Determination of Distributed Generation Hosting Capacity in Low-voltage Networks and Industry Applications

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Abstract

The growing trend of distributed generation in Low-voltage (LV) networks requires Electricity Distribution Businesses (EDBs) to consider how their networks will perform with this new technology. Of particular interest is the level of distributed generation that can be supported until power quality issues or overloading of assets results, collectively referred to as network congestion.

The concept of Distributed Generation (DG) hosting capacity is introduced which defines how much power can be injected per DG system into the network at a selected penetration level before steady-state voltages at the point of supply and/or the current ratings of equipment are likely to be exceeded. An approximate technique called DGHost is described, which requires only a few basic network parameters to accurately estimate DG hosting capacity. It leverages results from full power-flow simulations of over 20 thousand LV networks in New Zealand by using a *k*-nearest neighbour algorithm to identify a subset of "similar" simulation states within the results database. The impact of phase imbalance is addressed in the model and the tool has been expanded to incorporate network variables such as undersized neutral conductors and single phase transformers - factors identified by the GREEN Grid Network Analysis Group (NAG) as needing separate consideration.

Cross-validation techniques were used to optimise the method and to determine its practical estimation accuracy. Hosting capacities estimated by DGHost resulted in a better than two-fold reduction in error compared to alternative methods that rely on the same simplified network data inputs.

The DGHost approximation technique provides EDBs with a short to medium-term solution for managing increasing levels of small-scale DG, without the need for complete asset data collection and power-flow modelling, which may be impractical or cost-prohibitive. It is demonstrated how DGHost can be applied to streamlining the application process for small-scale DG such as rooftop solar photovoltaic systems and how it can identify parts of the distribution network vulnerable to congestion.

1. Introduction

The growth of distributed generation (DG), particularly rooftop solar photovoltaic (PV) systems, is a major emerging trend in the electricity industry worldwide. This trend is driven largely by falling technology costs, growing consumer preferences for energy self-sufficiency and supply options with reduced environmental impacts, and other factors [1]. Integration of this new generation capacity into distribution networks is a major technical and economic challenge which will require careful planning and analysis, to enable the rise of electricity 'prosumers' while avoiding unacceptable impacts on electrical power quality and reliability of supply.

Electricity distribution networks were originally designed for the unidirectional flow of power from the national high-voltage transmission grid to end users: businesses and households. This generally means that while low voltage (LV) networks (consisting of one or more distribution transformers, and all downstream circuits and equipment at 400 Volts) have some capacity for DG installations, their ability to host reverse power flows caused by DG installations is typically less than their ability to deliver power to customers [2]. Power export to the network by DG systems can cause network congestion, typically as a result of excessive voltage rise along LV feeders or the overloading of equipment in the network. Voltage levels in New Zealand distribution networks must be managed to comply with the voltage limits specified in the Electricity (Safety) Regulations 2010 (±6% of the nominal 230 V supply voltage).

Understanding DG hosting capacity allows Electricity Distribution Businesses (EDBs) to determine the maximum amount of DG power that can be injected into each LV network without adversely affecting network operation or breaching regulatory requirements. EDBs can use this information to specify appropriate connection requirements for DG connection applications and to identify where detailed connection studies are necessary. DG hosting capacity can also assist EDBs in meeting Electricity Industry Participation Code (EIPC) requirements to make publically available which parts of their network are currently subject to congestion, or are expected to become congested in the near future.

A large number of independent studies exist in the literature analysing the potential impacts of high DG uptake scenarios on electricity distribution networks, for example [3], [4], [5], [6] and [7]. These studies are motivated by the rapidly increasing installed solar PV capacity observed in many regions and the need to plan new networks and remedial efforts appropriately. However, there is a relative lack of methods for the approximation of DG hosting capacity where complete LV network data is unavailable, as is a common issue for EDBs. Where this has been addressed, such as in [8] and [2], the methods are either not directly applicable in the New Zealand context due to different operating practices and regulatory environments, or are impractical for the purposes of DG connection assessment and the determination of network congestion.

In this paper, Section 2 introduces DG hosting capacity. Section 3 then outlines the primary factors affecting DG hosting capacity. Section 4 covers the two available methods for finding DG hosting capacity values. Sections 5, 6 and 7 then discuss the development of DG hosting capacity approximation, links between the two available methods and the accuracy of the approximation technique. Finally, Section 8 briefly presents the two main industry applications for DG hosting capacity information.

2. DG Hosting Capacity

The specific ability of each LV network to host DG power exports can be quantified using the concept of DG hosting capacity. This is defined as the maximum uniform net real power injection (in Watts), per Installation Control Point (ICP) with DG installed, on a LV network which can be tolerated without causing voltage or current limits to be exceeded in the network. Defining DG hosting capacity in terms of net power injection is supported by [4], as it is found to be the critical parameter in relation to voltage and current limits in LV networks.

DG hosting capacity is specified for each medium to low voltage (typically 11 kV – 400 V) distribution transformer. All ICPs on downstream LV feeders connected to a transformer are subject to this transformer level DG hosting capacity value. As such, DG hosting capacity is independent of any particular DG applicant's location within the network. This is due to the practical limitations in generalising LV feeder or ICP specific DG power injection values as a useful metric.

Calculated DG hosting capacity for each LV network depends on where the individual DG systems are placed in a power-flow simulation. Some allocations of DG sites to ICPs will lead to higher overall DG hosting capacities than others. Therefore, DG hosting capacity must be represented stochastically as a distribution of values corresponding to a series of uniformly random DG allocations, at each given DG penetration level (explained in Section 4). Representative outputs can be taken from the distribution as working estimates of DG hosting capacity; for example, the 25th percentile (P25) as a conservative estimate, or the 50th percentile (P50) as a mid-point estimate.

DG hosting capacity is applicable for the majority of residential DG systems, which are typically rated below 10 kW. Larger systems may have greater impacts on distribution networks and will require specific studies in most cases. Figure 1 below shows an example of a geographical distribution of DG hosting capacity values, including urban and rural areas.

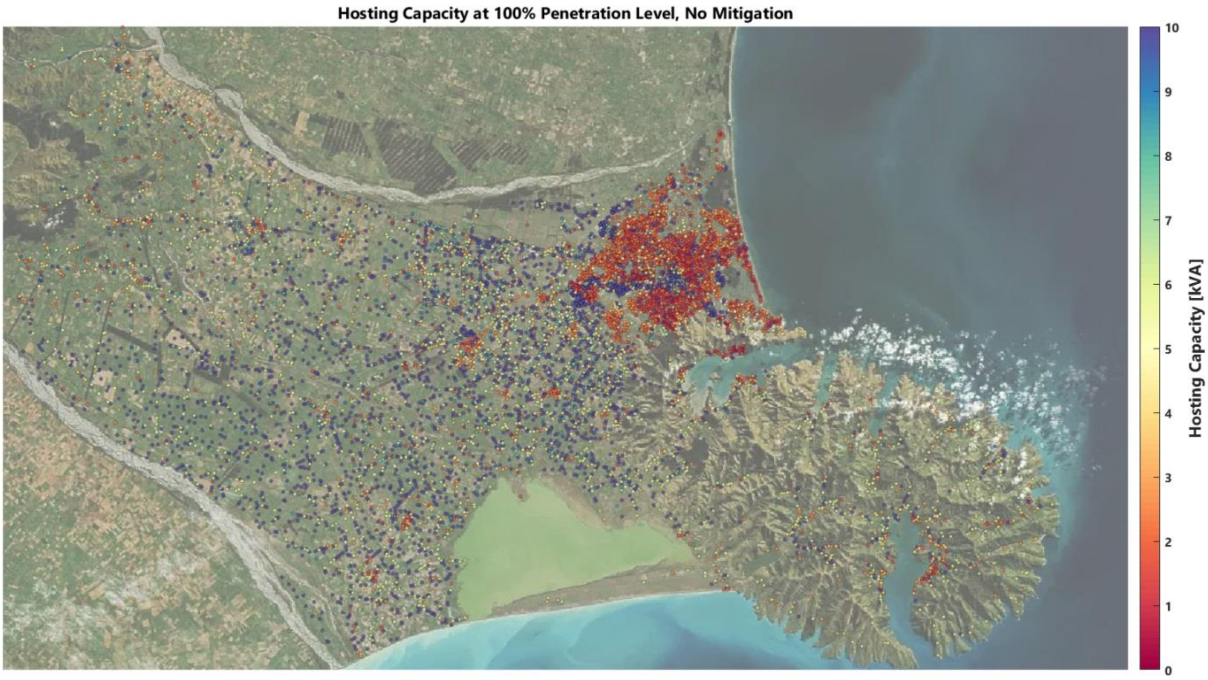

Figure 1: calculated DG hosting capacity values over the Christchurch region distribution network

3. Factors Affecting DG Hosting Capacity

DG hosting capacity is dependent on assumed DG penetration level, i.e. the proportion of customers who will install grid-connected DG systems in the LV network. At higher penetration levels, LV networks host less DG power injection per connection point on average, but can often tolerate more DG power export in aggregate due to an improved balance of power injection across the phases in three-phase LV networks. Figure 2 below shows this behaviour in DG hosting capacity (per ICP), and aggregate DG hosting capacity, for an example LV network. Volt-VAr response mode simulation results are also indicated, which will be discussed further below.

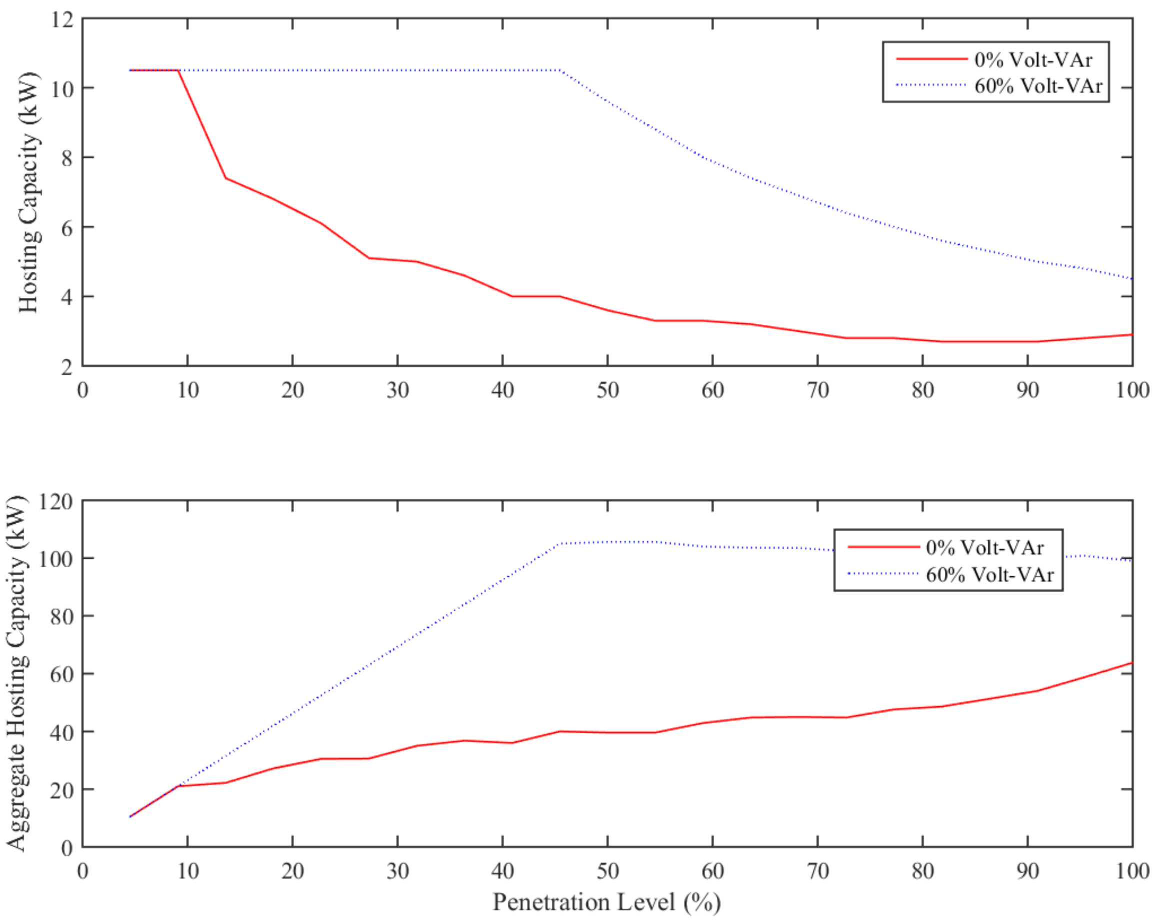

Figure 2: simulated per ICP and aggregate DG hosting capacity versus DG penetration level, with Volt-VAr mode enabled and disabled, for an example LV network (22 ICPs, 100 kVA transformer, maximum feeder |Z| = 0.2026 Ω)

Median simulated DG hosting capacity for all studied LV networks does not drop below 3.8 kW, the average DG system size being installed in New Zealand as of 2013 [9], until the DG penetration level reaches around 35%. However, this is subject to significant variance and DG hosting capacity can be much lower even at relatively modest penetration levels. The variance of DG hosting capacity drops significantly as DG penetration increases. This effect relates to the balance of DG power injection between phases, and the resulting impact of neutral currents on phase-to-neutral voltage rise, which diminishes as a greater number of DG systems inject power more evenly between the phases.

DG hosting capacity is generally lower in LV networks with longer, higher impedance conductors and/or smaller distribution transformers. This is because greater voltage rise will occur in the LV network for a given amount of DG net power injection, limiting the maximum amount of power that can be injected. LV networks with undersized neutral conductors (relative to the phase conductors) also tend to have lower DG hosting capacity values, as this exacerbates the issue of unbalanced DG injection and phase-to-neutral voltage rise. Multiple other factors contribute to differences in DG hosting capacity between LV networks, including the number of phases (single versus three-phase), number of ICPs and specific network topology.

LV network reinforcement and reconfiguration, and inverter voltage response functionality can increase the amount of DG that can be safely connected to LV networks, as demonstrated by [3], [10], [11] and [12]. These mitigation options reduce the impact of DG at high penetration levels on network reliability and power quality. Inverter power factor control (Volt-VAr response mode) is of particular interest as this is the most immediate mitigation option available to counteract voltage rise in most cases. The simulated efficacy of this response mode in raising DG hosting capacity is demonstrated for the example LV network in Figure 2, and also geographically in Figure 3 below.

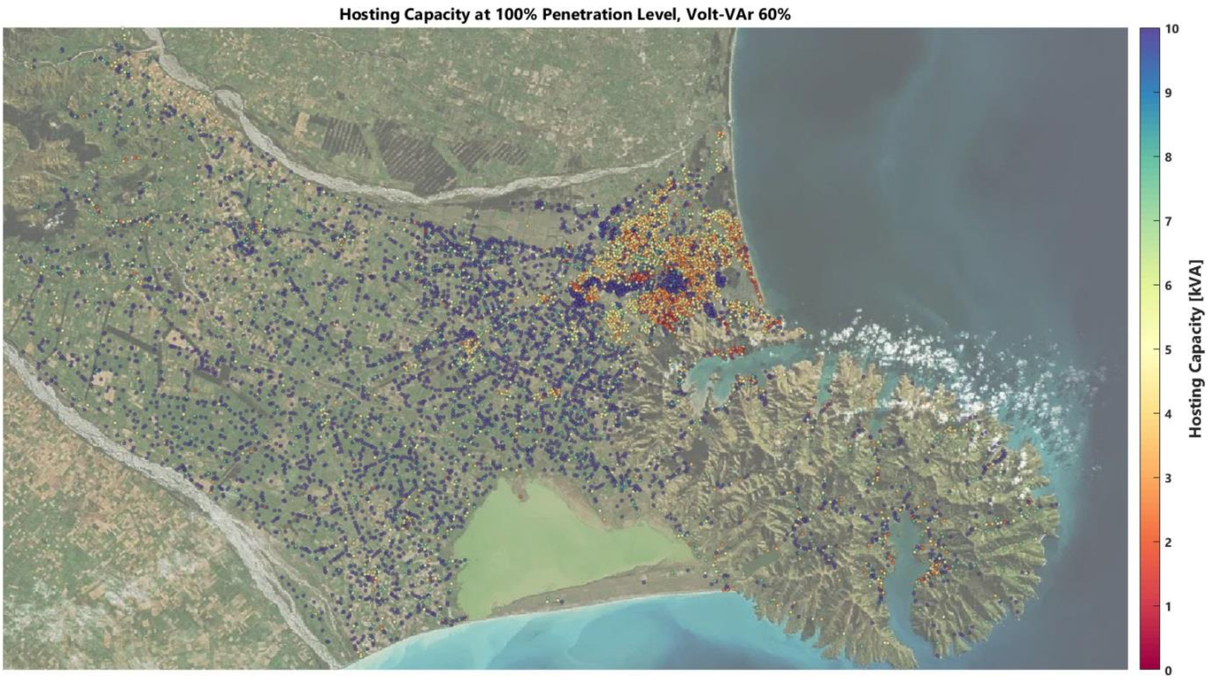

Figure 3: calculated DG hosting capacity values over the Christchurch region distribution network, with Volt-VAr mode active (set at maximum 60% VAr/rated VA response)

4. Determination of DG Hosting Capacity

Full network modelling and power-flow simulations are the primary means of determining DG hosting capacity. The full modelling approach, discussed in Section 4.1, is the preferred method as it provides output values reflecting the actual LV network configuration.

The main downside of this approach is that it requires complete model information for the LV networks to be studied. Electricity distribution networks are infrastructure assets with long operational lives and in some cases are many decades old. Consequently, equipment parameters and network connectivity are not well known, or may only exist as paper records for many assets. This lack of network information presents a unique challenge for the determination of available DG hosting capacity.

Section 4.2 introduces a new technique, named DGHost, developed by the GREEN Grid project to address this problem. The tool is designed to determine DG hosting capacity using only simple, readily available network parameters.

The detailed full modelling formulation and assumptions, approximation algorithm, optimisation processes and statistical validation will be made available in forthcoming GREEN Grid publications.

4.1 Full low-voltage network modelling and simulation

DG hosting capacity can be calculated directly via power-flow simulations using LV network models. The data required to carry out this analysis for each LV network, includes:

- Conductor types and parameters
- Geometry of over-head lines
- Distribution transformer parameters
- Network connectivity, including the locations of ICPs

This data is used to create functional models of the LV networks. DG hosting capacity for each individual LV network is then determined from time-independent power-flow simulations by iteratively increasing DG system net real power export until voltage limits at the point of supply, or equipment current ratings are reached. Net real power injection from each DG site is stepped up in increments of 100 Watts until a constraint is encountered, with the final unconstrained value taken as the DG hosting capacity.

Simulations are performed over a range of possible allocations of DG sites via a Monte Carlo process, in order to provide a representative distribution of DG hosting capacity values for each LV network. Each of the values in the distribution corresponds to a different randomly simulated allocation of DG sites (including actual phase connections) to ICPs in the LV network.

4.2 DG hosting capacity approximation method

The approximation of DG hosting capacity offers a solution for EDBs where full network data is unavailable, i.e. where DG hosting capacity cannot readily be determined via power-flow simulations. DGHost provides accurate DG hosting capacity estimates for the majority of LV networks, with minimal input information. The technique is based on a *k*-nearest neighbour (*k*-NN) regression algorithm and relies on a reference data set of full simulation results derived from available LV network model data, provided by several New Zealand EDBs.

The *k*-NN algorithm requires selected input parameters to find the *k* most similar networks in a multidimensional solution space. After the *k*-NN set is found, estimated DG hosting capacity for each LV network is calculated using a distance-weighted average across this small sample region of the solution space. The input parameters need to be sufficiently independent of one another, provide an accurate lookup in terms of DG hosting capacity, and must be easy to obtain for the LV networks to be analysed. After detailed consideration and testing, the following parameters were selected:

- Total number of connected ICPs on the LV network
- Distribution transformer VA rating
- Maximum magnitude feeder impedance on the LV network
- DG penetration level

To adjust the *k*-NN estimation, control parameters covering dimension scaling, inverse distance weighting and subset size are specified. A global control parameter optimisation process is then carried out in order to minimise absolute prediction error, via cross-validation of the entire reference data set.

DGHost analysis requires LV networks to be simulated using consistent assumptions. As such, results will be representative of networks with 'typical' topography and electrical parameters. Consequently, DGHost may not produce valid estimates of DG hosting capacity for LV networks with less common features, such as:

- LV single-wire earth return (SWER) feeders
- Meshed, non-radial networks

Catering for these different networks types is possible, but requires either data set filtering, or the creation of independent solution data sets simulated with the relevant network features in place.

5. Development of DG Hosting Capacity Approximation

The initial approach to DG hosting capacity approximation was based on statistical clustering of LV networks. This built on previous GREEN Grid research. The analysis was performed on the Orion distribution network, and revealed four broad clusters roughly analogous to city, suburban, rural and industrial groups, as reported in [13].

While the identified clusters are useful for general categorisation of LV networks, the simulated variance of maximum voltage within each of these clusters remained unacceptably high for the purposes of establishing recommended connection requirements. Following the clustering work, the capability to model each LV network was developed, and full modelling was undertaken on the LV networks of three New Zealand EDBs.

Subsequent to this work, LV network data was used to produce a large data set of simulated DG hosting capacity results. This provided the necessary dense, multidimensional solution space to allow the accurate estimation of DG hosting capacity, via the *k*-NN approach. The sample region found is localised around the point of interest and is much more likely to contain a similar subset of networks than any of the four original clusters, exhibiting significantly lower variance in DG hosting capacity.

During early development work, several alternative prediction techniques were tested including naïve Bayes classification, support vector machines and artificial neural networks. The *k*-NN method was found to provide the greatest prediction accuracy (lowest error) overall using when simple input data that would be available to most EDBs. *k*-NN regression techniques are readily optimisable via cross-validation, computationally efficient and do not require strong assumptions about the underlying structure of the data [14]. As such, this approach is highly effective for the determination of DG hosting capacity.

6. Links Between Full Modelling and Approximation

Full network modelling provides DG hosting capacity results as a direct output of the power-flow simulations. The same LV network models are also used to populate a reference data set, allowing DGHost to be used for LV networks without complete data. The accuracy and usefulness of DGHost is therefore improved over time as more full simulation results are added to the relevant reference data set. Figure 4 shows this link between full network modelling and DGHost. Note that multiple reference data sets exist, covering various network types and settings.

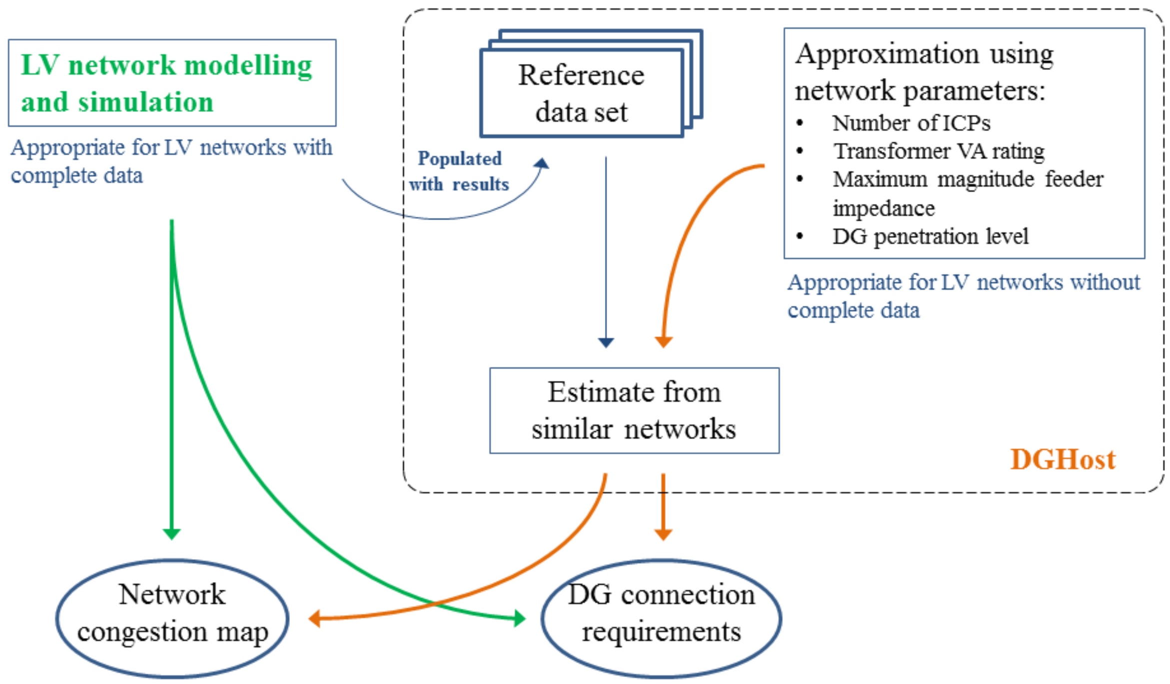

Figure 4: overview of links between full modelling and approximation of DG hosting capacity

As of April 2016, the primary reference data set consists of DG hosting capacity values for 20,427 individual LV networks simulated in excess of 21 million distinct states, covering three New Zealand EDBs and almost 300,000 customer connection points.

7. DGHost Accuracy

The median absolute DGHost estimation error for DG hosting capacity found via cross-validation of the existing data set, over all LV networks and all simulated penetration levels, is approximately 400 Watts. However, in practical applications of the tool, there may be some additional error due to varying data quality and regional differences between distribution networks.

The approximated DG hosting capacity of LV networks is typically more accurate at higher DG penetration levels. The reason for this relates to the balance of DG power injection between phases, as discussed in Section 3. Variance in DG hosting capacity is lower at higher penetration levels, and consequently estimation error is reduced.

Figure 5 shows distributions of DGHost estimation error as a percentage of actual simulated DG hosting capacity for all studied LV networks, by penetration level. These distributions are defined in terms of the difference between P50 (median) estimated and actual values. The percentage error is consistent across most penetration levels, showing that estimates remain accurate in situations where DG hosting capacity is lower and export congestion is likely to be a greater concern. The median estimation error is well below 10% of actual values across all DG penetration levels. The approximation can be biased towards underestimation, if required for conservatism.

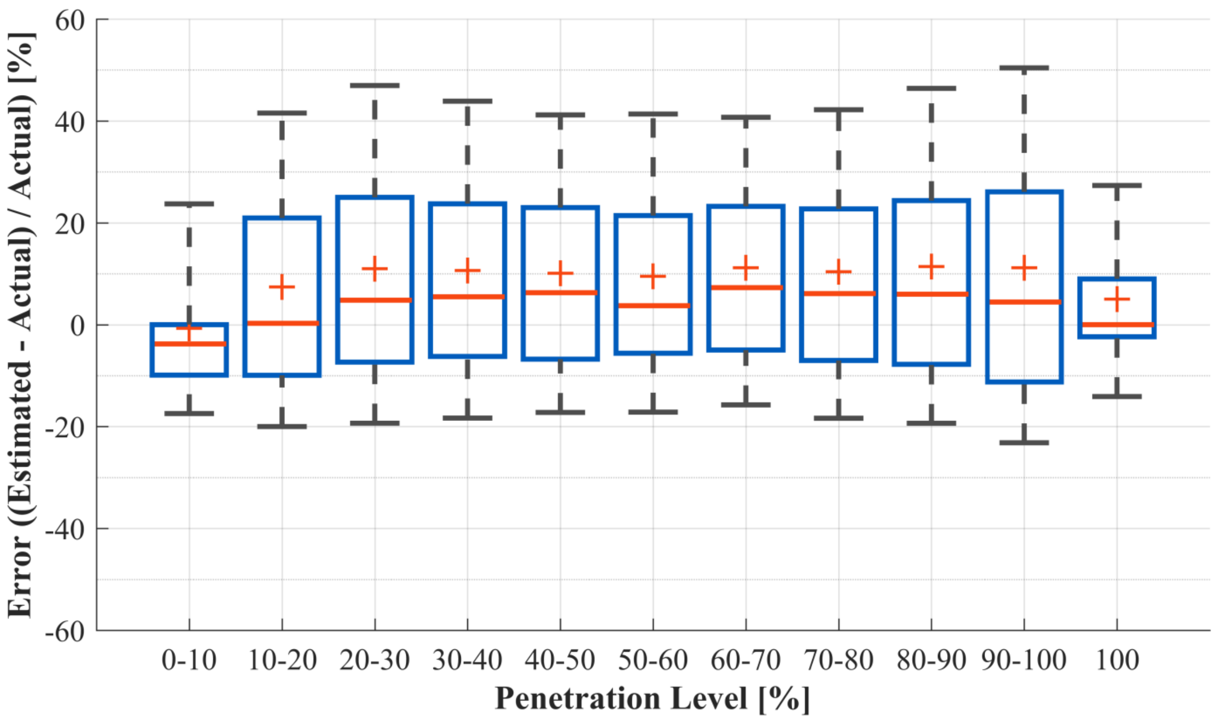

Figure 5: DGHost percentage estimation error distributions by penetration level (red line - median, red cross – mean, blue box – 25th and 75th percentiles, whiskers - 10th and 90th percentiles)

As a final comparison, simplified two bus circuit models were constructed to provide a reference to the accuracy found via DGHost. These models produce estimates with median absolute error exceeding 1,500 W, even when the models are globally optimised via cross-validation using the same full reference data set as DGHost. This shows that DGHost performs considerably better than direct calculation of DG hosting capacity using the same limited input data.

8. DGHost Industry Applications

DGHost has two main industry applications, both discussed in the small-scale distributed generation (SSDG) connection guideline for New Zealand [15]. These are to assess the connection of SSDG to LV distribution networks by EDBs, and to quantify network export congestion.

As detailed in the SSDG guideline, and summarised in Table 1, the process for reviewing applications to connect SSDG is based on categorising where each applicant's DG system maximum power export capacity lies in relation to identified DG hosting capacity levels, H_1 and H_2. H_1 represents the base hosting capacity of the LV network under consideration, whereas H_2 represents the DG hosting capacity with inverter power factor control (Volt-VAr mode) available[1]. The main suggested connection requirement is to make inverter power factor control mandatory if an applicant's DG system falls above H_1. If above H_2, the application will likely require detailed impact studies.

Table 1: Summary of requirements for DG connection applications

DG maximum net real power injection (P)	Requirements for connection
$P \leq H_1$	➢ No inverter voltage response required (but enabled if available)
$H_1 < P \leq H_2$	➢ Volt-Watt and Volt-VAr response modes required, and must be simultaneously enabled
$P > H_2$	➢ Connection is by negotiation, on a case-by-case basis ➢ Manual assessment is necessary

DGHost can also be used by EDBs to identify which locations on their network are subject to export congestion, or are likely to become congested in the near future. This assessment is required by the Electricity Industry Participation Code (EIPC) 2010, Clause 6.3(da), and is explained in detail in [15]. The resulting information can be used to inform prospective DG applicants of network congestion, and by EDBs to target network areas which are in need of closer monitoring or expedited reinforcement.

Conclusion

DG hosting capacity analysis has been developed to allow the New Zealand electricity industry to understand and quantify the ability of LV distribution networks to incorporate small-scale, inverter connected DG power injection. This can assist EDBs with the practical challenges of assessing DG connection applications and implementing appropriate mitigation requirements, while minimising the number of detailed studies that need to be undertaken. DG hosting capacity can also be used more broadly to understand DG export congestion in LV networks and identify networks that are close to their limits.

DGHost has been developed in parallel to address a relative lack of LV network data available to many EDBs. DGHost delivers the advantage of accurate working estimates of DG hosting capacity for LV networks, without placing an immediate burden on EDBs for the provision of large amounts of network information. The median estimation error produced by the tool is acceptably low relative to the 3.8 kW average solar PV system size in New Zealand. DGHost also outperforms simple calculation methods using the same limited input data, by a significant margin.

The New Zealand electricity sector is currently in an advantageous position, being earlier along in the PV uptake process compared with many other parts of the world. This provides

[1] H_2 is found by conducting full network simulations with Volt-VAr response mode active on all DG systems, providing a second multidimensional solution space. This allows DGHost to estimate the increased DG hosting capacity values, assuming inverter response functionality is available.

the opportunity to learn from and avoid mistakes associated with the uncoordinated management of large volumes of DG connecting to distribution networks. Using DG hosting capacity analysis, the connection of increasing amounts of DG can be achieved with minimal costs and disruption, to the benefit of EDBs, future DG owners and New Zealand as a whole.

Future Work

Future GREEN Grid publications will cover various related topics, including:

- LV network modelling and simulation of DG hosting capacity
- Detailed *k*-NN approximation methodology for DG hosting capacity
- The SSDG connection guideline [15] prepared by the EPECentre and EEA for industry dissemination

Ongoing modelling of the impact of DG on distribution networks aims to extend the analysis to the medium voltage level. This may inform further developments of DG hosting capacity and DGHost. General improvements to the modelling and approximation of DG hosting capacity will also be made over time as more experience and user feedback is gained.

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