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Review of Distributed Generation Interconnection Standards

Authors:
Luke Schwartfeger, David Santos-Martin

Co-authors:
Alan Wood, Neville Watson, Allan Miller

Presenter:
Luke Schwartfeger

Electric Power Engineering Centre (EPECentre)
University of Canterbury
Christchurch, New Zealand

Abstract

Grid operators, worldwide, are experiencing higher distributed generation penetration levels. This new paradigm is starting to show its effects and in order to maintain the safety and reliability of the network, most distribution system operators are adopting international standards or defining their own. Besides available international standards, a large variety of national or local requirements appear to give an answer to those local necessities. These local factors are highly dependent on the geography, grid structure, type of technology and the amount of current penetration level of distributed generation.

In New Zealand, the recent rapid uptake of distributed generation, in particular for photovoltaics, and the diversity of distribution companies' guidelines, along with the vision of a future common framework for New Zealand has inspired the review of all international standards and a cross comparison with local guide lines has been performed. The purpose of this analysis is to build a picture of these standards and give a brief insight into the current stance the national distribution companies have via their policies.

1. Introduction

There is an ongoing global effort to define standards/guidelines that allow the accommodation of increasing penetration level of distributed generation (DG), in particular photovoltaic (PV) systems. These standards are both intended for international and nation-specific guidance. One such development was the IEEE 929-2000, a standard primarily based on PV systems, being replaced by the IEEE 1547, which deals with all types of generation. The next revision of the IEEE 1547-2003 is being discussed in 2014 [1]. IEC 61727-2004 is for PV systems network interconnection requirements and alongside the IEEE 1547 targets issues in a similar manner assisting in the global aim for unifying standards. The EN 50438 is the European standard for micro generation connected in parallel with the network [2] and requires similar specification as the IEEE 1547. The German standards, the VDE-AR-N 4105:2011 (VDE) for low voltage and BDEW-2008 (BDEW) for medium/high voltage, comprehensively detail the requirements of the majority of DG possibilities. In New Zealand, the AS 4777-2005 (grid tied inverter based DG up to 10 kVA per phase) is commonly referenced in the distribution company guidelines however recently a major review is being conducted to develop the AS/NZS 4777.

The purpose of this paper is to compare the main requirements for interconnecting DG worldwide and in New Zealand, covered in the most used standards.

The main standards reviewed were the IEEE 1547 [3], VDE-AR-N 4105 [4], BDEW 2008 [5] and IEC 61727 [6]. The table below outlines the power and voltage levels covered by each of the standards.

TABLE I.
POWER AND VOLTAGE LEVELS COVED BY OF STANDARDS

	System Type	Voltage	Power
IEEE 1547	Sync, Async., Inverter (All)	Primary/Secondary distribution voltages	≤10 MVA
VDE-AR-N 4105	All	Low voltage (≤ 1 kV)	< 100 kVA
BDEW 2008	All	Medium (1 kV to 66 kV)	No limit
IEC 61727	Photovoltaic	Low voltage	≤ 10 kVA

Alongside the standards, New Zealand Distribution Company guidelines were also reviewed to provide a brief perspective on the situation with DG. Vector Limited's, Aurora Energy Limited's, Powerco's and Orion New Zealand Limited's policies are presented as examples in this paper.

This paper covers four major areas; voltage magnitude, voltage frequency, power quality and protection.

2. Voltage Magnitude

The network voltage magnitude can be greatly affected by DG as they inject power in a power system where previously only loads had been. This is thoroughly considered in every standard. Hereafter, the different standards requirements under normal and abnormal operation conditions are presented. Furthermore, the network support contribution is also treated, and divided as steady state and dynamic.

2.1 Normal Operation Conditions

2.1.1 Over/Under Voltage

Traditional methods of voltage magnitude control rely on the power flow being in a singular direction (i.e. the voltage drop over the network elements was never reversed) however this is no longer the case with DG supplying. Due to this, over/under voltage protection is required to ensure appropriate voltage levels.

Tables II and III show the standards' requirements for the over/under voltage protection for LV and MV/HV networks respectively. Note that where a range is specified, any value may be adjusted by the network operator.

TABLE II.
OVER AND UNDER VOLTAGE SETTINGS

IEC 61727		IEEE 1547		VDE-AR-N4105	
Voltage Range	Disc. Time (1) (seconds)	Voltage Range	Max Disc. Time (seconds)	Voltage Range	Max Disc. Time (seconds)
< 50%	0.10	< 50%	0.16		
50% to 85%	2.00	50% to 88%	2.00	< 80%	0.2
85% to 110%	Continue Operation	88% to 110%	Continue Operation	80% to 110%	Continue Operation
110% to 135%	2.00	110% to 120%	1.00	> 110%	0.2
>135%	0.05	> 120%	0.16		

(1) In contrast to the other standards, for this one the time is not given as maximum value but as a remaining value before disconnecting

In contrast to VDE and IEEE standards, the IEC 61727 states that the DG must not disconnect if the time is smaller than the disconnection time.

The BDEW has settings outlined for three positions depending on the system; the generator, transfer point/network connection and transformer busbar. Disconnection devices are required at the transfer point and the generator. Table III shows the protection settings for the long and short time voltage protection respectively with instantaneous and averaged time measurements.

TABLE III.
BDEW OVER/UNDER VOLTAGE PROTECTION SETTINGS

At Network Connection		At Transformer Station		At Generator	
Instantaneous Voltage Level	Disc. (seconds)	Instantaneous Voltage Level	Disc. (seconds)	Instantaneous Voltage Level	Disc. (seconds)
1.00 to 1.30	$T_{instant} \leq 0.1$	1.00 to 1.30	$T_{instant} \leq 0.1$	1.00 to 1.30	$T_{instant} \leq 0.1$
0.10 to 1.00	$T_{instant} \leq 2.7$	0.10 to 1.00	$T_{instant} \leq 0.3$	0.10 to 1.00	$T_{instant} \leq 0.3$
1.00 to 1.30	$T_{avg} = 60$	1.00 to 1.30	$T_{avg} =$ 1.5 to 2.4	0.10 to 1.00	$T_{avg} = 1.0$

Vector outlines two voltage ranges with corresponding disconnection times, 230 - 253 V (0.5 seconds) and 200 - 230 V (2 seconds).

2.1.2 Permissible Voltage Change

Permissible voltage change is the difference in terms of voltage between the system with and without DG. Only the VDE and BDEW cover this topic.

The VDE's allowable voltage change that is caused by all the connected generation on the

network must be less than 3%. If the network operator requires it, this value may be deviated from so to sustain steady state stability.

For the BDEW, a 2% change in voltage is the maximum that all DG may alter MV/HV networks by. For calculating the voltage changes, the complex load-flow method should be used and the displacement factor shall be accounted for.

2.2 Network Voltage Support

This topic is split into steady-state and dynamic sections. Steady-state refers to the slow variation of the DG output to support the immediate network. Dynamic is when a higher voltage area of the network suffers voltage drops and it is intended to avoid network collapse by sustaining the network so unintentional disconnections occur. Some standards may treat dynamic support also as low voltage ride through capability (LVRT).

2.2.1 Steady State

IEEE 1547 states that no active voltage regulation of any kind can be performed and that the network voltage of the system should not adversely be affected. IEC617272 requires that the PV system shall have a lagging power factor greater than 0.9, when the output is greater than 50% of the rated power.

The VDE requires steady state support if the network operator chooses to. The reactive power capability required to the LV systems is shown in Table IV only if the operating voltage is within ±10% of the nominal and the active power output is above 20% of the rated amount.

TABLE IV.
VDE-AR-N 4105 REACTIVE POWER CAPABILITY LIMITS

S_{max} <= 3.68 kVA	0.95 under-excited to 0.95 over-excited
3.68 kVA < S_{max} <= 13.8 kVA	characteristic curve from network operator with 0.95 under-excited to 0.95 over-excited
S_{max} > 13.8 kVA	characteristic curve from network operator with 0.90 under-excited to 0.90 over-excited

The two methods of determining the reactive power required is by a power factor/active power characteristic or a fixed power factor provided by the network operator. The response time of the system to change the reactive power output must be within 10 seconds. For DG with generators directly coupled to the grid a maximum transition period of 10 minutes from start up to the set point is required.

In the BDEW for MV/HV systems, the network operator will specify whether steady state support will be required. In terms of the reactive power capability by MV/HV generators, the power factor should always be able to be between 0.95 under-excited and 0.95 over-excited. When a change in active power output occurs, either the reactive power output will be determined by a characteristic or variably set by the network operator/control scheme. The control mode may be through: reactive power or power factor set point, power factor/active power characteristic or reactive power/voltage characteristic. Therefore, the reactive power of the DG must be adjustable.

TABLE V.
RESPONSE TIMES FOR STEADY-STATE
VOLTAGE SUPPORT CONTROL MODES

Fixed power factor or reactive power	Number of minutes specified by the network operator
Power Factor/Active Power Characteristic	Within 10 seconds
Reactive Power/ Voltage Characteristic	Between 10 seconds and 1 minute. Specified by network operator

2.2.2 Dynamic

VDE states explicitly that the systems at this network level do not require dynamic support. The IEEE 1547 requires disconnection from the network in the event of a fault whilst IEC 61727 requires that the DG do not have to cease to energize for disturbances shorter than the clearing times.

In the BDEW, participation in dynamic support is required. For this the generator must:

- not disconnect during a fault
- support voltage through reactive power injection during a fault
- limit its own inductive power draw

The BDEW, as well as other national standards, specify for the MV level a voltage magnitude and time profile which defines the region where the DG must remain connected, as well as the reactive power requirements.

Vector's Distribution Code requires DG to operate such that the voltage and voltage stability of the network is maintained in accordance with the responsibility imposed by the Electricity Governance Rules [7]. The power factor must be between 0.95 lagging to 0.95 leading [8].

Aurora states that no DG shall actively regulate voltage at the connection point nor shall it force the voltage at other points on the network outside of their specified range although it is preferred that the DG shall export reactive power [9]. If the generation is purposed to supply a customer load and does not export power, the power factor must be greater than 0.95, if only supplying to the network, 0.85 to 0.9 leading is required.

3. Voltage Frequency

The other major factor of the network besides voltage magnitude is its frequency. DG must remain in synchronism with the network with respect to the frequency and support frequency.

3.1 Over/Under Frequency

All the standards explicitly state values for over and under frequency protection as shown in Table VI.

TABLE VI.
OVER/UNDER FREQUENCY SETTINGS

IEC 61727		VDE-AR-N 4105	
Operating Range	Disc. (seconds)	Operating Range	Disc. (seconds)
49 to 51 Hz	0.2	47.5 to 51.5 Hz (-5% to +3%)	< 0.1
IEEE 1547 (≤ 30 kW)		IEEE 1547 (> 30 kW)	
Operating Range	Disc. (seconds)	Operating Range	Disc. (seconds)
59.3 to 60.5 Hz (-2% to +1%)	0.133	59.3 to 60.5 Hz (-2% to +1%)	0.133
		57 to 59.3 Hz	0.16-300

In the BDEW, the sum of time for the protection relay trip and the switch device action cannot exceed the 0.2 second clearing time. The operating range is 47.5 Hz to 51.5 Hz, outside of this range the DG must disconnect.

Vector outlines two ranges out of normal operation, 45 to 47.3 Hz and 50.2 to 52 Hz, where the system must disconnect within 2 seconds

3.2 Frequency Support

Neither IEEE 1547 nor IEC 61727 require any frequency support.

The VDE splits this section into variable and non-variable DG. When over frequency between 50.2 and 51.5 Hz occurs in the network, with variable generators the active power generated must be reduced with a 40% gradient per Hz, and increased back to the maximum active power output in 10% increments per minute. The system must disconnect if the frequency is below 47.5 Hz and above 51.5 Hz and no restrictions are in place between 47.5 Hz and 50.2 Hz. Non-variable generators, alternatively, may disconnect within the 50.2 to 51.5 Hz range. Systems that are partially variable may disconnect if their range is exceeded. If disconnection is required, it must be done within 1 second. In the event of under frequency, only disconnection below 47.5 Hz is required.

The BDEW states that when over-frequency happens, above 50.2 Hz, the instantaneous active power must be reduced by a gradient of 40% of the available capacity of the generator per Hz. The active power output may be increased back when the frequency is less than 50.05 Hz and does not exceed 50.2 Hz.

As with voltage support, Vector requires any DG to aid in sustaining the correct frequency of the network as per the Electricity Governance Rules.

3.3 Reconnection

The reconnection of one or more generators particularly after an outage or fault needs to be well controlled so as to avoid nuisances to the network.

TABLE VII.
RECONNECTION (STANDARDS)

Standard	Conditions
IEEE 1547	Normal voltage and frequency for 5 minutes
IEC 61727	Normal voltage and frequency for 20 seconds to 5 minutes
VDE-AR-N 4105(1)	Voltage between 85% to 110% Between 47.5 Hz and 50.05 Hz At least 1 minutes For short interruptions, reconnection may be immediate
BDEW 2008	At least 95% nominal voltage Between 47.5 Hz and 51.5 Hz Delay to allow for switching operations

(1) Specific synchronization tolerances are defined for synchronous/asynchronous generators

The BDEW and VDE both require a gradual increase of supply of 10% per minute but only for systems greater than 1 MVA.

Aurora requires 5 minutes of normal operation for a generator to reconnect; alternatively reconnection may occur if authorized by the Aurora System Controller.

Powerco requires at least 1 minute of normal operation before reconnection.

4. Power Quality

The introduction of a large amount of DG into a network creates new sources of current harmonics, the possibility of unbalanced phases, DC injection via inverter based systems and network disturbances.

4.1 Current Harmonics and Inter-harmonics

As an established issue with power system networks, harmonics have been well studied and standards/guidelines have been developed to deal with the problems on distribution networks. The VDE and BDEW refer to the German version of the IEC 61000 Electromagnetic Compatibility standards and the IEEE 1547 refers to the IEEE 519-1992 which has been superseded in 2014. The IEEE 1547 standard refer to the values from in IEEE 519 which are displayed below.

TABLE VIII.
IEEE 1547 AND IEC 61727 HARMONIC LEVELS

Ordinal #	3-9(1)	11-15(1)	17-21(1)	23-33(1)	33+(1)	Even	THD
% of fundamental	< 4.0%	< 2.0%	< 1.5%	< 0.6%	< 0.3%	25% of odd harmonics	< 5%

(1) Odd

The VDE refers to DIN EN 61000.3.2 (up to and including 16 A) and DIN EN 61000.3.12 (above 16 A and up to 75 A) to specify the allowable generated current harmonics.

Table IX shows the maximum harmonic and inter-harmonic levels produced by the generator.

$$I_{max\text{-}harmonic} = i_{max\text{-}harmonic} \cdot S_{kV} \quad (1)$$

Equation (1) explains the harmonic level being presented in A/MVA. S_{kV} is the apparent short circuit power at the network connection point excluding the generator contribution and I_{vzul} is the maximum permissible harmonic current. Unlike other standards which specify "one-size-fits-all" values, the VDE defines the harmonics' magnitudes dependent on S_{kV}, accounting for the network location characteristics.

TABLE IX.
VDE-AR-N 4105 HARMONICS

Ordinal #	3	5	7	9	11	13	17	19	23	25
$i_{max\text{-}harm.}$, A/MVA	3	1.5	1	0.7	0.5	0.4	0.3	0.25	0.2	0.15
Ordinal #	$25 < v^{(2)} < 40^{(1)}$		Even		$40 < v < 178$		$\mu^{(3)} < 40$		$40 < \mu < 178$	
$i_{max\text{-}harm.}$, A/MVA	0.15 - 25/v		1.5/v		4.5/v		1.5/ μ		4.5/ μ	

1 Odd, 2 Harmonic order, 3 Inter-harmonic order

The BDEW specifies values like the VDE, but with the addition of accounting for multiple generators being connected at the same point as expressed in equation (2), where S_{unit} and S_{plant} are the power supplied by the generator and the the total generation respectively.

$$I_{max\text{-}harmonic} = i_{max\text{-}harmonic} \cdot S_{kV} \cdot S_{unit} / S_{plant} \quad (2)$$

Table X shows the admissible harmonic current for a 10 kV network, although 20 and 30 kV are also specified in the standard.

TABLE X.
BDEW 10 KV HARMONIC LEVELS

Ordinal #	5	7	11	13	17	19
$i_{max\text{-}harm.}$, A/MVA	0.058	0.082	0.052	0.038	0.022	0.018
Ordinal #	23	25	$25<v<40^{(1)}$	Even	$\mu^{(2)}<40$	$\mu,v^{(3)}>40$
$i_{max\text{-}harm.}$, A/MVA	0.012	0.010	$0.01 \cdot 25/v$	0.06/v	0.06/μ	0.18/μ

1 Odd, 2 Inter-harmonic order, 3 Harmonic order

New Zealand distribution companies refer within their DG guidelines to the NZECP 36 [10]. This standard does not contain current harmonics values for MV or LV, therefore the distribution companies also refer to other standards as shown in Table XI.

TABLE XI.
HARMONIC STANDARDS REFERENCED BY DISTRIBUTION COMPANIES

Orion	AS/NZS 61000.3.2 (Up to 16 A) AS/NZS 61000.3.4 (Greater than 16 A)
Aurora	NZECP36 Inverters - AS 4777.2 (2005) IEEE 519-1992 Interim Policy Statement – Harmonic Control [12]
Vector	IEEE 519-1992 (Voltage range of 230 V to 66 kV

4.2 Voltage Unbalance

The VDE is the only one that specifies a maximum difference of 4.6 kVA between each phase on

the network.

On Vector's network during normal operating conditions and over a week period, 95% of the 10 minute mean RMS values of the negative phase sequence current must comply with the requirements of BS EN 50160:1995 and be within 0% to 2% of the positive phase sequence current.

4.3 DC Current Injection

The IEEE 1547 specifies 0.5% of rated output current as the maximum DC injection allowed. The IEC 61727 states <1% of the RMS rated current.

Aurora and Vector both specify 0.5% of the rated current as the DC injection limit.

4.4 Flicker and Fluctuation

The IEEE 1547 and VDE refer to several other standards regarding flicker and fluctuation as shown in Table XII.

TABLE XII.
FLICKER AND FLUCTUATION STANDARDS - STANDARDS

Standard	Referred Standard
IEEE 1547	IEEE Standard 519-1992, IEEE P1453, IEC/TR361000.3.7, IEC 61000.4.15, IEC 61000.21
VDE	DIN EN 610000.3.3, DIN EN 610000.3.11 (Up to 75 A)

The BDEW outlines voltage flicker in a similar manner to the referred standards.

Vector, Orion and Aurora refer to the AS/NZS 61000 series of standards regarding disturbances.

5. Protection

The protection schemes implemented on DG must safeguard themselves as well as the network. Threats to safety of people and equipment can result if islanding is not effectively dealt with. Overcurrent and short circuit current is also covered.

5.1 Islanding

Islanding is an issue that has risen with the installation of DG since supplying circuits on traditional networks were relatively simple to disconnect from in the event of a network fault or disturbance. Now with multiple supplies for a network, a tripped line may be energized.

There are two type of islanding protection, active and passive. The majority of islanding cases are protected against through over/under voltage/frequency protection. Table XIII outlines the standards requirements.

TABLE XIII.
ANTI-ISLANDING REQUIREMENTS

IEEE 1547 and IEC 61727	VDE-AR-N 4105	BDEW 2008
Active or Passive	Active or Passive	Not specified
Cease to energize within 2 seconds of the formation of the island	Disconnect in 5 seconds	Network operator may have special requirements

As the BDEW deals with MV/HV systems which are likely to be major supplies to the network, the network operator must specify special conditions.

Vector does not allow the supply to the network whilst there is an outage. Within 2 seconds of the formation of an island, the generator must cease to energize the network however they can supply their own loads through open tie.

Powerco requires automatic disconnect after 2 seconds. Aurora requires it within 3 seconds.

5.2 Over/Short Circuit Current

In general all forms of DG contribute to fault levels, therefore all standards require to assess its impact.

The VDE requires the distributed generator to provide their system's value of the short circuit current. If the power generation gives rise to a greater short circuit current larger than the rated value, limiting measures must be agreed upon between the generator owner and network operator.

The BDEW requires the short circuit current at the transfer point be provided including the time-dependent evolution. Also requires both over-current time protection as a form of short-circuit protection and distance protection with the circuit breaker located at the transfer point.

The VDE and BDEW both outline approximate values for the estimate of the short circuit current of the system depending on the generation type. They are 8×, 6× and 1× rated current for synchronous, asynchronous and inverter based generation respectively.

The IEC 61727 refers to the IEC 60364-7-712 which states the PV supply cable must be protected by the short circuit or over-current device.

6. Discussion

As the DG classification possibilities are diverse, spanning different technology, voltage and rating levels, it has been found that there is also a wide spectrum in terms of the scope that standards target. The IEEE 1547, VDE-AR-N 4105 and BDEW 2008 encompass a wide domain whilst others such as the IEC 61727 is very narrow only focusing on low voltage and low rating PV systems. The standards target common issues however have different requirement structures and values. For example, the VDE and BDEW both explicitly address network support however the IEEE 1547 does not.

Many DG standards are being continually developed. Standards such as the IEEE 1547 and the EN 50438 are being reviewed within less than 10 years. Another standard currently under review is the AS 4777-2005 which will be released in the near future.

In many cases the standards aim to give specific values and operating behaviours however in some cases the requirements must be completed by network analysis, such as for the network fault current.

Many distribution companies' guidelines mention all the issues within the standards. However the latter specify values and practices more deeply. For instance, the outlining of the over/under

voltage settings is predominant throughout the standard whereas some distribution companies just states that it is a requirement.

The latest draft of the AS/NZS 4777 covers DG via inverters and connected to low voltage networks. This scope has changed from the previous which only specified power ratings per phase. Further analysis may need to be fulfilled by every New Zealand distribution company before adopting all its specific values. Alternatively, a common framework could be developed based on the AS/NZS 4777 with different values as per region or distribution company. This would be similar to the European EN 50438 where each country defines their own values taking into account their local differences.

7. Acknowledgement

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