Review of Curtailment Methodology and Alignment to Australian Standards (with Additional Comments)

Prepared for: Ausgrid

November 2023

Reference:

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Disclaimer:

Contents

1 Introduction

Ausgrid has requested the Australian Power Quality Research Centre at the University of Wollongong (UOW) undertake a review of the response provided by the Australian Energy Regulator (AER) in relation to the methodology that they have adopted to model curtailment of Customer Energy Resources (CER) and more specifically solar photovoltaic generation, which is termed embedded generation for the purposes of this report. The scope of the work undertaken was as follows:

- A review of relevant activities by other Distribution Network System Providers (DNSPs) including their Regulatory Proposals.
- A review of applicable standards and other relevant documents related to standards for steady state voltage magnitude as well as embedded generation curtailment voltages.
- Assessment of the impact of supply voltage magnitude on customers.
- Provision of UOW advice and recommendations with reference to the Ausgrid 2024-2029 Regulatory Proposal draft determination.

The layout of this report is as follows:

- Section 2 provides a review of the submissions from other DNSPs with a focus on NSW.
- Section 3 provides a review of Australian standards for steady state voltage magnitude, specifically, AS 60038 and AS 61000.3.100. The relevant voltage magnitude settings for embedded generation as specified in AS 4777.1 and AS 4777.2 are also reviewed.
- Section 4 contains a quantitative assessment of the relationship between supply voltage magnitudes and costs to customers. The output of models which quantify the relationship between supply voltage magnitude and additional energy consumption as well as equipment loss of life are presented.
- Section 5 collates and summarises the data in Section 2 – 4 to provide a range of observations and recommendations.
- Section 6 provides some additional comments from the review of modelling processes and subsequent discussions with Ausgrid.

2 Review of Other DNSP Activities

2.1 Research Methodology

This section of the report has been compiled by conducting a comprehensive review of articles published by the AER under determinations and access arrangements. The key documents examined for each DNSP include the following:

1. The regulatory proposal submitted by the respective DNSP.
2. AER's draft decision on capital expenditure.
3. Reports from Energy Market Consulting Associates (EMC[a]) that are relevant to Customer Energy Resource (CER) integration.

In-depth reviews were conducted for the submissions of Endeavour Energy and Essential Energy, as they provided a more detailed assessment of PV curtailments in their regulatory submissions. Additional submissions from other DNSPs, namely Evoenergy, Power and Water Corporation, Energex, and Ergon Energy, were also reviewed. Furthermore, this report incorporates research studies from various publishers such as IEEE and MDPI to provide a comprehensive overview of the subject matter.

2.2 Endeavour Energy's DER Integration Strategy and Business Case

Endeavour Energy has proposed a capital expenditure (capex) of $50.1 million for investments in CER integration. This allocation includes $32.7 million for low voltage (LV) augmentation, $12.4 million for the implementation of a Distributed Energy Resource Management System (DERMS) with a focus on flexible energy exports, and an additional $5 million for distribution transformer monitoring. Endeavour Energy asserts that these strategic investments are aimed at realizing the potential of approximately 6,000 GWh of renewable energy, which might otherwise be subject to curtailment. Presently, 23% of Endeavour Energy's residential customer base has adopted rooftop solar solutions. Projections indicate an anticipated increase to 42% by the year 2030, a forecast grounded in the insights of the Australian Energy Market Operator's (AEMO) 2022 Integrated System Plan, specifically the Step Change scenario [1], [2].

In partnership with researchers from the University of Wollongong's Australian Power Quality Research Centre, Endeavour Energy has successfully developed a LV network simulation tool. This tool effectively leverages the capabilities of the open-source electrical power flow engine known as OpenDSS to conduct time-series power flow simulations.

2.2.1 Endeavour Energy's Hosting Capacity Model

Endeavour Energy has detailed the development of their LV network simulation tool, as referenced in [1]. This tool serves the purpose of assessing the implications of anticipated increase in residential photovoltaic (PV) installations, electric vehicles (EVs), and energy storage systems. Several critical factors have been modelled to gauge constraints on DER export, encompassing:

- DER Inverter Curtailment: This constraint arises from inverter trip settings and response modes.
- Distribution Transformer Capacity: Constraints stem from factors such as overloading and the thresholds for maximum and minimum demand voltages.
- High Voltage Feeder Capacity: These constraints result from the potential overloading.

Figure 1 illustrates the progression of input data into the developed simulation tool, leading to the derivation of outputs essential for the Endeavour Energy DER Integration Business Case.

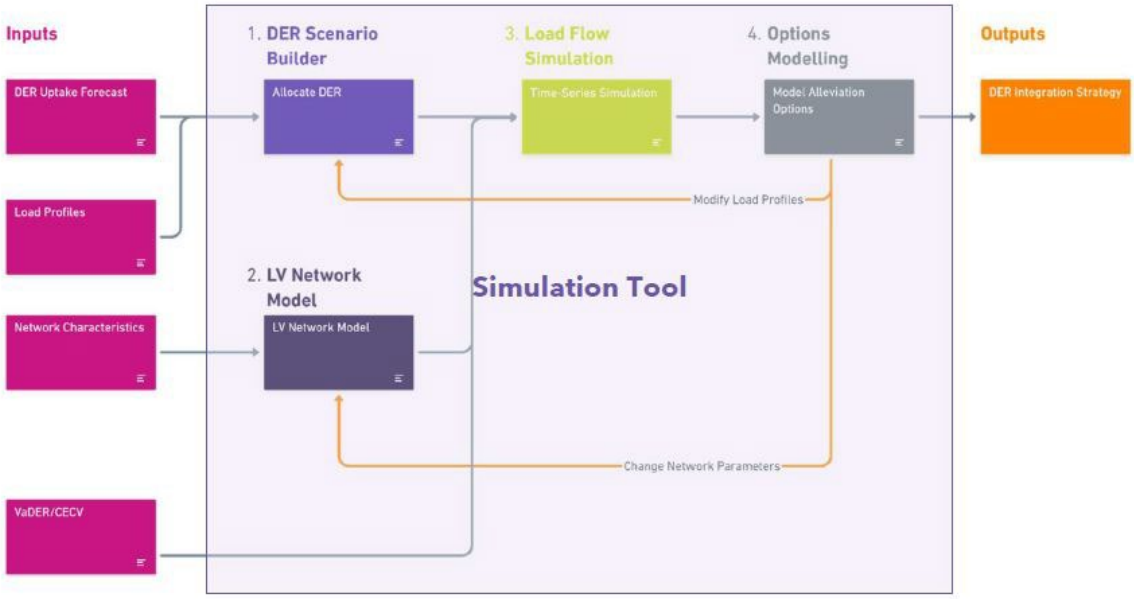

Figure 1: Inputs, Processing and Outputs of Endeavour Energy's Simulation Tool [1]

The LV network models that were developed exhibit a radial topology. Given the extensive scale and intricacy of these models, the focus of the load flow analysis was exclusively directed towards the downstream network emanating from the distribution transformer. This analysis was underpinned by the utilization of real-world data, as detailed in [1]. It is important to note that the high voltage (HV) network itself was not explicitly integrated into the load flow analysis. Instead, an approximation of its network characteristics was employed to account for the upstream influences. The development of network model files essential for the OpenDSS software was facilitated using MATLAB.

In the simulation tool the existing PV systems and the forecasted PV systems of the Endeavour Energy's LV network are modelled differently as outlined in Figure 2.

- Existing PV Systems: The PV-customer inverters that currently exist are exclusively modelled utilizing the Volt-Watt control function. These models adhere to the settings delineated in the AS 4777.2:2015 standard.
- Forecasted PV Systems: In contrast, the inverters of the new PV customers are modelled to operate in a dual Volt-VAr and Volt-Watt mode, in accordance with the standards set forth in AS 4777.2:2020. Notably, the Volt-VAr function is configured to function in reactive power priority mode. This prioritization directs the inverter to emphasize the generation of reactive power when the active power output of the inverter approaches proximity to the inverter rating.

Characteristic / PV System Modelled	PV Systems Installed prior to 2022	PV Systems Installed Post 2022
Size	4.9 kW *(average size of systems installed prior to 2022)*	7 kW *(average size of systems installed in 2022)*
Inverter Settings	AS/NZS 4777.2.2015 Volt-Watt Enabled	AS/NZS 4777.2.2020 Volt-VAr, Volt-Watt Enabled

Figure 2: Distinctions between Modelling Existing PV Systems vs Forecasted PV Systems (adopted from [1])

The PV panels are modelled to be oversized by 20% of their respective inverter rating. According to AS 4777.2:2020, inverters are expected to disconnect from the grid if the average voltage exceeds 258 V over a 10-minute period. However, due to the unavailability of high-resolution data, the inverters are configured to disconnect when the local voltage exceeds 258 V at 30-minute intervals. This adjustment introduces a minor margin of error in the calculated customer curtailment values and voltage measurements.

To compute energy curtailments of PV systems in LV feeders, a three-step process is followed. Initially, inverter controls, including Volt-VAr, Volt-Watt settings, and inverter tripping functions, are disabled, and a time series simulation scenario is executed to record customer power output. Subsequently, inverter controls and tripping functions are enabled, and a parallel simulation scenario is conducted to record customer power output. Finally, the energy curtailed by customer PV systems per time step is computed as the difference between the two scenarios, multiplied by the time step duration. For a more comprehensive understanding of the methodology employed to predict rooftop PV energy curtailments for customers, additional information can be found in [3].

Endeavour Energy's forecasted model for curtailment energy profile exhibits a swift increase from a minimal initial level, in line with expectations, as illustrated in Figure 3. By the end of the forthcoming regulatory control period, it is projected that curtailment energy will have reached 200,000 MWh.

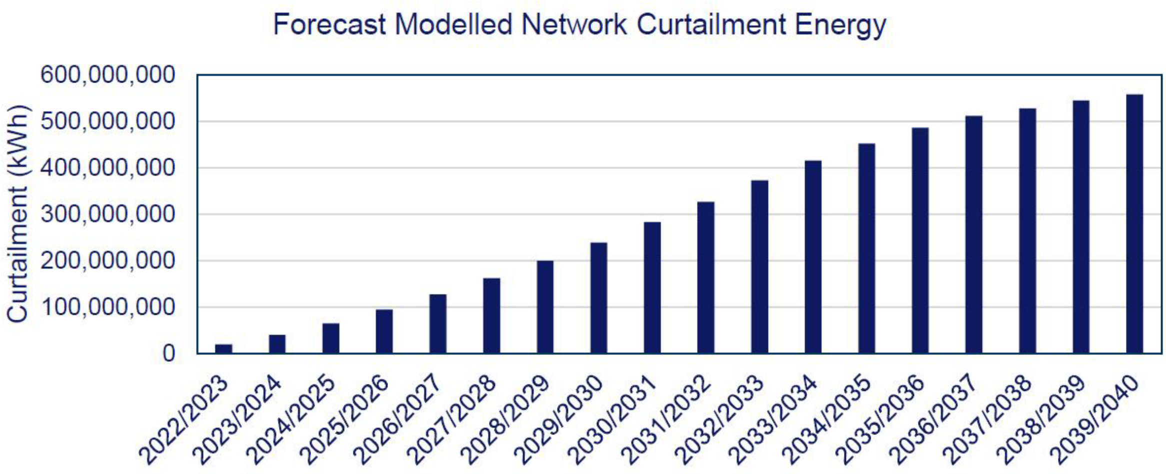

Figure 3: Curtailment Energy Forecast for Step Change Scenario [1]

2.2.2 AER's Draft Decision for Endeavour Energy

In AER's draft decision as outlined in [4], Endeavour Energy's forecast of $50.1 million was included for CER integration in the total capex forecast. In [5], EMC[a] concluded that the developed simulation tool was fit for purpose, the input assumptions are credible, and the approach to forecasting the level of curtailment is reasonable.

Furthermore, EMC[a] has reached the determination that approximating 30-minute time intervals, instead of the 10-minute intervals specified by the AS 4777.2:2020 standards, for inverter trip/disconnect when the average voltage surpasses 258 V is a reasonable approach. This decision is influenced by the cost considerations associated with obtaining high resolution 5-minute data from smart meters.

Endeavour Energy has applied static export limits of 5 kW for single-phase systems since 2015, and this limit will persist in the regulatory control period 2024-2029. Notably, it has been observed that the compliance rate with this export limit stands at only 22%. This is primarily due to a significant number of inverters not adhering to the Volt-VAr and overvoltage tripping settings specified in AS 4777.2. This scenario can lead to non-compliant systems benefiting from uninterrupted operation at the potential expense of their neighbours. However, in its base case scenario, Endeavour Energy has made the assumption that all new rooftop solar inverters will be compliant with AS 4777.2:2020 power quality response modes. To derive an alleviation profile, Endeavour Energy estimated the disparity in exported energy when customers are constrained to 5 kW and when they operate without such constraints.

2.3 Essential Energy's DER Integration Strategy

Essential Energy has submitted a capex proposal of $86.6 million for CER integration investments. At present, 26% of Essential Energy's customer base has rooftop solar installations. Projections indicate an expected increase to 47% by the year 2029. This forecast relies on Frontier Economics' modelling of rooftop solar adoption trends in NSW and is aligned with the AEMO 2022 Integrated System Plan, specifically following the Step Change scenario. It is noted that Essential Energy's network has the highest rooftop solar penetration in NSW [6], [7].

Essential Energy engaged Zepben to conduct a hosting capacity assessment. This involved the determination of the curtailment profile, representing the hosting capacity minus the export demand across a given timeframe. Zepben utilized the OpenDSS software to simulate each feeder in Essential Energy's network through power flow modelling. The primary aim of this modelling effort was to evaluate the impact of load and CER penetration levels on voltage violations in relation to the specified AS 4777.2 limits over time, with a specific emphasis on the upcoming regulatory control period [8].

2.3.1 Essential Energy Hosting Capacity Study

Zepben's modelling approach for hosting capacity forecasting is structured as depicted in Figure 4. Initially, base models that encompass the existing physical assets and the current network configuration are developed in a format suitable for the application of the OpenDSS power flow engine. These models undergo simulations using the OpenDSS power flow engine for the entire network, on an hourly basis for a full year, enabling the calculation of both power flow and voltage performance. After the base years modelling, the network demand for the forecasted year is adjusted. DER assets are subsequently integrated into the low voltage network, following the forecasted quantities and proportions outlined in the projections. The power flow and voltage performance of the entire network are re-evaluated through OpenDSS power flow engine simulations for each hour of the forecasted year. This iterative process repeats over the 15-year forecast period.

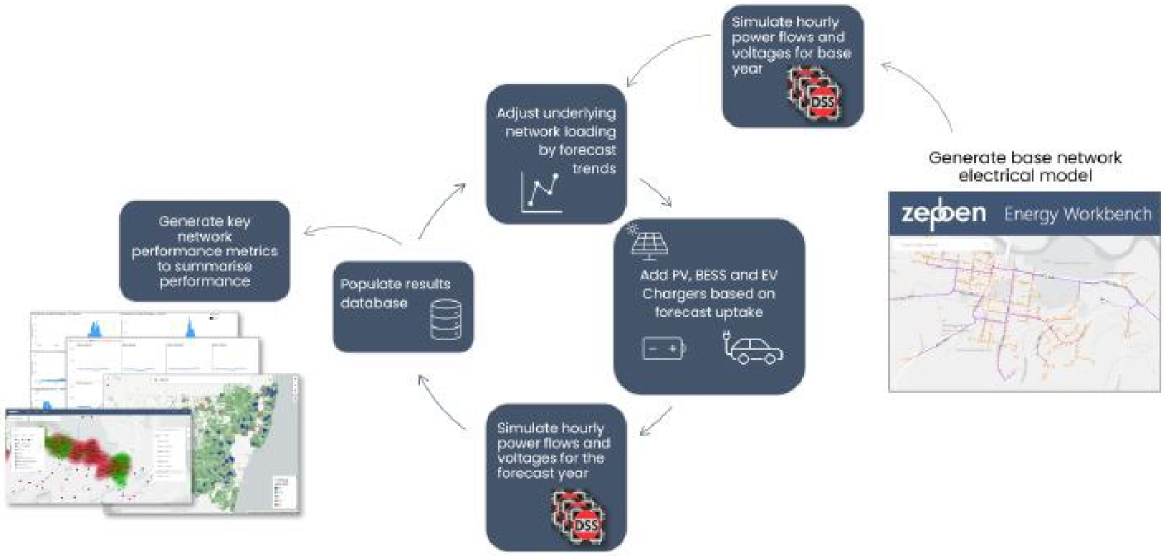

Figure 4: Essential Energy Hosting Capacity Modelling Process [8]

Each feeder was modelled in OpenDSS using a continuously connected MV and LV network. Essential Energy has established a Volt-Watt overvoltage threshold at 253 V, for greater than 1% of the year to define 'sustained' overvoltage. This aligns with the settings outlined in AS 4777.2:2015 and is appropriate, given that the majority of PV inverters currently in Essential Energy's network were likely installed under the prevailing 253 V limit. However, this limit is deemed conservative for two reasons: Firstly, the revised AS 4777.2:2020 sets the overvoltage limit at 258 V (averaged over 10 minutes), despite the Volt-Watt ramp down of output commencing at 253 V; Secondly, while a significant portion of currently installed PV inverters is non-compliant with the 2015 standard, this issue is expected to be progressively addressed as older systems are upgraded or replaced, particularly during the upcoming regulatory control period.

Figure 5 presents the outcomes of Zepben's analysis, depicting the curtailment of forecasted CER generation throughout the study period. The Central forecast is based on the ISP Step Change scenario, the Low forecast is based on the ISP Progressive Change scenario, and the High forecast is based on the ISP Strong Electrification scenario. The findings indicate that the curtailment of energy is projected to increase by more than two-fold during the upcoming regulatory control period, although it starts from a relatively low level, reaching approximately 3.5% without any interventions. In the High-case scenario, energy curtailment is anticipated to rise to around 7% by 2029 in the absence of any interventions [8].

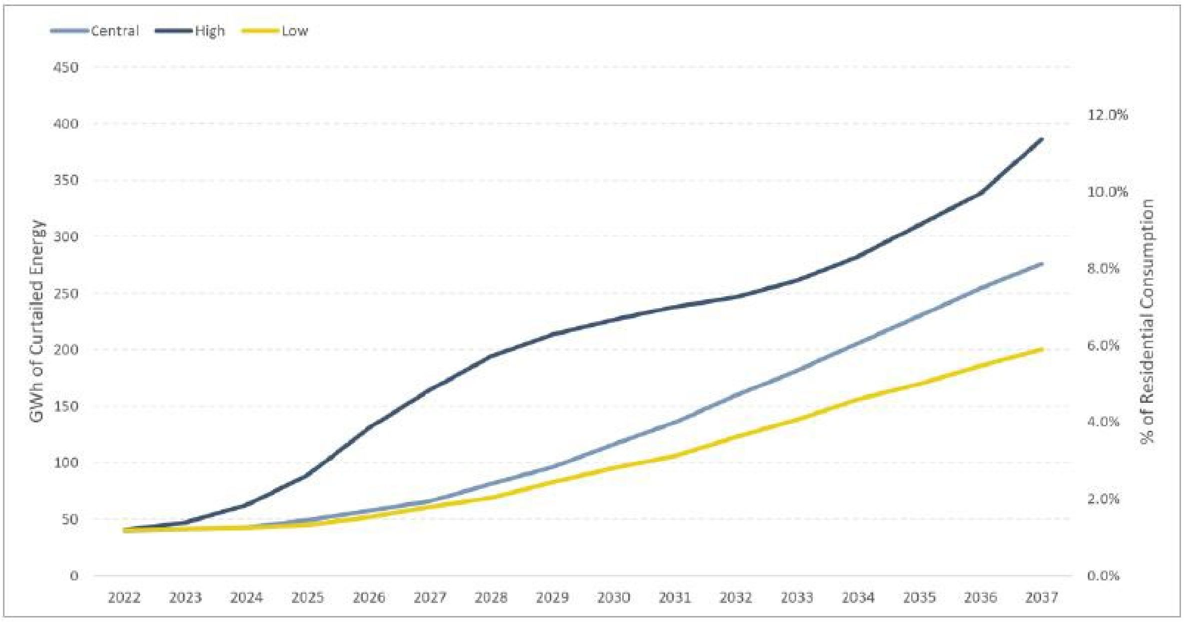

Figure 5: Zepben's Forecast of Generation Curtailment under ISP 2022-based Scenarios [8]

2.3.2 AER's Draft Decision for Essential Energy

AER identified certain elements in Essential Energy's CER integration expenditure proposal that appeared inconsistent with their provided guidance, potentially resulting in an overestimation of the benefits associated with the proposed investments. As an alternative, the AER's forecast for CER integration stands at $41.3 million, contrasting with Essential Energy's proposal of $86.6 million. Nevertheless, the AER determined that the variance in the alternative forecast at the total capital expenditure (capex) level was less than 4% and, therefore, not considered substantially different from Essential Energy's overall forecast. Consequently, Essential Energy's CER integration forecast of $86.6 million has been incorporated into the total capex projection [9].

In [10], EMC[a] concluded that the curtailment energy may be overstated somewhat in the last 10 years of the study period due to the conservative overvoltage limit setting in the model. The 253 V threshold for calculating curtailment of rooftop solar export is a conservative limit which tends to underestimate hosting capacity and overestimate the forecast volume of curtailment. It is suggested that a more suitable trigger point for over-voltage for new PV inverters would be 258 V.

EMC[a] provides additional insights by explaining that Essential Energy currently enforces static export limits of 5 kW for urban customers and 3 kW for customers in rural areas. Essential Energy has planned to lower these static limits to 1.5 kW for all LV customers, commencing in 2030. This transition represents a substantial reduction from the existing static export limits and results in a notable and abrupt change in curtailed energy in the counterfactual scenario. The connection between Zepben's hosting capacity analysis and the decision to implement these changes remains unclear.

2.4 Other DNSP Submissions

Evoenergy has proposed a 'readiness'-based DER program with a capex allowance of $5.5 million [11], [12]. Evoenergy has reported that it has conducted intrinsic hosting capacity analysis; however, readily accessible hosting capacity information for all parts of the LV network is not available. Additionally, there is limited visibility of directional power flows on the HV network. Evoenergy has noted a significant number of power quality incidents on the LV network, attributing them to DER, and has expressed concerns about the growing disparity between DER and non-DER customers. Evoenergy engaged Zepben to conduct its hosting capacity analysis.

According to EMC[a]'s assessment [13], while the description of Evoenergy's hosting capacity analysis is brief, it appears to align with the expected process. Evoenergy's process includes:

- Understanding the current state of the network, assessing potential thermal and voltage ranges that the network can accommodate.
- Gradually introducing photovoltaic (PV) penetration across each feeder in a uniform manner.
- Conducting power flow analysis to identify any network violations at the LV level, distribution transformer, or the HV level.

Furthermore, EMC[a]'s assessment determined that Evoenergy has presented a reasonable analysis of the future cost of curtailment. Evoenergy's calculations for future curtailments are based on two key factors: inverter tripping resulting from overvoltage and an assumed reduction in static export limits. Evoenergy's approach involves assuming a gradual reduction in static export limits for new customers at a rate of 0.1 kW per year, commencing from the current level of 5.0 kW in 2024-25. Consequently, Evoenergy's assumptions imply, for instance, static export limits of 4.3 kW for new PV customers connecting in 2029-30 and 2.9 kW for new PV customers connecting in 2039-40. However, Evoenergy has not provided an explanation for the rationale behind the chosen 0.1 kW per year reduction in new PV static export limits [13].

In the 'Power and Water Corporation - Determination 2024–29' [14], a static export limit of 5 kW is enforced on single-phase solar installations. This limitation serves as a rudimentary means to regulate solar export, aiming to address local power quality and system security concerns. Currently, due to the low visibility of the LV network, Power and Water Corporation faces challenges in evaluating how voltage constraints might affect the network in the future.

Energex and Ergon Energy submission for AER determination 2025–30 is currently ongoing and it is stipulated that the hosting capacity assessment may follow the procedure presented in [15].

2.5 Summary

In conclusion of the review of DNSP submissions and their corresponding draft decisions, it is noted that the EMC[a], the consultant commissioned to assist AER in their draft decisions for the regulatory submissions, anticipates that curtailments for new inverters should be computed in compliance with AS 4777.2:2020. This standard specifies that the Volt-VAr setting should trigger inverter trip/disconnect if the average voltage exceeds 258 V for a duration of 10 minutes.

3 Review of Standards and Regulation for Steady State Voltage Magnitudes and Embedded Generation Curtailment

3.1 Standards for Steady State Voltage Magnitude

There are two standards for steady state voltage magnitudes that are relevant for electricity supply networks in Australia; AS 60038 and AS 61000.3.100. AS 60038 specifies standard voltages for Australia. The current version of the standard was published in 2022 [16]. According to the scope of the standard, it specifies standard voltage values which are intended to serve:

- As preferential values for the nominal voltage of electrical supply and utilization systems, and
- As maximum, nominal and minimum reference values for both equipment and power supply in both electricity supply and utilization systems so that product and power system committees can co-ordinate their documents.

The standard specifies a voltage range of 230/400 V ±10% at the customer connection point under normal operating conditions. The allowance for a lower limit of -10% is an adjustment on the previous version of the standard which specified a lower limit of -6%.

AS 61000.3.100 [17] specifies limits and assessment criteria for steady state voltage magnitudes at the customer connection point. The current version of AS 61000.3.100 is yet to be updated to align with the lower limit of the latest version of AS 60038. However, the upper limit is equivalent, being 253/440 V.

AS 61000.3.100 also contain a preferred range for 50th percentile voltage. One a single-phase basis this range is 225 V – 244 V. the rationale for the preferred range as stated in the standard is as follows:

> *"The preferred 8% sub-range encourages network service providers to provide steady voltage that is closer to the 230 V nominal level where manufacturers tend to optimize the performance of their equipment to meet 'Mandatory Energy Performance Standards' test requirements. The preferred 8% sub-range also is aimed to cater for short duration voltage rise effects of distributed embedded generation, especially small scale photovoltaics."* [17]

3.2 Standards for Embedded Generation Curtailment

All inverters supplied in the Australian market which are used as the interface to the low voltage supply network must comply with the requirements of AS 4777.1 and AS 4777.2. There are two editions of AS 4777.2 which can reasonably be thought to be relevant to the bulk of inverter stock connected to low voltage supply networks: AS 4777.2:2015 [18] and AS 4777.2:2020 [19].

At the highest level there are two requirements predicated on supply voltage magnitude that will cause embedded generation to either cease or curtail generation output. These are either operation of the protection device to disconnect the inverter due to the supply voltage being outside of specified grid parameters (including anti-islanding) and operation of power quality response modes.

3.2.1 Protection Requirements

The AS 4777.2 requirements for operation of the protection device to disconnect the inverter due to overvoltage are given in Table 1. These voltage magnitudes are well in excess of the values specified by AS 60038 and AS 61000.3.100 and exceedances lead to complete disconnection of the inverter as opposed to curtailment of generation. As such, they are not strongly relevant to the considerations of this document.

Table 1: AS 4777.2 Voltage Limits for Operation of Protection Device

AS 4777.2 Edition	Parameter	Limit	Trip Delay	Maximum Disconnection Time
2015	Overvoltage 1 (V>)	260 V	1 s	2 s
	Overvoltage 2 (V>>)	265 V	instant	2 s
2020	Overvoltage 1 (V>)	265 V	1 s	2 s
	Overvoltage 2 (V>>)	275 V	instant	0.2 s

In addition to the value shown in Table 1, the maximum voltage magnitude, based on a 10-minute average, for sustained operation is 258 V (effectively 253 V + 2%) in both the 2015 and 2020 editions of the standard.

3.2.2 Power Quality Response Modes:

There are two power quality response modes that are relevant to this document: Volt-Watt and Volt-VAr. Further detail for each is provided below.

3.2.2.1 Volt-Watt Response Specifications

Volt-Watt response varies the output power of the inverter in response to the voltage magnitude at the terminals of the inverter. Volt-Watt response is a mandatory requirement for all inverters complying with AS 4777.2:2020 and optional for AS 4777.2:2015. Both the 2015 and 2020 editions of AS 4777.2 require Volt-Watt response to be enabled by default if the capability is present in the inverter.

In AS 4777.2:2020 the Volt-Watt response curve is defined by two values, V_{W1} and V_{W2}. V_{W1} is the voltage magnitude value at which active power output curtailment will begin while V_{W2} is the voltage magnitude value corresponding with the largest amount of curtailment. Figure 6 shows the example a Volt-Watt response curve provided in the 2020 edition of the standard. The default setpoints for V_{W1} and V_{W2} which apply to the Ausgrid network as specified in AS 4777.2:2020 are 253 V and 260 V respectively. The maximum active power curtailment values for V_{W1} and V_{W2} are 100% and 20% of rated power respectively.

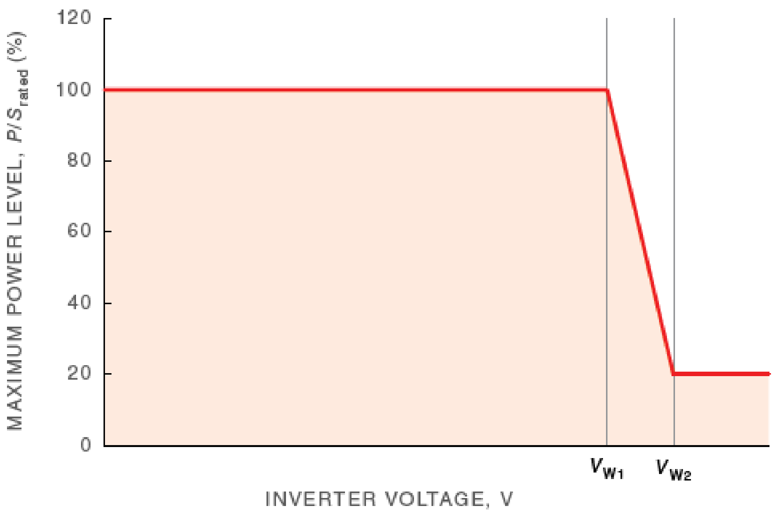

Figure 6: Example Volt-Watt Response Curve from AS 4777.2:2020 [19]

In AS 4777.2:2015 the Volt-Watt response curve is defined by four values, V_1, V_2, V_3 and V_4. For the purposes of Volt-Watt response, V_3 and V_4 are the critical values. V_3 is the voltage magnitude value at which curtailment will begin while V_4 is the voltage magnitude value corresponding with the largest amount of curtailment. Figure 7 shows an example of a Volt-Watt response curve for the 2015 edition of the standard. The default setpoints for V_3 and V_4 which apply to the Ausgrid network as specified in AS 4777.2:2015 are 250 V and 265 V respectively. The maximum active power curtailment values for V_3 and V_4 are 100% and 20% of rated power respectively.

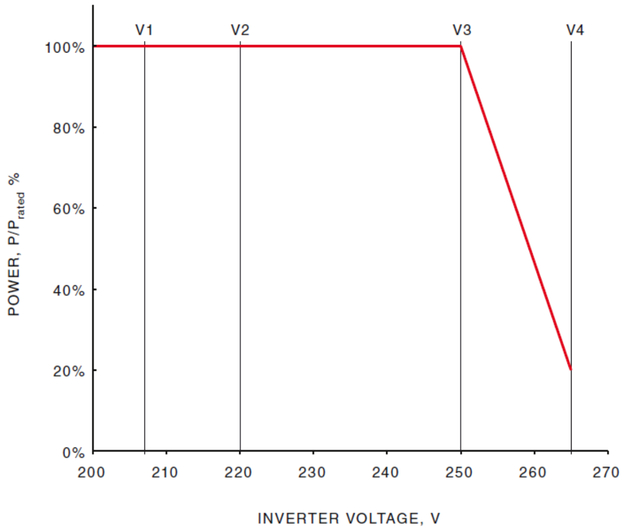

Figure 7: Example Volt-Watt Response Curve from AS 4777.2:2015 [18]

3.2.2.2 Volt-VAr Response Specifications

The Volt–VAr response mode varies the reactive power output of the inverter in response to the voltage at its terminals. Volt-VAr response is a mandatory requirement for inverters complying with AS 4777.2:2020 and optional for the 2015 edition. The 2020 edition of AS 4777.2 requires that that Volt-Watt response be enabled by default while the 2015 edition required Volt-VAr response to be disabled by default.

In AS 4777.2:2020 the Volt-VAr response curve is defined by four values, V_{V1}, V_{V2}, V_{V3} and V_{V4}. V_{V3} is the voltage magnitude value at which the mode is initiated for overvoltage while V_{V4} is the voltage magnitude at which maximum reactive power output is required. Figure 8 shows the example of a Volt-VAr response curve provided in the 2020 edition of the standard. The default setpoints for V_{V3} and V_{V4} which apply to the Ausgrid network as specified in AS 4777:2020 are 240 V and 258 V respectively. The default reactive power values (in percentage of rated power) for V_{V3} and V_{V4} magnitudes are 0% and 60% lagging respectively. The maximum reactive power value for V_{V4} is 100% lagging.

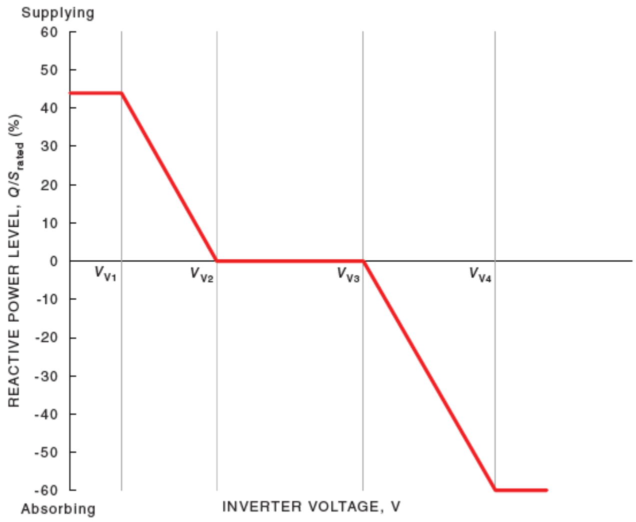

Figure 8 Example Volt-VAr Response Curve from AS 4777.2:2020 [19]

In AS 4777.2:2015 the Volt-VAr response curve is defined by four values, V_1, V_2, V_3 and V_4. V_3 and V_4 are the values relevant to overvoltage performance. V_3 is the voltage magnitude value at which the response mode will be initiated, while V_4 is the voltage magnitude value corresponding with the largest required reactive power magnitude. Figure 9 shows an example of a Volt-VAr response curve for the 2015 edition of the standard. The default setpoints for V_3 and V_4 which apply to the Ausgrid network as specified in AS 4777.2:2015 are 250 V and 265 V respectively. The default reactive power values (in percentage of rated power) for V_3 and V_4 are 0% and 30% lagging respectively. The maximum reactive power value for V_4 is 100% lagging.

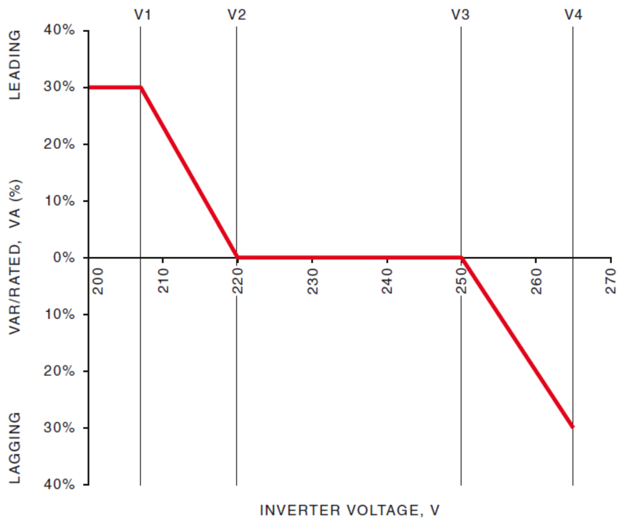

Figure 9: Example Volt-VAr Response Curve from AS 4777.2:2015 [18]

4 Impact of Steady State Voltage Magnitude on Customers

Any network operating condition where the upper limit for steady state voltage magnitude exceeds 230/400 V +10% presents a scenario where product/equipment design ratings will not align with operational values. In this situation, equipment cannot be guaranteed to operate as expected, may fail, may fail before rated lifespan, or may otherwise maloperate. In addition, studies have shown that supply at voltage magnitudes at and above the upper end of the allowable voltage range will result in additional energy consumption and additional heating in many equipment types [20], will result in additional energy usage [21], and will lead to loss of equipment life [22]. There is now a compelling body of evidence which clearly articulates that suppling or otherwise allowing customer voltage magnitudes to exceed the upper limit of the allowable range is highly undesirable, even if in many cases the customer is unaware of the situation. The APQRC have developed models that quantify the impact of steady state voltage magnitude on customers. These models have been applied to the Ausgrid network and the results are presented below.

4.1 Quantification of Additional Energy Usage

The APQRC has developed a model which utilises electricity consumption and appliance stock data available in the Residential Baseline Survey [23] combined with experimental data which quantifies the relationship between supply voltage magnitude and consumer equipment energy consumption available in [22] to determine the relationship between supply voltage magnitude and customer energy consumption. The model is predicated on the nominal voltage of 230 V being the origin point with supply voltage above 230 V resulting in increased energy consumption. The model assumed an electricity cost of 30 c/kWh and an average consumption per dwelling of 14.6 kWh per day (provided by Ausgrid). The 2022 electricity consumption and electricity supply stock data has been used on the model. Figure 10 shows the relationship between supply voltage and the additional energy cost for a single dwelling per annum. It should be noted that these costs are ongoing (i.e. occur year on year).

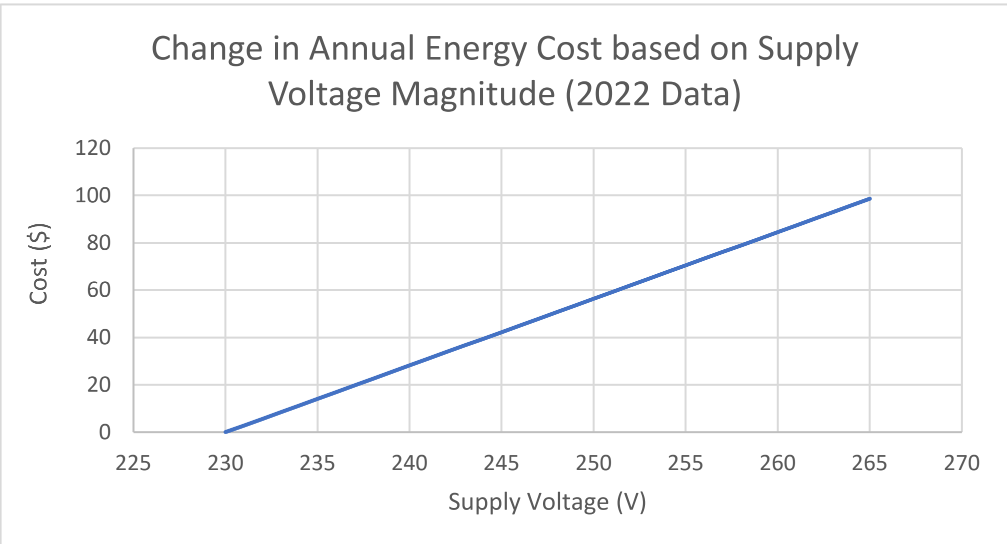

Figure 10: Relationship between Supply Voltage and the Additional Energy Cost for a Single Dwelling per Annum

4.2 Quantification of Impact of Equipment Life

The APQRC has also developed models which quantify the loss of life or accelerated depreciation for consumer equipment, specifically electronic devices and incandescent lighting. These again implement appliance stock data available in the Residential Baseline

Survey. The models are predicated on assumption for consumer equipment costs and rated lifespans. The output of the models is predicated on the relationship between supply voltage magnitude and appliance lifespan. For electronic equipment this relationship is taken from [22] while for incandescent lighting this relationship is defined in [24]. The model uses census data which reports that there are 3.36 million residential dwellings in NSW. Figure 11 shows the output of the model for electronic equipment, while Figure 12 shows the output of the model for incandescent lighting equipment.

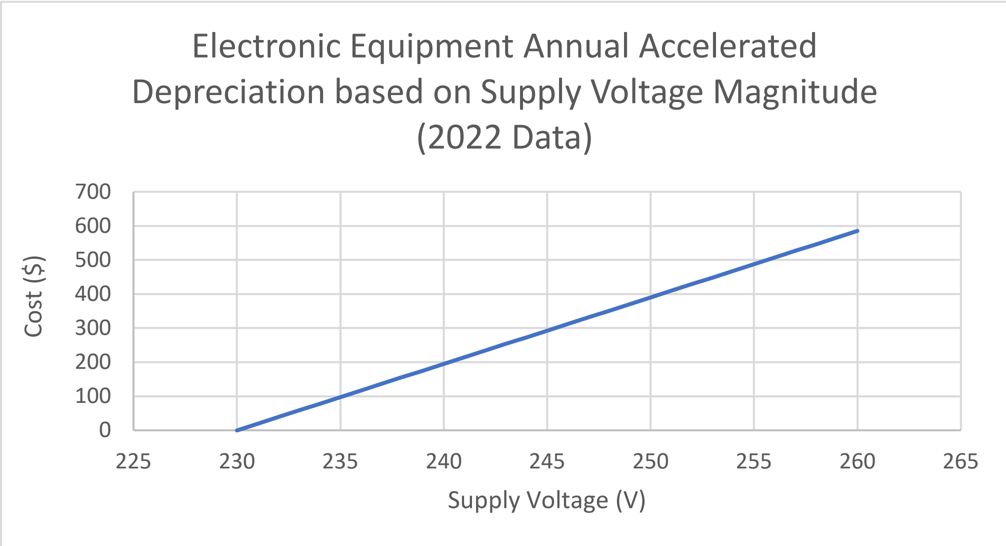

Figure 11: Relationship between Supply Voltage Magnitude and Accelerated Depreciation for Electronic Equipment

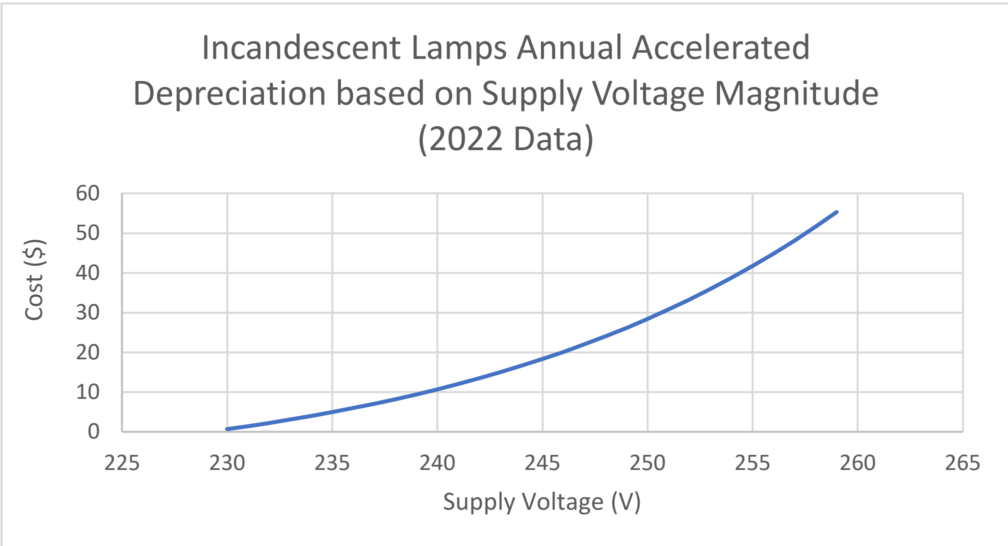

Figure 12: Relationship between Supply Voltage Magnitude and Accelerated Depreciation for Incandescent Lighting

5 University of Wollongong Observations and Recommendations

(i) Supply at 253 V will likely lead to curtailment of embedded generation

The NSW service and installation rules limit the voltage rise due to embedded generation to a maximum of 2% of 230 V (4.6 V) beyond the (customer) connection point. This 2% is further broken down to a maximum of 1% within the consumers mains and 1% within any submains. A further 1% voltage rise is allowed in the service mains between the point of common coupling and the connection point. These voltage rise limits are illustrated in Figure 13.

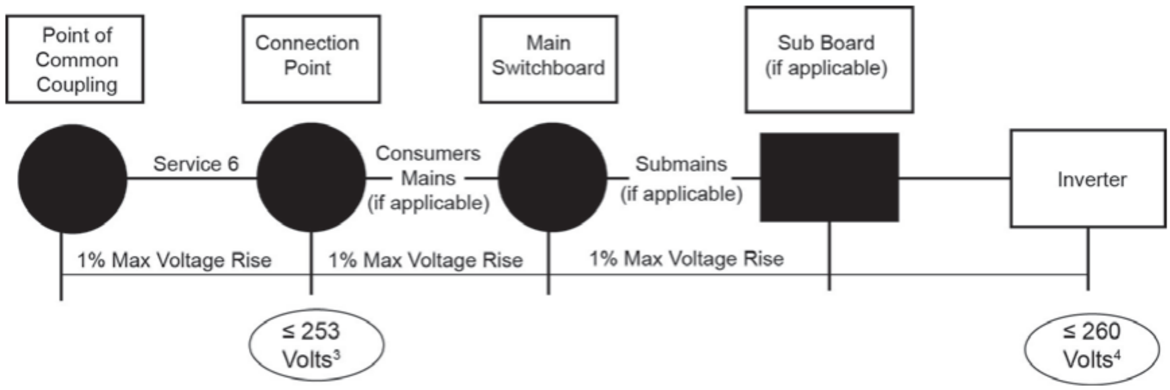

Figure 13: Voltage Rise Limits for Installations with Embedded Generation [25]

Lack of compliance to required embedded generation settings is well-known. As such, it is reasonable to assume that a large proportion of the inverter stock is likely operating with default AS 4777.2:2015 settings.

The default value for commencement of active power curtailment (Volt-Watt response) in AS 4777.2:2015 is 250 V. As such, any inverters installed and operating with the 2015 default values will begin to curtail active power output when the voltage magnitude at their terminals exceeds 250 V. With the requirements of the 2020 edition of the standard coming into force 12 months after publication date of December 2020, inverters complying with the 2015 edition of the standard could be sold and installed up until December 2021. Consequently, there is likely a large stock of inverters complying with AS 4777.2:2015 connected to the Ausgrid network which cannot be ignored.

In the case of AS 4777.2:2020, the default value for initiation of Volt-Watt response is 253 V. While this default value is higher than that specified in the 2015 edition of AS 4777.2 when the allowable voltage rise within an installation is considered it is clear that any supply voltage magnitude of greater than 250 V at the customer connection point can allow voltage magnitudes of greater than 253 V at the inverter terminals and as such will result in activation of the Volt-Watt response and curtailment of output. This is explained in further detail below.

It can easily be demonstrated that a supply voltage magnitude at the upper limit of the allowable range, 253 V, at the connection point combined with the allowable voltage rise of 2% (resulting in a maximum voltage magnitude of 257.6 V at the inverter terminals which is close to the sustained operation limit) will result in activation of the Volt-Watt response mode and curtailment of output if the default value of 253 V (AS 4777.2:2020) or 250 V (AS 4777.2:2015) is applied to the inverter settings. In order to ensure that the voltage magnitude at the inverter terminals is below the default values and in turn ensure that Volt-Watt response mode and the accompanying curtailment of generation does not occur, the supply voltage magnitude at the connection point must be maintained below 253 V less 2%, i.e. 248.4 V. For AS 4777.2:2015, the supply voltage magnitude at the connection point must be maintained below 250 V less 2%, i.e. 245.4 V, to ensure that Volt-Watt response is not activated.

Default values for initiation of Volt-VAr response are also below the voltage magnitudes likely to be seen at inverter terminals if the supply voltage magnitude is greater than 250 V at the customer connection point. While Volt-VAr response will not result in the same degree of active power curtailment as Volt-Watt response, ultimately the inverter rating is the total capability of the device to supply a combination of active and reactive power. Accordingly, as reactive power output requirements increase it is logical that active power output must be curtailed.

(ii) Use of 250 V as a curtailment setting is in line with the approach taken by other NSW DNSPs

Endeavour Energy used AS 4777.2:2015 edition Volt-Watt settings to model existing inverter stock. These settings will see inverters begin to curtail active power when the voltage magnitude at the inverter terminals reaches 250 V. In this scenario, the voltage at the customer connection point may be as low as 245.4 V if the full 2% allowable voltage rise is present in the customer installation. Endeavour Energy applied AS 4777.2:2020 edition default settings to model future inverters. These settings will see inverters begin to curtail active power when the voltage magnitude at the inverter terminals reaches 253 V. In this scenario, the voltage at the customer connection point may be as low as 248.4 V if the full 2% allowable voltage rise is present in the customer installation.

Essential Energy applied a Volt-Watt setting of 253 V at the inverter terminals. This is similar to the approach taken by Endeavour Energy for future inverters. In this scenario, the voltage at the customer connection point may be as low as 248.4 V if the full 2% allowable voltage rise is present in the customer installation.

Ausgrid has adopted a curtailment voltage of 250 V at the point of customer connection. If the full 2% voltage rise is present in the customer installation this will result in a voltage magnitude of 254.6 V at the inverter terminals. These values are in alignment with the Endeavour Energy (future inverter) and Essential Energy approaches.

In addition to the above, there appears to be some conflation between sustained operating limits and voltage magnitude where output curtailment will begin in the EMC[a] review. For both the 2015 and 2020 editions of AS 4777.2 the power quality response modes will begin to curtail output before the sustained operating voltage limit is reached. This is by design and aims to reduce voltage magnitudes such that the inverter can remain connected, albeit in a curtailed state.

(iii) Where embedded generation is present, supply at the customer connection point above 250 V will likely result in voltage magnitudes above 253 V at the terminals of consumer equipment

As described above, the NSW Service and Installation Rules [26] allow 2% voltage rise between the customer connection point and the inverter terminal for installations incorporating embedded generation (primarily solar photovoltaic). Where embedded generation is present, operating the network such that the supply voltage magnitude at the customer connection point is equal to the upper limit voltage magnitude limit of 253 V specified in AS 60038 and AS 61000.3.100 almost certainly ensures that voltage magnitudes at equipment terminals will exceed 253 V whenever any significant volume of local generation is being exported to the electricity supply system. As discussed below, allowing voltage magnitude at the terminals of customer equipment to exceed 253 V is not in the best interests of customers.

(iv) Reducing supply voltage magnitudes is in the best interest of customers

There are compelling reasons to ensure that the supply voltage magnitude at the terminals of consumer equipment is maintained below the upper voltage limit of 253 V specified in AS 60038 and AS 61000.3.100. Failure to do so results in:

- A mismatch between supply voltage and equipment design parameters. AS 60038 is designed to provide alignment between network operating voltages and equipment design parameters. The voltage magnitudes specified are effectively compatibility limits, which equipment designers should use in development of their products. Allowing voltage magnitudes at equipment terminals to exceed 253 V means that equipment cannot be expected to operate as intended or may result in a decrease in the rated lifespan of the equipment.
- Additional costs to customers by means of increased energy consumption. Section 4.1 indicates that these costs are in the tens of dollars, for each dwelling, per annum ongoing.
- Additional costs to customers due to accelerated depreciation of consumer appliances. Section 4.2 indicates that these costs can be significant, up to hundreds of dollars per dwelling per annum ongoing.

(v) Supply at voltage magnitudes below 250 V is 'no regrets'

DNSP activities to reduce voltages at the upper end of the allowable range will be 'no regrets'. These activities will result in benefits to customers including:

- Assurance that active power curtailment will be limited for inverters using AS 4777.2 default values for Volt-Watt and Volt-VAr response modes
- Reduced electricity bills
- Reduced costs associated with loss of life of consumer equipment
- Reduced carbon emissions where electricity supply is from fossil fuel based generation
- Increased embedded generation hosting capacity.

Conversely, allowing supply voltage magnitudes within a consumer premises to exceed the upper limit of 253 V will result in additional costs for customers and does not represent responsible operation of the network.

Based on the above, where supply voltages levels are presently high, any reductions in levels would be appropriate. Further to this, the suggestion in the EMC[a] Review that 258 V is an appropriate curtailment setting for voltage modelling ignores likely power quality response mode configurations for a large stock of inverters and appears to give tacit approval for voltage magnitudes within customer installations that exceed both Australian Standard voltages and National Electricity Rules requirements. This does not represent responsible operation of the network and will be to the detriment of customers.

6 Additional Comments Following Brief Review of Modelling Approach

On-line discussions were held with Ausgrid representatives on 17 November 2023 and 21 November 2023, which included presentation by Ausgrid of an overview of their application of AS 4777.2:2020 model[1] and their rooftop solar Cost-Benefit Analysis (CBA) model[2]. Following these discussions, and in combination with the details provided earlier in this report, the following comments are made.

In the evaluation of Ausgrid's rooftop solar Cost-Benefit Analysis (CBA) model, the strategy of modelling the threshold for solar export energy curtailment at the customer connection point (CCP) to nominally 250 V (actually implemented slightly lower at 248 V in the Ausgrid AS 4777.2:2020 model) is deemed to be reasonably sound, as also mentioned in Section 5(ii) of this report. The adherence to this voltage reduction aligns with the New South Wales (NSW) Service and Installation Rules [26], which permit a 2% voltage rise between the customer connection point and the inverter terminals for installations featuring embedded generation, notably solar photovoltaic systems. It is reasonable to assume that this 2% voltage rise will be fully apparent at times of high solar and light load, i.e. when curtailments are likely to occur. This regulatory allowance theoretically translates to a voltage magnitude of 253 V at the inverter terminals when the customer connection point voltage is maintained at 248 V. Importantly, this configuration complies with the AS 4777.2:2020 standard, which states that the active power curtailments must commence at 253 V.

In contrast to Ausgrid's approach, other DNSPs, specifically Endeavour Energy and Essential Energy, have opted not to incorporate the 2% voltage rise within an installation into their modelling. Instead, these entities have modelled the customer connection point voltage to align precisely with the customer inverter voltage. This divergence from accounting for the 2% voltage rise is considered a more conservative modelling strategy relative to the actual operating scenario.

Due to constraints within the hosting capacity model and the unavailability of more granular smart meter data, Ausgrid is presently unable to conduct an accurate simulation of the Volt-VAr response as delineated in AS 4777.2:2020. Nevertheless, Ausgrid has adopted two precautionary assumptions to address the potential reduction in curtailments resulting from the Volt-VAr operational mode of customer inverters:

a) Firstly, Ausgrid has not undertaken a simulation of a sustained cut-off period for customer inverters at voltages exceeding 258 V, as required in Section 4.5 of AS 4777.2:2020. Instead, it is assumed that the inverters will restrict their output to only 20% across the voltage range above 260 V (at the inverter terminals).

b) Secondly, it is noteworthy that, despite the majority of existing customer inverters on Ausgrid's network utilizing default AS 4777.2:2015 settings that commence curtailments at 250 V, Ausgrid adopts a conservative approach that employs the AS 4777.2:2020 standard, which initiate curtailments at 253 V for all customers.

Upon examination of Ausgrid's CBA model, it has come to light that Ausgrid's methodology to estimating customer curtailments is conservative in other aspects:

[1] Ausgrid's "Application of AS4777 2000" provided as a spreadsheet in Ausgrid email on 24 Nov 2023
[2] Ausgrid's "Rooftop Solar CBA Model" provided as a flow diagram in Ausgrid email on 21 Nov 2023

(i) It has been discerned that in certain instances, the customer connection point (CCP) voltage is construed as the voltage at the point of common coupling (PCC), typically represented by the 3-phase main busbar that serves the customer. In such cases, there exists the potential for the voltage rise within the customer installation to surpass the stipulated 2%, thereby rendering the estimated curtailment values more conservative.

(ii) It is our understanding that solar installations comprise of a significant proportion of customer PV panels intentionally oversized relative to their corresponding inverter ratings. Endeavour Energy adopts a modelling approach wherein customer PV panels are considered to be oversized by approximately 20% of the respective inverter rating. This deliberate oversizing practice is observed to potentially contribute to active power curtailments due to the operation of the Volt-VAr response mode in the reactive power priority mode, as outlined in the AS 4777.2:2020 standard. The reactive power priority mode inherent in inverters tends to curtail active power output during periods of high solar irradiation, a measure taken to align with mandated reactive power export limits.

(iii) In the context of low voltage (LV) distribution networks, which commonly employ underground mains, the prevailing R/X ratio tends to be low. This characteristic of LV networks implies that the voltage regulation achieved through the Volt-VAr response mode of inverters may be limited. Taking these aspects into consideration, a reasoned conclusion can be drawn that the estimated active power curtailments derived from modelling the Volt-VAr response modes of inverters may not exhibit substantial variance from the values estimated by the Ausgrid's CBA model.

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