Hosting Capacity Maximization of Distributed Energy Resources through Simultaneous Optimized Volt-Var Curve and Network Reconfiguration

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***Abstract*—Distributed Energy Resources (DERs) integration into distribution systems becomes problematic when the penetration level exceeds the system DER hosting capacity. Although several studies propose to quantify DER hosting capacity, methodologies to maximize it in distribution systems are scarce. Some approaches propose installing var compensators, incurring in costly solutions; others propose reduced cost solutions like network reconfiguration or optimized Volt-Var curve. Nevertheless, the combination of these approaches has not been proposed. Therefore, this paper proposes the simultaneous network reconfiguration and optimized setting of grid-tie inverter Volt-Var curve to maximize DER hosting capacity and minimize power losses. The uncertainties are addressed using Monte Carlo simulation, whereas Non-Dominated Sorting Genetic Algorithm II handles the multi-objective problem. The simulations are performed using Matlab and OpenDSS software, considering the IEEE 33-bus test system. Finally, the results demonstrate the superiority of the proposed approach against previous studies that performed network reconfiguration and Volt-Var optimization separately.**

***Index Terms*—Distributed energy resources, hosting capacity maximization, volt-var curve optimization, network reconfiguration.**

I. Introduction

The proliferation of Distributed Energy Resources (DERs) in electric power systems requires planning and operation strategies to overcome power quality issues [1]. In particular, DERs integration to distribution systems becomes problematic when the penetration level exceeds the system DER hosting capacity, since it leads to violations of power quality constraints like reverse power flow in substations and overvoltage. Therefore, maximizing hosting capacity is crucial to enable customer service expansion by allowing more power from prosumers and load supply without violations of power quality constraints [2], [3].

Although several studies propose to quantify DER hosting capacity, methodologies to maximize it in distribution systems are scarce. Some researchers propose installing var compensators to increase DER hosting capacity, incurring in costly solutions. In [4], [5], on-load tap changer (OLTC) transformers and static var compensator (SVC) were used to increase DER hosting capacity of distribution systems, as these devices assist in the maintenance of the network voltage profile. The system DER hosting capacity was maximized in [6] using SVC and static synchronous compensators (STATCOM). Additionally, optimal operation of capacitor banks, substations' OLTC, voltage regulators, and network reconfiguration were proposed in [7] to minimize the problems caused by the DER integration. Genetic Algorithm was employed in [8] to increase the capacity to integrate DERs into distribution systems through the installation of switched capacitors and voltage regulators, system reconfiguration, and adjusting the power factors of the inverters associated with photovoltaic modules. It is important to mention that these power factors remain fixed regardless of changes in bus voltage. The optimized allocation of fixed and switched capacitor banks and voltage regulators was performed in [9] to minimize system voltage deviation and, consequently, increase DER hosting capacity.

Furthermore, other papers proposed cost-effective solutions like network reconfiguration or optimized Volt-Var curve of grid-tie inverters. In [10], Non-Dominated Sorting Genetic Algorithm II (NSGA-II) was used to optimize the distribution system configuration with the purpose of reducing power losses, improving the voltage profile, and maximizing the capacity to accommodate photovoltaic modules in the 33 and 69-bus test systems. A mixed integer nonlinear programming approach was proposed in [11] to increase DER hosting capacity, considering the network reconfiguration. A hybrid particle swarm optimization algorithm was developed in [12] to find an optimal network topology that reduces the issues caused by the integration of DERs.

The Volt-Var control curve provided by the IEEE 1547-2018 standard was adopted in [13] to increase DER hosting

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capacity of the IEEE 123-bus test feeder. In [14], the particle swarm optimization algorithm was considered to increase the capacity to integrate DERs into medium voltage distribution systems by determining the best Volt-Var control curve set-points. The slime mould algorithm was employed in [15] to increase DER hosting capacity and reduce network voltage deviation, by defining the optimized locations and sizes of DERs and energy storage systems (ESSs), in addition to the optimized Volt-Var control curve set-points.

Some studies incorporate network reconfiguration along with voltage control through devices that can provide reactive power support. In [16], binary particle swarm optimization and optimal power flow were utilized to minimize the system power losses through network reconfiguration and the control of switching capacitors. A mixed-integer second-order cone programming model was formulated in [17] to reconfigure the distribution system and determine the optimized location and size of DERs, taking into account their reactive power capability. In [18], the authors proposed a novel approach to minimize power losses and carbon dioxide emissions through simultaneous distribution system reconfiguration and allocation of DERs and SVCs. A modified binary gray wolf optimization was proposed in [19] for achieving an efficient and optimally coordinated operation of OLTC transformers, shunt capacitors, and voltage regulators. These devices were integrated with network reconfiguration to minimize the energy demand of the distribution system.

Nevertheless, the cost-effective solutions proposed in [10]–[15] focus on either network reconfiguration or Volt-Var optimization independently, limiting the identification of comprehensive solutions to maximize DER hosting capacity. Additionally, most studies that aim to maximize this capacity do not thoroughly assess the potential negative impacts of their methodologies on power losses [11], [12], [14], [15]. The studies discussed in [10], [11], [13], [14] do not include evaluations on both 24-hours analysis and the uncertainties associated with DERs and loads, which are crucial for identifying robust and practical solutions.

Additionally, the optimization approaches proposed in [16]–[19], despite implementing network reconfiguration combined with reactive power support to control the system's voltage, do not leverage the Volt-Var control function of DERs' grid-tie inverters. Consequently, the installation of reactive power compensation devices is required to regulate the voltage profile of the system. Moreover, the studies carried out in [16]–[19], do not explicitly consider the maximization of DER hosting capacity in their analyses. Therefore, the motivation of this research is to address shortcomings in the previously mentioned state of the art by optimizing the system's configuration and the Volt-Var control curve, aiming to increase DER hosting capacity and reduce power losses, all within the context of uncertainties associated with DERs and loads.

For this reason, this paper proposes the simultaneous network reconfiguration and optimized setting of grid-tie inverter Volt-Var curve to meet DER hosting capacity maximization and, at the same time, to minimize power losses. By mutually considering network reconfiguration and Volt-Var optimization, the solution space is explored more comprehensively, leading to better overall system performance. Both approaches are selected in this paper due to their cost-effectiveness compared to competing solutions. By strategically modifying the system's topology and leveraging the Volt-Var control function inherent in smart inverters, it is possible to avoid the installation of other commonly employed devices, including OLTC transformers, voltage regulators, var compensators, among others. This choice results in a reduction in investment costs for the system operator. Furthermore, to address the uncertainties associated with DERs locations, irradiance, and load profiles, the Monte Carlo simulation (MCS) is adopted. Finally, the proposed methodology employs the NSGA-II to address the multi-objective optimization problem and is assessed using the IEEE 33-bus test system.

The remainder of the paper is organized as follows: the proposed methodology is depicted in Section II. Distribution system and simulation setup are discussed in Section III. Results and discussion regarding the optimization problem are presented in Section IV. Concluding remarks are provided in Section V.

II. Methodology

Given the conflicting objective functions of maximizing DER hosting capacity and minimizing power losses, a multi-objective optimization approach is necessary. For this reason, this paper adopts the NSGA-II due to its ability to handle multi-objective optimization problems and generate a diverse set of Pareto-optimal solutions. By combining genetic operators and non-dominated sorting, NSGA-II effectively guides the evolutionary search process towards optimal solutions [20].

Fig. 1 shows a flowchart outlining the multi-objective optimization approach proposed to maximize DER hosting capacity and minimize power losses. In Fig. 1, s is the s^{th} scenario randomly generated by the MCS; g is the DER penetration level of the system (in percentage); k is the NSGA-II generation; and max denotes the maximum value of each one of these variables.

The steps of the proposed methodology are:

1) Initialize the parameters of NSGA-II and input data: The NSGA-II parameters are determined by the number of individuals, crossover probability, mutation probability, and the number of generations. The decision variables in this optimization problem consist of two components. The first one includes the set-points that characterize the Volt-Var control curve (V_1^{inv}, V_2^{inv}, V_3^{inv}, and V_4^{inv}). Since this study considers the IEEE 1547-2018 standard, the lower and upper boundaries of these decision variables are 0.88 and 1.10 pu, respectively; whereas the reactive power set-points of the Volt-Var curves are -44% and +44% of the DER apparent rated power [21]. The second component of the decision variables encompasses the specific tie or sectionalizing switches that must be opened to achieve the optimized network topology. From an operational point of view, it is essential to maintain the radial feature of the distribution system during the reconfiguration process [22].

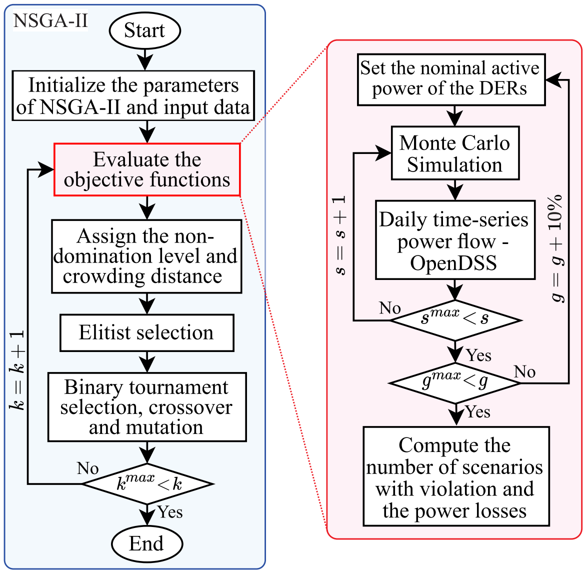

Fig. 1. Flowchart of the proposed methodology.

Furthermore, it is necessary to define the percentage of consumers with DER in the system. In this case, 20% of consumers were considered, based on [3]. The databases for load and DER generation must be defined. For the tests presented in this study, real irradiance data from the city of Salvador, Brazil, collected by the National Institute of Meteorology [23], were utilized. Regarding load profiles, real data provided by the Geographic Database of the Distributor [24] were used. It is important to notice that these data, collected over a period of 3 years from 2018 to 2020, have a sampling interval of 1 hour. In each Monte Carlo scenario, daily curves of load and irradiance are randomly chosen from the database. This extended time frame was deliberately chosen to ensure that the proposed methodology remains suitable for long-term applications, eliminating the need for modifications based on seasonal variations.

2) Evaluate the objective functions: The optimization problem proposed in this paper presents high complexity due to the consideration of uncertainties about DERs locations, irradiance, and load profiles. To address this complexity and effectively consider these uncertainties, this paper adopts MCS. This technique enables the generation of multiple random samples, facilitating a comprehensive exploration of the behavior of the system and capturing a wide range of possible scenarios. Therefore, s^{max} scenarios are randomly generated by the MCS for each one of the DER penetration levels ranging from 0% to 100% with an increment of 10%. While alternative increment values of the DER penetration level could be considered, a reduction in this value increases computational time. For the specific case study conducted in this paper, employing a 10% increment proved adequate, leading to an enhanced DER hosting capacity and reduced power losses.

For each of these scenarios, a daily time-series power flow analysis is conducted using the OpenDSS software [25], considering the population generated by NSGA-II, which includes the network configuration and the Volt-Var control curve. Based on tests conducted in this paper, a total of 500 scenarios proved to be adequate to attain convergence in the MCS. Following this, the number of scenarios with violations and the system's power losses can be computed. Furthermore, the DER penetration level is defined as the ratio between the installed DERs power and the total load active power [26].

Equations (1)–(10) provide the problem formulation for the multi-objective optimization problem discussed in this paper.

$$\min f_1 \sum_{s}^{s^{max}} \sum_{g}^{g^{max}} \frac{P_{s,g}^{losses}}{s^{max} g^{max}} \tag{1}$$

$$\min f_2 \sum_{s}^{s^{max}} \sum_{g}^{g^{max}} \frac{V_{s,g}}{s^{max} g^{max}} \times 100\% \tag{2}$$

subject to

$$\sum_{ki \in \Omega_l} P_{ki} - \sum_{ij \in \Omega_l} (P_{ij} + R_{ij} I_{ij}^2) - P_i^d = 0; \forall i \in \Omega_b \tag{3}$$

$$\sum_{ki \in \Omega_l} Q_{ki} - \sum_{ij \in \Omega_l} (Q_{ij} + X_{ij} I_{ij}^2) - Q_i^S + Q_i^d = 0; \forall i \in \Omega_b \tag{4}$$

$$\left(P_i^{DER}\right)^2 + \left(Q_i^{DER}\right)^2 \leq \left(S_{rated}\right)^2; \forall i \in \Omega_b \tag{5}$$

$$P_i^{DER} \geq 0.05\ P_{rated}; \forall i \in \Omega_b \tag{6}$$

$$-0.44\ S_{rated} \leq Q_i^{DER} \leq 0.44\ S_{rated}; \forall i \in \Omega_b \tag{7}$$

$$-2.2\ P_i^{DER} \leq Q_i^{DER} \leq 2.2\ P_i^{DER}; \forall i \in \Omega_b \tag{8}$$

$$0.88 \leq V_n^{inv} \leq 1.10;\ \ n = 1, 2, 3, 4 \tag{9}$$

$$V_m^{inv} \leq V_n^{inv};\ \ \forall m < n \tag{10}$$

Objective functions (1) and (2) aim to minimize the power losses of the distribution system and the number of scenarios with violations, respectively. The first violation evaluated in this paper encompasses the voltage level of the buses, which should be between 0.93 pu and 1.05 pu for systems with nominal voltage between 1 kV and 69 kV, according to Module 8 of the Procedures for Electric Energy Distribution in the National Electric System (PRODIST) [27]. The second violation involves the issue of reverse power flow at the substation, as it affects the coordination of overcurrent protection and the operation of voltage regulators [28], [29]. In (1) and (2), the variables $P_{s,g}^{losses}$ represent the power losses of the system for each Monte Carlo scenario s and DER penetration level g, while the binary variable $V_{s,g}$ denotes the presence of a violation in the corresponding Monte Carlo scenario, taking the value of 1 for a violation and 0 otherwise.

Constraints (3) and (4) represent the active and reactive power balances at each bus, respectively. In these equations, P_{ki} and Q_{ki} are the active and reactive power flows in branch ki; while P_{ij} and Q_{ij} are the active and reactive power flows in branch ij, respectively. P_i^d and Q_i^d are the active and reactive power demands at bus i. R_{ij} and X_{ij} are the resistance and reactance of the branch ij, respectively. Finally, Ω_b is the set of buses and Ω_l is the set of branches.

Constraints (5)–(8) are based on the IEEE 1547-2018 standard, which specifies the attributes of reactive and active power control requirements of the inverter-based DERs. Constraint (5) represents the apparent power limit of the DERs; the minimum steady-state active power is presented in (6); and the reactive power limits of the DERs are described in (7) and (8). In (5)–(8), P_i^{DER} and Q_i^{DER} are the active and reactive powers provided by the DERs; and S_{rated} and P_{rated} are the rated apparent and active powers of the DERs. Constraints (9) and (10) present the limits regarding the Volt-Var control curve set-points.

3) Assign the non-domination level and crowding distance: By evaluating the objective functions for the population, it is possible to assign a non-domination level and crowding distance to each individual. These measures are crucial in multi-objective optimization, as they help to identify the trade-offs between different objectives and determine the diversity of solutions in the population. The non-domination level indicates the relative superiority of individuals in terms of their objective function values, whereas the crowding distance assesses the density of individuals in the objective space [20].

4) Elitist selection: The elitist selection aims to preserve the best solutions from one generation to the next. After evaluating the population based on their non-domination levels and crowding distances, the algorithm identifies the set of individuals that belong to the non-dominated front. The elitist selection strategy ensures that this set of individuals survives to the next generation. By prioritizing the preservation of the best solutions, the NSGA-II effectively promotes convergence towards the Pareto-optimal front.

5) Binary tournament selection, crossover, and mutation: Binary tournament selection is employed to choose individuals for reproduction, in which pairs of individuals are randomly selected from the population and compared based on their fitness [30]. The genetic operator crossover is applied to the selected individuals to create new offspring individuals. This process involves exchanging genetic information between the parents, resulting in diverse and potentially superior solutions [30]. To introduce diversity and explore new regions of the search space, mutation is applied to the offspring solutions.

Finally, the solutions generated by this algorithm encompass the optimized network configuration and grid-tie inverter Volt-Var curve settings, which simultaneously maximize the DER hosting capacity and effectively minimize power losses in the distribution system. It is crucial to emphasize that, differently from other papers in the literature, this study does not aim to allocate DERs in specific buses of the distribution system. Instead, the DERs' locations are randomly defined for each Monte Carlo scenario. Therefore, the optimization method searches for an optimized solution that minimizes the objective functions independently of the DERs' locations.

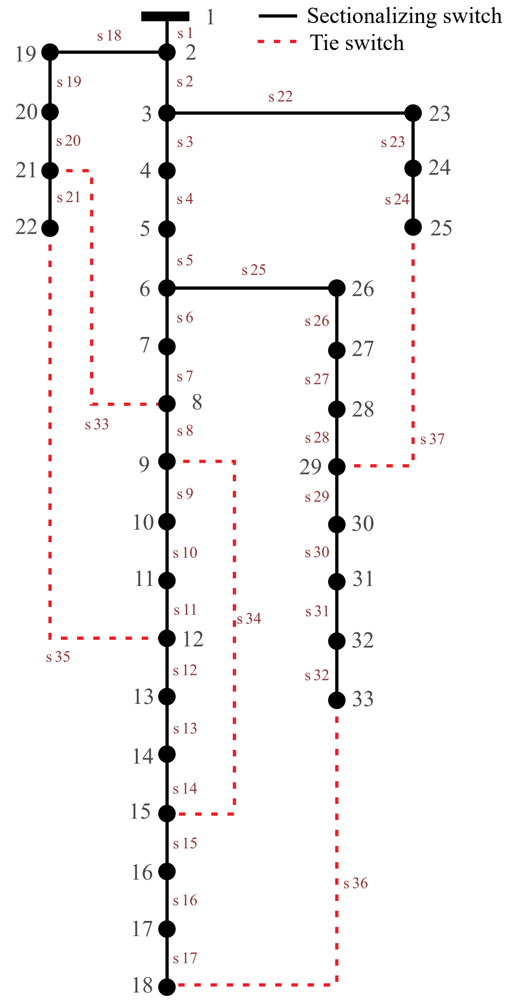

Fig. 2. Representation of the 33-bus test system.

III. Distribution system and simulation setup

The IEEE 33-bus test system, depicted in Fig. 2, was adopted to evaluate the methodology proposed in this paper. This system presents a total load of 3.715 MW and 2.300 MVAr, with a nominal voltage of 12.66 kV. The information regarding the loads and lines are depicted in [31].

The NSGA-II was implemented in the MATLAB environment, which calls the OpenDSS via a COM Interface every time that the power flow is required [25], [32]. The NSGA-II simulation was performed considering a population of 100 individuals, with a crossover probability of 90%, a mutation probability of 10% and a maximum number of generations of 100. These parameters were selected considering the influence of each NSGA-II parameter on the algorithm performance [30].

IV. Results and discussion

Fig. 3 shows the Pareto front resulting from the optimization problem presented in this paper, which considers the simultaneous network reconfiguration and optimized setting of grid-tie inverter Volt-Var curve. This graph includes the objective

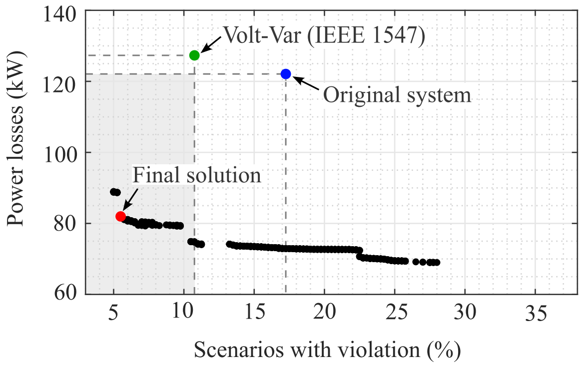

Fig. 3. Pareto front considering the proposed methodology.

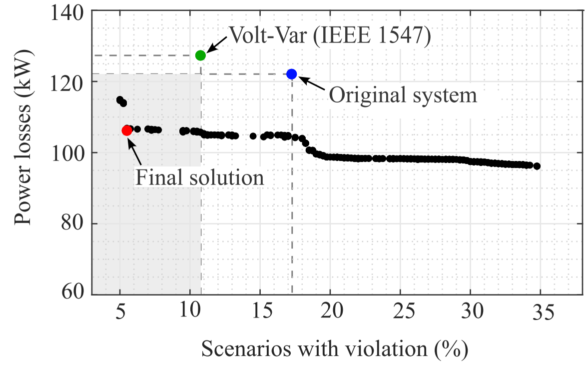

Fig. 4. Pareto front considering the optimized Volt-Var curve.

function values for: the original system configuration without Volt-Var control (blue point); the original system configuration with the Volt-Var curve suggested by the IEEE 1547-2018 standard (green point); the Pareto front with the optimized network configuration and grid-tie inverter Volt-Var curve setting (black points); and the final solution chosen to evaluate the system performance (red point).

Initially, it is evident that the implementation of the Volt-Var control suggested by the IEEE 1547-2018 standard in the grid-tie inverters reduced the number of scenarios with violations; however, it resulted in increased power losses. The increased reactive power absorption by the grid-tie inverters, necessary to minimize overvoltage issues, contributes to higher power losses in the distribution system. This trade-off between the number of scenarios with violations and power losses highlights the importance of considering both objectives when optimizing the system configuration.

In the context of Pareto optimality, all solutions within the Pareto front are considered equally valid from a multi-objective optimization perspective. Therefore, the decision maker's preferences become crucial in selecting the most appropriate solution, as different solutions may align better with specific criteria and priorities. In this study, a primary criterion was established: the chosen solution should not lead to a deterioration of either f_1 or f_2 compared to the original system. As a result, the solution that effectively reduces scenarios with violations without significantly increasing power losses was given priority. This selected solution is highlighted in red in Fig. 3.

The selected solution involves opening switches s_7, s_9, s_{14}, s_{28}, and s_{32}, and adjusting the set-points that define the Volt-Var control curve (V_1^{inv}, V_2^{inv}, V_3^{inv}, and V_4^{inv}) to 1.006, 1.045, 1.047, and 1.048, respectively. This optimized solution achieved a reduction of 32.9% in f_1 and 68.1% in f_2 when compared to the original system.

A. Comparative Analysis

To demonstrate the effectiveness and superiority of the proposed methodology in terms of DER hosting capacity and power losses, it was compared with the following approaches:

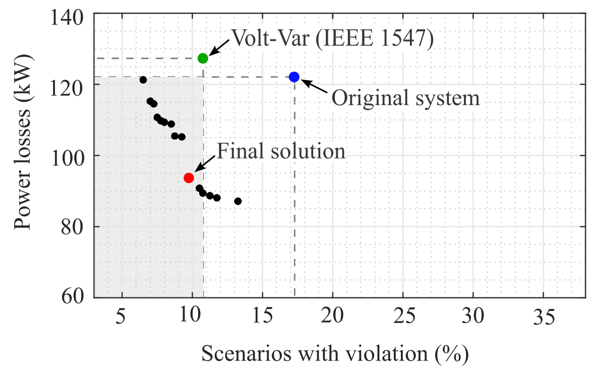

Fig. 5. Pareto front considering the optimized network reconfiguration.

- Approach 1: Original system configuration without Volt-Var control.
- Approach 2: Original system configuration with the Volt-Var curve suggested by the IEEE 1547-2018 standard.
- Approach 3: Original system configuration with the optimized grid-tie inverter Volt-Var curve setting [14], [15].
- Approach 4: Optimized system configuration without the Volt-Var control [10]–[12].
- Approach 5: Optimized system configuration and grid-tie inverter Volt-Var curve setting (proposed approach).

Approach 3 was previously proposed in [14], [15], whereas approach 4 was introduced in [10]–[12]; and they were applied to the problem discussed in this paper to enable a comparison with the methodology proposed in the current study. The Pareto fronts for approaches 3 and 4 are presented in Figs. 4 and 5, respectively. The same criteria used in Fig. 3 were adopted to choose the final solution in Figs. 4 and 5. The selected solution for approach 3 involves adjusting the set-points that define the Volt-Var control curve (V_1^{inv}, V_2^{inv}, V_3^{inv}, and V_4^{inv}) to 1.027, 1.040, 1.046, and 1.049, respectively. Additionally, the chosen solution for approach 4 requires opening switches s_{10}, s_{13}, s_{26}, s_{33}, and s_{36}.

Fig. 6 presents the objective function values for the five approaches, along with their variation in relation to the original system without Volt-Var control. Based on these graphs, it is

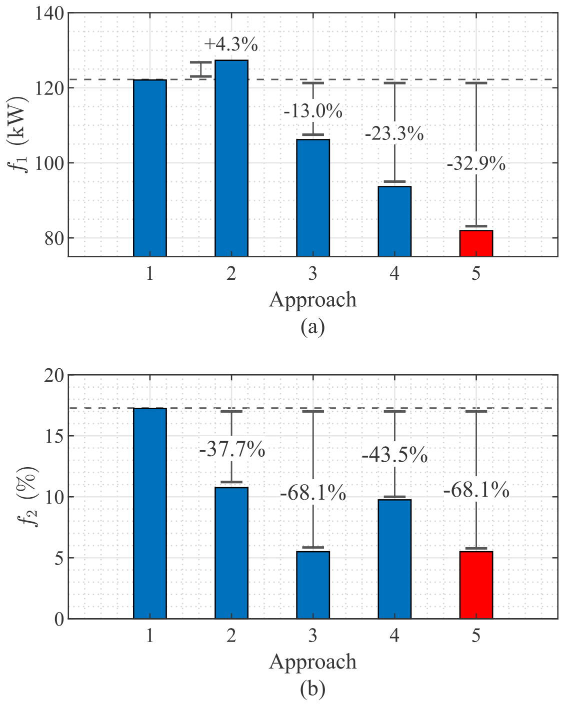

Fig. 6. Comparative analysis of the objective function values, considering (a) power losses and (b) number of scenarios with violation.

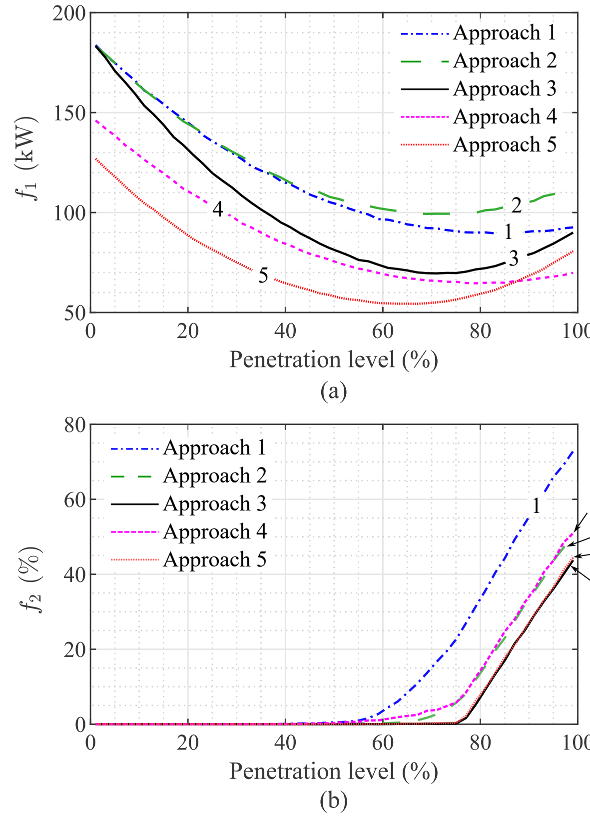

Fig. 7. Objective function values for each penetration level, considering (a) power losses and (b) number of scenarios with violation.

possible to notice that the proposed methodology, highlighted in red in Fig. 6, achieves a significant maximization of DER hosting capacity while effectively minimizing power losses. These results illustrate the superiority and effectiveness of the approach proposed in this paper when compared to the others.

Fig. 7(a) presents the average value of power losses for each penetration level. Fig. 7(b) shows the ratio between the number of scenarios violating technical constraints and the total number of Monte Carlo scenarios generated for each penetration level. Both results were obtained for each approach evaluated in this study.

Based on Fig. 7(a), it is evident that the relationship between power generated by DERs and power losses exhibits a U-shaped curve. Initially, as the DER penetration level increases, the power losses decrease. However, beyond a certain point, the power losses start to increase with further increments in the DER penetration level. Among the evaluated approaches, approach 2 stands out as the only one that increased the power losses when compared to the original system. This is due to the presence of overvoltage issues in the system, leading the Volt-Var control, suggested by the IEEE 1547 standard, to set the grid-tie inverters to absorb reactive power. Approach 3 reduced the power losses by increasing the Volt-Var set points (V_1^{inv}, V_2^{inv}, V_3^{inv}, and V_4^{inv}) compared to the Volt-Var curve suggested by the IEEE 1547 standard. This adjustment helps decrease power losses by providing reactive power to the buses without overvoltage issues. However, for the buses with overvoltage issues, the Volt-Var control set the grid-tie inverters to absorb reactive power in order to reduce the bus voltage. Furthermore, approach 4, which is based on network reconfiguration, also effectively reduced power losses by finding the optimized system topology. Finally, the proposed approach demonstrates the most favorable outcome, with overall lower values of power losses compared to the other approaches. This showcases the effectiveness of the proposed methodology in optimizing the system configuration to achieve superior performance in terms of power losses.

From the analysis of Fig. 7(b), it is noticed that no violations occurred for penetration levels up to 40%. However, beyond this value, the percentage of scenarios with violations increases with the increment of the penetration level, with the system experiencing issues related to overvoltage and reverse power flow in the substation. Regarding DER hosting capacity, approaches 2 to 5 exhibited improvements compared to the original system. Among them, approaches 2 and 4 presented similar behavior, with the approach that considers the Volt-Var curve suggested by IEEE 1547 standard presenting a slightly lower percentage of violations compared to the approach that only performed the optimized network reconfiguration. Furthermore, approaches 3 and 5 demonstrated similar behavior for all DER penetration levels, both achieving substantial reductions in violations compared to the original system, as shown in Fig. 7(b). However, the proposed method, represented by approach 5, outperformed approach 3 by achieving a lower power loss value.

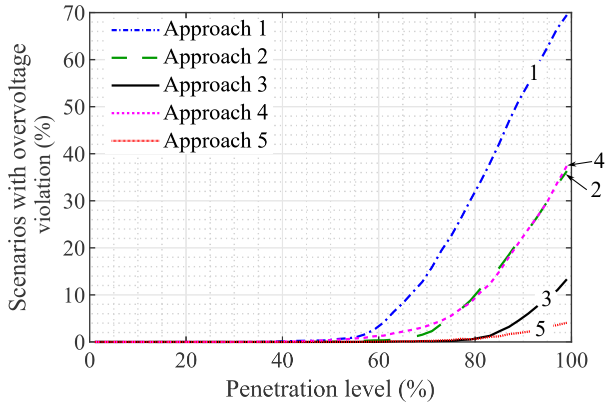

Fig. 8. Overvoltage violation for each penetration level.

In the distribution system evaluated in this study, the technical constraint that most significantly impacts the DER hosting capacity is overvoltage. Therefore, the proposed optimization algorithm prioritized the reduction of the overvoltage problem to maximize the DER hosting capacity, making the system better suited to integrate a higher penetration of DERs. Fig. 8 shows the ratio between the number of scenarios presenting overvoltage issues and the total number of Monte Carlo scenarios generated for each penetration level.

All the compared approaches succeeded in achieving lower overvoltage issues in the distribution system. Among them, approaches 2 and 4 exhibited similar behaviors. Additionally, the adjustment of the Volt-Var control curve proved to be more effective in mitigating voltage regulation problems compared to the optimized network reconfiguration. Notably, the proposed approach presented the lowest value of overvoltage violations, indicating its superior performance in addressing these challenges.

Fig. 9 illustrates the average voltage profile of the distribution system obtained from multiple Monte Carlo scenarios, representing the results for the proposed approach. The voltage profile is presented for each bus and for different levels of DER penetration, ranging from 0% to 100%.

From the analysis of Fig. 9, it is possible to notice that the voltage profile exhibits a direct correlation with the penetration level of DERs; as the DER penetration level increases, the voltage levels also rise accordingly. Additionally, the buses located farther away from the substation tend to experience lower voltage levels due to the increased impedance in the line sections, leading to a voltage drop along the distribution network. With the increase in DER penetration level, the voltage drop at the distant buses decreases due to the proximity of the distributed generators to the loads. Despite these variations, the voltage levels presented in Fig. 9 consistently meet the technical constraints specified by PRODIST, remaining within the range of 0.93 and 1.05 pu.

V. Conclusion

This paper proposed a novel approach that simultaneously optimizes network reconfiguration and grid-tie inverter Volt-Var curve settings to maximize DER hosting capacity while minimizing power losses. The results demonstrate significant reductions of 32.9% in power losses and 68.1% in scenarios violating technical constraints, compared to the original system. The proposed methodology outperforms previous approaches where network reconfiguration and Volt-Var optimization are performed separately, highlighting its effectiveness in enhancing DER hosting capacity and system performance. Furthermore, the proposed approach substantially mitigates overvoltage problems, which are the critical violations limiting DER integration. The comprehensive evaluation of uncertainties in DERs generation and load, along with the use of the NSGA-II optimization algorithm, further enhances the reliability and robustness of the proposed methodology.

In conclusion, this paper has contributed significantly to the field of distribution system operation in the following ways:

1) The proposed methodology offered a cost-effective solution by eliminating the need for additional equipment such as var compensators.
2) By mutually considering network reconfiguration and Volt-Var optimization, the proposed approach promoted substantial improvements in overall system performance.
3) The incorporation of uncertainties related to DERs and loads, in addition to a 24-hour analysis, enhanced the reliability and practicality of the approach.

In upcoming research, it is important to evaluate the impacts of modifying the step value of DER penetration level on the accuracy of the results and simulation time. Additionally, incorporating a comparative analysis with other hosting capacity enhancement techniques, such as distributed flexible alternating current transmission systems (D-FACTS), OLTC transformers, and ESSs, should be explored as part of future work.

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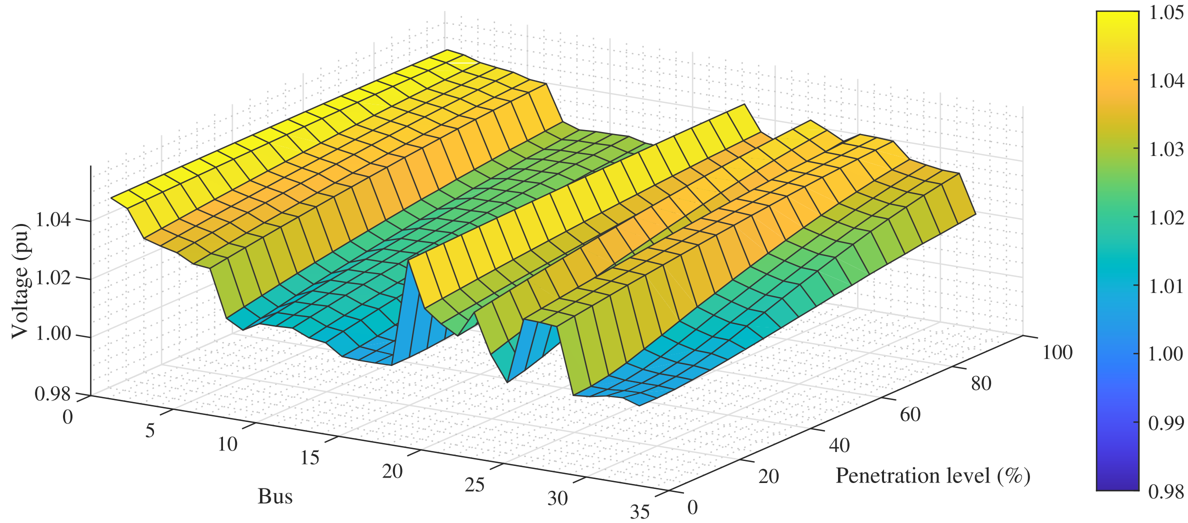

Fig. 9. Voltage profile of the distribution system for the proposed approach.

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