EPJ Web of Conferences **351**, 01001 (2026) https://doi.org/10.1051/epjconf/202635101001
HEREM 2025

Optimal integration of Distributed Energy Resources using a sensitivity-Based GEPSO Approach in Distribution Networks

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Abstract. The growing energy demand has highlighted the need for reliable, decentralized, and self-sustained power systems. In this context, optimal integration of distributed energy resources (DERs) into distribution networks is vital for improving voltage stability and reducing power losses. However, conventional DER planning methods are computationally intensive and may produce inconsistent solutions under varying load conditions. This paper presents a sensitivity-based Generalized Particle Swarm Optimization (GEPSO) framework for optimal siting and sizing of DERs in radial distribution systems. The methodology is implemented in two stages. First, site-specific geographical and meteorological data are evaluated to determine realistic DER capacity limits. Second, these feasibility constraints are embedded within the GEPSO algorithm to identify optimal DER locations and sizes. Load flow analysis is performed using the forward–backward sweep method on a real 69-node Ramchandrapura feeder and the IEEE 33-node test system under multiple loading and DER penetration scenarios. Simulation results demonstrate an average active power loss reduction of approximately 36%, with up to 3.3% improvement compared to conventional PSO, while enhancing the minimum bus voltage by about 3–4%. The key contribution of this work is the integration of site-specific feasibility assessment with a sensitivity-guided GEPSO framework for efficient DER planning applications.

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1 Introduction

The accelerating global energy crisis and the rapid depletion of fossil fuel reserves have highlighted the need for sustainable and self-reliant power system. Ensuring long-term energy security and reliable grid operation requires a strategic transition from conventional fossil-fuel-based generation to cleaner and decentralized energy resources. The continued dependence on fossil fuels has intensified the urgency for modern energy solutions that can support stable, resilient, and environmentally responsible power systems. Distributed Energy Resources (DERs) have emerged as an essential component in this transition, offering benefits such as reduced transmission losses, improved voltage support, and enhanced grid flexibility. However, their integration also introduces operational challenges, including voltage fluctuations, increased power losses, and coordination issues arising from improper siting or sizing.

Over the past decade, the increasing participation of independent energy producers and consumers has shifted this centralized framework toward a decentralized configuration. Managing DER penetration within this evolving structure requires informed planning and advanced control strategies to maintain system stability and efficiency. Maintaining a balance between electricity generation and consumption is crucial for grid reliability. An imbalance, either deficit or surplus, may cause operational disturbances, outages, or inefficient resource utilization. Effective DER integration at the distribution level plays a key role in maintaining this balance, especially under restructured grid environments. While DER deployment enhances renewable participation and system resilience, optimal placement remains a critical challenge to avoid adverse effects such as voltage deviation and increased losses [1]. This work investigates these issues and proposes an improved approach for optimal DER deployment.

1.1 Global Energy Landscape

The global energy sector is undergoing a major transformation, driven by concerns over resource depletion, climate change, and rising electricity demand. Many countries continue to use conventional fossil resources based on economic feasibility and availability, while others are accelerating renewable energy adoption supported by policy interventions and technology advancements [2]. Fossil fuels dominated production for decades, peaking around 2010, followed by a gradual decline as countries shifted toward renewable technologies. Renewable energy generation has risen sharply, from 200 TWh in 1990 to nearly 9,000 TWh in 2024, supported by advancements in solar, wind, hydro, and bioenergy systems [3]. Hydropower has grown steadily, while nuclear power has shown moderate fluctuations with renewed interest in recent years. Several major economies, including the United States, Germany, Poland, Japan, and Turkey, have significantly reduced their reliance on fossil-fuel-based electricity generation [4]. The rapid expansion of global renewable energy capacity, projected to reach approximately 4,500 GW by 2025. This growth necessitates advanced grid infrastructure and optimized planning strategies to ensure stable operation with high renewable penetration. The global shift toward decentralized renewable energy systems has promoted community-level energy production, improved resilience, and reduced transmission losses. Energy storage technologies, grid modernization initiatives, and supportive policy frameworks have further strengthened this transition.

The monthly distribution of global generation by energy resources during 2023, reflecting seasonal variations in renewable output, particularly wind and hydro [6]. Despite discoveries of new fossil reserves, long-term sustainability concerns remain. Recent researches show the steady decrease in fossil-based generation growth, driven by environmental policies and the rising adoption of renewable resources [2]. DER technologies enable decentralized generation using accessible resources such as solar PV, wind, and small hydro, enhancing system flexibility and supporting grid balancing [7]. However, DER integration presents key challenges, including intermittency, bidirectional power flow, protection coordination, and hosting capacity limitations [10]. These require smart grid technologies, advanced control frameworks, and optimized planning practices.

1.2 Distributed Energy Resources

DERs operate at the distribution level and typically function alongside local loads. Their behavior is influenced by variability, resource availability, and dynamic interactions with the grid. Effective modeling and planning are necessary to ensure reliable and efficient integration [11]. Smart grid technologies facilitate real-time monitoring and efficient DER management, but technical challenges persist. Bidirectional power flow may cause voltage regulation issues, protection miscoordination, and thermal loading of distribution assets. DER intermittency may further introduce power quality issues such as flicker and harmonics. These challenges require adaptive grid management strategies and targeted infrastructure reinforcement. The adoption of DER also depends on local resource availability and economic feasibility. Hybrid energy systems combining solar, wind, and storage have gained attention due to their improved efficiency and stability. While installation costs for DER technologies have declined, small-scale systems still involve significant upfront investment. Ensuring optimal deployment requires careful consideration of voltage stability, network losses, and system reliability.

1.3 Challenges and Limitations of DER

Key challenges associated with DER integration include,

1. Dispersed Nature of Resources: Resource availability varies geographically, increasing uncertainty in generation planning.
2. Intermittency: Dependence on weather conditions can disrupt voltage profiles and power quality.
3. Grid Integration Issues: Unplanned DER deployment may lead to voltage imbalance, reverse power flow, and operational instability.

4. Energy Storage Requirements: Large-capacity storage is vital to support intermittent renewable generation.
5. Reliability and Quality of Supply: High DER penetration may elevate network losses and cause voltage deviations without proper optimization.

1.4 Problem Statement

Growing and unpredictable load demand increases planning complexity. Major issues include,

1. Need for optimal DER penetration to maintain system parameters.
2. Significant losses in radial distribution networks.
3. Risk of voltage imbalance and reverse power flow due to improper DER placement.
4. High R/X ratios limiting conventional load-flow accuracy.
5. Requirement for a reliable, computationally efficient optimization method for siting and sizing DER units.
6. The primary gap identified is the lack of an integrated framework that combines geographical feasibility analysis with sensitivity-based swarm optimization under multiple loading conditions for DER planning.

1.5 Objectives

The optimization is formulated as a multi-objective problem, with primary emphasis on minimizing active power losses, while voltage deviation minimization is treated as a secondary but mandatory operational constraint. The objectives of this work are,

- To assess the potential of selected locations using local geographical parameters for DER deployment.
- To improve voltage profiles across all nodes of the test feeder.
- To minimize distribution network losses.
- To determine optimal DER size and location using a Sensitivity-Based GEPSO approach integrated with HOMER-Pro assessments.

2 Methodology

The approach integrates load assessment, feasibility analysis, sensitivity evaluation, and optimization to ensure technically feasible and robust DER planning.

2.1 Load Survey

A comprehensive load survey is conducted to understand the electricity consumption patterns of the selected Ramchandrapura feeder. This data is crucial for accurately modeling the selected distribution network and in estimation of more accurate DER capacities and location.

2.2 Feasibility Analysis using HOMER-Pro

The initial step involves conducting a feasibility analysis of the chosen location. This likely includes assessing the suitability of the selected feeder and analyzing local geographical conditions. The HOMER software has been used for conducting feasibility analysis of the chosen location regarding its energy resource potential.

2.3 Methodology Application on Ramchandrapura 69-Node feeder and IEEE 33-Node Standard Test System

A sensitivity based GEPSO methodology is applied on the selected 69-Node Test System, Ramchandrapura. After getting satisfactory results, same approach is applied on standard IEEE-33 node system also. This serves as a validation step, demonstrating the effectiveness of the chosen optimization techniques in reducing power losses and minimizing voltage deviation within the distribution network.

The Fig.1 outlines a process for optimizing the location and size of DER. It begins with gathering input data and conducting a sensitivity analysis to determine feasibility. If feasible, it identifies potential locations for DER penetration based on factors like meteorological data, wind and solar potential, DER costs, GHG emissions, and renewable penetration.

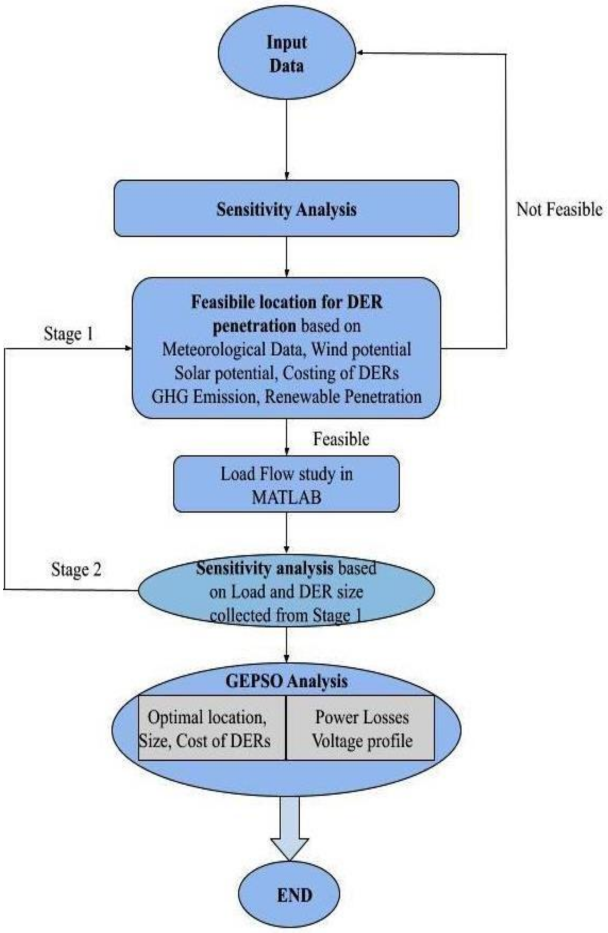

Fig.1. Flow chart of the proposed approach

The primary goal of the proposed research work is to improve the integration of DER and optimize their efficiency in the distribution system. This will be achieved by strategically positioning DER units to reduce losses and ensure voltage remains within acceptable limits. The use of multi-objective optimization techniques, along with simulation tools like HOMER, contributes to a comprehensive and systematic approach for achieving these objectives. The findings from this proposed work can potentially inform decision-making processes in the deployment of DER in distribution network, contributing to more resilient and sustainable energy infrastructure. The main contribution of the research is based on the GEPSO technique followed by sensitivity-based approach are as follows,

- It focuses on minimization of network losses, which is the most substantial measure of distribution network.
- The Voltage deviation factor drives the quality measure of distribution system which describes the system stability and reliability concern.
- Load variation in distribution system need to be focused in each load flow studies as the consumer consumption patterns directly affects the system parameters and operations. DER integration needs to be optimized under multiple load conditions.
- Intermittent nature of the renewable based energy sources directly affects all the system parameters. A simple multi-objective approach has been presented to counter this problem.

2.4 Load Flow Analysis (Forward–Backward Sweep)

The Newton-Raphson method, Gauss-Seidel method, and the fast-decoupled methods are widely recognized as efficient and reliable techniques for load flow studies, particularly in high voltage transmission systems. However, their performance tends to be suboptimal when applied to radial distribution networks. The challenges arise from high R/X ratios and unbalanced loading conditions in radial distribution networks, leading to inaccurate outputs and requiring a greater number of iterations for convergence. These methods cannot be directly applied to radial distribution network solutions without modification.

2.4.1 Forward/Backward Sweep Method

This method is known as a popular technique for load flow analysis in radial distribution Network. It involves iteratively solving power flow equations by progressing through the network, updating node voltages and power flows. This method is particularly useful for radial distribution systems with single or multiple feeders. In the analysis of power system load flow, the forward-sweep and backward-sweep methods serve as two approaches used iteratively to solve power flow equations. Their purpose is to determine and refine the steady-state operating conditions of the network through an iterative process.

2.4.2 Forward Sweep Method

The forward sweep method starts with known values, typically the generator real and reactive power outputs and the initial voltage magnitudes and angles. It then proceeds to calculate the node voltages and power flows throughout the system in a forward direction, moving from the generators towards the loads. The calculations involve solving power flow equations for each node, updating individual voltages and angles, and then advancing to the next node in the forward direction. The forward sweep continues until convergence is achieved, i.e., the calculated values match the specified system conditions.

2.4.3 Backward Sweep Method

After the forward sweep, the backward sweep method is employed to fine-tune and improve the solution obtained from the preceding forward sweep. It starts at the load buses and moves backward towards the generators. During the backward sweep, the unknown variables such as voltage magnitudes and angles are systematically updated based on the power flow equations. This iterative process considers the updated values obtained from the preceding forward sweep. This process continues until convergence is reached, refining the solution obtained from the forward sweep and ensuring consistency in the power flow calculations. The combination of forward and backward sweep methods helps to iteratively improve the accuracy of the solutions. Same process is repeated until the system reaches a steady-state condition, where the calculated values for voltages and power at each node satisfy the specified criteria and converge to a stable solution. Load flow studies are essential for guaranteeing the dependable and effective operation of power systems. This is achieved by scrutinizing voltage levels, power losses, and line loading across various operational scenarios.

The equations for the forward-backward sweep method [8] used in optimal planning of distribution networks with increased penetration of DER are,

Bus voltage equations (Forward Sweep):

$$P_i = \sum_{k\in Parent\ of\ i} P_{ki} + P_{DER_i} \tag{2.1}$$

$$Q_i = \sum_{k\in Parent\ of\ i} Q_{ki} + Q_{DER_i} \tag{2.2}$$

$$V_i = \sqrt{(P_i^2 + Q_i^2)} \tag{2.3}$$

Branch power flow equations (Forward Sweep):

$$P_{ij}^m = \frac{V_i^2 - 2V_iV_j\cos\left(\theta_{ij}^m\right) + V_j^2}{Z_{ij}^m} \tag{2.4}$$

$$Q_{ij}^m = \frac{V_i^2 - 2V_iV_j\sin\left(\theta_{ij}^m\right) + V_j^2}{Z_{ij}^m} \tag{2.5}$$

Voltage angle equations (Forward Sweep):

$$\theta_{ij}^m = \tan^{-1}\left(\frac{Q_{ij}^m}{P_{ij}^m}\right) \tag{2.6}$$

DER power injection equations (Backward Sweep):

$$P_{DER_i} = P_{DER_i} - \sum_{k\in Children\ of\ i} P_{DER_{ki}} \tag{2.7}$$

$$P_{DER_i} = P_{DER_i} - \sum_{k\in Children\ of\ i} P_{DER_{ki}} \tag{2.8}$$

Voltage regulation for DER (Backward Sweep):

$$V_{reg_i} = V_i - V_{ref_i} \tag{2.9}$$

Updated DER power output (Backward Sweep):

$$P_{DER_i} = P_{DER_i} + K_{pi}.V_{regi} + K_{i_i}.\sum_{k\in Parents\ of\ i} V_{reg_{ki}} \tag{2.10}$$

$$Q_{DER_i} = Q_{DER_i} + K_{qi}.V_{regi} + K_{i_i}.\sum_{k\in Parents\ of\ i} V_{reg_{ki}} \tag{2.11}$$

Where,

P_i and Qi are the active and reactive power at bus i,

P_{ki} *and* Q_{ki} are the active and reactive power contributions from parent bus k to bus i,

P_{DERi} and Q_{DERi} are the active and reactive power injected by DER at bus i,

V_i is the voltage magnitude at bus i,

P_{ijm} and Q_{ijm} are the active and reactive power flow on branch m,

Z_{ijm} is the impedance of branch m,
θ_{ijm} is the angle diff. between the voltages at buses i and j,
V_{regi} is the voltage regulation at bus i,
V_{refi} is the reference voltage at bus i,
$K_{pi}, K_{qi},$ and$K_{ii}$are the proportional, integral, and derivative gains for the DER controller at bus i,
V_{regki} is the voltage regulation at the parent bus k contributing to bus i.

These equations represent the forward-backward sweep method for power flow analysis and optimal planning in distribution networks with increased DER penetration. Adjustments to parameters and control gains can be made based on specific characteristics of the distribution system and DER. The load flow equations are inspired from references [14-18].

Constraints

Power Flow Equations:

$$V_i \, for \; i = 1,2, \dots N \qquad (2.12)$$

$$P_i - P_{Loadi} - P_{Lossi} = 0 \; for \; 1,2, \dots N \qquad (2.13)$$

Voltage Limits:

$$V_{(t)}^{min} \le \mathrm{V}_{(t)} \le \mathrm{V}_{(t)}^{\max} \qquad (2.14)$$

The DER output from each generator must be kept less than the power demand so DER generation constraints are given as,

Active Power Limits:

$$PG_{(t)}^{min} \le \mathrm{PG}_{(t)} \le \mathrm{PG}_{(t)}^{\max} \qquad (2.15)$$

Reactive Power Limits:

$$PG_{(t)}^{min} \le \mathrm{PG}_{(t)} \le \mathrm{PG}_{(t)}^{\max} \qquad (2.16)$$

$$Q_{(i)}^{min} \le \mathrm{V}_{(i)} \le \mathrm{V}_{(i)}^{\max} \text{ for i } = 1,2,\dots,\mathrm{N} \qquad (2.17)$$

2.5 Sensitivity Analysis Framework

It Identifies which input parameters have the most significant impact on the output or response of a system. In the case of planning for DER systems, it helps to determine the factors, like wind velocity or solar radiation, have the most influence on the overall generation capacity. It provides insights into which parameters should be closely monitored or controlled to optimize system performance.

2.6 PSO & GEPSO Algorithm Description

2.6.1 Particle Swarm Optimization

PSO was initially devised for tackling nonlinear equations, drawing inspiration from the collective behavior observed in Bird swarming. Within PSO, the optimization approach emulates the kinetics of specific cluster of particles. Each individual particle signifies a prospective result. These particles navigate each solution space, adjusting their new location based on their individual experiences. The process follows the information shared in collective way within the swarm. The underlying principle mimics the collaborative exploration observed in group behaviors of birds or fish, aiming to collectively find optimal solutions.

2.6.2 Generalized Particle Swarm Optimization (GEPSO)

GEPSO, an enhanced extension of the traditional PSO algorithm, builds upon the nature-inspired optimization principles derived from the social behavior of bird flocking and fish schooling. In the standard PSO framework, particles navigate the search space in pursuit of an optimal solution by integrating knowledge from their own historical experiences and the shared experiences of neighboring particles. The “generalized” in GEPSO typically implies that the algorithm incorporates additional features, modifications, or variations beyond the basic PSO framework. These modifications could include different strategies for updating particle positions and velocities, adapting the algorithm to specific problem domains, or incorporating additional parameters to enhance exploration and exploitation abilities. GEPSO algorithms are often tailored to address specific challenges in optimization problems [10].

2.7 HOMER-Pro Based Capacity Assessment

In conjunction with the integration of PSO and GEPSO with Distribution Network Planning, a comprehensive feasibility analysis has been conducted using HOMER Pro. The proposed work focuses on the incorporation of DER into the proposed distribution network, with particular emphasis on a Solar and Wind power plant integrated with a battery storage grid-tied system. HOMER Pro, a powerful simulation and optimization software designed for hybrid renewable energy systems, has been employed to evaluate the techno-economic viability and performance of the proposed DER integration. Table 1 shows, the configuration for the generator bus is supplied from an infinite bus with a voltage of 33/11kV. The load profile consists of an 8 MVA three-phase urban load. The system features 69 nodes, representing a real load feeder. On the supply side, the voltage is 11 kV in three phases, whereas on the distribution side, it is stepped down to 0.415 kV. The feeder design is a radial feeder, which is commonly used in distribution feeder for effective power distribution in urban settings.

Table 1 System parameter

S. No.	Parameter	Configuration	Remark
1	Load Profile	8 MVA	Three/single phase urban load
2	Nodes	69	Real Load feeder
3	Voltage Supply Side	11 kV	Three phase
4	Voltage Distribution Side	0.415 kV	Three phase
5	Feeder Design	Radial feeder	Distribution feeder

The analysis considers various parameters, including solar and wind resource availability, battery storage capacity, grid interaction, and overall system costs. By leveraging the capabilities of HOMER Pro, the research aims to optimize the design and operation of the renewable energy system, ensuring that the proposed distribution network not only meets reliability and efficiency goals but also adheres to economic and sustainability criteria. Fig.2, shows the designed simulation model in HOMER atmosphere, which is connected to two buses of AC and DC, connecting converter for DC-based sources.

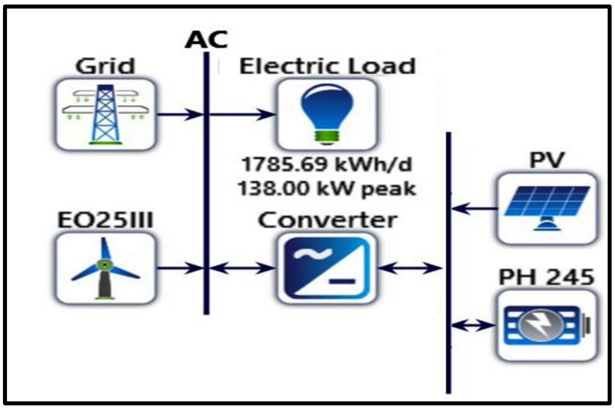

Fig. 2. HOMER model of proposed integration

Load Sensitivity Cases

Case	Full Load	80% Load	50% Load
Load	100% of Feeder cap.	80% of Feeder cap.	100% of Feeder cap.

Generation Sensitivity Cases

Case	1	2	3	4	5
DER capacity	50% of Feeder cap.	40% of Feeder cap.	30% of Feeder cap.	20% of Feeder cap.	0% of Feeder cap.

Major findings and outcomes of HOMER work,

1. Based on economic and geographical analysis by HOMER simulation it has been analyzed that the selected location is capable enough to generate renewable power from solar-based resources.
2. Wind-based resources will not be effective enough throughout a year due to low wind velocities at the location but for specific months it can feed the utility.
3. Battery storage will be a very costlier arrangement for the site due to its large size and low life span.
4. Level of GHG has been reduced to considerable level

Fig.3 represents the designed single line diagram of Ramchandrapura69 node practical feeder system. A comprehensive analysis is undertaken for a 69-Node distribution feeder, specifically focusing on the Ramchandrapura feeder. The load data utilized in the proposed work is derived from an actual load survey conducted in the authentic location of the Ramchandrapura feeder, ensuring the realism and accuracy of the findings. The impedance parameters incorporated in the analysis are taken from standard data.

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2.8 Ramachandrapura Feeder (69-Node)

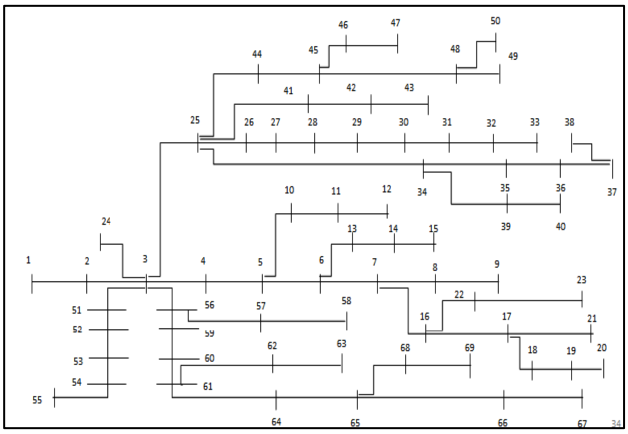

Fig. 3. Ramchandrapura (69-Node) Test System

2.8.1 IEEE 33-Node Test Feeder

In order to validate and cross-verify the results obtained from the applied optimization techniques and methods on the Ramchandrapura feeder, an IEEE 33-node system has been chosen as an additional case study. This standardized test system serves as a benchmark for power distribution network analysis and allows for a comparative assessment of the effectiveness of the applied technology. The single line diagram of IEEE-33 node system is illustrated in Fig.4.

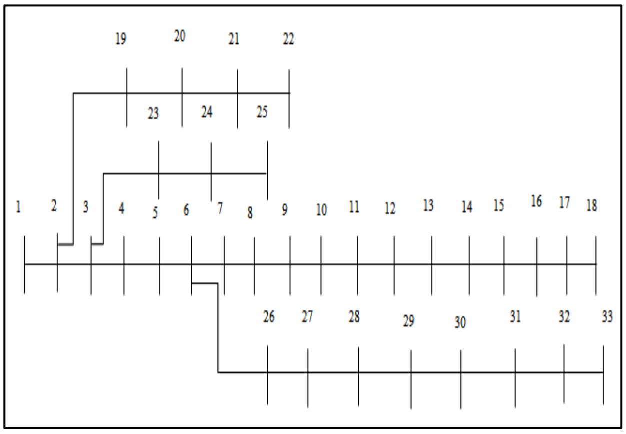

Fig. 4 (IEEE-33 Node) Test System

By applying the same PSO and GEPSO methodologies to this secondary test case, the study aims to establish a robust foundation for the generalizability of our findings.

3 Results and Discussion

The proposed research encompasses a comprehensive exploration of load flow study scenarios devoid of DER and in instances where PSO and GEPSO techniques are applied. The investigation is bifurcated into two feeder configurations as a Ramchandrapura69-node feeder and IEEE 33-node test feeder. The experimental work is organized based on the parameters and data sets presented in Table 2.

Table 2. Structured overview of the simulation framework and calculated DER capacity

Cases	**DER capacity (%) kW**	**Optimal Size calculated by GEPSO**	
		Load	**DER Capacity (kW)**
Case 1	**50%:** 0-4000 kW	Full Load	3663.2
		80% Load	3657.3
		50% Load	3680
Case 2	**40%:** 0-3200 kW	Full Load	2941.03
		80% Load	2926.62
		50% Load	2957.91
Case 3	**30%:** 0-2400 kW	Full Load	2391.6
		80% Load	2356.9
		50% Load	2290.3
Case 4	**20%:** 0-1600 kW	Full Load	1599.99
		80% Load	1600
		50% Load	1517.77
Case 5	0%: 0 kW (baseline with no DER integration.	Full Load	0
		80% Load	0
		50% Load	0

3.1 Voltage Profile Improvement

Fig 5 illustrates the voltage profile for a 69-bus feeder under full load conditions with 50% DER penetration. The chart compares the voltage magnitude (in per unit) at each bus node for three scenarios. The "Without DER" line likely exhibits significant voltage drops along the feeder due to the increasing load. The "PSO Case with DG" line demonstrates improved voltage profile with reduced voltage drops compared to the "Without DER" case, indicating the positive impact of DER integration and PSO-based optimization. The "GEPSO Case with DER" lies above the PSO line, suggests that GEPSO achieved further improvement in voltage profile compared to PSO, potentially resulting in a more stable and uniform voltage distribution across the feeder.

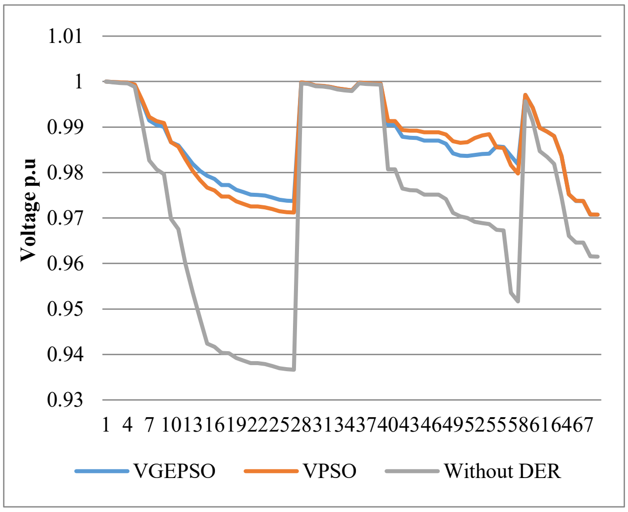

Fig. 5. Voltage profile at Ramchandrapura -69 node at full Load and Loss Reduction Analysis

Fig.6. analyzes total active power losses for the Ramchandrapura-69 node test feeder under full load conditions and 50% DER capacity. The top graph compares the total active power losses across three scenarios: without DER, with DER optimized using GEPSO, and with DER optimized using PSO. Without DER, the losses are the highest at 192.0587 kW, while incorporating DER reduces the losses significantly to 120.1471 kW with GEPSO and further to 116.8801 kW with PSO, showing a slight advantage for PSO.

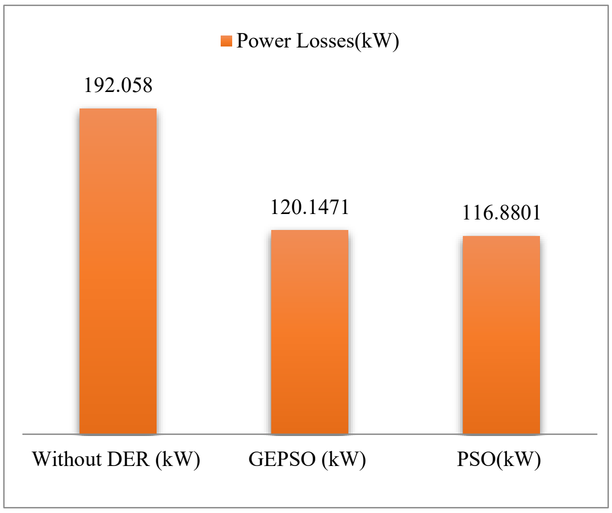

Fig. 6. Total Active Power Losses with 50% DER capacities& full Load- Ramchandrapura-69 Node

Fig.7. illustrates the distribution of active power losses across individual nodes for the same scenarios. In the normal case (without DER), losses are consistently higher at most nodes, while DER integration significantly reduces losses, with PSO and GEPSO showing comparable performance across the network.

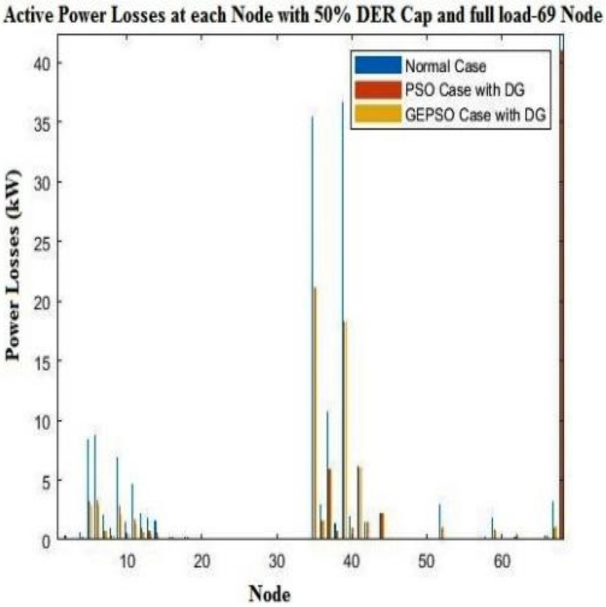

Fig. 7. Active Power Losses at individual node with 50% DER capacities& full load- Ramchandrapura-69 node

Fig. 8. (a), (b), (c) and (d)shows the active power losses at the IEEE-69 node test feeder under different scenarios of DER capacity and loading conditions. In all cases, losses are highest in the "Without DER" scenario, as there is no contribution from DER to offset the load.

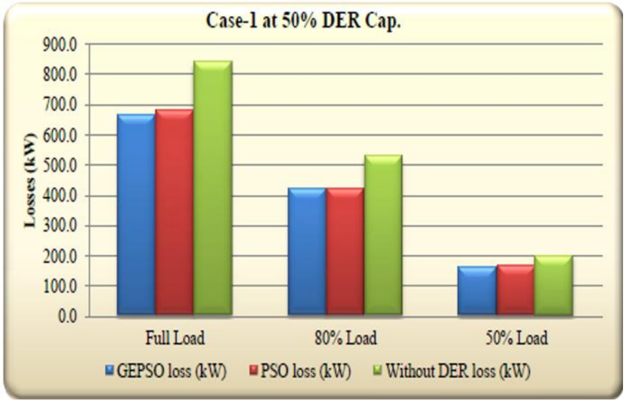

Fig. 8.(a) Active power losses at Ramchandrapura-69 node feeder at 50% DER capacity

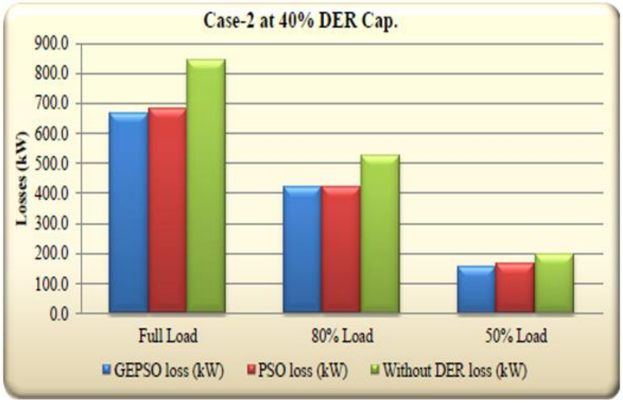

Fig. 8.(b) Active power losses at Ramchandrapura-69 node feeder at 40% DER capacity

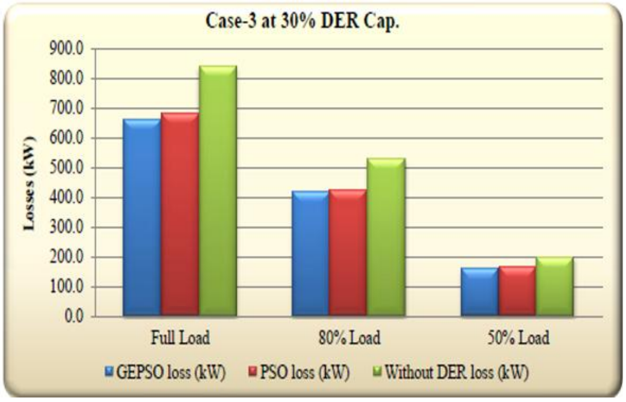

Fig. 8.(c) Active power losses at Ramchandrapura-69 node feeder at 30% DER capacity

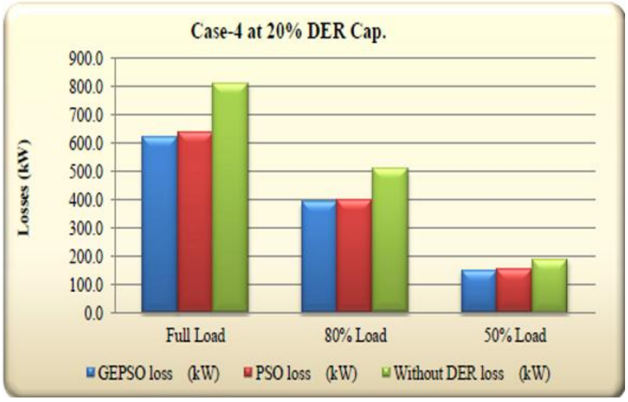

Fig. 8.(d) Active power losses at Ramchandrapura-69 node feeder at 20% DER capacity

3.2 GEPSO vs. PSO Performance Comparison

GEPSO consistently outperforms PSO in minimizing losses across different DER capacities and load conditions, albeit with minor differences in certain cases. For example, at 20% DER penetration and full load, GEPSO achieves Active power loss of 622.3 kW compared to PSO's 638.10 kW, showing its superior capability to optimize DER placement and sizing.The losses obtained under different scenarios are consistent with the typical loss percentages in distribution networks. For example, at 50% DER penetration and full load (6 MW feeder load), GEPSO's Active power loss of 60.2 kW represents approximately 3% of the total load, within the expected range for optimized distribution systems.The reduction in losses achieved by GEPSO and PSO is in line with practical observations that optimal DER placement helps to balance the power flow, reduce line loading, and mitigate voltage drops, thereby minimizing both active and reactive losses.

4 Conclusion

The proposed work is centered on optimizing the integration of DER. This involves determining the ideal size and placement of DER to be incorporated into the distribution network, ensuring minimal losses and voltage fluctuations. The challenge arises due to the intermittent nature of renewable-based DER, which limits practical solutions in real-world scenarios. To address this, an operational feeder with real load data is chosen to strategize the optimal penetration of DER. The proposed GEPSO-based approach achieves an average active power loss reduction of approximately 36% across all evaluated scenarios, with an improvement of up to 3.3% compared to conventional PSO, while also improving the minimum bus voltage by approximately 3–4% under full-load conditions. These numerical metrics are reported for both the real 69-node Ramchandrapura feeder and the IEEE 33-node test system. The proposed work can be summarized into two main parts as follows,

4.1 Geographical evaluation by HOMER

The geological conditions and potential for DER generation at the chosen location were assessed using the HOMER software tool. The previous sections of the study presented a comprehensive solution, incorporating solar and wind capacities, derived from a detailed cost analysis. The simulations conducted through HOMER indicated that an optimal solution for the selected case study would be a grid-tied hybrid system, combining solar and wind resources.

4.2 Optimization by PSO and GEPSO approaches by MATLAB

The optimization tools employed in this research are PSO and GEPSO. The study includes a comparison of three sets of results, normal load flow analysis, PSO-based optimization, and GEPSO-based optimization. To assess the impact of variable load profiles across multiple generations, a sensitivity-based stochastic approach is utilized. The sensitivity analysis reveals that the responses in losses and cost are more sensitive towards changes in load as compared to change in DER capacity.

The novelty of this work lies in incorporating real geographical conditions such as solar radiation, wind velocity, and temperature for the selected test feeder. Based on these conditions, the capacity of DER has been categorized. Subsequently, the GEPSO technique was employed to determine the optimal location and size of DER. To validate the effectiveness of GEPSO, its performance was compared with that of the well-established PSO technique. Finally, the proposed approach was applied to the standard IEEE 33-node test feeder to further validate its applicability and generalizability.

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