

Voltage and Reactive Power Control in Distribution Networks Based on the Optimal Allocation of Photovoltaic Systems: Case Study Mazar-e-Sharif Distribution Network

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Manuscript submitted October 14, 2025; accepted November 3, 2025; published November 21, 2025.

doi: 10.12720/sgce.14.2.25-39

Abstract: In recent years, the growing demand for reliable, sustainable energy in Afghanistan, particularly in urban areas such as Mazar-e-Sharif, has highlighted the need to improve power distribution network performance. This study proposes a hybrid framework for voltage and reactive power control by optimally allocating Photovoltaic (PV) systems in the 117-bus Mazar-e-Sharif distribution network. Using the Genetic Algorithm and DIgSILENT PowerFactory, the optimal PV location (Bus 12) and capacity (7.22 MW) were determined. Results show a 20.69% reduction in active power losses (from 4.73 MW to 3.75 MW), an 84.78% reduction in reactive losses (from 1.84 Mvar to 0.28 Mvar), and a minimum voltage improvement from 0.916 p.u. to 0.965 p.u. outperform conventional Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) methods without reactive power control and provides a practical solution for enhancing grid resilience in developing regions.

Keywords: optimal allocation, Mazar-e-Sharif distribution network, Photovoltaic system, power quality, voltage and reactive power control

1. Introduction

Sustainable development, as one of the most significant long-term goals for nations, particularly in developing societies, is directly linked to sustainable, reliable, and affordable access to energy [1]. In countries like Afghanistan, limited access to energy not only impedes economic growth, industrialization, and infrastructure expansion but also directly impacts the quality of life, public health, education, and social welfare [2, 3]. Currently, Afghanistan's energy system faces multiple challenges, including heavy reliance on imported energy from neighboring countries, high transmission and distribution losses (approximately 30 to 40%), limited grid coverage (with access for less than 30% of the population, especially in rural areas), poor power quality, and aging infrastructure [4, 5]. These issues result in grid instability and elevated economic and social costs.

In such circumstances, utilizing Renewable Energy Sources (RES), particularly solar energy, is emerging as an essential solution for ensuring sustainable energy supply, reducing import dependency, and enhancing grid resilience [6, 7]. Afghanistan possesses a high potential for RES, especially solar irradiation, with an average daily irradiation exceeding 6.5 kWh/m² and a technical potential of over 222,000 MW in the solar energy sector, making the country one of the most promising regions for the development of Photovoltaic

(PV) systems [8].

Despite this high capacity, the widespread integration of PV sources into electrical distribution networks presents significant technical and operational challenges [9, 10]. The intermittent and unpredictable nature of energy generation from these systems can lead to voltage fluctuations, degradation of power quality, and reduced dynamic and static grid stability. These challenges are particularly pronounced in urban networks, such as Mazar-e-Sharif, which feature complex structures and diverse load profiles.

In recent years, extensive studies have been conducted on the optimal placement and power control of renewable energy resources in distribution networks [11, 12]. However, most studies focus on idealized systems and fail to address real-world constraints in developing countries, such as power quality, reactive power management, and unique grid structures. This gap underscores the need for a practical, localized framework for PV integration in regions like Mazar-e-Sharif.

The current study addresses this research gap by developing a hybrid approach aimed at improving the performance of the Mazar-e-Sharif distribution network. This approach utilizes intelligent optimization algorithms (including the Genetic Algorithm) for the optimal placement of PV systems in the network, coupled with smart reactive power management. The objective is to simultaneously reduce energy losses and improve the voltage profile while maintaining power quality parameters within international standards. For this purpose, detailed network modeling was performed using the specialized software DlgSILENT PowerFactory, and various solar energy penetration scenarios were analyzed within technical and operational constraints.

The key contribution of this study is to present an integrated and applied framework that not only optimizes the placement of solar systems but also incorporates reactive power management strategies. This framework is designed not only to enhance the network's technical performance but also to provide an effective foundation for sustainable energy development in underserved regions of Afghanistan.

The remainder of this manuscript first introduces the fundamental concepts of energy generation, distributed generation technologies, and associated power quality issues. It then analyzes the current state of the Mazar-e-Sharif electrical network, describing optimization methods for PV placement and reactive power management. Subsequent chapters present the network model design, algorithm implementation, evaluation of various scenarios, and analysis of the results. Finally, the conclusion, recommendations, and avenues for future research are discussed.

2. Introduction

2.1. Background on Optimal DG Placement

Extensive research has explored the optimal placement of Distributed Generators (DGs) in distribution networks, aiming to reduce losses, enhance voltage profiles, and improve reliability. Both domestic (Iran) and international (Europe, Asia) studies, utilizing real and standard networks, have employed metaheuristic algorithms (e.g., Genetic Algorithm (GA) and Particle Swarm Optimization (PSO)) to report significant loss reduction and voltage improvement. For example, a study on the Kabul network in Afghanistan using Multi-Objective Particle Swarm Optimization (MOPSO) analyzed hourly loss reduction and voltage enhancement [13]. Additionally, in another study [14], machine learning approach was used to improve voltage and reduce power losses.

2.2. Advantages and Challenges of DG Integration

DGs offer considerable technical (e.g., power loss reduction, reliability improvement, voltage regulation, power quality) and economic (e.g., network expansion costs reduction) benefits [15]. However, challenges persist, including protection coordination issues [16], uncertainty of renewable sources [17], and the

inherent complexity of optimal DG placement and sizing.

2.3. Performance Indices and Optimization Techniques

Performance indices such as Voltage Profile Improvement Index (VPII), Loss Reduction Line Index (LLRI), and Environmental Impact Reduction Index (EIRI) are commonly used for DG evaluation. Metaheuristic algorithms, notably the GA and PSO, are primary tools for optimal DG placement due to their robust search capabilities in complex solution spaces [18, 19]. Additionally, Fuzzy Logic is often integrated to manage uncertainties [20].

2.4. Research Gap and Contribution

Despite numerous studies on DG placement, there is a distinct gap in focused research on real distribution networks in specific geographical contexts with unique operational characteristics. This study addresses this gap by investigating optimal DG placement in the real 117-bus Mazar-e-Sharif distribution network using the GA and actual network data. This work provides a practical solution for enhancing the technical performance of the Mazar-e-Sharif grid, thereby improving the operational credibility of DG integration strategies.

3. Proposed Method

3.1. Problem Formulation

The reactive power of the PV system can be calculated from the following relationship:

$$a = (\text{sign}) \tan(\cos^{-1}(PF_{PV}))$$

$$Q_{PV_i} = aP_{PV_i} \quad (1)$$

If sign = +1, the PV injects reactive power, and if sign = -1, the PV consumes reactive power.

The active and reactive powers injected at bus i , where the PV is installed, are given by the following relationships.

$$P_i = P_{PV_i} - P_{Di} \quad (2)$$

$$Q_i = Q_{PV_i} - Q_{Di} = aP_{PV_i} - Q_{Di} \quad (3)$$

Here, P_{PV_i} and Q_{PV_i} are the active and reactive power of the PV system at bus i , P_{Di} and Q_{Di} are the active and reactive power consumed at bus i . Considering the above relationships and the power loss equations, the active power losses can be rewritten as follows.

$$P_L = \sum_{i=1}^N \sum_{j=1}^N \left[\alpha_{ij} [(P_{PV_i} - P_{Di})P_J + (aP_{PV_i} - Q_{Di})Q_J + \beta_{ij} [aP_{PV_i} - Q_{Di})P_J - (P_{PV_i} - P_{Di})Q_J] \right] \quad (4)$$

Changes in power losses due to changes in PV injected power are a parabolic function. Therefore, at minimum losses, the rate of change of losses with respect to injected power will be zero.

$$\frac{\partial P_L}{\partial P_{PV_i}} = 2 \sum_{j=1}^N \left[\alpha_{ij} [P_J + aQ_J] + \beta_{ij} (aP_J - Q_J) \right] = 0 \quad (5)$$

The above relationship can also be written as:

$$\alpha_{ij}[P_j + aQ_j] + \beta_{ij}(aP_j - Q_j) + \sum_{\substack{j=1 \\ j \neq i}}^N (\alpha_{ij}P_j - \beta_{ij}Q_j) + a \sum_{\substack{j=1 \\ j \neq i}}^N (\alpha_{ij}Q_j + \beta_{ij}P_j) = 0 \quad (6)$$

$$\left\{ \begin{array}{l} X_i = \sum_{\substack{j=1 \\ j \neq i}}^N (\alpha_{ij}P_j - \beta_{ij}Q_j) \\ Y_i = \sum_{\substack{j=1 \\ j \neq i}}^N (\alpha_{ij}Q_j + \beta_{ij}P_j) \end{array} \right\} \quad (7)$$

By combining the equations

$$\alpha_{ij}(P_{PVi} - P_{Di} + a^2P_{PVi} - aQ_{Di}) + \beta_{ij}(Q_{Di} - aP_{Di}) + X_i + aY_i = 0 \quad (8)$$

At the end of the relationship, it provides the optimal PV capacity for each bus i , in order to minimize losses. Any PV capacity other than this value, placed at bus i , will result in higher losses.

$$P_{PVi} = \frac{\alpha_{ij}(P_{Di} + aQ_{Di}) + \beta_{ij}(aP_{Di} - Q_{Di}) - X_i - aY_i}{a^2\alpha_{ii} + \alpha_{ii}} \quad (9)$$

Considering the ability or inability of the PV system to inject reactive power, the relationships can be expressed as follows.

If the PV system is only capable of injecting active power $PF_{PV} = 1$ the optimal capacity to achieve the optimal location can be calculated according to the following.

$$PF_{PV} = P_{Di} - \frac{1}{\alpha_{ii}} \left[\beta_{ii}Q_{Di} + \sum_{\substack{j=1 \\ j \neq i}}^N (\alpha_{ij}Q_j + \beta_{ij}P_j) \right] \quad (10)$$

If the PV system is capable of injecting both active and reactive power, (i.e., $0 < PF_{PV} < 1$ sign = +1) the active and reactive power of PV system is determined to minimize power losses and improve the voltage profile.

Finally, by placing the obtained PV capacity from the previous relationships for each bus, running a load flow, and calculating losses, the optimal location is determined. The optimal PV location corresponds to the location that has the minimum losses for the obtained capacity. The flowchart of the proposed method is illustrated in Fig. 1.

Furthermore, to study the sitting for a greater number of PV units, after finding the optimal location and capacity using (Genetic Algorithm at each stage, the load data is updated. The siting algorithm is then implemented on the studied network with the updated load information to determine the locations of subsequent units.

The Genetic Algorithm is a computational model based on evolutionary processes, which is highly applicable for solving optimization problems. In this manuscript, possible solutions to the problem, which form the population, converge towards the best and most optimal solution through an evolutionary process. In essence, from the existing population, several solutions with higher fitness are selected as parents for the next generation. Then, by applying crossover and mutation operators to the selected solutions, the population of the next generation is produced, and this process continues until an optimal solution is reached.

In this paper, the capacity of photovoltaic systems is determined with the aim of controlling the reactive power voltage of the grid. The total reactive power losses of distribution networks over 24 h can be calculated using the following relationship.

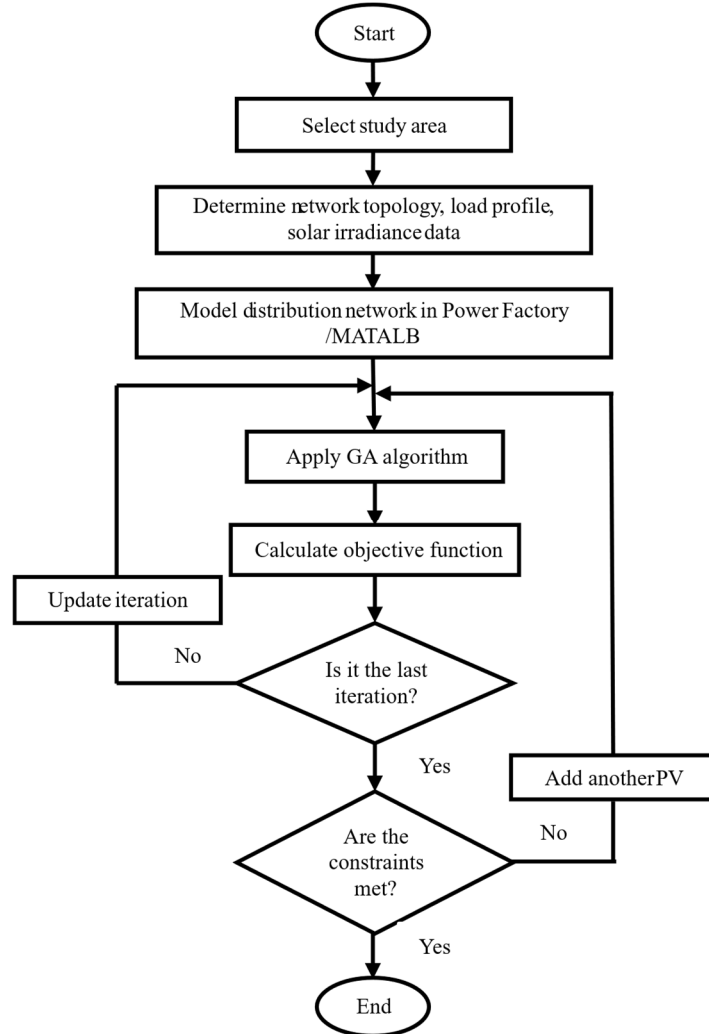


Fig. 1. Proposed flowchart for optimal placing PV systems.

$$Minimize P_{loss} = \sum_{i=1}^{24} \sum_{i=1}^{N_{br}} (R_i \times |I_i|^2) \tag{11}$$

where N_{br} is the number of branches, and R_i and I_i are the resistance and current of the i -th branch.

3.2. Problem Constraints

The constraints considered in this problem are expressed as follows.

Power Constraints

$$\sum_{i=1}^N P_{PVi} = P_{loss} + \sum_{i=1}^N P_{Di} \tag{12}$$

Range of active and reactive power generation by PV

$$P_{PV \min} \leq P_{PV} \leq P_{PV \max} \tag{13}$$

$$Q_{PV \min} \leq Q_{PV} \leq Q_{PV \max} \tag{14}$$

Bus voltage limits

$$|V|^{\min} \leq |V_i| \leq |V|^{\max} \tag{15}$$

Number of Photovoltaic Systems

where

- P_{PV_i} : Active power generated by the PV system
- P_{Di} : Active power demand
- P_{loss} : Active power losses
- $P_{PV\ min}$: Minimum active power generation by PV
- $P_{PV\ max}$: Maximum active power generation by PV
- $Q_{PV\ min}$: Minimum reactive power generation by PV
- $Q_{PV\ max}$: Maximum reactive power generation by PV
- $|V|^{\max}$: Maximum allowable voltage (1.1 p.u.)
- $|V|^{\min}$: Minimum allowable voltage (0.9 p.u.)

4. Simulation Results and Discussion

Introduction to the Real 117-Bus Mazar-e-Sharif Network

- The 117-bus Mazar-e-Sharif network: This network is a real and larger model of a radial distribution network, including more details such as the number of substations and separate loads. This model better represents the complexity and scale of a real network and is therefore more suitable for serious research
- The 33-bus network: This network is a smaller, standard model often used in research papers and studies as a reference network for initial evaluation and comparison of different methods, as shown in Fig. 2. Due to its simplicity, the results obtained from it can be easily compared with results from other studies.

Applications: In electrical engineering research, the proposed method is usually first tested on a small, standard network like the 33-bus network to preliminarily confirm its performance. Then, to demonstrate the efficiency and generalizability of the method, it is applied to a larger, real network like the 117-bus Mazar-e-Sharif network.

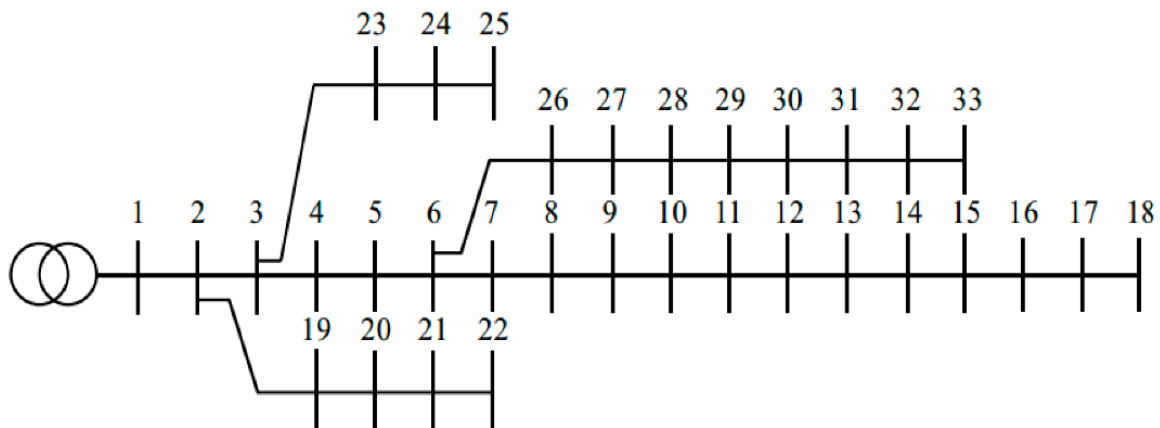


Fig. 2. 33-Bus test distribution system.

4.1. Simulation of 33-Bus Test Distribution System

The simulation results using GA show the network voltage profile after DG installation compared to the base case. The injection of active power at bus number 6 led to a significant increase in voltage levels across all network buses. The obtained voltage values indicate a substantial improvement, especially in the end buses. For instance, the minimum voltage was recorded at bus number 33 with a value of 0.932558 p.u., which is improved compared to the base case. These results confirm the effectiveness of the optimization method in enhancing the network voltage quality. Additionally, the results of applying the proposed method are compared to the several heuristic methods, as illustrated in Table 1. The findings confirmed that the proposed method can effectively reduce power losses and improve voltage values.

In this subsection, two different modes of DG operation are considered in the following two scenarios.

Table 1. Heuristic Method Used in Reconfiguration

Heuristic method	After DG installation
Ref. [11]	$P_{loss} = 139.51 \text{ kW}$, $V_{min} = 0.9378$
Fireworks	$P_{loss} = 139.98 \text{ kW}$, $V_{min} = 0.9413$
Gravitational search	$P_{loss} = 134.61 \text{ kW}$, $V_{min} = 0.9604$
Ant Colony optimization	$P_{loss} = 139.5 \text{ kW}$, $V_{min} = 0.9378$
Bacteria foraging optimization	$P_{loss} = 139.5 \text{ kW}$, $V_{min} = 0.9378$
Whale optimization	$P_{loss} = 139.5697 \text{ kW}$, $V_{min} = 0.93781$
Genetic algorithm (proposed method)	$P_{loss} = 106.61 \text{ Kw}$, $V_{min} = 0.92781$

4.1.1. Scenario 1

Unity power factor mode of DG operation: In this scenario, it is assumed that the DGs generate active power and no reactive power is generated/consumed by them. Different numbers of DGs are allocated in the network using the proposed method, The results of the proposed method are compared with other methods; that is, loss sensitivity, as can be seen in the proposed method, has better performance in loss reduction over the other methods. In the case of one DG placement, among the four algorithms, three of them propose bus 6 to install the DG. To show the performance of the proposed method in finding the optimal generation of the

In this section, the simulation results of the 33-bus distribution network in DigSILENT software are presented as the network's base case (without the presence of photovoltaic systems). These results are used as a benchmark for analysis and comparison in subsequent scenarios involving PV.

The voltage gradually decreases from the reference slack bus (Bus number 1) and reaches its minimum value at the network's terminal buses. This phenomenon, which is caused by the voltage drop along the distribution lines, clearly shows the need for voltage quality improvement in these buses. The voltage values at the network's terminal buses are noticeably below the nominal value of 1.0 per-unit, which can negatively impact the performance of electrical equipment and network stability.

In addition to the voltage drop, power loss is one of the most important technical parameters in assessing network performance. These losses, which are mainly created due to the resistance of the transmission lines and the current flowing through them, impose significant economic costs on the network.

A comprehensive analysis of the simulation results in the base case identified the current status of the 33-bus network from two key aspects: voltage drop and power losses. These findings justify the importance of utilizing distributed generation systems like PV for improving power quality and reducing losses, and they are used as a performance benchmark for comparison with subsequent optimization scenarios.

4.1.2. Scenario 2

In this scenario, a Photovoltaic (PV) system, assumed to inject only active power, is modeled within the 33-bus distribution network. The location and capacity of this system are determined based on the optimization

algorithm's results, selected as Bus 6 and 2.55 MW, respectively. The objective of this section is to analyze the impact of optimal active power injection on loss reduction and voltage profile improvement in the network.

Fig. 3 displays the network voltage profile after DG installation and compares it with the base case. As the graph indicates, active power injection at Bus 6 leads to a significant increase in voltage levels at buses across the entire network. The voltage values obtained from the simulation demonstrate a remarkable improvement, particularly at the end buses. For instance, the minimum voltage in this case is observed at Bus 33 with a value of 0.932558 p.u., which shows an improvement compared to the base case. This confirms the effectiveness of the optimization method in enhancing the network's voltage quality.

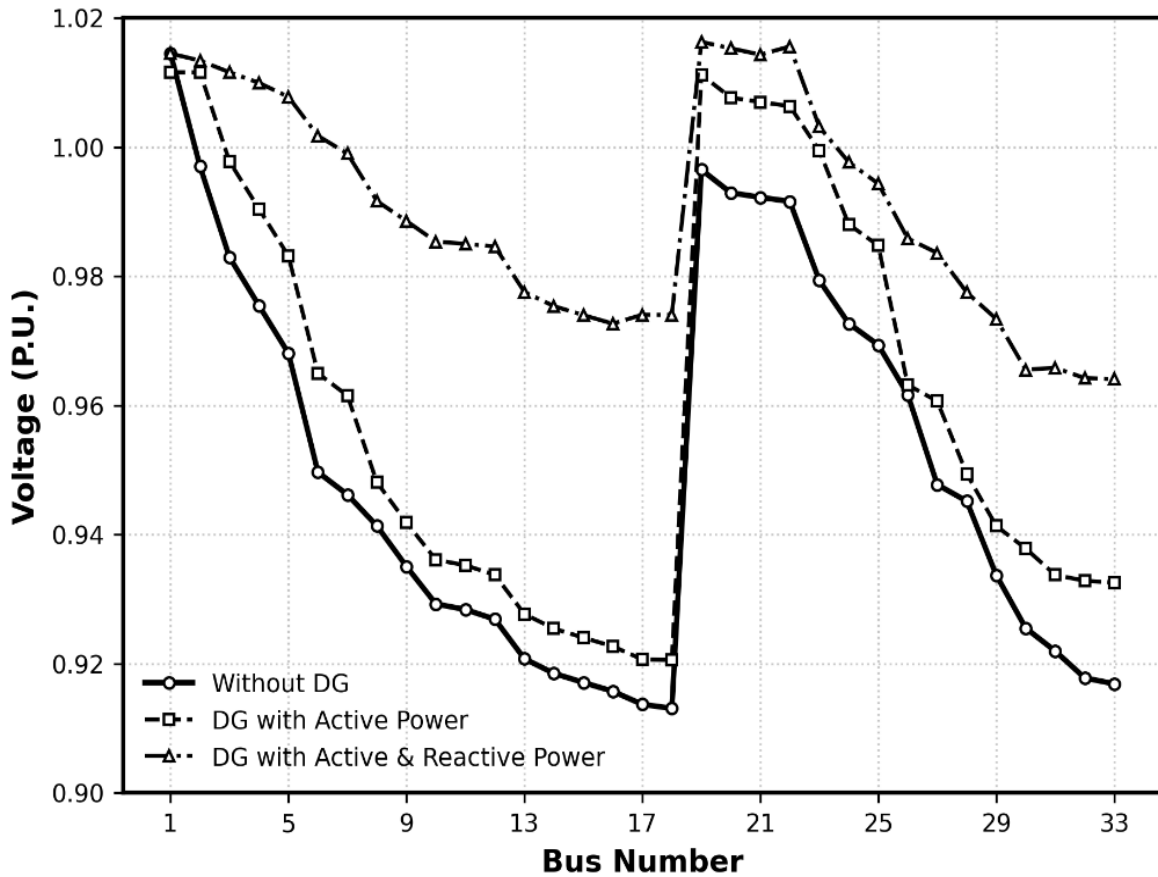


Fig. 3. Voltage variations of the bus in the presence and absence of DG with active and reactive power.

Active Power Losses: As observed in the results table (Scenario 2), the active power losses decreased from 202.68 kW in the base case to 106.61 kW after DG installation. This significant reduction indicates a substantial improvement in network performance. Consequently, the overall network efficiency has increased by 47.4%.

Reactive Power Losses: Furthermore, reactive power losses also decreased from 135.16 kVAr in the base case to 78.48 kVAr in the second scenario. This reduction is due to the reactive power injection by DG and the improved voltage profile. The percentage reduction in reactive power losses is calculated to be 41.9%.

The results of these scenarios are summarized in Table 2. Additionally, the details of the proposed PV unit for both scenarios are shown in Table 3.

Table 2. Comparison of the First Scenario and the Second Scenario

Loss Type	Scenario 1	Scenario 2
Active Power Loss (kW)	202.68	106.61
Reactive Power Loss (kVAR)	135.16	78.48
V_{max} (p.u.)	1.0000	1.0145
V_{min} (p.u.)	0.9130801	0.920056
Average Voltage (p.u.)	0.9484539	0.960924

Table 3. Results Obtained from the Placing and Sizing of a PV Unit

Scenario	Location	Capacity (MW)	P.V. Capacity (MWp)	Losses (MWh)	Minimum Voltage	Bus
Without PV	-	-	-	1775.4	0.9131	18
PV with Active Power Generation	6	2.55	2.55	932.8	0.9682	18
PV with Reactive Power Generation	6	1.75	1.75	450.22	0.97344	18

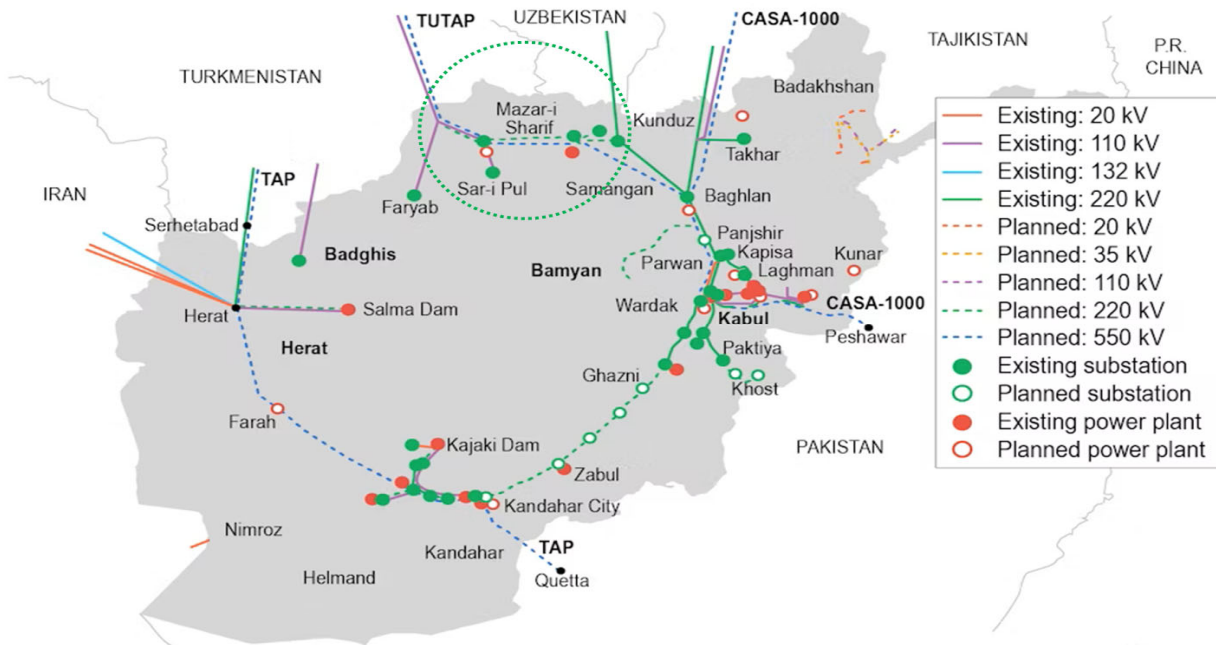


Fig. 4. Current and future power system map of Afghanistan.

5. Overview of Afghanistan’s Power System and the Mazar-e-Sharif Network

5.1. Overview of the Afghanistan Power System

The map of the Afghanistan Power System delineates the nation’s comprehensive electrical infrastructure, as shown in Fig. 4. This encompasses transmission lines, substations, diverse power plants—including hydroelectric, thermal, and solar facilities—and critical cross-border interconnections with neighboring countries such as Uzbekistan, Tajikistan, Turkmenistan, and Iran. A focal point of the network is Kabul Province, with the map detailing regional grids and utilizing color-coding to distinguish different voltage levels, ranging from 110 kV to 500 kV. It also identifies key energy projects currently under construction.

5.1.1. The Key Hub of Mazar-i-Sharif

A pivotal component of this system is the electricity distribution network in Mazar-e-Sharif. As the capital of Balkh Province in northern Afghanistan, Mazar-i-Sharif is a major urban center with an estimated population of approximately 500,000 residents (projection for 2025). The city holds profound religious significance, being home to the renowned Shrine of Hazrat Ali (AS), a site that attracts millions of pilgrims

annually, especially during the Nowruz celebrations.

Strategically located near the border with Uzbekistan, Mazar-i-Sharif serves as a vital commercial and agricultural hub, famous for its production of high-quality saffron and grapes. The city’s international airport further cements its role as a crucial gateway for regional trade and transportation. Its strategic position and economic vitality make its electrical infrastructure integral to the stability and development of the northern Afghan power grid.

Table 4. Simulation of 117 Bus Mazar-e-Sharif Distribution System

Feature	Mazar-e-Sharif 117-Bus Network (Real Network)
Number of Buses	117
Number of Branches	117
Number of Substations	85
Number of Loads	474
Network Structure	Radial (Explanatory)
Rated Voltage	20 kV
Total Load (Active Power)	56.35 MW
Total Load (Reactive Power)	33.34 Mvar
Power Losses (Active)	4.73 MW
Power Losses (Reactive)	18.4 Mvar

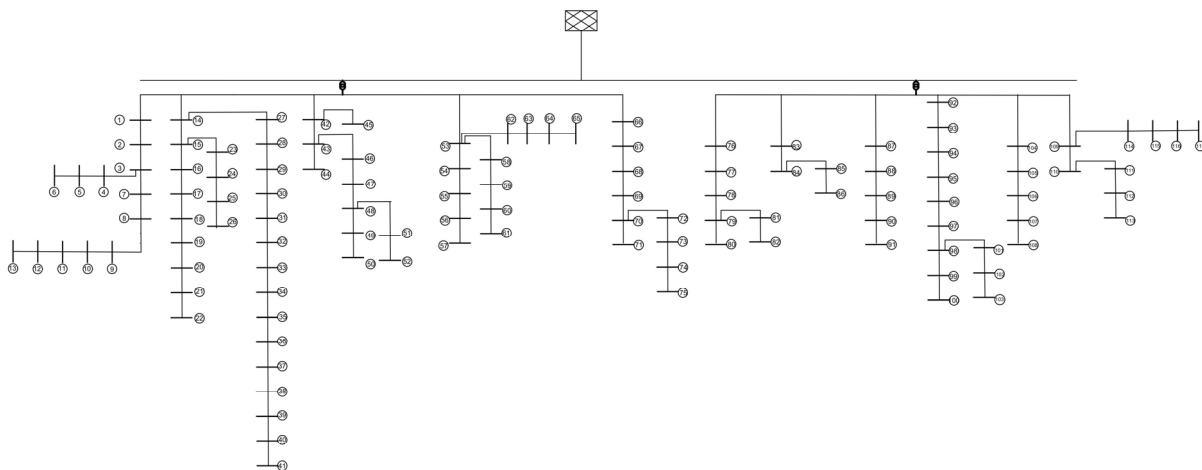


Fig. 5. 117 bus Mazar-e-Sharif distribution system.

The initial configuration and specifications of the 117-bus system are shown in Table 4 and Fig. 5, respectively. Simulation results indicate a 20.69% reduction in active power loss (from 4.73 MW to 3.75 MW) and an 84.78% reduction in reactive power loss (from 1.84 MVAR to 0.28 MVAR). Applying the Genetic Algorithm to the 117-bus reconfiguration problem improved the voltage profile to 0.964969 p.u. compared to the initial 0.91571449 p.u. A comparison with other heuristic methods demonstrates the competitive performance of the proposed approach.

In this phase of the studies, to demonstrate the impact of the reactive power generated by PV systems on the selection of their optimal location and capacity, simulations were carried out considering two scenarios:

1. The network under study without the presence of PV (Scenario 1)
2. The network under study, with the presence of PV, and assuming active and reactive power generation (Scenario 2)

For each of the different scenarios, the proposed algorithm for conducting optimal placement and capacity determination studies is applied to the distribution network under study.

5.1.2. Scenario 1

from the reference bus (Bus number 1), which is connected to the upstream network. This voltage drop

occurs due to the resistance and reactance of the lines, as well as the current flow required to supply the numerous loads (474 loads) throughout the network.

A detailed examination of the data reveals that the voltage at many of the network's end buses, particularly at buses like Bus 17 with a voltage of 0.9157144 per-unit, is significantly lower than the nominal value of 1.0 per-unit and even falls below the standard minimum of 0.95 per-unit.

This situation indicates a serious power quality issue in the network and clearly confirms the need for corrective measures, such as installing PV distributed generation systems, to improve the voltage profile and reduce power losses. The severe voltage drop at the end buses can disrupt the operation of connected equipment and compromise the overall system stability.

In addition to the voltage drop, power loss is one of the most critical technical parameters for assessing network performance. These losses, primarily caused by line resistance and the current flowing through them, impose significant economic costs on the network. The results in the table clearly illustrate the amount of energy wasted. The goal of optimization is to maximize the reduction of these losses and increase network efficiency.

5.1.3. Scenario 2

In this scenario, a Photovoltaic (PV) system, assumed to inject only active power, is modeled within the 117-bus distribution network. Based on the optimization algorithm results, the system's location and capacity are set at Bus 12 and 7.22 MW, respectively. This section aims to analyze the impact of optimal active power injection on loss reduction and voltage profile improvement.

Analysis of Voltage Profile Impact:

- Overall Status: After installing the DG at the optimal Bus 12, active power injection increased the voltage levels across the entire network.
- Key Bus Voltages:
 - At Bus 12 (the DG location), the voltage increased from 0.949658 p.u. in the base case to 0.964969 p.u.
 - This improvement extended to more distant points. The voltage at Bus 33 improved from 0.916877 p.u. in the base case to 0.932558 p.u.
- Minimum Voltage (p.u.) and Location:
 - Base Case: The minimum voltage was 0.9157144 p.u. at Bus 17.
 - With Active Power: After PV installation at Bus 12, the minimum voltage increased to 0.964969 p.u.

Analysis of Power Loss Reduction:

According to the data provided, a significant reduction in both active and reactive power losses is observed from Scenario 1 to Scenario 2:

- Active Power Losses: Decreased from 4.73 MW to 3.75 MW. This reduction of 0.98 MW represents a 20.69% improvement in real power transmission/distribution efficiency.
- Reactive Power Losses: Decreased dramatically from 1.84 MVar to 0.28 MVar. This substantial reduction of 1.56 MVar equates to an 84.78% improvement, indicating highly effective reactive power management in the system.

The results of applying the proposed method on 117-bus distribution network are summarized in Table 5. Furthermore, the voltage profiles for this network before and after installation the PV system are shown in Fig. 6.

Table 5. Comparison of Power Losses in the Base Case and the Second Scenario

Loss Type	Scenario 1	Scenario 2
Active Power Loss (MW)	4.73	3.75
Reactive Power Loss (kVAR)	1.84	0.28
Vmax (p.u.)	1.005674	1.00195
Vmin (p.u.)	0.9181842	0.9119558
Average Voltage (p.u.)	0.955915808	0.972230956

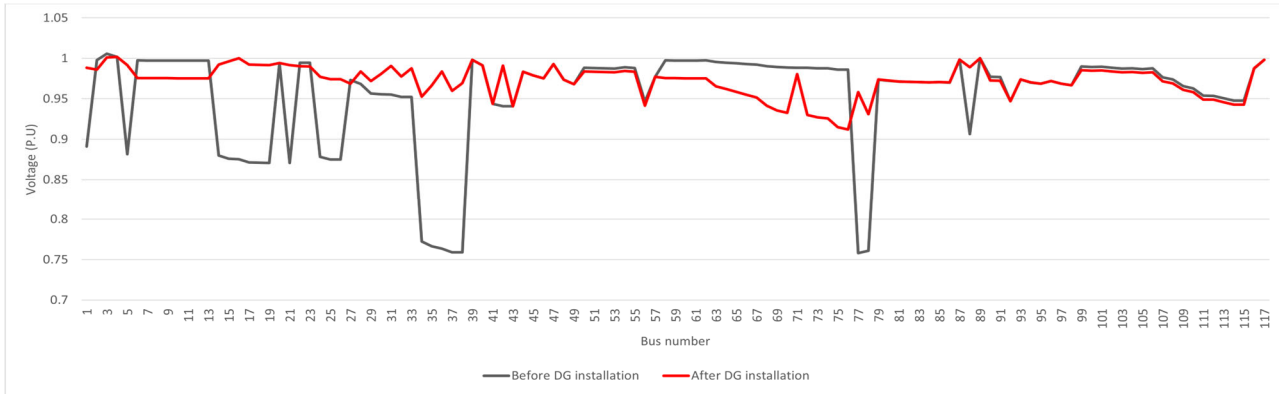


Fig. 6. Comparison of the network voltage profile before and after the installation of PV systems for scenario 2.

5.2. Economic Implications and Cost-Benefit Analysis

The proposed PV integration not only improves technical performance but also offers significant economic benefits. The total installed capacity in the optimal scenario is 7.22 MW, with an estimated capital cost of \$0.85/Wp (based on 2025 market prices from IEA and DNV reports), resulting in a total investment of \$6.14 million.

Annual energy savings from loss reduction amount to 8.53 GWh (calculated from the 20.69% active loss reduction over typical annual load). At a local electricity tariff of \$0.08/kWh (from World Bank 2024 data for Afghanistan), this translates to annual revenue of \$682,400. The payback period is approximately 4.2 years, assuming a 25-year system lifespan and 5% annual maintenance costs.

Additionally, the reduction in CO₂ emissions is estimated at 6,200 tons/year (using EPA emission factors of 0.727 tons CO₂/MWh for Afghanistan’s grid mix), contributing to environmental sustainability and potential carbon credit revenue of \$124,000 annually (at \$20/ton market rate).

The details of cost-benefit analysis are summarized in Table 6.

Table 6. Cost-Benefit Summary

Item	Value
PV Capacity	7.22 MW
Capital Cost	\$6.14 million
Annual Savings	\$682,400
Payback Period	4.2 years
CO ₂ Reduction	6200 tons/year

6. Conclusion

In this research, an optimal and efficient hybrid method was presented for the placement and sizing of Photovoltaic (PV) systems in distribution networks. The core of this method integrates a Genetic Algorithm (GA) to identify optimal installation locations with an analytical approach to accurately calculate the capacity

of Distributed Generation (DG) units, with the primary objective of minimizing power losses.

The effectiveness of the method was evaluated in two stages: first on the standard IEEE 33-bus test network, and then on a real-world 117-bus network in the city of Mazar-e-Sharif.

The key achievements of this research are as follows:

1. **Significant Reduction in Power Losses:** The deployment of PV systems capable of simultaneous active and reactive power injection led to a considerable improvement in network efficiency. Specifically, active power losses were reduced by 20.69% and reactive power losses by 84.78%.
2. **Complete Voltage Profile Correction:** Following the optimal installation of PV systems, the voltage profile across all network buses, including end buses that previously experienced severe voltage drops, was fully corrected and stabilized within the permissible and desirable range.
3. **Innovation in PV Modeling:** This research took a step beyond conventional models, which focus solely on active power generation, by utilizing the full potential of PV inverters for reactive power generation. This enables greater efficiency and added value for the network even during low-light hours or at night.
4. **Practical Validation in a Real Network:** The successful implementation and effectiveness of the method in the real 117-bus Mazar-e-Sharif network clearly demonstrates its practicality and generalizability to other distribution networks.

In summary, this research demonstrates that optimal placement and sizing of photovoltaic systems with reactive power support capability serves not only as a source of clean energy but also as a comprehensive solution to overcome fundamental challenges in distribution networks, including high losses and poor voltage quality. The findings of this study can provide valuable guidance for network planners and operators in optimizing network performance in the presence of distributed generation resources.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, Abdul Farooq Bikzada and Sina Shakeri; methodology, Abdul Farooq Bikzada and Sina Shakeri; software, Abdul Farooq Bikzada and Sina Shakeri; validation, Farooq Bikzada, Sina Shakeri and Seid Esmaeili; formal analysis, Abdul Farooq Bikzada and Sina Shakeri; investigation, Farooq Bikzada, Sina Shakeri and Seid Esmaeili; resources, Farooq Bikzada; data curation, Farooq Bikzada, Sina Shakeri and Seid Esmaeili; writing—original draft preparation, Farooq Bikzada and Sina Shakeri; writing—review and editing, Farooq Bikzada, Sina Shakeri and Seid Esmaeili; visualization, Farooq Bikzada and Sina Shakeri; supervision, Sina Shakeri and Seid Esmaeili; project administration, Farooq Bikzada; funding acquisition, Sina Shakeri. All authors had approved the final version.

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