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Impact of Distributed Generation Placement and Penetration Level on Voltage Profile and Loss Reduction in a Radial Distribution Network: An ETAP-Based Study

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ABSTRACT

Radial distribution networks are widely used in power systems because of their simple configuration and low installation cost, but they are susceptible to voltage drops and high real power losses, especially at buses far from the substation. These problems become more severe under increasing load demand and can reduce power quality, reliability, and system efficiency. Distributed generation offers a practical means of improving voltage profiles and reducing feeder losses when appropriately located and sized. This study examines the effect of distributed generation placement and penetration level on voltage profile improvement and loss reduction in an IEEE 6-bus radial distribution network. Two candidate locations were evaluated: Bus 5, identified as the weakest bus, and Bus 6, representing the remote end of the feeder. Load-flow simulations were performed in ETAP for distributed generation penetration levels ranging from 0% to 110% of the base-case loading condition. The results show that distributed generation improves bus voltages and reduces total system losses up to an optimal penetration range of approximately 60% to 70%. Beyond this range, losses increase because of changes in current distribution and power-flow direction. Comparative results indicate that placement at Bus 5 gives better loss reduction and stronger voltage support than placement at Bus 6. The study confirms that distributed generation location and size are critical to efficient radial distribution system performance.

KEYWORDS
Distributed generation, radial distribution network, voltage profile improvement, loss reduction, optimal penetration level

I. INTRODUCTION

Electric power distribution systems play a critical role in delivering electricity from transmission networks to end users. Among the various configurations employed in practice, radial distribution systems are the most widely adopted due to their simple structure, ease of protection coordination, and relatively low installation cost. Despite these advantages, radial feeders are inherently associated with several technical challenges that affect operational efficiency and power quality.

One of the most prominent challenges in radial distribution systems is voltage drop along the feeder. Because power flows unidirectional from the substation to downstream loads, the cumulative impedance of the line sections causes a progressive reduction in voltage magnitude toward the remote buses. This phenomenon often results in the lowest voltage levels occurring at the tail end of the feeder, which may approach or violate acceptable operating limits under heavy loading conditions (Kersting, 2012). Sustained under voltage can degrade equipment performance, reduce system reliability, and compromise customer satisfaction.

In addition to voltage drop, radial networks experience significant real power losses due to the resistive components of distribution lines. These losses are commonly referred to as I^2R losses, as they are proportional to the square of the current flowing through the conductor and the line resistance. Since radial systems often supply dispersed loads over long distances, high current magnitudes can lead to substantial energy dissipation and reduced overall system efficiency (Grainger & Stevenson, 1994). Minimizing these losses remains a central objective in distribution system planning and operation. Another inherent limitation of radial feeders is the lack of alternative power flow paths. Unlike meshed networks, radial configurations have a single supply route for each load point. Consequently, they are more vulnerable to voltage instability, higher losses under peak loading, and limited operational flexibility. These characteristics highlight the need for effective technical solutions that can enhance voltage regulation and reduce feeder losses without requiring major structural modifications.

Distributed generation has emerged as a promising approach for addressing these challenges. Distributed generation refers to small to medium scale generation units installed close to load centres within the distribution network. When properly integrated, distributed generation can provide local power support, reduce feeder currents, improve voltage profiles, and decrease line losses (Ackermann et al., 2001)). In modern power systems, the increasing penetration of renewable energy sources such as solar photovoltaic and wind generation has further accelerated the adoption of distributed generation technologies. However, the technical benefits of distributed generation are strongly dependent on its location and size. Improper placement may lead to suboptimal voltage improvement or minimal loss reduction. Furthermore, excessive penetration of distributed generation can cause reverse power flow, voltage rise beyond permissible limits, and increased system losses due to altered current distribution patterns (Eltamaly & Al-Saud, 2014). Therefore, careful assessment of both siting and penetration level is essential to ensure that distributed generation enhances, rather than degrades, network performance.

Although numerous studies have examined optimal distributed generation placement using analytical or optimization techniques, there remains a need for practical, simulation based comparative studies in radial systems that clearly demonstrate how performance varies with penetration level at different strategic buses. In particular, comparative analysis between installation at a weak voltage bus and at a remote feeder end can provide valuable insight for distribution planners seeking technically sound and easily implementable solutions. The objective of this study is to evaluate the impact of distributed generation placement and penetration level on voltage profile improvement and loss reduction in a radial distribution network. Specifically, the study compares the performance of distributed generation installed at the weakest bus and at the remote bus of the feeder. Load flow simulations are performed for penetration levels ranging from zero to 110 percent to determine the optimal operating range and to identify the penetration level at which system losses begin to increase. The findings aim to provide practical guidance for effective distributed generation integration in radial distribution systems.

II. LITERATURE REVIEW

The integration of distributed generation into distribution networks has attracted considerable attention over the past two decades. A substantial body of research has focused on determining optimal placement, appropriate sizing, and acceptable penetration limits in order to improve voltage regulation and reduce system losses while maintaining operational security.

A. Distributed Generation Placement Techniques

Recent studies show that the effectiveness of distributed generation depends strongly on proper siting and sizing. Poor placement may produce limited technical benefits, while optimal placement improves voltage profile and reduces feeder losses. Optimization methods such as particle swarm optimization, ant colony optimization, topology-based methods, and machine learning have been used to identify suitable DG locations in radial distribution networks (Haider et al., 2021; Ogunsina et al., 2021; Owosuhi et al., 2024; Jain & Gupta, 2024). These studies confirm that DG should be placed at buses where it can provide maximum voltage support and loss reduction.

B. Loss Minimization Methods

Loss reduction is a major reason for integrating DG into radial distribution systems. When DG is placed close to load centres, it reduces the current drawn from the substation and lowers I^2R losses in feeder sections. However, excessive DG penetration may change current flow patterns and increase losses, especially when reverse power flow occurs. Recent studies therefore emphasize that DG must be optimally sized, not merely added in large capacity.

C. Voltage Profile Improvement Studies

Distributed generation can improve voltage profile by injecting power near weak or heavily loaded buses. This reduces voltage drop along radial feeders and improves voltage stability at downstream buses. ETAP-based and optimization-based studies have shown that proper DG placement improves minimum bus voltage and enhances overall feeder performance (Salman et al., 2022; Owosuhi et al., 2024). However, unsuitable placement or excessive penetration can cause voltage rise and operational problems.

D. Hosting Capacity Studies

Hosting capacity refers to the maximum DG level a distribution network can accept without violating technical limits. Recent studies identify overvoltage, reverse power flow, thermal overload, harmonics, and protection coordination issues as major constraints to DG integration (Koirala et al., 2022; Qamar et al., 2023). Therefore, DG penetration should be increased only within the safe operating capacity of the feeder.

E. Findings from Literature

The literature generally agrees that DG placement and penetration level are critical to distribution network performance. Properly located and sized DG improves voltage profile and reduces losses, while excessive or poorly placed DG may cause reverse power flow, voltage rise, and increased losses. The studies also show that optimization and simulation-based approaches are useful for identifying suitable DG locations and acceptable penetration levels.

F. Positioning of the Present Study

This study builds on previous work by using ETAP to examine the impact of DG placement and penetration level in an IEEE 6-bus radial distribution network. The study compares DG installation at Bus 5, the weakest bus, and Bus 6, the remote feeder bus. By varying DG penetration from 0% to 110%, the research identifies the placement option and penetration range that provide the best voltage improvement and loss reduction.

III. METHODOLOGY

A. Description of the Test System

The test system considered in this study is a six-bus radial distribution network modeled using ETAP software. The single line diagram of the six - bus radial distribution network used in this study is shown in Figure. 1.

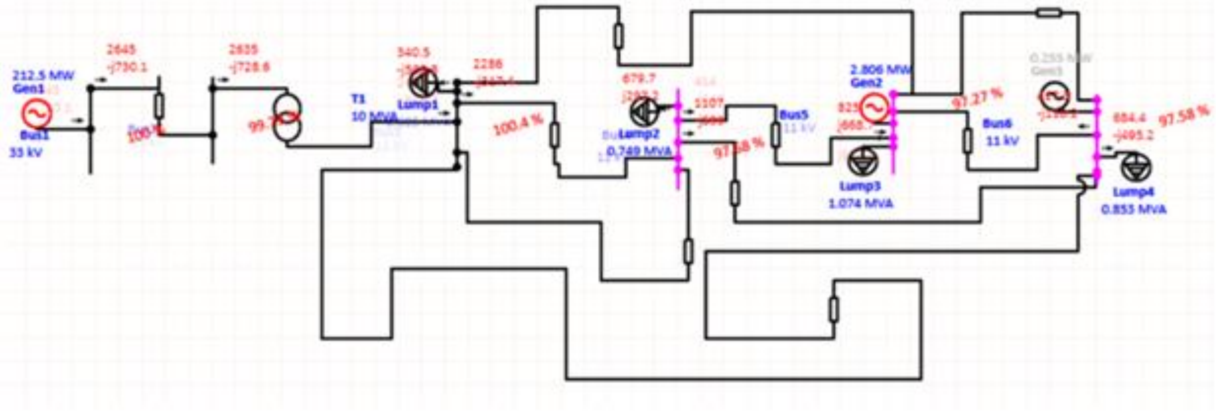

Figure: 1 – The Single Line Diagram of the Six – Bus Redial Distribution Network

The radial distribution network studied comprises six sequentially arranged buses supplied from a single substation. Radial systems, while simple and easy to operate, experience progressive voltage drops and higher line losses (Kersting, 2012). Using a previously developed ETAP model, the network was adapted to assess the impact of distributed generation while retaining original feeder parameters and loads. Under base case conditions without local generation, voltage declines along the feeder, with Bus 5 exhibiting the lowest magnitude and Bus 6 representing the remote end. These buses were selected for distributed generation placement to evaluate effects at weak and distant nodes. The base case serves as the reference scenario for all subsequent analyses.

B. ETAP Modelling

Load flow analysis was conducted in ETAP to assess voltage magnitudes and system losses under varying distributed generation (DG) penetration levels. ETAP applies established power flow techniques suitable for radial networks, including backward–forward sweep and Newton–Raphson methods (Kersting, 2012), computing bus voltages, branch currents, and total real power losses for each scenario. Network parameters, including line impedances and loads, were kept constant. The substation was modelled as a slack bus with fixed voltage, and loads were assumed constant. Protection devices and dynamic controls were excluded, focusing on steady-state performance. DG units were modelled as injections at Bus 5 or Bus 6, with sizes varied to represent 0–110% of base case load. Each penetration level was simulated separately to obtain corresponding voltage profiles and system losses.

C. Performance Indices

The impact of distributed generation integration was assessed using voltage profile improvement and system loss reduction. Voltage improvement was evaluated by comparing bus voltage magnitudes at each penetration level with the base case values, with emphasis on the weakest and remote buses to determine the influence of DG placement on voltage support. Voltage regulation remains a key measure of power quality and system reliability (Grainger & Stevenson, 1994). System loss reduction was determined from the total real power losses obtained from load flow results and compared with the base case loss. Since distribution losses vary with the square of line current, local generation can reduce feeder current and losses up to an optimum point (Méndez et al., 2006). The optimal penetration level was identified as the point with minimum total loss, while the level where losses began to increase was considered the practical upper limit for DG integration.

D. Mathematical Modelling Analysis

The mathematical model used in this study is based on load-flow analysis, DG penetration level, voltage profile evaluation, and system loss calculation. The load connected at each bus is represented as complex power

$$S_i = P_i + jQ_i$$

Where $S_i$is the apparent power at bus i, $P_i$is the active power demand, and Q_i is the reactive power demand.

The total active load of the system is obtained as:

$$PL_{total} = \sum PL_i$$

Where PL_{total} is the total active power demand of all load buses.

The DG penetration level is defined as the ratio of the DG active power output to the total active load demand:

$$\text{DG penetration (\%)} = \left(P_{DG}/PL_{total}\right) \times 100$$

Therefore, the DG size at any penetration level is:

$$P_{DG} = (\alpha/100) \times PL_{total}$$

Where α is the selected DG penetration level in percentage?

The voltage magnitude displayed in ETAP as percentage is converted to per unit as: $V_{pu}=V_{\%}/100$

This allows voltage results such as 97.58% to be reported as 0.9758pu.

The voltage improvement due to DG placement is evaluated as:

$$\Delta V_i = V_{iDG}-V_{ibase}$$

Where V_{iDG} is the bus voltage after DG integration and V_{ibase} is the voltage before DG installation.

The real power loss in each feeder section is calculated from the line current and resistance as:

$$P_{loss}=I^2 R$$

For a three-phase feeder, this becomes:

$$P_{loss}=3I^2 R$$

The total system loss is the sum of the losses in all line sections

$$P_{loss,total}= \sum P_{loss,ij}$$

The percentage loss reduction is calculated as:

$$\text{Loss reduction } (\%) = \left[\frac{P_{loss,bae}-P_{loss,DG}}{P_{loss,base}}\right]\times 100$$

The optimal DG penetration level is the value that gives the minimum total system loss:

$$\alpha_{opt}=\min P_{loss,total}(\alpha)$$

These equations show that DG reduces feeder current by supplying part of the load locally. Since line loss is proportional to the square of current, proper DG placement reduces losses and improves voltage profile. However, when DG penetration becomes too high, reverse power flow may occur, causing losses to increase again.

IV. RESULTS

A. Base Case Analysis without Distributed Generation

The base case scenario represents the operation of the radial distribution network without distributed generation support. Under this condition, the voltage profile demonstrates the characteristic behaviour of a radial feeder, in which voltage magnitude gradually decreases from the source bus towards the downstream buses. This reduction is mainly due to line impedance and the cumulative loading effect along the feeder. The simulation results show that the most severe voltage depression occurs at Bus 5, which records the lowest voltage magnitude in the network. The base case voltage magnitudes are presented in Table 1 and illustrated in Figure 2. This result establishes the base case condition as the reference for evaluating the impact of distributed generation integration in subsequent analyses**.**

Table 1: Base Case Voltage Profile

Bus	**1**	**2**	**3**	**4**	**5**	**6**
Voltage (p.u)	1.00	0.9961	0.9912	0.9408	0.9242	0.9375

This confirms Bus 5 as the weakest bus under base case conditions. Bus 6, located at the end of the feeder, also experiences relatively low voltage, although its magnitude remains slightly higher than that of Bus 5. The observed voltage distribution reflects the electrical distance of each bus from the substation and the loading pattern along the feeder. In terms of system losses, the total real power loss under the base case condition is 0.121 per unit. This value serves as the reference for evaluating the impact of distributed generation integration. The relatively high loss level is consistent with the nature of radial systems, where feeder currents must supply all downstream loads, resulting in significant resistive losses.

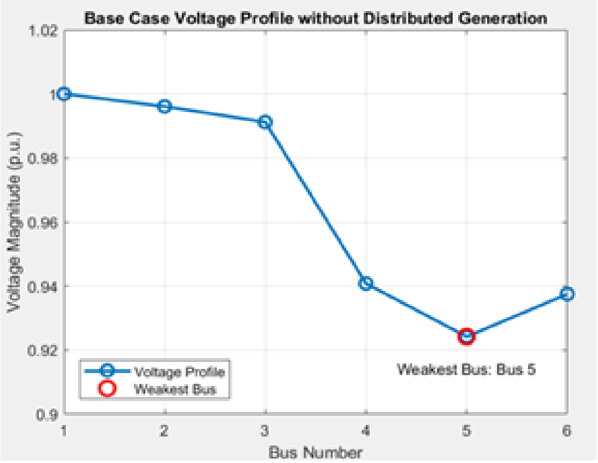

Figure: 2 – Base Case Voltage Profile without Distribution Generation

B. Distributed Generation Installed at Bus 5

When distributed generation is installed at Bus 5, a noticeable improvement in voltage profile is observed across the network. As the penetration level increases from 0 percent to 110 percent, the voltage magnitude at Bus 5 increases steadily, reflecting the direct local support provided by the generation unit. The improvement is also propagated to adjacent buses, particularly Bus 4 and Bus 6, due to reduced current flow in upstream line sections.

Table 2: Voltage Profile with DG at Bus 5

Bus	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**	**110%**
1	1.000	1.000	1.000	1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000.

2	0.9961	0.9963	0.9965	0.9966	0.9968	0.9970	0.9971	0.9973	0.9975	0.9976	0.9978	0.9979
3	0.9912	0.9924	0.9936	0.9948	0.9960	0.9972	0.9984	0.9995	1.0007	1.0018	1.0029	1.0040
4	0.9408	0.9443	0.9477	0.9511	0.9544	0.9577	0.9610	0.9642	0.9674	0.9706	0.9737	0.9768
5	0.9242	0.9288	0.9334	0.9380	0.9425	0.9469	0.9513	0.9557	0.9600	0.9643	0.9685	0.9727
6	0.9375	0.9412	0.9448	0.9484	0.9519	0.9555	0.9589	0.9624	0.9658	0.9691	0.9725	0.9758

The voltage trend demonstrates that moderate levels of distributed generation significantly enhance voltage stability in the weakest section of the feeder. The most substantial improvements occur between 0 percent and approximately 70 percent penetration, beyond which the incremental gains in voltage become smaller.

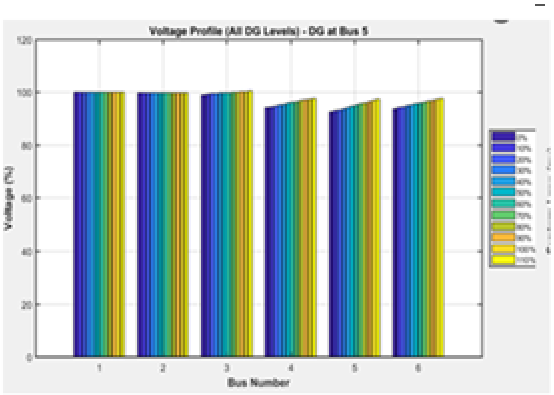

Figure: 3 – Voltage Profile (All DG Leve) DG at Bus 5

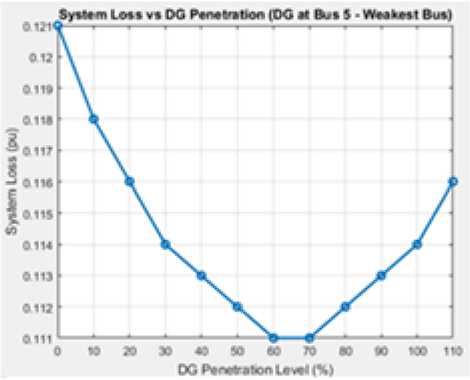

Figure: 4 – System Loss vs DG penetration (DG at Bus 5, Weakest Bus)

The system loss curve associated with this placement exhibits a clear nonlinear pattern. The corresponding loss values for DG installed at Bus 5 are presented in Table 3. The voltage profile for all levels of distributed generation (DG) penetration with the DG connected at Bus 5 is illustrated in the grouped bar chart presented in Figure 3. Figure 4 presents a graph of total system losses as a function of DG penetration level, with the DG installed at the remote bus (Bus 6).

Table 3: Total System Loss with DG at Bus 5

Penetration (%)	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**
Loss (pu)	0.121	0.118	0.116	0.114	0.113	0.112	0.111	0.111	0.112	0.113	0.114	0.116

As penetration increases from 0 percent to about 60 to 70 percent, total system losses decrease from 0.121 per unit to approximately 0.111 per unit. This represents the minimum loss point and corresponds to the optimal penetration range. Within this range, distributed generation effectively supplies local loads and reduces feeder current, thereby minimizing resistive losses.

Beyond approximately 70 percent penetration, losses begin to increase. The upward trend becomes evident from 80 percent onward and continues through 110 percent penetration. This behaviour indicates that excessive generation alters the power flow pattern, leading to increased current in certain sections of the network and diminishing the loss reduction benefit. The penetration level at which losses begin to increase marks a practical operational limit for efficient distributed generation integration at Bus 5.

C. Distributed Generation Installed at Bus 6

When distributed generation is installed at Bus 6, voltage improvement is also observed throughout the feeder. The voltage at the remote bus increases consistently as penetration rises, and upstream buses benefit from reduced current flow due to partial local supply of demand. The overall voltage profile shows progressive enhancement from the base case up to the highest penetration level. However, the degree of voltage support at the weakest bus differs from that achieved with placement at Bus 5. While Bus 6 placement improves voltage at the feeder end, it does not provide the same level of corrective support at Bus 5 as direct installation at that location. This highlights the influence of electrical positioning within the feeder.

Table 4: Voltage Profile with DG at Bus 6

Bus	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**	**110%**
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1000	100.00
2	0.9961	0.9963	0.9965	0.9966	0.9968	0.9970	0.9971	0.9973	0.9974	0.9976	0.9978	0.9979
3	0.9912	0.9924	0.9936	0.9948	0.9960	0.9971	0.9983	0.9994	1.0006	1.0017	1.0028	1.0039
4	0.9408	0.9442	0.9476	0.9509	0.9542	0.9575	0.9608	0.9640	0.9672	0.9703	0.9735	0.9766
5	0.9242	0.9278	0.9314	0.9350	0.9385	0.9421	0.9456	0.9490	0.9524	0.9559	0.9592	0.9626
6	0.9375	0.9412	0.9450	0.9486	0.9522	0.9559	0.9594	0.9630	0.9665	0.9700	0.9734	0.9769

The loss trend for distributed generation at Bus 6 also follows a nonlinear pattern similar to that observed for Bus 5 placement, although the magnitude of loss reduction is smaller. Losses decrease from the base case value of 0.121 per unit to approximately 0.116 per unit within the moderate penetration range. The minimum loss region again occurs around 60 to 70 percent penetration.

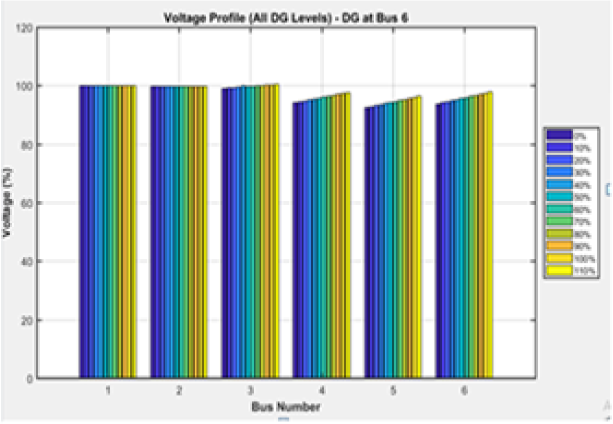

Figure: 5. Voltage Profile (All DG Level) at Bus 6

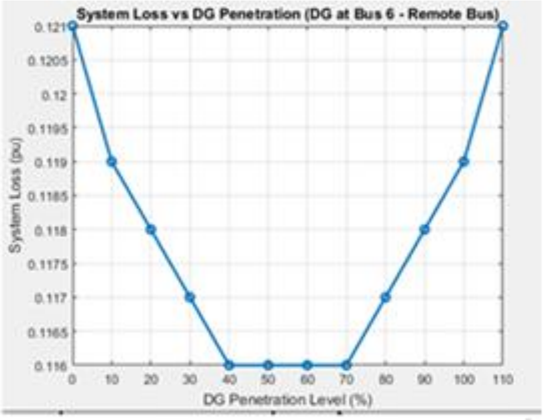

Figure: 6. System Losses vs DG at Bus 6 – Remote Bus

After this point, losses begin to rise gradually, and by 110 percent penetration they approach the base case value. The corresponding loss values for DG installed at Bus 6 are presented in Table 5.) The voltage profile for all levels of distributed generation (DG) penetration with the DG connected at Bus 6 is illustrated in the grouped bar chart presented in Figure 5. Figure 6 presents a graph of total system losses as a function of DG penetration level, with the DG installed at the remote bus (Bus 6).

Table 5: Total System Loss with DG at Bus 6

Penetration (%)	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**
Loss (pu)	0.121	0.119	0.118	0.117	0.116	0.116	0.116	0.116	0.117	0.118	0.119	0.121

Comparative analysis indicates that distributed generation placement at Bus 5 yields greater loss reduction than placement at Bus 6. Although both locations improve voltage levels and reduce losses within the optimal range, Bus 5 installation provides stronger correction at the weakest node and achieves a larger overall decrease in system losses. These findings demonstrate that strategic siting at an electrically weak bus offers superior technical benefits compared to installation solely at the remote end of the feeder.

V. DISCUSSION

A. Comparison of Distributed Generation Placement Locations

The comparative analysis of distributed generation placement at Bus 5 and Bus 6 shows that both locations improve voltage profile and reduce system losses. However, their effectiveness differs depending on their electrical position within the feeder.

For voltage support, placement at Bus 5 produces the strongest improvement because Bus 5 is the weakest bus in the base case condition. Injecting power directly at this point significantly improves its voltage magnitude and also supports neighboring buses. This effect is most noticeable at moderate penetration levels, where voltage recovery is achieved without causing overvoltage. In comparison, placement at Bus 6 improves the remote-end voltage but provides less correction at Bus 5. This indicates that voltage support is more effective when distributed generation is located at the bus with the highest voltage depression. For loss reduction, Bus 5 placement also performs better than Bus 6 placement. The greater reduction in total system losses suggests that installing distributed generation near the area of highest voltage drop and load concentration reduces feeder current more effectively. Although Bus 6 placement also reduces losses within the optimal penetration range, its effect is lower and the loss profile remains closer to the base case.

Overall, the results show that strategic siting of distributed generation is essential for effective distribution network performance. Placement at Bus 5 provides better targeted voltage correction and greater loss minimization than placement at Bus 6. Therefore, distributed generation should be located at electrically weak buses rather than selected only based on feeder-end position.

B. Analysis of Loss Increase at High Penetration

The loss curves obtained for both placement scenarios exhibit a characteristic nonlinear pattern. Initially, losses decrease as distributed generation penetration increases. This reduction occurs because local generation supplies a portion of the load demand, thereby decreasing the magnitude of current flowing from the substation through upstream feeder sections. Since line losses are proportional to the square of current, even moderate reductions in current produce noticeable decreases in total system losses.

However, beyond the optimal penetration range of approximately 60 to 70 percent, the loss curve begins to rise. This behavior can be explained by the changing direction and magnitude of power flow within the feeder. When distributed generation output exceeds local demand at the installation bus, surplus power flows upstream toward the substation. This reverse power flow increases current in certain line segments, which in turn increases resistive losses. As penetration continues to rise, the benefit of local load supply is offset by the additional current circulating within the network. Furthermore, higher levels of distributed generation can alter voltage magnitudes and current distribution in ways that increase total feeder current rather than reduce it. Once the generation size surpasses the level that balances local demand and feeder loading, additional capacity does not translate into further efficiency gains. Instead, it leads to higher losses and reduced overall effectiveness. The observed increase in losses beyond the optimal point therefore reflects the physical limitations of radial power flow characteristics.

C. *Practical Implications*

The findings of this study have important implications for distribution system planning and operation. First, the results emphasize the importance of correct distributed generation siting. Installing generation at an electrically weak bus provides more effective voltage regulation and greater loss reduction than installation at a location that is not directly associated with the most critical voltage deficiency. Strategic siting can therefore maximize technical benefits without requiring excessive generation capacity. Second, the results demonstrate that increasing distributed generation penetration indefinitely does not guarantee continuous performance improvement. There exists an optimal penetration range within which voltage support and loss reduction are maximized. Beyond this range, additional generation may lead to higher losses and potential operational concerns. Limiting penetration to an appropriate level is therefore essential for maintaining system efficiency.

Finally, the study highlights the relevance of hosting capacity considerations. The point at which losses begin to increase serves as an indicator that the feeder is approaching its technical integration limit under the given configuration. Hosting capacity is influenced by voltage constraints, power flow direction, and network impedance characteristics. Careful assessment of these factors is necessary before approving high penetration levels of distributed generation. Overall, effective distributed generation integration requires coordinated decisions regarding both location and size. A balanced approach that considers voltage regulation, loss behavior, and network limits is essential for achieving sustainable performance improvements in radial distribution systems.

VI. CONCLUSION

This study examined the technical impact of distributed generation placement and penetration level on voltage profile improvement and loss reduction in a six bus radial distribution network modeled in ETAP. The base case analysis confirmed the inherent characteristics of radial feeders, including progressive voltage drop toward downstream

Buses and relatively high real power losses. Bus 5 was identified as the weakest bus under base case conditions, while Bus 6 represented the remote end of the feeder.

The integration of distributed generation at both candidate locations resulted in significant voltage improvement and loss reduction within a defined penetration range. When installed at Bus 5, distributed generation provided stronger corrective support at the weakest node and achieved a greater overall reduction in system losses compared to installation at Bus 6. Although placement at the remote bus also enhanced voltage levels and reduced losses, the magnitude of improvement was comparatively smaller. The loss characteristics for both placement scenarios followed a nonlinear pattern. Losses decreased progressively as penetration increased up to approximately 60 to 70 percent. Beyond this range, further increases in penetration resulted in rising losses due to changes in current distribution and the onset of reverse power flow. The results therefore indicate that the optimal penetration range for the studied system lies within 60 to 70 percent of the base case loading.

From an engineering perspective, the findings demonstrate that both the location and size of distributed generation critically influence network performance. Strategic placement at electrically weak buses can significantly enhance voltage stability and energy efficiency without requiring excessive generation capacity. The study underscores the importance of technical evaluation prior to distributed generation integration in radial systems.

RECOMMENDATIONS

Based on the results of this investigation, several recommendations can be made for practical distribution system planning.

First, distributed generation should be preferentially installed at electrically weak buses where voltage support is most needed. Placement at such locations provides stronger local voltage correction and greater system wide loss reduction compared to installation solely at the feeder end.

Second, penetration levels should be maintained within the identified optimal range of approximately 60 to 70 percent for the studied network configuration. Exceeding this range may diminish technical benefits and lead to increasing losses.

Third, coordinated voltage control strategies should be considered when integrating distributed generation at moderate to high penetration levels. Appropriate regulation settings, reactive power management, and feeder control coordination can help maintain acceptable voltage limits and prevent adverse operational effects.

Finally, further research may extend this work by incorporating multiple distributed generation units, reactive power control capabilities, time varying load conditions, and protection coordination analysis. Optimization based approaches and probabilistic assessment methods may also provide deeper insight into hosting capacity limits and long term operational performance.

REFERENCE

[1] Acharya, N., Mahat, P., & Mithulananthan, N., "An analytical approach for DG allocation in primary distribution network," International Journal of Electrical Power & Energy Systems, vol. 28, no. 10, pp. 669–678, 2006.
[2] Ackermann, T., Andersson, G., & Söder, L., "Distributed generation: A definition," Electric Power Systems Research, vol. 57, no. 3, pp. 195–204, 2001.
[3] Adegoke, S. A., Sun, Y., Adegoke, A. S., & Ojeniyi, D., "Optimal placement of distributed generation to minimize power loss and improve voltage stability," Heliyon, vol. 10, no. 21, Article e39298, 2024.
[4] Ahmadi, B., Ceylan, O., & Ozdemir, A., "Reinforcement of the distribution grids to improve the hosting capacity of distributed generation: Multi-objective framework," Electric Power Systems Research, vol. 217, Article 109120, 2023.
[5] Barker, P. P., & de Mello, R. W., "Determining the impact of distributed generation on power systems," Proceedings of the IEEE Power Engineering Society Summer Meeting, vol. 3, pp. 1645–1656, 2000.
[6] Eltamaly, A. M., & Al-Saud, M. S., "Optimal placement and sizing of distributed generation in distribution systems using particle swarm optimization," Electric Power Components and Systems, vol. 42, no. 5, pp. 512–524, 2014.
[7] Grainger, J. J., & Stevenson, W. D., Power System Analysis, 3rd ed., McGraw-Hill, 1994.

[8] Haider, W., Hassan, S. J. U., Mehdi, A., Hussain, A., Adjayeng, G. O. M., & Kim, C.-H., "Voltage profile enhancement and loss minimization using optimal placement and sizing of distributed generation in reconfigured network," Machines, vol. 9, no. 1, Article 20, 2021.

[9] Hung, D. Q., Mithulananthan, N., & Bansal, R. C., "Analytical expressions for DG allocation in primary distribution networks," IEEE Transactions on Energy Conversion, vol. 25, no. 3, pp. 814–820, 2010.

[10] Jain, A., & Gupta, S. C., "Optimal placement of distributed generation in power distribution system and evaluating the losses and voltage using machine learning algorithms," Frontiers in Energy Research, vol. 12, Article 1378242, 2024.

[11] Keane, A., Ochoa, L. F., Borges, C. L. T., Ault, G. W., Alarcon Rodriguez, A., Dent, C. J., Pilo, F., & Rosehart, W., "State of the art techniques and challenges ahead for distributed generation planning and optimization," IEEE Transactions on Power Systems, vol. 28, no. 2, pp. 1493–1502, 2013.

[12] Kersting, W. H., Distribution System Modeling and Analysis, 3rd ed., CRC Press, 2012.

[13] Koirala, A., Van Acker, T., D'hulst, R., & Van Hertem, D., "Hosting capacity of photovoltaic systems in low voltage distribution systems: A benchmark of deterministic and stochastic approaches," Renewable and Sustainable Energy Reviews, vol. 154, Article 111899, 2022.

[14] Méndez Quezada, V. H., Rivier, J., & Gómez, T., "Assessment of energy distribution losses for increasing penetration of distributed generation," IEEE Transactions on Power Systems, vol. 21, no. 2, pp. 533–540, 2006.

[15] Ogunsina, A. A., Petinrin, M. O., Petinrin, O. O., Offornedo, E. N., Petinrin, J. O., & Asaolu, G. O., "Optimal distributed generation location and sizing for loss minimization and voltage profile optimization using ant colony algorithm," SN Applied Sciences, vol. 3, Article 248, 2021.

[16] Owosuhi, A., Hamam, Y., & Munda, J., "A new framework for active loss reduction and voltage profile enhancement in a distributed generation-dominated radial distribution network," Applied Sciences, vol. 14, no. 3, Article 1077, 2024.

[17] Qamar, N., Arshad, A., Mahmoud, K., & Lehtonen, M., "Hosting capacity in distribution grids: A review of definitions, performance indices, determination methodologies, and enhancement techniques," Energy Science & Engineering, vol. 11, no. 4, pp. 1536–1559, 2023.

[18] Rajabi, A., Elphick, S., David, J., Pors, A., & Robinson, D., "Innovative approaches for assessing and enhancing the hosting capacity of PV-rich distribution networks: An Australian perspective," Renewable and Sustainable Energy Reviews, vol. 161, Article 112365, 2022.

[19] Salman, M., Hongsheng, S., Aman, M. A., & Khan, Y., "Enhancing voltage profile and power loss reduction considering distributed generation (DG) resources," Engineering, Technology & Applied Science Research, vol. 12, no. 4, pp. 8864–8871, 2022.

[20] Singh, D., & Goswami, S. K., "Optimal allocation of distributed generations based on nodal pricing for profit, loss reduction, and voltage improvement," International Journal of Electrical Power & Energy Systems, vol. 32, no. 6, pp. 637–644, 2010.