IET Generation, Transmission & Distribution

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INDUSTRY ARTICLE OPEN ACCESS

Increasing the RES Hosting Capacity of the Cyprus Distribution System Focusing on Export Limitation Schemes

Phivos Therapontos[1,2] | Savvas Panagi[1,3] | Rafail Konstantinou[1] | Charalambos A. Charalambous[2] | Petros Aristidou[3]

[1]Distribution System Operator, Electricity Authority of Cyprus, Nicosia, Cyprus | [2]Department of Electrical and Computer Engineering, University of Cyprus, Nicosia, Cyprus | [3]Department of Electrical and Computer Engineering and Informatics, Cyprus University of Technology, Limassol, Cyprus

Correspondence: Phivos Therapontos (ptherapo@eac.com.cy)

Received: 5 February 2025 | **Revised:** 7 October 2025 | **Accepted:** 26 November 2025

ABSTRACT

The penetration of renewable energy sources (RES) in Cyprus's power system has increased significantly in recent years. However, this growth poses substantial challenges, primarily due to limitations in distribution networks arising from network congestion and voltage security issues. This paper presents a comprehensive review of existing solutions for enhancing RES hosting capacity, together with a robust methodology for evaluating their effectiveness. To address voltage-related challenges, centralised voltage control strategies at power transformers are combined with adaptive inverter settings to ensure stable operation under increasing RES penetration. Network reinforcements and medium-voltage (MV) upgrades are also considered as complementary measures. At the low-voltage (LV) level, export limitation schemes (ELS) tailored for residential prosumers are proposed, with optimal limits determined for both single- and three-phase installations at targeted RES penetration levels. The effectiveness of the proposed solutions is validated using real MV and LV networks from the Cyprus distribution system, ensuring alignment with the strategic planning framework of the distribution system operator of Cyprus. The findings provide a scientific basis for optimising RES integration, addressing both operational and strategic challenges in modern power systems.

1 | Introduction

The renewable energy sources (RES) penetration has experienced a remarkable increase worldwide in recent years [1]. The installed capacity of photovoltaic (PV) systems connected to the Cyprus distribution system have surpassed 900 MW, with an additional 400 MW expected to be connected by 2027 [2]. This RES penetration is substantial, considering that the historical maximum load demand is only 1.2 GW. Consequently, the Cyprus power system is currently facing significant challenges that hinder further increase in RES penetration [3].

In many areas of the island, the RES installed capacity has already reached hosting capacity, which is limited due to network congestion and voltage security issues [4]. This challenge is more pronounced in rural areas due to the abundance of land availability at relatively low cost. However, the network in these areas has limited capacity since it was built to meet the traditionally low demand of local consumers.

Hosting capacity limitations have also been identified in the low-voltage (LV) network of the Cyprus distribution system. In recent years, most residential households in many suburban areas have installed rooftop PV systems to cover their energy needs. However, this significant PV penetration has led to voltage increases and network congestion. Figure 1 illustrates the maximum busbar voltages and the distribution transformer loading under different RES penetration levels. In this analysis, RES penetration is defined as the percentage of consumers with a PV system (prosumers). It is evident that for RES penetration scenarios above 60%, a considerable number of busbars experience voltages exceeding the maximum allowable limits. At the

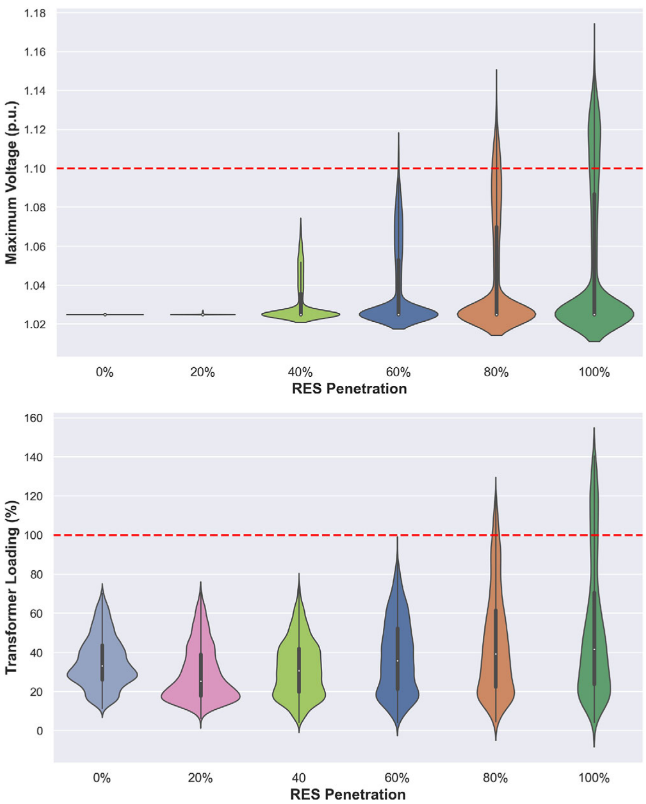

FIGURE 1 | Maximum voltage and transformer loading for different RES penetration levels in the Cyprus DN.

same time, the loading of distribution transformers surpasses their rated capacity, reaching up to 160% at the 100% RES penetration scenario. Therefore, it is imperative to implement appropriate measures that will enable the targeted expansion of the RES hosting capacity in both the medium-voltage (MV) and low-voltage (LV) distribution networks.

Several solutions have been proposed in the literature for planning PV-rich distribution networks [5–7]. In this work, emphasis is placed on planning recommendations for medium-term up to 60% PV penetration, focusing on exploiting the existing network capabilities. However, higher RES penetrations are also analysed to develop the foundations for a smooth transition towards 'net zero.' These capabilities include the adoption of new stricter grid code requirements for inverter-based resources (IBRs), the implementation of intelligent centralized voltage control on power transformers, export limitation schemes and network reinforcements [5].

The grid code requirements for IBRs have been regularly updated over the past decades to ensure their optimal integration into the power grid. Figure 2 depicts the grid codes' major modifications. The first generations of IBRs did not allow any reactive power compensation and therefore operated at unity power factor [8]. As a result, significant voltage rise was often observed at the point of common coupling (PCC). Subsequently, some grid codes were revised, requiring the IBRs to operate at a constant power factor below unity, thereby absorbing reactive power (underexcitation) [9]. This measure contributed in mitigating overvoltage conditions. Nevertheless, under this open-loop strategy, IBRs

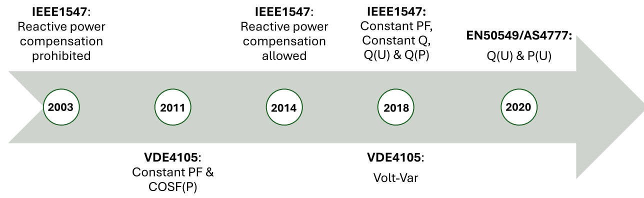

FIGURE 2 | IBRs grid code requirements.

were compelled to absorb reactive power even when voltages were within nominal limits. This often led to undervoltage conditions and excessive reactive power absorption, ultimately increasing equipment loading and causing potential operational inefficiencies. Over the last decade, the COSF(P) (Figure 3a) method has been widely adopted. This method requires adjusting the IBR power factor according to active power generation [9]. While it has improved voltage profiles, the reactive power compensation remains unrelated to the PCC voltage.

In 2018, the revised version of VDE 4105 included the volt-var ($Q(V)$) method, which modifies the injection or absorption of reactive power according to the voltage at the PCC (Figure 3b). The analysis in [10] found that volt-var control from IBRs can mitigate voltage-related issues, provided that the inverter capacity is sufficient. During peak active power generation conditions, the voltage rise necessitates significant absorption of reactive power. When the inverter reaches its apparent power capability, it is compelled to curtail either active power injection or reactive power absorption. Since inverters are commonly set to operate in P-priority mode, the ability to absorb reactive power is restricted [11]. In addition, stricter reactive power control has been shown to increase equipment loading. Furthermore, the German standard VDE 4105 for interconnecting IBRs to the LV network raises concerns regarding voltage stability. VDE 4105 specifically suggests that system operators should investigate possible voltage instabilities when the total installed capacity of the IBRs operating with $Q(V)$ characteristic, exceeds 50% of the distribution substation power [9]. Similarly, voltage stability issues have been identified for steep droop settings characteristics of the $Q(V)$ curve [12].

In 2019, the EN 50549 and in 2020, the AS/NZS 4777 standards have proposed the use of the volt-watt ($P(V)$) method in combination with the $Q(V)$ characteristic [13, 14]. $P(V)$ characteristic presented in Figure 3c, effectively mitigates overvoltages since it forces IBRs to reduce their active power generation when the PCC voltage exceeds a predifined threshold (V4). Nevertheless, this method may cause excessive and inequitable RES curtailments. As curtailment levels are determined by the local voltage conditions in each area, the $P(V)$ scheme inherently results in an uneven distribution [15].

In more recent manuscripts, network reconfiguration has been promoted as a promising solution for alleviating both voltage and network congestion issues [16]. The network topology changes dynamically based on real-time measurements across the network [17]. Although this method is extremely effective, it has high costs as well as strict observability and controllability requirements.

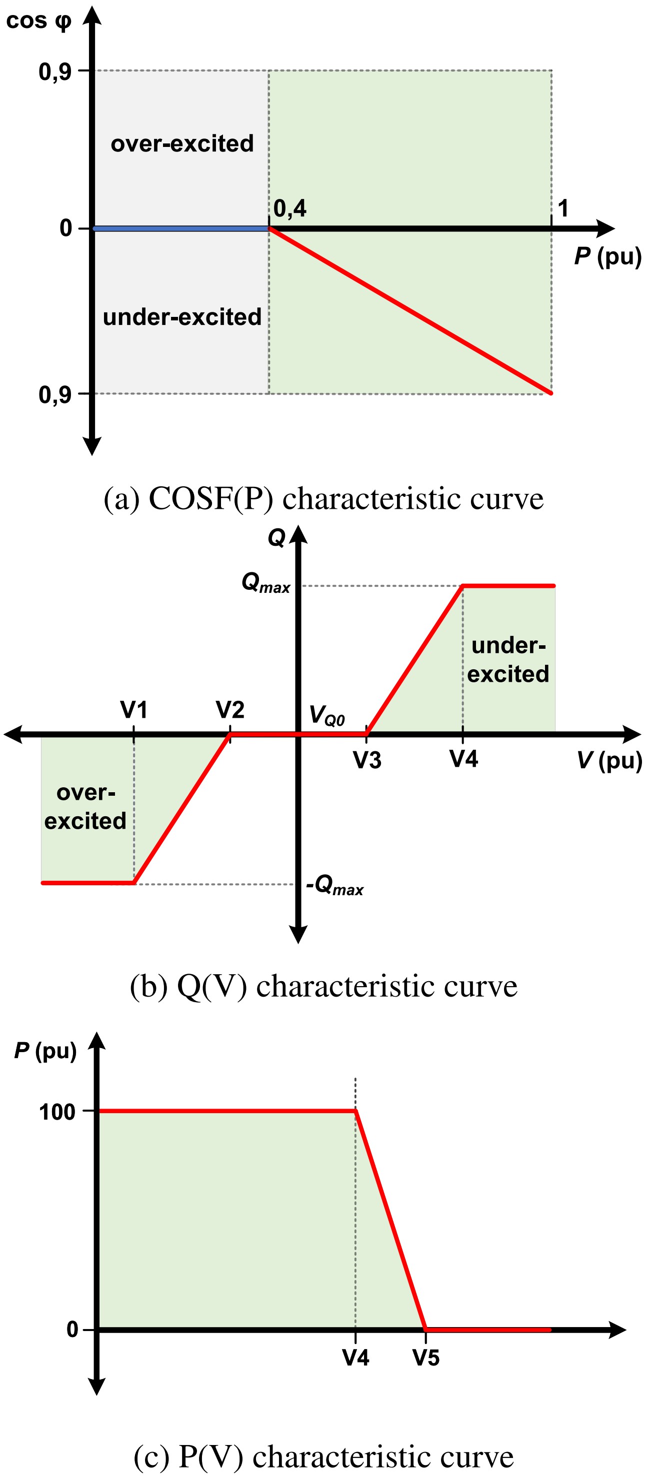

FIGURE 3 | Examples of IBR decentralised control schemes.

Furthermore, the impact of residential battery energy storage systems (BESS) on the operation of the distribution system has been evaluated in [6, 18]. Residential BESS has shown only limited effectiveness in reducing grid issues. This is mainly because during low demand conditions, BESS are often fully charged before peak PV generation. As a result, a significant amount of energy generated from RES is unavoidably injected into the grid. However, [19] demonstrated that BESS can help mitigate overvoltage issues by absorbing reactive power from the network.

In contrast, stand-alone BESS installed at distribution substations or across the feeders, can improve the hosting capacity of the distribution network [20]. In particular, hydrogen-based energy storage has emerged as a promising long-term solution to provide seasonal storage potential and mitigating both voltage and congestion issues [21]. However, based on the European legislation, DSOs are not allowed to own or operate BESS. This creates obstacles on the timely roll-out of BESS, while at the same time the operation of the BESS will be based only according to the market signals [22].

Recent publications have investigated the possible benefits of demand response. Demand response refers to the modification of the active or reactive power consumption or production in response to price signals. Studies have shown that demand response can improve the operation of power systems [23]. Nonetheless, the number of flexible devices within each household is limited, and these typically account for only a minor share of total electricity consumption. Consequently, aggregate demand-side flexibility remains relatively constrained. More importantly, the effectiveness of demand response depends on the extent to which end-users are both willing and able to adjust their consumption patterns.

In [24], export limitation schemes (ELS) have been applied to LV prosumers to increase the network hosting capacity. An ELS defines the maximum amount of active power that a prosumer may inject into the system (more information in Section 2). Studies have found that ELS can significantly mitigate both voltage and loading issues. In [25], it has been demonstrated that the hosting capacity of distribution networks can be increased up to 50% with ELS, causing only 5% annual loss due to curtailments. To minimize RES curtailments, a mixed integer linear programming (MILP) has been used to calculate the optimal ELS settings. Nevertheless, in this study, the modelled PV systems were assumed to operate at a unity power factor while a single common ELS was estimated for both three-phase and single-phase prosumers [26].

Recently, the concept of dynamic operating limits has emerged [27, 28]. Dynamic operating limits, also referred to as operating envelopes, are continuously estimated based on the current and forecasted grid conditions. The updated export limits are then communicated to prosumers. Hence, export limits are not fixed for each prosumer but are calculated according to the network capacity [28]. Although this solution reduces curtailment of renewable energy, it is complex to implement and introduces fairness concerns among prosumers. Specifically, it requires advanced monitoring of the LV network to calculate the dynamic ELS, as well as a robust communication infrastructure to transmit the updated values to the prosumers.

Methodologies for assessing and improving the hosting capacity of distribution systems have been extensively investigated over the last decade [29–31]. However, each power system has its own unique characteristics and therefore, tailored solutions must be developed and validated for each system. Previous works have evaluated the impact of RES penetration on the Cyprus distribution system and proposed solutions to increase its hosting capacity. Initially, in [32] various constant power factor values were assessed to mitigate voltage issues in real MV network in Cyprus. In [33], the authors focused their analysis specifically on the impact of different COSF(P) reactive power compensation schemes for decentralised voltage control by IBRs. In [6], the analysis evaluated the impact of RES penetration on the neutral voltage in unbalanced three-phase low-voltage networks. Similar analyses have been performed in [34, 35], where the impact of uncontrollable electric vehicle (EV) charging was also considered.

The literature review highlights a critical shortcoming: the lack of an updated roadmap to ensure the timely enhancement of the Cyprus distribution system's hosting capacity. This shortcoming poses significant risks for integrating the additional, predicted distributed energy resources into the distribution system. In this paper, several solutions proposed in the literature are reviewed, and a methodology is introduced to evaluate their effectiveness in increasing the hosting capacity in the Cyprus distribution networks.

A MV rural network and a LV suburban network, where their hosting capacity is currently inadequate to meet the growing demand for new RES installations, are examined. A Monte-Carlo (MC) approach is implemented to assess the effectiveness of the proposed solutions in the Cyprus MV distribution network using historical data. In addition, a metaheuristic algorithm is applied to calculate the optimal ELS for single- and three-phase LV prosumers. Finally, based on the results of this evaluation, recommendations are provided to the Cyprus DSO for maximizing RES hosting capacity.

The major objectives of this work are:

- To identify effective solutions that will allow the Cyprus distribution system to achieve up to 60% PV penetration in the short- to medium-term, with emphasis on exploiting existing network capabilities.
- To estimate export limitation schemes (ELS) for LV network prosumers that ensure optimal distribution system operation while minimizing curtailed RES energy.

The novelties of this manuscript are summarized as follows:

- The development of a comprehensive methodology to evaluate the effectiveness of various solutions for increasing RES hosting capacity in Cyprus' distribution networks, using a Monte Carlo approach with historical data.
- The introduction of a robust optimization framework for calculating optimal ELS settings for both single-phase and three-phase LV prosumers, considering different RES penetration scenarios.
- The provision of specific recommendations for the Cyprus DSO to maximize RES hosting capacity.

The rest of the paper is organized as follows: Section 2 presents the selected solutions for increasing the hosting capacity of the distribution system of Cyprus. Section 3 describes the Monte-Carlo-based methodology to compare the alternative solutions and develops the optimization framework for the export limitation scheme. Section 4 introduces the case studies are described, while Section 5 evaluates the proposed solutions for increasing MV hosting capacity and calculates the optimal ELS. Finally, Section 6 summarizes the main findings and insights.

2 | Selected Solutions for Increasing RES Hosting Capacity of Cyprus Distribution System

The integration of new RES into the power grid is subject to compliance with specific network criteria, defined by grid code requirements. These criteria in Cyprus include ensuring that equipment loading remains below 100% and that voltage levels are maintained within the nominal range of 0.9 to 1.1 p.u. Additionally, for MV connections, an additional constraint mandates that the voltage variation before and after the interconnection of IBRs must not exceed 2% [9].

To enhance the RES hosting capacity while maintaining voltage stability and preventing equipment overloading, the implementation of effective mitigation strategies is essential. As presented in Section 1, numerous solutions have been proposed to increase hosting capacity. However, only a subset of solutions is considered suitable for the Cyprus system, based on the characteristics summarized in Table 1. The selected solutions are categorized as follows: (i) decentralised control from IBRs; (ii) centralised control from transmission substations; (iii) network reinforcements and upgrades; and (iv) export limitations schemes. These solutions were chosen for their substantial impact on enhancing hosting capacity, their high practical applicability, and their ability to avoid imposing unequal constraints on different prosumers. Moreover, decentralised and centralised controls have an extremely low implementation cost.

2.1 | IBRs Decentralised Control

Currently, in Cyprus, all IBRs are mandated to perform voltage control using the COSF(P) characteristic, as illustrated in Figure 3a. This control strategy requires IBRs to commence reactive power absorption once their active power output exceeds 40% of their installed capacity.

In this analysis the volt-var ($Q(V)$) control method, depicted in Figure 3b proposed by grid codes [9, 13] is considered. Under this scheme, IBRs dynamically inject or absorb reactive power based on the voltage measured at their terminals. This constitutes a closed-loop control approach, where voltage serves as the feedback variable. Specifically, as long as the voltage at the point of common coupling (PCC) remains within the range defined by V2 and V3, the inverter does not contribute reactive power. However, if the PCC voltage reaches the thresholds V1 or V4, the inverter is required to inject or absorb the maximum allowable reactive power to stabilise the grid.

The volt-watt ($P(V)$) control method has not been considered in the analysis despite its significant impact on mitigating voltage issues. This is because it distributes curtailments unfairly between IBR owners [36]. Since voltage increases with distance from the distribution substation, IBRs located further from the substation are forced to reduce more active power compared to other IBRs installed on the same feeder. In addition, this method

TABLE 1 | Description of solutions for increasing HC.

Solution	Cost	Impact	Fairness	Applicability
Volt-var - $Q(V)$	Low	Medium	Moderate	High
Volt-watt - $P(V)$	Low	Medium	Low	High
RLDC (HV/MV)	Low	High	High	High
OLTC (MV/LV)	Very high	High	High	Low
Volt-watt	Low	Medium	Low	High
Network reconfiguration	Very high	High	High	Low
Residential BESS	High	Moderate	High	Moderate
Stand alone BESS	High	High	High	Low
Demand response	Low	Moderate	High	Moderate
Export limitation	Low	High	High	High
Dynamic export limitation	High	High	Moderate	Low
Network reinforcement	High	High	High	High
Voltage upgrading	Very high	Very high	High	Low

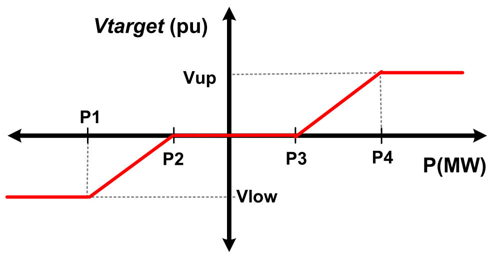

FIGURE 4 | Reverse line drop compensation (RLDC) characteristic used in substation control.

penalises IBRs when the voltage of the distribution network is higher than V4 (see Figure 3c), but below the maximum allowable limit (V5).

2.2 | Substation Control

Most power transformers at transmission substations are equipped with on-load tap-changing (OLTC) capabilities. However, their target voltage is typically maintained at a fixed set point, which lacks adaptability to varying operating conditions. To enhance voltage regulation under different scenarios, reverse line drop compensation (RLDC) methods can be employed. The RLDC characteristic, depicted in Figure 4, shows that the target voltage of power transformers is dynamically adjusted based on the active power flow through the transformer [37].

Specifically, under conditions of excessive reverse active power flow (towards point P1 in the figure), the target voltage is reduced, thereby lowering the voltages across the MV feeders. Conversely, during periods of high loading (towards point P4 in the figure), the target voltage is increased to compensate for the voltage drop in the distribution network [38]. This adaptive control strategy enhances voltage stability and improves the overall resilience of the power system.

Centralised control is considered in this analysis because it offers a very low cost for implementation and a significant impact on the voltage across the whole MV network. In contrast, OLTC capability at distribution substations has not been considered due to its high cost and limited applicability.

2.3 | Network Upgrades

Network reinforcement has traditionally been employed to enhance the current-carrying capability of electrical equipment. While this approach effectively mitigates network congestion, its impact on voltage regulation is relatively moderate [5]. A commonly adopted strategy to increase network capacity is the addition of power transformers at transmission substations. However, the feasibility of installing additional transformers is highly dependent on the spatial constraints of each substation.

An alternative approach involves upgrading the operating voltage, which can significantly enhance the hosting capacity of RES by addressing both voltage stability and congestion-related challenges. Since 2004, the Cypriot DSO has initiated a gradual transition of the MV distribution system from 11 to 22 kV. As a result, a large portion of the installed equipment is already rated for 22 kV, despite currently operating at 11 kV. Both network reinforcement and voltage upgrades-particularly the latter-entail substantial capital expenditures, as they necessitate the widespread replacement of existing infrastructure. However, both solutions are considered in the analysis, as their impact on hosting capacity is extremely high, while at the same time a noticeable part of the network is already prepared to operate at 22 kV.

2.4 | Export Limitation

The concept of ELS has recently been introduced as a strategy to mitigate the impact of RES on the power grid [24, 39]. These schemes regulate the output of RES systems to ensure that power

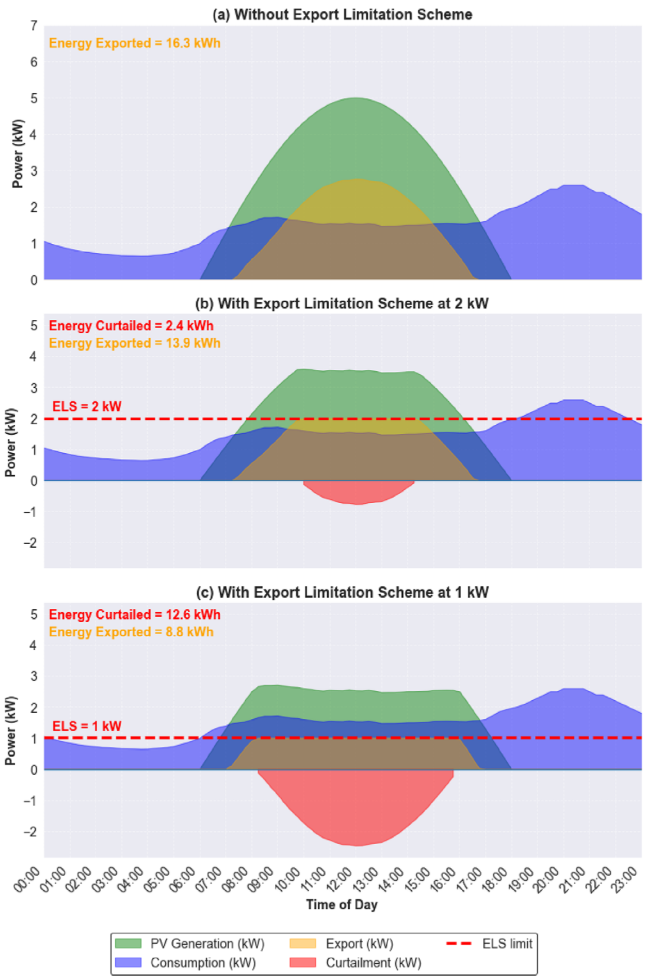

FIGURE 5 | Power flow profile with/without ELS.

exported to the grid remains below a predefined threshold, as illustrated in Figure 5. It can be observed in Figure 5a that, without any ELS applied, all unconsumed energy (yellow area) is exported to the grid. In Figure 5b, where the export limit is set to 2 kW, whenever the exported power exceeds this threshold, the PV system reduces its active power generation (red area) to comply with the scheme. Further reducing the ELS setting, as illustrated in Figure 5c, results in higher curtailments. It should be noted that the amount of curtailed energy is directly related to the self-consumption of the prosumer: the higher the consumption during PV generation, the lower the resulting curtailments.

The export limitation value is determined by the DSO and can be set as low as zero in congested areas, thereby mitigating equipment overloading and voltage stability issues. Various types of export limitation schemes exist, including timed-export connections, which permit grid export only during specified periods, and export-limited connections, where the maximum export is restricted to a value below the installed capacity of the RES system [40].

This solution promotes the installation of BESS while incentivizing prosumers to increase their self-consumption. Hence, a prosumer with a very high self-consumption might experience minimal RES curtailment. For this reason, this solution is preferred, as it combines a strong impact on hosting capacity with fairness among prosumers.

TABLE 2 | Description of MV scenarios.

Scenario	Decentralized voltage control	Centralized voltage control
BaU	COSF(P)	Constant
SC1	$Q(V)_1$	Constant
SC2	$Q(V)_2$	Constant
SC3	$Q(V)_3$	Constant
SC4	$Q(V)_1$	RLDC
SC5	$Q(V)_2$	RLDC
SC6	$Q(V)_3$	RLDC

3 | Methodology

This section outlines the methodologies proposed in this paper. The first part details the approach used to assess the effectiveness of the solutions on an MV feeder, while the second part presents the methodology for determining the optimal export limitation settings for the LV residential prosumers.

3.1 | MV Analysis

To evaluate the hosting capacity of MV distribution networks under the proposed solutions outlined in Section 2, a Python-based computational framework was developed, which utilises DIgSILENT PowerFactory as the simulation engine [41].

The analysis begins by defining a set of potential solution combinations, known as scenarios (Table 2). Additionally, the MV distribution network must be modelled in PowerFactory. Subsequently, feeder measurements and PV generation profiles are collected. The hosting capacity for each scenario is then assessed using Algorithm 1. The methodology employs a Monte Carlo (MC) approach, where random variables include operating conditions (historical daily profiles), as well as the number, location and capacity of newly introduced PV parks. In this analysis, a MC approach is employed, as it offers a balance between computational efficiency and representativeness compared with alternative methods, such as deterministic worst-case analysis or complete time-series simulations. For these reasons, MC has been widely adopted in hosting capacity studies and is therefore applied here to assess the hosting capacity of the Cyprus distribution network [31].

For each scenario, 1000 quasi-dynamic (time-sweep load flow) simulations are conducted using randomly selected historical data. In each simulation, six representative time points per day are evaluated: 4 PM, 8 PM, 12 PM, 4 AM, 8 AM and 12 PM. Upon completion of each scenario analysis, the aggregated results of the 6000 simulated operating points are used to assess the frequency of constraint violations and other technical parameters of the system. In each representative scenario, if no violations are identified, the PV installed capacity is defined as the hosting capacity

ALGORITHM 1 | MV hosting capacity assessment.

Require: Network data, MV feeder measurements, PV generation profiles, scenarios

for each Scenario **do**
  while number of simulations < 1000 **do**
    Randomly select a day
    Randomly select the number of new PVs
    Randomly select the installed capacity of new PVs
    Randomly select the locations of new PVs
    Perform quasi-dynamic simulations
    if no violations occur **then**
      Save PV installed capacity
    end if
  end while
end for

ALGORITHM 2 | Optimal ELS calculation.

Require: Monte Carlo scenarios (Figure 6), network data

while number of PSO iterations < r **do**
  Select new ELS using PSO (Equations 3–4)
  Apply ELS to all prosumers
  for each MC scenario **do**
    Perform quasi-dynamic simulation
    Calculate energy generated from RES ($\text{Energy}_{\text{RES}}$)
    Calculate curtailed energy from RES ($\text{Curtailed}_{\text{RES}}$)
    Calculate number of voltage violations (V_{voltage})
    Calculate number of loading violations (V_{loading})
    Compute PI (Equation 1)
  end for
  Compute TPI (Equation 2)
end while

of that scenario. A comparative evaluation across scenarios then provides insights into the effectiveness of the proposed solutions in enhancing the hosting capacity of the MV distribution system under study.

The analysis evaluates the following technical parameters:

- Maximum MV feeder loading (%)
- Power transformer loading during $N-1$ contingency (%)
- Maximum voltage (p.u)
- Maximum voltage rise at PCC (p.u)

3.2 | Optimal Export Limitation in LV Systems

The proposed methodology for determining the optimal settings of the ELS is outlined in Algorithm 2. Initially, MC scenarios are generated following the framework illustrated in Figure 6. Specifically, historical data from smart meters are collected. A RES penetration scenario is then selected, defined as the number of customers with rooftop PV systems. To reduce computational complexity, a subset of days from each month is randomly selected for analysis. For each chosen day, customer load profiles and PV system characteristics are assigned stochastically.

The selected scenarios are subsequently processed in Algorithm 2. The initial export limitation settings are applied uniformly across all prosumers connected to the LV network. Quasi-dynamic simulations are then conducted to compute bus voltages, equipment loading, total energy generated, and curtailed RES energy. After each simulation, a performance index (PI) is computed as defined in Equation (1) for each scenario.

$$\begin{aligned} \text{PI} = {} & \text{Energy}_{\text{RES}} \times W_{\text{RES}} - \text{Curtailted}_{\text{RES}} \times W_{\text{CUR}} - \\ & V_{\text{Voltage}} \times W_{\text{Voltage}} - V_{\text{Loading}} \times W_{\text{Loading}} \end{aligned} \tag{1}$$

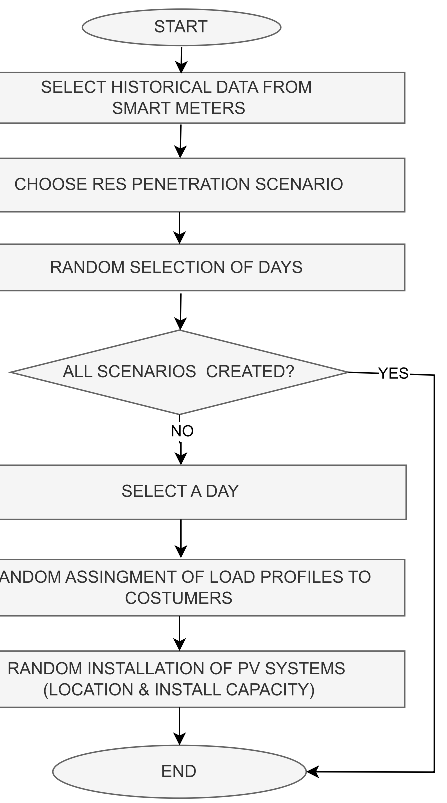

FIGURE 6 | Generation of MC scenarios for the ELS calculation

The PI quantifies the performance of the distribution network in terms of power quality under various RES penetration scenarios. The evaluation incorporates key parameters, including the total daily energy generated from RES ($\text{Energy}_{\text{RES}}$), the curtailed daily RES energy due to ELS ($\text{Curtailted}_{\text{RES}}$), the number of busbars (customers) experiencing voltage violations (V_{Voltage}), and the number of events in which equipment loading constraints are exceeded (V_{Loading}). A higher PI value indicates improved network performance and/or increased total RES generation. The weighting factors $W_{\text{RES}}, W_{\text{CUR}}, W_{\text{Voltage}}, W_{\text{Loading}}$ are determined by the DSO based on system characteristics and operational objectives. Increasing W_{Voltage} and W_{Loading} forces the optimisation process to converge towards more aggressive ELS settings to mitigate voltage and loading violations. In contrast, selecting higher values of W_{RES} and/or W_{CUR} promotes ELS settings that enable greater RES penetration with lower curtailments.

Once all selected scenarios have been analysed for different ELS configurations, the total performance index (TPI) is computed over the vector $\mathbf{PI} = [PI_1, \ldots, PI_N]$, where N represents the total number of simulations as shown in Equation (2).

$$\text{TPI} = \sum_{i=1}^{N} \text{PI}_i \tag{2}$$

The TPI serves as the objective function that is maximised in the particle swarm optimisation (PSO) algorithm. PSO is a metaheuristic optimisation method that iteratively searches for the optimal solution by considering both the best position of each individual particle (p_i^{best}) and the global optimum of the swarm (g^{best}) [42]. PSO is selected for calculating the optimal ELS settings because it provides a robust optimisation approach that can effectively explore the solution space. Compared with other methods, PSO requires fewer problem-specific assumptions, and converges to optimal solutions with reduced computational burden.

During each iteration, the particle velocities and positions are updated using PSO Equations (3) and (4), respectively. The particle positions correspond to specific ELS configurations [42]. The optimisation process terminates after a predefined number of iterations (r), and the optimal ELS settings are those that maximise the TPI.

$$u_i(t+1) = w \cdot u_i(t) + c_1 \cdot r_1 \cdot \left(p_i^{\text{best}} - \text{ELS}_i(t)\right) + c_2 \cdot r_2 \cdot \left(g^{\text{best}} - \text{ELS}_i(t)\right) \tag{3}$$

$$\text{ELS}_i(t+1) = \text{ELS}_i(t) + u_i(t+1) \tag{4}$$

Where:

- $u_i(t+1)$: velocity of particle i at iteration $t+1$
- $u_i(t)$: velocity of particle i at iteration t
- w: inertia weight
- c_1: cognitive coefficient
- c_2: social coefficient
- r_1, r_2: random numbers uniformly distributed in [0,1]
- p_i^{best}: best position of particle i
- g^{best}: global best position
- $\text{ELS}_i(t)$: export limitation settings of particle i at iteration t (single- and three-phase)
- $\text{ELS}_i(t+1)$: export limitation settings of particle i at iteration $t+1$ (single- and three-phase)

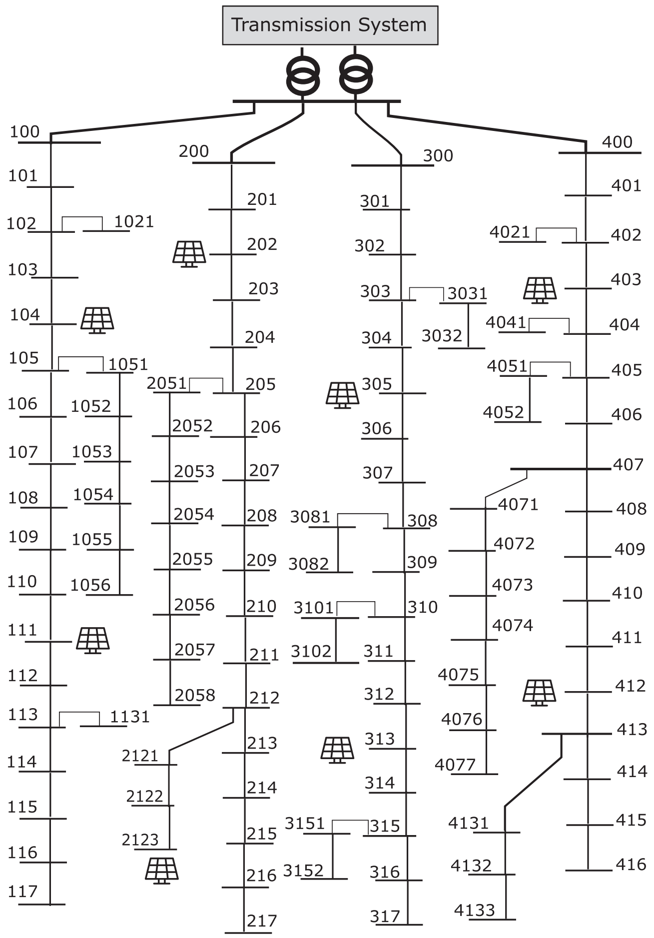

FIGURE 7 | MV rural distribution network model.

4 | Case Study

This section evaluates the performance of the proposed methodologies from Section 3 using real MV and LV networks of the Cyprus distribution system. A brief description of the MV and LV networks is first presented, followed by an overview of the parameters and assumptions adopted in each analysis.

4.1 | Cyprus Distribution System

4.1.1 | Medium Voltage

An 11 kV rural distribution network in Cyprus, depicted in Figure 7, has been modelled using data provided by the DSO of Cyprus. The network comprises four feeders supplying power to 176 distribution substations. Currently, eight PV units are installed, with a total capacity of 9 MW. The network is supplied by two parallel power transformers, each rated at 16 MVA and equipped with OLTC capabilities. Historically active and reactive power measurements recorded at the beginning of each feeder during 2023 have been spatially distributed along the feeders based on the nominal capacities of the respective distribution substations. All simulations have been performed using DIgSILENT PowerFactory software [41].

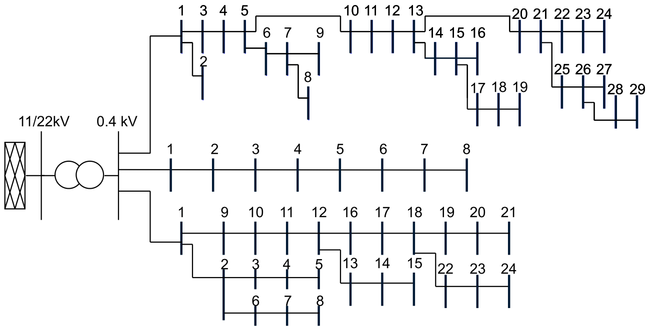

FIGURE 8 | Suburban LV distribution network model.

4.1.2 | Low Voltage

A suburban LV distribution network operating at 0.4 kV in Cyprus, illustrated in Figure 8, has been modelled using data provided by the DSO of Cyprus. The LV network consists of a dual-ratio 11/22 kV to 0.4 kV, 315 kVA delta-wye transformer supplying three LV feeders, with a total of 61 service points. All simulations have been performed using the PandaPower library in Python [43].

4.2 | Scenario Description

4.2.1 | MV Network Analysis

The selected scenarios for the MV case study are summarised in Table 2. In each MC iteration, the number of newly introduced PV systems is randomly determined using a uniform distribution in the range of 3 to 10. Their locations are selected uniformly among all available busbars. Their installed capacities are randomly assigned from a uniform distribution between 500 to 5000 kWp.

The configuration of each scenario, together with the specific settings for each solution type, is detailed as follows:

- IBR decentralised voltage control:
  - COSF(P): Configured according to Figure 3a
  - $Q(V)_1$: $V_2 = 0.97$ p.u., $V_3 = 1.03$ p.u., Droop = 40%
  - $Q(V)_2$: $V_2 = 0.98$ p.u., $V_3 = 1.02$ p.u., Droop = 50%
  - $Q(V)_3$: $V_2 = 0.99$ p.u., $V_3 = 1.01$ p.u., Droop = 50%
- Centralized voltage control via OLTC:
  - Constant: Fixed target voltage of 1.01 p.u.
  - RLDC: Configured with P1 = −8 MW, P2 = −2 MW, P3 = 2 MW, P4 = 8 MW, upper voltage limit $V_{\text{up}} = 1.01$ p.u., and lower voltage limit $V_{\text{low}} = 0.99$ p.u.
- Network reinforcement: All overhead transmission lines and underground cables are upgraded to the next available equipment with higher ampacity. These scenarios are denoted as ‘A’.
- Voltage upgrade: Equipment rated at 11 kV is upgraded and operated at 22 kV. These scenarios are denoted as ‘U’.

4.2.2 | Optimized Export Limitation Schemes (ELS)

For the LV case study, the analysis focuses exclusively on determining the optimal ELS settings for single-phase and three-phase prosumers. The IBR voltage control settings follow the COSF(P) characteristic, which is the standard configuration for Type A (residential) IBRs as specified by the Cypriot DSO. The probability mass function (PMF) of the installed PV capacity for single-phase and three-phase prosumers, obtained from [35], was used to generate the MC scenarios. It should be noted that the maximum allowable installed PV capacity for residential prosumers in Cyprus is 10.4 kW for three-phase connections and 4.16 kW for single-phase connections.

To achieve a balance between computational efficiency and accuracy, the PSO parameters were selected based on commonly adopted values in the literature [44]. The selected parameters include an inertia weight ($w = 1$), acceleration coefficients ($c_1 = c_2 = 2$), a swarm size of 5, and a total of 16 iterations. The parameter constraints are defined as follows: $\text{ELS}_{\text{Single-phase}}$ and $\text{ELS}_{\text{Three-phase}}$ vary from 0% to 100%, representing the fraction of PV installed capacity that can be exported to the grid.

The study is based on 30-min historical smart meter data from the Cyprus power system for 2022. To optimise computational time while maintaining accuracy, 10 days were randomly selected from each month for analysis.

5 | Results

This section presents the results of the MV and LV network analyses. Initially, the impact of combined solutions on MV hosting capacity is demonstrated. Subsequently, the optimal ELS settings for LV networks are derived. The MV and LV analyses are conducted independently due to their distinct geographical characteristics. Specifically, the examined MV network is located in a rural area with a limited number of residential prosumers and a significant presence of large-scale PV systems. In contrast, the LV network under investigation is situated in a suburban area with a high number of residential prosumers and no large-scale PV parks.

5.1 | MV Network Analysis Results

5.1.1 | Number and Types of Violations

Figure 9 presents the total number of constraint violations for each scenario. Four types of violations are considered: voltage, feeder loading, and power transformer loading with and without an additional power transformer. Voltage violations include scenarios where the voltage exceeds 1.1 p.u. at any busbar, or where the voltage rise at the PCC is above 2%. Feeder loading violations refer to simulations in which at least one feeder operates above 100% of its rated capacity. Power transformer violations correspond to simulations where, under the loss of one power transformer ($N-1$ criterion), the loading of the remaining transformer exceeds 100%.

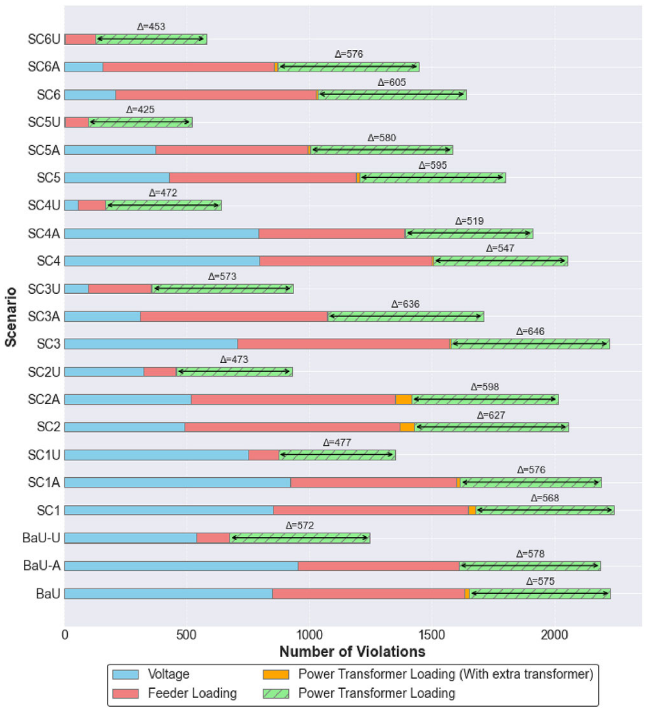

FIGURE 9 | MV system analysis: Number and type of violations for each scenario.

The results indicate that violations are significantly reduced across all scenarios when network reinforcement (A) and voltage upgrade (U) solutions are implemented. The impact of voltage upgrades is particularly pronounced, as they mitigate both voltage and equipment loading violations. Furthermore, in scenarios SC4U, SC5U and SC6U, voltage-related violations are almost completely eliminated.

Feeder loading violations are substantially reduced across all scenarios that incorporate voltage upgrades, while network reinforcement also provides a noticeable improvement. The impact of installing an additional power transformer at the transmission substation is shown in orange in Figure 9. The difference, Δ, in the number of violations with and without the additional power transformer ranges from 425 to 646. Although the extra transformer effectively eliminates transformer loading violations, it does not affect the violations occurring within the distribution network.

5.1.2 | Impact on Maximum Voltage Rise

The impact of the evaluated solutions on the maximum voltage difference before and after IBR integration, as well as on MV feeder loading, is presented in Figures 10 and 11, respectively. The X markers in each plot represent the average value for each scenario.

With regard to the maximum voltage difference, the decentralised IBR settings and the centralised voltage control methods from the power transformer have a significant impact, as shown in Figure 10a. This is evident from both the average value of each solution and the percentage of violations for each scenario.

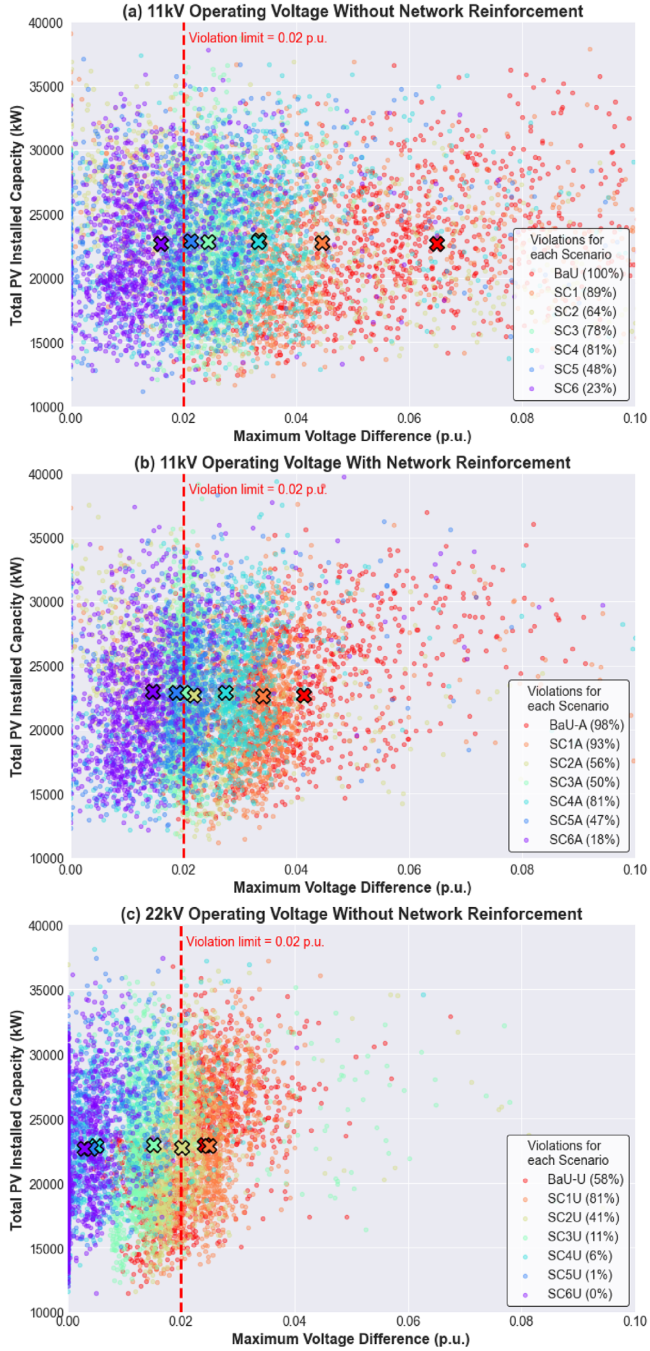

FIGURE 10 | MV system analysis: Maximum voltage rise.

Moreover, the results in Figure 10b,c indicates that network reinforcement and voltage upgrades reduce voltage variations, bringing them closer to the acceptable limits (set at 0.02 p.u. for maximum voltage deviation).

5.1.3 | Impact on Maximum Feeder Loading

With regard to the results for maximum feeder loading, it is shown that the IBR settings and the centralised voltage control have minimal impact. However, in Scenarios SC3 and SC6, which employ stricter settings (smaller $Q(V)$ deadband), the maximum feeder loading increases. This outcome was expected, since in

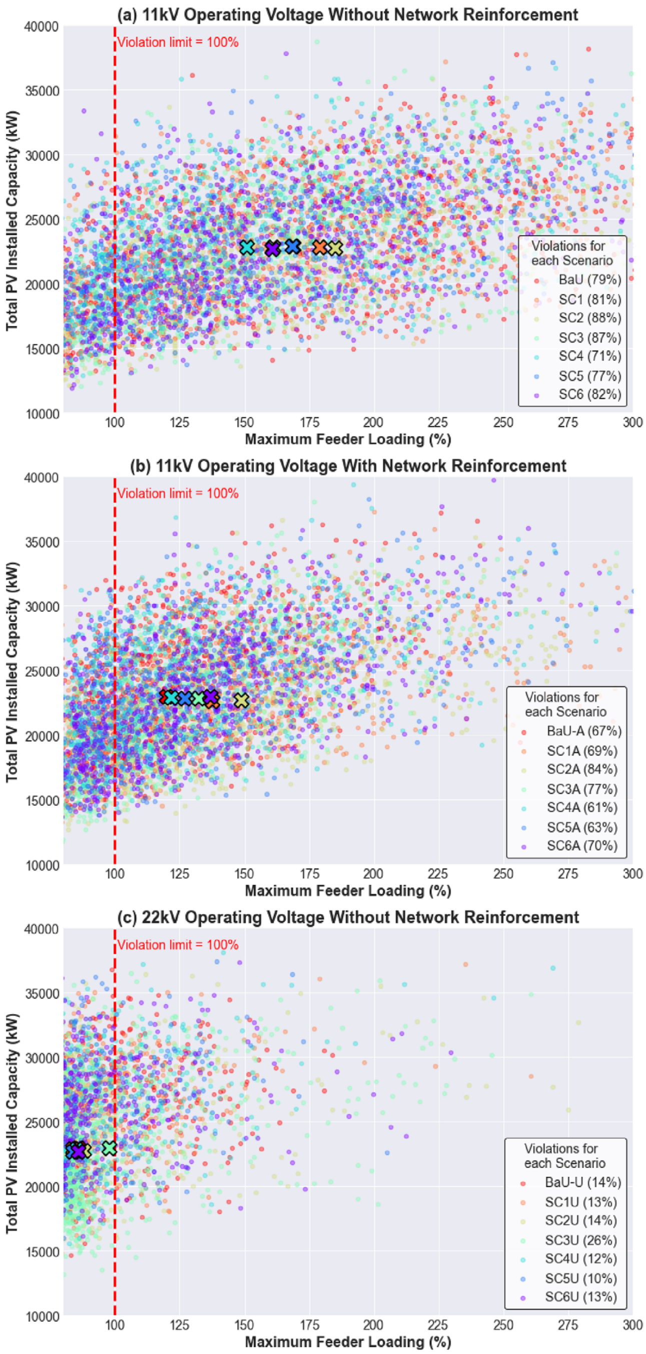

FIGURE 11 | MV system analysis: Maximum feeder loading.

those scenarios larger amounts of reactive power are absorbed to maintain voltages within the required limits. In contrast, network reinforcement and voltage upgrades have a substantial impact on maximum feeder loading. This is clearly illustrated in Figure 11b,c by the reduced spread of the scatter points.

5.1.4 | Impact on Hosting Capacity

The hosting capacity for each scenario, defined as the installed PV capacity that does not result in any constraint violations, is shown in Figure 12. The results demonstrate that hosting capacity increases when network reinforcement and voltage upgrade

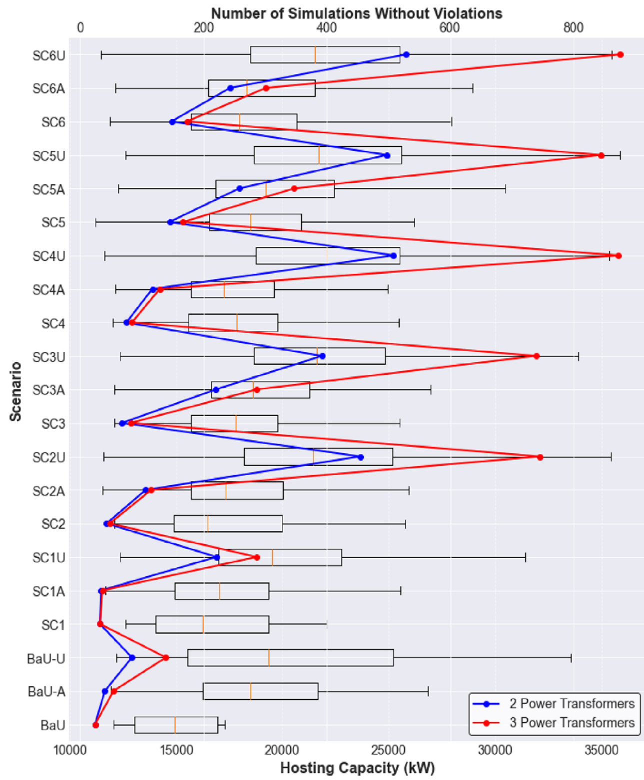

FIGURE 12 | MV system analysis: Hosting capacity.

solutions are implemented. In addition, stricter volt-var settings and RLDC contribute to further improvements. Although the increase in hosting capacity is not substantial, it is noteworthy that the number of simulations without violations is higher when the voltage upgrade solution is applied.

The improvement in hosting capacity is particularly evident when an additional 16 MVA power transformer is installed at the transmission substation (red line), compared with the existing configuration of two 16 MVA transformers (blue line). This suggests that the applied solutions have effectively minimised violations within the MV distribution system, shifting the primary limiting factor to the capacity of the transmission substation.

Overall, Scenarios SC2U, SC3U, SC4U, SC5U and SC6U maximise the MV network hosting capacity. Based on the median value of each scenario, SC5U achieves a slightly higher hosting capacity. This is attributed to the fact that the IBR settings in this solution correspond to $Q(V)_2$, which are neither overly strict ($Q(V)_3$) nor overly loose ($Q(V)_1$).

5.2 | Optimized ELS Calculation in the LV Network

Using the methodology outlined in Section 3, the optimal ELS settings were determined for each targeted RES penetration scenario, considering both single-phase and three-phase LV prosumers. The different sets of weighting parameters employed to compute the PI are summarised in Table 3.

TABLE 3 | Weight parameter values for PI calculation in (1).

Weight parameter	Acronym	S1	S2	S3	S4
RES generation	W_{RES}	1	1	1	1
RES curtailed	W_{CUR}	1	1	1	1
Voltage violation	W_{Voltage}	1	5	1	10
Loading violation	W_{Loading}	1	10	100	100

For this analysis, the weight parameter values corresponding to $S3 = [1, 1, 1, 100]$ were adopted, as these represent the preferred settings specified by the Cypriot DSO. Scenario S3, with a very high weight assigned to W_{Loading}, places significant emphasis on mitigating loading violations. The optimal ELS settings derived through the PSO algorithm for each RES penetration scenarios are shown in Figure 13. The x-axis represents the ELS for single-phase PV systems, while the y-axis corresponds to the ELS for three-phase systems.

The optimised ELS settings for single-phase (1Ph) and three-phase (3Ph) prosumers across different RES penetration levels are as follows:

- 40% RES penetration: 1Ph = 100%, 3Ph = 100%
- 60% RES penetration: 1Ph = 55%, 3Ph = 95%
- 80% RES penetration: 1Ph = 40%, 3Ph = 60%
- 100% RES penetration: 1Ph = 25%, 3Ph = 50%

The results indicate a clear trend whereby the ELS settings become more restrictive as RES penetration increases. It is noted that for a penetration level of 40%, the ELS settings are set to 100%. This result shows that at low penetration levels ELS should not be applied, since voltage and loading violations are mitigated without their use. This outcome is expected, as the number of violations, shown in Figure 1, increases significantly with higher RES penetration. Consequently, lower ELS thresholds are required to mitigate voltage and equipment loading violations.

Furthermore, the results highlight that the ELS values for single-phase prosumers are consistently lower than those for three-phase prosumers. This discrepancy arises because single-phase RES systems introduce voltage imbalance within the LV network. At lower RES penetration levels, where overvoltage is the primary limiting factor for hosting capacity, restricting the export from single-phase RES systems maximises TPI. However, at higher penetration levels, where equipment loading becomes the dominant constraint, imposing export limitations on three-phase RES systems also becomes necessary.

The optimal ELS settings were determined for RES penetration levels of 60%, 80%, and 100% were applied to evaluate the performance of the LV network. The results, illustrated in Figure 14, present the maximum busbar voltages and the distribution transformer loading under these conditions. A comparison with the initial results (Figure 1), where no ELS was applied, reveals a substantial improvement in both voltage regulation and transformer loading.

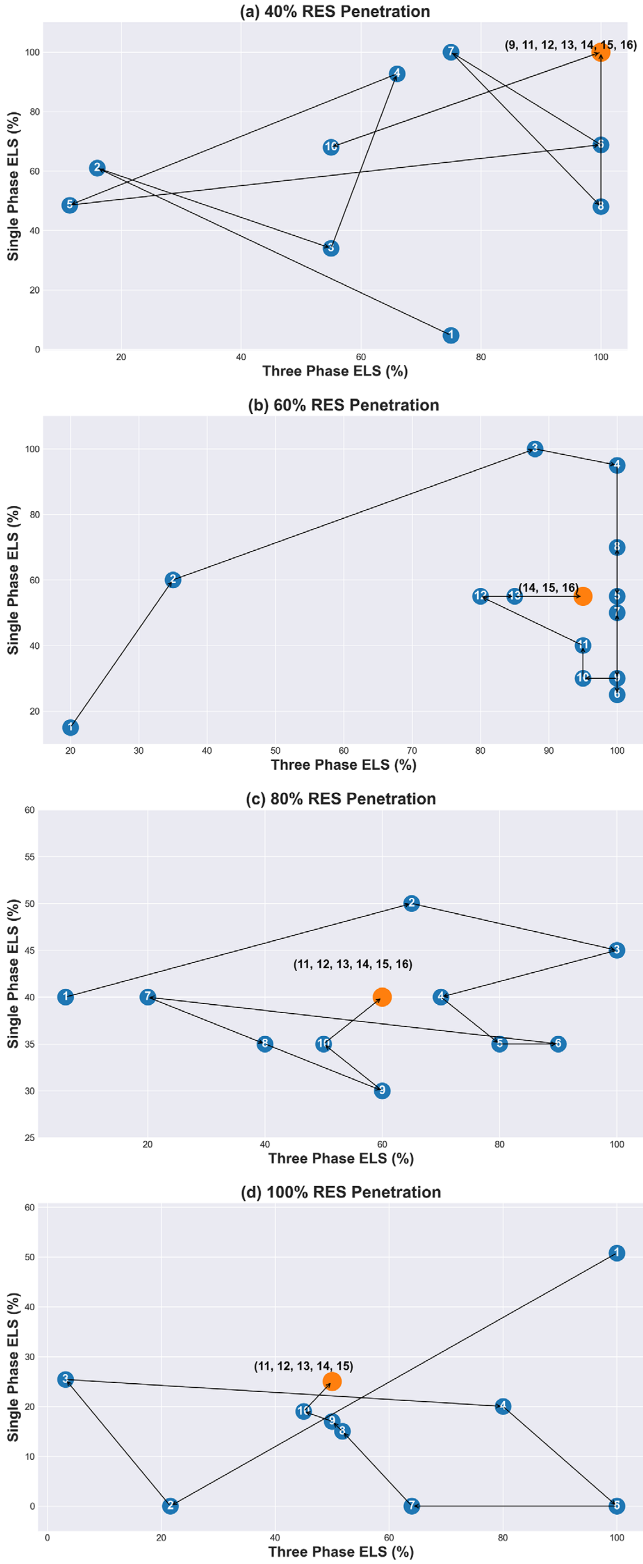

FIGURE 13 | LV system analysis: Evaluating ELS settings using PSO.

In particular, the transformer loading remains below 100%, as the weight parameter W_{Loading} was set to 100, heavily penalising loading violations in the optimisation process. Regarding maximum busbar voltages, a small number of violations persist for RES penetration levels exceeding 80%. This is attributed to the prioritisation of equipment loading constraints in the optimisa-

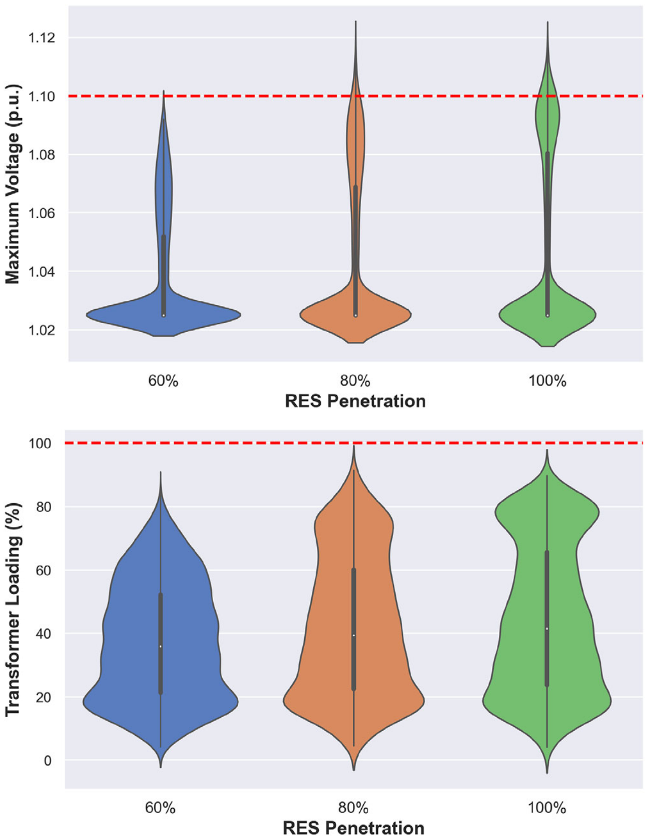

FIGURE 14 | LV system analysis: Maximum voltage and transformer loading for different RES penetration levels with ELS under weight category S3.

tion process, where the voltage weight parameter was assigned a lower value, leading to some residual voltage violations.

5.2.1 | Impact of Weight Selection on Optimal ELS Values

This subsection evaluates the impact of different weight parameter configurations from Table 3 on the optimised ELS settings. The results of the analysis are illustrated in Figure 15, where each category on the y-axis corresponds to a weight factor configuration from Table 3, while the x-axis represents the RES penetration scenario for which the ELS was optimised. The results for the 40% penetration scenario are not shown in Figure 15, since for all weight configurations the optimal ELS settings are 100% for both single- and three-phase systems (Figure 13).

The results confirm that the ELS values decrease as RES penetration increases, regardless of the weight factor configuration. However, the weighting of the violation-related factors, specifically W_{Voltage} and W_{Loading}, has a substantial influence on the optimised ELS values. Notably, higher violation weight factors result in lower ELS values. This occurs because greater weighting on violations in the TPI calculation places more emphasis on minimising constraint breaches, thereby necessitating stricter export limitations.

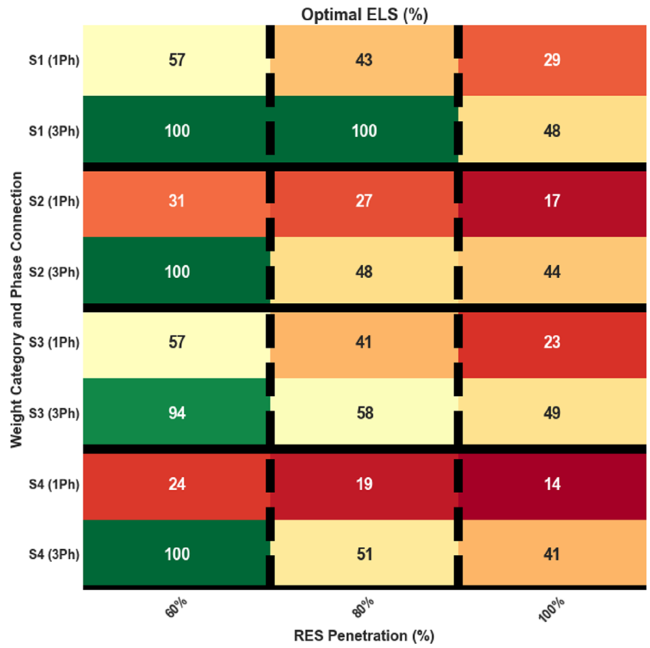

FIGURE 15 | LV system analysis: Impact of weight factors on optimal ELS calculation for different penetration levels.

In addition, the results demonstrate that increasing W_{Loading} leads to a reduction in the ELS for three-phase prosumers. This effect arises because three-phase prosumers typically install larger PV systems, which contribute to higher equipment loading, particularly during periods of low demand. Consequently, when the priority of avoiding equipment overloading is increased, stricter export limitations are imposed on three-phase prosumers.

6 | Conclusions

This study analysed two distribution network types where RES hosting capacity in Cyprus is currently limited: a rural MV network with large-scale PV parks and a suburban LV network with high residential prosumer participation. The results highlight the urgent need to enhance the hosting capacity of the Cyprus distribution system to accommodate the growing number of RES connections. The main objective of this study was to identify solutions that enable the distribution system to accommodate RES penetrations in the medium term, up to 60%. In selecting the solutions considered in this analysis, factors such as cost, impact on hosting capacity, fairness among prosumers, and applicability were taken into account. Based on the literature review, decentralised controls from IBRs, centralised control methods from power transformers, network reinforcements, voltage upgrades, and export limitation schemes were selected.

The results of the analysis indicate that for the MV network, leveraging existing infrastructure should be a priority. Transitioning IBR control from COSF(P) to stricter $Q(V)$ settings (preferably $Q(V)_2$) improves voltage regulation. Implementing RLDC at transmission substations with high RES penetration further minimises voltage violations. However, as RES penetration grows, transmission substation capacity may become a limiting factor, necessitating closer coordination between the

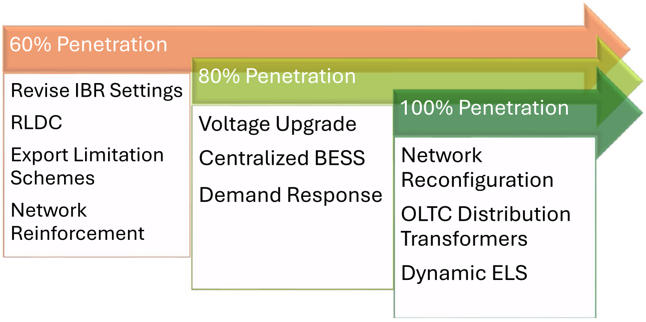

FIGURE 16 | Roadmap for increasing the RES hosting capacity of Cyprus up to 100% RES penetration.

DSO and TSO for strategic and timely network upgrades. In addition, upgrading MV network voltage, as already planned, will significantly enhance both voltage stability and equipment loading.

For the LV network, the results confirm that ELS are mandatory for RES penetrations beyond 60%. The DSO must enforce optimal ELS settings to prevent violations, although retroactive application to existing prosumers is impractical. Therefore, early implementation of ELS requirements is crucial. While ELS inevitably results in some curtailment, it can incentivize prosumers to adopt BESS, enhancing self-consumption and grid flexibility. By implementing these targeted solutions, the Cyprus power system can increase its RES hosting capacity while maintaining stability and reliability.

Strategic planning and timely regulatory action are key to enabling the country's energy transition. Although not investigated in sufficient depth in this manuscript, it may be inferred that for RES penetration levels exceeding 60%, the utilisation of existing infrastructure alone will be inadequate to enhance hosting capacity to the required extent (Figure 16). Achieving penetration levels of the order of 80% is expected to necessitate both an increase in the operating voltage and the deployment of large-scale centralised BESS. Concurrently, the Cypriot DSO should develop the capability to incorporate demand response mechanisms, including those originating from LV prosumers.

Penetration levels beyond this threshold will further require full observability and controllability of the entire distribution network. This will enable advanced operational measures such as network reconfiguration. Moreover, a noticeable share of distribution substations will likely need to be equipped with transformers featuring OLTC capabilities. Finally, the application of dynamic ELS schemes will be essential to enable the full exploitation of network capabilities under actual operating conditions.

Author Contributions

Phivos Therapontos: conceptualisation, data curation, formal analysis, investigation, methodology, visualisation, and writing –original draft. **Savvas Panagi:** data curation, formal analysis, investigation, methodology, software, validation, and writing – review and editing. **Rafail Constantinou:** methodology, visualisation and writing – review and editing. **Charalambos A. Charalambous:** data curation, funding acquisition, project administration, supervision, writing – review and editing. **Petros Aristidou:** conceptualisation, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, and writing – review and editing.

Acknowledgements

This project has received funding from the EU's Horizon Europe Framework Programme (HORIZON) under the grant agreement no. 101120278 (DENSE).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Research data are not shared.

References

1. IRENA, *Renewable Energy Highlights* (International Renewable Energy Agency, 2024).

2. *Ten Year Development Plan* (Cyprus Distribution System Operator, 2025).

3. P. Therapontos, R. Tapakis, A. Nikolaidis, and P. Aristidou, "Current and Future Challenges of the Cyprus Power System," in *Proceedings of the 13th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER 2022)* (IET, 2022), 313–318.

4. P. Therapontos and P. Aristidou, "The Impact of RES Curtailment Strategies for Congestion Avoidance on the Dynamic Frequency Performance of Low-Inertia Systems," in *2023 IEEE Belgrade PowerTech* (IEEE, 2023), 1–6.

5. W. J. Nacmanson and L. F. Ochoa, "Recommendations for the Planning of PV-Rich Distribution Networks: An Australian Case Study," in *IEEE General Meeting* (IEEE, 2022), 1–5.

6. A. Kotsonias, L. Hadjidemetriou, M. Asprou, and C. G. Panayiotou, "Operational Challenges and Solution Approaches for Low Voltage Distribution Grids—A Review," *Electric Power Systems Research* 239 (2025): 111258.

7. A. T. Procopiou and L. F. Ochoa, "Asset Congestion and Voltage Management in Large-Scale MV-LV Networks With Solar PV," *IEEE Transactions on Power Systems* 36, no. 5 (2021): 4018–4027.

8. *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, IEEE Std 1547-2018 (Institute of Electrical and Electronics Engineers, 2018).

9. *Power Generating Plants in the Low Voltage Network (VDE-AR-N 4105)* (Association for Electrical, Electronic & Information Technologies, 2019).

10. A. T. Procopiou and L. F. Ochoa, "On the Limitations of Volt-Var Control in PV-Rich Residential LV Networks: A UK Case Study," in *2019 IEEE Milan PowerTech* (IEEE, 2019), 1–6.

11. V. Vijayan, A. Mohapatra, and S. N. Singh, "Impact of Modes of Operation of Smart Inverters on Volt-Var Optimization," in *IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)* (IEEE, 2019), 1–5.

12. S. Krahmer, S. Ecklebe, P. Schegner, and K. Röbenack, "Analysis of Voltage Stability in Terms of Interactions of Q(U)-Characteristic Control in Distribution Grids," preprint, arXiv, February 8, 2022, https://arxiv.org/abs/2202.03986.

13. *Requirements for Generating Plants to Be Connected in Parallel With Distribution Networks - Part 1: Connection to a LV Distribution Network - Generating Plants up to and Including Type B (EN 50549-1)* (International Electrotechnical Commission, 2023).

14. *Grid Connection of Energy Systems via Inverters – Part 2: Inverter Requirements*, AS/NZS 4777.2:2020 (Standards Australia/Standards New Zealand, 2020).

15. M. Z. Liu, A. T. Procopiou, K. Petrou, et al., "On the Fairness of PV Curtailment Schemes in Residential Distribution Networks," *IEEE Transactions on Smart Grid* 11, no. 5 (2020): 4502–4512.

16. J. M. Home-Ortiz, L. H. Macedo, R. Vargas, R. Romero, J. R. S. Mantovani, and J. P. Catalao, "Increasing RES Hosting Capacity in Distribution Networks Through Closed-Loop Reconfiguration and Volt/Var Control," *IEEE Transactions on Industry Applications* 58, no. 4 (2022): 4424–4435.

17. R. A. Jacob and J. Zhang, "Distribution Network Reconfiguration to Increase Photovoltaic Hosting Capacity," in *2020 IEEE Power & Energy Society General Meeting (PESGM)* (IEEE, 2020), 1–5.

18. K. Petrou, L. F. Ochoa, A. T. Procopiou, et al., "Limitations of Residential Storage in PV-Rich Distribution Networks: An Australian Case Study," in *2018 IEEE Power & Energy Society General Meeting (PESGM)* (IEEE, 2018), 1–5.

19. V. Sharma, M. H. Haque, S. M. Aziz, and T. Kauschke, "Reducing Overvoltage-Induced PV Curtailment Through Reactive Power Support of Battery and Smart PV Inverters," *IEEE Access* 12 (2024): 123995–124008.

20. J. J. Cardoso, E. Francisco, M. Teixeira, P. G. Matos, and R. Mourão, "Storage-Driven Business Models: Unlocking Grid Hosting Capacity," paper presented at the CIRED 2024 Vienna Workshop, Vienna, Austria, 2024.

21. A. Fathollahi and B. Andresen, "Power Quality Analysis and Improvement of Power-to-X Plants Using Digital Twins: A Practical Application in Denmark," *IEEE Transactions on Energy Conversion* 40, no. 3 (2025): 1909–1921.

22. European Commission, "Directive (EU) 2019/944 on Common Rules for the Internal Market for Electricity and Amending Directive 2012/27/EU," in *Official Journal of the European Union* L 158 (2019): 125–199.

23. J. Yumbla, J. M. Home-Ortiz, T. Pinto, and J. R. S. Mantovani, "Maximizing PV Hosting Capacity in Unbalanced and Active Distribution Systems With EVs and Demand Response," *IEEE Access* 13 (2025): 152800–152811.

24. T. R. Ricciardi, K. Petrou, J. F. Franco, and L. F. Ochoa, "Defining Customer Export Limits in PV-Rich Low Voltage Networks," *IEEE Transactions on Power Systems* 34, no. 1 (2018): 87–97.

25. B. Aydin, R. Holt, and M. R. Almassalkhi, "Fairness-Aware Dynamic Hosting Capacity and the Impacts of Strategic Solar PV Curtailment," *Sustainable Energy, Grids and Networks* 43 (2025): 101869.

26. P. P. Vergara, J. S. Giraldo, M. Salazar, N. K. Panda, and P. H. Nguyen, "A Mixed-Integer Linear Programming Model for Defining Customer Export Limit in PV-Rich Low-Voltage Distribution Networks," *Journal of Modern Power Systems and Clean Energy* 11, no. 1 (2023): 191–200.

27. K. Petrou, A. T. Procopiou, L. Gutierrez-Lagos, M. Z. Liu, L. F. Ochoa, T. Langstaff, and J. M. Theunissen, "Ensuring Distribution Network Integrity Using Dynamic Operating Limits for Prosumers," *IEEE Transactions on Smart Grid* 12, no. 5 (2021): 3877–3888.

28. A. K. Karmaker, S. Behrens, B. Sturmberg, and H. Pota, "Managing Prosumer Exports in Distribution Networks Through Participatory Export Limits," in *IET Conference Proceedings CP876* (IET, 2024), 1148–1151.

29. *Capacity of Distribution Feeders for Hosting DER Working Group C6.24* (CIGRE, 2014).

30. E. Mulenga, M. H. Bollen, and N. Etherden, "A Review of Hosting Capacity Quantification Methods for Photovoltaics in Low-Voltage Distribution Grids," *International Journal of Electrical Power & Energy Systems* 115 (2020): 105445.

31. M. Bollen, T. T. de Oliveira, N. Etherden, S. Bhattacharyya, and S. Bahramirad, "20 Years of Hosting Capacity Studies, 2004–2024," in *CIRED 2024 Vienna Workshop* (IET, 2024), 217–220.

32. M. Patsalides, G. Makrides, A. Stavrou, V. Efthymiou, and G. E. Georghiou, "Assessing the Photovoltaic (PV) Hosting Capacity of Distribution Grids," in *Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MedPower 2016)* (IET, 2016), 1–4.

33. Z. Ali, N. Christofides, L. Hadjidemetriou, and E. Kyriakides, "Photovoltaic Reactive Power Compensation Scheme: An Investigation for the Cyprus Distribution Grid," in *2018 IEEE International Energy Conference (ENERGYCON)* (IEEE, 2018), 1–6.

34. A. Kotsonias, L. Hadjidemetriou, E. Kyriakides, and Y. Ioannou, "Operation of a Low Voltage Distribution Grid in Cyprus and the Impact of Photovoltaics and Electric Vehicles," in *ISGT-Europe* (IEEE, 2019), 1–5.

35. S. Panagi, P. Therapontos, C. Spanias, and P. Aristidou, "Impact of Uncontrolled Electric Vehicle Charging on Unbalanced Suburban Low-Voltage Networks," paper presented at the IEEE ISGT 2025, Malta, September 2025.

36. E. E. Ahmed, A. Demirci, G. Poyrazoglu, and S. D. Manshadi, "An Equitable Active Power Curtailment Framework for Overvoltage Mitigation in PV-Rich Active Distribution Networks," *IEEE Transactions on Sustainable Energy* 15, no. 4 (2024): 2745–2757.

37. *Enhanced Voltage Control EAVC Settings Calculation Guide*. *Reference F9183* (Fundamentals Ltd., 2018), www.fundamentalsltd.co.uk.

38. A. Mufaris, J. Baba, S. Yoshizawa, and Y. Hayashi, "Determination of Dynamic Line Drop Compensation Parameters of Voltage Regulators for Voltage Rise Mitigation," in *2015 International Conference on Clean Electrical Power (ICCEP)* (IEEE, 2015), pp. 319–325.

39. E. S. Chatzistylianos, G. N. Psarros, and S. A. Papathanassiou, "Export Constraints Applicable to Renewable Generation to Enhance Grid Hosting Capacity," *Energies* 17, no. 11 (2024): 2588.

40. *Flexibility Connections: Explainer and Q&A* (Energy Networks Association, 2021).

41. *PowerFactory 2023 - User Manual*, (DIgSILENT GmbH, 2023).

42. J. Kennedy and R. Eberhart, "Particle Swarm Optimization," in *Proceedings of ICNN'95-International Conference on Neural Networks*, vol. 4 (IEEE, 1995), 1942–1948.

43. L. Thurner, A. Scheidler, F. Schäfer, et al., "Pandapower—An Open-Source Python Tool for Convenient Modeling, Analysis, and Optimization of Electric Power Systems," *IEEE Transactions on Power Systems* 33, no. 6 (2018): 6510–6521.

44. D. Wang, D. Tan, and L. Liu, "Particle Swarm Optimization Algorithm: An Overview," *Soft Computing* 22, no. 2 (2018): 387–408.