Received Date: 9th November, 2025
Revision Date: 14th December, 2025
Accepted Date: 25th January, 2026

Comparative Analysis of Distributed and Centralized PV Integration in a Distribution Feeder Using DIgSILENT Power Factory

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Abstract— ***With the rapid growth of photovoltaic (PV) integration into distribution networks, maintaining voltage stability and minimizing feeder overloading have become significant technical challenges for utilities. This study aims to analyze the impact of distributed and centralized PV system integration on the operational performance of a distribution feeder modeled in DIgSILENT PowerFactory and categorized into four different zones. The network was simulated under two configurations: in the distributed PV system, nine PV plants with different generating capacity were strategically allocated across different buses to represent decentralized generation, while in the centralized PV system, the same total capacity was concentrated at the approximate load center. The feeder's performance is analyzed at 12 different level of PV penetration from 0 to 50% of total generation (14.11 MW), where the feeder was loaded at 3.34 MW. Through detailed load flow analysis, system performance was evaluated based on line loading, voltage profile, and PV bus characteristics. In the distributed system, the feeder's minimum loss was at 22% PV penetration with over 63% loss reduction. One the other hand, centralized system had minimum loss at 15% PV penetration with over 50% loss reduction. The large number of lines were operating under heavy overloading condition due to large localized power flow in the centralized system compared to that in distributed system under high level of PV penetration. The voltage profile of the distributed PV system is found to be uniformly improving with the increase in PV injection level. The results indicate that distributed PV integration provides more balanced voltage profiles along the feeder, significantly reducing voltage drops, line loading, and power loss. Conversely, the centralized PV configuration caused noticeable voltage rise near the point of connection and higher upstream line loading. The comparative findings demonstrate that distributed PV systems enhance network efficiency and voltage stability, while centralized PV setups offer simpler control but are more prone to localized overvoltage and uneven power distribution. Study also demonstrate that the hosting capacity of the feeder is more in dsitributed system. The study provides insights into how optimal PV placement strategies can improve the technical performance and reliability of modern distribution networks.***

Keywords — Solar PV, Distributed Generation, Centralized PV, Feeder Losses, Voltage Profile, DIgSILENT

I. Introduction and Background

The accelerating integration of renewable energy sources, particularly solar photovoltaic (PV) systems, has fundamentally transformed the global power sector throughout the past decade. As a pivotal enabler of the low-carbon transition, solar PV has experienced exponential growth, attaining a cumulative installed capacity surpassing 2 TW by mid-2025, supported by annual increments exceeding 600 GW in the prior year [1]. This momentum is propelled by precipitous reductions in module costs now below \$0.30/Wp-technological advancements including bifacial and tandem cells, and comprehensive policy mechanisms globally designed to expedite deployment in pursuit of net-zero objectives [2]. Notwithstanding these advancements, the proliferation of PV installations engenders substantial technical impediments within distribution networks, which were conventionally engineered for unidirectional power flow. High PV penetration levels, often exceeding 30% of feeder capacity, precipitate bidirectional power flows, voltage elevations, harmonic distortions, and escalated energy losses, thereby undermining system reliability and operational efficacy [3], [4].

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In scenarios where solar PV supports broader sustainability initiatives, these challenges are intensified by inherent infrastructural limitations, rendering networks vulnerable to PV-induced disturbances such as pronounced voltage instability and potential curtailment requirements without rigorous integration methodologies [5]–[7]. Consequently, a thorough examination of PV placement and capacity effects on feeder performance is essential to facilitate sustainable incorporation.

PV configurations broadly classify into centralized systems, characterized by large-scale arrays connected upstream proximate to substations, and distributed PV (DPV) systems, involving multiple smaller units dispersed along the feeder near consumption points. While equivalent in total output, these configurations produce markedly dissimilar effects on power flows, voltage profiles, line loadings, and loss magnitudes. Empirical studies consistently indicate that DPV yields superior voltage uniformity, reduced line stresses, and loss reductions of 13–20% compared to centralized arrangements under comparable penetration scenarios [8], [9].

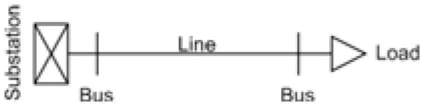

Fig. 1. Modeling approach of feeder in DIgSILENT

Exceeding 50% penetration levels exposes additional deficiencies in conventional analytical frameworks. Deterministic loadflow analyses and traditional optimization techniques inadequately account for the stochasticity, bidirectionality, and spatial variability inherent to renewables, thereby constraining precise assessments of hosting capacity [10], [11]. Hence, detailed, simulation-based evaluations at the feeder level are critical to identify optimal integration strategies and avert the need for extensive network reinforcements.

The body of literature on PV-distribution network interactions has evolved from initial economic evaluations to sophisticated techno-operational analyses [12], [13]. The scalability of centralized PV is tempered by susceptibilities to remote generation effects, resulting in 4–7% greater voltage gradients and up to 12% higher losses at 30% penetration [8]. In contrast, DPV's proximate generation mitigates these issues by 13–18% across diverse topologies [9]. Voltage regulation remains a central concern: decentralized and multi-agent control approaches have achieved 8–12% enhancements in stability while optimizing reactive power allocation [14], [15].

Dhital et al. [12] performed a techno-economic feasibility assessment of a 3-kW PV installation employing simulation and cost-benefit modeling, observing 9% energy loss reductions but noting overvoltage risks beyond 20% penetration. Shrestha et al. [5] investigated hybrid PV-battery systems via optimization and load-flow simulations on 11 kV feeders, revealing 12–16% reductions in feeder loading and improved voltage profiles through dispersed placements. Adhikary and Shrestha [6] utilized radial distribution modeling to evaluate distributed generation impacts, documenting 10% voltage profile enhancements and corresponding loss diminutions. Timilsina and Poudel [7] conducted case-study simulations targeting loss reduction in 11 kV feeders, attaining up to 15% efficiency improvements via strategic PV integrations. Yadav and Shakya [16] assessed PV minigrid efficacy using empirical measurements and performance metrics, identifying 5–8% loss decreases and voltage equalization advantages from distributed architectures under fluctuating loads.

Complementing these contributions, international investigations underscore DPV's advantages. Adaptive clustering algorithms for inverter coordination have diminished losses by approximately 20% in PV-dominant radial networks [17], whereas dynamic thermal rating evaluations have augmented hosting capacities by 25% by leveraging underutilized thermal headroom [18]. Centralized voltage control schemes can attenuate fluctuations by 10%, though they impose significant communication and computational demands [19]; hybrid central-local approaches, by comparison, deliver resilient performance amid irradiance variability [20], [21]. Furthermore, DPV bolsters transient stability-elevating relevant indices by 7-11% and limits voltage deviations to ±2% at penetrations above 50% [22], [23]. From a sustainability standpoint, DPV configurations exhibit 15% lower lifecycle emissions relative to centralized counterparts [24].

Although substantial research exists, direct comparisons of centralized and distributed PV using real-world feeder data from developing contexts are limited. Most analyses rely on standardized IEEE test cases, which overlook the imbalances, weaknesses, and resistive characteristics prevalent in actual radial distribution systems [14], [17].

This study addresses this gap by developing a precise model of an actual 11 kV feeder in DIgSILENT PowerFactory, incorporating geospatial-extracted line parameters, transformer specifications, and load profiles derived from ArcGIS. Two scenarios are examined: a centralized PV connection at near the substation bus bar and a DPV setup comprising nine smaller units positioned across the feeder. Total PV capacity is held constant, with penetration varied from 0% to 50% of aggregate demand.

II. METHODOLOGY

The analysis of the effect of centralized PV generation and distributed PV generation on distribution feeder is done through DIgSILENT modeling of actual 11 kV Nalinchowk feeder. The general approach for modeling of distribution feeder is presented in Figure 1. Where, the load represents transformer of each load center. As the modeling of whole network along with individual consumer's load is very complex, the transformer represents aggregated load demand of each load center. The system consists of 114 transformer, rating of each transformer ranging from 20 - 320 kVA, 181 buses, and 180 lines leading to total connected load of 13.915 MVA. The feeder consists of four different types of line used in different section of it. The value of different parameter's of line used in DigSILENT modeling is presented in Table I.

Table i

Specifications of conductors used

S.N.	Conductor Name	Size (mm^2)	Max. DC Resistance at 20°C (Ω/km)	Ampacity (A)
1	Dog (D)	100	0.2733	278
2	Rabbit (R)	50	0.2733	185
3	Weasel (W)	30	0.9077	134

The PV plants are placed strategically along the feeder to analyze the effect of distributed and centralized or single PV plant in distribution feeder. Figure 2 represents the geometrical layout of 11 kV feeder along with strategically placed distributed PV plants. On the other hand the Figure 3 represents the geometrical layout of the feeder with centralized or single PV plant connected to it. The total generation capacity of the plant in both the centralized system and distributed system is made equal to analyze the impact of equally stressed scenario. Based on availability of the space, the PV generation capacity in both the case is assumed to be 14.16 MW.

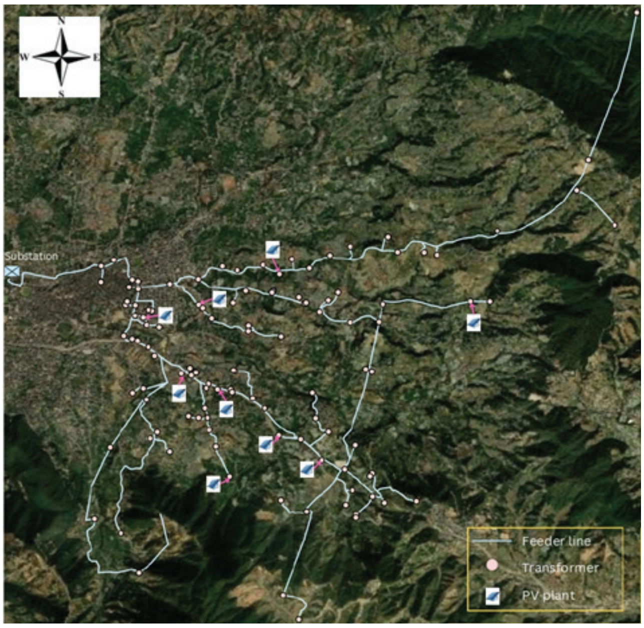

Fig. 2. Distributed PV plant

Fig. 3. Centralized PV plant

The total capacity of each distributed PV plant is presented in Figure 4. This unequal generation capacity of distributed generators replicates the possible real case scenario of multiple PV plants with different generation capacity connected to the distribution feeder.

The figure 3 represents the geometrical layout of the feeder under study with centralized PV system. The location of single PV plant is identified such that it supplies to the major portion of loads. Both the distributed and the centralized PV system is modeled in DigSILENT PowerFactory and the effect of different level of PV power injection to the plant is analyzed with the help of steady state power flow. The PV generation is varied from 0 - 50 % while the total load on the feeder is kept at 30% of connected load i.e. 3.34 MW at 0.8 power factor. The generation capacity of PV plants and load demand during different test scenario is presented in figure 5. Which shows that the PV injection is increased linearly between 0 to 7.06 MW i.e. approximately up to 110% greater than the connected load. This ensures the analysis in both the extreme cases i.e. very low PV generation and very High PV generation. The line loading, voltage profile and losses of the feeder is analyzed in this test scenario for both the distributed and centralized PV systems ensuring equal PV penetration in both the cases.

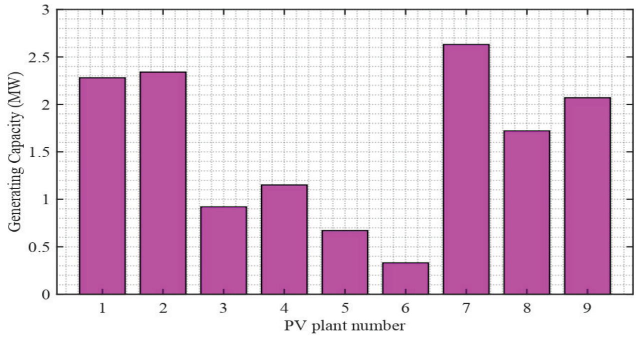

Fig. 4. Generation capacity of each distributed PV plant

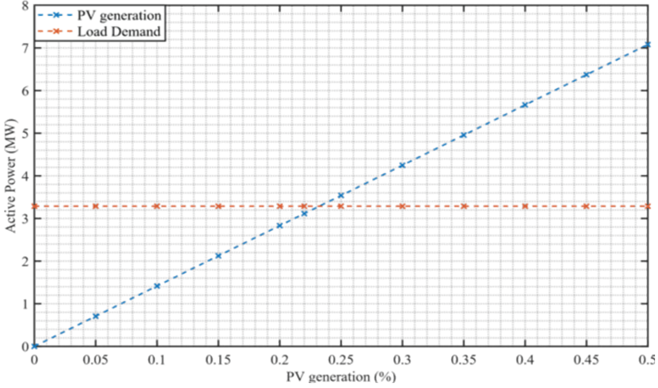

Fig. 5. Total Generation and loading level in different test scenarios

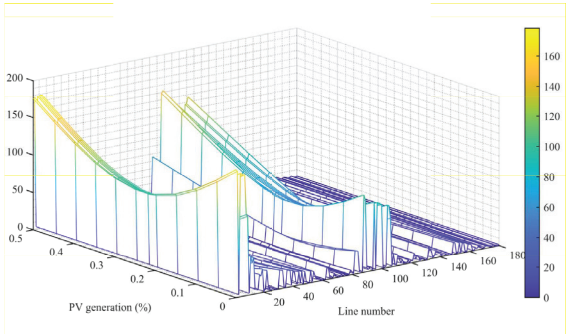

Fig. 7. Loading of different lines in a centralized system

of PV injection is increased from 0 to around 20 % the loading level on these lines is found to be decreasing exponentially in both centralized and distributed PV system as presented in the figures 7 and 6 respectively. This is because the the local generation is supplying the loads around it resulting into less power flow from the substation end and shorter path of power flow for distributed generation and hence less loading on major portion of lines. At around the 23% PV generation meets the total demand of 3.34 MW. In this scenario, though the total active power demand is fulfilled by the PV generation, the reactive power required for the loads and that required to account reactive power loss on the line are still being supplied from the substation end resulting into reduced but still heavy loading on the liens of zone 1 and zone 2 can be observed. Once the PV generation exceeds this level, the active power starts to flow towards substation end. And the line of zone 1 faces same stress in both the distributed and centralized system as the total excess reverse power flow towards the substation and the reactive power flow from the substation is same. However, in the centralized PV system, the all the generation is being supplied by one PV plant located at zone 3. Hence the power flow through the lines of zone 2 and 3 is very high and the loadings on the line of this section is very high compared to that of distributed PV system. In general, it is found that the distributed PV generation could lead to the more uniform and lower level of line loading compared to the centralized PV system in distribution system.

B. Total feeder loss

The total feeder loss is the cumulative loss on the line of each section of the network and is dependent of total power flow or line loading of each section. The figure 9 represents the cumulative total active and reactive power loss of the feeder. Initially when all the load demand of 3.34 MW is being supplied from substation end (zero PV condition) where the total active and reactive power losses are 187.93 kW and 205.53 kVar respectively. It's found that once the PV penetration starts increasing to same threshold value the losses are decreasing and as the penetration exceeds this value the total losses starts to increase exponentially. For distributed PV system the loss is found to be decreasing until the PV penetration exceeds 22% of total generating capacity. At this point the total active power loss and reactive power loss are found to be 68.84 kW and 75.98 kVar respectively i.e. the total losses are decreased by almost 63%. On the other hand, the threshold point for centralized PV system is found to be at 15%. In this scenario the total losses are 89.24 kW and 103.1 kVar reducing almost by 50% compared to that of at no PV condition. At low PV condition i.e. below 10% PV integration both the active and reactive power losses are almost same in the centralized as well as in the distributed PV system.

Fig. 8. 11 kV lines of the distribution feeder

However, the losses are found to be increasing almost in exponential manner as presented in figure 10 due to localized overloading of lines. The generation of PV at the minimum loss point is 3.10 MW for distributed and 2.12 MW for centralized system. The excessive losses in the centralized system at the higher level of PV penetration is due to heavily overloaded lines near PV power plant. It is found that the distributed losses in distributed system is well below the losses in centralized system beyond 10% PV integration and is similar below this level.

C. Voltage Profile

In distribution networks, maintaining voltage within permissible limits is crucial for reliable operation of customer loads and network equipment. Integration of PV systems, whether centralized or distributed, significantly affects the voltage profile due to the injection of active and reactive power at various points along the feeder. The voltage profile of the feeder buses under different level of PV injection for distributed and centralized system is presented in figures 11 and 12 respectively. Presence of PV plant near load centers reduces net current flowing from the substation end resulting in less voltage drop in the lines and improved voltage profile. For distributed system, the location of PV plants are distributed all over the feeder, as result the voltage profile is improving uniformly with increase in PV penetration. While the centralized PV system has PV plant only in one branch of the feeder. Hence the voltage profile of buses within zone 2 and zone 3 are improved significantly compared to the buses of zone 4. At higher PV penetration, the voltage profile of buses in zone 3 is abruptly increased due to high current flowing reverse direction. However, it is found that the voltage profile of all the buses around 20%

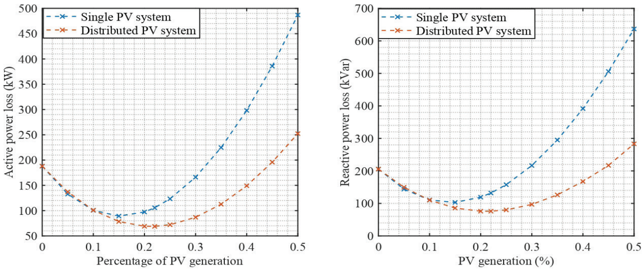

Fig. 9. Total active and reactive power losses of the feeder

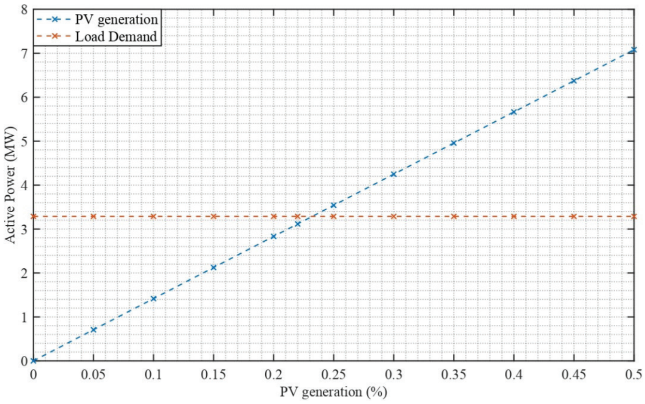

Fig. 10. Difference in active and reactive power loss in centralized and distributed system

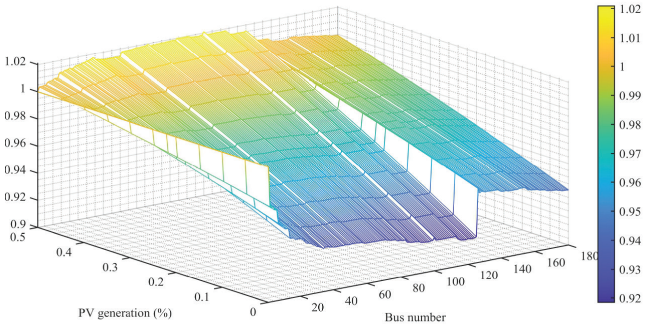

Fig. 11. Voltage profile of distributed PV system

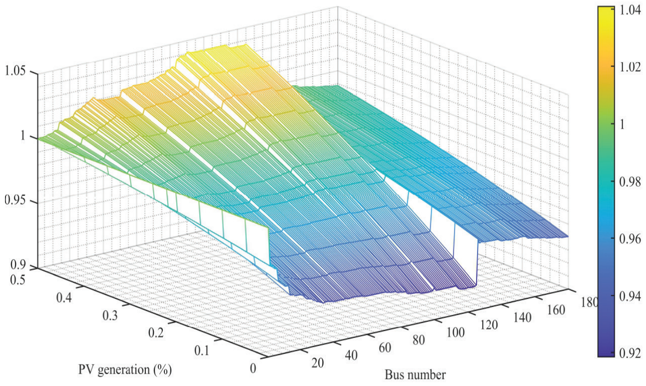

Fig. 12. Voltage profile of centralized PV system

PV injection is within the limit as per IEEE standard of ±5% for distribution level.

IV. Conclusion

This study investigated the comparative performance of distributed and centralized PV integration in a modeled distribution feeder categorized into four zones using DIgSILENT Power Factory. The analysis, conducted across twelve PV penetration levels ranging from 0% to 50% of the total generation capacity (14.11 MW), reveals that the spatial distribution of PV generation significantly affects feeder efficiency, voltage stability, and line loading characteristics.

In the distributed PV configuration, where nine PV units of varying capacities were strategically placed across the feeder, system losses were found to decrease substantially, reaching a minimum at 22% PV penetration with over 63% loss reduction compared to the base case. The distributed arrangement also yielded uniform voltage improvement throughout the feeder and reduced overloading in the main and lateral lines by balancing local power generation and demand. Conversely, in the centralized PV configuration, where the entire generation capacity was connected near the load center, the minimum system loss occurred at 15% PV penetration with over 50% reduction. However, as PV penetration increased, the centralized system exhibited localized overvoltage near the point of connection and heavy line loading in upstream sections due to concentrated power flow.

Overall, the results demonstrate that distributed PV integration enhances feeder performance more effectively than centralized deployment by providing smoother voltage profiles, minimizing network losses, and increasing the feeder's hosting capacity. Although centralized PV offers simpler control and maintenance, it poses operational challenges under higher penetration levels. Hence, strategic distribution of PV units across the feeder is technically more beneficial for ensuring reliable, efficient, and sustainable operation of modern distribution networks.

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