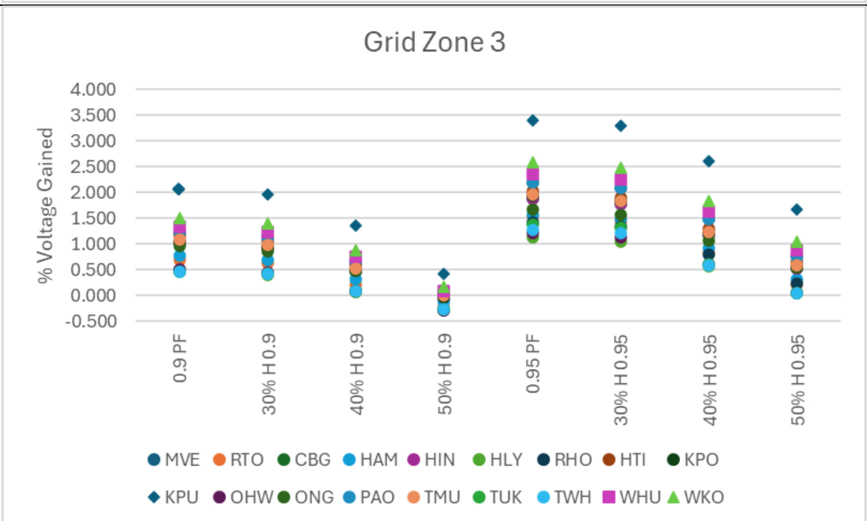


Figure 9: Bus reduction vs criteria in Grid Zone 3

The upper South Island "% voltage gained", presented in Figure 10**Error! Reference source not found.** to Figure 12**Error! Reference source not found.** below, has some similar characteristics to the upper North Island data, with some notable variances. At high hybrid transition points, there is still a decrease. For the first category, this occurs above 40%; however, for the second category, we had to include a 60% transition point in the analysis to detect this behaviour. Category one values are still generally lower than category two, implying that category two is more beneficial to the voltage profile.

Interestingly the pure power factor control in some cases delivers a lower gain than the hybrid limits with lower transition points. In the upper South Island, there are several stations, for example HKK (Hokitika), which import reactive power during light loading. The result is that the pure power factor control criteria limit the import of reactive power, while the hybrid criteria do not. This in turn creates a situation where the hybrid limits display a superior voltage profile.

In general, the voltage gain in the upper South Island is lower than the upper North Island's voltage gain. However, we expected this, since the voltage profile is worse in the upper North Island.

Figure 10: Bus reduction vs criteria in Grid Zone 9

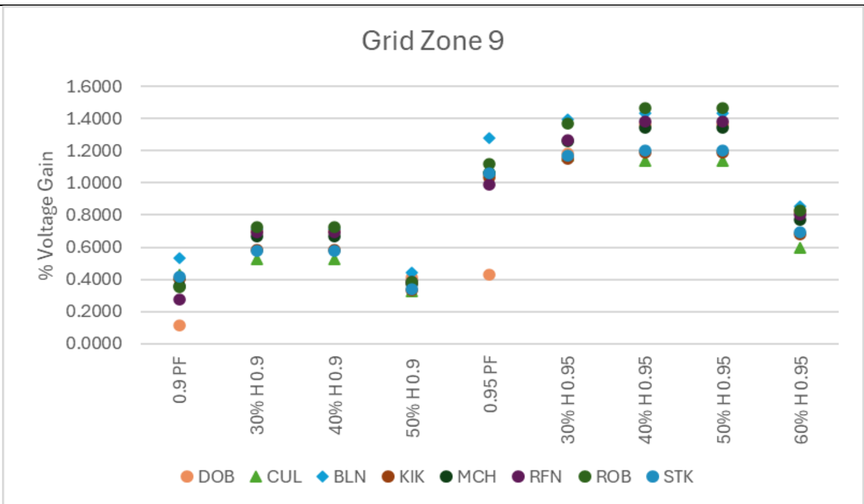


Figure 11: Bus reduction vs criteria in Grid Zone 10

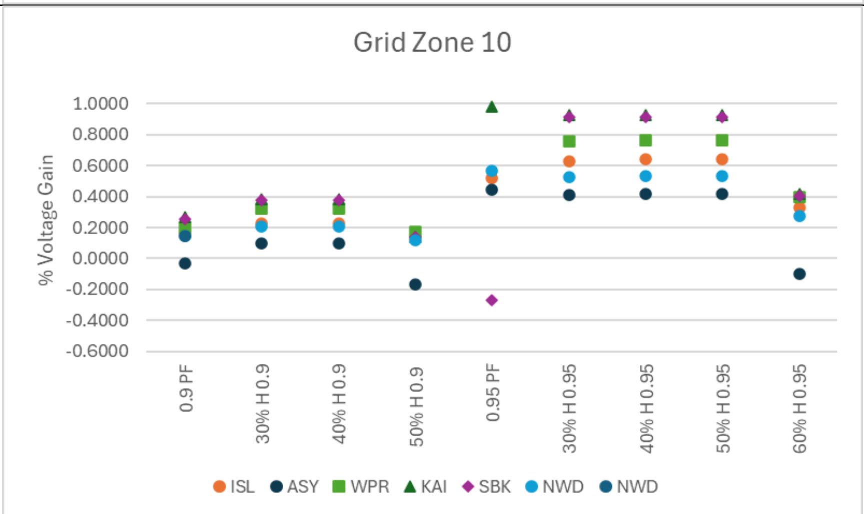
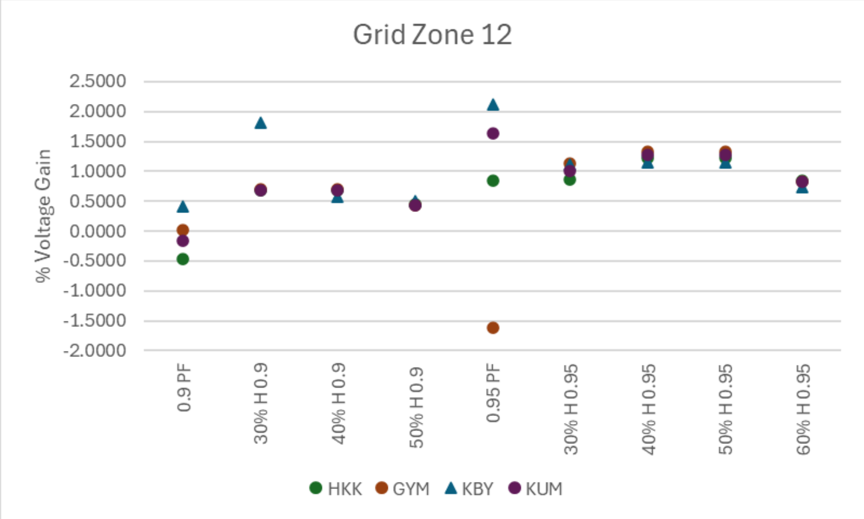


Figure 12: Bus reduction vs criteria in Grid Zone 12



6.3 MVAr requirements

This section discusses how the limiting criteria impacted on the reactive power at the stations analysed in the study. Figures 13 (upper North Island zones) and figure 17 (upper South Island) below **Error! Reference source not found.Error! Reference source not found.**indicate the percentage of stations which observed a change in their reactive power requirements for each criterion. At the high end, for the 0.95 power factor control, approximately 50% of stations observed a change in reactive power. These values tended to decline as the hybrid transition points increased. Generally, when compared to the 0.95 power factor limit and associated hybrid scenarios, far fewer stations observed a change for the 0.9 power factor limit and 0.9 hybrid scenarios.

Error! Reference source not found. Figures 14 to 16 and 18 to 20 display the 'difference' in reactive power for the upper North Island and upper South Island respectively. We can calculate this 'difference' by subtracting the base value from the value obtained for each criterion. Several stations display a similar shape to that seen in the voltage profiles, with the pure power factor control often requiring the largest change in reactive power, and a decline as the hybrid transition point increases. Also, the 0.9 power factor criterion and associated hybrid limits display a lower value than the 0.95 power factor and 0.95 hybrid limits.

There are stations such as ISL (Islington) which present a "flat" response to the increase in the hybrid transition point. This is where the station's active power sits above the hybrid transition points, limiting its reactive power with the power factor limit portion of the criteria. In the case of ISL, increasing the transition point beyond 50% results in a decrease in the reactive power difference.

Another observation is that some stations present a negative difference in reactive power, like HKK or KIN (Kinleith). When compared to the base case, these stations decrease their reactive power import.

Figure 13: Percentage of stations affected in each grid zone (1, 2 and 3)

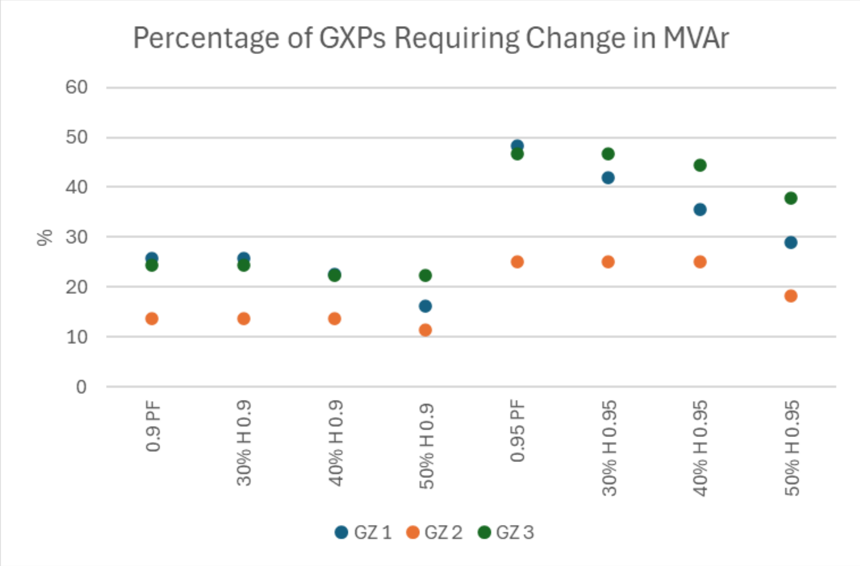


Figure 14: Reduction of MVAr export to transmission grid – Zone 1

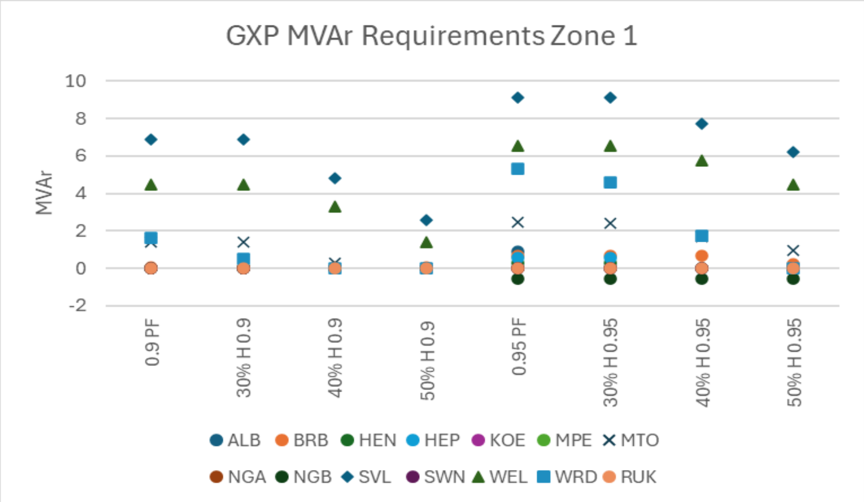


Figure 15: Reduction of MVAr export to transmission grid – Zone 2

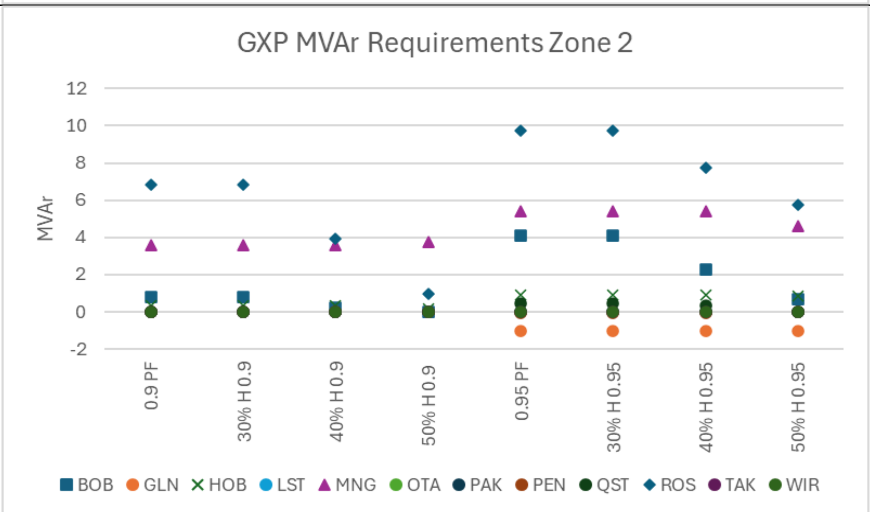


Figure 16: Reduction of MVAr export to transmission grid – Zone 3

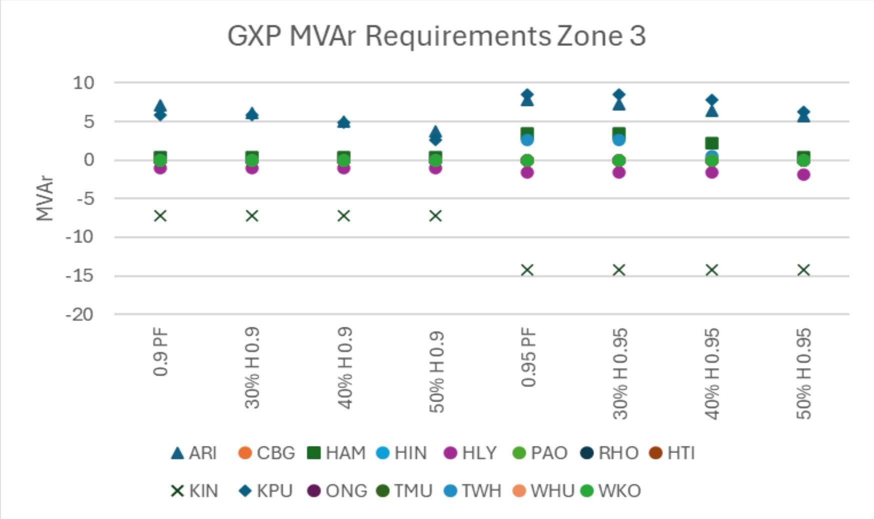


Figure 17: Percentage of stations affected in each grid zone (9, 10 and 12)

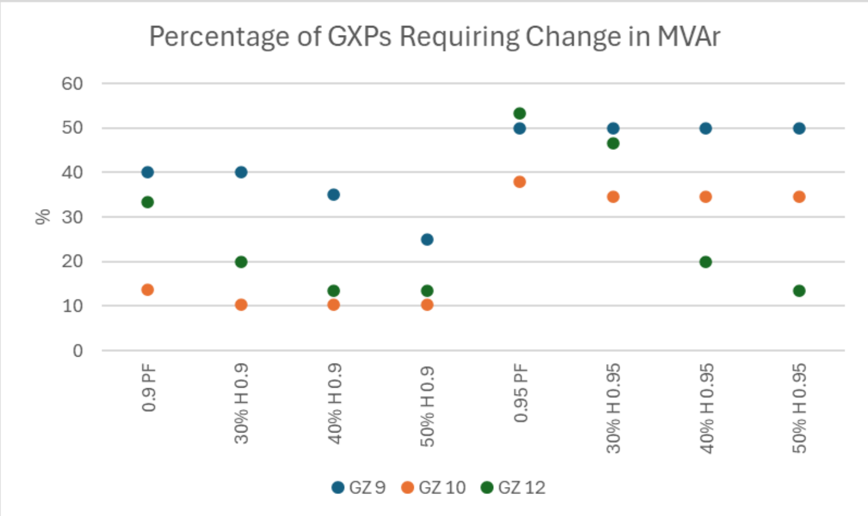


Figure 18: Reduction of MVAr export to transmission grid – Zone 9

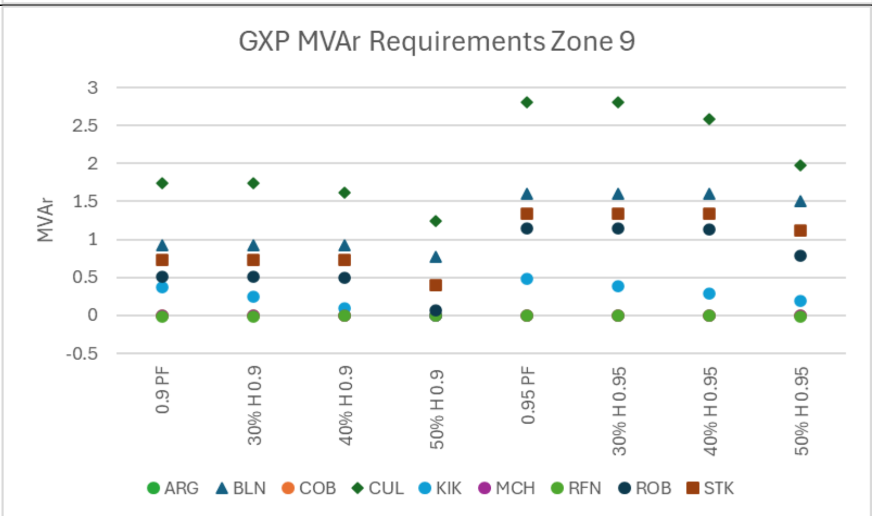


Figure 19: Reduction of MVAr export to transmission grid – Zone 10

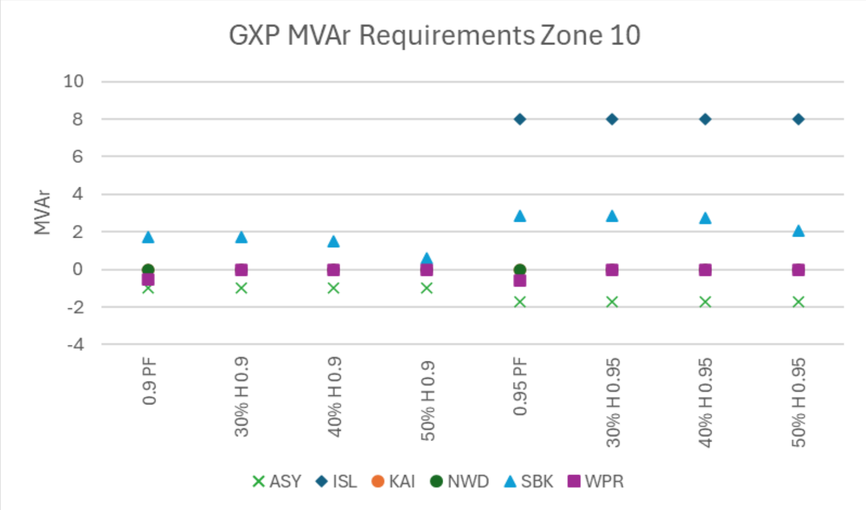
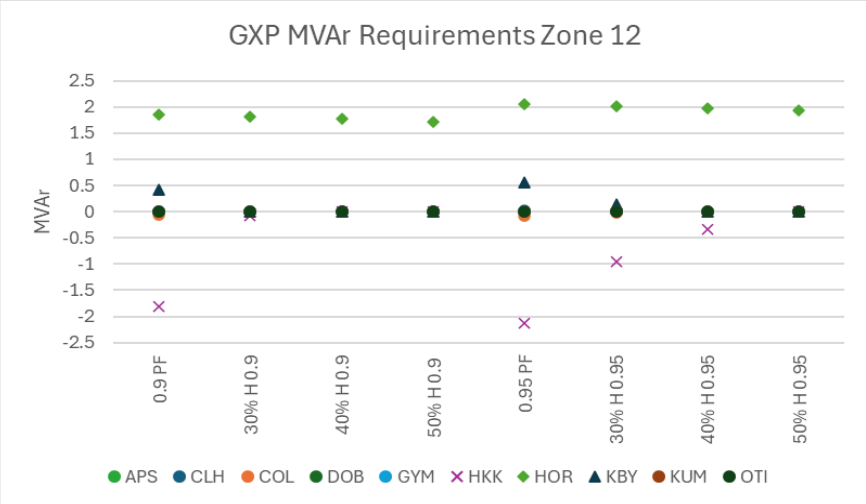


Figure 20: Reduction of MVAr export to transmission grid – Zone 12



6.4 Conclusions

For the voltage profiles, the 0.95 power factor and 0.95 power factor hybrid criteria outperform the 0.9 power factor based criteria, except for the test cases where the hybrid transition point is high (40% and above for upper North Island and 60% and above for upper South Island).

In many cases, the difference in reactive power requirements between the 0.9 power factor (and associated hybrid limits) and the 0.95 power factor is less pronounced compared to the changes in voltage profile (with some obvious exceptions). As the hybrid transition point increases, the reactive power requirements generally decrease. However, in some cases, the response is reasonably flat, indicating that increasing the hybrid transition points offers minimal benefit.

Based on the findings in this study, the '0.95 power factor hybrid limit, with a transition point of 30%' is the criterion that best balances voltage profile while minimally impacting reactive power requirements. This criterion promotes power system stability by relaxing the limit during light loading, while also ensuring a constrained voltage profile during significant loading.

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