INCREASE THE HOSTING CAPACITY OF 4-WIRE LOW VOLAGE SUPPLY NETWORK FOR EMBEDDED SOLAR GENERATORS BY OPTIMISING GENERATOR AND LOAD PLACEMENT ON THE THREE SUPPLY PHASES

Peter K.C. WONG
Jemena – Australia
peter.wong@jemena.com.au

Akhtar KALAM
Victoria University – Australia
akhtar.kalam@vu.edu.au

Robert A Barr
Electric Power Consulting - Australia
rbarr@epc.com.au

ABSTRACT

Australia has topped the world in the penetration of residential roof-top solar generation systems. These residential solar generation systems are connected to the Low Voltage (LV) supply network which is not designed for two-way flow of electricity. Localized voltage rises due to excess solar generation feeding energy back into the supply network is commonly experienced.

Supply utilities do not generally select the phases for the connection of solar generators. When load/generation is not balanced between the three LV supply phases, phase voltage unbalance arises as a result which aggravates the phase voltage condition due to neutral voltage shift. Balancing loads and solar generation on each phase is quite complex due to the stochastic nature of loads and solar generation. This paper proposes an allocation methodology based on minimizing voltage unbalance on the supply nodes, subject to the constraint that voltages on each supply node/bus are within the regulatory limits. The effectiveness of the approach is illustrated by computer modelling studies implemented in MATLAB© and Open Distribution System Simulator™ (OpenDSS), using load and network data of a real LV network in Australia.

INTRODUCTION

Australia has topped the world in the penetration of residential roof-top solar generation systems. With a population of only 24 Million, there are almost 1.5 Million grid connected residential solar installations approaching 5,000MW of installed capacity by June 2016, and the number continues to grow.

Similar to European LV network design, Australian electricity supply utilities run extensive 4-wire LV (230/400V) reticulations along the streetscape. The LV distribution network employs a Multiple Earthed Neutral (MEN) design where the neutral conductor is earthed at the distribution transformer and at points of connection into customer premises.

Automatic voltage regulation is implemented upstream of the distribution transformer on the Medium Voltage (MV) network using on-load tap changing transformers, shunt capacitor banks and in-line voltage regulators (for long rural lines). Distribution transformers are equipped with off-load tap changing facility only. MV automatic voltage regulation is designed with peak load period in mind, results in steady-state supply voltage at the high side of the prescribed range most of the time [1]. This high LV supply voltage is not confined to Australian practice but has also been reported in other countries, e.g. UK [2].

The growth in residential roof-top solar generation systems has highlighted the undesirability of this voltage regulation approach, as it results in little headroom for the voltage rise caused by the connection of embedded solar generators. In addition, imbalance between loads and generations on the three phases results in voltage unbalance which affects both network and customer equipment [3], [4], and will exacerbate the steady-state voltage problem. Unless these challenges are overcome in a cost effective manner, curtailment of solar installations or expensive network augmentation would be required to accommodate the increasing penetration of solar installations.

STANDARDS FOR VOLTAGE UNBALANCE

A number of standards exist for defining voltage unbalance using either phase-to-neutral (V_{an}, V_{bn}, V_{cn}) or phase-to-phase voltages (V_{ab}, V_{bc}, V_{ca}) [5], [6]:

- IEEE Standard 936 (1987): Phase voltage unbalance rate (PVUR)

$$PVUR = \frac{Maximum\ \{V_{an}, V_{bn}, V_{cn}\} - Minimum\ \{V_{an}, V_{bn}, V_{cn}\}}{Mean\ \{V_{an}, V_{bn}, V_{cn}\}} \text{ x } 100\% \quad (1)$$

- IEEE Standard 112 (1991): Modified phase voltage unbalance rate ($PVUR_{mod}$)

$$PVUR_{mod} = \frac{Maximum\ deviation\ from\ Mean\ \{V_{an}, V_{bn}, V_{cn}\}}{Mean\ \{V_{an}, V_{bn}, V_{cn}\}} \text{ x } 100\% \quad (2)$$

- NEMA (National Electric Manufacturers Associations of the USA) Standard (1993): Line voltage unbalance rate ($LVUR$)

$$LVUR = \frac{Maximum\ deviation\ from\ Mean\ \{V_{ab}, V_{bc}, V_{ca}\}}{Mean\ \{V_{ab}, V_{bc}, V_{ca}\}} \text{ x } 100\% \quad (3)$$

- IEEE Standard (1996) and IEC Standard 61000-4-27: Voltage unbalance true definition (VU_{TD})

$$VU_{TD} = \frac{Negative\ Sequence\ Voltage\ V_2}{Positive\ Sequence\ Voltage\ V_1} \text{x } 100\% \tag{4}$$

- CIGRE report (1986): Voltage unbalance (VU_{CIGRE})

$$VU_{CIGRE} = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}}$$
$$where\ \beta = \frac{|V_{ab}|^4 + |V_{bc}|^4 + |V_{ca}|^4}{(|V_{ab}|^2 + |V_{bc}|^2 + |V_{ca}|^2)^2} \tag{5}$$

- [5] defines a voltage unbalance factor that specifically takes into account zero sequence voltage that is unavoidable in 4-wire unbalance LV networks ($VU\%$):

$$VU\% = \frac{\sqrt{|V_2|^2 + |V_0|^2}}{|V_1|} \text{x } 100\% \tag{6}$$

where V_1, V_2 and V_0 are the positive sequence, negative sequence and zero sequence voltages respectively.

For a three-phase, four-wire, LV network where V_0 can take on substantial value, it is imperative that a definition of voltage unbalance takes V_0 explicitly into account. Equation 6 is therefore used to calculate voltage unbalance on the 4-wire unbalanced LV network in the rest of this paper.

OPTIMAL SOLAR GENERATOR PLACEMENT TO REDUCE UNBALANCE

Supply utilities do not generally select the phases for the connection of solar generators. For customers on single-phase supply, solar generators are connected to the same supply phase. For customers on three-phase supply, the solar generators are connected to the phase deemed suitable by the solar installers. The localized voltage rise, however, will be dependent on the phases where the solar generators are connected as well as the distribution of loads among the three phases. Balancing loads and solar generation on each phase will increase the capacity of the network to accommodate more solar generators without expensive network augmentation or implementation of new smart grid technologies. Customer loads and solar generation, however, are stochastic in nature hence we need a methodology to allocate loads and solar generation.

To tackle the issues of phase voltage rise and unbalance voltages, this paper proposes that loads and generators are allocated to the three supply phases of the LV network based on minimizing voltage unbalance on the supply network, with the constraint that voltages on each LV supply node/bus are within the regulated limits.

For a LV network with multiple nodes where voltage unbalance can be calculated, we define a composite index, the network voltage unbalance factor *f(x)*, as the average of the weighted, maximum voltage unbalance, on each supply node/bus over the period of simulation. This can be expressed mathematically as

$$f(x) = \frac{1}{M}\sum_{n=1}^{M} W_n * (VU\%_{\max})_n \tag{7}$$

Minimize *f(x)* subject to 216V $\le V_n \le$253V, where

$(VU\%_{max})_n$ = maximum voltage unbalance at the n^{th} mode
V_n = voltage on the n^{th} mode
M = number of node/bus
W_n = weight coefficient allocated to the n^{th} mode

W_n is normally set to 1 but can be set higher for the node/bus where 3-phase customer equipment, susceptible to voltage unbalance, have been installed.

We'll proceed to apply this methodology to a computer simulation study using a network model based on a real Australian supply network.

LV NETWORK MODEL FOR SIMULATION STUDIES

Due to the lack of data and real-time monitoring by utilities, it has been difficult to establish accurate LV network models to perform simulation studies incorporating the impact of customers' embedded solar generators. Network models based on generalised network characteristics have been used in the past for planning studies but they either produce conservative results or are used conservatively by utility engineers.

Mass rollout of smart meters to residential customers in Victoria, Australia, has open up an opportunity. Smart meter consumption data allows load model of individual customer or customer group to be established. In addition, it is now possible, through advanced data analytics performed on smart meter voltage and current data [7], [8], to accurately identify the phase and circuit connection of individual customer and derive line impedance between supply nodes. The key components for a LV network model are therefore available.

The network model is set up from the source MV zone substation. This approach is taken so that the voltage regulating devices on the MV network are included in the modelling and simulation. The LV distribution circuit used in the case study emanates from a 22kV/433V distribution substation supplied by a 22kV feeder from a 66/22kV Zone Substation. The LV circuit supplies eight customers of which two have solar generators installed (Table 1). The circuit forms part of the electricity distribution network operated by Jemena, an electricity distribution company in the state of Victoria, Australia. Details for the derivation of the various network parameters can be found in [9]. It is important to point out that there is a need to model both the LV neutral conductor and the earth connection as the loads are inherently unbalanced (due to 1-phase customer connections) so currents will flow in both the neutral conductor and earth, leading to voltages appearing on the neutral conductor. Many load flow software packages calculate phase-to-ground voltage results whereas the voltages received by customer equipment are the voltages between phases and neutral. Care should be taken to interpret load flow results when ground and neutral are not at the same potential [10]. In addition, neutral-point shifting will cause voltage increase to occur in one phase while voltage decrease in the other two phases. Ignoring to model neutral conductor will therefore lead to erroneous results [11].

Table 1. LV customer details

Customer	Supply	Max Load	PV
Cus 1 (Load 12)	3-phase	5kVA	
Cus 2 (Load 13)	B-phase	5kVA	
Cus 3 (Load 10)	3-phase	15kVA	
Cus 4 (Load 11)	3-phase	7.8kVA	
Cus 5 (Load 8)	3-phase	7kVA	4kW
Cus 6 (Load 9)	W-phase	5kVA	
Cus 7 (Load 14)	3-phase	9kVA	5kW
Cus 8 (Load 15)	3-phase	9KVA	

Figure 1 shows the single-line representation of the network model that has been set up in OpenDSS. OpenDSS uses Carson's Equations to derive the line and cable impedances. Monitors have been allocated to various line terminals and buses to record power parameters during simulation studies. MATLAB is used to drive the load flow simulations and analyse the results.

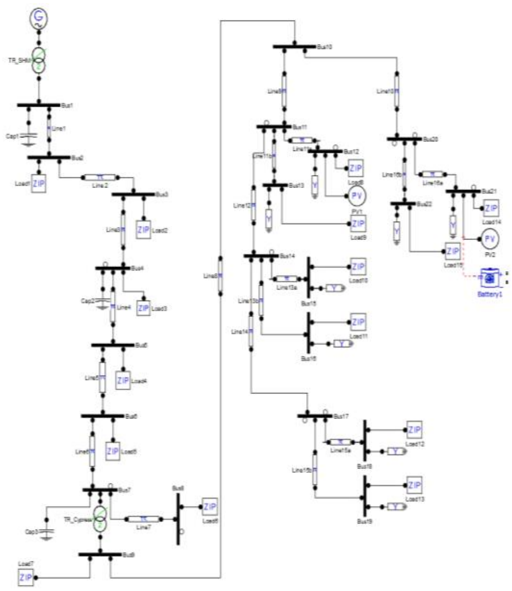

Figure 1. Single-line presentation of network model

RESULTS OF VOLTAGE UNBALANCE STUDIES

The two solar generators (PV1 and PV2) can each be connected to the red, white or blue phase of the three supply network, resulting in nine combinations. For each combination, load flow calculation is carried out and voltage unbalance determined for each LV bus using Equation 6. The network unbalance factor *f(x)* can then be calculated using Equation 7. Table 2 summarizes the result of the network voltage unbalance factor calculated for the nine combinations, with W_i set to 1 for each bus. It can be seen that minimum network voltage unbalance occurs when PV1 is connected to white phase and PV2 to blue phase. The current PV connection arrangement (both PV1 and PV2 connected to red phase) results in the largest network voltage unbalance factor.

Table 2. Network Voltage Unbalance Factor for Different Combinations of Phase Connection of Generators PV1 and PV2

Case number	PV1 connection	PV2 connection	Network voltage unbalance *f(x)*
1	R	R	0.869
2	R	W	0.557
3	R	B	0.617
4	W	R	0.547
5	W	W	0.795
6	W	B	0.436
7	B	R	0.634
8	B	W	0.438
9	B	B	0.719

The variation of the voltage unbalance for the various load buses is shown in Figures 2 and 3. By allocating the PV generators to minimise voltage unbalance, the voltage profiles are also improved as shown in Figures 4 and 5. While at present this phase balancing can only be carried out manually, with the advent of power electronics, dynamic switching of customer loads and PV generators among three phases may become economically feasible [6].

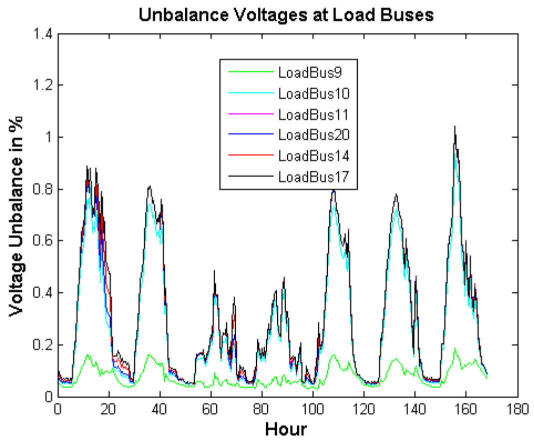

Figure 2. Modelled results with PV1 and PV2 both connected to red phase, showing the voltage unbalance on various load buses. This combination of PV allocations results in the highest voltage unbalance factor during the period of simulation

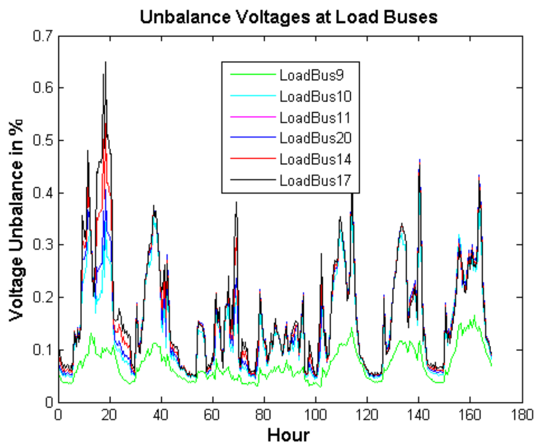

Figure 3. Modelled results with PV1 connected to the white and PV2 to the blue phase, showing the voltage unbalance on various load buses. This combination of PV allocations results in the lowest voltage unbalance factor during the period of simulation

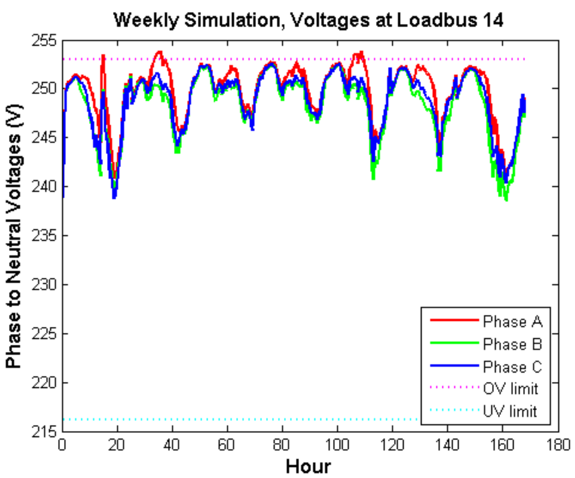

Figure 4. Modelled results with PV1 and PV2 both connected to red phase. Note voltages on Bus14 exceed the over voltage limits some of the time during the simulation

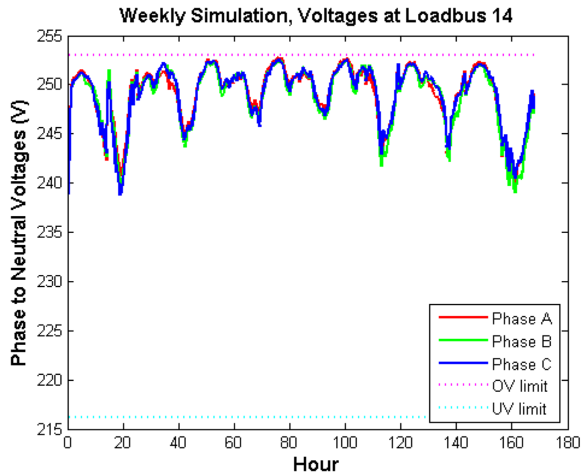

Figure 5. Modelled results with PV1 connected to the white and PV2 to the blue phase. Note voltages on Bus14 are within the voltage limits during the simulation

CONCLUSIONS

Excess generation from solar generators are known to cause localised over voltage issues. Many researches have been conducted on smart grid technologies to mitigate the over voltage effect. These approaches will generally require additional investment at a time when customers are already feeling the pain of high electricity prices. There is perhaps less focus on improvement to existing utility operational practices such as voltage control and generator placement. Operational practices can be cost effective means of increasing the hosting capacity of LV distribution network for solar generators. Lastly, computer simulation is an important tool for utility engineers and even more so with the increasing complexity of the power system. In this regard accurate network models are a pre-requisite for dependable computer simulation results.

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