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Network Services from Distributed Solar PV and Inverters

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Abstract

Networks Renewed is a major new project funded by the Australian Renewable Energy Agency (ARENA) that aims to demonstrate how solar PV, battery storage and inverters can support distribution networks in managing power quality. The path to implementation will be established by two commercial-scale demonstrations of controlled solar PV and energy storage in the regional Mid North Coast of NSW, and suburban Melbourne in Victoria. At the time of this conference the deployment of inverters and control technologies will have commenced towards pilot-scale demonstrations to test candidate control algorithms, several of which have been published in the engineering literature. These will develop into market-scale demonstrations to achieve useful power quality improvements on selected network segments, and also market trading revenues, should these materially improve the financial returns to customers from inverter control.

1. Introduction

1.1. Solar PV growth in Australia and impacts on networks

The Australian solar PV market has seen enormous growth and maturation over a short period of time. This was largely the result of generous incentives, like feed-in tariffs (FiTs) introduced by the state governments around 2008 and 2009 (Chapman et al. 2016). The growth in the solar PV market was accompanied by a significant reduction in system installation costs. Australia now has some of the cheapest installation costs in the world, due principally to a reduction in soft costs over the boom period between 2008 and 2012 (Barbose et al. 2015). In 2012, grid parity was achieved with the levelised cost of electricity (LCOE) of installed solar in Australia competing with residential grid electricity at 20c/kWh (Watt 2012).

The solar PV market is expected to remain steady in Australia with annual distributed grid-connected installations expected to increase marginally every year until 2030 (APVI 2016). It is therefore necessary for electricity grids to be adequately prepared for greater solar PV penetration on their grids. Essential Energy's regional network in New South Wales and United Energy's urban network in Victoria are two such grids in which, on some segments, high PV penetration is presenting voltage regulation challenges.

As of April 2016, there were more than 50,000 rooftop solar PV systems installed in United Energy's distribution network with a total installed capacity of more than 150MW. About 8.7% of customers use grid connected solar PV systems for residential consumption, with the greatest installed capacity per distribution substation occurring around residential complexes, such as retirement villages. Most Australian distribution networks have aging assets that are challenging to manage with high customer densities. The reduction in nominal voltage from 240 V to 230 V has resulted in many existing network segments being set at well above the new nominal voltage, so they are susceptible to voltage excursions with any additional injection of power by solar PV generation. Given that voltage regulation is already a problem with high customer densities, the impact of anticipated growth in solar PV is likely to be significant and will require new voltage regulation tools.

Since 2009, grid-connected solar PV has also risen sharply across Essential Energy's regional networks. Whilst the average installed solar capacity on feeders is relatively low, the variance is large and several feeders have very high installed solar capacity. On long rural network segments, data from Essential Energy have shown that there is a clear link between residential-scale solar PV generation and voltage excursions requiring network investment. Voltage management is challenging on rural feeders as impedance over long distances causes large voltage drops, making it difficult to keep voltage within the required envelope.

Networks Renewed is a major new project funded by the Australian Renewable Energy Agency (ARENA) that aims to demonstrate how solar PV, battery storage and inverters can be a valuable resource for managing power quality through voltage regulation, to help increase the amount of renewable energy that may be connected to Australian electricity distribution networks. The path to implementation will be established by two commercial-scale demonstrations of controlled solar PV and energy storage in the regional Mid North Coast of NSW (with Essential Energy), and suburban Melbourne in Victoria (with United Energy). These demonstrations will be of sufficient scale to achieve useful power quality improvements, and ideally, will achieve revenues from trading energy and ancillary services into the market. They will pioneer the aggregation of distributed solar and storage for voltage regulation in Australia.

1.2. Network solutions

The standard approach to voltage regulation for network businesses is based on an assumption of unidirectional power flow along the feeder that connects a distribution substation with customers. Under this assumption, voltage falls from the substation to the end of the feeder, hence the control problem becomes: *how can voltage be set for customers so that it is not too high at one end of the feeder, but not too low at the other end?*

Table 1 provides a summary of the most common voltage solutions deployed by utilities.

Table 1. Network solutions for voltage control

Network Solution and method of correction	Comments
Transformer taps Distribution transformer, typically with 5 or 7 tap settings at 2.5% voltage increments. Set at highest allowable voltage for minimum demand so that sagging voltage at far end of feeder is within allowable envelope.	Insufficient for longer feeders where voltage sag is very large. Requires manual setting and outage during setting change
On load tap changers (OLTC) Responds to changes in demand, automatically changing voltage at the zone substation without interrupting power supply.	Imprecise measure as voltage is changed for all feeders connected to zone substation. Potentially high maintenance

	with high operation costs.
Voltage regulators and line-drop compensators (LDCs) Power-electronic devices that can maintain voltage at a point in a network feeder under different load conditions. Can be used with LDCs, which maintain constant voltage at location remote to the regulator. Long rural networks often use series voltage regulators (SVRs).	Can provide fast response to sudden voltage change. Can be operated remotely. Available size range limits use to small parts of LV networks.
Network reconfiguration Transfer customers on far ends of feeder to adjacent transformer, or strategically install new transformer.	Limited to more urban networks with multiple customers and transformers in same area.
Load balancing Transfer customers between phases on a three-phase feeder to achieve balanced load, subject to variations between residential customers at different times of the day.	In some circumstances, may help to accommodate a higher number of PV systems.
Capacitors, reactors, and static VAr compensators (STATCOMs) Sinking or sourcing reactive power. Shunt connected capacitors typically installed at substations and switched capacitors along feeders to control reactive power flow, voltage and network losses. Reactors can reduce voltage rise in single-wire-earth-return (SWER) lines.	Flexible set of solutions for different circumstances. Reactive power may not be efficient on highly resistive networks. i.e. X is largely constant per km regardless of conductor type, when R >> X then use of P requires a smaller output and cost.
Reconductoring and upgrading distribution transformers Larger conductors used to reduce network impedance making it easier to regulate voltage within the required limits. For distribution transformers with underground cables and short overhead lines to supply customers, the transformer can be upgraded to a larger power rating.	Allows for future growth in demand and PV capacity. High capital cost.

1.3. Opportunities presented by inverter technologies

Inverters connecting solar PV generators and battery energy storage systems to the distribution network have been vastly improved in recent years. They now have a large and mostly untapped potential to help regulate voltage on distribution networks. Section 2 outlines currently available inverter-based network solutions for voltage control, Section 4 describes deployment and demonstration of inverter solutions in the Networks Renewed project, and Section 5 describes the commercial proposition for delivering these solutions to market.

2. Review of inverter-based solutions

2.1. Inverter market and capabilities

A large number of inverters are now installed across Australian distribution networks connecting 5.2 GW of solar PV capacity. A smaller number of these inverters may be considered "smart" with some of the advanced capabilities discussed in section 2.1.2. In October 2016, a substantially revised version of the Australian standard AS4777 was released. Most inverters presently available in Australia do not meet the new standard, however the new standard ensures that all new inverters will be, in effect, smart inverters.

Compared to solar PV there are not many battery inverters currently installed in the market (probably less than 10,000 units in total) and of those almost none have any smart-grid capability. It is only this year that any significant volume of battery inverters is being deployed into the Australian market with smart-grid functions.

2.1.1. Essential functions of smart inverters

Grid-connected inverters for solar PV and batteries have always had to fulfil basic requirements of network security and personal safety in order to gain connection approval under any country's electricity network standards or "grid codes". They must convert DC electricity to AC at a voltage, frequency, and phase that matches the network so that the network connection is functional and does not create disturbance or damage the device being connected. Another primary requirement is "anti-islanding" where inverters disconnect from the network when the network fails. Anti-islanding is important to prevent network personnel or the general public from unexpected exposure to live electricity cables.

2.1.2. Common functions of smart inverters

Table 2, adapted from Reiter et al.(2015), summarises common functions available with most smart inverters:

Table 2. Common functions of smart inverters, adapted from Reiter et al. (2015)

Function	Description
Connect/disconnect	Physically connects or disconnects from the grid in an orderly way
Adjust maximum generation level	Sets maximum generation that can be used to implement a curtailment order from the network or system operator
Adjust power factor	Adjusts reactive power level to provide a given leading or lagging power factor
Volt-VAr mode	Adjusts reactive power level to an explicit level that may be a function of real power or voltage
Frequency ride-through	Sets frequency parameters governing the conditions under which connection should be maintained
Voltage ride-through	Sets voltage parameters governing the conditions under which connection should be maintained
Event/history logging	Provides logged data on request
Status reporting	Provides status information on request

Smart inverters also have the capability to "ride through" short-term disturbances in frequency or voltage, providing dynamic grid support. When backed up by suitable control systems, smart inverters can quickly change their output in a direction that assists grid stability, as ancillary services and reactive power support.

Battery energy storage inverters are identical to solar PV inverters in almost all respects, however they can have an additional level of functionality. Advanced battery inverters are called “four-quadrant” inverters if they can provide reactive power when charging and discharging the battery, that is, for both positive and negative real power.

3. Potential control strategies

3.1. Basic control strategies

It is estimated that 50-60% of inverters installed since 2013, and all inverters installed from October 2016 under the revised AS4777, have smart capabilities. The available control strategies for a smart inverter acting singly and using only locally-sensed information are simply different ways of setting either the power factor presented to the grid or the reactive power absorbed. Power factor can be set to a constant value or according to the level of real power input or output or the customer voltage. Similarly for reactive power.

3.2. Review of advanced control strategies

Many advanced control strategies exist in the academic literature that have not yet been linked to practical demonstration. These are, however, valuable in presenting several candidate advanced methods that may be considered for the Networks Renewed demonstrations. In general, advanced control can be achieved by local intelligent control in which additional data and sensing are used to improve control decisions by individual inverters or controllers, or aggregated control in which a set of inverters are managed as a group with some central processing based on distributed data and sensing.

All advanced control methods would require some integration with the network management practices of the distribution network business. At the very least, the network operator needs to understand the impact of inverter controls, and to have a model for their anticipated response on each feeder under different load and generation conditions.

3.2.1. Coordinated active power-dependent voltage regulation

A means of voltage control put forward by Samadi et al. (2014) enhances a method proposed by the German Grid Code (GGC). The GGC method employs a generic function of reactive power versus real power, or Q(P) curve, across all PV inverters as a means to control the voltage profile throughout the grid. This does not consider the influence of location of individual inverters or the grid’s voltage profile and therefore can cause unnecessary consumption of reactive power, as well as creating potential instability in the system.

The authors propose to enhance the GGC method by a coordinated approach to calculating the Q(P) characteristics at each PV system using local information and a voltage sensitivity matrix. Each matrix is constructed of submatrices that are derived from partial derivatives of power-flow equations. As this calculation method only relies on local data, no communication between PV systems is necessary.

The study investigated two methods of active power-dependent (APD) voltage control, target bus (TB) voltage regulation and voltage profile (VP) regulation whose control parameters, slope factor (m) and active power threshold (P_{th}) are derived from voltage sensitivity matrices.

Slope factor is derived differently for each method. In the APD-TB method, reactive power is regulated at each node such that voltage variation at the target-bus remains at zero. The APD-VP method, on the other hand, employs weighting factors that identify the importance of voltage regulation at a given bus location compared to other buses. This weighting factor is derived as a function of local voltage magnitude sensitivity indices, which are elements of the local sensitivity matrix. Both identical and non-identical active power thresholds were also considered for each method

3.2.2. Coordinated volt-var control

Juamperez et al. (2014) simulated a control strategy using power factor dependent and voltage dependent reactive power from PV, matched with OLTC to mitigate voltage rise. To optimise active and reactive feed, a multi-objective genetic algorithm is centrally calculated to identify the optimal combination of bus voltage magnitude, transformer tap settings and reactive power inputs for the purpose of maintaining voltage control.

The feeder is divided into four areas, which simplifies formulation of the OLTC reference by allowing it to use average voltages for each area. Each area is given a weighting factor, which identifies the potential effect of reactive power outputs in those buses. Typically this would be related to the distance of the buses to the transformer station.

3.2.3. Coordinated control of energy storage inverters and tap changer transformers

A control strategy explored by Liu et al. (2012) integrates an OLTC transformer control method with coordinated charging and discharging of a distributed ESS. In this system, overall control is achieved through the actions of, and communication between, the tap changer regulator (TPC), the coordination controller (CC), and state-of-charge (SOC) controllers.

As a first response to voltage increase, the tap changer control instigates traditional line drop compensation (LDC) to bring the first bus (Bus 1) back within the system limits. Completion of Bus 1 regulation is communicated to the CC, which then initiates ESS charging only if Bus 2 or Bus 3 are outside voltage limits and if the SOC is less than the nominated SOC maximum. Battery discharge is also regulated by the CC, and is activated by peak load estimation when the SOC is greater than a specified minimum limit.

3.2.4. Coordinated reactive power control with communication between inverters

Castilla et al. (2016) put forward two new reactive power control methods that take advantage of communication capability between inverters.

The first of these novel methods (named Control Strategy 3 in the study) takes a conventional voltage droop function method (analogous to a frequency droop function), and adds a coordinated level of control through communication between inverters. The conventional droop function method simply injects reactive power according to locally measured voltage at inverter *i*. To achieve equal reactive power injection by all inverters, each inverter broadcasts the amount of reactive power it is generating Q_i such that an average reactive power Q_{avg} can be calculated. At this point a proportional-integral (PI) compensator adjusts the conventional droop function to achieve an equalised reactive power.

The second novel strategy (named Control Strategy 4 in the study) takes the same two-level approach to Control Strategy 3. However at the second level of control, where m_i is modified to determine m_a, the objective is entirely different. In this strategy, the droop function is modified to minimise whole system power losses, including those in PV inverters and underground cables. An additional difference in this strategy is the use of a master/slave communication configuration, as opposed to the multi-master configuration used in Control Strategy 3. To adjust the droop function in this strategy, several non-linear optimisation methods are available; this study employed the Nelder-Mead non-linear minimisation method. The optimisation method in this strategy uses a cost function that measures both power losses and the highest voltage occurring at any node. It should be noted that this strategy can result in more burden being placed on particular inverters, depending on their location.

4. Designing an Australian demonstration

4.1. Network characteristics

Australia's interconnected power system is geographically one of the largest in the world, and some customers are very widely dispersed, while others are in high-density urban centres. Very different networks are needed to delivery electrical energy to these customer groups. The Networks Renewed network partners include Essential Energy, which operates many long rural network segments, and United Energy, which includes some of the highest customer-per-kilometre network segments in Australia. As a general rule, urban networks with high customer density tend to have significant reactance per unit length, and voltage regulation strategies using reactive power capabilities of inverters are likely to be effective. In contrast, long rural networks and particularly single-wire-earth-return (SWER) segments are more resistive, and modifying the flow of real power using energy storage is likely to be the most efficient way to manage voltage.

4.2. Deployment and experimental design

The deployment phases of Networks Renewed include a pilot-scale demonstration to implement and test potential inverter control algorithms for voltage regulation until June 2017 at a relatively small scale, and then a market-scale demonstration to ramp up the deployment so that significant network impact can be achieved until June 2018. The demonstrations will deliver market returns as well to test comprehensive business cases for the project partners. The two network partners in Networks Renewed have segmented their demonstrations to achieve a good coverage of network conditions of interest to them.

4.2.1. Pilot-scale demonstrations

United Energy will test five solar-storage units at diverse customer sites to measure the local influence of inverter controls in different circumstances, and another five solar-storage units at customer sites on a single distribution substation to test methods for coordinated inverter actions using different control algorithms.

Essential Energy will test storage units at approximately 30 customer sites near the end of a lengthy rural distribution feeder where demand variance and solar PV generation is creating voltage excursions, and advanced solar PV inverters at approximately 10 customer sites in an urban setting where reactive power controls are expected to be efficient for regulating voltage.

4.2.2. Market-scale demonstrations

From July 2017 both network partners will expand the scale of their demonstrations on a semi-commercial basis: that is, with some subsidy to reflect anticipated near-term reductions in the cost of battery energy storage, but otherwise following a commercial model that is intended to be scalable and replicable on other networks. United Energy will increase the number of solar-storage units under control until there is sufficient network impact to provide a useful voltage correction. Essential Energy will increase the total number of inverters under control depending on the outcome of pilot demonstration and on customer appetite for the technology.

An important dimension being tested by Networks Renewed is the ownership model for energy storage to allow inverter control to provide voltage regulation services. United Energy is following a utility-ownership model in which the customer makes a contribution to the cost of storage that is controlled to their advantage while also providing network services. Essential Energy is following a customer-ownership model in which customers purchase energy storage outright, and obtain revenues for providing network services.

The revenues in the Essential Energy model are passed on via another Networks Renewed partner, Reposit Power, that controls distributed customer inverters for both customer and network benefits, in return for network services payments from the network business. This is an untried business model in Australia and rare worldwide.

5. The commercial proposition

5.1. Value propositions

Battery energy storage is a multi-purpose tool and its many applications can provide value to several stakeholder groups: customers, network businesses, retailers, and the market (and system) operator as shown in Table 3. Capturing multiple types of value simultaneously is called “value stacking” and this has been the goal of energy storage proponents since this potential was realised (Eyer & Corey 2010). Both the Victorian and the NSW demonstrations for Networks Renewed create the potential to achieve stacked benefits, at least for customers and the network operator.

Table 3. Potential Stacked Benefits arising from distributed Battery Systems

Stakeholder	Stacked Benefits
Customer	Increase in return on investment (ROI) of PV asset via energy arbitrage and self-consumption of solar energy. Accessing value from network support services for the local distribution business. Market returns from contingency services for the system operator and participation in aggregated trades in the wholesale energy market.
Network	Managing network voltage through battery inverter capabilities. Managing peak demand and peak local supply to defer network augmentation, perhaps indefinitely, leading to a capital offset value stream. Sharing the cost of storage and value obtained from it with customers to give economically efficient outcomes on both sides. Managing the increased variability of net customer demand due to increased residential solar uptake. Improving network reliability, though this is not clear or well understood at this time.

Retailer	Diversifying its business model. Improving customer retention rates. Hedging risks on the wholesale market. Accessing value from providing ancillary services. Accessing valuable data from their customers to gain an insight into how they consumer their energy. New way of communicating and engaging with their customers.
Market	Greater access for new market participants to broaden market competition.

5.2. The regulatory landscape

As noted in Section 1, FiTs played a large role in the expansion of the Australian solar PV market, however, most FiTs have now been dramatically reduced or removed altogether. Presently, consumers pay around 5-7c/kWh for electricity they feed into the grid, which is around 15 to 20c/kWh lower than the retail price of electricity. The issue of FiTs has been historically divisive, leading to volatility in policy and uncertainty in investment. Now that the market has matured, however, it is more pertinent to discuss incentives in terms of how they reflect the full spectrum of benefits of distributed energy resources. A recent report by the Essential Services Commission (2016), for example, found that the value of solar energy depends on when and where electricity is fed into the grid. The report argued that solar energy is more valuable when exported to the grid at times of peak demand and should also be valued for reducing transmission losses.

For Networks Renewed, the key technology standards that will impact deployment of demonstrations are: AS/NZ 4777.2:2015 – Grid connection of energy systems via inverters; AS4755-2007 – Demand response capabilities; and AS61000.3.100 – Steady state voltage limits in public electricity systems. The key updates from the newest version of standard AS/NZS 4777.2:2015 are that multiple phase systems now have a balance requirement; set-points and limits are now required to match those of DNSPs; inverters must have a demand response and power quality response mode; and, electricity safety requirements must align with international standards. In essence, AS/NZ 4777.2 will help align inverters with international standards (Harris 2016).

Changing technologies have, in the past, created challenges for network operators, leading to restrictions on grid-connected systems. For example, in Queensland Energex and Ergon originally restricted exports to the grid from battery storage until they could better understand management and impact implications. These export bans have been lifted with the production and release of the AS4755 Demand Response Enabled Device standard including energy storage devices.

6. Conclusion

The Networks Renewed project will demonstrate the potential of currently available smart inverter technology to improve power quality on the electricity grid through distributed solar PV and battery storage. This is an important step in addressing the ever-increasing penetration of distributed energy resources on Australia’s grids. Pilot scale and market scale demonstrations in both NSW and Victoria will see the deployment of inverters and storage devices to customer households. These will test a variety of smart control measures to influence power quality with a particular focus on voltage regulation. The project will then assess the value added to the grid and the electricity market by such measures and explore potential business cases that leverage this value.

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