Modelling and analysis of practical options to improve the hosting capacity of low voltage networks for embedded photo-voltaic generation

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Modelling and Analysis of Practical Options to Improve the Hosting Capacity of Low Voltage Networks for Embedded Photo-Voltaic Generation

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Abstract: Dwindling fossil fuel resources and concern of climate change resulting from the burning of fossil fuels have led to significant development of renewable energy in many countries. While renewable energy takes many forms, solar and wind resources are being harvested in commercial scale in many parts of the world. Government incentives such as Renewable Energy Certificates and Feed-in Tariffs have contributed to the rapid uptake. In Australia many residential customers have taken up roof-top Photo-Voltaic (PV) systems. These residential PV generations are embedded in the Low Voltage (LV) networks that are not designed to take intermittent, two-way flow of electricity. Utility engineers are faced with the challenge of a legacy electricity distribution network to connect increasing amount of embedded PV generation. This paper focuses on two aspects of the technical limitation – steady state voltage delivery and phase imbalance – and proposes how the technical limitations can be improved by optimizing the existing voltage control schemes, the balancing of loads and generations between the supply phases, and finally the adoption of smart grid methodologies. This prioritised approach provides a cost effective means of addressing the impact of embedded PV generation. The proposed method is verified by computer simulation on a realistic LV distribution network in the state of Victoria, Australia.

1. Introduction

Australia has topped the world in the penetration of residential roof-top solar generation systems. With a population of only 24 Millions, there are almost 1.5 Millions grid connected residential solar installations approaching 5,000MW of installed capacity in 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, to ensure all customers are supplied with voltages within the prescribed range (230V +10%/-6%). As peak load is generally driven by the use of air conditioners during hot summer days (which occurs infrequently in Victoria, Australia), this ‘fit and forget’ design philosophy 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. During daylight hours on weekdays the load consumption of many customers are low, resulting in solar installations exporting excess power back into the supply network, raising the voltage at the point of common coupling (PCC). There could be local voltage rise along the supply circuit instead of voltage drop [3], leading to over voltages. In addition, imbalance between loads and generations on the three phases results in voltage imbalance which affects both network and customer equipment [4], [5], and will exacerbate the steady-state voltage problem. While other issues have been reported [6], the steady-state voltage problems attract majority of customer complaints. 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.

2. Approach

In recent years smart grid technologies have been explored to address the steady state voltage problems identified above. One area of research focuses on smart grid devices that can be used to improve LV voltage regulation, such as on-load tap changing distribution transformers (also known as smart grid transformers), smart inverters and energy storage [7 - 11]. Another important area of research focuses on accurately modelling the LV distribution network so the effect of PV attributes such as size, relative location, interaction with other PV systems and loads can be simulated. In the latter statistical analysis such as Monte Carlo simulations are used extensively [12, 13].

Due to the lack of data and real-time monitoring by utilities, it has been difficult to establish accurate LV network models. Mass rollout of smart meters to residential customers in Victoria, Australia, has open up an opportunity. It is now possible to accurately identify the phase and circuit connection [14], as well as consumption of every LV customer, allowing the establishment of accurate LV network models. This paper demonstrates the establishment of a LV network model using SCADA and AMI data, and uses the model to illustrate a planning approach for Australian electricity distribution businesses to manage high penetration of LV residential solar generators in a cost effective manner. The remainder of this paper is organized as follows: Section 3 describes the network characteristics and Section 4 the computer modelling approach. Section 5 and Section 6 provide the network simulation results based on existing voltage control schemes. Section 7 proposes a new approach to allocate solar generators to the three phases to improve voltage imbalance and reduce localized voltage rise. Section 8 demonstrates the use of the LV network model to simulate the effect of smart grid voltage control technologies. Recommendation for utility engineers is summarized and concluded in Section 9.

3. Network Characteristics

The distribution circuit used in the case study is a 22kV/433V distribution substation (Cypress-Stillia) supplied by 22kV feeder (SHM14) from SHM 66/22kV Zone Substation. The circuit forms part of the electricity distribution network operated by Jemena, an electricity distribution company in the state of Victoria, Australia.

3.1. Distribution Circuit Characteristics

The MV supply network and the LV distribution circuit have the characteristics shown in Table 1. Figure 1 provides a geographic view of the LV distribution circuits.

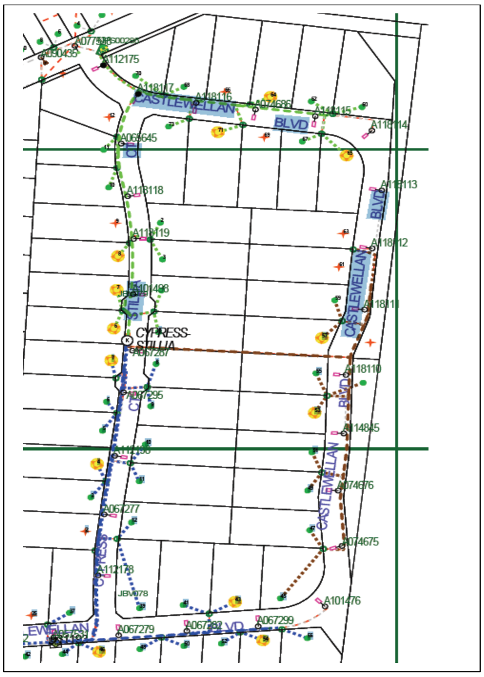


Fig. 1. LV Distribution Circuits from Cypress Stillia Distribution Substation

Table 1 Network Characteristics (provided by Jemena Electricity Networks)

Circuit Element	Characteristics			
Supply source (SHM 66kV side)	3-phase fault level = 7.1kA, 1-phase fault level = 4.0kA, voltage regulated at 67kV			
66/22kV transformers	40MVA, 66/22kV, delta/star, tap winding = 66kV, tapping range = 0.95 to 1.05, tap number = 16, impedance = 10% on 40MVA			
22kV feeder SHM14	Six overhead circuit segments, with a distribution substation at the end of each circuit segment. The overhead lines are 3-wire 19/3.25AAC.			
Cypress-Stillia distribution substation	Connected to the end of the fifth 22kV circuit segment. Comprises of a transformer: 300kVA, 22/0.433kV, delta/star, tap winding = 22kV, tapping range = 0.925 to 1.025, tap number = 4, impedance = 4% on 300kVA. There are 38 customers supplied from this substation arranged in three LV distribution circuits.			
LV Distribution Circuit #4 (coloured brown in Fig. 1) ex Cypress-Stillia distribution substation	Underground cables supplying eight customers. The cable forming the LV backbone is 185mm^2 Al 4C while the branch cable is 16mm^2 Cu 4C.			
Customer details on LV Distribution Circuit #4	Customer	Supply	Max Load	PV
	Cus 1	3-phase	5kVA	
	Cus 2	B-phase	5kVA	
	Cus 3	3-phase	15kVA	
	Cus 4	3-phase	7.8kVA	
	Cus 5	3-phase	7kVA	4kW
	Cus 6	W-phase	5kVA	
	Cus 7	3-phase	9kVA	5kW
	Cus 8	3-phase	9KVA	

3.2. Line Impedances

22kV feeder backbone of SHM14 comprises of 3-phase, 3-wire overhead conductors, single-point earthed on the 22kV neutral of the 66/22kV transformer. The three LV distribution circuits of Cypress-Stillia supply 38 customers via 3-phase, 4-wire underground cables (backbone & 3-phase customers) and 1-phase, 2-wire underground cables for 1-phase customers. A Multiple Earthed Neutral (MEN) system is implemented where the neutral conductors are earthed at customer points of connection (POC) as well as at the neutral of supply distribution transformer. The neutral to earth impedance is taken to be 1 Ohm at the supply distribution substation and 5 Ohms at the customer POC based on empirical measurements. Both the neutral conductor and the earth connection are modelled 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. The voltages received by customer equipment are the voltages between phases and neutral. The effect of the neutral conductor will be further examined in latter part of this paper.

3.3. Customer Loads

Customer load models are set up based on Supervisory Control and Data Acquisition (SCADA) and smart meter measurements over a summer week from 15 to 21 February 2015 when the maximum daily ambient temperature varied from 14.5^{o}C to 35^{o}C. This weekly data is chosen in the case study because they represent a wide range of load consumption which the supply network needs to accommodate, and impact of PV generation is generally at its highest during summer months. The loads are modelled as PQ loads and are specified in base load format (kVA, constant power factor). The base loads are modified by load shapes to gives time series variations of load over the course of the week. The methodology for the derivation of base loads and load shapes is shown in Table 2.

Table 2 Load Derivation

Loads	Method of derivation
SHM Zone Substation loads (excluding loads on 22kV feeder SHM14)	5-minutes snapshots from Supervisory Control And Data Acquisition (SCADA) system. The readings are aggregated and normalized to form 30-minute weekly load shape data. The maximum coincident demand is 18MVA.
SHM14 22kV feeder loads	5-minutes snapshots from SCADA system. The readings are aggregated and normalized to form 30-minute weekly load shape data. The maximum coincident demand is 9MVA.
Cypress-Stillia Distribution Substation Loads	Substation load shape is formed by summing the 30-minute smart meter kWh readings of all customers (except those on LV Circuit #4). The maximum coincident demand is 180kVA.
Customer 1 to 8 on LV Circuit #4	For each customer, the load shape is defined by the 30-minute smart meter kWh readings. For customers with roof-top PV systems, the smart meter readings (representing net of load and generation) are replaced with typical load readings. The maximum coincident demand of LV Circuit #4 is 38kVA.
Roof-top PV systems on LV Circuit #4	No direct measurements of PV output are available. PV output model [15] is used based on ambient temperature and solar irradiance data. Solar irradiance data (1-minute averages) provided by the Bureau of Meteorology are aggregated to form 30-minute snapshots of irradiance data. 5-minute snapshots of ambient temperature measurements by SCADA are aggregated to form 30-minute snapshots.

Care has been exercised to ensure the load models closely resemble actual customer loads. Figure 2 shows the load shapes used in the weekly simulation, while Figure 3 shows the daily load shapes in more details for 15 February 2015.

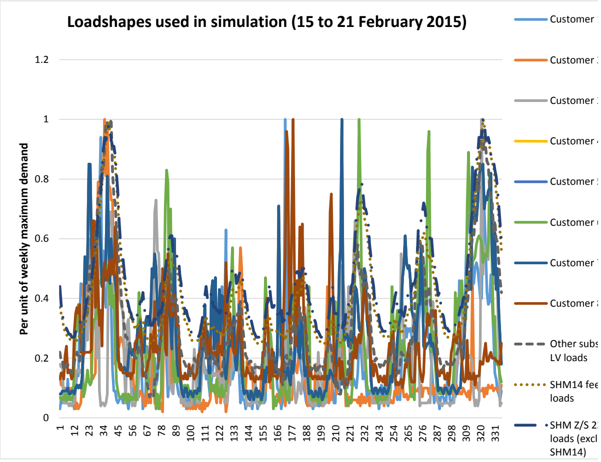


Fig. 2. *Weekly load shapes used in the simulation based on SCADA and smart meter measurements*

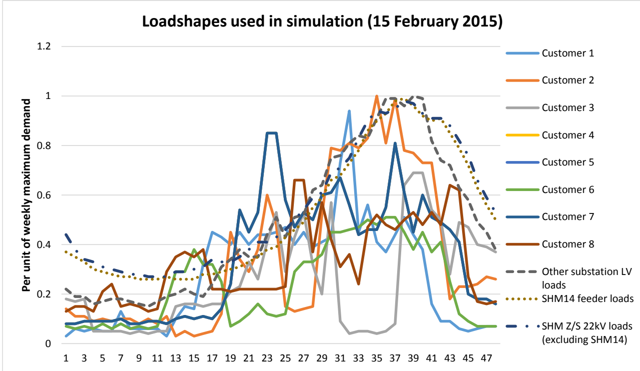


Fig. 3. *Load shapes used in the simulation for 15 February 2015 based on SCADA and smart meter measurements*

3.4. Customer PV Generators

Customer 5 and Customer 7 have roof-top PV systems installed on the R-phase. Due to the use of net metering, actual outputs of the PV generators are not available. PV output model based on input parameters of solar irradiance and ambient temperature time series data is used in the computer simulation, and has been shown to be fairly accurate [15]. An example of the modelled output of the PV generator at Customer 5 is shown in Figure 4. Note the solar generation varies considerably during the week due to cloud coverage. The effect of solar variability is therefore reflected in the modelled results.

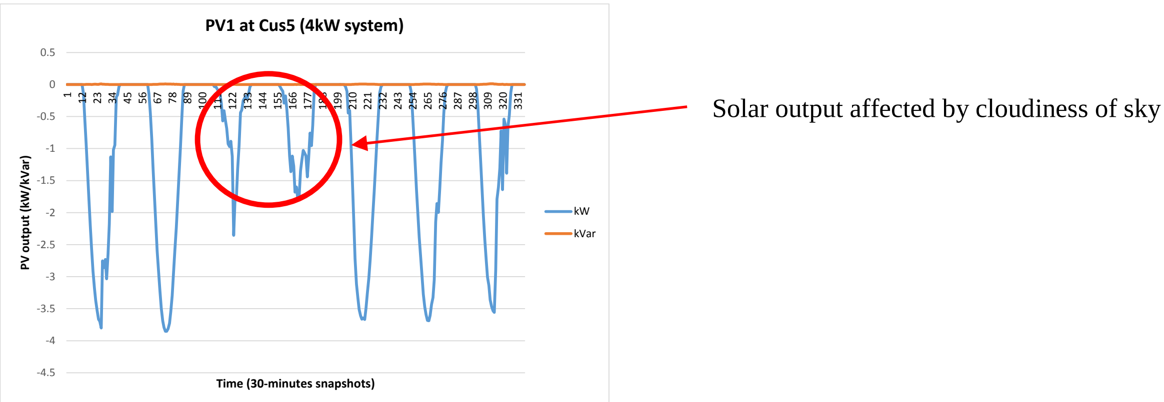


Fig. 4. *Output of 4kW roof-top solar generator installed by Customer 5*

4. Network Model & Computer Simulation

4.1. Network Model

The network model is set up in the Open Distribution System Simulator^{TM} (OpenDSS) [16], an open-source electrical system simulation tool for utility distribution systems, made available by the Electric Power Research Institute, Inc. (EPRI). OpenDSS includes comprehensive library of power delivery elements such as generators, transformers, lines, PV generators, storage batteries as well as control elements such as regulator control and capacitor bank control. Scripting is performed using text files. The flexibility and versatility of OpenDSS is further expanded by the use of an in-process Component Object Model (COM) interface which allows an external program to drive the various OpenDSS functions, provides external analytical capabilities as well as graphics for displaying results. In this project, MATLAB is used to drive OpenDSS through the COM interface.

The network model is set up in OpenDSS based on the network characteristics of Table 1 and load characteristics of Table 2. For line impedances, the series impedances published by the suppliers (positive, negative and zero sequence) for the overhead lines and cables assume balanced loadings on the three phases and regular transposition of the three phase conductors. As the LV distribution system considered here consists of single-phase, two-phase, and un-transposed three-phase lines serving unbalanced loads, it is necessary to retain the identity of the self and mutual impedance terms of the conductors and take into account the ground return path for the unbalanced currents. OpenDSS uses Carson’s Equation [17] to derive the self and mutual impedances of overhead and underground conductors taking into account the return path of current through ground. Ground connections for the MEN LV network have been explicitly modelled.

4.2. Single Line Representation of Network Model

Figure 5 shows the single-line representation of the network model that has been set up in OpenDSS. Monitors have been allocated to various line terminals and buses to record power parameters during simulation studies.

4.3. Voltage Control Devices

Table 3 lists the voltage control devices included in the network model. Some of these voltage control devices are currently utilized while others are being considered for future.

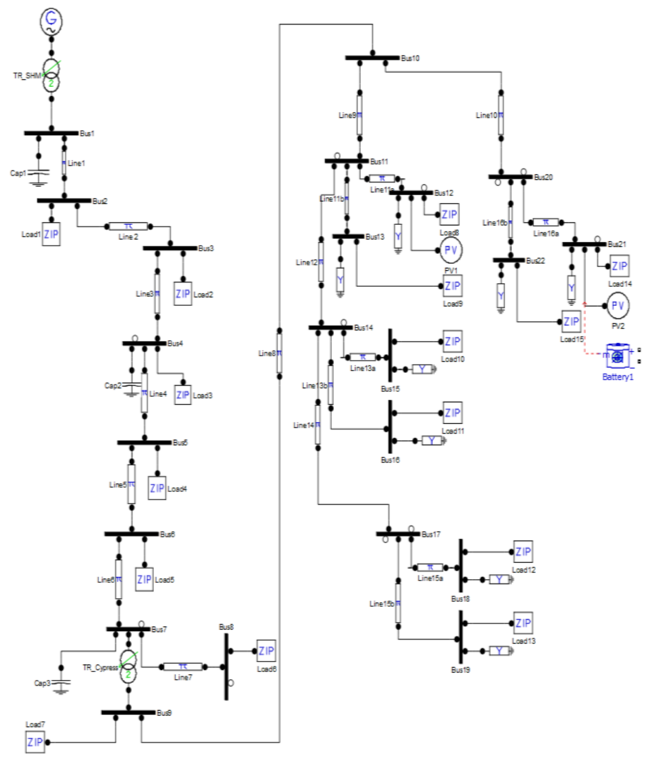


Fig. 5. Single-line presentation of network model

Table 3 Voltage Control Devices

Device	Function
On-load tap changer (OLTC) on 66/22kV transformer	Change the voltage on the 22kV side of the transformer by changing the ratio of the 66kV winding. The voltage control settings are implemented in the voltage regulating relay (VRR).
Substation capacitor banks	Adjust 22kV bus voltage by compensating for the reactive component of the customer loads. Arranged in two steps of 4MVar (3-ph) each.
Line capacitor banks	Adjust 22kV line voltage by switching pole-mounted capacitors to compensate for the reactive component of the customer loads flowing through the 22kV distribution line. Single step of 900kVar (3-ph) each.
22/0.433kV distribution transformer	The transformer is fitted with off-load tap changer on the 22kV side. It is generally set on tap 1 (22.55/0.433kV) at time of commissioning.
22/0.415kV smart grid distribution transformer (future)	The transformer is fitted with on-load tap changer on the 22kV side. The transformer specification used in the simulation consists of off-load tap +/-5% with 5 taps, and on-load tap +/-5% with 5 taps
Smart PV inverter (future)	Smart inverters fitted to PV generators to reduce their impact on network voltage while generating and/or to assist network voltage by acting as a DSTATCOM.
Storage battery (future)	Storage battery can assist with voltage changes caused by PV generation, by charging from excess PV generation during the day and discharging during the evening peak load period.

4.4. Network Simulations

Three-phase unbalanced load flow simulations are carried out, at 30-minutes intervals, over the week from 15 to 22 February 2015. There are 336 load flow solutions per network scenario. Automatic voltage regulation (such as tap change on OLTC transformer) is allowed to take place during the 30-minute time block when the conditions are satisfied.

The set of network scenarios (1 to 6) considers the effectiveness of various MV voltage control schemes in regulating the voltage on the 433V side of the Cypress-Stillia distribution transformer (Table 4). Each load flow solution returns the phase voltages (to earth) and the phase currents at selected network locations. For the 4-wire LV network, the solution also contains the neutral voltage and neutral current. The solution allows the derivation of the phase-to-neutral voltages and voltage imbalance.

Table 4 Network Scenarios for MV Voltage Control

	Network Scenario	Remarks
(1)	No voltage control, with SHM 66kV voltage kept at 67kV	This forms the base case where the effectiveness of various MV voltage control schemes can be compared.
(2)	VRR control for SHM 66/22kV transformer OLTC – flat voltage control	Flat voltage control is the standard control scheme applied by Jemena Electricity Networks.
(3)	VRR control for SHM 66/22kV transformer OLTC, with Line Drop Compensation (LDC)	LDC set to compensate for voltage drop along the SHM14 22kV distribution line to Cypress-Stillia distribution transformer (Bus7).
(4)	Voltage control by switching of SHM 22kV capacitor bank (Cap1) – 2 steps of 4MVar each	Cap bank control is based on Var setting, with voltage override.
(5)	Voltage control by switching of SHM14 line capacitors (Cap 2 & Cap 3) – 900kVar each	Cap bank control is based on voltage setting
(6)	All control schemes (2, 4 & 5) in service	Standard operational practice of Jemena Electricity Networks

5. MV Voltage Regulation

A number of voltage control schemes are used in the MV network. Power factor correction capacitors (Cap1, 2 & 3) are used to compensate for voltage drop due to reactive component of loads whereas the OLTC of SHM 66/22kV transformer changes the ratio of transformation to keep the 22kV voltage constant at the setting of the VRR. As these voltage control schemes affect all three supply phases, for the sake of clarity we have shown only the red-phase voltage on the 433V side of distribution substation (Bus9) in Figure 6. It can be seen that while OLTC (dotted yellow line) has the most beneficial effect in regulating voltage to within a narrow range, OLTC and capacitor combination (solid yellow line) results in a much 'flatten' voltage profile. This combination is adopted by the electricity distribution company Jemena and is used in the simulations unless stated otherwise.

One would notice that the LV supply voltage in this network is biased towards the high end of the allowable range, with the voltage hovering around 250V most of the time. This reflects the design of the network to cater for peak load condition, a common approach in Australian electricity distribution networks. As an alternative Scenario 3 explores the use of Line Drop Compensation (LDC) to provide a dynamic voltage set point for the SHM 66/22kV transformer OLTC control. The voltage set point is increased in proportion to load increase so as to keep the delivered voltage constant at a network location, generally the load centre. In this scenario we have set the LDC to keep the voltage constant at Bus7. The resultant voltage profile is shown in Figure 7. It can be seen that LDC has been effective in lowering the supply voltage during light load period while keeping the voltage at a sufficiently high level during peak load period. In practice the application of LDC requires careful planning when distribution feeders from the same substation are not homogenous (from load/generation distribution and impedance characteristics perspective). One possible approach is to supplement the LDC with local voltage control strategies such as LV shunt capacitors and voltage regulating distribution transformers, in accordance with the local conditions [8, 18].

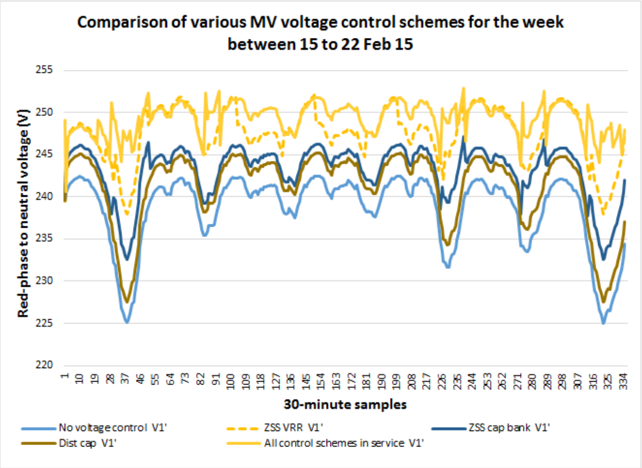


Fig. 6. Red phase voltage on 433V side of distribution substation showing the effect of various MV voltage control scheme on the voltage level during the period from 15 to 21 February 2015

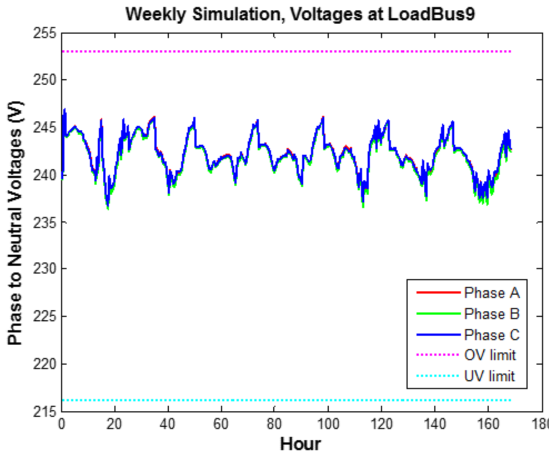


Fig. 7. The use of Line Drop Compensation has improved the voltage at the 433V side of the distribution substation (Bus9)

6. LV Voltage Regulation

6.1. LV Model to Include Effects of Circuit unbalance, Load Unbalance and Ground Connections

As discussed in 4.1, it is important to model the LV distribution network as 4-wire (R, W, B & N) and include the Multiple Earthed Neutral (MEN) ground connections at the customer points of connection. Figure 8 provides an example of the load flow result when the network is modelled as 3-wire balanced circuit, which is very different to that in Figure 9 which is for a 4-wire unbalanced circuit.

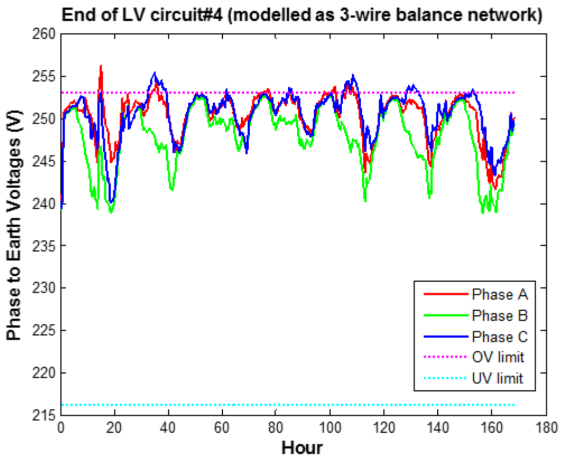


Fig. 8. *Voltages at the end of LV distribution circuit #4, with MV and LV network modelled as 3-wire balanced network*

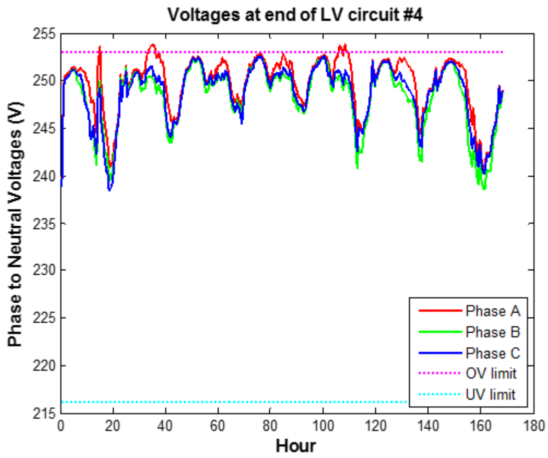


Fig. 9. *Voltages at the end of LV distribution circuit #4, with MV modelled as 3-wire unbalanced and LV as 4-wire unbalanced network*

6.2. LV PV Generation Caused Localized Voltage Rise and Voltage Imbalance

Excess generated power from PV system will travel along the distribution network until it is consumed by load, while raising the network voltage along the way. The voltage rise is therefore superimposed upon the network voltage. As the two PV generators in distribution circuit #4 are all connected to the red phase, one would expect the voltage rise effect to be more pronounced on the red phase of sparsely loaded buses. This is clearly seen on Bus17 as shown in Figure 9. The difference between the voltages on the three phases also gives rise to voltage imbalance. As the voltage in this distribution network is already on the high side, there are occasions during the week when the localized voltage rises have exceeded the prescribed over voltage limit (shown dotted in Fig. 9). When this occurs, PV inverters can trip on over-voltage and customer equipment may malfunction or their life span shortened.

7. Phase Imbalance & Optimal Solar Generator Placement

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.

Unbalance between the three phases in the LV network arises due to difference between loads and generations in each phase, and unbalanced phase geometry (lack of transposition and 1/2-phase supply spurs). This results in voltage appearing on the neutral connection (zero sequence voltage V_0), and phase voltages that are different in magnitude and no longer 120 degrees apart. Under these conditions the supply voltages can be resolved into positive (V_1), negative (V_2) and zero sequence (V_0) voltages for the purpose of analysis.

The neutral voltage shift will further compound the voltage problem as it will cause one phase voltage to go higher while the other two phases will go lower [19]. In addition, unbalanced voltages affect the performance and life expectancy of network assets as well as customer 3-phase equipment. As such it should be controlled in addition to voltage magnitudes [4].

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 three-phase four-wire LV distribution network, voltage unbalance (*VU*) that takes into account of negative sequence (V_2) and zero sequence (V_0) voltage components is defined as [5]:

$$VU\% = \frac{\sqrt{|V_2|^2 + |V_0|^2}}{|V_1|} \tag{1}$$

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

$$f(x) = \frac{1}{M}\sum_{n=1}^{M} W_n * (VU\%_{\max})_n \tag{2}$$

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

$(VU\%_{max})_n$ = maximum voltage unbalance at the nth mode

V_n = voltage on the nth mode

M = number of node/bus

W_n = weight coefficient allocated to the nth mode

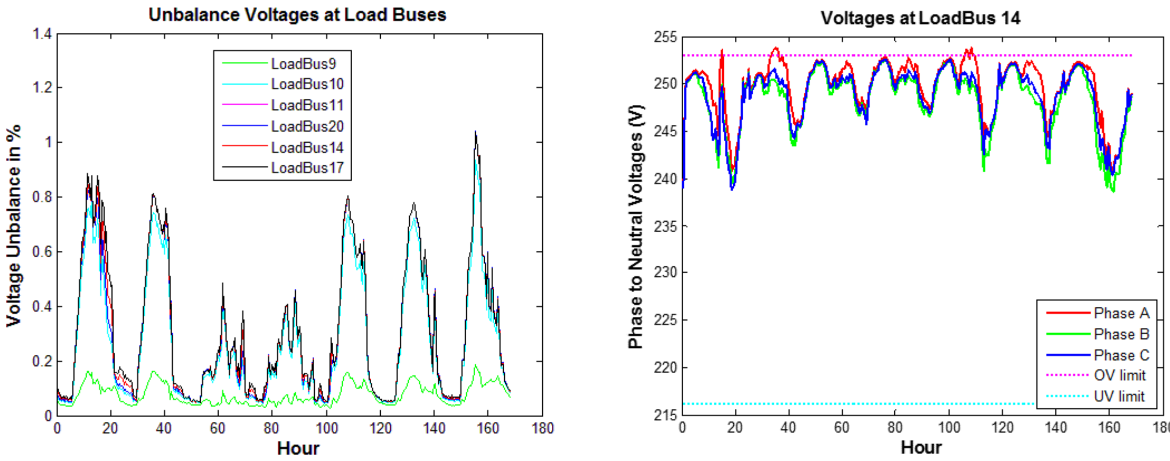
W_n is normally set to 1 but can be set higher for the node/bus where 3-phase customer equipment, susceptible to voltage unbalance, have been installed.

The methodology is applied to the network model where there are two PV generators, PV1 and PV2. Keeping the load allocation constant, the PV generators 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 (1). The network unbalance factor *f(x)* can then be calculated using Equation (2). Table 5 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 5 Network Voltage Unbalance Factor for Different Combinations of Phase Connection of Generators PV1 and PV2

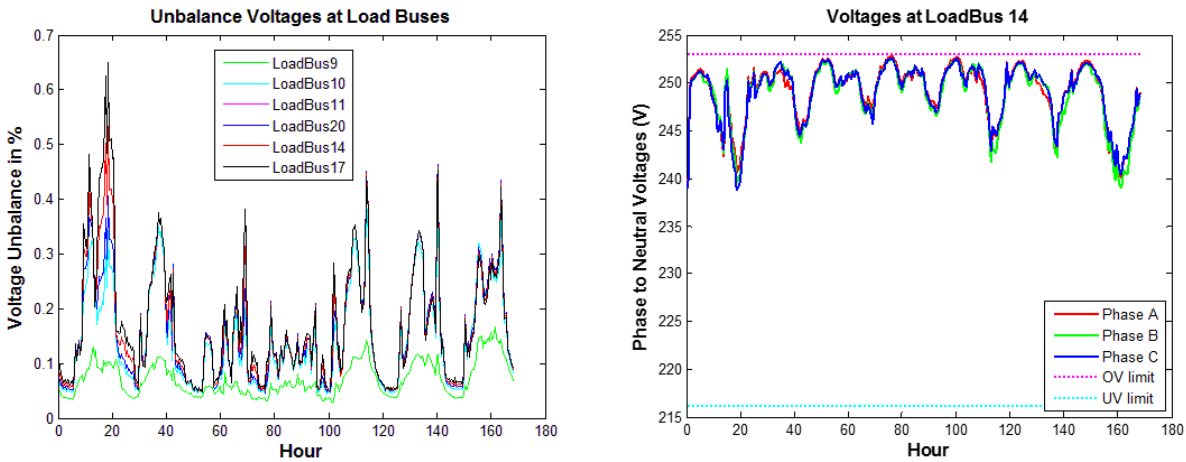
Case number	PV1 connection	PV2 connection	*Network voltage unbalance f(x)*
1	R	R	0.863
2	R	W	0.591
3	R	B	0.607
4	W	R	0.588
5	W	W	0.824
6	W	B	0.444
7	B	R	0.625
8	B	W	0.449
9	B	B	0.713

The variation of the voltage unbalance for the various load buses is shown in Figures 10a and 11a. By allocating the PV generators to minimise voltage unbalance, the voltage profiles are also improved as shown in Figures 10b and 11b. 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 [20].



a *b*

Fig. 10. Modelled results with PV1 and PV2 both connected to red phase. a shows the voltage unbalance on various load buses while b shows the voltages at Bus14. This combination of PV allocations results in the highest voltage unbalance factor and voltages on Bus14 exceed the over voltage limits some of the time during the period of simulation.



a *b*

Fig. 11. Modelled results with PV1 connected to white phase and PV2 connected to blue phase. a shows the voltage unbalance on various load buses while b shows the voltages at Bus14. This combination of PV allocations results in the lowest voltage unbalance factor and voltages on Bus14 are within limits during the period of simulation.

8. Smart Grid Voltage Control Technologies

Addressing the fundamental issues of voltage regulation and circuit imbalance will improve significantly the capacity of the LV network to host embedded PV generation without incurring substantial amount of additional investment. As the penetration of embedded generation continues to increase, other smart grid technologies can be deployed to further increase the hosting capacity. The LV network model is useful to simulate the effect of various smart grid voltage control technologies. Modelled results for the use of storage battery fitted to PV2 are shown in Figure12a and 12b.

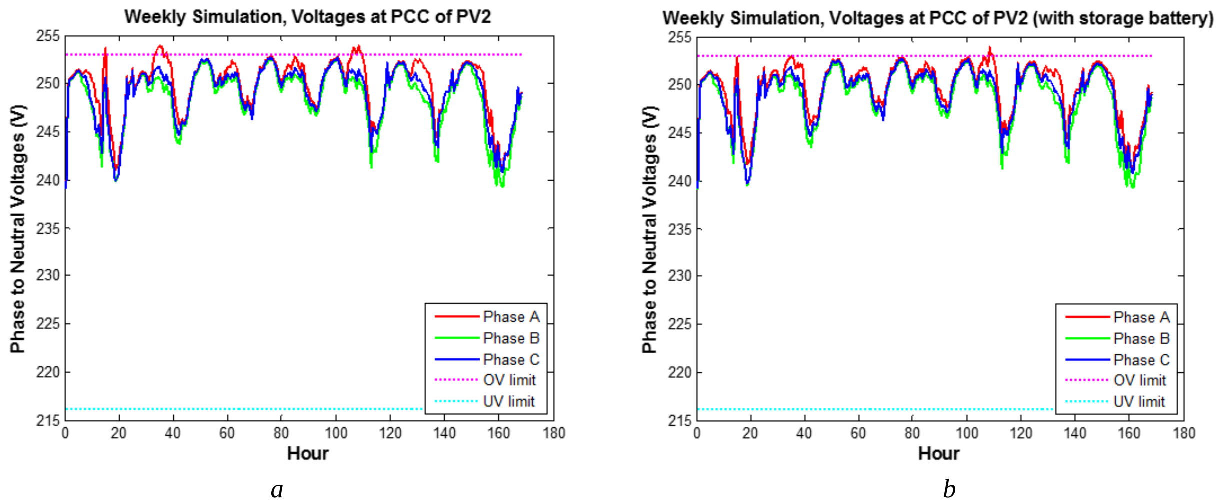


Fig. 12. Modelled results for voltages at Bus17 (Point of Common Coupling of PV generator PV2).
a: without storage battery
b: with storage battery to absorb excess PV generation during light load period. Note red phase over voltage has been reduced.

9. Summary of Recommendations for Utility Engineers

There is no doubt that legacy LV distribution networks are not designed with embedded PV generators in mind. Instead of limiting the amount of embedded PV generation, utility engineers have to look for cost effective ways to increase the hosting capacity of existing LV distribution network. This paper examines the options and recommends: (i) understand and improve the effectiveness of the existing MV voltage control schemes and convert the 'fit and forget' voltage control strategy to a more dynamic voltage control strategy; (ii) improve phase imbalance by allocating solar generators to the appropriate supply phases based on voltage imbalance calculation, and (iii) explore the use of smart grid technologies such as smart inverter, smart grid distribution transformer and battery storage. Last but not least, the establishment of an accurate LV network model is essential to evaluate the effectiveness of various voltage control strategies before proceeding to field trials.

10. Acknowledgments

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11. References

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