Guideline for the connection of small-scale inverter based distributed generation: an introduction and summary

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Abstract

Small-scale distributed generation (DG) in New Zealand, particularly photovoltaic (PV) generation, has been growing steadily over the past few years. In the last year alone to 31 March 2016, installed PV generation of all capacities has grown by a factor of about 1.6 to reach 37 MW. Approximately 90% (33 MW) of this installed PV capacity is made up of small-scale, single phase residential grid-tied systems with ratings below 10 kW. This corresponds, on average, to approximately 300-400 new PV systems being installed each month within low voltage (LV) distribution networks.

Traditionally, the flow of power in electricity distribution networks has been largely unidirectional. However, distributed generation introduces reverse power flows into the LV network when the power produced by DG systems is greater than what can be consumed locally. This introduction of reverse power flows and the dynamic behavior of DG system inverters can negatively impact the electricity network, causing issues such as over-voltage, phase imbalance, overloading of conductors and transformers, and create unique safety challenges. As such, each DG connection application received by electricity distribution businesses (EDBs) presently needs to be carefully considered for its impact on the electricity network. The resourcing demand imposed by larger numbers of connection applications, and the difficulty of technical assessment including congestion evaluation, are likely to increase substantially as DG uptake intensifies. This has prompted the Electric Power Engineering Centre (EPECentre) via its GREEN Grid programme, with the assistance of the electricity industry based Network Analysis Group (NAG), to develop a small-scale inverter based DG connection guideline for New Zealand EDBs. This has been developed on behalf of the Electricity Engineers' Association (EEA) specifically for the connection of inverter energy systems (IES) of 10 kW or less.

This paper summarizes key aspects of this guideline. This includes a streamlined connection application evaluation process that enables EDBs to efficiently categorize DG applications into three groups. These groups vary from those with minimal or moderate network impact that can be auto-assessed, to those most likely to cause network congestion that require manual assessment. These categories are determined by looking at the DG hosting capacity specific to the LV network that the DG is connecting to. For two of these categories, mitigation measures for connection, are prescribed. It is also shown how DG hosting capacity can be used to simply evaluate LV network congestion in order to satisfy Electricity Industry Participation Code (EIPC) Part 6 requirements. Key technical requirements for all IES, appropriate for New Zealand conditions, are also summarized.

1. Introduction and Issues to Address

Small-scale distributed generation (DG) in New Zealand, particularly photovoltaic (PV) generation, has been growing steadily over the past few years, as shown in Figure 1. In the last year alone to 31 March 2016, installed PV generation of all capacities has grown by a factor of about 1.6 to reach 37 MW [1]. Approximately 90% (33 MW) of this installed PV capacity is made up of small-scale, single phase residential grid-tied systems with ratings below 10 kW. This corresponds, on average, to approximately 300-400 new PV systems being installed each month within low voltage (LV) distribution networks.

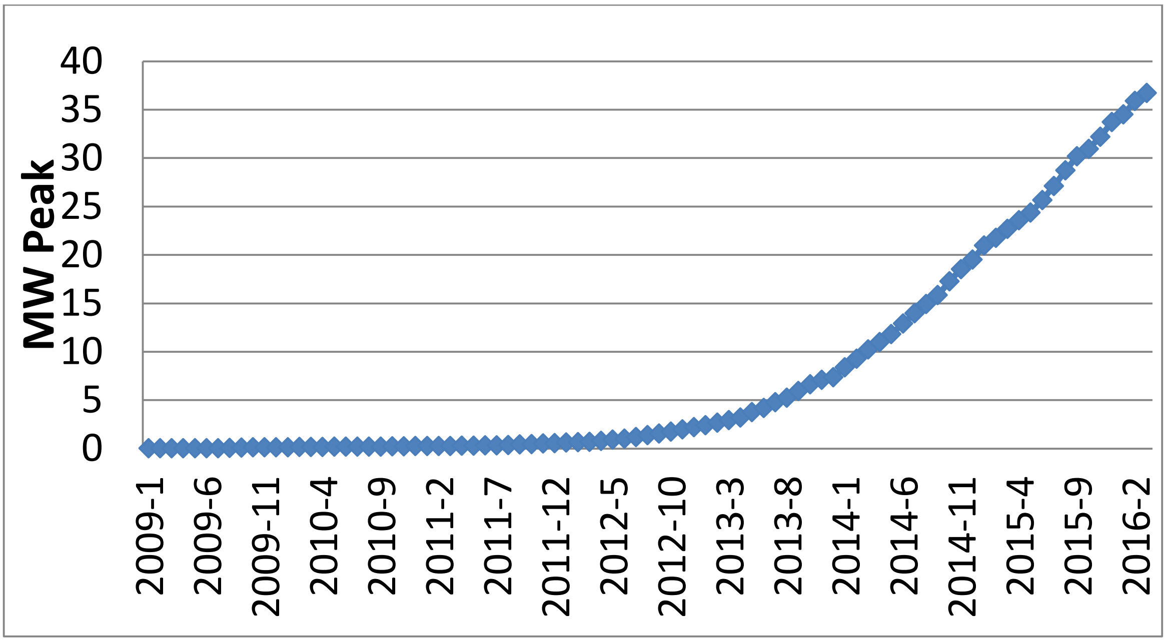

Figure 1 New Zealand photovoltaic (PV) uptake including all capacities: cumulative capacity 2009-2015 (Sources: Data since August 2013 is obtained from [1]. Data prior to this is obtained from [2] and [3])

Traditionally, the flow of power in electricity distribution networks has been largely unidirectional. However, distributed generation introduces reverse power flows into the LV network when the power produced by DG systems is greater than what can be consumed locally. The introduction of reverse power flows and the dynamic behavior of DG system inverters can negatively impact the electricity network, causing issues such as over-voltage, phase imbalance, overloading of conductors and transformers, and can create unique safety challenges.

In regard to over-voltage, distribution networks must be managed to comply with standard low voltage limits specified in the Electricity (Safety) Regulations 2010 (being ±6% of the nominal 230 V supply voltage). Distribution transformer tap settings are typically set at 1.04 per unit at the LV side to maintain feeder voltage under load. However, during instances of reverse power flow caused by DG power export, this tap setting has the effect of compressing the permissible voltage range downstream of the transformer. In this case, during reverse flow, the maximum permitted voltage rise from the distribution transformer to each point of supply is only 0.02 per unit, i.e. 4.6 V. Figure 2 illustrates an example where reverse power flow causes this margin to be exceeded, causing downstream over-voltage.

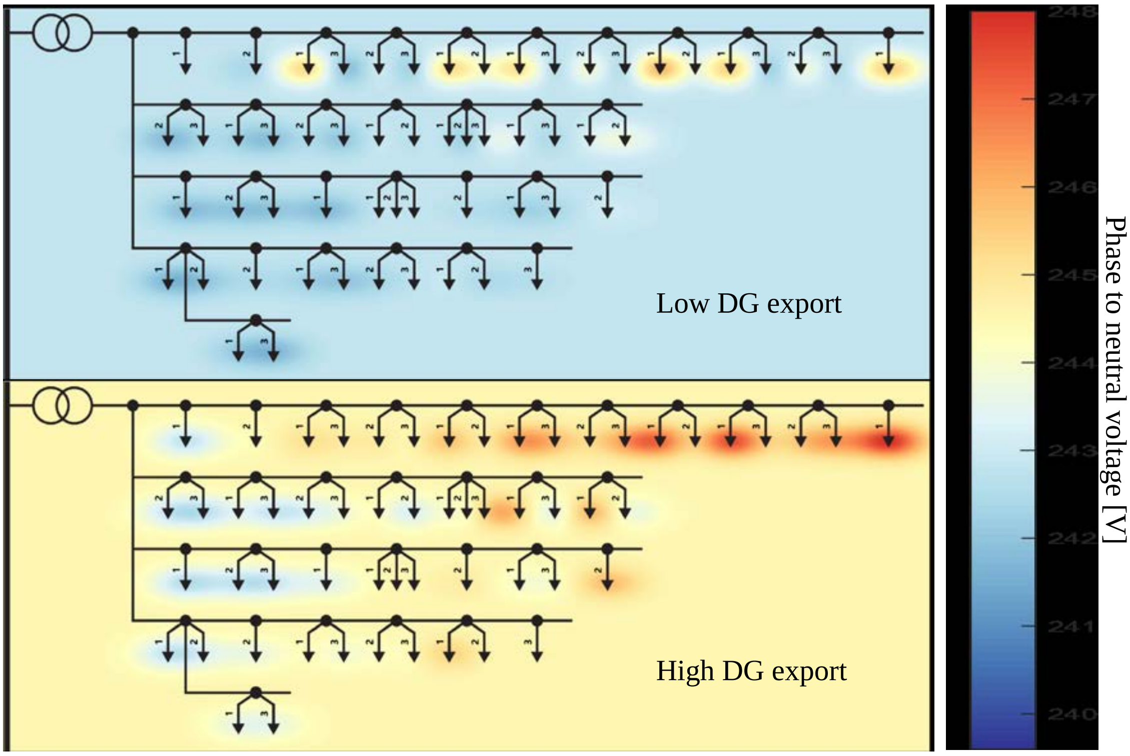

Figure 2 Examples of voltage effects caused by DG power export on a LV network, illustrated by colouring at the points of supply. For the low DG export case, 10% of ICPs are exporting and the network is load dominated. In the high DG export case 100% of ICPs are exporting and significant reverse power flow is occurring causing point of supply over-voltages at the downstream ends of feeders. The background colouring reflects the average network voltage.

For these various reasons, each DG connection application received by electricity distribution businesses (EDBs) presently needs to be carefully considered for its impact on the distribution network. In Australia, the approach taken to assess connection applications is to set arbitrary inverter kVA thresholds [4], below which applications are automatically assessed, and above which manual assessment is undertaken. This approach does not consider the specific characteristics of the network that the DG is connecting to. In Queensland, for example, these arbitrary thresholds are 3.5 kVA or 5 kVA for one to two-phase installations [5], depending on the network operator. In Germany, where PV uptake is very high, inverters are typically required to have real and reactive power control capabilities, and manual congestion assessment and LV network reinforcement are common [4].

In New Zealand, assessment of connection applications is typically a manual procedure. However, there exists no consistent approach to assessing applications and connection requirements across EDB’s. Furthermore, the technical complexity of this task has been compounded by the introduction of advanced inverter technology. Key aspects of this have now been captured in the recent update of some Parts of AS 4777:2005, to AS/NZS 4777:2015 – Grid connection of energy systems via inverters – Part 2: Inverter Requirements. This updates the Standard for requirements including protection settings, and advanced inverter features such as power quality response modes. This raises questions for EDBs processing connection applications regarding what inverter protection settings are appropriate for New Zealand conditions, how power quality response modes should be applied here, whether the new Standard provides all the appropriate information and most suitable requirements for the New

Zealand context, and whether inverters can perform as required. AS/NZS 4777 is discussed further in Section 2. Providing consistent connection requirements and standardization across EDBs would also be of major benefit to installers, inverter manufacturers, and consumers.

In addition to processing connection applications, EDBs are tasked to comply with the Electricity Industry Participation Code (EIPC) 2010, Clause 6.3(2)(da), which requires each EDB to publically disclose a list of all locations on its distribution network that it knows to be subject to export congestion[1]; or expects to become subject to export congestion within the next 12 months. Given the many thousands of LV networks in New Zealand, manual yearly assessment of every LV network for congestion is impractical. Instead, taking a reactive approach to identifying congestion if it arises is neither ideal nor compliant. Provision of a simple method that automates congestion evaluation for each LV network would be of benefit, such that only a much smaller subset of an EDB's networks would be flagged for needing closer congestion evaluation.

The resourcing demand on EDBs imposed by larger numbers of connection applications, and the difficulty of technical assessment including congestion evaluation, as discussed above, are likely to increase substantially as DG uptake intensifies. In order to manage these issues in the future, the Ministry of Business, Innovation, and Employment (MBIE) and members of the electricity distribution industry asked the Electric Power Engineering Centre (EPECentre), via its GREEN Grid programme[2], to investigate solutions. Various members of the distribution industry, now known as the Network Analysis Group[3] (NAG), provided assistance and feedback to the GREEN Grid programme for this task. This resulted in the development of the *Guideline for the connection of small-scale inverter based distributed generation* [6], written specifically for New Zealand EDBs. The Guideline is being released by the Electricity Engineers' Association (EEA) in draft form for comment at the 2016 EEA Conference. The Guideline covers the connection of inverter energy systems (IES) of up to 10 kW export power capacity, but may still be of assistance for connection of IES of higher capacity. This export threshold has been set to align with the EIPC 2010, Schedule 6.1, Part 1A, which allows for a simplified 1-stage application process for DG connections of 10 kW or less where inverters are used.

Section 2 describes the approach and methodology taken by the EPECentre to address these issues in developing the Guideline. Section 3 then describes the Guideline's DG connection application assessment process, and Section 4 describes congestion evaluation. This is

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[1] Export congestion as defined by the EIPC 2010, Part 1, means a situation in which a distribution network is unable to accept electricity exported from a distributed generation connection because the injection of an additional unit of electricity into the distribution network would—

> (a) directly cause a component in the network to operate beyond the component's rated maximum capacity; or
>
> (b) give rise to an unacceptably high level of voltage at the point of connection between the distribution network and the distributed generation.

[2] GREEN Grid is officially known as the *Renewal Energy and the Smart-grid* programme, but has adopted the acronym *GREEN - Gathering Renewable Energy in Electricity Networks*. Refer to the Acknowledgements for GREEN Grid funders and in-kind supporters.

[3] See the Acknowledgements for a list of NAG members.

followed in Section 5 by a summary of the Guideline's key technical requirements for both the DG installation and inverters.

2. Methodology to Develop the DG Guideline

The methodology applied to develop the Guideline included: literature review, LV network modelling, applying the concept of *DG hosting capacity*, consulting industry, reviewing Draft AS/NZS 4777 Part 2 and making submissions to Standards Australia, considering key technical and safety requirements relevant to New Zealand, and undertaking a programme of inverter testing.

This began with literature review examining how high intensities of small-scale DG are managed in other parts of the world, e.g. see [4], [7], [8], followed by research undertaken by GREEN Grid modelling DG in LV networks [9], [10].

It was identified that the concept of DG hosting capacity can be used to quantify how much power can be exported by DG into a LV network. This is used in the Guideline to determine both connection requirements, and network congestion. *DG hosting capacity* is defined as *the maximum real export power (in Watts), per ICP with DG installed, on a LV network which can be tolerated without causing voltage or current limits to be exceeded in the network*. As such, DG hosting capacity is uniform and allocated equally for each ICP with DG installed, and is independent of any specific DG's location within the LV network. The DG hosting capacity value reflects the ability of the network to accommodate DG. It is calculated for two thresholds, which are (i) a lower connection threshold H_1 above which mitigation measures are necessary, and (ii) an upper connection threshold H_2 above which mitigation via inverter reactive power control alone (specifically the Volt-VAr response mode) enabled for all connected DG, is insufficient. Hosting capacity, and its calculation, are described in detail in the Guideline [6], and in [11].

Industry consultation has been a vital part of the Guideline's development, particularly with assistance and feedback from the NAG. In 2013, Standards Australia released Draft AS/NZS 4777.2 updating the previous version with regard to inverter requirements, and this was finally published in 2015, as shown in Table 1. GREEN Grid made submissions to Standards Australia on behalf of the NAG, in May 2014, and again in May 2015, during this draft period. Various GREEN Grid changes were accepted, such as lowering the passive anti-islanding under-frequency set-point for New Zealand to 45 Hz (See Table 7) in order to coincide with South Island AUFLS tripping. GREEN Grid changes that were not accepted, but were deemed relevant to the New Zealand context, such as inverter Volt-VAr and Volt-Watt functions designed for New Zealand (see Figure 4 and Figure 5 in Appendix), have been included in the Guideline. GREEN Grid has also made a recent submission for Draft AS/NZS 4777.1:2016.

GREEN Grid has researched technical and safety requirements relevant to New Zealand, such as protection required for the inverter, and also for the LV network due to the presence of inverter based DG.

GREEN Grid has also been undertaking a continuing program of inverter testing, as inverters certified to AS/NZS 4777.2 have become available. The purpose of this testing is to determine how compliant inverters of all sizes up to 10 kVA are to the new AS/NZS 4777.2 Standard, how well they react to network disturbances, and whether the proposed Volt-VAr and Volt-Watt functions are practical in power quality response mode capable inverters. Current results of this testing are presented in [12].

Table 2 presents a timeline of events related to the development of the Guideline.

Table 1 AS 4777 update to AS/NZS 4777 – Grid connection of energy systems via inverters.

Existing Parts	Replacement Parts
AS 4777.1:2005 – Installation requirements ➢ Listed in the Electrical (Safety) Regulations 2010, under Schedule 2	Draft AS/NZS 4777.1:2016 – Installation requirements ➢ GREEN Grid made submission to Standards Australia on behalf of NAG, in May 2016
AS 4777.2:2005 – Inverter requirements AS 4777.3:2005 – Grid protection requirements	AS/NZS 4777.2:2015 – Inverter requirements ➢ Standard now in use, but it states a transitional period until 9th October 2016 during which AS 4777.2 and AS 4777.3, which it supercedes, may also be used. ➢ GREEN Grid made submission to Standards Australia on behalf of the NAG, in May 2014, and May 2015.

Table 2 Guideline development timeline.

NAG convened & methodology for LV network analysis established.	Initial DG impact analysis on LV networks. GREEN Grid informs EEA and NAG of issues relating to NZ adoption of Draft AS/NZS 4777.2	GREEN Grid/NAG review of Draft AS/NZS 4777.2 and comments submitted to Standards Australia	EIPC Part 6 modified to require EDBs to publish congestion information	GREEN Grid begins work on DG Connection Guideline & modelling tool to support Guideline & EIPC Part 6 changes.	GREEN Grid/NAG 2nd review of Draft AS/NZS 4777.2 and comments submitted to Standards Australia
Dec 2013	**March 2014**	**May 2014**	**Feb 2015**	**March 2015**	**May 2015**
Approximation method (DGHost) developed. First draft of DG Connection Guideline provided to NAG.	EEA and GREEN Grid collaborate to publish DG Guideline	DGHost trialled successfully	Draft DG Connection Guideline provided to EEA/ AMG	GREEN Grid/NAG review of Draft AS/NZS 4777.1 and submission	Draft DG Connection Guideline to be released by EEA for comment. Formal introduction of DGHost.
August 2015	**Sept 2015**	**Dec 2015**	**April 2016**	**May 2016**	**22 June 2016**

3. DG Connection Application Assessment Process

In order to progress through the connection application assessment flow diagram of Figure 3, a single input is required from the DG applicant, and this is the IES *maximum real export power*, *P*. The Guideline contains a proforma DG application form which EDBs may use and adopt as they wish. This form contains a table which the DG applicant fills in to calculate the IES *nameplate capacity*. In this table, the DG applicant also nominates the IES maximum real export power, which in most cases will be the same as the nameplate capacity, unless there is a power limiting device or non-zero load at peak export.

If the maximum real export power is ≤ 10 kW but non-zero, the third decision box is reached from which the application is then categorized according to one of green, amber, or red connection requirements. This is referred to as the *traffic light* system.

Table 3 shows an example of connection thresholds H_1 and H_2, defined in Section 2, to demonstrate the assessment process. The applicant wishes to install DG having a maximum real export power, *P*, of 4.5 kW. This is above the H_1 connection threshold of 2.7 kW, but less than the H_2 connection threshold of 7.2 kW, therefore the application is auto-assessed and granted with the requirement that the IES has voltage response modes available and enabled as specified by the amber coloured box in Figure 3.

Table 3 Example connection thresholds for a specific LV network

Hosting Capacity Outputs	
Connection threshold H_1 [kW] (upper limit for no mitigation)	Connection threshold H_2 [kW] (upper limit with mitigation – Volt-VAr response)
2.7	7.2

Hosting capacity connection thresholds H_1 and H_2 are obtained by full load flow simulation of the LV network. Alternatively, if simulation is impractical or if network data is incomplete, an approximation method may be applied such as the EPECentre’s *DGHost*. Both methods, and the modelling assumptions applied, are described in [6] and [11]. Note that the connection thresholds are pre-calculated for a specific LV network, and are not dependent on the location or size of the proposed DG or of any existing DG. This allows the hosting capacities to be available when the DG application is received by the EDB, thus enabling auto-assessment for the green and amber categories. This provides the benefits of: first, a streamlined connection requirements assessment process; and secondly, consideration of the specific characteristics of the network that the DG is connecting to rather than just applying an arbitrary kVA threshold to all networks.

The hosting capacity connection thresholds are a function of *penetration level*, which is defined as the proportion of ICPs in a given LV network that have export-capable DG installed. Hosting capacity decreases as penetration level increases. In order to look-up or to calculate the connection thresholds, the *long term penetration level*, γ_{LT}, must first be estimated. The Guideline recommends a long term penetration level within the range of 25% to 100% if the network has more than 5 ICPs, and a penetration level of 100% for a 5 or less ICP network. Assuming a penetration level of 100% is most conservative. The effect of setting a higher long

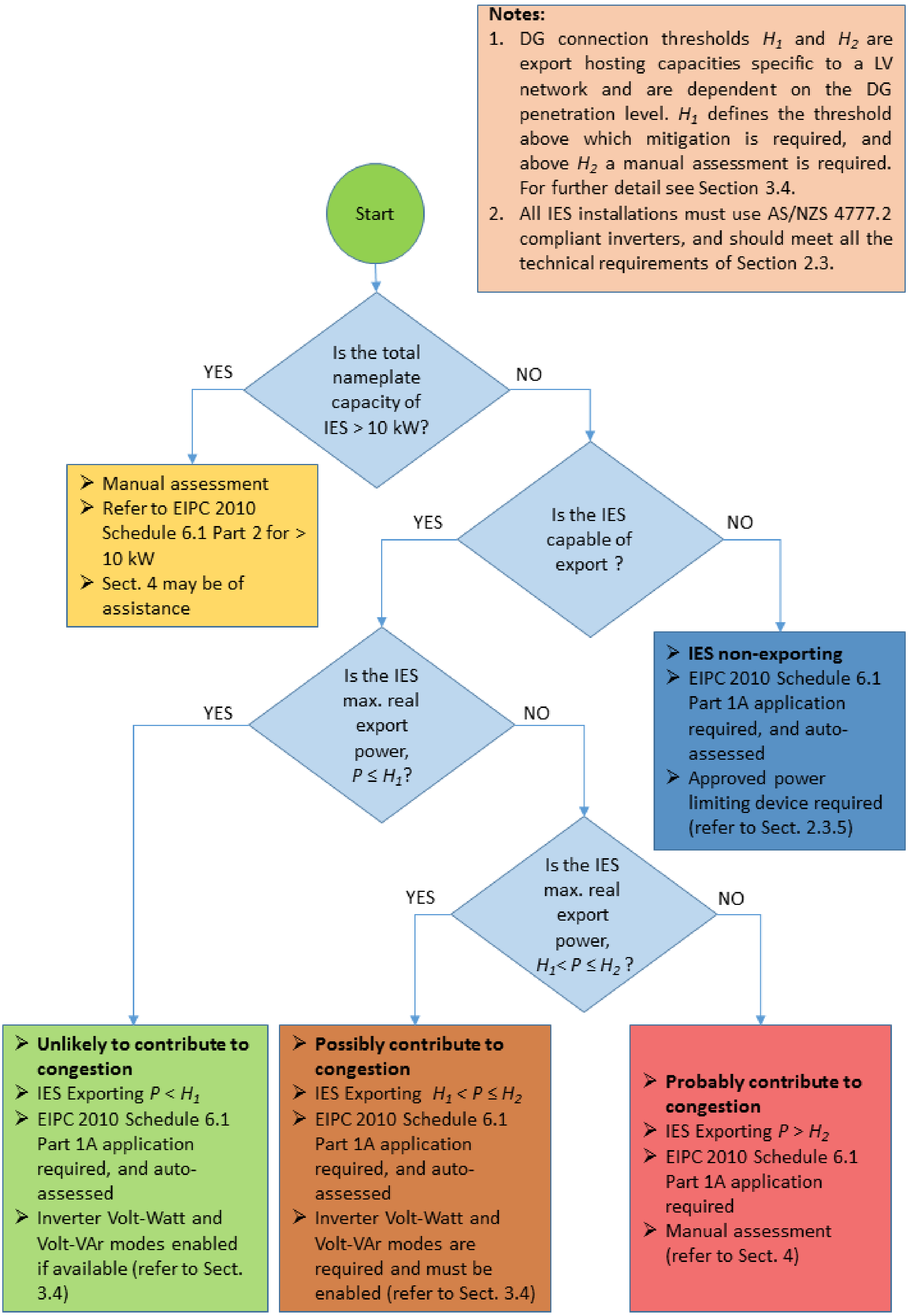

Figure 3 DG Guideline process flow diagram for assessing connection applications. Note that the diagram refers to sections in the Guideline.

term penetration level on the traffic light system is to lower the connection threshold where a Volt-VAr capable inverter is required, and where manual assessment is required. Conversely, setting a lower penetration level allows more connections using cheaper inverters that do not have volt-response modes, and also reduces manual assessments. A best estimate of the long term penetration level should be applied.

Note that the Guideline's traffic light system does not prohibit applications wishing to export over the H_2 connection threshold, where manual assessment is required under the red category. Under manual assessment, it is possible that an EDB may consider the amber category Volt-VAr enabled inverter requirement to still be sufficient in consideration of the technical circumstances of the application.

The DGHost approximation method enables hosting capacity to be estimated using simplified inputs provided by the EDB. Table 4 shows an example of the three LV network inputs required which are:

- number of ICPs,
- transformer rating, and
- the maximum feeder impedance.

Long term penetration level is an optional input that the EDB may additionally provide. All these inputs, together, yield the hosting capacity outputs of Table 3.

Table 4 Example inputs for determining a LV network's hosting capacity using DGHost

	Inputs			Optional Input
Network ID	Number of ICPs [N]	Transformer Rating [kVA]	Max Feeder Impedance [Ω]	Long-term Penetration Level γ_{LT} (%)
1	22	100	0.2026	63.6

4. Congestion Evaluation

DG hosting capacity can be used simply and effectively for export congestion evaluation and mapping for Code (EIPC) 2010, Clause 6.3(2)(da) compliance. Hosting capacity is found, as previously mentioned, either via the full simulation method, or via a method of approximation, such as the EPECentre's DGHost. The *aggregate export capacity* of a LV network is defined as the product of the number of ICPs, and the hosting capacity corresponding to the 100% penetration level. This capacity, obtained at full penetration, is considered a fundamental network congestion parameter. The *aggregate installed export power* is defined as the sum of the maximum real export power of all DG installed in a LV network. A LV network is considered congested if its *aggregate installed export power* is greater than or equal to its *aggregate export capacity*. This is expressed by the following inequality:

$$\sum_{i=1}^{D} P_i \geq N \cdot H(100)$$

Whereby, the left hand side represents the *aggregate installed export power*, and the right hand side represents the *aggregate export capacity*, and where

P_i is the ith installed DG system's maximum real export power (Watts)
D is the number of DG systems currently installed
N is the number of ICPs on the LV network
$H(100)$ is the LV network's hosting capacity connection threshold (Watts), determined at the 100% penetration level.

There are two connection thresholds, $H_1(100)$ or $H_2(100)$, which yield two aggregate export capacities. The connection threshold to use, $H_1(100)$ or $H_2(100)$, is decided based on whether the majority of connected DG would be expected to be operating the Volt-VAr response in the long term. If this was considered likely, then $H_2(100)$ should be used. For networks that currently have a low penetration level, $H_2(100)$ should be used assuming, that in the future, most AS/NZS 4777.2 compliant inverters on the market will have Volt-VAr response capability.

Table 5 shows an example of aggregate export capacity outputs from DGHost for the network described by Table 4. In order to perform the congestion evaluation, the EDB must keep a record of the network's aggregate installed export power. Table 6 shows that the network has an aggregate of installed export power of 25 kW, and an additional 5kW forecast to be installed on the network in the next 12 month period bringing the forecast aggregate installed export power in 12 months to 30kW. This network is known to have a majority of IES with Volt-VAr response modes operating, and this is expected to be the case in the future. Therefore the installed aggregate of Table 6 is compared to the aggregate capacity (mitigation – Volt-VAr response) of Table 5, which is 99 kW. The aggregate installed export power of 25 kW is well below 99 kW, so the network is well below a congested state now. A similar comparison, of 30 kW to 99 kW, shows that the network is also expected to be well below a congested state in 12 month's time.

Table 5 Aggregate export capacity outputs (in bold) from DGHost

Network ID	Aggregate export capacity (No Mitigation) $= N \cdot H_1(100)$ [kW]	Aggregate export capacity (Mitigation – Volt-VAr response) $= N \cdot H_2(100)$ [kW]
1	22 x 2.9 kW = **64 kW**	22 x 4.5 kW = **99 kW**

Table 6 Congestion evaluation parameters provided by the EDB

Network ID	Aggregate installed export power [kW]	Forecast aggregate installed export power in 12 months [kW]
1	25	30

This method allows an EDB to automate congestion evaluation for all of its many LV networks. Furthermore, the evaluation provides a measurement of the degree of congestion, thus assisting network planning. If the method flags a network as being congested, then a manual congestion assessment can then be undertaken to accurately determine if this is the case. As such, only a small subset of an EDB's LV networks need to be flagged for needing closer congestion evaluation.

5. DG Installation and Inverter Key Technical Requirements

The Guideline addresses questions for EDBs processing connection applications regarding what inverter protection settings are appropriate for New Zealand conditions, and how power quality response modes should be applied here. The guideline also refers to appropriate Standards and requirements for New Zealand, including safety and protection. The Appendix summarizes the most significant technical requirements for New Zealand provided in the Guideline.

6. Conclusions

This paper has described the need for, and has introduced the participants involved in, the development of the *Guideline for the connection of small-scale inverter based distributed generation*. It has also described the methodology applied, and has summarized key aspects of the Guideline. These include a streamlined connection application assessment process that enables EDBs to efficiently categorize DG applications into three groups. These groups vary from those with minimal or moderate network impact that can be auto-assessed, to those most likely to cause network congestion that require manual assessment. These categories are determined by looking at the DG hosting capacity specific to the LV network that the DG is connecting to. For two of these categories, mitigation measures for connection, are prescribed. It has also been shown how DG hosting capacity can be used to simply evaluate LV network congestion in order to satisfy EIPC Part 6 requirements. Key technical requirements for all IES, appropriate for New Zealand conditions, have also been summarized.

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Appendix – Technical Requirements

In regard to installation requirements, Draft AS/NZS 4777.1:2016, Clause 2.3, states that the rating limit for single-phase IES is 5 kVA. Therefore, the maximum current rating for single-phase connected IES is 21.7 A at 230 V. Furthermore, for multi-phase IES the unbalance between phases shall be no greater than 5 kVA. Therefore, for two-phase IES, the rating limit is 10 kVA.

Table 7 summarizes recommended inverter settings for protection of the distribution network. These include sustained voltage limit $V_{nom\text{-}max}$ and passive anti-islanding set-points (identified by *) specified for New Zealand according to AS/NZS 4777.2:2015.

Table 7 Recommended inverter settings for New Zealand

Parameter	Limit	Minimum trip delay time	Maximum disconnection (trip) time
$V_{nom-max}$ (10 minute average)	248 V		
Overvoltage 1*	260 V	1 second	2 seconds
Overvoltage 2*	265 V	-	0.2 seconds
Undervoltage*	180 V	1 second	2 seconds
Under-frequency[4] *	45 Hz	1 second	2 seconds
Over-frequency*	52 Hz	-	0.2 seconds
Minimum reconnection time	60 Seconds		
Volt response modes: Volt-VAr, Q(V) and Volt-Watt, P(V)	Applicability determined according to GREEN Grid traffic light system, Figure 3. GREEN Grid designed Volt-response curves shown in Figure 4 and Figure 5.		

GREEN Grid principally recommends the use of the Volt-VAr response mode. This is because Volt-VAr response will tend to minimise instances where DG owners located near the end of LV feeders, who are likely to encounter the highest voltages, are unfairly required to curtail real export power. AS/NZS 4777.2:2015 does not provide an example Volt-VAr response mode curve for New Zealand. GREEN Grid has therefore designed the Volt-VAr curve shown in Figure 4. At an over-voltage of 1.06 per unit (244 V), inverter lagging reactive power becomes fully activated, at a power factor of 0.8 lagging. Full power flow simulations by GREEN Grid of 20,427 LV networks from three New Zealand EDB's have shown this curve to be effective in countering over-voltage.

Figure 5 shows the Volt-Watt response curve designed by GREEN Grid, which differs to the example AS/NZS 4777.2:2015 curve, in order to complement and operate in tandem with GREEN Grid's Volt-VAr curve. The Volt-Watt response starts to rapidly curtail real power export only once the Volt-VAr response is fully activated. Actual use of Volt-Watt response is only intended as a *back-up* response for unplanned/unexpectedly high voltages, and substantially reduces the possibility of 246 V being exceeded at the IES terminals.

[4] The Under-frequency set-point value of 45 Hz for New Zealand was proposed by GREEN Grid in order to coincide with South Island AUFLS tripping, and was adopted by AS/NZS 4777.2:2015.

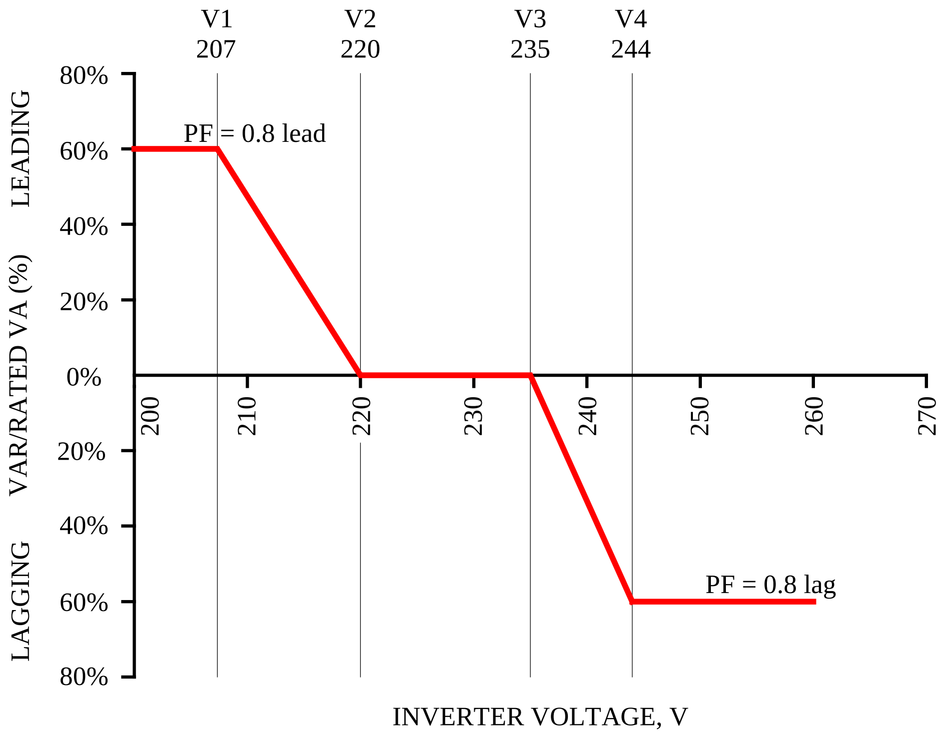

Figure 4 Curve for New Zealand Volt-VAr response mode.

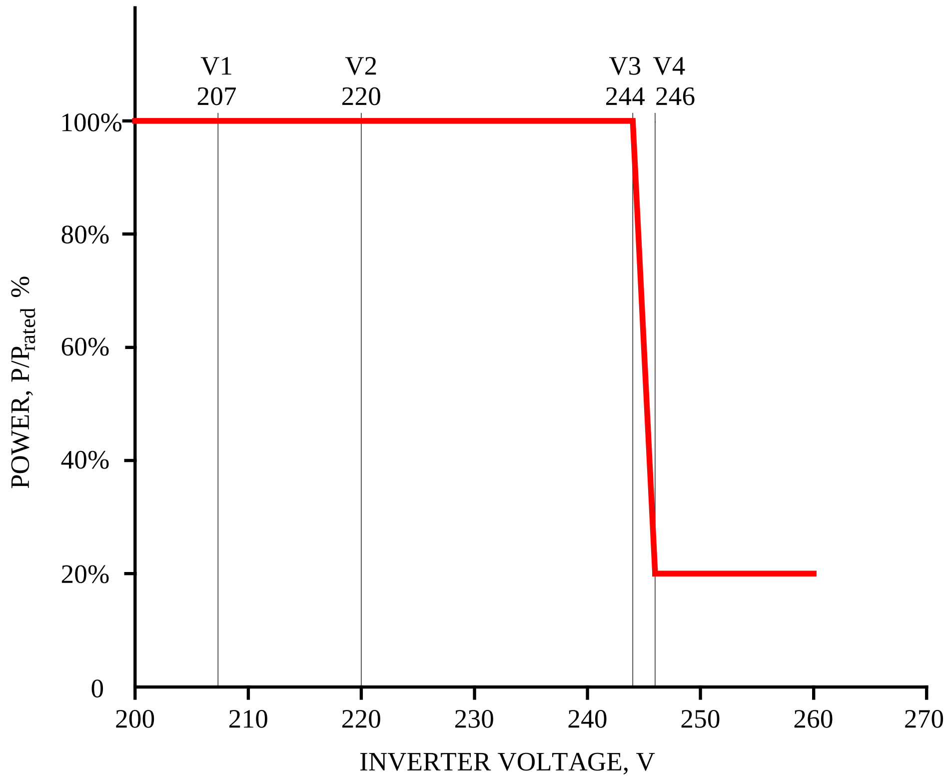

Figure 5 Curve for New Zealand Volt-Watt response mode.