Analysis of Indian Electricity Distribution Systems for the Integration of High Shares of Rooftop PV

Short Summary

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

On behalf of:

Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety

of the Federal Republic of Germany

Project

The project 'Integration of Renewable Energies in the Indian Electricity System (I-RE)' is part of the International Climate Initiative (IKI). The German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) supports this initiative on the basis of a decision adopted by the German Bundestag. The mentioned project has supported this study.

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Acknowledgments

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Preface

Dear readers,

India is the 4th largest electricity market in the world with the lowest energy tariffs in a regulated power sector. Adding large amounts of distributed renewable energy – such as 40 GW Solar Rooftop till 2022 – may cause additional stress to the DISCOM landscape responsible for buying, selling and distributing energy.

MNRE and GIZ have jointly agreed to initiate and execute a technical study with the objective to address the question: How much distributed Solar PV can be injected into the LV / MV distribution grid without seeing an adverse impact of technical nature?

The results of the report are very encouraging for DISCOMS and for the entire Solar Rooftop sector namely taking the fear away in facing large additions of Solar from a technical perspective.

I hope you find this report informative!

Yours sincerely,

Joerg Gaebler
Principal Advisor, IGEN-Solar, GIZ

Key findings at a Glance

1	Simulation results from the four feeders investigated show that **PV penetration levels of 75 % of distribution transformer capacity and higher can be implemented** without having to undertake any measures to contain voltage problems or overloading. This is significantly higher than the limits of usually 30 – 60 % prescribed by regulators in most Indian states today.
2	At very high penetration level (close to 100%), it could be observed that **Active Power Management Strategies** of either capping PV inverter capacity or the use of peak shaving storage performed best in resolving both voltage and loading issues.
3	**Automatic voltage control by tap changing transformers** at 132/33, 220/66 or 220/33 kV should be implemented in all distribution grids regardless of PV development. For lower voltage levels (66/11 or 33/11 kV level), this strategy is very beneficial, but not strictly required if the voltage control above is adequate.
4	Voltage problems in the distribution grid, caused by both load (undervoltage) and PV (overvoltage) can be efficiently eliminated by the **use of a wide area voltage measurement and control method** i.e. measuring the voltage at multiple points in the grid and operating the voltage control by transformers accordingly.
5	The **distribution grid codes need to be updated** to require voltage control capability from PV inverters, with the grid operator being in charge of the actual reactive power regime. These should be developed in coordination with the entities responsible for the operation and stability of the transmission system.

Contents

1. Introduction

Under the current national target based on National Solar Mission, 40 GW of rooftop PV shall be connected in India by 2022. To reach this target, a good understanding of the Indian power system, its regulatory frameworks, and the similarities and differences with other countries that have already deployed a large share of rooftop PV has to be developed by all stakeholders involved in the process.

Under the Indo-German technical cooperation, Government of Germany is cooperating with India and has commissioned a project "Integration of Renewable Energies in the Indian Electricity System (I-RE)" through the International Climate Initiative of the German Government. The project is financed by Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) and implemented by Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) in partnership with Ministry of New and Renewable Energy (MNRE). Considering the need for extensive capacity building in India, GIZ has commissioned Energynautics to conduct this study on the integration of rooftop solar PV into Indian distribution grids at the voltage levels of 33, 11 and 0.4 kV. Starting out with a desktop study on the characteristics and peculiarities of the Indian power system and its regulatory framework, and a comparison to other countries where PV integration has already progressed further, the scope of the study also includes detailed modelling and simulation of four different distribution grid feeders in Delhi and Bhopal. Data for the simulations were kindly provided by the local distribution companies, BSES Rajdhani Power Limited (BRPL), Delhi and Madhya Pradesh Madhya Kshetra Vidyut Vitaran Company Limited (MPMKVVCL), Bhopal.

The study intends to provide an overview of the characteristics of the Indian power system and its problems with regard to a large scale rooftop PV rollout, as well as a template for distribution companies on how to deal with rising PV shares, which studies to conduct and which technology options to select.

This report presents a shortened version of the main report, containing an overview of methodology and findings.

2. Preliminary Studies

2.1 Study on characteristics of Indian distribution grids

In the first phase of the study, information about the Indian power system relevant for the integration of rooftop PV was compiled. Shortly summarized, the following characteristics are of interest for the integration of solar PV and may lead to unique techno-economic challenges:

- Indian distribution grids are typically state owned, but operated by private or state-owned distribution companies (discoms) that also act as retailers. The tariffing structure is based on charging higher rates from customers with a higher yearly demand to cross-finance less financially stable residential customers.
- There exists slab-wise tariff structure charging higher rates from customers with higher yearly electricity consumption (mainly commercial and industrial) to cross-finance less financially stable residential & agricultural customers.
- The high conventional tariff system combined with a net metering scheme incentivizes high-demand customers to install PV, while less financially capable low-rate customers find it less economically viable to install PV systems for which they are offered capital subsidies (30% of capital cost) by the Central Government.
- The Indian government has set ambitious solar targets for the entire country and has also distributed those to the states. However, as electricity is mainly a state subject, enforcement of the targets is up to each state's Government electricity boards / distribution companies and state regulators. Significant progress has been made in setting the policy and regulatory frameworks right however still several challenges exists in accelerated deployment of rooftop PV.
- From a technical point of view, Indian distribution grids are less unique. Primary distribution at 66 or 33 kV, secondary distribution at 11 kV and the last mile at 0.4 kV, all operated as radial feeder grids, are not much different from the structures found in other parts of the world.
- However, in many cases, Indian distribution grids are somewhat lacking voltage control instances, with automatic voltage control by on-load tap changing transformers being the exception rather than the norm. Moreover, grids are often highly loaded and composed of aging and/or damaged equipment, leading to security of supply issues. Depending on the characteristic of each distribution grid, PV integration may even help to alleviate some of the issues currently experienced such as undervoltage and grid overloading. An increased amount of locally consumed generation can also reduce the quantity of technical losses in the distribution grid.

Following up on the high level analysis of the Indian system, a detailed comparison of the situation in India to a number of country study cases was conducted. The detailed study can be found in the long version main report, while only the conclusions from this task are presented in this summary. The chosen study cases were the following:

- Germany: Early adopter of PV technology with a high share of rooftop PV;
- California: Early adopter of PV technology with grid and tariffing structure similar to India;
- Australia: Similar structures and PV potential to India, high PV share;
- Brazil: Similar to India in economy and grid topology, but with a PV incentive system that has failed to take off so far.

Key characteristics of each system are given in Table 1.

Table 1: Key characteristics of country study cases

	India	Germany	California	Australia	Brazil
Peak load [GW]	148 (2016)	81.7 (2014)	47.3 (2015)	32.9 (2015)	60 (2015)
Minimum load [GW]	Ca. 80 (2016)	36.7 (2014)	16 (2015)	14.9 (2014)	unavailable
Yearly demand [TWh]	1090 (2016)	505 (2014)	259.5 (2015)	197.6 (2015)	463.3 (2015)
Conventional[1] generating capacity [GW]	264 (2016)[2]	108 (2014)	80 (2015)	47.25 (2015)	133.9 (2015)
Dominating primary energy (conventional)	Coal, hydro	Coal, nuclear	Natural gas	Coal, natural gas	Hydro, natural gas
Total PV capacity [GW]	9 (2016)	41.3 (2016)	5.5 (2015)	5.5 (2015)	0.021 (2015)
Rooftop PV capacity [GW]	Ca. 1 (2016)	Ca. 24 (2016)	Ca. 4 (2016)	Ca. 5 (2015)	0.016 (2015)
Targets for rooftop PV	40 GW by 2020	+2.5 GW annually, 52 GW total[3]	1 million units by 2017	33 TWh p.a. total ren. generation by 2020	7 GW by 2024

The conclusions that are drawn from these are manifold, but the most important ones are, once again, not of any technical nature, but related to regulation and tariffing.

Considering incentives, the pioneering countries in PV so far have all reached their impressive installed solar capacities (as of 2017, 45 GW in Germany) over a span of 10+ years, as opposed to India reaching for a similar target within five years. Also, all pioneers have kick-started PV development with high feed-in tariffs for solar power instead of a net metering scheme. This, however, has brought worldwide PV prices down through economy of scale, so that grid parity has been reached also in India, making a net metering scheme a feasible option as well. This is showcased by the case of California, where development was started with a feed-in tariff scheme, which is now successfully being switched to net metering.

Considering technical issues, the most important lesson that can be learned from the pioneering countries is that technical requirements for distributed generation, PV or other, have to be developed with a look ahead to the future where a large share of power is produced at the distribution grid level. Requirements will have to deal both with local issues in the distribution grid, as well as with the overall power system impact. Distributed generators will have to deal with both voltage control (local issue, reactive power) and frequency control (system issue, active power.) Requirements have to be designed jointly by the distribution company (discom) and the system and/or transmission grid operator to avoid having high shares of inadequately designed and partially uncontrollable generation in the grid. The importance of distribution grids and the generators connected to them to overall system stability will increase, necessitating a higher amount of communication between the different stakeholders involved in power system operation.

1. Including large hydro, run-of-river as well as reservoirs and pumped storage.
2. According to Central Electricity Authority, http://www.cea.nic.in/reports/monthly/installedcapacity/2016/installed_capacity-12.pdf
3. Germany has no solar target for a certain date, a corridor towards a target 52 GW installed capacity is set, currently at 2.5 GW p.a., which will allow for the target to be reached in 2022. The 52 GW must not be exceeded according to the current plan. The capacity is expected to be mostly rooftop, as support for utility scale PV has been strongly cut back since 2012.

Another important issue is the fact that Indian state regulation currently limits PV installed capacity on distribution grid feeders to a certain percentage of the capacity of the distribution transformer. Dating back to Californian regulation in the 1990s, developed to avoid reversed power flows in the distribution grids, these values in India are usually between 15 and 50 % (although some states allow 80 %.) In the other study case countries, such limits exist no longer, and operators routinely operate distribution grids at high reversed power flow levels. Retaining the limits will undoubtedly hinder PV development in India. This study also intends to shed light on reverse power flow operation, which is usually safely possible with only minor adjustments to protection settings.

2.2 Data collection and grid modelling

During the second phase of the study, detailed data on the distribution grid feeders to be modelled and simulated were collected from the local discoms. Besides the modelling tasks, these were also used to obtain information about the general technical structure of Indian distribution grids and develop recommendations for future studies in other grid areas. Besides grid plans and asset information from the discoms, this included measured operational data of voltage, loading and outage events.

Based on the collected data, models of five feeders – an urban and a rural/suburban feeder for each discom – were set up in DIgSILENT Powerfactory. Key characteristics of all five feeders are listed in the table below. Comparing those, the following facts are of special importance:

- The rural feeders supply comparable installed load capacities to the urban feeders, but their line lengths are longer by four to ten times, indicating possible voltage problems;
- The rural 11 kV grid in Bhopal is shorter than those in Delhi, but is supplied by a longer 33 kV grid structure without voltage control, resulting in similar issues;
- The urban feeders are rather lightly loaded and have strong lines, cables and transformers, making overloading less probable;
- Light loading of urban feeders can lead to reverse power flows even at low PV penetrations, may require a revision of protection settings;
- The rural feeders in Delhi may be used to evacuate power from a multi megawatt PV power plant, which may overload even the strong grid structure.

Analysis of the operational data provided by the discoms revealed some further issues that are relevant to PV integration in the distribution grids:

- All feeders, rural and urban, have their peak load in the evening or during the night, while at mid-day, demand is low. This will result in reversed power flows already at low penetration levels, and a low local consumption of PV power.
- Especially the rural feeders do experience voltage control issues even without PV.
- Voltage on the feeders in Delhi is routinely too low (an issue that could be alleviated by PV), but the 66/11 kV transformers are currently being upgraded to automatic voltage control, eliminating the problem.
- For the rural grid in Bhopal, the 132/33 kV transformer is the last instance of voltage control, manually controlled by the subtransmission (132 kV) grid operator. Voltage control is inadequate with both under- and overvoltages appearing during the day, possibly hindering PV integration.
- Outage times on the rural feeders are quite high, but it is not possible to distinguish clearly between data errors and actual outages.

3. Simulation Methodology

3.1 General approach

The general objectives of conducting a PV study at distribution grid level are the same as those of any renewable energy integration study:

- Get familiar with the impact of new technologies installed in the grid and the sensitivity of grid parameters;
- Assess how much generating capacity can be added to an otherwise unchanged system before operational issues (such as voltage range violations or thermal overloads) appear;
- Analyze the possible solutions for appearing problems and compare their cost and adequacy;
- Assess how much additional generating capacity can be added to the system if these solutions are implemented;
- Develop a strategy involving the most promising solutions.

In this study, the methodology used consisted of a worst case analysis – simulating the most unfavorable situation the grid may have to cope with – in the form of a quasi-dynamic load flow sweep across a day with very low load and high PV-feed-in. Simulations were conducted for the 33 kV and 11 kV levels, with different penetration levels of PV in the underlying 0.4 kV grids. Detailed 0.4 kV grid data was made available only for the urban grid in Delhi, for this grid, the low tension level was modelled in detail and considered in the simulations, while all other models used load/generation equivalents for the low tension grids.

For each model, load and PV feed-in were modelled on measured 15 minute characteristics, and the day with the lowest day-time load was selected from load data spanning across one year, and combined with the highest PV feed-in, also taken from annual data. Load flow calculations were conducted for PV levels between 20 % and 150 % of distribution transformer capacity, to identify the percentage at which the first violation of any operational parameter appeared.

Simulations were then modelled to include a number of different technology options implemented that have been used in other countries to boost PV hosting capacity of feeders. The technology options that enabled higher PV capacities than the initial base case run were classified as suitable, and an assessment of the optimal technical solution was conducted.

3.2 Model feeders

3.2.1 Delhi urban

The 11 kV feeder is set up as a radial grid with two branches, made up of a total of 3.1 km of single circuit 300XLPE underground cable with a maximum carrying capacity of 5.7 MVA. The structure is shown in Figure 1. There are four 11/0.4 kV substations on the feeder with two distribution transformers each. The transformers each feed a low voltage grid of their own and are not connected in parallel on the low voltage side. Due to the urban setting with high load density, distribution transformers are quite large, with seven 630 kVA units and one 990 kVA unit. The total installed transformer capacity is 5.4 MVA, so the supplying cables are sufficient to carry the full transformer capacity. Peak load is 2.5 MW. Short cable lengths and strong cables indicate that no large voltage swings can be expected on the feeder.

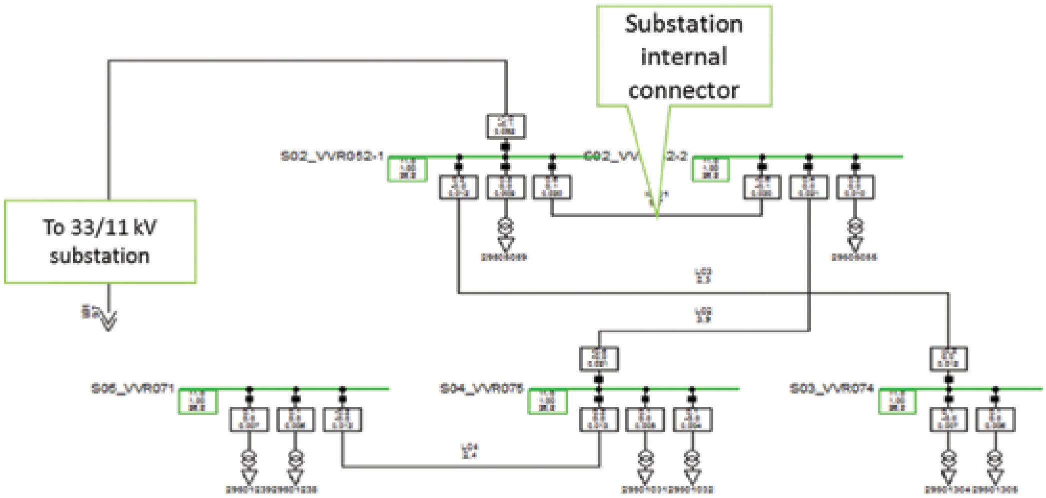

Figure 1: PowerFactory Single-Line-Dagram of 11 kV feeder.

Low voltage networks used are strictly radial, with each distribution transformer feeding three or four individual low voltage feeders. Average feeder length is 230 m, with lengths ranging from 36 to 720 m. A total of 4318 m of low voltage underground cable and 2146 m of low voltage OHL are installed in the area. Cable types are mostly 4x300 cables, OHL mostly Dog ACSR, no further information on the types was provided. Lengths of each feeder were provided by type, as were loading values[1] of each conductor on each feeder.

The low voltage grid is a TN system, meaning a separate neutral conductor exists. Some of the low voltage feeders show severe asymmetric loading with high current on the neutral conductor. The reason for this characteristic is still to be determined, as single phase customer connections are not uncommon in India, these may be causing the asymmetry.

3.2.2 Delhi rural

The two feeders for which data was supplied by BSES for analysis are located in a rural area. Both feeders have roughly similar characteristics, bridging distances of around 10 km with a mix of ACSR[2] OHL and underground cables (see Table 2.) The grid was modelled in PowerFactory according to the data delivered by BSES.

Table 2: Cable and line lengths and installed distribution transformer capacities of relevant 11 kV feeders.

	Feeder 1	Feeder 2
Dog type ACSR, 5.7 MVA	19.8 km	16.7 km
150 XLPE cable, 3.8 MVA	5.6 km	-
300 XLPE cable, 10.1 MVA	5.3 km	2.6 km
Total	30.7 km	19.3 km
Installed DT capacity	5.16 MVA	5.20 MVA

1 Unspecified whether average, maximum or snapshot loading.
2 aluminium conductor, steel reinforced

Feeder 1 supplies a higher number of customers with a peak load of 4.3 MW, is longer than the Feeder 2, and has more branches and a higher percentage of cables, while Feeder 2 is loaded with a maximum of 4 MW and equipped with with mostly OHL.

Both feeders have the main loads attached towards the end of the feeder. Longer cabled sections starting at the 66/11 kV substation pass by several villages – which are supplied by other feeders connected to the same substation– before branching out to the supplied villages a few kilometers outside. Based on the characteristic of the grid with considerably longer lines than those in urban areas, it can reasonably be expected to be more prone to voltage swings as load and generation characteristics change through the introduction of PV power.

BSES is currently retrofitting the three transformers at the 66/11 kV substation to automatically regulate the voltage on the 11 kV side and thus decouple it from voltage swings in the upstream network. Each transformer supplies a busbar section with five to seven 11 kV feeders. The sections are not connected to each other during normal operation and can thus be independently controlled by the transformers as well as by a switchable stepped capacitor bank attached to each section.

According to the information provided by BSES, an open field, utility scale PV power plant is proposed to be constructed in the area, with 3.5 MW of installed capacity.

Low voltage grids supplied by the two 11 kV feeders are of varying size and load, as evident by the delivered distribution transformer data and their location. Customers are marked as all residential by BSES, but given the topology, other customer classes such as water supply stations, agricultural and commercial customers can be expected. However, due to the provision of sufficient measured load time series data, customer classification is less important here.

3.2.3 Bhopal urban

The 11 kV feeder is located very close to a 132 kV substation. Inside the substation, voltage is stepped down from 132 to 33 to 11 kV. The only relevant upstream lines are two Dog type conductor ACSR circuits that connect two 33 kV busbars inside the substation.

Connection of 132 kV and 33 kV is implemented with two manually controlled on-load tap changing transformers of 40 and 63 MVA rating, controlled by the subtransmission operator. The large 33 kV busbar supplied multiple 33 kV feeders as well as the interconnector to the 33/11 kV busbar inside the same substation.

Two 33/11 kV transformers without on-load tap changing (OLTC) capability, rated at 5 and 8 MVA, supply the 11 kV busbar. The busbar is split in two isolated sections during normal operation, leaving the relevant 11 kV feeder and one other feeder to be supplied by the transformer rated at 5 MVA. Each 11 kV busbar section is equipped with a 1200 kVAr capacitor bank for reactive power compensation.

The feeder consists of a total of 2.7 km of OHL, with 1.33 km of Rabbit type ACSR rated at 2.9 MVA, 1.32 km of Raccoon type ACSR rated at 3.8 MVA, and a very short (40 m) section of 95AB air cable rated at 4.4 MVA. The structure is radial during normal operation, but for redundancy, the feeder can also be supplied from the other side, with an open connection to another 11 kV feeder at its end.

The 11 distribution transformers connected are smaller than on the urban feeder in Delhi, rated from 100 to 315 kVA, with mostly 200 kVA transformers installed. Installed transformer capacity is 2.22 MVA, and peak load according to MPMKVVCL is 1.08 MW, which is a light load of less than 20 % of line rating.

The 11 kV feeder supplies 11 low voltage grids with around 700 customers, domestic as well as office buildings.

3.2.4 Bhopal rural

For analysis of the issues to be expected with PV integration in a rural area, MPMKVVCL provided data on the structure of a distribution grid connecting some outskirts of Bhopal to the nearby villages. It consists of a larger 33 kV structure and detailed data of a single 11 kV feeder at the end of this structure.

The upstream network is connected to the subtransmission grid by a 132/33 kV substation with two transformers rated at 40 and 20 MVA, which supplies multiple 33 kV feeders. The relevant feeder mainly consists of a total of 9.4 km of double circuit OHL with Dog type ACSR conductors, carrying a maximum of 27 MVA, and 2.11 km of similar single circuit OHL carrying a maximum of 13 MVA. The feeder connects five 33/11 kV substations with a total installed transformer capacity of 36.3 MVA. Each substation has capacitor banks for power factor control connected to its 11 kV side, rated from 1200 kVAr in the smaller substations to 2 x 1500 kVAr in the larger ones.

Only two of the installed 33/11 kV transformers have on-load tap changing capability, and those are typically kept at a fixed setting as well. Combined with the manually switched 132/33 kV transformer operated by the subtransmission company, no active direct voltage control instance currently exists, and voltage in the grid is completely dependent on the voltage in the subtransmission grid. However, the shunt capacitors in the 132/33 kV substation are used to influence the voltage as well as compensate the power factor.

The relevant feeder which is modelled in detail is connected to the 33/11 kV substation at the end of the 33 kV feeder.

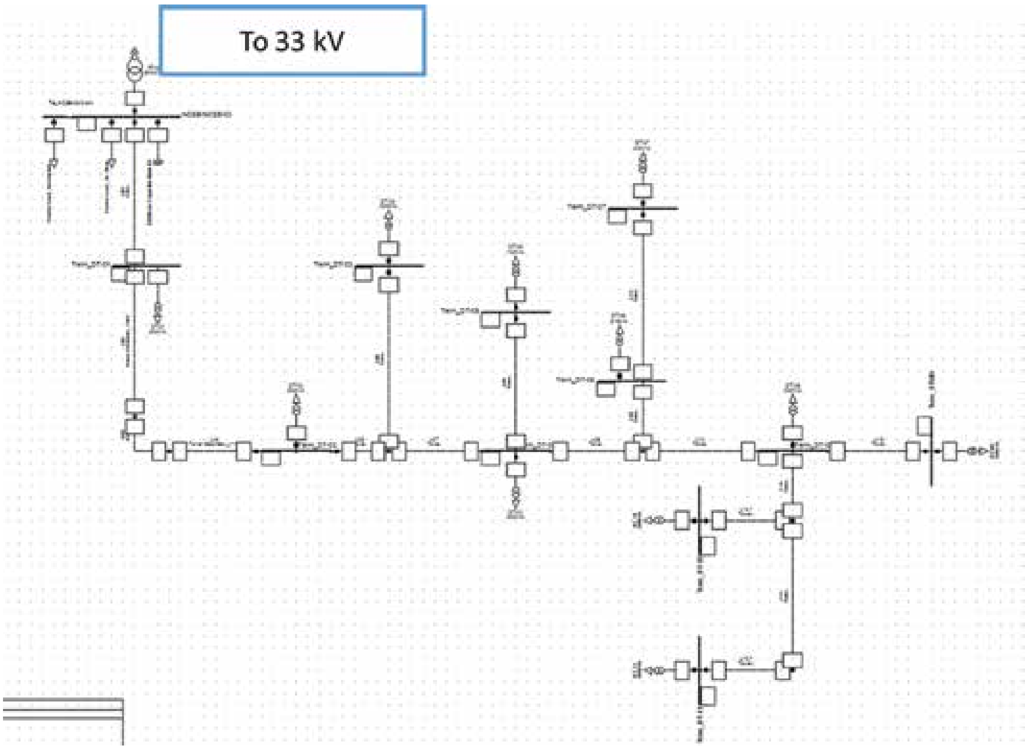

Figure 2: PowerFactory Single-Line-Diagram of Bhopal rural 11 kV feeder.

The 11 kV feeder to be analyzed connects several small villages outside Bhopal and consists of a total of 11 km of OHL. All lines are Raccoon type ACSR that carry a maximum of 3.8 MVA. The feeder is connected to the 33 kV level with a 5 MVA off-load tap changing transformer, fixed at a 1:1 per unit ratio. A total of four 11 kV feeders can be connected to the 11 kV busbar, but only two are connected in normal operation while the others are supplied by other substations.

The relevant feeder is a radial structure as shown in Figure 2. The feeder supplies a total installed capacity of 3.69 MVA of distribution transformers at a peak load of currently 1.55 MW.

This 11 kV feeder feeds 33 individual low voltage grids, mostly connected by 200 kVA distribution transformers. Those grids have radial structures and a mix of residential, commercial and agricultural customers, as specified by MPMKVVCL.

3.3 PV capacities and terminology

The installed capacity of a PV unit can be given either in installed panel capacity, usually referred to as megawatt peak MWp, or in inverter capacity, MW_{AC}. There can be a mismatch between the two values in either direction. In most cases, the inverter capacity will be lower than the panel capacity, as PV panels only reach their full power output under laboratory conditions. During actual operation, factors such as temperature and dust, along with non-ideal insolation, impact power output.

PV panels in India will usually not reach more than 70 % of their rated power output, especially due to the high temperatures on sunny days that decrease efficiency. In the following, all PV installed capacity will be considered as inverter capacity, with the inverter being sized to 70 % of panel capacity. This means that the full inverter capacity will actually be utilized during sunny days. All further capping of inverter size (see section 3.5) will be considered taking this inverter capacity as "full capacity."

3.4 Scenarios

Simulation scenarios were set up to provide worst case analysis for the actual grids that were modelled, as well as model cases for other distribution system operators. Scenarios vary slightly for each of the modelled grids. The following properties were considered:

- The distribution of installed PV capacity has a noticeable effect on the voltage profile, homogeneous distribution (likely case) and a concentration of capacity at the feeder end (worst case) were considered.
- For the rural feeders, the impact of utility scale free field PV installations connected directly to the 11 kV level (2.5 MW for Bhopal, 3.5 MW for Delhi) on the grid and its hosting capacity for rooftop PV was determined.
- A 25 % load increase (5 % per year with target year 2022) was considered, with the additional load considered to be mainly air conditioning.
- The topologies of the grids were modified to present model cases for different areas and discoms.

The scenarios used in the urban and rural networks are listed in Table 3 and Table 4.

Table 3: Scenarios for urban grids.

S. No.	Delhi Urban Scenarios	S. No.	Bhopal Urban Scenarios
1	PV equally distributed with normal load	1	PV equally distributed with normal load
2	PV equally distributed with adapted load	2	PV equally distributed with adapted load
3	PV at the end of the feeder with normal load	3	PV at the end of the feeder with normal load
4	PV at the end of the feeder with adapted load	4	PV at the end of the feeder with adapted load
5	PV at the end of the feeder with lower line cross section	5	PV equally distributed with the network fully cabled

Table 4: Scenarios for rural grids.

S. No.	Delhi Rural Scenarios	S. No.	Bhopal Rural Scenarios
1	PV power plant	-	-
2	PV equally distributed with normal load	1	PV equally distributed with normal load
3	PV equally distributed with adapted load	2	PV equally distributed with adapted load
4	PV equally distributed with a 3.5 MW PV power plant	3C[4]	PV equally distributed with a PV power plant at the end of the feeder
5	PV equally distributed with the network fully cabled	4	PV equally distributed with the network fully cabled

3.5 Technology options

Depending on the structure of the investigated distribution grid area and the technical issues arising with high shares of PV, different technology types can be used to mitigate the effects. All grids, urban and rural, may face transformer and/or line overloading issues at high PV shares. These may be addressed by the following solution approaches, ordered from lowest to highest additional cost:

- Topology changes (modifying the switching states during normal operation, if possible.)
- Capping PV inverters at a certain percentage of installed capacity (for Bhopal and Delhi, 75 % and 70 % of the inverter rating are possible without losing more than 3 % of energy annually, see Table 5.)
- Curtailing PV by remote control if the grid is overloaded.
- Demand side management to increase demand during PV peak (example: Agricultural pumps in rural grids.)
- Deployment of battery storage (optimized for peak shaving, see Figure 3.)
- “Copper in the ground,” meaning line and transformer reinforcements, as a last.

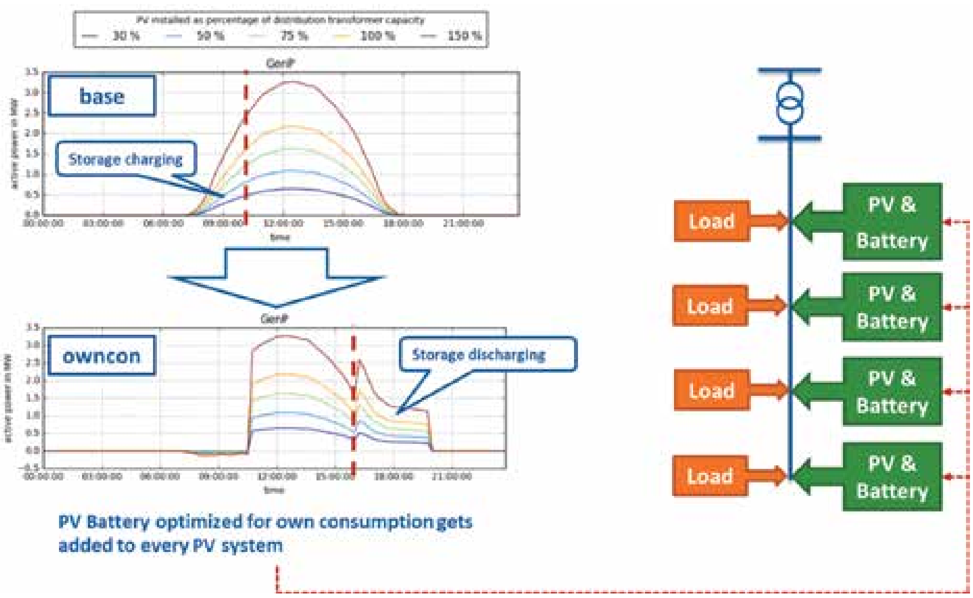

Figure 3: PV Battery implementation with own consumption optimization

Table 5: Relation of a cap and the amount of lost energy for two PV units in Indore (Madhya Pradesh) and Gurgaon (Delhi), based on measured real data

	Indore	Gurgaon
Active power percentage cap[5]	Annual energy loss	Annual energy loss
90 %	0.21 %	0.06 %
80 %	1.74 %	0.49 %
70 %	5.67 %	2.31 %
60 %	12.33 %	6.68 %
50 %	21.18 %	13.93 %
40 %	32.09 %	24.57 %
30 %	45.17 %	38.47 %
20 %	60.59 %	55.48 %

All measures that are effective in reducing asset overloading will also effectively mitigate PV induced overvoltages. However, in rural grids, voltage problems can occur much earlier than overloading due to the longer lines and cables. In this case, measures addressing voltage only are available, ordered from lowest to highest additional cost::

- Using shunt compensators which usually operate in power factor control mode to control the voltage directly.
- Operating PV inverters at a fixed non-unity power factor to reduce the voltage.
- Introducing active voltage control by PV inverters based on a Q-V characteristic[3] that controls reactive power based on measured voltage.
- Introduction of automatic voltage regulation of on-load tap changing transformers at 66, 33 or 11 kV.
- Refining the automatic voltage regulation by the transformer by adding a wide area monitoring system, which measures the voltage at different points in the grid and switches the transformer's tap changer accordingly.

While the urban grids are expected to experience no severe voltage rises at 11 kV level, voltages may rise along 400 V feeders. Besides the measures mentioned above, this can be addressed by the introduction of on-load tap changing distribution transformers which have already been successfully used in some areas in Germany and California.

The measures implemented in the simulations and their abbreviations are given in Table 6.

Table 6: Technology options deployed.

Measure (Abbrevation)	Description
base	Base case with no additional measures implemented.
oltc	On-load tap changing transformers with automatic voltage control are used between 33 and 11 kV (only Bhopal, part of base case in Delhi)
shunt V control	Existing shunt capacitors present in the network are used for automated voltage control.
wide area control	Voltage control by OLTC based on a wide area monitoring system. Including on-load tap changing DTs for the Delhi urban case.
fixed PF	Distributed PV units operate at a fixed power factor of 0.95 lagging.

3 Reactive power output (Q) is controlled based on voltage (V) measurements at the connection point.

Measure (Abbrevation)	Description
qvchar	Distributed PV units are equipped with a Q-V characteristic for voltage control
cap pv	PV output is capped to 70 % (Delhi) or 75 % (Bhopal) of inverter rating (less than 3 % annual energy loss)
storage ownConsumption	Storage batteries are installed at all PV units, with 1 kWh of storage per 1 kWp of PV, operation optimized solely for self-consumption.
storage peakShaving	Storage batteries are installed at all PV units, with 1 kWh of storage per 1 kWp of PV, operation optimized for self-consumption and grid impact.
dsm	Demand side management for all loads.
grid reinforcement	Overloaded assets are reinforced.

4. Simulation results

4.1 Visual representation of results

The description of results requires some visual representation, which may not be self-explanatory. In the following, the structure used in presenting the results in this section shall be explained briefly.

The main means of graphic representation of each scenario is a figure like the example given in Figure 4. From the left to the right, PV penetration is increased in the analyzed grid model from 15 or 20 to 150 % of the total capacity of installed distribution transformers. For each value, the maximum asset loading experienced by any asset is given in the upper graph, and the maximum voltage occurring anywhere in the grid model is given on the lower graph. These values are interpolated linearly to show a trend. The conditions in the base case, with the grid "as is" is represented by a black line, while the multiple colored lines represent the conditions under the implementation of different technology options.

The limits allowed during normal operation, both for loading and voltage, are given by dotted red lines. For each scenario, the PV penetration level at which one of the thresholds is crossed and a security or quality constraint thus violated, are given in an additional table, including the values for all different technology options.

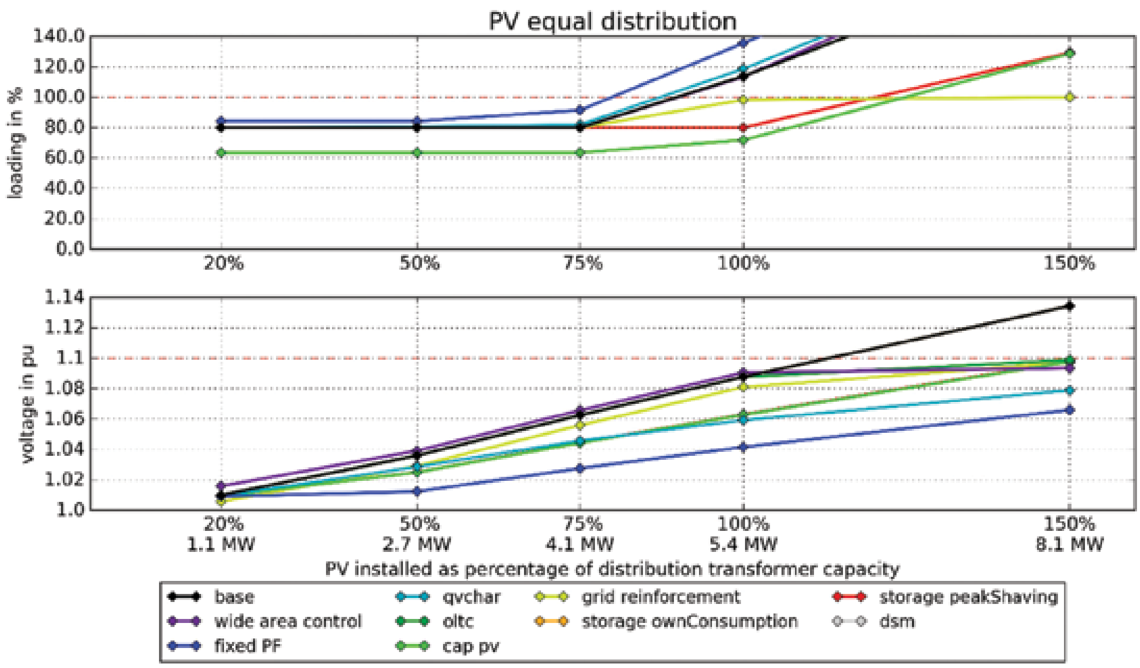

Figure 4: Result example as described in the text.

In this summary report, the figures are only given for the base case scenario for each feeder, while the results of the other scenarios are given in a table, with the coding used explained in Table 7. A more detailed presentation of results can be found in the long version main report. Some of the implemented technology options did not have any effect on PV hosting capacity and can thus be considered to be unsuitable. As all options were simulated for all feeders, these are also included in the results for clarity.

Table 7: Symbols used in results tables.

Impact	Symbol
Measure increases hosting capacity from base case, above 100 %	↑↑
Measure increases hosting capacity from bas case but stays below 100 %	↑
Measure has no effect	O
Measure reduces hosting capacity from base case	↓

4.2 Urban feeder Delhi

All simulation results in Delhi's urban network with a fully modelled generic LV network indicate loading problems to either occur first or occur at the same time as PV induced overvoltage becomes an issue (see Figure 5.) The loading issues mostly occur in cables reaching their maximum current carrying capacity.

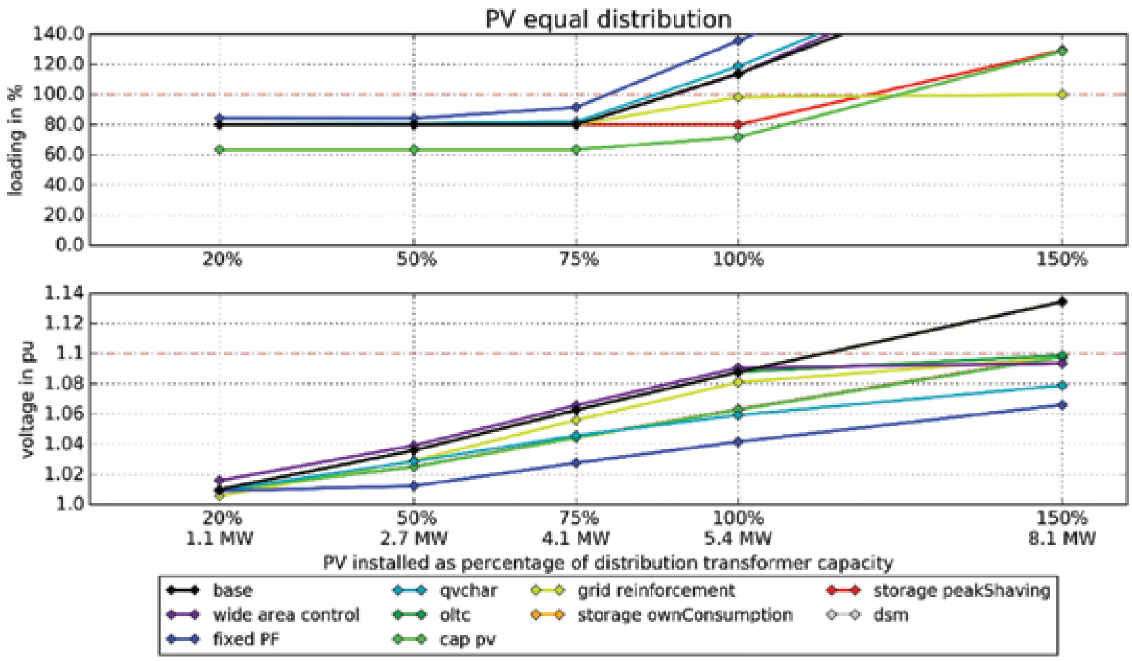

Figure 5: Simulation results for urban feeder with LV network and equal PV distribution.

This results in only two solutions - apart from the common approach of grid reinforcement - being viable to increase the installed PV capacity beyond the individual limits observed in each scenario. From Table 8 it becomes evident that only capping PV infeed or utilizing storage with peak shaving can increase the maximum of installed PV capacity without reinforcing grid assets.

However, results also show a generally high potential to incorporate residential PV systems in this rather well developed network. With an estimated maximum rooftop potential of approximately 100 % of distribution transformer capacity and a capability to include between 75 % and 100 % based on the selected scenario[4], the network should be able to handle the maximum amount of PV that can reasonably be expected to be installed without any measures taken. Capping PV or using batteries may become necessary if unfavorable placement of PV systems takes place or the projected load increase does not meet expectations.

4 Considering scenarios 1 through 4 that reflect conditions in the actual grid. Scenario 5, which has a lower hosting capacity for PV, is an artificial scenario with weaker lines.

Table 8: Overview of the maximum installed PV capacity as a percentage of the distribution transformer capacity for all scenarios and applied solutions of the urban network of Delhi.

Measure	Scenario 1: PV equally distributed with normal load		Scenario 2: PV equally distributed with adapted load		Scenario 3: PV at the end of the feeder with normal load		Scenario 4: PV at the end of the feeder with adapted load		Scenario 5: PV at the end of the feeder with lower cable cross-section	
base	90%		100%		75%		80%		55%	
oltc	90%	o	100%	o	75%	o	80%	o	55%	o
wide area control	90%	o	100%	o	75%	o	80%	o	50%	↓
fixed PF	80%	↓	85%	↓	65%	↓	70%	↓	50%	↓
qvchar	90%	o	95%	↓	70%	↓	75%	↓	55%	o
cap pv	150%	↑↑	150%	↑↑	140%	↑↑	150%	↑↑	105%	↑↑
storage own Consumption	90%	o	100%	o	75%	o	80%	o	55%	o
storage peakShaving	120%	↑↑	130%	↑↑	100%	↑↑	115%	↑↑	80%	↑↑
dsm	90%	o	100%	o	75%	o	80%	o	55%	o
grid reinforcement	150%	↑↑	150%	↑↑	150%	↑↑	150%	↑↑	150%	↑↑

4.3 Rural feeder Delhi

The rural network tends to have voltage issues in most scenarios (see Figure 6 for the base case) except when considering load increases. In these cases, distribution transformers that are already highly loaded in the base case are overloaded first.

A summary of results for each scenario and solution is shown in Table 9. All solutions coping with loading issues (capping PV, storage with peak shaving) can be helpful in Scenario 3, while the solutions dealing with voltage issues are not helpful here. Scenarios 2, 4 and 5, with the penetration being limited by voltage issues, offer a much higher variety of suitable solutions. Especially wide area control of the 66 kV/11 kV transformers allows for a significant increase of installed PV capacity, because of the expanded use of the full voltage bandwidth.

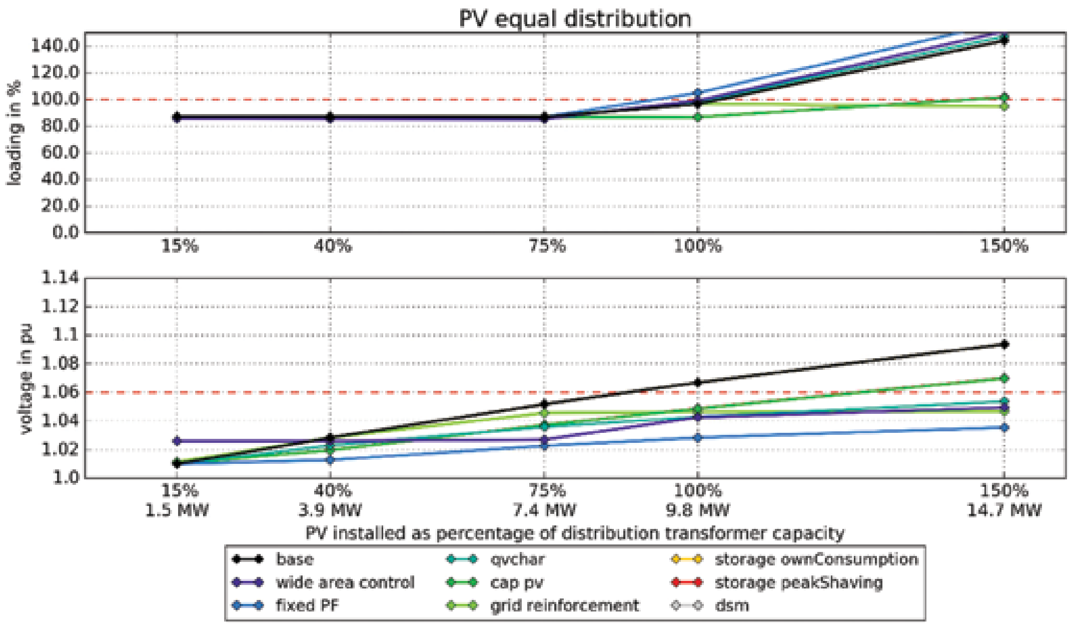

Figure 6: Simulation results of the rural feeder with two parallel MV feeders and equal PV distribution.

A combination of wide area control and a solution to reduce loading of network elements (either capping PV or storage with peak shaving) can probably be an effective way to include high amounts of PV, without the necessity of grid reinforcement. As an intermediate solution, using reactive power (either fixed power factor or Q-V-characteristic) could be an easy to implement and effective solution to increase the networks capability to handle residential PV installations.

Table 9: Overview of the maximum installed PV capacity as a percentage of the distribution transformer capacity for all scenarios and applied solutions of the rural network of Delhi.

Measure	Scenario 2: PV equally distributed with normal load		Scenario 3: PV equally distributed with adapted load		Scenario 4: PV equally distributed with 3.5 MW PV power plant		Scenario 5: PV equally distributed with network fully cabled	
base	90%		110%		25%		70%	
wide area control	105%	↑↑	110%	o	75%	↑	100%	↑↑
fixed PF	95%	↑	105%	↓	60%	↑	95%	↑
qvchar	105%	↑↑	110%	o	45%	↑	90%	↑
cap pv	150%	↑↑	150%	↑↑	50%	↑	145%	↑↑
storage own consumption	90%	o	110%	o	25%	o	70%	o
storage peak shaving	125%	↑↑	150%	↑↑	35%	↑	100%	↑↑
dsm	90%	o	110%	o	25%	o	70%	o
grid reinforcement	150%	↑↑	150%	↑↑	150%	↑↑	150%	↑↑

4.4 Urban feeder Bhopal

The networks in the urban feeder in Bhopal were simulated with models of the 11 kV and 33 kV level with the low voltage networks represented by load / generation equivalents. With a short feeder length and the feeder being directly attached to the voltage controlling substation, the Bhopal urban feeder experiences no overvoltage problems even at very high PV penetration levels (see Figure 7.) However, distribution transformers and some lines can eventually be overloaded if PV capacity exceeds transformer capacity. This may be addressed by simply reinforcing transformers and lines. To avoid costly reinforcements, alternative measures can be taken to control the active power feed-in of PV.

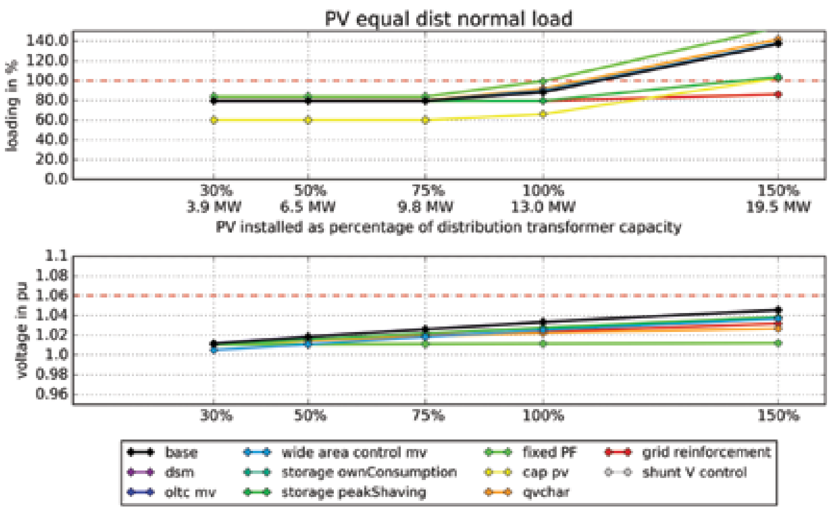

Figure 7: Simulation results for the urban feeder in Bhopal with rooftop photovoltaic plants equally distributed along the feeder with normal load considered

Curtailment of PV or a peak cap at a certain percentage of capacity may, if set up reasonably, prevent some of the overloading issues while losing only a small percentage of PV energy. This can in the long run still be cheaper than reinforcing the grid.

Deployment of PV storage batteries can also alleviate some of the issues, if an adequate charging strategy is chosen. If batteries are optimized for own consumption only, they will usually not reduce the mid-day PV peak and thus have no positive impact on grid loading. Setting PV batteries up to shave the PV peak on the other hand will reduce grid loading and overvoltage problems.

Table 10: Overview of the maximum installed PV capacity as a percentage of the distribution transformer capacity for all scenarios and applied solutions of the urban network of Bhopal.

Measure	Scenario 1: PV equally distributed normal load		Scenario 2: PV equally distributed adapted load		Scenario 3: PV at the end of the feeder normal load		Scenario 4: PV at the end of the feeder adapted load		Scenario 5: PV equally distr., cabled network	
base	110 %		115 %		110 %		110 %		110 %	
oltc	110%	o	115%	o	110%	o	110%	o	110%	o
shunt V control	110%	o	115%	o	110%	o	110%	o	110%	o
wide area control	110%	o	115%	o	105%	↓	110%	o	110%	o
fixed PF	100%	↓	105%	↓	90%	↓	95%	↓	100%	↓
qvchar	110%	o	110%	↓	105%	↓	110%	o	110%	o
cap pv	145%	↑↑	150%	↑↑	140%	↑↑	145%	↑↑	145%	↑↑
storage ownConsumption	110%	o	115%	o	110%	o	110%	o	110%	o
storage peakSh.	140%	↑↑	150%	↑↑	130%	↑↑	135%	↑↑	140%	↑↑
grid reinf.	150%	↑↑	150%	↑↑	150%	↑↑	150%	↑↑	150%	↑↑

4.5 Rural feeder Bhopal

The networks in the rural feeder in Bhopal were simulated with models of the 11 kV and 33 kV level with the low voltage networks represented by load / generation equivalents. The lines are longer but have a lower average cross section in comparison to the urban feeder, and there is a higher number of smaller transformers instead of a few large ones.

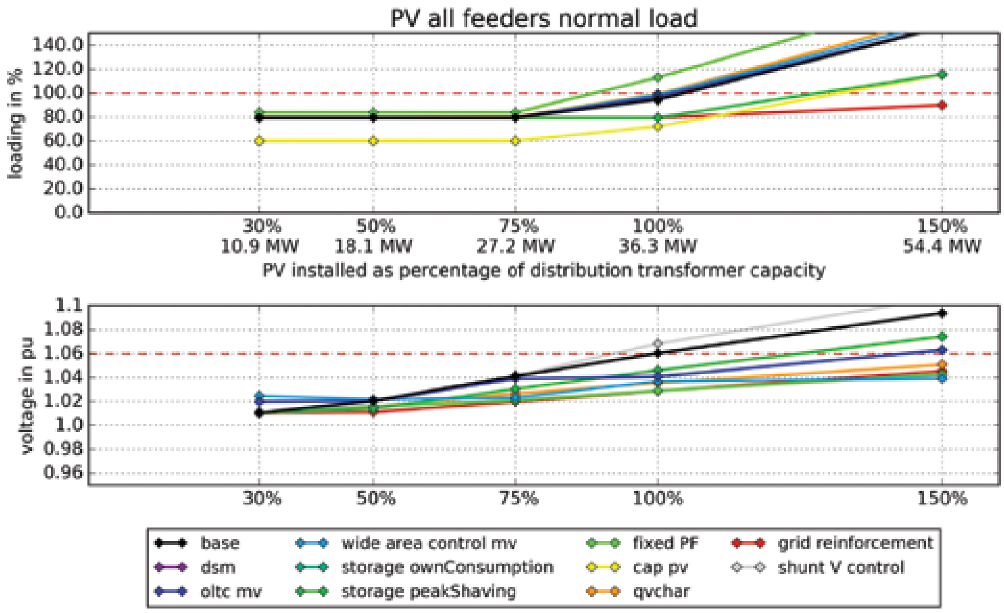

Figure 8: Simulation results for the rural feeder in Bhopal with rooftop photovoltaic plants equally distributed along the feeder with normal load considered

All issues can be resolved with simply reinforcing the network. If this is to be avoided, there are several different alternative solutions that can mitigate the problems. As in the urban feeder, active power control measures such as a cap of the PV peak or peak shaving batteries are suitable to alleviate both overvoltage and overloading problems. Only in the scenario with a large PV plant at the end of the feeder it does make sense to implement measures that directly control the voltage by reactive power feed-in of PV inverters. Both overvoltage as well as overloading problems occur with rising PV penetration, depending on the scenario (see Figure 8.)

Table 11: Overview of the maximum installed PV capacity as a percentage of the distribution transformer capacity for all scenarios and applied solutions of the rural network of Bhopal.

Measure	Scenario 1: PV equally distributed normal load		Scenario 2: PV equally distributed adapted load		Scenario 3C: PV equ. dist. with PV plant at end of feeder[6]		Scenario 4: PV equally distributed, fully cabled network	
base	100 %		105 %		65 %		105 %	
oltc	105%	↑↑	110%	↑↑	65%	o	105%	o
shunt V control	90%	↓	105%	o	60%	↓	100%	↓
wide area control	100%	o	110%	↑↑	65%	o	100%	↓
fixed PF	90%	↓	85%	↓	60%	↓	95%	↓
qvchar	100%	o	110%	↑↑	65%	o	100%	↑
cap pv	125%	↑↑	130%	↑↑	85%	↑	130%	↑↑
storage ownConsumption	100%	o	115%	↑↑	65%	o	105%	o
storage peakShaving	125%	↑↑	140%	↑↑	80%	↑	130%	↑↑
grid reinforcement	150%	↑↑	150%	↑↑	150%	↑↑	150%	↑↑

5. Conclusions

5.1 General conclusions

Simulation results from the four feeders show that PV penetration levels of 75 % of distribution transformer capacity and higher can be implemented without having to undertake any measures to contain voltage problems or overloading. This is significantly higher than the limits of usually 30 – 60 % prescribed by regulators in most Indian states today. Hosting capacity may be lower in other, weaker grids, or if additional free field PV power plants are connected.

In most cases, penetration levels of slightly above 100 % can be realized. As the minimum daily load is low on all of the analyzed grids, lines and transformers will get overloaded at penetration levels typically above 110 %, as little PV power is consumed locally during the simulated worst case days. To push installed capacity higher, active power control measures have to be implemented. These may include a fixed cap on 70 – 80 % of rated capacity, PV curtailment based on grid loading, or the use of peak shaving PV batteries.

5.2 Most relevant technical issues

As expected, the problems observed in the analyzed distribution feeders at high penetration levels of rooftop PV are somewhat different from the experiences in Germany and California due to the grid characteristics. Generally, the following can be stated:

- The urban grids are short and strong, enabling high penetration levels of rooftop PV. At shares above 100 % of distribution transformer capacity, some assets, mostly transformers, can be overloaded. The impact of PV on the voltage is low.
- The rural grids consist of weaker lines and are more highly loaded. With an unfavorable distribution of rooftop PV or the addition of free field PV units connected to the 11 kV level, overvoltage problems can occur at penetration levels of above 50 % already. With normal distribution, overloading becomes relevant at levels of 90 – 100 %.

All these results were obtained under the assumption that voltage control at the 66/11 or 33/11 kV (Delhi) or 132/33 kV (Bhopal) substations is adequate, and the voltage at the distribution grid busbar is no higher than 1.01 p.u. This is currently not always the case in Indian distribution grids. BSES is currently activating / upgrading all transformers stepping down to 11 kV to automatic voltage control, making the assumption valid for the future. In Bhopal, voltage control at the 132/33 kV transformers is done manually and by the transmission company, leading to large voltage swings at the 33 kV busbar especially in the rural grid. Under current conditions, this could severely limit PV penetration. For the urban grid, this issue is less pressing as PV has very little impact on voltage due to the short line lengths.

5.3 Performance of technology options in the simulations

As the model grids were able to absorb quite high penetration levels of PV, in most cases, there is no need for advanced technical solutions to avoid loading or voltage problems. However, at very high penetration levels, it could be observed that the active power management strategies of either capping PV feed-in at 70 or 75 % of inverter capacity or the use of peak shaving batteries performed best in resolving both voltage and loading issues. This is true for both rural and urban grids, as the mechanisms are the same. Both overvoltage and overloading are caused by active power feed-in, and if that is limited or shifted, problems are alleviated. However, both solutions have costs attached to them, both of which may be either be borne by the discom or by the client –either way, it will somewhat increase the cost of power from rooftop PV.

5.3.1 Peak shaving batteries

If battery storage is to be used to benefit PV integration, the units need to be procured and installed by the customers at their facilities. Many Indian homes are already equipped with backup batteries that could be used for PV storage. Prices for lithium ion and lead acid batteries have reduced by more than 40 % since 2013, keeping the price for a kWh of storage capacity in the same range as the price for a kWp of rooftop solar PV. [1][2] This means that the installation of 1 kWh of battery capacity for each kWp of installed solar capacity would roughly double the price of the installation. Currently, there is no grid parity for such a system, meaning that it would not work without an additional incentive scheme. However, as prices for PV and storage drop, this may be a feasible future scenario. The current backup battery boom in India also has the effect of reducing battery costs by economics of scale. In any way, an incentive has to be set for batteries to operate in peak shaving mode, instead of optimizing purely for own consumption, which may conflict with their use for backup during power outages.

5.3.2 Capping of inverters

The cheaper solution, having almost the same grid impact during extreme situations[5], is the capping of PV inverters. It is possible to cap PV feed-in at 70 – 75 % of the maximum value without losing more than 3 % of energy annually, while significantly increasing the hosting capacity of the grid. With an average increase of 3 – 4 % in generation cost for retrofitted systems, and less than that for new systems due to cost savings in a smaller inverter[6], this is an effective, but much cheaper solution than the use of PV storage batteries. This solution is also currently used for small rooftop PV units in Germany.

The impact of demand side management in grids with primarily residential customers is low due to the low potential for DSM in private households. However, the strategy should be given more attention when analysing grids with a high share of industrial or commercial customers.

5.3.3 Voltage control measures

For cases in which only voltage problems (overvoltage) can be expected – long lines, low load and unfavourable PV distribution – some voltage control solutions are applicable and feasible. Voltage control by the power transformers can be enhanced by a wide area control system, measuring the voltage on each feeder and setting the transformer taps accordingly. This solution requires some additional investments in communication, but will have multiple positive effects on grid operation, extending beyond PV integration:

- Voltage rises induced by PV are detected and alleviated.
- Voltage drop issues caused by high loading during evening and night can be detected and alleviated as well.
- The general quality of supply will be improved by improving the voltage profile.
- As continuous measurements have to be made at multiple points in each grid, the operator is supplied with a constant stream of operational data, can manage quality of supply more efficiently, and detect possible operational problems early on.

Wide area control is used in distribution grids in different countries already and is a generally accepted tool to improve voltage quality. It requires investments in communication infrastructure and will only be applicable if automatic on-load tap changing transformers are available. The distribution grid study for the German state of Rhineland Palatinate [3] estimated the cost at 50,000 € (INR 38,00,000) per 110/20 kV transformer[7], but the actual cost depends on the local conditions and used equipment and must be assessed for each project individually.

On-load tap changing transformers with automatic voltage control at least at the connection

5 PV batteries will always reduce the active power output of the system and thus have additional value to distribution grid and power system operation. The PV cap will only reduce it in situations of very high feed-in and has no impact during most of the year.

6 Inverters may be sized to a smaller rating if output is capped at 70 % anyways, but the software side has to be set up to reduce power at the DC side of the inverter already, to prevent overloading the inverter.

7 Power transformers used in Germany, role comparable to 66/11 or 132/33 kV transformers in India.

between transmission or subtransmission level (220 or 132 kV) and the distribution grid should be considered in all cases – otherwise, voltage problems may occur already without any PV installed. Besides facilitating PV integration, this will improve voltage quality significantly and alleviate current load-induced undervoltage issues.

5.3.4 Voltage control from PV inverters

Voltage control from the PV units themselves, on the other hand, cuts both ways. Reactive power from PV inverters can effectively control voltage, and can be obtained via a simple grid code requirement that most inverters on the market can fulfill already, but at the cost of increasing grid loading through reactive currents. In already highly loaded grids, caused either by high load or high PV feed-in, it may actually have a negative impact. In any way, requiring the capability for reactive power and voltage control from rooftop PV inverters is sensible, as it will give the operator an additional means of voltage control, that could also be used to alleviate pre-existing voltage issues (for example in cases where no automatic voltage control from power transformers is available.) The current provisions for activation of reactive power supply should be decided based on the characteristics of each individual grid. In the simulations for this study, the following could be observed:

- In already highly loaded grids, using a Q-V characteristic for inverters connected to the 0.4 kV level provides better results, as reactive power provision is only activated when it is really needed, reducing the probability of overloading caused by reactive currents.
- In grids with no loading issues, a fixed power factor of 0.95 lagging performed better than a Q-V characteristic in alleviating overvoltage problems. With Q-V characteristics implemented, the units closer to the 11 kV substation that do not "see" the full voltage rise at the end of the feeder will not contribute to voltage control, while with a fixed power factor, their reactive power behavior contributes to containing the voltage increase.
- If a large amount of PV power is injected into one node in the grid, either by inhomogeneous distribution of rooftop PV, or by a PV power plant, a Q-V characteristic performs better, if the grid is not prone to overloading.

Theoretically, PV inverters operating at leading power factors could also be used to alleviate low voltage problems during high load – this is, however, not a common use case, and was not investigated in detail in this study.

5.3.5 Reversed power flows and protection

The only direct impact of a reversal of power flow with a moderate flow that can be observed concerns the protection settings. Especially with the overcurrent protection typically used at medium and low voltage levels, the short circuit current contribution of the units feeding in between the protection relay and the location of the fault have to be considered. For PV, the short circuit current is no larger than the rated current of the inverter, leading to a moderate contribution that should nevertheless be considered in the calculation of protection settings.

The easy way around this problem would be to require the units on a feeder protected by an overcurrent relay to immediately disconnect at detection of a voltage drop (which indicates a short circuit nearby), or stay connected but not provide any short circuit current. If this requirement collides with low voltage ride through that may be required for other reasons, the short circuit current of all units on a feeder should be limited to

$$\sum I_{sc,unit} \leq I_{sc,max} - I_{sc,trigger}$$

6. Recommendations

6.1 Studies

The results from the four analyzed distribution grids show a great variety in results, but all of them display a high hosting capacity for rooftop PV. However, this can by no means be generalized. Each grid area needs to be analyzed on its own and checked for possible problems with rising PV shares. This does not necessarily require extensive simulation studies like those conducted in this study, some simple estimation approaches are provided in the long version main report.

Simulation studies at least for some example feeders are recommended to be conducted by each discom anyway, to develop a better understanding of the behavior of distributed generation and their impact on grid operation.

6.2 Technical solutions

Specific technical solutions need to be assessed for each grid area separately, but some recommendations can be drawn from the model cases analyzed in this study. Concerning voltage control, these are the following:

- Automatic voltage control by tap changing transformers at 132/33, 220/66 or 220/33 kV should be implemented in all distribution grids regardless of PV development, this is international good practice to ensure good voltage quality.
- Automatic voltage control by tap changing transformers at 66/11 or 33/11 kV level is very beneficial to voltage quality regardless of PV penetration, but not strictly required if the voltage control above is adequate.
- Voltage problems in the distribution grid, caused by both load (undervoltage) and PV (overvoltage) can be efficiently eliminated by the use of a wide area voltage control, measuring the voltage at multiple points in the grid and operating the voltage control by transformers accordingly.
- The capability for voltage control by rooftop PV inverters by provision of reactive power can easily be required by the grid code, and such a requirement is highly recommended and international good practice. The actual set points of the voltage control or fixed power factor, or the decision whether it is engaged at all, must be determined by the operator based on grid loading. If loading is low, reactive power for voltage control is beneficial. If loading is high, reactive currents may cause overloads. Generally, Q-V characteristics perform better in highly loaded grids and offer more control, while fixed offset power factors alleviate voltage problems in lightly loaded grids more effectively.
- PV power plants connected to the 11 or 33 kV level should be equipped with active voltage control by Q-V characteristic. If the grid experiences severe overloading issues, the grid operator may choose to disable the controls and run the unit at a fixed power factor, unity or offset.

Active power management of PV units will also play a large role in the future, leading to the following recommendations:

- Some degree of active power management and controllability should be required from all PV units, regardless of size and connection level.
- Centralized PV power plants connected to 11 kV and above should be remotely controllable so the grid operator can curtail active power in case of grid congestion. The exact conditions under which the operator may curtail must be clearly defined and subject to energy legislation and regulation.
- Rooftop PV units connected to the low voltage grid should either be capped at 70 to 75 %

of their maximum expected output[8], or be remotely controllable, or be equipped with a peak shaving storage. A cap is the cheapest and least complicated option.[9]

- If PV batteries are introduced, there should be an incentive to use them in peak shaving mode to maximized positive grid impact.

6.3 Legal and regulatory framework

Technical development needs to be supported by an adequate legal and regulatory framework. Most Indian states have a net metering scheme in place and specific regulations for application, installation and metering. For a large scale roll-out of rooftop PV and with regard to the technical solutions developed within this report, the following points need to be addressed in legal and regulatory development:

- The distribution grid codes should be updated to require voltage control capability from PV inverters, with the grid operator being in charge of the actual reactive power regime. It is recommended to align the requirements with the German low voltage grid code, as many inverters available on the market are compliant with that already due to Germany currently being the largest market for rooftop PV with advanced capabilities.
- The capping of PV at 70 or 75 %, if implemented, must be specified in grid code and net metering scheme, and must be checked for legal complications.
- For PV batteries, incentives have to be set by energy legislation, both for installation of batteries and for running them in peak shaving mode.
- If PV units can be remotely controlled by the grid operator, it needs to be specified in legislation and regulatory documents under which circumstances the operator is actually allowed to do so. For the case of active power curtailment, remuneration of lost energy must be agreed on[10].
- The high share of rooftop PV expected to be installed in India will also impact power system operation above the distribution level. Grid code requirements should be developed in coordination with the entities responsible for the operation and stability of the transmission system. As an example, frequency response of PV units will neither impact the distribution grid nor is it required for distribution grid operation, but will considerably impact transmission system operation.

8 PV units in India typically only reach a maximum output of around 70 % of their installed panel capacity due to dust and heat. The inverter can thus be undersized to around 70 % of panel capacity already. Any further reduction in DC/AC ratio will lead to energy loss. If a loss of 3 % annually is considered acceptable, the inverter can be capped at 75 % of its (already undersized) rating, leading to a DC/AC ratio of $1/(0.7 \cdot 0.75) = 1.9$, equivalent to an inverter rating of 53 % of panel capacity.

9 The German grid code requires a 70 % cap for non-controlled units below 13.8 kWp, and controllability for larger units. In India, communication infrastructure in the disitribution grid may be weaker, so the cap could also be the easier solution for larger rooftop units.

10 Example from Germany: If the unit is not capped, the operator can curtail up to 3 % of energy yearly without remuneration, for any reason. Additional curtailment must be remunerated. Curtailment due to emergencies in the grid is not remunerated.

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