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*Review Article*

# Impact of Rooftop Photovoltaics on the Distribution System

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This paper presents a review of the impact of rooftop photovoltaic (PV) panels on the distribution grid. This includes how rooftop PVs affect voltage quality, power losses, and the operation of other voltage-regulating devices in the system. A historical background and a classification of the most relevant publications are presented along with the review of the important lessons learned. It has been widely believed that high penetration levels of PVs in the distribution grid can potentially cause problems for node voltages or overhead line flows. However, it is shown in the literature that proper control of the PV resource using smart inverters can alleviate many of those issues, hence paving the way for higher PV penetration levels in the grid.

## 1. Introduction

Since the 1980s, many researchers have tried to study the impact of photovoltaics (PVs) on the distribution grid. It has been generally believed that once PV penetration exceeds a certain limit, problems and challenges could arise affecting the operation or security of the grid. Naturally, this would limit the hosting capacity of the grid for PVs. In order to increase this capacity, the utility could introduce mitigation techniques to counteract the negative effects of PVs or, alternatively, use various centralized or decentralized grid optimization solutions to coordinate PV operation with the rest of the grid. In this paper, we survey the publications that study the impact of rooftop PVs on the distribution system, focusing on voltage profile, system losses, power flow through the lines, and other operational and technical concerns.

Historically, the impact of PVs on the distribution grid was first observed in 1977 [1, 2]. Between 1977 and 1979 [3–5], some researchers performed economic analysis in order to assess the effectiveness of PV integration with the grid, and from that standpoint, they found no barrier for further installation of PVs. However, they expected that there could be some operational issues experienced by the utility. Another study in 1979 [6] emphasized that PV integration could introduce challenges into the grid operation and careful investigations need to be conducted. During this time, there were studies focusing on the reliability aspects of the grid [1], or issues such as safety, protection, and power quality [7].

The main concern during the 1980s was to estimate how much PV resource can be deployed in the system so that the ramp rate of conventional generation resources can still withstand their output power fluctuations [8–11]. It was believed that cloud coverage and movement in the sky and the geographical dispersion of PVs would collectively determine the levels at which PVs can be deployed in the grid. The authors in [10] concluded that a decrease in solar irradiance fluctuations by 10% could allow the penetration level to increase by up to 10%. Of course, this result was based on the 1980s PV technology when rooftop PVs were not controllable [8]. Another study in 1981 forecasted that PV integration could bring instability at the transmission level or it could exacerbate voltage imbalance [12]. Safety was (and still is) an issue as indicated in [13]. Nevertheless, some researchers in the early days recommended further PV integration in the grid regardless of the anticipated problems [14–18] or did not find any barriers to increasing the penetration level [19].

Since 1987, there have been several review publications focused on the impacts of renewable energy resources (RESs) or, in general, distributed energy resources (DERs) on the power grid [20]. However, focusing on a broad range of technologies would lead to generalizations of conclusions and findings. Table 1 provides a summary of the review publications that focus on RES. The majority of these do not distinguish in detail between the impact of PV on the distribution grid compared to the transmission network, or the impact of distributed rooftop PV compared to PV power plants (PV farms). In addition, in many of these publications, a detailed analysis of the impacts of PV on the power grid is missing due to the broad coverage of topics such as mitigation techniques, standards, policies, and projected growth. In [21], the authors provide a detailed analysis of reliability impact of PVs on the power grid. The same applies to [22] although it reviews the impacts of all RES technologies, and not just PVs. The review in [23] is mainly dedicated to the hosting capacity of the grid to DGs. Also, some of the review papers study the potential impacts of PVs for a specific country as in [24, 25] or for islands such as [26].

In order to keep the review focused, this survey only considers the impacts of distributed and rooftop PVs on the distribution grid. Section 2 of the paper presents a quantitative assessment of the existing literature on PV impact. Section 3 elaborates the main findings based on what has been reported in the literature on the impact of rooftop PV on the distribution grid. Interfacing PV inverters allow PV units to participate in reactive power support, which can help mitigate some of the negative effects discussed in this section. This aspect has been addressed in Section 4 of the paper. Future research directions and some existing challenges are presented in Section 5. Finally, concluding remarks appear in Section 6 of the paper.

## 2. Literature Review: Quantitative Assessment

Publications that address the impact of rooftop PVs on the distribution grid date back to 1970s. Since then, the number of publications has increased dramatically (see Figure 1).

Penetration level of PV units in the distribution networks is an important metric that has been defined differently across publications, and various researchers may indicate different metrics (see Table 2). It is important to specify the definition; otherwise, it can lead to inaccurate assumptions about the number or sizes of PV units considered in the system studies. It has been observed that publications that study the distribution network typically tend to define the penetration level as the ratio of the total rated power of PVs to the total rated power of the loads. On the other hand, publications that study the impact of rooftop PVs on the transmission grid often define penetration level as the ratio of the total rated power of PVs to the total rated power of conventional generation units. Also, many publications by researchers from Australia, United Kingdom, and Canada tend to define penetration level as the ratio of the number of houses with PV to the total number of houses connected to the feeder. On the contrary, publications by researchers from the United States, South America, and Africa often define penetration level as the ratio of total PV power to the total load.

One technical factor that has received much attention in the literature is the impact of PVs on voltage imbalance. Most publications have defined voltage imbalance as the ratio of negative sequence voltage to the positive sequence voltage. However, this is not followed by all researchers and some publications have used different metrics. Similar to what is stated above, without clarifying the definition that has been adopted by the publication, inaccurate conclusions may be made. A list of possible definitions for voltage imbalance has been provided in Table 3.

Some researchers have relied on expert knowledge, obtained from utility engineers, to analyze the impact of PVs on the grid. Others have studied feeders with actual or simulated data. Of course, these studies differ in many aspects, e.g., locations of PVs and how dispersed they are, presence of other distributed generator (DG) technologies, and presence of electric vehicles. It was also observed that participation of PVs in reactive power support (i.e., non-unity power factor) has only started to be considered recently. Furthermore, to simplify their analysis, many researchers have assumed the distribution system to be balanced and the solar irradiance to be deterministic, neither of which being accurate assumptions. In particular to address the latter, some researchers have performed probabilistic simulations to account for the effects of cloud coverage. These findings are listed in detail in Table 4 where references are sorted in an ascending order according to the publication years.

Rooftop PV panels are mostly installed at the low voltage level and are single phase. For simplicity, some researchers have modeled the system as a three-phase balanced network (sometimes a single-phase representative model) and have lumped single-phase PV units into equivalent three-phase ones. Others have modeled and simulated the detailed three-phase unbalanced distribution grid. The latter is especially necessary if the study is focused on the impact of PVs on voltage imbalance or operation of voltage-regulating devices that are sometimes single-phase (unganged) operated. Publications that have conducted three-phase unbalanced simulations are indicated in Table 4.

## 3. Impacts of Rooftop PVs on the Distribution Grid

Research studies focused on the impact of PVs on the distribution grid have approached the problem from different angles, as shown in Table 5. However, most of the lessons learned and conclusions made seem to be in agreement. For instance, most publications have identified voltage rise as one of the most important negative consequences of high PV penetration levels. However, regardless of similar conclusions, each paper adds a new perspective in terms of the impact factors or the simulation and testing

Table 1: Topics covered by various review publications on the impacts of RES on the grid.

| Source | | [26] | [27] | [28] | [29] | [30] | [31] | [32] | [33] | [34] | [24] | [35] | [36] | [37] | [38] | [39] | [40] | [41] | [42] | [43] | [44] | [45] | [46] | [47] | [48] | [49] | [21] | [22] | [50] | [23] | [51] | [52] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Impact on the grid | Voltage rise/ voltage support | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | | | √ | √ | √ | √ | √ | √ | | √ | √ | | | √ | √ | | √ |
| | Voltage fluctuations/ flicker | √ | √ | √ | √ | √ | √ | √ | | √ | | √ | √ | √ | √ | √ | | √ | √ | | √ | √ | √ | | √ | √ | | √ | | √ | √ | √ |
| | Voltage imbalance | √ | | √ | √ | √ | √ | | | | | √ | | √ | √ | | | | √ | | √ | √ | √ | | | √ | | | | √ | √ | √ |
| | Tap operations: VRs and OLTC | √ | √ | √ | √ | √ | √ | | √ | | | √ | | | | √ | | √ | √ | | √ | √ | √ | | | | | | | | | √ |
| | System losses | | √ | √ | √ | | √ | √ | √ | √ | | √ | √ | | √ | √ | √ | √ | √ | | √ | √ | √ | | | | | | | √ | √ | |
| | Protection/short circuit/ faultanalysis | | √ | √ | | √ | √ | | √ | √ | | √ | | √ | √ | √ | | √ | | | √ | | | | | √ | | | √ | √ | | |
| | Voltage sag/swell | √ | √ | | | | | | | √ | | | √ | √ | √ | | | | √ | | √ | √ | | | | | | | | | √ | |
| | Overloading/ congestion/ reverse power flow | | √ | √ | √ | | √ | √ | | | √ | √ | √ | | | | √ | √ | | | √ | √ | √ | | √ | √ | | | √ | √ | √ | √ |
| | Islanding | | √ | √ | √ | | √ | | √ | √ | | | | | | | | √ | | | √ | √ | √ | | | √ | | | √ | | √ | |
| | Reliability | | | √ | | | | √ | | | | | √ | | | √ | √ | √ | | | √ | | √ | | √ | √ | √ | | √ | | | |
| | Security | | | | | | | | | √ | | | √ | | | | | | | | | | √ | | | √ | √ | | √ | | | |
| | Harmonics/DC offset | | √ | √ | √ | √ | √ | √ | √ | √ | | √ | √ | √ | √ | √ | | √ | | | √ | | √ | | √ | √ | | √ | √ | √ | √ | |
| | Stability | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | | √ | √ | √ | √ | | | √ | √ | √ | √ | | √ | √ | | | | √ | √ | √ | |
| | Electric devices: transformers, lines, etc. | | | √ | √ | | | | | | | √ | | | | | | | | | | | √ | | | | | | | | √ | √ |
| | Peak load shaving | | | √ | | | √ | | | √ | | √ | | | | | | | | | | | | | | √ | | | √ | | | |
| | Economic analysis/ electricity market | | | | | | | √ | | | √ | √ | √ | | √ | | √ | | | | | | | √ | √ | √ | | | | | | |
| | Grid frequency | | √ | √ | | √ | | | | √ | √ | | √ | | √ | | | | | √ | √ | √ | | √ | √ | √ | | | √ | | √ | |
| | Environment | | | | | | | √ | | √ | | √ | √ | | √ | | √ | | | | | | | | | √ | | | √ | | | |
| | Planning and expansion/ energy savings/ maximum penetration | √ | √ | √ | | √ | √ | √ | √ | | | √ | √ | | | | | √ | | | | | | | | | | | √ | | | |
| Scope of review | Distribution level | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | √ | | | √ | √ | √ |
| | Transmission level | | | √ | | √ | | √ | | √ | | | √ | √ | √ | √ | √ | √ | | √ | | | | √ | √ | √ | | √ | √ | √ | √ | √ |
| | Defining indices for quantifying the impacts of RES | | √ | | | | √ | √ | | | | | | | | | | | | | | | | | | | √ | √ | | | | |
| | Only PV | √ | √ | √ | √ | √ | √ | | | √ | √ | √ | | | | | | | √ | √ | | | √ | √ | | | √ | | | | √ | √ |
| | Distinguish between different PV scales (i.e. rooftop vs. PV plants) | | | √ | √ | | | | | | | √ | | | | | | | | | | | | | | | √ | √ | √ | | | |

TABLE 1: Continued.

| Source | | [26] | [27] | [28] | [29] | [30] | [31] | [32] | [33] | [34] | [24] | [35] | [36] | [37] | [38] | [39] | [40] | [41] | [42] | [43] | [44] | [45] | [46] | [47] | [48] | [49] | [21] | [22] | [50] | [23] | [51] | [52] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mitigating techniques | PV reactive power | √ | √ | √ | √ | √ | √ | | √ | √ | √ | √ | | | | | √ | | √ | √ | √ | √ | √ | √ | | | | | √ | √ | √ | √ |
| | PV power curtailment | | √ | | | | | | | | √ | | | | | | | | √ | √ | √ | | √ | | | | | | √ | √ | | √ |
| | VRs and OLTC | √ | | | | | | | √ | | √ | √ | | | | | | | | | | √ | √ | | | | | | √ | √ | √ | √ |
| | Energy storage/ UPS | √ | | √ | | √ | √ | | | √ | | | | √ | | | | | √ | | √ | √ | √ | √ | | | | | √ | √ | √ | √ |
| | Capacitor banks | √ | | | | | | | √ | √ | | √ | | √ | | | | | | | √ | √ | √ | | | | | | √ | √ | | √ |
| | Controller design/network management | √ | | | | | | √ | √ | √ | √ | √ | √ | √ | | √ | √ | √ | | √ | √ | √ | √ | | √ | | √ | | √ | √ | √ | √ |
| | Demand response | | | | | √ | | | | | | | | | | | | | | | | √ | √ | | | | | | | | | |
| | SVC | | | | | | | | √ | | | √ | | | | | | | | | √ | √ | √ | | | | | | | √ | | √ |
| | Filters for harmonics | | | | | √ | | | | √ | | | | | | √ | | | | | √ | | √ | | | | | | | √ | √ | √ |
| | MPPT | | | | | | | | | √ | | | | | | | | | | | | | | √ | | | | | | | | √ |
| | UPFC/SSSC | √ | | | | | | | | | | | | | | | | | | | √ | | | | | | | | | | √ | |
| | Network reconfiguration/ DG allocation/ grounding modification | √ | | | √ | | | √ | √ | | | √ | | | | | √ | √ | | | √ | √ | | | | | | | | √ | | √ |
| | DSTATCOM or STATCOM | √ | | | | | | | √ | | | √ | | | | | | | | | √ | | √ | | | | | | | √ | √ | √ |
| | Voltage restorers/DVR | √ | | | | | | | | | | | | | | | | | | | √ | | √ | | | | | | | | | √ |
| | System monitoring/ forecasting | | | √ | √ | √ | | √ | √ | √ | √ | √ | | √ | | √ | √ | √ | √ | √ | √ | | √ | | | | | | | | √ | |
| Miscellaneous | Policy and standards | | | | | √ | | | | √ | | | | | | | | √ | | √ | √ | √ | √ | √ | | | | √ | √ | | | |
| | Installed capacity | √ | | √ | √ | | | √ | | | √ | √ | | | | | | | | | | √ | √ | √ | | | | | √ | | | √ |
| | Concept Of RES/ definition of DG | | | | √ | | | √ | | | | | √ | | | | | | | √ | √ | | | | √ | √ | √ | √ | √ | | | |
| | Case study is included | | | | √ | | | | | | | √ | √ | | | | | | | | | | | | √ | | | | √ | | | |
| | Benefits of DGs, connection between RES and markets | | | | | | √ | | | √ | | | √ | | | | | | | | | | | | | √ | | | | | | |
| | Historical perspective/ future perspective | √ | | | √ | √ | | | | | √ | √ | | | | | | | | √ | | | | | | | | | | √ | | |
| | Discussion of software computational tools | | | | | | | | | | | | | | | | | | | | √ | | | | | | | | | | | |
| | Cloud pattern | | | | | | | | | | | | | | | | | | √ | | | | | | | | | | | | | |

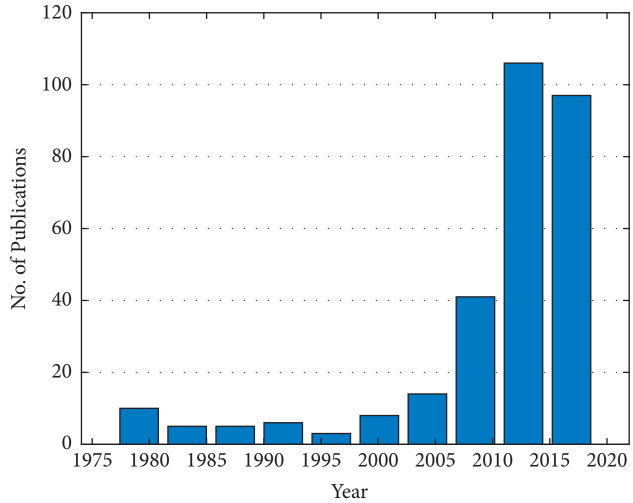


Figure 1: Timeline histogram of publications that are included in this survey.

Table 2: Definitions used for PV penetration level.

| Definition of PV penetration level | Reference |
|---|---|
| Ratio of total PV power to total demand, peak demand, feeder capacity, or main transformer capacity. This could involve either the instantaneous or the rated powers. | [1, 3–5, 11, 15, 16, 27, 53–129] |
| Ratio of the number of houses with PVs relative to the total number of houses. | [130–144] |
| Penetration level not defined. Instead, the total kW of PVs and loads are reported. | [19,128,145–214] |
| Ratio of the total PV power to the total load (demand and losses). | [215] |
| Ratio of total PV power to the total conventional generation. | [216–219] |
| Ratio of the roof area covered by PVs to the total roof area. | [220] |
| Ratio of the reverse power at the main substation transformer to the total power of the system. | [221] |
| Ratio of the instantaneous power by PV relative to the sum of both instantaneous powers of PV and load, which is referred to as the self-consumption rate (SCR). | [222] |

Table 3: Definition of voltage imbalance adopted by various publications.

| Definition of voltage imbalance | References |
|---|---|
| Percentage of negative sequence component of the voltage relative to the positive sequence component | [81, 89, 94, 183, 204, 209, 211, 223] |
| Percentage of the maximum deviation of a single-phase voltage magnitude relative to the average value of all phases | [58, 112, 133, 200] |
| Uses both definitions above | [140] |
| Voltage imbalance not quantified | [90, 103, 106, 128, 132, 161, 172] |
| Voltage magnitude difference between two phases | [91] |

environment. Some of the main findings in the literature are summarized in the following sections.

*3.1. Voltage Level.* In a traditional unidirectional distribution feeder, voltage magnitude at the end of the feeder is less than the source voltage. These voltage magnitudes need to be maintained within certain limits. Voltage regulation can be achieved in two ways [259]: by proper design of the system (e.g., conductor selection, substation and distribution transformer tap settings, and fixed capacitor banks) or by controlling devices such as VRs and OLTC. Once PVs are installed at the distribution grid, they can potentially interfere with both these methods which could affect the voltage profile along the feeder. This is because the power flow may not be unidirectional anymore. Even at low penetration levels where reverse power flow does not occur, current magnitude through the feeder and laterals may decrease, thereby reducing the voltage drop. Consequently, node voltages may increase, which can be exacerbated at low loading conditions.

If not properly coordinated, the interference of PVs with control mechanism of VRs, SCs, and OLTCs can be problematic for voltage control. As a remedy, the recent IEEE 1547 standard allows PVs to actively regulate the voltage at the point of common coupling (PCC) by absorbing (injecting) reactive power from (to) the grid in order to decrease (increase) node voltages.

If the PV power factor is fixed, voltage rise has a direct proportionality to the penetration level, i.e., higher penetration levels cause higher voltage levels. However, some publications (for instance, see [260]) have claimed that at

Table 4: High-level categories for publications included in this survey.

| Source no. | Year | Survey paper? | Includes DGs other than PVs | Involves probabilistic analysis | Includes electric vehicles | Assumes the system is balanced | Considers nonunity power factor | Highest % penetration level |
|---|---|---|---|---|---|---|---|---|
| [1] | 1977 | | | | | | | 110 |
| [3] | 1977 | | | | | | | 300 |
| [4] | 1979 | | | | | | | 300 |
| [5] | 1979 | | | | | | | 32 |
| [69] | 1981 | | | | | | √ | 55 |
| [227] | 1982 | | | | | | √ | |
| [147] | 1982 | | | | | √ | | 55 |
| [15] | 1982 | | | | | | | 50 |
| [109] | 1982 | | | | | | √ | 50 |
| [136] | 1982 | | | | | √ | √ | 40 |
| [16] | 1984 | | | | | | | 40 |
| [68] | 1986 | | | | | √ | √ | 58 |
| [67] | 1988 | | | | | | | 50 |
| [178] | 1988 | | | | | | | 34 |
| [146] | 1989 | | | | | | | 50 |
| [66] | 1990 | | | | | | √ | 6 |
| [19] | 1990 | | | | | | | 60 |
| [149] | 1992 | | | | | √ | | 50 |
| [150] | 1993 | | | | | √ | | 50 |
| [186] | 1993 | | | | | √ | | 50 |
| [231] | 1996 | | | | | | √ | 50 |
| [218] | 1996 | | | | | √ | | 90 |
| [220] | 1997 | | | | | √ | | 50 |
| [65] | 1999 | | | | | √ | √ | 50 |
| [70] | 1999 | | | | | √ | √ | |
| [148] | 2002 | | | | | √ | | |
| [217] | 2003 | | | | | | √ | 50 |
| [207] | 2003 | | | | | | √ | 60 |
| [194] | 2005 | | | | | √ | | 100 |
| [79] | 2006 | | √ | | | | √ | 100 |
| [85] | 2006 | | | | | | | |
| [167] | 2006 | | | | | √ | | |
| [206] | 2006 | | | | | | | 15 |
| [130] | 2007 | | √ | | | | | |
| [131] | 2007 | | | | | √ | | |
| [216] | 2007 | | | | | √ | | 42 |
| [91] | 2007 | | | | | | | 900 |
| [61] | 2007 | | | | | √ | | 20 |
| [27] | 2008 | √ | | | | | | 32 |
| [76] | 2008 | | | | | √ | √ | 50 |
| [236] | 2008 | | √ | | | | √ | |
| [238] | 2008 | | | | | √ | | 25 |
| [89] | 2008 | | | | | | | |
| [151] | 2008 | | | | | √ | | 800 |
| [168] | 2008 | | √ | √ | | √ | √ | 100 |
| [172] | 2008 | | | | | | √ | 100 |
| [173] | 2008 | | | | | | √ | 55 |
| [183] | 2008 | | √ | | | | | |
| [224] | 2009 | | | | | √ | | |
| [127] | 2009 | | | | | | | |
| [152] | 2009 | | | | | | | 30 |
| [169] | 2009 | | | | | | √ | 100 |
| [170] | 2009 | | | | | √ | √ | 20 |
| [180] | 2009 | | | | | | √ | 50 |
| [185] | 2009 | | | | | | | |
| [221] | 2009 | | √ | | | √ | | 50 |
| [197] | 2009 | | √ | | | √ | √ | 16 |
| [198] | 2009 | | √ | | | √ | | |

Table 4: Continued.

| Source no. | Year | Survey paper? | Includes DGs other than PVs | Involves probabilistic analysis | Includes electric vehicles | Assumes the system is balanced | Considers nonunity power factor | Highest % penetration level |
|---|---|---|---|---|---|---|---|---|
| [125] | 2010 | | | | | √ | √ | 10 |
| [223] | 2010 | | | √ | | | | 20 |
| [97] | 2010 | | | √ | | √ | | 13 |
| [114] | 2010 | | √ | | | | √ | |
| [192] | 2010 | | | | | √ | √ | 58 |
| [195] | 2010 | | | √ | | | √ | |
| [73] | 2011 | | | | | | | 200 |
| [80] | 2011 | | | | | √ | | |
| [83] | 2011 | | √ | | | √ | √ | 100 |
| [214] | 2011 | | | | | √ | | |
| [154] | 2011 | | | √ | | | | 200 |
| [102] | 2011 | | | √ | | √ | | |
| [103] | 2011 | | | | | | | |
| [184] | 2011 | | | | | | √ | 60 |
| [106] | 2011 | | | | | | | 60 |
| [187] | 2011 | | √ | | | | √ | |
| [126] | 2011 | | √ | √ | | | | 100 |
| [201] | 2011 | | | | | √ | √ | |
| [202] | 2011 | | | | | √ | | |
| [64] | 2012 | | | | | √ | | 10 |
| [71] | 2012 | | | | | | | 10 |
| [72] | 2012 | | | | | | | 10 |
| [177] | 2012 | | √ | | | √ | | 91 |
| [84] | 2012 | | | | | | | 20 |
| [165] | 2012 | | | | | | √ | |
| [171] | 2012 | | | | | | √ | 50 |
| [174] | 2012 | | | | | | √ | |
| [98] | 2012 | | | | | | √ | |
| [189] | 2012 | | | | | √ | √ | 15 |
| [113] | 2012 | | √ | | | | √ | |
| [116] | 2012 | | | | | √ | | 50 |
| [117] | 2012 | | √ | √ | | √ | | 70 |
| [239] | 2012 | | | | | | √ | |
| [120] | 2012 | | √ | √ | | √ | | |
| [200] | 2012 | | | √ | | | | |
| [78] | 2013 | | | | | | √ | |
| [188] | 2013 | | | | | | | |
| [81] | 2013 | | | | | | | |
| [82] | 2013 | | | | | | | |
| [145] | 2013 | | | | | √ | | |
| [225] | 2013 | | | | | | √ | |
| [90] | 2013 | | √ | | | | | 50 |
| [139] | 2013 | | | | | | √ | |
| [219] | 2013 | | | | | √ | | |
| [108] | 2013 | | | | | | | |
| [110] | 2013 | | √ | √ | | | √ | 100 |
| [128] | 2013 | | | | | | | 40 |
| [142] | 2013 | | | √ | | | | 50 |
| [143] | 2013 | | | √ | | | √ | 100 |
| [196] | 2013 | | | | √ | √ | | 100 |
| [121] | 2013 | | √ | | | √ | | |
| [124] | 2013 | | | | | | | 100 |
| [60] | 2013 | | | | | √ | √ | |
| [74] | 2014 | | | | | √ | √ | 78 |
| [212] | 2014 | | | | | | | |
| [77] | 2014 | | | | | | √ | |
| [230] | 2014 | | | | | √ | | |
| [199] | 2014 | | | √ | | | | 57 |

Table 4: Continued.

| Source no. | Year | Survey paper? | Includes DGs other than PVs | Involves probabilistic analysis | Includes electric vehicles | Assumes the system is balanced | Considers nonunity power factor | Highest % penetration level |
|---|---|---|---|---|---|---|---|---|
| [210] | 2014 | | | √ | | | | 50 |
| [153] | 2014 | | | | | √ | √ | |
| [160] | 2014 | | | | | | | 190 |
| [161] | 2014 | | | | | | √ | |
| [163] | 2014 | | | √ | | | √ | 50 |
| [95] | 2014 | | | | | | | |
| [179] | 2014 | | | | | | | 100 |
| [141] | 2014 | | | √ | | | | 100 |
| [191] | 2014 | | √ | √ | | √ | | |
| [205] | 2014 | | | | | | | |
| [129] | 2015 | | | | | | √ | 100 |
| [62] | 2015 | | | | | √ | | |
| [235] | 2015 | | | | | | √ | |
| [213] | 2015 | | | √ | | | | 50 |
| [87] | 2015 | | | | | √ | | |
| [92] | 2015 | | | √ | | | | 7.33 |
| [164] | 2015 | | | √ | √ | √ | | |
| [176] | 2015 | | | | | √ | | |
| [101] | 2015 | | √ | √ | | | √ | 4 |
| [181] | 2015 | | | | | √ | | |
| [107] | 2015 | | | | | | √ | 100 |
| [111] | 2015 | | | | | | √ | |
| [190] | 2015 | | √ | √ | | | | |
| [193] | 2015 | | | | | | √ | |
| [133] | 2015 | | | √ | | | | |
| [134] | 2015 | | | √ | | | | 100 |
| [135] | 2015 | | | | | √ | | 200 |
| [204] | 2015 | | | | | | | |
| [208] | 2015 | | | | | √ | √ | 50 |
| [123] | 2016 | | | | | | √ | 100 |
| [226] | 2016 | | | | | √ | √ | 15 |
| [75] | 2016 | | | | | | | |
| [211] | 2016 | | | | | | | |
| [228] | 2016 | | | | | √ | √ | 100 |
| [86] | 2016 | | | | | | | |
| [229] | 2016 | | | | | | | 200 |
| [137] | 2016 | | | | | | √ | 250 |
| [156] | 2016 | | | | | √ | √ | 100 |
| [157] | 2016 | | | | | √ | √ | |
| [158] | 2016 | | | | | √ | √ | |
| [159] | 2016 | | | | | √ | | 25 |
| [162] | 2016 | | | | | | √ | |
| [93] | 2016 | | | | | √ | | 100 |
| [94] | 2016 | | √ | √ | | | | 100 |
| [96] | 2016 | | | | | | | 100 |
| [100] | 2016 | | | | | √ | | 15 |
| [144] | 2016 | | √ | √ | √ | √ | | |
| [222] | 2016 | | | | | | | |
| [53] | 2016 | | | | | | √ | |
| [63] | 2017 | √ | | | | | | |
| [232] | 2017 | | √ | | | √ | | |
| [233] | 2017 | | | | | | | |
| [234] | 2017 | | | | | √ | | |
| [155] | 2017 | | | √ | | √ | | 100 |
| [166] | 2017 | | √ | | | | | 150 |
| [215] | 2017 | | | | | √ | | 100 |
| [88] | 2017 | | | | | √ | √ | 60 |
| [99] | 2017 | | | | | | √ | |

Table 4: Continued.

| Source no. | Year | Survey paper? | Includes DGs other than PVs | Involves probabilistic analysis | Includes electric vehicles | Assumes the system is balanced | Considers nonunity power factor | Highest % penetration level |
|---|---|---|---|---|---|---|---|---|
| [182] | 2017 | | | | | | √ | 100 |
| [105] | 2017 | | √ | √ | | | | |
| [140] | 2017 | | | √ | | | | 100 |
| [112] | 2017 | | | | | | | 100 |
| [115] | 2017 | | | √ | | | | 100 |
| [118] | 2017 | | | | | √ | | 100 |
| [132] | 2017 | | | | | | √ | 20 |
| [122] | 2017 | | | | | | | 100 |
| [203] | 2017 | | | | | | | 100 |
| [54] | 2017 | | | | | √ | | 100 |
| [237] | 2017 | | | | | √ | √ | |
| [175] | 2018 | | | | | | | 75 |
| [138] | 2018 | | √ | | | | | |
| [55] | 2018 | | | √ | | √ | | |
| [56] | 2018 | | | √ | | | | |
| [57] | 2018 | | | √ | | | √ | 200 |
| [58] | 2018 | | | | | | | |
| [209] | 2018 | | | √ | | | | |
| [119] | 2019 | | | | | | | |

extreme penetration levels, voltage levels become inversely proportional to penetration level. They supported their findings with analytical analysis and simulations.

*3.2. Line Losses.* Line losses are proportional to the square of current magnitude flowing through the line. Therefore, losses can reach a minimum value when the power injected by PVs equals the power absorbed by loads. Any increase in PV penetration beyond that level could result in reverse power flow and gradual increase of losses. In fact, there is a rule of thumb that line losses plotted against penetration level would resemble a *U*-shaped curve.

*3.3. Operation Instances of VRs, SCs, and OLTCs.* VRs, SCs, and OLTCs mechanically change their tap positions or switch status in order to regulate voltage. PVs may impact the frequency of these operation instances and can interfere with their control schemes. Of course, the intensity of this interference would be dependent on the control algorithm adopted and the feedback signals used. For instance, if SC changes its switch status based on the measured line current, PVs that are located midway between the SC and the end of the feeder would interfere in its operation because they would offset the line current [259]. This problem can be corrected if the SC's control algorithm is adjusted based on reactive power monitoring, provided PVs do not participate in reactive power support.

Another issue may happen with the line drop compensation control of VRs where the goal is to control the tap positions based on the current magnitude and line parameters in order to maintain the voltage at a particular downstream location, for instance, at the consumer side [259]. There are three control modes for VRs, namely, normal bidirectional mode (NBM), cogeneration mode (CGM), and reactive bidirectional mode (RBM). NBM mode is sensitive to direction of power. When there is no reverse power flow in the feeder, a VR that operates based on NBM would regulate the voltage on the downstream side. In this situation, PV power will not impact the operation of VR. However, once reverse power flow occurs, the VR may start regulating the voltage on the substation side, i.e., upstream of its location. Naturally, the substation voltage is dictated by the transmission system (infinite bus) and will not respond to the VR's actions. Thus, the net effect of VR will be to increase the voltage on the downstream side. This would worsen matters because the reverse flow of power is most likely already causing a voltage rise and now its negative effect will be combined with that of the VR's response.

This problem associated with NBM mode can be solved by switching to CGM mode because it controls the downstream voltage regardless of the power flow direction. However, the settings of LDC are selected based on the feeder's expected load profile. Since PVs change the load profile on the feeder, it might affect the operation of VRs. Another possible issue with CGM happens when the grid is reconfigured, for instance, during emergency situations when the feeder may be supplied from the downstream side. Here, a VR operating based on CGM mode will try to control the voltage at the upstream side which can be problematic [259]. If PV does not participate in reactive power support, all these problems can be solved by operating in RBM mode, because the controller would be sensitive only to reactive power. However, once PV starts participating in reactive power support, it will change the expected reactive power profile of the feeder, hence interfering with the VR. Also, RBM mode is sensitive to reactive power direction and it will exhibit the same problems as NBM once reversal in reactive power occurs.

The location of PV is another important factor that determines how much it may affect the operation of VRs. For

Table 5: Different aspects of PV impact on the distribution grid.

| Study area | Related references |
|---|---|
| Power fluctuations due to variability in solar irradiance | [11, 19, 61, 64, 67, 71–74, 86, 89, 96, 122, 123, 129, 131, 145, 146, 149, 174, 176, 178, 188, 198, 200, 208, 214, 216, 224, 226, 229, 232, 233, 235, 240–243] |
| Overvoltage caused by PVs | [68, 93, 104, 113, 139, 157, 158, 197, 201, 237, 244–251] |
| Effect of rooftop PV on the transmission grid | [12, 109, 128, 135, 145, 216–219, 221, 228] |
| Comparing the performance of PV in voltage correction to voltage regulators (VRs) or capacitor banks | [76, 192, 195, 231] |
| Effects of installing PVs at different locations in the grid with different voltage levels | [66, 69, 92, 148, 159, 227] |
| Power flow in the feeder (reactive power) | [67, 76, 78, 83, 84, 89, 112, 125, 153, 189, 197, 224, 239] |
| Power flow in the feeder (active power) | [65, 71–73, 76, 78, 83, 84, 89, 96, 112, 125, 133, 153, 189, 197, 201, 209, 214, 215, 224, 232, 239] |
| Load peak shaving | [61, 62, 231] |
| Relation with the grid size | [11] |
| Voltage profile | [19, 27, 53, 54, 56–78, 80–84, 86–91, 93, 94, 96–101, 103, 105–110, 112–116, 118–120, 122–125, 127–139, 142–145, 148, 151, 153–159, 161, 162, 164, 167, 168, 170–173, 175, 177, 180–184, 187–192, 194, 195, 199–204, 207, 209, 210, 212–216, 220–225, 227, 228, 230–237, 239, 241, 252, 253] |
| Voltage fluctuations or flicker | [27, 64, 75, 81, 88, 89, 99, 107, 110, 118, 138, 152, 153, 172, 174, 188, 189, 203–205, 208, 212, 215, 216, 229, 250, 254] |
| Reverse reactive power flow | [84, 89, 128, 224, 239] |
| Reverse active power flow | [7, 65, 67, 76, 78, 84, 86, 87, 89, 96, 97, 105, 107, 109, 123, 128, 129, 131–133, 137, 149, 189, 196, 201, 214, 224, 230, 232, 239] |
| Power losses | [54, 59, 60, 65, 70, 76, 79, 83, 84, 86–88, 96, 99, 101, 102, 107, 112, 114, 119, 125, 131–133, 136, 145, 151, 153, 156–158, 162, 168, 171, 173, 174, 183, 184, 189–191, 196–198, 200, 209, 214, 215, 220, 224, 227, 230–232, 236, 237, 239, 250] |
| Interaction with static capacitor banks, SCs, or SVCs | [59, 60, 70, 75, 76, 80, 82, 84, 107, 153, 185, 187, 188, 195, 200, 214, 223, 227, 235] |
| PV with the option of active power curtailment | [101, 114, 161, 162, 167, 170–173, 180, 195, 202, 207, 237, 250, 253] |
| PV contribution to reactive power support | [53, 57, 60, 65, 66, 68–70, 74, 76–78, 83, 84, 88, 98, 99, 101, 107, 109–111, 113, 114, 123, 125, 129, 132, 137, 139, 143, 153, 156–158, 161, 168–174, 180, 182, 184, 187, 189, 192, 193, 195, 197, 201, 207, 208, 225–228, 231, 235, 237, 239, 250, 255, 256] |
| Impact of PV on voltage imbalance | [7, 12, 56–58, 63, 71–73, 81, 89–92, 94, 103, 106, 110, 112, 115, 128, 132–134, 138, 140, 154, 160–162, 165, 172, 179, 182, 183, 187, 190, 195, 200, 203, 204, 209, 223, 252] |
| Impact of PV on power imbalance | [90, 91, 107, 109, 128, 160, 193] |
| Comparing distributed PVs to PV plants | [75, 80, 82, 86, 87, 116, 157, 158, 189, 257] |
| Effect of spatial allocation of PVs or loads | [56, 64, 65, 70, 82, 84–86, 100, 102, 114, 118, 120, 133, 140, 144, 148, 154, 156–158, 175, 177, 187, 195, 199, 209, 210, 223, 236, 239] |
| Transient behavior of terminal voltage | [226] |
| Power factor at the main substation | [65, 66, 70, 74, 136, 206, 227] |
| System response during the peak demand | [1, 55, 61, 65, 69, 70, 76, 78, 109, 140, 149, 150, 196, 224, 227, 232, 235, 257] |
| Comparing system behavior in summer vs. winter (seasonal response) | [1, 65–67, 70, 78, 95, 97, 102, 121, 122, 131, 138, 149, 176, 188, 214, 218, 222, 224, 227, 232, 235] |
| Effect of grounding wire on PVs | [128] |
| Effect of customer type (residential, commercial, industrial) | [7, 55, 69, 117, 124, 126, 137, 150, 153, 200] |
| Diversity factor (aggregate peak demand effect) | [7, 188] |
| Short circuit impedance of the transformer | [177] |
| Impact on the effective lifetime of the main transformer | [95, 96, 117, 126, 131, 166, 186, 206, 238] |
| Effect of substation transformer capacity at different PV penetration levels | [69, 109, 115, 131, 133, 135, 183, 186, 230, 238, 239] |
| Effect of feeder capacity, length, or cross-sectional size | [54, 57, 68, 69, 71–73, 75, 82, 83, 86, 93, 94, 96, 115, 118, 119, 121, 133, 137, 138, 142, 144, 154, 155, 157, 158, 177, 183, 195, 199–201, 210, 213, 222, 223, 232, 239] |
| Whether the system allows for microgrid configuration | [221, 232] |

Table 5: Continued.

| Study area | Related references |
|---|---|
| Tap operation: VRs or OLTC | [59, 74–76, 78, 81, 84, 86–88, 94, 96, 99, 100, 107, 109, 110, 122, 123, 128, 129, 153, 155, 168, 171, 174, 176, 183, 187, 188, 200, 213, 214, 230, 235] |
| Effect of system strength (R/X ratio) | [155, 177, 234] |
| Impact of PV on voltage swell/sag | [145, 169, 170, 194, 211] |
| Effects of cloud movements, cloud pattern, or shading | [19, 27, 59, 61, 64, 67, 75, 86, 96, 99, 100, 107, 109, 131, 146, 160, 178, 215, 218, 224, 240, 242, 243, 258] |

instance, in the case of LDC, the goal is to compensate for the expected voltage drop between the bus where the VR is installed and another bus of interest. A PV that is installed midway between the VR and the bus of interest will interfere with VR operations. However, the pattern of interference would be different if this PV is installed closer to the VR's location.

Similar to VRs, OLTC can be equipped with LDC control, although with a different time delay [261]. Therefore, PVs exhibit similar impact on the tap operation of OLTC. At high penetration levels of PVs, the voltage at PCC may rise, prompting the OLTC to lower the voltage on the feeder. The shortcoming of this scenario is that voltage control of the feeder becomes mainly dependent on PV power. So if a group of PVs disconnect or reduce power injection due to cloudy conditions, this could lead to voltage sag that, under extreme scenarios, could result in false tripping of protective relays [261].

*3.4. Impacts on the Upstream Grid.* At high penetration levels, the impacts of PVs could encroach further upstream of the main distribution transformer, mainly due to reverse power flow. Some researchers have explored this scenario [12, 109, 128, 135, 145, 216–219, 221], and most have reached a consensus that reverse power flow starts happening once penetration level exceeds approximately 30% (based on the definition of the ratio of total PV power to the total conventional generation power). This is when cosimulation of distribution and transmission networks may be beneficial and/or necessary.

It has also been reported in the literature that high level of PV penetration can make the electric grid more prone to instability. This is mainly due to two reasons: first, replacement of traditional rotary generation units with PV will reduce the system's inertia and second, possible widespread disconnection (or reduction in power) of PVs as a result of shading could lead to a sudden and significant imbalance between load and generation [145, 216, 217, 219, 221]. Although these conclusions are common among most researchers, some have found no probable impact on the transmission grid caused by PVs installed at the distribution level, for instance [109]. It is fair to assume that the severity of the above issues would be case dependent.

High PV penetration can also negatively affect the performance of synchronous generators. Simulations in [145] showed that when PV penetration reaches certain levels, phase angle difference between some buses will become larger more frequently, which could make it harder to maintain synchronization. Also, at high penetration levels, synchronous generators may need to operate at a lower power factor since their active power may have been partially replaced by that of the PVs. This degrades the generator's performance and may lead to overheating. Furthermore, in extreme situations with significant reactive power flow reversal, synchronous generators may be forced to operate in an underexcited mode which could lead to excessive heating of the stator end core as well as reduction in the margin of steady state stability.

Simulation studies in [145, 216] showed that on days with high wind and high cloud conditions, fluctuations in voltage magnitude can become more frequent since PV output power is weather-dependent. The obvious impact of rooftop PVs on voltage rise at the transmission level is recognized by many researchers; however, some have argued that voltage rise at the distribution level must still receive higher priority [135].

*3.5. Fast Changes in Power.* The amount of active power injected by the PV is determined by the solar irradiance at the ground level. While extraterrestrial solar irradiance is deterministic, cloud coverage and wind conditions can make it stochastic and highly variable at the ground level. Once PV penetration level exceeds a certain threshold, power fluctuations can become problematic. This is because fluctuations in power injected by the PVs will likely surpass normal load variations [67, 146, 188] and also voltage profile at the PCC will start following the irradiance profile [224, 226]. Ambient temperature adds an additional layer of complication because it has an impact on the power produced by the PVs [240]. These are particularly problematic if the PVs operate based on MPPT. Although power fluctuations manifest themselves in the voltage profile, no association has been found between them and voltage flicker [229].

The research in [11, 86] showed that the intensity of power fluctuations and spatial dispersion of PVs across the grid are inversely proportional, i.e., less severe fluctuations tend to correlate with larger dispersion of PVs. A similar correlation was observed in [243] between power fluctuations and the geographical service area of the distribution grid.

The authors in [240] observed that power fluctuations become less intense when the sky conditions show transition from sunny to cloudy. The opposite is true when the sky shows transitions from cloudy to sunny conditions. The authors have explained this phenomenon by associating it with ambient temperature, i.e., as the sky shows transitions from sunny to cloudy, both solar irradiance and temperature decrease. A decrease in irradiance decreases the output power of PVs, but temperature drop has an inverse effect. As a result, less intense fluctuations in PV powers occur.

In [72, 73, 224], the authors claim that reconfiguration of the distribution grid is the best approach to resolve voltage fluctuations compared to other approaches such as installing SVC or capacitor banks.

*3.6. Role of Rated Voltage.* Some researchers have investigated the effects of PVs for different rated voltage levels [66, 69, 92, 148, 159, 227]. The authors of [66] found that increasing the rated voltage of the grid reduces its sensitivity to the power factor of PVs. This means that PV participation in voltage regulation is more effective in a lower voltage grid than a medium voltage one. On the contrary, if PVs do not participate in reactive power support, the hosting capacity of medium voltage grid to PV would be higher than the low voltage one. Interestingly, the authors of [159] found that the cost of operation with PVs can be significantly reduced by simply decreasing the rated voltage from 240 V to 230 V.

*3.7. Hosting Capacity.* A few review papers have tried to summarize the maximum permissible PV penetration levels reported in the literature [27, 28, 30, 31]. However, deriving a general rule of thumb may not be practical. In fact, there is a consensus among publications that maximum penetration level of PVs in a feeder would be case dependent. This is in part due to varying characteristics among different feeders, for instance, the loading level, spatial distribution of PVs, lengths of the feeders and the laterals, sizes of the conductors, the control schemes adopted, and the voltage levels. Another aspect is that the limiting factor could vary from one circuit to another, e.g., maximum penetration level limited by voltage drop, line ampacity, or harmonics.

Most of the publications that have investigated the impacts of PVs on the distribution grid did so at different penetration levels. Some papers studied the impacts at penetration levels less than 100% while others considered levels as high as 300%. Table 5 lists the maximum penetration levels that have been used in the literature to investigate the impacts of PVs. It should be noted that this number represents the maximum penetration used for simulations and not a recommendation level. For the latter, the interested reader is referred to [27, 28, 30, 31].

*3.8. Power Flow through the Lines.* When PVs operate under a unity power factor, the active power flowing through the lines would be correlated with the PV penetration level. As PV penetration increases, active power flow decreases initially until PV power becomes close to the load level, after which an increase in PV penetration would increase the power flow in the lines again. Once PVs start to participate in reactive power support, they tend to inject or absorb reactive power to combat undervoltage or overvoltage conditions. This would change the flow of power through the lines, but the direction of change would be case dependent. It should be noted that PV penetration level is not the only factor that determines power flow in the feeders. Other important factors include solar irradiance, ambient temperature, conductor size, and load profile [224].

*3.9. Short Circuit Fault.* Most of the publications that study short circuit analysis focus on fault analysis of PVs at the medium-voltage level. There are few publications that have studied short circuit analysis specifically for rooftop PVs. Generally speaking, it has been observed that PV penetration increases fault voltage but decreases fault current at the main transformer [262, 263]. This is expected since the smart inverter of the PV limits the fault current contribution of the device. In addition, no publications were found that address the fault-right-through capabilities of rooftop PVs.

*3.10. Miscellaneous Effects.* Distribution grids are traditionally designed using radial configuration. The authors in [157, 158] investigated the potential impact of PVs if the grid is configured in a mesh topology. They concluded that the impact of PVs online losses is mainly driven by the penetration level and is less sensitive to grid topology.

Reverse power flow is one of the consequences of high PV penetration. However, the authors of [84] investigated this phenomenon from a different angle, i.e., if there is a reverse flow in active power but not in the reactive power which they referred to as counter power flow. They found no evidence to the impact of counter power flow on the grid.

Conservation voltage reduction (CVR) is a technique that enables utilities to save energy by lowering the voltages at the end of feeders, especially when the majority of loads are of the constant-impedance type. Traditionally, this has been done using VRs and SCs; however, the authors of [214] argued that with a proper control scheme, PVs can be utilized efficiently to achieve CVR.

The researchers of [83, 264] investigated how different ways of modeling loads would change the conclusions about the impact of PVs on the grid. They observed that modeling the loads as constant power, constant impedance, or a mixture of the two would result in different values for power losses (less than 10% difference). However, they concluded that the way loads are modeled does not have a noticeable impact on the maximum permissible PV penetration level or the voltage profile.

Maximum PV penetration level and voltage profile have been found to be dependent on the geometry of the three-phase lines and the relative distances between phases [71–73]. Of course, the lengths of feeders and laterals and any possible load imbalance need to be taken into account as well, especially for analyzing voltage profile under high PV penetration.

Finally, the authors of [61, 62, 231] argued that PV can help with load shaving. However, unlike commercial customers, the peak load of residential customers does not coincide with the peak hours of PV power.

## 4. Mitigating the PV Effects Using Interfacing Inverters

There are many mitigation techniques to counteract the negative effects of PVs (see Table 1). In this paper, we only focus on countermeasures that can be accomplished using the PV's interfacing inverter. Generally speaking, this inverter can curtail the active power of the PV and/or regulate its reactive power flow. Publications that have studied the capabilities of PV inverters are listed in Table 5. The following sections provide a high-level discussion.

*4.1. Reactive Power Control.* The PV inverter can regulate the phase shift of its output AC voltage with respect to the current and thereby control the reactive power injected or absorbed [265]. During instances of overvoltage, a PV can absorb reactive power from the grid in order to lower the voltage level. However, during undervoltage conditions, when PVs inject more reactive power in order to increase node voltages, a rise in the reactive component of the current could lead to higher losses. Some have also cited high power fluctuations, especially at high PV penetration levels, which could lead to rapid changes in voltage level. However, simulation studies in [123, 129] showed that this problem can be resolved by allowing PVs to participate in reactive power support.

*4.2. Effectiveness of PVs Relative to VRs and SCs.* The effectiveness of PVs in regulating voltage has been compared with other voltage controlling devices in [76, 192, 195, 231]. In [231], it was shown that PVs outperformed VRs and SCs in voltage regulation. In [76], simulation results showed that when PV penetration level exceeds 30%, it can effectively replace voltage regulating equipment without sacrificing the network performance. This conclusion was also confirmed in [195]. Optimization analysis in [266, 267] has reached the same conclusion although without citing a particular PV penetration level.

*4.3. Active Power Curtailment.* One way to eliminate the negative impacts of PVs is to curtail its active power when it becomes problematic. In [162], simulation results showed that PV active power curtailment can mitigate power imbalance (that is caused by PVs) and improve voltage profile; however, this solution comes at the expense of higher line losses. On the contrary, in [161], it was found that PV contribution to reactive power support is a more effective way to correct imbalance in the distribution system than active power curtailment. However, the authors emphasized that the effectiveness of this solution is dependent on other aspects such as penetration, irradiance, and cloud coverage.

Hosting capacity of the grid to PVs can be increased if active power curtailment is utilized [167]. It was shown in [171] that the reactive power margin by PVs increases if active power is curtailed which would be a useful mitigation source. This reactive power can be utilized to minimize tap operation instances of VRs or to resolve voltage quality issues such as voltage imbalance [172], voltage sag [170], or voltage fluctuations [172]. However, active power curtailment is in general not recommended because it causes significant energy losses [173, 202] and is unfair to PV owners [180].

## 5. Future Research and Remaining Challenges

Although research related to the possible impacts of PVs on the distribution grid has seemingly matured, there are still areas that require further exploration. One area of research pertains to control algorithms adopted for distribution systems with high PV penetration levels. Various centralized and decentralized approaches have been studied in the literature, but few succeed in considering all relevant aspects of PV control. For instance, in addition to the operational aspects (losses, voltage profile, etc.), it is necessary to consider asset management both for PV panels as well as other electrical components involved in voltage regulation. This would be an important feature for enabling the sustainable power grid of the future. Another area which is not adequately explored in the literature is simultaneous analysis of both transmission and distribution systems. In particular at high PV penetration levels, it may not be possible to decouple the two since the dynamics of the distribution grid cannot be masked from the higher voltage network anymore.

Studying the behavior of the distribution grid in the presence of high PV penetration would certainly be an important problem to take into account. However, it is equally important to consider situations where high PV penetration coincides with high penetration of other small-scale energy resources such as low-power wind turbines, community energy storage systems, and/or electric vehicles.

Yet another important aspect is to develop communication networks and models that can effectively handle high-penetration PV generation at high spatial and temporal granularity. As PVs start contributing more to reactive power support, this becomes more important. Different wireline and wireless technologies need to be investigated in order to identify which ones can offer acceptable levels of quality of service for the type of control objective intended.

PVs have mostly been viewed as devices that can affect the grid operation during longer time frames (minutely to hourly), which can be considered as quasi-steady state. However, at larger scales, PVs may also be able to participate in frequency regulation by providing different types of ancillary services. This needs to be analyzed, in particular in conjunction with expected subminute profile for demand and solar irradiance.

Finally, a multidisciplinary research approach is needed to combine accurate weather models with PV generation and the power grid operation. Current studies try to model cloud movement in the sky as a random variable, especially in probabilistic approaches. However, using a model-based weather data could improve the solar energy model and the accuracy of large scale power system studies. Such a model has not been applied in any of the applications studied in this paper. Both academic and industrial sectors will benefit immensely from such studies.

## 6. Conclusions

Changes in the global climate, population increase, and a rise in the energy consumption per capita are placing more stress on the modern distribution grids. The need for finding alternative and clean energy resources has pushed electric utilities to incorporate more PV resources into their networks. As the number and sizes of rooftop PVs increase, new challenges will be introduced for which the legacy distribution grid may not be prepared. These primarily stem from the fact that distribution systems have been traditionally designed and operated without considering bidirectional flow of power. This trend started to gradually but slowly change from the 1970s when the industry moved towards having DG units at the distribution level. The changes took a faster pace in the beginning of the 21st century as technological advances and environmental concerns paved the way for deployment of more renewable energy resources, including rooftop PV. The challenges that come with these new technologies are part of the journey towards having a sustainable power grid relying on clean energy. The impact of rooftop PVs on voltage profile, voltage imbalance, power losses, system stability, and operation of voltage control devices has been studied in the literature. This paper provides a survey of the technical challenges associated with high penetration of PVs in the distribution grid and summarizes the most important findings.

It has been shown in the literature that if a PV resource is coordinated with other voltage-regulating devices, and further, if it is allowed to participate in reactive power control, most technical challenges and operational issues can be solved. Hence, there will be no practical limits to how much PV resource the grid can host, which can create a path towards having a sustainable power grid.

## Abbreviations

CGM: Cogeneration mode
CVR: Conservation voltage reduction
DER: Distributed energy resource
DG: Distributed generator
DVR: Dynamic voltage restorer
LDC: Line drop compensator
MPPT: Maximum power point tracking
NBM: Normal bidirectional mode
OLTC: On-load tap changer
PCC: Point of common coupling
PV: Photovoltaic
RBM: Reactive bidirectional mode
RES: Renewable energy resource
SC: Switching capacitor
SCR: Self-consumption rate
SSSC: Static synchronous series capacitor
SVC: Static var compensator
UPFC: Unified power flow controller
UPS: Uninterruptible power supply
VR: Voltage regulator.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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