

Reactive Power Support from Distributed Generation to Maximize Active Power Injection in Distribution Networks

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Abstract

This paper investigates the role of reactive power support from Distributed Generation (DG) units in improving voltage compliance and maximizing active power injection in medium-voltage distribution networks. Using the IEEE 34-Node Test Feeder as a case study, a simplified single-phase equivalent model was developed, excluding voltage regulators, shunt capacitors, and step-down transformers to focus on the intrinsic voltage behavior of the feeder. An AC Optimal Power Flow (OPF) model was formulated in Pyomo and solved with Interior Point Optimizer (IPOPT) to evaluate two operational scenarios: (i) DG injecting a fixed 1 MW of active power without reactive power support, and (ii) DG injecting the same active power with optimized reactive power dispatch within ± 0.5 MVar, subject to apparent power constraints. Simulation results show that allowing reactive power flexibility increases the number of feasible DG connection points, improves minimum bus voltages, and reduces the occurrence of voltage limit violations. The findings suggest that modest reactive power capabilities can significantly enhance the hosting capacity of radial distribution feeders without requiring costly network reinforcements.

Keywords: distributed generation; reactive power support; optimal power flow; voltage regulation; hosting capacity; IEEE 34-node test feeder; Pyomo; distribution networks



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1. Introduction

The increasing integration of Distributed Generation (DG) into medium-voltage distribution networks has introduced both opportunities and operational challenges. In many regulatory frameworks, active power (P) from DG units enjoys priority dispatch, with limited or no requirements for reactive power (Q) support. This practice, while beneficial for maximizing energy yield from renewable sources, can lead to voltage profile violations, especially in long radial feeders or weak networks. Such violations often result in a curtailment of active power output, reducing the economic attractiveness of DG investments. In countries such as Ecuador, for instance, current regulations permit DG units of up to 1 MW to operate with priority active power dispatch, but without mandatory Q support, potentially exacerbating overvoltage or undervoltage issues depending on the connection point.

The academic literature has addressed voltage control in distribution networks from various perspectives, including optimal power flow (OPF) formulations that incorporate Q dispatch from DG to maintain voltages within permissible limits [1,2]. Several studies have demonstrated that reactive power capability can be leveraged to improve hosting capacity and minimize curtailment [3,4]. Other works focus on coordinated voltage control strategies

involving DG, capacitor banks, and on-load tap changers [5,6]. However, the majority of existing approaches either assume continuous Q availability or address multi-phase unbalanced models, leaving a gap in the simplified yet insightful analysis of how targeted Q dispatch impacts voltage compliance in radial feeders under fixed P injection constraints.

Recent research has further analyzed voltage regulation in active distribution networks, emphasizing the role of coordinated control strategies that combine distributed generators, capacitor banks, and on-load tap changers [3,5]. Other works have explored optimal reactive power dispatch from PV inverters to enhance hosting capacity and maintain voltage profiles within permissible limits [1,4]. Despite these advances, there remains a lack of benchmark studies that isolate the intrinsic contribution of DG reactive flexibility under passive feeder conditions. This work aims to fill that gap by quantifying the minimum reactive capability required to maintain voltage compliance and maximize active power injection without relying on external voltage support devices.

This study addresses the problem of maximizing the active power injection from DG units—fixed at their nominal 1 MW output—while ensuring that all bus voltages remain within standard operational limits (0.95–1.05 pu) by allowing the controlled injection or absorption of reactive power. The hypothesis is that enabling Q support within the DG's apparent power limit can significantly increase the number of feasible connection points for full P dispatch, while minimizing unnecessary Q exchange.

To investigate this, the IEEE 34-Node Test Feeder was adapted into a simplified single-phase equivalent model, focusing on phase A and excluding voltage regulators, shunt capacitors, and step-down transformers, thus representing a typical radial distribution feeder. An OPF model was formulated in Pyomo (Version 6.5, Sandia National Laboratories, Albuquerque, NM, USA) and solved using IPOPT (Version 3.14.5, COIN-OR Foundation, Pittsburgh, PA, USA), incorporating active and reactive power generation limits, voltage magnitude bounds, power flow equations, and apparent power constraints. Two scenarios were analyzed: (i) DG injecting only P with Q fixed at zero, and (ii) DG injecting P and optimally dispatching Q within ± 0.5 MVar.

Unlike previous studies that combine distributed generators with external voltage control devices or stochastic scenarios, this work deliberately isolates the sole contribution of DG reactive power flexibility under passive feeder conditions. This approach provides a benchmark to quantify the minimum reactive capability required to maintain voltage compliance and maximize active power injection without network reinforcement.

Preliminary results indicate that allowing Q support from the DG improves the minimum bus voltages across the feeder, reduces the number of voltage violations, and expands the set of buses in which 1 MW can be injected without breaching operational limits. These findings highlight the potential of reactive power flexibility as a cost-effective measure to enhance the hosting capacity of distribution feeders without extensive infrastructure upgrades.

2. System Modeling

The test system employed in this study is based on the IEEE 34-Node Test Feeder, a benchmark radial distribution network widely used for validating power flow and optimization algorithms [7,8]. The original system operates at a nominal voltage of 24.9 kV and includes various devices such as voltage regulators, shunt capacitors, and a step-down transformer to a 4.16 kV section. For the purposes of this work, a simplified single-phase equivalent of the feeder was developed, focusing exclusively on phase A. This approach allows for a reduced computational burden while preserving the essential electrical characteristics of the feeder [1].

Although the IEEE 34-node feeder is inherently unbalanced, the single-phase equivalent developed in this study reproduces the average voltage profile of phase A, which dominates the feeder's behavior under balanced loading assumptions. The original IEEE dataset indicates moderate phase unbalance (approximately 2–4%), and several prior studies have shown that single-phase abstractions can adequately capture the qualitative effects of reactive power flexibility on voltage profiles. This approach thus provides a simplified yet representative framework for benchmarking OPF-based analyses, while future work will extend the methodology to full three-phase unbalanced models.

This simplification was intentionally adopted to isolate the intrinsic voltage–power coupling of the feeder under purely passive conditions, thus allowing a transparent analysis of the effect of DG reactive power flexibility. In practical feeders, voltage regulators and capacitor banks mitigate such effects, but their exclusion here provides a lower-bound estimate of voltage compliance, representing a conservative hosting-capacity benchmark. Future work will extend the model to reintroduce these devices and evaluate coordinated Volt/VAR control strategies under realistic operating conditions. The resulting topology is shown in Figure 1, where the node numbering follows the IEEE standard but only the phase A connections are represented.

Line parameters were derived from the conductor configuration data provided in the IEEE dataset [8]. The positive-sequence resistance and reactance per mile for each configuration were used, and line lengths were converted from feet to miles to compute the series impedance of each segment:

$$Z_{ij} = (R_{config} + jX_{config}) \cdot \frac{\text{Length}_{ij} [\text{ft}]}{5280} \quad (1)$$

where R_{config} and X_{config} are the resistance and reactance per mile for the conductor configuration used by line i – j .

The series admittance for each line segment was then obtained as

$$Y_{ij} = \frac{1}{Z_{ij}} \quad (2)$$

Using these admittances, the network bus admittance matrix $\mathbf{Y}_{bus}$ was assembled following the standard nodal admittance formulation [9]

$$Y_{ii} = \sum_{k \in \Omega_i} Y_{ik} \quad (3)$$

$$Y_{ij} = -Y_{ji}, \quad i \neq j \quad (4)$$

where Ω_i denotes the set of nodes directly connected to node i . The resulting $\mathbf{Y}_{bus}$ is symmetric due to the passive nature of the network elements. Verification procedures were implemented to ensure matrix symmetry and the equality between each diagonal element and the negative sum of its corresponding off-diagonal entries.

The real and imaginary parts of $\mathbf{Y}_{bus}$ (conductance G and susceptance B matrices, respectively) were exported to Excel for subsequent use in the OPF formulation. The final single-phase model comprises 22 buses after node renumbering, with node 1 corresponding to the original IEEE bus 800, which serves as the slack bus in the OPF simulations.

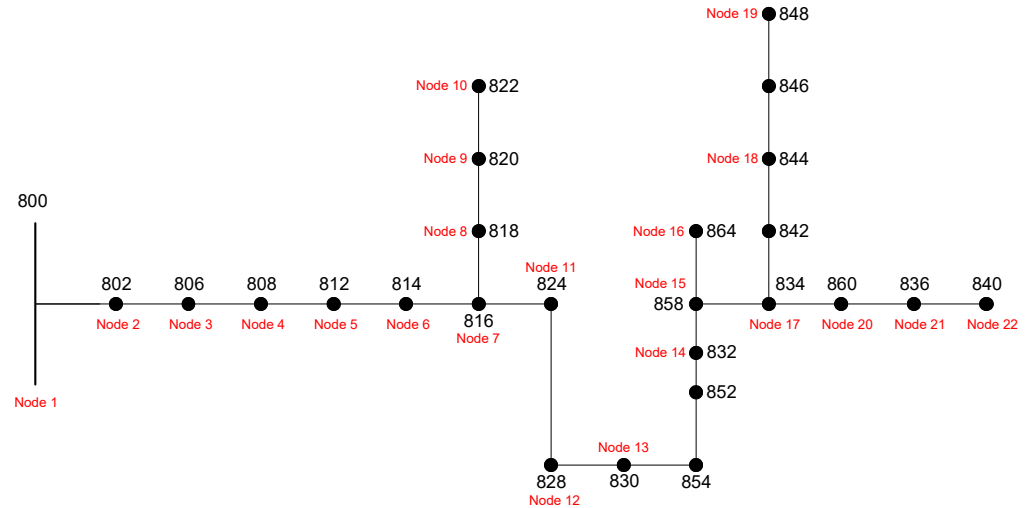


Figure 1. Single-phase equivalent topology of the IEEE 34-Node Test Feeder used in this study (phase A nodes have been renumbered in red).

3. Optimal Power Flow Formulation

The proposed Optimal Power Flow (OPF) model aims to determine the optimal dispatch of active (P_g) and reactive (Q_g) power from a single Distributed Generation (DG) unit connected at different buses of the simplified IEEE 34-Node Test Feeder, while ensuring that all voltage magnitudes remain within the permissible range of 0.95–1.05 pu. Two operational scenarios are analyzed: (i) DG injecting fixed active power (1 MW) with $Q_g = 0$, and (ii) DG injecting fixed active power (1 MW) with optimized Q_g within its apparent power capability. The formulation follows the classical AC OPF structure [10,11], adapted for a single-phase equivalent network.

3.1. Decision Variables

- P_g^i : Active power generation at bus i [MW];
- Q_g^i : Reactive power generation at bus i [MVar];
- V_i : Voltage magnitude at bus i [kV];
- θ_i : Voltage angle at bus i [rad].

3.2. Objective Function

The objective is to minimize the operational cost associated with active and reactive power generation:

$$\min C = \sum_{i \in \mathcal{N}} (c_P^i P_g^i + c_Q^i Q_g^i) \quad (5)$$

where c_P^i and c_Q^i are the marginal costs of active and reactive power, respectively. In this work, only the slack bus (node 1) is assigned non-zero generation costs, while the DG operates at zero marginal cost to emulate priority dispatch.

3.3. Constraints

3.3.1. Active Power Balance

For each bus i ,

$$P_g^i - P_d^i = \sum_{j \in \mathcal{N}} V_i V_j [G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j)] \quad (6)$$

where P_d^i is the active power demand at bus i , and G_{ij} and B_{ij} are the elements of the conductance and susceptance matrices obtained from $\mathbf{Y}_{\text{bus}}$.

3.3.2. Reactive Power Balance

$$Q_g^i - Q_d^i = \sum_{j \in \mathcal{N}} V_i V_j [G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j)] \quad (7)$$

where Q_d^i is the reactive power demand at bus i .

3.3.3. Voltage Magnitude Limits

$$V_{\min} \leq V_i \leq V_{\max} \quad \forall i \in \mathcal{N} \quad (8)$$

In this work, $V_{\min} = 0.95$ pu and $V_{\max} = 1.05$ pu, consistent with ANSI C84.1 standards [12].

3.3.4. Generator Capacity Limits

$$P_g^{\min,i} \leq P_g^i \leq P_g^{\max,i} \quad (9)$$

$$Q_g^{\min,i} \leq Q_g^i \leq Q_g^{\max,i} \quad (10)$$

3.3.5. Apparent Power Capability

$$\left(P_g^i\right)^2 + \left(Q_g^i\right)^2 \leq \left(S_g^{\max,i}\right)^2 \quad (11)$$

where $S_g^{\max,i}$ is the apparent power rating of the generator at bus i .

3.4. Solution Approach

The above formulation represents a non-linear programming (NLP) problem due to the trigonometric terms in the power flow equations. The model was implemented in Pyomo [13] and solved using IPOPT [14], an interior-point optimizer suitable for large-scale NLPs. The slack bus voltage magnitude and angle were fixed, and all other buses were initialized with nominal voltage and zero angle to improve convergence. For each scenario, the OPF was solved iteratively by placing the DG at each candidate bus in the feeder and recording the resulting bus voltages, power flows, and constraint violations. Although the mathematical structure of the proposed AC OPF follows conventional formulations, the originality of this work lies in its analytical use. The model is employed to quantify the incremental hosting-capacity benefit provided solely by DG reactive power flexibility in a passive feeder. Implemented in the open-source Pyomo framework, the formulation enables transparent, reproducible analysis and a systematic bus-by-bus evaluation of feasible DG connection points, establishing a methodological benchmark for future coordinated voltage-control studies.

4. Case Studies

Two operational scenarios were defined to assess the impact of reactive power support from Distributed Generation (DG) on the hosting capacity of the IEEE 34-Node Test Feeder. In both scenarios, the DG nominal active power output was fixed at $P_g^{\text{DG}} = 1.0$ MW, consistent with the maximum capacity allowed for priority dispatch in several regulatory frameworks [1]. The difference between scenarios lies in the treatment of reactive power dispatch. The analysis intentionally fixes the DG output at 1 MW, which represents the maximum rating allowed for priority dispatch under Ecuadorian and other Latin American

regulations. This simplification enables a clear benchmark assessment of reactive power flexibility under deterministic conditions, without the added complexity of stochastic load or voltage-control interactions.

4.1. Scenario Definitions

4.1.1. Scenario 1: Fixed Active Power, No Reactive Power Support

In this scenario, the DG injects $P_g^{\text{DG}} = 1.0$ MW and operates at unity power factor:

$$Q_g^{\text{DG}} = 0 \quad (12)$$

Reactive power support is provided exclusively by the slack bus, which also balances system losses.

4.1.2. Scenario 2: Fixed Active Power, Optimized Reactive Power Support

Here, the DG injects $P_g^{\text{DG}} = 1.0$ MW but can also inject or absorb reactive power within ± 0.5 MVar, subject to its apparent power capability:

$$-0.5 \text{ MVar} \leq Q_g^{\text{DG}} \leq 0.5 \text{ MVar} \quad (13)$$

$$(P_g^{\text{DG}})^2 + (Q_g^{\text{DG}})^2 \leq (S_g^{\text{max}})^2 \quad (14)$$

where $S_g^{\text{max}} = 1.5$ MVA in this study.

4.2. Simulation Procedure

The OPF formulation described in Section 3 was solved for each candidate bus connection of the DG, excluding the slack bus. The set of candidate buses is

$$\mathcal{B}_{\text{cand}} = \{2, 3, \dots, 22\} \quad (15)$$

For each bus $b \in \mathcal{B}_{\text{cand}}$, the OPF problem was configured with the DG located at b , and all other buses without generation except for the slack. Voltage magnitude limits were enforced as

$$0.95 \text{ pu} \leq V_i \leq 1.05 \text{ pu}, \quad \forall i \in \mathcal{N} \quad (16)$$

consistent with ANSI C84.1 [12].

Generation cost coefficients were set as

$$c_P^{\text{DG}} = 0 \text{ \$/MWh}, \quad c_Q^{\text{DG}} = 0 \text{ \$/MVarh} \quad (17)$$

$$c_P^{\text{slack}} = 100 \text{ \$/MWh}, \quad c_Q^{\text{slack}} = 100 \text{ \$/MVarh} \quad (18)$$

The cost structure described above prioritizes the dispatch from DG and minimizes unnecessary reactive power exchange from the slack bus.

4.3. Summary of Parameters

Table 1 summarizes the main parameters used in both scenarios.

For each scenario and each DG location, the simulation process generates the complete set of OPF outputs, including nodal voltages (in kV and pu), phase angles, and P_g , Q_g dispatch values for all buses. These outputs are then post-processed to count voltage violations and to determine the buses where the DG can operate at full capacity without breaching voltage limits.

Table 1. Simulation parameters for Scenarios 1 and 2.

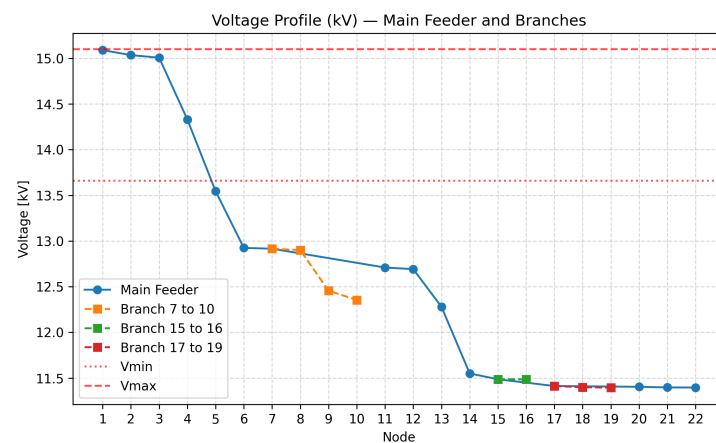
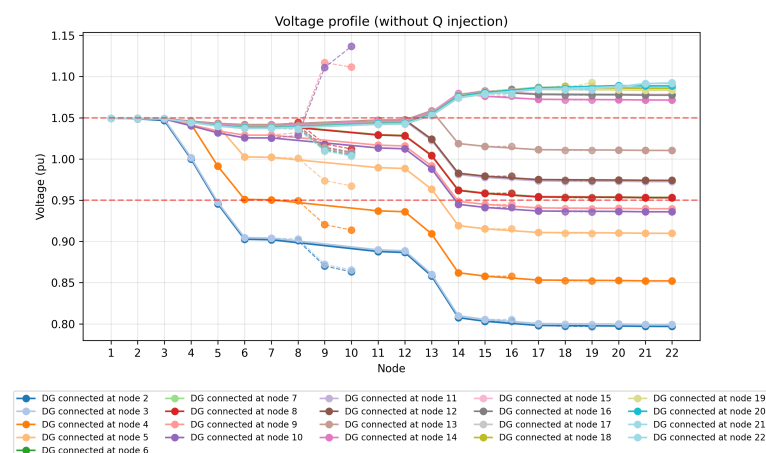
Parameter	Scenario 1	Scenario 2
DG Active Power, P_g^{DG} (MW)	1.0	1.0
DG Reactive Power, Q_g^{DG} (MVar)	0	± 0.5
DG Apparent Power, S_g^{max} (MVA)	1.0	1.5
Voltage Limits (pu)	[0.95, 1.05]	
Slack Bus Costs (c_P, c_Q)	100 \$/MWh, 100 \$/MVarh	
DG Costs (c_P, c_Q)	0 \$/MWh, 0 \$/MVarh	
Candidate Buses	{2, ..., 22}	
Solver	IPOPT	

5. Results and Discussion

This section presents the results obtained from the OPF simulations for the two scenarios defined in Section 4. The analysis focuses on voltage compliance, reactive power utilization, and the impact of Q support on the number of feasible DG connection points.

5.1. Voltage Profile Comparison

Figures 2–4 show the voltage profiles for the base case (no DG), Scenario 1, and Scenario 2, respectively.

**Figure 2.** Voltage profile of the IEEE 34-Node Test Feeder without DG.**Figure 3.** Voltage profile with DG injecting 1 MW and $Q_g = 0$ (Scenario 1). Multiple buses violate voltage limits.

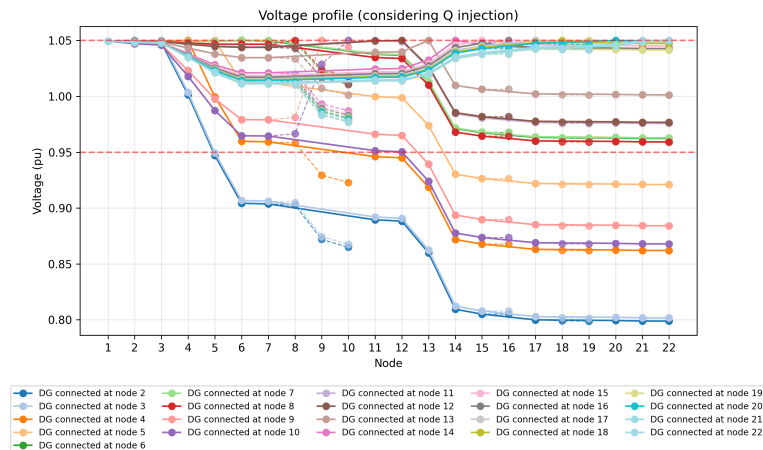


Figure 4. Voltage profile with DG injecting 1 MW and optimized Q_g within ± 0.5 MVar (Scenario 2). Voltage violations are reduced and $V_{\min}$ is improved.

The profiles show that in Scenario 1, voltages at the far end of the feeder drop below 0.95 pu for several DG connection points, forcing curtailment if voltage compliance is enforced. In Scenario 2, reactive power injection compensates for voltage drops, bringing all voltages closer to nominal values.

5.2. Voltage Compliance Analysis

For each candidate DG connection bus, the OPF outputs were post-processed to determine:

- Whether all bus voltages remain within 0.95–1.05 pu.
- The number of buses violating voltage limits (N_{viol}).
- The minimum and maximum voltages across the feeder ($V_{\min}$, $V_{\max}$).

Table 2 summarizes the results for both scenarios. It can be observed that in Scenario 2 (with Q support), the number of compliant DG connection points increases significantly.

Table 2. Voltage compliance summary for DG connection points (corrected).

Bus	Compliance	Scenario 1: $Q_g = 0$ (Corrected)			Scenario 2: $Q_g \in [-0.5, 0.5]$ MVar			
		N_{viol}	$V_{\min}$ (pu)	$V_{\max}$ (pu)	Compliance	N_{viol}	$V_{\min}$ (pu)	$V_{\max}$ (pu)
2	No	18	0.7968	1.0494	No	18	0.7987	1.0500
3	No	18	0.7991	1.0494	No	18	0.8016	1.0500
4	No	15	0.8520	1.0494	No	14	0.8619	1.0500
5	No	9	0.9097	1.0494	No	9	0.9210	1.0500
6	Yes	0	0.9529	1.0494	Yes	0	0.9622	1.0500
7	Yes	0	0.9535	1.0494	Yes	0	0.9628	1.0500
8	Yes	0	0.9530	1.0494	Yes	0	0.9591	1.0500
9	No	11	0.9395	1.1169	No	10	0.8841	1.0500
10	No	11	0.9358	1.1366	Yes	0	0.9682	1.0500
11	Yes	0	0.9724	1.0494	Yes	0	0.9681	1.0500
12	Yes	0	0.9740	1.0494	Yes	0	0.9681	1.0500
13	No	1	1.0082	1.0586	No	9	0.8956	1.0500
14	No	10	1.0067	1.0794	No	7	0.9125	1.0500
15	No	10	1.0060	1.0829	Yes	0	0.9681	1.0500
16	No	10	1.0055	1.0846	Yes	0	0.9680	1.0500
17	No	10	1.0051	1.0871	Yes	0	0.9680	1.0500
18	No	10	1.0048	1.0884	Yes	0	0.9680	1.0500
19	No	10	1.0036	1.0927	Yes	0	0.9680	1.0500
20	No	10	1.0046	1.0890	Yes	0	0.9679	1.0500
21	No	10	1.0039	1.0916	Yes	0	0.9679	1.0500
22	No	10	1.0037	1.0925	Yes	0	0.9679	1.0500

Overall, Scenario 2 exhibits the following:

- **Increase in feasible DG locations:** More buses satisfy voltage limits.
- **Higher $V_{\min}$:** Voltage profile is uniformly elevated due to local Q injection.
- **Same $V_{\max}$:** Remains close to the upper bound in both scenarios.

6. Discussion

These results highlight the potential of reactive power flexibility as a cost-effective measure to improve the hosting capacity of distribution networks, particularly in regulatory environments that currently prioritize active power dispatch without requiring reactive power support.

Future work will extend this study in the following directions:

- Considering three-phase unbalanced models to capture phase-specific voltage issues and asymmetrical loading.
- Evaluating coordinated control strategies among multiple DG units, capacitor banks, and voltage regulators.
- Performing techno-economic analyses to quantify the benefits of reactive power capabilities relative to their implementation costs.
- Extending the study to include variable load levels, stochastic generation profiles, and comparisons with standard Volt/VAR droop controllers to validate and generalize the proposed benchmark under realistic operating conditions.

Impact on Hosting Capacity

The hosting capacity, defined as the maximum DG penetration without violating voltage limits [15], is directly increased in Scenario 2. By leveraging reactive power flexibility:

- Buses that were infeasible in Scenario 1 (e.g., buses 4, 5) become feasible.
- Even in feasible locations, $V_{\min}$ improves by up to 1% pu.

This demonstrates that modest Q capabilities (here, ± 0.5 MVar) can meaningfully expand the viable DG siting options without network reinforcement.

The methodology and findings of this study are generalizable to other radial distribution feeders and can inform regulatory updates that better integrate reactive power flexibility into DG interconnection requirements.

7. Conclusions

This paper presented an optimization-based analysis of reactive power support from Distributed Generation (DG) units to maximize active power injection in distribution networks, using the IEEE 34-Node Test Feeder as a case study. A simplified single-phase equivalent of the feeder was developed, and an AC Optimal Power Flow (OPF) formulation was implemented in Pyomo to evaluate two scenarios: (i) DG injecting fixed active power without reactive power support, and (ii) DG injecting fixed active power with optimized reactive power dispatch within its apparent power limits.

The main findings are as follows:

- **Reactive power support increases voltage compliance:** Allowing the DG to inject or absorb up to ± 0.5 MVar significantly improved the minimum bus voltages and reduced the number of voltage limit violations across the network.
- **Expanded feasible DG connection points:** The number of buses where 1 MW can be injected without violating voltage limits increased from 8 to 13 in Scenario 2 compared to Scenario 1. The minimum bus voltage also improved by approximately 1% relative to the case without reactive power support. These results provide clear numerical evidence of the effectiveness of reactive power flexibility in enhancing

voltage compliance and hosting capacity, moving beyond qualitative expectations reported in previous studies.

- **Improved hosting capacity:** Even with moderate reactive power capability, the network's ability to host DG without reinforcement was enhanced.

The novelty of this study lies in its methodological isolation of DG reactive power flexibility in a passive distribution feeder, allowing the quantification of the intrinsic benefit of reactive support in enhancing voltage compliance and hosting capacity. The findings establish a lower-bound benchmark that can be used to evaluate the incremental value of coordinated Volt/VAR control in future, more complex scenarios.

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Abbreviations

The following abbreviations are used in this manuscript:

DG	Distributed Generation
OPF	Optimal Power Flow
IEEE	Institute of Electrical and Electronics Engineers
MVAr	Megavolt-Ampere Reactive
MW	Megawatt
pu	per unit
AC	Alternating Current
ANSI	American National Standards Institute
Ybus	Bus Admittance Matrix
P _g	Active Power Generation
Q _g	Reactive Power Generation

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