



ADDRESSING GRID-INTERCONNECTION ISSUES WITH VARIABLE RENEWABLE ENERGY SOURCES

SUMMARY DOCUMENT

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About IT Power

The IT Power Group, formed in 1981, is a specialist renewable energy, energy efficiency and carbon markets consulting company. The group has offices and projects throughout the world.

IT Power (Australia) was established in 2003 and has undertaken a wide range of projects, including designing grid-connected renewable power systems, providing advice for government policy, feasibility studies for large, off-grid power systems, developing micro-finance models for community-owned power systems in developing countries and modelling large-scale power systems for industrial use.

The staff at IT Power (Australia) have backgrounds in renewable energy and energy efficiency, research, development and implementation, managing and reviewing government incentive programs, high level policy analysis and research, including carbon markets, engineering design and project management.



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1 INTRODUCTION

Distributed generation (DG) technologies connect to the distribution network and while they can have positive impacts on that network, they can also have negative impacts at high penetrations if appropriate measures are not implemented. Photovoltaic (PV) systems are being rapidly deployed at an increasing rate and are reliant on a source of energy that can fluctuate daily, hourly and over even shorter periods. Although PV is the predominant focus of this Summary Document, the discussed grid impacts capture all those that other DG technologies (such as wind) are likely to have. Potential high penetration impacts include voltage fluctuations, voltage rise and reverse power flow, power fluctuation, impacts on power factor, frequency regulation and harmonics, unintentional islanding, fault currents and grounding issues.

This Summary Document is derived from the report 'Addressing Grid-interconnection Issues in Order to Maximise the Utilisation of New and Renewable Energy Sources' written for the APEC Energy Working Group. It describes each of these impacts along with the current approaches to address them. It is clear there is no 'one size fits all' solution for any of these impacts, and the technical solutions may not be implemented because of lack of appropriate policies and institutional frameworks. Thus, this Summary Document concludes with the need for government involvement and recommendations for further work.

2 ADDRESSING GRID INTEGRATION ISSUES

2.1 Voltage fluctuation and regulation

Voltage fluctuation is a change or swing in voltage, and can be problematic if it moves outside specified values. Extended undervoltage causes "brownouts" – characterised by dimming of lights and inability to power some equipment. Extended overvoltage decreases the life of most equipment and can damage sensitive electronic equipment.

DG systems are relevant to voltage regulation because they are not only affected by voltage fluctuations that occur on the grid, but can cause voltage fluctuations themselves – where the latter effects can be divided into voltage imbalance, voltage rise leading to reverse power flow, and power output fluctuations.

2.1.1 Grid-derived voltage fluctuations

Inverters are generally configured to operate in grid 'voltage-following' mode and to disconnect DG when the grid voltage moves outside set parameters. This is both to help ensure they contribute suitable power quality as well as help to protect against unintentional islanding. Where there are large numbers of DG systems or large DG systems on a particular feeder, their



automatic disconnection due to the grid voltage being out of range can be problematic because other generators on the network will suddenly have to provide additional power.

To avoid this happening, voltage sag tolerances could be broadened and where possible, Low Voltage Ride-through Techniques (LVRT) could be incorporated into inverter design. LVRT allows inverters to continue to operate for a defined period if the grid voltage is moderately low but they will still disconnect rapidly if the grid voltage drops below a set level. In Germany, LVRT standards are now incorporated into grid-connection standards.

Inverters can also be configured to operate in 'voltage-regulating' mode, where they actively attempt to influence the network voltage. Inverters operating in voltage-regulating mode help boost network voltage by injecting reactive power during voltage sags, as well as reduce network voltage by drawing reactive power during voltage rise. However, Australian Standard AS4777.2 requires that inverters operate at close to unity power factor (ie. inject only real power into the grid) unless they have been specifically approved by electricity utilities to control power factor or voltage. In addition, even in voltage-regulation mode external factors may force the voltage outside normal limits – in which case the inverter disconnects.

Thus, connection standards need to be developed to incorporate and allow inverters to provide reactive power where appropriate, in a manner that did not interfere with any islanding detection systems. Utility staff may also need to be trained regarding integration of such inverters with other options used to provide voltage regulation - such as SVCs (Static VAR Compensator) or STATCOMS (static synchronous compensators).

2.1.2 Voltage imbalance

Voltage imbalance is when the amplitude of each phase voltage is different in a three-phase system or the phase difference is not exactly 120°. Single phase systems installed disproportionately on a single phase may cause severely unbalanced networks leading to damage to controls, transformers, DG, motors and power electronic devices.

Thus, at high PV penetrations, the cumulative size of all systems connected to each phase should be as equal as possible. All systems above a minimum power output level of between 5-10kW typically should have a balanced three phase output. The maximum single phase power rating will depend on local conditions and the network to which they are connected.

2.1.3 Voltage rise and reverse power flow

Traditional centralised power networks involve power flow in one direction only: from power plant to transmission network, to distribution network, to load. In order to accommodate line losses, voltage is usually supplied at 5-10% higher than the nominal end use voltage. Voltage regulators are also used to compensate for voltage drop and maintain the voltage in the designated range along the line.



With the introduction of distributed generation, power flows and voltages in the network are determined by the mix of centralised and distributed generators as well as the load. With significant levels of DG on feeders, localised overvoltage can occur, and the voltage at the load end may be greater than the voltage on the normal supply side of the line – this is known as the voltage rise and can result in reverse power flow.

The most common technical impact of reverse power flow is activation of network protection devices designed to stop ‘upstream’ current flow. Destabilisation of voltage regulators’ control systems can also occur - because they are not designed for both forward and reverse power flow. In addition to having negative impacts on end-use equipment, voltage rise can have negative customer equity impacts for system owners towards the end of the line as the voltage rise will be greater at that point.

The four most common approaches currently used to minimise voltage rise and reverse power flow are applied to the PV systems themselves and involve (i) ensuring PV systems are smaller than the daytime load, (ii) use of a minimum import relay (MIR) to disconnect the PV system, (iii) use of a dynamically controlled inverter (DCI) to gradually reduce PV output, and (iv) use of a reverse power relay (RPR) to disconnect the PV system if the load drops to zero or reverses direction.

Of these, a DCI set to maximise PV output while avoiding export would allow greatest use of the PV system. However, all these measures not only limit voltage rise but also restrict the potential penetration of PV systems, limiting their contribution to sustainable energy production. Alternatives to these revolve around changes to the network or customer loads, and while they are not currently used, they could be implemented with appropriate policy settings.

They include (i) decreasing the network’s series impedance so that it has low voltage drop along its length, (ii) requiring customer loads to operate at improved power factor, (iii) requiring customers with large loads (who create the need for the high upstream voltage), to incorporate some form of load-shedding scheme, (iv) the use of discretionary loads at times of high network voltage, to soak up the extra power provided by PV, and (v) the use of storage to soak up the extra power provided by PV. All these may cause inconvenience and incur costs for stakeholders who do not necessarily benefit directly from the PV systems. In addition, large loads suitable for load shedding and discretionary loads may not be readily identified.

Thus, optimising PV output, operation of loads and the structure of the network is likely to require appropriate coordination/management of the different stakeholders and options available to them. It essentially requires some mix of investment in lower impedance infrastructure as well as in complex monitoring and control functionality in order to achieve voltage regulation throughout the distribution network. This is not a trivial task and indicates an important role for government and appropriate policy.



2.1.4 Power output fluctuation

Fluctuations in power output are an inherent problem for DG reliant on renewable energy resources such as sunlight and wind. Short-term fluctuations (seconds) can cause problems with power quality (both voltage and power factor, that can manifest as light flicker or variable motor speed for example), while longer term fluctuations require back-up generation to maintain power supply. Short-term fluctuations can also result in tap-changers and capacitor switches continually 'hunting' as they attempt to maintain power quality, which results in increased wear of these devices, as well as an increased number of switching surges.

Three approaches to minimise the impact of such fluctuations are geographical dispersion, forecasting and storage. Other options to manage such fluctuations involve the use of voltage control and are discussed below in Section 2.2. It is likely that coordinated use of all these approaches is likely to be required to minimise power output fluctuation from renewable energy generation.

2.1.4.1 Geographical dispersal

Short term intermittency of PV can be reduced through geographical dispersal. Very little or no correlation in output over 1 min time intervals has been found for sites as little as 2 kms apart and even within a single 13.2MW PV plant. However, as the assessed time intervals increase, the level of correlation increases, but the greater the distance between sites, the lower the correlation. Note that dispersal is not as feasible in relatively small areas that are subject to the same weather conditions (for example, on network feeders) and of course is only effective during daylight hours.

2.1.4.2 Solar forecasting

Solar forecasting is a technique that is currently being developed through international efforts to provide better forecasting and management tools to manage the variability of intermittent solar energy (both PV and solar thermal). Forewarning that output is likely to diminish could be used to prepare alternative sources of power, and output by solar plants could even be preemptively curtailed in order to reduce the ramp rate required by backup generation.

2.1.4.3 Storage

Various types of storage including batteries, electric double-layer capacitors, Superconducting Magnetic Energy Storage (SMES), flywheels, compressed air and pumped hydro can be used to regulate power output. In addition to reducing the amount of voltage rise on feeders, storage can be used to provide services such as peak shaving, load shifting, demand side management and outage protection. Storage can help defer upgrades of transmission and distribution systems, and can help with 'black starts' after a system failure. It can also help provide several ancillary services, including contingency reserves (spinning reserve, supplemental reserve, replacement reserve), and voltage and frequency regulation.



However the costs, benefits, maintenance, reliability and life cycle of storage systems are still being improved. Systems having separate batteries associated with each DG system, separate batteries associated with each DG system but under coordinated operation, and a single battery at the community level are being investigated. While batteries and other forms of storage have significant potential to enable higher penetration of many types of DG, realising that potential will not only require careful consideration of how best to develop storage options, but also how to integrate them into electricity networks along with DG.

2.2 Power factor correction

Poor power factor on the grid increases line losses and makes voltage regulation more difficult. Inverters configured to be voltage-following have unity power factor, while inverters in voltage-regulating mode provide current that is out of phase with the grid voltage and so provide power factor correction. This can be either a simple fixed power factor or one that is automatically controlled by, for example, the power system voltage.

A number of factors need to be taken into consideration when using inverters to provide power factor correction.

(i) to provide reactive power injection while supplying maximum active power, the inverter size must be increased.

(ii) the provision of reactive power support comes at an energy cost, and how the VAR compensation is valued and who pays for the energy has generally not been addressed.

(iii) simple reactive power support can probably be provided more cost-effectively by SVCs or STATCOMS, which have lower energy losses, however inverter VAR compensation is infinitely variable and has very fast response times. In areas where rapid changes in voltage are experienced due to large load transients (eg. motor starts) then an inverter VAR compensator may be justified.

(iv) while this sort of reactive power compensation is effective for voltage control on most networks, in fringe of grid locations system impedances seen at the point of connection are considerably more resistive, and so VAR compensation is less effective for voltage control. In these situations, real power injection is more effective for voltage regulation.

Studies into the use of inverters to regulate network voltage at high PV penetrations have found that in order to achieve optimal operation of the network as a whole, some form of centralised control was also required. In addition, reactive power injection by inverters may be limited by the feeder voltage limits, and so coordinated control of utility equipment and inverters, as well as additional utility equipment, may be required.

2.3 Frequency variation and regulation



Frequency is one of the most important factors in power quality and must be uniform throughout an interconnected grid. Disruptions in the balance between supply and demand lead to frequency fluctuation. Frequency regulation is generally maintained by control loops built into the power generating sources on the network.

With the increasing penetration of intermittent energy sources such as wind and solar, frequency control becomes more difficult. Although the contribution to power fluctuation from PV systems is currently much smaller than that from wind turbines, as the number of grid-connected PV systems increases, the issue of frequency fluctuation will become more noticeable.

DG inverters may of course be able to help with frequency control, and can provide frequency control in milliseconds, which is significantly faster than conventional generation. However, special control algorithms would need to be developed to take advantage of the fast response times, and at present DG is unproven in this application.

Note that inverters can only provide frequency control when they can inject power into the network (eg. during daylight hours for PV), and DG linked to combined heat and power plant are restricted in their ability to provide frequency regulation because of their thermal loads.

Most importantly, where inverters are configured to disconnect from the grid when the frequency moves outside set limits (as a form of islanding detection), their ability to provide frequency support may be compromised. If the power system frequency falls outside the trip limits then all the DG will also disconnect, exacerbating the power imbalance and leading to a need to shed more load to avert a complete system shutdown. New frequency ride through systems that do not interfere with the anti-islanding protection systems will need to be developed to cope with this situation as penetration levels increase.

2.4 Harmonics

Harmonics are currents or voltages with frequencies that are integer multiples of the fundamental power frequency. Electrical appliances and generators all produce harmonics and in large volumes (eg. computers and compact fluorescent lamps), can cause interference that results in a number of power quality problems.

The existing inverter standards in Australia (AS4777.2) for small PV systems require that the inverter must produce less than 5% total harmonic distortion on injected current with tight limits on specific harmonics. This is much more stringent than for loads of equivalent rating. Most grid-connected inverters for DG applications put out very low levels of harmonic current, and because of their distribution on the network are unlikely to cause harmonic issues, even at high penetration levels.

While the most common type of inverters (current-source) can not provide the harmonic support required by the grid, voltage-source inverters can, but do so at an energy cost and there are a variety of harmonic compensators that are likely to be cheaper. Labeling that identifies the type of



inverter (voltage or current source) would help purchase of voltage source or current source inverters as required, as would financial compensation for reducing energy losses if voltage source inverters are installed. Note that, unless specially configured, PV inverters disconnect from the grid when there is insufficient sunlight to cover the switching losses, meaning that no harmonic support would be provided outside daylight hours.

2.5 Unintentional islanding

Unintentional islanding occurs when distributed generation delivers power to the network even after circuit breakers have disconnected that part of the network from the main grid. This can cause a number of different problems including safety issues for technicians and the general public, maintenance of fault conditions and damage to equipment.

Since islanding is a well-known problem, grid inverter technology has developed to include anti-islanding features as are required by local regulations and standards. Islanding detection methods can be divided into five categories: passive inverter-resident methods, active inverter-resident methods, passive methods not resident in the inverter, active methods not resident in the inverter, and the use of communications between the utility and DG inverter.

As outlined in the main report, each of these approaches has strengths and weaknesses that relate to possible non-detection of islanding and reduced power quality – but only in unusual circumstances. In addition, on a weak grid, an inverter may cut out prematurely or, more likely, may not reclose rapidly enough (ie. reconnect to the grid). In this situation, the network operator could specify more reasonable tolerance limits and shorten the reclose time, or some form of short-term storage could also be used to bridge the gap.

The best options to improve islanding detection may be those based on improved communications between the utility and the inverter. These could help overcome the problems associated with failure to detect an island condition, with false detection of island conditions, and failure to reclose and so provide grid support. However, because such a system is unlikely to be perfect, it should include some redundancy in the form of autonomous active island detection options. Communications-based systems are also likely to be higher cost.

It is likely that different mixes of these methods will be required in different locations, and that phasing out or replacing less effective methods will not be a simple task, and will likely involve a coordinated approach by government, utilities and installers and owners of DG systems.

2.6 Other issues

Other issues, that are of less importance and for space reasons have not been included here, include fault currents and effective grounding, DC injection and high frequency waves and of course the impacts of DG on subtransmission and transmission networks.



3 CONCLUSIONS

3.1 Possible impacts of DG on networks

When considering increasing levels of penetration of DG in electricity networks, it must be remembered that the original design of networks did not envisage DG in the distribution system. The design of networks was based on more centralised generation sources feeding into the transmission system, then subtransmission and distribution systems. The security, control, protection, power flows and earthing of the network was predicated on a centralised generation model with a small number of source nodes, with communication and control linking major generators and nodes. When installing DG, very low penetration (typically 5-10% of connected load) on a distribution system can generally be tolerated without significant problems. The threshold where problems occur depends heavily on the configuration of the network, length of lines involved (and hence impedances) and the concentration and time dependence of the load and generation in the area.

When penetration of DG rises above the minimum threshold to moderate levels of penetration (typically 10-20% of connected load) more significant issues arise in the network. More DG may be accommodated by making changes to the network such as minimising VAr flows, power factor correction, increased voltage regulation in the network and careful consideration of protection issues such as fault current levels and ground fault overvoltage issues. In many countries, the level of penetration is already at this middle stage and significant network modification is under consideration to allow expansion of DG without taking the next significant step of major design and infrastructure change.

At high levels of penetration, a point is reached (which is very network dependent) where significant changes have to be made to accommodate these higher levels of DG. This third stage will probably require significant overall design and communications infrastructure changes to accommodate coordinated protection and power flow control. Although there are a number of communications protocols developed for distributed generation, the use, coordination and the design philosophy behind this are very much under research and development, the microgrid concept being one example. The full use of microgrids within the wider electricity network is again still very much in the R&D stage.

There is increasing pressure to quickly implement DG on electricity networks, but to do this without careful preparation beyond a relatively low penetration level will require the development of safe and carefully integrated protection and control coordination.

3.2 The need for government involvement

The types of technology solutions likely to be required may be different in different jurisdictions, simply because they have different electricity networks, different renewable energy resources,



different mixtures of conventional and renewable energy generators, different matches between generation and load, different government priorities and ultimately, different technical capacities within government and the private sector.

Thus, addressing these technical problems requires more than just the technical solutions described above. It will require policy and regulatory frameworks to coordinate the development and deployment of the different technologies most appropriate for particular areas. These frameworks may be different for different jurisdictions, and so no single approach is likely to be appropriate.

If governments choose to put in place appropriate regulation, standards and agreements, and put in place the related mechanisms for enforcement, then best practices are more likely to be implemented. Of course for this to occur, the government needs to know what is required, based on industry research and expert advice.

Government and educational institutions may need to assist with information dissemination (regarding new rules and regulations), promotion of the use of best practices and facilitation of training for the appropriate public entities and private companies. This could be an important factor in some regions, because inadequate technical capability will restrict the uptake of best practice, even if the willingness is there. Governments will need to balance the introduction of the regulations and standards with provision of adequate training.

3.3 Recommendations for further work

3.3.1 Technical projects

3.3.1.1 High penetration of larger-scale RE into transmission networks

This project would be similar to the project reported here but would focus on the transmission-level impacts of larger-scale intermittent RE. It could initially involve a desktop review of work undertaken worldwide that identified the issues along with the various approaches being used to minimise any negative impacts, then could identify best practices as well as required R&D activities.

3.3.1.2 Standards

There are many different renewable energy and grid connection standards in place in different countries and even within some countries. A comprehensive survey could be used to determine what standards exist across a range of Committees including PV, wind, utility committees within the IEC and in the US (IEEE). This could include an assessment of the degree to which they promote or inhibit uptake of RE and changes being made in some countries to accommodate more renewables. The project could then comment on possible improvements and where there needs to be more discussion and/or research to identify best practice. This project could also



comment on possible improvements to standards for end-use equipment that would assist with DG penetration (eg. harmonics and power factor). In addition to focusing on technical standards, it could look at non-technical issues such as grid-connection agreements with utilities.

3.3.1.3 *Case study projects of high penetration RE DG in remote areas*

Case studies can be used to highlight both best practice and worst practice, but possibly most importantly, how to turn a substandard project into best practice. The following case studies are for particular locations and projects but here are used as examples of how to highlight best and worst practice in three different scenarios: (i) high penetration PV, (ii) integration of battery storage with wind and solar, and (iii) a comparison of projects that have wind/flywheel storage, PV/ flywheel storage and PV/no storage. There are many other projects that could be drawn on to illustrate best and poor practice. These should be chosen to be representative of the different types of projects in different jurisdictions. They could be made available through a web-based searchable database in a standardised format that could include contact details of people closely involved with the project. Such a database could even allow project operators to enter their own project's details, which could then be vetted by a moderator. This could allow very rapid development of a comprehensive database with reduced effort.

High penetration PV

At Umuwa solar farm in Australia a 300kWp solar system has been connected to a 600-1200kWp grid. This has resulted in 40-50% RE penetration that has resulted in poor quality control, outages and diesel stations not generating at optimal efficiencies. As a result, the government is more reluctant to develop remote RE systems. Similarly, high penetration of renewables on the Hawaii islands have reduced fuel use but have also created grid management issues. By reviewing the history of such projects, including the processes that were followed for project development, as well as the technical outcomes, valuable lessons may be learned for others who are considering similar projects.

Integration of battery storage with wind and solar

At King Island in Australia a combined wind/solar system with battery storage is a good example of poor integration of these technologies on a remote grid, and it is preventing further integrated projects of a similar nature. It would be useful to understand why the battery storage did not work as expected, as well as carry out a theoretical assessment of other viable storage/integration technologies that could be used (eg. flywheels). This could be compared to projects considered to have been more successful, or trials which have more carefully examined the issues, such as those at McAlpine Creek or Sacramento Municipal Utility District, USA.

Comparison of different projects with high renewable penetration (wind/flywheel storage, PV/ flywheel storage and PV/no storage)



The RE system at Coral Bay in Australia uses wind/flywheel storage, the Marble Bar system uses PV/flywheel storage, while the Norfolk Island uses only PV with no storage. US examples use Li-ion and ZnBr batteries, with and without load and grid management changes. A comparison of such systems would provide valuable information regarding their relative effectiveness and costs. This may help identify the storage issues on small grids that are too large for batteries, but have a significant penetration of RE.

3.3.2 Non-technical projects

3.3.2.1 *A handbook of best practice policies*

Appropriate policies are not only required to directly drive uptake of RE but also enable the development of the industry more generally, especially in terms of innovation. Staged development of the renewable energy industry requires a framework of policies that changes over time as the industry moves through different stages of development. In addition to policies that drive uptake, such a framework needs to help with the development of other aspects of industry development such as grid-connection agreements, local government regulations including solar access, the application and enforcement of standards, training and accreditation of technicians, and information and awareness raising etc. Many different policies and variations of policies are currently used worldwide with differing degrees of success, and it can often be the details of a policy design that can distinguish between success and failure. There is a need for a concise summary of the different policies that are available, their pros and cons and the circumstances in which they are most likely to be required and effective. This should include how such policies can be managed over time as the RE industry moves through different stages of development. Policy-makers are generally very time poor and so it is possible that rather than a hard copy handbook, the outcomes of this project may be better communicated through a web-based resource, the core of which was a concise summary with links to more detail on particular policies as required. The outcomes of this project could be updated annually through such a database to take account of latest best practice developments in technologies, products, installation methods, standards and regulations.

3.3.2.2 *Training package for regulators and policy-makers for best practice RE*

Policy makers and regulators do not necessarily have access to information on best practice RE technologies and how to promote it in their own jurisdictions. In order to enhance their regulation and policy-making capacity, a short/intensive training package could be developed covering the basics of regulation/policy making and promotion of best practice RE. This could be based on the handbook of best-practice policies above but could include more technical information and be structured in a format suitable for training, most probably through workshops. It could also be targeted to suit particular audiences depending on where the workshop is held. As a result, policy-makers & regulators will be more aware of types of best practice RE which are likely to suit



the way their own energy system is regulated. This will enable faster adaptation of energy policies and regulations to facilitate uptake.

3.3.2.3 *Training package for utilities and RE installers for best practice RE*

Utilities and RE installers do not necessarily have access to information on best practice RE and how to promote it in their jurisdictions. In order to enhance their technical capacity a short training package could be developed covering the basics of best practice technical options for RE. This could include:

- i) Review of advantages of RE for urban and rural areas, with a focus on best practice
- ii) Review of current technical best practice for selected countries.
- iii) Case studies, examples and an analysis of the current situation in a number of jurisdictions / projects involving RE
- iv) Examples of where adoption of best practice has proved to be effective for the development of sustainable energy technologies
- v) Tools/suggestions for utilities and RE installers to take appropriate and tailored actions.
- vi) Workshops for the outcomes of this project to be communicated to utilities and RE installers

Utilities and RE installers will become more aware of best practice RE, which will enable faster adoption of best practice RE. This could take the form of a handbook as well as workshop materials that could be updated annually to take account of latest best practice developments in technologies, products, installation methods, standards and regulations.

3.3.2.4 *Community ownership of RE projects*

In different countries various models have been used to promote and enable community ownership of RE systems. This allows ownership by people that may not be able to afford their own system or have the space or technical capacity to develop one. It can also help reduce system costs through economies of scale and can, for example, result in PV systems being placed on commercial networks where output is better matched to demand. It would be useful to survey the different approaches taken globally to enable community-ownership of RE systems, and so develop models that could be applied in different jurisdictions depending on their circumstances.



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