



## Research Paper

# Increasing photovoltaic hosting capacity in distribution networks in Puerto Rico: Seasonal and technical characteristics analysis and solutions

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## ABSTRACT

The growing dependence on electrical devices has increased the demand for energy security, which has led many users to adopt photovoltaic (PV) systems as a reliable energy source. This trend occurs in regions such as Puerto Rico, where natural disasters like hurricanes and storms often disrupt the power supply. Despite the environmental and energy security benefits, the massive integration of PV systems poses challenges for the electricity sector, such as overvoltages, overloads, and other power quality issues, especially during peak generation periods. This study evaluates the hosting capacity of PV systems (HCPV) in real distribution networks in Puerto Rico, analyzing six feeders with different characteristics in topology, length, load, voltage, and geographical location. Increasing PV penetration scenarios and time variations were simulated by modeling detailed distribution feeders using OpenDSS, and the results were processed in MATLAB. Strategies to increase HCPV, such as using a battery energy storage system (BESS) and the Volt-VAR control function of smart inverters (SI), were also evaluated. The results show that HCPV varies seasonally and that feeders operating at 13.2 kV are less susceptible to voltage violations than those operating at 8.32 kV and 4.16 kV. In addition, the combination of BESS with the Volt-VAR function of the SI was the most effective strategy for increasing the HCPV. In conclusion, the technical characteristics of the feeders and seasonal conditions significantly influence the HCPV, as well as the occurrence of thermal and voltage violations in the power grid.

## 1. Introduction

Electric service users have expressed a growing need for greater energy security in recent years, driven by the increasing reliance on electrical devices in their daily lives. This need for greater energy security has led many users to adopt self-generation sources, such as photovoltaic (PV) systems, which are in constant technological evolution, reaching efficiencies above 21% thanks to improvements in cell design and materials (Amar et al., 2021). In addition to their higher efficiency, these systems offer resilience in the face of power system failures, providing a reliable alternative during supply interruptions (Belding et al., 2020). A clear example of this is seen in Puerto Rico, where natural phenomena like storms and hurricanes regularly affect the electrical infrastructure, leaving many users without power for days. As a result, the adoption of PV systems has experienced rapid growth; the installed capacity of distributed generation increased from 228 MW in 2021 to approximately 945 MW in 2024, and to over 1144 MW in the first quarter of 2025 (Negociado de Energía de Puerto Rico, 2024). This growth confirms that PV systems have become an effective solution to ensure a continuous power supply.

However, although PV systems offer benefits such as reduced carbon emissions and greater energy independence, their massive integration presents significant challenges to the electrical sector. Among the main challenges are power quality issues associated with reverse power flow during periods of excessive generation, such as midday, which can cause overvoltages, network element overloads, and harmonic insertion (Chaudhary and Rizwan, 2018). These phenomena also affect protection systems, requiring adjustments and updates to ensure system stability (Holguin et al., 2020). For example, De Silva et al. (2019) and Suryavanshi and Korachagaon (2019) analyze power quality issues associated with high levels of PV penetration in Sri Lanka and India, respectively. Both studies agree that the main problems are overvoltages, voltage imbalance, and harmonic injection.

Given this situation, it is essential to determine the hosting capacity of PV systems (HCPV) in distribution networks. This helps establish the maximum amount of PV generation that can be integrated without compromising the infrastructure or quality of the supplied power (Zain ul Abideen et al., 2020). In addition, there are different approaches to HC analysis, including deterministic, stochastic, and time-series methods. The deterministic method assumes that the exact location and size

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of the PV systems are known. An example of this method is provided in Navarro and Navarro (2017) and Fan et al. (2017). On the other hand, the stochastic method randomly assigns the locations and sizes of the PV system, considering multiple scenarios, as seen in Torquato et al. (2018). Finally, the time-series method evaluates the HC over a given time period, considering variations in generation and demand; this method is applied in Wang et al. (2018) and Huaman-Rivera and Irizarry-Rivera (2023).

Moreover, the literature describes various strategies to increase HC, such as the use of energy storage systems and advanced smart inverters (SI) functions. Battery energy storage systems (BESS), both distributed and centralized, help mitigate reverse power flow caused by excess generation, improving system behavior. For example, Wang et al. (2021) and Giacomini et al. (2022) show a significant increase in hosting capacity (HC) when using distributed BESS. Regarding SI, functions like Volt-Watt and Volt-Var play a crucial role. The Volt-Watt function regulates the active power injected to prevent overvoltages at the point of common coupling (PCC), while Volt-Var manages reactive power to maintain voltage levels within required levels. In Huaman-Rivera et al. (2023) and Wanzeler et al. (2018), these combined functions are shown to significantly improve HC.

Despite the significant progress reported in the literature on HCPV studies, most research is based on test or hypothetical distribution feeders, which do not adequately reflect the complexities and operational constraints of real networks. In addition, few studies incorporate the impact of seasonal variability in solar generation, an important factor in tropical regions such as Puerto Rico. Although strategies such as BESS and SI functions have been widely studied, their combined impact on real feeders with diverse characteristics remains largely unexplored. In the specific case of Puerto Rico, the current interconnection policy limits PV penetration to 15% of the feeder's peak load, requiring customers to cover additional technical studies to exceed that threshold (Autoridad de Energía Eléctrica de Puerto Rico, 2008). This conservative limit could be unnecessarily restricting the integration of distributed generation. In this context, this work aims to fill these gaps through a detailed analysis of six real feeders with different operational characteristics, using the OpenDSS distribution network simulation tool, connected to MATLAB for result processing.

The article is organized as follows: Section 2 presents the background and key concepts related to HC analysis, evaluation methods, and limiting factors. Section 3 describes the methodology used. Section 4 presents the results and discussion. Finally, Section 5 provides the conclusions of the study.

## 2. Background

### 2.1. Photovoltaic system hosting capacity

The term HC was previously used in other contexts, such as the capacity of the web server or refugee resettlement, before being adopted in the electrical power sector to refer to the adoption of distributed energy resources (DER) (Umoh et al., 2023). HC was first introduced by André Even in March 2004 during the discussion of the European project EU-DEEP to analyze the effects of the high integration of DER in distribution networks (Bendík et al., 2022). Since then, the concept has been widely adopted by network operators, regulators, and researchers in the field of electrical engineering.

HC is commonly defined as the maximum amount of DER that can be integrated into a distribution network without violating performance limits while keeping the system's operation within an acceptable range, without the need for modifications to the existing infrastructure (Zain ul Abideen et al., 2020). This concept is illustrated in Fig. 1. Similarly, the term PVHC refers to the maximum PV penetration limit that a distribution network can support without compromising its operational

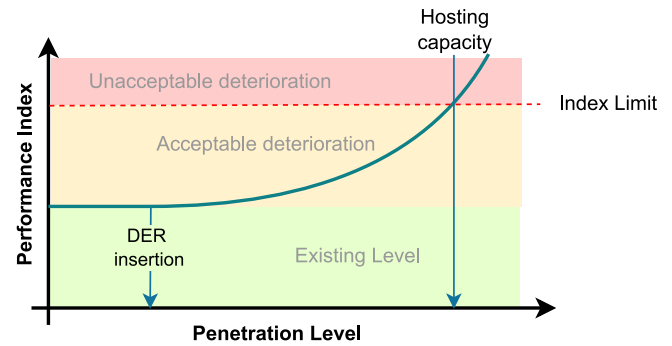


Fig. 1. Concept of hosting capacity.

stability (Umoh et al., 2023). The PV penetration level is expressed in Eq. (1).

$$PV_{Penetration} = \frac{PV_{power}}{S_{max}} \times 100 \quad (1)$$

where  $PV_{Penetration}$  is the PV penetration level,  $PV_{power}$  is the sum of the nominal capacity of the PV systems, and  $S_{max}$  is the maximum load of the feeder. The identification of the PV penetration limit is based on various indicators or limiting factors, such as voltage rise, thermal overload in conductors and transformers, phase imbalance, and system protection issues (Hamdan et al., 2023). However, evaluating PVHC in a network is a complex challenge, as it depends on several technical factors. These include the power of the installed PV systems and the type of system (whether centralized or distributed). On the other hand, specific network characteristics also influence the evaluation, such as whether it is a 3-wire or 4-wire system, and whether the feeder is residential, urban, or commercial. Additionally, line impedances, feeder lengths, and whether the lines are overhead or underground play a crucial role. The capacity of transformers and lines is also a significant factor in determining the PV penetration limit (Bendík et al., 2022).

### 2.2. Methodologies PVHC analysis

The choice of methodology for calculating PVHC is closely related to data availability, result resolution, and the specific objectives of the study (Qamar et al., 2023; Islam and Hossain, 2023). In the literature, various methods exist, along with others still under development, but three main methods have been identified: deterministic, stochastic, and time-series. Each of these methods presents different characteristics, as shown in Table 1.

A common characteristic among all methods is the use of power flow analysis to determine voltage and current values in distribution networks (Zain ul Abideen et al., 2020). Although the methods vary significantly in their implementation, they all follow a similar general process for HC calculation, as detailed in Fig. 2. This figure illustrates three methodologies used for PVHC analysis: the deterministic method, the stochastic method, and the time-series method. Each approach follows a series of specific steps to assess the impact of PV penetration on a power grid, considering different levels of uncertainty and variability in the data. The following subsections address the mentioned methods.

#### 2.2.1. Deterministic method

The deterministic method is a basic approach for evaluating HC in distribution networks, starting with data collection and network modeling, followed by load flow simulation (Umoh et al., 2023). It does not consider uncertainties in PV production or user consumption, assuming these parameters are fixed (Mulenga et al., 2020). The size of PV units is increased until a violation of network limits, such as overvoltage or overload, is reached. However, this method

**Table 1**  
Comparison of the most commonly used HC analysis methods.

Characteristics	Methods		
	Deterministic	Stochastic	Time-series
Data requirement	A few	Medium	High
Complexity	Simple	Complex	Complex
Computational time	Low	High	High
Scenario requirement	Worst case	Realistic scenario	Realistic scenario
Output accuracy	Approximate	Depends on uncertainties, mostly accurate	Depends on the scenario chosen, mostly accurate

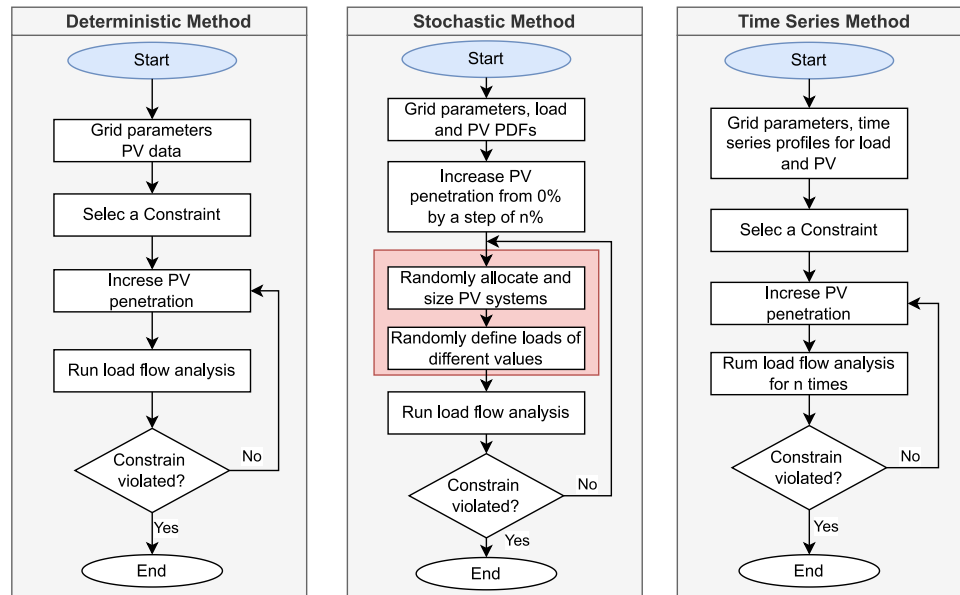


Fig. 2. Methodologies PVHC analysis.

does not adequately address computational complexity or the inherent uncertainties of larger systems, especially concerning the X/R ratio in low-voltage networks (Hamdan et al., 2023). While deterministic approaches are simple, they have limitations as they do not account for dynamic variations in demand and generation (Umoh et al., 2023).

### 2.2.2. Stochastic method

The stochastic method considers uncertainty and unknown variables in PV system implementation, such as generation, location, and size. Sometimes, load consumption behavior is also treated as an unknown variable (Umoh et al., 2023). This method starts with a model of the existing distribution system, where PV systems of various sizes are added at randomly selected locations, considering the probability of occurrence based on probability distribution functions (PDFs). This random allocation is then evaluated to identify potential adverse effects on the feeder. The results provide a range of HC values (Stanfield et al., 2017). Several approaches exist for generating random scenarios, with Monte Carlo simulation being the most commonly used. Since DER integration involves numerous unknown variables, using stochastic techniques that allow some variables to vary while keeping others constant proves to be an effective strategy (Zain ul Abideen et al., 2020).

### 2.2.3. Time-series method

The time-series method is a technique used to evaluate HC in distribution networks, allowing the capture of daily voltage and power fluctuations using real data (Zain ul Abideen et al., 2020). Although it follows a process similar to the deterministic method, this approach uses actual measurements of loads and PV generation. The data can be historical time-series profiles, either real or synthetic, adjusted

to the time scale of the analysis (Umoh et al., 2023). This method offers greater accuracy than the stochastic approach, especially when evaluating devices that adjust their parameters, such as automatic regulators (Qamar et al., 2023). However, despite more accurately representing the dynamics of DER, its implementation can be time-consuming and require significant data processing (Islam and Hossain, 2023).

### 2.3. Limiting factor HC

The increase in PV systems can lead to violations of the operational criteria of the distribution network. The main violations of operational standards, also known as limiting factors for HC calculation, are thermal and voltage violations (Smith, 2013). A summary of the main limiting factors for HC studies is presented in Table 2.

#### 2.3.1. Voltage violations

The HC of a feeder is primarily limited by voltage violations. Overvoltages typically occur when reverse power flow happens due to excessive PV generation, while undervoltages can arise from increased demand, such as during electric vehicle (EV) charging (Bendik et al., 2022). Various standards regulate voltage limits in distribution networks, with ANSI C84.1 being one of the most widely used. This standard establishes that voltage levels should remain within the range of 0.95 p.u. to 1.05 p.u. to avoid overvoltage and undervoltage violations (Fatima et al., 2020). Additionally, voltage imbalance is another relevant issue, occurring when the voltages of the three phases in a three-phase system are not equal. According to ANSI standards, voltage imbalance should not exceed 3% of the average phase voltage (Ahmadian et al., 2020).

**Table 2**  
Monitoring criteria and flags for distribution PV analysis.  
Source: Smith (2013).

Category	Criteria	Basis	Flag
Voltage	Overvoltage	Feeder voltage	1.05 Vpu
	Voltage deviation	Deviation in voltage from no PV to full PV	3% at primary 5% at secondary $\frac{1}{2}$ band at regulators
	Unbalance	Phase voltage deviation from average	3% of phase voltage
Loading	Thermal	Element loading	100% normal rating
Protection	Element fault	Deviation in fault current at each sectionalizing device	10% increase
	Sympathetic breaker tripping	Breaker zero sequence current due to an upstream fault	150 A
	Breaker reduction of reach	Deviation in breaker fault current for feeder faults	10% decrease
	Breaker/Fuse coordination	Fault current increase at fuse relative to change in breaker fault current	100 A increase
Harmonics	Individual harmonics	Harmonic magnitude	3%
	THDv	Total harmonic voltage distortion	5%

### 2.3.2. Thermal violations

Excess energy generated by DER devices during periods of low consumption and high generation flows through transformers and distribution lines back to power plants. Transformers and lines have a rated current capacity, and exceeding this limit leads to overheating of these components, resulting in various operational failures (Zain ul Abideen et al., 2020).

### 2.3.3. Protection

Protection devices (PD) installed in distribution networks operate directionally. This means that PDs are designed to disconnect a section of the network when a certain amount of energy flows in the reverse direction (Zain ul Abideen et al., 2020). The reverse power flow resulting from DER integration can cause incorrect or unnecessary operation of PDs, leading to system outages (Holguin et al., 2020).

It has been demonstrated that PV generation can affect the fault current detected by PDs, potentially impacting the protection zone of a PD as well as the time-dependent coordination between PDs. The scope of protection analysis is limited to steady-state analysis of distribution networks under fault conditions, excluding issues that require dynamic or time-domain simulation of PV systems in the distribution network. The four possible protection violations caused by steady-state PV fault current injection are: protection underreach, loss of coordination between PDs, nuisance tripping, and sympathetic tripping (Reno et al., 2017).

### 2.3.4. Harmonics

Distortion in the normal voltage or current waveform is defined as harmonics, primarily caused by non-linear loads, whose use has significantly increased at various points in the electrical system (Qamar et al., 2023). New energy generation methods, changes in consumer energy use behavior, and the incorporation of power electronics into the system have led to issues such as supraharmonics, low-frequency subharmonics, and interharmonics. Harmonics must be kept within the limits established by the IEEE 519 standard (Sahu et al., 2024). Literature indicates that harmonics significantly limit HC. In Essackjee and King (2019), it was observed that the increase in small residential PV systems raises harmonic pollution levels, resulting in losses within the network.

## 2.4. Methodologies increase HC

### 2.4.1. Battery energy storage systems (BESS)

BESS consists of a battery bank with specific arrays designed to supply current and voltage as needed. To maximize the use of energy

generated by PV systems, energy storage is utilized to supply power during periods when PV generation is insufficient to meet the load demand (Fatima et al. (2020)). BESS can be centralized — located at substations or distribution transformers — or distributed, primarily installed in residential homes with PV systems.

The amount of energy available in a battery bank is commonly referred to as the state of charge (SOC) and can be calculated using Eq. (2) (Astero and Söder, 2017).

$$SOC(t+1) = \begin{cases} SOC(t) + \eta P_b(t) & \text{Charging} \\ SOC(t) - P_b(t)/\eta & \text{Discharging} \end{cases} \quad (2)$$

where,  $\eta$  is the charging and discharging efficiency of the battery, typically between 95% and 99%.  $P_b(t)$  is the active output power of the battery at time  $t$ . The SOC (State of Charge) is usually limited to 50% in lead-acid batteries and 20% in lithium-ion batteries to extend the battery's lifespan.

In Azibek et al. (2022) and Huaman-Rivera and Irizarry-Rivera (2023), it is highlighted how BESS contributes to increasing the HC by reducing reverse energy flows and storing excess generation in the batteries.

### 2.4.2. Smart inverter

The inverter plays a key role in converting the energy produced by PV systems from direct current (DC) to alternating current (AC). Additionally, SI contributes to increasing the HC through various control mechanisms. Some examples of inverter control include synchronization with the grid, balancing the DC connection voltage, and regulating active/reactive power.

- **Reactive power controller:** Reactive power control is useful for managing the controllable reactive power available in DER. SIs incorporate the Volt-VAR function, which uses the concept of reactive power control. This function establishes a correlation between the reactive output power of an inverter and the voltage at the PCC (Wanzeler et al., 2018). Capacitive reactive power operates under undervoltage conditions, while inductive reactive power works under overvoltage conditions. In IEEE 1547 standards, the maximum limit for reactive power absorption or injection is set at 44% of the inverter's nominal capacity (IEEE, 2020). Fig. 3(a) shows the curve of the Volt-VAR function.
- **Active power controller:** Active power control is the ability to modify and control the active power produced by DER, taking into account factors such as voltage regulation, frequency control, network limitations, or specific control strategies.

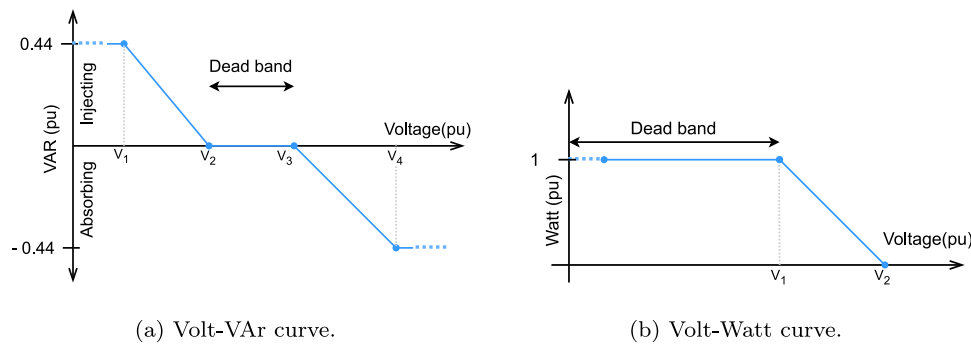


Fig. 3. Smart inverter function.

SI incorporates the Volt-Watt function. This function is used to limit the real output power of each PV system individually to mitigate overvoltages that can occur when traditional voltage regulation systems fail to prevent them (Wanzeler et al., 2018). Fig. 3(b) shows the curve of the Volt-Watt function.

Beyond traditional control functions such as Volt-VAR and Volt-Watt, other advanced inverter-based control strategies are being developed to improve the integration of PV systems. For instance, in Afghoul et al. (2021) implemented fractional-order controllers in shunt active power filters supplied by PV emulators. Their results showed significant improvements in voltage regulation and harmonic compensation, highlighting the potential of robust control techniques to address power quality challenges in high PV penetration scenarios.

### 2.5. Network reconfiguration

Feeder reconfiguration is a technique used to improve voltages, reduce energy losses, and increase the HC of PV generation in distribution systems. This process optimizes the feeder topology by adjusting the locations of PV systems and primary impedances, modifying the state of switches to manage violations of performance limits (Jacob and Zhang, 2020).

Techniques such as Particle Swarm Optimization and genetic algorithms are used to maximize the HC. In Qamar et al. (2023), it is noted that reconfiguration, whether static or dynamic, can improve HC by up to 51.8% by adjusting voltage regulators and capacitor banks.

## 3. Methodology

### 3.1. MATLAB and OpenDSS co-simulation mechanism

The methodology used to evaluate the impact of HCPV and strategies to increase HC is illustrated in the flowchart in Fig. 4. This process for modeling and analysis is divided into two key stages. In the first stage, all actions are carried out in OpenDSS, a software specialized in the modeling of distribution networks and power flow analysis. OpenDSS features a COM Server interface, which allows interaction with MATLAB. During this first stage, the distribution feeder is simulated, incorporating its technical characteristics and generating files that represent different PV penetration scenarios. To increase HC, both BESS and the Volt-VAR control function of the SIs are integrated into the model. In this study, we use these tools as methods to improve the HCPV in the network. In the second stage, the power flow solution is carried out for each hour and PV penetration scenario using MATLAB, which performs the network analysis based on the data obtained from OpenDSS. Voltage and current levels at each node of the system are compared with the previously established constraints, focusing on violations due to overvoltages and thermal limitations. These results allow us to summarize the HC under different operating conditions. The HC analysis over time is performed through a methodology based

on time-series. This technique involves running hourly simulations of the system over a typical day, considering both variations in demand and PV generation. We use meteorological and load data to adjust the PV penetration scenarios, allowing us to identify critical hours in which voltage problems, such as overvoltages, may occur. The simulated PV penetrations range from 10% to 150% of the system's peak demand, with increments of 10% in each scenario. In this way, the model provides a detailed view of the network's behavior, enabling the evaluation of limitations and opportunities to integrate higher levels of distributed generation without compromising the reliability and quality of the supply.

### 3.2. Sizing and arrangement of the elements

#### 3.2.1. PV systems

The layout of PV systems is done simultaneously in all transformers. To do this, Eq. (1) is applied to determine the capacity of the PV array that needs to be installed on the secondary side of the transformer, next to the load, to supply a specific percentage of the load. Fig. 5 illustrates this concept. For example, if we have a transformer with a 20 kVA load and a target penetration of 10% PV systems in the feeder, a 2 kVA PV system will be installed, representing 10% of the transformer load. The same logic is followed for each transformer in the feeder.

In this way, different PV penetration scenarios are generated, ranging from 10% to 150%, with 10% increments, aiming to study and determine the PVHC of the analyzed feeders.

#### 3.2.2. Battery energy storage systems

For the case studies where BESS was considered, these were located in the model alongside each PV system in the feeder for the different PV penetration scenarios. The capacity of the BESS varies according to the level of PV penetration, as they were designed to store 100% of the power generated by the PV systems. Therefore, as PV penetration increases, the size of the BESS will also increase. Although it is common in the design and sizing of storage systems to consider backup energy for critical loads, in this case, it was not possible to apply this criterion due to the lack of detailed information about the loads. Instead, a design focused on ensuring 100% self-consumption of the generated solar energy was chosen.

#### 3.2.3. Smart inverter

The sizing of the SI was carried out following the guidelines of the IEEE 1547 standard, which states that the maximum reactive power delivery, whether by injection or absorption, is limited to 44% of the inverter's nominal capacity (IEEE, 2020). Additionally, a DC-AC ratio of 1.1 was considered, as PV systems do not always generate 100% of the energy for which they were designed. The Volt-VAR operation curve was configured according to Rylander et al. (2016), using the parameters  $[V1, V2, V3, V4] = [0.92, 0.98, 1.02, 1.08]$ , as shown in Fig. 3b. This default configuration, proposed by the Voltage Regulation Subgroup of the IEEE 1547 standard, is designed to be a standard solution adaptable to any scenario.

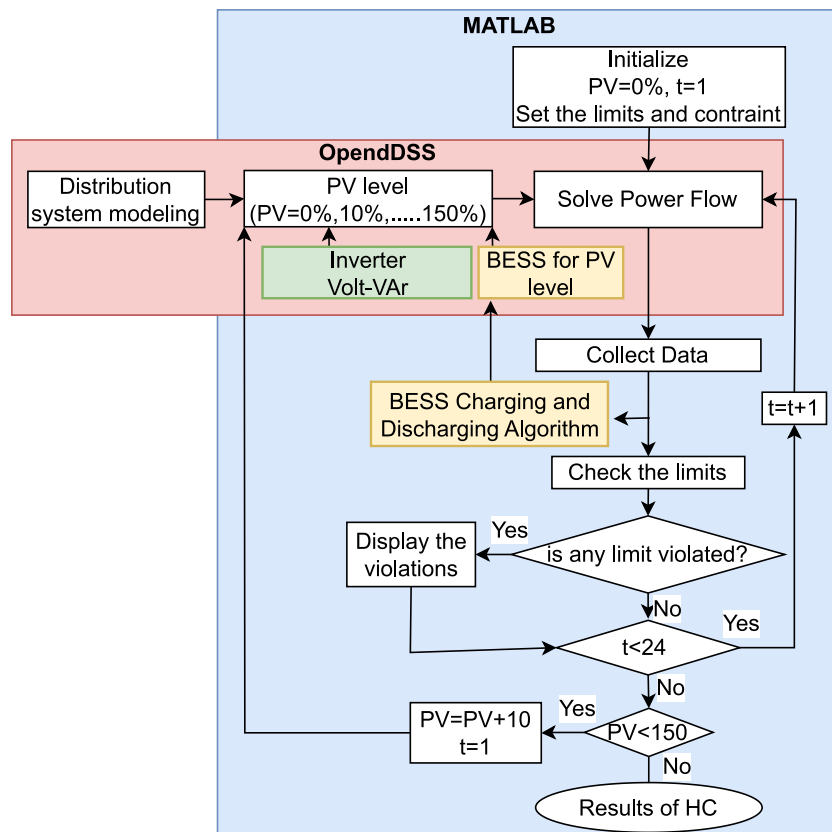


Fig. 4. Algorithm to evaluate the HC of PV systems.

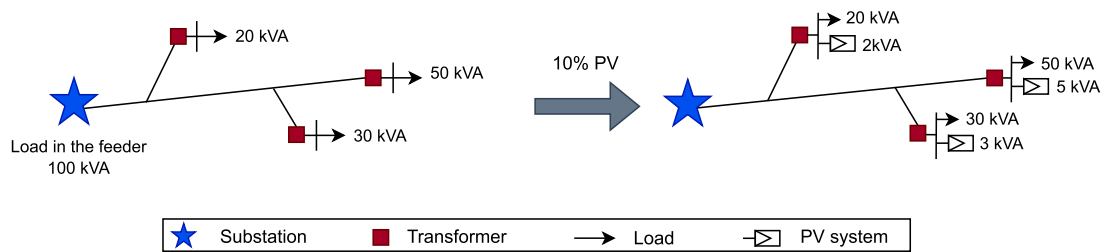


Fig. 5. Layout and sizing of PV systems for different penetration levels.

### 3.3. Feeders to study description

Models were implemented for each of the six feeders under study using the OpenDSS simulation software. The selected feeders have one of three typical distribution voltage levels in Puerto Rico: 4.16 kV, 8.32 kV, and 13.2 kV, which are shown in Fig. 6. In our OpenDSS feeder model, we did not include the service conductors from the distribution transformers to the customer loads; we modeled the distribution transformers with loads directly connected to the secondary transformer side.

Table 3 provides an overview of the characteristics of each feeder. Feeders with significantly different characteristics were selected to obtain a more comprehensive view of how various factors, such as distribution voltage levels, the number of loads, and feeder length, influence the HC analysis results. The classification of the feeders as commercial, residential urban, and rural is based on LLC (2023).

#### 3.3.1. Load profiles

The available information about real electrical loads in the feeders is limited, as no specific database detailing these values was found.

However, an estimation of the power of the loads connected to the distribution transformers was made based on their capacity using (AuthORITY, 2002) as a source. Additionally, the study (LLC, 2023) provides an estimate of the feeder load and demand profiles. From this data, and in order to perform a time-series analysis, several daily demand profiles per unit were defined according to the characteristics of the feeder. These profiles are shown in Fig. 7.

Moreover, according to various sources consulted for modeling the load profiles, such as Alshareef and Morsi (2017) and Jones et al. (2021), it was observed that loads vary significantly depending on the seasons (summer, winter, autumn, and spring), weekdays and weekends, and depending on the type of feeder (commercial, residential). These variations can include demand peaks on specific days or during certain hours, depending on typical consumer behavior.

Due to the lack of sufficient real data on how loads fluctuate throughout the day and the year in the different feeders, various assumptions were made to generate approximate load profiles. It is important to note that these profiles are not exact representations of reality, but approximations based on the expected behavior of the loads. These assumptions were necessary to proceed with the HC studies in

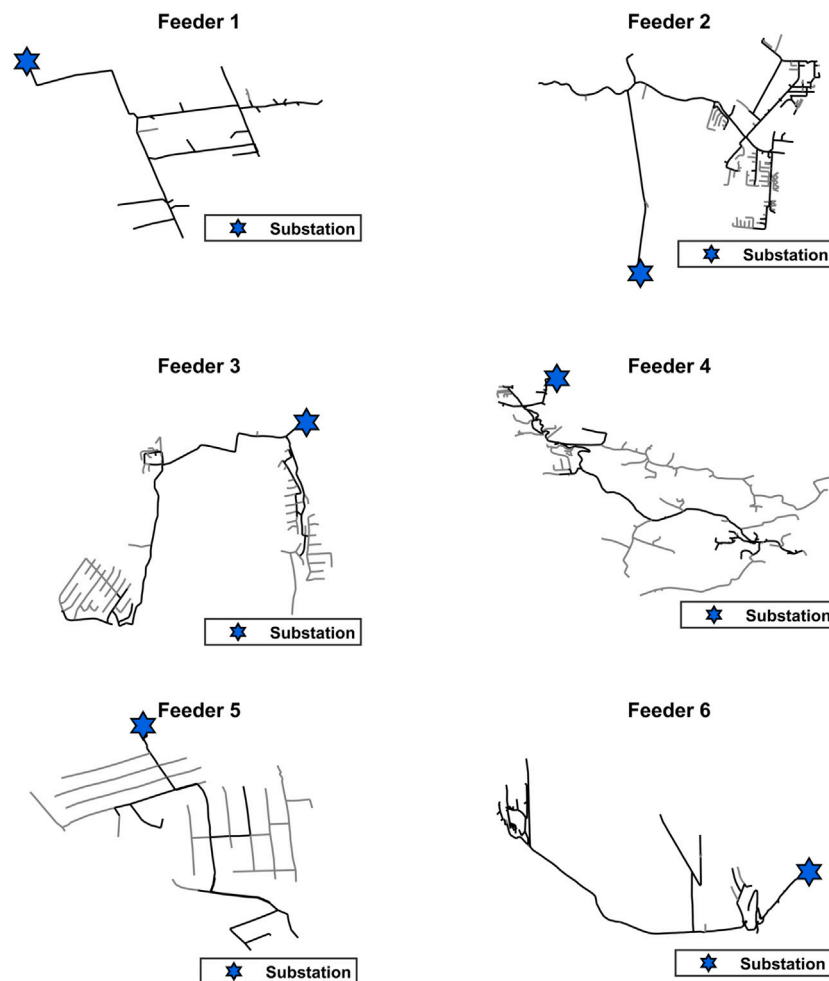


Fig. 6. Topology of distribution feeder.

Table 3  
Feeder details.

Name feeder	Location	Feeder type	Line to line voltage (kV)	Feeder length (miles)	Distribution transformers
Feeder 1	San Juan	Urban, commercial	4.16	2.14	16
Feeder 2	Ponce	Urban, commercial	13.2	19.4	225
Feeder 3	Caguas	Rural, residential	13.2	8.7	150
Feeder 4	Ponce	Rural, residential	8.32	25.6	210
Feeder 5	Bayamon	Urban, residential	4.16	8.7	174
Feeder 6	Arecibo	Urban, residential	13.2	9.8	46

the different feeders and analyze how specific characteristics, such as the voltage level, may influence the HC.

### 3.3.2. Temperature and irradiance profiles

Fig. 8 shows temperature and irradiance profiles for six feeders located in different areas of Puerto Rico. It is observed that during the summer, the values of temperature and irradiance are significantly higher compared to winter. This pattern reflects the typical seasonal influence on climatic conditions, where in the summer there is greater solar exposure and warmer temperatures.

In each feeder, the irradiance peaks occur around noon, coinciding with the time of maximum solar incidence, while the temperature follows a similar pattern, reaching its peak a few hours later due to the cumulative heat effect. However, the differences between the regions may result from local factors such as altitude, proximity to the sea, and specific atmospheric conditions.

## 4. Results

### 4.1. Feeders behavior with 0% PV penetration

The six feeders exhibit characteristic daily demand patterns, with active power peaks occurring around midday for commercial feeders and at night for residential ones, as seen in Fig. 9. Feeder 1, located in a predominantly commercial urban area, stands out due to its high levels of active power, reflecting a more significant load associated with economic activities. In contrast, Feeder 6, which has lower installed capacity and load, demonstrates more moderate demand levels. Rural feeders, such as Feeder 3 and Feeder 4, exhibit more pronounced variations in their profiles, possibly due to dispersed residential usage patterns and lower load density.

In Fig. 10, the voltage profiles of the feeders are shown. It can be observed that the voltage levels decrease as the lines move further from the substation. This behavior is evident in all feeders but is more

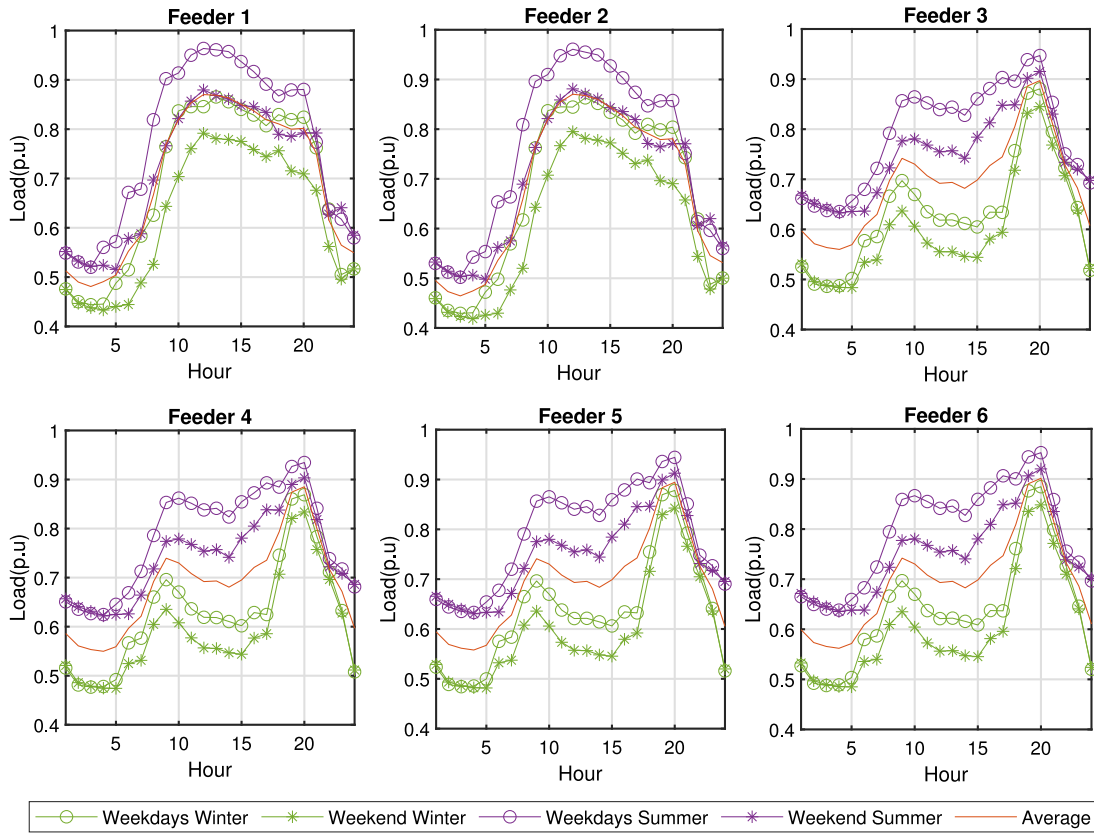


Fig. 7. Per-unit load profiles of distribution feeders.

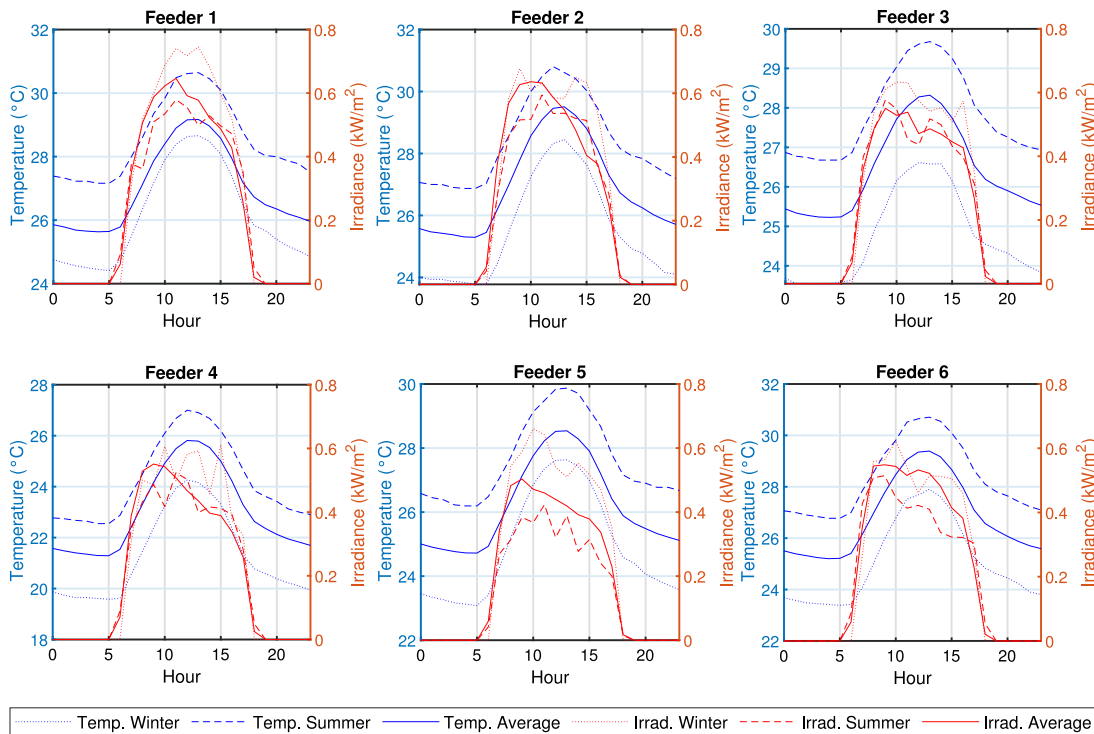


Fig. 8. Temperature and irradiance profiles.

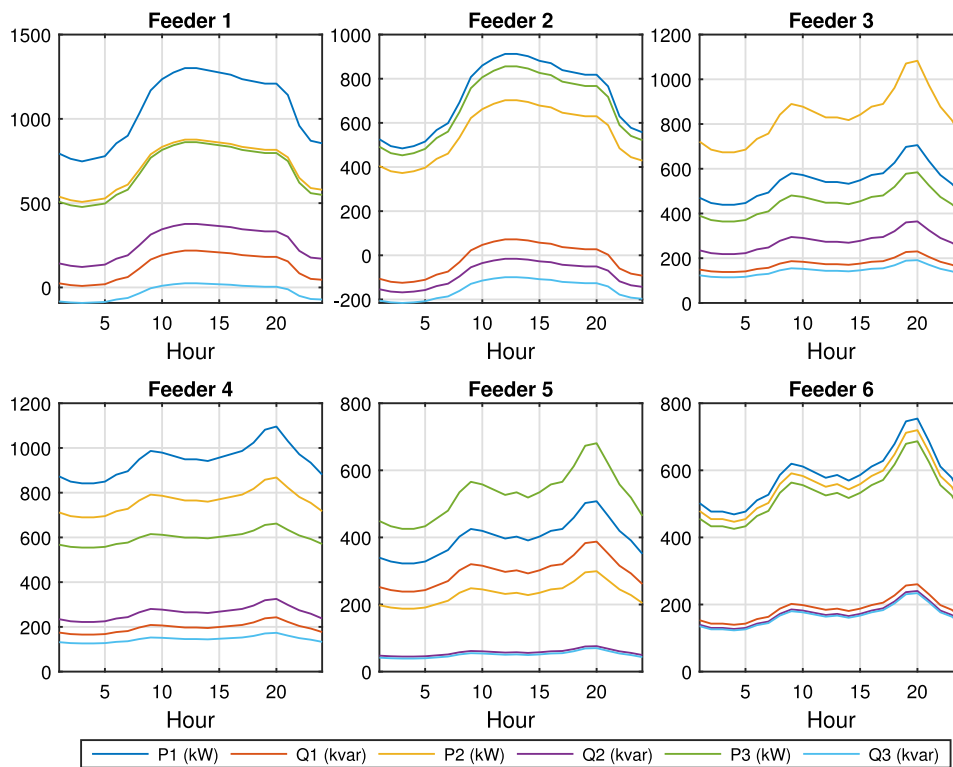


Fig. 9. Power profiles of the feeders.

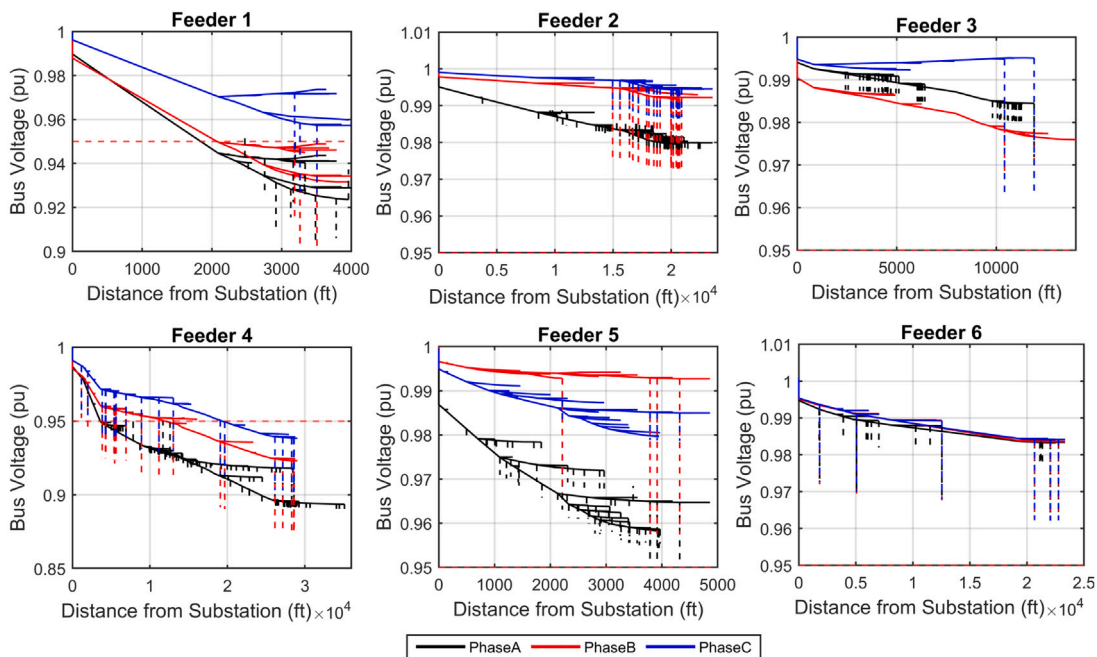


Fig. 10. Voltage profile of the feeders at noon.

pronounced in the longer ones, such as Feeder 4. Due to its rural configuration and 25.6 km length, it is more vulnerable to voltage drop. In contrast, urban feeders, like Feeder 2, show greater dispersion in voltage values between phases, indicating imbalances that could be related to the mix of commercial loads. Furthermore, in some feeders, such as Feeders 1, 4, and 5, the voltage levels in the most distant branches fall below 0.95 Vpu, violating the limits established by the standards.

The current in the feeders also follows a typical pattern, decreasing as the distance from the substation increases, as observed in Fig. 11. In the case of Feeders 1 and 4, the load generates segments where the current approaches the line capacity limits, representing a potential risk of overload in certain line segments. On the other hand, Feeders 6 and 3, with lower load levels and residential clients, show relatively low currents in most of their sections.

In general, commercial urban feeders, such as Feeders 1 and 2, handle significant loads and face challenges related to voltage balance and

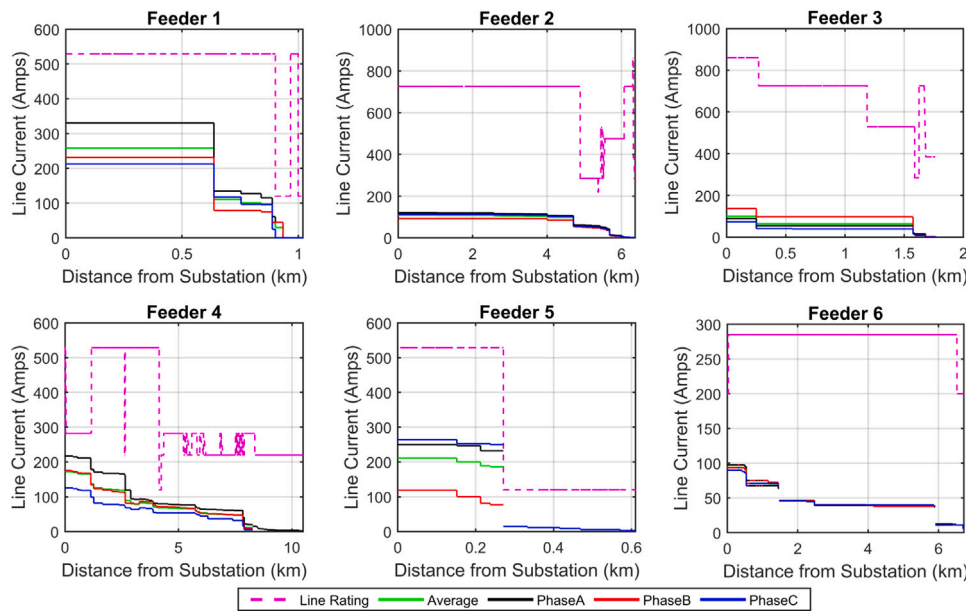


Fig. 11. Current profile of the feeders at noon.

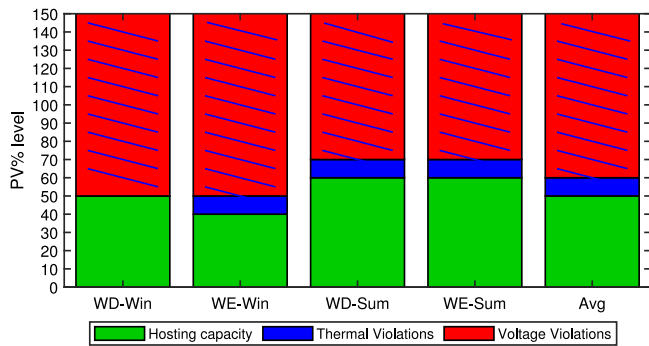


Fig. 12. HCPV Feeder 1 (Urban-commercial, 4.16 kV, 2.14 mi). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

potential local overloads. Rural feeders, such as Feeder 4, experience challenges associated with higher voltage drops due to their lengths and lower load density. Conversely, Feeder 6 shows adequate performance, although its low installed capacity could limit its flexibility in accommodating increases in PV systems.

#### 4.2. Case studies

##### 4.2.1. Analysis of PVHC by season of the year

###### • Feeder 1: Urban-commercial, 4.16 kV, 2.14 mi

Fig. 12 shows the HCPV in Feeder 1, an urban-commercial feeder with specific operational characteristics. The graph illustrates the levels of PV penetration (%) during different seasons of the year: winter weekdays (WD-Win), winter weekends (WE-Win), summer weekdays (WD-Sum), summer weekends (WE-Sum), and the annual average (Avg). The bars are divided into three categories: HC (green zone), voltage violations (red zone), and thermal violations (blue zone), with voltage or thermal violations highlighted by diagonal lines when both occur simultaneously.

The analysis shows that the HCPV levels vary according to the season of the year. In summer, the increase in energy demand due to the use of cooling systems coincides with higher PV generation. However, although PV generation is greater during this period,

the increase in load is even higher, allowing for a greater HCPV as generation balances with local consumption, slightly reducing reverse power flows.

In contrast, during winter, energy demand decreases due to lower electricity use, and PV generation also drops slightly due to lower temperatures and reduced solar irradiance. Nevertheless, the decrease in load is more significant than the reduction in PV generation, which limits the HCPV levels. These conditions increase the likelihood of reverse power flows, leading to a higher frequency of voltage violations and thermal overloads.

However, there is no significant variation in HCPV between weekdays and weekends within the same seasons.

It is important to note that voltage and thermal violations tend to occur simultaneously throughout the year and across different types of days, suggesting a direct relationship between the two for this feeder. For Feeder 1, the average HCPV is estimated at 50% PV penetration, with this limit being reached before significant voltage and thermal violations begin to appear.

Fig. 13 identifies the locations within the feeder where violations occur, whether due to voltage or thermal, and how these violations increase as PV penetration levels increase. At 60% PV penetration, thermal violations begin to appear on the line segments closest to the substation and on transformers located on one of the feeder branches.

As PV penetration reaches levels of 70% or higher, there is a significant increase in thermal violations, affecting more line segments along the feeder. In addition, these violations extend to the transformers, indicating thermal overloads in these devices. At the same time, voltage violations increase considerably, especially at the end of the feeder, where the effects of reverse power flows are more pronounced.

Fig. 14 shows how the voltage levels in the feeder progressively increase with increasing PV penetration. In the figure, each point represents the voltage level at the feeder nodes at different times of the day, while the colors indicate the distance of each node from the substation.

It can be observed that voltage levels peak around midday, coinciding with periods of higher solar irradiance and increased temperatures during the day, following a pattern consistent with PV generation curves. Additionally, voltage violations begin to appear at 70% PV penetration, highlighting the impact of distributed generation on system stability.

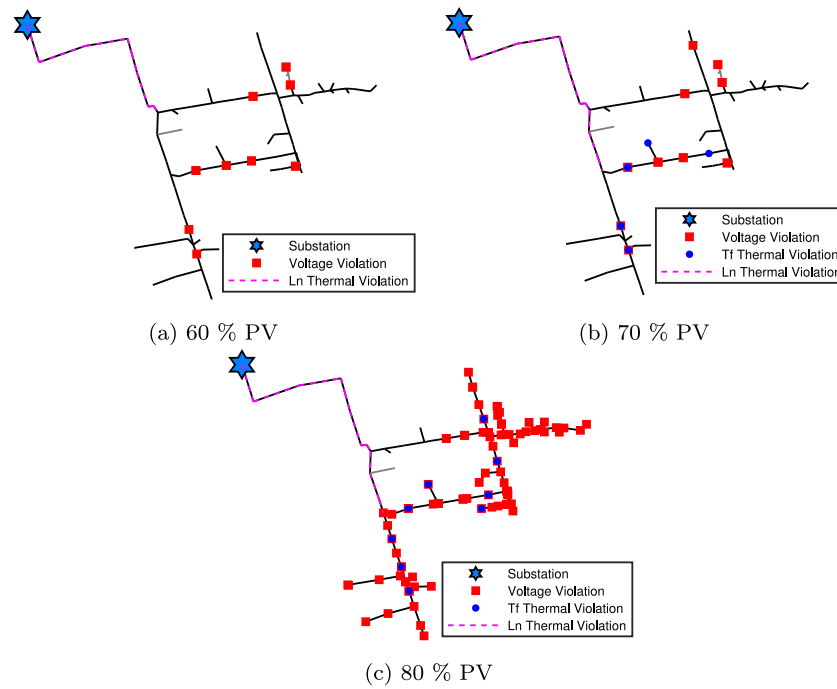


Fig. 13. Network topology of feeder 1, nodes where violations occur.

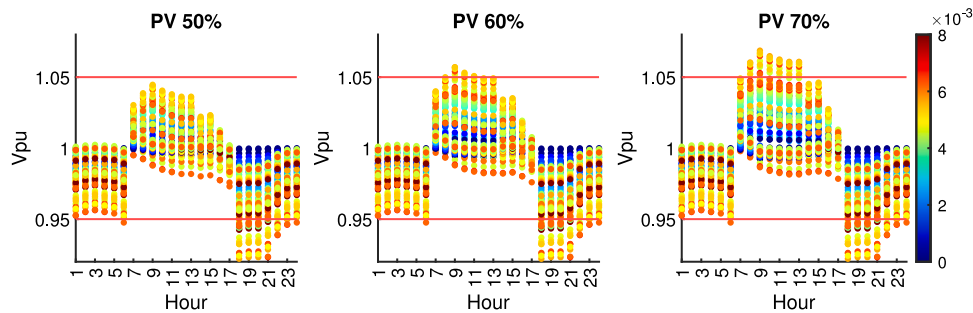


Fig. 14. Voltage profile, Feeder 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

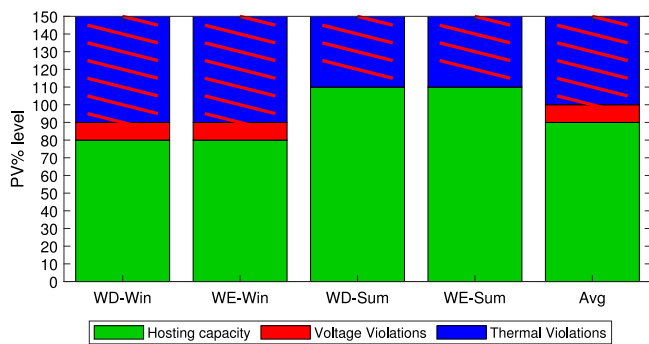


Fig. 15. HCPV Feeder 2 (Urban-commercial, 13.2 kV, 19.4 mi).

Although the topology of this feeder has a semi-square configuration, the results show that voltage violations mainly occur at nodes farthest from the substation. This pattern suggests that the distance from the power source plays a significant role in determining the susceptibility of nodes to the impacts of increased PV generation.

- **Feeder 2: Urban-commercial, 13.2 kV, 19.4 mi**

Fig. 15 shows the results of the HCPV levels analysis in Feeder 2, evaluated across different seasons of the year. A significant difference in HCPV is observed in this feeder depending on the season. This variation can be attributed to the fluctuations in energy demand and PV generation throughout the year. On average, the feeder can accommodate PV penetration levels up to 90%, without thermal or voltage violations. However, significant voltage violations are observed during the winter. These voltage violations occur before thermal ones, suggesting that the main limitation in this feeder is voltage regulation during the winter, when the load decreases, increasing the likelihood of reverse power flows, especially with high PV penetration.

As PV penetration increases, thermal and voltage violations extend across the feeder, moving toward nodes closer to the substation, as detailed in Fig. 16. Thermal violations tend to occur more frequently on main lines, while voltage violations are more common along branches. In longer feeders like Feeder 2, voltage violations are usually more severe, while thermal violations are less frequent due to the lower load density.

The voltage profile of Feeder 2, shown in Fig. 17, illustrates PV penetration levels of 90%, 100%, and 110% during a typical day. As PV penetration increases, the voltage levels progressively rise. For PV penetration levels above 100%, voltage levels exceed the maximum limit of 1.05 Vpu around midday, especially at nodes farthest from the substation.

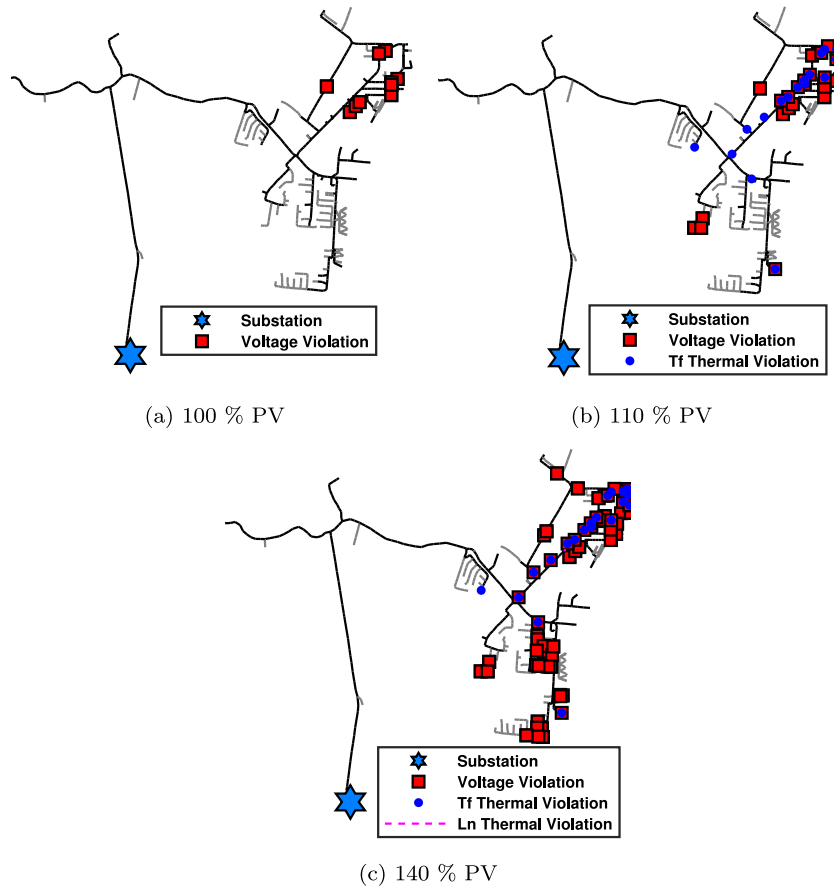


Fig. 16. Network topology feeder 2, nodes where violations occur.

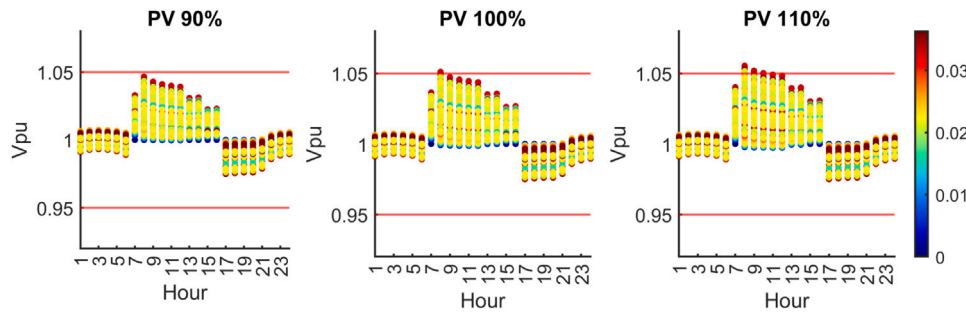


Fig. 17. Voltage profile, Feeder 2.

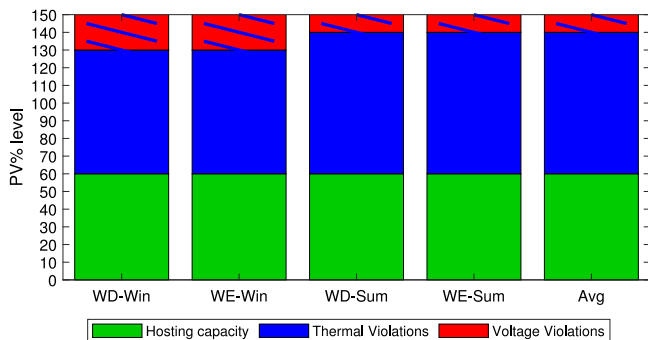


Fig. 18. HCPV Feeder 3 (Rural-residential, 13.2 kV, 8.7 mi).

• **Feeder 3: Rural-residential, 13.2 kV, 8.7 mi**

The results of the HCPV analysis for Feeder 3, evaluated under different temporal conditions, are presented in Fig. 18. In this feeder, there is little variation in HCPV between winter and summer, nor between weekdays and weekends. This can be attributed to the fact that it is a rural residential feeder, where seasonal changes in load are not as pronounced throughout the year, as energy demand remains relatively constant in these types of areas. Furthermore, residential loads in rural areas tend to be more stable, which reduces consumption fluctuations over time.

On average, the feeder can support PV penetration levels of up to 60% without causing thermal or voltage problems. However, as PV penetration exceeds 60%, thermal violations begin to occur in all seasons of the year.

Fig. 19 shows how thermal violations mainly occur in the transformers. Additionally, most of the load is concentrated at the end of the feeder. For a PV penetration of 110%, additional thermal

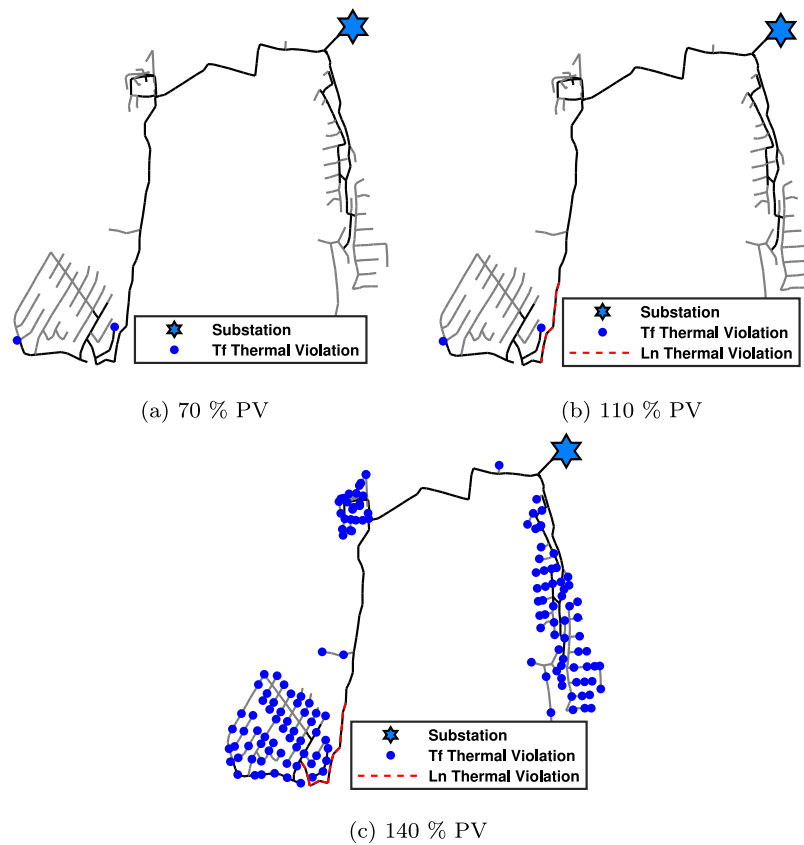


Fig. 19. Network topology of feeder 3, nodes where violations occur.

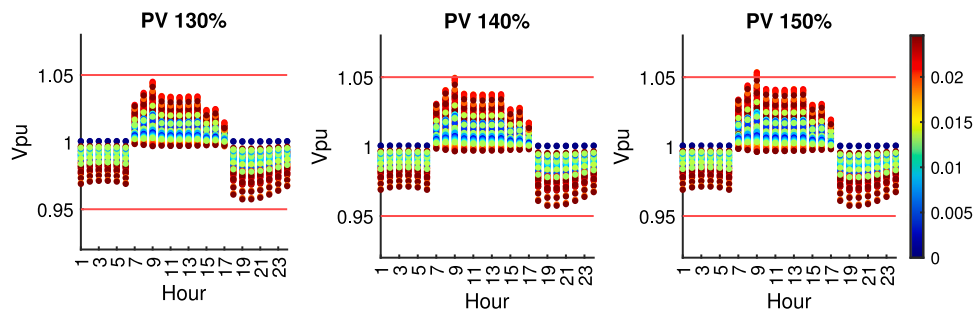


Fig. 20. Voltage profile, Feeder 3.

violations occur along the lines that serve the branches where most of the load is located. The absence of voltage violations is partly due to the feeder’s voltage level, which is 13.2 kV, a level less prone to voltage violations.

Voltage violations occur much later than thermal violations, and these only manifest at high levels of PV penetration, as observed in Fig. 20, where the effects of PV penetration on the feeder’s voltage profile are detailed.

• **Feeder 4: Rural-residential, 8.32 kV, 25.6 mi**

Fig. 21 presents the HCPV results for Feeder 4, evaluated across different seasons of the year. In general, no significant differences are observed on weekdays across different seasons. However, in winter, thermal and voltage violations occur simultaneously at PV penetration levels above 50%. In contrast, during the summer, voltage violations appear first. However, this season, the HCPV is 60%, which could be attributed to the higher load during this

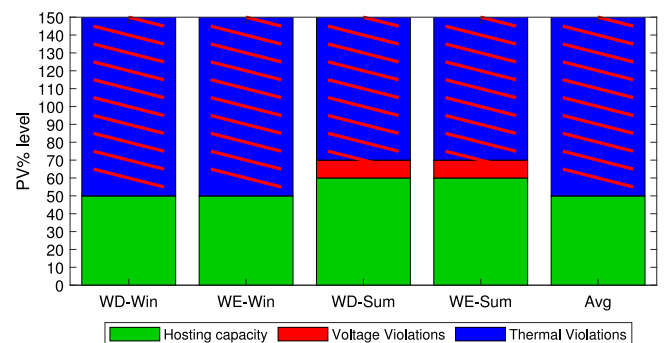


Fig. 21. HCPV Feeder 4 (Rural-residential, 8.32 kV, 25.6 mi).

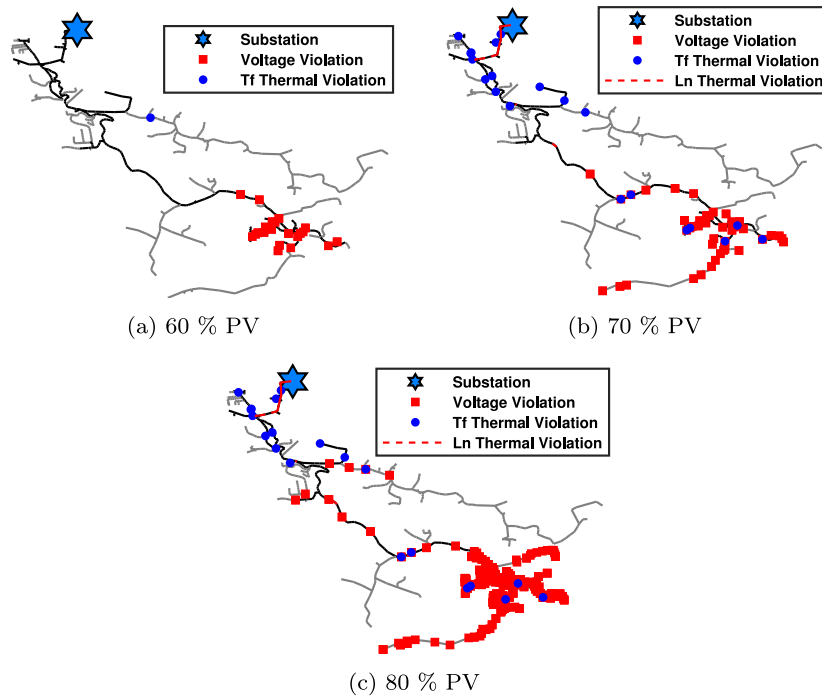


Fig. 22. Network topology of feeder 4, nodes where violations occur.

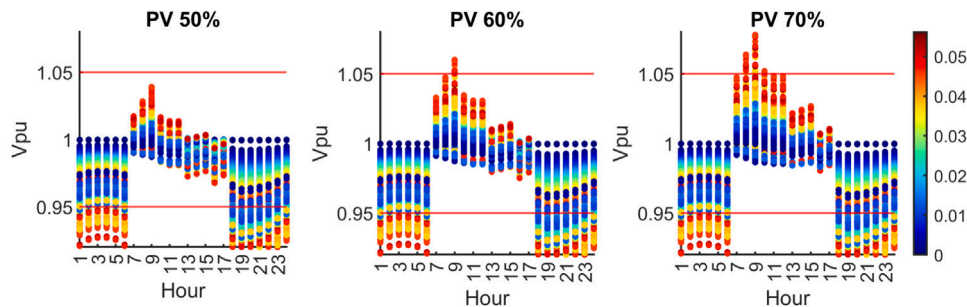


Fig. 23. Voltage profile, Feeder 4.

period, allowing for better integration of PV generation without causing violations.

Fig. 22 shows that voltage violations occur mainly at the feeder’s endpoints, which may be due to its length and the increased susceptibility of the farthest nodes to load or generation variations. This is further confirmed in Fig. 23, where violations are observed at the most distant nodes for PV penetration levels above 50%, especially around midday.

Additionally, Fig. 22 reveals that thermal violations occur in different branches than those where voltage violations appear, demonstrating that voltage and thermal violations do not always coincide. This highlights the importance of analyzing both phenomena separately, as they are not necessarily correlated.

• **Feeder 5: Urban-residential, 4.16 kV, 8.7 mi**

Fig. 24 presents the HCPV analysis results for Feeder 5, evaluated under different temporal conditions. On average, the system can support up to 70% PV penetration without experiencing thermal or voltage violations. Although no significant differences are observed between weekdays, contrasts are evident across the seasons. This contrast is mainly due to the increased energy demand in summer, particularly in urban and residential areas, driven by the higher use of air conditioning systems. The proximity of loads to generation points reduces reverse power flow, mitigating

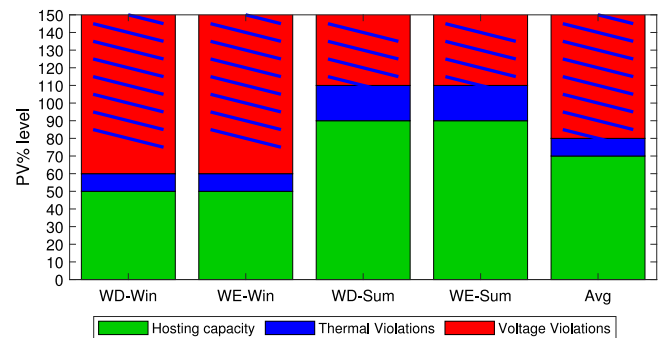


Fig. 24. HCPV Feeder 5 (Urban-residential, 4.16 kV, 8.7 mi).

problems associated with excessive PV generation and enhancing the HCPV.

In all seasons, the primary issue is the occurrence of thermal violations, followed by voltage violations. Fig. 25 shows that thermal violations occur mainly at the transformers. However, when PV penetration is high, such as at 100%, thermal violations

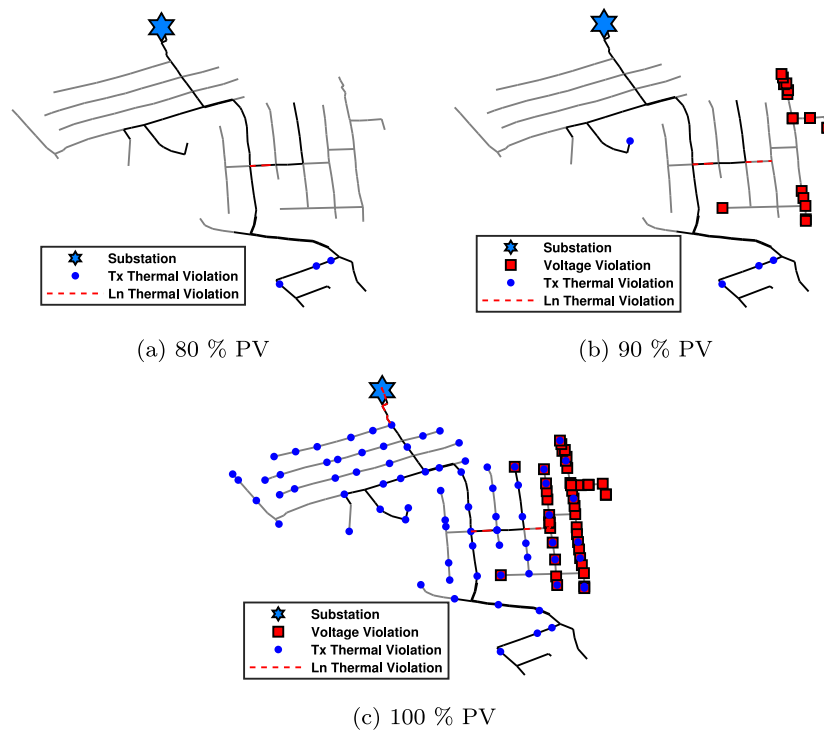


Fig. 25. Network topology of feeder 5, nodes where violations occur.

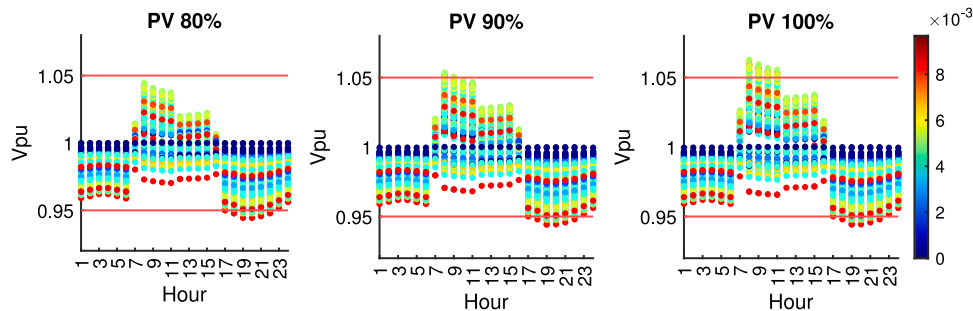


Fig. 26. Voltage profile, Feeder 5.

are also observed in the main lines, especially around midday, when PV generation exceeds consumption.

On the other hand, voltage violations mainly occur in the farthest branches of the feeder, where load and generation variations have a greater impact. These voltage violations occur after thermal violations, appearing at PV penetration levels close to 90%, as shown in Fig. 24. Finally, Fig. 26 provides a more detailed view of how the voltage evolves throughout the day.

• **Feeder 6: Urban-residential, 13.2 kV, 9.8 mi**

Fig. 27 presents the HCPV analysis results for Feeder 6, evaluated across different seasons of the year. On average, the system can accommodate up to 40% PV penetration without experiencing thermal or voltage violations. Although no significant differences are observed between weekdays, there are notable variations across the seasons of the year. While PV generation increases in summer, the results show that load growth exceeds that of generation, leading to higher thermal stress on the system.

In all seasons, the primary issue identified is thermal violations, while no voltage violations are recorded. This is due to the feeder operating at a voltage level of 13.2 kV, which makes it less susceptible to voltage variations. Additionally, the low load density, consisting of only 46 transformers, contributes to the stability of the system.

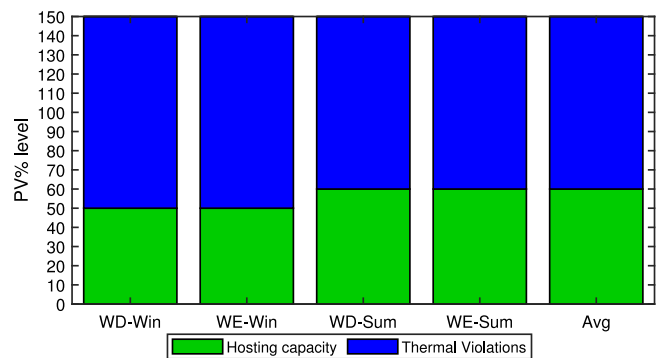


Fig. 27. HCPV Feeder 6 (Urban-residential, 13.2 kV, 9.8 mi).

Thermal violations mainly occur in low-capacity transformers, particularly those with rated capacities of 15 kVA and 25 kVA. Fig. 28 shows that these thermal violations primarily occur at the transformers, and from 120% PV penetration, they also begin to appear in lines closer to the substation. Although voltage levels

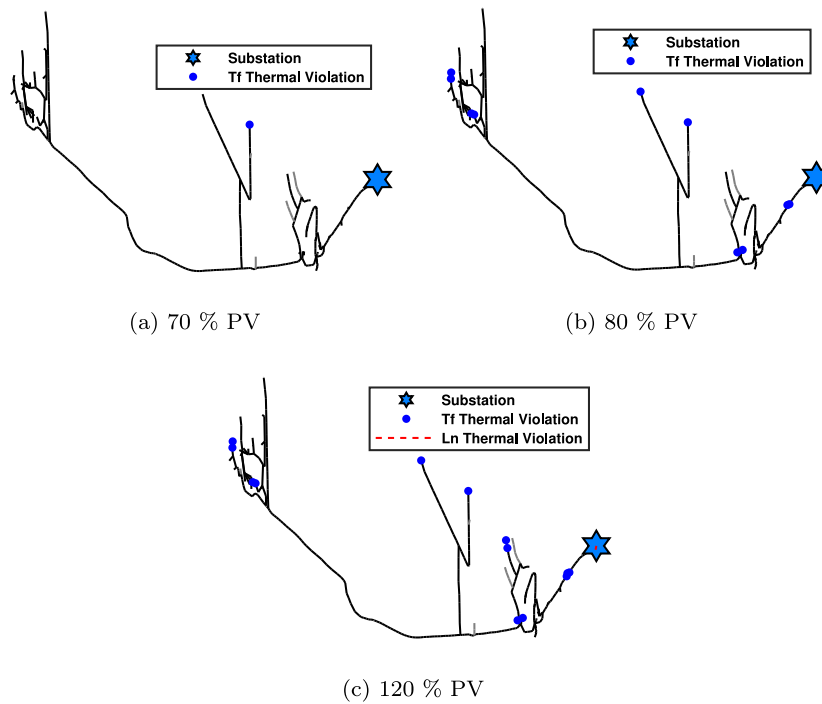


Fig. 28. Network topology of feeder 6, nodes where violations occur.

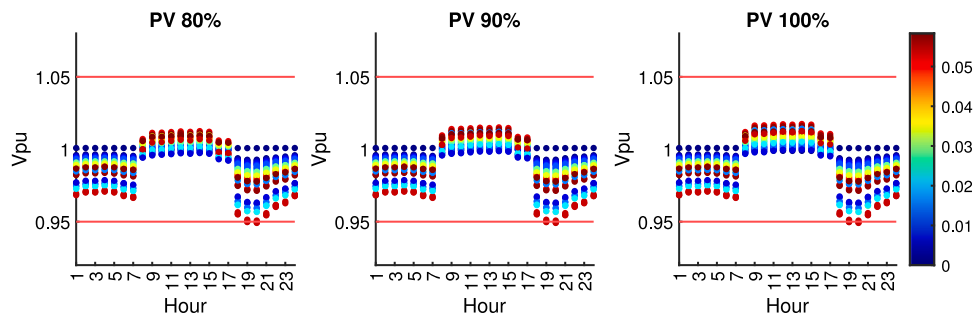


Fig. 29. Voltage profile, Feeder 6.

Table 4  
Summary of case studies implemented to increase HCPV.

	Case I	Case II	Case III	Case IV
PV	x	x	x	x
BESS		x		x
Smart Inverter (Volt – VAR)			x	x

increase around midday due to high PV generation, they remain within the permissible limits. Fig. 29 provides a more detailed view of how voltage evolves throughout the day.

#### 4.2.2. Methods to increase HCPV

In this section, various methods to increase HCPV are explored, including the use of BESS and the implementation of SI with voltage control functions, such as the Volt-VAR mode. Additionally, the impact of these approaches on the increase in HCPV across different feeders will be analyzed, taking into account their specific technical characteristics. Table 4 presents the various case studies implemented to increase HCPV.

Where:

Case I: Includes only PV without BESS or Volt-VAR control.

Case II: Includes PV with BESS but without Volt-VAR control.

Case III: Includes PV with Volt-VAR control but without BESS.

Case IV: Includes PV, BESS, and Volt-VAR control.

Fig. 30 presents the results obtained for each feeder in the different case studies. Although Case I was previously analyzed individually for each feeder, the general comparison reveals that the HCPV varies between 50% and 90%, depending on the technical characteristics of each feeder. In most feeders, the first violations that appear are thermal, mainly caused by transformers with limited capacities; it was identified that there are some transformers in the feeders with capacities equal to or less than 25 kVA, which restricts their ability to integrate high levels of PV. On the other hand, voltage violations are closely linked to the voltage level of the feeder. In 13.2 kV feeders, such as Feeder 2, these violations tend to appear only when PV penetration exceeds 90%, while in lower voltage feeders, such as Feeder 4 of 8.32 kV, they may appear from PV penetration levels close to 50%.

It is observed that Case II, which incorporates BESS, significantly contributes to the reduction of thermal violations across all feeders. This strategy allows increasing the HCPV levels by between 20%, as in Feeder 1, and up to 90% in Feeders 2, 5, and 6. These results are due to the reduction of reverse power flows, since the energy generated by the PV systems is partially absorbed by the batteries during their

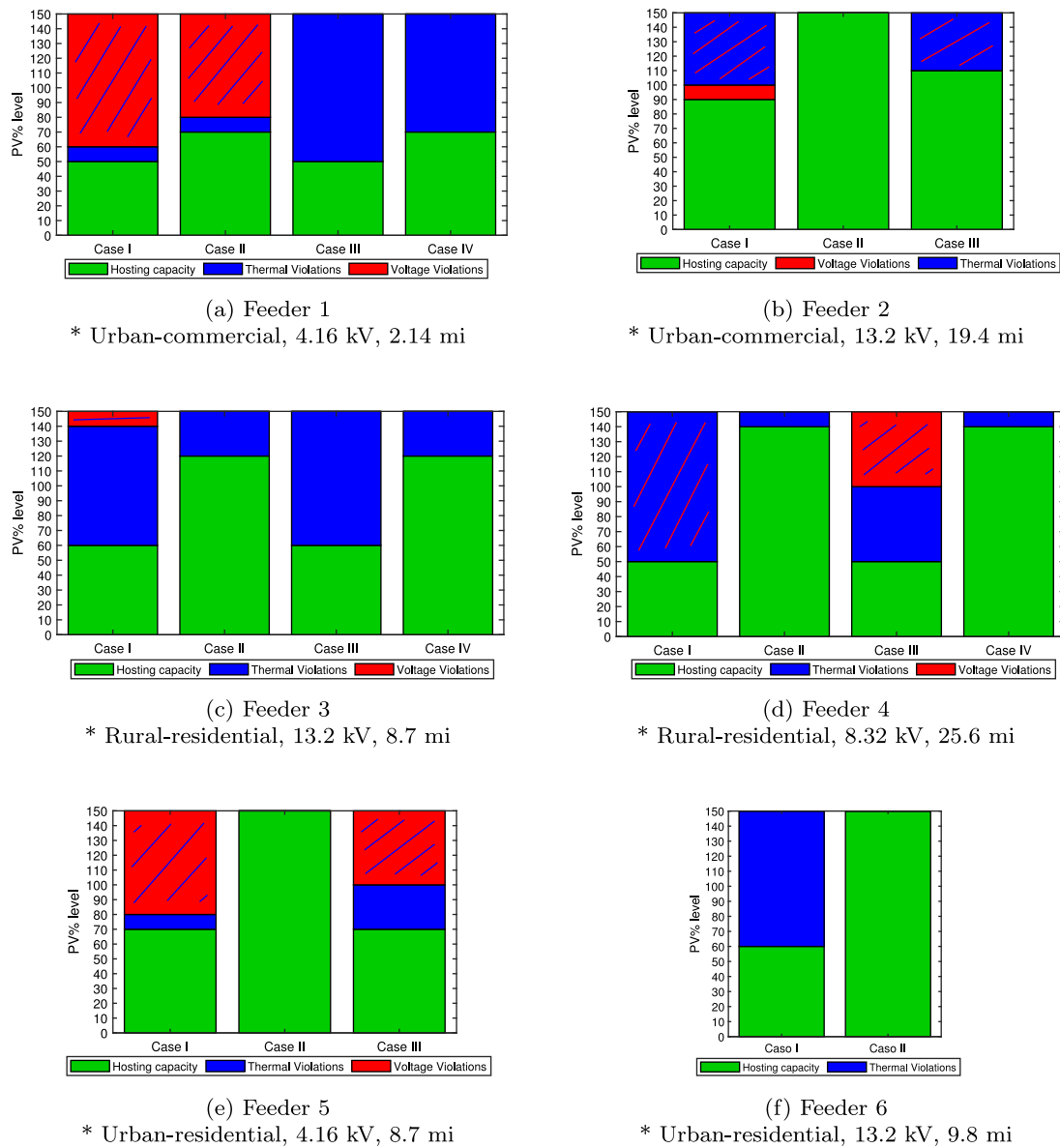


Fig. 30. Results per feeder for the case studies implemented to increase HCPV.

charging process, which helps balance the power flow in the network. Additionally, the use of BESS helps relieve overload in transformers and lines, and in turn, contributes to reducing voltage violations by counteracting the increase in voltage levels caused by reverse power flows.

On the other hand, Case III shows that implementing the Volt-VAR function in inverters has a significant impact on reducing voltage violations. In feeders 1, 2, and 3, violations are eliminated, while in feeders 4 and 5, they are significantly reduced. This is due to the ability of Volt-VAR control to stabilize voltage levels by injecting or absorbing reactive power. However, this function has little to no effect on mitigating thermal violations, as reverse power flows persist, causing overloads in the grid components and exceeding their operational limits. It is worth noting that Feeder 6 did not present voltage violations even with high PV penetration, which is related to its voltage level of 13.2 kV and its moderate line length. For this reason, Case III was not applied to that feeder.

Finally, Case IV demonstrates that the combination of BESS with SI maximizes the increase in HCPV. This is due to the synergy between the reduction of reverse power flows, caused by the BESS charging,

and the voltage control provided by the Volt-VAR function of the SI. In Feeder 1, this combination eliminates voltage violations, although thermal violations remain at levels similar to those observed in Case II, which confirms that Volt-VAR has a limited impact on this type of constraint. These results indicate that the combination of BESS and Volt-VAR is especially effective when voltage violations persist after the use of BESS, or in feeders where voltage violations are more critical than thermal ones. It is worth noting that in Feeders 2 and 5, Case II was sufficient to eliminate all violations, so the application of Case IV was not necessary.

### 5. Conclusions

The analysis of the initial state of the feeders revealed that some branches show voltage levels below the permissible limits and sections of the line with currents close to their maximum capacity. These results underscore the importance of conducting an initial assessment to identify problems that may worsen with increased PV system penetration.

A contribution of this study is the analysis of HCPV, including seasonal variations in demand and irradiation. In Puerto Rico, seasonal differences are marked by an increase in temperature during the

summer, which increases the use of air conditioning and refrigeration systems. Although PV generation may also increase this season, the higher growth in electricity demand compared to generation reduces reverse power flows, allowing for a higher HCPV in summer than in winter. This behavior is evident in Feeders 1, 4, and 6, where the HCPV increases by approximately 10% during the summer. In Feeders 2 and 5, the increase reaches up to 30%. On the other hand, although no increase in HCPV is observed in Feeder 3, a 10% reduction in voltage violations is recorded.

Additionally, it was observed that the HCPV varies significantly among the analyzed feeders, with values ranging from 50% to 90%, depending on their technical and operational characteristics. The results indicate that feeders operating at 13.2 kV, such as Feeder 2, are less prone to voltage violations, even when they are extensive and heavily loaded. In contrast, feeders with lower voltage levels (8.32 kV and 4.16 kV) experience simultaneous voltage and thermal violations. However, it was identified that thermal violations are not always associated with voltage violations, but rather, in many cases, they result from transformers or lines operating under high loads.

Regarding the mitigation strategies, in Case II using BESS, a partial reduction of thermal and voltage violations was observed. This strategy allows for a decrease in the loading of network elements and an increase in HCPV between 20% and 90%, depending on the feeder. In Case III, the use of the Volt-VAR function of smart inverters almost completely mitigated voltage violations, although it did not eliminate thermal ones, which limited the increase in HCPV in most cases. Finally, in Case IV, which combines BESS and Volt-VAR, a similar behavior to Case II was obtained in terms of HCPV increase, but with the additional advantage of eliminating voltage violations.

This research presents a detailed and novel analysis of HC in real distribution feeders in Puerto Rico, incorporating seasonal variability and the different technical characteristics of each network. Unlike previous studies based on test systems, this work provides realistic results that can guide decision-making for both utility companies and regulatory entities. Notably, the findings indicate that the current 15% PV penetration threshold in Puerto Rico is conservative, and that higher levels of integration are technically feasible through the implementation of appropriate mitigation strategies.

#### CRediT authorship contribution statement

**Huaman-Rivera Anny:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Irizarry-Rivera Agustin:** Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Calloquispe-Huallpa Ricardo:** Writing – review & editing, Visualization, Methodology, Investigation.

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#### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Anny Huaman-Rivera reports financial support was provided by US Department of Energy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

Data will be made available on request.

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