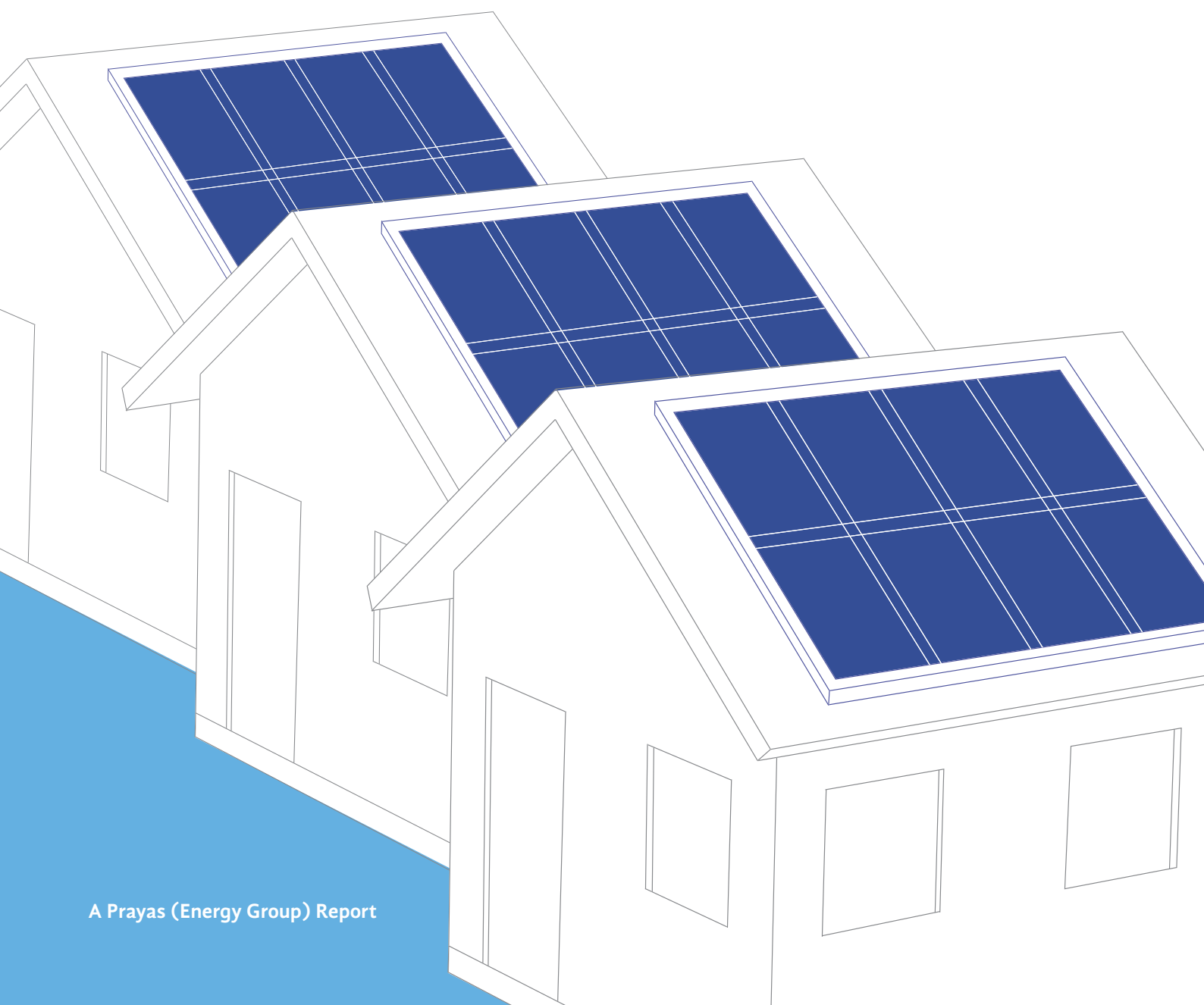


Grid Integration of Distributed Solar Photovoltaics (PV) in India

A review of technical aspects,
best practices and
the way forward



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BRIDGE TO INDIA (BTI)

BRIDGE TO INDIA was founded in 2008 and has offices in New Delhi, Mumbai, Bangalore, and Munich, Germany. A highly specialised company operating in the Indian solar market, its businesses include strategic consulting, market intelligence and project development. For more information on BTI, please see <http://www.bridgetoindia.com>.



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NCPRE at IIT Bombay was launched in 2010 as a part of the Jawaharlal Nehru National Solar Mission of the Government of India. The objective of the centre is to be one of the leading Photovoltaic (PV) research and education centres in the world within the next decade. The centre is located at IIT Bombay which has a strong tradition of inter-disciplinary activity and is thereby uniquely suited to take up this challenge. For more information on NCPRE, please see <http://www.ncpre.iitb.ac.in/>.



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Foreword



Renewable energy is expected to play an increasingly prominent role in the Indian power sector in the coming decades given its various benefits. We need to view this source of energy as strategic resource which will in the long run form the cornerstone of our energy security. The Government of India has been striving to increase the share of renewables in the energy mix which has resulted in strong growth in large MW-scale grid-connected renewable energy. At present the contribution of renewables to the overall installed capacity of the country stands at more than 12%, not including large hydro.

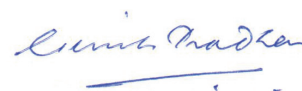
Solar power, especially from photovoltaics, has taken off in the country in a big way after the launch of the National Solar Mission in 2010, leading to an installed capacity of over 2.6 GW in just four years. This was an exciting time for me as Additional Secretary and Special Secretary in the Ministry of Power and as Secretary in the Ministry of New and Renewable Energy, during which period we laid out the detailed ground work for the policy-regulatory framework under the solar mission. The biggest success of our efforts was to capture the global reduction in PV equipment prices and help reduce the price of solar PV power from INR 18/kWh to INR 7-8/kWh through a competitive price discovery policy in India.

However, the solar mission is not only about large power plants, but also about smaller distributed kW-scale solar PV applications (particularly rooftop PV connected to the LT grid) which are expected to grow significantly in the coming years. From a consumer perspective, grid parity is close at hand if one were to compare unsubsidised rooftop PV electricity prices (INR 7-8/kWh) with consumer tariffs (Rs 7-10/kWh) for the commercial, industrial and high-end residential segments in various states. These are expected to bring along associated challenges of reliably integrating large number of small PV systems in the distribution grid, especially since the grid was not designed for a large share of distributed generation nor a two way flow of electricity.

This new report from Prayas (Energy Group), a collaborative exercise with NCPRE, IIT-Bombay and Bridge To India, fills an important knowledge gap in the sector. Prayas has been consistently contributing to the development of the power sector through its public spirited and comprehensive policy analysis. This report looks at the existing and upcoming technical challenges arising from the high penetration of distributed PV as well as potential solutions. The report succinctly captures the international experience and evolution of technical standards regarding grid interconnection of distributed PV. It covers issues arising from both the solar system and the distribution grid perspective. Based on extensive stakeholder consultations, the report which analyses the Indian situation thoroughly is of relevance and value for utility professionals, regulators, manufacturers and developers alike. I am sure that this timely and detailed publication will contribute to a more informed discussion looking to the future, ultimately leading to a smoother and faster development of the distributed PV sector.

The Forum of Regulators has also brought out a model set of regulations for roof top PV and is united in its approach at pushing renewables to the fullest extent. The Central Electricity Authority (CEA) is very near publishing the technical standards for connectivity of distributed generation/rooftop PV. Thus all three elements including policy and regulatory framework, the technical specifications and the commercial framework seem to be well placed for faster implementation on ground.

I congratulate Prayas (Energy Group) for another excellent report and wish them success for their future work.



Gireesh B. Pradhan
(Chairperson, Central Electricity Regulatory Commission &
Forum of Regulators)

Abstract

Distributed solar photovoltaics (PV) is expected to witness significant growth in India owing to increasing economic viability and a facilitating policy-regulatory framework in most states. Distributed Generation (DG) can provide various system benefits in terms of improved grid reliability and power quality, deferring grid investments, reduction in T&D losses, etc. However, since the distribution grid was not designed keeping in mind the potential high penetration of DG, there are valid technical concerns from utilities about power quality and the general impact of DG on the low tension (LT) grid. This study reviews global and Indian DG policies and regulations from a technical perspective, and points to the emerging challenges and potential solutions.

The study clearly brings out that existing Central Electricity Authority (CEA) technical inter-connection regulations for DG follow global best standards for power quality (DC injection, harmonics and flicker) and safety in terms of anti-islanding. As the cumulative penetration increases, the CEA can re-evaluate the existing allowable voltage and frequency operating range factoring in the operating conditions in India. Additional features which provide system benefit like reactive power support for an improved voltage profile, power-frequency droop for over-frequency regulation, intentional islanding and fault ride through capabilities like Low/High Voltage Ride-Through (LHVRT) and Low/High Frequency Ride-Through (LHFRT) should be considered by the CEA while revising its standards. Most inverters in the Indian market already possess these capabilities at practically no extra cost.

From the perspective of the distribution grid, there is significant global experience of reliably integrating very high penetrations of DG. Considering DG penetration limits, the CEA can recommend that State Electricity Regulatory Commissions (SERCs) and utilities automatically allow distributed PV interconnections with a simplified approval process on a First Come First Served (FCFS) basis up to the threshold of 15-30% of the distribution transformer capacity. Beyond this limit, screening and additional technical studies should be done to assess if further penetration can be allowed. Well established cost-effective technological solutions exist to increase hosting capacity.

Finally, a simple application, inspection and certification process coupled with an adequate database is crucial for the growth of the sector. Self-certification for very small systems up to 10 kW can ease and quicken this process. SERCs can play an important facilitating role by putting regulations in place to address such issues.

Since distributed solar penetration in India is still very low, the country is well placed to learn from the global experience, revise its technical regulations appropriately and stay ahead of the curve. An institutionalised consultative process with all stakeholders would greatly help to critically assess the evolving technical challenges and their solutions and facilitate a clear technical framework for distributed solar PV deployment.

Introduction

Distributed solar PV is expected to grow significantly in the coming years due to increasing economic viability. However since the grid was not particularly designed for large scale distributed generation, utilities are concerned about the implications of variable solar generation on the power quality, its impact on the LT distribution grid and the safety of its work force. These apprehensions and fears are heightened due to a lack of clear documentation and understanding of these concerns and their potential solutions.

To address these concerns, we describe the technical issues involved, both on the PV system side and on the distribution grid side based on a review of global and Indian policies and regulations. Further, the report documents existing technical standards and practices, and proposes a possible way forward for a structured and effective grid integration of distributed PV. This study specifically addresses (1) the quality of the solar power being injected into the grid, (2) safety issues, (3) ways in which distributed PV can support the grid and help its own reliable integration, and (4) the interaction of distributed PV and the distribution LT grid.

With this study, we hope to initiate a serious and objective discussion on the technical challenges and potential solutions of large scale distributed PV. A greater common understanding of the issues would help facilitate faster distributed PV deployment.

Chapter 1 lays out the context of distributed PV in India, while Chapter 2 details the policy-regulatory framework in the country. Chapters 3 and 4 are the crux of the report, and describe the technical issues and solutions for the solar system and the distribution grid respectively. Finally, Chapter 5 summarises the analysis and observations and lays down recommendations for a way forward, and is available for download separately at <http://prayaspune.org/peg/publications/item/276.html>
More details are available in the Annexures.

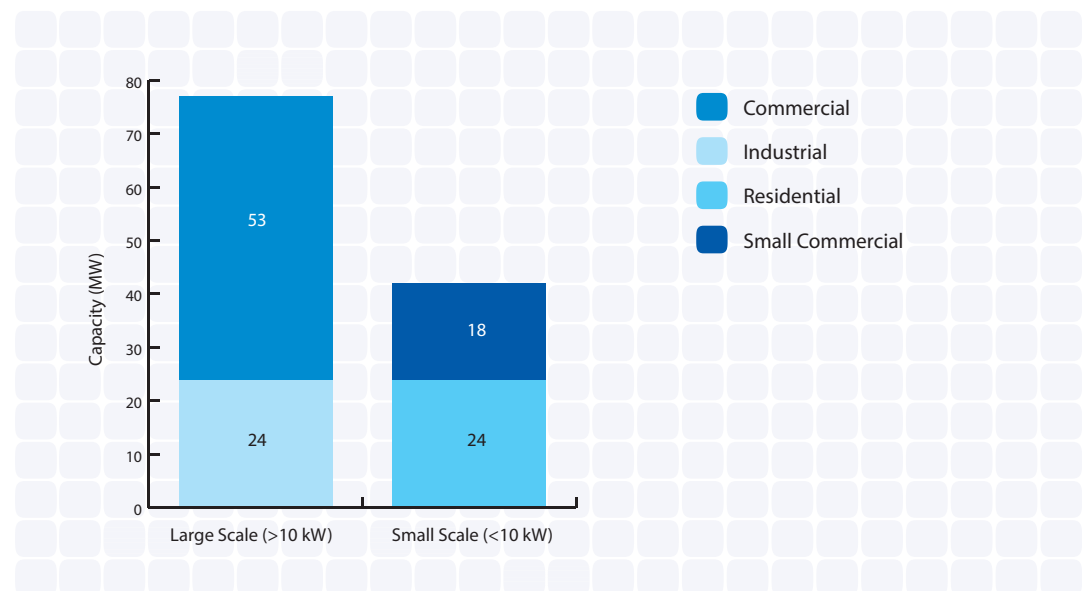
This research was carried out as a collaborative effort between researchers at the Prayas (Energy Group), BRIDGE TO INDIA, National Centre for Photovoltaic Research and Education (NCPRE), Indian Institute of Technology (IIT) Bombay and the Energy and Resources Group (ERG) at the University of California, Berkeley. Two roundtable discussions with sector stakeholders were held at IIT, Bombay, the first one in November 2013 to kick start discussions and the second one in March 2014 to discuss the first draft report. These meetings along with several stakeholder interactions and interviews were very useful for fine tuning the report.



The challenge

India is currently witnessing a transition in its solar market. The initial emphasis was on large-scale, grid connected projects driven by the Gujarat state solar policy (2009), National Solar Mission (2010) and policies of other states, namely Karnataka, Rajasthan, Andhra Pradesh and Tamil Nadu. Subsequently, net-metering policies that have been announced by nine states in India focus on distributed solar¹. In 2013, India had a cumulative distributed solar capacity of about 160 MW. 117 MW of this capacity is connected to the grid as shown in Figure 1. This constitutes about 5% of the total installed solar capacity in India (2,200 MW in 2013)². Out of the 117 MW of grid connected distributed PV capacity, nearly 60 % (71 MW) is by commercial category consumers. This suggests that offsetting expensive grid prices is a priority for this category of consumers. The overall distributed solar segment has grown by 85% each year between 2010 and 2013, and is likely to accelerate on account of falling prices of PV modules and components, as well as policy support for distributed solar from the central government and various state governments.

Figure 1: Distributed solar capacity in India in 2013³



Bridge To India has performed a detailed projection of the expected market growth based on grid parity⁴ across different states and consumer segments, net metering policies and the power deficit (See Figure 2). In the median case (assuming that some net metering policies are implemented and intelligent power management solutions to optimise diesel power replacement are in place), the Indian distributed PV market is expected to grow at 66% per year in the next five years (2013-2018), to a cumulative total of ~2,300 MW⁵. In the conservative (base) case, (assuming that no net metering policies are implemented and no intelligent power management solutions to optimize diesel power replacement are in place) the market will grow to ~1,500 MW in 2018. The aggressive case (potential of ~3,000 MW in 2018) assumes that net metering is deployed across most states in India, and includes a solution to optimise solar plus diesel systems. Another study from KPMG has pegged the growth at a slightly higher level resulting in 4-5 GW by 2016-17⁶.

1 In this report, we use the term distributed solar PV to refer to solar PV installations of any size that are connected to the grid at distribution voltages (below 33 kV). These installations could be either ground-mounted or rooftop systems

2 BRIDGE TO INDIA market research and analysis

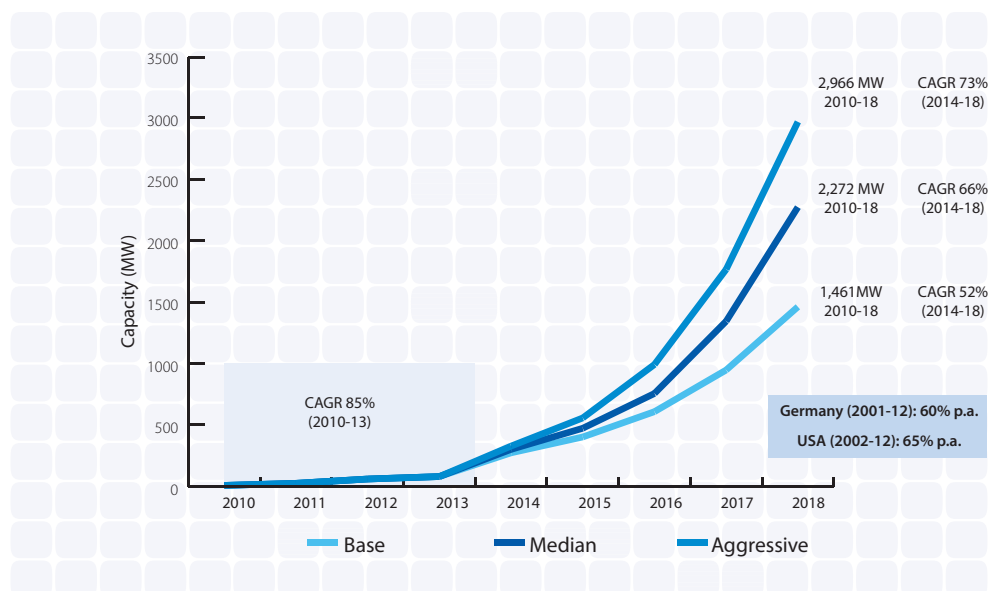
3 Ibid

4 For the purpose of this report, grid parity is the price at which the levelised price for solar electricity equals the retail consumer price of grid electricity.

5 BRIDGE TO INDIA analysis based on market research

6 The Rising Sun – II: Grid parity gets closer, September 2012: bit.ly/1tfMcm6

Figure 2: Growth of distributed solar capacity – three scenarios⁷



In the initial years, distributed solar is likely to be focused more in the urban areas in states with net metering policies, especially within the commercial, industrial and high use residential category of consumers, since they pay the highest tariffs. This indicates that the majority of the growth of distributed solar up to 2018 will be concentrated in very select areas in urban India. The technical implications of this projected growth on the existing distribution infrastructure (especially considering the weak nature of the Indian grid) are important and raise critical questions. Can the current distribution grid reliably handle a sharp growth of variable, intermittent, distributed PV power generation? What are the safe threshold levels for distributed solar penetration above which the grid might be destabilised? Are the current regulations and technical standards adequate to handle this growth? If not, what changes are needed in the technical standards? What are the potential solutions for integrating such distributed solar generation?

These questions are not unique to India. They are being asked by many countries with a high penetration of distributed solar PV. There is significant global experience available on these questions, which should be built upon while exploring the technical issues in India. These questions are only going to achieve greater importance, since more growth is expected in the rooftop segment than in utility projects globally⁸.

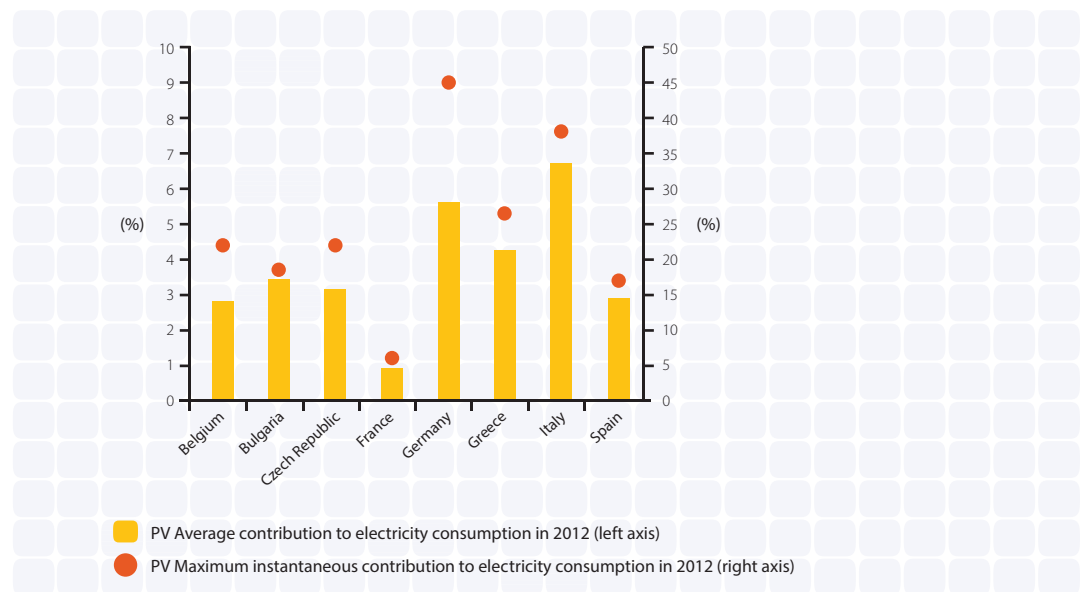
Our study systematically reviews such issues which are likely to emerge owing to the increasing penetration of distributed solar PV in India, as well as the potential changes in regulations and technical standards that could be adopted to address these issues. We hope that this report will contribute to initiate a discussion on the emerging issues and facilitate a greater common understanding of the sector.

⁷ BRIDGE TO INDIA analysis

⁸ EPIA Global Market Outlook for Photovoltaics, 2014-18: bit.ly/UnwshD

While average annual PV contributions to electricity consumption in most countries may still be small considering the diurnal nature of PV generation, its instantaneous contribution is much higher and needs to be taken into consideration for actual system operation. As shown in Figure 3, in 2012, Germany had an annual average contribution from PV of ~ 5.5%, but experienced an instantaneous maximum contribution of ~ 45%⁹. This increased to 6.5% in 2013 and resulted in a higher instantaneous contribution of 49%¹⁰. Given the rapid speed with which PV penetration can increase with the right policy framework or with grid parity, it is imperative for all stakeholders in India (especially system operators, regulators, policy makers, and developers) to learn from this global experience, work together towards understanding future issues and prepare in advance to tackle them.

Figure 3: Annual average and maximum instantaneous PV contribution to electricity consumption in some European countries in 2012 (%)⁹



⁹ EPIA, Global Market Outlook for Photovoltaics, 2013-17: bit.ly/1aGKprQ

¹⁰ EPIA Global Market Outlook for Photovoltaics, 2014-18: bit.ly/UnwshD



2

Regulatory and policy environment in India

This section summarises the policy-regulatory framework for grid connected distributed PV systems in various Indian states. It highlights some of the policy targets, incentives and the technical requirements mandated by the regulatory commissions and the Central Electricity Authority (CEA) of India which is the nodal national agency for setting up technical regulations within the country.

2.1 National technical regulations in India

There are three important regulations by way of which the CEA outlines the technical and safety requirements for distributed generation.

- The CEA's 'Technical Standards for Connectivity of the Distributed Generation Resources' Regulations, 2013¹¹ are applicable to any solar system that is connected at voltage level below 33kV. The CEA regulations cover the roles and responsibilities of the developer/system owner and of the Distribution Company (DISCOM), the equipment standards and codes of practice for safety, and the system requirements for safe voltage, frequency, harmonics, etc.
- The CEA's 'Installation and Operation of Meters' Regulation 2006 (draft amendment in 2013 includes distributed solar generation) regulates metering standards.
- The CEA's 'Measures of Safety and Electricity Supply Regulations, 2010' govern safety for generators. The CEA regulation 'Technical Standards for Connectivity of the Distributed Generation Resources' mentions that safety standards should be in accordance to this code. However, these safety codes are aligned more towards large-scale thermal power plants as opposed to small-distributed solar plants.

In addition, states in India have also prescribed some technical requirements for distributed solar PV through government policies, and regulations brought out by the SERCs.

2.2 Policy-regulatory environment in India

As of June 2014, seven states in India - Gujarat, Andhra Pradesh, Uttarakhand, Tamil Nadu, West Bengal, Karnataka and Kerala - have released a final distributed solar or net metering policy-regulatory framework. The framework in Delhi and Punjab is still in a draft stage¹². The section below provides state wise details on the policy-regulatory framework.

Gujarat

Gujarat was the first state in India to announce a dedicated rooftop policy¹³. During the first phase, 5 MW was implemented in the city of Gandhinagar. The model is now being rolled out in five other cities in Gujarat, aimed at creating a total of 25 MW of rooftop solar power. The Gujarat government announced that it plans to install a total of about 60 MW by 2017 through rooftop units on residences¹⁴. The current policy functions on a 'gross metering'¹⁵ model, where a fixed, preferential tariff is paid to the generators for each unit sold to the grid. However, it is likely that Gujarat will soon move to a net-metering route for promoting rooftop solar¹⁶.

11 Central Electricity Authority, Technical Standards for Connectivity of the Distributed Generation Resources, 2013: bit.ly/1cvEaKL

12 BRIDGE TO INDIA, India Solar Handbook, June 2014 edition: bit.ly/1m8Mcj5

13 Details of the Gandhinagar rooftop program: bit.ly/1ntHnxq

14 'Gujarat govt. plans 60 MW of solar power through roof-top units in next 3 years', Business Standard, 23rd September 2013: bit.ly/1a2kl43

15 Gross metering is a mechanism whereby the utility purchases all the generated solar energy exported to the grid. Unlike net metering, there is no adjustment against the consumer's consumption from the DISCOM.

16 'New net-metering policy to power Gujarat's solar-rooftops', Financial Express, 25th January 2014: bit.ly/1eRNctj

Andhra Pradesh

Andhra Pradesh announced its net metering policy¹⁷ in March 2013. The policy is limited to consumers with three phase connections. This unfortunately does not include most residential consumers who might want to augment their current consumption with solar to hedge against a rise in the price of electricity. However, the government has decided to provide a 20% subsidy for rooftop solar systems up to 3 kW capacity, solely in the domestic consumer category, in its order¹⁸ of June 2013. The surplus energy injected into the grid will be compensated by the APDISCOMs at the pooled cost decided by the Andhra Pradesh Electricity Regulatory Commission (APERC) for that year. The settlement of the surplus energy injected will be on a half yearly basis for seven years. Technical details of the net metering system have not been addressed so far.

Uttarakhand

The Uttarakhand Renewable Energy Development Agency (UREDA) has released its policy¹⁹ aimed at promoting grid-connected rooftop and small-sized solar PV power plants in the state in August 2013.

The scheme offers a net metering facility for grid connected rooftop solar plants. The solar system owner will be compensated for the excess power supplied to the grid at a tariff of INR 9.20/kWh. Eligible plant capacities under the scheme are 300 W to 100 kW (with battery) and up to 500 kW (without backup). The policy aims for 5 MW by 2015. Technical details have not been addressed so far.

Tamil Nadu

Tamil Nadu was the first state in India to offer a net metering policy. It was included in its flagship solar policy of 2012²⁰. The final order²¹ on LT connectivity and net metering was announced on 13th November 2013. The highlights are:

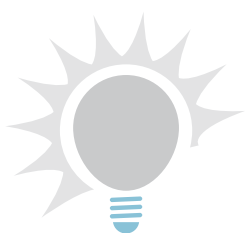
- A generation based incentive (GBI) of INR 1.50/kWh for the first two years, INR 1.00/kWh for the next two years and INR 0.50/kWh for the subsequent two years is available for domestic (residential) consumers. However the GBI is currently applicable to projects registered before March 2014.
- This regulation is limited to government-run institutions and residential consumers. It is not applicable to commercial consumers and industries.
- The grid penetration has been capped at 30% of the distribution transformer capacity.

The technical requirements of equipment and electrical parameters (current, voltage, frequency, harmonics, etc.) are governed by CEA's 'Technical Standards for Connectivity of the Distributed Generation Resources' Regulations 2013.

West Bengal

West Bengal initiated a policy²² on co-generation and generation of electricity from renewable sources of energy on June 2012. This policy contains a net metering solar rooftop model promoting own captive use. The main highlights of the policy are:

- The policy targets 16 MW of rooftop and small PV installations by 2017.
- Under the West Bengal Electricity Regulatory Commission (WBERC) regulation²³, grid integrated rooftop PV is allowed only for institutional consumers like hospitals, government departments, academic institutions, etc.



17 Andhra Pradesh Net Metering Policy: bit.ly/LUfX7H

18 Order of Government of Andhra Pradesh, Energy Department: bit.ly/OYUEnG

19 Uttarakhand Net Metering Policy: bit.ly/1bM6xIG

20 Tamil Nadu Solar Energy Policy, 2012: bit.ly/1cvKbVv

21 Tamil Nadu Order on LT Connectivity and Net Metering: bit.ly/1acnJFI

22 West Bengal 'Policy on Co-generation and Generation of Electricity from Renewable Sources of Energy': bit.ly/1kITtpH

23 West Bengal Electricity Regulatory Commission (WBERC) 'Cogeneration and Generation of Electricity from Renewable Sources of Energy' Regulations, 2013: bit.ly/1ggHgoC

- The minimum allowed system size for rooftop solar PV according to the WBERC regulation is 5 kW.
- Connectivity of rooftop solar PV to the grid is allowed at LV or MV, or 6 kV or 11 kV of the distribution system of the DISCOM as considered technically suitable by the DISCOM and the developer.
- Solar injection is permitted only up to 90% of yearly electricity consumption.

The policy is a part of the DISCOM's need to meet the targets as described by the renewable purchase obligation (RPO) provided in the regulation. According to the RPO, the minimum quantum of electricity that the DISCOMs should procure from solar should be 0.3% by 2018. The DISCOMs can procure a maximum of 5% of the total consumption in their area of supply.

Delhi (Draft)

The Delhi Electricity Regulatory Commission (DERC) released a draft net metering policy²⁴ in November 2013. It does not provide any financial incentives to its consumers.

The main highlights are:

- The grid penetration is capped at 15% of the distribution transformer capacity.
- The energy generated from the solar PV system shall be capped at 90% of the energy drawn by the consumer from the grid. In addition, all energy accounts shall be settled at the end of the financial year. No carryover is permitted.
- The accuracy class of the solar meter to be installed is necessitated at 0.2S class accuracy.

The technical requirements of equipment and electrical parameters (current, voltage, frequency, harmonics, etc.) are governed by the CEA's 'Technical Standards for Connectivity of the Distributed Generation Resources' Regulations 2013.

Kerala

The Kerala State Energy Regulatory Commission (KSERC) released its draft net metering regulations²⁵ in January 2014 and finalised its regulations on 10th June 2014²⁶. These apply to all utilities and consumers availing electricity at voltage levels of and below 11000 volts. The main highlights are:

- Individual and third party ownership is allowed but the system sizing cannot be of a size less than 1 kW and above 1 MW. The system capacity will also have to be in line with provisions related to the connected load or contracted demand at each voltage level as per the Kerala Electricity Supply Code 2014.
- The DISCOM is obligated to allow non-discriminatory connections at LT level subject to other provisions, and only till the cumulative capacity of the solar energy systems connected to a particular LT distribution feeder is less than 80% of the average minimum load of all the consumers of the said feeder between 8 AM and 4 PM.
- The DISCOM is obligated to provide energy banking facility without any charge.
- About metering, the regulations require a solar meter to be installed at the delivery point to measure solar electricity generated. Additionally both the solar and the net meter should be able to download meter readings using meter reading instrument (MRI) or wireless equipment or such other devices.
- Consumers are obligated to comply with safety standards, especially with regard to the manually operated isolating switch and anti-islanding.

²⁴ Delhi Draft Net Metering Policy: bit.ly/1khsCMq

²⁵ Kerala Draft Net Metering Regulations: bit.ly/LWYQXv

²⁶ Kerala State Electricity Regulatory Commission 'Grid Interactive Distributed Solar Energy Systems' Regulations, 2014: bit.ly/1rWR5w1

- Consumers have the right to avail Open Access (OA) for wheeling excess electricity from one premises to use in another premises another owned by him within the area of supply of the licensee subject to certain conditions.
- If the consumer is not an obligated entity for solar RPO, the RPO will be credited to the local DISCOM.
- The cross-subsidy surcharge would be exempted for self and third party owned systems.

The technical requirements of equipment and electrical parameters (current, voltage, frequency, harmonics, etc.) are governed by the CEA's 'Technical Standards for Connectivity of the Distributed Generation Resources' Regulations 2013, while the safety and metering requirements are also governed by appropriate CEA regulations.

Punjab (Draft)

The Department of Non-Conventional Energy Sources in Punjab announced the guidelines on net metering for grid interactive rooftop Solar Photovoltaic (SPV) power plants²⁷ in August 2013. The policy is open to all consumers across the state. The main highlights are:

- The policy provides an individual project capacity range from 1 kW to 500 kW with or without battery backup.
- The maximum capacity of the rooftop solar PV system shall not be more than 80% of the sanctioned connected load/contract demand (in KVA converted to KW at a normative power factor of 0.95) of the consumer on the AC side at the output of the inverter based on rated inverter capacity, and the minimum capacity shall not be less than 1 KW.
- The energy generated from the solar PV system shall be capped at 90% of the energy drawn by the consumer from the grid. In addition, all energy accounts shall be settled at the end of the financial year. No carryover is permitted.
- The interconnection applications shall be approved by the DISCOM (Punjab State Power Corporation Limited) after a feasibility check within 30 days of the receipt of the application. After the construction of the plant and verification by the Punjab Energy Development Agency, PSPCL shall install the bi-directional meter within 10 days and the plant will be commissioned from that date.

Karnataka

The Karnataka Electricity Regulatory Commission (KERC), on 10th October 2013, announced the tariffs²⁸ for grid-connected solar PV projects. The tariff order specifies the benchmark tariffs for grid connected solar PV and rooftop and small solar plants (with and without Ministry of New and Renewable Energy (MNRE) subsidy)

- Rooftop and small solar plants: INR 9.56/unit
- Rooftop and small solar plants: INR 7.20/unit (with subsidy)

Meanwhile, more recently the Government of Karnataka has finalised a new solar policy²⁹ on 22nd May 2014 which will be effective until 2021. Among other things, it aims to promote solar rooftop generation with a target of 400 MW, both through net metering (with a focus on self-consumption) and gross metering (based on KERC tariff orders). For net metering, surplus energy injected into the grid will be compensated by the utility at KERC determined tariffs.

For grid connected rooftop, all eligible consumers can set up projects within the prescribed capacity limit. Additionally, projects would also be allowed on third party roofs.

27 Punjab Draft Net Metering Guidelines, August 2013: bit.ly/1gJJSbd

28 KERC Tariff Order for Solar Power Generation: bit.ly/1d9Ricn

29 Government of Karnataka, revised Solar Policy, 2014: bit.ly/1nOiSw5

With regard to evacuation facilities, it notes that for an LT connected solar plant, DISCOMs will allow interconnection at 11 kV or below as per norms fixed by the CEA/MNRE guidelines/KERC orders. However it also states that DISCOMs “will define specific guidelines on the standards for connectivity to the network.”

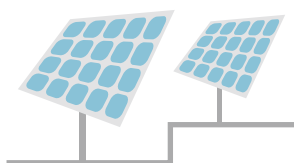
Chhattisgarh

The Chhattisgarh State Electricity Regulatory Commission (CSERC) brought out a tariff order for solar rooftop plants on 14th August 2013³⁰, under which rooftop systems with a capacity of only more than 50 kW and up to 1 MW would be considered. Such rooftop plants are envisaged to be mainly set up for self-consumption, and only the excess power would be sold to the DISCOM. The tariff at which rooftop power would be compensated has been fixed at 50% of the generic levelised tariff determined for Solar PV-based Power Projects. The regulations mandate solar systems to provide advanced communication interface and data acquisition systems.

Solar Energy Corporation of India (SECI)

The MNRE launched a pilot scheme for the promotion of large scale grid-connected rooftop solar PV projects³¹ to be implemented by the SECI. The pilot scheme targets large area roofs of government offices, public sector units, commercial establishments, hospitals, cold storages, warehouses, industry and educational institutions. The scheme is being released in phases of approximately 10 MW each, allocated to various cities in the country. Bidding for four phases of the scheme has been completed. The two main features of this rooftop PV scheme are:

- Two possible business models are allowed.
 - Capex Model in which bidders bid in INR/Wp with a ceiling of INR 90/Wp. Successful developers would then sell the solar system to interested consumers at the price of the winning bid less the 30% capital subsidy.
 - RESCO Model in which electricity can be sold to interested consumers at a maximum levelised tariff of INR 6.75/kWh³² with an assured subsidy of INR 2.7 cr/MW from SECI. Bidders need to bid in INR/kWh for calculating the levelised tariff over 25 years with an 11% discount rate.
- Capital subsidy of 30% of the project cost would be provided. The disbursement of the capital subsidy is linked to the performance of the plants: 20% will be disbursed at the time of commissioning subject to a minimum performance ratio of 75%; a further 5% will be disbursed after 1 year, and another 5% after 2 years, if the capacity utilisation factor (CUF) of the project exceeds 15% for the two years.



Phase-4 bidding results³³ indicate the lowest price discovery in the Capex model to be INR 63/Wp for 1.5 MW capacity in Maharashtra. A 30% capital subsidy will be provided on this cost. Under the RESCO model, the lowest levelised tariff discovered is INR 4.726/kWh, again in Maharashtra for a capacity of 1 MW. This includes a capital subsidy of INR 2.7 crore/MW³⁴.

30 Chhattisgarh Solar Rooftop Tariff regulations, 2013: bit.ly/1lhnNqw

31 SECI, Large scale grid connected rooftop solar PV projects, Phase 1: bit.ly/1mPSXo6 ; Phase 2: bit.ly/1dLep7u ; Phase 3: bit.ly/1jH559G

32 The tariff allowed in earlier phases was INR 6/kWh

33 Bidding results from Phase 4 of the SECI auctions: <http://bit.ly/We68Y4>

34 BRIDGE TO INDIA, INDIA Solar Weekly Market update, July 14th, 2014

Tables 1 and 2 provide an overview of the state policies and some of the technical parameters specified in the policies or the ERC regulations. The second table compares these state parameters with the CEA's technical standards. All these parameters are discussed in detail in the next section and have been tabulated here for comparison.

Table 1: Overview of net metering/rooftop policies/regulations in India

	Chhattisgarh (ERC order)	Gujarat	Andhra Pradesh	Uttarakhand	Tamil Nadu
Date of launch	August 2013	September 2011	March 2013	August 2013	November 2013
Capacity	Not specified	Phase 1: 5 MW Phase 2: 60 MW (planned)	Not specified	5 MW	350 MW
Type of metering (Net/Gross)	Gross	Gross	Net	Net	Net
PPA off-taker	DISCOM	Torrent Power	All A.P. DISCOMs	UPCL ³⁶	TANGEDCO ³⁷
Financial incentives	FiT at 50% of the large scale PV plants.	FiT through competitive bidding ³⁹	Pooled cost paid half- yearly for 7 years ⁴⁰	None	Generation based incentive (GBI) ⁴¹
Connection voltages	• 50-100 kW→415V, TP, LT • 100-1000 kW→11kV, TP, HT	• <6 kW→240V, SP ⁴² , LT • 6-100 kW→415V, TP, LT • >100 kW→11kV, TP, HT ⁴³	Not specified	• <4 kW → 240V, SP, LT • 4-75 kW → 415V, TP, LT • 75 kW-5MW→11kV, TP, HT • 1.5-3MW→ 11kV/33kV, TP, HT	• <4 kW → 240V, SP, LT/415V, TP, LT • 4-112 kW →415V, TP, LT • >112 kW → HT/EHT ⁴⁴
Metering requirements	'Installation and Operation of Meters', 2006 The Grid Meter (GM) and Solar Meter (SM) shall be interface type as envisaged in the CEA metering regulations. (may also comply with the Time of Day (ToD) requirements) Also the SM would record net solar energy export reading indicated as SE(N).	'Installation and Operation of Meters', 2006	0.2 class accuracy, tri-vector, non-ABT energy meter	Not specified	'Installation and Operation of Meters', 2006 Bidirectional meter Solar meter for GBI Check meter if >20 kW

35 This net metering policy is to contribute towards meeting the New and Renewable Sources of Energy (NRSE) policy, 2012, target of 1000 MW for solar power generation. This NRSE policy includes both solar PV and solar thermal projects. There is currently no net metering specific capacity.

36 Uttarakhand Power Corporation Limited (UPCL)

37 Tamil Nadu Generation and Distribution Company (TANGEDCO)

38 Kerala State Electricity Board (KSEB)

39 Winning bidders were Azure Power - INR 11.21/kWh and Sun Edison - INR 11.78/kWh. The bidders must pay INR 3/kWh to the rooftop owner

West Bengal	Delhi (draft)	Kerala	Punjab (draft)	Karnataka (ERC tariff order and policy)	SECI
August 2010	November 2013	June 2014	August 2013	October 2013 and May 2014	January 2013
16 MW	Not specified	Not specified	1000 MW ³⁵	400 MW	~10 MW in first 3 phases; 50 MW in 4th phase.
Net	Net	Net	Net	Net and gross	As per existing state policy where project is set up
DISCOMs	All Delhi DISCOMs	KSEB ³⁸	PSPCL	DISCOMs	Residential/commercial/ industrial consumers
Generation based incentive (GBI)	None	After the yearly settlement period, excess net electricity banked will be purchased by KSEB at APPC	None	Rooftop plants → INR 9.56/unit (without subsidy) INR 7.20 (with 30% MNRE subsidy)	30% capital subsidy; Accelerated Depreciation
100 kW – 2 MW → LV or MV or 6 kV or 11 kV or any other voltage as found suitable by the DISCOM	• <10 kW → 240V, SP, LT/415V, TP, LT • 10-100 kW → 415V, TP, LT • >100 kW → HT/EHT	• <5 kW → 240V, SP, LT • 5-100 kW → 415V, TP, LT • 100 kW-3 MW → 11kV, HT ⁴⁵	• <7 kW → 240V, SP, LT • 7-100 kW → 415V, TP, LT • > 100 kW → 11kV, HT	• Up to 5 kW → 230V, SP, LT • 5 kW-50 kW → 415V, TP, LT • > 50 kW → 11kV, TP, HT	• Up to 10 kW → 240V, SP, LT/ 415V, TP, LT • >10-100 kW → 415V, TP, LT • >100 kW → HT/EHT (11kV/33kV/66kV)
Not specified	'Installation and Operation of Meters', 2006 Bidirectional meter-1.0 class or better, MRI and AMR compliant ⁴⁶ Solar meter- 0.2S class accuracy Check meter if >20 kW	'Installation and Operation of Meters', 2006 Solar meter shall be installed at the delivery point of the solar energy system	'Installation and Operation of Meters', 2006. Class 1 meters up to 25 kW; > 25 kW up to 100 kW LT AC 3-Phase 4-Wires CT operated static DLMC compliant energy meter; Class 0.5s > 100 kW HT TPT meter, DLMS compliant & AMR compatible, Class 0.5s	'Installation and Operation of Meters', 2006	'Installation and Operation of Meters', 2006 If Transformer is required, a bidirectional electronic energy meter (0.5 S class) shall be installed for the measurement of import/ Export of energy. Digital Energy Meters to log the actual value of AC/DC voltage, Current & Energy generated by the PV system provided. Energy meter along with CT/PT should be of 0.5 accuracy class

40 Andhra Pradesh Energy Department's policy on net metering for solar grid interactive roof-top and small solar PV power plants in the state. Provision for payment for excess/surplus energy injected into the grid. June 2013.

41 INR 2.00/kWh for the first two years, INR 1.00/kWh for the next two years, INR 0.50/kWh for the subsequent two years

42 SP=Single Phase, TP=Three Phase, LT= Low Tension, HT= High Tension, EHT= Extra High Tension

43 Gujarat Energy Research and Management Institute (GERMI)

44 MNRE, "Solar Policies - Salient features": bit.ly/1dFpM6j

45 According to the Kerala Rooftop PV regulations, June 2014, in line with supply code regulations: bit.ly/1rWR5w1

46 MRI: Meter Reading Instrument; AMR: Automatic Meter Reading

Table 2: Technical parameters of state net metering policies and ERC regulations compared to CEA regulations

Parameters	SECI	Chhattisgarh ⁴⁷	West Bengal	Gujarat	Andhra Pradesh
DC injection	Not specified	Shall be avoided by using an isolation transformer at the output of the inverter	Not specified	<0.5% of rated current (IEEE1547, AS4777)	Not specified
Harmonics⁵⁰	THD < 3%	As per CEA	Not specified	IEEE519	IEEE519
Over and under voltage and frequency trip functions	V<80% V>115% And f≥53 Hz f<47 Hz	Required but not specified	Not specified	Not specified	Required but not specified
Solar PV Panels	IEC 61215/IS14286; IEC 61730 (1 and 2); IEC 61701/IS 61701	Complying with relevant IEC/BIS/CEA standards	Not specified	IEC61215/IS14286, IEC61646, IEC62108, IEC61701, IEC61730 Parts I & II	IEC61215/IS14286, IEC61730 Parts I & II
Islanding protection	Required	Required	Not specified	Required	Required
Flicker	Not specified	Not specified	Not specified	IEC 61000	Not specified
Maximum allowable penetration on the DT⁵¹	Not specified	Not specified	5% of total consumption in the area of supply	Not specified	Not specified
Metering	CEA Regulations on 'Installation and Operation of Meters', 2006	CEA Regulations on 'Installation and Operation of Meters', 2006	Not specified	CEA Regulations on 'Installation and Operation of Meters', 2006	Not specified

47 Chhattisgarh Solar Rooftop Tariff regulations, 2013: bit.ly/1lhnNqW

48 Tamil Nadu Energy Development Agency (TEDA), 'Guidelines for Grid-connected Small Scale (Rooftop) Solar PV Systems for Tamil Nadu : bit.ly/1cF30Vn

49 CEA, 'Technical specification of grid interactive rooftop solar PV system for SewaBhawan': bit.ly/1dFUPwE

Uttarakhand	Tamil Nadu ⁴⁸	Delhi (draft)	Kerala	Punjab (draft)	CEA ⁴⁹
Not specified	Not specified	<0.5% of rated output at interconnection point or <1% of rated inverter output current	CEA 'Technical standards for connectivity of the distributed generation resources' regulations, 2013	< 0.5% of full rated output at interconnection point or 1% of rated inverter output	<0.5% of rated current (IEEE1547,AS4777)
Not specified	IEEE519	IEEE519	Same as above	IEEE 519	IEEE519
Not specified	Required but not specified	V<80% (<2s) V>110% (<2s) And f≥50.5 Hz (0.2s) f<47.5 Hz (0.2s)	Same as above	V<80% (<2s) V>110% (<2s) And f≥50.5 Hz (0.2s) f<47.5 Hz (0.2s)	V<80% (<2s) V>110% (<2s) And f≥50.5 Hz (0.2s) f<47.5 Hz (0.2s)
Not specified	IEC 61215 IEC 61646	Required but not specified	Same as above	As per Indian/ IEC standards	IEC 61215 IEC 61730 IEC 61646
Not specified	Required	Required	Same as above	Required	Required
Not specified	IEC 61000	IEC 61000	Same as above	IEC 61000	IEC 61000
Not specified	30%	15%	Draft regulations allowed up to 50% of rated DT capacity. Final regulations have changed it to 80% of minimum daytime load (8 am-4pm) on DT.	30% of DT capacity ⁵²	Not specified
Not specified	IS13779 or IS14697	CEA Regulations on 'Installation and Operation of Meters', 2006, IS13779 or IS14697	CEA Regulations on 'Installation and Operation of Meters', 2006	CEA Regulations on 'Installation and Operation of Meters', 2006	CEA Regulations on 'Installation and Operation of Meters', 2006

50 The SECI rooftop bidding program specifies a THD requirement of less than 3%.

51 Distribution Transformer

52 Punjab Energy Development Agency (PEDA), Net Metering Guidelines Draft, February 2013: bit.ly/1kUGBML



3 The solar system perspective

This section of the report deals with the standards and regulations around system level components, mainly the inverter and other Balance of System (BOS) components. It examines the technical regulations, as well as the electrical parameters associated with them. In light of the corresponding standards in Germany, the U.S. and Australia, the report reviews India's standards, analyses their adequacy and suggests potential options going forward.

3.1 Key technical specifications of the inverter

The inverter forms the heart of a grid-tied solar PV system and is responsible for the quality of power generated/injected into the grid. The inverter handles most regulatory requirements on electrical parameters such as voltage, frequency and harmonics. There are six important requirements that are mandated by most technical standards across the world. These could be categorised into the ones which affect the quality of the solar power being injected into the grid, namely harmonics, flicker, DC injection, and the operating parameters which are affected by the grid, namely voltage range, frequency range and anti-islanding.

3.1.1 Harmonics

Harmonics are electric voltages and currents that appear in the grid as a result of non-linear electric loads. Harmonic currents can cause a voltage drop and result in distortion of the supply voltage. They can also cause resonance in the supply system and load components, leading to excess heating, malfunctions, premature failures and reductions in the lifetime of the transmission and distribution systems as well as of electrical components. In the solar system, harmonics are caused in the conversion of DC to AC power by the inverter. An LC section low-pass filter is normally fitted at the inverter output to reduce the harmonics.

Current regulations – India and abroad

- **Germany** adopts the International Electrotechnical Commission (IEC) 61000-3-2⁵³, 61000-3-12⁵⁴ standards that stipulate equipment standards for harmonics. These standards are for LV equipment with input current $\leq 16\text{A}$ (IEC 61000-3-2) and with input current $> 16\text{A}$ and $\leq 75\text{A}$ (IEC 61000-3-12).
- The **USA** adopts the IEEE 519⁵⁵ which addresses the limitations for current and voltage harmonic contaminations through Individual Harmonic Limits and Total Harmonic Distortion (THD) limits. The voltage distortion limit established by the standard for general systems is 5% THD. In this standard, the Total Demand Distortion (TDD), determined by the ratio of available short circuit current to the demand current (I_{sc}/I_L), is used as the base number to which the limits are applied. There are specific limits mentioned for various harmonics for different TDD values. The actual measurement that one takes with a typical harmonic analyser is a snapshot and provides an instantaneous measurement that is referred to as THD. IEEE does not provide equipment standards like the IEC.
- In **Australia**, the AS4777 states that the total harmonic distortion (THD) (to the 50th harmonic) shall be less than 5%.
- **India** also adopts the IEEE 519 on similar lines of Australia and the USA.

The present harmonics standard in India is adequate and in line with the best global practices. Additionally, the adoption of IEEE 519 is not a major economic or technical hurdle for the inverter manufacturers to incorporate into their systems.

53 IEC 61000-3-2: bit.ly/LUblOO

54 IEC 61000-3-12: bit.ly/1lBxVca

55 IEEE 519: bit.ly/1bM13Hs

3.1.2 Flicker

Random or repetitive variations in the root mean square (RMS) voltage between 90% and 110% of nominal voltage can be generated by the solar system and produce a phenomenon known as 'flicker'. Flicker is so named because of the rapid, visible change of luminance in lighting equipment.

Current regulations – India and abroad

- **Germany** adopts the IEC 61000-3-3⁵⁶, 61000-3-11⁵⁷ standards to control flicker. The standards state that:
 - The P_{st} value shall not be greater than 1, (P_{st} = perception of light flicker in the short term, observed over 10 minute intervals) and
 - The P_{lt} value shall not be greater than 0.65 (P_{lt} = perception of light flicker in the long term, observed over 2 hours of 12 P_{st} samples)

These values are the conventional irritation thresholds for human perception as defined by the IEC. The P values are measured using standard curves that plot the number of voltage changes per minute versus the percentage of voltage change.

- The **USA** also adopts the IEC 61000-3-3, -3-11 standards to control flicker.
- **Australia** adopts the IEC standard into their AS/NZS 61000.3.3 for equipment rated less than or equal to 16 A per phase and AS/NZS 61000.3.5 for equipment rated greater than 16 A per phase. This standard mirrors the IEC standard.
- **India** also adopts the IEC 61000-3-3, -3-11 standards to control flicker like Germany and USA.

The IEC 61000-3-3 and IEC 61000-3-11 standards are mostly followed globally to curtail flicker. The IEC 61000-3-3 provides the flicker limits for LV equipment (<16A) and IEC 61000-3-11 provides the flicker limits for LV equipment (≤75A). The IEEE currently does not have standards for flicker limitations like the IEC. The CEA standards mandate the same IEC standard for flicker as is adopted globally.

3.1.3 DC injection into AC grid

DC current within the low voltage AC network could cause significant disturbances within distribution and measurement transformers. The most significant being "half cycle saturation", where a transformer, which normally operates with a very small exciting current, starts to draw as much as a hundred times the normal current. This results in the transformer operating beyond the design limits. Other effects within transformers include excessive losses (i.e. overheating)⁵⁸, generation of harmonics, acoustic noise emission, and residual magnetism⁵⁹. In addition, there is evidence for the seriousness of corrosion risks associated with DC currents in the grid. PV inverters can cause a DC bias due to the following mechanisms: imbalance in state impedances of switches, different switching times for switches, and imperfection in implementing the timing of drivers⁶⁰.

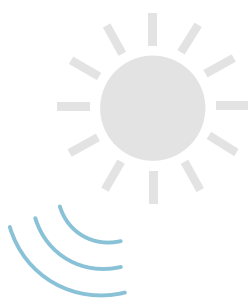
56 IEC 61000-3-3: bit.ly/1eTAXQM

57 IEC 61000-3-11: bit.ly/1j2R98U

58 Department of Trade and Industry (DTI), "DC Injection into Low Voltage AC Networks", June 2005: bit.ly/1eEYTwo

59 De La Ree, Liu & Lu 1993: bit.ly/WeOHGX, De Leon et al. 2000: bit.ly/1ns25N0, Fuchs, Roesler & You, 1999: bit.ly/1mRbmCD

60 Masoud K, Ledwich G, "Grid Connection Without Mains Frequency Transformers", Journal of Electrical and Electronics Engineering, Australia, Vol19, June 1999



Current Regulations – India and abroad

- **Germany** adopts the VDE0126-1-1⁶¹ standard to limit DC injection. The standard states that an automatic disconnection device should not allow more than 1A of DC to be injected into the grid. In the case of DC injection exceeding 1A, disconnection is mandatory in 0.2 seconds. No other standard mentions a requirement for disconnection time due to DC injection other than the VDE 0126-1-1.
- **USA** has a permissible level of DC injection which should not exceed 0.5% of the full rated output at the interconnection point, according to IEEE 1547⁶².
- In **Australia** according to the AS4777, the DC output current of the inverter at the AC terminals shall not exceed 0.5% of its rated output current or 5 mA, whichever is greater.
- In **India**, the CEA regulated current DC injection limit is in line with the IEEE 1547 standard, wherein the maximum permissible level of DC injection is 0.5% of the full rated output at the interconnection point.

It is appropriate for India to adopt best global standards to ensure that solar power of reliable quality is being injected into the grid. In each of the above three parameters, existing CEA regulations follow global best standards, i.e. for harmonics (IEEE 519), flicker (IEC 61000) and DC injection (IEEE 1547). Today's inverters are perfectly capable to meet these standards, hence utilities should have no cause for worry with regard to the quality of solar power being injected into the grid.

3.1.4 Voltage range

Voltage fluctuations or violations can result from the operation of the solar system or a fault in the distribution grid. A safe operating voltage range needs to be specified for the inverter to ensure the safe and reliable operation of the distribution grid and the PV system. The need for additionally defining voltage-time operating bands in regulations is to ensure that the PV stays connected as long as it is beneficial for the operation of the grid, and should disconnect when it is detrimental to the grid.

Current regulations – India and abroad

- In **Germany**, the VDE-AR-N 4105 directive (from January 2009) states that inverters should disconnect from the low voltage (LV) grid within 0.1 second, if the voltage exceeds 110% or drops below 80%. The BDEW medium voltage directive (from January 2012) has a nominal operating range of 90-110% of the voltage but additionally includes the Low Voltage Ride-Through (LVRT) function, wherein inverters have to stay connected to the grid in the event of a fault for the time limits specified in Table 3. Inverters are required to stay connected to the grid because they can help support the grid return to its quiescent state. For more details on Low/High Voltage Ride-Through (LHVRT), See Section 3.2.2 and Annexure B.
- The **USA** allows for wide permissible voltage fluctuations (from 50% to 120%), according to IEEE1547, with different disconnection times within the permissible voltage range.
- In **Australia**, the AS4777⁶³ - 2005 standard states that the AC voltage has to be compatible with AS 60038 (now replaced by AS 61000.3.100). According to AS 61000.3.100, the inverter requirements for steady state voltage should be within the range of +10% (253V) and -6% (216V) of the nominal supply voltage (230V). The preferred operating range is +6% (244V) and -2% (225V) of the nominal supply voltage. This is measured as a ten-minute average. The grid protection device needs to operate when the grid supply is disrupted and the grid voltage is outside the preset parameters of $V_{min} = 200-230\text{ V}$ and V_{max} is 230-270V. The proposed modification to AS 4777 has a different grid protection range of 180-265 V

61 VDE 0126-1-1: bit.ly/1aUjBKD

62 IEEE 1547: bit.ly/LUcBS7

63 AS4777: Grid connection of energy systems via inverters: bit.ly/1mIASVQ

while for sustained operation, the inverter must disconnect within 3 seconds if the average 10 minute period exceeds the maximum nominal operating range of 244-258 V.

- In **India**, the CEA mandates disconnection from the grid in 2 seconds if the voltage of the grid exceeds or falls below the operational range of 80-110% of the nominal voltage. Reconnection⁶⁴ is allowed only after the voltage is in the prescribed limits and is stable for 60 seconds.

The standard operating voltage range of the Indian grid is often violated due to a number of contributing reasons. This is especially true on feeders in tier 2 and 3 cities that often see low voltage but is also true of pockets in large metros. Given this reality, the CEA can consider extending the operating voltage range factoring in actual Indian voltage conditions. Under low voltage conditions, it will ensure that inverters stay connected and actually assist in boosting tail-end voltages⁶⁵. As the cumulative penetration of PV increases, the CEA could also consider mandating the Low/High Voltage Ride-Through (LHVRT) function (for more details, See Section 3.2.2). The LHVRT function ensures that the inverter does not automatically disconnect for certain temporary faults in the grid, as it may benefit the grid in recovery following the fault. Voltage-time limits above which an inverter must not disconnect are specified. Below these voltage-time limits, an inverter need not stay connected, but may stay connected provided it benefits the grid and does not undermine any protective function or anti-islanding detection function.

3.1.5 Frequency range

Frequency is one of the most important factors in power quality and it must be kept constant throughout the grid. If more power is taken from the grid than is fed in by the generators, the frequency will drop, and in case of a power surplus, the frequency rises. This fluctuation in frequency can damage the electrical equipment used by consumers. Resonance from frequency fluctuations may damage turbine blades and therefore generators need to be tripped.

Current Regulations – India and abroad

- The standard grid frequency in **Germany** is 50Hz and the operation range for the inverter is set at 47.5 to 51.5 Hz. Additionally, the German VDE and BDEW standards have both mandated the 'droop function' for frequency fluctuations to prevent sudden disconnection of all inverters from the grid at the same time in the event of the grid frequency exceeding the frequency operational bandwidth. Due to the high penetration of PV in the German grid, sudden disconnection of PV systems could greatly destabilise the grid. The 'droop function' of the inverters requires them to stay connected when the grid frequency crosses 50.2 Hz. The inverters shall reduce their power in steps of 40% per Hz until 51.5 Hz, after which the inverters are required to shut down. See Section 3.2.3 for a detailed discussion on the 50.2 Hz issue.
- The standard grid frequency in the **USA** is 60 Hz. There are different frequency fluctuation limits for distributed energy resources (DER) of capacity less than 30 kW and greater than 30 kW as declared by the IEEE 1547 (See Table 3).



64 "Soft-Start" Reconnection Concepts - "After power is restored to a circuit and voltage and frequency have returned within their normal ranges for a specified time period, the I-DER systems will also reconnect and start operating. If all I-DER systems started exactly at the same time with a jump in real power output, the circuit could experience a sharp transition which could cause instability and possibly voltage spikes or even sharp frequency increases or oscillations. Two methods can be used to ameliorate such a sharp transition: either the I-DER systems ramp up over time to their normal output level, or they randomly reconnect within a time window of a few minutes." From 'Recommendations for updating technical requirements for inverters in Distributed Energy Resources': bit.ly/1hlykaz

65 The inverter could be allowed to remain connected to the grid even if voltage bands mentioned in Table 3 are violated, if it can be assured that its presence improves the situation. This may require the inverter to use some or all of its capability to go into voltage regulation mode at the cost of real power capacity which will in turn require control functions to appropriately use real and reactive capability to maintain voltages. It will require a careful audit of the control functions and appropriate commercial mechanisms. Hence, such a function could be considered in the future.

- The standard grid frequency in **Australia** is 50 Hz. The grid protection device needs to operate when grid supply is disrupted and grid frequency is outside the preset parameters of $f_{\min} = 45\text{--}50\text{ Hz}$ and f_{\max} is 50–55 Hz. The proposed modification to AS 4777 has a different grid protection range of 47–52 Hz while for sustained operation, the inverter must function normally between 47–50.2 Hz. Beyond 50.2 Hz, the inverter current should reduce output till 51.5 Hz and stop thereafter, essentially a power-frequency droop function.
- The standard grid frequency in **India** is also 50 Hz. The CEA has mandated the system to be equipped with protective functions for over and under frequency trip functions, if the frequency reaches 50.5 Hz or 47.5 Hz with a disconnection time up to 0.2 seconds⁶⁶. Reconnection is allowed only after the frequency is in the prescribed limits and is stable for 60 seconds.

As the cumulative solar penetration increases, the CEA must look at implementing the power-frequency droop function on the higher frequency side to allow inverters to alter their active power to help over-frequency regulation. (For more details, See Section 3.2.3 and Annexure B). Additionally, it should also mandate the Low/High Frequency Ride-Through (LHFRT) functionality in the coming years. Especially on the lower frequency side, the inverter may remain connected to assist the grid when there are (transient) deviations below 47.5 Hz which may be caused by large grid disturbances. The Low Frequency Ride-Through (LFRT) feature will ensure that the inverters support the grid frequency by supplying active power during the crucial transient period, and do not trip simultaneously or before the steam-turbine generators protections are configured to trip. (For more details, See Section 3.2.4).

3.1.6 Anti-islanding function

Islanding refers to the condition in which a distributed solar system continues to supply to a load even though grid power from the utility is no longer present. Islanding can be dangerous to utility workers, who may not realise that a circuit is still powered when working on repairs or maintenance. For that reason, the inverter in the PV systems must detect islanding and stop supplying power if the grid is down. This feature is referred to as ‘anti-islanding’. The island so formed is known as an ‘unintentional island’. There are two methods to detect an islanding operation: passive and active. Passive techniques are based on measurement of instantaneous voltage, instantaneous frequency, phase deviations, vector surge relay, and detection of voltage and current harmonics at the point of interconnection. Passive techniques rely on distinct patterns or signatures at the point of interconnection to the grid. In the active method, schemes including the voltage shift method, slip mode frequency shift, active frequency drift (AFD), ENS (impedance measurement), and reactive power fluctuation are employed. These introduce deliberate changes or disturbances into the connected circuit and then observe the response⁶⁷. On the other hand, a PV system could disconnect from the grid and continue to supply power to the consumer loads of that particular building using a battery storage system or in synergy with the diesel backup generator. This is known as an ‘intentional island’. This feature of the inverter should be explored in India, where there are frequent power outages during the day.

66 Central Electricity Authority, ‘Technical Standards for Connectivity of the Distributed Generation Resources’, 2013: bit.ly/1cvEaKL

67 Renewable Energy World India, “Evaluation of anti-islanding protection schemes”, Kona Eswararao and Gamesa R&D, April 2012: bit.ly/1v8hld

Current regulations- India and abroad

- In **Germany**, the VDE 0126-1-1:2013-08 is the standard for an automatic disconnection device between a PV system and the public, low voltage grid. The standard includes detection methods such as over/under voltage and frequency detection, but also monitors the grid impedance (ENS). The PV system must disconnect from the grid within 5 seconds at a change of impedance of 1 ohm (Ω) resistance. The IEC 62116 is the test procedure for islanding prevention measures for utility-interconnected photovoltaic inverters in other European countries.
- In the **USA**, the standard for anti-islanding protection is UL 1741, harmonised with the IEEE 1547. In this standard, the requirement of the inverter being tested is to detect an island condition and cease to energise the grid within 2 seconds of the formation of the island.
- In **Australia**, according to AS4777, under/over voltage and frequency requirements offer passive anti-islanding protection. The inverter set-points should be in the range of $f_{\min} = 45-50$ Hz, $f_{\max} = 50-55$ Hz, $V_{\min} = 200-230$ V, and $V_{\max} = 230-270$ V for a single phase system. The inverter should disconnect within 2 seconds if the set points are crossed. Reconnection is permitted when voltage and frequency are in the acceptable range for at least 1 minute, and the inverter energy system and the electricity distribution network are synchronised and in-phase with each other.
- In **India**, prevention of unintentional islands is a requirement in all inverters and is strictly mandated by the CEA in the 'Technical Standards for Connectivity of the Distributed Generation Resources', 2013. This is a technical requirement for inverters in several state solar policies in India. The MNRE currently mandates the UL1741⁶⁸ / IEEE1547 for anti-islanding protection for utility scale projects commissioned under the National Solar Mission (NSM)⁶⁹.

The current anti-islanding protection standard adopted is appropriate for the Indian context. The safety of electrical technicians is ensured with this functionality. However, given the frequent black-outs in India, ways of utilising solar power (otherwise wasted) during this time should be examined.

Intentional Islanding: An additional advanced function of special relevance to India (with occasional black/brownouts during the daytime) is 'intentional islanding'. This feature allows the solar PV system to disconnect from the grid in the event of a grid failure and continue to supply pre-decided critical consumer loads⁷⁰. This is possible in two ways, (a) the hybrid inverter works in the off-grid mode, continues to charge batteries which power certain loads or (b) the inverter continues to function in grid-tied mode in synergy with the larger backup system, most likely diesel based generators. The second option is more feasible for larger loads, most of which have existing diesel generation backup facilities. Utilities are well versed with such backup facilities, which already have the required safety features which prevent energising the local grid (reverse flow). Using distributed solar PV in such an intentional island mode is technically feasible and can also reduce costs compared to costlier diesel generation⁷¹. This intentional islanding feature is mentioned as a note in the CEA 'Installation and Operation of Meters', 2006 draft⁷² amendment regulation released in 2013, but is omitted in the final CEA 'Technical standards for connectivity of the distributed generation resources', 2013 regulations. The CEA should consider allowing this functionality in the future based on pilot projects and further studies which should focus on critical issues such as technical specifications for safe automatic isolating equipment

68 UL1741: bit.ly/1djuU2f

69 Details: bit.ly/1dzlfMU

70 Rocky Mountain Institute (RMI), "Microgrids: Providing safe harbor in a storm", 10th January 2013: bit.ly/1qf7afv

71 The SECI guidelines for rooftop projects already allow this. 'In case of grid failure, or low or high voltage, solar PV system shall be out of synchronization and shall be disconnected from the grid. Once the DG set comes into service PV system shall again be synchronized with DG supply and load requirement would be met to the extent of availability of power. 4 pole isolation of inverter output with respect to the grid/ DG power connection need to be provided.' bit.ly/Ucc6al

72 CEA, 'Installation and operation of meters', 2013 draft: bit.ly/1fqC3ab

at appropriate locations, challenges around anti-islanding control for multiple distributed generators within a micro-grid⁷³, safety concerns for personnel and legal liabilities with regard to intentional islanding, etc.

Table 3: Comparison of technical standards/codes followed by India, USA, Germany and Australia

Parameter	India- CEA ⁷⁴	USA - FERC ⁷⁵	Germany - BnetzA ⁷⁶	Australia – AER ⁷⁷
Voltage band	<ul style="list-style-type: none"> • V<80% (<2s) • V>110% (<2s) 	<ul style="list-style-type: none"> • V<50% (≤0.16s) • 50%≤V<88% (≤2s) • 110%<V<120% (≤1s) • V≥120% (0.16s)⁷⁸ 	<ul style="list-style-type: none"> • V<80% (<0.1s) • V>110% (<0.1s)⁷⁹ for low voltage and, • V≤0-30% (<0.15s) • 30%<V<70% (<0.5s) • V<90% (<1.5s) • V>110%⁸⁰ for medium voltage 	<ul style="list-style-type: none"> • V< 216V (-) • V> 253V(<3s) as per AS 60038⁸¹
Harmonics	IEEE 519	IEEE 519	IEC 61000-3-2 IEC 61000-3-12	AS 4777
Flicker	IEC 61000-3-3, IEC 61000-3-11	IEC 61000-3-3, IEC 61000-3-11	DIN EN 61000-3-3, DIN EN 61000-3-11	AS/NZS 61000.3.3, AS/NZS 61000.3.5
DC injection	<0.5% of full rated output current	<0.5% of full rated output current ⁸²	<1A [VDE0126-1-1] ⁸³	5% of its rated output current or 5 mA
Frequency	<ul style="list-style-type: none"> • f≥50.5 Hz (0.2s) • f<47.5 Hz (0.2s) 	<ul style="list-style-type: none"> • f>60.5 Hz (≤0.16s) • f<59.3 Hz (≤0.16s) [DER≤30 kW] • f>60.5 Hz (≤0.16s) • f<57.0 Hz (≤0.16s) • f<{59.8-57.0} Hz (≤0.16s and 300s) [DER>30 kW] 	<ul style="list-style-type: none"> • 47.5Hz<f<50.2Hz • 50.2Hz<f<51.5Hz [droop function] 	<ul style="list-style-type: none"> • f>55Hz (<2s) • f<45Hz (<2s)
Anti- islanding	UL1741/ IEEE1547	UL1741/ IEEE1547	>1Ω (<5s) [VDE 0126-1-1:2013-08]	AS 4777

In addition to the standards for various electrical parameters (voltage, frequency, flicker, etc.) and functions (anti-islanding, etc.) that the inverter has to adhere to, there are also standards for the operational safety, protection and efficiency measurements of the inverter itself⁸⁴.

73 Grid edge report, Green Tech Media (GTM), 2014: bit.ly/VzQsOg

74 The Central Electricity Authority (CEA) advises the government on matters relating to the National Electricity Policy and formulates plans for the development of electricity systems. It also specifies technical and safety standards: bit.ly/1dH7rnQ

75 The Federal Energy Regulatory Commission (FERC) has jurisdiction over interstate electricity sales, wholesale electric rates, hydroelectric licensing, natural gas pricing, and oil pipeline rates: 1.usa.gov/1e3Aaib

76 Bundesnetzagentur (BnetzA) is a regulatory office for electricity, gas, telecommunications, post and railway markets: bit.ly/1gdMfnz

77 The Australian Energy Regulator (AER) performs economic regulation of the wholesale electricity market and electricity transmission networks in the National Electricity Market (NEM), and enforces the National Electricity Law and National Electricity Rules: bit.ly/1lflx3d

78 IEEE 1547

79 VDE-AR-N 4105 low voltage directive

80 BDEW medium voltage directive

81 Australian PV Association, PV integration on Australian distribution networks: bit.ly/1mHx8XC

82 IEEE 1547

83 The VDE 0126-1-1 standard states that in the case of a DC current injection greater than 1A, disconnection is mandatory in 0.2 second. The other standards do not mention a requirement for disconnection time.

84 The following standards are mandated by MNRE for all large-scale projects commissioned under the NSM and for off-grid, decentralised and rooftop installations. Efficiency measurements – IEC 61683, Charge controller / Maximum Power Point Tracker (MPPT) – IEC 62093, Environmental testing – IEC 60068-2, Electromagnetic Compatibility (EMC) – IEC 61000 series (includes most electrical requirements as discussed in sections below) and Electrical safety – IEC 62109 – 1 and 2

3.2 Additional⁸⁵ inverter functions-for high cumulative penetration

There are some additional inverter functions that regulators across the world are increasingly mandating as the overall penetration of distributed solar in the grid increases. These inverter functionalities not only facilitate distributed solar grid integration but can also support the grid in fault recovery and in maintaining grid parameters within the normative range. The four important ones considered here are reactive power support, Low/High Voltage Ride-Through (LHVRT), Low/High Frequency Ride-Through (LHFRT) and power-frequency droop. Most of these have also been recently mandated for large scale wind power plants and generators using inverters according to the amendment to the 'CEA Technical Standards for Connectivity to the grid' on 15th October 2013⁸⁶.

3.2.1 Reactive power support

Reactive power (measured in var) arises due to phase differences between voltage and current in the system. This phase difference is created by electric and magnetic fields in inductive and capacitive loads (devices that have motors or capacitor banks).

Utilities in India mandate customers with a high load requirement (industries) to maintain a power factor close to one. A power factor close to one indicates that the loads are not introducing any reactive power demands on the grid. The demands are met locally by using devices that provide reactive power. For instance, when a motor needs reactive power, it is not necessary to go all the way back to electric power generators on the transmission grid to get it. One can simply use a capacitor bank at the location of the motor and it will provide the required reactive power. This way, consumers have to invest in additional equipment that will allow them to maintain a power factor close to one. However, not all consumers (residential, small commercial) are mandated by the utilities to invest in such additional infrastructure. In such cases, there may still remain a small amount of reactive power demand on the grid and the onus is on utilities to manage this effectively.

Role of inverters in reactive power support

This situation is now changing in those countries that have a fairly large penetration of distributed inverters and other power conditioning devices. Traditionally, while the control of the grid's electrical parameters came from the utilities, the presence of a large number of distributed power conditioning units presents an opportunity for utilities and grid management personnel to utilise these devices to ensure a more stable grid. Solar inverters are ideally operated in such a way that no reactive power is introduced in the grid. Almost all inverters in the international and Indian market (See Section 3.3) are designed to maintain a power factor close to one. Many countries are now discussing the possibility of operating the inverters on the network at a non-unity power factor (say ± 0.9) when required by the operators for grid support. As a network support function, under low voltage conditions, the inverter should not draw reactive power, but may contribute to voltage support by supplying reactive power below a certain limit. Drawing reactive power at voltages lower than a specified limit should be prohibited. Under high voltage conditions, the inverter should trip beyond a specified voltage limit, but up to some specified voltage limit (lower than the absolute higher limit) it may attempt to help the grid by absorbing reactive power.

Current Regulations - India and abroad

- **Germany** was the first to mandate reactive power support from inverters through the VDE-AR-N 4105 regulation.
- The **USA** has not presently mandated the need for reactive power support in line with the interconnection standard, IEEE 1547. However, discussions are in process to implement

⁸⁵ Additional refers to functions not presently mandated by CEA technical standards.

⁸⁶ These apply to large MW scale generators connected at HT and not to distributed generators.: bit.ly/TxXemE

it in the near future. A recent report⁸⁷ on recommendations for smart inverters has recommended mandating this function in California.

- **Australia** has also proposed this feature in their new AS4777 standard.
- **India** does not have a reactive power support regulation for distributed generation at present⁸⁸.

Table 4 summarises the regulation mandated for inverter manufacturers:

Table 4: Reactive power support regulations of Germany (VDE-AR-N 4105) and Australia (AS4777)

Country	Inverter output	Power factor requirements
Germany	< 3.68 kVA ⁸⁹	Not required
	3.68 kVA to 13.8 kVA	Power factor between 0.95 _{lagging} and 0.95 _{leading}
	>13.8 kVA	Power factor between 0.90 _{lagging} and 0.90 _{leading}
Australia (proposed)	Rated output current <20A per phase	Power factor between 0.95 _{lagging} and 0.95 _{leading}
	Rated output current >20A per phase	Power factor between 0.90 _{lagging} and 0.90 _{leading}

Implications of reactive power support on inverter sizing

As a principle, all electrical components need to be usually designed for apparent power (kVA) requirements. If inverter sizing is done only for active power, then there would be a loss of active power if the system has to operate at a non-unity power factor⁹⁰. In order to be able to provide reactive power (without reducing active power), the inverter would have to be oversized in relation to the magnitude of the required phase shift. For example, a 20 kW system with a 0.9 leading and lagging requirement would necessitate a 22.2 kVA inverter.

Benefits of reactive power support

Apart from improving the local voltage profile (See Figure 4)⁹¹, reactive power support can also help reduce transmission losses, support integration of more PV resources in the grid and transmission of more active power⁹². Such reactive power support can be operationalised in two ways: have a pre-set power factor, or vary the power factor automatically in a dynamic way as a function of the local voltage. The second option seems to be the logical way ahead.

87 'Recommendations for updating technical requirements for inverters in Distributed Energy Resources': bit.ly/1h1Ykaz

88 However, the draft (February 2013) PEDAs guidelines on net-metering mention the following, "While the output of the inverter is greater than 50%, a lagging power factor of greater than 0.9 should operate.": bit.ly/1kUGBmI

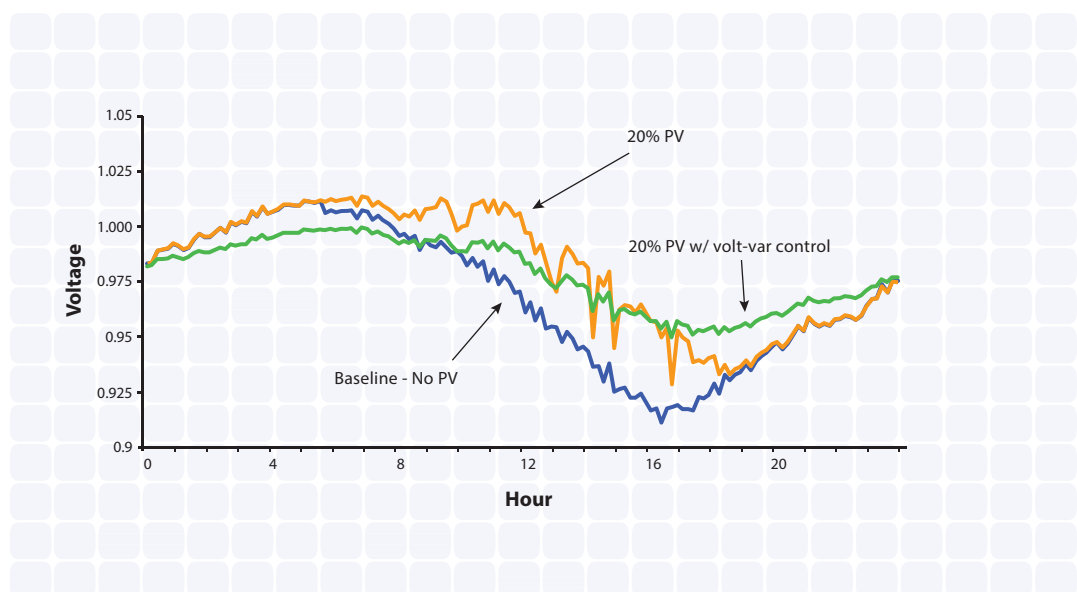
89 3.68 kVA = 230 V * 16 A

90 bit.ly/1m4BQ7Z

91 NREL, "Updating Technical Screens for PV System Interconnection": 1.usa.gov/OuZisW

92 SMA, 'PV grid integration', 4th revised edition, May 2012: bit.ly/1qf86Ri

Figure 4: Feeder Voltage response with advanced var control



3.2.2 Low/High Voltage Ride-Through (LHVRT)

Fault Ride-Through (FRT) features enable grid-tied inverters to stay connected to the grid during voltage or frequency fluctuations of extremely short durations⁹³. Low/High Voltage Ride-Through (LHVRT) is one such feature. At the time of a failure (short-circuit or lightning strike), a high current flows through the grid leading to a momentary voltage sag. This would typically trigger the inverter to trip and disconnect until the voltage on the grid stabilises. In such instances, inverters tripping (in a high DG solar penetration scenario) can cause the line voltage to decrease further, which in turn can cause other inverters on the line to trip. This can result in a “cascading effect” that would ultimately rapidly take down all the inverters connected to the distribution network. LHVRT allows inverters to stay connected if such voltage excursions are for very short time durations and the voltage returns to the normal range within a specified time frame. LHVRT does not require the inverter to stay connected if the fault persists beyond a specified time.

Current regulations- India and Abroad

Traditionally, inverters compliant with interconnection standards such as IEEE 1547 (USA), UL1741 (USA), VDE 0126-1-1 (Germany) or AS4777 (Australia) were required to disconnect in the event of disturbances/failures in the grid. This was required as a safety feature to prevent unintentional islanding.

- **Germany** now mandates LVRT capabilities in inverters connected to both low voltages and medium voltages. The VDE-AR-N 4105 code of practice enforced from January 2012 mandates LVRT capabilities in all grid-tied inverted at the LV level. Earlier, the BDEW medium voltage (MV) directive, enforced from January 2009, modified the requirements for PV inverters connecting to the MV grid in Germany based on the Transmission Code, 2007⁹⁴.

The failure ride-through requirements are summarised as follows:

- Generating units must not disconnect from the grid in the event of a voltage drop to 0% of nominal voltage for a period of 150 milliseconds.
- If after 150 milliseconds the voltage does not recover to 30% of nominal, then there is no requirement to stay connected.

As per the BDEW initial directive, inverters were only required to remain connected during faults and resume operations once the grid is stable. Reactive power support from these

⁹³ “Implementation of Voltage and Frequency Ride-Through Requirements in Distributed Energy Resources Interconnection Standards”, Sandia, April 2014: 1.usa.gov/1ptzw5W

⁹⁴ The Transmission Code, 2007: bit.ly/1gpuD9T

inverters during a fault was added as a requirement only from 1st April 2011 when the complete version of the FRT requirement was enforced. PV inverters of distributed systems in Germany now provide complete dynamic grid support by remaining connected to the grid and also providing reactive power support during faults to assist grid recovery.

- In the **USA**, the Californian utility CAISO, in its interconnection procedures of 2010⁹⁵, recommended extending FERC Order 661-A⁹⁶ to all generator types including solar PV. Currently, the FERC order 661-A dictates wind turbines to ride through normally cleared three phase faults and any voltage behavior caused by it. IEEE is in the process of including FRT requirements for distributed energy generators by updating the IEEE 1547 standard. A recent report⁹⁷ on recommendations for smart inverters recommends mandating this function in California.
- The standards in **Australia** do not currently mandate the LVRT feature for solar PV inverters. However, the National Electricity Rules⁹⁸ in Australia require that the LVRT function be present for wind farms.
- **India** currently does not require inverters to have the LHVRT functionality. While this is unproblematic at lower penetration levels, it could be an issue at very high penetration levels.

3.2.3 Power - Frequency droop characteristics

The “50.2 Hz problem” experienced in Germany forced regulators, grid operators and inverter manufacturers to allow inverters to alter their active power in situations where frequency regulation might be required. The nominal frequency of Germany’s grid is 50.0 Hz. Inverters were initially calibrated to tolerate a deviation until 50.2 Hz. If the grid frequency increased beyond 50.2 Hz, inverters were programmed to stop injecting power into the grid. This was done in order to decrease power and therefore bring back frequency to acceptable limits. However, since there was a large penetration of distributed PV in the grid and all inverters shut down at the same instant, the frequency dropped suddenly. This in turn forced inverters to switch back on, all at the same time, leading to a ‘yo-yo’ effect, with inverters switching between on and off states (See Figure 5). This undermines the overall stability of the grid and can cause harm to distribution transformers, protective switchgear and cables.

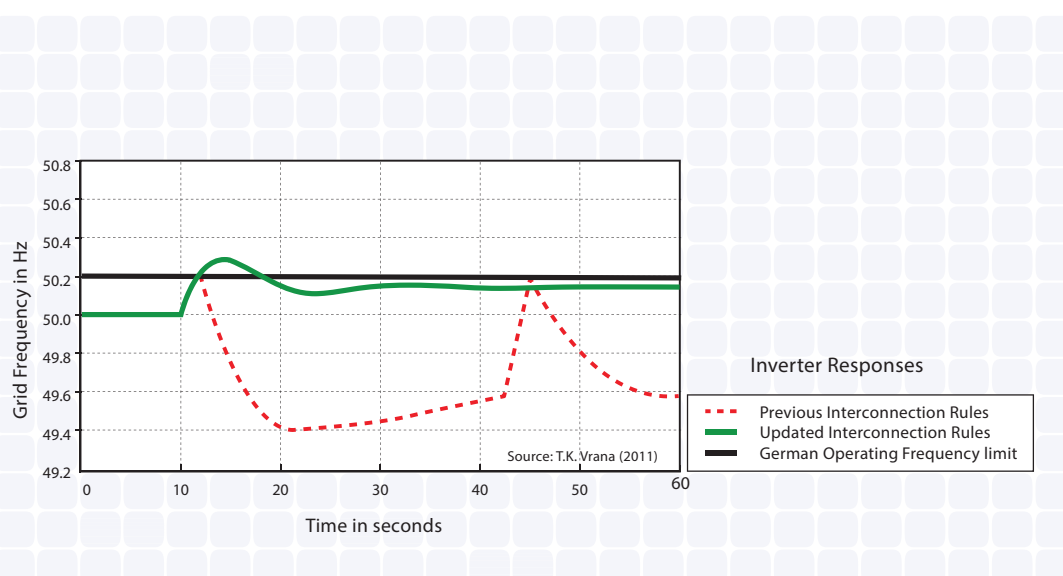
95 CAISO interconnection procedures: bit.ly/1hbnf5H

96 FERC Order 661-A: 1.usa.gov/1g6yIFZ

97 Recommendations for updating technical requirements for inverters in Distributed Energy Resources: bit.ly/1h1Ykaz

98 The National Electricity Rules (NER) govern the operation of the National Electricity Market (NEM). The Australian Energy Regulator monitors the NEM under the NER.

Figure 5: Example of improved performance with inverter controls that implement a droop function for over-frequency conditions instead of tripping⁹⁹.



In order to remedy this, Germany amended the BDEW regulation on 26th July 2012. The regulation now mandates all distributed solar plants greater than 10 kW that were commissioned after 1st September 2005 to retrofit devices that would prevent inverters from switching off abruptly. Under the modified functionality, inverters will be required to stay connected when the grid frequency crosses 50.2 Hz. The inverters shall reduce their power in steps of 40% per Hz until 51.5 Hz, after which the inverters are required to shut down. This ramping down of active power of the inverters will stabilise the grid and stop all inverters on the distribution grid from automatically switching off at the same time – instead making them operate at a reduced power output.

Such a requirement does not exist either in the USA, Australia or India at present but has been proposed in California and Australia.

Power-Frequency droop retrofitting requirement in Germany

There are approximately 315,000 inverters of diverse power rating that need to be retrofitted to include this functionality in Germany. The retrofitting would in the vast majority of cases consist of a software update or a change of the parameter settings of the solar inverter. The process started in 2012 and the inverters are to be retrofitted by 2015. Initial estimates suggested that this exercise could cost EUR 170 million. Additional costs of EUR 20 million would be incurred for modifying emergency equipment and for administrative costs at utilities and inverter manufacturers¹⁰⁰. The costs would be amortised by all consumers of the utility, with 50% of the amount charged with the grid fees and 50% with the EEG- Erneuerbare-Energien-Gesetz (German Renewable Energy Act) surcharge.

3.2.4 Low/High Frequency Ride-Through (LHFRT)

Another possible FRT feature is the LHFRT. This only becomes important when the reliable supply of electricity is dependent on distributed generators (in high DG penetration scenarios). In such a case, immediate disconnections when momentary frequency disturbances occur may not be advisable. LHFRT allows inverters to stay connected if such frequency excursions are for very short time durations and the frequency returns to the normal range within a specified time frame. Unnecessary outages can be prevented by avoiding any cascading possibilities.

⁹⁹ "The Integrated Grid: Realising the Full Value of Central and Distributed Energy Resources", Electric Power Research Institute (EPRI), 2014: bit.ly/1m2F1df

¹⁰⁰ bit.ly/1f8hRfg

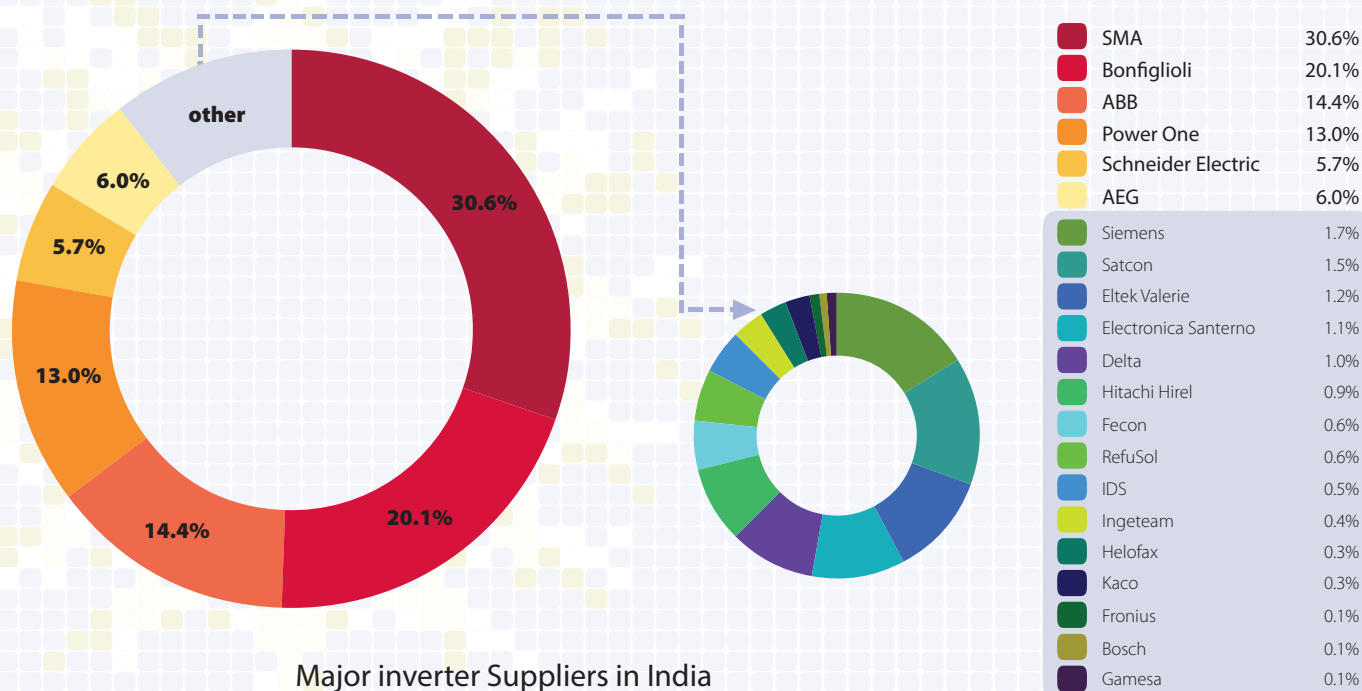
3.2.5 Advanced functions for future consideration

In addition to the above four functions, there are several other advanced functions which could provide enhanced flexibility and control of the distributed PV generators to help better grid integration. Some of these are (a) Maximum Generation Limit Function, (b) Volt-Watt Function, (c) Watt – Power Factor Function etc., (d) Reactive power support at night¹⁰¹ etc. Communication between the operator and the inverter is necessary for some advanced features. Two-way communication or a simple broadcast is required to communicate some flags (binary signals) and some real numbers – at some discrete time intervals. This may be required for mode-selection and set point change for frequency/voltage regulation, as well as alleviation of transmission congestion. This should be a part of the features of large and moderately sized inverters if overall penetration is high. These functions could be considered by the CEA in the future as solar penetration increases.

3.3 Are current inverters meeting the technology standards?

To determine if the inverters available in the Indian market today comply with the six regulations discussed in section 3.1, a market survey of the prominent inverter suppliers in India was conducted. Figure 6 shows the market share across different inverter suppliers in India.

Figure 6¹⁰²: Inverter market share in India in 2013



101 Some countries are also exploring the option of inverters supplying reactive power during the night. They absorb real power from the grid at night and supply reactive power back to the grid by providing a phase shift with very low losses (bit.ly/1pUSQLT). This feature is currently available only for central inverters of capacity above 500 kW as it is not economically feasible for small string inverters.

102 BRIDGE TO INDIA market research

Four major inverter companies, which hold the majority of the market share, and two other inverter companies¹⁰³ were surveyed. Table 5 compares these inverters against the major technical features of inverters described in the report, as regulated by CEA standards. In addition, inverters having additional inverter functions (currently not being mandated under Indian regulation) are tabulated. The inverters in the market are classified into two categories based on their capacity and functions thereof:

- String inverter- up to 30 kW
- Central inverter- higher than 30 kW

Table 5: Technical features of some inverters available in the Indian market

Technical features	ABB ¹⁰⁴		Bonfiglioli		Powerone		SMA		Su-Kam		Swelect	
	String	Central	String [±]	Central	String	Central	String	Central	String	Central	String	Central
Harmonic current injection	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
DC injection	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
Flicker control	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
Anti-islanding	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓
Reactive power support	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✗	✗
Low voltage ride through (LVRT)	✓	✓	-	✓	✓	✓	✓	✓	✗	✗	✗	✗
Frequency regulation	✓	✓	-	✓	✓	✓	✓	✓	✗	✗	✗	✗

It was observed that all the six CEA mandated features were present in all the inverters surveyed. However, the additional inverter features were present in most inverter companies with high market share but not in all the companies surveyed. During the survey¹⁰⁵, it was understood that these advanced inverter functions come at practically no additional cost to consumers. The costs for these advanced functions were research costs for the companies which are hard to quantify separately.

Hence, in a nut shell, today's inverters can support the grid during faults and help in grid recovery. Technical standards need to recognise these system benefits and mandate them in new installations in due time. Our review indicates that all these additional capabilities are easily available at practically no extra costs in inverters available in the market today. Such changes in technical standards should be made in the next round of update of the CEA regulations as PV penetration increases. Open discussions and consultations with industry and utilities about these additional functions would give the remaining inverter manufacturers sufficient time to conduct their research and incorporate these features into their inverters, as and when the CEA mandates them.

¹⁰³ Due to a lack of response while conducting the survey, many other inverter manufacturers have not been considered.

¹⁰⁴ Earlier, the ABB string inverters did not provide the reactive power support and LVRT function (only available in their central inverters). With the recent acquisition of Powerone, ABB is retracting their string inverters from the market and replacing them with those of Powerone for the string inverter segment. Source- ABB completes acquisition of Power-One: bit.ly/1ctl6An

[±] Bonfiglioli does not have string inverters in its product portfolio. However, their small central inverter models cater to loads ranging from 30 kWp to 170 kWp.

¹⁰⁵ Source: BRIDGE TO INDIA market interviews

If such changes are not made in due time, retrofits can become very costly (as in the 50.2 Hz case in Germany) and logistically difficult since DG solar growth can be very fast. Specifically the CEA can consider mandating the following functions by 2016-17:

- Fault ride through capabilities like LHVRT and LHFRT under sections 5 [11], [6] [a, b]. Anti-islanding specifications would also have to be updated to be in synergy with these FRT capabilities.
- Reactive power support in fixed power factor or dynamic mode.
- Power-frequency droop function when cumulative PV penetration is high. Reduction in active power can kick in at 50.2 or 50.5 Hz and come down linearly till 51.5 Hz.

All these three functionalities can be initiated in a pre-determined auto-response mode and do not need any communication infrastructure. The CEA should mandate such functionality on systems only above a certain size (say 10/20 kW) to avoid any cost disadvantage on smaller systems. This size threshold may vary from function to function.

3.4 Key technical specifications of other components

3.4.1 Metering

The CEA mandates technical requirements of meters through the regulation 'Installation and Operation of Meters, 2006'. A draft amendment¹⁰⁶ was released in 2013 to include renewable energy meters for distributed solar generation. The standards mentioned in the regulation are:

- IS 13779¹⁰⁷ is applicable to static watt-hour meters of class 1 and 2.
- The IS 14697¹⁰⁸ provides the standards for static transformer operated watt-hour and VAR-hour meters, of accuracy class 0.2 S and 0.5 S.

Since meters have different accuracy classes, the CEA in its amendment of the regulation (installation and operation of meters) in 2010 specifies the accuracy class for different voltage levels:

- ≤ 650 V – class 1.0 or better
- > 650 V and ≤ 33 kV – class 0.5 S or better

Current regulations – India and abroad

- **Germany** adopts the DIN EN 62053-21 VDE 0418-3-21:2003-11 and DIN EN 62053-22 VDE 0418-3-22:2003-11¹⁰⁹ standards, which are equivalent to the IEC 62052-11¹¹⁰ and 62053-21/22 standards. Germany also adopts the Measuring Instruments Directive (MID) approved meters, which is applicable in the European Union (EU). A MID approved instrument will have passed specific conformity assessment procedures and have MID markings which allow the instrument to be used in any EU member state.

In Germany, the following requirements have to be met:

- Meters connected to the low voltage (LV) grid (up to 1 kV) have to be of accuracy class 1 (MID class B) for active power measurement and class 2 (MID class A) for reactive power measurement.
- Meters connected to the medium voltage (MV) grid (1 kV to 72.5 kV) should be of accuracy class 0.5 S (MID class C) for active power measurement and class 1 (MID class B) for reactive power measurement.

¹⁰⁶ CEA draft metering regulations, 2013: bit.ly/1fqC3ab

¹⁰⁷ IS 13779: bit.ly/1g3x54h

¹⁰⁸ IS 14697: bit.ly/1hhZdWJ

¹⁰⁹ VDE, IEC 62053-21:2003: bit.ly/1hWY3za

¹¹⁰ IEC 62052-11: bit.ly/1b1iEA3

- The **USA** follows the ANSI C12.16 and C12.20¹¹¹ for the accuracy and performance of meters. The 0.2 class and 0.5 class of accuracy as per ANSI is equivalent to the 0.2 S and 0.5 S class of accuracy as per IEC.
- **Australian** standards are aligned for the most part with the IEC standards as mentioned above. They are AS/IEC 62052-11, AS/IEC 62053-21/22 and AS 1284.1¹¹² (induction watt hour meters).
- In **India**, the IS 13779 and IS 14697 standards are equivalent to the IEC 62052-11¹¹³ and 62053-21/22 standards.

The accuracy of meters used in India as mandated by the CEA is sufficient and not overly stringent. Although the CEA mandates metering requirements throughout the country, some SERCs have specified slightly divergent requirements at times. Several state solar policies also mention metering requirements that are not in line with the CEA requirements. Table 6 captures this variation.

Considering the limited availability of bi-directional net meters (especially single phase), another option for metering could be to use two standard energy meters, one generation and the other a load meter (both uni-directional), and work out the net import/export of energy. This can be cost-effective and easy to implement compared to a net meter. The CEA could consider allowing either option in order to facilitate adoption of different business models.

Table 6: Comparison of metering requirements among state¹¹⁴ policies in India

	Gujarat	AP	Uttarakhand	TN	Delhi (draft)	Kerala	Punjab (draft)
Technical standards	CEA ¹¹⁵	CEA	CEA	CEA	CEA	CEA	CEA
No of meters	2	2 ¹¹⁶	1	3 ¹¹⁷	3 ¹¹⁸	2	1
Type of meter	Not specified	Tri-vector	Not specified	Not specified	Not specified	Not specified	Not specified
Metering arrangement	Feed in tariff	Net metering	Net metering	Net metering with GBI	Net metering	Net metering	Net metering
Accuracy class (minimum requirement)	Not specified	0.2	Not specified	As per CEA	Solar meter- 0.2 S ; Bidirectional ¹¹⁹ meter-1.0	CEA	Not specified
Check meter¹²⁰ requirement	Not specified	Not specified	Not specified	Mandatory above 20 kW	Mandatory above 20 kW	Solar Meter mandated	Not specified

111 ANSI C12.16/C12.20: bit.ly/1gxTHeV

112 AS 1284.1: bit.ly/1qBmqVE

113 IEC 62052-11: bit.ly/1b1iEA3

114 West Bengal and Karnataka have been excluded from this table as metering details are not available.

115 Refers to CEA's Installation and operation of Meters' Regulation, 2006 and amendments.

116 A solar meter is mentioned as an option in the policy in addition to the RE meter.

117 A solar meter (for Generation Based Incentive), RE bidirectional meter and check meter (only for capacity greater than 20 kW)

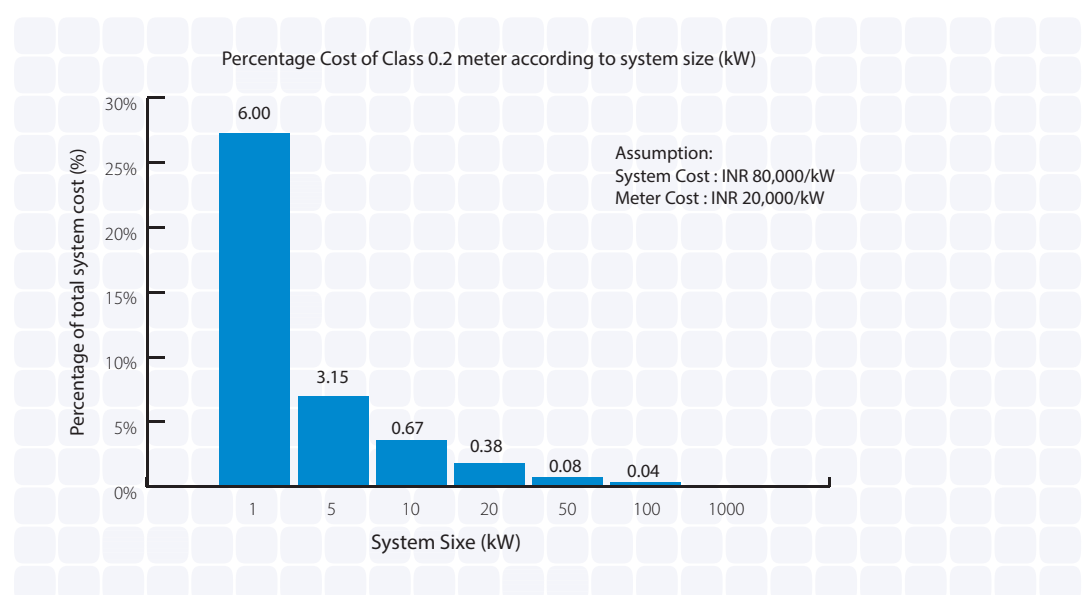
118 Ibid

119 A bidirectional meter measures the flow of current in both directions. It is used in net metering, where it shows the net amount of electricity consumed by the consumer.

120 A check meter is another meter, which is used in addition to the main meter, to validate the main meter for any accuracy errors, and is used as a backup meter if the main meter fails.

Economic impact of overly stringent metering requirements: The CEA minimum accuracy class requirement for consumer meters in the distribution network is either class 1 or class 0.5 S. The cost of a class 1 bidirectional meter is around INR 19,000 and that of a class 0.5 S bidirectional meter is around INR 25,000. However, the Andhra Pradesh policy recommends that the meter accuracy class should be 0.2, and the cost of a 0.2 class non-ABT, bidirectional meter ranges from INR 20,000–35,000. Similarly Delhi mandates a meter accuracy class of 0.2 S. Figure 7 represents the meter cost (assumed to be INR 30,000) as a percentage of the total system cost (assumed to be INR 80,000/kW). The meter costs are a significant percentage in lower capacity systems (<20 kW), and imposing higher accuracy classes than already mandated by the CEA will add to the cost of the overall system and should be avoided. Similarly, the need for a check meter above 20 kW should also take into consideration the economic impact on the consumer. The higher burden (especially on smaller systems) can significantly affect the willingness of consumers to adopt distributed solar, which in turn can slow down the distributed solar market. As such it will be desirable for all the state net metering policies to conform to the CEA guidelines to limit the impact of the metering cost on the overall PV system cost.

Figure 7: Meter cost as a percentage of system cost



3.4.2 PV Modules

The CEA specifies design qualifications and quality standards for both crystalline (c-Si) and thin film modules. In addition, the MNRE also specifies standards through the National Solar Mission.

Current regulations – India and abroad

- The standards for PV modules recommended by the CEA and/or the MNRE¹²¹ are the same as those followed by the **USA**¹²² and **Germany**. They are:
 - IEC 61215¹²³ for crystalline silicon PV modules
 - IEC 61646¹²⁴ for thin-film PV modules.

¹²¹ MNRE, 'Minimal technical requirements/standards for spv systems/plants to be deployed': bit.ly/LaGPAQ

¹²² 'SEI API PPA Install Grid Connect Guidelines': bit.ly/L2IDLs

¹²³ IEC 61215: bit.ly/1eUseFZ

¹²⁴ IEC 61646: bit.ly/1hhX0dT

- IEC 61730¹²⁵
 - Part 1- requirements for construction of the module
 - Part 2- requirements for testing and for safety qualification
- IEC 61701¹²⁶ that specifies the salt mist corrosion testing for modules that are used in coastal corrosive atmospheres
- In **Australia**, in addition to the above mentioned PV module standards, AS/NZS 5033¹²⁷ (Installation and safety requirements for PV arrays) is also applicable.

The IEC standards apply to all modules, used in Indian solar PV projects, either manufactured in India or imported into India. The standards adopted by India for the PV modules are sufficient and adequate. They consider the environmental effects of the Indian weather conditions also into their quality check process. Adopting the IEC standards also provides a uniform platform for module manufactures and project developers. These requirements must be harmonised and explicitly mentioned across state solar policies in India.

3.4.3 Data Acquisition Systems

Data Acquisition Systems (DAS) are a combination of a software application programme and electronic hardware for monitoring PV plants and reporting data to a remote location. This can be considered to be a subset of the Supervisory Control and Data Acquisition (SCADA) programme to monitor distributed generation resources. DAS and SCADA are useful in system monitoring and analysis, help to reduce losses, further optimise by continuous improvements, and document performance, thus minimising uncertainties, reducing risk and maximising security and returns.

Current regulations – India and abroad

There are no specific regulations of SCADA systems used for distributed solar plants in Germany and in the USA.

- The IEC 61850¹²⁸ is the global standard for communication networks and systems for power utility automation. This includes SCADA functionalities as well. It is adopted in Germany.
- In the USA, FERC Order 661-A contains SCADA requirements for wind plants. These are sometimes applied to large-scale PV plants. Further details on SCADA for power system applications can be found in the IEEE standard 1547.3¹²⁹ ‘IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems’, which provides the guidelines for SCADA for power system applications¹³⁰.
- In Australia, AS4418.1¹³¹ is a standard for SCADA applications for multi-utility purposes. This standard describes the generic telecommunications interface and protocol for SCADA systems.
- In India, the CEA regulations currently have not considered DAS like SCADA.

Data acquisition from distributed solar plants becomes critical in the planning and operation of the grid, especially in high penetration scenarios. However, SCADA systems come at a significant cost. In India they typically cost INR 75,000 (basic system without reporting functions) to INR 300,000 (with data reporting functions)¹³². Currently, there is no immediate need to mandate SCADA systems for distributed PV systems since the penetration is low and it comes at a significant cost to the consumer as discussed above. Costs for such systems would hopefully come down with higher deployment. However, as penetration levels increase, data from these

¹²⁵ IEC 61730 parts I and II: bit.ly/Mi75tf, bit.ly/1dqObe1

¹²⁶ IEC 61701: bit.ly/MQrc1E

¹²⁷ AS/NZS 5033: bit.ly/PzSH1n

¹²⁸ IEC 61850: bit.ly/LZdj0m

¹²⁹ IEEE 1547.3: bit.ly/1eZHdNj

¹³⁰ “PV Plant Performance Requirements for Interconnection”: bit.ly/1bJZ3oI

¹³¹ AS 4418.1: bit.ly/1hhMhLy

¹³² BRIDGE TO INDIA market research; Interview with Protocol India and EV Renewables (EPC company)

systems becomes crucial in grid management – especially for larger plants. The CEA may look at introducing data reporting requirements for plants above a specific capacity (say 100 kW). This data should be accessible as part of a central database for utilities, SLDCs, etc.

3.4.4 Protection devices

Protection devices are needed to prevent damage to the grid, the system and the personnel in the event of voltage fluctuations, frequency fluctuations, unintentional islanding, etc. They are a requirement in almost all the state solar policies in India and are also mandated by the CEA regulation 'Technical Standards for Connectivity of the Distributed Generation Resources', 2013. Typical protection devices in solar systems consist of surge protective devices, DC and AC isolator switches and an isolation transformer¹³³.

Apart from standards for meters, PV panels, data acquisition systems, and protections devices, we have looked in detail at other BOS components like mounting structure, cables, batteries, junction boxes, switch gears, charge controllers, etc. Details of standards with regard to these components are provided in Annexure C. A tabulated summary of the standards is provided in Table 7.

Table 7: Overview of standards for solar system components in the USA, Germany and India

Components		Standards			
		USA	Germany	Australia	India
PV module	Crystalline	IEC 61215, IEC 61730-I&II, IEC 61701	IEC 61215, IEC 61730-I&II, IEC 61701	IEC 61215, IEC 61730-I&II, AS/NZS 5033	IEC 61215(CEA)/IS 14286, IEC 61730-I&II(CEA), IEC 61701/IS 61701 (MNRE)
	Thin film	IEC 61646, IEC 61730-I&II, IEC 61701	IEC 61646, IEC 61730-I&II, IEC 61701	IEC 61646, IEC 61730-I&II, AS/NZS 5033	IEC 61646 (MNRE), IEC 61730-I&II (CEA), IEC 61701/IS 61701 (MNRE)
Meters	Renewable energy meter	ANSI C12.16, ANSI C12.20	DIN EN 62053-21 VDE 0418-3-21:2003-11, DIN EN 62053-22 VDE 0418-3-22:2003-11, MID	AS/IEC 62052-11, AS/IEC 62053-21/22, AS 1284.1	IS 13779, IS 14697 (CEA)
SCADA		IEEE 1547.3	IEC 61850	AS 4418.1	None
Protection devices	Surge protective devices	UL 1449	DIN CLC/TS 50539-12 (VDE V 0675-39-12): 2010-09, prEN 50539-11, EN 61643-11	AS/NZS 1768	Relevant international standard (CEA & MNRE)
	Isolator switch	UL 98, UL 508	IEC 60364-7-712, DIN VDE 0100-712, IEC 60947-3	AS/NZS 60898/IEC 60947	IEC 60947-I,II & III/ IS 60947-I,II & III (MNRE)
	Isolation transformer	Not mentioned	IEC 61558-2-6	Not mentioned	IEC 61727(CEA); some SERCs have mandated it
Module mounting structure		UL 2703	None	AS/NZS 1170.2	None
Junction boxes		IEC 60670, UL 50	DIN EN 50548 (VDE 0126-5): 2012-02	AS 1939	IEC 529- IP 54, IP 21 (MNRE)
Cables and connectors		UL 62, UL 758, EN 50521	VDE 0285, VDE 276, EN 50521, VDE-AR-E-2283-4: 2011-10	AS/NZS 5000.1, AS/NZS 3191, AS/NZS 3000	IEC 60227/IS 694, IEC 60502/IS 1554-I&II, IEC 60189, EN 50521 (MNRE)
Battery		IEC 61427	IEC 61427, DIN EN 61427	AS 4086	IEC 61427, IS 1651, IS 13369 or IS 15549 (MNRE)
Charge controller		UL 1741	IEC 60068-2, IEC 62093/EN 62093:2005	IEC 62093	IEC 60068-2, IEC 62093 ¹³⁴ (MNRE)

¹³³ DERC (draft), TNERC and CSERC regulations note that: 'To avoid DC injection into the grid and to ensure other power quality parameters, the AC output of the inverter shall be connected through an Isolation Transformer to the grid'. Transformer-less inverters are also available in the market and should be considered if they meet minimum safety requirements since they could offer a cost advantage. For more information on this issue: <http://bit.ly/1yl6MAG>

¹³⁴ Not needed if integrated with an inverter

3.5 Certification and Testing

A favourable policy-regulatory framework with approaching grid parity can enable exponential growth of distributed solar PV. Germany, having over 1.4 million systems with an installed capacity of 35.7 GW that has been achieved in just the last few years, is a prime example. This can overwhelm the utility management system in terms of procedural logistics with regard to permissions, inspections, certification, etc.

Hence the process for certification/permitting has to be graded in nature with smaller systems having a simpler process – essentially being allowed to self-certify¹³⁵. Accredited third party validators could help the utility in this process. Safety with regard to the anti-islanding feature and other protection devices, and compliance of the equipment and system with the CEA standards, are the two most important checks that should be performed.

Such certification processes have to be coupled with random checks with heavy fines/blacklisting for non-compliance. An effective monitoring and verification system to ensure compliance with new additional mandatory functions (as and when they are incorporated in the CEA standards) would be needed as some of these functions can be disabled locally. Data acquisition systems for larger projects can help monitor compliance.

With regard to testing, section 5[8](2) of the CEA standards mandates measuring DC injection, harmonics and flicker prior to commissioning and additionally once each year. This should be made applicable only above a certain project size (say > 100 kW).

A possible framework for certification and testing is suggested in Table 8. See Annexure G for an indicative process flow for utilities for screening applications for grid-tied distributed PV systems. Annexure H has details on the application process in Tamil Nadu and Kerala.

Table 8: A possible framework for certification and testing

System size	0-10 kW	10 - 100 kW	> 100 kW
Equipment certificates, especially for inverters	Standard test certificate from accredited laboratory declaring conformity with CEA standards ¹³⁶ .		
System installation certificate (pre-commissioning)	Self-certification	Certified Energy Auditor / Licensed Electrical Contractor / Self-certification for MNRE accredited channel partners (1A certification)	Certified Energy Auditor / Electrical Inspector
Annual testing	NA	NA	Only for high penetration zones

Note - System owners would need to provide an appropriate declaration for safety with the system installation certificate.

¹³⁵ Germany has no active permitting process for installations smaller than 30kW and does not require visits by the distribution grid operator or other local permitting authorities. Some of the procedures can be done online. Similarly, in England, certified installers can directly connect to the system to the grid and notify the utility thereafter.

¹³⁶ For Germany, "A unit certificate confirming conformity with all requirements of the medium voltage directive has become mandatory for each generation unit (i.e., each inverter type) at the same time as the dynamic grid support capability. The manufacturer receives this certificate following comprehensive testing of the respective device by specially authorized testing institutes. A simulation model, which may be used to simulate the behavior of the inverter in the event of an error, is also part of the respective certificate. In addition, the date of commissioning is decisive for the certification obligation." From SMA, 'PV grid integration', 4th revised edition, May 2012: bit.ly/1qf86Ri



4

The grid perspective

While the last section dealt with equipment standards and electrical parameters related to the solar system, this section focuses on LT grid integration. The key question in this section is: What are the effects of distributed solar on the LT grid? The answer to this question depends on the quantum of distributed solar capacity in the grid, the load pattern and the existing supply quality among other things. Therefore in order to understand the grid perspective, it is important to ask how much distributed solar the grid can reliably integrate.

There are various challenges and benefits of distributed solar PV on the grid. Some of the emerging challenges and DISCOM concerns at high penetrations are a) safety of the utility work personnel due to potential islanding, b) quality of the power being injected in the grid and wear and tear of the grid equipment, c) reverse power flows and associated loss of voltage regulation, d) phase balance, e) variable and partially unpredictable nature of solar generation and the higher transaction costs arising from a high number of small generators, etc. Similarly there are a number of benefits accruing to the grid from high penetration of solar PV. These are a) increased grid supply reliability from lower transformer loading and back-up supply, b) improved power quality – especially voltage profile with associated reactive power support, c) deferring grid investments and avoiding costlier peak power purchases, d) reduction in T&D losses, etc. For more details on these issues, see Annexure D.

4.1 Distributed solar PV integration in LT grid – some international experiences

This section only looks at the technical issues at the LT distribution grid level. It does not elaborate any issues that may arise at the transmission level or at the level of grid dispatch, since these are affected by many other parameters like the overall quality of the grid, the energy mix, type of electrical equipment on the distribution feeder, demand-supply patterns, grid management and forecasting skills, and even the weather, among other things. Similarly this section does not look at any system wide penetration or policy targets at the broader level of a country/state or utility service area since these caps are generally based on a combination of commercial and technical considerations arising as a result of the cumulative penetration of distributed solar and not just the penetration at a feeder/transformer.

The issue of safe grid penetration levels for distributed renewable energy is a widely researched and hotly debated topic. The penetration limit stems from the technical ability of the grid to reliably integrate distributed solar capacity. One obvious lesson is that there is no one 'silver bullet' benchmark that is applicable to all grids across the world. Penetration is highly dependent on a variety of factors (loads, climate, grid quality, consumer behavior, etc.) and hence will vary from place to place. Several studies conducted across the world, point to different 'safe penetration limits'.

To further compound the problem, there is no universally accepted definition for grid penetration. There are several ways in which grid penetration can be defined for any given sample study area of the distribution network. The most prominent ones define penetration as:

- The ratio of PV capacity to the peak load demand
- The ratio of PV capacity to the minimum daytime load
- The PV capacity as a percentage of the distribution transformer rated capacity

USA

California:

California was one of the first areas with relatively large scale capacity of distributed PV. Its older rule allowed for automatic approval for applications up to the threshold of 15% of line section annual peak load as measured on the substation¹³⁷. The rationale behind its primary solar PV penetration threshold was that as long as maximum DG generation on a line section was always below minimum load, issues such as unintentional islanding, voltage deviations, etc. would be negligible¹³⁸.

This primary threshold level of 15% has become a widely used rule of thumb. In 1999, the California Public Utilities Commission (CPUC) issued an order to address interconnection standards in California resulting in a revised CPUC Rule 21. The review process made interconnections for small low-impact generators quick and efficient at low penetration levels¹³⁹. The basis for the 15% number came from some statistical analysis and rules of thumb which suggested that the annual minimum load on a line section is approximately 30% of the annual peak load. Thus one-half of this estimated annual minimum load or a threshold of 15% was selected as a conservative number to ensure that there is no risk of distributed generation capacity exceeding the load. Using the peak load as a reference is common practice because data on minimum load is not easily available or reliable¹⁴⁰. The 15% threshold was then adopted in the FERC 'Small Generator Interconnection Procedures (SGIP)' guidelines and consequently by other states for their interconnection procedures.

While reviewing PV interconnection applications in regions with a high level of PV deployment in California, the 15% interconnection threshold value is often exceeded. This has warranted further studies by utilities to ensure safety of the grid. Due to an increasing number of penetrations crossing the 15% threshold, California, among other states, has since modified its 15% threshold to 100% of minimum daytime load¹⁴¹. This still ensures that load is never exceeded on a line section, but with a less conservative safety margin than under the previous rule. This was done to ensure that a PV system interconnection should not be forced into a study process solely because it had failed one or more initial technical review screens¹⁴². This also minimises the risk that a PV system will cause adverse impacts such as reverse power flow beyond the substation.

Hawaii

At the end of 2013, the total installed capacity of rooftop solar was 300 MW. The Hawaiian electric company (HECO), representing three Hawaiian electric utilities noted that 10% of the customers of HECO in the island Oahu have rooftop solar¹⁴³. Increasingly there are a number of distribution circuits having PV capacity larger than the daytime minimum load. The utilities have established additional policies to ensure that additional distributed solar PV does not destabilise the grid. An interconnection study has to be carried out now in areas of high rooftop solar installations before installing and interconnecting new systems. This effectively slowed down the rate of new rooftop solar installations in the last quarter of 2013¹⁴⁴.

137 There are further screens in addition to the penetration limit, like short circuit current contribution, etc.

138 NREL, "Updating Interconnection Screens for PV system Integration": 1.usa.gov/OuZisW

139 *ibid*

140 US Department of Energy, "Beyond the 15% rule", September 2011: 1.usa.gov/1dDa1Nk

141 CPUC, RULE 21, details: bit.ly/1k8dDt0; Daytime is 10am-4pm for fixed PV, 8am – 6pm for tracking PV

142 Freeing the grid, best practices in state net metering policies and interconnection procedures: bit.ly/1jEG5Rb

143 Hawaiian Electric, "Rooftop PV enjoys another strong year in Hawaii": bit.ly/1gThV6d

144 Star advertiser, "PV installations up 39% in 2013 across HECO's service area": bit.ly/1hljTsH

Europe

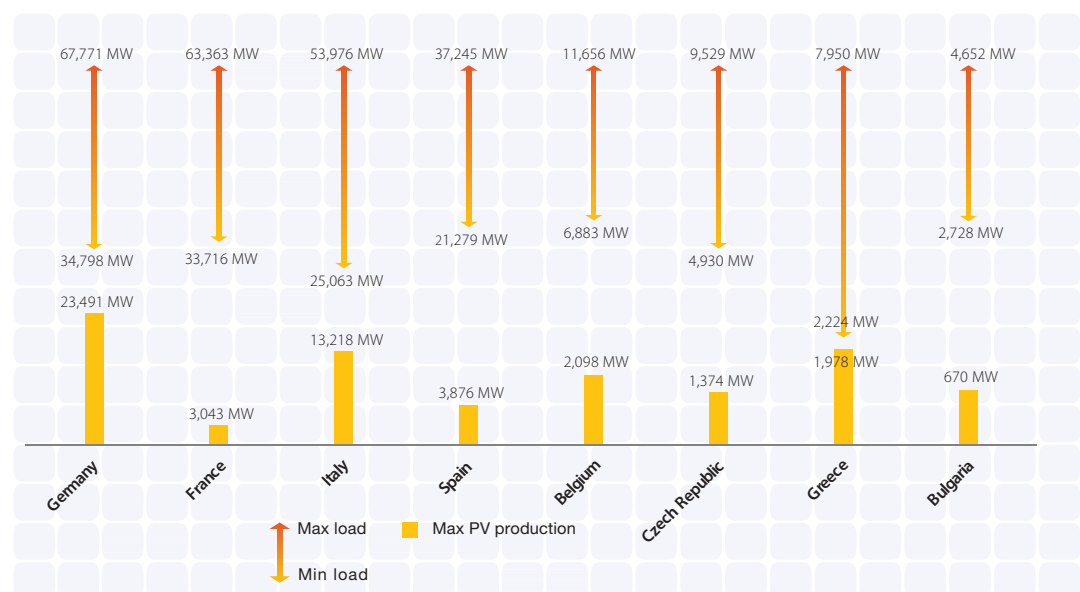
Germany

Germany is a classic case study of very high penetration of distributed solar PV¹⁴⁵. It presently has an installed capacity of 35,715 MW (as of December 2013). But what is most interesting is that 65% of this capacity is at the LV level (230 V / 400 V) and 35% at the MV level (11 to 60 kV)¹⁴⁶. Figure 8 shows that maximum instantaneous power provided by PV in comparison with the load between May and September in Germany has already reached 49%¹⁴⁷. However this is a national average and does not take into account regional variations. Given that the solar resource is much better in southern Germany, most of the solar PV capacity is located in the south of the country. Hence the local instantaneous penetrations in the south are bound to be even higher. There are many LV grids in which PV capacity can exceed peak load by a factor of 10!¹⁴⁸ Interestingly, Germany does not recommend any penetration limit under its BDEW or VDE ARN 4105 regulations. However, it has been able to reliably integrate large scale PV due to the adoption of various technical solutions such as LVRT, reactive power support, power-frequency droop characteristic, etc.

Greece and Italy

Some other countries in Europe have an instantaneous contribution of 20-25% with Greece topping the list with 77%. Italy too has a very high penetration with its maximum PV production of 13.2 GW being more than 50% of the minimum load of 25 GW.

Figure 8: Maximum and minimum country load profiles during mid-day peak between May and September and in comparison with maximum PV production¹⁴⁹.



Examples from the recent past show that countries are becoming increasingly capable of reliably handling large amounts of renewables in their grid. There have been specific instances, such as on 11th May 2014 at noon, when wind, solar PV, biomass and hydro contributed 43.5 GW (74%) of the instantaneous power requirement in Germany¹⁵⁰ (See Figure 9).

¹⁴⁵ Data from Bundesverband Solarwirtschaft, reported in "Recent facts about photovoltaics in Germany", Fraunhofer Institute, p. 34: bit.ly/1hBZCPI

¹⁴⁶ Thomas Ackermann, "What matters for successful integration of distributed generation": bit.ly/1fv20Pz

¹⁴⁷ EPIA Global Market Outlook for Photovoltaics, 2014-18: bit.ly/UnwshD

¹⁴⁸ "Time in the Sun: The Challenge of High PV Penetration in the German Electric Grid", Power and Energy magazine, IEEE, March-April 2013: bit.ly/1oMcia6

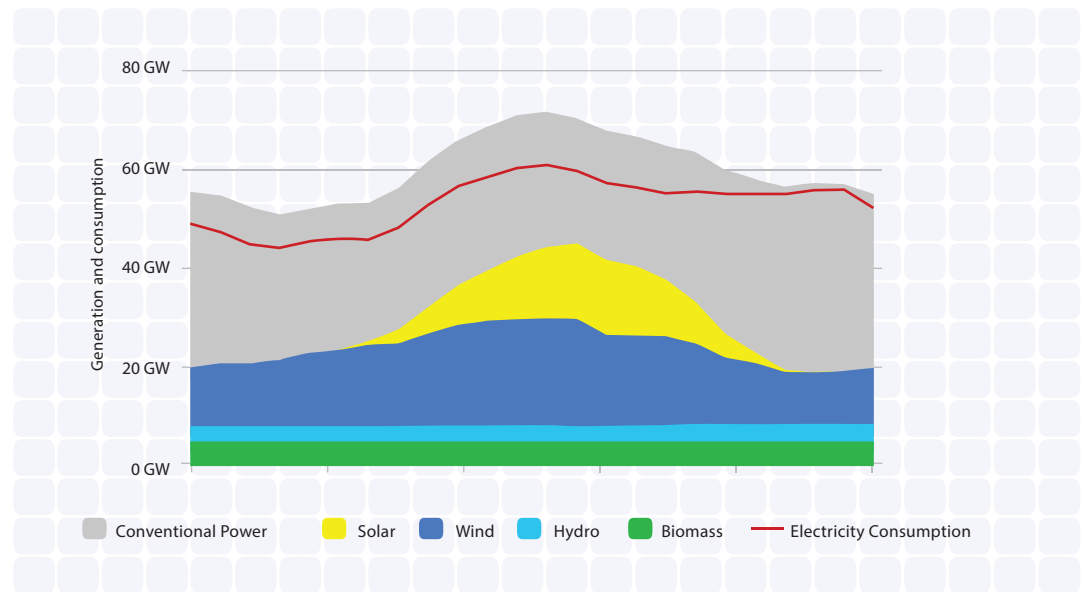
¹⁴⁹ EPIA Global Market Outlook for Photovoltaics, 2014-18: bit.ly/UnwshD

¹⁵⁰ Data from Agora Energiewende: <http://bit.ly/1tLhdy>

Similarly, in Australia, on 29th September 2013 at 12.30 pm, solar power contributed to 9.34% of electricity demand in the National Electricity Market and 28% in the state of South Australia¹⁵¹.

In February 2002, the International Energy Agency (IEA) published a paper¹⁵² on the impacts of power penetration from photovoltaic power systems in distribution networks. The agency conducted a study to determine the upper limits to the amount of PV that can be fed into the power system without causing problems. The study showed that, for loads above the minimum load, the penetration of PV can rise as high as 158% of the maximum load on a single LV line and up to 75% of the maximum load on all MV/LV transformers in an MV ring, without any significant problems.

Figure 9: Renewable Energy meeting 74% of instantaneous load in Germany on 11th May, 2014



151 Sunwiz, Solar Industry Intelligence: bit.ly/1d6wpig

152 IEA, "Impacts of power penetration from photovoltaic power systems in distribution networks": bit.ly/1INNiOX

4.2 Indian experience

India is just beginning to deploy distributed PV at some scale and thus has limited experience in dealing with its technical challenges. With regard to primary technical penetration thresholds, there are presently four Indian states (Tamil Nadu, Delhi, Kerala and Punjab) that have recommended penetration limits for distributed solar under their respective policies/regulations (See Table 9). Tamil Nadu mandates that the penetration of distributed PV into the grid shall not exceed 30% of the distribution transformer (DT) rated capacity, while Delhi and Punjab have proposed levels of 15% and 30% respectively¹⁵³. Kerala, on the other hand, had initially proposed a limit of 50% of the DT capacity but has finalised a different metric allowing up to 80% of minimum daytime (8am-4pm) load.

Since a safe penetration threshold is a factor of various variables like load patterns, grid supply quality, consumer behaviour, weather patterns, etc., it necessarily varies from place to place. Hence the higher penetration thresholds of TN, Punjab and Kerala are welcome. The learning and experiences in these states will be very valuable to other states.

Table 9: Examples of distributed PV penetration limits in Indian states

Country	State	Penetration limit as a percentage of rated distribution transformer capacity
India	New Delhi (draft)	15%
	Tamil Nadu	30%
	Kerala	80% of minimum daytime load on DT (as measured between 8 am – 4pm)
	Punjab (draft)	30%

4.3 Lessons for India

The above International and Indian experiences bear out that there is no one safe penetration limit - it varies from region to region. Many countries like Germany, Italy, Greece and states like California, Hawaii etc. in the USA have areas which have managed very high penetrations without much trouble.

“In many cases, even when PV penetration is substantially above 15%, the supplemental studies do not identify any required system upgrades. There are many circuits across the United States and Europe with PV penetration levels well above 15%, where system performance, safety, and reliability have not been materially affected.”¹⁵⁴

This indicates that a 15-30% threshold is a relatively conservative benchmark and that significantly higher penetration can be reliably integrated with existing technical solutions.

Hence the CEA can make a recommendation to the SERCs to automatically allow distributed PV interconnections with a simplified approval process on a First Come First Served (FCFS) basis up to the threshold of 15-30%. For such a process, utilities will need to have updated information on penetration levels of distributed solar and available capacity on their DTs in the public domain. Importantly, such a penetration limit should not be interpreted as fixed upper limit but as the first checkpoint for additional screening and technical studies. Presently section 4 (6) (a, b) of the CEA standards mandates that the utility should undertake an inter-connection study to determine the maximum net capacity of DG at a particular location. This should be modified so that such studies are to be undertaken only after the first check-point penetration limit of 15-30% of rated DT capacity is reached.

¹⁵³ Numbers for Delhi and Punjab are still in the draft stage and subject to finalisation.

¹⁵⁴ NREL, “Updating technical screens for PV interconnection”: 1.usa.gov/1loOfiK

The Forum of Regulators (FoR) has also recommended a similar approach. In its working group report titled, 'Evolving Net-metering Model Regulation for rooftop based solar PV projects'¹⁵⁵ it notes that the penetration levels be introduced in a "phased manner so that the utilities have sufficient time to undertake technical studies." Until that time, the penetration level should be fixed at 15% of peak DT capacity "to avoid any technical issues in the initial phase. The cap of 15% can be reviewed based on technical studies conducted by the utility or based on standards subsequently defined by CEA."

Once the penetration threshold (15-30%) is reached, utilities can perform some preliminary screening checks based on ratios such as **"Minimum load to generation ratio, Stiffness factor, Fault ratio factor, Ground source impedance ratio, etc."** (See Table 13, Annexure F) to ascertain if the system effects of the distributed PV have become significant enough to warrant additional detailed technical studies. It may well be the case that there is no problem in increasing the present threshold. Changes may be needed in safety settings or hardware upgrades to further increase the hosting capacity of the local grid. Detailed loading, voltage profile and fault studies may need to be conducted based on the preliminary screening checks to further understand the impacts of distributed PV on the grid and its hosting capacity. **Annexure F has some potential outlines to help DISCOMs monitor the health of the distribution grid based on certain metrics and conduct further detailed studies. The CEA can specify a broad template (outlining the parameters and methodology) for such technical studies.**

As cumulative distributed solar deployment picks up, utilities should conduct sample studies in high penetration pockets to ascertain if a higher threshold in comparison to the recommended starting point of 15-30% would be technically justified. They can go a step forward and proactively carry out studies in potential high penetration areas before the thresholds are reached. In addition to factoring in DG deployment into network planning, such steps would allow for faster deployment¹⁵⁶.

4.4 Potential adaptations to increase the hosting capacity of LT grids

Each LT grid can accommodate some level of distributed PV generation without any modifications. As we have seen in the earlier section, practically no technical issues are expected at low penetration levels. The challenge posed by distributed solar power to grid integration and grid management is essentially at very high penetration levels. Loading, voltage profile and fault studies conducted by utilities at high penetrations may conceptually throw up four possibilities, namely,

- No equipment (feeder, transformer, etc.) upgrade or protection setting change will be required and further distributed PV deployment up to a point can be considered.
- No equipment (feeder, transformer, etc.) upgrade, but protection settings will require to be tweaked to incorporate more PV.
- No equipment (feeder, transformer, etc.) upgrade, but protection hardware will require to be upgraded to allow more PV.
- Both equipment (feeder, transformer, etc.) and protection hardware need to be upgraded to enhance the hosting capacity of the LT grid.

From a purely technical perspective, hosting capacity can always be increased to accommodate more PV based on existing technical solutions (as we have seen in Section 3.2), but cost sharing arrangements would need due considerations. Some potential solutions are noted below.

¹⁵⁵ Forum of Regulators, "Evolving Net-metering Model Regulation for rooftop based solar PV projects": bit.ly/1o2V9Y2

¹⁵⁶ IREC, Integrated Distribution Planning Concept Paper, May 2013: 1.usa.gov/TxZ2Ms

Potential solutions to increase hosting capacity of distribution grid under very high penetration¹⁵⁷

A detailed study on a range of possible technical solutions was carried out under the project PVGRID¹⁵⁸. Some important solutions are noted below:

Distribution Grid Adaptations:

- Voltage control through On Load Tap Changer (OLTC)¹⁵⁹ for MV/LV transformer and booster transformers along long feeders.
- Network reinforcement and increasing cable and transformer capacity, thereby directly increasing the grid's PV hosting capability.
- Static VAR Compensators (SVC): SVCs can provide instantaneous reactive power and help maintain voltage levels. However, in high PV penetrations scenarios, with most inverters providing VAR control, this investment can easily be deferred or be completely unnecessary. In fact a recent study by the National Renewable Energy Laboratory (NREL) concludes that at higher penetration levels, the existing VAR compensators can completely be eliminated if all inverters on the grid provide VAR compensation functions¹⁶⁰.

Consumer Side Adaptations:

- Additional inverter functions (LHVRT, LHFRT, power-frequency droop characteristics, reactive power support as a function of local voltage, etc.) supporting grid integration of distributed solar and providing grid support. "Advanced inverters can mitigate voltage-related issues and potentially increase the hosting capacity of solar PV by as much as 100%"¹⁶¹.
- Reducing injection of solar PV power into the grid to overcome voltage and congestion issues through
 - Increased self-consumption of PV,
 - Curtailment of power injected at point of common coupling (PCC) by limiting it to a fixed value
 - Storage during periods of peak solar generation
 - Load shifting through tariff incentives or demand response

¹⁵⁶ Cost implications and cost sharing will be crucial policy and regulatory issues but are beyond the scope of this study.

¹⁵⁸ The PVGRID project publications: bit.ly/UnxXwm

¹⁵⁹ "Voltage regulators, or OLTCs, are typically constructed as autotransformers with automatically adjusting taps. The controls measure the voltage and load current, estimate the voltage at the remote (controlled voltage) point, and trigger the tap change when the estimated voltage is out of bounds. Multiple tap change actions may be performed until the voltage is brought within bounds. The taps typically provide a range of $\pm 10\%$ of transformer rated voltage with 32 steps. Each step of voltage is therefore 0.625% of the rated voltage", From NREL, "Distribution System Voltage Performance Analysis for High-Penetration Photovoltaics": 1.usa.gov/OMljE2

¹⁶⁰ NREL, "Distribution System Voltage Performance Analysis for High-Penetration Photovoltaics": 1.usa.gov/OMljE2

¹⁶¹ Barun et al., "Is the distribution grid ready to accept large-scale photovoltaic deployment? State of the art, progress, and future prospects", 2011

Interactive Adaptations:

- A communication protocol and platform¹⁶² between DISCOMs/SLDCs and solar systems. This allows SLDCs to directly control PV generation in emergency situations by sending appropriate signals. Similarly, reactive power support can also be initiated in response to utility signals rather than as a part of a pre-set function. Such communication is also helpful in changing any operational set points.

While India is presently not experiencing high penetration scenarios, it would be in the country's interest to critically engage and understand the emerging technical challenges and solutions. Early preparatory work on this front would allow for a smoother development of the distributed PV sector as it is expected to grow exponentially in the coming years.



¹⁶² In Germany, according to §6 of the German renewable energy act (EEG), PV systems with an installed capacity of more than 100 kW must participate in feed-in and grid security management. The BDEW stipulates this for all plants feeding in at the medium voltage level. The grid security management requirements in Germany are: Remote-control reduction of feed-in capacity in grid overload situations, via a radio ripple control receiver, limitation of feed-in power in up to ten adjustable levels (for example, 0%, 30%, 60%, 100% of the agreed installed active power), setting of the required target value in less than one minute, and gradual increase of power at a maximum rate of 10% per minute.



5 Summary of observations and recommendations for a way forward

Distributed solar PV (particularly the rooftop segment) is expected to grow significantly in the coming years due to increased economic viability for certain consumer segments (commercial, industrial and high-use residential) in particular geographical areas in India. While many states have already put in place favourable net metering policies, some state ERC regulations support rooftop projects through the feed in tariff route. By some estimates, India could install 3 - 5 GW¹⁶³ of distributed solar in the next three - five years.

However, since the grid was not particularly designed for large scale distributed generation, utilities are concerned about the implications of variable solar generation on the power quality, its impact on the LT distribution grid and the safety of its work force. These apprehensions and fears are heightened due to a lack of clear documentation and understanding of these concerns and their potential solutions in the Indian context.

Distributed PV can provide various system benefits but at the same time, very high penetrations raise certain technical concerns with regard to the grid. Up to a point, DG solar can help in increasing the grid reliability (reducing peak shortages and loading on transformers), power quality (improving voltage and power factor profiles, etc.), deferring grid related investments (on transformers) and reducing T&D losses. However some of the common technical concerns at very high levels of penetration (India is far away from such a scenario) are tail end voltage control, excess generation leading to reverse power flows resulting in (a) transmission grid congestion, (b) voltage rise in long feeders, (c) over-loading of equipment in shorter feeders with high demand density and more complicated grid balancing due to the variability and partial unpredictability of solar generation. (See Annexure D)

In this study, we describe the technical issues involved, both for the PV system as well as the distribution grid, based on a review of global and Indian policies and regulations. Further, we document existing technical standards and practices, and propose a possible way forward. This study specifically addresses (1) the quality of the solar power being injected into the grid, (2) safety issues, (3) ways and means in which DG can support the grid and help its own reliable integration, and (4) the interaction of distributed solar PV and the distribution LT grid.

With this study, we hope to initiate a serious and objective discussion on the technical aspects of distributed solar PV. By beginning the discussion on the issues emerging from high DG penetration and learning from the international experience, India can manage the technical issues likely to emerge in due time better. A greater common understanding of the issues would help facilitate faster distributed PV deployment.

5.1 Key observations

5.1.1 Global context

There has been a strong growth of distributed solar PV across the world. Germany has been leading the way with 65% of its total installed solar capacity of 35.7 GW¹⁶⁴ in 2013 connected to the low voltage grid (240 V or 400 V)¹⁶⁵. The USA (particularly California), China and Australia have also seen rapid growth in distributed solar in recent times. (See Annexure E.) A significant amount of knowledge generation through their experiences is available in the public domain, and a continuous process towards learning and improvement is underway. It is vital that India leverages this experience to create a facilitating framework allowing smoother and more efficient deployment of solar DG.

¹⁶³ BRIDGE TO INDIA market research and analysis

¹⁶⁴ The Germany Federal Network Agency: bit.ly/1INGi4o

¹⁶⁵ Thomas Ackermann, "What matters for successful integration of distributed generation": bit.ly/1fv20Pz

5.1.2 Concerns of distribution utilities

Distributed kW scale solar PV plants (mainly rooftop) are only now beginning to be deployed in many states with the help of supporting policies and regulations. Hence utilities presently have limited experience in dealing with distributed solar PV systems connected mainly to the LT distribution grid. They have some valid concerns (listed below) regarding distributed solar PV as it is finally their responsibility to maintain reliable grid supply.

- **Power quality:** DISCOMs are apprehensive about the quality of the power being injected into their distribution grids. This is mainly to do with flicker, harmonics and DC injection.
- **Safety:** Utilities are rightly concerned about the safety of their personnel, especially while working around the possibility of the formation of an unintentional island from the operation of the distributed solar PV systems.
- **Low voltage distribution grid:** They are also concerned about the impact on the LV distribution grid (voltage levels, power factor, higher wear and tear of equipment, etc.) from high penetration of a large number of distributed solar generators.
- **Transaction Costs:** Another logistical worry for utilities is the significantly higher transaction effort in terms of metering, inspection and certifications.

5.1.3 Variation of some technical requirements across states

Many Indian states as well as the central government through the MNRE/SECI have been promoting rooftop photovoltaics (RTPV) for the last few years. While most state regulations have referred to national CEA interconnection standards ('Technical Standards for Connectivity of the Distributed Generation Resources', 2013) with regard to technical issues, there have been two areas where there are some variations across states. The first one is with regard to limits on system sizes and allowed inter-connection voltages. The details are provided in Table 10. These generally tend to be in line with state supply code regulations.

The second is with regard to metering requirements. Some state regulations mandate meters of a higher accuracy class in comparison with the CEA metering regulations, 2006 (with the 2013 amendment for renewables). Both these variations have a direct bearing on the cost, especially for small kW scale installations.

Table 10: Comparison of technical norms of system size and interconnection voltages by states

Voltage (Volts)	State	240	240/415	415	11,000	11,000/33,000
System size (kW)	Gujarat	< 6		6-100	> 100	
	Uttarakhand	< 4		4-75	75-1500	1500-3000
	Tamil Nadu		< 4	4-112		> 112 (HV/EHT)
	Delhi (draft)		< 10	10-100		> 100 (HV/EHT)
	Kerala	< 5		5-100	100-3000	
	Punjab (draft)	< 7		7-100	>100	
	Karnataka	Up to 5		5-50	> 50	
	West Bengal	LV or MV or 6 kV or 11 kV or any other voltage as found suitable by the DISCOM				
	Chhattisgarh			50-100	100-1000	
	MNRE ¹⁶⁶	Up to 10		10-100		100-500
	SECI Scheme		Up to 10	10-100		> 100 (incl 66 kV)

166 MNRE guidelines for grid connected rooftop and small solar power plants programme: bit.ly/Vikmqb

5.1.4 Inverter and power quality

The inverter is at the heart of the solar PV system ensuring power quality and grid integration. The three important technical parameters which can affect the quality of the power being injected into the grid are harmonics, flicker and DC injection. In each of these three parameters, existing CEA regulations follow global best standards (See Section 3.1) as noted below.

- Harmonics- IEEE 519, wherein THD < 5%
- Flicker- IEC 61000
- DC injection - IEEE 1547 standard, wherein the maximum permissible level is 0.5% of the full rated output at the interconnection point.

Our market survey shows that today's inverters are capable of meeting these standards, thus addressing the power quality concerns of distribution utilities.

5.1.5 Inverter functioning range

Apart from the three basic parameters mentioned above, the solar system is allowed to function only within a certain range of voltage and frequency and is thus subject to the quality of the grid. These ranges vary from country to country. The CEA presently permits the system to function within a range of 80-110% of the nominal voltage, and between a 47.5-51.5 Hz frequency band. (See Sections 3.1.4 and 3.1.5.)

Presently, the moment the grid parameters move outside this range, the solar system is required to stop injecting power within a certain time frame. However advanced standards allow solar generators to remain connected to the grid if the voltage or frequency excursions are only temporary, thus avoiding nuisance tripping of the system. These are called Fault Ride-Through (FRT) functionalities (See Sections 3.2.2 and 3.2.4), namely the Low/High Voltage Ride-Through (LHVRT) and the Low/High Frequency Ride-Through (LHFRT).

5.1.6 Inverter support to the grid

Today's inverters are capable not only of reliably integrating with the distribution grid and maintaining the power quality mandated by it, but can also provide additional support to improve some grid characteristics and assist in fault recovery. Through the LHVRT and LHFRT functions, inverters can stay connected to the grid in times of momentary grid faults/failures. Inverters can provide grid supporting functions like power-frequency droop (See Section 3.2.3) (helping grid recovery) and reactive power support (See Section 3.2.1) to help maintain local grid parameters within their normative limits, at times in a more cost effective manner than centralised options. Such smart functionality in inverters comes practically at no extra costs in most cases and can be activated and incorporated without serious technical challenges. A significant share of the string inverter market in India is already capable of providing most of these functionalities.

The IEEE 1547 (the reference guideline for DG) is being revised, and many of these functions considered above are likely to be included. A draft version (IEEE 1547a) already allows some of these functions. More advanced functions, some of which may require communication capability (between inverter and utility/energy markets) are being considered in some countries. Examples of such functions are: limiting maximum active power upon instruction from the utility, supporting instructions to connect/disconnect, ability to update default settings in response to changing grid conditions, etc¹⁶⁷.

¹⁶⁷ 'Recommendations for updating technical requirements for inverters in Distributed Energy Resources': bit.ly/1hlykaz

5.1.7 Inverter and safety

Islanding refers to the condition in which a distributed solar system continues to energise the circuit even when the grid power from the utility is unavailable. Islanding can be dangerous to utility workers, who may not realise that a circuit is still powered when working on repairs or maintenance. To ensure safety, most countries including India mandate the anti-islanding (See Section 3.1.6) functionality, which requires the PV system to stop energising the grid as soon as grid power is unavailable. An emerging function is 'intentional islanding' which allows distributed solar PV to continue to power certain loads when the grid is down with adequate safety considerations. This is of utmost relevance in India where load shedding or power cuts are common in most DISCOM service areas.

5.1.8 Distributed PV penetration

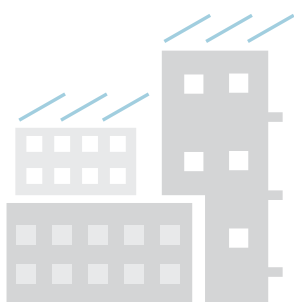
An important aspect of distributed solar pertains to its safe and reliable integration into the LT grid, especially with regard to very high penetration levels at the distribution transformer level. In California (one of the first jurisdictions to adopt behind-the-meter distributed solar PV at a significant scale) the rationale behind its primary solar PV penetration thresholds was that as long as maximum DG generation on a line section was always below the minimum load, issues such as unintentional islanding, voltage deviations etc. would be negligible¹⁶⁸. Based on this rationale and considering that typical distribution circuits in the US had their minimum load at roughly 30% of peak load, California adopted a conservative 15% penetration threshold. (See Section 4.1.) This penetration limit was the first checkpoint for supplemental studies and not an upper cap on deployment. The 15% screening under rule 21 has been recently updated to allow DG solar penetration automatically up to 'minimum daytime load' on any feeder. Minimum daytime load tends to be significantly higher than the minimum 24-hour load.

However global experience shows that there is no cause for worry even at much higher penetrations.

“In many cases, even when PV penetration is substantially above 15%, the supplemental studies do not identify any required system upgrades. There are many circuits across the United States and Europe with PV penetration levels well above 15%, where system performance, safety, and reliability have not been materially affected.”¹⁶⁹

Significantly higher penetrations are also being managed effectively. Germany presently has an installed capacity of 35,700 MW (as of December 2013). 65% of this capacity is at the LV level (230 V / 400 V) and 35% at the MV level (11 to 60 kV)¹⁷⁰. More significantly, maximum instantaneous power provided by PV in comparison to the load between May and September (varying between maximum of 67.7 and minimum of 34.7 GW) has already reached 49%. However, since most of the solar is concentrated in southern Germany, many LV grids have PV capacity, which can exceed peak load by factor of 10!¹⁷¹ As can be seen, there is no one safe reliable penetration number with international consensus, as it is a function of a variety of variables including load patterns, grid quality, consumer behaviour, etc.

As far as India is concerned, the CEA has not stipulated any penetration limit in its regulations. However some SERCs are specifying penetration limits in terms of a percentage of the DT's rated capacity. Tamil Nadu mandates that the penetration of distributed PV into the grid shall not exceed 30% of the distribution transformer (DT) rated capacity while Delhi and Punjab have proposed 15% and 30% respectively¹⁷². Kerala, on the other hand, had initially proposed a limit of 50% of the DT capacity but has finalised a different metric allowing up to 80% of minimum daytime (8am-4pm) load. (See Section 4.2.)



168 "Updating Technical screens for PV System Integration": <http://1.usa.gov/OuZisW>

169 Ibid

170 IEA, "What Matters for Successful Integration of Distributed Generation": bit.ly/1fv2OPz

171 "Time in the Sun: The Challenge of High PV Penetration in the German Electric Grid", Power and Energy magazine, IEEE, March-April 2013: bit.ly/1oMcia6

172 Numbers for Delhi and Punjab are still in the draft stage and subject to finalisation.

A safe penetration threshold is a factor of various variables like load patterns, grid quality, consumer behaviour, etc. and hence will vary from place to place. The learnings and experiences in these states would be very valuable to other states.

5.1.9 Potential solutions to increase hosting capacity of distribution grid under very high penetrations

In many cases, studies conducted for medium-high penetrations may reveal that no system changes (equipment or protection settings) are needed to allow for higher DG deployment. In some cases, it may be that only protection settings and/or protection equipment needs modification. To further increase the hosting capacity of the network, several options exist. A detailed study on such technical solutions was carried out under the project PVGRID¹⁷³. Some of the important solutions are noted below.

Distribution Grid Adaptations:

- Network reinforcement and increasing cable and transformer capacity, thereby directly increasing the grid's PV hosting capability
- Voltage control through On Load Tap Changer for MV/LV transformer and booster transformers along long feeders
- Reactive power support through Static VAR Compensators (SVC)

Consumer Side Adaptations:

- Additional inverter functions (LHVRT, LHFRT, power-frequency droop characteristics, reactive power support as a function of local voltage, etc.) supporting grid integration of distributed solar and providing grid support. "Advanced inverters can mitigate voltage-related issues and potentially increase the hosting capacity of solar PV by as much as 100%"¹⁷⁴.
- Reducing injection of solar PV power into the grid to overcome voltage and congestion issues through
 - increased self-consumption of PV
 - curtailment of power injected at PCC by limiting it to a fixed value
 - storage during periods of peak solar generation
 - load shifting through tariff incentives or demand response

Interactive Adaptations:

- A communication protocol and platform¹⁷⁵ between DISCOMs/SLDCs and solar systems. This allows SLDCs to directly control PV generation in emergency situations by sending appropriate signals. Similarly, reactive power support can also be initiated in response to utility signals rather than as a part of a pre-set function. Such communication is also helpful in changing any operational set points.

India is presently far away from the high penetration scenarios found in California, Italy, Germany, etc. In spite of the high penetration of distributed solar PV in California, the state still does not have support functionality like LHVRT, LHFRT, reactive power support, power-frequency droop control, etc. Hence it is important to understand that the technical issues noted here are only to

¹⁷³ The PVGRID project publications: bit.ly/UnxXwm

¹⁷⁴ Barun et al., "Is the distribution grid ready to accept large-scale photovoltaic deployment? State of the art, progress, and future prospects", 2011

¹⁷⁵ In Germany, according to §6 of the German renewable energy act (EEG), PV systems with an installed capacity of more than 100 kW must participate in feed-in and grid security management. The BDEW stipulates this for all plants feeding in at the medium voltage level. The grid security management requirements in Germany are: remote-control reduction of feed-in capacity in grid overload situations via a radio ripple control receiver, limitation of feed-in power in up to ten adjustable levels (for example, 0%, 30%, 60%, 100% of the agreed installed active power), setting of the required target value in less than one minute and gradual increase of power at a maximum rate of 10% per minute.

initiate a discussion in India to facilitate preparatory work. In a nutshell, till the distributed solar penetration becomes very high (at the substation level), concerns regarding safety and supply quality at the local grid level can be addressed through easily available technical solutions in a cost effective manner by way of changes in technical standards and ERC regulations. Making changes to standards early in the development of the sector will ease grid integration challenges and lower costs in the future by avoiding the need to make any retroactive changes.

5.2 Recommendations for a way forward

Based on our analysis and comprehensive stakeholder consultation thus far, we propose some technical suggestions for a way forward for faster and more effective deployment of distributed PV.

5.2.1 Amendments to the CEA's 'Technical Standards for Connectivity of the Distributed Generation Resources' Regulations, 2013

a. Modifications in existing voltage/frequency functions and new additional functions:

The CEA at present permits the system to function within a range of 80-110% of the nominal voltage and between a 47.5-51.5 Hz frequency band. (See Sections 3.1.4 and 3.1.5.) While these ranges are appropriate for existing solar penetration, based on further studies, the CEA can consider extending the operating voltage and frequency range to better reflect Indian operating conditions¹⁷⁶ if this helps in grid recovery after faults. On the low voltage side, the inverters may be allowed to remain connected at voltages slightly below the present limit of 80%, if they support the grid by supplying reactive power.

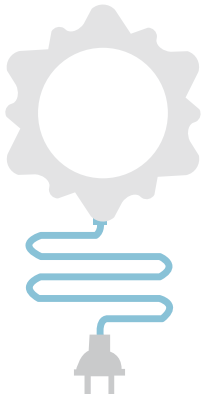
Earlier it was thought that in order to handle distributed solar with regard to grid disturbances, it was necessary to mandate immediate disconnection. This belief is also reflected in IEEE 1547. However, present day inverters can support the grid during low voltage and low frequency transients and assist in grid recovery following large grid disturbances. Hence LHVRT and LHFRT should be allowed under sections 5 [11] [6] [a,b]. When the technical standards are updated, fault ride through capabilities should be implemented and the safe operating range should be revisited. Anti-islanding specifications should also be updated to be in synergy with these FRT capabilities.

Similarly additional functions like reactive power support for voltage support and power-frequency droop for over-frequency regulation support should be considered as the cumulative deployment increases. Similarly, re-connection of distributed PV systems to the grid after faults would need to be done in a soft manner to avoid voltage or frequency spikes and oscillations if all systems were to reconnect at the same time. This can be achieved in two ways, either by gradually increasing active power output, or randomly re-connecting within a small time window.

All such functionalities can be initiated in a pre-determined auto-response mode and do not need any communication infrastructure. Our review indicates that all these capabilities are easily available at practically no extra costs in inverters available in the market today. The CEA should mandate such functionality on systems only above a certain size (say 10 kW) to avoid any cost disadvantage on smaller systems. This size threshold may vary from function to function.

Technical standards need to recognise system benefits of such changes and mandate them for new installations in the next round of update of technical standards. If such changes are not made in due time, retrofits can become very costly (as in 50.2 Hz case in Germany (See Section 3.2.3), and logistically difficult since distributed solar growth can be very fast. Data acquisition systems for larger plants (> 100 kW) can help monitor compliance.

¹⁷⁶ The standard operating voltage range (80-110%) specified for distributed solar PV operation is often violated in India due to a number of reasons.



b. Consider allowing intentional islanding:

An additional function of special relevance in India (with occasional black/brownouts during daytime) is 'intentional islanding'. This feature allows the solar PV system to disconnect from the grid in the event of a grid failure and continue to supply pre-decided critical loads on the consumer side of the meter¹⁷⁷. This is possible in two ways, (a) the hybrid inverter works in an off-grid mode, and continues to charge batteries which power certain loads or (b) the inverter continues to function in grid-tied mode in synergy with the larger backup system, most likely diesel based generators. The second option is more feasible for larger loads, most of which have existing diesel generation backup facilities. Utilities are well versed with such backup facilities, which already have the required safety features which prevent energising the local grid (reverse flow). Using distributed solar PV in such an intentional island mode is technically feasible and can also reduce costs compared to costlier diesel generation. This intentional islanding feature is mentioned as a note in the CEA 'Installation and Operation of Meters', 2006 draft¹⁷⁸ amendment regulation released in 2013, but is omitted in the final CEA 'Technical standards for connectivity of the distributed generation resources', 2013 regulations. The CEA should consider allowing this functionality in the future based on appropriate studies and pilot projects. Adequate technical specifications for safe automatic isolating equipment at appropriate locations, challenges around anti-islanding control for multiple distributed generators within a micro-grid¹⁷⁹, safety concerns for personnel and legal liabilities with regard to intentional islanding are crucial issues which merit serious discussion.

c. Distribution transformer level penetration:

Global experience indicates that a 15-30% threshold is a relatively conservative benchmark and that significantly higher penetration can be reliably integrated with existing technical solutions. **Hence the CEA should recommend SERCs to automatically allow distributed PV interconnections with a simplified approval process on a First Come First Served (FCFS) basis up to the threshold of 15-30%.**

For such a process, utilities will need to have updated information on penetration levels of distributed solar and available capacity on their DTs in the public domain. Importantly, such a penetration limit should not be interpreted as a fixed upper limit, but as the first checkpoint for additional screening and technical studies. At present, section 4 (6) (a,b) of the CEA standards mandates that the utility should undertake an inter-connection study to determine maximum net capacity of DG at a particular location. This should be modified so that such studies are to be taken up only after the first check-point penetration limit of 15-30% of rated DT capacity is reached.

Once the penetration threshold (15-30%) is reached, utilities can perform some preliminary screening checks based on ratios such as minimum load to generation ratio, stiffness factor, fault ratio factor, ground source impedance ratio, etc. (See Table 13, Annexure F) to ascertain if the system effects of the distributed PV have become significant enough to warrant additional detailed technical studies. It may well be the case that there is no problem in increasing the present threshold. Changes may be needed in safety settings or hardware upgrades to further increase the hosting capacity of the local grid. A larger penetration may be allowed, based upon DT capacity and on studies which assess anti-islanding ability, ground fault over-voltages (if generation is not effectively grounded), over-current device co-ordination and voltage regulation. Detailed loading, voltage profile and fault studies may need to be conducted based on the preliminary screening checks to further understand the impacts of distributed PV on the grid and its hosting capacity.

Annexure F has some potential outlines to help DISCOMs monitor the health of the distribution grid based on certain metrics and conduct further detailed studies. The CEA can specify a broad template (outlining the parameters and methodology) for such technical studies.

177 Rocky Mountain Institute (RMI), "Microgrids: Providing safe harbor in a storm", 10th January 2013: bit.ly/1qf7afv

178 CEA, Draft Installation and Operation of Meters, 2013: bit.ly/1fqC3ab

179 Green Tech Media (GTM), "Grid Edge Report", 2014: bit.ly/VzQsOg

As cumulative distributed solar deployment picks up, utilities should periodically conduct sample studies at high penetration pockets to ascertain if a higher threshold in comparison to the recommended starting point of 15-30% would be technically appropriate. They can go a step forward and proactively conduct studies in potential high penetration areas before the thresholds are reached. In addition to factoring in DG deployment into network planning, such steps would allow for faster deployment¹⁸⁰. From a purely technical perspective, the hosting capacity can always be increased to accommodate more PV (See Section 5.1.9), but cost and cost sharing arrangements would need due considerations.

- d. Advanced future inverter functions:** There are certain advanced inverter functionalities¹⁸¹ (such as limiting maximum power output, providing status and measurements on current energy and ancillary services, supporting utility commands to connect/disconnect, etc.), which can be useful for grid management in high penetration scenarios. Most of these advanced functionalities need communication protocols in place to communicate with the utility or power markets. Such communications possibilities also allow changing pre-set inverter parameters in response to changes in the power system. A committee headed by the CEA including utilities, manufacturers, developers, NCPRE, Central Power Research Institute (CPRI), etc. should critically look into all such advanced functionalities and recommend revisions to technical regulations from time to time.
- e. Testing:** Section 5 (8) (2) of the CEA regulations mandates measuring DC injection, harmonics and flicker prior to commissioning and once a year thereafter. This should be made applicable only above a certain project size (say > 100 kW).

5.2.2 Uniform technical standards across states

As seen in earlier sections, technology is more than capable of reliably and cost-effectively integrating large amounts of DG into the LT distribution grid resulting in significant systemic benefits. One of the most important supporting role that can be played by the government in facilitating this transition is assisting in moving towards uniform technical standards (to the extent possible) across all states. State technical regulations should mirror CEA regulations and need not be more stringent. Non-standard technical regulations, procedures and specifications across states can act as a strong barrier, resulting in additional costs for manufacturing and deployment and thereby slowing down the growth of this sector. This is especially important for metering regulations.

5.2.3 Solar system size and connection voltages

Most states limit the size of the solar system with respect to inter-connection voltages. Single-phase connections are allowed up to 5 or 10 kW, while three phase inter-connections are limited roughly between 50-100 kW. Systems larger than this size are mandated to inter-connect to an 11 or 33 kV system. These tend to be in line with state supply code regulations and such an approach has also been seconded by the Forum of Regulators¹⁸². However, to get the maximum benefit out of distributed generation at a lower cost (when solar system size is smaller than the minimum daytime load), a larger system may be allowed to be connected at the LT level on a case by case basis as long as it is meeting all the technical requirements. DT capacity, anti-islanding ability, ground fault over-voltages (if generation is not effectively grounded), over-current device co-ordination, and voltage regulation would need due consideration in such cases. Mandating inter-connection to a higher 11/33 kV voltage in such cases does not benefit the system in any way, but only results in higher costs.

¹⁸⁰ IREC, "Integrated Distribution Planning Concept Paper", May 2013: 1.usa.gov/TxZ2Ms

¹⁸¹ 'Recommendations for updating technical requirements for inverters in Distributed Energy Resources': bit.ly/1h1Ykz

¹⁸² Forum of Regulators, Minutes of the 39th meeting: bit.ly/1r3nCAE

5.2.4 Certifications and inspections

After achieving grid parity and with a facilitating policy framework, growth of distributed solar can be exponential (as is seen in Germany having over 1.4 million systems with an installed capacity of 35.7 GW which has been achieved only in the last few years) and can overwhelm the utility management system in terms of procedural logistics with regard to permissions, inspections, certification, etc. Hence the process for certification/permitting has to be graded in nature with smaller systems having a simpler process - being allowed to self-certify¹⁸³. Accredited third party validators could help the utility in this process. Safety with regard to the anti-islanding feature and other protection devices, and compliance of the equipment and system with the CEA standards, are the two most important checks to be performed. Such certification processes have to be coupled with random checks with heavy fines/blacklisting for non-compliance. A possible framework is suggested in Table 11. See Annexures G and H for more information.

Table 11: A possible framework for certification and testing

System size	0 - 10 kW	10 - 100 kW	> 100 kW
Equipment certificates, especially for inverters	Standard test certificate from accredited laboratory declaring conformity with CEA standards ¹⁸⁴ .		
System installation certificate (pre-commissioning)	Self-certification with appropriate declaration for safety.	Certified Energy Auditor/ Licensed Electrical Contractor/Self-certification for MNRE accredited channel partners (1A certification)	Certified Energy Auditor/ Electrical Inspector
Annual testing	NA	NA	Only for high penetration zones

Note: System owners would need to provide an appropriate declaration for safety with the system installation certificate.

5.2.5 Best practices and safety guidelines

India presently has a set of generic standard safety codes that are applicable to all power plants. The CEA in consultation with industry experts should formulate comprehensive safety guidelines and best practices for installation, testing and commissioning tests for distributed solar systems. However, a solar PV specific safety and certification protocol is absent. The National Electrical Code (NEC) codes of the USA (detailed in Annexure I) provide a good starting point for the development of such a solar specific safety code. This is of paramount importance considering the growth of the sector and the entry of a high number of new developers and system integrators in the market. Apart from safety guidelines, a manual on best installation and O&M practices could be brought out by industry associations.

¹⁸³ Germany has no active permitting process for installations smaller than 30kW and does not require visits by the distribution grid operator or other local permitting authorities. Some of the procedures can be done online. Similarly in England, certified installers can directly connect to the system to the grid and notify the utility thereafter.

¹⁸⁴ For Germany, "A unit certificate confirming conformity with all requirements of the medium voltage directive has become mandatory for each generation unit (i.e., each inverter type) at the same time as the dynamic grid support capability. The manufacturer receives this certificate following comprehensive testing of the respective device by specially authorized testing institutes. A simulation model, which may be used to simulate the behaviour of the inverter in the event of an error, is also part of the respective certificate. In addition, the date of commissioning is decisive for the certification obligation." From SMA, 'PV grid integration', 4th revised edition, May 2012: bit.ly/1qf86Ri

5.2.6 Database

Section 4 (8) of the CEA regulations mandates the utility to send information (capacity installed, generator capabilities, commissioning date etc.) to the state transmission utility (STU) and further to the state load dispatch centre (SLDC). This is a welcome step and all utilities should maintain such a database on DG projects in their jurisdiction. An appropriate authority should collate all such utility databases into a national database. Such a database would be very valuable for future grid planning.

5.2.7 State regulations

The SERCs should issue distributed solar PV regulations to integrate all the above aspects and help bring in clarity with regard to emerging technical issues and potential solutions. It should also clearly lay out a procedural framework to facilitate effective and quick deployment.

Since distributed solar penetration in India is still very low, it is well placed to learn from the global experience, revise its technical regulations appropriately and stay ahead of the curve. An institutionalized consultative process with all stakeholders would greatly help to critically assess the evolving technical challenges and their solutions, and facilitate a clear technical framework for distributed solar PV deployment.

Annexures

A. Types of distributed solar PV systems

Distributed solar systems can be broadly classified into three types depending on their interaction with the grid: grid-tied solar systems, off-grid solar systems and hybrid solar systems.

Grid-tied solar systems

These are inter-connected with the utility power grid. There is typically no source of backup power supply (battery), making the system efficient and keeping capital, maintenance and installation costs low. If distributed power can be fed into the grid through a net-metering process or another process that allows the generator to make use of the grid, such as 'banking'¹⁸⁵, the grid can be considered as a virtual battery. Standard grid-tied solar systems rely on the following components in addition to the standard set of equipment (such as PV modules, junction boxes, mounting structures, etc.): a grid-tied inverter (GTI) or micro inverter, and a power meter

Off-grid solar systems

An off-grid solar system (also called a 'standalone' system) is completely independent of the grid. Off-grid systems come with batteries that are expensive and decrease overall system efficiency. In most cases, diesel generators are used to supplement the energy produced by solar. Thus the batteries are only used if there is no alternative, or if stored solar power is cheaper than the alternative (e.g. diesel).

Hybrid solar systems

Hybrid solar systems combine the best from grid-tied and off-grid solar systems. These systems can either be described as off-grid solar with grid backup power, or grid-tied solar with extra battery storage. Hybrid solar systems are less expensive than off-grid solar systems. In this system, a backup diesel generator is generally not needed since electricity from the grid is cheaper than diesel in India.

Table 12: Key features of different types of distributed solar systems

	Grid-Tied	Off-grid	Hybrid
Grid proximity	Very important	Not important	Very important
Equipment and maintenance cost	Low	Very high	High
Backup power supply	Typically none	Battery/diesel generator	Battery
Storing excess power in the grid (e.g. net metering)	Possible	Not possible	Possible
Grid outage effects	High	Zero	Medium
Extra components required	<ol style="list-style-type: none"> 1. Grid-tied Inverter (GTI) or micro inverters 2. Power meter 	<ol style="list-style-type: none"> 1. Solar charge controller 2. Battery 3. DC disconnect 4. Off-grid inverter 5. Backup generator (optional) 	<ol style="list-style-type: none"> 1. Charge controller 2. Battery 3. DC disconnect 4. Battery-based Grid-tied inverter 5. Power meter

¹⁸⁵ It is a facility wherein the distributed PV can bank electricity with the grid and can withdraw it at a later period for accounting purposes.

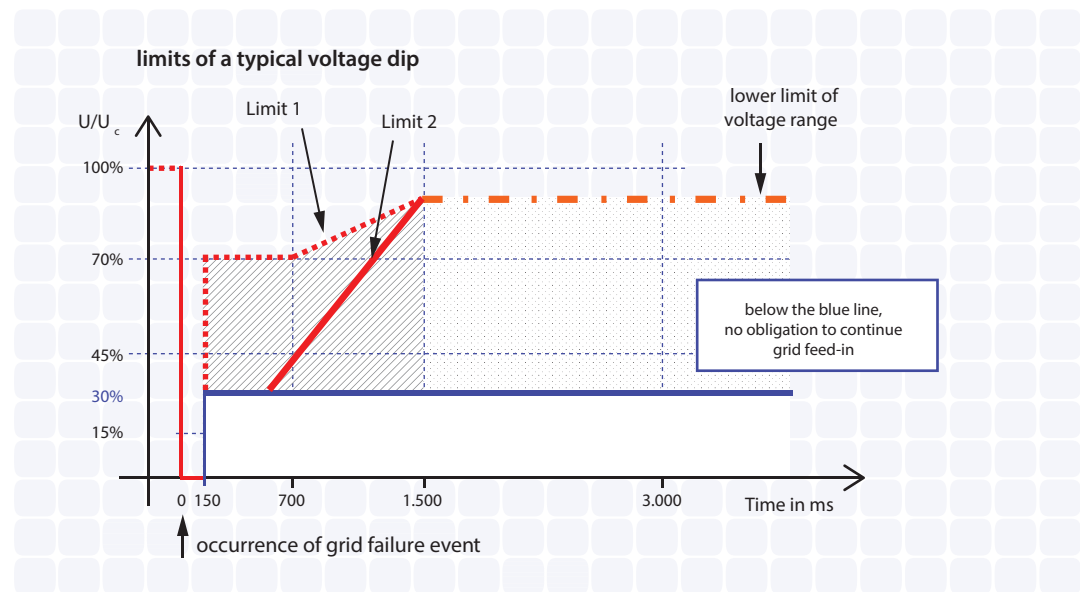
B. Low Voltage Ride-Through (LVRT) and power-frequency droop function

LVRT

The BDEW medium voltage directive mandates LVRT functionality for dynamic grid support in Germany. Figure 10 captures the behavior required of solar systems. Essentially the generating facility must not disconnect during voltage dip, and the required behaviour is as follows^{186, 187}:

- Continuous, stable operation above Limit 1
- May disconnect in accordance with the grid operator between Limit 1 and Limit 2
- May disconnect below Limit 2 and below 30% V_{nom}

Figure 10: LVRT Requirements under the BDEW directive for Germany¹⁸⁸



186 Knopf Hannes, "The German BDEW technical guideline for generating plants connected to the medium voltage grid – an overview of its requirements and their implementation in SMA inverters": bit.ly/1vShNGp

187 Christian H. Benz, W.-Toku Franke, Friedrich W. Fuchs, "Low Voltage Ride Through Capability of a 5 kW Grid-Tied Solar Inverter", 14th International Power Electronics and Motion Control Conference, EPE-PEMC, 2010

188 German BDEW technical guidelines for generating plants connected to the medium voltage grid. BDEW, June 2008

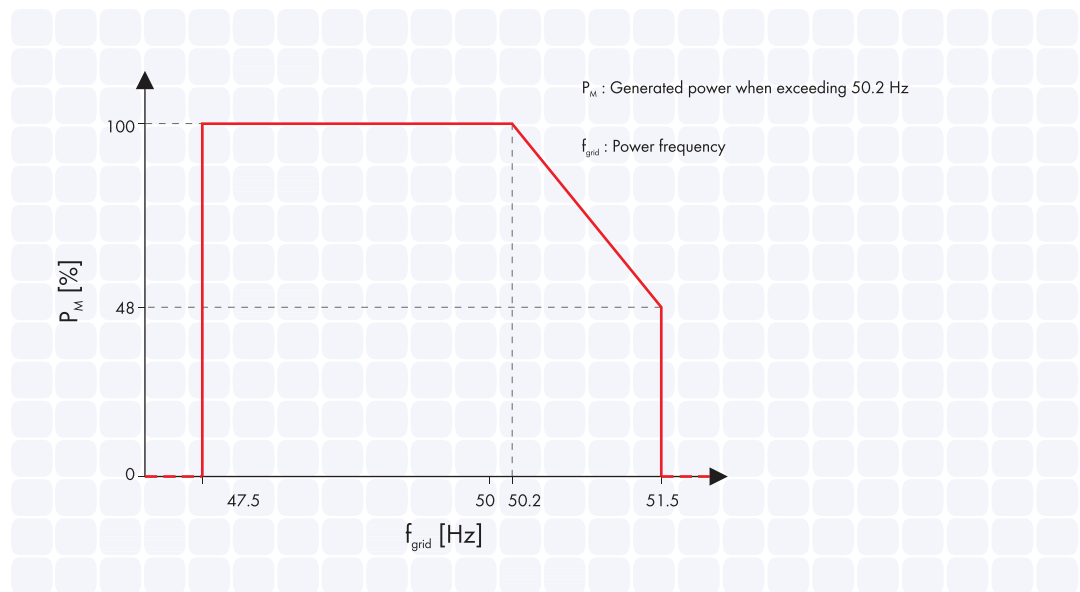
Power-frequency droop

The BDEW and VDE directive both mandate the power-frequency droop function in Germany.

“Since the sudden disconnection of large PV power generation capacities always has a negative effect on the grid stability, the medium voltage directive now demands frequency-dependent power regulation in the inverter: The devices should reduce their current power with a gradient of 40 percent per Hertz from 50.2 through 51.5 Hz and only disconnect from the grid above 51.5 Hz.”¹⁸⁹

The required behavior is captured in Figure 11.

Figure 11: The frequency/active power characteristic curve in accordance with the VDE code of practice.



189 SMA, 'PV grid integration', 4th revised edition, May 2012: bit.ly/1qf86Ri

C. Technical standards for other Balance-of-System (BOS) components

The BOS in a PV system includes the mounting structure, cables, batteries, junction boxes, switch gears, charge controllers, etc.

Module mounting structure

Mounting structures are a topic of discussion in India. Many utility scale power plants installed in Gujarat and Rajasthan under the NSM in 2011-12 have reported significant corrosion due to poor quality of materials used. Tamil Nadu is the only state in India that specifies a mounting structure standard. The Tamil Nadu Energy Development Agency (TEDA) has provided detailed guidelines in the 'Guidelines for Grid-connected Small Scale (Rooftop) Solar PV Systems for Tamil Nadu'¹⁹⁰. It notes that the structure should have adequate strength and appropriate design and be made of either hot dip galvanized steel or aluminum. It should be able to withstand wind speeds up to 150 km/h.

Current regulations – India and abroad

- Germany does not regulate module-mounting structures at present.
- In the USA, the UL 2703 code is a quality check which tests the mechanical loading limits for the mounting structures and clamps. The structure and clamps should be able to withstand 30 pounds per sq. ft. (psf) of static load with 50% overload margin in both positive and negative directions. The mounting structure should be made of an electrically conductive material such as aluminum or steel.
- In Australia, the module mounting structures should comply with the Australian/New Zealand wind loading standard, AS/NZS 1170.2¹⁹¹. This is similar to the UL 2703, but it looks at only the wind loading.
- The CEA does not currently regulate mounting structures in India.

Some developers still do not view mounting structures as an important component, which results in significant quality compromises. The result is frequent replacement and consequently down-time in PV systems. Basic standards of structural strength and corrosion resistance like those mentioned in UL 2703 could be looked at.

Junction boxes

A junction box is an enclosure where all PV strings of any PV array are electrically connected and where protection devices can be located, if necessary. It also serves as a protection device when a fault occurs in the DC circuit.

Current regulations – India and abroad

- The DIN EN 50548 (VDE 0126-5): 2012-02 is mandated in Germany as the junction box standard.
- IEC 60670 and UL 50 are the standards for junction boxes and enclosures in the USA. According to the NEC 690.35 code of the USA (See Annexure I), if the PV system is ungrounded, the junction box should be labelled with a warning of a 'shock hazard'.
- In Australia, the AS 1939¹⁹² is used to determine the degree of protection by the enclosures for electrical equipment. The standard includes the IP (ingress protection) codes which categorises enclosures based on the degree of protection.

¹⁹⁰ TEDA, 'Guidelines for Grid-connected Small Scale (Rooftop) Solar PV Systems for Tamil Nadu': bit.ly/1cF30Vn

¹⁹¹ AS/NZS 1170.2: bit.ly/Oplkfu

¹⁹² AS 1939: bit.ly/1hikHhf

- In India, the CEA does not mandate standards for junction boxes. In the absence of a CEA regulation, the MNRE has issued technical requirements for junction boxes in its policy document for small-scale solar power plants under the flagship NSM¹⁹³. These regulations mandate that the junction boxes should be rated IP 54¹⁹⁴ for outdoor purposes and IP 21 for indoor purposes as per IEC 529. These standards address the prevention of particle entry, but do not provide any guidelines on how the junction box can be used for DC current protection and other insulation criteria like the IEC codes. TEDA guidelines note that the junction boxes shall be made of thermo plastic with IP 65 protection for outdoor use and IP 54 protection for indoor use¹⁹⁵.

The current IP standards mentioned by the MNRE are sufficient and could be specified by the CEA as well.

Cables and connectors

The CEA does not mandate standards for the cables and connectors for PV systems in India. The MNRE, on the other hand mandates the following under the NSM:

IEC 60227¹⁹⁶/IS 694 and IEC 60502¹⁹⁷/IS 1554 (part 1 & 2) for cables under its regulation for PV plants deployed under MNRE programmes¹⁹⁸.

EN 50521 as the standard for the solar connectors to test their safety and performance.

Current regulations – India and abroad

- In Germany, the VDE 0285¹⁹⁹ standard is the equivalent of IEC 60227 and VDE 276 is the equivalent of IEC 60502.
- The UL 62²⁰⁰ and UL 758²⁰¹ are the standards that are USA specific. The purpose of each of these standards is to determine if the cables and connectors meet the following three requirements: electrical properties, mechanical properties and flammability²⁰².
- The AS/NZS 5000.1²⁰³ and the AS/NZS 3191²⁰⁴ are the equivalent of IEC 60502 and IEC 60227 respectively in Australia. In addition, AS/NZS 3000 is the standard for general wiring rules to be followed in Australia, which is applicable to PV systems as well.
- The IS 694²⁰⁵ and IS 1554²⁰⁶ standards are applicable to and sufficient for Indian conditions and the testing procedure for the cables are the same as those used in IEC standards.

193 MNRE, 'Jawaharlal Nehru National Solar Mission – Building Solar India. Guidelines for off-grid and decentralized solar applications and rooftop and other small solar power plants': <http://bit.ly/1aMWEZR>

194 MNRE, 'Minimal technical requirements of standards for SPV systems / plants to be deployed during FY 2012-2013 under the programmes of the MNRE': <http://bit.ly/LaGPAQ>

195 TEDA, 'Guidelines for Grid-connected Small Scale (Rooftop) Solar PV Systems for Tamil Nadu': bit.ly/1cF30Vn

196 IEC 60227: bit.ly/1kGC0me

197 IEC 60502: bit.ly/1ny0Sol

198 MNRE, 'Minimal technical requirements of standards for SPV systems / plants to be deployed during FY 2012-2013 under the programmes of the MNRE': bit.ly/LaGPAQ

199 VDE 0285: bit.ly/1ey4ykE

200 UL 62: bit.ly/1buqB1f

201 UL 758: bit.ly/1fIO3t5

202 UL, "How to Make a Cord or Cable for US and European Markets?": bit.ly/1m9XD5Q

203 AS/NZS 5000.1: bit.ly/1noXkKn

204 AS/NZS 3191: bit.ly/1oSP6FP

205 IS 694: bit.ly/1qeHzjy

206 IS 1554 parts 1 and 2: bit.ly/1eZZp9E, bit.ly/1iUTVha

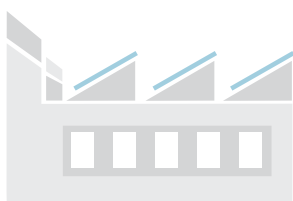
Battery

The batteries are generally used more in off grid systems than in grid tied systems. The types of batteries used mainly in PV systems are vented (flooded) type and valve regulated type. The BIS has released a draft document (ET 11(6497))²⁰⁷ in 2013 that mandates standards for batteries for solar PV application. This regulation is applicable to all batteries made of lead-acid and nickel. It is a comprehensive testing procedure to determine the useful life of a battery. The battery is put through 150 cycles of discharging and charging, assuming that the daily discharge is in the range of 2-20%. The cycles are continued until the battery capacity has decreased to 80% of its rated capacity, which is considered as the end of the useful battery life. This is in line with the international IEC 61427²⁰⁸ standard that is accepted globally. In Australia, the AS 4086²⁰⁹ is the standard for secondary batteries used in stand-alone power systems.

Charge Controller

Solar charge controllers are also known as charge regulators or just battery regulators. They limit the rate of current being delivered to the battery bank and protect the batteries from overcharging. Good charge controllers are crucial for keeping the batteries healthy, which ensures that their lifetime is maximised. A charge controller is typically integrated with the battery-based inverter. The IEC 62093 standard is the most widely used standard globally, for the testing procedure for all BOS components of PV systems in natural environments.

If the charge controller is integrated with the inverter, the MNRE states that it need not comply with IEC 62093²¹⁰. However, the MNRE mandates that the charge controller should comply with IEC 60068-2 which tests it through a variety of temperature and moisture conditions. (This is adopted by most countries with minor modifications to suit country/region specific requirements.)



207 BIS, 'Secondary cells and batteries for solar photovoltaic application: General requirements and methods of test': bit.ly/1eGe8Ux

208 IEC 61427: bit.ly/1ey8MZy

209 AS 4086: bit.ly/1fw5GGc

210 MNRE, 'Minimum technical requirements for SPV': bit.ly/LaGPAQ

D. Challenges and benefits of distributed solar on the LT grid

Challenges at high penetration and concerns of grid operators

Since the grid was not designed for large scale distributed generation, there are concerns about the implications of variable solar generation (in high penetration scenarios) on the grid's power quality and its impact on the LT distribution grid. The main challenges and concerns are listed below. These are based on the existing literature and inputs from interviews with several DISCOMS. Most of these are relevant at only very high penetration of distributed solar PV.

Safety

Utilities are rightly concerned about the safety of their personnel, especially while working around the possibility of the formation of an unintentional island from the operation of the distributed solar PV systems.

Power Quality and Impact on LT grid

DISCOMs are apprehensive about the quality of the power being injected into their distribution grids. This is mainly to do with flicker, harmonics and DC injection. They are also concerned about the impact on the LT distribution grid (voltage levels, power factor, higher wear and tear of equipment, etc.) Due to the intermittent nature of solar power, voltage fluctuation is one potential issue associated with grid integration. The intermittency in power occurs mainly due to two phenomena known as 'ramping' (the rapid output variations that occur as clouds pass overhead) and 'cloud edge effect' (where the edge of a cloud acts like a lens, when the sun is behind it, and could magnify the insolation by up to 25%, for a few seconds).

Reverse power flows

In a distribution network, whenever the PV generation exceeds the local network demand, reverse power flow occurs. In such a condition, power flows back from the distribution transformer to higher transmission voltages. This can affect power exchanges between transmission areas and even result in congestion of transmission network. In long feeders (and high penetrations scenarios), reverse power flow may result in voltage rises and lead to loss of voltage regulation²¹¹. In short feeders with a high demand density, a reverse power flow results in over-loading system components (transformers and feeders). Voltage rise can be tackled partly by reactive power support from inverters (See Section 3.2.1) and from static VAR compensators.

Tail end voltage challenges

When many inverters are connected to a single feeder on the distribution network, there is a tendency of the voltage on that feeder to increase²¹² – especially on exceptionally sunny days.

Phase balance: With increasing number of small scale distributed PV (up to 5/10 kW) connected to the grid through single phase inverters, the voltage in each phase can vary compared to each other if careful planning is not done²¹³.

211 NREL, "Distribution System Voltage Performance Analysis for High-Penetration Photovoltaics": [1.usa.gov/OMljE2](https://www.nrel.gov/docs/fy11osti/50562.pdf)

212 Jadeja K, "Major technical issues with increased PV penetration on the existing electrical grid", 2012: [bit.ly/1opGtCz](https://www.researchgate.net/publication/312511111)

213 In Australia, the new AS4777 standard has proposed that the system imbalance between the phases in a three-phase system should not exceed 20A or 2% of the voltage (APVA, PV integration on Australian distribution networks: [bit.ly/1mHx8XC](https://www.apva.org.au/publications/pv-integration-on-australian-distribution-networks)).

Non-controllable variability and unpredictability

Variability refers to the solar energy source not being constant while unpredictability refers to our inability to accurately predict the generation of solar energy (especially due to cloud cover). At very high penetrations, utilities are concerned with reliable system dispatch and grid balancing, especially since a centralised forecasting and scheduling system for renewables is not yet operational in the country.

Transaction costs

Another logistical worry for utilities is the significantly higher transaction effort in terms of metering, inspection and certifications.

Benefits at low and high penetration levels

Distributed solar PV can potentially offer several benefits to the grid. Some of these are listed below.

Increasing reliability of the grid

India faces significant challenges with grid reliability either due to peak power shortages or due to frequent blowouts from overloading of transformers. Distributed generation can help improve reliability in two ways:

- It can reduce the loading on the transformer, thereby preventing blowouts.
- It can serve as a back-up supply (in synergy with a diesel generator and/or with battery storage)

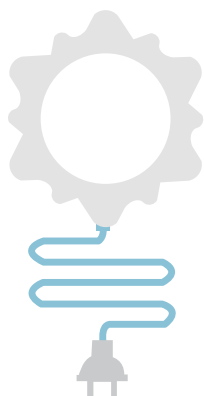
Power quality

The installation of inverters with advanced features can actually improve electrical parameters such as voltage profile. Inverters introduce intelligent power conditioning capabilities at the tail-end of the grid, which previously did not exist. Especially at low penetration levels, there have been several studies that show improvement in critical grid parameters²¹⁴. Another study notes that

“PV penetrations up to 50% reduce system losses and feeder peak loads while having positive or negligible effects on transformer aging, voltage regulator wear, and voltage quality. At higher penetrations we observe diminishing benefits for system losses and, in some scenarios, undesirable impacts on other metrics.”²¹⁵

Deferring grid investments

In many areas the distribution transformers are overloaded beyond their rated capacities. Distributed solar can reduce the loading on the transformers and defer any investments in transformers, circuit breakers and other grid equipment²¹⁶.



214 NREL, Renewable systems interconnection: 1.usa.gov/1iUX4wx

215 Cohen, M.A. and Callaway, D.S., “Modeling the Effect of Geographically Diverse PV Generation on California’s Distribution System”, 2013

216 G. Pepermansa, J. Driesenb, D. Haeseldonckx, R. Belmansc, W. D’haeseleer, “Distributed generation: definition, benefits and issues”: <http://bit.ly/1eDIXZE>

Avoiding peak power purchase

During peak times, such as hot summer afternoons with high air-conditioning loads, the supply is, more often than not, unable to meet the demand in India, often resulting in power cuts. During such situations, additional generation capacity is needed, which is often procured on a short term basis from power exchanges. Distributed generation can help utilities to reduce shortages and costly peak power purchases.

Reduction of Transmission and Distribution (T&D) losses

India has one of the highest T&D losses in the world of around 20%²¹⁷. Meeting the loads locally through grid-connected distributed PV systems can reduce T&D losses. This is primarily because of the proximity to the load. According to the IEA, on site production of electricity could result in cost savings in T&D of up to 30% of electricity costs.

²¹⁷ CEA, "Highlights of power sector": bit.ly/QKqNk2

E. Distributed PV regulations and experience in other countries

India's experience with distributed solar is limited. Net metering and rooftop policies have just been announced and little capacity addition has taken place. This is likely to change very soon. The question therefore is: Are India's regulations mature enough to handle this growth? The answer to this question can be found by looking at countries like Germany, USA and Australia all of which have significant experience in distributed PV. The regulations of these countries have evolved over time, to incorporate demands from increasing penetration levels of distributed solar.

Germany

Germany has the maximum number of grid-connected solar PV installations in the world. The total cumulative installed capacity in Germany stands at of 35.6 GW as of December 2013²¹⁸. 98%²¹⁹ of all solar systems are distributed (rooftop or land-based) installations connected to voltages between 240 V and 400 V. Germany currently has two directives that regulate the connection of solar PV plants to the distribution grid.

- The BDEW medium voltage directive²²⁰
The BDEW medium voltage directive came into effect on 1st January 2009. This directive regulates all solar PV plants of capacity greater than 100 kW that are connected to the medium voltage (10 to 30 kV). This regulation is very relevant for India, since the CEA's 'Technical Standards for Connectivity of the Distributed Generation Resources, 2013' is applicable to solar plants connected below 33 kV. As we showed in Section 3.2, there are additional inverter features that India's regulations must start to incorporate.
- The VDE code of practice²²¹
The VDE 4105 code of practice came into effect on 1st January 2012. It regulates all solar PV plants connected to the LV grid (230 V or 400 V). The VDE regulation, similar to the BDEW directive, is also very relevant for India since the connection voltages fall under the CEA's categorisation of 'distributed solar'. The VDE is one the most widely accepted codes internationally and several safety related matters need to be adopted into India's regulations.

We have chosen Germany as a reference of comparison because of the vast experience the country has in integrating solar PV technology in the distribution grid. In addition, German equipment standards, technical regulations and safety issues are among the most mature in the world. They form the basis of standards in most European countries.

USA

The USA has the third largest capacity of installed PV in the world as of 2013. In Q3 2013, it crossed the 10 GW mark for cumulative installed PV capacity²²². Although, utility scale projects lead the market, smaller distributed residential and non-residential PV form a significant chunk, with the residential PV segment increasing slowly (See Figure 12). While the USA has no national renewables policy (apart from some fiscal incentives) like Germany, several states have set renewable energy goals that include solar PV. This pattern is very similar to India's federal energy policy structure, where each state can independently decide on energy policy matters.

218 As per the German Federal Network Agency

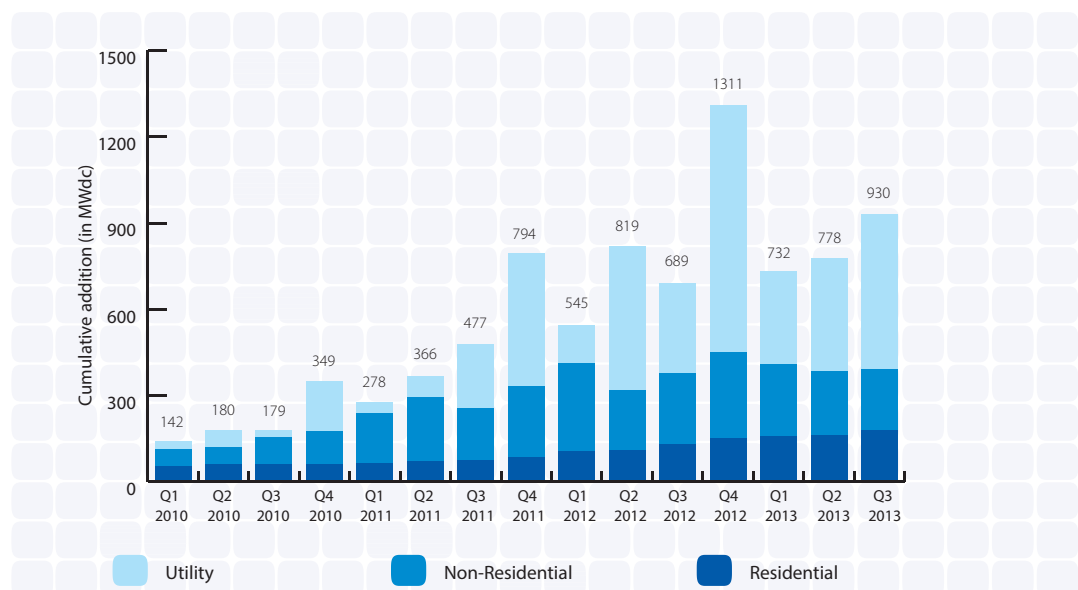
219 Wirth, H., "Does PV power overload the grid?", in 'Recent facts about photovoltaics in Germany', p. 37: bit.ly/1kLnSR8

220 BDEW medium voltage directive: bit.ly/1equGxK

221 VDE-AR-N 4105: bit.ly/1IBvxIA

222 Solar Energy Industries Association (SEIA): bit.ly/TO0U3d

Figure 12: PV installations in the USA by market segment. Q1 2010- Q1 2014²²³



The states of California, Arizona and New Jersey lead the solar market in terms of installed capacity, driven by the 'Renewable Portfolio Standards (RPS)'²²⁴ mandated by state governments.

There are interconnection procedures of distributed energy resources by the Federal Energy Regulatory Commission (FERC). However, they apply only to systems that are connected at the transmission level and for inter-state energy transfers. The FERC's procedures generally do not apply to distribution-level interconnection, which in turn is regulated by state Public Utilities Commissions (PUC).

In 2005, the FERC issued procedural guidelines for commissioning solar PV systems under 20 MW. These regulations came to be known as the 'Small Generator Interconnection Procedure (SGIP)' and the 'Small Generator Interconnection Agreement (SGIA)'. The SGIA contains the contractual provisions for the interconnection and spells out who pays for improvements to the utility's grid system (if needed). The procedure includes provisions for three levels of interconnection:

- The "10-kilowatt (kW) Inverter Process", for certified, inverter-based systems no larger than 10 kW;
- The "Fast Track Process", for certified systems no larger than 2 MW; and
- The default "Study Process", for all other systems no larger than 20 MW"²²⁵.

The state Public Utility Commission (PUC) regulates the interconnections in the distribution grid. These regulations vary from state to state. The California Public Utility Commission (CPUC), for instance, introduced Rule 21 in 1999, which identified screens²²⁶ for quick interconnection of small generators to the grid, which was later adopted by the FERC in the SGIP.

There are various standards and codes that help regulate the interconnection of distributed generators to the grid, such as IEEE 1547, ANSI, IEC, NEC and other IEEE standards. These are adopted by all the state PUCs to regulate the interconnections of distributed generators to the grid. A detailed discussion on each of these standards is available in Section 2 of this report.

²²³ SEIA, US PV installations by market segment, Q1 2010 – Q1 2014.

²²⁴ It is a regulation in the USA that requires an increased production of energy from renewable energy sources.

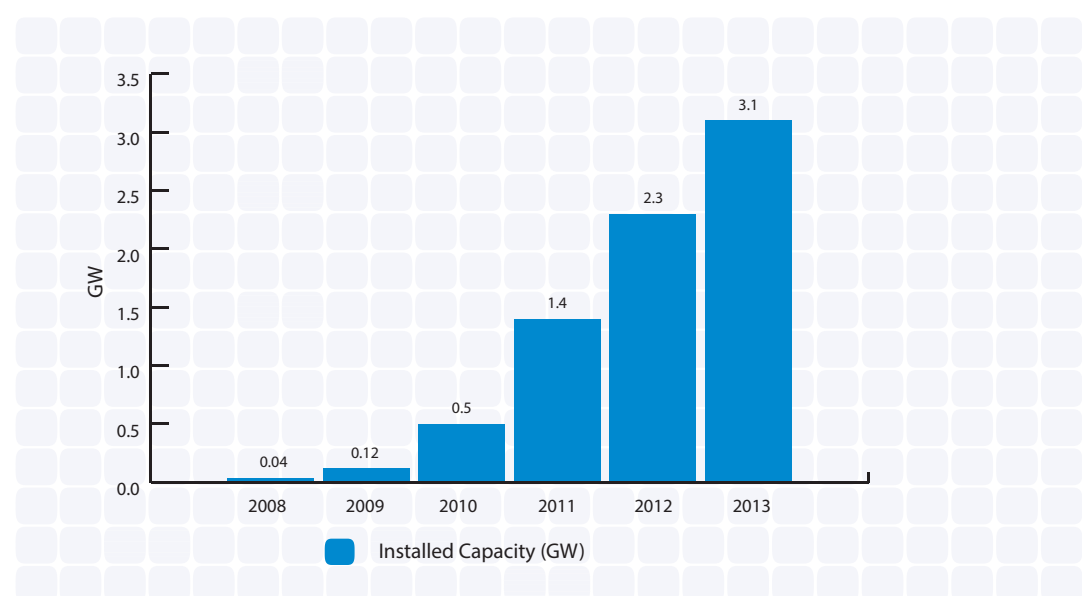
²²⁵ Database of State Incentives for Renewables and Efficiency (DSIRE), 'Interconnection standards for small generators': bit.ly/1c6OZUJ

²²⁶ A set of objective questions which act as a screening procedure to determine qualification for quick interconnection to the grid without a detailed supplementary study.

Australia

Australia has reached nearly 3.1 GW of solar PV capacity in small scale systems²²⁷ (See Figure 13²²⁸). Queensland leads the PV market in Australia with almost one-third of the installed PV capacity²²⁹. Unlike the United States, Australia's solar industry is dominated by rooftop PV plants, and the nation has very little utility-scale PV. The growth of solar PV in Australia has been primarily due to the national and state policies and schemes promoting solar PV. The key national policy which promotes solar in Australia is the Mandatory Renewable Energy Target (MRET), announced in 2001 and later expanded in August 2009, which was further divided in January 2011 into the Large-scale Renewable Energy Target (LRET) and the Small-scale Renewable Energy Scheme (SRES). These schemes provide financial incentives to the solar power generators through large-scale generation certificates (LGCs) and small-scale technology certificates (STCs) for the amount of electricity produced, which are purchased by liable entities under obligation from these generators. The other major drivers of solar PV in Australia are their feed in tariffs which are state run schemes. This federal structure is very similar to the USA and India.

Figure 13: Total small solar PV capacity in Australia



There are two key Australian Standards related to the installation of small scale solar systems:

- AS4777: 'Grid connection of energy systems via inverters', which is similar to the IEEE 1547 standard in the USA; and
- AS/NZS 5033: 'Installation and safety requirements of PV arrays'.

According to the AS4777, the maximum allowed capacity of the inverters should not be more than 10 kVA per phase. Therefore, for 230V (single phase), the maximum allowed PV capacity is 10 KW and for 400V (three phase) it is 30 kW. For higher PV capacities, the utility approves based on grid conditions. This is effective in the proliferation of small scale rooftop PV within the country.

227 Australian Clean Energy Regulator, which is the government body responsible for administering legislation to reduce carbon emissions and increase the use of clean energy.

228 Australian PV institute: bit.ly/1lufAjz

229 Solar Server Magazine: bit.ly/1mQrrby

F. Potential outline for further technical studies on high grid penetration scenarios

1. Proceedings of an NREL workshop, 'High-Penetration Photovoltaic Standards and Codes'²³⁰ provide some useful pointers on studying distributed power systems with high PV penetration. The presentation by Phil Baker notes that traditional measures of PV penetration may not be very useful for high PV penetrations scenarios where one is trying to understand specific issues that may arise with regard to power system operation. Below are excerpts from his presentation.

“Additional penetration measures are needed to generally define the ability of the power system to handle a specific level of PV at specific sites and/or sections of the system.”

Some of the limitations of traditional peak load PV penetration measures are noted as follows.

“Power system impedance and regulator settings vary greatly from site to site, so “peak load to PV power ratios” don’t necessarily tell us how much the voltage regulation will be influenced by PV on the circuit, or don’t provide a good indication of grounding compatibility or the risk of ground fault overvoltage during light load conditions or don’t provide a good indication of the risk of islanding during light load conditions.

The key areas of focus for Distribution and Sub-transmission Impact studies should be as follows

- Voltage Regulation (steady state conditions, fluctuating conditions [flicker], tap changer cycling issues) reverse power flow issues)
- Fault Currents and Protection Coordination (impact on fault levels, device coordination, interrupting ratings, ground fault current detection desensitisation)
- Ground Fault overvoltages (this is important especially for non-effectively grounded DG, of which PV devices are often configured that way)
- Islanding (important especially in complex situations with multiple DG present or with fast reclosing present and no live-line reclose blocking)

The presentation points out the following “Penetration Ratios for Engineering Analysis” which could be used as **“only guides for establishing when distribution and sub-transmission system effects of DG become “significant” to the point of requiring more detailed studies and/or potential mitigation options. They must be applied by knowledgeable engineers that understand the context of the situation and the exceptions where the ratios don’t work.”** (See Table 13)

- Minimum load to generation ratio: the annual minimum daytime load on the relevant power system section divided by the aggregate DG capacity on the power system section
- Stiffness factor: the available utility fault current divided by distributed solar system rated output current in the affected area
- Fault ratio factor: available utility fault current divided by distributed solar system fault contribution in the affected area
- Ground source impedance ratio²³¹: the ratio of zero sequence impedance of distributed solar system ground source relative to utility ground source impedance

230 IEA, 'High penetration photovoltaic standards and codes', May 2010: 1.usa.gov/1kGZ0N9

231 Useful when DG or its interface transformer provides a ground source contribution. Must include effect of step-up transformer if present.

Table 13: Penetration Ratios for Engineering Analysis

Type of ratio	What is it useful for? (Note: These ratios are intended for distribution system impacts of distributed solar system listed below and not necessarily the overall bulk system stability impacts)	Suggested penetration level ratios (a)		
		Very low penetration (very low probability of any issues)	Moderate penetration (low to minor probability of issues)	Higher penetration (e) (increased probability of serious issues)
Minimum daytime load to generation ratio (b)	1. Ground fault overvoltage analysis (use ratios shown when DG is not effectively grounded)	>10 Synchronous Gen	10 to 5 Synchronous Gen	Less than 5 Synchronous Gen
	2. Slanding analysis (use ratios 2/3 of those shown)	> 6 Inverters (d)	6 to 3 Inverters	Less than 3 Inverters
Fault ratio factor ($I_{SCUtility}/I_{SCDG}$)	1. Overcurrent device coordination 2. Overcurrent device ratings	>100	100 - 20	Less than 20
Stiffness factor ($I_{UtilitySC}/I_{RatedDG}$)	1. Voltage regulation (this ratio is a good indicator of voltage influence. Wind/PV have higher ratios due to their fluctuations. Besides this ratio, may need to check for current reversal at upstream regulator devices.)	>100 PV/Wind	100 to 50 PV/Wind	Less than 50 PV Wind
		>50 steady source	50-25 steady source	Less than 25 steady source
Ground source impedance ratio [c]	1. Ground fault desensitisation 2. Overcurrent device coordination and ratings	>100	100-20	Less than 20

Notes:

- Ratios are meant as guides for radial 4-wire multi-grounded neutral distribution system DG applications and are calculated based on aggregate DG on relevant power system sections.
 - 'Minimum load' is the lowest annual load on the line section of interest (up to the nearest applicable protective device). Power factor of load is assumed to be 0.9 inductive.
 - Useful when DG or it's interface transformer provides a ground source contribution. Must include effect of step-up transformer if present.
 - Inverters are weaker sources than rotating machines therefore a smaller ratio is allowable.
 - If DG application falls in this 'higher penetration' category it means some system upgrades/adjustments are likely needed to avoid power system issues.
- A recent report from NREL titled, "High-Penetration PV Deployment in the Arizona Public Service System" describes the effort in modeling and studying high penetration PV areas in Arizona. Phase 1 has "focused primarily on model development, data acquisition design and deployment, and utility scale inverter deployment". The abstract of the study is noted below.

Abstract:

In an effort to better understand the impacts of high penetrations of photovoltaic generators on distribution systems, Arizona Public Service and its partners have begun work on a multi-year project to develop the tools and knowledge base needed to safely and reliably integrate high penetrations of utility - and residential-scale photovoltaics (PV). Building upon the APS Community Power Project - Flagstaff Pilot, this project will analyze the impact of PV on a representative feeder in northeast Flagstaff. To quantify and catalog the effects of the estimated 1.3 MW of PV that will be installed on the feeder (both smaller units at homes as well as large, centrally located systems), high-speed weather and electrical data acquisition systems and

digital “smart” meters are being designed and installed to facilitate monitoring and to build and validate comprehensive, high-resolution models of the distribution system. These models will be used to analyze the impacts of the PV on distribution circuit protection systems (including anti-islanding), predict voltage regulation.

Table 14 captures the data collection effort in this study. In addition to the above data points, the GIS data (which gives locations, distances and other basic information (e.g. equipment type, rating, etc.) for lines and equipment on the feeder), transformer impedance data, loading data, etc. is required to sufficiently describe and model the system.

Table 14: Data collection effort for modelling and studying high penetration PV areas in Arizona

Measurement type interval		Data availability	Data collected (sample)	Data points	Analysis supported
Environmental parameters		1 sec	“Real-time”	Solar irradiance, temperature, wind	Steady-state model validation, PV O&M, Grid operations, Cost-benefit
Customer Load		60 min	Day-behind	kWh	Steady-state model validation, Cost-benefit
PV inverter generation	Data stream 1	15 min	Day-behind	kWh	Steady-state model validation, Cost-benefit
	Data stream 2	1 sec	“Real-time”	kWh, V, I, kVAr, harmonics, other PQ	Steady-state model validation, Grid operations
Feeder device electrical parameters		10 sec	“Real-time”	I	Steady-state model validation, Grid operations
Feeder head (substation) electrical parameters		10 sec	“Real-time”	kW, V, I, kVAr	Steady-state model validation, Grid operations
Feeder point electrical parameters	Data stream 1	1 sec	“Real-time”	kWh, V, I, kVAr, harmonics, other power quality	Steady-state model validation, Cost-benefit, Grid operations
	Data stream 2	8 kHz	Day-behind	kWh, V, I, kVAr, harmonics, other power quality	Dynamic model validation

G. Indicative process flow for utilities for screening applications for grid tied distributed PV systems.

An indicative process for screening applications is given below.

Step A. Application

The applicant sends a formal request to the DISCOM to apply for a PV system interconnection along with completed forms and detailed technical information on system size, inter-connection voltage, metering, PV modules, inverters, anticipated short circuit current contribution at the network connection, safety and protection devices, etc. including single line diagram (SLD), etc. The applicant also submits the relevant equipment certificates which certify them to be as per the CEA/MNRE technical standards.

Step B. Initial review

After receiving the required documents from the applicant, the DISCOM conducts an initial review to check if the system satisfies the standards specified by the CEA, especially with respect to inverter specifications, safety aspects like anti-islanding and protection devices, etc. It also checks if the penetration of distributed solar as a percentage of the rated DT capacity is within the threshold specified by the SERC (maybe 15-30%). It may also do a quick screening based on the ratios provided in Appendix D. If the application meets all these criteria, it qualifies for a simplified inter-connection²³², and the inter-connection should be allowed without any further studies. If the application does not qualify for a simplified inter-connection, further data collection and studies would have to be carried out (Step F).

Step C. Interconnection agreement and installation.

The applicant and the DISCOM enter into an interconnection agreement that specifies the technical information and the clear roles and responsibilities of all concerned stakeholders. Following this, the system is installed at the consumer's premises with appropriate PCC as agreed upon in the interconnection agreement.

Step D. Pre-commissioning check and commissioning of the PV system

Once the system is installed and ready to be commissioned, a final system pre-commissioning check is required. Accredited third party validators could help the utility in this process. The process for permitting has to be graded in nature with smaller systems (<10kW) having a simpler process - being allowed to self-certify with an appropriate declaration for safety. For medium sized systems, certified Energy Auditor/Licensed Electrical Contractor/MNRE accredited channel partners (1A certification) could certify the system. For large systems (>100 kW), only a Certified Energy Auditor or Electrical Inspector would be permitted to certify based on tests performed according to written instructions from the equipment manufacturer or the system integrator that have been approved by both the applicant and the utility. These tests simulate various abnormal conditions expected to cause the system to trip offline, including faults, over/under voltage, frequency disturbances phase imbalance and intentional islanding operation. A commissioning certificate would be issued by the DISCOM/Electrical Inspector subject to the test results which should conform to the CEA requirements. More details on this process are noted in Section 3.5.

²³² Simplified Interconnection means the minimum amount of review that is necessary to ascertain that all the thresholds set forth in the initial review process were met.

Step E. Informing the state transmission utility (STU) and the state load dispatch center (SLDC)

After commissioning, the DISCOM informs the STU about all newly interconnected PV systems to help the STU plan future transmission capacity better. The STU in turn informs the SLDC about the new addition so that they are better equipped to manage grid supply, especially as distributed solar penetration increases. The DISCOM must also maintain a database of all distributed solar projects commissioned in its jurisdiction and data on DT loading and solar penetration levels. This will help in keeping track of the PV systems in each distribution network as well as penetration levels. These will in-turn assist in the studies which might be needed in the future.

Step F. Grid monitoring and studies if not qualified for simple inter-connection

As PV penetrations increase, the DISCOM will have to monitor grid parameters closely to see if any changes are needed. Monitoring can be based on metrics suggested in Table 13 and further studies conducted if needed.

Step G. Action after study

The loading, voltage profile and fault study conducted by the DISCOM can throw up four possibilities, namely

- No equipment (feeder, transformer, etc.) upgrade or protection setting change will be required and further distributed PV deployment up to a point is allowed.
- No equipment (feeder, transformer, etc.) upgrade, but protection settings will require to be tweaked to incorporate more PV.
- No equipment (feeder, transformer, etc.) upgrade, but protection hardware will require to be upgraded to allow more PV.
- Both equipment (feeder, transformer, etc.) and protection hardware need to be upgraded to enhance the hosting capacity of the LT grid.

H. Distributed PV application process steps in Tamil Nadu and Kerala

Table 15: Distributed PV Application Process Steps in Tamil Nadu and Kerala

No.	Tamil Nadu ²³³	Kerala ²³⁴
1	Apply to TANGEDCO for setting up solar system. It will be registered in a computerised database upon paying application fee of INR 100.	Apply to local distribution licensee to connect solar system to the distribution grid with application fees.
2	TANGEDCO to verify technical feasibility (cumulative penetration below 30% of DT capacity and system size < connected/sanctioned load). It will give a Technical feasibility Intimation Letter to the consumer within 10 working days from application letter.	Within 15 days, the DISCOM will intimate the consumer about the feasibility to connect after checking for condition of 80% of minimum daytime load on DT. Feasibility valid for 1 month.
3	Consumer to get system installed within 6 months (validity of letter)	After receiving feasibility letter, consumer will submit application with all stipulated documents and technical details.
4	Consumer to send TANGEDCO a readiness letter for safety inspection	Licensee will check application within 3 working days and intimate on the next working day the required registration fees and any defects in the application.
5	Within 10 days of receiving the letter, TANGEDCO (system < 10 kW) and Electrical Inspector (> 10 kW) will complete safety inspection.	After receiving the fees, it will register the scheme and assign a registration number. This is valid for 6 months.
6	Within 5 days, safety certificate will be issued.	After installation by Licensed Electrical Contractor, consumer will get Electrical Inspector to check and give commissioning certificate as per CEA Regulations, 2013.
7	Change of meter to bidirectional meter.	Utility will test the system in accordance with CEA regulations, 2013, within 15 days of receipt of the Electrical Inspector's Certificate.
8		After successful test, utility and consumer shall execute a connection agreement. Commissioning will happen within 7 working days after agreement.

233 TEDA, Solar Net-metering Consumer Guide: bit.ly/1j8XsfN

234 Kerala ERC, Grid Interactive Distributed Solar Energy Systems Regulations, June 2014: bit.ly/1rWR5w1

I. Guidelines, safety and best practices for installation and testing protocols

One of the major concerns of the DISCOMs with regards to distributed PV systems is safety. Most of the DISCOMs do not have any prior experience in deploying distributed solar systems on their grid and are concerned about the safety of their personnel when operating a line that is energised by a PV system. Unfortunately, there is no comprehensive safety and best installation process dedicated to distributed solar systems in India. The CEA in its guidelines for distributed sources of power ('Technical Standards for Connectivity of the Distributed Generation Resources, 2013') mentions that the safety and installation process shall be governed by the earlier CEA regulation 'Measures relating to Safety and Electricity Supply, 2010'. However, this regulation is a general guideline for electricians and technicians for safe practices for larger sources of energy and its transmission and distribution. This does not specifically provide any guideline for distributed PV unlike in other countries. India can adopt standards that exist in other countries where distributed PV is far more mature. In particular, the USA regulates safety related issues with regard to distributed PV systems in its National Electrical Code (NEC) article 690. This article is a comprehensive document that details safety and best installation processes for PV. Germany has the DIN VDE 0100-712 standard for requirements for special installations or locations of solar photovoltaic (PV) power supply systems.

The National Electrical Code (NEC) in the USA has issued various codes which suggest the best practices to be followed while installing and maintaining PV systems. The NEC is adopted by almost all the states in the USA and even other countries like Mexico and Puerto Rico, while the applicability of the German standard DIN VDE 0100-712 is limited to Germany. Even in India, the CEA in its 'Measures relating to Safety and Electricity Supply, 2010' regulation mentions that the NEC codes can be adopted in certain situations. However, the CEA regulations do not detail its applicability to the Indian context. Therefore, the CEA can adopt the NEC codes which are specific to PV systems and adapt it to Indian conditions. The NEC article 690 provides comprehensive guidelines for PV system installation, while taking care of safety issues. Many other articles of the NEC may also apply to most PV installations (article 110, 250, 300, 310, 480). But article 690 is exclusively for solar photovoltaic systems and overrules the requirements of other articles within the code which differ from it (690.3).

The NEC article 690 is divided into nine sections. The main sections that are concerned with the installation of distributed solar in India are discussed in brief below. Our suggestion to the CEA is to put in place a distributed solar specific safety and best practices regulation building on these guidelines.

1. Circuit requirements

This section of the article helps in sizing the circuit accurately by determining the maximum possible current and voltage that can flow within the existing PV configuration. Since the open circuit voltage (V_{oc}) of a PV module varies with temperature, it is important to size the circuit according to the coldest possible temperature of the region to ensure that it is less than the maximum input voltage of the inverter and less than the voltage rating of cables, switch gear and overcurrent devices (usually 600V). The article provides a table (690.7), which contains a voltage correction factor that corrects the open circuit voltage based on the temperature.

$$V_{max} = V_{oc} \times VCF \times \text{Modules in series}$$

Similarly, the max current (I_{max}) is 25% more than the rated short circuit current (I_{sc}) (690.8A), because PV modules, PV source circuits, and PV output circuits can deliver output currents higher than the rated short-circuit currents for more than 3 hours near solar noon.

$$I_{max} = I_{sc} \times 1.25$$

Therefore, circuit conductors and overcurrent devices shall be sized to carry not less than 125% of the max current (690.8B). Overcurrent protection devices are required on generally all source circuits, with the exception of those which have no back feed and when the total I_{max} is less than the conductor ampacity (690.9).

2. Disconnection means

Means to disconnect the photovoltaic system from supplying electricity through the conductors is required as a safety measure in the event of any faults or emergencies. Switches or circuit breakers should be provided to disconnect the PV system from all the other conductors of the building (690.13). The disconnecting means should be located at a readily accessible location (690.14C). But, the grid interactive inverters can be mounted on roofs or areas that are not readily accessible (690.14D). Also, the switch or circuit breaker used in ungrounded conductors shall be manually operable.

3. Wiring methods

Open wiring is an extremely dangerous scenario for personnel and different sections in the article combat this with efficient and safe methods. The circuit conductors should be installed in a raceway, if the PV source and output are installed in a readily accessible location and operate at maximum voltages greater than 30V (690.31A). The objective is to make the conductors not-readily accessible. It also allows for ungrounded PV systems and wiring and protection methods for ungrounded PV systems (690.35).

4. Grounding

Grounding of electrical systems minimises the effects of lightning and surges on equipment, in addition to offering personnel safety. In PV systems greater than 50 Vdc, one of the current carrying conductors should be grounded to limit imposed voltages from outside sources and stabilise the voltage to earth during normal operation (690.41). The grounding connection should be made at any single point on the photovoltaic output circuit, to eliminate multiple paths to ground in the circuit (690.42). The exception being that if there is a Ground-Fault Protection (GFP) device in the circuit, the grounding shall only be at that point. Exposed non-current-carrying metal parts of module frames, equipment, and conductor enclosures, shall be grounded in accordance with 250.134 or 250.136(A) regardless of voltage, since they are likely to become energized (690.43).

5. Markings

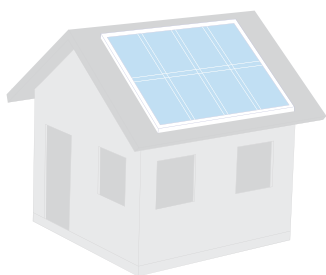
Markings on the PV modules and other equipment with its specifications make it easy for the installer/energy consumer to identify and inspect it. The installer should provide a permanent label for the DC PV system indicating the rated voltage, rated current, maximum voltage, maximum rated current of the charge controller (if installed) and short circuit current (690.53). Also, all interactive system(s) points of interconnection with other sources shall be marked at an accessible location at the disconnecting means as a power source and with the rated AC output current and the nominal operating AC voltage (690.54). If the main service disconnect and PV system disconnect are not in the same location, there should be a readily visible permanent plaque at the service entrance which describes the location of the PV system disconnect in detail (690.56).

6. Connection to other sources

The regulations related to connecting to the electricity grid which contains other sources of power are also detailed in this section. Due to safety concerns, if the load disconnect is connected to multiple power sources, it should be able to completely disconnect from all the power sources when turned off (690.57). According to the NEC, in a grid-interactive system, the inverters used must be listed (certified) by an authorized certification firm and identified for interactive system use (690.60). The inverter should also isolate the PV system from the grid in the event of loss of voltage in the grid, to prevent unintentional islanding. However, the PV system (with batteries or grid PV in intentional island mode) can function as a stand-alone system, to supply to loads not connected to the grid (690.61). The PV system can be interconnected by two methods based on location of PCC: supply side (DISCOM side) of the disconnecting means, or the load side (premises side) of the disconnecting means. Now, while interconnecting the PV system to the supply side (grid side), it should be ensured that the sum of the rating of the overcurrent devices connected to the PV system does not exceed the rating of the grid (690.64). On the load side, NEC Article 690.64 states that a load side connection is allowable at any distribution equipment on the premises, as long as the connection is made at a dedicated circuit breaker or fusible disconnection means. When the distribution equipment including switchboards and panel boards is fed simultaneously by a primary source of electricity, and by one or more grid interactive inverters, the interconnecting provisions of the grid interactive inverters should comply with certain points, few of which are mentioned here.

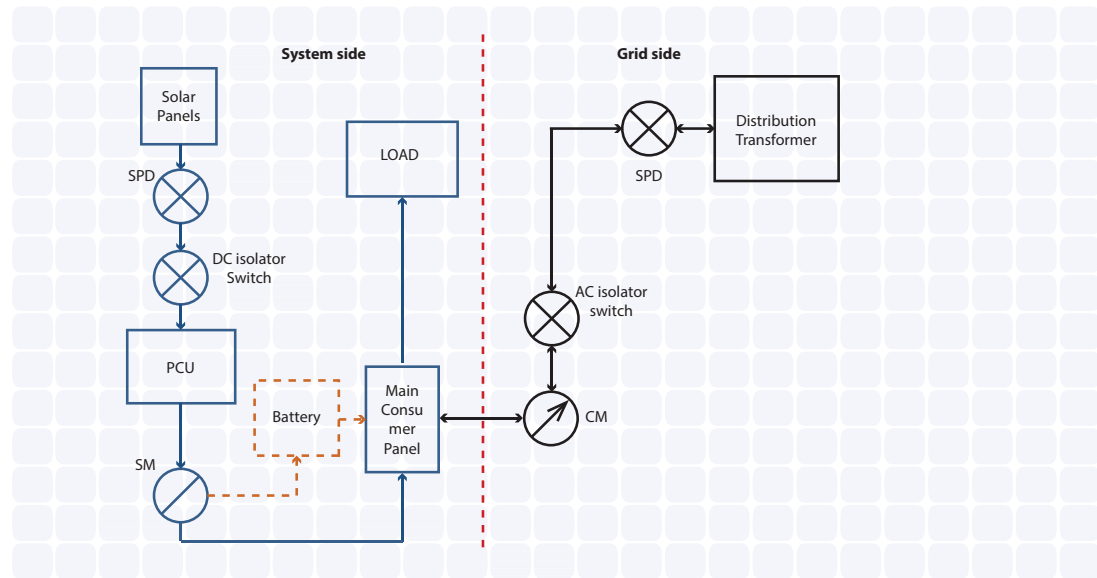
- The sum of the ampere ratings of the overcurrent devices feeding the busbar should not exceed 120% of the busbar or conductor rating.
- The Article 690.64(B) of the 2008 NEC also helps to determine the PV breaker location when the sum of the breakers feeding a busbar is greater than the rating of the busbar. In such cases the PV breaker must be installed at the opposite end of the bus from the main breaker or feeder lugs, and a label must indicate that the breaker may not be relocated.
- The Article also states that labelling is required for equipment containing an overcurrent device that supplies power to busbars or conductors that are fed from multiple sources. The label must indicate all sources of power to the busbar or conductor.

The information given above is not extensive and could be missing certain exceptions in various articles mentioned above. The data has been sourced from the NEC of 2005, 2008 and 2011. The NEC is updated every three years and certain codes mentioned may be deleted or modified in later publications. The NEC is not a legally binding document unless it is adopted by the ruling authority of the state. The information provided above is only suggestive for the Indian context due to the lack of such codes on installation and safe practices.



J. Overview of a grid interactive system

Figure 14: Overview of a basic grid interactive system



SPD- Surge Protective Device, PCU- Power Conditioning Unit, SM- Solar Meter, CM- Consumer Meter.

The figure above provides an overview of a basic grid interactive system. The battery is considered as an optional component in a grid interactive system. The main protection devices in the DC circuit side are the SPD and the DC isolator switch. The main protective devices in the AC circuit side are the AC isolator switch (located in the consumer premises) and the SPD (located at the transformer). The DC produced by the solar panels passes through the protective devices into the PCU, where it is converted into AC. This is then measured and recorded by the solar meter. The current then charges the battery, if it is provided, and flows into the busbar in the main consumer panel. It is in the main consumer panel that the electricity from the solar panels and the DISCOM flows to the consumer loads. If the solar energy produced exceeds the demand of the loads, it flows to the DISCOM side. The consumer meter is a bidirectional meter which measures the net flow of electricity through the meter. The current flows through the AC protective devices into the overhead distribution lines. Here, considering a low penetration scenario, it caters to the other loads connected to the grid. In high penetration scenarios where the demand is also low, the electricity injected into the grid may flow back to the distribution transformer.

Glossary of terms

A

ABT - Availability Based Tariff
AC - Alternating Current
AER - Australian Energy Regulator
AFD - Active Frequency Drift
AMR - Automatic Meter Reading
APPC - Average Pooled Purchase Cost
ANSI - American National Standards Institute

B

BDEW - Bundesverband der Energie- und Wasserwirtschaft (Federal Association of the Energy and Water Industry)
BIS - Bureau of Indian Standards
BnetzA - Bundesnetzagentur (Federal Network Agency)
BOS - Balance of System

C

CAGR - Compound Annual Growth Rate
CEA - Central Electricity Authority
CEC - California Energy Commission
CM - Consumer Meter
CPUC - California Public Utilities Commission
CSERC - Chhattisgarh State Electricity Regulatory Commission
c-Si - crystalline silicon
CUF - Capacity Utilization Factor
CWET - Center for Wind Energy Technology

D

DAS - Data Acquisition Systems
DC - Direct Current
DER - Distributed Energy Resources
DERC - Delhi Energy Regulatory Commission
DG - Distributed Generation
DISCOM - Distribution Company
DOE - Department of Energy
DT - Distribution Transformer

E

EEG - Erneuerbare-Energien-Gesetz (Renewable Energy Act)
EHT - Extra High Tension
EPC - Engineering, Procurement and Construction
EU - European Union

F

FCFS - First Come First Served
FERC - Federal Energy Regulatory Commission
FIT - Feed in Tariff
FoR - Forum of Regulators
FRT - Fault Ride-Through

G

GBI - Generation Based Incentive
GFP - Ground-Fault Protection
GTI - Grid-Tied Inverter

H

HECO - Hawaiian Electric Company
HELCO - Hawaii Electric Light Company
HT - High Tension
HV - High Voltage

I

IEA - International Energy Agency
IEC - International Electrotechnical Commission
IEEE - Institute of Electrical and Electronics Engineers
IFC - International Finance Corporation
IS - Indian Standard

K

KERC - Karnataka Electricity Regulatory Commission
KIUC - Kauai Island Utility Cooperative
KSERC - Kerala State Energy Regulatory Commission
KSEB - Kerala State Electricity Board
KVA - Kilo Volt Ampere

L

LDC - Load Dispatch Center
LGC - Large-scale Generation Certificate
LHFRT - Low/High Frequency Ride-Through
LHVRT - Low/High Voltage Ride-Through
LRET - Large-scale Renewable Energy Target
LT - Low Tension
LV - Low Voltage
LVRT - Low Voltage Ride-Through

M

MECO - Maui Electric Company
MID - Measuring Instruments Directive
MNRE - Ministry of New and Renewable Energy
MPPT - Maximum Power Point Tracker
MRET - Mandatory Renewable Energy Target
MRI - Meter Reading Instrument
MV - Medium Voltage

N

NCPRE - National Centre for Photovoltaic Research and Education
NEC - National Electrical Code
NLDC - National Load Dispatch Center
NREL - National Renewable Energy Laboratory
NSM - National Solar Mission

O

OA - Open Access
OLTC - On Load Tap Changer

P

PCC - Point of Common Coupling
PCU - Power Conditioning Unit
PEDA - Punjab Energy Development Agency
PPA - Power Purchase Agreement
PTC - PVUSA Test Conditions
PUC - Public Utilities Commission
PV - Photovoltaic
PVUSA - Photovoltaic Utility Scale Applications

R

RMS - Root Mean Square
RPO - Renewable Purchase Obligation
RPTV - Rooftop Solar PV
RPS - Renewable Portfolio Standard
RSI - Renewable Systems Interconnection

S

SCADA - Supervisory Control and Data Acquisition
SECI - Solar Energy Corporation of India
SEIA - Solar Energy Industries Association
SERC - State Electricity Regulatory Commission
SGIA - Small Generator Interconnection Agreement
SGIP - Small Generator Interconnection Procedure
SLD - Single Line Diagram
SLDC - State Load Dispatch Centre
SM - Solar Meter
SPD - Surge Protective Device
SRES - Small-scale Renewable Energy Scheme
STC - Small-scale Technology Certificate
STC - Standard Test Conditions
STU - State Transmission Utility
SVC - Static VAR Compensators

T

T&D - Transmission and Distribution
TANGEDCO - Tamil Nadu Generation and Distribution Corporation
TDD - Total Demand Distortion
TEDA - Tamil Nadu Energy Development Agency
THD - Total Harmonic Distortion

U

UL - Underwriters Laboratory
UPCL - Uttarakhand Power Corporation Limited

V

VDE - Verband der Elektrotechnik, Elektronik und Informationstechnik e.V

W

WBERC - West Bengal Electricity Regulatory Commission

Distributed solar photovoltaics (PV) is expected to witness significant growth in India owing to increasing economic viability and a facilitating policy-regulatory framework in most states. Distributed Generation (DG) can provide various system benefits in terms of improved grid reliability and power quality, deferring grid investments, reduction in T&D losses, etc. However, since the distribution grid was not designed keeping in mind the potential high penetration of DG, there are valid technical concerns from utilities about power quality and the general impact of DG on the low-tension distribution grid.

To address these concerns, the report documents existing technical standards and practices both on the PV system side and on the distribution grid side based on a review of global and Indian policies and regulations. Further, the report outlines potential solutions and proposes a possible way forward for a structured and effective grid integration of distributed PV.

With this study, we hope to initiate a serious and objective discussion on the technical challenges and potential solutions of large scale distributed PV. A greater common understanding of the issues would help facilitate faster distributed PV deployment in India.