Australian Power Quality and Reliability Centre

Solar Photovoltaic Inverter Behaviour

Technical Note 17
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UNIVERSITY OF WOLLONGONG

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1. Introduction

In the modern electricity network, inverter equipment forms an important interface between renewable energy resources and the electricity grid. Such renewable energy resources include rooftop solar photovoltaic (PV) panels. A typical residential solar PV generation system, with the inverter indicated in the red box, is shown diagrammatically in Figure 1 below.

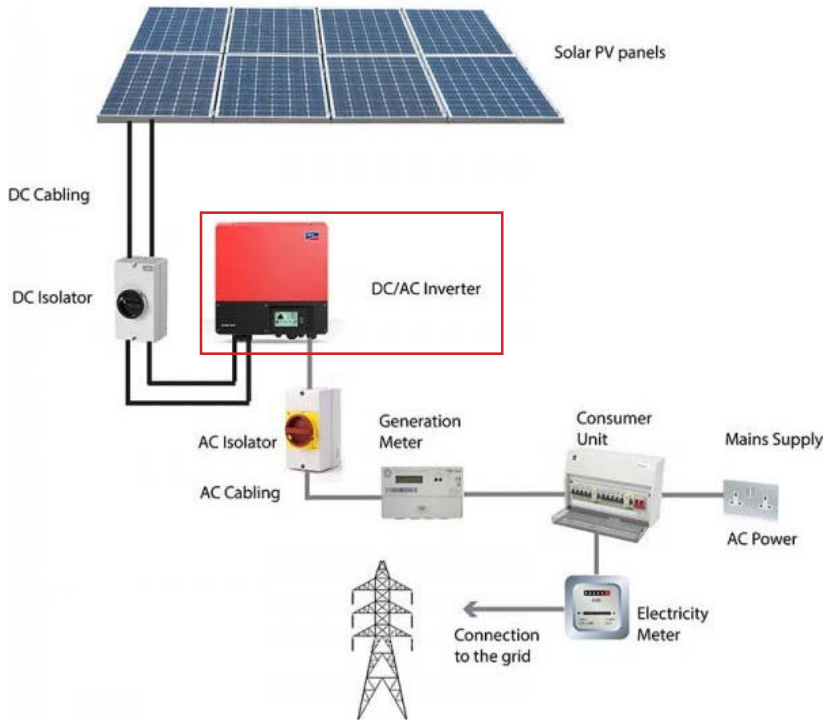

Figure 1: Typical Solar PV System
(from http://www.361energy.org/generation/solar-pv/)

An important aspect of operating an electricity network is to maintain voltage levels at customer premises within a specified range so that connected equipment can operate properly and without damage. This voltage range is specified in national voltage standards.

One of the challenges to integrating solar PV is that the normal operation of solar PV systems can lead to increased voltage levels at customer premises which, if excessive, can cause the PV inverter to disconnect from the grid resulting in loss of revenue from the PV system. In addition to loss of generation revenue, excessively high voltages can also reduce the lifespan of other appliances connected nearby.

This Technical Note outlines what actions can and are being undertaken in order to ensure appropriate voltage levels. Initially, voltage standards are explained then the causes of voltage rise is addressed. This is followed by an outline of what is being done to reduce PV system related voltage rise. Finally, suggestions are given with respect to the options available to customers to assist them in maintaining voltage levels within specifications and hence keep their systems operating.

2. Voltage Standards

Two Australian standards deal with the preferred voltage range on low voltage (LV) distribution networks. AS 60038 [1] specifies standard voltages that should be used for the preferred nominal voltages of the electricity network, and as reference values for equipment and system design. AS 61000.3.100 [2] describes how to monitor the electricity network and apply the limits specified in AS 60038. The following Clause, reproduced from Endeavour Energy's Customer service standards for connection customers [3], summarises the requirements of AS 61000.3.100:

> *Low voltage customers are supplied at a nominal voltage of 230V line to neutral. Where low voltage customers are supplied by more than one phase, the line to line nominal voltage is 400V.*
>
> *Endeavour Energy's objective is to maintain a supply voltage that complies with Australian Standard AS 61000.3.100. This standard specifies steady state voltage limits of +10% to -6% of the nominal voltage (253V to 216V for a nominal voltage of 230V) at the connection point. These limits apply to 10 minute root mean square (rms) voltages and are 99th and 1st percentile limits. This means that the 10 minute rms voltage may be above the upper (+10%) limit for 1% of time and below the lower (-6%) limit for 1% of time, when measured over a period of at least seven days and disregarding periods of supply interruption.*

The voltage limits given apply at the point of connection (i.e. the point of supply established between the Network Service Provider (NSP) and the customer's installation). AS 60038 [1] further defines a utilisation voltage range to allow for voltage drops within the customer's installation due to the operation of connected electrical equipment. AS/NZS 3000 [4] limits this voltage drop to 5% so the utilisation voltage range is +10%, - 11% i.e. 253 V to 205 V.

3. What Causes Voltage Rise?

To a first approximation, a PV inverter can be modelled as a current source. When the current from the inverter is injected into the combined impedance of the network and installation, a voltage rise will occur at the point of injection if all other variables are kept constant. As mentioned above, if this voltage rise is excessive, the overvoltage protection of the inverter will operate to disconnect the inverter from the customer's installation.

3.1 Influence of the Distribution Network

The distribution network as seen from the point of connection of the customer's installation makes a significant contribution to voltage rise at the main switchboard resulting from PV inverter operation. Factors contributing to voltage rise include zone substation medium voltage (MV) float voltage; distribution transformer tap setting; LV distributor construction and conductor size; location of the customer's installation on the LV distributor; and the size of the service conductors. All of these factors affect the voltage and impedance seen from the point of supply (connection).

3.2 Influence of the Installation

The components of the customer's installation can have the greatest influence on the voltage rise at the PV inverter. The main components of influence include the installation cabling and the PV inverter itself. The cabling includes that of the consumer mains and the submains/final subcircuit connecting to PV inverter terminals. The higher the total impedance of these cables the greater will be the voltage rise. The rating of the PV inverter will also have an effect; the greater the rating the higher the voltage rise.

4. What is Being Done to Reduce Voltage Rise?

The following expression shows the approximate relationship between voltage rise (ΔV) and the resistance (R) and reactance (X) of the installation/network, and the change in active (ΔP) and reactive (ΔQ) power.

$$\Delta V \approx \Delta P \times R + \Delta Q \times X$$

It can be seen that voltage rise can be reduced by decreasing R, X, ΔP and ΔQ.

Consequently, the problem of voltage rise due to PV inverter operation has been addressed by changes to grid-connected inverter standards as well as the Service and Installation Rules as outlined below. In particular, the introduction of power quality response modes in the grid-connected inverter standards, notably the Volt/Watt and Volt/Var responses, allows customer solar photovoltaic systems to generate more energy than would otherwise be the case as it allows for voltage levels to be managed by reductions in inverter outputs as opposed to the complete disconnection that was previously the case.

4.1 Change of Standards and Service Rules

The Service and Installation Rules of NSW [5] now specify a 2% maximum voltage rise between the point of supply and the inverter output terminals (with a maximum of 1% rise across both the consumers mains and the final subcircuit to the inverter) when the PV inverter is delivering maximum power (Clause 8.6.13 of the Rules) i.e. 4.6 V based on a nominal voltage of 230 V. Conductor sizes to achieve this requirement are also given (Table 8.3 of the Rules). This limit has been taken from the revised grid-connected inverter standard AS/NZS 4777.1 [6]. This is shown diagrammatically in Figure 2 (taken from [6]). It should be noted that the Service and Installation Rules allow for a voltage rise of up to 2% between the main switchboard and the inverter provided the combined voltage rise across the service conductors and the consumers mains is less than 1%.

The Service and Installation Rules also specify a passive anti-islanding overvoltage disconnection limit of 260 V (Table 8.2 of the Rules), derived from AS/NZS 4777.2 [7]. This requires disconnection of the inverter within 2 s (after a 1 s delay). There is also a limit specified in [7] for sustained operation for voltage variations which has a default value of 255 V. If the average voltage for a 10 minute period exceeds this limit, the inverter is required to disconnect from the network within 3 s. Endeavour Energy requires this limit to be set to 258 V (the maximum allowed) (Clause 5.3 in [8]).

In addition to the above, many network service providers have also been taking proactive steps to reduce voltage levels on LV networks. These actions work together with the changes to the standards and Service rules to provide an electrical environment suitable for integration of solar PV generation.

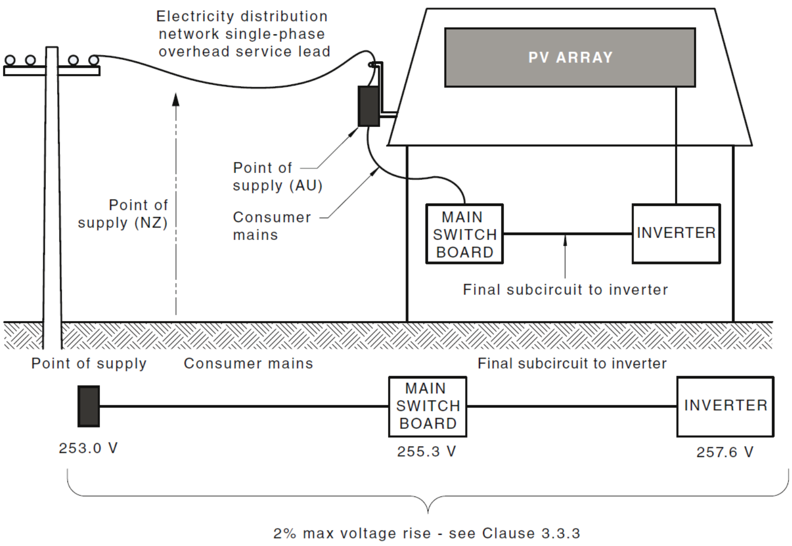

Figure 2: Specification of maximum 2% voltage rise (Figure C1 in AS/NZS 4777.1 [6])

The Service and Installation Rules allow varying of the output power factor (PF) of the inverter in order to help limit voltage rise (Clause 8.6.9 of the Rules). AS/NZS 4777.2 [7] describes in detail the inverter power quality response modes (Clause 6.3 in [7]), some of which allow for the control of output power and/or PF in order to help control voltage rise. Of main interest in this regard are the Volt Response Modes, namely the Volt-Watt Response and the Volt-Var Response. The National Distributed Energy Resources Grid Connection Guidelines [9] recommend that these two response modes be available and enabled for all inverter energy systems. Both these response modes use the volt response reference values V1 to V4 which have default values 207 V, 220 V, 250 V and 265 V respectively (Table 9 in [7]). V2 can be varied between 216 V to 230 V, V3 between 235 V to 255 V, and V4 between 244 V to 265 V.

4.2 Use of Inverter Volt-Watt Response

The volt-watt response mode varies the output power according to the voltage at the inverter terminals. The inverter progressively lowers the real power output as the voltage exceeds the threshold voltage resulting in the inverter operating at reduced power while the voltage is high. The default power levels (with respect to rated power) are 100% (at V1), 100% (at V2), 100% (at V3) and 20% (at V4). An example response curve is shown in Figure 3 using default values.

The volt response reference values can be varied by individual network operators to suit their network conditions, for example, Endeavour Energy has changed V3 to 255 V (Clause 5.3 in [8]).

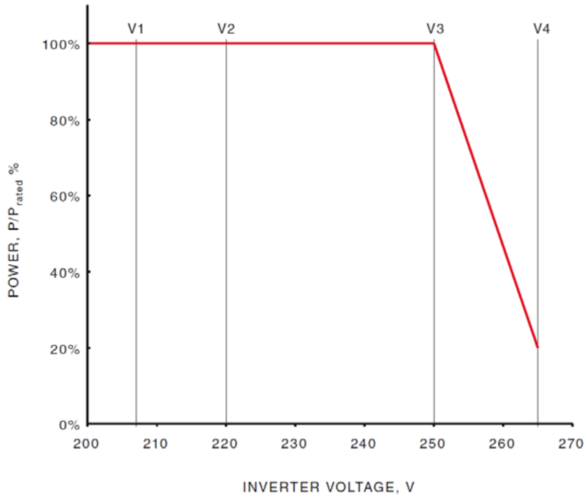

Figure 3: Example response curve for the volt-watt response (Figure 2(A) in AS/NZS 4777.2 [7])

4.3 Use of Inverter Volt-Var Response

The volt-var response mode varies the reactive power output of the inverter according to the voltage at the inverter terminals. Voltage is managed by controlling reactive power import or export based on measured voltage. The default var levels (% of rated VA) are 30% leading (at V1), 0% (at V2 and V3) and 30% lagging (at V4). The V1 var value can be varied from 0 to 60% leading while the V4 var value can be varied from 0 to 60% lagging. An example response curve is shown in Figure 4 using default values.

The volt response reference values as well as V1 and V4 var levels can be varied by individual network operators to suit their network conditions e.g. Endeavour Energy has changed V3 to 248 V, V4 to 260 V, V1 var level to 60% leading and V4 var level to 60% lagging (Clause 5.3 in [8]).

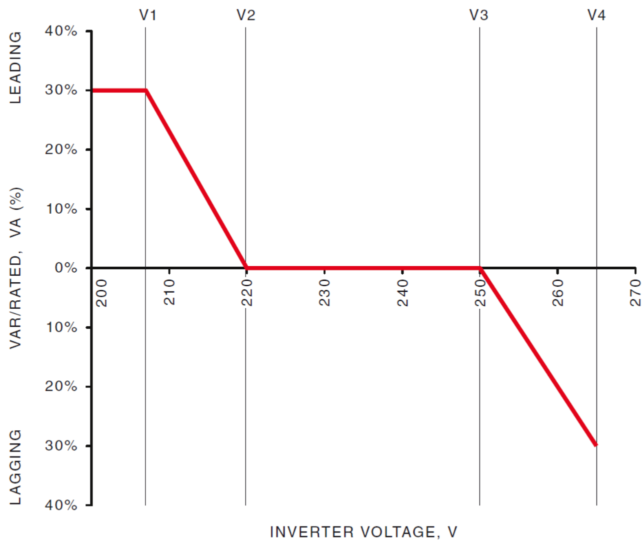

Figure 4: Example response curve for the volt-var response (Figure 3 in AS/NZS 4777.2 [7]).

The integration of both volt-watt and volt-var response modes requires careful consideration to choose suitable reference values and power/var levels to achieve optimum outcomes [10]. Recently, Energy Networks Australia (ENA) has recommended new default power quality response reference values and power levels for inverter manufacturers to use in order to increase network PV hosting capacity and net energy exports [11]. For the Volt-Watt Response, ENA recommends V3 being changed from 250 V to 253 V and V4 from 265 V to 260 V, with all other reference values and power levels being kept the same as previously. For the Volt-Var Response, it is recommended to change V3 from 250 V to 240 V and V4 from 260 V to 258 V, with the V1 power level changing to 44% rated VA and the V4 power level changing to 60% rated VA. It is also recommended that Volt-Var Response be enabled (ON) by default as is the case for the Volt-Watt Response.

5. What Can You Do?

Customers can help minimise the voltage rise issues associated with solar PV operation by maximising self-consumption of the solar PV electricity, especially during the middle of the day when network loads are generally smaller. This minimises the current injected back into the distribution network. This can be achieved in several ways including:

- Moving as much energy consumption as possible to the middle of the day. This could involve running air conditioning to pre-cool or pre-heat premises, using microwaves, ovens or cooktops for meal preparation, operating appliances such as washing machines, dishwashers or swimming pool pumps. This approach is becoming more viable with the increasing availability of internet-connected appliances. For multi-phase installations, care must be taken to ensure that loads and PV generation are on the same phase or phases for this strategy to be effective.

- Install battery storage. This allows excess solar PV output to be directed to the batteries and not to the distribution network. NSPs treat battery systems the same as other forms of generation and consequently they are subject to energy export limitations at times as is the case for the solar PV system by itself (e.g. Clause 5.1.4 in [8]). Battery systems remain quite expensive so a cost/benefit analysis should be undertaken before purchase.

6. Summary

The proliferation of rooftop solar PV systems has led to increased voltage levels at customer premises with the potential of disconnecting the PV inverter from the grid and/or reducing the life of connected electrical appliances.

This Technical Note has outlined what has been done to remedy this problem by changes to the Service and Installation Rules, the Wiring Rules, energy system inverter design/operation standards and NSP generator connection codes.

Finally, suggestions are given about how customers can help keep voltage within specifications by maximising energy consumption during the middle of the day and by the possible installation of battery systems.

7. References & Additional Reading

[1] AS 60038–2012, Standard voltages, Standards Australia.

[2] AS 61000.3.100–2011, Electromagnetic compatibility (EMC) Part 3.100: Limits–Steady state voltage limits in public electricity systems, Standards Australia.

[3] Endeavour Energy, Customer service standards for connection customers, 10 July 2017, Clause 3.2.2.1.

[4] AS/NZS 3000:2018, Electrical Installations (Wiring Rules), Standards Australia.

[5] State of NSW, Service and Installation Rules of NSW, Division of Energy, Water and Portfolio Strategy, NSW Department of Planning & Environment, July 2018.

[6] AS/NZS 4777.1:2016, Grid connection of energy systems via inverters Part 1: Installation requirements, Standards Australia.

[7] AS/NZS 4777.2:2015, Grid connection of energy systems via inverters Part 2: Inverter requirements, Standards Australia.

[8] Endeavour Energy, Grid connection of embedded generation through inverters, Mains Design Instruction MDI 0043, 25 July 2017.

[9] Energy Networks Australia, National distributed energy resources grid connection guidelines: Technical guidelines for low voltage EG connections, ENA Doc 040-2019, December 2019.

[10] Australasian Power Technologies, Inverter power quality response modes, Transmission & Distribution, Issue 5, Oct/Nov 2019, pp30-31.

[11] Energy Networks Australia, “Power Quality Response Modes”, CMPJ0204-02 Draft v2.0, 2019.

8. Australian Power Quality & Reliability Centre

In July 1996, Integral Energy set up Australia's first Power Quality Centre at the University of Wollongong. The Centre's objective is to work with industry to improve the quality and reliability of the electricity supply to industrial, commercial and domestic users. The Centre specialises in research into the monitoring, assessment and control of network and other disturbances affecting the quality of voltage supply, providing input to national and international standards bodies, training in power quality and reliability issues at all levels, and specialised consultancy services for solution of power quality and reliability problems. You are invited to contact the Centre if you would like further advice on quality of supply.

9. About the Authors

Dr Vic Smith commenced his career in 1973 as an engineering cadet with the Sydney County Council electricity distribution utility and concurrently studied for his undergraduate degree at the NSW Institute of Technology, Sydney. Upon graduation, he was employed as an electrical engineer with the Sydney County Council and worked in a variety of areas including zone substation construction, design and maintenance of protection systems for substations and distribution networks, design of distribution networks, estimating for distribution network alterations and additions, routine and type testing of high voltage switchgear, cables and transformers, dielectric evaluation testing, impulse and interference testing of electronic equipment, cable fault location, electromagnetic interference complaint investigations and dissolved gas analysis of transformer oils.

In 1997, Dr Smith joined the Integral Energy Power Quality Centre at the University of Wollongong as a research engineer and was responsible for the day-to-day running of the Centre including administration and budgetary control, research, organisation of courses and seminars, consultancy and publicity.

After 19 years with the Centre Dr Smith formally retired from full-time work in July 2016 but continues his association with the Centre as an Honorary Senior Fellow.

Mr. Sean Elphick graduated from the University of Wollongong with a BE(elec) (hons) degree in 2002. In 2003 he joined the then Integral Energy Power Quality Centre. He is currently the Research Coordinator for the Australian Power Quality and Reliability Centre and provides support for the projects that the Centre is engaged on. This work often involves undertaking power quality surveys and preparing reports. He is heavily involved in the production of the Power Quality Compliance Audit, a power quality survey involving most electricity distributors in the eastern states. His interests lie in power quality monitoring methodology, instrumentation, power quality standards and renewable energy integration.

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