IET Generation, Transmission & Distribution

Research Article

ISSN 1751-8687
Received on 9th November 2014
Revised on 21st July 2015
Accepted on 21st August 2015
doi: 10.1049/iet-gtd.2014.1076
www.ietdl.org

Impact of solar photovoltaics on the low-voltage distribution network in New Zealand

Jeremy D. Watson[1], Neville R. Watson[1] ✉, David Santos-Martin[2], Alan R. Wood[1], Scott Lemon[2], Allan J.V. Miller[2]

[1]*Department of Electrical and Computer Engineering, University of Canterbury, Private Bag 4800, Christchurch, New Zealand*
[2]*Electric Power Engineering Centre, University of Canterbury, Private Bag 4800, Christchurch, New Zealand*
✉ *E-mail: neville.watson@canterbury.ac.nz*

Abstract: Residential rooftop-mounted solar photovoltaic (PV) panels are being installed at an increasing rate, both in New Zealand and globally. There have been concerns over possible issues such as overvoltage and overcurrent. These PV systems are mostly connected at low voltage (LV). This study presents a case study of simulating the entire LV network from a single utility, comprising 10,558 11 kV–415 V transformers and their associated distribution feeders. These results are also presented by network type. Various solar PV penetration levels are added to the model and the power-flow results are presented. From these results, possible maximum limits of solar PV penetration are investigated and measures to alleviate overvoltage problems are simulated. The effect of using PV inverters with voltage regulation is simulated. Results show that some minor overvoltage problems can be expected in the future, particularly in urban areas. However, in most cases the overvoltage would not be much higher than the statutory limit of 1.06 p.u.

1 Introduction

Concerns over fossil fuel depletion and climate change have caused a high level of interest in renewable energy. As a result, residential rooftop-mounted solar photovoltaic (PV) panels are being installed at an increasing rate, both in New Zealand and globally [1, 2]. This is despite the fact that New Zealand has never had subsidies for PV generation and the buy-back rate for energy export is well below the demand rate. The influx of distributed generation will pose new challenges for electrical power distribution [3–5] and it is important to understand these before they occur, hence the purpose of this paper. PV systems connected to the low-voltage (LV) distribution network may cause overvoltage [6], particularly when high solar radiation coincides with times of low loading, as well as overloading of conductors and transformers. Protection and safety are also of concern. The aim of this study is to determine the impact of PVs on the distribution network in New Zealand. The questions which will be answered are regarding the issues PV generation could potentially cause, and how these can be mitigated effectively.

Many valuable previous studies have been performed to evaluate the potential impact of PV. For example, the authors [7–9] have evaluated the impact of distributed generation on the voltage profile along distribution lines; however, most studies have focused on representative or typical networks [8–19]. This does give an insight into the likely problems that may be experienced, but are of limited applicability to other networks and do not give information on the proportion of the LV network that may experience problems. The LV network in New Zealand may well be different to overseas LV feeders, especially as New Zealand is a relatively small island power system. It is therefore important to study the effect of PV systems in a New Zealand distribution system. Another difference to previous studies is that this work assesses the impact of PV generation on a complete distribution system of a single utility. The motivation for doing this is to see how much of the distribution system will experience the violation of limits (voltage magnitudes or overcurrent in conductors). The supplementary question is to what extent will power-factor control on PV inverters alleviate these overvoltages. A perceptive comment from [17] indicates that the 29 feeders they studied do not necessarily represent the whole LV grid. The question is not whether a test feeder will have issues or not, but how much of the whole distribution system. As indicated in [7] the UK network is like the New Zealand system in that it is already operated close to its upper statutory voltage limit in order to allow for voltage drop across the network. The operating voltage does affect the hosting capacity for PV and this was not considered in many of the previous contributions.

Although there are similarities across the aforementioned PV impact studies, there are also differences. For example differences exist in: simulation technique (power flow or time domain and also whether deterministic or probabilistic approach), load modelling, PV modelling, type of network represented and level of detail, phenomena of interest and the findings. A brief summary of these studies is provided in Table 1.

In Section 2, this paper discusses the methodology of the study performed, describing how the LV network, PV systems and loads are modelled. The power-flow method is also discussed. Section 3 presents the results of the study, focusing on potential overvoltage problems. Methods to mitigate overvoltage problems are investigated, and the effectiveness of these are determined. Finally, the conclusions of the study are presented in Section 4.

2 Methodology

At present, the geographical information systems (GSI) and supervisory control and data acquisition (SCADA) systems hold geographic and other information on the network for control and monitoring purposes, but cannot run a power flow of the system. A power-flow model of the medium voltage (MV) is available and maintained separately from the SCADA, but there is no power-flow model of the LV (415 V system). To model the effect of residential PV a three-phase power-flow model first needed to be developed and the approach taken was to download the data held in the GIS and SCADA systems and develop a preconditioning program to trace out the network and create a database that a power-flow program could use directly. This included coping with the small number of imperfections/inaccuracies in the GIS and SCADA data. A purpose built power-flow program was developed, and verified against two commercial programs (for one feeder). Studies were

Table 1 Literature review of PV impact studies on distribution networks

Ref.	Electricity network	Comments	Analysis method	Conclusions/contribution
[7]	One representative 11 kV feeder and all LV connected (Leicester, UK).	$\|V\|$ and losses	Unbalanced load flow. Time series	The 50% scenario assumes a 2160 W array on half of all houses, even this very high penetration of PV will cause only small increases in average network voltages (2 V). Peak loadings would be unaffected, since PV output and peak loads do not coincide in the UK.
[8]	One representative LV network from Malaysian system.	$\|V\|$ and unbalance	Unbalanced load flow (OpenDSS). Time series	Voltage rise still within limits for 200% PV penetration.
[9]	Canadian benchmark test system.	$\|V\|$	Time domain (PSCAD/EMTDC)	2.5 kW/house is acceptable.
[10]	Representative networks (from NREL).	$\|V\|$	Load flow (powerworld simulator)	Penetration level up to 20% acceptable.
[11]	16 feeders	$\|V\|$ and overcurrent. Three scenarios for PV location	GridLAB-D	50% penetration acceptable (PV power/peak load apparent power).
[13]	One LV feeder (from Denmark).	$\|V\|$	Load flow (power factory). Time series	Effect of reactive power control methods on PV hosting capacity.
[14]	One LV feeder modelled in detail.	$\|V\|$	Time domain (MATLAB/SIMULINK and power system blockset). Time series	PV effect on $\|V\|$.
[15]	Two LV distribution feeders from two actual distribution systems (Australia). Limited LV representation.	$\|V\|$, harmonics, loss of PV	Load flow (PSS SinCal)	Harmonics not a major concern.
[16]	Simplistic 3 node LV system.	$\|V\|$	Time domain (MATLAB/SIMULINK).	Presents a simulation tool rather than tangible results.
[17]	Representative LV networks from Belgium used.	$\|V\|$, unbalance, neutral displacement	Load flow (NEPLAN)	Gives a good representation of the expected effects for feeders which are similar. It has not been verified that these feeders are representative of the whole LV grid.
[18]	Contrived test system taken from previous publications.	$\|V\|$	Time domain (ATP)	Probabilistic approach to PV placement.
[19]	IEEE 13 and IEEE 34 bus test system.	$\|V\|$ and unbalance	Unbalance 3-phase load-flow (custom)	Scheduling of single-phase DG can reduce voltage unbalance factors. It also released substation capacity.
[22]	IEEE 34 bus test system.	$\|V\|$ and V regulator operation	Load flow (OpenDSS). Time series	Contribution is the modelling method.

then performed to determine the proportion of the network that would experience issues due to the PV. Moreover, clustering was performed to see how dependent these issues were on the type of network. Finally, different inverter characteristics (volt–var responses) were simulated and this resulted in the standard being drafted (AS/NZS4777.2) to be modified for New Zealand conditions. This work has demonstrated the feasibility of performing a power-flow analysis on a complete distribution system and has shown that GIS and SCADA data, with preconditioning, can give a power-flow model that is useful for such studies. It has also demonstrated the

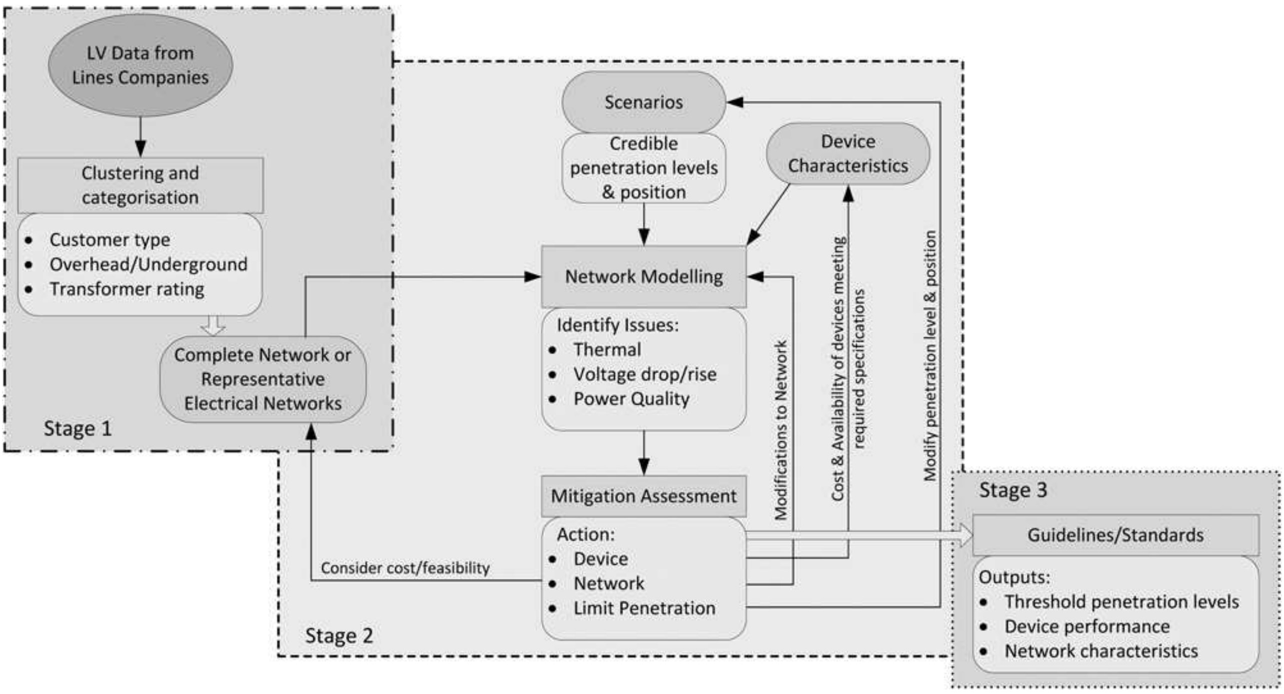

Fig. 1 *Master-plan for evaluating the impact of new technology*

IET Gener. Transm. Distrib., 2016, Vol. 10, Iss. 1, pp. 1–9

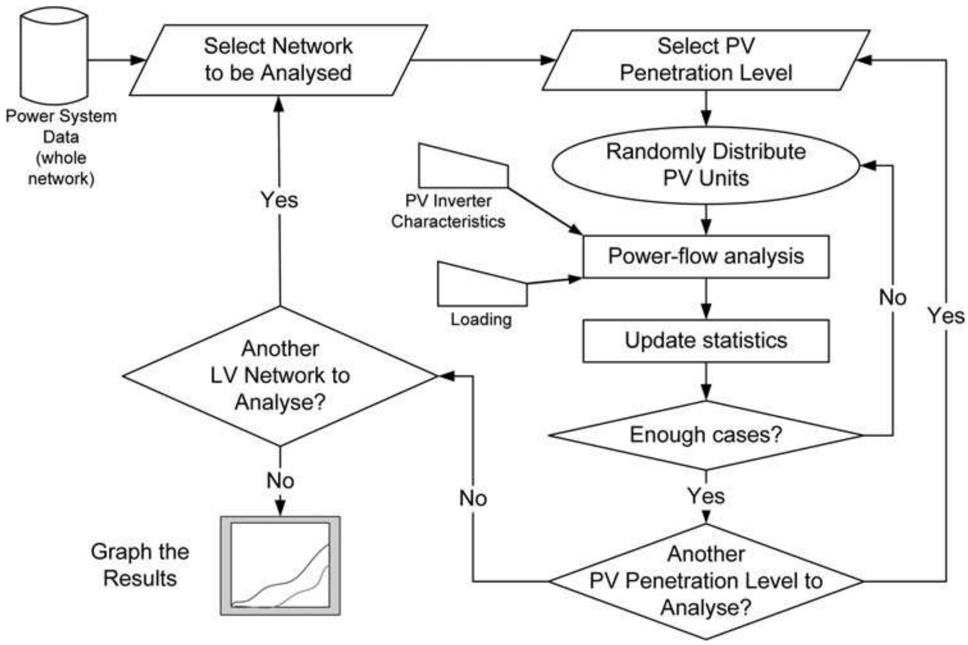

Fig. 2 *Flowchart of analysis procedure*

ability of the inverter volt–var response to increase the PV hosting capacity of a network.

Some researchers have performed time-series simulations whereby each time period is analysed separately and load profiles or probability density functions are used to determine what is running in each time period [20–22]. Although this provides information on voltage, current and power levels throughout the day and week, it does not help with the objectives of this study, which is to determine the ability of the network to cope with PV. The system must be designed to cope with the extremes that it will experience and hence only the credible extreme conditions are investigated.

This study is part of the larger GREEN grid project, which is investigating the possible effects of new technologies and mitigation options when adopting new technologies such as renewable generation and energy efficient technologies [23]. The aim is to inform policy makers and influence standards to facilitate the adoption of these new technologies. Fig. 1 gives an overview of the process for evaluating new technologies. Fig. 2 gives more details on the Monte Carlo type simulation performed. Although the LV is often meshed in structure it is normally operated as a radial system. The normally open switch gives flexibility in the event of a contingency. Therefore, the distribution system effectively consists of many LV networks connected to a common MV system (which operates as a meshed network). Each LV network comprises an equivalent of the upstream network as seen from the 11 kV busbar, 11 kV/415 V transformer, and the entire LV network connected to the transformer.

2.1 LV network modelling

A GIS spreadsheet containing the lengths, conductor types, number of loads on any conductor, and peak load values was obtained from the local utility company. Parent, branch and asset IDs allowed the construction of each network. The line impedances and transformer ratings were also provided. Time-varying load information was not available, nor the exact location of loads. These were assumed to be distributed equally along the conductor, with the last installation connection point (ICP) placed at the end of a feeder. Exact load values for each ICP were not available, and the transformer load was distributed equally amongst ICPs. In practice, the load distribution is less reliable in those cases where the feeder supplies a significant number of non-residential loads. A program in MATLAB was written to construct each LV distribution feeder, assign loads to network nodes, look-up conductor impedances, current limits and transformer ratings. This was used as input to a program which processes the power flow of each LV transformer and associated feeders, returning the voltage at each node, all branch currents, and other statistics.

All results are also calculated by the type of distribution network: city centre, urban, rural, or industrial. These categories were found by cluster analysis of the network parameters (length, number of ICPs, and load power) and are similar to previous studies [24–26]. The network utility company is presently working on making the GIS transformer location available, and this will be used to verify the clustering process. To cluster networks into the categories stated above, *k*-means clustering was applied.

1. *k*-cluster centres are spawned in the *n*-variable space.
2. Each point is assigned to the nearest cluster (Euclidean distance used).
3. The new centre of each cluster is then computed by averaging all its data points. If a centre has no data points it is reassigned randomly.
4. Iterate steps 2 and 3 until convergence to a given tolerance.

This groups the LV networks into *k* distinct clusters. To find the appropriate number of clusters, the silhouette statistic was used to evaluate the clustering fit. The silhouette statistic evaluates how good a cluster fit is by comparing:

$a(I)$ – the average distance from point I in a cluster to all the others in the same cluster; and
$b(I)$ – the minimum distance from point I in a cluster to all other points, minimized across clusters.

Then the silhouette statistic is calculated by

$$s(I) = \frac{b(I) - a(I)}{\max(a(I), b(I))}$$

This is averaged over all data points; the metric lies between −1 and 1 by the definition. It is commonly accepted that a statistic $s(I) < 0.2$ represents poor clustering, whereas a value above 0.5 represents a good fit. With large data sets, this is computationally expensive. It has therefore become standard to use a modified form for speed,

Table 2 Typical network sizes

Area	City	Urban	Industrial	Rural
number of residential loads	15	68	0	3
number of commercial loads	27	3	1	1
peak load per ICP, kW	9.13	5.58	544.96	39.68

evaluating how close each point is to its centre $a(I)$, compared to the nearest other centre $b(I)$. The number of cluster variables was varied and the optimum number of clusters was found to be four, with a silhouette statistic of 0.71. Since the silhouette statistic is close to 1, we can conclude that the data contains clear evidence of clustering. By inspection, these clusters may be classified into the categories of 'City', 'Urban', 'Rural' and 'Industrial'. The result of the clustering process was that in the 10,558 LV networks modelled, there are 358 transformers classified as City, 1962 as Urban, 327 as Industrial, and 7937 as Rural. Table 2 shows the typical network sizes.

The extensive LV network data provided by the utility is generally of high quality. A small proportion of the data are estimates, which may be inaccurate in a few cases. In particular a few very high loads, and conservatively-estimated current ratings of a few unknown conductors, affect the proportion of conductors which appear to exceed their current ratings. Nevertheless, for the simulation of overvoltage the effect is not significant.

2.2 PV modelling

An actual solar PV installation was measured, and the results were used in the model. The EnaSolar 5 kW inverter was modelled at an output power of 3.7 kW. The authors plan to monitor, model and simulate other solar PV installations as well.

A stochastic modelling approach was taken for the uptake of PV units due to the uncertainty regarding which customers will adopt PV. The approach is similar to that taken for electric vehicle studies [27–31]. In this study, the term 'penetration level' refers to the proportion of PV units (number of loads with PV divided by the total number of loads). The solar PV installations were distributed randomly throughout the network. The PV systems are modelled as fixed current injections; however, the current spectra were shifted between iterations in accordance with the voltage angle (using the previous iteration estimate). By doing this the correct phase relationship between the terminal voltage and current spectrum is maintained.

2.3 Load modelling

2.3.1 Unbalance: The single-phase loads were distributed across the phases, with each successive load being assigned to the next phase. This results in the system being either balanced or only slightly unbalanced. The local utility has little difficulty in mitigating unbalance by changing the connection of any particular ICP.

2.3.2 Load profile: In New Zealand, the instantaneous power consumption of an average house can range from 0.1 to 10 kW, with a typical average of about 1 kW [32]. Actual load profiles were investigated in this regard. The utility has a limited amount of measurement data in terms of loading level (hence average demand per house) and maximum demand (from maximum demand indicators at the transformers). This does not, of course, go down to the individual ICP level. These figures were:

At peak load after diversity: 3 kW/house.
At low load (in summer, during the day) after diversity: 0.6 kW/house.

These figures were used to scale the load in simulation. As the loading given was from the distribution transformer maximum demand indicators, a factor of 0.2 was used to reduce residential loads from the 'peak load' to a 'low load' level.

2.4 Power-flow method

A network admittance matrix-based unbalanced three-phase power-flow written MATLAB was used to solve for the voltages in each LV network. The loads were represented as constant power loads, although modelling them as constant impedance loads was also performed for comparison. At peak load, the difference between the two methods did not exceed a couple of volts. The program converts the load power for impedances, solves the linear system of equations for voltages, then uses the estimated voltages

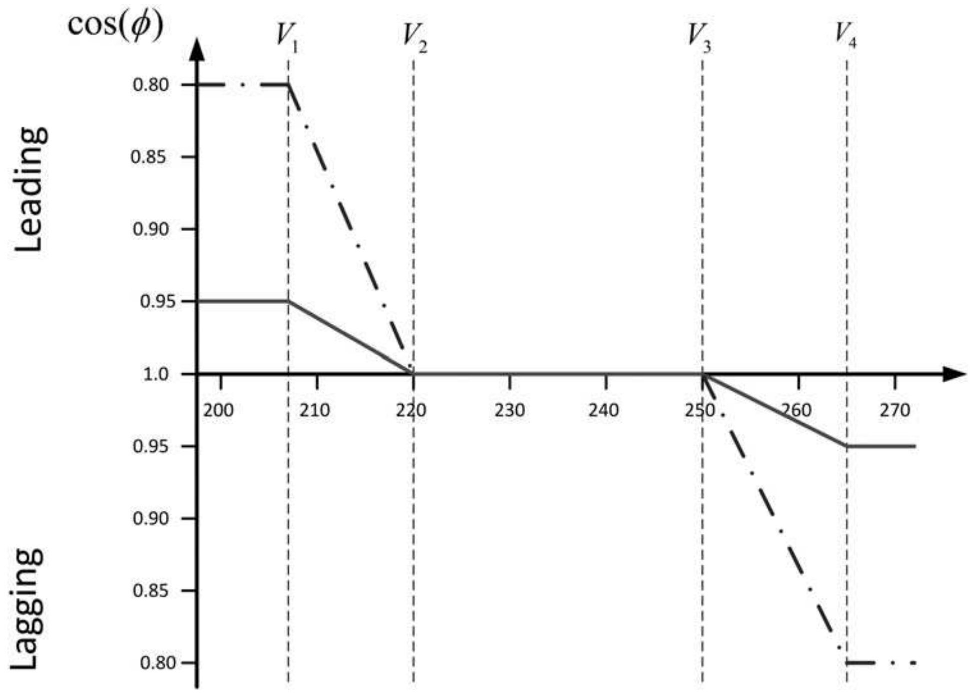

Fig. 3 *Power-factor control of draft AS/NZS4777.2*

IET Gener. Transm. Distrib., 2016, Vol. 10, Iss. 1, pp. 1–9

to recalculate the load impedances. The algorithm iterates until the power mismatch at every node is less than 0.1 W.

The whole Orion LV network is simulated 100 times at each PV penetration level, and this is used to plot the extent of overvoltage problems at various PV penetration levels and in different types of LV networks. The location of the PV generation, and the load distribution is randomised to reflect the fact that neither PV installations nor loads are constant in power or evenly distributed physically. The selection of 100 simulations was chosen in order to understand the distribution of the results. It was impractical to use a larger number of simulations due to computational constraints.

2.5 Mitigation

Three different ways of mitigating potential overvoltage problems were simulated.

(i) *Reactive power control:* This was simulated, based on the power-factor control specified in the draft Australian/New Zealand standards (AS/NZS4777.2) depicted in Fig. 3. However, the upper voltage threshold had to be modified to suit New Zealand standards, as the statutory limit in Australia is 1.10 p.u. In New Zealand, the statutory voltage limit is 1.06 p.u., and therefore, reactive power control would not be activated until the voltage is already well over the limit. Therefore, the voltage threshold of 240 V was used instead of 250 V (which is specified in the draft AS/NZS4777.2 standard). The power-factor was altered in response to the terminal voltage. The shapes of the curve are those in Table 3. To keep the inverter within its current rating the real power is reduced to give a constant apparent power when applying Q control.
(ii) *Transformer secondary voltage:* A significant number of 11 kV–415 V transformers in New Zealand have tap settings, which allow the transformer secondary voltage to be adjusted. However, many newer transformers do not have the option of different tap positions. For the simulation, the secondary voltage was simply reduced from the utility-supplied figure of 415 V (about 1.05 p.u.) to 410 V (about 1.03 p.u.).
(iii) *Adopting 1.10 p.u. as an upper voltage limit:* In New Zealand, the statutory overvoltage limit is 1.06 p.u. Some other countries have adopted 1.10 p.u. as the statutory upper voltage limit.
(iv) *Other ways:* According to the utility, the first low cost mechanism to manage overvoltage on the urban feeders is to use the line drop compensation at the zone substation on the 11 kV (reduces voltage at low load). Demand-side management, battery storage and so on are other ways in which overvoltage may be mitigated. These are not investigated in this paper. The draft AS/NZS4777.2 standard specifies what is known as a 'volt–var' and 'volt–watt' response. AS/NZS4777.2 leaves it to the utility to specify which of the two responses is required in the PV inverter to deem compliance. The comparative effectiveness depends on the R/X ratio of the network. For networks with low R/X ratios (≤1) the voltage magnitude is strongly linked to the reactive power (vars) and more weakly to the real power (watts). With high R/X ratio systems the converse is true and varying the real power controls the voltage magnitude more successfully.

Table 3 Reactive power control investigated by simulation

Voltage, V	Power factor (option 1)	Power factor (option 2)
<208	0.95 leading	0.80 leading
208–220	0.95 to unity (linear)	0.80 to unity (linear)
220–240	unity	unity
240–255	unity to 0.95 lagging (linear)	unity to 0.80 lagging (linear)
255+	0.95 lagging	0.80 lagging

Table 4 Proportion of nodes which are undervoltage by classified categories

Cluster	City	Urban	Industrial	Rural	Total
percentage of networks within cluster	20.67%	16.72%	32.56%	8.38%	11.06%

3 Results and discussion

Peak load without PV is modelled first, followed by reduced load with increasing levels of solar PV.

3.1 Peak load, no solar PV

At the yearly peak load, with no solar PV, the modelling suggests that 11.06% of the LV network has undervoltage problems (Table 4). Naturally there are no overvoltage problems. Note that in reality the transformer secondary voltage may be higher than the utility-supplied figure of 415 V, which would reduce the figures in Table 4.

A total of 11,599 branches (5.2%) exceed their current ratings in the simulation. Some of these may not be genuine overcurrent cases. The GIS data, which the simulations are based on, contains estimates for unknown data. This is a consequence of old buried cables and overhead conductors being implemented before modern 'as built' processes and a GIS system were implemented. On a positive note the distribution network owner is proactively updating records to eliminate these data gaps. The GIS data contains estimates for:

- load distribution, particularly of non-residential loads;
- unknown conductors (conservatively estimated to highlight potential problems).

No actual voltage measurements from the utility were available to be compared with the simulation results, since the utility could not supply the GIS information with the data for confidentiality reasons. Neither current nor power measurements were available at each ICP; and the DSO has no record of undervoltage problems unless a customer complains. Hence, verification was performed by modelling one transformer and associated feeders in PSS SinCal (Siemens) and also SimPowerSystems (MathWorks) to ensure the developed power flow was giving the correct results.

3.2 Reduced load, varying solar PV penetration

The load was reduced according to figures supplied by the utility as in Section 2.3, and PV was added to the simulation. The results in Figs. 4–8 show the simulated performance of the LV network in regards to overcurrent, reverse power flow, and overvoltage. Fig. 4

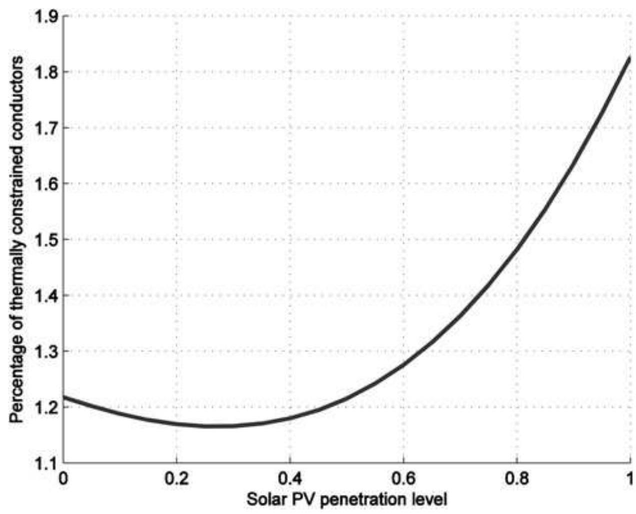

Fig. 4 *Overloaded conductors*

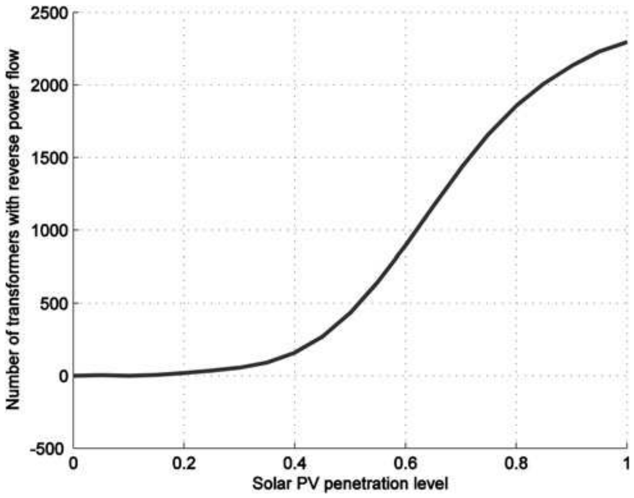

Fig. 5 *Number of transformers with reverse power flow*

shows that a little solar PV can help combat overcurrent (thermal constraint), as long as the PV is generating during times of peak load (unfortunately not the case in residential areas where the load peaks at winter evenings). As the penetration level is increased, the number of overloaded conductors dramatically increases as the reverse power flow dominates. As mentioned previously, there is a small proportion (∼1%) of outliers in the data, and these constitute many of the thermally constrained conductors in Fig. 4.

The number of transformers with reverse power flow is shown in Fig. 5. Very few cases are found until the solar PV penetration level reaches 0.25 or higher.

A comparison of how each type of LV network copes with solar PV is shown in Fig. 6, with further details shown in Fig. 7. Fig 8 shows the 5th and 95th percentile results in order to see the approximate distribution. Note that the deviation of the results in each category is strong related to how many LV networks are present in the group.

The percentage of networks with overvoltage simply measures the proportion of LV networks with some part of the network above the voltage magnitude limit. Figs. 6 (dash-dot line) and 8*a* show that the urban LV network is able to host 10-15% solar PV penetration without significant problems. Above this level overvoltage problems increase sharply. However, the overvoltage is generally not much higher than the statutory limit of 1.06 p.u.

City/commercial areas (Fig. 6, dashed line and Fig. 8*b*) are generally more compact, have larger loads and a higher-rated transformer than urban areas. Hence they are better equipped to cope with solar PV. Since the city centre is more compact the impedance is lower. The loading is unlikely to be low during day-time in the city centre, unlike residential areas.

In rural areas of New Zealand, each LV network usually has only a few ICPs on it (often all part of one farm). The distance between farms means that MV (MV, typically 11 kV) is reticulated along the roads and individual 11 kV/415 V transformers supply each farm (and in many cases several transformers per farm due to dedicated transformers being supplied for the irrigation pump load). Hence there is a minimal LV network associated with each ICP. In this simulation rural LV networks cope with solar PV relatively well (Figs. 6 and 8*c*), since the peak load is quite high and the maximum solar capacity modelled is low (one per ICP). The PV size is insignificant compared to the pumps and farm shed loads, although these are often not operational which may possibly lead to overvoltage problems in the small local LV network. One would expect larger solar/wind/hydro installations at farms due to the larger areas available, however, these ought to be connected at MV rather than LV. Solar PV was not found to be an issue in industrial networks. As expected the industrial networks did not have any overvoltage problems for all penetration levels.

The results show that the statistics for a large system are very stable. When the PV units are randomly distributed over the whole system some LV networks may have more units and hence more problems (probably), but others will have less PV units and hence less problems. Therefore, the statistics for the complete system (proportion of overvoltages and proportion of lines with overcurrent) is reasonably static (low standard deviation).

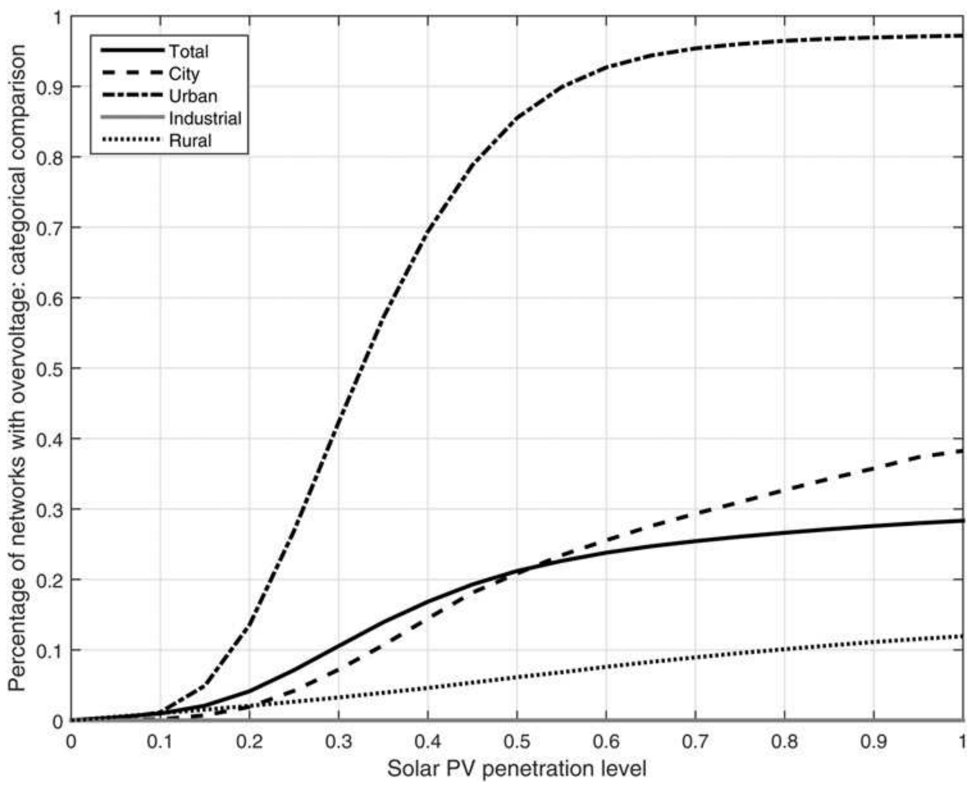

Fig. 6 *Percentage of networks with overvoltage problems by classified categories*

IET Gener. Transm. Distrib., 2016, Vol. 10, Iss. 1, pp. 1–9

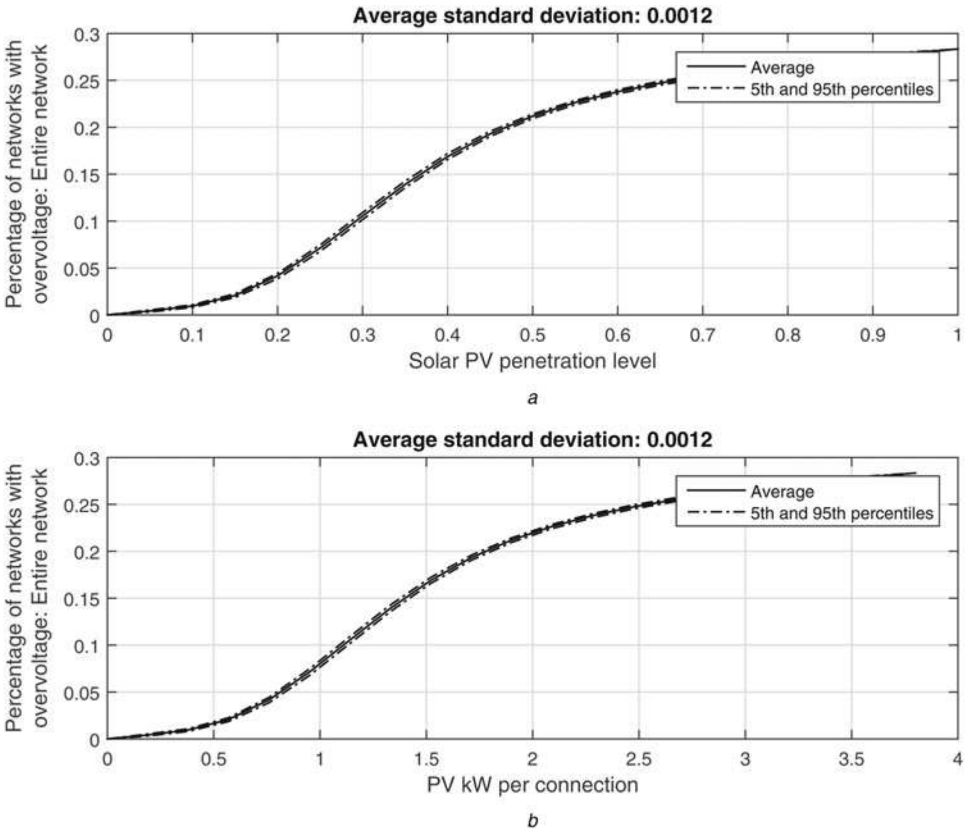

Fig. 7 *Total proportion of networks with undervoltage problems*

a Against solar PV penetration level
b Against PV kW per connection

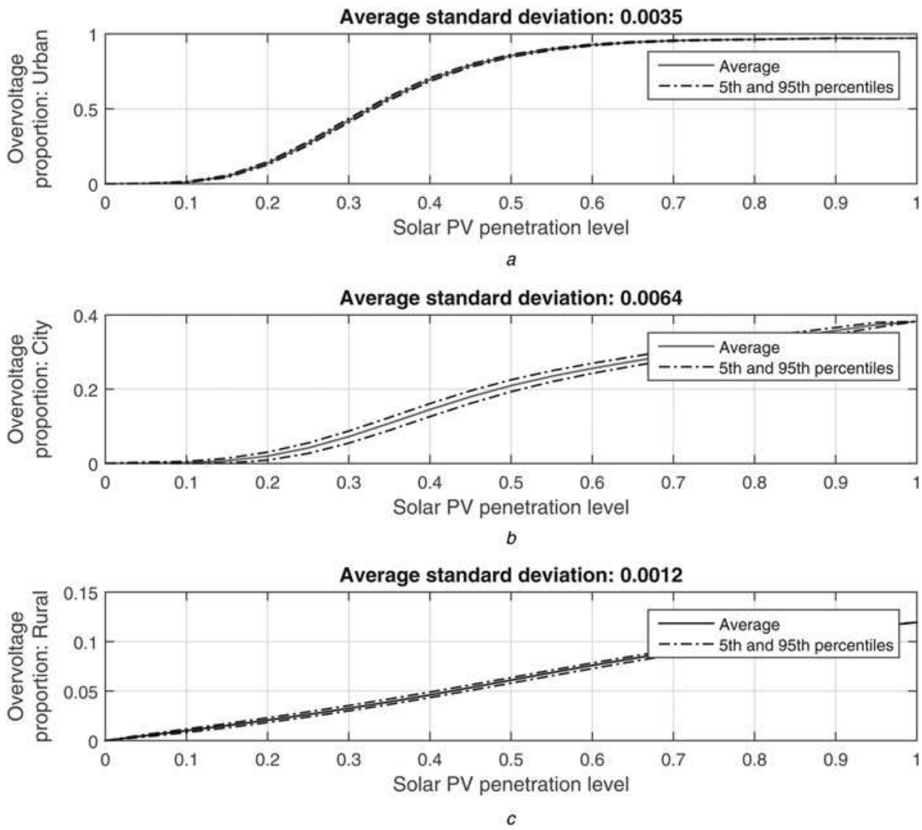

Fig. 8 *Percentage of*

a urban networks with overvoltage problems
b city networks with overvoltage problems
c rural networks with overvoltage problems

3.3 Mitigation of overvoltage

As urban networks are by far the most likely to experience overvoltage problems, the mitigation analysis will focus solely on these networks. Urban networks are most likely to experience extreme conditions (i.e. low load, high solar PV generation; and high load, without solar PV generation); hence this extreme condition study best applies to urban networks.

3.3.1 Reactive power control: Reactive power control is commonly used to limit overvoltage. Although the increase in allowable PV penetration is moderate, it must be noted that extreme overvoltages are substantially reduced. This is due to the fact that reactive power control is only activated at ICPs with a high voltage magnitude. The limits with every solar PV system having reactive power control and real power roll-back are given in Tables 5 and 6. The maximum allowable proportion of urban networks experiencing overvoltage is chosen in the first 'Threshold' column. A threshold of 5% means that 5% of urban networks may experience overvoltage problems. The maximum allowable PV penetration is then determined in the second column, and the corresponding improvement over the base case is given in the third column.

As Table 6 shows, reactive power control with a minimum power-factor of 0.95 for the PV inverters makes little difference. The R/X ratio of the distribution system is high (about 1.0) which reduces the effectiveness of reactive power control alone. The results with a minimum power factor of 0.80 are somewhat better (Table 6).

3.3.2 Reduced transformer secondary voltage: Reducing the transformer secondary voltage allows a significantly higher penetration level of solar PV, as shown in Table 7. However, at peak load undervoltage problems are significantly worse, and the number of overcurrent branches increases, as do the line losses.

Sometimes the transformer secondary voltage is set at the high end of the allowable range. This alleviates the likelihood of undervoltages occurring and reduces losses. However, often the range of loading does not require this as the voltage variation is not that great. This is illustrated in Fig. 9, where a sample recorded steady-state voltage histogram from a site on the network is displayed. The site could not be identified in the simulation for confidentiality reasons. Reducing the transformer secondary voltage would increase the hosting capacity for PV. The utility manages overvoltage by applying line drop compensation (or apparent current boost) at the zone substation, which provides a lower MV voltage (typically 10.9 kV) at times of low load and higher voltage (typically 11.2 kV) at high load. The 'apparent current boost' settings could be modified in the future to better manage the risk of overvoltage caused by PV.

Table 5 Results: reactive power control, based on ASNZS 4777.2. The minimum power-factor is 0.95

Threshold, percentage of networks with overvoltage problems	Maximum allowable PV penetration level, %	Increase in PV penetration over base case, %
1% urban	11	1
5% urban	17	2
10% urban	20	2

Table 6 Results: reactive power control based on ASNZS 4777.2. The minimum power factor is 0.80

Threshold, percentage of networks with overvoltage problems	Maximum allowable PV penetration level, %	Increase in PV penetration over base case, %
1% urban	13	3
5% urban	20	4
10% urban	23	5

Table 7 Results: decreased transformer secondary voltage (1.03 p.u., 410 V)

Threshold, percentage of networks with overvoltage problems	Maximum allowable PV penetration level, %	Increase in PV penetration level over base case, %
1% urban	17	7
5% urban	25	9
10% urban	30	12

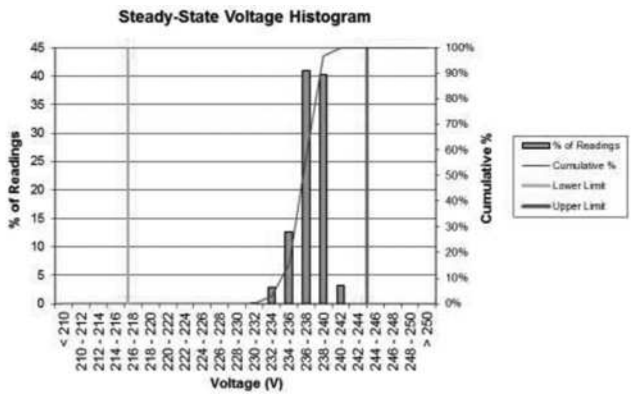

Fig. 9 *Steady-state voltage histogram*

Table 8 Results: 1.10 p.u. statutory limit

Threshold, percentage of networks with overvoltage problems	Maximum allowable PV penetration level, %	Increase in PV penetration level over 1.06 p.u. statutory limit, %
1% urban	30	20
5% urban	46	31
10% urban	54	36

3.3.3 Higher statutory upper voltage limit (1.10 p.u.): Many countries have 1.10 p.u. as the upper voltage statutory limits. In most of these cases, the higher limit is due to legacy issues and the long lifetime of the assets in the power system. This allows a much higher penetration of PV on the LV network, as shown in Table 8, however the higher limit for voltage does place a more stringent requirement on product design.

4 Conclusions

This work has demonstrated the feasibility of performing a power-flow analysis on a complete distribution system and has shown that GIS and SCADA data, with preconditioning, can give a power-flow model that is useful for such studies.

The potential impact of distributed PV generation on a LV network in New Zealand has been investigated. *K*-means clustering has been used to categorise parts of the LV network into city, urban, industrial and rural networks. The hosting limit (allowable penetration level) for PV on these different types of LV networks has been found. Urban networks were found to have the least capacity to host PV. Nevertheless, each LV network is different, and there is a wide variance as to how much a specific LV network can cope with.

Methods to increase this maximum allowable penetration level have been evaluated. Reactive power control with an appropriate voltage trigger level does increase the hosting capacity, but needs to be extended to a power-factor of 0.80 to be significant (0.95 limit gives minimal improvement). Changing transformer tap-position to reduce the secondary voltage does increase hosting capacity significantly if it can be performed without under-voltages occurring. Overvoltages are perhaps best managed at lower to medium PV uptake levels by utilising line drop compensation at the zone substation transformer.

According to the simulation results, overloading of conductors will only occur for very high PV penetration levels (>0.45). Some overvoltage problems can be expected in the future, particularly in urban areas as the penetration level increases. In most cases, the overvoltage would not be much higher than the statutory limit of 1.06 p.u. However, although the number of overvoltages and overloaded conductors is low for relatively high PV penetration levels, it is still very expensive to reinforce the system when underground work is required.

This work also showed the ineffectiveness of the initial power-factor control proposed by the draft AS/NZS4777.2 standard. This is mainly due to the voltage limits in Australia being different to New Zealand. Moreover, controlling the power-factor to be 0.95 has insufficient impact and a power-factor of 0.80 is required to have a significant impact. Only requiring PV inverters of 5 kW rating or greater to have a volt–var or volt–watt response is not sufficient as the large number of smaller PV inverters can be just as detrimental – and the use of the large number of micro-inverters is becoming a popular concept.

5 Acknowledgments

The authors wish to acknowledge Glenn Coates and Andrew Mulligan of Orion NZ Ltd for supplying the low-voltage network data and associated report and answering many related questions. The financial support from Ministry of Business, Innovation and Employment (MBIE), Electricity Engineers' Association and Transpower NZ Ltd was also gratefully acknowledged.

6 References

1 Zahedi, A., Lu, J.: 'Economic evaluation of grid-connected solar PV production cost in New Zealand'. Int. Conf. on Power System Technology (POWERCON 2012), Auckland, New Zealand, 30 October–2 November 2012, pp. 1–4
2 Miller, A., Williams, J., Wood, A.R.: 'Photovoltaic solar power uptake in New Zealand'. Electricity Engineers' Association (EEA) Conf. and Trade Exhibition, 2014
3 Latheef, A., Negnevitsky, M., Muttaqi, K., Perera, S.: 'Present understanding of the impact of distributed generation on power quality'. Australasian Universities Power Engineering Conf., 2008, 14–17 December 2008, pp. 1–6
4 Trichakis, P., Taylor, P.C., Lyons, P.F., Hair, R.: 'Predicting the technical impacts of high levels of small-scale embedded generators on low-voltage networks', *IET Renew. Power Gener.*, 2008, **2**, (4), pp. 249–262
5 Marti, P., Velasco, M., Fuertes, J.M., Camacho, A., Miret, J., Castilla, M.: 'Distributed reactive power control methods to avoid voltage rise in grid-connected photovoltaic power generation systems'. 2013 IEEE 22nd Int. Symp. on Industrial Electronics (ISIE), Taipei, Taiwan, 28–31 May 2013, pp. 1–6
6 Walling, R.A., Saint, R., Dugan, R.C., Burke, J., Kojovic, L.A.: 'Summary of distributed resources impact on power delivery systems', *IEEE Trans. Power Deliv.*, 2008, **23**, (3), pp. 1636–1644
7 Thomson, M., Infield, D.G.: 'Impact of widespread photovoltaics generation on distribution systems', *IET Renew. Power Gener.*, 2007, **1**, pp. 33–40
8 Tie, C., Gan, C.: 'Impact of grid-connected residential PV systems on the Malaysia low voltage distribution network'. 2013 IEEE 7th Int. Power Engineering and Optimization Conf. (PEOCO), Langkawi Island, Malaysia, 3–4 June 2013, pp. 670–675
9 Tonkoski, R., Turcotte, D., El-Fouly, T.: 'Impact of high PV penetration on voltage profiles in residential neighborhoods', *IEEE Trans. Sustain. Energy*, 2012, **3**, (3), pp. 518–527
10 Elsaidi, A.: 'Photovoltaic (PV) type solar generators and their effect on distribution systems', M.Sc. Thesis, University of Missouri, 2013
11 Hoke, A., Butler, R., Hambrick, J., Kroposki, B.: 'Maximum Photovoltaic Penetration Levels on Typical Distribution Feeders', 2013. http://www.nrel.gov/docs/fy12osti/55094.pdf
12 Schneider, K.P., Chen, Y., Engle, D., Chassin, D.: 'A taxonomy of North American radial distribution networks', IEEE Power & Energy Society General Meeting PES '09, 2009, pp. 1–6
13 Demirok, E., Casado González, P., Frederiksen, K.H.B., Sera, D., Rodriguez, P., Teodorescu, R.: 'Local reactive power control methods for overvoltage prevention of distributed solar inverters in low-voltage grids', *IEEE J. Photovolt.*, 2011, **1**, (2), pp. 174–182
14 Ali, A., Pearsall, N., Putrus, G.: 'Impact of high penetration level of grid-connected photovoltaic systems on the UK low voltage distribution network'. Int. Conf. Renewable Energies and Power Quality (ICREPQ'12), Santiago de Compostela (Spain), 28–30 March 2012
15 Chant, T.I., Shafiullah, G.M., Oo, A.M.T., Harvey, B.E.: 'Impacts of increased photovoltaic panel utilisation on utility grid operations – a case study'. 2011 IEEE PES Innovative Smart Grid Technologies Asia (ISGT), Perth, Australia, 13–16 November 2011, pp. 1–7
16 Conti, S., Raiti, S., Tina, G.: 'Simulink modelling of LV photovoltaic grid-connected distributed generation'. 18th Int. Conf. on Electricity Distribution, Turin, June 2005, pp. 6–9
17 Gonzalez, C., Geuns, J., Weckx, S., *et al.*: 'LV distribution network feeders in Belgium and power quality issues due to increasing PV penetration levels'. 2012 3rd IEEE PES Int.l Conf. and Exhibition on Innovative Smart Grid Technologies (ISGT Europe), 14–17 October 2012, pp. 1–8
18 Chen, P., Kezunovic, M.: 'Analysis of the impact of distributed generation placement on voltage profile in distribution systems'. IEEE Power and Energy Society General Meeting (PES), 2013, 21–25 July 2013, pp. 1–5
19 Jan-E-Alam, M., Muttaqi, K.M., Sutanto, D.: 'Assessment of distributed generation impacts on distribution networks using unbalanced three-phase power flow analysis'. IEEE Power and Energy Society General Meeting, 2011, 24–29 July 2011, pp. 1–8
20 Salles, D., *et al.*: 'Assessing the collective harmonic impact of modern residential loads – part I: methodology', *IEEE Trans. Power Deliv.*, 2012, **27**, (4), pp. 1937–1946
21 Jiang, C., Salles, D., Xu, W., Freitas, W.: 'Assessing the collective harmonic impact of modern residential loads – part II: applications', *IEEE Trans. Power Deliv.*, 2012, **27**, (4), pp. 1947–1955
22 Mather, B.A.: 'Quasi-static time-series test feeder for PV integration analysis on distribution systems'. IEEE Power and Energy Society General Meeting, 2012, 22–26 July 2012, pp. 1–8
23 Green Grid project, http://www.epecentre.ac.nz/greengrid/
24 Li, Y., Wolfs, P.: 'A statistical study on topological features of high voltage distribution networks in Western Australia', 20th Australasian Universities Power Engineering Conf. (AUPEC), 2010, pp. 1–6
25 Li, Y., Wolfs, P.: 'Preliminary statistical study of low-voltage networks under a representative HV network in Western Australia'. 21st Australasian Universities Power Engineering Conf. (AUPEC), 2011
26 Goeke, T., Wellssow, W.H.: 'A statistical approach to the calculation of harmonics in MV systems caused by dispersed LV customers', *IEEE Trans. Power Syst.*, 1996, **11**, (1), pp. 325–331
27 Frame, D., Ault, G., Huang, S.: 'The uncertainties of probabilistic LV network analysis'. IEEE Power and Energy Society General Meeting, 2012, 22–26 July 2012, pp. 1–8
28 Frame, D., Ault, G.: 'Exploring the uncertainties of probabilistic LV network analysis'. CIRED 2012 Workshop Integration of Renewables into the Distribution Grid, 29–30 May 2012, pp. 1–4
29 Papadopoulos, P., Skarvelis-Kazakos, S., Grau, I., Cipcigan, L.M., Jenkins, N.: 'Predicting electric vehicle impacts on residential distribution networks with distributed generation', IEEE Vehicle Power and Propulsion Conf. (VPPC), 2010, 1–3 September 2010, pp. 1–5
30 Papadopoulos, P., Skarvelis-Kazakos, S., Grau, I., Awad, B., Cipcigan, L.M., Jenkins, N.: 'Impact of residential charging of electric vehicles on distribution networks, a probabilistic approach'. 45th Int. Universities Power Engineering Conf. (UPEC), 2010, 31 August–3 September 2010, vol., no., pp. 1–5
31 Papadopoulos, P., Skarvelis-Kazakos, S., Grau, I., Cipcigan, L.M., Jenkins, N.: 'Electric vehicles' impact on British distribution networks', *IET Electric. Syst. Transp.*, 2012, **2**, (3), pp. 91–102
32 New Zealand Electricity Authority, Electricity in New Zealand 2011. https://www.ea.govt.nz/dmsdocument/12292