Analysis and Management of the Impacts of a High Penetration of Photovoltaic Systems in an Electricity Distribution Network

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***Abstract*--Small scale grid connected photovoltaics (PV) have rapidly increased in Australia over the past decade. This rapid increase has heightened network utility concerns about the impact of these systems on customer power quality. This paper depicts work undertaken to explore PV system integration from a network utility point of view. Additionally utility strategies to minimise the negative impacts are explored. This was done by analysis of network and PV data from selected case study areas as well as producing models based on data. The results have indicated that current penetration levels are too low to cause significant power quality issues, however power factor and current harmonic issues have been identified. Simulated increases in PV penetration suggest negative growing adverse integration effects including voltage rise and current swing issues. Management strategies suggested are; a PV monitoring program, energy storage, limitation of PV penetration on distribution transformers, implementation of reactive power support, lowering system voltage and implementation of network infrastructure. Through effective management PV integration risks can be reduced and network benefits are fully realised.**

***Index Terms*--Distributed power generation, load management photovoltaic systems, power distribution, power quality, power system harmonics, power system simulation, voltage control.**

I. INTRODUCTION

Australian supply utility electrical distribution network planning and operation methods have remained largely unchanged for the past 30 years, with power flow traditionally from generator to consumer. Recent years have seen the advent of high power consumer electronics, such as air conditioning, accentuating load peaks. In addition to this distributed generation (any power generator connected to the grid that is not a centralised power plant) in Australia has become more popular due to government incentives, climate change debate and many other factors. In fact by 2030 distributed generation is predicted to meet 40% of Australia's energy requirements, with the main producer expected to be grid connected photovoltaics (PV) [1]. This increase has occurred recently at a rapid rate in fact Endeavour Energy (one of the main distribution supply utilities in NSW, Australia) went from receiving approximately 3 PV connection applications per day in 2007 to approximately 150 applications in June 2010.

The changing load profile coupled with the rapid rise in PV systems in Australia has made supply utilities concerned about the cumulative effect on the distribution network, in particular the quality of power that they are delivering to consumers. The voltage, power factor, and harmonic content of the power delivered to consumers are regulated by industry quality of supply standards and there is a concern that a high penetration of PV systems will violate the standards in regards to these parameters [18]. In addition to this utilities are aware of the potential to use PV systems to benefit utilities.

This paper aims to provide an insight into what large scale integration of PV systems is doing to the distribution network's power quality both at current penetrations and at predicted increased penetrations. Following on from this increased understanding management strategies are suggested which would allow supply utilities to minimise the negative impacts and maximize the benefits of grid connected PV.

II. PV AND THE GRID

Grid connected PV systems comprise of photovoltaic panels which are connected to the electricity grid via an inverter. They produce DC power which is converted to AC power by the inverter which then syncs to the electricity network. The amount of power generated depends on a number of factors including: panel orientation, system efficiencies, weather, and season [2].

A. Integration benefits

Research into this topic thus far has indicated the following potential benefits into PV integration with the network.

- Ohmic transmission losses are reduced as the consumed power is generated closer to the load [5]
- There is potential for peak load reduction, thus allowing supply utilities to delay line upgrades resulting in economic benefits [1].
- PV systems generate renewable power and thus are seen to be a valid alternative to fossil fuels.

B. Integration Issues

PV system output is solely dependent on the sun. Generation tends to peak at the middle of the day whilst peak generation times tend to be between 6:30 – 10:30am and 4:00

– 10:30pm [3]-[4]. This mismatch coupled with the inverter characteristics can cause the following integration issues.

- Large amounts of PV systems can cause voltage rise at the load. This is caused first by current reduction reducing the voltage drop in the lines thus raising the potential to that of the distribution transformer tap [5]. The voltage can then rise further as the PV systems attempt to drive more current to the generator, thus needing a larger voltage at the load end [6]. It follows that the issue is accentuated when load is low and PV production is high.
- PV systems are designed to only supply real power (thus maximise the financial benefits to the consumer). However if PV supplies the loads real power requirements the grid still has to supply the reactive power. This causes the system power factor to decrease and thus implies inefficient transmission [7].
- Inverters can inject current harmonics into the network; this amount is regulated by industry standards [8]. The problem here comes when there are many inverters of the same manufacturer connected to a feeder (in this case the harmonics can add together as they are the same frequency) and cause system harmonics. Current harmonics can cause voltage harmonics and together they increase losses in the network through heating [9].

Although it is not a focus of this paper it should be noted that a possible negative area of PV is in system protection. Many PV systems connected to the grid together can cause islanding (a situation where the grid is disconnected but the voltage is maintained by the PV systems) however it has been shown that with modern inverters this situation is unlikely to occur except in exceptional circumstances [10]-[12]. Another protection problem is that PV systems are current limited, meaning in the event of a small fault the current contributed by the systems has the potential to mask the fault from system protection [13].

III. Case Study Areas

The main area examined in this study was the “Blacktown Solar Cities” area. The “Solar Cities” program was created by the Australian Government and one of the outcomes was to create regions that were heavily populated with PV systems, allowing high penetration studies to be conducted [14]. In addition to this the majority of systems in the area are 1.1kW and by eliminating the small number of different size systems this study was able to produce consistent results due to the PV size. Distribution transformers (11kV to 415V) in this Solar Cities area with a significant number of PV systems were identified, along with highly penetrated 415V feeders. Figure 1 below depicts the “Blacktown Solar Cities” area with a few of the case study areas circled.

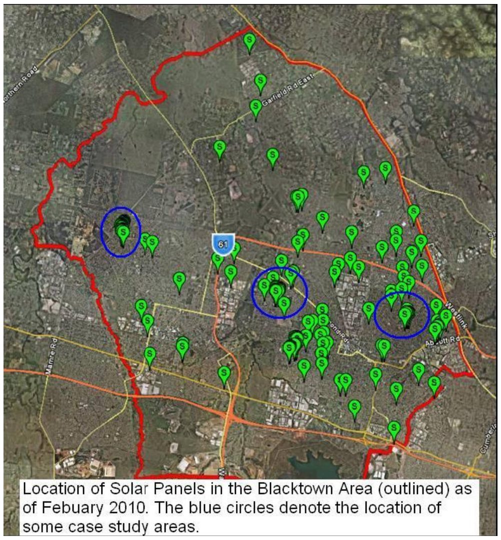


Fig 1. "Blacktown Solar Cities" area with case study areas circled

Physical data was collected from these sites including: PV output power, transformer and customer voltages, current and voltage harmonics, system current (at the distribution transformer and at the zone substation) and system power. Data was recorded using *GridSense PowerMonic* recorders [15] and Endeavour Energy’s SCADA system. This data enabled investigation into current PV integration issues. Note that not all data was available at all case study areas due to resourcing issues.

The analysis of the field data allowed physically accurate models to be built to simulate the likely effects of increased PV penetration in the case study areas. The simulations were built using *Power World* simulation software [16]. An example of a simulation of one of the case study areas is shown below in figure 2. Using this software we were able to investigate predicted PV integration issues. Note that the PV systems have been modelled as negative loads as they act more like current sources in the network then voltage.

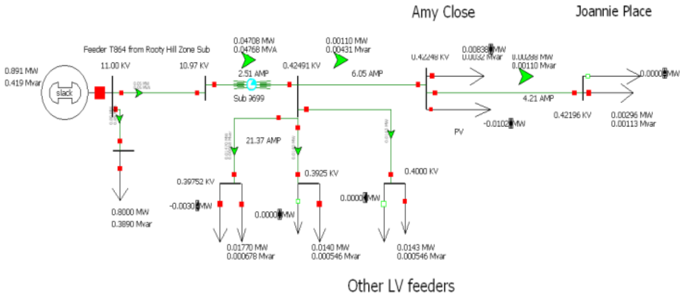


Fig 2. Power World simulation example used for one of the case study areas (this is a low penetration simulation)

IV. Photovoltaic System Performance

The first work with this report was analysing PV system output in order to characterise the PV systems for network utilities. It was expected that in summer during the middle of the day that actual PV system output would be close to quoted output value e.g. a 1.1kW system would produce around 1kW.

Analysis was done on 127 randomly selected 1.1kW systems in the "Blacktown Solar Cities" area. Average production values are shown in table 1 below.

	kWh/day	Peak (kW)	Percentage of expected peak (%)	Time of Peak
PV March Total	7.06	0.49	44.55	1:00pm
PV March Sunny	9.79	0.71	64.55	12:30pm
PV July Total	3.99	0.37	33.64	12:00pm
PV July Sunny	6.08	0.55	50.00	12:00pm

Table 1. Average peak production of 1.1kW PV systems in the Blacktown area

It was also seen that production on cloudy days was not neglible but rather was around 18% on average of quoted values (i.e. around 0.2kW for a 1.1kW system).

Average PV system output is this low on average because of mismatched peaks lowering the average. To investigate this further 40 randomly selected systems were plotted in figure 3 below and compared against the expected production. From this graph we can still see that peak production is around 70% of the quoted value.

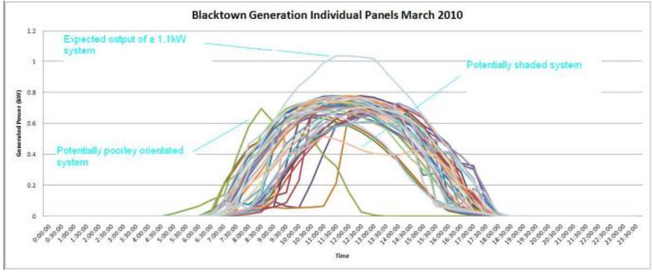


Fig 3. Generation profiles of 40 random 1.1kW systems in the Blacktown Area.

This reduced level of PV system production was not isolated to 1.1kW systems in Blacktown. Larger panels in other case study areas showed on average that peak production at 70% of rated production was the norm.

One of the reasons behind lower then quoted outputs is a lack of educated installation. During field examinations of panels it was seen that many panels were installed at incorrect orientations and/or in shaded locations, thus lowering their output. An example of this is shown in figure 4 below. Another reason behind the low output is inherent system inefficiencies in the field not meeting quoted outputs. Additionally the quoted outputs of the inverter have actually been found to be the maximum outputs in laboratory conditions, not normal outputs.

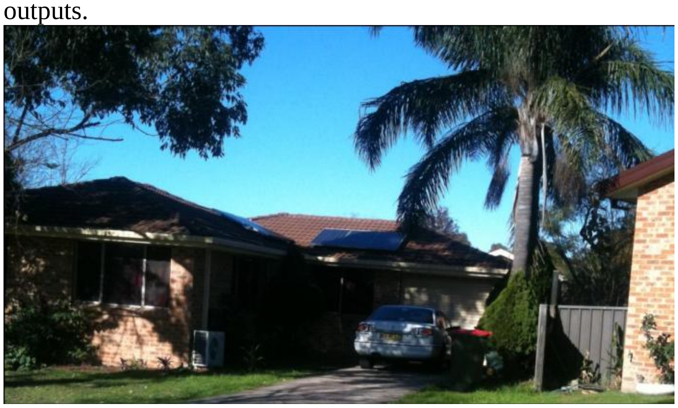


Fig 4. Photo from field survey. Note the shading at 2pm as well as the split orientation to the west and north (North is towards the camera, which is ideal orientation for the southern hemisphere).

In addition to the PV output discovery it was found that there was a mismatch between residential peak loads, as the research suggested. Peak production time on a sunny day was around midday whereas average load peaks were at 7am and 9pm as is shown in the results of figure 5 below. Note that these PV production times are suited for an industrial load.

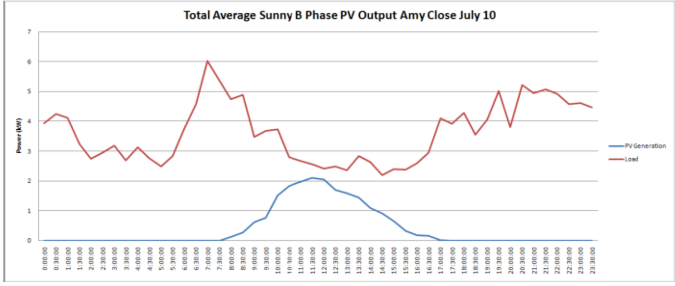


Fig 5. PV output comparison with load profile for one of the case study areas.

V. CURRENT PV INTEGRATION ISSUES

A. *Voltage rise at the load*

In only one of the case study areas we were able to measure voltage at the load compared to the voltage at the distribution transformer. In this case whilst the penetration was high (78%) the feeder was quite short and thus had low impedance. The results from the recorder are shown in figure 6 below.

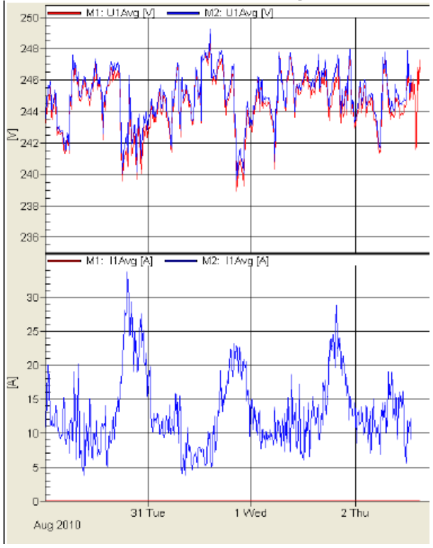
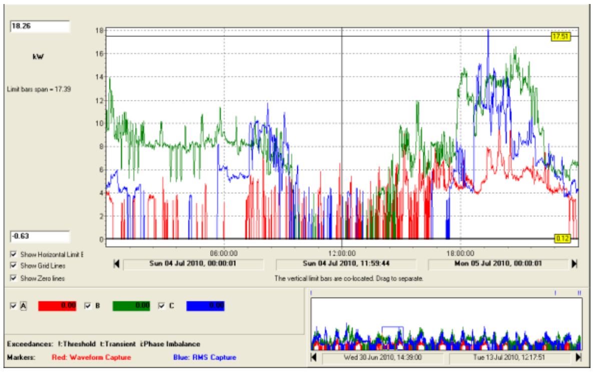


Fig 6. Voltage and current levels recorded. The red lines are measured at the load end of the feeder whilst the blue is measured at the substation. Note the date lines indicate midnight so midday is halfway between.

The above figure shows that voltage levels are affected by increased system load, shown by the lower load end voltage with high current. However during the midday periods of low load (accentuated by PV system interaction with the grid) there is no evidence of voltage rise at the load end. In the time period that the above measurements were taken PV input was limited due to average weather. Data recorded on better days (such as in figure 7) shows that on days of fairer weather PV system input was enough to cause backfeeding on the feeder and potentially voltage rise at the load. During this time period voltage recording was only available at the substations thus there is no data to show voltage rise associated with feeder backfeeding. Data taken from other case study areas was also recorded at the substations, and throughout the course of the study no significant voltage rise was recorded at the distribution substations. Because of this load voltage rise was simulated for the case study areas. Results of this study are shown in VI. A on page 4.



The vertical limit bars are co-located. Drag to separate.

Exceedances: !:Threshold t:Transient i:Phase Imbalance

Markers: Red: Waveform Capture Blue: RMS Capture

Fig 7. Real power measurements for the 2nd of July. Note how all phases exhibit periods of no real power, possibly due to PV back feeding

It should be noted here that supply utilities in Australia have definitely seen evidence of substantial voltage rises at loads due to PV. These scenarios have been primarily in rural locations with long, high impedance feeders (usually supplying one property) and high power PV (around 10kW). These situations were identified as the rise in voltage activated the inverter islanding protection causing it to disconnect, resulting in customer complaints as their PV system wasn't generating into the network. This scenario has the potential to be quite common in an Australian context, especially with increased penetration of larger systems on high impedance feeders.

B. *Power factor decrease*

At current penetrations, in multiple case study areas there has been evidence of power factor drops, with power factor even reducing to 0 (when on the border of the LV feeder back feeding). Figure 8 below shows the power factor of two of the different case study areas.

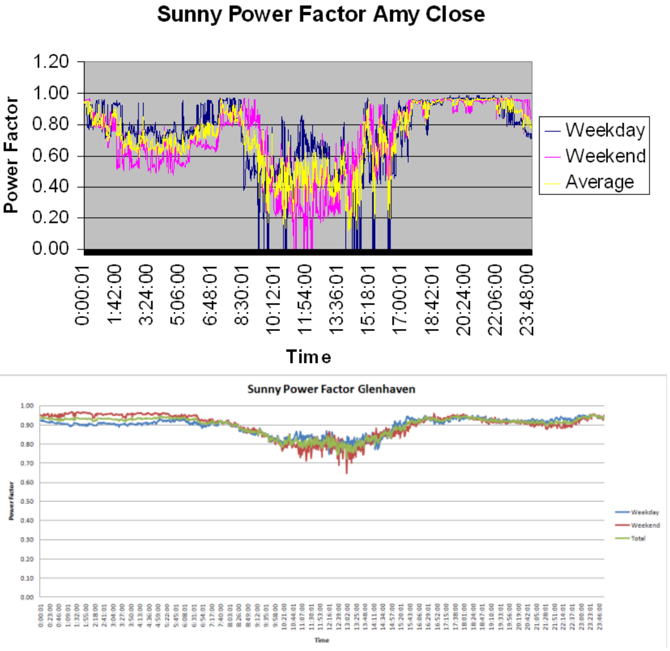


Fig 8. Power factor from 2 different case study areas, note that weekend and weekday times have been isolated in order to isolate the effect of different loads. The top case study has higher penetration and thus exhibits larger decreases, even reducing to zero at periods of high generation and low load.

This lowering of system power factor at the distribution transformers translates to lower system efficiency, negating the benefits in reduced transmission losses. Calculations into a numeric value for reduced system efficiency were outside the scope of this work.

C. *Harmonic injection to the grid*

In all case study areas there was evidence of current harmonic injection into the network. A typical example of one case study current total harmonic distortion (THD) levels is shown below in figure 9.

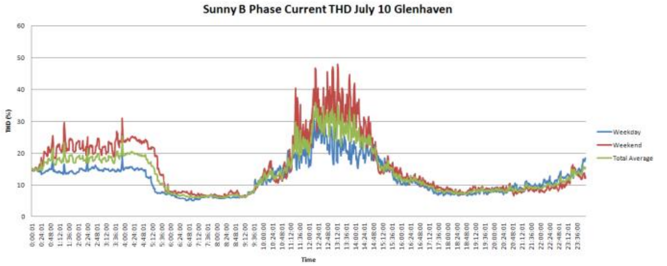


Fig 9. Current THD levels. Note the obvious rise in THD during PV generation times.

However THD is not necessarily the best measure of harmonics from PV. This is because the fundamental current is reduced by PV generation, thus making the harmonics larger by comparison and increasing the THD value. Thus a better measure of harmonic injection is the 5th harmonic (as the 3rd is usually attenuated in the transformers). Figure 10 below shows recordings of 5th harmonic values at one of the case study areas.

Fig 10. Voltage and current 5th harmonic values. Note the rise (especially in current harmonics) between the date lines which is when the PV is generating

Thus it appears the inverters are injecting current harmonics into the network but this is not having significant impact on the voltage harmonics. Additionally the level of current harmonics suggests that the inverter harmonics are adding (assuming the inverter harmonics are limited to the levels stated in standards), thus it is possible to envisage higher penetrations inducing higher harmonic values.

From results from all of the case study areas there doesn't seem to be a strong correlation between current harmonics and voltage harmonics; i.e. the current harmonics do not seem to be inducing voltage harmonics. The main concern with current harmonics is that they lead to increased losses in the network.

VI. PREDICTED PV INTEGRATION ISSUES

It should be noted that in the following simulations % penetration refers to the number of houses on the network which have a 1.1kW PV system installed. This is a small sized panel and thus the conclusions reached are possibly an underestimation as average system size in the Endeavour Energy franchise is approximately 2kW. 1.1kW systems were chosen to be consistent with the recorded results, thus increasing the accuracy of the models.

A. Voltage rise at the load

Individual feeders with fair penetration saw an insignificant effect to load level voltage when recorded. However as expected when higher penetrations were modeled further it was evident that voltage rises across a network increase as penetration increases. This is shown in figure 11 which depicts the line to line average load voltage of one of the case study areas as penetration increases.

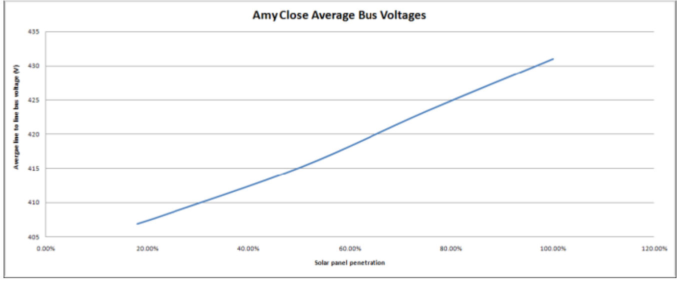


Fig 11. Voltage rise of a distribution network with increasing PV penetration

With the model used for the simulation it should be noted that average line impedance values of R= 1.2Ω/km and X = 0.5914Ω/km were used. Additionally no load adjustment was made as PV penetration increased.

It is interesting to see here that voltage levels rise steadily with increased PV penetration. Other modelled case study areas exhibited the same behaviour. However despite the rise in voltage for most of the case study areas examined voltage levels never rose above accepted Endeavour Energy standards. As expected the highest voltage rises were for the high impedance rural lines which were modelled, with these scenarios exhibiting voltages outside of acceptable levels.

B. Network current swings

One concern identified when conducting these simulations was the possibility of extreme current swings on the network. These result from the PV systems generating at full capacity (modeled as 70% of quoted values) and then all simultaneously shutting off due to an event such as increased voltage triggering the inverter islanding protection. It is definitely feasible for a scenario such as this to occur in a distribution system with high penetration as the PV systems are likely to cause back feeding and thus high voltages in the system.

Compounding the problem is the fact that inverter islanding protection voltage levels are generally set to lower then the utility accepted voltage levels, for example in Endeavour Energy accepted single phase voltage is up to 262.2V (compared to AS3000 maximum voltage level of 253V) whereas inverter max voltage levels are typically around 251V [17]. An example of predicted current swings with increased PV system penetration is shown in figure 12, note that current swings of up to 140A can be experienced by the network. This problem is accentuated in an Australian setting by the lack of standardised voltage levels amongst the various network utilities. This diverse range of voltage levels increase the probability of inverter switch off, and thus current swings, especially amongst European manufactured inverters (as they typically have lower voltage thresholds).

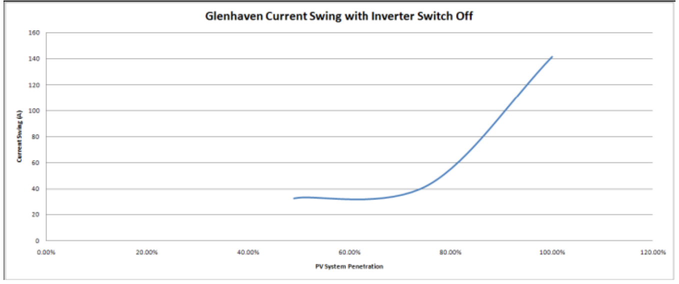


Fig 12. Current swings in the network on one of the case study areas.

The major problem associated with current swings of this size is they would appear to the network to be similar to switching surges and as such could affect the voltage stability of the system and possibly cause faults. Additionally the current swings would be extremely unpredictable as they are a factor of dynamic generation and individual feeder load levels.

In addition to the current swing problem associated with inverter switch off is the impact on the consumers. Switch off in periods of potential high generation impacts on the customers tariff incentives and can possibly leave the utility liable for the damages incurred if the voltage is outside of acceptable limits, as has been shown in the high generation, high impedance cases discussed in section V. A.

C. Power factor decrease

The trend for power factor decrease with increased PV system penetration was mirrored in the modeling scenarios. As in the field case studies at the point of back feeding the power factor drops to zero, but interestingly in the modeling the power factor starts to increase as power is supplied back into the system as is shown in figure 13 below.

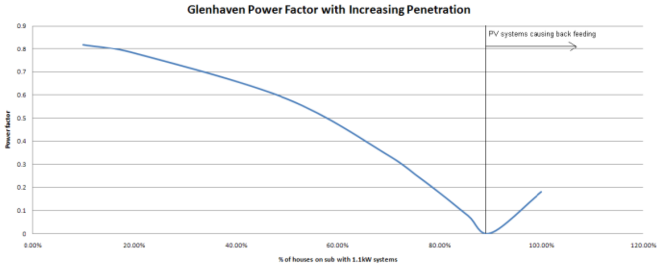


Fig 13. Modeled power factor with increasing penetration.

This is an interesting scenario as it is possible to envisage a distribution network, with 100% PV system penetration, cycling from 0.8 to 0 to 0.2 and back to 0.8 each day as the PV systems generate throughout the day. This is a problem as a low power factor implies the system is not operating as efficiently as it could be.

D. *Medium voltage network back feeding*

In the modeling scenarios it was also noted that as penetration approached 100% that back feeding was seen along the medium voltage network. Powers up to 12kW could be seen to be feeding back through the distribution transformer.

In a scenario where all distribution transformers were similarly loaded with PV systems the medium voltage feeders could feed power back to the zone substations. This has implications for traditional supply utility unidirectional protection schemes.

VII. RISK MANAGEMENT OPTIONS

There is great potential to implement strategies now when penetrations are low to mitigate the potential problems of PV system integration which are likely to be exacerbated in the future with increased penetrations. If strategies are investigated and implemented now it is likely that expenditure due to PV systems will be minimised, and the potential benefits in load reduction will be maximised. Risk management strategies based on this research are listed below.

It would be beneficial to roll out a monitoring program on highly penetrated distribution substations. This is because the scenarios built in this research are only indicative of potential problems; they may be more or less depending on the circumstances. Thus by implementing an ongoing monitoring program when potential problems occur, supply utilities will be equipped to mitigate problems swiftly and effectively. A centralised location for investigating PV effects will also assist in streamlining the monitoring program. An example of the benefits is that supply utilities would be able to identify voltage level problems early and thus line augmentation can be conducted keeping voltage levels within quality of supply standards, rather than fixing the problem after quality of supply standards have been breached.

One potential solution too much of the problems encountered with PV is implementing a storage program. The largest source of the problems associated with PV system integration is the mismatch in peak residential load times with PV generation times. By lobbying for legislative changes which have the potential to change this fact much of the problems associated with PV systems are mitigated and the systems actually become beneficial to the network, potentially saving a large amount of money. One such change is an innovation already being trialled. Time of use tariffs have the potential to shift loads that are not so time critical, such as pool filtering, to times when the PV is generating. This has the potential to decrease peak loads and increasing loads during generation. Another option is a similar avenue but from a generation point of view. By offering time of generation tariffs to PV systems it could be enough incentive for customers to introduce storage options into their PV systems, thus changing the time that power is fed into the network from the middle of the day to times of peak load. For example battery systems or electric cars being charged by the PV systems in the middle of the day and feeding into the grid during afternoon peak load times.

There is also scope to implement policy in the near future to limit the amount of PV systems on a LV distribution transformer. Results of this thesis have indicated that a penetration of around 70% of houses with 1.1kW systems will lead to an acceptable system power factor and acceptable voltage levels (around 245V). Policy such as this has already been implemented in the Netherlands to limit penetration to 70% on a low voltage feeder [17].

Another management option to be considered is the provision for more investigation into solutions for PV system's impact on network efficiency. If the impact of power factor and harmonic distortion is indeed causing significant drops in network efficiency as predicted, there is scope to implement infrastructure to mitigate these problems in a preventative way. For example if penetration gets to a certain level on a distribution substation it could be beneficial to identify this substation early and install reactive power compensation as well as harmonic filters on the substation.

It has also been observed that there is some discrepancy in the protection levels for inverters. Some inverters are designed for a maximum voltage of around 250V whilst the Endeavour network standards dictate a level of 262.2V over a 10 minute interval is acceptable. This discrepancy can lead to inverters not operating when the grid is seen to be at an acceptable level, possibly causing system shutoff and current swings on the network. By setting up a standard amongst PV inverter manufacturers selling inverters in Australia such a problem is easily avoided and thus the issue of current swings on the network can largely be avoided.

Alternatively to control the voltage rise associated with PV system integration it is possible to lower the system voltage. This can be done in two ways; by lowering the voltage in individual feeders by using the fixed taps at the distribution transformers or by amending current policies and bulk changing the system voltage to be lower. Whilst this option will have the advantage of controlling the voltage rises associated with PV and also potentially bring the standard voltage levels in line with AS3000 there is the problem of high loads. This was shown in section V. A page 3 the high loads outside of generation times have a greater impact then the PV generation. As such many utilities are understandably reluctant to lower system voltages and exceed the lower voltage thresholds during periods of high load [19].

Another recent alternative to control the issues associated with PV system integration include the incorporation of reactive power compensation into the inverters. Reactive power compensation works by having an intelligent inverter which is able to dynamically change the level of reactive power that the inverter supplies. This has a similar effect to the switching in of capacitor banks into the distribution grid and is theoretically effective in minimising the voltage variation at the load end of the network. Essential Energy (the major rural NSW network utility) is currently undertaking extensive trials into this technology. Unfortunately there is currently no incentive for consumers to either switch inverters or to buy an inverter with reactive power support. This implies that current government policy needs to be examined to explore the economic feasibility of incentives for implementing this technology [19].

When designing protection systems for a network it is vital for PV systems to be included in these calculations. Whilst the levels calculated using current techniques are likely to be appropriate even with PV systems installed it would be beneficial to include the PV systems in the calculations to be sure of customer and network safety. Such a management option is easy to implement and has the potential to increase the safety of the network. Provision also needs to be made in the calculations of the possibility of reverse power flow on the network interfering with uni directional protection systems.

VIII. CONCLUSIONS

Analysis of case study areas indicates that current PV system penetration levels are not high enough to significantly infringe on supply utility quality of supply standards. Current levels of PV system integration have been shown to cause increased current harmonic distortion and a decreased power factor at the distribution substations, which could result in lowering system efficiency. It has also been shown that actual field performance of PV systems has been proven to have far less than the optimal performance that was expected. PV system output is in fact limited to 65 to 70% of the quoted PV output power. Field surveys have indicated that this is due to the challenges associated with the installation of a large amount of residential PV systems.

Modelling scenarios show that increased PV system penetrations are likely to cause increased voltage levels as well as have a detrimental effect on the system power factor.

Additionally in the event of PV system shutoff due to voltage protection schemes, current swings of up to 140A might be observed in the network.

This work has highlighted the importance of supply utilities engaging more proactively in implementing management strategies to mitigate expected integration issues and maximise potential benefits. Such management options include implementing a monitoring program, looking into storage options, limiting the of the amount of PV systems on distribution transformers, implementation of network infrastructure to limit potential efficiency problems, standardisation of inverter protection schemes, reactive power implementation in inverters, lowering of system voltage and the inclusion of PV system impact when designing protection systems.

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XI. BIOGRAPHY

Simon Lewis was born in Sydney, Australia on 27th of October 1988. He graduated from the University of New South Wales in 2010 with first class honors. He is currently employed at Endeavour Energy (NSW distribution supply utility) and is pursuing a career in power engineering. The work presented in this report is a summary of his honours thesis which can be made available on request.