Application of low voltage Statcom to correct voltage issues caused by Inverter Energy Systems

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***Abstract*— Electricity distributors in Australia are experiencing high penetration of small scale distributed generation, such as solar photovoltaic systems, particularly on houses connected to the low voltage network. Distributed generation is challenging the traditional operating paradigm and can result in occurrences of voltage rising, or even exceeding, statutory limits. This results in the inverter energy systems continuously disconnecting and being unable to generate. This paper presents the results of Ergon Energy's investigation into the application of low voltage static compensators through a desktop study, modelling, laboratory testing, and field trials.**

***Index Terms*—power conditioning, power distribution, solar energy, static power converters, statcom**

I. Introduction

Residential solar photovoltaic (PV) system penetration levels in Queensland, Australia are amongst the highest levels in the world at approximately 24% [1]. In some cases PV connected to the low voltage (LV) network can cause power quality issues for distribution network service providers (DNSPs). The most common issues are overvoltage and phase unbalancing, along with capacity overloading and disruption to protection schemes [2] [3] [4].

Traditionally issues with overvoltage were managed by changing the distribution transformer tapping, upgrading LV backbone conductors, or by upgrading the customer's service cable. The effectiveness of tap-changing to manage LV voltage rise is limited due to voltage drop during evening peaks when there is no PV generation. Changes to LV backbone conductors can be costly, especially if new poles are required to support increased conductor weight.

DNSPs have identified a need for a low cost network side solution for automated voltage management of the LV network, in order to provide both choice and improved value for customers. The LV Statcom (static compensator) is a solution that offers voltage management on LV distribution networks through the controlled injection or absorption of reactive power.

The investigation began with a desktop study of voltage impacts for low, medium and high voltage networks, and modelling of an LV network. Laboratory testing of LV Statcoms was then performed, followed by a field trial of LV statcoms on an LV network with high penetration of PV generation.

II. Background

A. *Ergon Energy*

Ergon Energy is a state government-owned corporation responsible for distribution of electricity to 97% of the area of Queensland and the Torres Strait, Australia. The supply region is characterised as being large, over 1 million square kilometres and sparsely populated, with approximately 720 000 customers.

B. *Network Voltage Regulation*

Traditionally voltage regulation via reactive power plant has been realised at transmission and sub-transmission substations. Shown below in Figure 1 are vector diagrams showing the impact load, PV and Statcoms have on the voltage levels. Load will reduce voltage, PV will cause the voltage to rise when exporting, and a Statcom consuming reactive power will reduce the voltage. The size of voltage drop and rise is dependent upon power levels and network impedances.

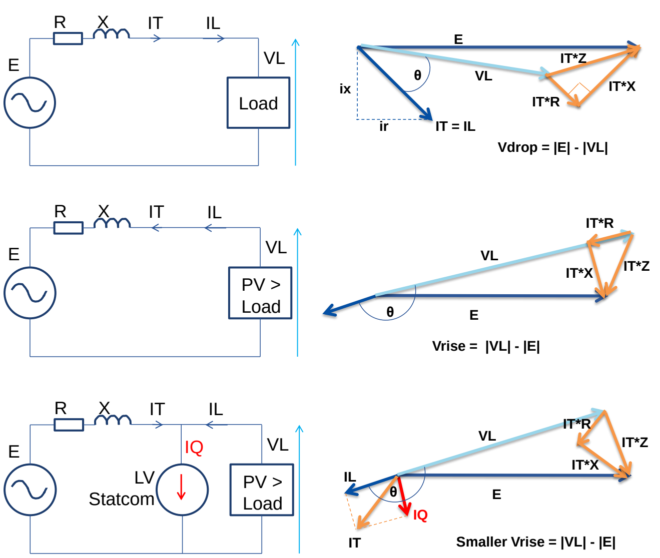

Figure 1. Voltage vector diagrams.

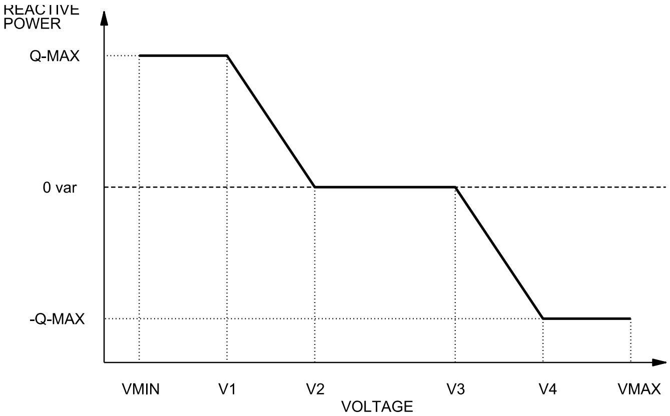

Figure 2. Statcom volt-var response curve.

Figure 2 shows a volt-var response curve that is supported by a number of statcoms and modern PV inverters. When the voltage is low, the Statcom supplies reactive power (acts like a capacitor) and lifts the voltage. When the voltage is high, the Statcom consumes reactive power (acts like an inductor) and lowers the voltage. The interval between V2 and V3 is a deadband where the Statcom does not interact with the network.

C. *Customer Owned Inverter Functionality*

Reactive power control (RPC) is a standard offering in most new inverters. Previous research has suggested using reactive power control functionality of inverters to minimise voltage rise and increase the penetration levels of PV systems [2] [3] [4].

These advanced grid features have been developed as a result of issues in other distribution networks, particularly in Germany [5]. These controls allow more inverters to be connected to the grid and reduce the negative impact the systems can have on the network. RPC is now a mandatory requirement for inverters that comply with AS/NZS 4777.2:2015 [6]. Ergon Energy considers that while the reactive power functionality of customer owned inverters is beneficial, a network-side solution was needed as another option to respond to issues related to existing PV inverters that did not have RPC.

III. TYPICAL LV NETWORK DESKTOP STUDY

Desktop modelling was performed using a set of representative LV networks to evaluate the capacity likely to be required of LV Statcoms. The intent of this modelling was to determine the amount of reactive power support required from a LV Statcom, to increase the inverter energy system (IES) size to 5 kVA (1Ø) for each customer. The modelling assumed there was 100% penetration, taking into consideration network voltage and capacity constraints. This modelling was completed first with each IES having a unity power factor, and then secondly with each IES having a lagging (inductive) power factor of 0.9. The use of reactive power control in IES was highlighted in [7] as providing significant benefit in managing LV voltages, and this model.

A. *Representative LV Networks*

Given the diversity in LV network configurations, a set of 21 representative LV networks were used that were derived from more than 80 000 within Ergon Energy's distribution network. These networks were clustered on distribution transformer size (10 kVA to 500 kVA), network class (urban, rural and SWER), and construction type (overhead and underground). For each cluster, average conductor lengths and customer numbers were determined.

Given the driver for LV Statcoms is addressing voltages outside statutory limits, it was assumed that customer demand matched the after diversity lowest daytime demand, to reflect worse case during the day when PV generates, and the IES instantaneous output was equal to its maximum rated output (factoring in typical inefficiencies and losses in the IES). Hence, the highest amount of realistic overvoltage on a given LV network was modelled.

B. *Results*

The results from this analysis are shown in Table 1 for the cases of customer IES with unity power factor, and lagging (inductive) 0.9 power factor. While this analysis considers 100% penetration of IES of the maximum 5 kVA system size, which is an extreme case and unlikely to occur on most LV networks, it does provide a considerable test for what size LV Statcoms would be required, and how they compare to using modern inverter stock with reactive power control that meet the requirements of [6].

In summary, these results show:

- In at more than half of the representative networks, a modest 20 kVA 3Ø (or 10 kVA 1Ø) Statcom would be able to support 100% IES penetration level, even with inverters operating on fixed unity power factor. Importantly these networks are the smaller ones (<100 kVA) which make up over 50% of Ergon Energy's LV networks, and are those more likely to experience voltage issues sooner, given the lower diversity of customer loads, and higher network impedance.
- Enabling RPC in all inverters with this functionality to operate on a range of up to 0.9 lagging (inductive) power factor, would allow nine of the remaining ten networks with overvoltage issues to be rectified with a Statcom no larger than 20 kVA 3Ø (or 10 kVA 1Ø). The exception is the 100 kVA overhead urban network, whereby a combination of reactive power control in inverters, a Statcom, and additional network or customer-side solutions will be required (such as export limiting of inverters and/or upgrading to lower impedance conductor).

TABLE I. RESULTS OF DESKTOP ANALYSIS.

Representative LV Network	Number of Customers	IES with unity Power Factor		IES with 0.9 lagging (inductive) Power Factor	
		Max IES Capacity Per Customer (kVA) Without LV Statcom	LV Statcom Size Required (kvar) to Achieve 5kVA IES per Customers	Max Capacity Per Customer (kVA) Without LV Statcom	LV Statcom Size Required (kvar) to Achieve 5kVA IES per Customers
Urban 10 kVA (1ø)	2	1.5	8.5 (1ø)	2.8	2.9 (1ø)
Urban 25 kVA	3	3.3	4 (3ø)	5	N/A
Urban 50 kVA	7	2.2	19 (3ø)	5	N/A
Urban 50 kVA-UG	8	2.4	17.5 (3ø)	5	N/A
Urban 63 kVA	5	4	4.6 (3ø)	5	N/A
Urban 100 kVA	20	1.3	115 (3ø)	1.7	50 (3ø)
Urban 100 kVA-UG	20	1.9	57 (3ø)	4.5	5 (3ø)
Urban 200 kVA	44	1.5	2 x 45 (3ø)	3.9	12 (3ø)
Urban 315 kVA	38	1.5	79 (3ø)	3.4	19 (3ø)
Urban 315 kVA-UG	38	3.3	37 (3ø)	5	N/A
Urban 500 kVA-UG	38	3.4	40 (3ø)	5	N/A
Rural 10 kVA (1ø)	1	2.5	3.25 (1ø)	4.4	0.5 (1ø)
Rural 25 kVA (1ø)	2	2.8	5.8 (1ø)	5	N/A
Rural 50 kVA	4	3.2	7.2 (3ø)	5	N/A
Rural 63 kVA	3	5	N/A	5	N/A
Rural 100 kVA	7	3.1	12 (3ø)	5	N/A
Rural 200 kVA	14	2.3	44 (3ø)	3.3	17.5 (3ø)
SWER 10 kVA (1ø)	1	1.5	2.1 (1ø)	2.2	0.3 (1ø)
SWER 20 kVA (1ø)	1	2.4	0.3 (1ø)	3.5	0.1 (1ø)
SWER 25 kVA (1ø)	2	1.6	9.5 (1ø)	2.1	3.5 (1ø)

Note: "UG" indicates an underground network

- Optimal placement of the Statcoms is essential to achieve voltages along the network within statutory limits. Generally the best location will be to connect at the electrically furthest customer from the distribution transformer, on larger and split feeders, two smaller Statcoms may be required to more evenly provide reactive power support, as was the case for Urban 200 kVA underground representative network. Also worth noting is that in field deployment, the electrically optimal placement of a Statcom may not be achievable due to site suitability, and so greater levels of reactive power support may be required of the Statcom/s.

IV. CASE STUDY

The case study involved the laboratory testing and field trialling of commercially available LV Statcoms from three suppliers. There was a mix of single phase and three phase devices, and Statcoms and switched capacitor devices. The Statcom Solutions product was introduced late into the project and was only evaluated in the field trials (no laboratory testing was undertaken).

A. Product Details

Table 2 shows details of the three products tested. The Varentec (ENGO) units were 10 kvar switched capacitors, which could be used in single or three phase configurations, to boost the voltage through capacitive reactive power. An initial tap change was performed at the distribution transformer during installation to lower the voltage, with the Varentec unit providing dynamic voltage support at times of high load and/or low generation.

The ZBB Energy Corporation (ZBB) units were 20 kvar three phase Statcoms. The ZBB unit could raise and lower the voltage through capacitive or inductive reactive power.

TABLE II. PRODUCT DETAILS.

Name	Varentec	ZBB Energy Corporation	Statcom Solutions
Series	ENGO	STATCOM	Starsine
Model	V10		dSTATCOM d315
Rating	10 kvar (1Ø)	20 kvar (3Ø)	5 kvar (1Ø)
Modes	1Ø or 3Ø, Cap only	3Ø, Cap and Ind	1Ø or 3Ø, Cap and Ind
Quantity of units trialled	6	2	4
Cooling	Passive	Active	Passive
Technology	Switched capacitor	Statcom	Statcom
Voltage Change	4 – 8 V	3 – 6 V	3 –-6 V
Notes	Can only raise voltage	Does not correct unbalance voltages	5 kvar on 2Ø, 2x5 kvar on 1Ø

The unit could only be used in a three phase environment, and could not perform out of balance correction as the reactive power was equally distributed to all phases.

The Statcom Solutions (SS) units were 5 kvar single phase Statcoms. The SS units could raise and lower the voltage through capacitive or inductive reactive power. The units could perform single phase correction and could also operate in single or three phase configuration.

B. Laboratory Testing

Figure 3 shows the electrical connections for the laboratory testing. The Statcom under test was placed between upstream and downstream impedance and connected to a variable voltage source. Three power quality meters were used to measure Source, Statcom and Load values.

Laboratory testing was performed to review the performance of the LV Statcom against a range of criteria including: anti islanding, harmonic currents, voltage support with varying source and voltage support with varying load, response time, electrical connections and communications and control.

Figure 4 shows the ENGO unit maintaining a constant voltage at the load, while the source voltage is increasing. The ENGO supplies less capacitive reactive power as the voltage increases.

The ENGO unit operated with a voltage set point and deadband, rather than the preferred volt-var response curve. Testing was performed with both a 1 V and 3 V band and it was determined that having a 3 V band would result in less occurrences of capacitor switching and potentially increase product life.

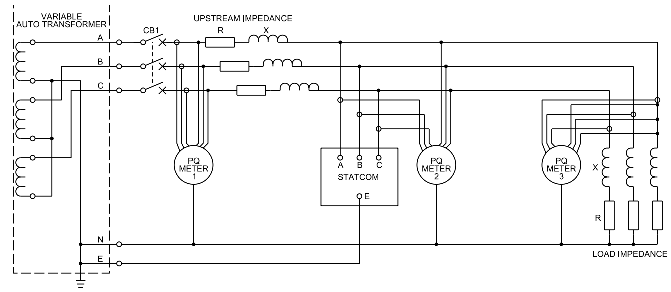

Figure 3. Electrical connection of laboratory test.

Testing of response time for the ENGO unit showed with an output change from 0 to 100%, the response time measured was approximately 60 ms.

Figure 5 shows the ZBB unit performing voltage control with a varying load. It can be seen there was out of balance voltages and the ZBB unit continued to supply or consume similar levels of reactive power on all phases. The performance was generally in alignment with the desired volt-var performance curve, except for out of balance correction.

Data obtained during the laboratory testing was insufficient to determine the exact response time. The ZBB unit showed with an output change from 0 to 100%, the response time measured was a maximum of 12 s.

Both the ENGO and ZBB units generally performed well during the laboratory testing and gave enough confidence in the units to progress to field trials.

C. Field Trials

1) ENGO units

The ENGO units were installed at three locations. Location 1 was single customer 10 kVA distribution transformer. Location 2 was a 10 kVA distribution transformer supplying two customers. For these two sites, the ENGO was installed directly under the distribution transformer. Location 3 was at the end of a three phase open wire overhead LV feeder, approximately 170 m from the 100 kVA distribution transformer. An ENGO unit was installed on each phase and two cross arms were used for mounting. Later in the project a fourth ENGO unit was installed at location 3. The unit was installed on C phase approximately 90 m from the distribution transformer. For all three locations the distribution transformer was reduced by one tap during installation, reducing the nominal voltage by 2.5 %. This allowed head room for the daytime voltage to rise from solar PV, with the ENGO units provided voltage support during the evening period of high load. All three locations had high penetration levels of solar PV and locations 1 and 2 were sites with existing voltage issues.

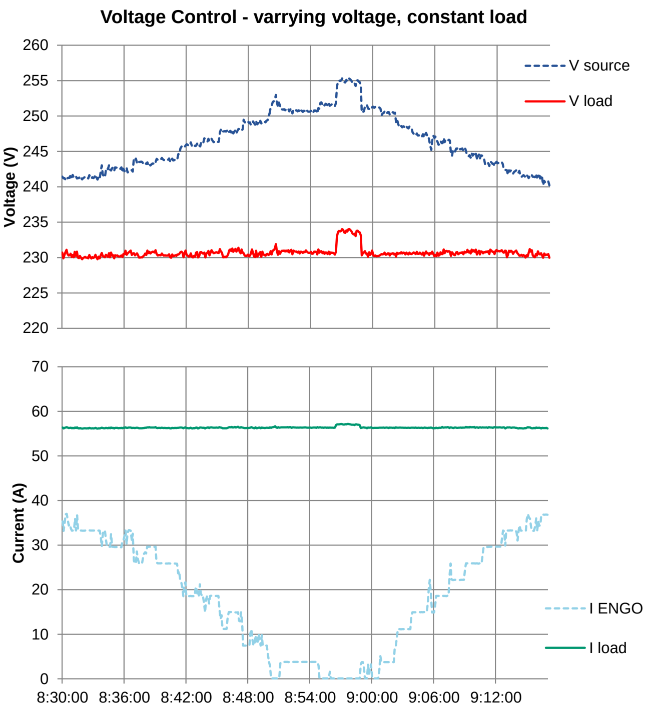

Figure 4. ENGO labratory results.

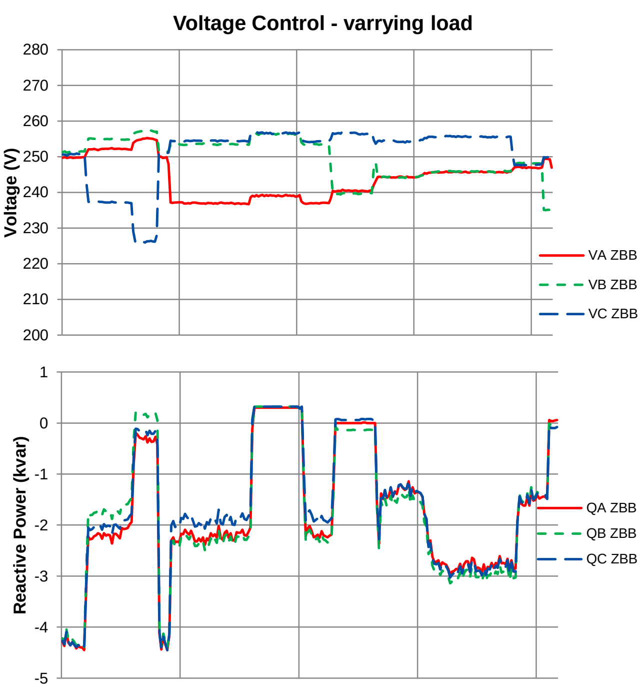

Figure 5. ZBB labratory results.

2) ZBB units

The ZBB units were installed at two locations. A 200 kVA distribution transformer supplied an overhead 95 mm^2 aluminium aerial bundled conductor in two directions. A ZBB unit was installed at each end of the bundled conductor. Location 1 was approximately 315 m and location 2 was approximately 210 m from the transformer. Each ZBB unit was installed directly onto the pole and connected to the LV feeder through service fuses. No outage was needed for installation. The distribution transformer had approximately 66 kW of solar PV connected and Location 1 was a known site of overvoltage and phase unbalance issues.

3) SS units

The SS units were installed at a single location, which was location 1 of the ZBB units. The ZBB unit at location 1 was removed and replaced with the SS units. The SS units were installed on crossarms and connected into the LV network through Ergon service fuses. There was one unit each connected to A and B phase, and two units connected to C phase, making a total of four units at this location. An additional communications box was required to be installed to house modem/routers connected to each unit. The SS units trialled operated with a voltage set point and deadband (rather than volt-var control), both adjustable via software.

V. Discussion

Figure 6 shows the average voltage profile of 20 days of 1 min data from ENGO location 2. There are 7 days of “off” data and 13 days of “on” data. The ENGO unit was set to regulate at 240 V with a 3 V deadband. The solid red line shows improved voltage regulation compared to the blue dashed line, especially during the evening 17:00-23:00 period. The data at this site is from winter and hence no air conditioner load and thus less voltage sag in the evening, with average voltage reducing to approximately 236 V. Overall while acting as a single phase unit, the ENGO demonstrated fast, accurate and responsive voltage support at times of high load.

At ENGO location 3 installing the additional unit on C phase, introduced behaviour not expected at C phase of ENGO location 3. This unit operated at full capacitance level close to 100 % all of the time, even when the voltage was within the set point band. When multiple ENGO units on the same phase are separated by a small amount of impedance, the units did not operate as expected. The vendor provided feedback into the issues, but did not provide a solution.

The ZBB units did not perform well during the field trial. No voltage improvement was observed at either location. The ZBB unit at location 1 failed in service after 3 months of operating. The unit at location 2 stopped operating after four months in service. Many local and remote fixes were attempted on both units, but could not resolve the issues. Both units were removed from site.

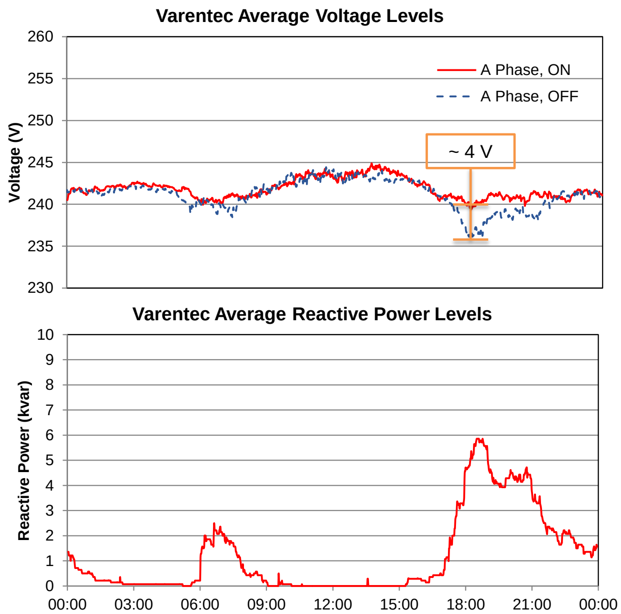

Figure 6. ENGO voltage improvement during field trial.

Figure 7 shows voltage histograms of when the SS units were on and off. The SS units provided significant voltage improvement at this site. The units have greatly reduced day time high voltages, provided voltage support in the evenings and corrected the significant out of balance issue on A phase.

VI. Conclusion

Laboratory and field testing demonstrated the potential benefits to LV management that can be achieved by using a Statcom or switched capacitor device. The trials showed that a system sized at 10 kvar per phase can provide a 4-8 V shift, which is sufficient for managing voltage both at peak demand and at peak generation time for home IES.

The trialled devices demonstrated that the key advantages of using a Statcom or switched capacitor product for LV management are shunt connection, fast response and low cost. The shunt connection minimises installation costs by removing the need for an outage and avoids customer issues associated with failed series-connected devices.

The response of the devices can be sub-cycle which enables the devices to remove voltage fluctuations on the network caused by intermittent generation or loads. A passively cooled device provides for an LV management solution that has increased reliability and a low life cycle cost, due to low operation and maintenance costs. The devices also have the potential to provide phase balance, if used in a three phase configuration, reducing system losses and improving customers' power quality.

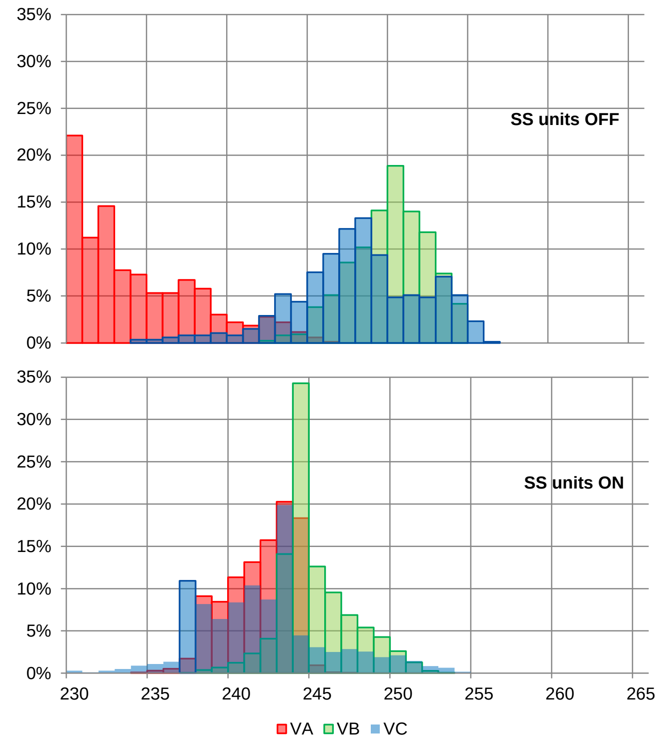

Figure 7. SS voltage improvement histogram.

VII. References

[1] Energy Supply Association of Australia, "Renewable Energy in Australia - How do we really compare?," 29 September 2015. [Online]. Available: http://www.energycouncil.com.au/energy_you/renewable_energy_in_australia.

[2] G. Kerber, R. Witzmann and H. Sappl, "Voltage limitation by autonomous reactive power control of grid connected photovoltaic inverters," in *Compatibility and Power Electronics*, Badajoz, 2009.

[3] E. Demirok, P. C. González, K. H. B. Frederiksen , D. Sera, P. Rodriguez and R. Teodorescu, "Local Reactive Power Control Methods for Overvoltage Prevention of Distributed Solar Inverters in Low-Voltage Grids," *IEEE Journal of Photovoltaics*, vol. 1, no. 2, pp. 174-182, 2011.

[4] B. Ernst and B. Engel, "Grid integration of distributed PV-generation," in *IEEE Power and Energy Society General Meeting*, San Diego, CA, 2012.

[5] T. Stetz, F. Marten and M. Braun, "Improved Low Voltage Grid-Integration of Photovoltaic Systems in Germany," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 2, pp. 534-542, 2013.

[6] AS/NZS 4777.2:2015, "Grid connection of energy systems via inverters - Inverter requirements," Standards Australia, Sydney, NSW, 2015.

[7] D. Condon and D. McPhail, "Voltage regulation of distribution networks using inverter reactive power functionality - Australian utility experience," in *IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, Brisbane, Qld, 2015.