Steady State Voltage Compliance

AMS – Electricity Distribution Network

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Table of Contents

1 EXECUTIVE SUMMARY

AusNet Services is a regulated Victorian Distribution Network Service Provider (DNSP) that supplies electrical distribution services to more than 745,000 customers. Our electricity distribution network covers eastern rural Victoria and the fringe of the northern and eastern Melbourne metropolitan area.

As expected by our customers and required by the various regulatory instruments that we operate under, AusNet Services aims to maintain service levels at the lowest possible cost to our customers. To achieve this, we develop forward looking plans that aim to maximise the present value of economic benefit to all those who produce, consume and transport electricity in the National Electricity Market (NEM).

This report presents our forward looking investment plans to manage the existing and emerging voltage constraints in the AusNet Services' distribution (22 kV and low voltage) network largely due to the growth in residential solar photovoltaic (PV) installations. This is to ensure that the regulatory compliance requirements are met, whilst accommodating customer solar PV installation connections. This report outlines the current and estimated future levels of compliance, the impact to customers, the need for further augmentation, the costs and benefits of potential options to mitigate voltage issues and proposals of forward looking programs for implementation in the next (2022-26) regulatory period.

Based on the Electricity Distirbution Code, the allowable range for steady state voltage is 216 V to 253 V in the low voltage network. Voltages outside the steady state limits may cause equipment damage and reduced life spans. For solar PV customers, voltage breaches may cause solar inverters to stop generating and disconnect from the network, preventing customers from generating and exporting electricity.

There is a strong growth in solar connections in our network and this will continue to accelerate with falling costs of solar PV and small scale RET scheme, change in customer preferences and policy announcements such as Victorian State Solar Homes Program. Currently there are approximately 54,000 customers connected to distribution substations identified with voltage non-compliance issues. The number of customers connecting to distribution substations experiencing non-compliant voltages is estimated to increase to approximately 235,000 by 2025 if not addressed.

AusNet Services has already carried out significant low cost improvements to manage voltage compliance. These include voltage regulating relay (VRR) setting changes at zone substations and line regulators, distribution transformer tap changes, measures to mandate Volt-VAr and Volt-Watt control and development of an optimisation platform (Distributed Energy Network Optimisation Platform). However, the need for further rectification work has been identified as economic to achieve the network performance required to accommodate the anticipated solar uptake and achieve voltage compliance.

AusNet Services has developed an Advanced Meter Infrastructure (AMI) data enabled economic approach to carry out an options analysis and propose a preferred solution for each constrained distribution substation that maximises the net economic benefit to customers. The economic assessment observes actual customer voltage performance and values the unserved generation of rooftop-solar due to voltage constraints using the feed-in-tariff (FiT).

Four program options are considered, with Options 2 and 3 following the economic approach. The Option 4 uses a similar approach to Options 2 and 3 considering multiple solutions to remove constraints in the low voltage and the 22 kV network to allow for zero constraints, however the preferred solution does not have the most positive net benefit to all customers.

The key parameters of the four program options are tabulated below.

	Option 1: Do nothing	Option 2: Address existing voltage issues	Option 3: Address existing and future voltage issues	Option 4: Aiming for zero constraints
Cost ($ million)	-	18.9	38.1	626.1
Cost per customer ($)	-	23	47	767
NPV Benefit ($ million)	-	53	453	66
Number of customers voltage performance improved by 2025	-	53,000	228,000	235,000
Number of solar customers voltage performance improved by 2025	-	16,000	93,000	95,000
Number of customers without any voltage improvements by 2025	235,000	182,000	7,000	Aiming for 0
Percentage of 2025 customer base without any voltage improvements	29%	22%	1%	Aiming for 0%
Total export enabled of previously unserved generation over 2022-26 (GWh)	0	183	969	1380
% Export enabled of previously unserved generation over 2022-26	0%	13%	70%	Aiming for 100%

AusNet Services propose Option 3 at a cost of $38 million ($2018) over 2022-26, which represents a prudent and efficient network augmentation investment to address voltage constraints.

Applying a discount rate of 6.44% per annum, this proposed program option has a net economic benefit of $453 million (Real $2018) over the forty-five-year assessment period. It will improve the voltage performance of approximately 228,000 customers and will enable export 70% of previously unserved generation over 2022-26.

2 INTRODUCTION

2.1 Purpose

The purpose of this document is to describe the strategies to manage steady state voltage across the electricity distribution network.

This report outlines existing regulatory and compliance requirements on voltage and the impact of roof-top solar PV installations on the electricity distribution network and its customers.

This document presents the current and estimated future levels of voltage compliance, the work that has been carried out to-date to improve voltage compliance levels and the need for further augmentation.

AusNet Services has developed an economic approach to value the impact of voltage. This report presents an assessment of potential options and proposed plans to maintain compliance with prudent and efficient investments in line with our customers' expectations and regulatory requirements.

2.2 Scope

The scope of this document is limited to the strategies to manage the steady stage voltage across the AusNet Services' electricity distribution network. It excludes the sub-transmission lines exiting the zone substations.

2.3 Asset management objectives

As stated in *AMS 01-01 Asset Management System Overview*, the high-level asset management objectives are:

- Comply with legal and contractual obligations;
- Maintain safety;
- Be future ready;
- Maintain network performance at the lowest sustainable cost; and
- Meet customer needs.

As stated in *AMS 20-01 Electricity Distribution Network Asset Management Strategy*, the electricity distribution network objectives are:

- Improve efficiency of network investments
- Maintain long-term network reliability
- Implement REFCLs within prescribed timeframes
- Reduce risks in highest bushfire risk areas
- Achieve top quartile operational efficiency
- Prepare for changing network usage.

3 STEADY STATE VOLTAGE AND OUR CUSTOMERS

3.1 Regulatory requirements

The Electricity Distribution Code regulates the distribution of electricity by a distributor to its customers. Clause 4 details the regulatory obligations for the quality of supply for a number of parameters, including voltage.

Clause 4.2.1 of the Electricity Distirbution Code states that:

> *a distributor must maintain a nominal voltate level at the point of supply to the customer's electrical installation in accordance with the Electrical Safety (Network Assets) Regulations 1999*[1] *or, if these reguations do not apply to the distributor, at one of the following standard nominal voltages:*
>
> *(a) 230V;*
>
> *(b) 400V*
>
> *(c) 460V*
>
> *(d) 6.6kV*
>
> *(e) 11kV*
>
> *(f) 22kV; or*
>
> *(g) 66kV*

Table 1 is reproduced from the Electricity Distribution Code and lists the allowable variations from the relevant standard nominal voltage.

Table 1: Standard Nominal Voltage Variations

STANDARD NOMINAL VOLTAGE VARIATIONS				
Voltage Level in kV	**Voltage Range for Time Periods**			**Impulse Voltage**
	Steady State	**Less than 1 minute**	**Less than 10 seconds**	
< 1.0	+10% - 6%	+14% - 10%	Phase to Earth +50%-100% Phase to Phase +20%-100%	6 kV peak
1-6.6	± 6 % (± 10 % Rural Areas)	± 10%	Phase to Earth +80%-100% Phase to Phase +20%-100%	60 kV peak
11				95 kV peak
22				150 kV peak
66	± 10%	± 15%	Phase to Earth +50%-100% Phase to Phase +20%-100%	325 kV peak

Thus, for the low voltage network, the allowable range for steady state voltage is 216 V to 253 V.

3.2 Functional compliance

With electricity distribution companies having hundreds of thousands of electricity customer connections spread over a large geographic area, achieving 100% compliance for all customers at all times is not economically nor practically possible.

[1] This Subordinate Law was repealed on 8 December 2009 by the Electricity Safety (Installations) Regulations 2009

While distributors have a responsibility to respond to individual customer complains of non-compliant power quality, many instances of localised and brief power quality non-compliance go unnoticed.

AS 61000.3.100 *Electromagnetic compatibility (EMC) Part 3.100: Limits – Steady state voltage limit in public electricity systems* specifies limits in low voltage and medium voltage public electricity systems at the customer connection point.

This standard also sets out a method for assessing the global level of power quality disturbances at low voltage and assess the 'functional' compliance of the electricity distribution network.

Table 2 is reproduced from AS 61000.3.100, Table D1 and lists the power quality network performance requirements for functional compliance at low voltage.

Table 2: Power Quality Network Performance Requirements for Functional Compliance at Low Voltage

Power quality measure	Units	Minimum network compliance requirement		Required confidence level		Individual site power quality limit	
		Percentile of sites % of N	Quantile of sites p	Percentile	z_c	Limit value Q_{limit}	Limit type
$V_{99\%}$	Volts	95%	0.95	90%	1.282	253*	Upper
$V_{50\%\ upper}$	Volts	95%	0.95	90%	1.282	244†	Upper
$V_{50\%\ lower}$	Volts	95%	0.05	90%	1.282	225†	Lower
$V_{1\%\ lower}$	Volts	95%	0.05	90%	1.282	216*	Lower
V_{spread}	Volts	95%	0.95	90%	1.282	37*	Upper

Notes:

$V_{x\%}$ is the voltage percentile and is the value of the voltage below which x% of measurements fall over a survey period

V_{spread} is the difference between the $V_{99\%}$ voltage and the $V_{1\%}$ voltage on an individual channel of measurement over a survey period

Thus, functional compliance to $V_{99\%}$ requires 95% of customers have a voltage less than 253 V 99% of the time and functional compliance to $V_{1\%}$ requires 95% of customers to have a voltage greater than 216 V 99% of the time.

3.3 Customer impact of non-compliance

Voltages lower than the steady state limits may cause equipment to fail to operate as intended. Motor driven equipment may fail to start and motors may overheat and trip or be damaged.

Voltages greater than the steady state limits may cause equipment insulation degrade faster than intended resulting in a reduced life span of customer appliances.

AS/NZS 4777.2 *Grid connection of energy systems via inverters Part 2: Inverter requirements* mandates that an inverter must disconnect from the network if:

- The average AC voltage over any 10 minute period goes over 255 V (default set-point) where the set-point lies in the range 244 V to 258 V
- The voltage is over 260 V for 1 second.

Thus, the voltage breaching one or both of these limits will disconnect a customer's solar inverter preventing the customer from generating and exporting electricity.

3.4 Impact of solar on the electricity distribution network

In a traditional electricity network, with no distributed generation installed on the distribution network, as the load on a distribution line increases, the voltage level on the distribution line decreases. In addition, as the distance from a zone substation along a distribution line increases, the voltage level along the distribution line decreases.

These two factors means that historically the voltage levels on distribution lines have been set at close to the top of the allowable voltage band at periods of low load that the start of distribution line to allow for the voltage drop due to increases in load and allow for the voltage drop along the distance of the distribution line (Figure 1).

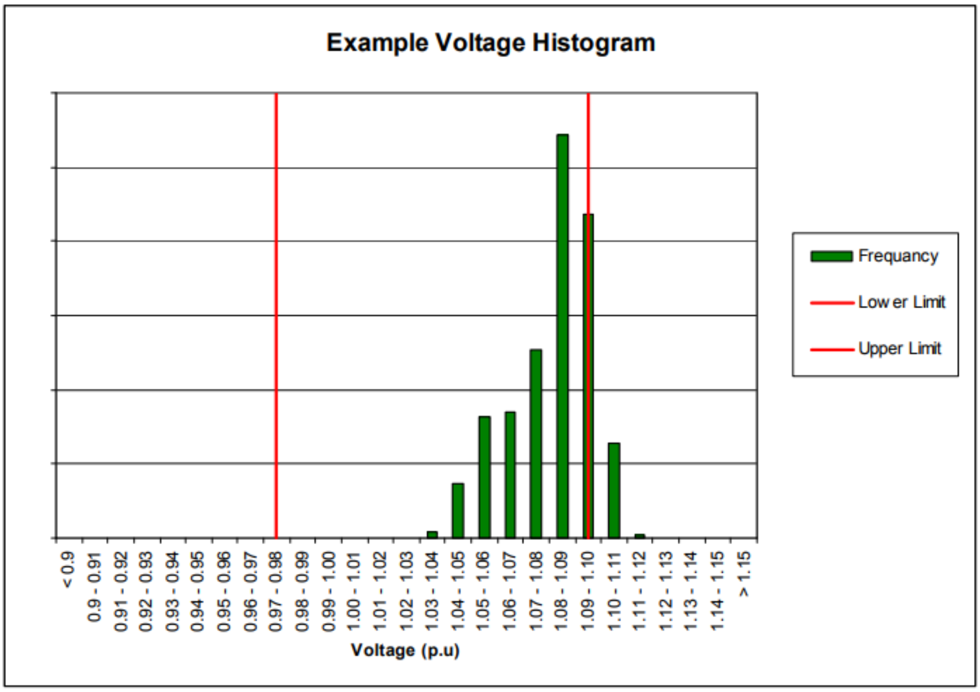

Figure 1: Example of a typical voltage histogram[2]

This situation is changing with customers installing rooftop solar systems.

When a customer with a solar installation is producing more power than they can use within their premise, they export the excess power into the electricity distribution network. In order for a solar inverter to export power to the electricity distribution network, it must put out a higher voltage than the network to force it back.

AS/NZS 4777.2 says that the maximum voltage rise in a solar installation must be 2% of 230 V (4.6 V).

This means that in a system that has the voltage biased towards the top of the allowable voltage range, rooftop solar may increase the voltage to the point that it is outside the allowable range.

For example, if the electricity distribution network has a steady state voltage at the top of the compliant range at 253 V, on a good solar day when no one is at home, the solar installation will be at full export and the voltage may be raised to 253 + 4.6 = 257.6 V.

In this instance, this would result in the solar inverter tripping off on overvoltage. Once the inverter has tripped off the voltage will return to within the compliant range and the solar inverter will turn on again, raising the voltage and potentially tripping again in 10 minutes.

Whilst the inverter has tripped off, in addition to not being able to export any additional solar power into the distribution network, the customer is also unable to use any solar power within their own premises.

[2] S. T. Elphick, V. W. Smith, V. J. Gosbell & R. A. Barr, "The Australian long term power quality survey project update," in 14th International Conference on Harmonics and Quality of Power, ICHQP 2010, 2010, pp. 1-7.

3.5 Victorian Government Solar Homes Program

Following the Victorian state election in November 2018, the state government made a number of election commitments relating to the Solar Homes program.

The Victorian State Solar Homes Program design includes the following rebates:

- Solar PV rebate for 650,000 homes
- Solar PV rebate for 50,000 rental properties
- Solar hot water rebate for 60,000 homes
- Battery rebate for 10,000 homes

According to the Solar Victoria website (www.solar.vic.gov.au), currently the Solar Homes package includes two rebates for the installation of solar PV or the installation of solar hot water to eligible householders.

The Solar Homes program consists of half price solar panels for up to 650,000 eligible households. This is in addition to the existing approximately 350,000 solar systems already installed in Victoria. Accordingly, AusNet Services expect that this subsidy will lead to a significant increase in solar panel installations within its network area.

AusNet Services are currently receiving 135 connection applications per day to connect rooftop solar installations to its network. In the first two months of 2019, AusNet Services had more than twice the number of applications for solar connections from the equivalent months in 2018. It is expected that solar connections will be more than doubled from 2018 to 2019.

In addition to the January 2018 (base) solar PV uptake forecast, AusNet Services have created a moderate and a high (full) uptake of solar forecast incorporating the Solar Homes package. The base forecast excludes the impact of the Solar Homes program. Both moderate and high (full) uptake of solar shows a distinct increase in the solar installations with the introduction of the Solar Homes Program.

The moderate (Mod) case models the effects of the declining Small-scale Technology Certificates that are declining over the period to zero by 2030[3]. This reduction is expected to result in a high early uptake that then tapering off as prices stabilise or increase.

The high (full) uptake forecasts considers the full Solar Homes package adding 20,000 new solar installations per annum over the 10-year period, whereas the moderate uptake shows a relatively reduced uptake due to the expected reduction in the value of small-scale technology certificates (STC). The moderate and full uptake of solar forecast estimates approximately 140,000 and 200,000 new solar customers adding approximately 1000 MW and 1500 MW of installed solar capacity to the network by 2030.

Figure 2 and Figure 3 show the annual and cumulative solar customer growth in AusNet Services network based on the base, moderate and full solar uptake forecast.

[3] http://www.cleanenergyregulator.gov.au/RET/Pages/About%20the%20Renewable%20Energy%20Target/When-does-the-Renewable-Energy-Target-end.aspx

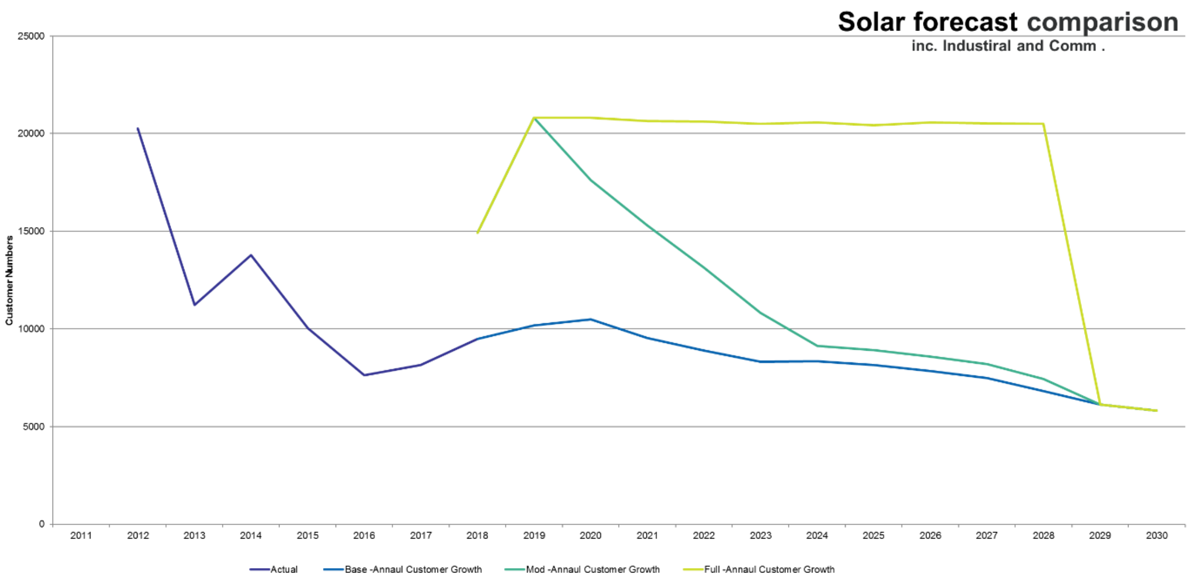

Figure 2: Annual solar customer growth based on AusNet Services' forecast of solar uptake

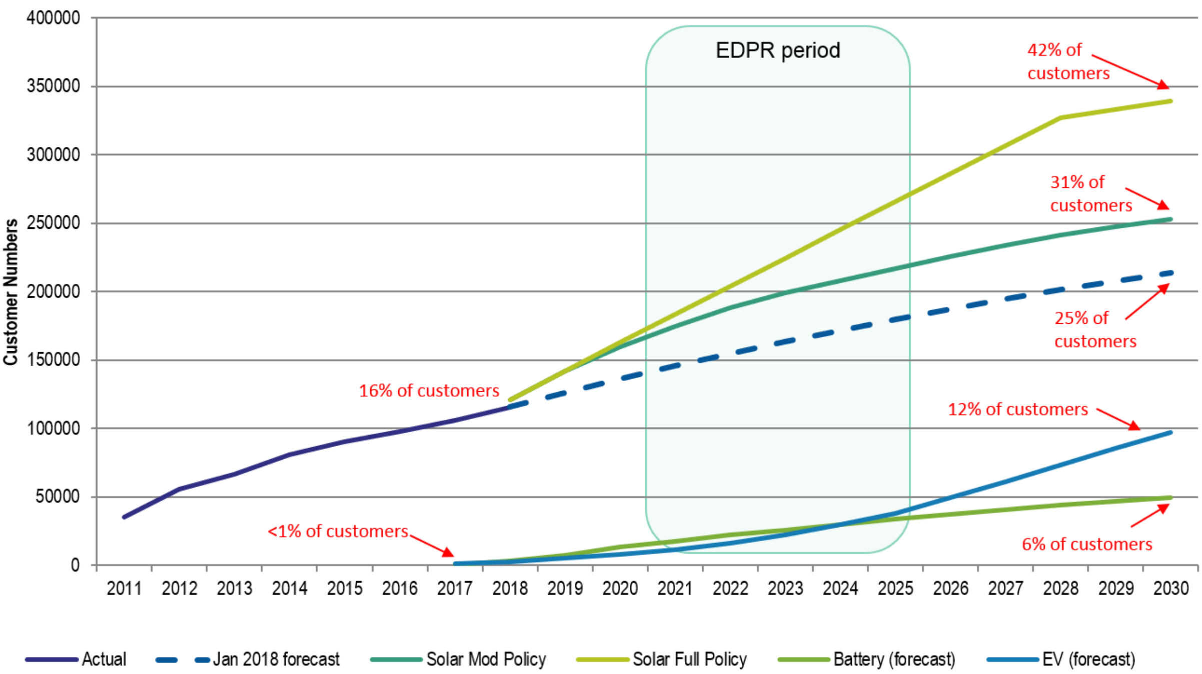

Figure 3: AusNet Services' forecast of DER uptake

The battery and electric vehicle (EV) uptake forecast is also shown in Figure 3. A relatively low uptake of both battery and EV is estimated in the 2022-26 regulatory period and not expected to have a material impact.

4 NETWORK PERFORMANCE

4.1 Voltage complaints

AusNet Services currently has a reactive program that aims to resolve power supply issues raised by customers.

Figure 4 shows the historic count of voltage complaints over each month from 2017 to early 2019. There is a distinct increase in the number of complaints in summer months in comparison to winter months. In many cases, the causes for voltage complaints are solar inverter trips due to high voltages and identification of high voltages by solar PV installers at customer premises during the installation process.

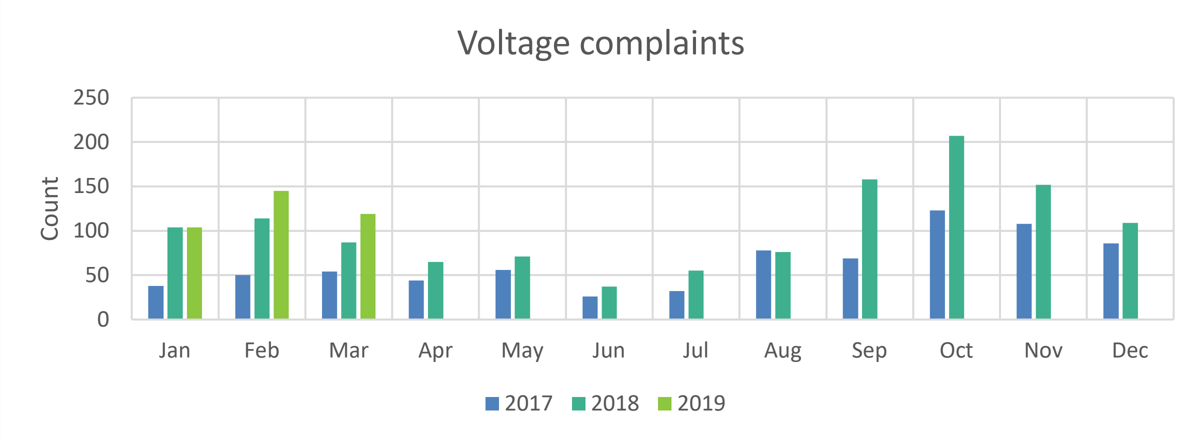

Figure 4: Historic count of voltage complaints

The total number of complaints have increased by threefold in 2018 in comparison to the number of complaints in 2017. This is reflective of the capital expenditure in responding to voltage complaints from customers as tabulated in Table 3.

Table 3: Capital spend in addressing voltage complaints (source: Annual Regulatory Accounts in Real $2018)

Program	2016	2017	2018
Supply Improvement	371,840	791,027	1,338,870

The work carried out to address individual voltage complaints are mostly in the low voltage (LV) network and includes:

- Adjusting distribution transformer taps (this work is operational expenditure and is not included in Table 3)
- Upgrading distribution transformers
- Rearranging the network to distribute customers evenly
- Reducing circuit load by re-conductoring the circuits or splitting circuits

This work is only carried out after extensive field investigations and validation of desktop studies using AMI data.

The increase in voltage complaints suggest that further work is required to address voltage non-compliance issues to support our customers and their network experience.

4.2 Voltage compliance

AusNet Services has developed the *Voltage Compliance* tool within the *Explore* suite of tools that allows monitoring of the voltage compliance levels from smart meter data and how they are changing over time (refer Section 5.3).

The target for ‘functional compliance’ to AS 61000.3.100 is 5% of customers experiencing a non-compliant voltage for at least 1% of the time (refer Section 3.2).

Figure 5 shows the overall network voltage compliance graph, which shows a reduction in the percentage of customer experiencing non-compliant voltages for at least 1% of the time from 30% to 10%.

Figure 5: Improvement in voltage compliance across our network[4]

The improvement in voltage compliance seen in Figure 5 is primarily due to the setting changes made on voltage regulators. Many of the regulators were changed from line-drop compensation to uncompensated settings. These setting changes were made gradually starting from year 2014. Section 4.3 describes the improvements made at various levels in the network, including several examples.

It can be seen that significant low cost improvements have been made to manage voltage compliance. However, to achieve the improvement required to achieve functional compliance, further, more expensive, rectification work is required.

Options for managing voltage compliance into the future will include work such as:

- Adjusting distribution transformer tap settings
- Installation of new voltage regulating relays and regulators that can support reverse power flow at zone substations and line voltage regulators
- Re-conductoring low voltage circuits with larger conductors (to reduce the voltage drop or rise along the circuit)
- Splitting low voltage circuits (to reduce the length of the circuits reducing the voltage drop or rise along the circuit)
- Employing non-network solutions

4.3 Current progress on addressing voltage issues

4.3.1 Voltage regulating relay setting changes at zone substations

As mentioned in Section 4.2, AusNet Services' have been making setting changes in voltage regulating relays (VRR) at zone substations leveraging the smart meter data and in-house analytic tool *Explore*. In many instances, the VRRs were changed from line-drop compensation to uncompensated settings.

LDC uses an internal model of the impedance of the distribution line to determine how much voltage buck or boost is required for a given load current level. The voltage regulating relay then regulates the voltage to the set-point at the load centre in the network downstream.

Figure 6 show the percentage of customers on high voltage breach ($V_{99\%}$ > 253 V) and low voltage breach ($V_{1\%}$ < 216 V) supplied by Lilydale (LDL) zone substation.

[4] The graphs show the voltage breaches based on the meter readings and the number of meters.

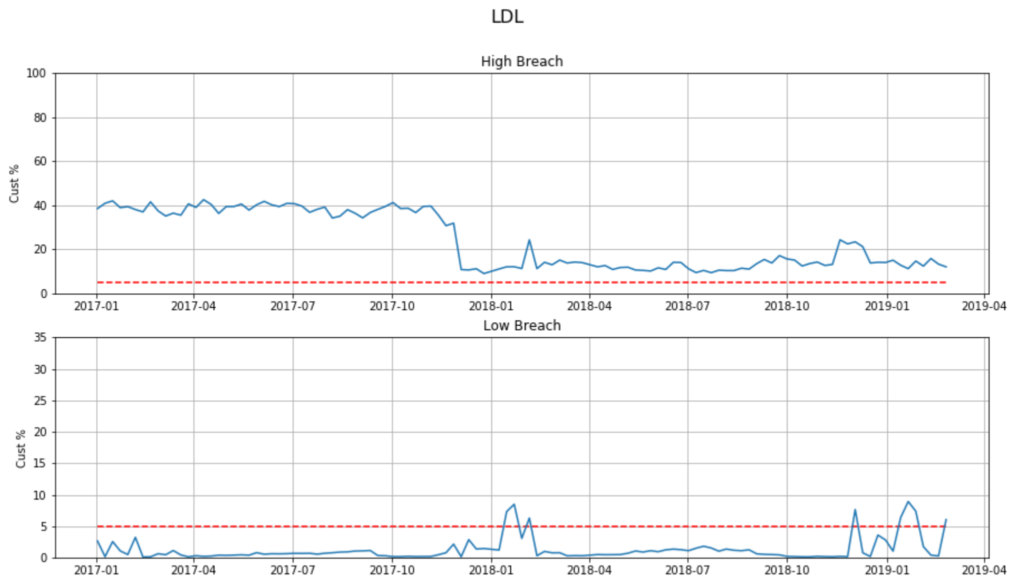

Figure 6: Customers (%) on high and low breach from 2017 to 2019 supplied by Lilydale ZSS

Figure 7 shows the voltage distribution of customers supplied by Traralgon (TGN) zone substation at four points in time.

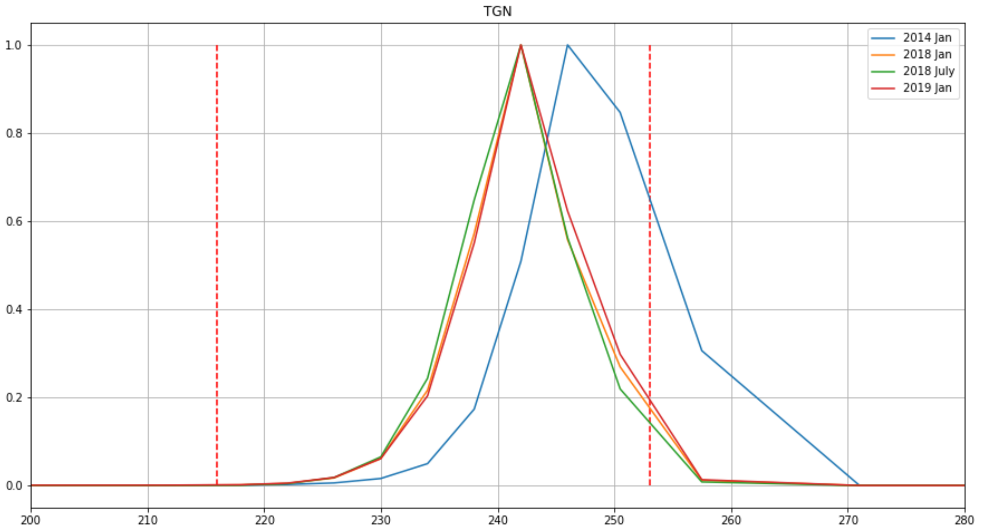

Figure 7: Voltage distribution of customers supplied by Traralgon ZSS

Setting changes were made in December 2017 and January 2015 at LDL and TGN ZSS, which resulted in 91% and 84 % improvement respectively in the number of customers experiencing non-compliant voltages.

The percentage improvements were assessed by calculating the difference in the number of recorded voltages samples that were outside the 216 V to 253 V range before and after setting changes were made over a week.

4.3.2 Voltage regulating relay setting changes at line regulators

Similar to the zone substations, setting changes were also made in VRRs of line regulators. Figure 8 and Figure 9 show the improvement made in the number of customers in voltage breach due to setting changes made in January 2019 in VRRs for Feeders FTR12 and FTR21.

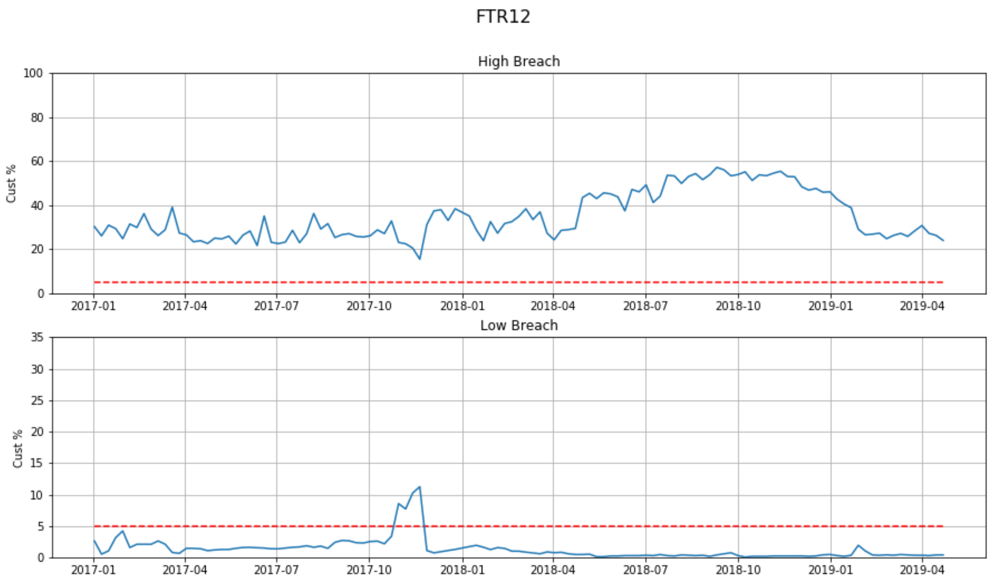

Figure 8: Percentage of customers with voltages breaches on Feeder FTR12

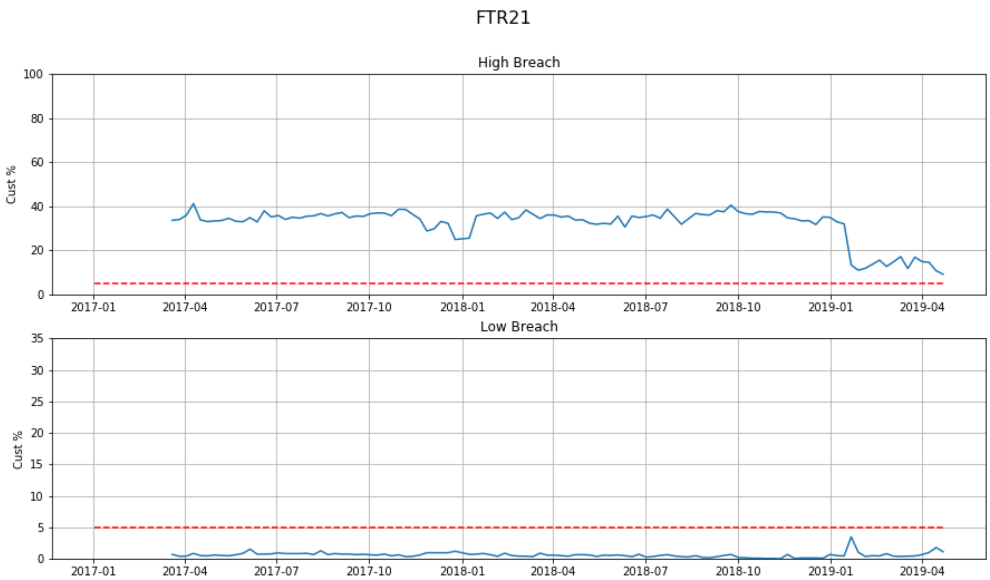

Figure 9: Percentage of customers with voltage breaches on Feeder FTR21

The setting changes made 74% to 87% in improvement in the number of customers experiencing non-compliant voltages.

4.3.3 Distribution transformer tap adjustments

As mentioned in Section 3.4, the voltage levels in the low voltage network are biased to the high end of the allowable range to allow for voltage drop due to load. This currently still exists as evident in Figure 10, which shows the distribution of LV voltages in the AusNet Services network using smart meter data over a week in November and June 2018.

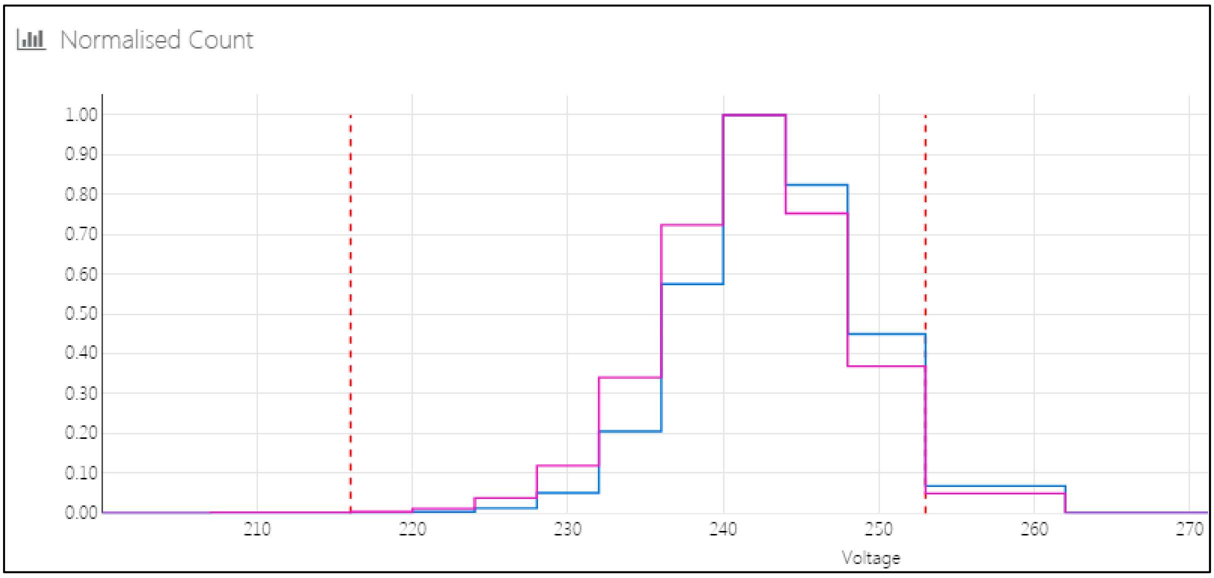

Figure 10: Voltage distribution of the network over a week (Blue: Nov 2018, Magenta June 2018)

Distribution transformers have an off-load tap setting (Figure 11), which is used adjust the output of the output of the transformer relative to the input.

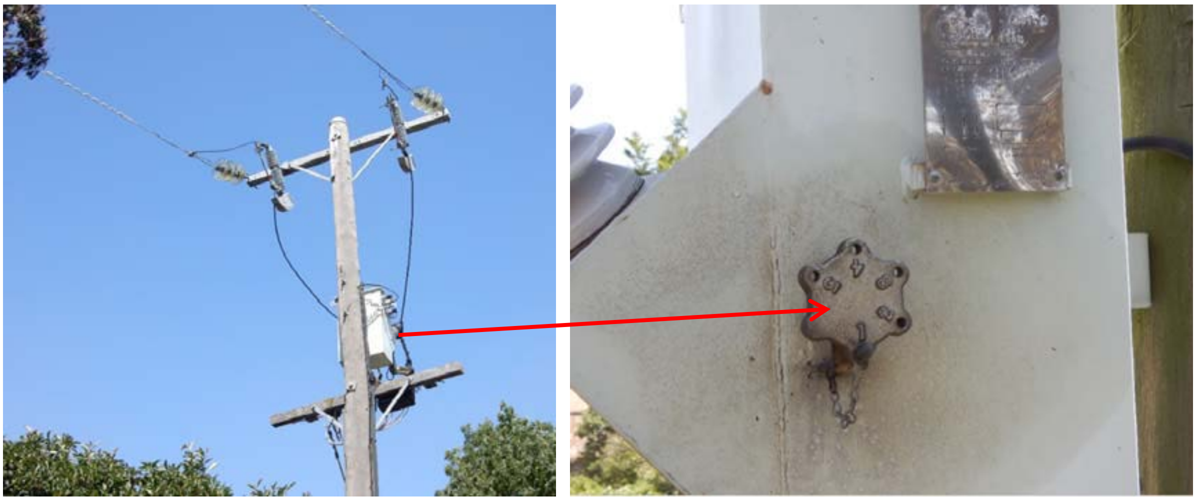

Figure 11: Distribution Transformer Tap Setting

Figure 12 is a trace of the voltage before and after a distribution transformer tap setting adjustment. The red dotted lines are the upper and lower bands of allowable voltage and the blue line is when the adjustment took place.

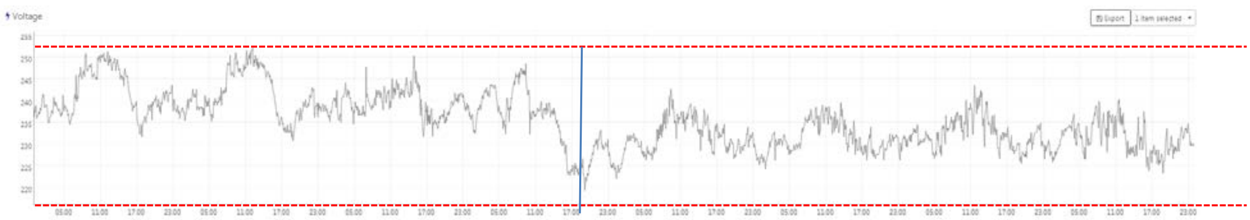

Figure 12: Example voltage before and after a distribution transformer tap setting adjustment

At present AusNet Services do not have visibility of current tap positions of its distribution transformer fleet. Tap adjustments are only made on a reactive basis prompted mostly by customer complaints.

4.3.4 Volt-Var and Volt-Watt control

The Energy Networks Australia DER Connection Policy Guidelines, released on 07 March 2019, Section 4.10.1 IES Power Quality Response Modes, require Volt-Var and Volt-Watt response modes specified in Clause 6.3.2.2 and Clause 6.3.2.3 of AS/NZS 4777.2 to be enabled.

To ensure a consistent approach across the state of Victoria for installers and customers and the industry more broadly, Victorian Distributed Network Service Providers (DNSPs) have agreed on the following settings.

The Victorian power quality response modes are:

- Volt-Var response mode (AS/NZS 4777.2 Table 11)
- Volt-Watt response mode (AS/NZS 4777.2 Table 10)

The proposed settings for each mode are shown in Table 4 and Table 5

Table 4: Mandatory: Volt-Var response mode

Reference	Voltage in Volts	Var % Rated VA
V_1	208	44% (exporting Vars)
V_2	220	0%
V_3	241	0%
V_4	253	44% (sinking Vars)

Table 5: Volt-Watt response mode

Reference	Voltage in Volts	Power % Rated Power
V_1	207	100%
V_2	220	100%
V_3	253	100%
V_4	259	20%

In addition, the setting included in Table 6 is proposed for sustained operation for voltage variations. As per Clause 7.5.2 of AS/NZS 4777.2, the inverter shall operate the automatic disconnection device within 3 s when the average voltage for 10-minute period exceeds the value of $V_{nom\text{-}max}$ where $V_{nom\text{-}max}$ lies in the range 244 to 258 V.

Table 6: Sustained operation for voltage variations

Reference	Voltage
$V_{nom\text{-}max}$	258 V

Victorian DNSPs have recommended that the above settings are incorporated into Solar Victoria's Notice to Market. The proponent/electrical contractor/installer must ensure the Victorian power quality response modes have been set in the inverter(s) and must not be changed without written approval from the DNSP. These settings must be validated and tested by the electrical contractor/ installer.

As high voltage breaches cause solar inverters to trip preventing the customers using and exporting the energy produced (refer Section 3.4), implementing these settings would enable the solar installations to help control the voltage by providing reactive power support.

It is expected that as more customers apply the settings, the reactive power support would enable more solar customers to be connected to the network with reduced levels of non-compliance. In the short term, only customers with new installations would have these settings and its effects will be insignificant. However, as more customers install new inverter energy systems, the additional reactive support may enable more connections in the medium to long term.

4.3.5 Distributed Energy Network Optimisation Platform (DENOP)

Distributed Energy Network Optimisation Platform (DENOP) is a cloud-based software platform that is designed to monitor, control and orchestrate to optimise network operations and services efficiently for all customers. It is designed to cover a diverse portfolio of distributed energy resources and is capable of integration either directly or via third-party management platforms.

The DENOP system would allow three levels of control:

1. **Local control**: Inverter native functions and local control unit
2. **'Microgrid' control system**: Aggregated fleet control software
3. **Network optimisation**: AusNet Services DENOP

Figure 13 illustrates the envisaged overall control system architecture with implementation of DENOP.

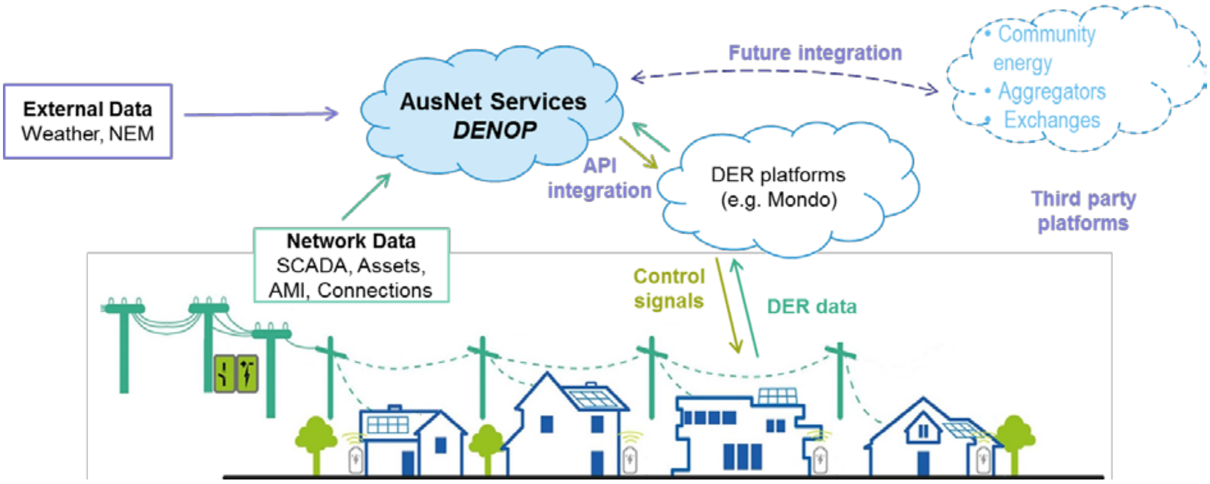

Figure 13: Envisaged control system architecture with DENOP

In the current regulatory period, AusNet Services has completed two trials incorporating customer-based DER and an optimisation platform:

1. Community Minigrid trial
2. Networks Renewed trial

Details of these trials are given in the following sections.

By implementing these trials, AusNet Services' is continuing to learn from operation of DENOP. A future scenario of high distributed energy resources (DER) is likely to involve multiple DER management platforms serving multiple customer types. AusNet Services can gain value and provide better customer outcomes through integration of these platforms to optimise DER operations against network parameters.

Community Minigrid trial

This trial was carried out on a typical 3 phase urban network, powering 14 homes in a suburban street with a combination of solar panels, 10 kWh batteries and the main power grid. DENOP was first developed for this trial.

Residences were equipped with advanced energy management, communications, monitoring and safety systems. This enabled the individual participants to capture, store and optimise the use of both solar and grid energy.

In addition, all 14 homes can operate as a unified energy system, i.e. a mini grid. Energy can be shared between homes and the mini grid can interact with the main power grid, as well as operate independently.

Networks Renewed trial

This trial was carried out in partnership with The University of Technology Sydney (UTS), AusNet Services' Commercial Energy Services' product brand Mondo Power, AusNet Services and Totally Renewable Yackandandah (TRY).

It was conducted on a typical rural single wire earth return (SWER) network in Yackandandah and involved installation of different combinations of rooftop solar systems, battery storage systems and Mondo Ubi[5] on 14 homes.

The trial was able to demonstrate that behind the meter technology such as solar PV and battery storage systems can be used to manage voltage excursions issues on the network. This was achieved using DENOP, which allowed remote access to inverter set points such as active and reactive power control, battery charging and discharging rates, as well as implementing Volt/VAr algorithms.

The main aim of the trial was to determine whether reactive power support alone could enable participant voltage to remain within the Electricity Distribution Code. Therefore testing specifically focussed on issuing commands to source and sink reactive power from battery and solar inverters.

The graphs in Figure 14 shows how reactive power alone was able to keep voltage within the required range.

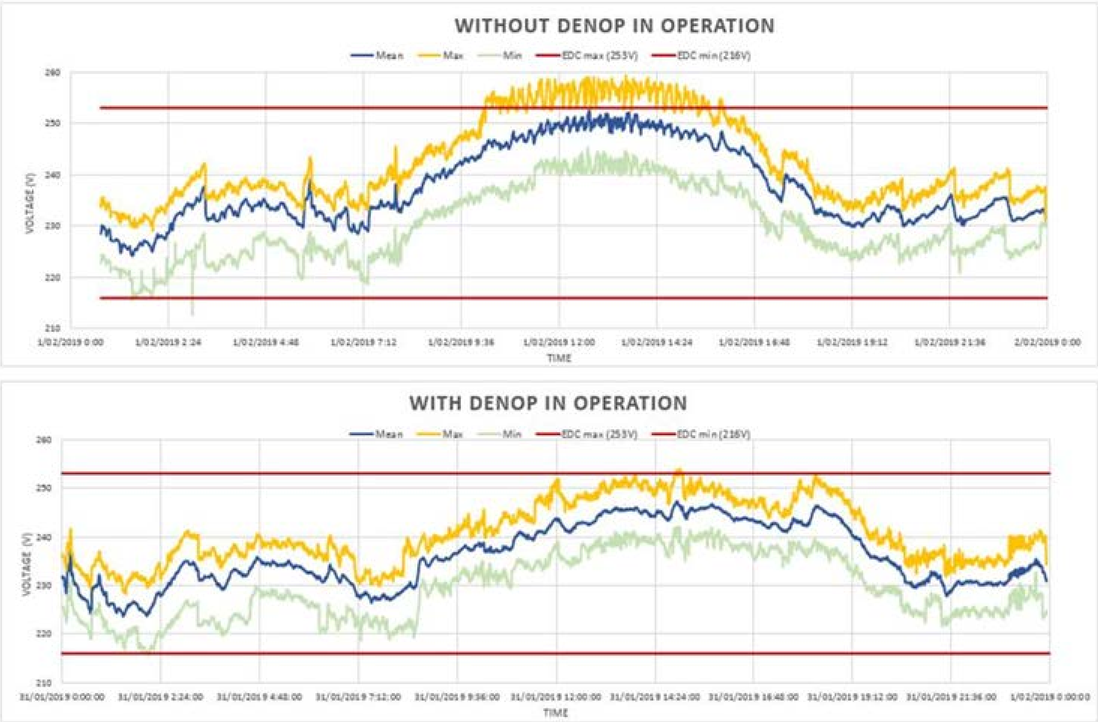

Figure 14: Voltage traces at customer site with and without DENOP in operation

[5] Mondo Ubi™ is a smart energy monitoring and managing system. https://www.reb.org.au/uploads/4/7/8/6/47865749/18_11_reb_reb_mondo_offer_your_guide_to_ubi_and_mini_grids.pdf

5 NETWORK ANALYSIS

This section presents the details on the network analysis that has been carried out using both a modelling and analytical approach.

5.1 Internal modelling the 22 kV distribution network

AusNet Services' high voltage (HV) distribution network consists of 348 feeders. Of which, 14% are classified as Long Rural, 42% are classified as Short Rural and 44% are classified as Urban.

The HV distribution network generally operates at a voltage of 22 kV. Some customers, in remote and low population density rural areas, are supplied by Single Wire Earth Return (SWER) 12.7 kV distribution networks.

The majority of our customers are supplied by low voltage (LV) reticulation via distribution transformers.

Several simulation studies have been carried out to understand the impact of the LV-connected small-scale residential and commercial solar connections on the 22 kV feeders.

Three HV feeders have been modelled each of which are representative of the following feeder characteristic with high expected penetration of solar.

1. **Urban**: HPK11 fed from Hampton Park (HPK) zone substation
2. **Short Rural**: KLO14 fed from Kalkallo (KLO) zone substation
3. **Long Rural**: SMR24 fed from Seymour (SMR) zone substation

These studies excluded modelling of the LV network.

Each of these feeders is described in the following sections.

HPK11

HPK11 is an urban feeder supplying approximately 5,200 customers with a total feeder length of 20 km. This feeder does not have any regulators, capacitor banks or SWER ISOs.

The load on HPK11 is forecasted to increase from 241 A recorded in 2017 to 251 A (P50) by 2021 and 243 A (P50) by 2025.

The installed solar is forecasted to increase from 3.3 MW in 2017 to 6.6 MW to 10.6 MW by 2025 based on the base and full uptake of solar forecasts.

Figure 15 shows the voltage profiles along the highlighted route of HPK11.

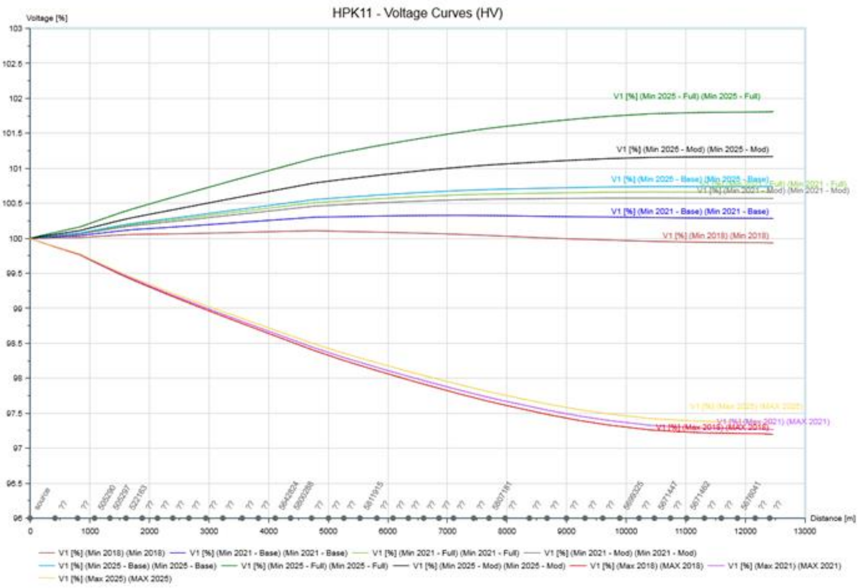

Figure 15: Voltage profile along the highlighted route of HPK11 feeder

KLO14

KLO14 is a short rural feeder supplying approximately 4,000 customers with a total feeder length of 277 km. KLO14 has 2 capacitor banks, one line regulator and 8 SWER ISOs.

The load on KLO14 is forecasted to increase from 196 A recorded in 2017 to 260 A (P50) by 2025.

The installed solar is forecasted to increase from 2.5 MW in 2017 to 6.2 MW to 10.2 MW by 2025 with the base and full uptake scenarios.

Figure 16 shows the voltage profiles along the highlighted route of KLO14, including the SWER Isolation transformer and SWER conductor beyond the 26,000m mark.

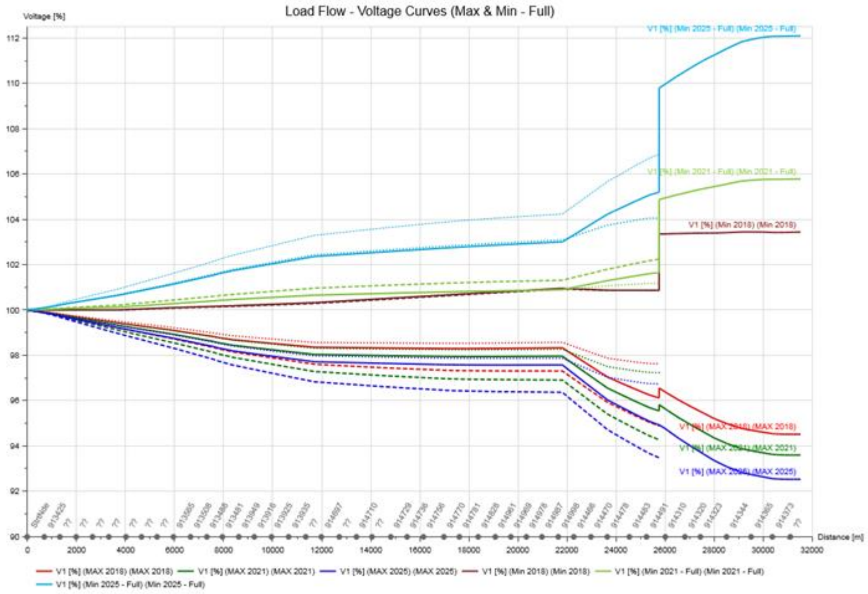

Figure 16: Voltage profile along the highlighted route of KLO14 feeder

SMR24

SMR24 is a long rural feeder supplying approximately 3,200 customers with a total feeder length of 486 km. This feeder has 2 regulators, 2 capacitor banks and ten SWER ISOs.

The load on SMR24 is forecasted to increase from 287 A recorded in 2017 to 298 A (P50) by 2025. The installed solar is forecasted to increase from 2.5 MW in 2017 to 5.2 MW to 8.5 MW by 2025 based on the base and full uptake of solar forecasts.

Figure 17shows the voltage profiles along the highlighted route of SMR24 including the boost and buck performance of the Avenel Line Voltage Regulator (LVR).

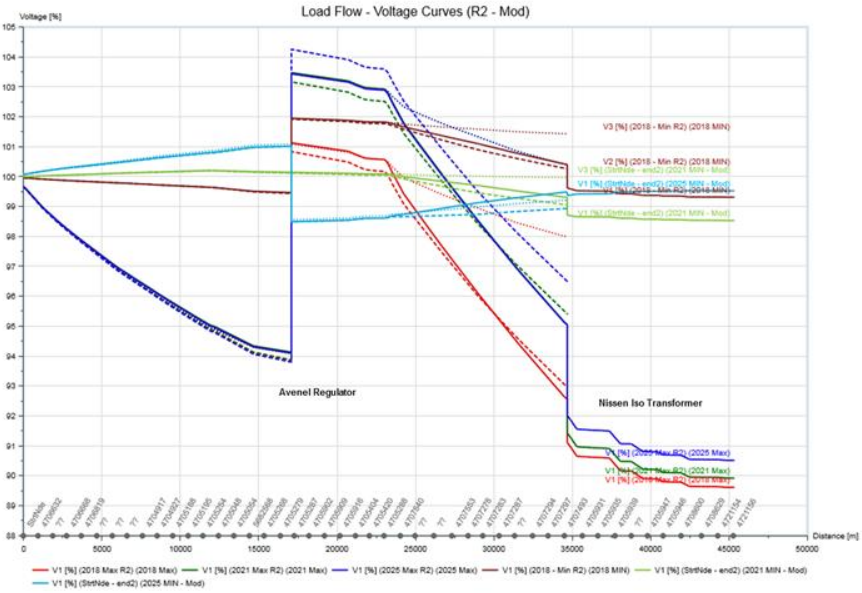

Figure 17: Voltage profile along the highlighted route of SMR24 feeder

5.1.1 Overview of the methodology

The modelling is undertaken using the actual and the forecasted 2021 and 2025 high demand and low demand levels.

The methodology applied is summarised as follows:

1. For each feeder, SCADA data is used to determine the maximum and minimum demand level and the corresponding time period during 2017/2018.
2. AMI data is then extracted for the selected maximum and minimum demand periods. This includes the installed solar, real and reactive power loading levels aggregated to each distribution substation for the chosen feeders.
3. The extracted loading data are scaled up/down for the forecasted maximum and minimum demands.
    a. *Minimum demand*: The actual installed solar capacities and the actual aggregated load values at each distribution substation and forecasts of feeder installed solar uptake are used to estimate the loading at each distribution substation for 2021 and 2025.
    b. *Maximum demand*: The actual load values during the maximum demand period at each distribution substation and P50 forecasts of feeder maximum demand forecasts are used to estimate the loading at each distribution for 2021 and 2025.
4. Load flows are carried out for 2018, 2021 and 2025 minimum (min) and maximum (max) demand scenarios, with setting adjustments of regulators and capacitor banks to assess the impact on the 22 kV voltage for increase in demand and solar penetration taking into account of base, moderate and high (full) uptake forecasts.

5.1.2 Key findings

The key findings of the network simulations are:

1. 22 kV conductor voltage rise is typically in the order of 1 to 7%
2. 22 kV conductor voltage drops are in the order 5 to 10%
3. This bandwidth is identified as an issue for the traditional voltage control via VRRs considering the customers located towards the end of the feeder.
4. SWER networks experience large voltage deviations on both on high and low sides. In some instances, the voltages exceed +/-10% of nominal at the very far end, indicating that the high loads and high penetration of solar are an issue in the 12.7 kV SWER network.

5.2 Research collaboration with the University of Melbourne

AusNet Services has also collaborated with the University of Melbourne to study the effects of increasing solar PV penetration on typical feeders found in rural and urban areas of distribution network.

This study modelled both LV and HV networks of a rural feeder (MYT7 supplied by the Myrtleford Zone Substation) and an urban feeder (CRE21 supplied by the Cranbourne Zone Substation).

The key study findings are summarised below.

5.2.1 Business as Usual (no feeder optimisation)

- The studied HV-LV networks could host up to 10% of PV penetration (10% of residential customers with a PV system) before customers experience voltage issues.
- The number of affected customers beyond the hosting capacity increases almost exponentially with PV penetrations.
- Utilisation of assets increases almost linearly with PV penetrations
  - HV lines in the Urban network are likely to exceed their operational limits at high PV penetrations (>70%).
  - Distribution transformers are unlikely to exceed their operational thermal limits.

5.2.2 Using off-loads taps of distribution transformers

The use of off-load tap changers were investigated as a potential solution to mitigate voltage issues.

The study considered the following tap position cases:

1. BAU off-load taps: All distribution transformers have the current (assumed) off-load tap positions (nominal position 3, 22 kV/433 V).
2. One reduced off-load tap: All distribution transformers reduce their BAU off-load tap position by one tap (position 2, 22 kV/422 V).
3. Two reduced off-load taps: All distribution transformers reduce their BAU off-load tap position by two taps (i.e. to position 1, 22 kV/411 V).

The cases presented above uses a very optimistic assumption, as the existing tap positions of the distribution transformer fleet are not known and could be biased to either side, leaving no capacity for adjustments.

- Using off-load tap adjustments, the PV hosting capacity of the studied HV-LV networks increased to 20% for the rural network and 60% to the urban network.
- The number of customers experiencing voltage issues beyond the hosting capacity is reduced when compared to the Business as Usual case for both urban and rural networks.
  - The number of affected customers for the rural network now increases almost linearly with PV penetrations.
- The loading utilisation of assets is larger than the Business as Usual cases due to increased reverse power flows (facilitated by less PV curtailment due to lower voltages seen by customers).
  - HV lines in the Urban network are likely to exceed their operational limits at an earlier PV penetration (60%).
  - Distribution transformers are now likely to exceed their operational limits at high PV penetrations (>80%).

The maximum loading utilisation of distribution transformers and HV lines for scenario cases 1, 2, and 3 for an urban feeder are shown in Figure 18 and Figure 19 respectively.

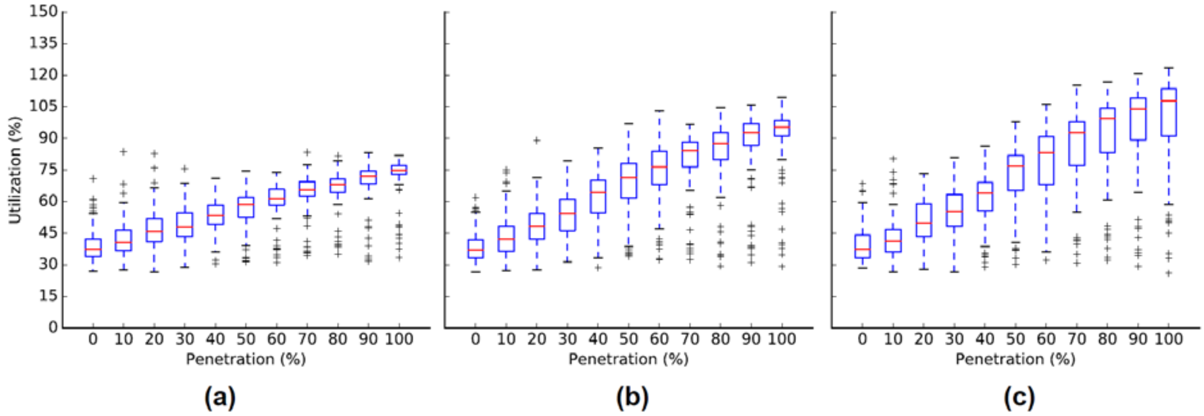

Figure 18: Maximum utilisation of distribution transformers for cases 1 (a), 2 (b) and 3 (c)

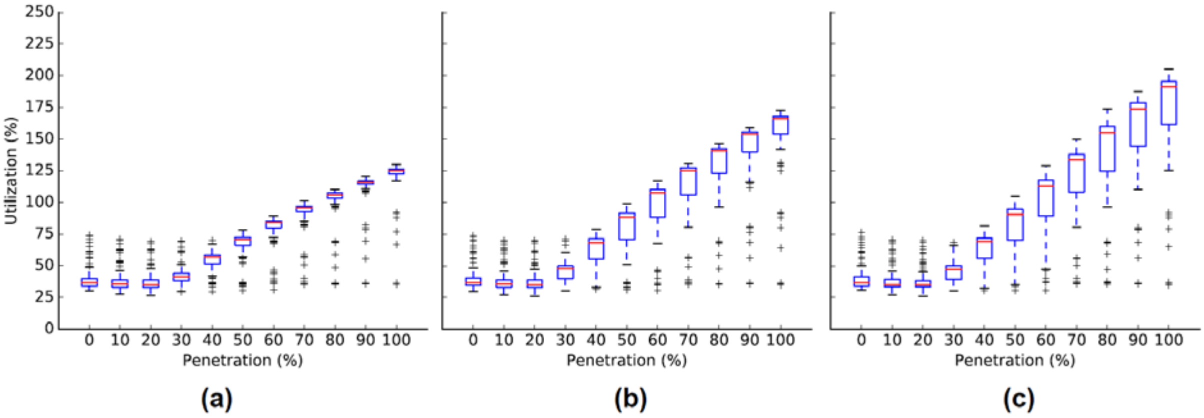

Figure 19: Maximum utilisation of HV lines for cases 1 (a), 2 (b) and 3 (c)

5.2.3 Role of Volt-Watt Control

Figure 20 shows the Volt-Watt response curve with default settings as specified in AS/NZS 4777.2.

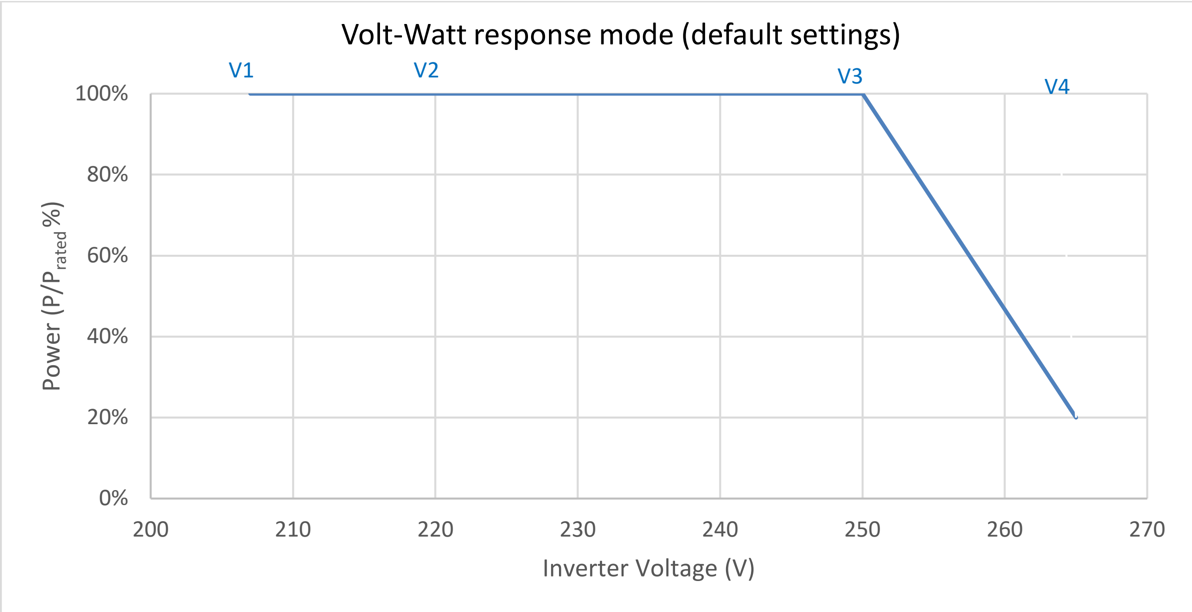

Figure 20: Volt-Watt settings specified by the standard AS/NSZ 4777.2

- The Volt-Watt settings specified by the standard AS/NSZ 4777.2 do result in curtailment and therefore help reducing the corresponding effects.
- However, due to the values adopted by the standard, Volt-Watt control does not fully mitigate voltage issues. Curtailment is activated at 1.085 p.u. and allows PV systems to generate even beyond 1.15 p.u.

  More conservative settings could provide more benefits.
- Consequently, voltage solutions across the network (e.g. using off-load taps or OLTCs) will reduce the curtailment done by the Volt-Watt control but also increase reverse power flows.

5.2.4 Effects on Customers

- Due to Volt-Watt control, the higher the PV penetration, the higher the curtailment faced by customers (due to higher voltages).
- Customers in the rural network were found to face larger curtailment (almost double) than urban customers (due to higher voltages found in the rural network for the same penetration).
- Despite the type of network, customers located at critical points (remote ends) are likely to experience much higher levels of curtailment than those connected closer to the substations (due to higher voltages).

5.2.5 Network type

- The level and severity of issues largely depends on the type (i.e. urban, rural) and characteristics of the network (i.e., distance, impedance, type of customers, SWER, etc.)
- Rural networks will face higher voltages compared to urban ones, as they cover larger areas (longer lines, higher impedance)
- Urban networks largely comprised by residential customers will experience significant HV reverse power flows as the aggregated PV generation by far exceeds local consumption.

5.2.6 Location of PV systems

- PV systems clustered at the furthest points of HV feeders are likely to result in voltage issues.
  - Large impedance between these areas and the head of the feeder.
  - More severe in rural networks than urban due to their larger distances and hence higher network impedances.
- PV systems clustered close to the primary substation are less likely to result in voltage issues.
  - Small impedance between these areas and the head of the feeder.

Consequently, for a given PV penetration in an HV feeder (urban or rural), different locations of solar PV installations can result in less or more impacts.

5.3 Voltage compliance using advanced metering analytics

Advanced Metering Infrastructure (AMI) has given AusNet Services greater visibility of steady state voltage performance. Using AMI data, AusNet Services has developed a suite of analytical tools called *Explore*.

As part of *Explore* suite of tools, the *Voltage Compliance* tool determines, whether the voltages at an individual customer level are within the $V_{1\%}$ and $V_{99\%}$ ranges specified in AS 61000.3.100 *Electromagnetic compatibility (EMC) Part 3.100: Limits – Steady state voltage limit in public electricity systems*.

This is used by AusNet Services to monitor steady state voltage compliance (refer Section 4.2).

Further details on the *Voltage Compliance* tool can be found in Appendix A.

5.3.1 Substation Health tool

The *Substation Health* tool is another tool that has been developed as part of the *Explore* suite of tools.

This analyses voltage compliance issues at a distribution substation level to make high level recommendations on the remediation steps.

The Substation Health tool leverages the data generated from the *Voltage Compliance* tool and uses various trend analysis techniques to determine which substations supply customers who experience ongoing, consistent voltage compliance issues.

An analysis based on the voltage profiles of the meters connected to the substation is conducted. Based on simulating the tapping up or down of the substation voltages, recommendations are made as to actions needed to bring the voltage of the customers connected to the substation back within voltage limits.

Table 7 shows the categories of possible solutions and issued identified by the *Substation Health* tool.

Table 7: Classification of possible solutions or issues by the *Substation Health* tool

Possible solution / Issue identification	Description
Opportunity to tap	Identifies the substations where the likely solution is an adjustment to the distribution transformer tap setting to bring customers voltages levels back into compliance with AS 61000.3.100.
High voltage (HV) control issue	Identifies the substations where the voltage non-compliance issues are due to inadequate upstream high voltage control. The most likely solution is replacement of control equipment in the upstream HV network (i.e. 22 kV and 12.7 kV for SWER).
Low voltage bandwidth issue	Identifies the substations where customers are experiencing voltages that are outside of both upper and lower limits of AS 61000.3.100. The most likely solution is the reconfiguration of the low voltage network by either re-conductoring or splitting low voltage circuits.

Figure 21 shows a summary snapshot of the *Substation Health* tool.

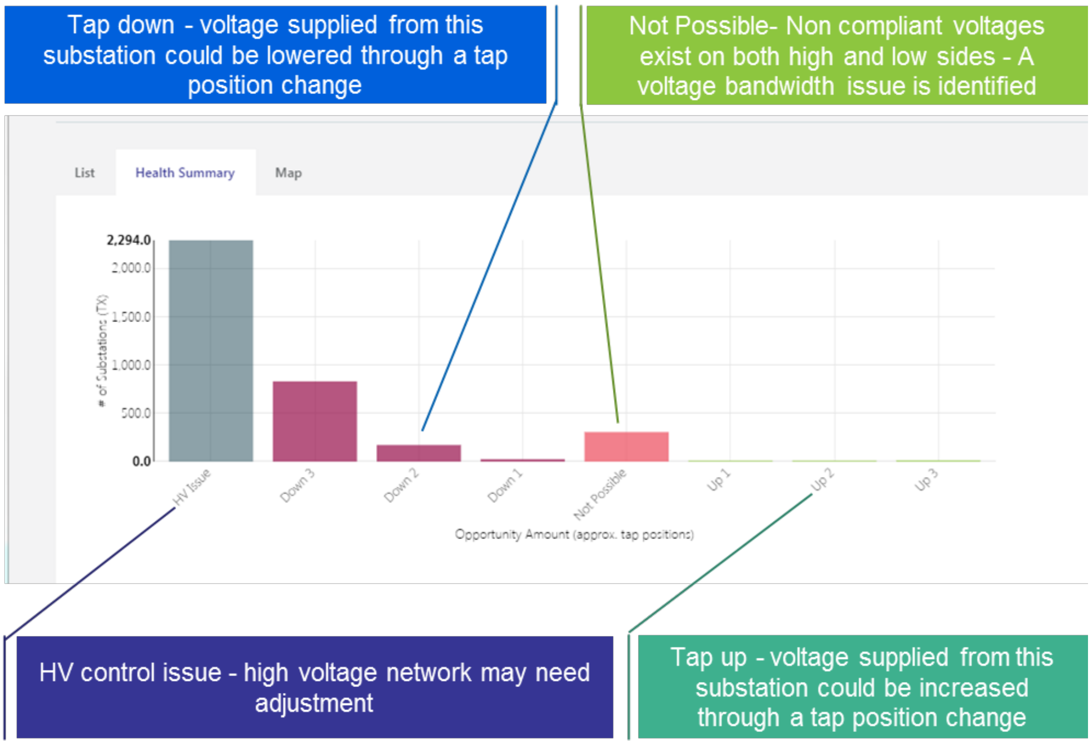

Figure 21: A snapshot of the Substation Health tool

Further details of the *Substation Health* tool can be found in Appendix B.

5.3.2 Existing voltage compliance

At present, the *Substation Health* tool has identified that the approximately 54,000 customers experiencing voltage non-compliance issues (refer Section 4.2) are supplied by approximately 4,200 substations, which is approximately 7% of AusNet Services distribution substation fleet.

Figure 22 shows the breakdown of existing voltage non-compliance issues based on the above classifications.

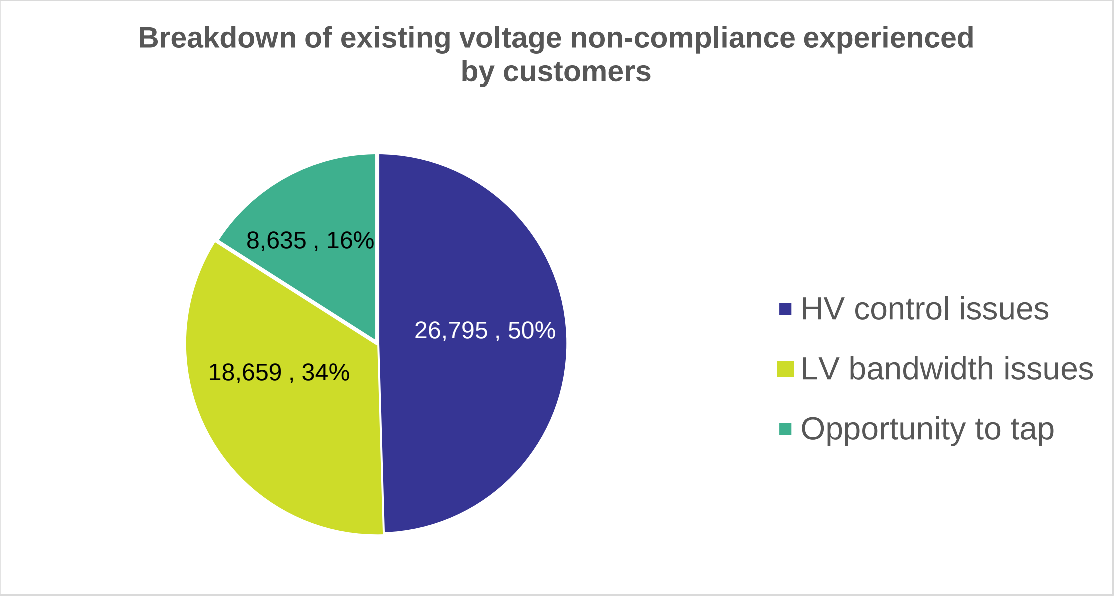

Figure 22: Breakdown of existing voltage non-compliance issues/solutions experienced by customers

5.3.3 Future voltage compliance

In addition to the *Substation Health* tool, AusNet Services has developed a methodology to estimate future voltage compliance issues.

This is a statistical assessment based on historical trends, solar uptake forecasts and design standards for volt per watt profiles.

This assessment identifies the distribution substations that are likely to have customers experiencing a breach of the upper voltage limits based on the increased solar generation during the period specified by the solar forecast.

Similar to *Substation Health*, it quantifies the distribution transformer tapping opportunities to make recommendations on actions needed to bring the voltage of customers connected to the substation back within the voltage limits. The classification of possible solutions and issues identified by this methodology is same as the *Substation Health* tool and shown in Table 7.

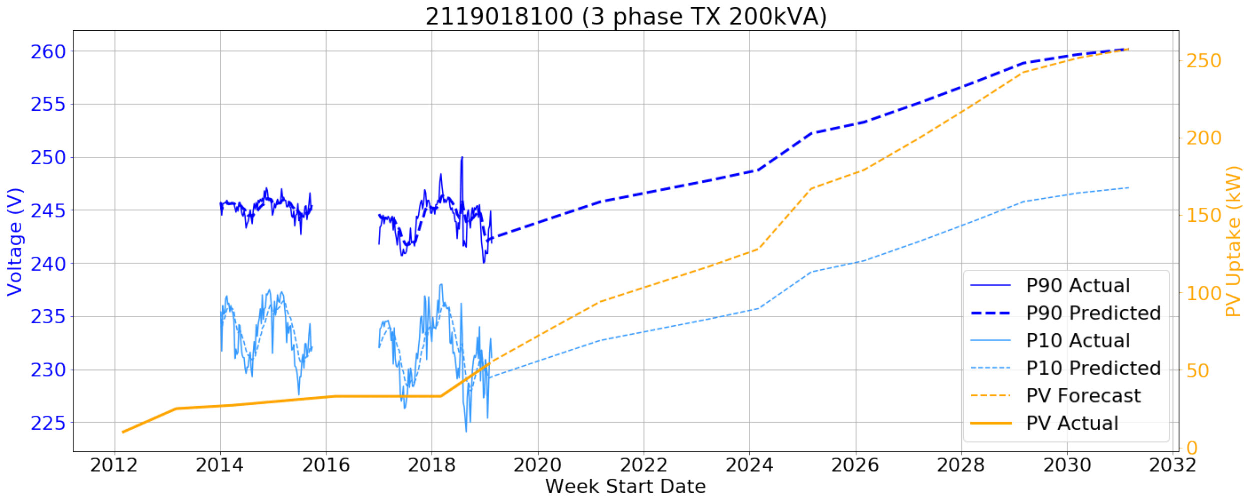

Figure 23: Voltage extrapolation for sample substation

Figure 23 shows an overlay of PV uptake and estimated voltage rise for a sample substation.

Further details of future voltage compliance estimation methodology referred as the Preliminary Tactical Hosting Capacity Assessment is included in Appendix C.

Based on the assessment, approximately 7,400 substations (~235,000 customers) are expected to be supplying customers experiencing voltage non-compliance issues over the next six years (2019 to 2025).

The majority of future non-compliant substations are identified in the immediate future. This is reflective of the knee point in the PV uptake post 2018 as shown in Figure 23 for a sample substation.

Figure 24 shows the number of customers forecast to be experiencing non-compliant voltages by 2025.

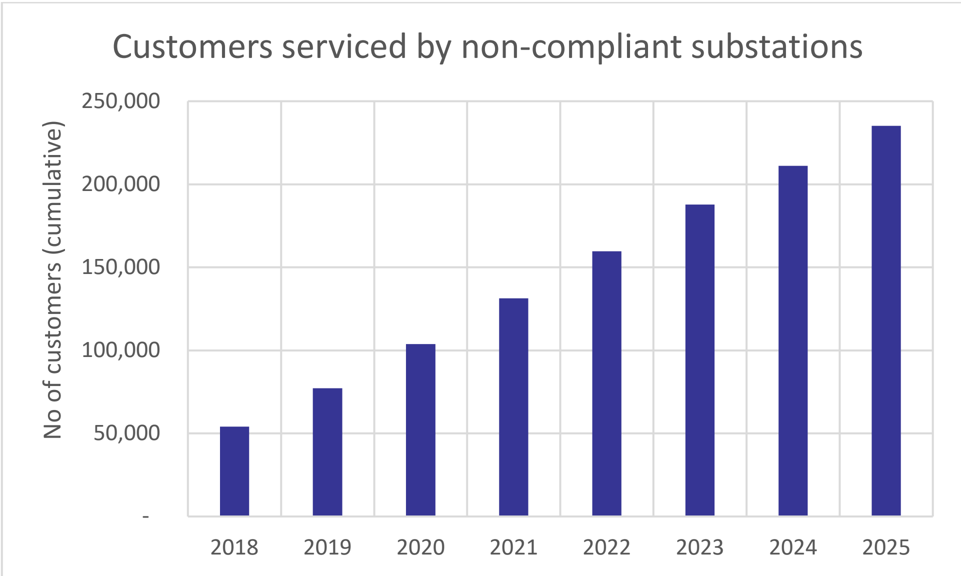

Figure 24: Number of customers forecast to be experiencing non-compliant voltages by 2025

Figure 25 shows the forecast count of customers experiencing non-compliant voltages based on the classification of voltage issues by 2025. This highlights that a greater number of issues attributed to the HV network will be experienced going forward.

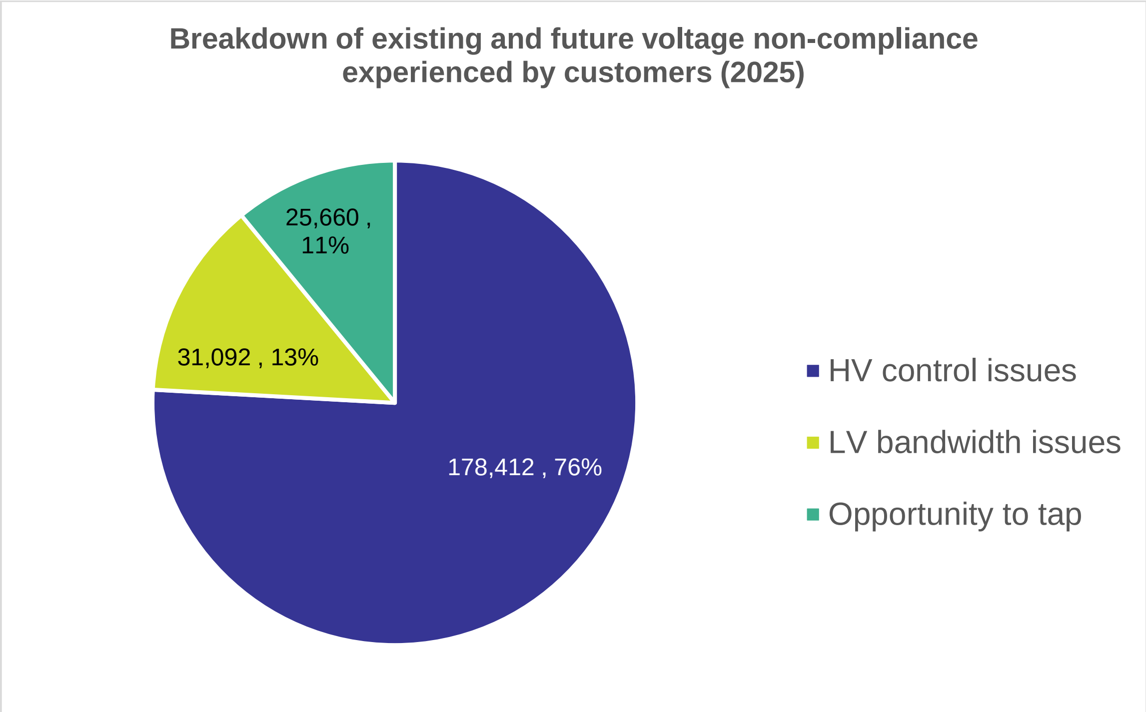

Figure 25: Breakdown of existing and future voltage non-compliance by 2025

6 IDENTIFIED NEED

Traditionally, distribution networks have been uni-directional, designed to deliver energy from centralised generation sources to customer load centres in the low voltage network. However, bi-directional power flows are expected to increase due to increased adoption of solar PV where excess energy is exported to the grid requiring the network to handle minimum demands as well as maximum demand periods.

As a result, voltage levels are required to be maintained within the prescribed limits irrespective of the direction of the power flow as presented in Section 3.

Advanced Metering Infrastructure (AMI) has given AusNet Services greater visibility of steady state voltage performance. Using AMI data, AusNet Services has developed a suite of analytical tools which has enabled the business to understand and monitor voltage compliance issues.

These tools have identified that approximately 4,200 distribution substations are currently non-compliant and approximately 7,400 additional distributions substations are estimated to be non-compliant during the next few years (2019 to 2025) as detailed in Section 5.3.

The current progress in addressing voltage issues is described in Section 4.3. This includes setting changes in voltage regulators in the high voltage 22 kV network from forward line drop compensation (LDC) to uncompensated settings.

AusNet Services have used uncompensated settings to overcome the resulting over voltages in the 22 kV network with the adoption of solar generation in the distribution network.

However, as the penetration of solar generation increases more feeders are likely to experience reverse power flow.

Figure 26 shows the percentages of zone substations that are likely to experience reverse power flows based on the base, moderate and high (full) solar uptake forecasts.

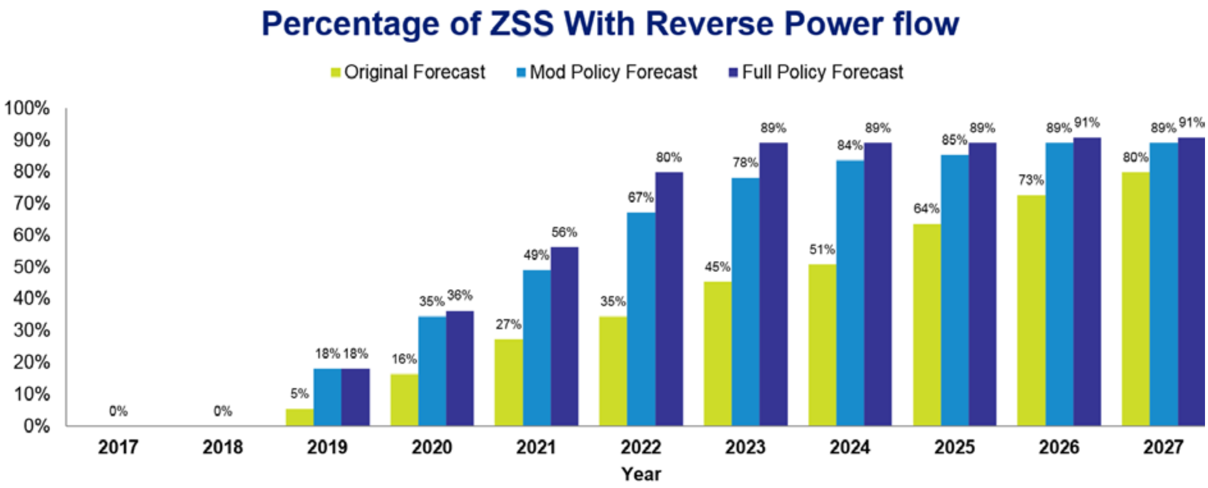

Figure 26: Percentage of zone substations with reverse power flow

It is not possible to reduce the voltage set points further in flat settings without compromising the number of customers experiencing low voltage breach, generally during high demand periods. The number of customers experiencing low voltage breach during summer months is already increasing as can be seen in Figure 5.

The existing VRRs with uncompensated settings alone is not sufficient to regulate the voltage for both maximum and minimum (including reverse power flow) loading scenarios expected throughout the day.

Therefore, compatible VRRs and regulators are needed at zone substations and line regulators to accommodate customer generation whilst adhering to compliance requirements.

Furthermore, augmentation is also required on the SWER network to facilitate the estimated solar customer growth in these areas.

AusNet Services' design requirements for new undergrounded estates require the construction of network assets that can supply an average diversified maximum demand of 4 kVA per lot. However, the network is limited to supplying between 1.5 to 3 kVA per lot and sometimes less where existing lots are sub-divided in the older residential network areas. At the time when power flow was uni-directional and gas hot water was available the design limit criteria was1.5 kVA per lot.

The forecast suggests that the number of solar customers is expected to more than double and the installed solar capacity is also expected to increase given the size and mix of solar systems estimated to be installed.

Figure 27 shows the increase in average installed residential solar capacity per customer from 2009 to 2018. Therefore, further rectification work in the LV network is required to achieve compliance and improve hosting capacity.

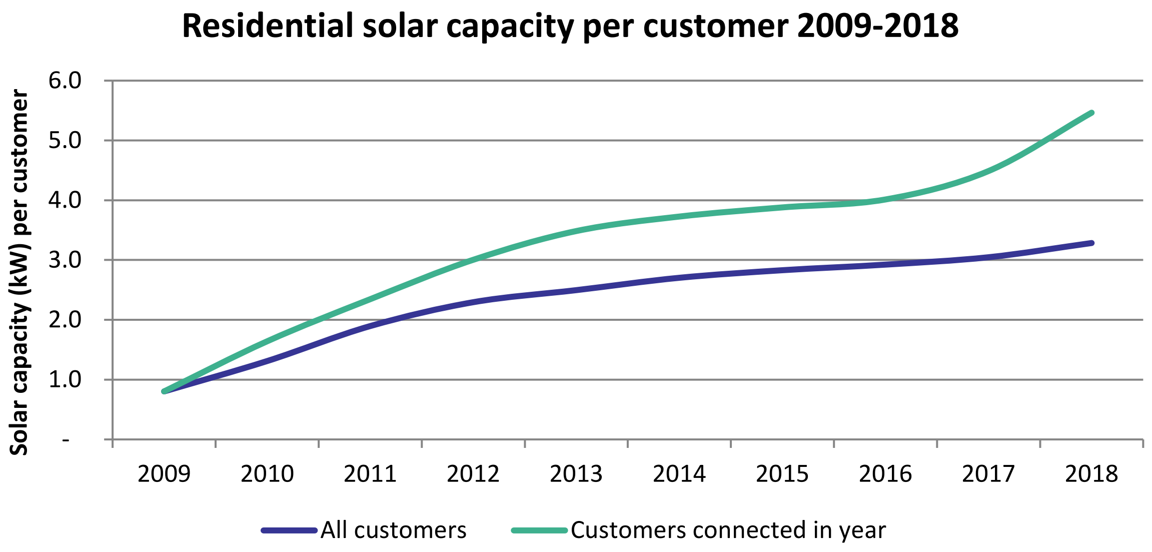

Figure 27: Residential solar capacity from 2009 to 2018 in AusNet Services network

As detailed in Section 4.3, AusNet Services has also carried out several trials on a software control platform, DENOP, to optimise the network operation to enable a diverse portfolio of DER and flexible integration.

At present, it is necessary for AusNet Services to take conservative view on level of DER that can be connected to the network due to limitations in its monitoring and LV network information.

Hence, investment is still needed to acquire more data and operationalise the capabilities required to support DER on an ongoing basis and adhere to compliance requirements.

The next section presents the options assessments based on the identified needs as part of an economic analysis. The economic analysis allows comparison of costs and benefits of each option to determine the most economical solution and the preferred timing.

7 ECONOMIC ASSESSMENT OF THE IMPACT OF OVERVOLTAGE ON SOLAR GENERATION

7.1 Overview of approach

AusNet Services has developed an economic approach to valuing the impact of overvoltage on solar generation. This approach uses the outputs of the *Substation Health* tool and future voltage compliance assessment, which classify potential solutions to the existing and future voltage non-compliance issues at a distribution substation level.

The approach estimates the cost of solar generation, which is constrained due to voltage non-compliance issues and compares this to the cost of augmentation options.

The following is a summary of the approach:

1. A solar forecast with a moderate uptake is applied to each non-compliant distribution substation to determine the expected exported energy to the distribution network.
2. The expected exported energy is valued using the minimum feed-in tariff (FiT*)*.
3. The network topology is extracted from AusNet Services' geo-spatial system, SDMe, to determine where in the network the constrained substations are positioned and the critical equipment likely to be causing the voltage non-compliance, i.e. zone substation, line voltage regulator, distribution substation etc.
4. The expected exported energy is aggregated to the equipment that has been identified as causing the voltage non-compliance issues. This is the value of constrained expected exported energy due to voltage non-compliance and forms the value of unserved generation.
5. The constrained expected exported energy per annum is used to calculate the benefits of potential network and non-network solutions. The costs and benefits of potential solutions are described in Sections 7.8 to 7.10.
6. A net present value (NPV) assessment is made to determine the highest NPV option. A potential solution is justified when the value of estimated enabled export of previously unserved generation exceeds the cost of the augmentation.
7. The justified NPV option within the 2022-26 year period with the largest net benefit is then included in EDPR submission as the most economical solution.

7.2 Solar uptake forecast

The estimated solar uptake in the AusNet Services network is described in Section 3.5.

The economic model uses the moderate uptake of solar forecast that is developed for each distribution substation[6]. Based on the moderate uptake, it is estimated that AusNet Services network will have approximately 1.4 GW of installed solar capacity by 2035, which is twice the installed capacity in 2020.

Figure 28 shows the network wide forecast comparison of installed capacity of solar uptake.

[6] Substation level solar customer forecasts are used in the economic model. These forecasts are 0.6% lower on average over 2018 to 2030 than the solar customer number forecast underpinning our energy forecast.

This minor discrepancy is due to the treatment of large solar sites in the forecasts and due to rounding. In any case, this means that our DER augmentation proposal is based on a slightly more conservative solar customer forecast.

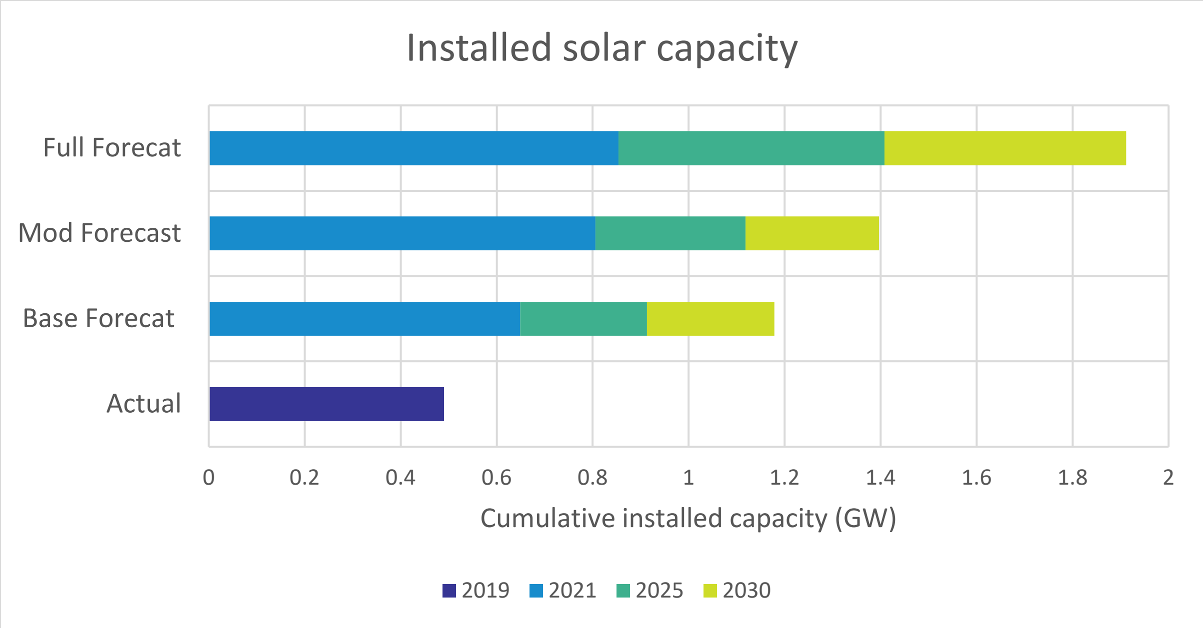

Figure 28: AusNet Services' forecast comparison of installed capacity of solar uptake

7.3 Expected daily energy export from solar installations

A high level analysis is carried out on the daily average exported energy of solar customers connected to the AusNet Services' network.

The data suggests that every additional kW of installed solar exports approximately 3 kWh in summer and approximately 1 kWh in winter.

Figure 29 and Figure 30 show the daily average exported solar generation in a summer month (November 2017) and a winter month (June 2018).

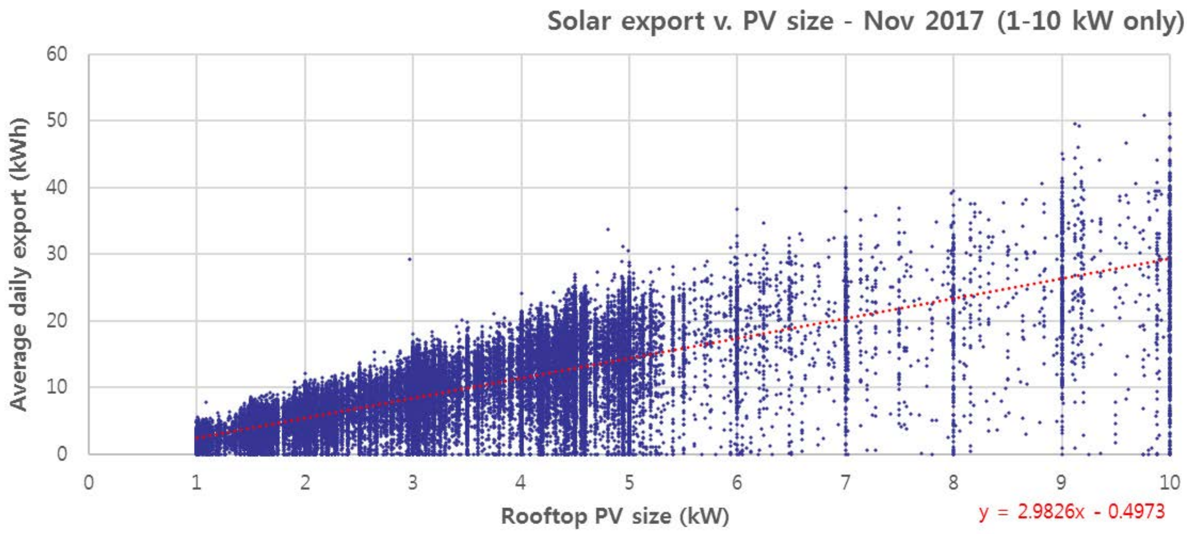

Figure 29: Daily average export of solar generation in November 2017

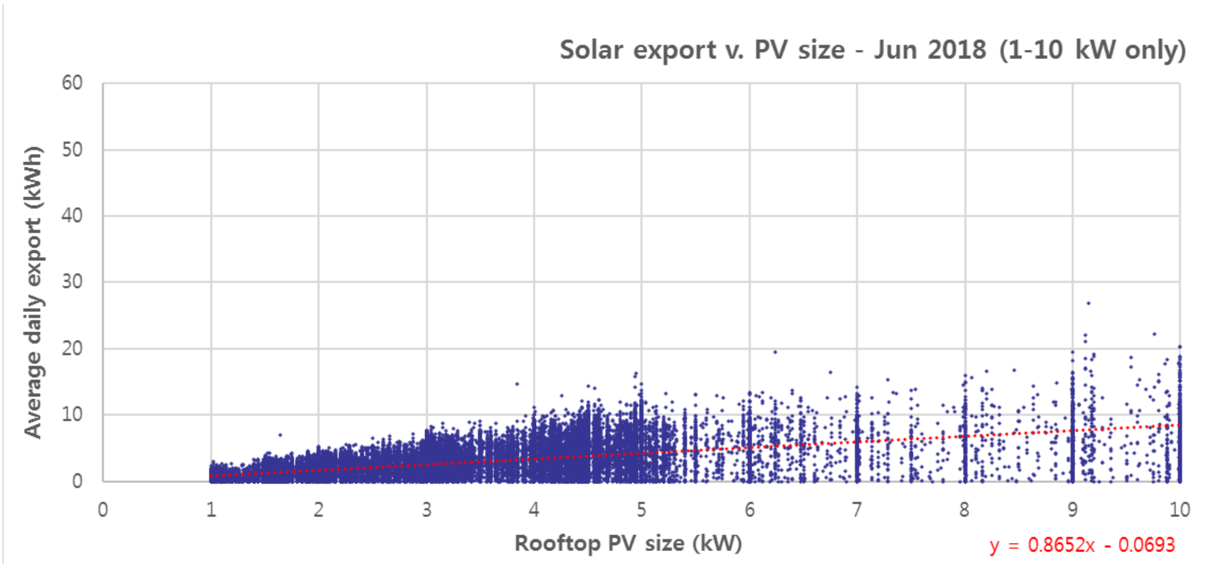

Figure 30: Daily average export of solar generation in June 2018

The analysis only includes customers on AusNet Services' solar tariff, which encompasses the majority of solar customers. It also includes solar installation systems up to 10 kW.

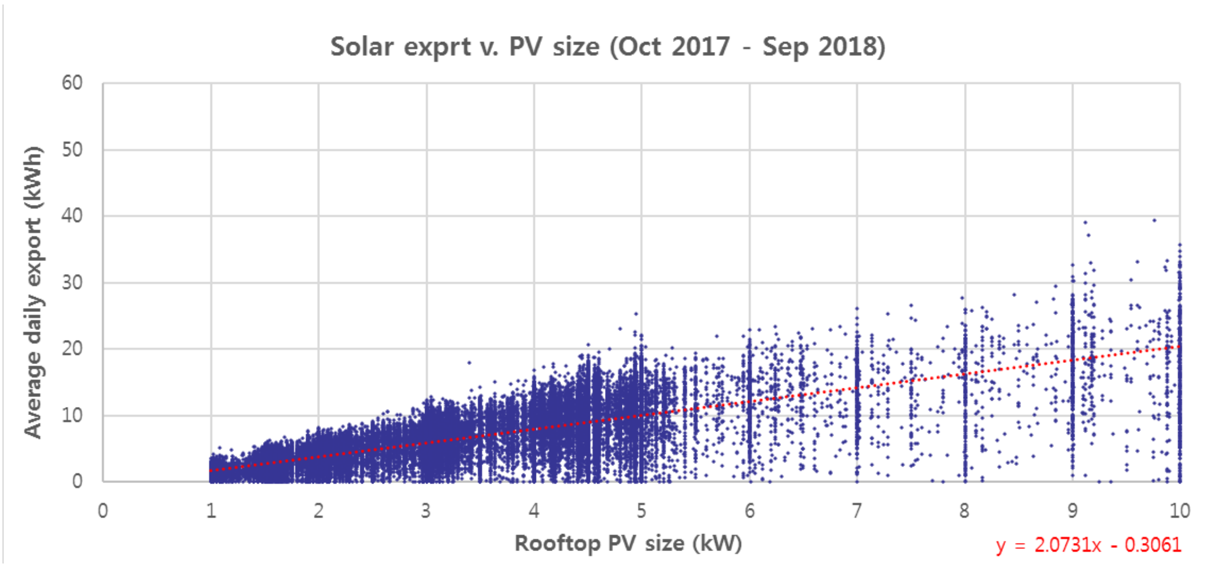

Figure 31: Daily average export of solar generation over a year

Figure 31 shows the average daily export over a year for solar installations up to 10 kW. Based on the analysis above, 2 kWh of daily exported energy is assumed for each 1 kW of solar installation taking into account of impact of seasonal variations on solar energy generation.

7.4 Feed-in tariff (FiT)

Feed-in tariff (FiT) is the rate that an electricity retailer must pay to its small renewable energy generator customers for electricity they produce and export into the grid. As set out in the Electricity Industry Act 2000, the Essential Services Commission (ESC) is required to determine the minimum FiT for each financial year.

In 2017, the ESC concluded its inquiry into the true value of distributed generation. This included a major body of research examining the energy value and network value of distributed generation. In addition, industry consultations have also been carried out in setting the minimum FiT.

The methodology of establishing the minimum FiT comprises the following components[7]:

- the value of electricity produced by small scale renewable generators, based on the avoided cost of purchasing the same amount of electricity from the wholesale market – National Electricity Market (NEM), accounting for price changes throughout the day and seasonally. This includes:
  - wholesale electricity price forecast, both a single rate and time-varying;
  - avoided value of network (distribution and transmission) losses;
  - avoided ancillary service charges and market fees; and
- avoided social costs of carbon;

The ESC's final decision includes two minimum FiT rates to apply from 1 July 2019, the single rate feed-in tariff and/or the time varying feed-in tariff, of which each retailer must offer at least one. The minimum FiT rates and the breakdown for 2017, 2018 and 2019 are tabulated in Table 8 and Table 9 respectively.

Table 8: Minimum FiT rates that apply for financial years 2017, 2018 and 2019[7]

<table>
<tr><th rowspan="2">Period</th><th rowspan="2">Weekday</th><th rowspan="2">Weekend</th><th colspan="3">Rate (c/kWh)</th></tr>
<tr><th>From 1 July 2019</th><th>From 1 July 2018</th><th>From 1 July 2017</th></tr>
<tr><td>Single</td><td colspan="2">applies at all times of the day and week</td><td>12</td><td>9.9</td><td>11.3</td></tr>
<tr><td>Off peak</td><td>10pm to 7am</td><td>10pm to 7am</td><td>9.9</td><td>7.1</td><td rowspan="3">N/A</td></tr>
<tr><td>Shoulder</td><td>7am to 3pm, 9pm to 10pm</td><td>7am to 10pm</td><td>11.6</td><td>10.3</td></tr>
<tr><td>Peak</td><td>3pm to 9pm</td><td>n/a</td><td>14.6</td><td>29</td></tr>
</table>

Table 9: Breakdown of the FiT rates that apply for financial years 2017, 2018 and 2019

Component	2017-18	2018-19	2019-20
Forecast solar-weighted average wholesale electricity price	8.1	6.8	8.9
Avoided market fees and ancillary service charges	0.1	0.1	0.07
Value of avoided distribution and transmission losses	0.6	0.5	0.49
Value of avoided social cost of carbon	2.5	2.5	2.5
FiT rate (c)	11.3	9.9	12.0

The FiT is an industry accepted metric of valuing the energy generated by small scale renewable generation. As described above, it encapsulates the avoided value of wholesale energy purchases, network loses, ancillary service fees, market fees and social costs. Therefore, FiT is used in the economic assessment to estimate the value of unserved energy due to voltage non-compliance.

AusNet Services also engaged Frontier Economics to evaluate the use of FiT as a proxy for the value of solar generation and exports. Frontier Economics concluded that the use of the FiT provides a reasonable measure to estimate benefits of solar exports and it is also in line with the Australian Energy Regulator's regulatory investment test for distribution (RIT-D). The RIT-D guideline includes fuel cost savings and changes in electrical losses as acceptable categories of market benefit. Frontier Economics report identified the following key benefit categories arising from additional solar exports:

- Avoided generation dispatch costs – greater solar PV exports will reduce the volume of electricity required to meet consumer demand. This will in turn reduce the amount of electricity that wholesale generators are required to produce, leading to a saving equal to the short run marginal

[7] https://www.esc.vic.gov.au/electricity-and-gas/electricity-and-gas-tariffs-and-benchmarks/minimum-feed-tariff

cost of the grid sourced generation that is displaced as a result of the additional solar PV exports (which is generally reflected in spot prices).

- Avoided network losses – as electricity flows through networks, a proportion of energy is lost due to electricity resistance and the heating of conductors. Rooftop solar PV panels are located closer to the point of consumption than utility-scale generators, so electricity exported from rooftop solar PVs is transported a shorter distance through electricity networks. It follows that an increase in rooftop solar PV exports would be expected to reduce network losses.
- Environmental benefits – greater solar PV exports will reduce the amount of electricity required to be generated by coal and gas fired plants in the NEM, thereby reducing the amount of greenhouse gas emissions that are produced in meeting electricity demand.

The FiT also includes forecasts of avoided market fees and ancillary services charges. Frontier Economics report concluded that this should not be included since it reflects a redistribution of costs rather than a net market saving. However, the avoided market fees and ancillary services charges only represents a very small proportion of the total FiT (i.e. less than 0.6%) and therefore will not have a material impact to the valuation of DER benefits.

The full Frontier Economics report is included in Appendix D.

7.5 Value of unserved generation

The economic model uses single rate of FiT of 12 cents/kWh and calculates the unserved energy of voltage non-compliant distribution substations as follows:

$$\begin{aligned}&\mathit{Unserved\ energy\ of\ distibution\ substation\ per\ annum}\ (\$)\\&\quad= \mathit{Installed\ solar\ capacity}\ (kW)\\&\quad\times \mathit{Expected\ daily\ energy\ export\ per\ 1\ kW\ of\ solar\ instation}\ \left(\frac{kWh}{kW}\right) \times 365\\&\quad\times\ FiT\ \left(\frac{\$}{kWh}\right)\end{aligned}$$

The economic model uses the unserved generation from the existing non-compliant substations from 2018. For future voltage non-compliant substations, the model only uses the unserved generation from the year which the voltage non-compliance is identified.

A proportion of the value of unserved energy forms the benefit of various proposed solutions based on the expected improvement listed in Sections 7.8 to 7.10.

7.6 Key project financial evaluation metrics

The table below presents the key financial metrics used in the economic model.

Table 10: Key project financial metrics

Description	Units	Value
Valuation year		2018
Discount rate	%	6.44
Useful life Based on the technical life of proposed augmentation solutions.	years	45

7.7 Classification of voltage control issues

Both *Substation Health* and future voltage compliance estimation provide the tapping opportunities in terms of number of available tapping steps. Based on these values recommendations can be made on actions needed to bring the substation back within voltage limits. Table 7 in Section 5.3 summarises the classification of possible issues and solutions with the aid of in-house analytical tools.

At present, AusNet Services do not have visibility of current tap positions and tapping range of its distribution transformer fleet. The only available most up-to-date source of data of transformer tap details are voltage complaint investigation notes. Based on these investigations majority of distribution transformers have total tap steps of 5 or 7.

Table 11 to Table 13 show three different transformer tapping specifications.

Table 11: 22000 / 240 V transformer tapping specifications with 5 taps

Tap	HV Volts	LV Volts	Ratio
1	22000	240	91.7
2	21450	240	89.4
3	20900	240	87.1
4	20350	240	85.3
5	19800	240	83.3

Table 12: 22000 / 250 V transformer tapping specifications with 5 taps

Tap	HV Volts	LV Volts	Ratio
1	22550	250	90.2
2	22000	250	88.0
3	21450	250	85.8
4	20900	250	83.6
5	20350	250	81.4

Table 13: 22000 / 250 V transformer tapping specifications with 7 taps

Tap	HV Volts	LV Volts	Ratio
1	24200	250	96.8
2	23650	250	94.6
3	23100	250	92.4
4	22550	250	90.2
5	22000	250	88.0
6	21450	250	85.8
7	20900	250	83.6

The economic model uses a very conservative assumption on current tap positions and tapping range of distribution transformers. It is assumes that all distribution transformers are currently at tap position 2 with tapping range of 7 taps. As a result, following three voltage control issues are identified.

1. **HV control issue**: A high voltage control issue is identified for distribution substations that have been identified with opportunities of tapping up more than 4 steps or tapping down more than 2 tap steps. The most likely solution is replacement of control equipment issue in the HV network.
2. **LV bandwidth issue**: This applies to distribution substations where no tapping opportunities are identified. Customers supplied by these substations are exposed to voltages that are outside of both upper and lower limits of AS 61000.3.100. The likely solution are to reconfigure the low voltage network by either re-conductoring or splitting low voltage circuits or implementing a non-network solution to control the voltage. Figure 32 shows a snapshot from the in-house analytical tool *Explore* illustrating the excessive voltage swings caused by the load demand and solar generation.

3. **Tap setting**: Tap adjustment is the most likely solution for distribution substations with tapping up opportunities with less than 4 steps or tapping down with less than 2 tap steps to address voltage non-compliance.

Figure 32: Snapshot from Explore showing voltage swings due to load and generation

Figure 33 illustrates the constrained distribution substations and the critical equipment likely to be causing the voltage non-compliance.

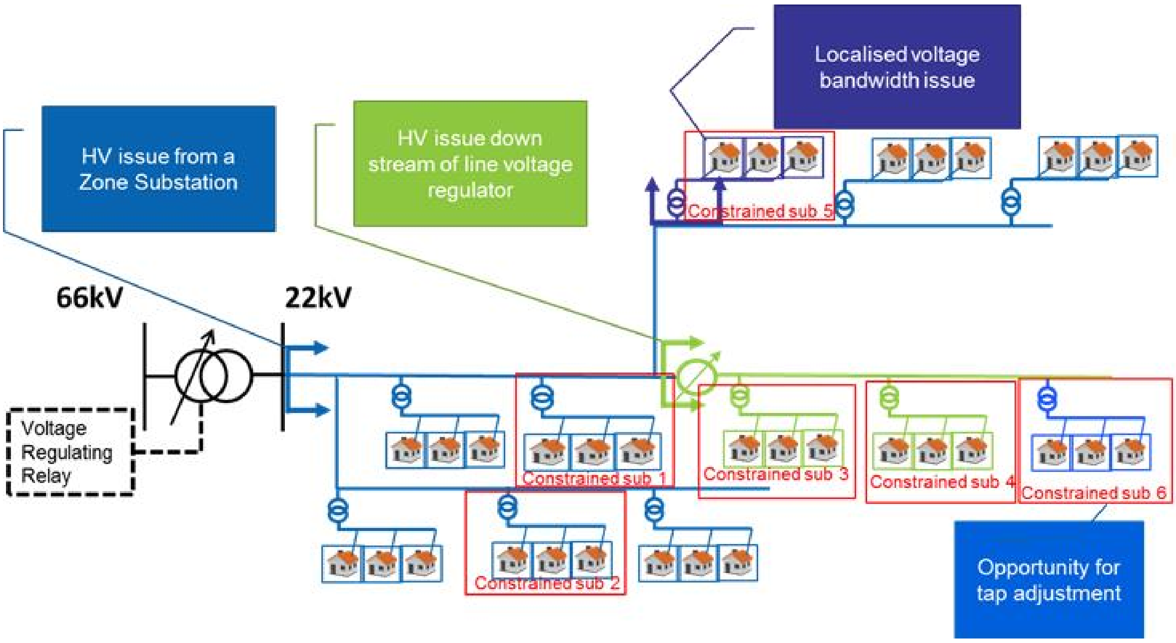

Figure 33: Schematic showing the network topology and critical equipment likely to be causing voltage non-compliance

In the economic model, the unserved energy from the constrained distribution substations are aggregated to the equipment that has been identified as causing the voltage non-compliance issues.

The control equipment that apply to HV control issues are zone substation VRRs, line regulators and SWER ISO transformers.

In the above schematic, the aggregated unserved generation from constrained substations 1 and 2 are used to justify the upgrade of zone substation VRR. Similarly, the unserved generation form constrained substations 3, and 4 are used to justify the upgrade of line voltage regulator. Although constrained substation 6 is identified with opportunities for tap adjustments, it is also included in the justification of the line regulator, since the line regulator is likely to have an influence in the voltage performance. If the constrained substation 6 is justified under HV control issue, it is then excluded from economic assessment for tap adjustments.

In summary, the upstream control equipment is identified solely based on constrained distribution substations with HV control issues. Then the constrained distribution substations identified with tap adjustments are also included in the economic model for justification of the applicable upstream control equipment. It is likely that fixing the upstream control issue would resolve the voltage non-compliance of downstream constrained distribution substations identified with tap adjustments. Therefore, tap adjustments are only considered for distribution substations where the upstream control equipment causing voltage issues is not identified or not justified.

The unserved energy due to localised LV bandwidth issues are identified at the distribution substation level. The upstream control equipment is not likely to have a significant impact on these substations as the limiting elements are on the low voltage network. Separate options are tested in the economic model to address the LV bandwidth issue.

7.8 Options assessment – HV control issue

The economic analysis of HV Control issue tests six options to determine which is the most efficient to address the voltage non-compliance present in the respective control area.

These options are:

1. Replace voltage regulating relays (VRR) on existing transformers with compatible modern equivalents that allow reverse power flow compensation at zone substations (ZSS). It is expected that the new voltage regulation relays will enable:

   a. The bus voltages to be maintained within specified requirements, while allowing for embedded distribution generation or co-generation.

   b. Remote engineering access to interrogate the relay. Accept a voltage set-point for the relevant bus(es) digitally from the SCADA system, SCADA controls are provided to raise and lower a set point in approximately 0.5% steps.

   c. Enable winter/summer voltage set-points, or for the situation where load power or current needs to be reduced during contingency events, the relay can be put into Buck, Boost or Normal voltage modes.

   It is expected that VRR replacements would make 80% improvement in voltage performance based on experience with past setting changes as described in Section 4.3.1. A total project cost of [C.I.C] per zone substation is used in the economic model. This option is only considered for customers located between the ZSS and the next critical voltage regulating equipment in the HV network.

2. Replace existing line voltage regulator with modern new line voltage regulator that includes modern control and more tapping steps. It is expected that line regulator replacements would make at least 70% improvement based on experience with past setting changes as discussed in Section 4.3.2. The expected benefits of new VRRs are the same as in point 1 above. A total project cost of [C.I.C] per line regulator replacement is used in the economic model. This option is only considered for customers located downstream of the voltage regulator and the next downstream critical voltage regulating equipment in the HV network.

3. Replace the voltage regulating relays on existing line regulators with compatible modern equivalents that allow reverse power flow compensation and remote access to operate the relay. A total project cost of [C.I.C] per line regulator VRR replacement is used in the economic model with 50% expected improvement. This option is only considered for customers located downstream of the voltage regulator and the next downstream critical voltage regulating equipment in the HV network.

4. Undertake SWER re-conductoring. The average cost of SWER re-conductoring is approximately [C.I.C] per km depending on the required scope of works such as replacement of poles, crossarms etc. It is assumed on average approximately 20 km of SWER replacement is required per project with a total cost of [C.I.C]. The expected improvement in

voltage performance is 80%. This option is only considered for customers located downstream of a SWER ISO transformer.

5. Replace SWER ISO transformers with SWER voltage regulators with modern control and more tapping steps. A total project cost of [C.I.C] per SWER voltage regulator replacement is used in the economic model with 50% expected improvement. This option is only considered for customers located downstream of a SWER ISO transformer.

6. Employ DENOP. The DENOP system allows distribution constraints evaluation and integrates the dynamic operation of network and customer DER assets.

   The integration of DENOP into AusNet Services' IT systems is covered under the technology program – integration of distributed energy resources. The economic model only includes the expected costs associated with integration of local sensing equipment and administration and engineering costs. A total project cost of [C.I.C] at HV network level is used in the economic model with 30% expected improvement. This option is considered for all constrained distribution substations and applied at the critical regulating equipment level in the network hierarchy depending on the location of the constrained substation.

Table 14 summarises the costs and the expected improvement associated with each option to address a HV control issue.

Table 14: Costs and expected improvement associated with options for HV control issue

Level in the HV network hierarchy	Options	Unit cost ($) (per HV element)	Expected Improvement (%)
Zone substation	New ZSS VRR	[C.I.C]	80%
Zone substation	DENOP (per feeder)		30%
SWER ISO	New SWER voltage regulator		50%
SWER ISO	SWER re-conductor		80%
SWER ISO	DENOP		30%
Line regulator	New VRR for line regulator		50%
Line regulator	New line regulator		70%
Line regulator	DENOP		30%

7.9 Options assessment – Voltage bandwidth issue

The economic analysis of voltage bandwidth issue tests three options to determine which is the most efficient to address the non-compliance present in the respective control area for low voltage bandwidth issues.

These options are:

1. Re-conductor LV circuits with larger conductors. The average cost of low voltage conductor replacement is approximately [C.I.C] per m. It is assumed on average approximately 0.5 km of low voltage conductor replacement is required per project with a total cost of [C.I.C] . The expected improvement in voltage performance is 80%.

2. Split the low voltage (LV) circuit. This option involves a combination of shifting customers between the low voltage circuits and constructing new sections of low voltage circuits. A total project cost of [C.I.C] is used in the economic model with 60% expected improvement.

3. Employ DENOP. Similar to HV control issue options assessment, only the expected costs associated with establishment of local sensing equipment and administration and engineering costs are included in the economic model. A total project cost of [C.I.C] at LV network level is used in the economic model with 30% expected improvement.

Table 15 summarises the costs and the expected improvement associated with each option to address LV control issue.

Table 15: Costs and expected improvement associated with options for LV bandwidth issue

Options	Unit Cost ($) (per distribution substation)	Expected Improvement %
LV re-conductor	[C.I.C]	80%
Split circuit		60%
DENOP		30%

7.10 Options assessment – Tap Adjustments

The economic model tests the tap adjustment option as detailed in Section 7.7. A total project cost of [C.I.C] is used in the economic model with 80% expected improvement. This is based on the average contractor [C.I.C] administration and engineering (studies) costs associated with the tap change.

Table 16: Costs and expected improvement associated with options for tap adjustments

Options	Unit Cost ($)	Expected Improvement %
Tap adjustment	[C.I.C]	80%

7.11 Economic Assessment Results

The economic assessment compares the cost and benefits of each applicable option detailed above and determines the most economical option that is justified in next the regulatory period (2022-26). This section presents the results of the economic assessment.

Four program options are considered:

1. Do nothing different (counterfactual)
2. Address economic existing voltage non-compliance issues
3. Address economic existing and forecast future voltage non-compliance issues
4. Address all existing and forecast future voltage non-compliance issues (Aim for zero constraints)

7.11.1 Program Option 1 – Do nothing different (counterfactual)

The Do nothing different (counterfactual) option assumes that AusNet Services would not undertake any investment, outside of the normal operational and maintenance processes.

Under this option, the voltage non-compliance would only be managed as a reactive measure as part of voltage complaint investigations.

Since this option assumes no investment outside of the normal operational and maintenance processes, this is a zero investment cost option.

Based on the moderate uptake of solar forecast, 'do nothing different' will result in approximately 235,000 customers (29%) with non-compliant voltages by 2025, including approximately 95,000 customers (44%) with solar installations with non-compliant voltages by 2025.

Approximately 12,500 substations are identified as supplying customers experiencing non-compliant voltages resulting in approximately 1380 GWh of unserved generation with a total value of $166 million for the duration of the next regulatory period (2022-26).

The present value of unserved generation over the 45 year (2018 to 2063) period is approximately $692 million.

7.11.2 Program Option 2 – Addressing economic existing voltage non-compliance

This program option aims to address existing voltage non-compliance issues identified by the *Substation Health* tool.

There are currently approximately 54,000 customers experiencing non-compliant voltages. Results from the economic model show that it is economic to address these for approximately 48,000 customers at present and will benefit approximately 53,000 customers by 2025. This will leave approximately 6,000 customers with non-compliant voltages, but does not take into account any new voltage non-compliance issues that develop. It is estimated that by 2025 there will be approximately 181,000 more customers experiencing voltage non-compliance issues that there are currently.

This program option will allow 183 GWh of previously unserved generation to be exported (13% improvement) with a total value of $22 million over 2022-26.

The total cost of the program is $18.9 million.

Table 17 tabulates the costs, present value of gross benefits, present value of net benefits (gross benefit – cost) and the number of justified projects.

Table 17: Summary of justified projects to address existing voltage compliance

Justified augmentation options	Justified costs ($ 2018)	Present value of gross benefit 2018 – 2063 ($ 2018)	Present value of net benefit 2018 – 2063 ($ 2018)	No of justified projects
New ZSS VRR	[C.I.C]	43,088,022	34,688,022	30
New SWER voltage regulator		-	-	-
SWER re-conductor		-	-	-
New VRR for line regulator		1,881,264	1,551,264	11
New line regulator		-	-	-
DENOP – HV		3,878,221	2,528,221	27
LV re-conductor		9,259,191	5,959,191	33
LV split circuit		8,314,891	4,564,891	75
DENOP – LV		3,776,515	2,216,515	156
Tap adjustments		1,642,919	1,448,669	259
Total	18,884,250	71,841,023	52,956,773	591

Figure 34 shows the economic timing of the proposed justified projects. Although majority of projects are justified in the year 2021, AusNet Services intend to implement a smoothed spend profile over the five years to allow for resources required for implementation.

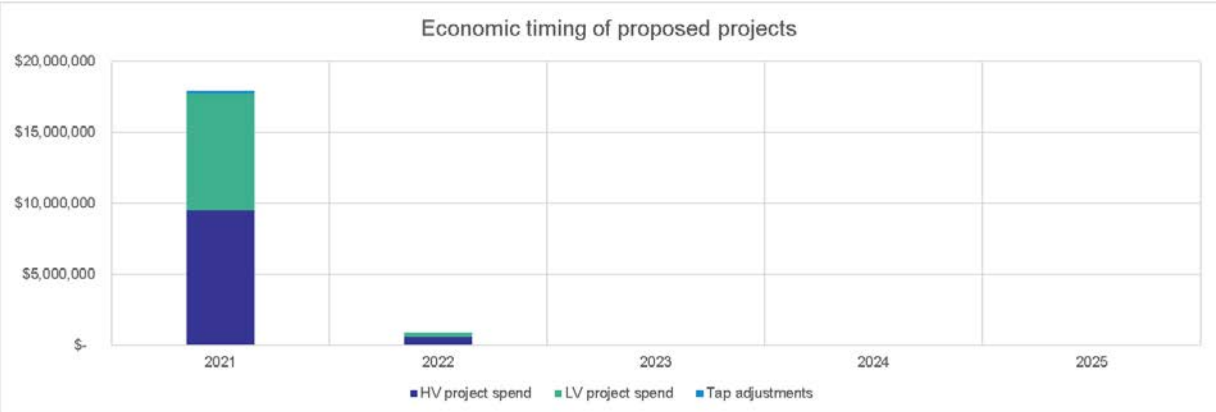

Figure 34: Economic timing of proposed projects to address exiting voltage non-compliance

7.11.3 Program Option 3 – Addressing existing and future voltage non-compliance to improve the hosting capacity

This program option aims to address both existing and forecast future voltage non-compliance issues identified by the *Substation Health* tool and future voltage compliance assessment methodology.

It is estimated that by 2025 there will be 235,000 customers experiencing non-compliant voltages. Results from the economic model show that it is economic to address these issues for approximately 228,000 customers, with 70% improvement in export enabled of previously unserved generation over the next regulatory period.

This will allow 969 GWh of energy to be exported with a total value of $116 million over 2022-26.

This will leave 7,000 customers (1% of customer base) without any voltage improvements by 2025.

The total cost of the program is $38.1 million.

Figure 35 compares the unserved generation (exports) due to current and emerging voltage constraints pre and post program option 3.

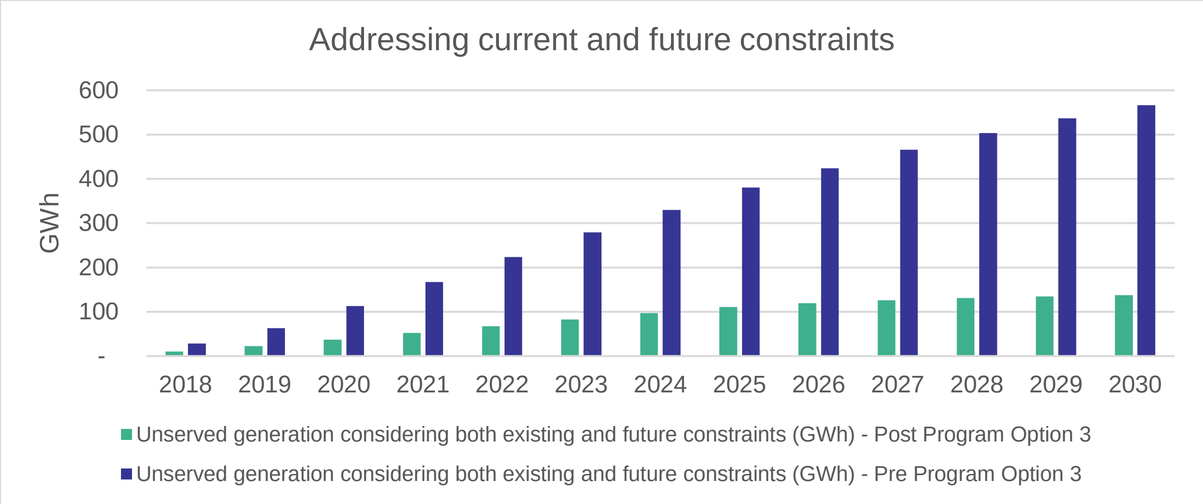

Figure 35: Unserved generation pre and post program option 3

Table 18 tabulates the costs, present value of gross benefits, present value of net benefits (gross benefit – cost) and the number of justified projects.

Table 18: Summary of justified projects to address existing and future voltage compliance

Justified augmentation options	Justified costs ($ 2018)	Present value of gross benefit 2018 – 2063 ($ 2018)	Present value of net benefit 2018 – 2063 ($ 2018)	No of justified projects
New ZSS VRR	[C.I.C]	395,404,460	383,084,460	44
New SWER voltage regulator				0
SWER re-conductor				0
New VRR for line regulator		2,208,394	1,758,394	15
New line regulator		9,340,766	7,540,766	6
DENOP - HV		24,065,212	21,915,212	43
LV re-conductor		37,762,004	26,062,004	117
LV split circuit		16,258,476	9,108,476	143
DENOP – LV		5,531,955	3,211,955	232
Tap adjustments		681,956	468,206	285
Total	38,103,750	491,253,223	453,149,473	885

Similar to program option 2, majority of projects are justified in the year 2021 as most of the emerging non-compliant substations are identified in year 2019. However, AusNet Services intend to implement a smoothed spend profile over the five years to allow for resources required for implementation.

7.11.4 Program Option 4 – Aiming for zero constraints

The aim of this option is to address all existing and future voltage non-compliance issues, regardless of whether the economic assessment is positive or most economic.

This program considers multiple solutions to remove constraints in the low voltage and the 22 kV network and is based on the solution with the greatest benefit, regardless of whether this benefit is positive or not. The assessment is carried out at a very high level and represents the order of augmentation required to aim for zero constraints.

The total cost of the program is $626 million.

Table 19 tabulates the project costs and number of projects for each augmentation option considered.

Table 19: Summary of projects considered for zero constraints

Augmentation options	No of projects	Project cost ($)	Total costs ($)
New ZSS VRR	49	[C.I.C]	[C.I.C]
DENOP for applicable feeders between the ZSS and the next critical voltage regulating equipment	311		
New line regulator	52		
DENOP for applicable locations between downstream of the line regulators and the next critical voltage regulating equipment	52		
SWER re-conductor	252		
DENOP for applicable locations downstream of SWER ISOs	252		
LV re-conductor	1361		
DENOP – LV	1361		
Tap adjustments	1612		
DENOP on substations flagged for tap adjustments	1612		
HV re-conductor	300		
Distribution transformer (capacity) upgrade	2500		
Total	9714	-	626,109,000

Addressing all constraints will yield a present value of gross benefit of $692 million ($ 2018 with an useful life of 45 years), based on the identified existing and future voltage non-compliance issues.

7.12 Sensitivity analysis

Table 20 presents the justified costs, present value of gross benefits, net economic benefits (in real $2018), the proportion of customers addressed, unserved generation and the proportion of exports enabled under a variety of sensitivities for Program Option 3.

The economic assessment is tested for the following sensitivities:

1. FiT rates, varied by ±3 cents per kWh from the base rate of 12 cents/kWh
2. Average daily export, varied by 1kWh per installed kW from the base value of 2kWh/kW
3. Proposed option costs, varied to ±25% of the base option costs
4. Proposed improvement rates, set to 20% for all options for low improvement and 90% for all options for high improvement
5. Discount rate of 6.44%, varied to ±2% per annum of the base discount rate

Table 20 suggests that the low cost augmentation does not necessarily provide the highest net economic benefit. The average daily export per installation has a significant impact on the net economic benefit as well as the proportion of customers addressed and exports enabled. The base case lies in the mid-point of all sensitivity scenarios considered.

Table 20: Sensitivity analysis of Program Option 3 – addressing existing and future voltage non-compliance

Scenario	Justified costs ($M)	Gross present value of benefits ($M)	Net present value of benefits ($M)	Enabled export of previously unserved generation over 2022-26 (GWh)	Remaining constrained export over 2022-26 (GWh)	Total constrained export prior to augmentation over 2022-26 (GWh)	Export enabled over 2022-26
High average daily export	47.83	748.75	700.92	1484	586	2070	72%
Low discount rate	46.21	722.87	676.65	986	394	1380	71%
High improvement	19.46	619.71	600.24	1233	148	1380	89%
High FiT	43.32	619.88	576.57	981	399	1380	71%
Low cost option	33.73	497.19	463.46	984	396	1380	71%
Base case	38.10	491.25	453.15	194	82	276	70%
High cost option	41.44	485.32	443.88	954	426	1380	69%
Low FiT	31.79	362.67	330.88	949	431	1380	69%
High discount rate	31.70	349.15	317.45	951	429	1380	69%
Low average daily export	23.95	235.40	211.45	459	231	690	66%
Low improvement	16.72	136.20	119.48	270	1110	1380	20%

7.13 Conclusion and next steps

This report outlines the identified need and the non-compliance mitigation investment that AusNet Services have assessed over the 2022-26 regulatory period. It serves to support AusNet Services' revenue request for the 2022-26 EDPR period.

Table 21 compares the costs and benefits of the four program options.

Table 21: Comparison of the four program options

	Program Option 1	Program Option 2	Program Option 3	Program Option 4
Cost ($ M)	-	18.9	38.1	626.1
Cost per customer ($)	-	23	47	767
NPV Benefit ($ M)	-	53	453	66
Number of customers voltage performance improved by 2025	-	53,000	228,000	235,000
Number of solar customers voltage performance improved by 2025	-	16,000	93,000	95,000
Number of customers without any voltage improvements by 2025	235,000	182,000	7,000	Aiming for 0
Percentage of 2025 customer base without any voltage improvements	29%	22%	1%	Aiming for 0%
Total export enabled of previously unserved generation over 2022-26 (GWh)	0	183	969	1380
% Export enabled of previously unserved generation over 2022-26	0%	13%	70%	Aiming for 100%

The Program Option 1 is a zero investment cost option in which constraints are addressed as part of voltage complaint investigations. This program does not add any value than what is currently being delivered. The rise in the number of voltage complaints suggest that further actions are needed.

Program Option 2 considers augmentation solutions based on existing non-compliance. AusNet Services consider that addressing the existing issues alone is not sufficient given that the solar installations are estimated to almost triple by 2025.

AusNet Services do not consider it is economically justifiable to augment the network to guarantee export from all customers at all times. This is the option considered in Program Option 4 with a cost of approximately $626 million. This program does not deliver the most value to our customers.

AusNet Services propose Program Option 3 with a cost of $38.1 million as the prudent and efficient investment in network augmentation to address voltage constraints. This program is developed based on an assessment of the level of augmentation that delivers net benefits to customers.

This option will proactively address the existing voltage issues and will take further measures to address the expected significant uptake in the solar installations. There is currently approximately 0.5 GW of solar PV in AusNet Services network and the Victorian Solar Homes policy has the potential to increase this to approximately 1.1 GW to 1.4 GW by 2025.

AusNet Services intends to commence the proactive voltage compliance program in September 2019.

8 OTHER RELEVANT PROGRAMS

8.1 Customer Supply Compliance program

This is a reactive program that addresses quality of supply issues identified by customers within AusNet Services' electricity distribution network. It focuses on taking immediate corrective actions in response to customer complaints.

Where customer issues can be resolved by adjusting transformer tap settings or phase balancing, these are allocated to the appropriate operational cost code and are not included in this program.

The typical work undertaken under this program includes:

- Upgrading distribution transformers
- Rearranging the network to distribute customers evenly
- Reducing circuit loading by upgrading, or splitting circuits
- Splitting LV networks by installing new distribution substations

The expenditure for this program has been forecasted on historical spend rates.

In conjunction with the proactive voltage compliance program, AusNet Services expects a declining trend in the expenditure for this program. The total cost of the program over 2022-26 period is $5.58 million (real $2018).

8.2 LV Network Capacity program

This is a proactive program that aims to manage the performance of the LV network, particularly during periods of high load.

This program focuses on minimising outages caused by transformer failures and LV fuse operations due to overloads. AusNet Services has developed advanced techniques to identify overloading of distribution transformers using AMI data and in the process of developing techniques to identify fuse overloading.

The typical work undertaken under this program includes:

- Upgrading distribution transformers
- Rearranging the network to distribute customers more evenly
- Reducing circuit overloading by upgrading or splitting circuits
- Splitting LV networks by installing new distribution substations

The expenditure for this program has been forecasted on historical spend rates.

The voltage compliance program largely addresses the compliance during minimum demand periods due to solar generation and export. Although some augmentation options are the same between the two programs, the objectives and the problems they address are different. Therefore, an overlap between the two programs is not expected.

The total cost of the program over 2022-26 period is $10.45 million (real $2018).

8.3 Technology program – Integration of Distributed Energy Resources

This program addresses the requirements of the technology platform to enable better visualisation, optimisation and orchestration of DER.

Traditionally the most modelling of the network has occurred at higher voltage levels, with little to no analysis being done on the LV network. Uptake of DER and bi-directional flows places an emphasis on the LV network to understand its impact on the upstream network as customers produce and consume electricity.

At AusNet Services, the power-flow models of the network are currently derived from the geo-spatial system, SDMe, and fed into a power-flow engine, namely Siemens PSS Sincal. Only the 22 kV network data is extracted into the Sincal platform with load data approximated by a manual process involving SCADA measurements and AMI data.

AusNet Services have identified significant limitations in the current modelling process:

- Lack of usable data for the LV section of the network.
- Lack of automation and incorporation of times-series AMI and SCADA data as inputs to the model

A fully functional HV to LV model will enable AusNet Services to better plan, integrate and manage the impact of DER allowing 'what if' scenario analysis.

In the current regulatory period, AusNet Services has carried out a trial on the HPK21 feeder to test the HV to LV modelling concept. AusNet Services plans to extend its learnings from this trial in the next regulatory period.

In addition, the technology program also includes activities on establishment of the foundation required for a future ready forecasting model and DENOP.

The investments proposed in this program of work comprise of the following activities:

- Future Ready Forecasting Model – Enhancement of current Demand Forecasting model, including automation, additional data inputs and inclusion of DER uptake forecast
- HV LV Modelling – Development of the foundation for a HV to LV network load flow model and analytical capability for entire network to enable better planning. This includes the extension of HPK21 trial in current regulatory period, using PSS Sincal.
- GIS Network Data Quality Improvements – Work to improve the quality of data in the GIS, to overcome current limitations of SDMe. This will feed into the HV to LV Model.
- Spatial Application Rationalisation – Work to rationalise existing SAMS and SAMS OPS spatial applications into the SDMe Network Viewer, and repoint downstream interfaces from SAMS and SAMS OPS to SDMe or the Data Lake
- Demand Response Management Enablement – Productionise demand response incentives for residential and DER customers, including payment structures and innovative tariff options.
- Distributed Energy Resource Control/Optimisation (DENOP) – Work to expand and productionise the DENOP platform under trial in the current period
- P2P trading – Activities to facilitate AusNet Services providing meter data to third party trading platforms. This investment includes funding to enable manual data transfer to and from retailers, with data collected and sent via email.

The total cost of the program over 2022-26 period is $9.63 million.

Further details of the proposed program are included in the Technology Program – Integration of Distributed Energy Resources.

APPENDIX A VOLTAGE COMPLIANCE TOOL

Advanced Metering Infrastructure (AMI) has given AusNet Services greater visibility of steady state voltage performance. The smart meters deployed in AusNet Service's distribution network are capable of capturing instantaneous voltage and current samples every five minutes.

The *Voltage Compliance* analytics determines whether the voltages at an individual customer level are within the $V_{1\%}$ and $V_{99\%}$ ranges specified in AS 61000.3.100 (refer Section 3.2).

AS 61000.3.100 states that '*[t]he measurement of steady state voltage at a* site *shall be based on consecutive 10 minute r.m.s. voltage measurements … over a one week period*'[8].

In assessing the steady state voltage performance at a site, it is expected that there will be excursions on occasions outside limits for short periods cause by abnormal switching configurations and/or abnormal loadings. To allow for this type of event, the retesting of sites is permitted to determine site acceptability.

To this end AS 61000.3.100 states '*[w]here a single one week test shows that a site does not meet the limits detailed in Clause 5, a site is deemed to be acceptable and in compliance with this standard if a second one-week test shows that the limits have been achieved*'[9].

A.1 Data collection (first-pass)

The *Voltage Compliance* tool uses five-minute instantaneous voltage samples collected from the smart meters of over 98% of properties on the AusNet Services distribution network. This data, along with other data points such as current, power factor and frequency, are collected and transmitted every one to three hours (depending on which communications network the meter utilises).

Herein, this set of data is referred to as Power Quality (PQ) data.

The PQ data voltage samples are grouped into 16 distinct 'bins', with each bin representing a voltage range. The 288 points collected per day (5 minute samples equate to 12 samples/hour x 24 hours/day = 288) are allocated into a voltage bin.

The voltage bins are described in Table 22.

Table 22: Definition of Voltage Bins

Bin	**1**	**2**	**3**	**4**
Voltage	$0 \geq v < 120$	$120 \geq v < 207$	$207 \geq v < 216$	$216 \geq v < 220$
Bin	**5**	**6**	**7**	**8**
Voltage	$220 \geq v < 224$	$224 \geq v < 228$	$228 \geq v < 232$	$232 \geq v < 236$
Bin	**9**	**10**	**11**	**12**
Voltage	$236 \geq v < 240$	$240 \geq v < 244$	$244 \geq v < 248$	$248 \geq v < 253$
Bin	**13**	**14**	**15**	**16**
Voltage	$253 \geq v < 262$	$262 \geq v < 280$	$280 \geq v < 500$	$500 \geq v$

The voltage bins are split out by phase[10].

[8] AS 61000.3.100, Clause 4.1 Measurement of steady state voltage
[9] AS 61000.3.100, Clause 6 Site retesting
[10] Identification of LV network phase is performed by a separate analytics application called "PhaseID"

For each 24-hour period, one series is returned for each meter in the following format:

“NMI_DEVICEID”: [

{

“timestamp”: 1547474400000 (0:00 timestamp in milliseconds since epoch),

“voltP**x**CntDBin**yy**”: 0 (count of samples that fall within this bin)

}

]

Where:

x: the connected meter phase (a, b or c)

yy: the voltage bin number (from 01 to 16)

A.2 Calculations process (second-pass)

To satisfy the requirements of AS61000.3.100 with respect to 1st-percentile ($V_{1\%}$) and 99th-percentile ($V_{99\%}$) voltage limits, the following rules are applied to each meter’s phase voltage:

$V_{1\%}$ < 216 V → assign phase as **Low Breach**

$V_{99\%}$ > 253 V → assign phase as **High Breach**

If any of a meter’s phases are marked as being either **Low Breach** or **High Breach**, that meter is marked as **Non Compliant**. This rules-based analysis is conducted on a weekly basis.

For each meter, the results from the previous week’s run are compared to the results of the current run. Table 23 describes the outcome of this comparison for each scenario.

Table 23: Voltage Compliance Outcomes

Previous Run	Current Run	Voltage Compliance Result
Compliant	Compliant	Compliant
Non-Compliant	Compliant	Compliant
Non-Compliant	Non-Compliant	Non-Compliant
Compliant	Non-Compliant	Non-Compliant

A.3 Presentation of results

Using the data generated from Appendix A.2, a summary table is generated. The meters are grouped by their upstream distribution transformer (substation), and contains the following fields:

- Upstream zone substation (e.g. ELM)
- Upstream feeder (e.g. ELM13)
- Upstream substation / transformer (e.g. 2112006900)
- Number of meters reporting power quality data (PQ)
- Total number of Non-Compliant meters (Low Breach)
- Total number of Non-Compliant meters (High Breach)
- Total number of Non-Compliant meters

Figure 36 shows this data being displayed in AusNet Service’s in-house data visualisation application *Explore*. The data in the two plots have been aggregated (summated) up to the zone substation per breach type.

Historical data from 2014 has been processed to produce a long-term trend. It is possible to assess the voltage compliance of the entire electricity distribution network down to an individual distribution transformer.

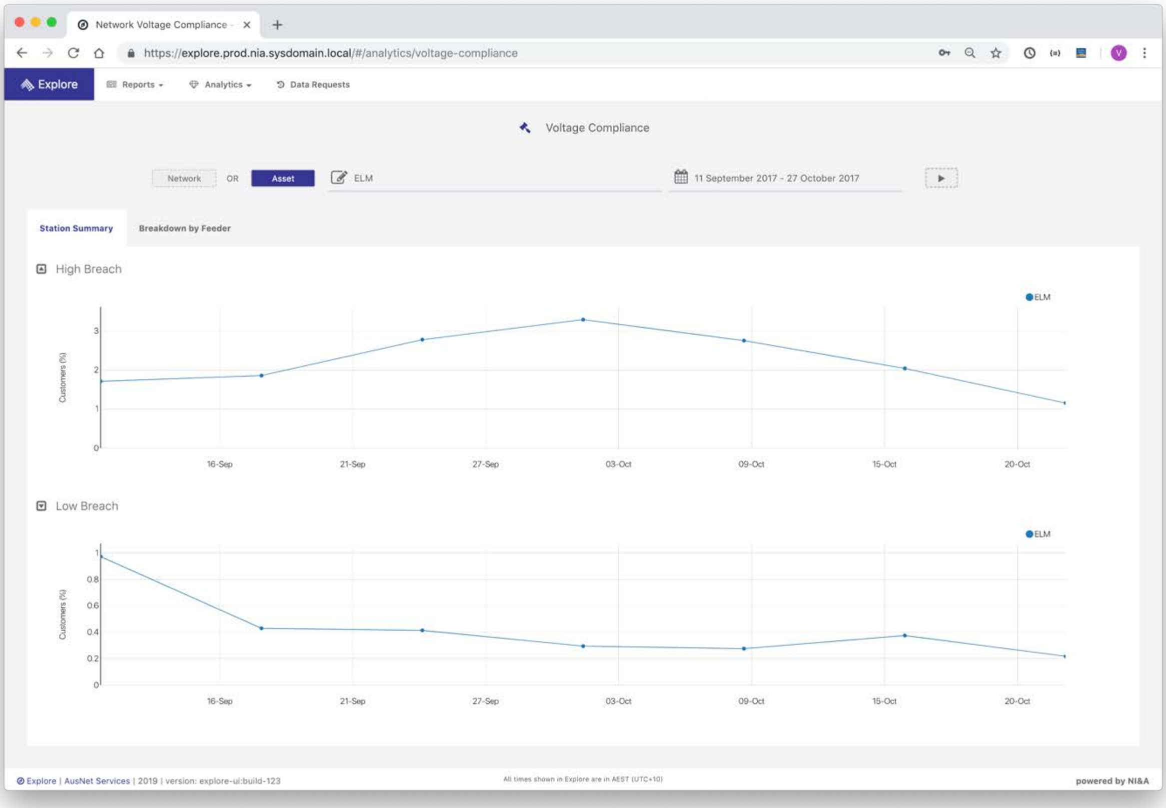

Figure 36: Voltage compliance results in *Explore*

APPENDIX B SUBSTATION HEALTH TOOL

The *Substation Health* tool leverages the data generated from the *Voltage Compliance* tool (refer Appendix A) to provide high-level recommendations on how voltage levels at distribution transformers (substations) can be brought back to within the nominal steady state voltage limits specified in AS 61000.3.100.

It is important to note that this is not an assessment conducted on every distribution transformer on the AusNet Services distribution network. It is a targeted analysis based on distribution transformers where voltage compliance issues have been identified.

The *Substation Health* assessment analytics has a number of stages, which uses various trend analysis techniques to determine which substations have had ongoing, consistent voltage compliance issues.

Following this, an analysis based on the voltage profiles of the meters connected to the substation is conducted. Based on simulating the tapping up or down of the substation voltages, recommendations are made as to actions needed to bring the substation back within the steady state voltage limits.

B.1 Data Collection

Using the data generated from Section A.3, the following conditions must be met in order for a substation to be considered for analysis:

- It must have at least one communicating smart meter sending Power Quality data; and
- The substation must have continuous breaching throughout the selected date period.

The date period selected is 15 months from the date of analysis. Using 15 months rather than 12 months increases the confidence of the proceeding analytics, as it incorporates all seasons, with a particular focus on the summer months.

Like the *Voltage Compliance* tool, the *Substation Health* tool uses voltage PQ data when the voltage profile analysis is conducted (documented in Section B.3).

B.2 Trend analysis (first-pass)

B.2.1 Linear (1st order) trend line calculation

For each substation in the Voltage Compliance list, a linear (1st order) trend line is generated for both low and high breach scenarios. This determines whether, for the 15 month period, the percentage of non-compliance trends positively or negatively. Further analysis will not be conducted if both low and high breach scenarios have a gradient of -0.5 or less. Figure 37 illustrates this analysis for an example substation over the 15 month period, where the linear trend for high breaches is positive ($m = 0.02$).

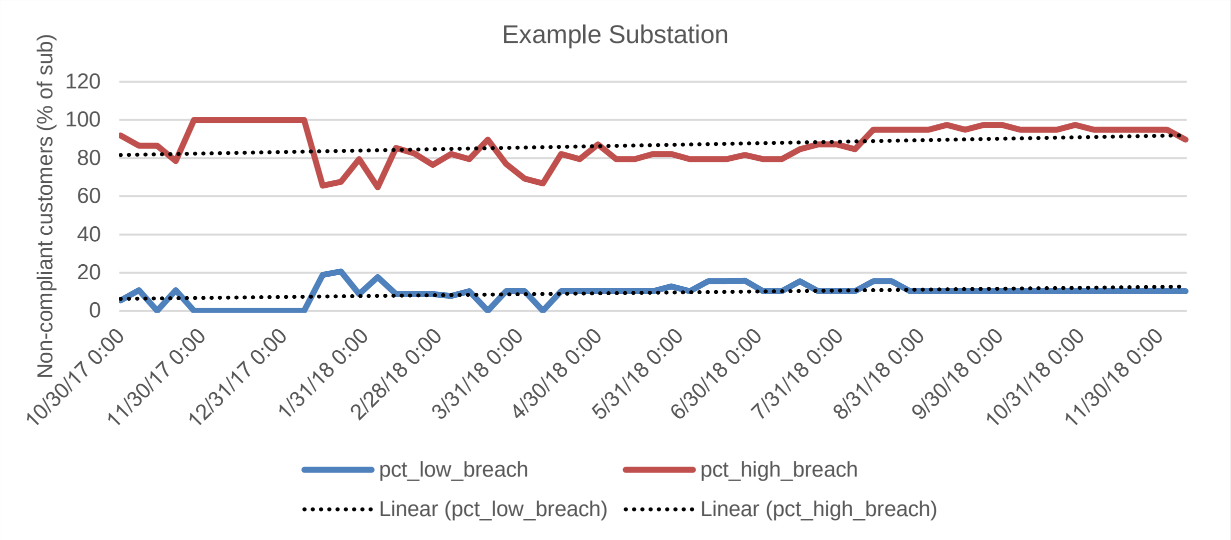

Figure 37: Linear trend analysis on example substation

B.2.2 Median and 75th percentile calculation

The next step is to see whether, for both low or high breach scenarios, the median (50th percentile) and 75th percentile percentages are above 0.6 (60%). This determines whether the percentage of non-compliance is consistently high across the analysis period. In the case of the example above:

$$lBr_{0.5} = 0.103\,, lBr_{0.75} = 0.103$$

$$hBr_{0.5} = 0.8685\,, hBr_{0.75} = 0.949$$

This indicates that there are consistent high-breach voltage compliance issues for the example substation.

In this specific example only the high-breach scenario will progress to further analysis.

B.2.3 Cubic (3rd order) trend line calculation

The final step involves calculating a third-order (cubic) trend line, to determine the point where the trend of non-compliance is at its greatest.

Once the 3rd order trend line is calculated, the derivative is taken, in the form:

$$x^3 + x^2 + x + c \rightarrow \frac{dy}{dx} = 3x^2 + 2x + 1$$

The maximum point of the derivative curve will indicate is the point where the upward trend steepest (i.e the maximum gradient of the 3rd order trend line). This is an approximate indicator of when problems may have been most noticeable, and therefore will be the starting date for analysis in the Movement Opportunity analysis (described in Section B.3).

For the example substation, this is highlighted with the blue arrow in Figure 38.

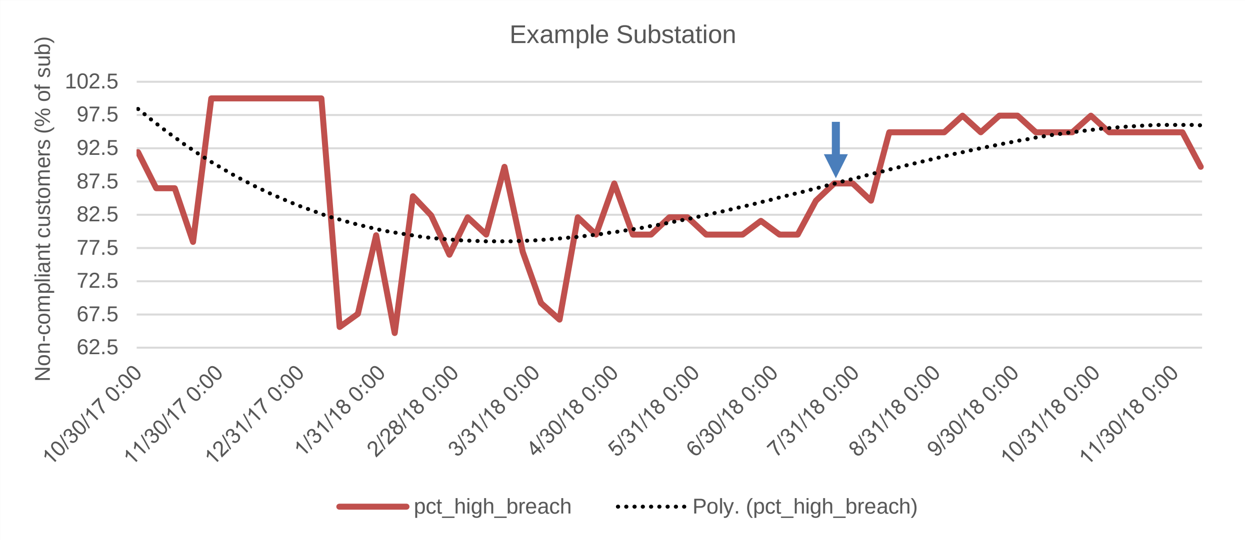

Figure 38: Cubic trend line analysis on example substation

The date (31 July 2018) is the date that the Movement Opportunity analysis will use as its starting date. As described in detail in Section B.3, the analysis will be conducted in detail from this date until the current date of analysis.

B.3 Movement opportunity analysis (second-pass)

Movement opportunity analysis uses PQ voltage data, which has been 'rolled up' by day. It is in the same data format as the *Voltage Compliance* analysis (Section A.1).

The analysis is conducted from the starting date calculated from Section B.2, until the current time (Monday of the current week).

A probability density function (PDF) curve is generated for each meter. The PDF curve is per unitised (normalised from 0 to 1).

A PDF curve for the example substation is shown in Figure 39. The blue dotted lines represent the lower and upper bounds for nominal steady state voltage limit compliance (216 V and 253 V respectively).

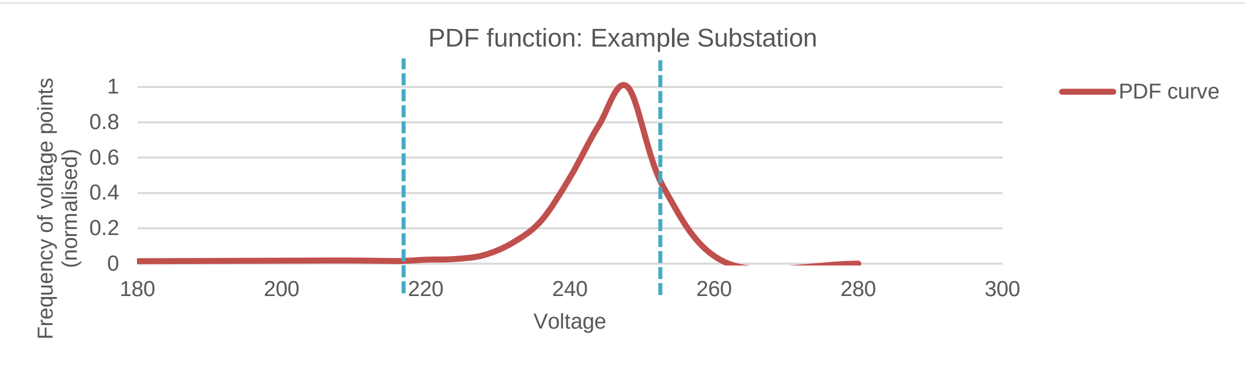

Figure 39: Probability density function (PDF) curve for example substation

B.3.1 Calculating low-breach and high-breach ratios

Ratios are then calculated for low-breach (LB) and high-breach (HB). These ratios numerically determine how skewed the PDF curve is. It will be left-skewed if there are high-breach issues and right-skewed if there are low-breach issues.

This is a simple division of the areas under the curve, as shown in the equations below:

$$Ratio_{HB} = \frac{\int_{253}^{500} PDF}{\int_{216}^{253} PDF}$$

$$Ratio_{LB} = \frac{\int_{0}^{216} PDF}{\int_{216}^{253} PDF}$$

A non-zero value for both $Ratio_{HB}$ and $Ratio_{LB}$ indicates that the PDF curve is very wide. This scenario will automatically flag the analysis week for that substation as **Not Possible to Tap** and move on to the next week.

A large positive value for either of these ratios indicates a significant level of skewing in the PDF curve. Further analysis is then conducted.

For the example substation, $Ratio_{HB} = 0.3678$ and $Ratio_{LB} = 0.0139$, which is indicating that the PDF curve is left-skewed.

B.3.2 Determining peak of PDF curve

Obtaining the peak of the PDF curve, relative to the mid-point of the PDF curve, enables the quantification of movement needed to achieve the optimal voltage profile. For analysis, it is approximated that one tap position of a substation is approximately equal to 4-6 V. This is equivalent to the width of the voltage profile bins of the PDF curve for voltage readings inside or around the 216 to 253 voltage thresholds.

B.3.3 Determining width of PDF curve

A simple count of how many voltage bins fall within the PDF curve is obtained, using a pre-set threshold to eliminate noise at either end of the PDF curve. For analysis, a threshold of 0.02 is used. This means that it will not include voltage bins that contain less than 2% of the total number of voltage samples, in order to calculate the width of the PDF curve.

B.3.4 Determining optimal position of PDF curve

The analytics calculates how the PDF curve will fit within the lower and upper bounds of voltage compliance (the blue dotted lines in Figure 39). Each iteration will shift the PDF curve down or up by 1 voltage bin until it reaches an optimal point. The direction and number of positions are then recorded if the analytics can successfully optimise the curve (it will be flagged as **Tap Up/Down xxx**). If after 4 attempts, it is not possible to keep the curve within the voltage compliance bounds, it will flag that week as **No Opportunity to Tap** and it will move on to the next week.

B.4 Final analysis

Using the data from the Movement Opportunity analysis, one final check is conducted to see whether there were multiple instances where **No Opportunity to Tap** was raised. Furthermore, if the 95th percentile of low-breach and high-breach ratios are non-zero, the entire substation is flagged as **Not Possible to Tap**.

The results for each substation are then ranked on a set criteria of non-compliance. The results are weighted as given in Table 24.

Table 24: Resutls Weighting

Criteria	Weight (%)	Description
'Floating' low voltage	20%	If the peak of the PDF curve is to the left of the mid-point, and the low-breach ratio is much greater than 1. (0: False, 1: True)
Wide voltage profile	30%	Determines whether the PDF curve is very wide, such that any movement of the curve will make it low-breach or high-breach. (0: No, 1: Yes)
Voltage profile peak deviation	40%	Determines how far away the peak is from the mid-point. The further away it is, the higher this number becomes. (Min: 0, Max: 1, increment by 0.2 for each bin it is away from the mid-point)
Voltage profile shift feasibility	10%	If the opportunity to tap is greater than 5 bins, trying to move this profile may encroach low or high voltage compliance. (Min: 0, Max: 1, increment by 0.2 if the opportunity to tap is less than or equal to 5 bins)

The summation of each of the criteria formulates an **Abnormality Rating** ranging from 0 to 100, where the higher the **Abnormality Rating**, the lower the substation's perceived health. Using this **Abnormality Rating**, substations are prioritised for remediation works.

$$S_{abnormality} = (0\ or\ 1) \times 20 + (0\ or\ 1) \times 30 + (0, 0.2 \ldots 1) \times 40 + (0, 0.2 \ldots 1) \times 10$$

APPENDIX C PRELIMINARY TACTICAL HOSTING CAPACITY

It is necessary to consider network voltages and constraints in future periods in order to maintain a strong electricity distribution network. *Voltage Compliance* and *Substation Health* are current production Network Intelligence and Analytics (NIA) applications that identify non-compliant substations and recommend transformer tapping opportunities. *Voltage Compliance*, and *Substation Health* analyse historical voltage data and provide recommendations at the present point in time.

Tactical Hosting Capacity is an in-development NIA application that estimates the amount of export that a particular substation can support given the constraints of the distribution network.

In contrast, *Preliminary Tactical Hosting Capacity* (PTHC) is a forward-looking approach with the objective of analysing network voltages considering the customer solar uptake forecast for the next decade.

PTHC methodology simplifies principles of *Tactical Hosting Capacity* in order to provide an assessment relating to future periods. This appendix defines the PTHC methodology for assessing the impact of increased solar generation in the distribution network during the period 2022-26.

C.1 Methodology

The methodology for assessing the following are within the scope:

- Identify distribution substations that are likely to breach upper voltage limits with respect to increased solar generation during the period 2022-26
- Quantify transformer tap opportunity for these distribution substations in terms of tap direction and tap amount
- From these, identify distribution substations with no tap opportunity

The following are not within the scope of this methodology:

- Identifying low and high voltage breaches with respect to demand – effect of customer demand on voltage breaches is not considered in this analysis

C.2 Voltage Extrapolation

Below algorithm is applied for each substation in AusNet Services' Distribution Network.

C.2.1 Extract Substation Parameters

- Information from Spatial Data Management Electricity (SDMe) Database is the primary source of substation standing data. This analysis utilised the SNET Database to access substation data (data is imported to SNET daily from SDMe). Each substation is then classified as one of:
  - "SWER" – Single Wire Earth Return
  - "1 phase TX" – Single Phase Substation
  - "3 phase TX" – Three Phase Substation

This classification and the substation kVA rating are key input parameters to the voltage estimation model.

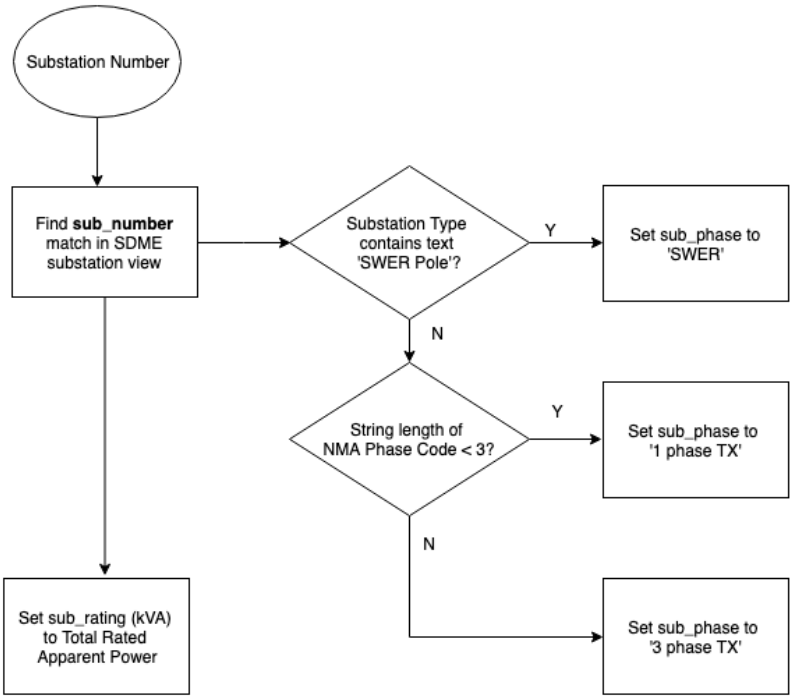

Figure 40: Substation Parameters

C.2.2 Calculate Voltage Percentiles

PQ Data

Smart meters deployed in AusNet Services' distribution network are capable of capturing instantaneous voltage and current samples every five minutes. This analysis utilises voltage data from the smart meters of over 98% of properties on the AusNet Services distribution network[11]. This data, along with other data points such as current, power factor and frequency, are collected every one to three hours (depending on the communications network used by the meter).

Herein, this set of data is referred to as Power Quality (PQ) data.

PQ Bins

The PQ data voltage samples are grouped into 16 distinct 'bins', with each bin representing a voltage range. The 288 points collected per day (5 minute samples equate to 12 samples/hour x 24 hours/day = 288) are allocated into a voltage bin. The voltage bins are described in Table 22.

This analysis uses voltage bin data (PQ Bins) because computing cost of using Raw PQ data is not feasible.

Sub PQ Bins

PQ Bins are further aggregated by substation to derive substation PQ bins and stored in the SNET Database. Bin Count for a particular substation represents the sum of voltage samples within the respective voltage range from all the smart meters in a distribution substation for a given day.

Sub Voltage Percentiles

The first step to estimating voltage percentiles is to fetch daily substation voltage bin counts. Data is available from 2014-01-01 to 2015-10-01 and from 2017-01-01 to 2019-02-01. Note that there is a gap in data as a result of migrating to a new platform due to be back populated. 2017 and 2018 voltage data is sufficient for the purpose of this analysis.

Secondly, Sub PQ Bins are grouped by week starting every Monday. For example, Weekly entry for 2014-01-06 includes a summation of Sub PQ Bins from 2014-01-06 to 2014-01-12. Weekly Monday

[11] Currently, there is no communication channel to approximately 2% of the smart meter population.

aggregation was selected so that results can be compared with current NIA voltage compliance analytics.

Thirdly, 90th Percentile Voltage (P_{90}) and 10th Percentile Voltage (P_{10}) is estimated for each week through linear approximation using bin frequencies and bin midpoints. P_{99} and P_{01} are not used because the voltage bin size is not granular enough for linear approximation.

Table 25: Sub PQ Weekly Bins for a substation

week_start_date	sub_number	b01	b02	b03	b04	b05	b06	b07	b08	b09	b10	b11	b12	b13	b14	b15	b16	sum
2014-01-06	2119018100	0	0	11	89	558	1818	3170	5046	15805	59132	64716	11624	96	0	0	0	162065
2014-01-13	2119018100	0	0	26	281	1380	4243	10557	21984	54869	104156	52643	6347	19	0	0	0	256505
2014-01-20	2119018100	0	0	5	108	575	1819	3566	5723	17107	75622	87032	12001	24	0	0	0	203582

Table 26: Cumulative Sub PQ Weekly Bins Normalised by Weekly Bin Sum

week_start_date	b01	b02	b03	b04	b05	b06	b07	b08	b09	b10	b11	b12	b13	b14	b15	b16
2014-01-06	0.0	0.00000	0.000068	0.000617	0.004060	0.015278	0.034838	0.065974	0.163496	0.528362	0.927683	0.999408	1.0	1.0	1.0	1.0
2014-01-13	0.0	0.00000	0.000101	0.001197	0.006577	0.023118	0.064276	0.149981	0.363892	0.769950	0.975182	0.999926	1.0	1.0	1.0	1.0
2014-01-20	0.0	0.00000	0.000025	0.000555	0.003379	0.012314	0.029831	0.057942	0.141972	0.513429	0.940933	0.999882	1.0	1.0	1.0	1.0

Nth percentile voltage (P_N) for each week can be approximated as follows:

1. $Calculate\ the\ following:$

$$P = Normalised\ bin\ sums\ from\ \text{Table 27}$$

$$b_1 = Maximum\ bin\ index\ such\ that\ P <= P_N$$

$$b_2 = Minimum\ bin\ index\ such\ that\ P > P_N$$

$$v_1 = Midpoint\ of\ bin\ b1$$

$$v_2 = Midpoint\ of\ bin\ b2$$

$$p_1 = P[b_1], ie. Normalised\ bin\ sum\ for\ bin\ index\ b_1$$

$$p_2 = P[b_2]$$

2. $Fit\ a\ linear\ equation\ to\ (p_1, v_1), (p_2, v_2)$

$$v_n = m * p_n + c$$

3. $Calculate\ v_n\ by\ substituting\ p_n\ to\ the\ equation$

$$P_{90} = v(0.9) = m * 0.9 + c$$
$$P_{10} = v(0.1) = m * 0.1 + c$$

Applying the above procedure generates two timeseries $P_{90}(t)$ and $P_{10}(t)$ with data points generated for Monday of each week. Chart below illustrates these time series for a sample substation.

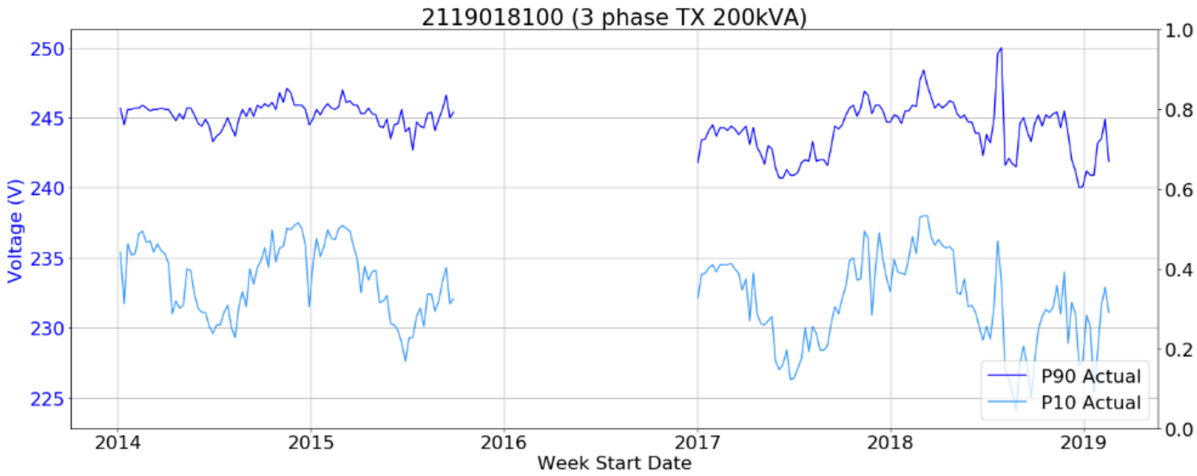

Figure 41: Voltage percentile time series

Finally, an Exponentially Weighted Moving Average (EWMA) is applied to the two time series to smooth out any outliers and capture the voltage percentiles trend.

A 12 point EWMA (i.e. 12 weeks) is used generate $P_{90_{EWMA}}(t)$ and $P_{10_{EWMA}}(t)$.

This process is summarised in Figure 42.

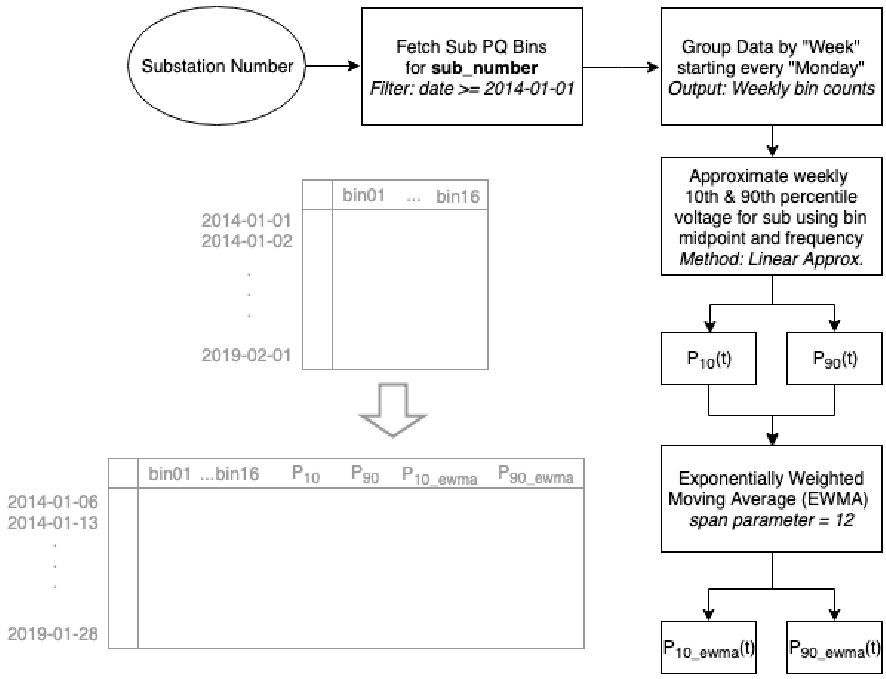

Figure 42: Substation Voltage Percentiles

C.2.3 Calculate Voltage Change from Solar Uptake

The basis for calculating the change in voltage is to use a “Volt/kW factor” to estimate the change in voltage when substation is exporting additional solar PV kW.

Volt/kW Factor

Calculation of the Volt/kW factor is based on the Low Voltage (240 V) network design rule of a maximum conductor voltage-drop of 6%. A load power factor close to 1.0 is assumed with a transformer winding voltage drop of 2%.

The total network Thevenin equivalent impedance (Z_{th}) is calculated by adding the transformer TX impedance (Z_{TX}) to the LV conductor equivalent impedance.

300 kVA Transformer Worked Example:

$TX\ Rating\ is\ 300\ kVA\ at\ 250V\ (open\ circuit\ voltage)$

$kVA\ per\ phase\ is\ 100\ kVA$

$Current\ per\ phase\ is\ 400\ A$

$Z_c\ equivalent\ conductor\ impedance\ is: Z_c\ =\ 6\%\ Volts/Rated\ Amps\ =\ 15V/400A\ =\ 0.0357$

$Z_{TX}\ equivalent\ transformer\ impedance\ is: Z_{TX}\ =\ 2\%\ Volts/Amps\ =\ 5V/400A\ =\ 0.0125$

$(Use\ 2\%\ because\ load\ power\ factor\ is\ less\ than\ 0.8)$

$Z_{th}\ =\ Z_{TX}\ +\ Z_c\ =\ 0.05\ ohm$

$Now\ 8\%\ Volt\ drop\ at\ rating\ is\ 20V\ and\ kW/ph\ rated\ is\ 100kVA$

$Therefore\ \boldsymbol{Volt/kW}\ =\ 20/100\ =\ 0.2\ V/kW$

The following table was derived using the method illustrated in the worked example.

Table 27: Volt/kW Factor

Sub Phase	TX kVA	kW/Volt (6%)	Volt/kW	253 - V99	HC kW/ph
3 phase TX	1000	15.500	0.065	13	202
	750	11.000	0.091	13	143
	500	8.500	0.118	13	111
	315	5.300	0.189	13	69
	300	5.100	0.196	13	66
	200	3.400	0.294	13	44
	100	1.700	0.588	13	22
	63	1.000	1.000	13	13
	50	0.850	1.176	13	11
	25	0.425	2.353	13	5.5
	10	0.170	5.882	13	2
1 phase TX	100	2.500	0.400	13	33
	50	1.250	0.800	13	16
	25	0.625	1.600	13	8
	16	0.400	2.500	13	5
	15	0.375	2.667	13	5
	10	0.250	4.000	13	3
SWER	20	0.500	2.00	13	7
	16	0.400	2.50	13	5
	15	0.375	2.67	13	5
	10	0.250	4.00	13	3
	5	0.125	8.00	13	2

Substation parameters (Sub Phase Type and Sub kVA Rating) described in section C.2.1 can be used to look up the Volt/kW factor for a given substation. For example, 10kW of additional solar export in a 3-phase 200kVA substation results in a voltage rise of approximately 3 V as per the above model.

$$\Delta v = 0.294 \frac{V}{kW} * 10kW = 2.94V$$

Solar Forecast

Distribution Substation Solar PV Forecast – moderate policy scenario is used for this analysis (190212 List of NMIs by D substation Mod Policy modified.xlsx).

This Dataset contains a year-ending PV kW forecast for each substation from 2019 to 2030. PV Forecast is linearly interpolated at Weekly Mondays so that it data can be joined with voltage percentiles dataset. See Figure 43 for illustration of Solar Forecast for a sample substation.

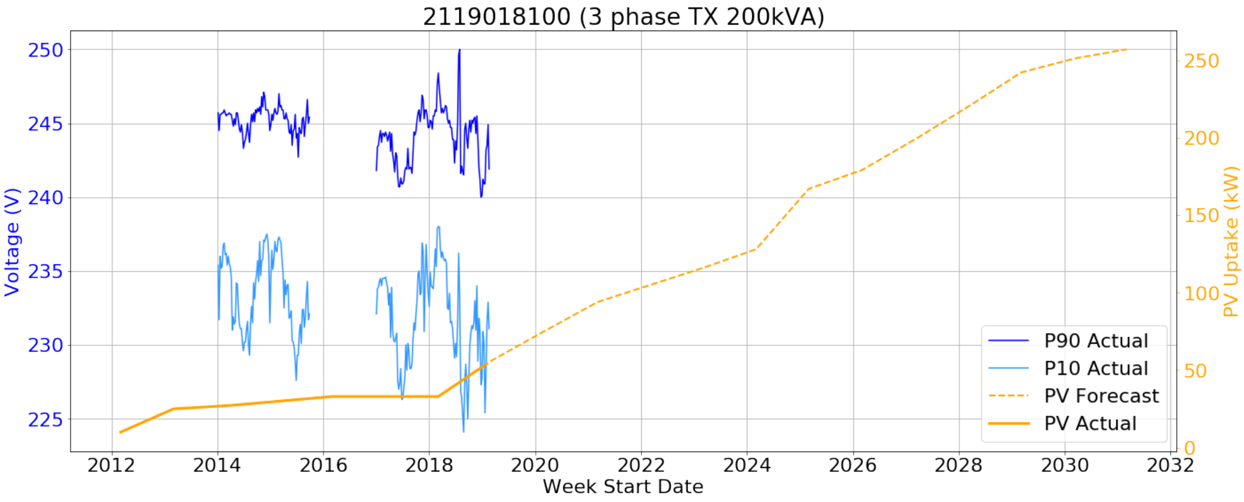

Figure 43: Solar Forecast for sample substation

Solar Export Factor

It is assumed that 30% of Solar PV Capacity will be exported to the grid. This value is a reasonable assumption based on previous analysis of smart meter data.

Voltage Rise

Let G = solar generation (kW) in the substation from solar forecast at each point in time

Hence, voltage rise due to increased solar generation can be estimated as,

$$\Delta v = (Export\ Factor) * \left(Factor_{V/kW}\right) * \Delta G$$

C.2.4 Extrapolate Voltage Percentiles

$P_{90_{EWMA}}(t)$ and $P_{10_{EWMA}}(t)$ are used to approximate the voltage percentiles at the last date with voltage data available i.e. analysis was conducted at: $t_0 = 2019 - 02 - 01$

Voltage percentiles for future dates can be extrapolated using equations given below.

$$P_{90_{Pred}}(t_n) = P_{90_{EWMA}}(t_0) + (Export\ Factor) * \left(Factor_{V/kW}\right) * (G_{t_n} - G_{t_0})$$

$$P_{10_{Pred}}(t_n) = P_{10_{EWMA}}(t_0) + (Export\ Factor) * \left(Factor_{V/kW}\right) * (G_{t_n} - G_{t_0})$$

Figure 44 illustrates $P_{90_{Pred}}(t)$ and $P_{10_{Pred}}(t)$ for a sample substation.

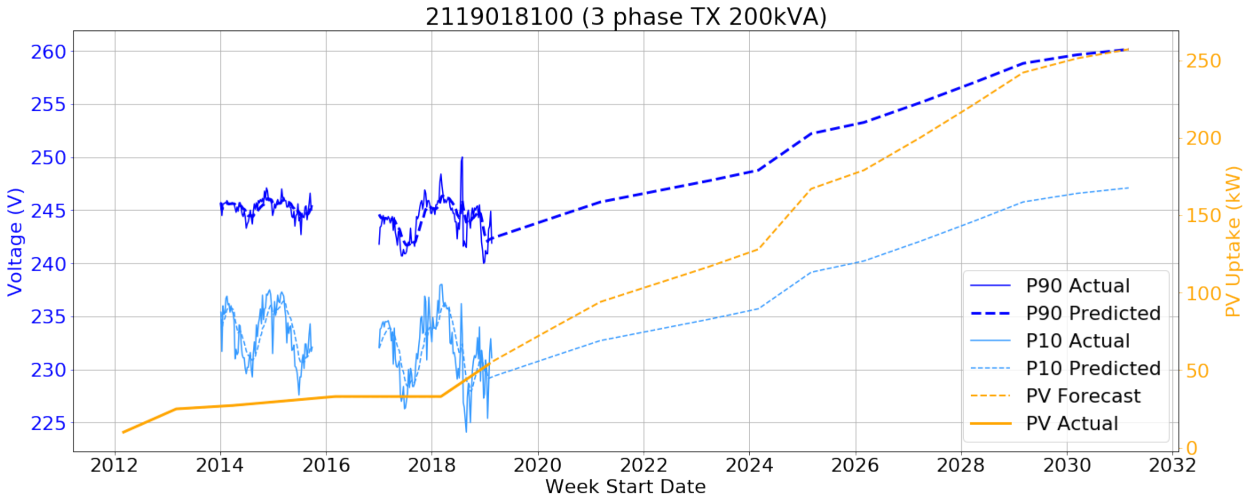

Figure 44: Voltage extrapolation for sample substation

C.3 Voltage Breach Analysis

C.3.1 Electricity Distribution Code

Electricity Distribution Code (EDC) Version 9A Section 4.2.2 Table 1 allows steady voltage variation range of +10% (253 V) and -6% (216 V) from nominal voltage (230 V).

C.3.2 Australian Standard

Australian Standard AS6100.3.100-2011 Part 3.100 specifies a nominal steady state voltage range between 216 V and 253 V.

C.3.3 Voltage Breach

Voltage Limits

Voltage limits of 216 V (Lower) and 253 V (Upper) are used for this PTHC Methodology consistent with EDC and AS 61000.3.100.

Voltage Low Breach

A Low Breach (LB) is identified when 10th percentile voltage at $t = t_{LB}$ is less than 216 V where t_{LB} = 2019-02-01.

It is appropriate to use a voltage value at the present point in time because the PTHC model does not take customer demand into consideration.

$$LB\ Condition: \quad (P_{10_{Pred}}(t_{LB}) < 216V)\ ||\ (P_{10_{Pred}}(t_{LB}) > 253V), \quad t_{LB} = 2019-02-01$$

Voltage High Breach

A High Breach (HB) is identified when 90th percentile voltage at $t = t_{HB}$ is greater than 253 V where t_{HB} = 2025-12-31.

It is appropriate to use a voltage value at the end of the planning period as solar uptake forecast is trending upwards during the period considered.

$$HB\ Condition: \quad (P_{90_{Pred}}(t_{HB}) > 253V)\ ||\ (P_{90_{Pred}}(t_{HB}) < 216V), \quad t_{HB} = 2025-12-31$$

For the sample substation, there is no voltage low breach since $P_{10_{Pred}}(t_{LB})$ is within operating limits. However, since $P_{90_{Pred}}(t_{HB})$ is greater than 253 V, a potential voltage high breach is identified between 2019 and 2025. The high breach year is estimated to be 2025 (at the end of the year).

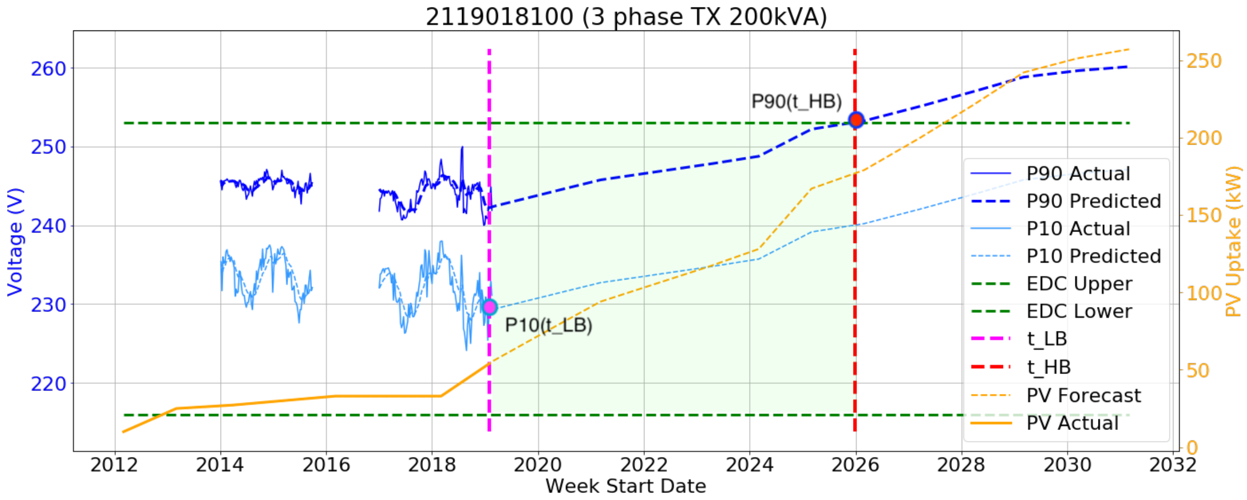

Figure 45: Example with voltage high breach

Shown below is another example substation when no voltage breaches are identified as $P_{10_{Pred}}(t_{LB})$ and $P_{90_{Pred}}(t_{HB})$ are within operating limits.

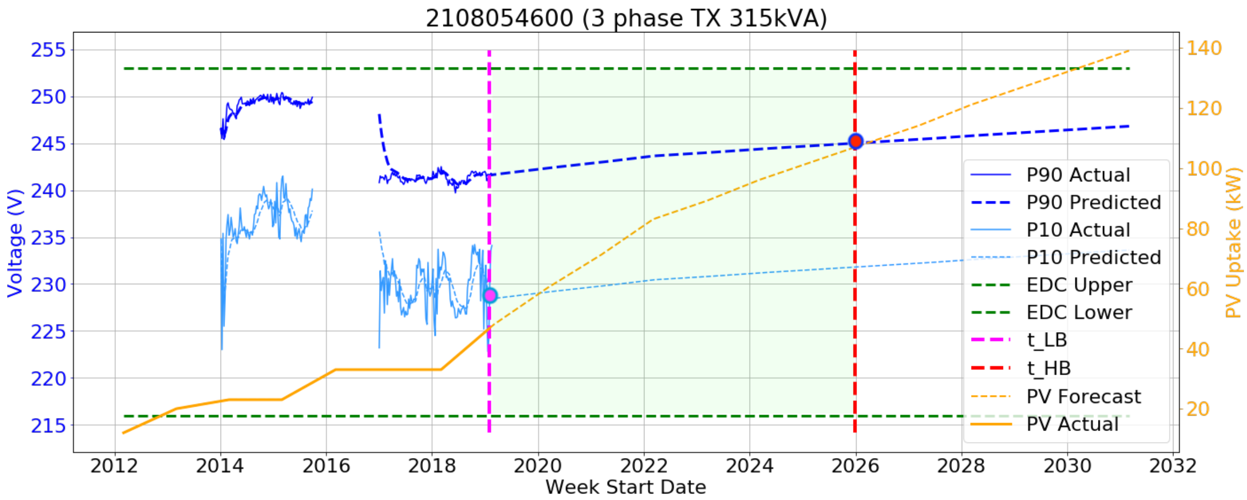

Figure 46: Example with no voltage breach

C.4 Transformer Tap Opportunity

Then next stage of PTHC assessment was to identify opportunities to prevent voltage breaches by changing the tap position of the distribution transformer.

C.4.1 Tap Change Notation

Tap Direction

A negative tap direction indicates a tap down from current tap position and positive tap direction indicates a tap up from current tap position.

Tap Amount

Tap amount is an integer indicating number of taps to be changed from current position.

Distribution transformers are not identical and have varying tapping specifications. Therefore, it was assumed that a single tap change is equivalent to a 4V change at low voltage side of the transformer, which is consistent with calculations performed for the *Substation Health* application.

Example: Tap change of –3 indicates 3 taps down from current position

C.4.2 Tap Change Feasibility

Note that a tap change may not be practically feasible for a particular substation due to limitations of the distribution transformer. A field inspection is required to determine whether a tap change is possible since there is no record of current transformer tap position and the number of taps in each direction. This is because distribution transformers have manual tap changers that require a field crew to attend the site and change the tap.

C.4.3 Tap Opportunity Calculation

The following algorithm was used to calculate transformer tap opportunity:

$Let,$

$$\mathrm{n_t} = \text{tap change relative to current position}$$

$$\mathrm{N_t} = \text{tap change options} = [-8, -7, -6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, 7, 8]$$

$For\ each\ n_t\ in\ N_t:$

$$P_{90_{tapped}}(t) = P_{90_{Pred}}(t) + 4 * n_t$$

$$\mathrm{v}_{90_{\max}} = \mathrm{P}_{90_{\text{tapped}}}(\mathrm{t_{HB}}), \qquad \mathrm{t_{HB}} = 2025 - 12 - 31$$

$$\mathrm{v}_{90_{\text{tap\_opportunity}}} = \left(\mathrm{v}_{90_{\max}} \geq 216\right) \& \left(\mathrm{v}_{90_{\max}} \leq 253\right)$$

$$\mathrm{v}_{90_{\text{margin}}} = 253 - \mathrm{v}_{90_{\max}}$$

$$\mathrm{P}_{10_{\text{tapped}}}(\mathrm{t}) = \mathrm{P}_{10_{\text{Pred}}}(\mathrm{t}) + 4 * \mathrm{n_t}$$

$$\mathrm{v}_{10_{\min}} = \mathrm{P}_{10_{\text{tapped}}}(\mathrm{t_{LB}}), \qquad \mathrm{t_{LB}} = 2019 - 02 - 01$$

$$\mathrm{v}_{10_{\text{tap\_opportunity}}} = \left(\mathrm{v}_{10_{\min}} \geq 216\right) \& \left(\mathrm{v}_{10_{\min}} \leq 253\right)$$

$$\mathrm{v}_{10_{\text{margin}}} = 216 - \mathrm{v}_{10_{\min}}$$

$$\mathrm{v}_{\text{margin}_{\text{dif}}} = \text{abs}\left(\mathrm{v}_{90_{\text{margin}}} - \mathrm{v}_{10_{\text{margin}}}\right)$$

$$\text{Tap Opportunity} = \mathrm{T_{opp}} = (\mathrm{v}_{90_{\text{tap\_opportunity}}}) \& (\mathrm{v}_{10_{\text{tap\_opportunity}}})$$

Tapped percentile voltages $P_{90_{tapped}}(t)$ and $P_{10_{tapped}}(t)$ are calculated by adding voltage change as a result of transformer tap change. $P_{90_{tapped}}(t)$ and $P_{10_{tapped}}(t)$ are then tested for voltage breaches (as described in Section C.3.3) to calculate transformer tap opportunity.

Optimal Tap Change

Optimal tap change is the tap change that minimises $v_{margin_{dif}}$, i.e tap change to mitigate voltage breach in both directions.

Tap Down Opportunity

Tap down opportunity is the maximum number of downward tap changes that can be made without breaching the voltage low limit of 216 V.

Overall Tap Opportunity

In this analysis, a substation has opportunity to tap if any tap change n_t results in $T_{opp} = True$

Sample Calculation

The following result table was generated by applying the tap opportunity calculation algorithm.

Table 28: Tap Opportunity Calculation

n_t	T_{opp}	$v_{10_{min}}$	$v_{90_{max}}$	$v_{margin_{dif}}$	$Optimal$
-8	False	205.9	220.3	42.8	
-7	False	209.9	224.3	34.8	
-6	False	213.9	228.3	26.8	
-5	True	217.9	232.3	18.8	
-4	True	221.9	236.3	10.8	
-3	True	225.9	240.3	2.8	OPTIMAL
-2	True	229.9	244.3	5.2	
-1	True	233.9	248.3	13.2	
0	True	237.9	252.3	21.2	
1	False	241.9	256.3	29.2	
2	False	245.9	260.3	37.2	
3	False	249.9	264.3	45.2	
4	False	253.9	268.3	53.2	
5	False	257.9	272.3	61.2	
6	False	261.9	276.3	69.2	
7	False	265.9	280.3	77.2	
8	False	269.9	284.3	85.2	

The following can be inferred from Table 29:

- Tap change opportunities to mitigate voltage low breach: [-5, -4, -3, -2, -1, 0, 1, 2, 3]
- Tap change opportunities to mitigate voltage high breach: [-8, -7, -6, -5, -4, -3, -2, -1 ,0]
- Tap change opportunities to mitigate voltage breach: [-5, -4, -3, -2, -1, 0]
- Substation tap change opportunity: True
- Optimal tap change opportunity: -3

C.5 Output Format

Output of PTHC assessment is a csv output that includes the following fields for each distribution substation.

Table 29: Definition of output fields

Field Name	Field Description	Document Reference
SUB_NUMBER	Substation Number	
KVA_RATING	kVA Rating of the distribution transformer	C.2.1
SUB_PHASING	3 phase TX, 1 phase TX, or SWER	
IS_HIGH_BREACHED	TRUE if $HB\ Condition$ is satisfied	C.3.3
HIGH_BREACH_YEAR	Year of voltage high breach (Value is set to 9999 if $HB\ Condition$ is not satisfied)	
IS_LOW_BREACHED	TRUE if $LB\ Condition$ is satisfied	
LOW_BREACH_YEAR	Year of voltage low breach (Value is set to 9999 if $LB\ Condition$ is not satisfied)	
TAP_OPPORTUNITY	TRUE if there is opportunity to tap (Value is BLANK if there is no voltage breach)	C.4.3
TAP_DOWNOPP_DIRECTION	Maximum tap down opportunity direction (U=Up, D=Down, NC=No Change, BLANK)	
TAP_DOWNOPP_AMOUNT	Maximum tap down opportunity amount (positive integer or BLANK)	
TAP_OPTIMAL_DIRECTION	Optimal tap change direction (U=Up, D=Down, NC=No Change, BLANK)	
TAP_OPTIMAL_AMOUNT	Optimal tap amount (positive integer or BLANK)	
IS_PROCESSED	FALSE if an error was raised when analysis was run (e.g. data limitations)	
ERROR	Description of error or BLANK	
IS_IN_TXH	TRUE if the substation is already included in Substation Health	

C.6 Interpretation of Results

The primary objective of PTHC is to identify voltage breaching substations with no opportunity to tap. The following filter can be applied to identify substations that are likely to breach the upper voltage limit of 253 V (between now and 2025 year-end) and cannot be tapped down to bring the voltage back within operating limits.

(IS_HIGH_BREACHED = TRUE) & (TAP_OPPORTUNITY = FALSE)

APPENDIX D VALUE OF RELIEVING CONSTRAINTS ON SOLAR EXPORTS – FRONTIER ECONOMICS REPORT

APPENDIX E ACRONYMS

AMI	Advanced Metering Infrastructure
BAU	Business As Usual
DENOP	Distributed Energy Network Optimisation Platform
DER	Distributed Energy Resources
DNSP	Distribution Network Service Provider
EDC	Electricity Distribution Code
ESC	Essential Services Commission
EWMA	Exponentially Weighted Moving Average
FiT	Feed in Tariff
HB	High Breach
HV	High Voltage (greater than 1000 V)
ISO	(SWER) Isolating Transformer
LB	Low Breach
LDC	Line Drop Compensation
LV	Low voltage (used to refer to the 230 V/400 V network)
NEM	National Electricity Market
NIA	Network Intelligence and Analytics
NPV	Net Present Value
OLTC	On-Load Tap Changer
PQ	Power Quality
PTHC	Preliminary Tactical Hosting Capacity
p.u.	Per unit
PV	Photo Voltaic
REFCL	Rapid Earth Fault Current Limiter
RET	Renewable Energy Target
SDMe	Spatial Data Management – Electricity (AusNet Services' geospatial system)

SWER	Single Wire Earth Return
TRY	Totally Renewable Yackandandah
TX	Transformer
UTS	University of Technology Sydney
VRR	Voltage Regulating Relay
ZSS	Zone Substation