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Method for determining a PV generation limit on low voltage feeders for evenly distributed PV and Load

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Abstract

This paper presents a novel method for assessing the maximum allowable PV generation on low voltage feeders. It identifies a relationship between load, total feeder impedance, terminal count and PV generation at which the upper voltage limit for the line is breached. Identifying such a relationship alleviates the need for Distribution Network Service Providers (DNSPs) to perform load flow calculations on a case by case basis. It also increases a DNSP's understanding of power flow in low voltage feeders and potentially enables them to develop improved strategies for managing PV on their networks. Using feeder models provided by a DNSP servicing the Australian city of Sydney's Greater West region, a substantial number of load flow calculations were performed for wide variations in feeder impedance, load and PV generation. The PV generation range is chosen such that a breach of the upper voltage limit occurs on the line. The feeder voltage profile from these simulations are analysed in Matlab to determine PV generation limits. For evenly distributed PV and load, results show a linear relationship between this PV generation limit and load for a given terminal count and a second relationship between the PV generation limit and terminal count. It is then demonstrated that through the combination of these two relationships the PV generation limit can be determined for a given load, terminal count and total feeder impedance.

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Keywords: Photovoltaics (PV), Photovoltaic Generation Limits, Voltage Rise, Voltage Limits, PV Hosting Capacity, Low Voltage Feeders

1. Introduction

The deployment of PV is increasing rapidly around the world [1]. Australia is no exception and installed PV capacity there is approaching 5% of total installed generation capacity. In Australia's case the vast majority of this increased deployment is small scale (< 5 kW) systems connected to the low voltage network [2]. Around one in ten Australian households now has such a PV system. The increase in PV penetration levels is introducing additional variation in what are already highly variable network power flows, increasing the difficulty for network utilities to maintain voltage levels between regulated limits. Seasonal and daily variability and uncertainty in both load, particularly peak load, and PV generation complicates matters further.

For these and other reasons, there is a growing need for tools to assist DNSPs in managing this increase in PV penetration [3]. The purpose of this study is to establish a generalised relationship between feeder impedance, load and PV generation limits for a group of residential feeder types within the network of a Distribution Network Service Provider

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(DNSP) servicing a 24,500 km square area in the Australian city of Sydney's Greater West region. The method for establishing the relationship is general and can be applied to any radial network. The PV generation limit is defined in this paper to be the level of PV generation a feeder can accommodate before the upper voltage limit is breached for a given load along the feeder.

The relationship is ascertained through analysis of the feeder voltage profile acquired from a large number of load flow calculations. DIgSILENT is used to perform these simulations, using feeder models provided by the DNSP, while Matlab is used to analyse the data and summarise the results. The feeder types within the DNSP network of relevance to this study are all residential urban, semi-rural and rural lines given that virtually all PV deployed in Australia to date has been small systems of less than 5kW, located on residential housing. Using the feeder model provided by the DNSP as a template, the total feeder impedance (the *X/R* ratio of the feeder is kept constant), load and PV generation are varied across a large range, and a load flow calculation performed for each instance. The PV generation range is such that a breach of the upper voltage limit at some point across the feeder is ensured. The feeder voltage profile is recorded and the PV generation limit determined for each combination of feeder impedance and load. Load and PV generation is assumed to be distributed evenly along the feeder for all simulations. Of particular interest to a DNSP is to know the amount of PV generation a feeder can host without causing a breach of the upper voltage limit. A load flow calculation would reveal this generation limit but only for that particular network case and assumed load and PV profiles. A DNSP's network typically consists of a wide range of feeder types, experiencing highly variable PV and load behaviour. Performing a separate load flow calculation to determine the PV generation limit for all cases where PV is being deployed would be a large and costly exercise. The scope of the task also increases if a DNSP wants to develop strategy for managing PV on their network. The identification of a relationship between feeder impedance, load and maximum PV could relieve the need for the DNSP to perform dedicated load flow calculations in every instance, and make strategy development easier.

Previous work in this area includes [4] in which a mathematically developed expression for calculating the voltage at a single point on a line, due to a single PV system, is presented. The results showed that the size limit of the PV system is dependent upon position as well as load orientation. In [5], estimation of maximum allowable distributed generation (DG) through analysis of voltage sensitivities is presented. It gives accurate results for singular DG installations and suggests an approach for multiple installations (responsibility voltage factor) although multiple iterations of the method are required. In [6] the PV capacity for a feeder based on the number of participating villages is examined. The key finding is that even though the amount of permissible PV per village decreases with increasing village participation, the total amount of permissible PV for the feeder increases. Total permissible PV plotted against village participation takes the form of an increasing decaying exponential. Work in [7] gives similar results, showing that more PV in aggregate can be installed on a feeder when distributed along the line compared to a singular system at the end of the line. In [5], for specific case studies, along with confirming that the allowable short-circuit power reduces exponentially with feeder distance, it is also shown that maximum PV connection power as a percentage of short-circuit power is independent of cable and transformer type. It should be noted that the short-circuit power does vary according to transformer and cable type. In [10], for a singular feeder type, a simple equation is derived for estimating the PV generation limit for a given load, transformer tapping and power factor. Load and PV is assumed to always be located at the end of the feeder. In [12], the impacts on steady-state voltage, voltage variability and regulator tap changes are quantified as a function of PV generation for a specific feeder. In [11] and [12], the maximum generation for a singular DG unit is determined. Again, this is for a specific feeder configuration. Papers [16] and [17] propose methods for determining the optimum size and location for singular DG units and [18]-[22] propose methods for voltage control in the presence of DG. The work presented here extends the existing literature by determining PV generation limits for a large range of feeder configurations and loads. Also, the network context examined is one of low voltage feeders with multiple, small-scale PV installations. This is representative of the situation which causes most concern for Australian DNSPs regarding penetration levels and associated voltage rise. Finally, through the large number of load flow simulations that are undertaken, the derivation of a relationship between maximum PV generation, terminal count, total feeder impedance and load was possible. This is similar to work presented in [10] and [12] but broader in scope.

The rest of this paper is structured as follows. Section 2 presents the study methodology, the DIgSILENT feeder model and the approaches undertaken towards the development of a generalised relationship between feeder impedance, load and PV generation. Section 3 presents the findings from the methods described in Section 2 and in Section 4 the merits of the generalised relationship are discussed, as well as how it might be improved. Section 5 gives concluding comments.

Nomenclature

Ω	Ohms
R	Resistance
X	Reactance
kW	Kilowatt
P	Voltage-dependent real power
P_{ref}	Power at V_{ref}
V	Voltage (rms)
V_{ref}	Reference voltage, 230 V
$maxPVc_{offset}$	max PV/customer when load/customer equals 0 kW
$maxPVph_{offset}$	max PV/phase when load/phase equals 0 kW
$maxPVphfl$	max PV/phase * feeder length
FL_{offset}	In calculation of $maxPVphfl$, the feeder offset length
$maxPVphfl_{offset}$	In calculation of $maxPVphfl$, $maxPVphfl$ at FL_{offset}
tc	Terminal count

2. Methodology

2.1. Model

The DIgSILENT model provided by the DNSP is a generalised example of an urban residential feeder; Fig. 1 below gives a schematic of the model. The distribution transformer (DTx) steps down the voltage from 11kV to 400 V and is rated at 500 kVA. The 11 kV voltage source is assumed to be stiff and does not change with power flow. The DTx has a positive and zero sequence impedance of 4%, the tap setting is such that the phase to neutral voltage at its terminals is 249.7 V. A setting between 245 V and 255 V is typical for the DNSP, to account for the expected drop in voltage at peak load. The feeder cable is three phase, four wire, rated at 1 kA with R=0.707 Ω/km and X=0.284 Ω/km. Supply is at 50 Hz. A terminal is the point on the feeder where the customer is connected; each terminal has 2 customers connected. The customer connections are single phase, two wire, rated at 1 kA with impedances of R=1.49 Ω/km and X=0.097 Ω/km. The length of these connections is 20 m. This example feeder model has 3 terminals, each with 2 customers connected. Each customer is assumed to have a PV system and customer loads and PV are distributed evenly across the 3 phases over the feeder as a whole. The time-varying behaviour of customer load and PV generation is not modelled in this study so the relationship being sought can be thought of as the maximum PV generation injected into the network for a given coincident load. Simulations are performed at 20^0 C.

This feeder model is a template, and in the attempt to establish a generalised relationship between feeder impedance, load and PV generation limit, the number of terminals and distance between terminals (terminal distance) was varied. Changing the distance between terminals gives the required change in feeder impedance. In this paper, the terms "feeder length" and "terminal distance" can be inferred to mean "impedance". The X/R ratio of the feeder cable impedance, single phase customer connection impedance and the DTx impedance and tap setting is not altered in this study. Voltage measurements are made at the feeder terminals

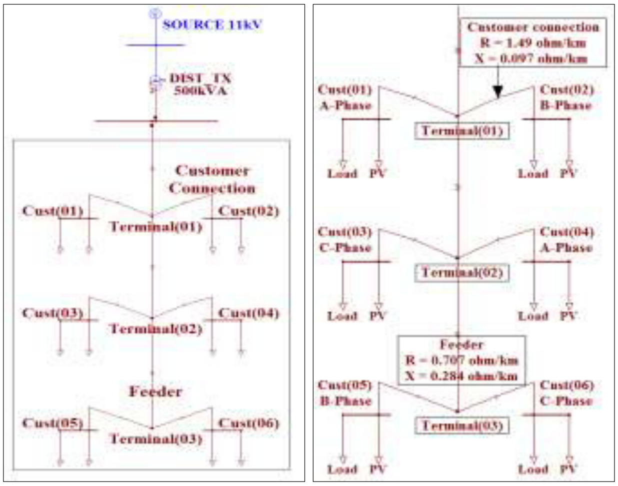

Fig. 1 (a) DIgSILENT model of three terminal feeder; (b) Boxed section of Fig. 1 (a)

All loads are modelled as constant impedance with a power factor of 1. Constant impedance means power drawn is proportional to voltage squared, (1).

$$P = P_{ref}\left(\frac{V}{V_{ref}}\right)^2 \quad (1)$$

PV generation is modelled as negative load with a power factor of -1 injecting constant power. Constant power means current injected in inversely proportional to voltage, (2).

$$P = P_{ref} \quad (2)$$

2.2. DIgSILENT scripting language (DPL)

The DIgSILENT scripting language (DPL), allows for multiple load flow calculations to be performed for a feeder model. Feeder parameters can also be altered for each calculation thus allowing for the execution of multiple load flow calculations which cover a large range of feeder parameters. DPL cannot update the number of terminals so models were created with terminal counts of 3, 6, 9, 12 and 15. These terminal counts ensured PV and load were balanced across 3 phases. 15 terminals gave the maximum number of nodes that DIgSILENT allows in the software version available for the study.

2.3. Voltage Profile

A DPL script was written which updated the load (kW) and PV generation (kW) per customer and terminal distance for each load flow calculation, the ranges for these values being:

- Load: 0-10 kW with 1 kW step size
- PV Generation: 1-50 kW with 1 kW step size
- Terminal distance: 5-50m with 5m step size

For each calculation, the voltage magnitude is recorded for each terminal, giving the voltage profile for the feeder. The voltage data was then imported into Matlab. For each load and terminal distance variation Matlab identifies the first breach of the upper voltage limit (according to AS61000.3.100 this is 253 V, +10% of the nominal 230 V). With the DTx at 249.7 V, this is a change of 3.3 V. The PV generation magnitude and voltage profile at this breach point is then analysed.

Scrutiny of these results revealed that the highest voltage point always occurred at the end of the feeder. Knowing the voltage at the end of the feeder would always reach 253 V first, this voltage was then used as the voltage reference in the next step to identify a relationship between load, feeder length and PV generation limit.

2.4. Investigation into the Relationship between Maximum PV Generation and Load

With the voltage at the end of feeder indicating the maximum allowable PV generation (max PV), further work involved plotting the max PV/customer for a range of customer loads (0-10 kW), terminal distance (5-50 m) and number of terminals. Terminal counts were 3, 6, 9, 12 and 15. This work revealed the same linear relationship between max PV/customer and load/customer for all terminals counts.

2.5. Investigation into Relationship between Max PV/Phase, Terminal Count and Feeder Length

To see how max PV/phase varied according to terminal count, max PV/phase plots were developed for each terminal count (3, 6, 9, 12 and 15) with load kept constant at 10 kW/phase while feeder length was increased from 50 m to 1000 m. Fig. 2 gives the max PV/phase (kW) curve for each terminal count for 10 kW load/phase. Feeder length range is from 50 m to 1000 m with 10 m increments.

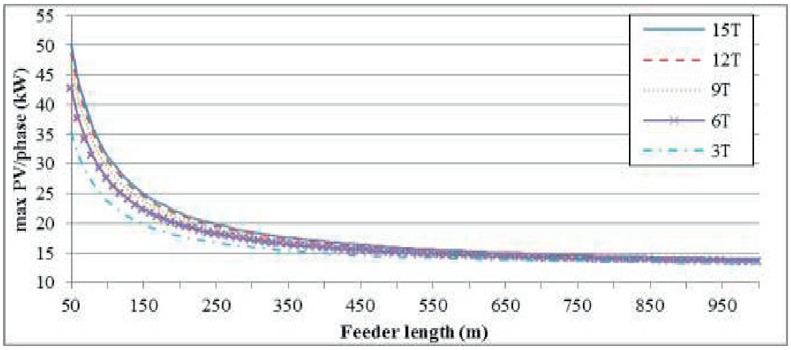

Fig. 2. Curves for each terminal count showing the max PV/phase (kW) for 10 kW load/phase. Feeder length ranges from 50 m to 1000 m in 10 m increments. The top curve is 15 terminals (15T) while the bottom curve is for 3 terminals (3T).

An increase in feeder length is achieved by increasing the terminal distance. For example, a feeder length of 1000 m gives an interval distance of 333 m (1000/3) for a 3 terminal feeder and an interval distance of 67 m (1000/15) for a 15 terminal feeder. As expected the shorter the terminal interval length the higher the max PV/phase. The lower impedance due to the reduced length gives less voltage rise (power flowing towards the DTx) allowing more PV to be installed. There is a relationship through which the max PV/phase curve for 6T through to 15T can be derived from the 3T curve. This relationship is discussed in Section 3

3. Results

3.1. Relationship between Max PV/Customer and Load/Customer

For a 15T feeder, Fig. 3 shows the relationship between load/customer (0-10 kW) and max PV/customer for a given feeder length (50-500 m) required for the end of the feeder to reach the maximum limit of 253 V, a 3.3 V change.

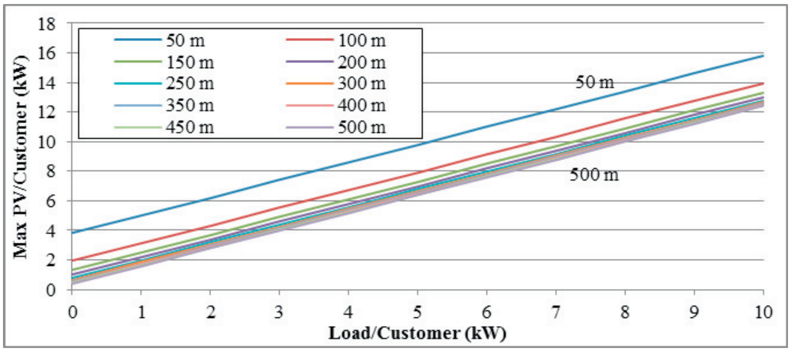

Fig. 3 max PV/customer (kW) versus load/customer (kW) for a 15 terminal feeder with feeder length ranging from 50 m to 500 m in 50 m increments. The top line is for 50 m and the bottom for 500 m.

The linear relationship between max PV/customer and load/customer for all terminal counts (3T to 15T) is the same. The relationship takes the simple form of

$$max\ PV/customer = C_v * (load/customer) + maxPVc_{offset} \quad (3)$$

Where $maxPVc_{offset}$ is the max PV/customer when load/customer equals 0 kW and C_v is a constant equal to 1.2. Note that the relationship (3) holds for max PV/phase and load/phase, giving (4)

$$max\ PV/phase = C_v * (load/phase) + maxPVph_{offset} \quad (4)$$

Where $maxPVph_{offset}$ is the max PV/phase when load/phase equals 0 kW.

3.2. Relationship between Max PV/phase, Terminal count and Feeder Length

To further develop the method it was necessary to determine a relationship between max PV/phase and terminal count. Referring to Fig. 2, the relationship between the curves is non-linear with respect to feeder length. It was discovered that multiplying each curve by feeder length produces a linear plot, see Fig. 4.

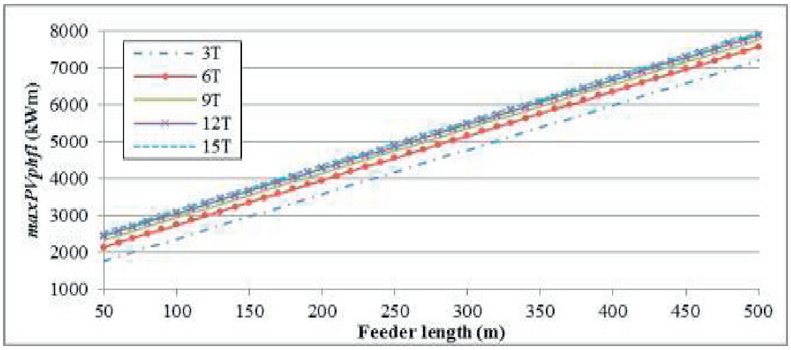

Fig. 4 max PV/phase*feeder length (*maxPVphfl*) versus feeder length for terminal count 3 to 15. This plot is a linearised version of Fig. 2. The top plot is for 15 terminals and the bottom for the 3 terminals case.

From Fig. 4, for each plot (3T to 15T), the relationship between feeder length and *maxPVphfl* has the form:

$$maxPVphfl = C_{vfl} * (feeder\ length - FL_{offset}) + maxPVphfl_{offset} \quad (5)$$

Where FL_{offset} is the feeder offset length (in this case 50 m) and $maxPVphfl_{offset}$ is *maxPVphfl* at FL_{offset}. C_{vfl} is a constant equal to 12. The curves (3T to 15T) in Fig. 4 also have a relationship which relates terminal count to *maxPVphfl* and is independent of feeder length. Fig. 5 is simply Fig. 4 with feeder length and terminal count switched and shows that the *maxPVphfl* curves for each feeder length are of the same form. The offset between each curve can be calculated using (5). The curves in Fig. 5 have the form:

$$f(x) = C(1 - e^{-kx}), k > 0 \quad (6)$$

This is the same as discovered in [6] that with increasing village participation (equivalent to terminal count) maximum allowable PV generation increased as per an increasing decaying exponential. Referring to Fig. 5, a curve fitting using the form of (6) was attempted on the 50 m curve in Fig. 5. The fit was poor so a variation on the increasing decaying exponential, (7), was used instead, giving a superior fit.

$$f(x) = C_L(1 - e^{-kx}) - C_{offset}, k > 0 \quad (7)$$

Equation (8) gives the fit for the 50 m curve from Fig. 5.

$$maxPVphfl = 6800\left(1 - e^{-0.52\left(\left(\frac{tc}{3}\right)+3\right)}\right) - 4180 \quad (8)$$

Where *tc* is the terminal count. Through (8) it is possible to determine the max PV/phase for all terminal counts for a feeder length of 50 m. When combined with (5) it is possible to calculate the *maxPVphfl* for any feeder length. Dividing *maxPVphfl* by feeder length then gives the max PV/phase at that feeder length for a 10 kW load/phase.

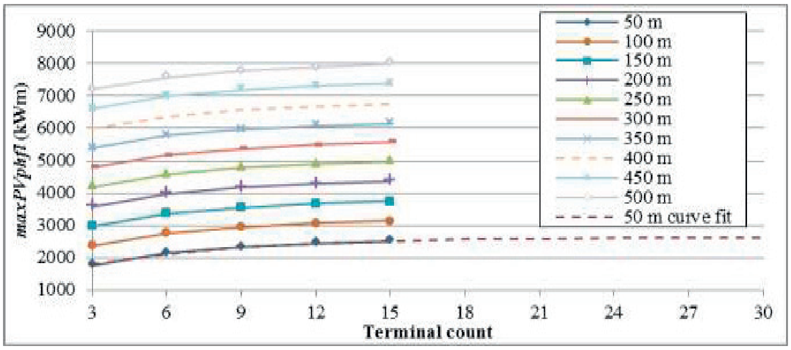

Fig. 5 *maxPVphfl* versus terminal count. Fig. 4 with feeder length and terminal count switched. Included is the 50 m curve fit. The curves range from 50 m (bottom) to 500 m (top) in 50 m increments

Using (5) and (8), the 15T max PV/phase curve (refer to Fig. 2) for 10 kW load/phase was derived. Fig. 6 shows how the derived curve compares with the actual 15T curve. The error between the two curves is below 1.2% for all feeder lengths

3.3. Estimation of Max PV/Phase

Using (4), (5) and (8) it is possible to determine the max PV/phase for any load/phase, feeder length and terminal count, given the network configuration and cable assumptions used for this study. For example, in order to estimate the max PV/phase for a 15 terminal feeder, with 75 kW load/phase and a length of 200 m the DNSP would first use (8) to determine the *maxPVphfl* for 15 terminal, 50 m long feeder with 10 kW load/phase, getting 2520 kWm. We then use (5) to get the *maxPVphfl* at 200 m, 4320 kWm, and then divide by feeder length (200 m) to get the max PV/phase, 21.6 kW. Finally, (4) is used to determine the max PV/phase for 75 kW load/phase, giving 99.6 kW. In DIgSILENT; a load flow calculation for a 200 m long, 15 terminal feeder with 99.6 kW PV/phase and 75 kW load/phase gives an end of feeder voltage of approximately 252.98 V, confirming the estimation method.

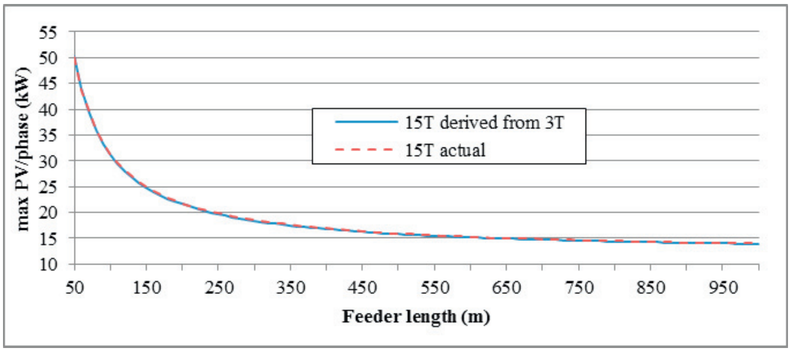

Fig. 6 15T curve derived from 3T and original 15T curve. Curves give max PV/phase (kW) for 10 kW load/phase. Feeder length ranges from 50 m to 1000 m with 10 m increments

4. Discussion

As shown in section 3.3, the method by which the max PV/phase is estimated is accurate given the assumptions involved, and simple to use. The method does not explicitly consider the dynamics of PV generation and load profiles; hence the maximum PV generation relationship is with respect to coincident load. It is also restrictive in that it assumes evenly distributed PV and load. Note, however, that the assumption of evenly distributed PV and load has parallels with the use by DNSPs of an After Diversity Maximum Demand (ADMD) metric when determining network capacity. ADMD is essentially the average demand per customer and is used by DNSPs for network planning. The load/customer and PV/customer parameters might, in this context, be considered the average load/customer and average PV/customer. The robustness of the tool will be assessed in future work by gradually reducing the diversity of the PV deployment whilst maintaining the equivalent average PV/customer and comparing results with those of a detailed model. Therefore, there is scope for a more sophisticated method.

Other potential improvements include taking into account cables with different *X/R* ratios, non-unity power factor PV injection and loads, and different customer connection impedances. Changing the tap setting (voltage) at the DTx would also impact on max PV levels. In reference to cable types, there are a limited number (~ 40) within the DNSPs network and it would be a relatively straightforward exercise to apply the method for each cable type. It is expected that changing the above parameters will yield different values for the constants C_L, k, C_{offset}, C_v and C_{vfl}. Increasing the sophistication of the model will include deriving the relationship between these constants, feeder and customer connection impedance, terminal count, maximum allowable voltage and load.

5. Conclusion

The work presented in this paper determining the PV generation limit for a large range of feeder configurations and loads extends the existing literature in useful ways. The network context examined is representative of the situation which causes most concern for Australian DNSPs regarding penetration levels and voltage rise. Through the undertaking of a large number of load flow simulations the derivation of a relationship between maximum PV generation, terminal count, total feeder impedance and load was obtained. The PV generation limit is defined to be the level of PV generation a feeder can accommodate before the upper voltage limit is breached. It is assumed that all load and PV are evenly distributed along the feeder and that load and PV are at unity power factor. The *X/R* ratio of the feeder cable is kept constant. Under the assumptions stated, it was discovered that the upper voltage limit breach always occurred at the end of the feeder. A method was then developed using the end of feeder voltage as the voltage reference. It was demonstrated that the method effectively and accurately determined the maximum PV generation for a given feeder impedance, terminal count and load. The model has the potential to be used by DNSPs to estimate PV generation limits for a wide range of feeders and load profiles, alleviating the need to perform separate load flow calculations for all cases where PV is being deployed. It could also be used as a tool in other PV related research, research where estimates of maximum PV levels are required.

References

[1] Renewable Energy Policy Network for the 21st Century 2012, *Renewables Global Status Report.* Available from: <http://www.map.ren21.net/GSR/GSR2012_low.pdf>.

[2] Australian PV Association 2012, *PV in Australian Report.* Available from: < http://www.apva.org.au/PVReport2012>.

[3] Braun M, Stetz T, Brundlinger R, Mayr C, Ogimoto K, Hatta H et al. Is the distribution grid ready to accept large scale photovoltaic deployment? State of the art, progress and future prospects. *Progress in Photovoltaics 2012, 6;681-697.*

[4] Conti S, Raiti S, Tina G, Vagliasindi U. Study of the impact of PV generation on voltage profile in LV distribution networks. *IEEE Porto Power Tech Conference,* 2001

[5] Ayres H.M, Freitas W, De Almeida M.C, Da Silva L.C.P. Method for determining the maximum allowable penetration of distributed generation without stead-state violations. *IET Generation, Transmission and Distribution 2010, 4;495-508.*

[6] Jenicek D, Inam W, Ilic M. Locational dependence of maximum installable PV capacity in LV networks while maintaining voltage limits. *North American Power Symposium, 2011*

[7] Canova A, Giaccone L, Spertino F, Tartaglia M. Electrical impact of photovoltaic plant in distributed network. *IEEE Transactions on Industry Applications 2009, 45;341-347.*

[8] Degner T, Arnold G, Reimann T, Engel B, Breede M, Strauss P. Increasing the photovoltaic system hosting capacity of low voltage distribution networks. *21st International Conference on Electricity Distribution, 2011*

[9] Bollen M, Hassan F. Integration of distributed generation in the power system. Wiley, 2011.

[10] Shayani R.A, Goncalves De Oliviera M.A. Photovoltaic generation penetration limits in radial distribution systems. *IEEE Transactions of Power Systems 2011, 26;1625-1631.*

[11] Paatero J.V, Lund P.D. Effects of large-scale photovoltaic power integration on electricity distribution networks. *Renewable Energy 2007, 32;216-234.*

[12] Shao M, Walling R, Cleary J. Steady-state methodology for investigating the relationship between photovoltaic (PV) facility size, location, and voltage impact. *Power and Energy Society General Meeting, IEEE 2012*

[13] Tang L, Yan A, Marti L, Fuerth J. Determination of distributed generation capacity from a voltage regulation perspective. *Transmision and Distribution Conference and Exposition, IEEE PES, 2012*

[14] Karimi-Zare P, Seifi H. Maximum allowable penetration level determination of a DG in a distribution network. *Energy Conference and Exhibition, IEEE International, 2012*

[15] Varma R.K, Berge J, Axente I, Sharma V, Walsh K. Determination of maximum PV solar system connectivity in a utility distribution feeder. *Transmission and Distribution Conference and Exposition, IEEE PES, 2012*

[16] Abri R.S.A, El-Saadany E.F, Atwa Y.M. Distributed generation placement and sizing method to improve the voltage stability margin in a distribution system. *2nd International Conference on Electric Power and Energy Conversion Systems, 2011*

[17] Ochoa L.F, Padilha-Feltrin A, Harrison G.P. Evaluating distributed generation impacts with a multiobjective index. *IEEE Transactions on Power Delivery 2006, 21;1452-1458*

[18] O'Gorman R, Redfern M. The impact of distributed generation on voltage control in distribution systems. *18th International Conference on Electricity Distribution, CIRED, 2005*

[19] Bollen M.H.J, Sannino A. Voltage control with inverter-based distributed generation. *IEEE Transcations on Power Delivery 2005, 20;519-520*

[20] Viawan F.A, Karlsson D. Voltage and reactive power control in systems with synchronous machine-based distributed generation. *IEEE Transactions on Delivery 2008, 23;1079-1087*

[21] Liu X, Aichhorn A, Liu L, Li H. Coordinated control of distributed energy storage system with tap changer transformers for voltage rise mitigation under high photovoltaic penetration. *IEEE Transactions on Smart Grid 2012, 3;897-906*

[22] Watanabe M, Matsuda K, Futakami T, Yamane K, Egashira R. *China International Conference on Electricity Distribution, 2012*