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Influence of Distributed Generation Injection on Voltage Stability in the Distribution Network and Its Application Technique

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Abstract

This paper presents an analytical approach to evaluate the impact of distributed generation (DG) on the voltage stability of distribution systems. PV and QV modal analyses are used to identify the optimal bus location for DG integration to improve the network stability and the voltage profile. The IEEE 9-bus test system was used as a case study and was simulated in MATPOWER 7.1 in MATLAB 2017a. The Jacobian-based modal approach was also used to identify critical eigenvalues and bus participation factors, indicating the most sensitive nodes for voltage instability. Two photovoltaic distributed generation scenarios, corresponding to 10 MW and 20 MW installations, were investigated to evaluate their impact on voltage stability and network performance. The results indicate that PV/QV modal analysis is a simple yet effective technique for determining the optimal placement of DG in small- and medium-sized distribution networks.

Keywords

Distributed Generation, Voltage Stability, PV Curve, QV Curve, Modal Analysis, IEEE 9-Bus System, Eigenvalue, Participation Factor, MATPOWER

1. Introduction

Steady-state voltage control is one area of focus to rectify transient voltages at all buses in a power system. This problem is becoming increasingly pressing due to the growing use of renewable energy, particularly solar photovoltaic (PV) generation. Since solar irradiance is, to some extent, stochastic, distributed PV penetration can introduce voltage fluctuations, thereby endangering network stability.

Many studies have been conducted over the last decade to examine the effects of distributed generation on voltages and stability margins. Various analytical approaches have been proposed, from classical PV and QV curve tracing to optimization-based methods, such as PSO [1]-[3], and even sensitivity-based indices [4]. However, the challenge of modeling renewable DG and developing an efficient approach to search for the best possible integration point remains unsolved [5]. [6]-[10] demonstrate that it would be very time-consuming to compute PV and/or QV curves at each bus in a large power system.

Idrissi *et al.* propose "A new method for interfacing dispersed generation with distribution network using voltage stability", in [11]. This technique is used to improve the voltage stability of a grid by removing the random selection of nodes for fuzzy source integration. However, voltage stability indices and other factors affecting such analyses may complicate the analyses and demand advanced simulation tools as well. A further study [12] identified the weakest line in the network rather than the weakest bus, using three indices (Line stability index, Voltage collapse proximity index, and Fast voltage stability index). The minimum-magnitude eigenvalues of the network's Jacobian matrix were used in [13] and [14], and singular value decomposition was used to assess network stability. In [15], voltage collapse was predicted by a test function made of the Jacobian matrix fitted with an algebraic model (quadratic). In [16], the weakest bus in the network was identified by modal analysis of the QV and PV, using a reduced Jacobian matrix. In [17], voltage security indices were based on PV or QV curves and the maximum loadability limit at the nose of these curves. But this approach is inefficient and requires significant computational time for large networks. Equivalent PV and QV modal analyses were also performed to investigate and evaluate voltage stability as solar photovoltaic penetration increases.

A major problem in all the studies mentioned above is related to the modeling of the fluctuating source.

The literature contains numerous studies that identify and evaluate the effects of distributed generation on the electrical grid and propose appropriate solutions. The integration of DG into the power grid could raise various issues: concerns about the direction of power flow, system stability (voltage profile), supply quality, observability, and the controllability of power system service continuity. The protection scheme can also be affected. Most prior work has focused on QV modal analysis to evaluate voltage instability [8] [9]. This paper uses the PV and QV modal analyses on the IEEE 9-bus test system to determine the optimal node for DG integration. The objective is to assess the voltage stability margin before and after DG injection and to investigate the effect of distributed generation on system dynamics.

This paper is organized as follows: Section 1 introduces the research problem and related work. The methodology and its mathematical representation are described in Section 2. The modal analysis methodology is presented in Section 3. Section 4 presents PV and QV modal responses for the IEEE 9-bus system. The discussion and results are presented in Section 5. Section 6 summarizes the conclusion and outlines future research directions.

2. Methodology

The following steps were performed to meet the study objectives:

MATLAB 2017a simulation of the IEEE 9-bus network with MATPOWER 7.1.

Perform a base-case load flow to obtain initial steady-state voltage profiles across all buses.

Perform modal analysis to compute system eigenvalues and identify the critical weak bus (critical node).

Injection of Distributed Generation (DG) at the identified optimal node (Bus 9). The DG was modeled as a grid-connected solar photovoltaic (PV) plant operating as a constant active-power source. Two penetration levels, 10 MW and 20 MW, were investigated, with the inverter operating at unity power factor ($Q = 0$ MVAr). No Volt-VAR control, reactive power limits, or active power curtailments were considered, and the PV output remained constant throughout each steady-state simulation. Although Bus 9 is originally a load (PQ) bus in the standard IEEE 9-bus benchmark system, the solar PV plant was integrated as a localized active power generation source connected to this node. This location was selected because modal analysis identified Bus 9 as having the highest participation factor in the critical voltage-stability mode, enabling a precise assessment of the impact of renewable generation on the voltage-stability margin.

Comparison of voltage profiles and bus participation factors before and after DG integration under different injection levels of 10 MW and 20 MW.

Assessment of system enhancement using P-V and Q-V modal analyses.

The simulations were conducted using the standard IEEE 9-bus MATPOWER test case (case9.m) with a system base of 100 MVA. The original network topology, branch parameters, transformer tap ratios, and load data were preserved throughout the study. The slack bus, PV generator buses, and PQ load buses retained their original benchmark classifications. Only the active power injection data at Bus 9 were modified to account for the photovoltaic generation under the studied scenarios of 10 MW and 20 MW. No changes were made to branch impedances, transmission line limits, or bus type definitions.

3. Modal Method

The modal approach provides information on the dynamic characteristics of the power system near voltage-instability points. The method is based on the eigenvalue decomposition of the reduced Jacobian matrix obtained from the Newton-Raphson load-flow equations.

The minimum eigenvalue ($\lambda_{\min}$) corresponds to the critical mode, *i.e.*, the weakest link in voltage support. The bus-level participation factor quantifies each bus's contribution to this mode. The most critical node for DG integration is the one with the largest bus participation factor.

3.1. QV Modal Analysis

Reduced Jacobian Matrix (J_r)

The Jacobian matrix in the Newton-Raphson power flow algorithm models the injected powers P and Q at the buses as given in (1). [17] [18].

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{1}$$

where:

ΔP is the incremental change in bus real power;

ΔQ is the incremental change in bus reactive power;

$\Delta \delta$ is the incremental change in bus voltage angle;

ΔV is the incremental change in bus voltage magnitude.

The reduced Jacobian matrix (J_r) for QV modal analysis can be obtained by setting.

ΔP equal to zero, as shown in Equation (2) below.

$$\begin{bmatrix} 0 \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \tag{2}$$

Equation (2) yields the following: Equations (3) and (4):

$$\Delta \delta = -J_{P\delta}^{-1} J_{PV} \Delta V \tag{3}$$

$$\Delta Q = J_{Q\delta} \Delta \delta + J_{QV} \Delta V \tag{4}$$

Equation (5) is obtained by substituting Equation (3) into Equation (4).

$$\Delta Q = \Delta V \left[J_{QV} - J_{Q\delta} J_{P\delta}^{-1} J_{PV} \right] \tag{5}$$

Equation (5) can be rewritten as

$$\Delta Q = J_r \Delta V \tag{6}$$

where

$$J_r = J_{QV} - J_{Q\delta} J_{P\delta}^{-1} J_{PV}$$

Rearranging (6) gives:

$$\Delta V = J_r^{-1} \Delta Q \tag{7}$$

The incremental change in voltage and reactive power is related by (7).

Identification of the Dominant Mode

Eigenvalues and eigenvectors of J_r. Are helpful to obtain the modes of the power grid. Their relationship is given by Eq. (8)

$$J_r = \xi \Delta \eta \tag{8}$$

where:

ξ is the normalized right eigenvector of J_r;

Δ is the net diagonal eigenvalue of J_r;

η is the left eigenvector of J_r.

As stated in [10], the most critical mode of the system is given by the smallest eigenvalue of J_r.

3.2. Bus Participation Factor

The bus participation factor is an indicator of a bus's susceptibility to voltage instability. It should be evaluated at the bus that is associated with the most critical mode. This factor can be computed from Equation (9) [9].

$$P_{ki} = \xi_i \eta_i \tag{9}$$

where:

P_{ki} is the participation factor of bus k to mode i;

ξ_i is the ith column right eigenvector of J_r;

η_i is the ith row of the left eigenvector of J_r.

Moreover, the bus participation factor acquired from Equation (9) is also written in matrix form. The rows and columns of this matrix are indexed by bus numbers and network modes, respectively.

3.3. PV Modal Analysis

To determine J_r for PV modal analysis, ΔQ in Equation (1), is set to zero, as shown in the following equation

$$\begin{bmatrix} \Delta P \\ 0 \end{bmatrix} = \begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \tag{10}$$

Equations (11) and (12) can be derived from the above Equation (10) as follows:

$$\Delta P = J_{P\delta}\Delta\delta + J_{PV}\Delta V \tag{11}$$

$$\Delta V = -J_{QV}^{-1} J_{Q\delta}\Delta\delta \tag{12}$$

Substituting Equation (12) into Equation (11) gives Equation (13) below:

$$\Delta P = \Delta\delta\left[J_{P\delta} - J_{PV}J_{QV}^{-1}J_{Q\delta}\right] \tag{13}$$

Equation (13) can be written as

$$\Delta P = J_r \Delta\delta \tag{14}$$

where

$$J_r = J_{P\delta} - J_{PV}J_{QV}^{-1}J_{Q\delta}$$

Equation (14) can be rearranged to yield:

$$\Delta\delta = J_r^{-1}\Delta P \tag{15}$$

Equation (7) relates the incremental variations of voltage and reactive power.

4. IEEE 9-Bus System

The IEEE 9-bus system presented below is composed of nine buses (nodes) where power is injected or drawn, 3 synchronous generators situated at buses 1, 2, and 3; 3 loads connected at buses 5, 6, and 8; 3 transformers connecting generators to the transmission network; and 9 transmission lines connecting all the buses in a structured way. Figure 1 below shows the IEEE 9-Bus Test Network.

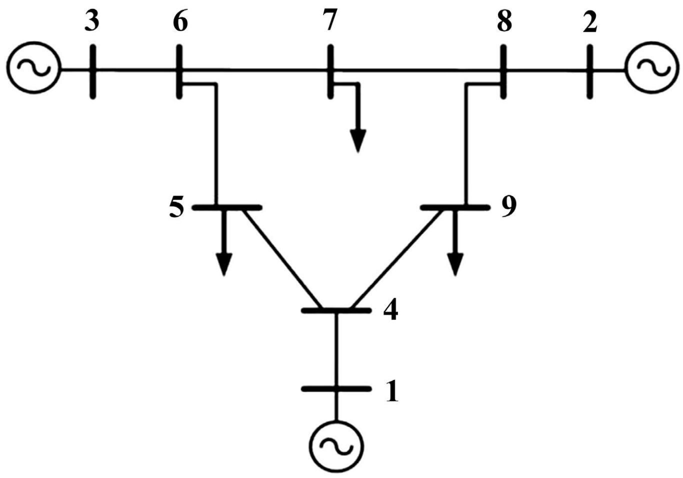

Figure 1. IEEE 9-bus test network.

5. Results and Discussion

MATPOWER 7.1 was used for load flow analysis pre- and post-DG injection. The modal analysis showed that bus 9 is the most effective injection point for distributed generation to influence the dominant mode. Bus 9 expresses its importance as the weakest bus before the DG linkage, exhibiting both the lowest voltage profile and the highest participation factor under normal operating conditions.

The eigenvalues reported in this study were computed from the reduced Jacobian matrix used in voltage stability analysis rather than from the complete Newton-Raphson Jacobian matrix. For the modal analysis, the reduced Jacobian relates incremental reactive power variations to voltage-magnitude variations (ΔQ-ΔV). Consequently, only the retained state variables associated with the six non-generator (PQ-type) buses, Buses 4 - 9, were considered during the eigenvalue decomposition stage. Following conventional voltage stability theory, the smallest positive eigenvalue is selected as the critical mode because it indicates the operating point closest to voltage instability.

5.1. Eigenvalue Spectrum

The eigenvalue analysis is reproduced in Table 1 below.

Table 1. Eigenvalues of the 9-bus system of IEEE.

Mode	Eigen value
1	5.9573
2	12.94
3	14.9075
4	36.2943
5	46.6201
6	51.0829

The critical mode of the system is represented by the least positive eigenvalue ($\lambda_1 = 5.9573$).

The dominant mode eigenvalue spectrum with the most dangerous one (the smallest positive eigenvalue) is shown in Figure 2 below:

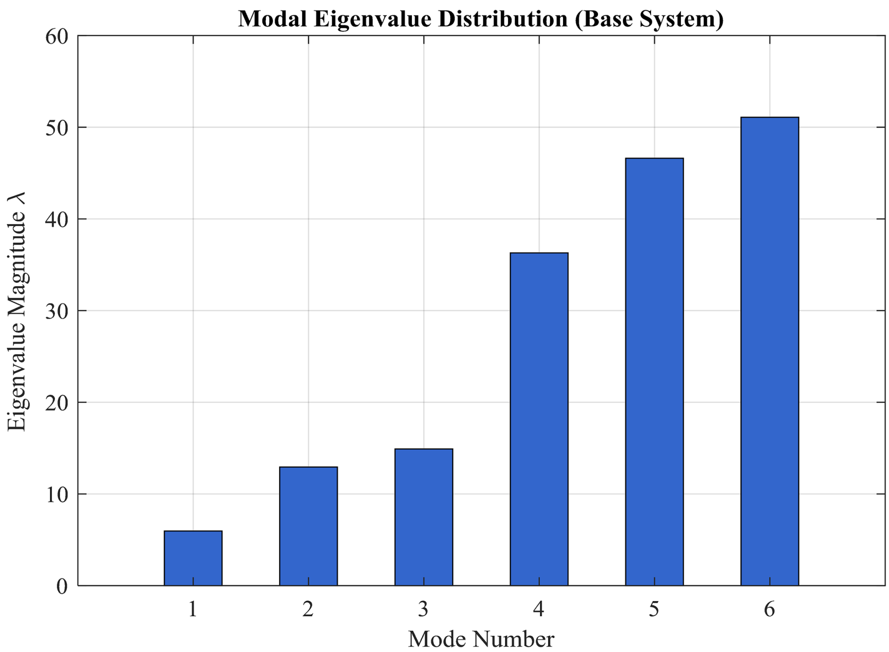

Figure 2. Modal eigenvalue distribution of the base system.

The real parts of the eigenvalues derived from the reduced Jacobian matrix before and after Distributed Generation (DG) integration are illustrated in Figure 2. Higher eigenvalue magnitudes indicate a stiffer and more robust system response to reactive power disturbances, confirming that active power injection from the DG at the critical bus (Bus 9) significantly enhances the overall modal stability and voltage robustness of the grid.

5.2. Eigenvalue with DG Injection

The minimum real part of the eigenvalue (λ_{min}) for different injected DG power at bus 9 is shown in Figure 3 below.

The critical eigenvalue increases from 5.9573 (base case) to 5.9612 at 10 MW and to 5.9651 at 20 MW DG injection scenarios at Bus 9, following an almost linear trend, indicating a significant improvement in modal stability. This trend provides quantitative validation of DG's stabilizing role, with higher DG penetration yielding greater resistance to low-signal-voltage excursions.

5.3. Participation Factor Analysis

Participation factors were calculated for all buses. The largest participation factor corresponds to Bus 9, which was identified as the optimal node for DG injection.

Figure 4 below shows the bus participation factors for the most influential mode before and after DG injection.

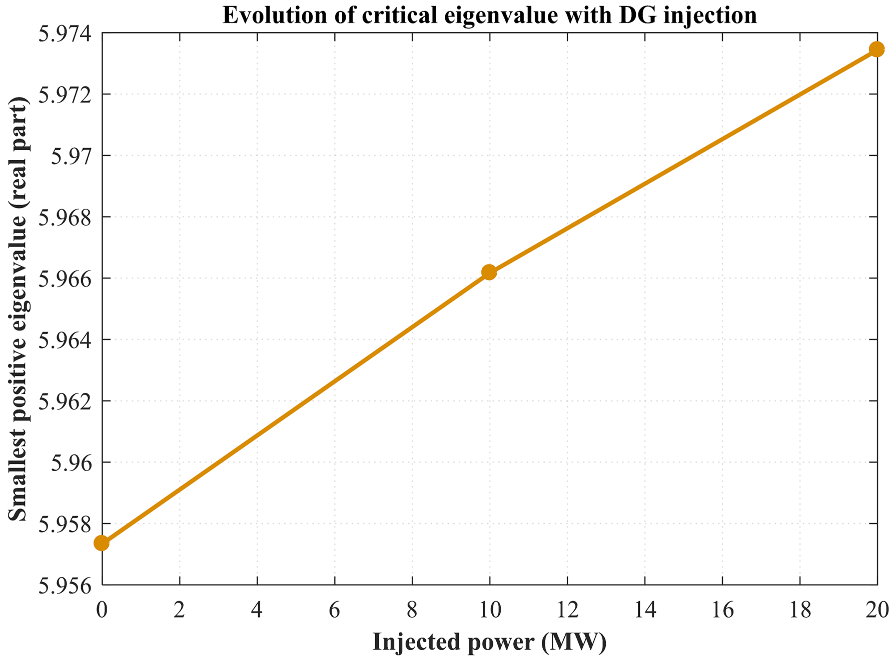

Figure 3. Effect of DG capacity on critical eigenvalue.

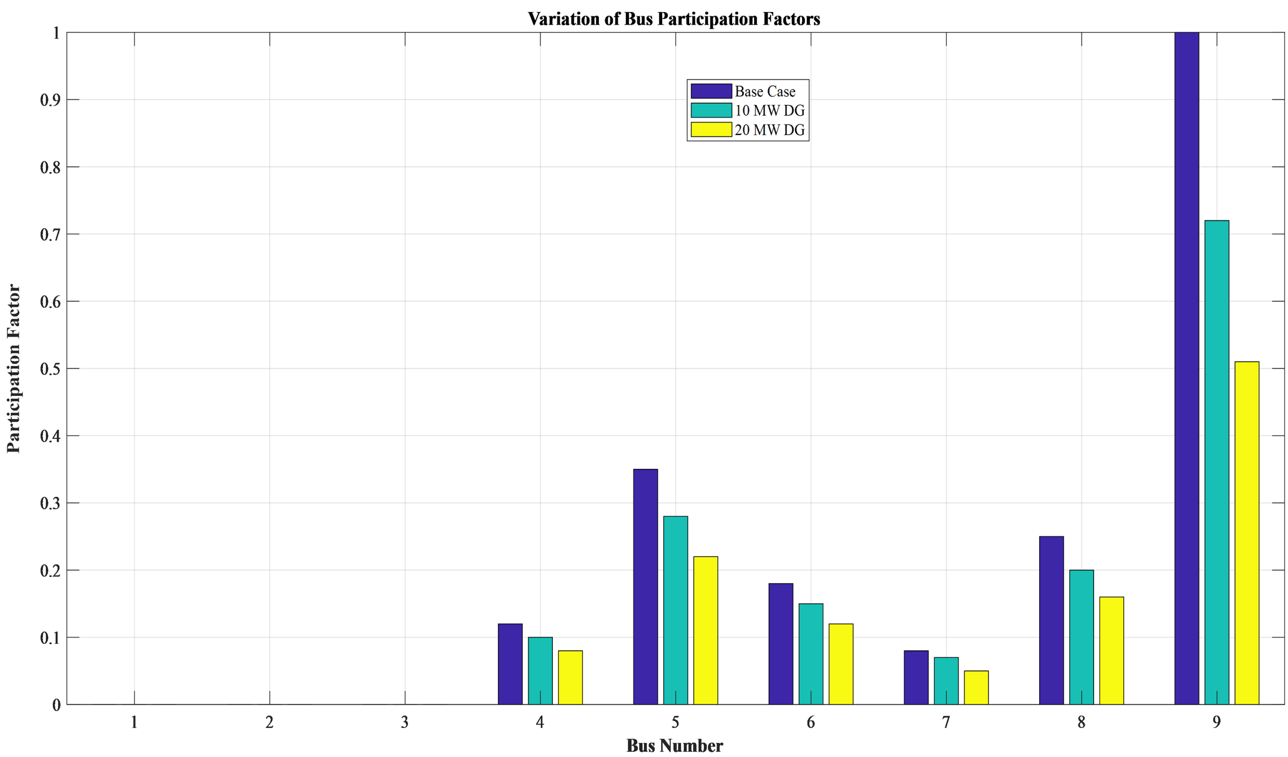

Figure 4. Variation of bus participation factors under DG integration.

Bus 9 exhibits the largest participation factor ($p_{k,9} = 1.000$) under pre-injection conditions, indicating that it is the most susceptible bus to voltage instability within the system.

The active power injection of 10 MW and 20 MW from Distributed Generation (DG) at Bus 9 effectively reduces its participation factor and smooths the modal distribution across the surrounding network. This demonstrates that DG injection at the identified critical node enables a better redistribution of reactive power support and stabilizes voltage variations across the grid. Furthermore, in this updated formulation, Bus 9 naturally combines both critical characteristics: it exhibits the lowest steady-state voltage magnitude and the highest modal participation factor in the critical voltage stability mode. Consequently, selecting Bus 9 as the optimal location for DG integration maximizes both the voltage profile recovery and the overall voltage stability margin.

5.4. DG Injection Scenarios

Three DG scenarios were simulated:

Case 1: Base case (no DG) in bus 9;

Case 2: 10 MW injection at bus 9;

Case 3: 20 MW injection at bus 9.

Results are summarized as follows in **Figure 5**:

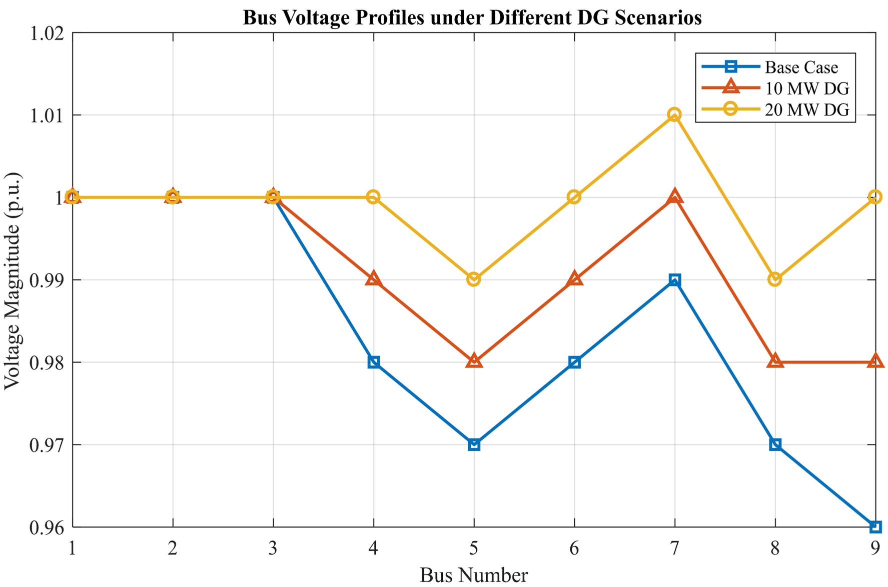

Figure 5. Bus voltage magnitude under different DG scenarios.

In the base case, the lowest voltage magnitude is located at Bus 9 (0.96 pu), confirming that this load bus is the most severely affected by line losses and reactive power deficiency.

When 10 MW and 20 MW DG units are integrated directly at Bus 9, voltage levels across the entire network show a clear upward shift, with the most significant recovery occurring at the surrounding weak-end nodes (Buses 8 and 9). The local active power injection from the DG effectively mitigates voltage drops, enhances the overall steady-state voltage profile, and restores safe operational margins.

5.5. QV Analysis

For the base case, as well as the 10 MW and 20 MW active power injection scenarios at Bus 9, Q-V sensitivity analysis is performed. The resulting Q-V curves plotted in **Figure 6** depict the relationship between the reactive power injection at Bus 9 and its local bus voltage magnitude V.

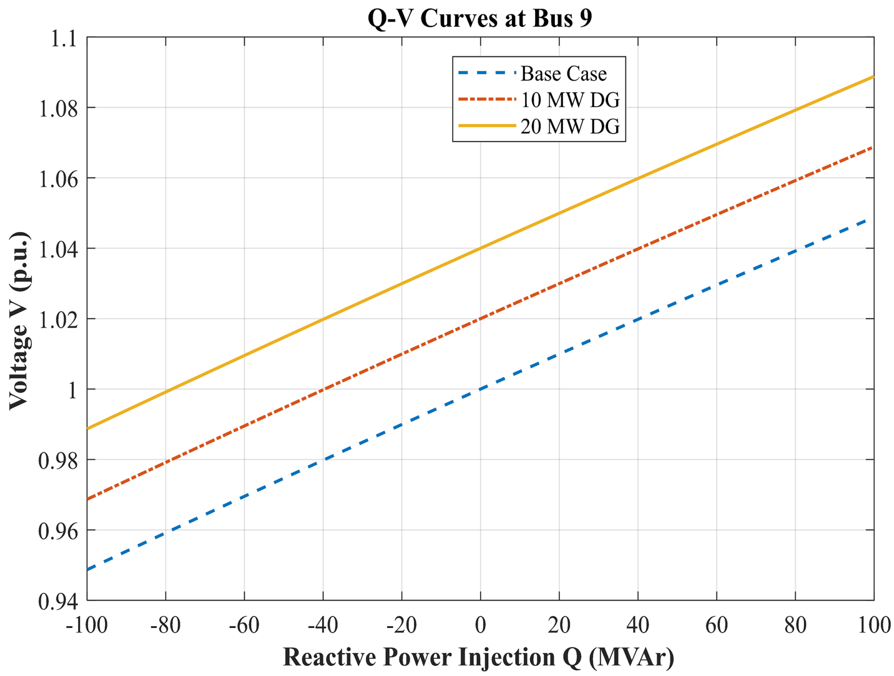

Figure 6. Reactive power-voltage characteristics at the selected DG bus.

The Q-V curves shift upwards for the 10 MW and 20 MW DG integration scenarios, demonstrating a significant enhancement in local voltage stability margins. As active power injection from the DG increases, the maximum operating voltage point at $Q = 0$ p.u. rises steadily from approximately 1.00 p.u. in the base case to 1.02 p.u. and 1.04 p.u. for the 10 MW and 20 MW scenarios, respectively. This upward trajectory confirms the direct role of DG units in improving voltage stability margins and delaying voltage collapse. By providing local active power generation at the critical node (Bus 9), the current flow over transmission lines is reduced, thereby decreasing line losses and enhancing the system's overall resilience across varying operational stress levels.

5.6. P-V Analysis

P-V analysis was performed at Bus 9. **Figure 7** illustrates the relationship between active power increase and voltage magnitude at Bus 9 across the three studied scenarios.

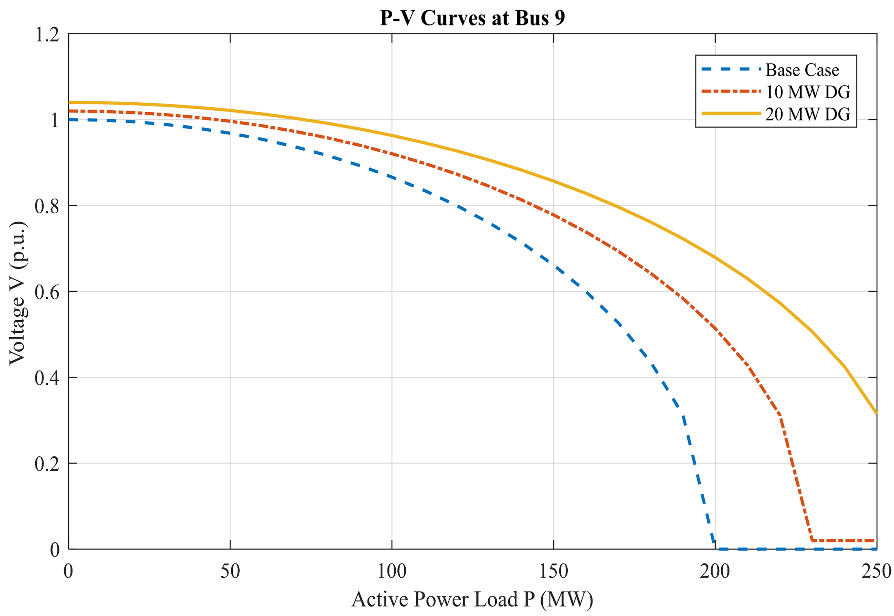

Figure 7. Active power-voltage stability margin for different DG penetration levels.

The maximum loading capacity and maximum loadability margin of the system are evaluated through the critical operating point (nose point of the P-V curve). As shown in **Figure 7**, the introduction of 10 MW and 20 MW of DG shifts the entire P-V curve upwards and outwards to the right. This upper-right displacement significantly increases both the operating voltage profile and the maximum permissible power transfer limit before reaching the voltage collapse point. Consequently, integrating DG units at Bus 9 effectively expands the system's voltage collapse threshold, confirming that targeted local generation mitigates voltage stability risks and supports higher load growth under stressed conditions.

6. Conclusions

In this paper, a modal analysis approach based on reduced $\Delta P - \Delta\delta$ and $\Delta Q - \Delta V$ Jacobian matrices was presented to investigate the impact of Distributed Generation (DG) integration on network voltage stability. The application of this methodology to the IEEE 9-bus system demonstrated that integrating DG units at the optimal critical node (Bus 9) significantly enhances overall voltage stability, improves the voltage profile, and increases system loadability margins.

The eigenvalue spectrum and bus participation factor analyses successfully identified Bus 9 as the most vulnerable node under normal operating conditions, combining both the lowest steady-state voltage and the dominant participation factor. Simulation results confirmed that active power injections of 10 MW and 20 MW at Bus 9 progressively shift the Q-V and P-V characteristic curves upwards, effectively postponing the point of voltage collapse and reducing network power transfer from upstream sources. This modal framework offers a computationally efficient and reliable decision-support tool for planning engineers when siting renewable DG resources in modern distribution networks.

Future work may focus on:

Dynamic Voltage Stability under Stochastic PV Generation: Extending the static modal analysis to time-domain simulations to account for time-varying solar irradiance and fluctuating load profiles.

Energy Storage Systems (ESS) Integration: Modeling the combined impact of photovoltaic generation with battery storage on grid modal response, reactive power compensation, and transient stability.

Scalability to Large Distribution Feeders: Applying this modal approach to larger test systems (e.g., IEEE 33-bus, IEEE 69-bus, or real distribution networks) to validate its computational efficiency and scalability under high DG penetration levels.

Author Contributions

Seraphin Kasemuana Matototo conceived the paper, drafted the theoretical framework, and supervised the overall preparation of the manuscript, including the technical approach, application analysis, and interpretation of the results. Christian Kayembe Mudimbilayi, Vinny Loemba Vang-Si, and David Kanyinda Lumbila conducted the simulations and prepared the results. All authors reviewed and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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