White Paper

Overvoltage – The Hidden Electricity Thief

Background

Electricity supply to end use consumers is comprised of two fundamental components. Voltage is the ‘pressure’ at which electricity is supplied and determines whether appliances and equipment will be able to operate. Current is the ‘volume’ of electricity which flows to consumers, much like the number of litres of water supplied to a home or business. The product of voltage and current (obtained by multiplying the two together) is the power delivered to consumers, measured in kilowatts.

Australian Standard AS 60038 [1] specifies the acceptable voltage range for electricity supply to end use customers. Prior to 2000, the acceptable voltage range for supply to end use consumers was 240V, ±6%. From 2000 onwards, the standard changed to align with international voltage standards, with a nominal voltage of 230V. In order to make the transition easier for electricity companies, an asymmetric voltage tolerance was included, being 230V +10% or -6%.

The Problem

Although the Australian Standard officially changed in 2000, the asymmetric voltage tolerance allowed by AS 60038 has resulted in minimal change from the previous 240V (±6%) system. Traditionally, network engineers have configured the electricity grid for one-way electricity flows and generally regarded higher voltage levels on the low voltage network as a ‘good thing’.

The result is that despite all appliances sold in Australia since 2000 being required to operate with best efficiency at 230V, the actual voltage received by the majority of electricity users for the majority of the time is between 240V and 250V [2] and is continuing to rise with the rapid growth in rooftop solar.

The Energy Security Board (ESB) have identified oversupply of voltage as a key issue, commissioning a study by the University of New South Wales (UNSW) shown in Figure 1 [2]. The study confirmed that the average voltage supplied to most consumers is well above Australia’s nominal voltage level of 230V, stating:

“*Even though the nominal voltage on the grid is 230 volts,* ***the researchers found 95 per cent of readings were higher than that level.***”[2].

The Energy Security Board, said the findings pointed to a *“material level of technical non-compliance”* [3] by the networks, and a *“backlog of compliance issues”* [3] that needed work.

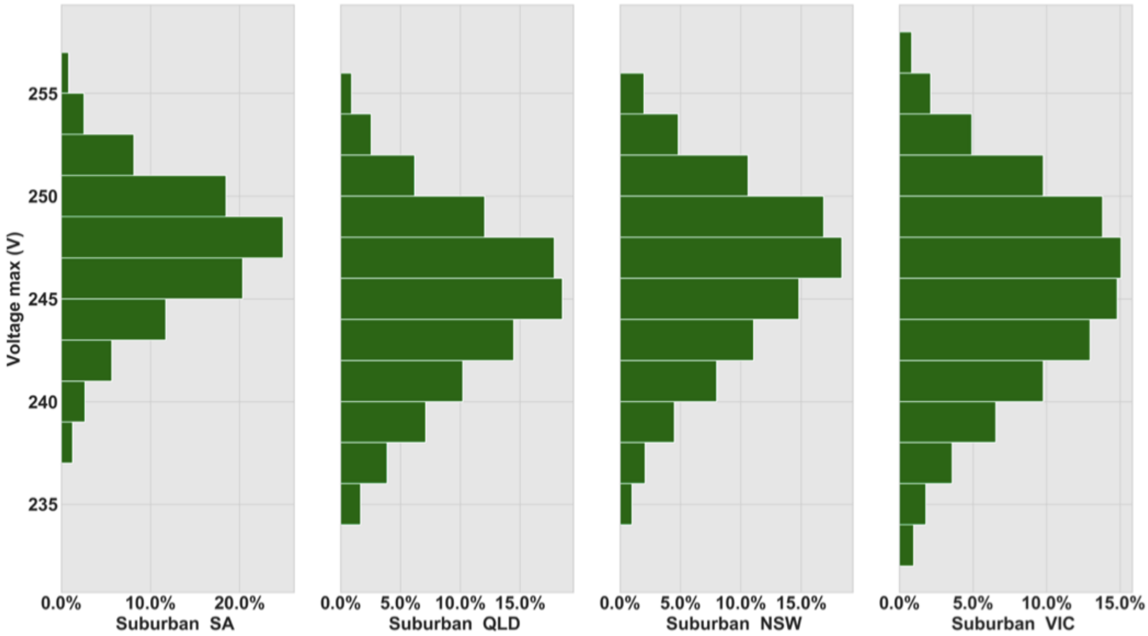

Figure 1: Voltage levels across the NEM from ESB cover note on the UNSW Voltage Report [2]

The issue of oversupply of voltage has also been identified as far back as 2010 by the University of Wollongong National Power Quality Audit, who stated “Since the inception of the survey it has consistently been found that some 25 % - 30 % of LV sites record 95th percentile steady state voltage levels which are above the upper low voltage limit (230 V + 10%).” [4]. An example of the findings is shown in Figure 2:

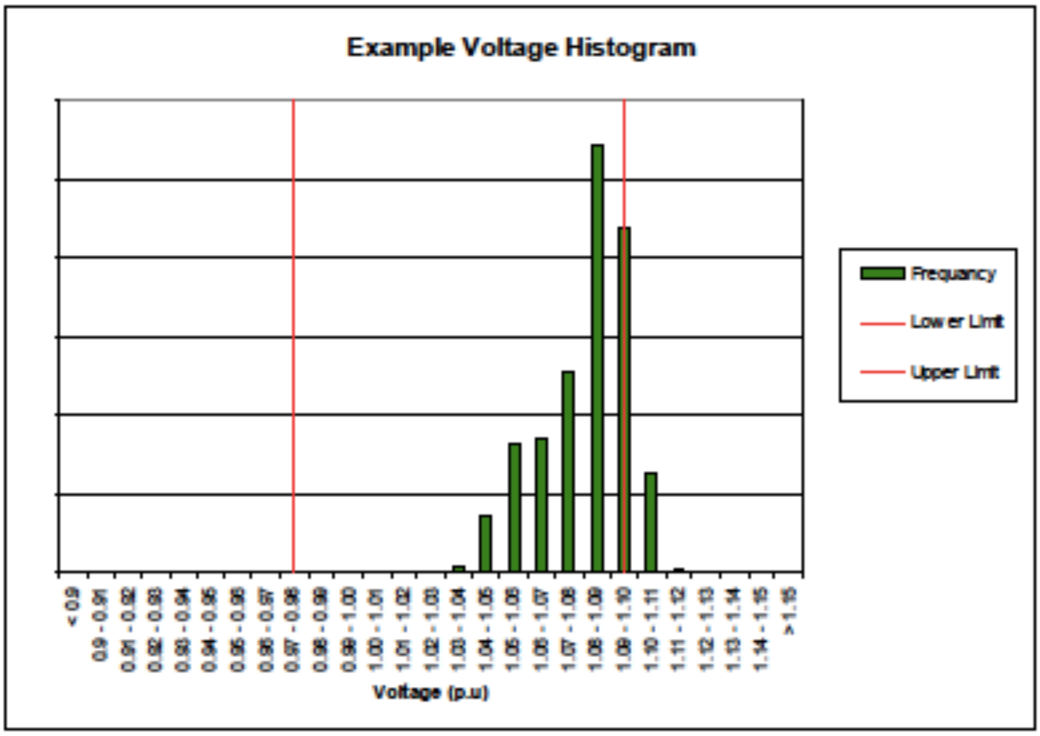

Figure 2: Example Voltage Histogram [4]

Clearly, electricity is currently supplied to the vast majority of consumers at a higher voltage than is needed. Energy is thus wasted unnecessarily on a system-wide scale. The consequences of this problem are:

- Higher bills as consumers are essentially force fed more electricity than their appliances actually require to operate satisfactorily;
- Increased greenhouse gas emissions as more energy than necessary is generated and fed to consumers;
- Reduced appliance lifetimes as appliances designed to operate satisfactorily at 230V are supplied at 240V or more for the majority of their service lives; and
- Less ability of rooftop solar to generate power, as the solar inverters which connect panels to the grid are unable to push their clean power out into a grid which is operating at too high a voltage. This results in tripping of the solar inverters, reducing the energy they deliver back to the grid and also reducing feed-in tariff payments to end-users.

The Technical Solution

The solution to this problem is, in principle, simple: reduce the voltage at which power is provided to reflect the voltage at which it is required, while managing the extremes of voltage observed now. In practice this means reducing the average supply voltage from between 240V and 250V to the nominal Australian Standard of 230V.

Network companies currently control voltage levels and other power quality parameters using traditional technology such as on-load tap changers, voltage control relays and where available information from interval meters (sometimes referred to as smart meters). These control systems mostly lack the ability to control voltage dynamically and monitor the low voltage network in real time, resulting in inefficient solutions which rely on off-line monitoring and inexact estimation of the network status. Moreover, the voltage control systems were never developed to operate an electricity network with multi-directional power flows, such as networks with significant solar generation. Blunt instrument solutions to voltage control and system stability such as shut down of large volumes of solar generation during peak solar output times are increasingly being employed. The advent of further new technology such as electric vehicle charging and distributed battery storage will further highlight the inadequacies of existing monitoring and control systems on the low voltage network, and if left unaddressed will result in more frequent shut down of distributed solar generation.

The challenge with reducing the voltage level across all low voltage networks is that the weakest low voltage networks will not be able to supply voltage above the minimum level specified in the Australian Standard (230V -6% = 216V). It is estimated that the significant majority of low voltage networks will operate satisfactorily at a lower voltage level than they presently operate and that only 5% of low voltage network will require some form of intervention to maintain voltage levels within the Australian Standard lower limit.

Globally voltage reduction is a well-established approach to energy efficiency. The concept is commonly referred to as Conservation Voltage Reduction or CVR. The implementation of CVR results in an increased ability to host distributed generation from solar panels, as well as reductions in energy bills for commercial and residential consumers. In general, the amount of energy it can save depends on the particular load characteristics and the particular characteristics of the network.

International industry research organizations such as the Electric Power Research Institute and Pacific Northwest National Laboratories have conducted laboratory experiments on CVR factors for common residential and commercial appliances. In Australia, the University of Wollongong has studied the effects of voltage on consumer equipment [11]. The research has established that most appliances have a CVR factor of at least 50% and will consume less energy when lowering the voltage. The exception is power electronics-based devices that exhibit near-zero load-to-voltage sensitivity.

One of the concerns people may have with CVR is its impact on electrical devices. However, the research [11] has shown most electrical equipment consumes less electricity without significant loss of performance, adverse consequences or negative impacts on the appliances when operated at a reduced voltage. In fact, they tend to operate more efficiently with reduced voltage, meaning that when supplied at a higher voltage the equipment heats up excessively. An example is shown in the appendix to this paper.

CVR programs have been shown to deliver efficiency factors (EF), which fall in the range 0.6 to 1.0. An EF of 1.0 means a 1% reduction in voltage equates to 1% reduction in energy consumption. Recent trials by Electricity NorthWest in the UK resulted in EFs close to 1.0 [5], while United Energy in Australia found an average EF of 0.7 in its system-wide trials between 2017 and 2019 [6]. The latter EF would correspond to an average energy saving of 0.7% for each 1% reduction in voltage.

Cost/benefit analyses and return on investment

Implementation of a CVR program across the entire Australian National Electricity Market (NEM) would require investment to monitor low voltage levels, reset current operating points and to address the weakest parts of the low voltage networks which will require reinforcement. Low voltage monitoring technology is cost effective and available for deployment on a national scale. Technology solutions to reinforce voltage supply are readily available and generally cost significantly less than the traditional 'build more poles and wires' approach. Ongoing monitoring of low voltage network status and performance will be needed to ensure low voltage networks continue to operate within the Australian Standard for voltage.

The high solar installation levels over much of Australia results in the world's highest household rooftop PV penetration and continuing demand for even more growth gives us the opportunity to catalyse development to become the world-leading developer of easing the global transition to renewable energy. With both low voltage network diagnostics and equipment to rectify voltage issues being developed, managed and sold by Australian owned businesses, there is further opportunity to boost manufacturing and development within Australia and establish Australia's global leadership in smart grid solutions.

It is estimated that a NEM-wide live monitoring and CVR program would cost in the order of $250 million and practically would take two years to fully implement.

The financial benefits which would result from a NEM-wide CVR program have been estimated to be:

- $1.06b / 3.8TWh savings per annum [7] which **is $110 pa per NEM Customer per annum**
- A NEM-wide reduction in peak demand of 1,500MW [8], resulting in avoided future investment in generation, transmission & distribution. **This is equivalent to the Liddell coal fired power station being removed permanently**
- **Emissions saving of 3.07m $tC0_2e$** (NEM) per annum, resulting in $95m pa savings (NEM) [9]. This would accumulate to over 30 million tons of carbon saved over ten years.
- 652 GWh recovered solar energy (NEM) per annum [10] resulting **in $65m pa total consumer savings**
- Increased appliance lives for customers, resulting in $317m savings (NEM) per annum [11] which is $35 pa per NEM Customer
- **Annual Benefits: $1.91b**

The Regulatory Solution

Obviously if CVR presents such a compelling investment case, why has there been such limited action on its implementation in the Australian National Electricity Market? The answer to his question lies within the complex regulatory structures of the electricity industry, and in particular the separation of technical and economic regulation of the industry.

The implementation of CVR comes at a cost, the majority of which would be borne by the distribution network companies, while the majority of the benefits resulting from CVR are experienced by electricity consumers. Within the present regulatory system, nobody who is able to implement voltage reduction solutions has any financial incentive to do so beyond altruism. It is distributors who would need to invest to reduce voltage levels, but it is consumers and the environment who would benefit.

However, distributors would be motivated to make a systemwide investment to reduce voltage levels if regulators made a relatively simple change to the existing Service Target Performance Incentive Scheme (STPIS). The STPIS is a proven successful mechanism for delivering sustainable reliability benefits to consumers.

The STPIS scheme [12] incentivises distribution network companies to implement sustainable improvements to consumer service levels and penalises network companies of service levels decline. The STPIS scheme has an in built ‘cap and collar’ upper and lower limit to the amount of incentive or penalty applied.

The existing STPIS scheme contains a provision for power quality measures within the current framework, however the actual power quality measures are yet to be determined.

CVR could be quickly implemented by including the requirement to monitor and demonstrate improving performance on voltage optimization measures which incentivise a narrower range of actual voltage levels around the 230V target to be achieved over time. This could be implemented with no change to the current ‘cap and collar’ on revenue withing the STPIS scheme. This results in zero risk to consumers.

The AER could incentivise a CVR program with this minor amendment to the existing STPIS incentive program, effectively filling section 4 of the regulation framework by requiring a voltage optimisation measure as part of STPIS, delivering much needed financial relief to individual and small business consumers through bill savings of between 3.5 to 4%.

Conclusion

Energy costs are front of mind for many consumers, particularly individual and small business consumers who are experiencing financial stress due to the global pandemic. Oversupply of voltage to the majority of electricity consumers is endemic and is easily rectified. A simple change to an existing regulatory system which was established for just this purpose is available. Ongoing delay results in consumers paying an excess amount of $108 per annum for their electricity; 3 million tonnes of CO_2 being created unnecessarily; 650 GWh of roof top solar generation going to waste; excess demand of 1500 MW on the electricity grid; and early failure of appliances costing consumers $317m per year.

References

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[7] AER RIN data excluding HV connections and using AEMC analysis of national average residential retail electricity price ($0.28c/kWh)
[8] AER RIN data with average cost $280/MWh during peak events
[9] Emissions reduction 0.83 kg CO2-e/kWh from Australian Government "National Greenhouse Account Factors", July 2017. Carbon price estimated at $30/ tonne CO2-e
[10] Assumes solar penetration of 30%, average solar output of 6000kWh/annum, 10c/kWh feed-in tariff and average 4% solar curtailment
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Appendix 1

How CVR works

The simple example of an incandescent lightbulb illustrates the CVR concept. Granted, incandescent bulbs are being phased out of the electricity grid, but the example is used to illustrate the physics with an easily understood example. The lightbulb is basically a resistor. Using Ohm’s law, the power consumed by the lightbulb varies with the square of the voltage. Therefore, lowering the voltage on the lightbulb will lower the energy consumed by the light. The term “Efficiency Factor” (EF) is used to identify the load-to-voltage sensitivity of an electrical device.

For an ideal incandescent lightbulb, the EF would be 2, meaning reducing the voltage by 1% results in a 2% drop in the energy consumed by the lightbulb. In reality, incandescent lightbulbs are not perfect resistors, because the resistance of the lightbulb changes as the bulb heats up. Laboratory experiments have shown the EF for an incandescent lightbulb is actually around 1.5 because of this effect.

Efficiency Factors are important to understand the impact that reduced voltage has on certain devices. In the commercial arena, induction motors are known to operate as constant power demand loads when operating at their full power. This would imply that loads involving induction motors have a low or even negative EF. Interestingly however, those same induction motors exhibit different load characteristics when they are operating at less than their maximum load [11], exhibiting favourable EF’s under lightly loaded conditions.

Most electrical equipment exhibits a positive load-to-voltage sensitivity (EF). Most equipment has an EF of at least 50% and will consume less energy when lowering the voltage. Some equipment exhibits near-zero load-to-voltage sensitivity. These devices are mostly power electronics-based with switched power supplies that automatically adjust the voltage delivered to the power supplies’ internal components.

The significant diversity of equipment connected within any individual premise or business, coupled to the large volume of connected equipment to any one low voltage feeder network results in aggregated EF’s which are consistently favourable to connected customers [5], [6].

Appendix 2

About the Author

Ty Christopher, is a former General Manager, Asset Management with Endeavour Energy with over 35 years experience in the electricity supply industry. Ty developed and implemented internationally-recognised processes and results in coordinated infrastructure management, including the introduction of risk-based total asset management approaches. He led the establishment of the 'NSW Demand Management Code of Practice' and introduced new technology into the electricity supply industry; such as large scale battery storage, embedded generation, and digital asset management techniques. Ty is the Director Energy Futures Network at the University of Wollongong, focussing on coordinated research into the future of energy supply. In this role, Ty is passionate about reducing customers' energy costs and improving the carbon footprint of energy supply.

Ty holds a B. E. in Electrical Eng (Hons), an MBA (with Distinction), and Advanced Dip. Project Management. He is a Fellow of Engineers Australia, a Chartered Professional Engineer and an Honourary Professorial Fellow at the University of Wollongong.