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Voltage Control and Impact of Increasing Harmonics Associated with Power Converters in Wind, Solar and Battery Farms

Background on South Australian Power System

The South Australian power system is a 3 GW system that is at world leading penetration of both grid connected and embedded (within the distribution system) renewable generation sources. The majority of these generation source use power converters or inverters.

The South Australian network on has two interconnectors. One is a double circuit AC power line with a rating of ± 650 MW. The second is a single circuit DC interconnector with a rating of ± 200 MW. The power flow across the DC interconnector is governed by MW setpoints as determined by the national dispatch control system. The DC interconnector does not automatically alter its MW power flow following network events. However, it provides local voltage support similar to an SVC or STATCOM. Design has started on a third interconnector consisting of a new double circuit AC power line with a rating of ± 800 MW, but it will not be available for full power transfer until late 2024 at the earliest.

The South Australian network has summer peak loads in the range of 2700 to 3200 MW. The winter peak loads are in the range of 2000 to 2400 MW. The average load is approximately 1400 MW. The minimum system demand has now dropped to 117 MW. This is purely driven by the amount of embedded solar PV within the distributed network. AEMO the national network operator is predicting that in 2023 there will be times when the minimum system demand will fall to zero or even become negative. This is likely to occur during lunch time or solar noon during spring and autumn. This type of system demand behaviour is now referred to the ‘Duck Curve’.

There is a total of approximately 3100 MW of synchronous generation. All of this plant is fossil fuel fired, using natural gas and diesel. The only two coal fired power stations were retired in 2017. Some of the existing plant is expected to retire in the next 2 to 3 years.

There is a total of approximately 2700 MW of grid connected renewable non synchronous generation connected to the network consisting of :

- 2100 MW of wind power
- 400 MW of solar PV, and
- 200 MW of battery

There is a number of wind, solar and battery facilities currently under construction or being commissioned.

There is approximately 1800 MW of embedded solar PV, which mainly consists of residential and commercial installations.

Currently 68% of all electricity is generated by renewable sources, which is considered as being world record penetration for a GW scale network with such limited interconnector capacity.

Issues That Have Emerged with Increased Renewable Generation

No major issues were observed while renewable generation penetration was in the 0-25% range.

However, once renewable generation started occurring in the 30-40% range network impacts were becoming visible.

High steady state voltage across multiple voltage ranges were being observed. At many locations our transmission transformers were starting to operate a bottom or lowest tap and could not buck the system to reduce volts. This starting forcing the distribution zone substation transformers to also start operating at lower tapping ranges.

The reduced dispatch of synchronous generation resulted in falling system strength, in parts of the network, where there was poor ability to maintain a stable voltage waveform following system disturbances. This resulted in low short circuit ratios across the network and started to limit the amount of renewable generation. The allowable amount of grid connected renewable generation was now dependent on the number of synchronous generators on- line at any time. As the penetration or renewable generation increased these issues became more significant to network operations.

The reduced amount of synchronous generation being dispatched led to reduced system inertia as well as reduced fault levels across the network. Protection settings across the whole network had to be reviewed and altered in several locations. This also led to operating conditions where certain types of network events would cause the loss of multiple generators and trigger overloading/tripping of our interconnectors resulting in high rates of change of frequency (RoCoF). The surviving generators and existing load shedding systems could no longer adequately respond.

By late 2016 South Australia had such an event during stormy conditions. The state was operating with well over 60% renewable generation and was at relatively high levels of import. There were some tornados that damaged and tripped three major transmission lines in a very short period of time. Several wind farms and some synchronous generators tripped as a result of the network disturbances. The AC interconnector overloaded and tripped. The network experienced a RoCoF of 8.5 hertz per second. This caused a blackout in South Australia.

As the penetration of embedded solar PV kept steadily increasing a new phenomenon was being observed. It is referred to embedded solar PV shake-off. Due to falling system strength, system disturbances were starting to have larger voltage swings across the network. The inverters on the earlier generation of solar PV units simply could not ride through the voltage fluctuations, became unstable and shutdown or tripped. This shake-off effect can cause approximately 25% shutdown across the entire network. We have experienced the loss of approximately 400 MW of PV generation due to this effect.

Due to the increasing levels of embedded PV and the speed at which the generation can change, depending on the time of day and cloud conditions it is getting harder to control system volts with traditional static plant such as reactors and capacitor banks. Where such plant needs to be manually switched network operators simply cannot keep up. Some of the automated systems can result in cascade operation of these banks resulting in very large voltage step changes approaching system voltage stability limits. It is emerging that more SVCs and STATCOMs may be needed to cope with this.

All of these impacts lead to the requirement to constrain the MW output of grid connected renewable generation. Renewable energy was being ‘spilled’ to stay below various stability limits.

With the increase in inverter-based generation the levels of harmonics or total harmonic distortion on the network was increasing. The first issue to be overcome was how to accurately measure the distortion across various parts of the network and to identify the sources.

There was an instance of a solar farm that was in the process of connecting and commissioning its second stage of development by adding another 110 MW of plant. Due to the harmonic content and interaction with the power system this second stage was constrained to a maximum of 20 MW until harmonic filters could be commissioned. Retuning the inverter firing sequences was not enough.

Impacts and Solutions Being Implemented

Following the state wide blackout in 2016 AEMO identified an inertia shortfall for part of the South Australian network. Four synchronous condensers were installed and commissioned by mid 2021. They were installed in two of our major substations near the area of the largest concentration of renewable generation. These machines have both increased the inertia on the power system as well as system strength. These synchronous condensers were fitted with flywheels. Since commissioning the grid connected renewable generators have not encountered any network constraints based on inertia and system strength, where before this generation was being constrained for at least 10% of the calendar year.

The Hornsdale BESS (150 MW/195 MWh) has recently completed a two year trial/development period to test its ability to provide synchronous inertia to the network. It has recently been given approval by AEMO to provide this functionality on an ongoing basis.

The solar PV shake-off effect has reduced the ability to gain interconnector outages as AEMO is now treating the loss of approximately 400 MW of embedded solar PV in response to a network event as credible. We are required to provide a seven day PV forecast where the expected PV generation will not exceed at certain MW threshold before the outage can be approved.

The national network operator normally operates the transmission network with voltage setpoint in the range of 1.05 to 1.06 per unit to minimise network losses. This can no longer be tolerated as load rejection events will result in unacceptably high voltages that approach or can exceed stability limits. Voltage set points have now been reduced.

The standard tapping ranges have been changed for all new transformer purchases to ensure more bucking taps. This only helps for sites where new transformers are planned.

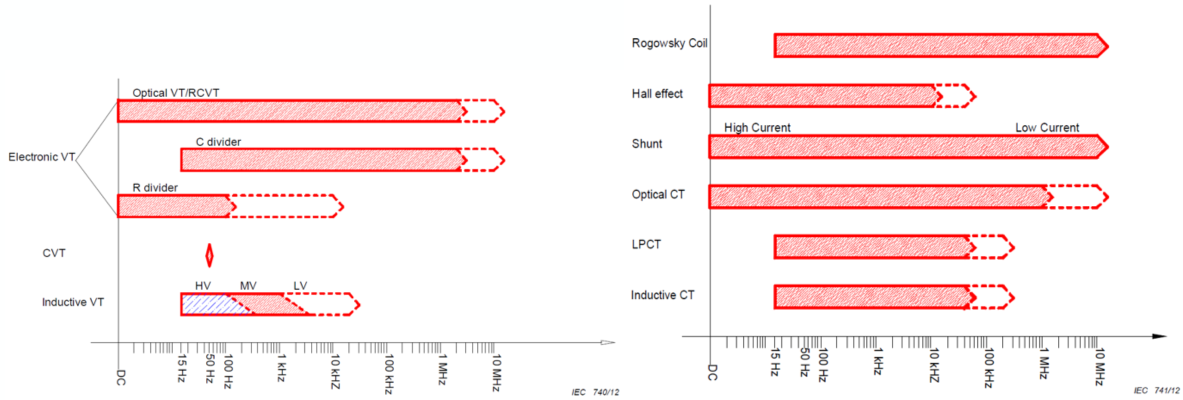
Three new 50 MVAr shunt reactors have been installed on our 275 kV network. Five more are planned for the next 3-5 years.

All new “large” inverter-based grid connected generators with a capacity 100 MW or more are now required to install harmonic filters. Previously developers believed that the firing sequence of the inverters alone would be sufficient to damp any harmonic distortion to acceptable limits. The National Electricity Rules make the transmission network owners responsible for monitoring and complying with harmonic limits. Where individual sites/facilities can be shown to be the cause of excessive harmonic distortion they can be directed to install filters. However, where single sources cannot be identified as the cause, network owners will be expected to install their own harmonic filters. This is anticipated to help reduce the harmonic content caused by smaller embedded renewable generators and or power converter based loads.

In South Australia a project will install power quality metering at several nodes and generator connection points across the network to identify where harmonic filtering will be required. It is anticipated that three network connected filters may be required in the next 3-5 years.

Measuring Harmonics

This is not as simple as installing power quality meters and connecting them to existing CTs and VTs. The type and operating voltage of the VT has major impact on the measurements presented to the meter. Figure 1 below shows the frequency response characteristics of various type of VT & CT.



Source: TR 61869-103:2012

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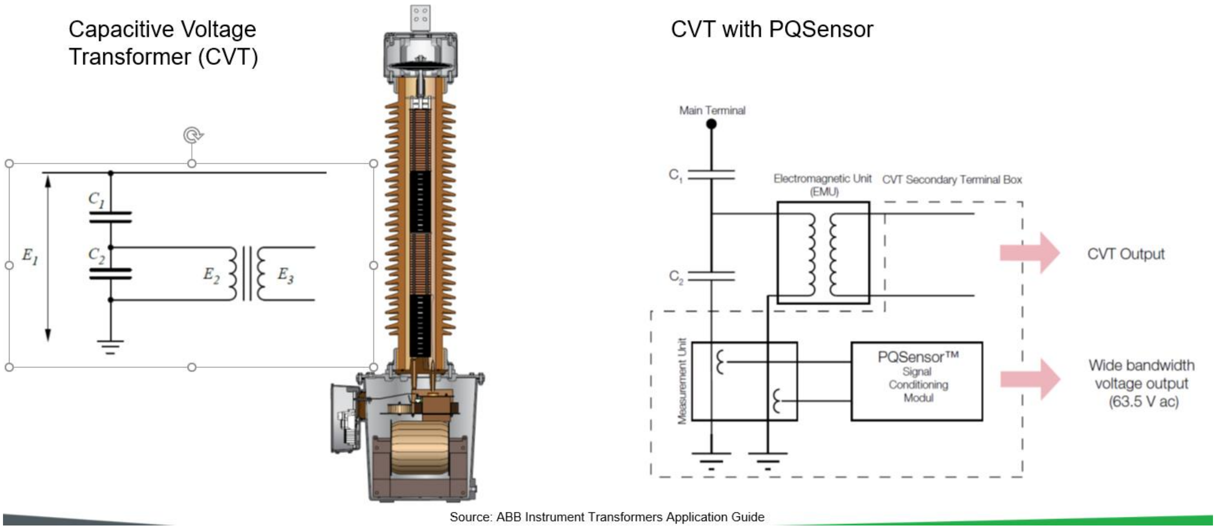
Figure 1 Frequency Characteristics of VTs and CTs

The minimum requirement is to identify harmonic content up to the 50th harmonic. At transmission level the total harmonic distortion is not allowed to exceed 3%. Inductive VTs appear to only suitable for up to 22 kV application. We have yet to assess their suitability for 33 kV measurements. For 66 kV and above they are unsuitable. Similarly CVTs to do not correctly identify the harmonic content other than to show that harmonic are present.

Trials have been implemented by installing devices called PQ Sensors and connecting them to CVTs. A device has been selected that can be retrofitted to many makes and models of CVTs. The PQ Sensors have a signal conditioning module that provides a wide band voltage output suitable for harmonic monitoring. Figure 2 below shows the conceptual application.



Source: ABB Instrument Transformers Application Guide

Figure 2 Example of CVT with and without PQ Sensor

These devices are now being installed at each new transmission connection point for renewable generators.

A recent installation of power quality monitoring with a PQ Sensor has shown the impact of harmonic filters associated with an adjacent solar farm on a near-by part of the network. When the solar farm is running during daylight hours the harmonic filters are turned on. However, at night when the solar farm, and its inverters are shut down, the filter banks are also turned off to help reduce system voltage. The PQ meter shows an increase to total harmonic distortion as soon as the filters are turned off at night (but still within acceptable limits).

Figure 3 below illustrates what can happen if a harmonic filter is turned off when the inverter based generators are still in service. This event resulted in some damage at the wind farm collector substation.

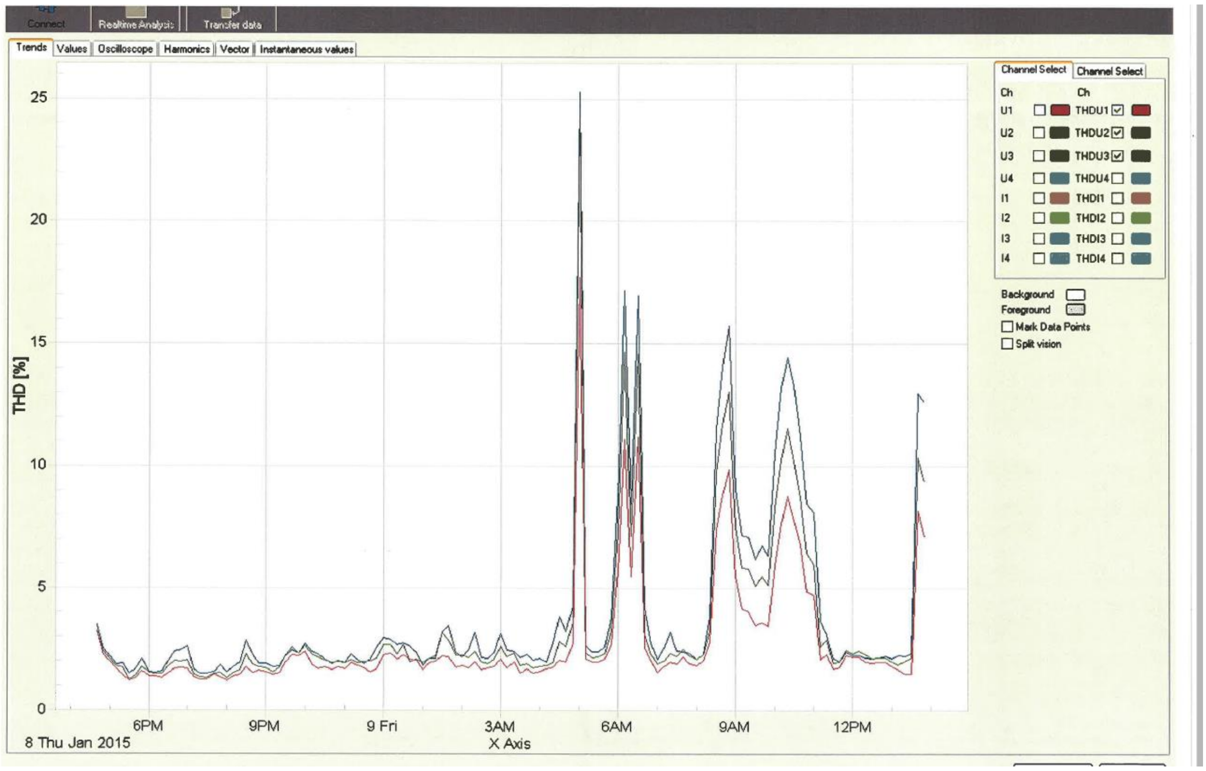


Figure 3 The impact of having a harmonic filter out of service for a wind farm

Conclusion

This presentation shows that system strength and system inertia can be solved. However, voltage and harmonic distortion control will be significant issues as the penetration of inverter based generation increases with time.

Submitted,

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