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Voltage Probability Analysis - PV and Load in Low Voltage Networks

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Abstract

Growing penetrations of distributed PV generation in electrical networks pose new voltage management challenges for Distribution Network Service Providers across Australia. This paper uses a year of half hourly load and PV data gathered from 300 residences to perform voltage probability analysis on a typical residential low voltage feeder with high PV penetrations. A number of possible voltage management scenarios are considered. These include the impact of varied levels of demand-side management to reduce peak demand, PV system tripping on high voltage and storage. Results show that PV system tripping on high voltages can effectively manage potential high voltage excursions and seemingly reasonable levels of demand-side management at times of peak demand can effectively reduce low-voltage excursions. Modest sized storage systems are also shown to be effective at reducing low-voltage excursions. To achieve a DSM voltage management target, the probabilistic method presented is considered a deferrable load and/or storage capacity sizing strategy, and also a method to determine potential impacts on customers due to required PV and load tripping.

Introduction

The deployment of photovoltaic (PV) generation is increasing around the world (Oosterveer and Mol, 2006) Australia is no exception with installed PV capacity by 2014 representing more than 7% of total installed generation capacity (Solar PV map, 2015), having risen from insignificant levels as recently as 2009. Nearly all of this deployment is small scale (< 5 kW) single phase residential systems connected to the low voltage network (Australian Photovoltaic Institute, 2013). These systems are raising a number of challenges, notably with voltage management, for the distribution network service providers (DNSPs) across Australia. In particular, PV can reduce minimum network flows (or even reverse them) driving up network voltages.

This paper conducts a voltage probability analysis for a typical low voltage residential feeder hosting both load and PV generation. The data set is a year of actual half-hourly load and PV data for 300 residences in Sydney, Australia. Voltage probability data is obtained by running a large number of load flow calculations in DIgSILENT, with load and PV profiles selected randomly from the 300 PV and load data sets available. The 300 PV and load datasets are altered to represent different voltage management scenarios including: demand side management (DSM), PV tripping on high voltage, load tripping on low voltage and battery storage. Due to the significant data set available, and the large number of load flow calculations conducted, a probability analysis approach to these voltage management scenarios is possible. Taking a probabilistic approach differs from previous work looking at the voltage profiles of residential feeders in the presence of PV, which tend to be deterministic in nature. An example of this is (Tonkoski et al., 2012), where for the voltage analysis conducted, each house is assigned the same net load value between ±6.25 kW.

PV inverters can be used to control voltage rise, either through real power curtailment (Lin et al., 2012) or reactive power absorption (Keane et al., 2011). This paper looks at real power curtailment only. In (Lin et al., 2012), a financial analysis is conducted. The optimal PV installation capacity, taking into account the required real power curtailment to ensure voltage levels are maintained, is calculated using a net present value (NPV) analysis. This paper, as opposed to a financial analysis, presents an impact analysis, looking at the probabilistic PV system downtime to ensure an upper voltage limit (253 V) is not breached.

Load shifting algorithms, peak load shifting to PV generation periods, are used in (Malik and Havel, 2014) and (Yao et al., 2013). In (Malik and Havel, 2014) the objective of the algorithm is to maximize the energy transfer from the PV system to the electric water heater (EWH), in (Yao et al., 2013) it is to minimise the energy bill for the customer. In (Argiento, 2012), load tripping and microgeneration is controlled to ensure load demand is met during a “load event”, where load demand exceeds generation. Load tripping and microgeneration is controlled to balance load through minimisation of a cost of energy function.

The above papers on load shifting and load tripping present methods which optimise the DSM control of participating generation and/or load to achieve an objective. This paper takes advantage of probabalistic analysis to illustrate the key message that a significant reduction in low voltage excursion is possible without complex DSM control techniques. The work on battery storage in this paper is equivalent to simulation of load shifting, where the probabalistic energy capacity (battery size or deferrable load) required to ensure a low voltage level is not breached is determined. This approach is also considered a novel battery sizing strategy, compared to what is currently proposed in the literature, (Yang et al., 2014) for example. A probabilistic analysis on the impact of load tripping on low voltage is also presented, as opposed to deterministic (Argiento, 2012).

Along with battery and/or deferrable load sizing, to achieve a DSM voltage management target, the probablistic method presented can also be used to determine the impact of required PV and load tripping on customers.

The paper is structured as follows. Section 2 presents the method, describing the dataset and the low voltage feeder model. Section 3 presents the results of the analysis for a range of different PV penetrations and voltage management options, and Section 4 provides concluding comments and suggests possible areas of extension.

Method

Dataset

The dataset used for the voltage analysis is provided by Ausgrid, Australia’s largest (by customer) distribution network service provider (DNSP). Ausgrid operates an electricity network in NSW, Australia, including Sydney. The data is sourced from 300 randomly selected solar customers in Ausgrid’s electricity network between 1 July 2010 and 30 June 2011, a years’ worth of data.

Feeder model – DIgSILENT

The characteristics of the feeder used for analysis are those typically used by Endeavour Energy. Endeavour Energy is the DNSP servicing Greater Western Sydney. Voltage standards for Endeavour and Ausgrid are 230+10%/-6%. Customers are evenly distributed across the phases. Each customer connection consists of a load and PV system. Figure 1 presents the DIgSILENT schematic of the feeder. A 400 m long feeder with 20 terminals hosting 40 customers is used for the study, a typical urban feeder. Overhead (OH) line is used for the analysis as the majority of Australia's residential low voltage network consists of OH line. Residential low voltage feeders are designed based on load, to ensure voltage remains within regulation limits. Therefore, a low voltage residential feeder with different characteristics to the one used in this paper is still expected to experience experiencing similar voltage measurements as acquired in this analysis. As a result, the voltage probabilities resulting from the analysis of a typical OH line feeder will be representative of what is likely to occur for the majority of OH line feeders in a residential low voltage network

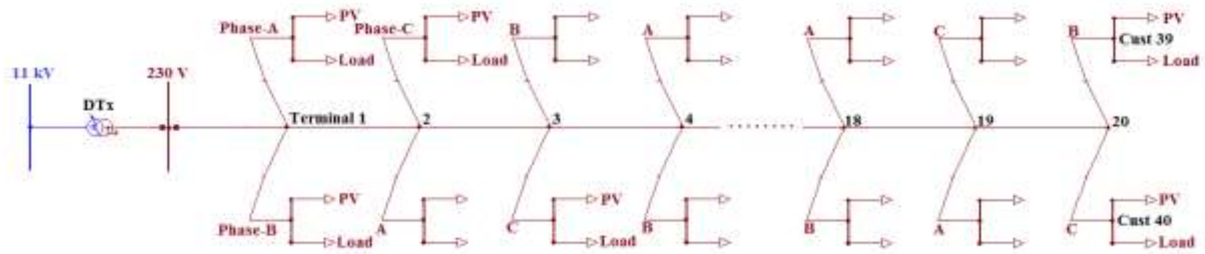

Figure 1. Schematic of DIgSILENT feeder model

Voltage Probability Analysis

The voltage probability analysis examines the impact of varying load and PV profiles on voltage levels when applied to the forty customers connected to the DIgSILENT feeder model described in Section 2.2. The analysis is performed for five different scenarios. For all scenarios, the load and PV profile for each of the forty connected customers are randomly selected from the 300 available. Using DIgSILENT, a load flow calculation is then performed at hourly intervals across the year between the times of 10 am and 10 pm. For each load flow calculation the voltage for each customer is recorded. The end of the feeder is where the lowest voltage occurs during peak load times. The random load and PV profile selection is implemented a further nineteen times and the load flow calculations repeated for the year. The first of the five scenarios' for which the voltage analysis is performed leaves the load and PV profiles unaltered; this scenario is referred to as the reference scenario. For the remaining scenarios, either the dataset is altered or a voltage control method simulated.

Demand side management

In this scenario a demand side management control is modelled. The load datasets are altered such that the top 5% of customer load samples are decreased by 50% to model the effect of demand side management measures targeting peak demand.

PV inverter tripping on high voltage

In this scenario PV inverter tripping on high voltage is modelled. After each load flow calculation, the voltage at each customer is examined, moving sequentially from the end of the feeder towards the DTx. If over-voltage is detected at a customer then their PV system is tripped off and the load flow calculation repeated. This process is repeated until no over-voltage is detected; a tripped PV system will remain tripped. Once no more over-voltages are detected the PV downtime due to tripping is then calculated. This process is repeated for increases in PV system size, 1pu to 1.5pu in 0.1pu steps.

Load tripping on low voltage

In this scenario load tripping on low voltage is modelled. The load tripping process is the same as for PV inverter tripping, the only difference being that the tripping of load occurs when a voltage less than 216 V is detected. The average PV system size is 1.7 kW, so a reasonable comparison in the downtime between load and PV can be made, 1.7 kW is the amount of load “tripped” when a voltage lower than 216 V is detected.

Battery storage

In this final scenario, households own battery storage to ensure voltages are maintained above a lower voltage limit. After each load flow calculation, the voltage of the two customers at the end of the feeder is recorded. If the voltage for either customer is under the lower voltage limit (230 V, 220 V or 216 V) then the load of every customer is incrementally reduced until the voltage is within the limit. For each day, the amount of energy required to ensure the voltage remains above the limit is recorded. This analysis produces probabilistic battery storage capacity requirements to keep voltages above a set limit.

Results

Reference scenario

For the reference scenario, the voltages recorded for the customers at the end of the feeder are arranged into a voltage histogram, Figure 2, showing the impact of PV generation and load on voltage spread. The DTx no-load voltage is 250 V. Examining Figure 2, load produces a voltage spread of 49 V, over three times that of PV at 14 V. Also, the total percentage of voltage recordings below 216 V is only 0.7%, showing how a small number of high load periods have a large impact on voltage spread.

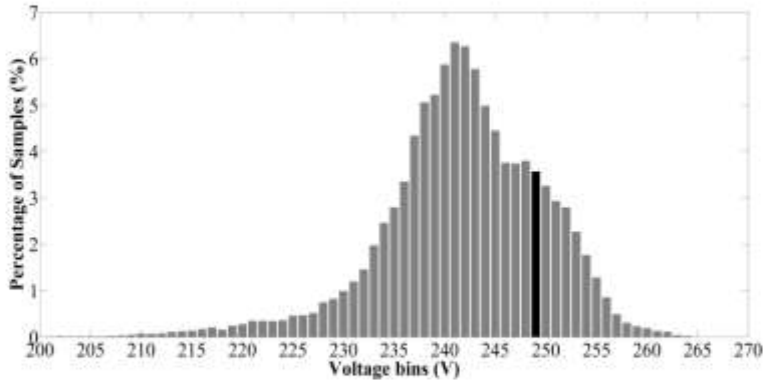

Figure 2. Voltage histogram – reference scenario. The highlighted bar indicates the DTx voltage tap setting.

Demand side management

The next scenario examines the impact of decreasing peak load demand on low voltage excursion. Figure 3 gives the voltage histogram for when the top 5% of load samples are reduced by 50%, significantly, the number of voltage recordings below 216 V falls to zero. Whilst a 50% decrease in load appears significant, the top 5% of load samples for all customers is, on average, approximately three times that of the customers mean of the evening peak load and in some cases it is over ten times. The peak load demand reduction is therefore relatively not large. Comparing Figure 3 to Figure 2 shows the extent to which low voltage excursion can be reduced for relatively small reductions in peak load demand. This reduction should not require complex control systems and could be achieved through tariffs and in-house displays (Australian Senate Committee Report on Electricity Prices, 2013)

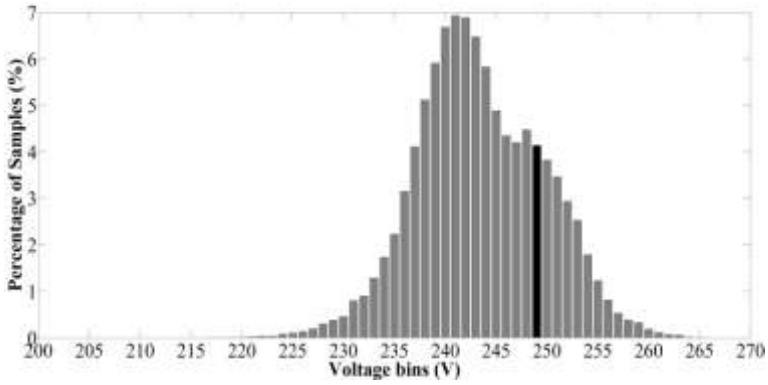

Figure 3. Voltage histogram 50% reduction in top 5% of samples

PV inverter tripping on high voltage

The next scenario models PV inverter tripping on high voltage. For customers 8, 16, 24, 32 and 40, Figure 4 gives the PV downtime as a percentage plotted against a PV multiplier ranging from 1pu to 1.5pu. Figure 4 shows that PV downtime time for each customer increases linearly with PV system size. As expected, it is the customer at the end of the feeder who experiences the most PV downtime. These results show that PV can be accommodated by LV feeders with just an appropriately set trip voltage, complex control/communication systems are not necessary. With an increase in PV system size though, the PV downtime for customers located towards the end of the feeder becomes significant.

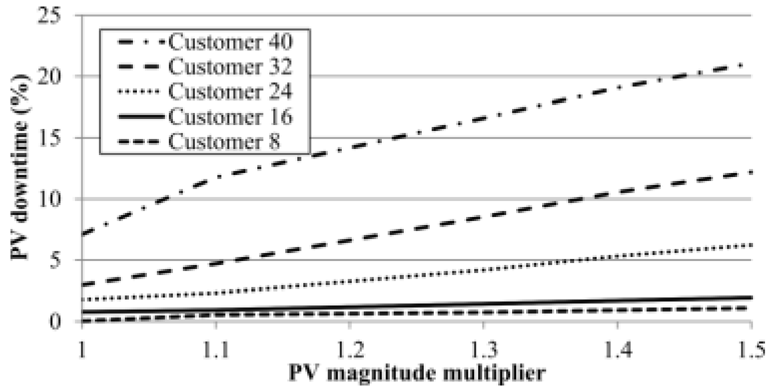

Figure 4. PV downtime (%) v increase in PV system size (1pu to 1.5pu)

An obvious solution is a reduction in the DTx tap setting. A recent report (Energex Power Quality Strategic Plan 2015-20, 2014) by Energex, a network operator servicing South East Queensland, Australia, estimated that 75% of their DTx's were tapped too high. The consequence of a decrease in the DTx tap setting is more breaches of the lower voltage limit, although this can be mitigated with peak load reduction. For a DTx setting of 243 V, one tap setting lower, the reduced peak load dataset (Section 3.2) and the PV system tripping at the upper voltage limit were combined. The PV downtime is reduced dramatically; for PV system size at 1.5pu, Customer 40 only experienced 3.6% downtime, compared to over 20% at a DTx voltage of 250 V. With peak load reduction, breaches of the lower voltage limit are mitigated, there are still recorded voltages below 216 V, but these only constitute 0.07% of the total. The lowest recorded voltage was 209 V, still 9 V higher than the lowest recorded voltage for the reference scenario. To give an idea of the level of PV penetration, due to the stochastic nature of the analysis, we need to revert to mean peak load and mean rated PV capacity values. The mean peak load for all homes is 1.3 kVA and the mean rated PV capacity is 1.7 kW. At 1pu the PV penetration, the ratio of mean PV capacity and mean peak load, can be estimated to be 1.3 at 1pu and 1.96 at 1.5pu.

Load tripping on low voltage

The next scenario examined tripping load at the lower voltage limit. At a DTx voltage of 250 V the number of load trip events is negligible, only six and four trip events in winter and summer respectively. For customers 8, 16, 24, 32 and 40, Figure 5 gives the seasonal cumulative number of trip events when the DTx voltage is at 243 V. As expected, results show that the majority of load tripping occurs for the customer at the end of the feeder, customer 40, and drops quickly for customers closer to the DTx. The majority (80%) of each trip event are only one hour or less in duration.

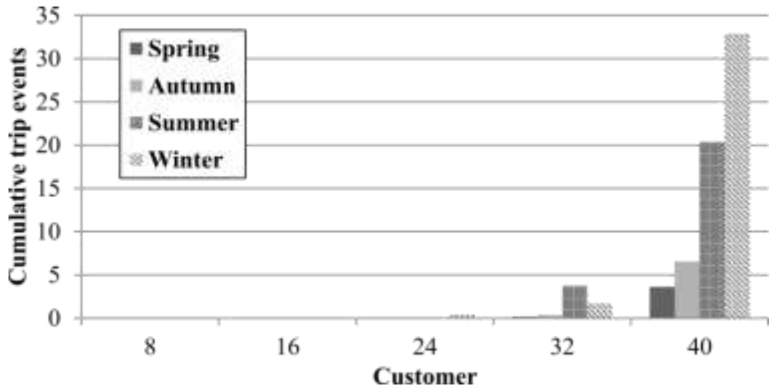

Figure 5. Seasonal average daily load trip duration for customers 8, 16, 24, 32 and 40. DTx voltage at 243 V

Battery storage

The final scenario simulated households owning battery storage to ensure voltages are maintained above a lower voltage limit. Also examined is the capability of the household PV system to charge the battery to ensure energy requirements are met. Figure 6 is a histogram presenting the probable amount of energy required to ensure voltage levels are maintained above 230 V, 220 V and 216 V during the peak demand period. Figure 6 shows how little storage capacity per household is required to ensure voltage levels are maintained. Probabilistically, 2 kWh of storage will ensure voltage levels remain above 216 V for all days, above 220 V for 99% of days and above 230 V for 98% of days.

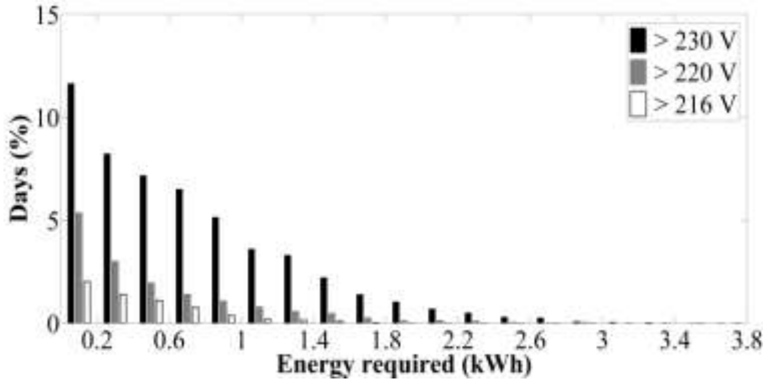

Figure 6. Histogram of energy required to ensure voltage stays above 230, 220 and 216 V during the peak demand period

Conclusion

This paper presents a voltage probability analysis using load and PV data from 300 customers. The analysis consists of a number of different scenarios. The first scenario, with an unaltered dataset, shows that the impact of load on voltage range is far greater than that of PV, with the lower voltage being almost three times that of the upper voltage range. The second scenario decreases the top 5% of load samples by fifty percent; results show the effectiveness of DSM at reducing voltage excursion as a result of peak load. The next scenario examines the impact on customer PV system uptime when trip conditions are applied at the upper voltage limit. Results show PV tripping prevents over-voltage but can have a significant impact on PV system downtime. The impact of load tripping at the lower voltage limit was also examined; results show that voltage can be maintained above the lower voltage limit with only customers at the end of the feeder experiencing any noticeable inconvenience. The final scenario examined the battery storage capacity required to maintain voltage levels above a lower limit during peak demand period. Results show that the storage capacity required to ensure voltage levels is around 2 kWh for all voltage levels.

The probabalistic analysis presented illustrates that a significant reduction in voltage excursion is possible without complex DSM control techniques. To achieve a DSM voltage management target, it also demonstates its effectiveness as a method for determining the deferrable load and/or storage capacity required and the potential impact on customers due to PV and load tripping.

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