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The Full Cost of Electricity (FCe-)

Integrating Photovoltaic Generation

PART OF A SERIES OF WHITE PAPERS

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THE FULL COST OF ELECTRICITY is an interdisciplinary initiative of the Energy Institute of the University of Texas to identify and quantify the full-system cost of electric power generation and delivery – from the power plant to the wall socket. The purpose is to inform public policy discourse with comprehensive, rigorous and impartial analysis.

The generation of electric power and the infrastructure that delivers it is in the midst of dramatic and rapid change. Since 2000, declining renewable energy costs, stringent emissions standards, low-priced natural gas (post-2008), competitive electricity markets, and a host of technological innovations promise to forever change the landscape of an industry that has remained static for decades. Heightened awareness of newfound options available to consumers has injected yet another element to the policy debate surrounding these transformative changes, moving it beyond utility boardrooms and legislative hearing rooms to everyday living rooms.

The Full Cost of Electricity (FCe-) study employs a holistic approach to thoroughly examine the key factors affecting the *total direct and indirect costs* of generating and delivering electricity. As an interdisciplinary project, the FCe- synthesizes the expert analysis and different perspectives of faculty across the UT Austin campus, from engineering, economics, law, and policy.

In addition to producing authoritative white papers that provide comprehensive assessment and analysis of various electric power system options, the study team developed online calculators that allow policymakers and other stakeholders, including the public, to estimate the cost implications of potential policy actions. A framework of the research initiative, and a list of research participants and project sponsors are also available on the Energy Institute website: energy.utexas.edu

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This paper is one in a series of Full Cost of Electricity white papers that examine particular aspects of the electricity system.

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Integrating Photovoltaic Generation

Cost of Integrating Distributed Photovoltaic Generation to the Utility Distribution Circuits

Suma Jothibasu, Anamika Dubey and Surya Santoso
Department of Electrical and Computer Engineering
The University of Texas at Austin

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ABSTRACT:

Under state Renewable Portfolio Standards (RPS), the state is usually obligated to produce a fraction of its electric power generation from renewable energy sources. Currently, solar energy is second only to wind in its contribution to renewable electric power generation. The International Energy Agency (IEA) estimates that by 2050, solar photovoltaic (PV) power generation will contribute to 16% of the world's electricity, with 20% of the total PV capacity from residential installations. Residential PV allows power to be locally generated, and thereby reducing the need for power transmission from large generating stations. However, large-scale PV generation at the distribution level causes more grid concern, since the grid is designed for unidirectional power flow to serve loads downstream from the distribution-level substation.

Given the above motivation, the study aims to estimate the cost of maximizing PV capacity that can be integrated in a distribution grid, without any grid impacts. The study is organized into three PV accommodation limits. In the first part, the concept of Range-1 PV hosting capacity is introduced. Range-1 capacity is the largest PV generation that a distribution circuit can accommodate without making operational changes to the circuit or upgrading the infrastructure. In the second part, Range-2 PV hosting capacity is presented. It is the PV generation capacity that the distribution circuit can accommodate when few operational changes are allowed in the equipment already installed in the power distribution circuit. Note that accommodating up to Range-1 and Range-2 PV capacities does not require any integration costs, except for some minimal cost associated with the operational changes in the existing devices. Finally, the hosting capacity of the given circuit is increased beyond Range-1 and 2 capacities with the help of additional infrastructure upgrades such as smart inverters and energy storage. The corresponding increased hosting capacity is referred to as the Range-3 hosting capacity.

The study utilizes three representative utility distribution circuits provided by Electric Power Research Institute (EPRI). It is shown that a significant amount of Range 1 PV capacity can be integrated into the circuit without requiring any equipment upgrades or operational changes. Depending on the circuit characteristics, Range 1 capacities can be as low as 15.5% (i.e., 2600 kW in one particular circuit) or over 100% (i.e., 3870 kW in another circuit) of the median value of the daytime (between 7am and 7 pm) peak load demand. Factors limiting Range 1 capacities involve overvoltage at the secondary service wire and reverse power flow conditions. Yet, these results suggest a relatively substantial amount of rooftop PV can be integrated without causing any adverse grid impacts and without incurring any grid integration cost.

Depending on the limiting factors, the PV penetration level can be increased by allowing appropriate operational changes (Range 2). For example, transformer tap operation can be modified to address overvoltage condition at the secondary service wire. In the circuit evaluated, such operation results in improving capacity from 15% (Range 1) to 47% (Range 2). It is also observed that tap operations increases with high PV penetration. However, the incremental cost of additional tap operations is not significant, and so can be considered to be part of regular transformer maintenance costs.

Circuit's hosting capacity can be further increased to Range 3 by incorporating smart inverters and energy storage systems. The study shows that for one of the circuits, Range 2 capacity from about 47% can be increased to Range 3 of about 80% by requiring only 30% PV installations with smart inverter technologies. The incremental cost of upgrading the PV inverters with smart inverter functionality is a fraction of the total PV system cost (likely a few hundred to $1,000 per unit of inverter). Utility may consider various incentive approaches to help customers offset the cost, as other options such as including line regulators to mitigate the over-voltage concern would require a huge investment by the utility. Unfortunately, the same applies for circuits requiring energy storage to achieve Range 3 hosting capacity. The cost of energy storage systems would be significant and so including energy storage is unjustifiable for the sole purpose of increasing PV penetration.

Although the study reported herein evaluates three representative utility distribution circuits, it shows that a relatively significant PV generation can be integrated with no or little costs to utilities and their customers. At such levels, PV generation impacts are non-existent or can be addressed by appropriate circuit operational changes. However, increasing feeder PV generation capacity using energy storage technologies likely incurs a significant cost. ■

1 | INTRODUCTION

The global concern with reducing CO_2 emissions has catalyzed the development of new technologies that can tap renewable energy sources. Harvesting solar energy has recently attracted great interest.

In early 2014, the total solar global capacity surpassed 150 GW [1]. Present technologies that utilize solar energy include photovoltaics (PV) and concentrated solar power (CSP) generation. Solar PV employs semiconductor modules to directly convert solar energy into electrical energy, whereas CSP uses a mechanical interface to convert concentrated solar rays into electricity. Since this study is on the distribution circuits, we focus only on solar PV that can be easily integrated at a residential scale.

The decline in PV panel cost and sustained supportive governmental policies have promoted the growth of PV. Since 2010, the world has added more solar photovoltaic (PV) capacity than in the previous four decades. The United States' PV installation amounts close to 17.5 GW, with California leading the nation in solar applications. In 2013, for example, California added 2 GW of PV, which is 57% of total U.S capacity additions. Further Solar Energy Industries Association (SEIA) has listed 799 new major solar projects throughout the nation that represent over 43 GW of PV capacities. By 2050, the International Energy Agency (IEA) predicts that solar PV will contribute to 16% of the world's electricity and that the U.S.'s PV capacity will be 599 GW [1].

Additionally, residential PV installations are growing and are significant contributors to the total capacity additions. As a matter of fact, in 2014, the total amount of PV capacity installed was greater at the residential-scale than the utility-scale [2]. IEA predicts that the global residential rooftop PV will represent 20% of the total PV capacity by 2050. Residential PV installations allow self-sufficient power generation. Also, surplus energy from residential sources can be exported to the distribution grid. However, large amounts of energy generation at the distribution level might require adding new controls and upgrades in the power grid.

To understand high PV penetration scenarios, the U.S Department of Energy has supported several research projects under the SunShot Initiative [3-6]. The National Renewable Energy Laboratory (NREL), in collaboration with Southern California Edison (SCE), evaluated the impacts of the high level of PV penetration on distribution feeders [5]. The study indicates that with large-scale PV integration, voltage regulation issues, potential overvoltage situations, and voltage fluctuations with PV variability are more likely to occur. The issues were reported to have been resolved by allowing the PV inverters to inject reactive power while operating at a fixed power factor.

NREL also studied the repercussions of high PV penetrations in the distribution grid in Hawaii [6]. The first worst issue for the circuit at a PV penetration limit of 50-55% is predicted to be due to back feed into the substation, which can possibly reduce the lifetime of the OLTC transformers by 40%. In Germany, the effects of high PV penetration [7] include local overvoltage, loading issues on distribution feeders, risk of mass disconnection of anticipated PV generation, resource variability, generation uncertainty, and the lack of stabilizing inertia that is typical of conventional generators. Note that the stabilizing inertia refers to the stored inertia of the conventional generators, which assists in maintaining the electric power system frequency in an event of load and generation imbalance. These experiences hint that there is a limit on the amount of PV that can be integrated in a given distribution circuit without causing any undesirable effects.

The limit on the amount of PV that can be integrated in a distribution grid without any grid impacts is called the PV hosting capacity of the circuit. Installing more PV than the circuit's hosting capacity can cause adverse effects, such as overvoltage or other overcurrent protection related problems in the system. To accommodate more PV than the hosting capacity, the grid requires new enabling technologies, such as smart inverters and/or energy storage units

An inverter is a power electronic interface that converts PV output power (DC power) to the AC grid. The inverter can be controlled to supply or absorb reactive power, in addition to the active power injection. Similar to a capacitor boosting the voltage by injecting reactive power, the inverter can be controlled to inject/absorb reactive and solve the under-voltage or over-voltage problems in the grid. Therefore, the smart inverter can help accommodate more PV generation in the grid. However, the inverter can only solve the voltage related concern in the grid.

Energy storage is a solution to the mitigate problems related to reverse power flow, and it can also provide other ancillary services to the distribution system. However, the cost of energy storage limits its large-scale installations. Other solutions to the problem of overvoltage and reverse power flow are line uprating, installing voltage regulation equipment, and advanced volt/var equipment.

OBJECTIVE OF THE STUDY

The primary objective of the study is to determine the total integration cost, including its cost components, of accommodating large-scale distributed PV generation in a distribution circuit. The study is organized into three sections. First, the PV generation that can be accommodated in a given distribution circuit without causing any adverse impacts is calculated. The corresponding PV capacity is referred to as the Range-1 PV hosting capacity. It is evaluated under the following conditions:

1) No operational changes in voltage regulation equipment such as on-load tap changer (LTC) transformers and capacitor banks are considered.

2) No upgrade of infrastructure/assets such as smart inverters or energy storage units is made to the grid.

For instance, consider a distribution circuit that exhibits an overvoltage condition on accommodating a PV hosting capacity of more than 30% of peak load demand during daylight hours, without any operational changes and infrastructure upgrades in the grid. This accommodation limit is referred to as the Range-1 PV hosting capacity of the circuit. Note that accommodating Range-1 PV capacity does not incur any cost of integration.

Second, the analysis is repeated while enabling operational changes in voltage regulation equipment already present in the grid. For example, LTC transformer operations can mitigate the overvoltage condition and can help add an additional 5% of PV capacity. Thus, the circuit could accommodate a PV capacity equivalent to 35% of feeder daytime hours peak load, without any adverse impact on the grid. The corresponding PV capacity is referred to as the Range-2 PV hosting capacity. Since voltage-regulation equipment is already installed in the distribution circuit, allowing operational changes in the equipment would not incur any further cost of integration. However, additional costs might be associated with each equipment operation.

Third, the analysis proposes to include infrastructure and asset upgrades, such as smart inverters and energy storage units, independently. The effectiveness of each upgrade solution is evaluated by calculating the improvement in the PV hosting capacity after deploying the corresponding grid upgrade. The extent to which each upgrade could improve the amount of PV that can be accommodated in the grid varies depending on its characteristics. The corresponding PV hosting capacity is represented as Range-3(x), where x corresponds to each upgrade deployed in the grid. Note that the cost of each technological upgrade depends on various factors. The study seeks to estimate the cost of grid upgrades that would allow the distribution system to accommodate high penetrations of PV generation.

1.1 ORGANIZATION OF THE STUDY

The report is organized as follows. Section 1 presents the introduction and the objective of the study. Section 2 details the various impacts of PV integration on the distribution grid. The methodology to evaluate the PV hosting capacity of a distribution grid is presented in Section 3. Section 4 presents the results of Range-1 and Range-2 PV hosting capacities for different distribution circuits. Note that PV hosting capacities corresponding to Range-1 and Range-2 in the distribution circuit would incur zero/minimal cost of integration. Range-3 hosting capacity with upgrades such as smart inverter and energy storage is calculated in Section 5. The cost estimates for each of the upgrades and the corresponding increase in the hosting capacity is presented in the Section 5.

1.2 SUMMARY OF THE STUDY

The PV hosting capacities are calculated for three representative distribution circuits provided by Electric Power Research Institute (EPRI). The Range-1 PV hosting capacities of the circuits are calculated to be as low as 15.5% (i.e., 2600 kW in one particular circuit) and over 100% (i.e., 3870 kW in another circuit) of the median value of the daytime (between 7am and 7 pm) peak load demand. The Range-1 PV capacities were observed to be limited either by reverse power flow or the voltage related impact criteria. It is to be noted that there is no cost associated with integrating up to Range-1 PV capacity in the distribution grid, since there is no change in the distribution circuit.

Based on the limiting criterion, the circuits are clustered into two groups. Range-1 hosting capacities of the circuits that are limited by reverse power flow are grouped into Cluster 1 and the circuits that are limited by overvoltage concern are grouped into Cluster 2. Among the three circuits, two of them are in Cluster 1 and one circuit in Cluster 2. The hosting capacities of the circuits are increased beyond Range-1 capacity by a few operational changes specific to each cluster.

The Cluster 1 circuits experience reverse power flow at the substation transformer when PV capacity more than the minimum load of the circuit is integrated in the grid. So, for Range-2 capacity, the value is calculated by relaxed assumptions i.e., by allowing reverse power flow of about 10% of the substation transformer rating. The relaxed assumption significantly increases the Range-2 hosting capacity of the Cluster 1 circuits. There is no obvious cost associated with the relaxed reverse power flow limit, on the assumption that the transmission network can take power flow of about 10% of the transformer rating.

The hosting capacity of the circuits can be further increased to Range-3 capacity by including upgrades in the grid. The Range-2 hosting capacity of the Cluster 1 circuits, are already significantly high of about 77% and 150% of the respective median peak load of the circuits. To further increase the hosting of the circuits, energy storage should be installed to store the excess energy that is exported through the substation transformer. The cost of increasing the hosting capacity further is unjustifiably high, due to high cost of energy storage.

The Cluster 2 circuits that experience voltage related impact criterion indicate that the grid is weak and requires external support in terms of reactive power or external devices to regulate the voltage. The existing voltage regulation devices are allowed to participate in the voltage regulation to increase the hosting capacity. With the existing regulation devices functioning, the increase in the hosting capacity of the circuit is about 30% of median peak load of the circuit. It is also observed that the number of tap operations increased with high PV penetration. However, the incremental cost of additional tap operations is not significant, and so can be considered to be part of regular transformer maintenance costs.

The Range-2 hosting capacity of Cluster 2 circuit is about 47% of the median peak load of the circuit and it is limited by over-voltage concern, so additional devices to regulate the voltage is included in the circuit to increase the hosting capacity to Range-3 capacity. In this study, PV inverters are allowed to actively regulate the voltage at the point of interconnection. The smart inverter functionality is included in the existing PV inverters with an additional cost likely a few hundred to $1,000 per unit of inverter. It was observed that only 30% of the inverters with smart inverter functionality increased the hosting capacity significantly from 47% to about 80%. The incremental cost of upgrading the PV inverters with smart inverter functionality is a fraction of the total PV system cost (likely a few hundred to $1,000 per unit of inverter). Utility may consider various incentive approaches to help customers offset the cost. Other options such as including line regulators to mitigate the over-voltage concern would require a huge investment by the utility. The investments and the corresponding increase in hosting capacity are studied in detail in the following chapters.

Although the study reported herein evaluates three representative utility distribution circuits, it shows that a relatively significant PV generation can be integrated with no or little costs to utilities and their customers. At such levels, PV generation impacts are non-existent or can be addressed by appropriate circuit operational changes. However, increasing feeder PV generation capacity using energy storage technologies likely incurs a significant cost.

2 | GRID IMPACTS AND COST OF INTEGRATING PV GENERATION TO THE DISTRIBUTION CIRCUIT

Recent studies on the value of solar components have ignored the cost of PV integration, claiming that the cost is expected to be small compared to the savings incurred due to the reduced cost of generation, reserve and fuel [8]. In contrast, Brown et.al points out that considering the cost associated with integrating PV in the distribution grid is critical for evaluating the effectiveness of solar integration [9]. These differences in opinions call for a thorough study of the impact PV integration has on the distribution grid, as well as the cost of mitigating the impact of PV integration.

2.1 GRID IMPACTS OF PV INTEGRATION

There are three categories of concerns related to the impact high PV penetration has on the distribution grid: voltage, loading, and protection-related [10]. Voltage issues include bus overvoltages, voltage deviations, and unbalanced conditions in a three phase system. Loading issues arise when service transformers and conductors are overloaded and thermal limits are violated. Finally, protection-related issues occur when protection elements, such as relays, reclosers, breakers, network protectors and fuses operate improperly. Such misoperations occur when PV interferes with the existing protection elements in the distribution grid. Each of the three issues are explained in detail in the following sections.

VOLTAGE RELATED ISSUES

High PV penetration can degrade the voltage quality at the point of common coupling (PCC), where the load is connected. Voltage quality is expected to be in accordance with the specifications of American National Standard Institute (ANSI). It is possible for high PV penetration to cause the voltage at the PCC to increase when power is over-generated (overvoltage), significantly ramp-up (deviation) or is unbalanced in some way. The following sections elaborate on each of these conditions.

Overvoltage

Overvoltage is common on sunny days when the load demand is low, and the PV panels are generating at their maximum capacity, typically between 10 am and 2 pm. Figure 2-1 depicts a typical net transformer load in Hawaii between 2010 and 2013, with an actual reverse power flow condition that occurred in August 2013 [11]. Note that an overvoltage condition might arise at low load levels and is likely to get exacerbated during reverse power flow conditions. The reverse power flow due to high PV penetration in a distribution grid is depicted in Fig. 2-2 (a). The phasor diagrams of voltages in subfigures Fig. 2-2 (b and c) correspond to cases with and without PV in the distribution grid, respectively. The magnitude of source voltage (V_{source}) in Fig 2-2 (b) can be observed to be less than the magnitude of the voltage at the end (V_{end}), due to backfeed from the PV sources to the substation. However, when there are no PVs integrated in the

FIGURE 2-1

Average transformer load (MW) 2010-2013 [11]

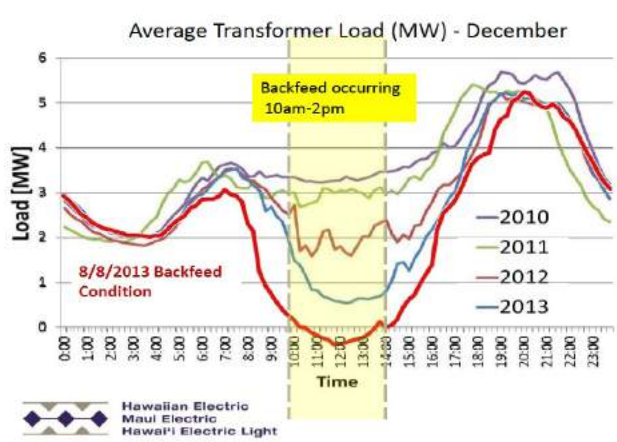


FIGURE 2-2

(a) Net current flowing towards the substation due to high PV integration. (b)Phasor voltages with PV. (c) Phasor voltages without PV in the grid.

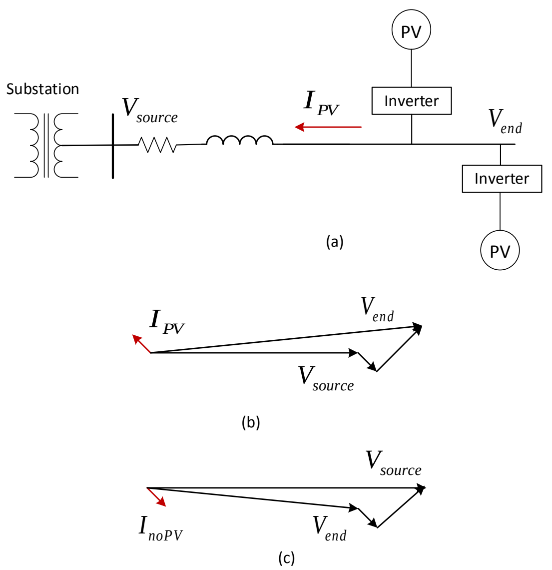
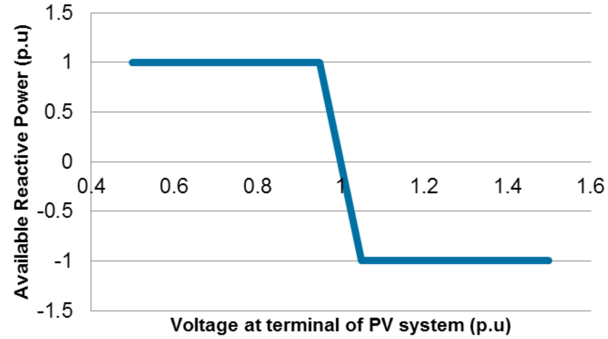


FIGURE 2-3

Voltage profile with change in reactive power



grid, the V_{source} magnitude is always more than the magnitude at the end of the feeder.

The maximum allowable range of voltage at any bus is 5% of the rated voltage, i.e. 1.05 per unit (p.u.), as specified by ANSI C84.1. The per-unit values are obtained by scaling the quantity by their rated values. The per-unit overvoltage limit is expressed as,

(2-1)

$$V_i < 1.05 \text{ p.u.}$$

where, V_i is the voltage at any bus i in the distribution feeder. Long durations of overvoltage above the specified limit can affect the reliable operation of equipment and other electronic devices connected to the grid. Overvoltage condition can be rectified locally by allowing the PV inverter to absorb reactive power. Figure 2-3 shows the change in voltage profile at the terminal of the PV system with reactive power supplied by the PV inverter. The reactive power is expressed in per unit (p.u.) of the rated inverter output (kVA). The smart inverter can supply reactive power if the voltage magnitude is below 1 p.u., and can absorb reactive power if the voltage is above 1 p.u., thereby maintaining the voltage within an acceptable range.

Voltage deviation

Voltage deviation occurs in PV systems when PV power generation unpredictably varies. This occurs typically when there is cloud interference on the PV output. The steady-state voltage deviation of PV integration is expressed as in (2-2)

(2-2)

$$V_i - V_i^b < 0.03$$

where V_i^b is the voltage at a bus i before PV integration, V_i is the voltage at the bus i when the PV is generating at its peak. The reason for measuring voltage deviation with respect to the voltage before PV integration is to record the impact of sudden impact of sudden increase in PV generation from zero to rated capacity or vice versa. The voltage deviation should be within the limits specified by ANSI C84.1 which specifies that the primary wire should not vary by more than 3%, and the secondary by 5%. The voltage deviation problem is more critical during the maximum load conditions, therefore the voltage deviation is studied at maximum load conditions.

Voltage unbalance

The unplanned integration of PV on residential rooftops (mostly single-phase connections) can cause voltage unbalance in the three phase system. This phenomenon occurs when more power is injected (into the distribution grid) in a single phase than in the other two phases. The ANSI C84.1 limits voltage unbalance to less than 3%, as in (2-3).

(2-3)

$$\frac{\text{Max. voltage deviation from avg. phase voltage}}{\text{avg. phase voltage}} < 0.03$$

Power losses and line overloading can occur when power injection is unbalanced in the three-phase system of the distribution network. However, this voltage unbalance problem can be rectified by modifying the circuit topology in two ways. First, the single-phase load can be transferred from the highest loaded phase to one of the other two more lightly loaded phases. Second, the PV can be connected to the highest loaded phase. Since mitigating voltage unbalance are performed on a regular basis by utility as a part of their standard maintenance, voltage unbalance is not considered to limit PV integration in this study.

LOADING CONCERNS

The net peak load at a substation transformer can be offset by the power generated by PV. However, if the minimum load duration matches the maximum PV generation period, power can flow in the reverse direction, towards the substation, violating the thermal limits of the substation transformer. Thermal loading is an important problem only in utility-scale PV integration. However, thermal loading is not a major concern for residential PV integration and is not dealt with in this study [10].

PROTECTION RELATED PROBLEMS

The conventional grid protection elements include overcurrent relays, circuit breakers, and fuses that interrupt fault currents in the grid. With high PV penetrations, these protection devices have reportedly misoperated. Various problems related to these protection elements when distributed PV is generated in the distribution grid are detailed in this section.

Reverse power flow

Figure 2-1 illustrates a reverse power flow condition when the transformer load becomes negative during the day; i.e. the power is fed back to the grid. Reverse power flow is a major concern in secondary grid and spot networks [12], which are common in big cities. Unlike radial distribution circuits, these networks contain protectors that are designed to open in case of even a small fraction of reverse power flow. For reference, example distribution feeders laid out in radial, spot and grid topology are shown in Figures 2-4 – 2-6. It is specified in IEEE Std. 1547-2003 [13] that the PV integration should not cause the opening of the network protectors. Therefore, if the distribution circuit is laid out in spot or grid topology, then the PV installed capacity is not allowed to cause any reverse power flow.

Given a radial network, the presence of On-Load Tap Changer (OLTC) transformers poses a limit on the reverse power flow. The tap changing transformer is limited in its ability to handle reverse power. For instance, a Y-y single resistor tap changer transformer with a 23 MVA rating has only 42% reverse power capability. The reverse power capability of the transformer depends on vector group, the size of transformers, the resistance of the bridging resistor and power factor [14].

Forward flow fault currents

Figure 2-7 shows the I-V characteristics of PV with variation in irradiance and temperature. The PV system is usually operated to inject the maximum power (the product of voltage and current injected). The maximum power point is indicated in the figure as the knee region of the curves. There are power electronic control devices called the Maximum Power Point Tracker (MPPT) in the market to always track the maximum power point for a PV module.

In case of fault in the system, the voltage at the PV terminal can drastically reduce. From the Figure 2-7, it can be observed that when the voltage at the PV terminal decreases, the current output from the module can increase. A conservative fault study considers the PV inverter short-circuit current (I_{sc}) to be about 200% of its rated value (current that is injected during rated voltage condition). It is assumed that during fault, PV's contribution towards any fault is twice the rated current. The fault current might potentially interfere with the overcurrent protection of the conventional distribution

FIGURE 2-4

An example radial distribution feeder

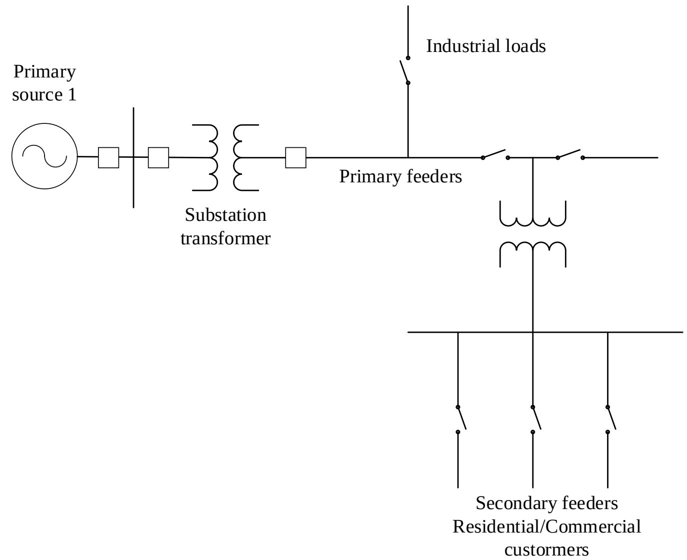


FIGURE 2-5

An example distribution feeder in spot configuration

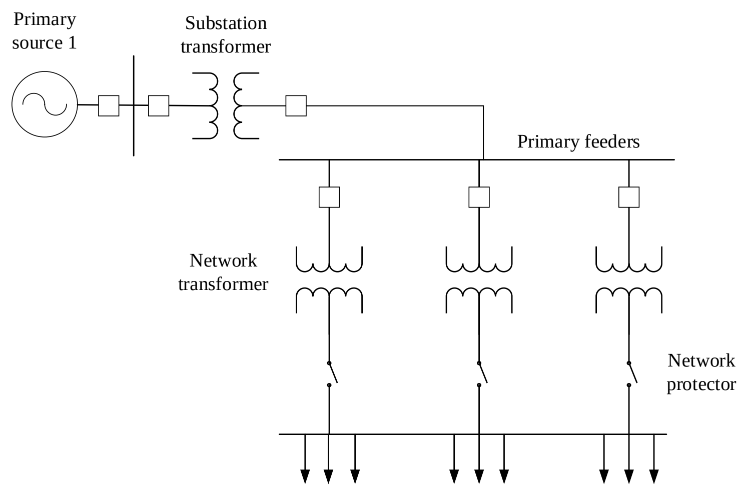


FIGURE 2-6

An example distribution feeder in grid topology

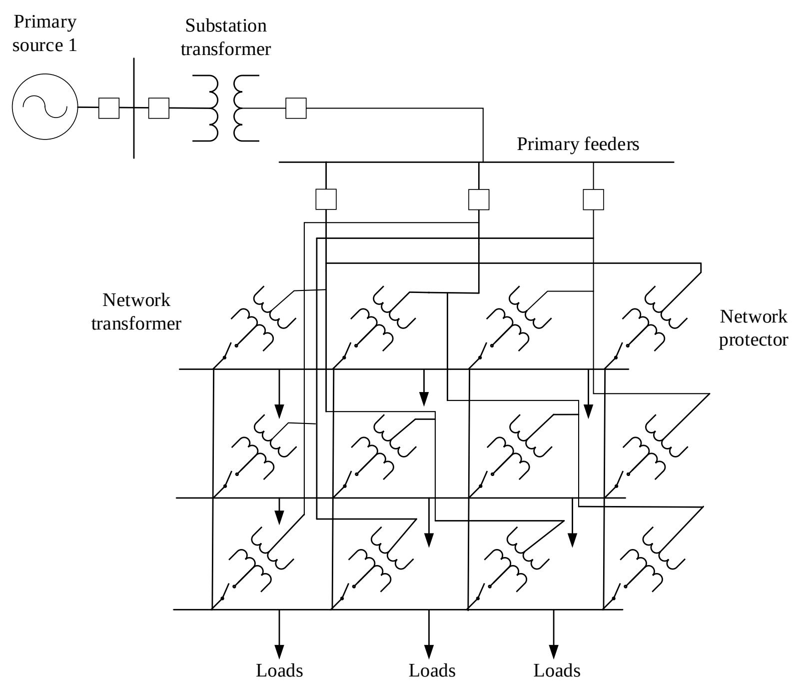
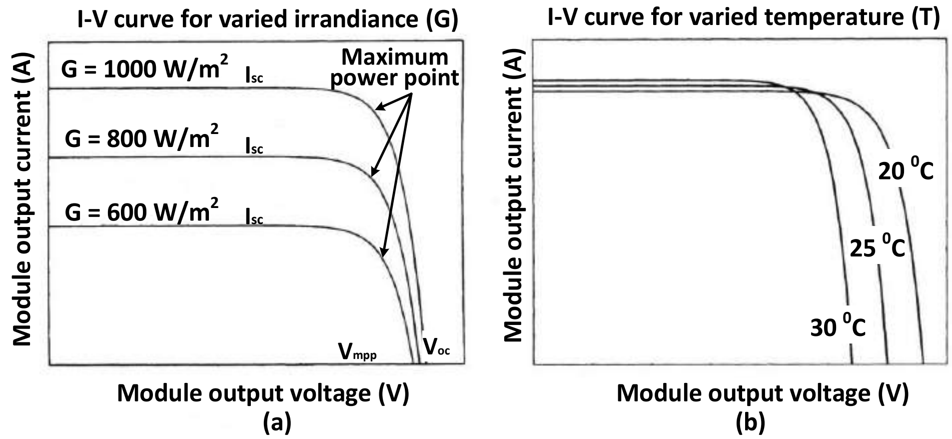


FIGURE 2-7

I-V characteristics of PV with change in (a) irradiance and (b) temperature



grid. Two of the main concerns due to the fault contribution by PV are sympathetic tripping and reduction of breaker reach. The two conditions are explained briefly in the following sections.

Sympathetic tripping of relays

To isolate the faults in a feeder from the main feeder, the feeder head is usually installed with a breaker controlled by a relay that senses current in the feeder. Sympathetic tripping is an unnecessary isolation of the healthy feeder due to a fault in an upstream parallel feeder. A scenario with a fault at a parallel feeder of a circuit is illustrated in Figure 2-8. In the given scenario, both the substation and the PV at Feeder 1, contribute to the fault. Therefore, a high current is sensed by both relays at the line feeder 1 and at the parallel feeder. The relays trip both the breakers and thus isolating the feeders from the main circuit (see Figure 2-9). The tripping of the healthy feeder is undesirable, as isolation of only the faulty feeder is expected.

Breaker reduction of reach

A breaker is expected to identify and isolate any fault in a distribution system. However, high PV penetration can cause the breaker to go blind to faults in the grid, such as when the substation fault current is below the breaker's reach. Breaker reach is defined here as the minimum current that the breaker detects as a fault. Breaker reduction of reach occurs when there is a high impedance fault and also high reverses power flow from the distributed generation towards the substation. Therefore, it is required to evaluate the PV capacity that can be accommodated in the distribution grid without reducing the reach of the breaker.

FIGURE 2-8

A three-phase bolted fault in the parallel feeder. The current from the healthy feeder feeds the fault in the parallel feeder.

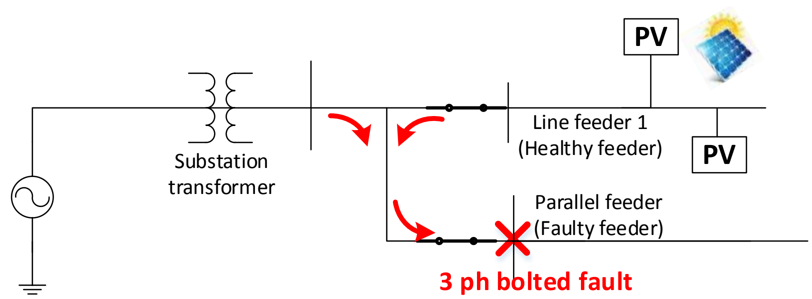
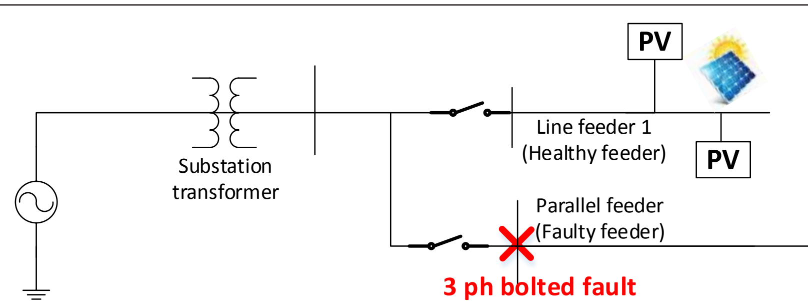


FIGURE 2-9

Sympathetic tripping occurs in the healthy feeder in the case of a three-phase fault



3 | PV HOSTING CAPACITY OF DISTRIBUTION CIRCUITS

As discussed in Chapter 2, integrating high proportions of photovoltaic (PV) generation in the distribution grid might result in voltage and current related concerns. In order to determine the limit on the maximum amount of PV that can be integrated in the grid, the hosting capacity of the grid is calculated. In this section, a detailed framework for evaluating the PV hosting capacity for different impact criteria is discussed. In order to evaluate the feeder's PV hosting capacity, a large number of possibilities in size and location of PV panels are considered. A stochastic analysis framework based on the Monte Carlo method is used for generating multiple PV deployment scenarios by varying PV locations and sizes [10, 15, 16]. The grid impacts of each PV deployment scenario are then evaluated by performing three-phase load flow analysis at both minimum and maximum loading conditions of the distribution grid.

The hosting capacity that is calculated without any operational changes or grid upgrades is referred as Range-1 hosting capacity. Other PV hosting capacities of the grid are Range-2 (with operational changes), and Range-3 (with grid upgrades). The same stochastic analysis framework is used to determine a circuit's three Ranges of hosting capacities, with corresponding changes in the grid.

This section first introduces the concept of PV hosting capacity. Next, loading conditions of the distribution circuit under which the study is conducted are discussed. The detailed framework to calculate the Range-1 hosting PV capacity for both voltage- and current-based criteria is presented. Based on the analysis, an overall Range-1 PV capacity is determined. Finally, the method to determine Range-2 and Range-3 PV hosting capacities is detailed.

3.1 CONCEPT OF PV HOSTING CAPACITY

PV hosting capacity is defined as the largest PV capacity (kW) that can be accommodated in a given distribution circuit without necessitating any operational changes or upgrades in the grid. Note that, PV hosting capacity is not a limit on a single installation (e.g. a home), but for a distributed residential scale PV installations. The concept of hosting capacity estimation based on one of the impact criteria, i.e. voltage limit violation, is depicted in Figure 3-1. The ANSI voltage regulation standard (C84.1) states that under normal operating conditions, the voltage level at any bus on the circuit should not exceed 1.05 p.u. Therefore additional PV can't be integrated at any bus in the feeder if the voltage at any bus in the feeder exceeds the threshold value. From Figure 3-1, the PV generation that corresponds to 1.05 p.u. voltage limit is called the hosting capacity of the given distribution circuit.

Similarly, the hosting capacity of a distribution feeder can be evaluated in terms of other impacts on the grid such as,

1) Highest voltage deviation in primary and secondary wire voltages, and

2) Reverse power flow at the substation.

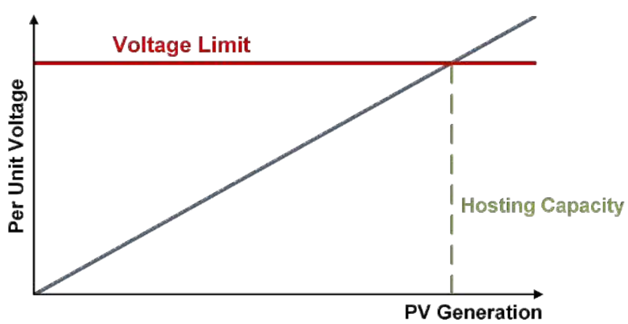
The adverse effects for each of the impact criteria are quantified from the threshold specified by ANSI (see Table 3-1). As illustrated in Figure 3-1, hosting capacity is the amount of PV generation that the circuit can accommodate without violation of a threshold corresponding to the impact criteria. Therefore, it is possible that varying amounts of hosting capacities can be obtained for the same distribution grid, corresponding to each impact criteria.

TABLE 3-1 Threshold for Selected Impact Criteria

IMPACT CRITERIA	THRESHOLD (P.U.)	
	Primary wire	Secondary wire
Overvoltage	1.05	1.05
Voltage deviation from base case	0.03	0.05
Reverse power flow	Power flow reversal at the substation	

FIGURE 3-1

PV Hosting Capacity is limited for each bus based upon a maximum per unit voltage of 1.05 p.u.



3.2 LOADING CONDITIONS

The total load served by a substation transformer varies throughout the day and year. For instance, in Texas, the peak load during summer is higher than during winter. In summer, a large fraction of the energy demand is represented by air-conditioners to cool office spaces and residential homes. Also, demand response can alter the net load at the transformer, i.e. if electric vehicles and energy storages are charged/discharged depending on the loading conditions, the peak load can be shifted. Therefore, the minimum and maximum loads of a distribution grid are affected by seasonal variations and the demand response characteristics.

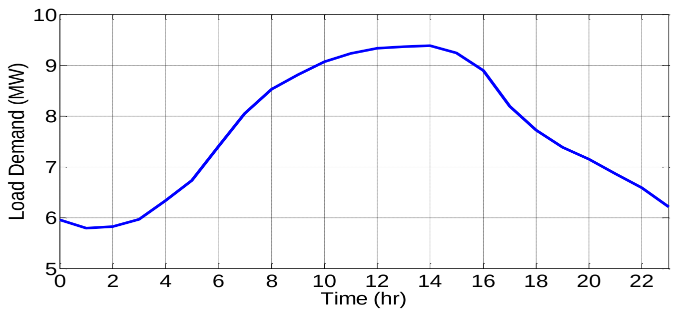
Identifying representative loading conditions of the distribution grid is important in our study because the maximum capacity of distributed PV generation that can be accommodated in a distribution grid is related to the loading conditions of the grid. Overvoltage and reverse power flow concerns in a distribution grid are more likely to occur when the PV is generating at its rated peak power capacity and there is a low load demand at the transformer [5, 6]. Whereas, voltage deviation from the base case is more critical during peak load conditions.

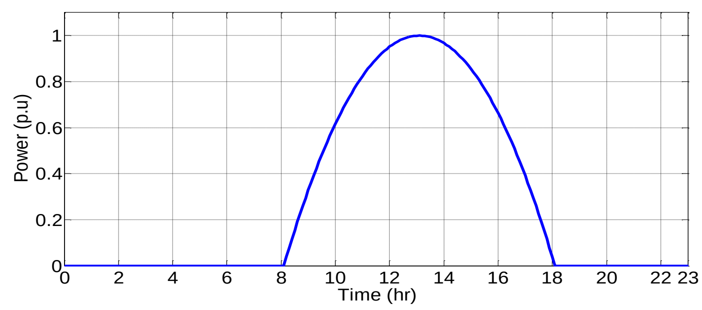
Residential load demand profiles vary considerably depending on location and season of the year. A typical residential load profile during a summer day in the northeastern seaboard of the U.S is shown in Figure 3-2(a). Figure 3-2(b) shows the typical PV generation curve during a clear sky condition, assuming that the daylight time is between 7 am and 7 pm. Since, we are analyzing the impacts of PV generation in the grid, we find the circuit's maximum and minimum load demand during the peak PV generation period (10 am to 2 pm). A conservative study is then performed with the loading conditions to evaluate the impacts on the grid.

Minimum and maximum load demand during the duration of maximum PV generation (10 am to 2 pm) is statistically determined from load demand measured at the substation. It is assumed that the daylight period is between 7 am and 7 pm for the entire year as shown in Figure 3-2(b).

FIGURE 3-2

(a) Typical daily load demand at the substation transformer. (b) Typical PV generation curve





PV CAPACITY RANGES

The evaluation of Range-1 PV capacity corresponding to various impact criteria is presented in the following sections. The impact criteria are broadly classified into voltage and overcurrent protection based impacts. The Monte Carlo framework for generating PV deployment scenario is explained in Section 3.3. The framework to create deployment scenarios remains the same for all the impacts. The quantification and determination of the Range-1 PV capacity, however, differ for each impact criteria. Finally, from all the calculated Range-1 PV capacities, an overall Range-1 PV capacity is calculated.

Additional PV generation beyond the Range-1 PV hosting capacity can be accommodated in the grid by allowing operational changes in voltage regulation equipment and deploying grid upgrades. Operational changes in the voltage regulation equipment such as the voltage regulators and capacitors can improve the amount of PV generation that a distribution circuit can accommodate to Range-2 PV capacity. Range-3 PV hosting capacity is the amount of PV generation that the grid can accommodate with grid upgrades such as smart inverter, energy storage or line upgrades. Note that the Range-2 and Range-3 PV hosting capacities are calculated using the similar Monte Carlo method after incorporating the necessary operational changes and upgrades in the grid, respectively. The method is briefly explained in Section 3.7. The following sections elucidate the calculation of Range-1 PV capacity.

3.3 VOLTAGE BASED RANGE-1 PV HOSTING CAPACITY

Voltage based impacts on the grid due to PV generation include overvoltage condition, voltage deviation, and voltage unbalance. Since voltage unbalance in three phases of the distribution circuit can be rectified by physical modification in the circuit, it is not included as an impact criterion to evaluate hosting capacity in the study.

First, a base case model of the selected distribution feeder is developed. Existing PV systems are incorporated in the base case model and then three-phase load flow analysis is conducted for the base case. Next, stochastic analysis to better understand the impacts of future PV generation on distribution feeders is conducted. The analysis evaluates the impact of multiple PV deployment scenarios by varying potential PV locations and sizes. The defined framework for the same is discussed in three steps as follows.

STEP 1:
CREATE PV DEPLOYMENT CASES

Incremental PV generation in the x-axis of Figure 3-1 for the evaluation of Range-1 PV capacity involves numerous potential PV deployments obtained by varying the location and size of PV systems installed in the distribution grid. Therefore, there is a need for a defined algorithm to generate multiple PV deployment scenarios [10]. A Monte Carlo based algorithm is outlined in this section for the generation of PV deployment scenarios. The overall framework for creating M deployment scenarios for each of the N penetration levels is illustrated in Figure 3-3. Let M and N be 100 and 50 respectively. Therefore, there are totally 5,000 deployment scenarios considered for the study.

The creation of deployment scenarios requires primarily identifying all possible future PV locations in the grid and the corresponding sizes of PV. For a given distribution circuit, simulating all possible PV deployment scenarios (x_j^i) is impractical. The PV hosting capacity is, therefore, calculated by simulating a finite number of PV deployment scenarios. The details of further simulation steps and terminologies used are explained as follows:

Customer Penetration Level ($Cust^i_{pen}$)

The customer penetration level is defined as the percentage of customers equipped with PV systems in a given distribution circuit. So, an i^{th} customer penetration level is obtained by populating an $i\%$ of the customers with PV panels.

PV Penetration Level (PV^i_{pen})

PV^i_{pen} is defined as the total PV generation capacity integrated to the distribution circuit corresponding to the i^{th} customer penetration level ($Cust^i_{pen}$). Thus, for each customer penetration level ($Cust^i_{pen}$), a PV penetration level (PV^i_{pen}) is obtained.

PV Deployment Scenarios (x_j^i)

The distribution of PV panel location and size at a given customer penetration level ($Cust^i_{pen}$) is not deterministic. Corresponding to each customer penetration level, multiple deployment scenarios with different locations and sizes for PV panels are possible. For this reason, x_j^i represents j^{th} PV deployment scenario corresponding to $Cust^i_{pen}$.

Monte Carlo Based Method

The Range-1 PV hosting capacity is calculated by simulating a finite number of PV deployment scenarios (100 scenarios in the study, i.e. M = 100) at a particular customer penetration level, using the Monte Carlo approach. The methodology to systematically simulate stochastic PV deployment scenarios is illustrated in Figure 3-4. First, 2% of customers are deployed with PV arrays (i.e. $Cust^2_{pen}$). Note that the customer locations are selected randomly from the pool of customers served by the distribution feeder. The PV array size is also determined based on the customer load type (commercial/residential) and their peak load demand. The installed PV array size is drawn from the PV array distribution shown in Figure 3-5. If the selected PV size obtained from the distribution is more than the rated customer load to which it is

FIGURE 3-3

Stochastic analysis framework.

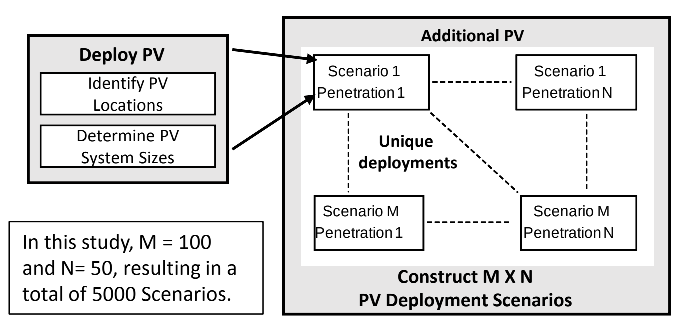
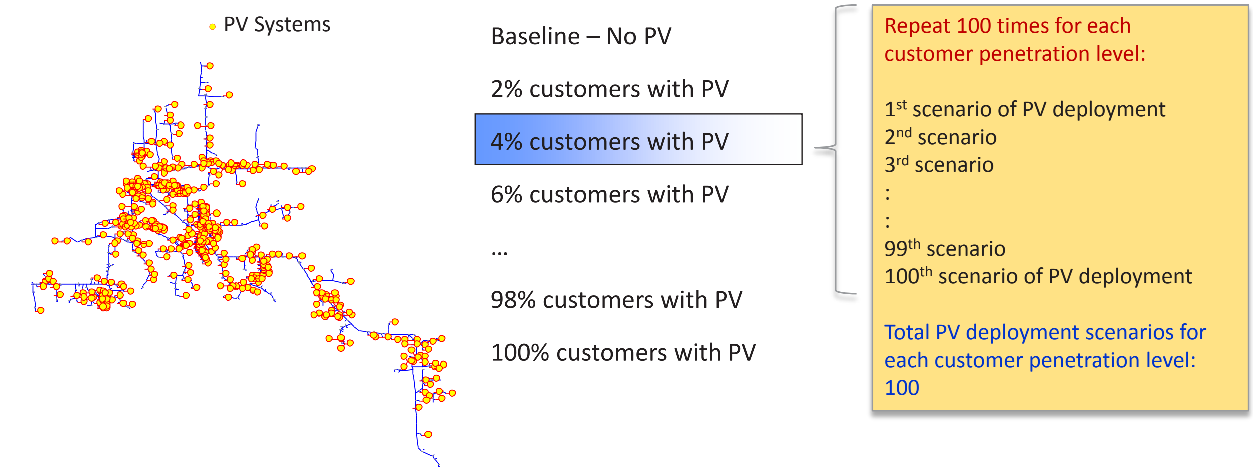


FIGURE 3-4 Stochastic analysis framework [10].

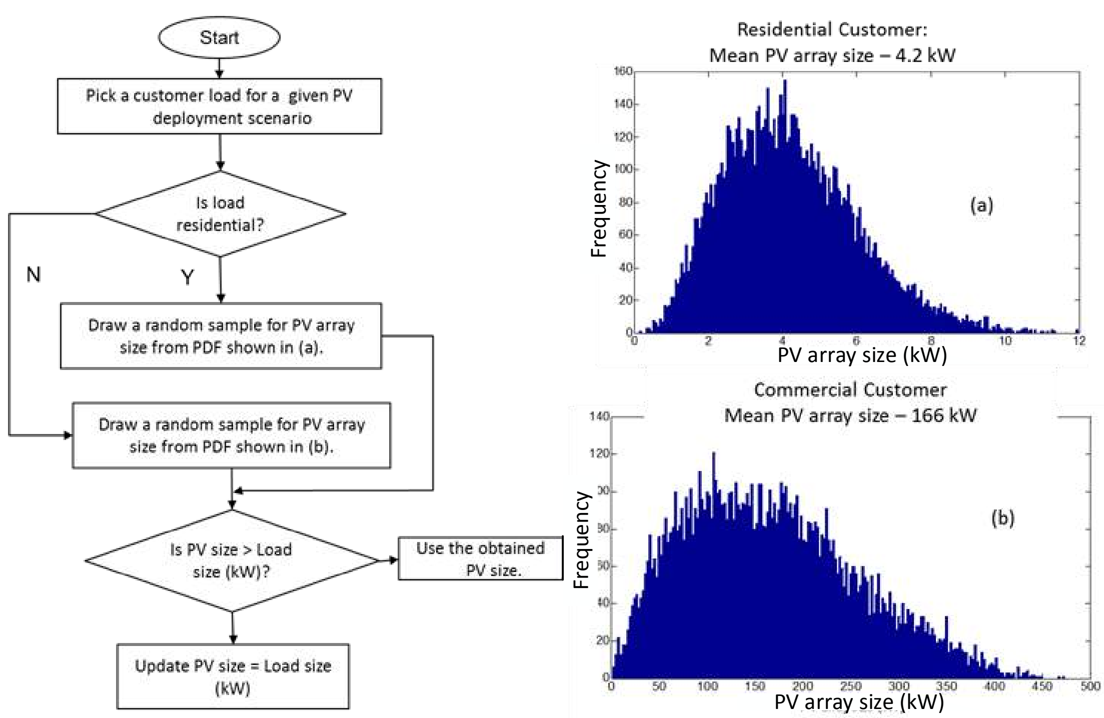


connected, the PV size is set to the rated customer load demand.

The customer penetration is then increased by another 2% increment, so that the total customer penetration level becomes 4%, i.e. $Cust^{4}_{pen}$. Additional PV systems are deployed at the remaining customer loads where a PV system is not already present. The process is repeated until the customer penetration level reaches 100% ($Cust_{pen}^{100}$). This process gives a total of 50 PV deployment scenarios (N is 50), one at each customer penetration level ($x_1^2, x_1^4, ..., x_1^{100}$). The above process of 2% incremental customer penetration is repeated 100 times. Thus, there are 100 unique stochastic PV deployment scenarios at each of the 50 customer penetration levels, resulting in a total of 5,000 scenarios.

FIGURE 3-5

Flowchart to select the PV array size, from distribution of PV array size for residential (a) and commercial customers (b)



STEP 2
QUANTIFY FEEDER IMPACTS

Once PV deployment scenarios are simulated, the load flow analysis is done for each PV deployment scenario. The PV systems are considered to be generating at their peak rated capacity. Note that the use of PV-based reactive power or other PV-based means of regulating voltage is not considered in the Range-1 PV hosting study. Thus, the simplest PV models with no capability for generating or absorbing reactive power are simulated. Range-3 PV hosting capacity analysis includes smart-inverters with the capability to regulate feeder voltages by modulating the reactive power.

In this section, since we are concerned with the voltage quality impacts due to high PV integration in the grid, PV capacity is calculated with respect to following two impact criteria: bus overvoltage and voltage deviation. Voltage deviation is defined as the difference between the bus voltages during full PV generation and the base case as expressed in Equation (2-2). The thresholds for each of the impact criteria are defined in Table 3-1.

STEP 3
DETERMINE RANGE-1 PV HOSTING CAPACITY

The Range-1 PV hosting capacity of a distribution feeder is the amount of PV generation that the grid can accommodate without violating the defined threshold for any given impact criteria. It is assumed that no operational changes in voltage regulation equipment and no upgrades are included in the grid. To evaluate voltage-based Range-1 capacity, load flow analyses for all 5,000 deployment scenarios are performed. Since the thresholds specified for voltage based criteria differ for primary and secondary nodes of the circuit (see Table 3-1), we ought to analyze the impact criteria for primary and secondary nodes separately. The primary nodes correspond to the primary distribution circuit supplying electric power from the substation to the service transformers at high voltage level (13.8-kV/4.16-kV). The secondary nodes are the low voltage nodes, typically of voltages 120V/240V/480V, which directly supply the ready-to-use electric power from the service transformer to the customer loads. The Range-1 hosting capacities correspond to overvoltage and voltage deviation calculated for primary and secondary nodes separately.

The calculation of Range-1 PV hosting capacity based on overvoltage condition for the primary nodes is explained below. Load flow analysis is performed for each deployment scenario at a single load condition that is considered to be a representative minimum condition, while PV is generating at its peak. The basis for choosing the representative load condition is explained in the following sections. From the load flow analysis and the maximum primary node voltage is recorded. A set of all 100 such maximum voltages (V^i_{max}) recorded for each of the 100 deployment scenarios corresponding to the $Cust^i_{pen}$ is given below,

(3-1)

$$V^i_{max} = \{V_{max}(x^i_1), V_{max}(x^i_2), V_{max}(x^i_3) \ldots,\ V_{max}(x^i_{100})\}$$

where $V_{max}(x^i_j)$ is the largest primary voltage among all nodes for jth deployment at the customer penetration $Cust^i_{pen}$. Similarly, V^i_{max} for all 50 customer penetrations (0%, 2%, …, 100%) is recorded. The 5,000 entries are plotted against the corresponding PV penetration level (PV^i_{pen}) in kW. It is to be noted that the PV^i_{pen} for each deployment scenario (x^i_j) corresponding to $Cust^i_{pen}$ may be different, because of the stochastic nature in size of installed PV.

From the load flow analysis, Range-1 PV hosting capacity for primary node overvoltage is calculated to be equal to the lowest PV generation (kW) for which at least one scenario (x^i_j) observes an overvoltage. It is defined as,

(3-2)

$$\text{Range-1 PV hosting capacity} = \{min(PV^i_{pen}) \,|\, (\max(V^i_{max}) > 1.05)\}$$

where, V^i_{max} is a set of maximum primary voltages recorded for all PV deployment scenarios simulated at $Cust^i_{pen}$. PV^i_{pen} is the PV penetration corresponding to $Cust^i_{pen}$.

In a similar way, the Range-1 PV hosting capacity corresponding to primary node voltage deviation is defined as,

(3-3)

$$\text{Range-1 PV hosting capacity} = \{min(PV^i_{pen}) | (\max(V^i_{dev} > 0.03)\}$$

where, V^i_{dev} is a set of maximum voltage deviations from the base case observed in primary nodes of the circuit for all PV deployment scenarios simulated at $Cust^i_{pen}$.

SIMULATION VALIDATION

The voltage based Range-1 hosting capacities are evaluated for an actual utility distribution circuit, the details of which are given in Table 3-2.

Loading conditions

The load demand for the circuit is available for 315 days only. Since we do not have the irradiance data, the daylight for the year is assumed to be between 7 am and 7 pm, with peak PV generation between 10 am and 2 pm. The statistical representative value for minimum and maximum load demands during the duration when the PV generates at its peak is evaluated.

The minimum load demand measured at the substation between 10 am and 2 pm throughout the year (315 days) is plotted in Figure 3-6, against days expressed in percentile values. Note that for a few days over the year, a minimum load as low as 5.274 MW and as high as 14.39 MW is recorded. Since the minimum load of 5.274 MW occurs only on one particular day, a statistically representative minimum load condition must be determined. From Figure 3-6, the minimum load corresponding to 10 percentile value is 6.29 MW. The 10 percentile value signifies that there are 32 days (10% of 315) that experience load demand value less than 6.29 MW. The 10 percentile load value is used for the calculation of hosting capacity of the circuit. It is considered appropriate to choose 10 percentile value so that any outliers in the measured data are removed.

Similarly, the maximum load demand measured at the substation during the time period 10 am to 2 pm is plotted in Figure 3-7. On a similar argument, the representative maximum load is chosen to be the value corresponding to 90 percentile value. It can be inferred from the similarity between Figures, 3-6 and 3-7 that the loading conditions during the time period 10 am to 2 pm do not vary much. The hosting capacity corresponding to representative minimum and maximum load demands are calculated in the following sections.

FIGURE 3-6 Minimum load demand measured at the substation between 10 am to 2 pm.

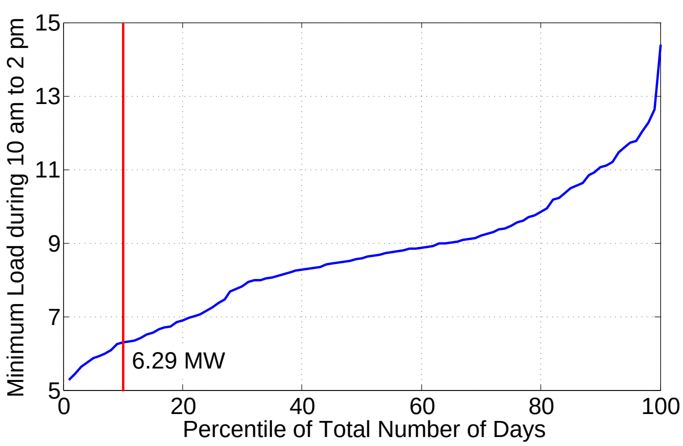
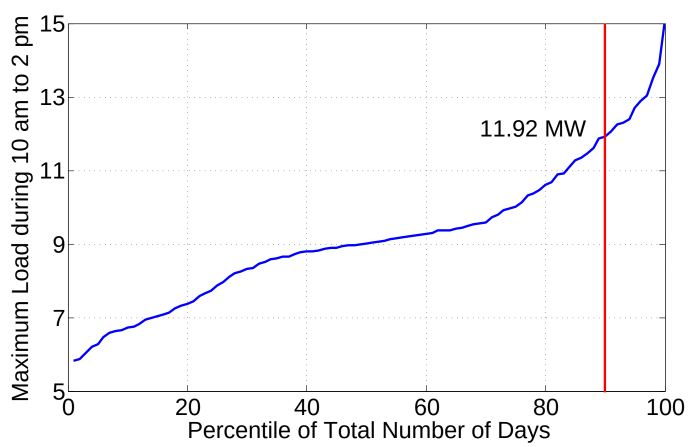


FIGURE 3-7 Maximum load demand measured at the substation between 10 am to 2 pm.



Base Case for Steady State Stochastic Analysis

First, a three-phase model of the selected distribution feeder is simulated, which includes all primary and secondary wires, substation transformer, control elements, and individual customer loads. Then a load allocation algorithm is implemented so that the peak active power demand matches with its measured value. Next, the feeder is checked for its reactive power output and capacitor banks are switched on/off to match the measured peak reactive power demand.

Load flow analysis is performed at the feeder's representative maximum and minimum load conditions determined in Section 3.2. The loads are multiplied by a multiplier to match the statistically obtained loading conditions of the feeder. The voltages at all the nodes are recorded separately for the corresponding loading conditions as the base case values. Optimal transformer tap settings and capacitor switching status are determined by the load flow analysis software for the base case at each loading condition. Since we are evaluating Range-1 PV hosting capacity in this chapter, the controls on capacitor and regulators are frozen at the present state and never altered throughout the analysis.

Simulation Results for Stochastic Steady-state PV Analysis

The existing PVs are included in the circuit and steady-state stochastic analysis is performed to identify the maximum PV penetration that does not create any adverse effects in the feeder. The stochastic analysis is done at both maximum (operating at peak load) and minimum load conditions during daylight hours. The simulation steps are explained in the following sections.

STEP 1
PV DEPLOYMENT SCENARIO

As described earlier in this chapter, the Monte Carlo based algorithm generates various scenarios at different customer load locations. One hundred different PV deployment scenarios are simulated at fifty different customer penetration levels for a total of 5,000 different deployments.

TABLE 3-2 Circuit Characteristics

COMBINED FEEDER CHARACTERISTICS OF THE CIRCUIT	
System voltage (kV)	12.47
Number of customers	1220
Service Xfmr connected kVA	30687
3ph SCC at substation	166
Primary circuit miles total	7.65
Longest length from the substation (miles)	1.6
%residential by load	71
No. feeders on the Sub bus	2

STEP 2
QUANTIFYING THE FEEDER IMPACTS

The feeder Range-1 PV hosting capacity for the voltage related issues is measured with respect to the following two impact criteria:

1) Highest overvoltage in primary and secondary wires

2) Highest deviation in primary and secondary wire voltages from the base case value

The detailed analysis and results are discussed in the following section.

STEP 3
DETERMINING THE RANGE-1 PV HOSTING CAPACITY

The voltage based PV Range-1 capacities are calculated from the load flow analysis for all the 5,000 deployment scenarios. During daylight time representative minimum load condition, the result for the overvoltage criterion is shown in Figure 3-8, and during representative maximum load condition, the result for the voltage deviation

FIGURE 3-8

Maximum Voltage Value for the Primary and Secondary Wire.

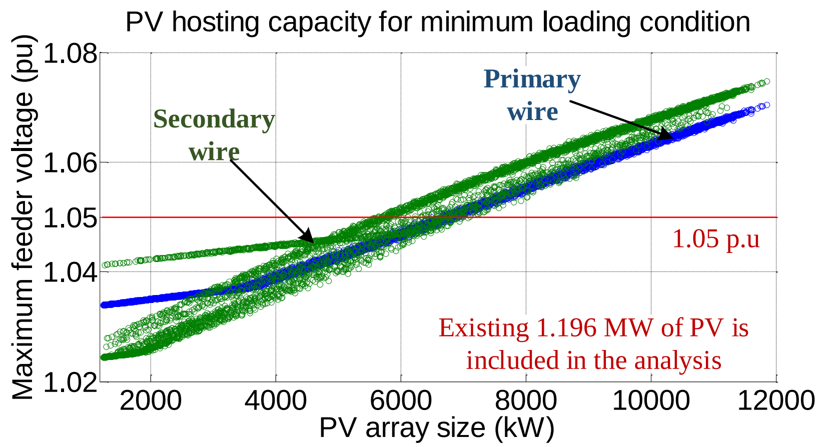
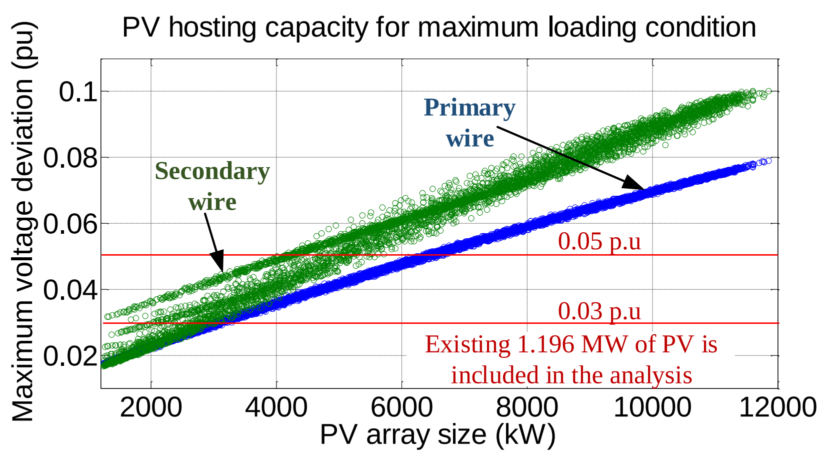


FIGURE 3-9

Maximum Voltage Deviation for the Primary and Secondary Wire.



criterion is shown in Figure 3-9. Figures have 10,000 points each, corresponding to 5,000 points of primary (blue pointer) and secondary wires (green pointer), respectively. Every point in Figure 3-8 corresponds to $V_{max}(x_j^i)$, i.e. the maximum voltage for the deployment scenario x_j^i, obtained from load flow analysis.

The first violation of the overvoltage criterion for primary wire is observed to be 6.65 MW at the representative minimum load of the circuit. Existing 1.196 MW PV systems are taken into account in the PV capacity calculation. Similarly, the analysis is performed for the representative maximum load condition and the Range-1 PV hosting capacity is calculated to be 9.92 MW (the figure is not shown). It can be inferred that the minimum loading condition limits the Range-1 capacity of the given distribution circuit more than the maximum loading condition for overvoltage criterion.

The first violation of voltage deviation criterion on primary wires occurs on accommodating 4.196 MW (not shown in the figure) of total PV generation (including 1.196 MW of existing PV) during daylight time minimum load condition. However during the maximum loading condition, the distribution circuit can accommodate only 3 MW of PV capacity, including 1.196 MW of existing PV (see Figure 3-9), without causing a largest deviation of more than 0.03 p.u. in primary voltage. Therefore, the threshold for primary voltage deviation is more critical during the maximum loading condition. Similarly, the Range-1 hosting capacity of the circuit corresponding to voltage deviation in the secondary wire is calculated to be 4.13 MW during maximum load conditions at a maximum voltage deviation of 0.05 p.u. It is to be noted that since the hosting capacity is calculated based on the first violation of the impact criteria, it is possible that the estimated value might change if the number of deployment scenarios are increased from 5,000 to a higher value. However, Figure 3-9 shows that the variation in the impact criteria with the deployment scenarios is not significant, so the error between the actual hosting capacity and the estimated value might be insignificant.

PROTECTION BASED RANGE-1 PV HOSTING CAPACITY

Protection based limits on the distribution system can be violated due to PV over-generation and contribution of PV generators to faults in the feeder. The most common impact is a reverse power flow condition, where the power is fed back to the primary circuit of the service transformer. The analysis framework for evaluating Range-1 hosting capacity based on the reverse power flow criterion is discussed in this section.

STEP 1
CREATE PV DEPLOYMENT CASES

The framework to create PV deployment scenarios for the study is similar to that explained in Section 3.3. First, for a given customer penetration level (for instance 2%, i.e., $Cust^{2}_{pen}$), PV systems are deployed at the selected customer locations. Next, the customer penetration is increased by 2% increments (e.g., from $Cust^{2}_{pen}$ to $Cust^{4}_{pen}$), and additional PV systems are deployed at the remaining customer loads where a PV system is not already present. The process is repeated until the customer penetration level reaches 100% ($Cust^{100}_{pen}$). The same process is repeated 100 times, resulting in 100 unique stochastic PV deployment scenarios at each customer penetration level, with a total of 5000 scenarios.

STEP 2
QUANTIFYING FEEDER IMPACTS

PV hosting capacity is calculated based on the capacity that violates the steady state current limit for the distribution grid. Since there is a difference in the limit imposed based on topology of the distribution grid, i.e. radial, spot or secondary grid networks, the impact criteria is defined to be power flow reversal at the feeder head. In this case the circuit is fed by only one substation transformer. Therefore, a single point for the reverse power flow is selected. The threshold for the impact criteria is set to be reversal of power flow in the line feeder towards the substation transformer (see Figure 3-10).

Considering a conservative estimate, the analysis assumes a representative minimum load and peak rated PV generation. This assumed condition is similar to that in Figure 2-1, where it can be observed that the net transformer load becomes negative during the afternoon of August 2013, corresponding to the duration when PV generation is at the peak.

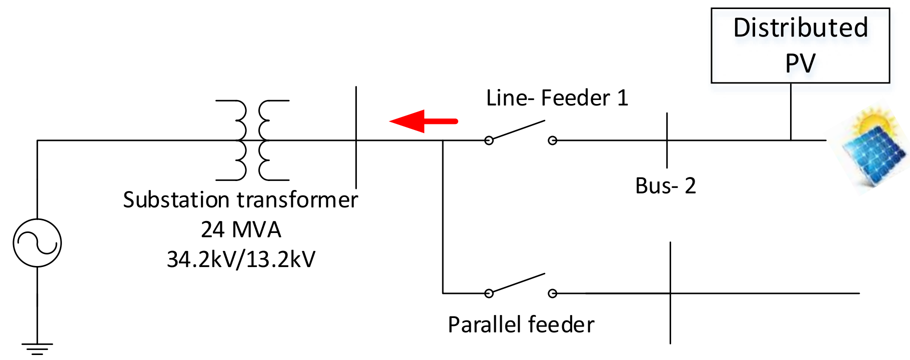
As discussed in the previous section, the multi-phase load flow analysis for 5,000 deployment scenarios is conducted. For each of the scenarios, the current flow and power at the secondary of the service transformer are noted.

STEP 3
DETERMINING RANGE-1 PV HOSTING CAPACITY

Range-1 PV hosting capacity corresponds to the PV capacity (kW) at which the direction of power flow reverses, i.e. the power is fed back from the distribution grid towards the service transformer. In the future study, the reverse power flow will be calculated considering that the substation transformer can allow reverse power flow. The reverse power capability of the tap changing transformer at the substation is limited by about 40-70%, depending on the vector group, MVA rating, type of transformer used (resistor or reactor-type)

FIGURE 3-10

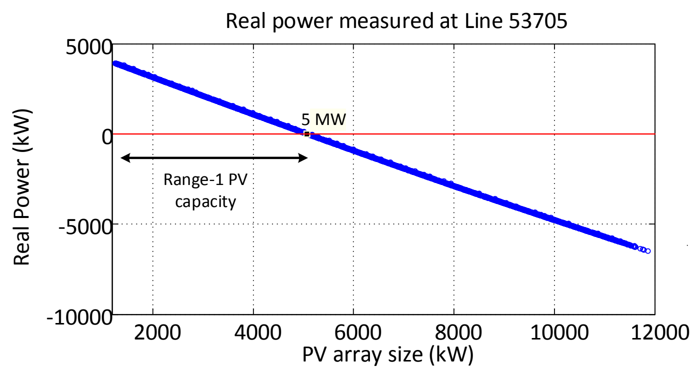
Reverse power flow at a distribution circuit



and power factor. However, for this study, the threshold for the reverse power flow is set to be the instant when the power flow reverses at the service transformer and flows towards the substation.

Power flow from the substation transformer is noted from load flow analyses corresponding to 5000 scenarios and is plotted in Figure 3-11. It can be observed that the net load at the service transformer decreases with increased PV penetration in the grid. Also comparing the Figs. 3-9 and 3-11, the power flow in the feeder from the 5000 scenarios are not sparse and so it can be concluded that the power flow in the feeder is independent of PV location in the grid. Further, the power flow direction reverses on adding 5.07 MW of total PV generation. The negative values of power flow indicate that power is fed back to the substation. The capacity is close to the representative minimum load demand of the circuit, which is 6.29 MW. Therefore, it can be inferred that the reverse power flow occurs on integrating a PV capacity of about its daylight time minimum load.

FIGURE 3-11 Reverse power flow at the substation of the distribution circuit



3.4 OVERALL RANGE-1 PV HOSTING CAPACITY

The overall Range-1 hosting PV capacity is determined from Range-1 capacities corresponding to each impact criterion. The Range-1 capacities corresponding to critical loading conditions are utilized in the overall Range-1 PV capacity calculation. The critical

TABLE 3-3 Loading Conditions for a Conservative Study

IMPACT CRITERIA	CRITICAL LOAD	
	Min Load	Max Load
Overvoltage	✓	
Voltage deviation from base case		✓
Reverse power flow	✓	

loading conditions for different impact criteria are summarized in Table 3-3.

The Range-1 PV hosting capacity varies for each impact criteria. The overall Range-1 PV capacity is calculated to be 3 MW (including existing PV capacity) and is observed to be limited by voltage deviation in the primary circuit lines. The hosting capacity is usually represented in terms of the peak load of the circuit [10]. The absolute peak load of the circuit is 9.6 MW that occurs on only one day of the year. It is proposed to represent the PV hosting capacity in terms of the maximum load that is observed commonly during the daylight time (7 am to 7 pm), when the PV is generating. Therefore, the hosting capacity is represented in terms of median value of peak load demand during daylight time. The median daylight time peak for the circuit is calculated to be 7.898 MW. The overall hosting capacity of the Circuit is calculated to be 38% of the median daylight time peak load.

3.5 RANGE-2 AND RANGE-3 PV HOSTING CAPACITIES

The Range-1 PV hosting capacity is evaluated without any operational changes and upgrades in the grid. The evaluation of PV capacities for Ranges 2 and 3 is similar to Range-1 PV capacity calculation, except some changes in the assumptions/inclusion of upgrades in the circuit. The circuit considered for the study is modified by allowing operational changes in the existing voltage regulation equipment for Range-2 calculation. Instead of freezing the control elements in the grid, they are allowed to vary to reach the nominal voltages. The voltage regulation equipment can mitigate most of the voltage related concerns and help accommodate more PV in the grid. To accommodate additional PV beyond the Range -2 hosting capacity, upgrades needs to be considered in the grid.

Range-3 PV capacity is calculated by including grid upgrades such as smart inverter and energy storage in the grid, independently. Each upgrade improves the hosting capacity of the circuits by a different measure and the corresponding cost varies with the upgrade. Let the corresponding range be referred as Range-3(x), where x refers to the upgrade considered. The study aims to find the increase in the hosting capacity and the cost associated with the increase in hosting capacity.

4 | ZERO COST OF PV INTEGRATION

High PV penetration in a distribution grid can cause several undesirable effects on the grid. However, the grid can accommodate certain fraction of PV without causing any adverse impacts. Chapter 4 focuses on evaluating the PV hosting capacity that does not incur any extra cost of integration or some minimal cost of integration in the grid.

The analysis primarily involves determining PV capacity that can be accommodated in the circuit without any operational changes and grid upgrades (Range-1). Since a few operational changes in the grid do not incur any integration cost, the analysis is repeated considering some operational changes in the grid. The corresponding PV capacity is called the Range-2 PV hosting capacity. Accommodating PV capacity up to Range-2 capacity may not incur any cost of integration or some minimal cost of integration. The analysis is performed on three utility distribution circuits, and the results are presented in the following sections.

4.1 CIRCUITS FOR THE STUDY

Three actual utility distribution circuits are analyzed for the study [17, 18]. The characteristics of the distribution circuits are presented in Table 4-1. Note the three circuits have unique characteristics with respect to voltage level, short circuit strength, feeder length, type and number of customers in the feeder.

4.2 RANGE-1 HOSTING CAPACITY

The maximum PV array size that can be accommodated in a distribution without any operational changes in the existing regulation equipment and upgrades in the grid is referred to as the Range-1 hosting. The Range-1 hosting capacity of the circuits is calculated in the following sections. Since no changes are made in the circuit, there is no cost associated with integrating up to Range-1 PV capacity in the distribution grid.

CIRCUIT A

Circuit A is an actual distribution network at 12.47 kV level with 48 miles of total length of all primary conductors/cables. The maximum length of the feeder from the substation is only about 3 miles. The distribution network serves 1,379 customers (96% residential load). The absolute peak and minimum load demand obtained from yearly demand at the substation are measured as

TABLE 4-1 The Characteristics of the Selected Distribution Circuits

SYSTEM PARAMETERS	CIRCUIT A	CIRCUIT B	CIRCUIT C
System voltage (kV)	12.47	12.47	34.5
Number of customers	1379	867	3885
Service Xfmr connected kVA	16310	19320	69373
Total feeder kVar	1950	2400	3300
Subtransmission voltage (kV)	115	115	230
3ph SCC at substation	114	475	422
Circuit miles (total electrical length of all primary conductors)	48	8	74
Longest length from the substation (miles)	3	2.5	8
%residential by load	96	39	87
No. feeders on the Substation bus	1	2	2

7.12 MW and 1.234 MW, respectively. Additionally, the median value of the daytime (7am to 7pm) peak load demand for the distribution circuit is equal to 3.735 MW. The representative minimum and maximum load demand are 1.77 MW and 5.79 MW respectively. They are determined based on the 10^{th} and 90^{th} percentiles of load demand between 10 am and 2 pm, respectively.

The PV hosting capacity of the circuit is calculated using the stochastic framework detailed in the previous chapter. The results of the study are presented in Fig. 4-1. It can be observed that the hosting capacity of the circuit is limited only by reverse power flow criteria on integrating PV capacity more than 1.73 MW or 46% of median peak load of the circuit. This value is approximately equal to the representative minimum load of the circuit (1.77 MW) that was considered for the simulation. There are no violations of any voltage related concern.

FIGURE 4-1

Circuit A: Range-1 PV hosting capacity

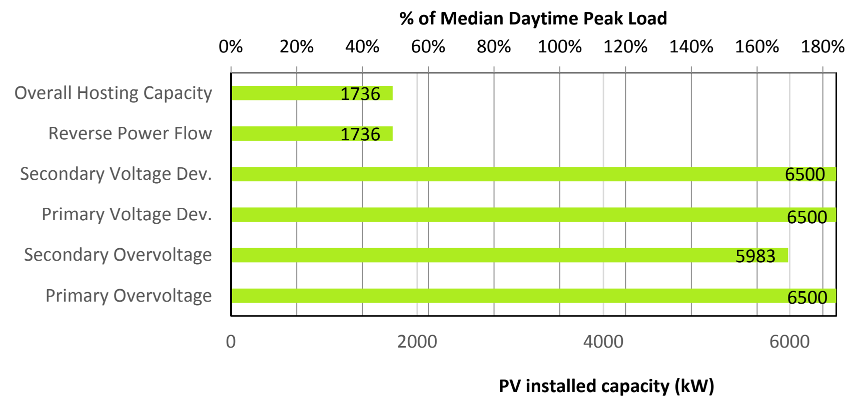


FIGURE 4-2

Circuit B: Range-1 PV hosting capacity

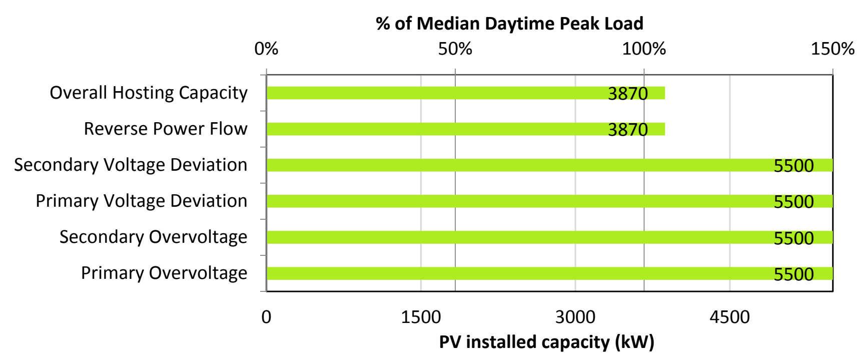
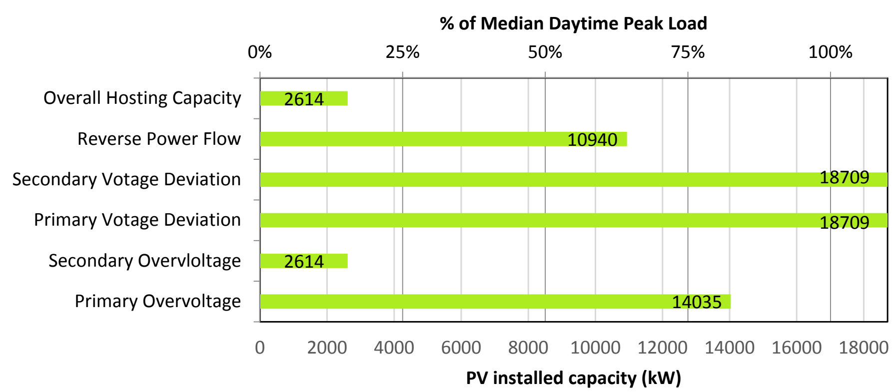


FIGURE 4-3

Circuit C: Range-1PV hosting capacity



CIRCUIT B

Circuit B is also a distribution network at the 12.47 kV level. It is shorter than the other circuits, with a total primary circuit length of about 8 miles. The farthest end of the feeder is 2.5 miles from the substation. The network serves 867 customers (39% residential load). The circuit's absolute peak and minimum load demand are 5.23 MW and 2.05 MW, respectively. The representative minimum and maximum load values of the circuit are 2.9 MW and 4.24 MW, respectively. The median daylight time peak load of the circuit is 3.71 MW.

The PV hosting capacity analysis is carried out on the circuit, and the results of the study are summarized in Figure 4-2. It can be observed that the overall Range-1 PV hosting capacity of the circuit is also limited only by the reverse power flow condition at 3.870 MW (Figure 4-2), which is 1 MW more than the representative minimum load of the circuit of 2.9 MW. However, it is expected that there is a reverse power flow when the PV capacity equal to the representative minimum load (10 percentile value of 2.9 MW) is integrated in the grid. Reverse power flow in a distribution circuit depends on various factors. Therefore, further research on the circuit characteristics is required to explain the unexpected behavior. However, it is generalized that there can be reverse power flow, when a net PV array size greater than the minimum load of the circuit is integrated in the circuit.

The optimal tap setting of the substation transformer during the simulation was set to '-4' taps. It can be observed that the current tap setting eliminated all the voltage related impacts on the grid. Also, since the circuit spans for a shorter distance compared to the other circuits, there is no overvoltage related concern in the grid.

CIRCUIT C

Circuit C is a 34.5 kV distribution circuit with the longest feeder length of 8 miles from substation compared to the other circuits. The circuit is extremely large, with a total primary circuit length of 74 miles and serving 3885 customers (87% residential load). The circuit's absolute peak and minimum load demand are 28.67 MW and 6.113 MW, respectively. The representative maximum and minimum load values of the circuit are 21.86 MW and 10.93 MW, respectively. The median daylight time peak load of the circuit is 16.88 MW.

The hosting capacity of the feeder is calculated and presented in Fig. 4-3. The overall hosting capacity of the feeder is 2.6 MW, which is 15.5% of median day time peak load. It is limited by the secondary overvoltage condition. Even though the voltage class of the feeder is greater than the other circuits, the overall hosting capacity of the feeder is lesser compared to the other feeders. The reason for the low hosting capacity can be due to the longer circuit miles of the feeder. The presence of single voltage regulation equipment (LTC transformer) at the feeder head is not sufficient to regulate the voltage of the feeder. Further reverse power flow occurs at 64% of median peak load of the circuit, which is when 10.940 MW of PV array is integrated in the grid. The value again corresponds to the representative minimum load that was considered for the analysis (10.93 MW).

The Range-1 hosting capacities for all three circuits are calculated to be 47%, 104% and 15.5% of the respective median daytime peak load of the circuits. The hosting capacities of the circuits vary widely. The wide range in the hosting capacity values between the circuits indicates that circuit characteristics (such as short-circuit capacity at the substation, length of the feeder, number of customer loads, number of voltage regulation devices, voltage class of the feeder) affect the maximum amount of PV that can be accommodated in the grid. Further research is required to identify the relationship between the circuit characteristics and the PV hosting capacity of the circuits.

Among the three circuits, only the hosting capacity for the Circuit C is limited by the secondary overvoltage concern. It indicates that circuit requires external devices to regulate the voltage within the limits. The hosting capacities of Circuits A and B are limited by reverse power flow concern. Reverse power flow at the substation is observed when PV capacity more than the minimum load of the circuit is integrated in the grid. For the ease of analysis the circuits are classified into two clusters based on the impact criterion that limits the Range-1 hosting capacity. Forming clusters can be relevant since solutions are proposed for the circuits based on the impact criteria that limits the hosting capacity of the circuits. The analysis for the circuits is here forth separated into two clusters namely Cluster 1 and Cluster 2.

4.3 RANGE-2 (A) HOSTING CAPACITY: (Cluster 1 Circuits)

Since the hosting capacity of the two Circuits A and B are limited by reverse power flow concern, they are clustered together as Cluster 1 circuits. PV hosting capacity based on reverse power flow is defined as the PV penetration level that is likely to cause power to flow back towards the substation. The reverse power is a concern because the rating of the transformer to allow the power in the reverse direction is typically reduced. For a 23 MVA it was calculated that the reverse power capability is reduced by 40% [14]. Further in light of increasing PV installations, a public utilities commission in California came up with distributed generation interconnection standards (2015) that limit the power being exported to the substation [19]. If power is exported back to the substation and net installed PV (kW) is more than 15% of the peak load, the standard recommends supplemental reviews such as

1. Ensuring that the maximum penetration is less the minimum load,
2. Power quality and voltage test,
3. Safety and reliability test, and
4. Transmission dependency and transmission stability test.

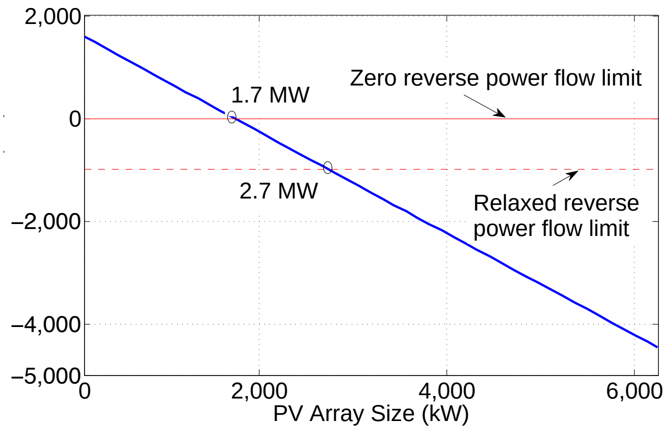
Except the first condition, actual field tests may be required to evaluate the other conditions in a distribution grid. The fourth condition is based on the transmission circuit that is feeding the distribution circuit. Since conventional distribution grids are designed for uni-directional current, it is possible that excess power exported from the distribution grid can cause stability issues at the transmission grid. Therefore, in the Range-1 hosting capacity calculation, the reverse power flow from the distribution grid is strictly restricted and is not allowed to flow through the substation. However, since a small fraction of power from the distribution grid would not affect the transmission stability, the hosting capacity is recalculated based on the relaxed assumption that the reverse power flow of 10% of the substation transformer can be allowed to flow through the transformer to the transmission network. Note that the 10% reverse power flow allowance is for illustration purpose only. The actual allowance is likely dependent on the transformer technology and characteristics. The transformer capacity and the corresponding relaxed reverse power limit is tabulated in Table 4-2.

TABLE 4-2 Transformer Rating and Relaxed Reverse Power Flow Limit

	CktA (MVA)	CktB (MVA)
Substation transformer rating	10	41
Reverse power flow limit (10% of rating)	1	4.1

The hosting capacities of the circuits are recalculated with the relaxed reverse power flow limit and it is referred as the Range-2(a) hosting capacity. The power flow measured at the substation transformer of Circuit A is plotted in Fig. 4-4. The solid line is the reverse power flow limit that restricts the reverse power flow towards the substation. The dashed line is the relaxed power flow limit fixed at 1 MW, which is calculated from 10% of the substation transformer rating (10 MVA). It can be observed that when 2.7 MW of PV is integrated in the grid, a reverse power flow of more than 1 MW flows towards the substation. So, the Range-2(a) hosting capacity of the Circuit A is still limited by the reverse power flow limit and it is 2.7 MW (see Fig. 4-5). The new hosting capacity, however, has increased from 47% to 77% of the median daytime peak load, with the new relaxed power flow limit.

FIGURE 4-4 Power flow at the substation transformer of the Circuit A



The transformer of Circuits B is overrated to about 40 MVA. Therefore, even when all the customers are assumed to have PV integrated to the grid, the reverse power flow is within the relaxed reverse power flow limit, so the new hosting capacity of the Circuit B is not limited by the reverse power flow constraint. The hosting capacity of Circuit B is shown in Fig. 4-6. The Range-2(a) is increased to 150% of the median peak load, which corresponds to 100% customer penetration, i.e. all the customers have PV installations.

There are no direct costs associated with integrating PV capacity equal to Range-2(a) capacity. However, further details on the circuit and the transmission network may be required to estimate the cost associated with allowing more reverse power flow through the substation transformer.

4.4 RANGE-2(B) HOSTING CAPACITY: (Cluster 2 Circuit)

Range-2(a) hosting capacities of all the circuits were calculated in the previous section. Only the overall hosting capacity of the Circuit C (Cluster 2) is limited by secondary overvoltage concern. Therefore, the effect of voltage regulation devices in increasing the PV hosting capacity is studied in this section. A new PV hosting capacity called the Range-2(b) is evaluated by allowing operational changes in the existing voltage regulation devices such as on-load tap changer (LTC) transformer and capacitors installed in the grid.

The LTC transformer can regulate the voltage by varying the tap position of the transformer. A typical LTC transformer model is shown in Fig. 4-7. The voltages V_S and V_L are at the

FIGURE 4-5 Range-2(a) hosting capacity of Circuit A

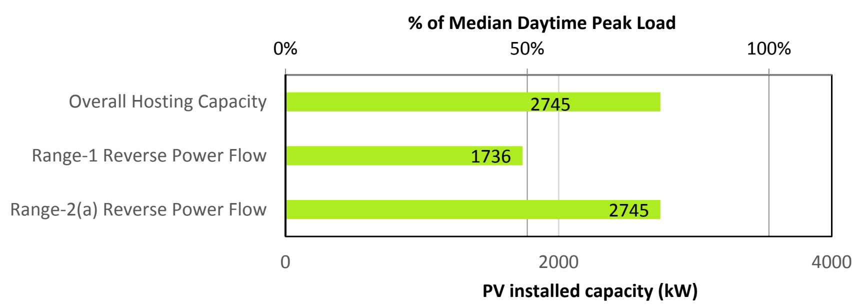
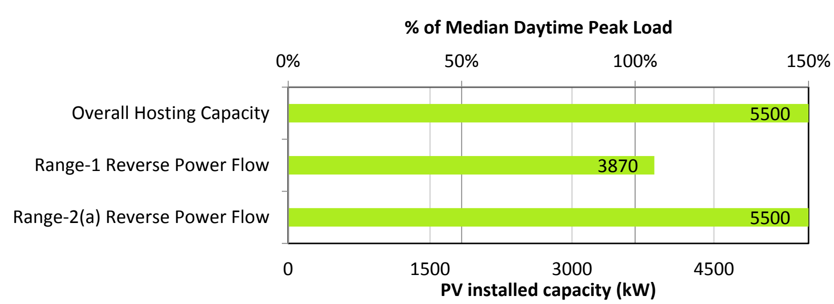


FIGURE 4-6 Range-2(a) hosting capacity of Circuit B

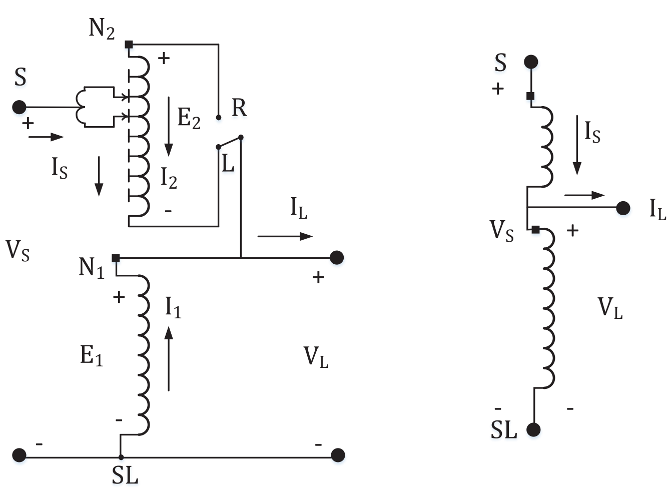


primary and secondary side of the transformer respectively. The terminal S is attached with a tap changing mechanism that varies the number of windings in N_2, thereby regulating the voltage at the secondary side of the transformer.

The voltage at the secondary of the transformer as a function of primary voltage is expressed in terms of regulator ratio a_R. The regulator ratio is related to the ratio of the turns N_1 and N_2.

$$V_S = a_R V_L$$
$$a_R = 1 + \frac{N_2}{N_1}$$

FIGURE 4-7 LTC transformer and tap changing mechanism



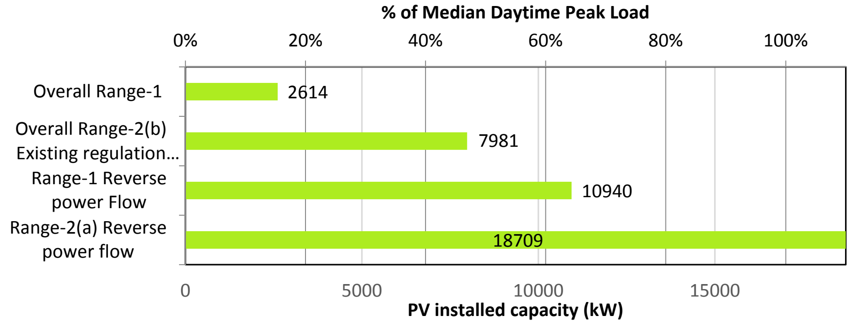
The other existing voltage regulation device is a capacitor bank. The capacitor bank typically increases the voltage of the feeder. Capacitors are helpful during under-voltage conditions, but since high PV penetration in the grid causes overvoltage conditions in the grid, switching off the capacitor banks can help maintain the voltage profile within limits.

Range-1 hosting capacity of Circuit C is 15.5% of median peak load and it is limited by overvoltage concern at the secondary wires of the feeder. The tap position of the LTC transformer and status of the capacitors in the circuit for the Range-1 capacity calculation were recorded to be '0' tap setting and all the capacitors were 'off'. In literature, Range-1 hosting capacity is calculated by disabling the regulator and capacitor control in the circuit. The rationale for the assumption is that the regulating devices like Load Tap Changing (LTC) transformers or capacitors are not fast enough, and, therefore, transient overvoltage conditions may be observed. Also, since it is believed that the numbers of tap operations increase with renewable power integration, the controls are disabled. However, since the study focuses on the steady state voltage, the regulation capability of the existing devices is included in the analysis. Also, the number of tap changes in the devices is limited to vary by about 3 tap positions at a time.

Range-2(b) PV hosting capacity for the Circuit C is calculated by allowing the LTC transformers to actively regulate the voltage and the capacitors are switched based on the voltage of the grid. The results of the study are presented in Fig. 4-8. Overall Range-2(b) hosting capacity increased from 15.5% to 47% of median peak load of the circuit. The increase in hosting capacity is made possible by a change in 2 tap operations from '0' to '-2' taps. Also similar to Cluster 1 circuits, Range-2(a) hosting capacity of the Circuit C is calculated (see Fig. 4-8). It is observed that the hosting capacity of the circuit with respect to reverse power flow is increased up to 112% of the median daytime peak load (18.7 MW), which is 100% customer penetration. However, the overall hosting capacity of the circuit is still 7.9 MW, because the circuit is limited by overvoltage concern in the secondary wires of the circuit.

FIGURE 4-8

Range-2(b) hosting capacity of Circuit C



The above analysis to calculate the hosting capacity is performed by a snapshot study considering the worst case when PV is generating at its peak and the load of the circuit is at the representative minimum load value. The tap operations measured in this simulation may not give a correct estimate on total number of tap operations over a day. Therefore, a yearly simulation is performed to calculate the tap operations over the year.

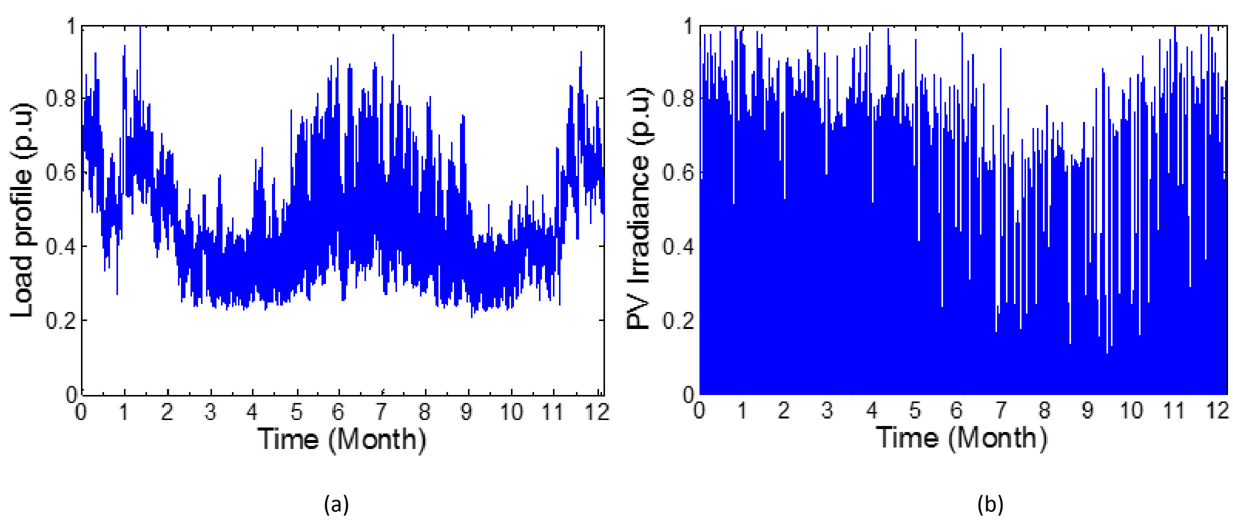
Yearly simulations are performed to calculate total number of tap operations of the LTC transformer. The worst case scenario that all the customers have PV (100% PV penetration) is considered for the study. For the simulation, load profile for one year at 1 hour resolution is applied to every load. The power measured at the substation over the year is plotted in Fig. 4-9 (a). Real time PV profile data over a year at 1 minute resolution is shown in Fig. 4-9(b) [20]. The same profile is applied to every PV in the grid, on an assumption that all the PVs in the grid, irrespective of the location in the feeder, experience the same irradiance.

The snapshot study showed that transformer moved from 0 to -2 taps. However, yearly simulation with 100% PV penetration showed about 12% increase in the tap operations. Without PV integrated in the grid, a total of 887 tap operations were recorded at the substation transformer, whereas when 100% PV are integrated, a total of 993 tap operations were recorded. Therefore, the cost of including the existing regulation equipment was calculated based on the 12% increase in tap operations.

The cost of increase in tap operation is calculated based on the following ballpark estimates. The average lifetime of On Load Tap Changing Transformer (OLTC) is about 50 years and it is serviced about 6 times in its lifetime. Considering that the average cost of a single maintenance is $25k, the total maintenance cost over the transformer's lifetime is about $150k. Assuming that the maintenances are directly related to number of tap operations and the total number of tap operations per year remains the same over 50 years, the cost per tap

FIGURE 4-9

Yearly simulation (a) Power measured at the substation. (b) Yearly PV profile.



operation is calculated to be \$3.38 as follows,

$$\text{cost per operation} = \frac{\$150\text{k}}{887 * 50} = \$3.38$$

$$\text{incremental cost for 10 years with PV integration} = \$3.38 * 10 * (993 - 887) = \$3.58\text{k}$$

The total cost of increased tap operations over 10 years is calculated to be \$3.58k. The cost estimate for the increased LTC tap operations is minimal compared to the total maintenance cost over 10 years, which could be in order of millions. Therefore, the incremental cost can be considered as the part of the total maintenance cost. So, the increase in hosting capacity from 15% to 47% of the PV penetration is achieved with minimal cost of PV integration.

To increase the hosting capacity beyond 47%, additional grid upgrades need to be included in the circuit and the corresponding hosting capacity is called the Range-3 hosting capacity. The cost associated with the Range-3 hosting capacity is calculated in the next chapter.

4.5 SUMMARY

The PV hosting capacities are calculated for three representative distribution circuits provided by Electric Power Research Institute (EPRI). The Range-1 PV hosting capacities of the circuits are calculated to be 15.5% (i.e., 2600 kW in one particular circuit) or over 100% (i.e., 3870 kW in another circuit) of the median value of the daytime (between 7am and 7 pm) peak load demand. The Range-1 PV capacities were observed to be limited either by reverse power flow or the voltage related impact criteria. It is to be noted that there is no cost associated with integrating up to Range-1 PV capacity in the distribution grid, since there is no change in the distribution circuit.

Based on the limiting criterion, the circuits are clustered into two groups. Range-1 hosting capacities of the circuits that are limited by reverse power flow are grouped into Cluster 1 and the circuits that are limited by overvoltage concern are grouped into Cluster 2. Among the three circuits, two of them are in Cluster 1 and one circuit in Cluster 2. The hosting capacities of the circuits can be increased beyond Range-1 capacity by a few operational changes specific to each cluster. Cluster 1 circuits experience reverse power flow at the substation transformer when PV capacity more than the minimum load of the circuit is integrated in the grid. For Range-2 capacity, the assumption is relaxed to allow reverse power flow of about 10% of the substation transformer rating. The relaxed assumption significantly increases the Range-2 hosting capacity of the Cluster 1 circuits. There is no obvious cost associated with the relaxed reverse power flow limit, on the assumption that the transmission network can take power flow of about 10% of the transformer rating.

The Cluster 2 circuits that experience voltage related impact criterion indicate that the grid is weak and requires external support in terms of reactive power or external devices to regulate the voltage. The existing voltage regulation devices are allowed to regulate and thereby increase the hosting capacity. With the existing regulation devices functioning, the increase in the hosting capacity of the circuit is about 30% of median peak load of the circuit. It is also observed that tap operations increase with high PV penetration. However, the incremental cost of additional tap operations is not significant, and so can be considered to be part of regular transformer maintenance costs. The hosting capacity of the circuits can be further increased to Range-3 capacity. The investments and the corresponding increase in hosting capacity are studied in the following chapter.

5 RANGE-3 PV HOSTING CAPACITY

The Range-1 and Range-2 PV hosting capacities of distribution circuits were evaluated in the previous chapter without and with operational changes in the grid, respectively. Accommodating up to Range-2 PV capacity (kW) incurs minimal cost of integration. Integrating more PV than the Range-2 hosting capacity would incur additional cost of integration. This chapter aims to identify grid upgrades that could increase the PV hosting capacity of the grid beyond Range-2 and the cost associated with each upgrade.

In Chapter 4, the circuits were grouped into two clusters based on the impact criteria that affect the hosting capacity of the circuits. Among Cluster 1 circuits, only Circuit A is still limited by reverse power flow concern with a hosting capacity of about 77% of the median peak load of the circuit. Hence, energy storage is included in the circuit and the corresponding increase in hosting capacity is compared with the cost of energy storage. Among Cluster 2 circuits, the hosting capacity of Circuit C is 47% and it is limited by secondary overvoltage condition. So smart inverter is included in the analysis to regulate the voltage and to increase the hosting capacity further to Range-3.

5.1 RANGE-3 (A) HOSTING CAPACITY: (Cluster 1 Circuits)

Range-2(a) hosting capacity of the Cluster 1 circuits is limited by reverse power flow condition. The excess energy that flows back towards the substation is proposed to be stored using energy storage; thereby the hosting capacity of the circuit can be increased beyond 77%. The size and rating of the energy storage is calculated in this section of the chapter. Also, the cost of the corresponding energy storage size is obtained.

The cost of small scale energy storage is rapidly dropping [21]. For electric vehicle application, the cost of small-scale energy storage has reduced by about 59% from $1000/kwh to $410/kwh between the years 2007 and 2014. Though the same trend does not follow the cost of energy storage for large-scale transmission and distribution applications, the cost of storage for the application is around $3500 – $10,000/kW for about 5 hours capacity [22].

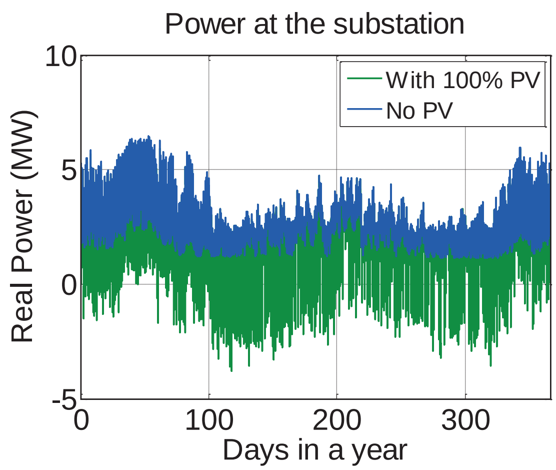
There are various developing energy storage technologies in the market. Some of the technologies, like sodium sulfur and lead acid based battery technologies, are mature in market. Some other battery technologies, like sodium nickel chloride, only have some recent installations. Others, such as Vanadium Redox battery and Zinc bromine based battery, have limited field demonstrations and are largely at the laboratory scale. The cost figures for our applications are calculated based on the existing installations as of 2013 [22].

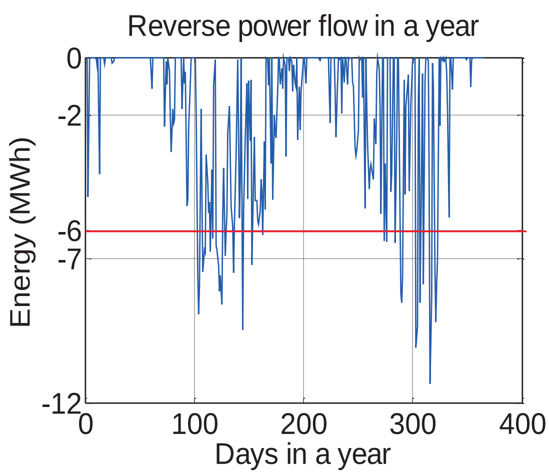
ENERGY STORAGE SIZING

Reverse power towards the substation is observed when 2.7 MW of PV is integrated in the grid. The maximum amount of reverse power flow when 100% PV is integrated in the grid is about 4.75 MW (see Fig. 4-4). Since reverse power flow is about 10% of the transformer rating, i.e. 1 MW is allowed to flow through the transformer, the energy storage should be sized to store at least 3.75MW of power. Hence, the size of the energy storage is chosen to be 4 MW. The value is calculated based on a snapshot study considering the worst case scenario of PV generating at its peak and the load is at the representative minimum. The energy rating of the energy storage is calculated based on the total energy that is exported. The energy exported can be calculated from the time series simulation.

The yearly simulation is performed similar to the method as discussed in Section 4-4 and the same yearly profile shown in Fig. 4-9 is used for the study to measure the power at the substation transformer. The power and energy at the substation with 100% PV in the grid is measured and plotted in Fig. 5-1 (a). The power measured at the substation (see Fig. 5-1) shows reverse power flow during most of the

FIGURE 5-1 Yearly simulation (a) Power measured at the substation. (b) Energy exported.





days in a year. Actually, about 273 days experience reverse power flow towards substation, with PV integration. The energy exported is calculated from the product of power exported to the substation and the corresponding hours in a day and plotted in Fig. 5-1 (b). The median value of the net energy exported to the substation is calculated to be 6 MWh. The energy storage size is decided based on the median value of the net energy that is exported towards the substation. Hence, the energy storage for our application is at least 6 MWh.

COST OF ENERGY STORAGE

The energy storage to reduce reverse power flow in Circuit A is sized at 4 MW and 6 MWh rating. The cost of the storage is obtained from actual installation of similarly rated energy storage installed as of 2013 from [22] and tabulated in Table 5-1. From the data, a storage size greater than 6 MWh is chosen. The cost of energy storage for our application varies from about $6.6 million to $10 million. Therefore, an average of $8.5 million is chosen for our analysis.

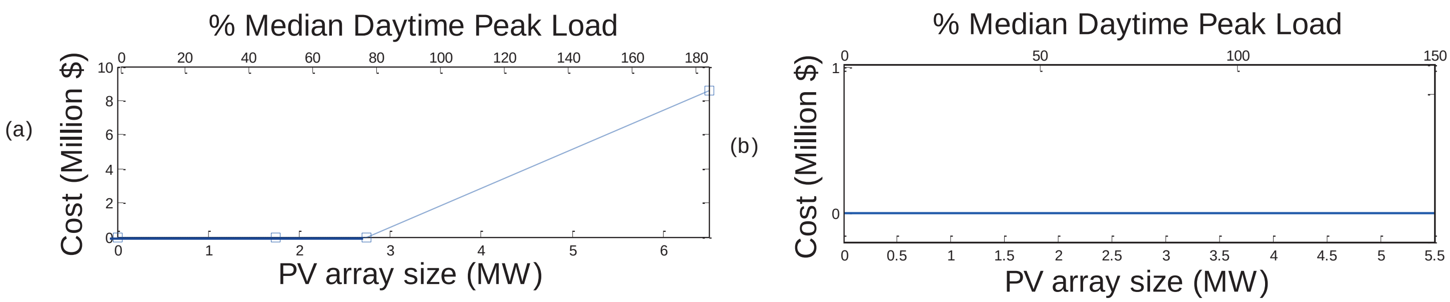
The cost of integrating PV in the Circuit A and B is plotted in Fig. 5-2. The cost of integrating of PV in the Circuit A is assumed to increase linearly up to $8.8 million, as shown in Fig. 5-2(a), whereas the cost of integrating PV in Circuit B is zero.

TABLE 5-1 Cost of Various Energy Storage Technologies [22]

TECHNOLOGY [*]	ENERGY STORAGE SIZE (INSTALLED CAPACITY *)	ENERGY STORAGE COST ($/KW)	ENERGY STORAGE COST FOR OUR APPLICATION (> 6MWH)
Sodium Sulfur Battery	7.2 MWh	6,600	$ 6.6 Million
Sodium Nickel Chloride Battery	6 MWh	10,000	$ 12 Million
Vanadium Redox Battery	2 * 4 MWh	6,000	$7.2 Million
Lead acid Battery	8 MWh	10,000	$10 Million
Zinc Bromine Battery	2 * 4 MWh	3,500	$7 Million

FIGURE 5-2

Cost of PV integration (a) Circuit A. (b) Circuit B



5.2 RANGE-3 (B) HOSTING CAPACITY: (Cluster 2 Circuits)

The hosting capacities of the Cluster 2 circuits are limited by secondary overvoltage concern. Circuit C is the only circuit in Cluster 2 in our study. The Range-2 hosting capacity of the circuit is calculated to be 7.9 MW, which is 47% of median daytime peak load of the circuit. The Range-2 hosting capacity of the circuit is calculated by allowing the existing regulation devices such as LTC transformers and capacitors to regulate the voltage. The existing regulation devices are usually installed at the primary of the distribution circuit. Since the overvoltage is observed at the secondary wire of the distribution circuit, it is proposed in this section that voltage regulation at the secondary wires can help improve the hosting capacity of the distribution feeder.

Conventionally, the utilities regulate the voltage with the help of regulation devices installed at the primary wire. But with increased PV penetration, the need for voltage regulation at the secondary wires of the distribution circuits has increased. There are some recent devices in market to regulate voltage at the secondary wires of the distribution feeder [23]. These devices vary the reactive power output based on the voltage and thereby regulate the voltage at the secondary of the feeder. Since the new amendment to the IEEE standard [24] allows the PV inverters to actively regulate the voltage at the point of interconnection, this section considers upgrading the existing smart inverter to regulate the voltage. The upgrade required for the smart inverter operation is inclusion of extra controllers in the existing equipment. The average cost of upgrading the inverter into a smart inverter is estimated to be $ 600 per unit.

SMART INVERTER FUNCTIONALITY

An inverter is a power electronic device that converts the DC power from PV panels into AC power output. A smart inverter can be programmed to regulate the voltage at the point of interconnection by varying the output of the inverter. Based on the method that is used to control the voltage, three smart inverter functionalities are defined.

Fixed power factor control

The inverters for our study are considered overrated by 10% more than their rated apparent power. The apparent power (S) of the inverter is expressed usually in kVA and it is expressed in terms of real power (P) in kW and reactive power (Q) in kvar, as in (5-1)

(5-1)

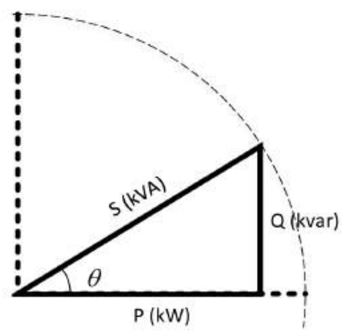
$$S = \sqrt{P^2 + Q^2}$$

The power factor (pf) of the inverter relates the real power with the apparent power output of the inverter by the relation in (5-2). The representation of the real, reactive and apparent power is shown in Fig. 5-3.

(5-2)

$$pf = \cos\theta = \frac{P}{S}$$

FIGURE 5-3 Real, reactive and apparent power representation.



In this smart inverter control mode, the power factor of the inverter is fixed at a particular value. Therefore, reactive power output of the inverter would also be a fixed fraction of the apparent power and it would be according to the relation (5-2).

Volt-var control mode

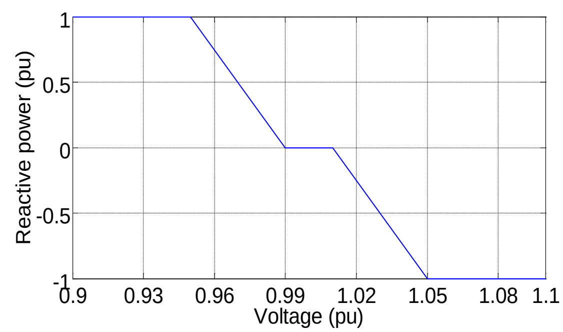
Instead of fixing the power factor of the inverter at a fixed value, it can be helpful to vary the reactive power according to the voltage at the point of interconnection of the PV. The inverters are usually rated for maximum real power output. By increasing the apparent power of the inverter by 10%, the inverter can inject/absorb reactive power equivalent to 45% of reactive power. The calculation for the same in corresponding percentages is shown in the following equation (5-3),

(5-2)

$$Q = \sqrt{110^2 - 100^2} = 45$$

The reactive power output of the inverter can be varied from 0 to 45% based on the voltage. The reactive power output of the inverter is typically controlled based on a volt-var curve similar to the one shown in Fig. 5-4. The reactive power and the voltage values are represented in p.u values. It can be observed that the reactive power is negative (absorbed) when the voltage is more than 1 p.u (rated value) and is positive (injected) when the voltage is less than 1 p.u.

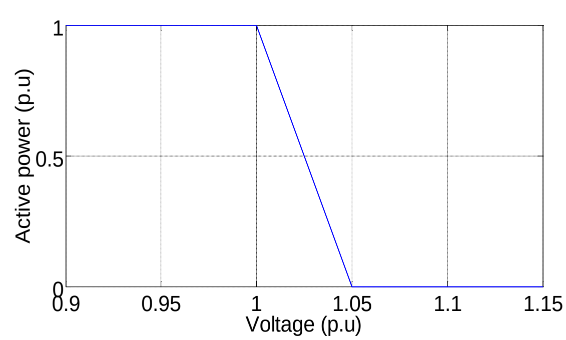
FIGURE 5-4 Reactive power output as a function of voltage



Volt-watt control mode

Another method to control the voltage at the terminal of the PV interconnection is to vary the real power output of the PV. When the voltage at the terminal is more than the rated value, the real power output of the PV is reduced. In the Fig. 5-5, the volt-watt reduces the PV power output to zero when the voltage exceeds 1.05 p.u.

FIGURE 5-5 Real power output as a function of voltage



Curtailing the PV power output can lead to loss in revenue that can be otherwise obtained by generating the PV output, assuming Net Metering is installed in the system. The opportunity cost associated with not generating the power need to be provided to the customer as incentive for the customer to not generate the real power. Therefore, it may be better to upgrade the inverter to absorb reactive while still injecting the real power output (voltvar) instead of curtailing the real power output of the PV system.

PV HOSTING CAPACITY WITH SMART INVERTER FUNCTION

The inverters are controlled by all of the above described control modes, such as volt-var, volt-watt and fixed power factor. The corresponding increase in hosting capacity that is achieved by each of the control modes is studied. From the study, assuming that all the customers have smart inverter, it was observed that the hosting capacity was increased to 18.7 MW or 112% of median peak load. The hosting capacity corresponds to the condition when all the customers have PV, i.e. 100% PV penetration. Therefore, the smart inverter has been demonstrated to show that it can eliminate all the secondary overvoltage condition in the distribution grid and increase the hosting capacity to the maximum.

Since the smart inverter is an upgrade that is made by the customer, enforcing every customer to make the upgrade may not be possible. Therefore, the effect of having only a certain percentage of total inverters having smart inverter functionality is studied. There are a total of 3890 customers in the circuit. Various possibilities from 10% to 100% of the customers having smart inverter are considered. The result of the study is presented in Table 5-2.

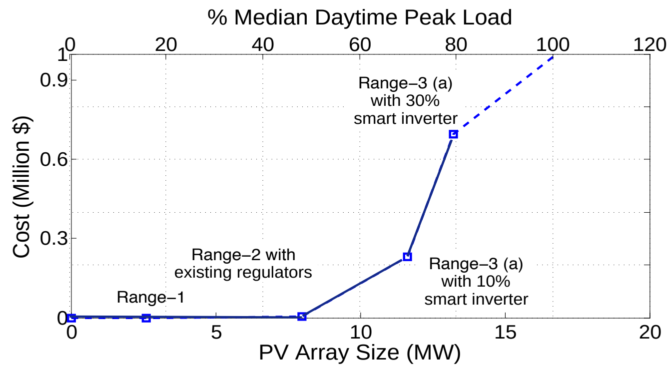
It can be observed that if only 30% of the total customers have smart inverter, the hosting capacity of the circuit is increased from 47% (Range-2 capacity) to 79% of the median peak load of the circuit. Further, if 30%-50% of the PV inverters in the grid have smart inverter functionality, the PV hosting of the circuit can be increased between 79% and 112%. Therefore, the hosting capacity of the circuit can be significantly increased without the need for any expensive equipment if 30-50% of the customers have smart inverters.

TABLE 5-2 Range-3(b) PV Hosting Capacity

% OF INVERTERS	NUMBER OF INVERTERS	OVERALL HOSTING CAPACITY (KW)	OVERALL HOSTING CAPACITY (% OF MEDIAN PEAK LOAD)	COST OF SMART INVERTERS ($1000)
10	385	11640	69	231
30	1160	13230	79	696
50	1940	18710	112	1164
80	3110	18710	112	1866
100	3890	18710	112	2334

Inclusion of the smart inverter functionality to a PV inverter is a decision of the customer owning it. The study has demonstrated that smart inverters can alleviate the overvoltage concern in the grid; thereby eliminating the other conventional methods to mitigate overvoltage concern in the distribution grid such as use of line regulators and transformer upgrades which can cost a few millions. Smart inverter installations by the customers can be promoted by the utility providing the right incentive towards the installations.

FIGURE 5-6 Cost of PV integration in the Circuit C.



COST OF SMART INVERTER

Smart inverters are some modifications in control algorithm of the prevalent maximum power point tracker (MPPT) controllers in the market. The cost of the MPPT charge controller in market is in the range of $500 - $1600, for an average size of 4 kW PV system [25]. We assume in our analysis that the cost is $600 per unit of MPPT controller. Based on the assumption, the costs of smart inverters are calculated and included in the Table 5-2. The cost of PV integration for Circuit C is plotted in Fig. 5-6.

5.3 SUMMARY

The PV hosting capacities of all three distribution circuits are increased to the maximum customer penetration, i.e. every customer has PV. The cost of achieving the penetration level is studied for each of the circuits. For Circuit A, the cost of increasing the hosting capacity from 77% to 180% (peak load of the circuit) is about $8.5 million, due to inclusion of energy storage. Therefore, increasing feeder PV generation capacity using energy storage technologies likely incurs a significant cost. Whereas, the cost of increasing the hosting capacity in Circuit B is zero, i.e., PV capacity equal to peak load of the circuit can be added without any grid concern. The Circuit C requires additional voltage regulation devices like smart inverter to improve the hosting capacity, and the cost of achieving the maximum penetration was about $2 million, which is much less compared to that of Circuit A. The inference from the study is that the cost of PV integration can be significantly high depending on the circuit characteristics. Depending on the impact criteria the hosting capacities of the circuit can be increased by either adding energy storage or smart inverter. However, the cost of energy storage systems is significant and so including energy storage is unjustifiable for the sole purpose of increasing PV penetration.

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