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Loss Minimization and Reliability Improvement in Distribution Systems Using Hybrid Optimization for DG Siting

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Distributed generation (DG) is an important approach to increase distribution system reliability by providing an alternate source of power to critical load locations. The authors present a novel technique to reduce active power loss, enhance reliability and voltage profile by allocating the DG in distribution network (DN). The proposed novel technique is a hybrid method in which genetic algorithm (GA) is combined with analytic hierarchy process (AHP) to address the multiobjective problem. The minimization of power outage cost and active power loss costs are two objectives which is optimized by the AHP-GA technique. In this method the weights for multicriteria are obtained using AHP in first stage, and in second stage GA is used to optimize the objective function. The proposed technique is validated on IEEE 69-node distribution networks. The results demonstrate significant benefits: a reduction in total cost about 62.70 % due to losses, a decrease in line loss of 79.73%, a reduction in reactive power loss of 76.83%, and an improvement of more than 45% in reliability indices. This approach improves optimization efficiency by reducing search space, balancing cost, reliability, and system performance in practical distribution system.

Keywords: Distributed generation, Analytic hierarchy process, Genetic algorithm, Distribution network, Power outage cost, Reliability indices

1 Introduction

Human lives are become easier and more dependent on technology on a daily basis in almost every area of life, including entertainment, employment, health, and even interpersonal relationships. This is due to daily advancements in technology and research so demand of uninterrupted power increased day by day. Therefore, challenges for distribution engineers to provide reliable power supply to the consumers is a crucial issue this day. The reliability of distribution systems remains vital for power networks to maintain uninterrupted premium power service to users. The reliability functions as the central parameter in modern distribution systems to maintain continuous power delivery and reduce both active power losses and reactive power losses while delivering better service quality to customers. By applying advanced technologies such as distributed generation (DG), automation, and smart grid solutions, utilities can significantly improve reliability, reduce costs, and support sustainable energy systems. Reliability improvements not only benefit consumers but also contribute to the overall resilience and efficiency of the power grid. So, DG are one of the energy sources that are directly or indirectly connected to the distribution network on the customer side and they are becoming an important component of electricity networks. We have a number of benefits as a result of the introduction of distributed generation into the distribution network, including decreased network losses, greater system reliability, improved voltage profile, power factor, and network stability, as well as favourable effects on the economy and environment. An increasing number of DGs are linked to the distribution network, posing both advantages and difficulties for grid maintenance and operation. Recently, a number of studies in this field have been carried out and numerous authors have tackled optimal DG placement problems using a range of heuristic and traditional methods. But when the size and placement of DG are not chosen properly, network characteristics including stability, voltage profiles, and network losses become worse than they would be without DG[1-4]. There are various technical, financial, and environmental benefits of installing dispersed generation[5-6]. In[7-9], authors focused on active power loss reduction in distribution network with proper placement of multiple DG units with different types such as DG delivering either active and reactive power or only active power.

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A strategy based on a genetic algorithm[10-13] has been established by authors to minimise active power losses in distribution networks with improvements in voltage fluctuation. This approach relates to the optimal size and location of various types of distributed generation units. To find the optimal location and size of DG is a complex problem with nonlinear objective function and nonlinear constraints. Selecting suitable sites for DG installation is crucial to achieving multiple objectives, including voltage regulation, power loss reduction, peak load management, and system reliability and resilience improvement[14-17]. The allocation process considers factors such as load demand, network constraints, environmental considerations, and economic feasibility to determine the most advantageous deployment of DG units.

Integration of DG in radial networks has gained importance in recent years. To accommodate the bidirectional power flows and the fluctuation of renewable energy sources, the existing infrastructure must be restructured in order to integrate DG into the electrical distribution network. N. Kaur *et al.*[18] have suggested a novel method for multiple DG placement Particle Swarm Optimization (PSO) combined with a fuzzy decision-making approach realises multi-objective optimisation and accounts for competing goals in order to determine the ideal locations and sizes of distributed generators for voltage-dependent household, business, and industrial loads. In[19-20] authors have suggested multi objective PSO technique for multiple DG integration in the distribution grid. The authors have analysed the effect of DG integration on distribution network with respect to reliability criteria and also enhance the overall system reliability[21]. PSO is used to optimize integration of renewable energy in distribution systems, decreasing greenhouse gas emissions, power losses and costs, within voltage limits on a 31-bus system[22]. The author in[23] has developed and implemented of a hybrid ABC-CS optimization algorithm for optimal multi-DG placement in radial distribution networks. The algorithm integrates the strengths of Cuckoo Search (CS) and Artificial Bee Colony (ABC) to minimize line losses, incorporate penalty functions and enhance voltage profiles. In[24-25], authors have presented an analytical approach for siting and sizing of DG in radial DN considering time varying load and demand response by the engineers. In[26], authors have suggested a novel technique based on genetic algorithm to calculate various reliability parameters and its effect on the consumers response. The authors have proposed hybrid genetic particle swarm optimization (GPSO) and Non dominated Sorting genetic algorithm II (NSGA II) to solve the optimal problem of DG allocation in distribution network[27-28]. In[29-30], Bacterial Foraging Algorithm (BFA) and Swarm Moth Flame Optimization (SMFO) have been introduced by authors for the placement of DG and capacitors in radial DN. In[31-34], the researchers have suggested the technique for calculating reliability indicators Such as system average interruption duration index (SAIDI), and energy not served (ENS) and implementing genetic algorithms, equilibrium optimizer. The authors introduce a time-series power flow method for unbalanced distribution systems with on-load tap changers and PV generation. Using fuzzy logic for voltage control, it predicts initial voltages via Lagrange functions and refines them with forward/backward analysis. Authors have also discussed various issues and challenges while restructuring of power networks.

Numerous objectives and constraints are proposed in the literature, and two main approaches to solving the problem are distinguished: 1) utilising the Analytic Hierarchy Process (AHP) to weights and criteria, and 2) utilising GA to determine optimum positions and capacity of DGs. The goal of the first strategy is to locate DGs by employing a multi-objective technique to optimize many objective functions at once. This problem can be resolved by applying the judgement matrix concept to maximise the advantages of DG. This method uses a weighted sum of several objective functions to combine all of the objectives into a single one. The idea of the AHP algorithm can be used to determine weights. The second method, which is based on GA, seeks to locate DGs by simultaneously optimising all objective functions.

2 Problem Statement

The proposed flowchart used in this paper to find out the reliability indices, optimum position, and capacity of DG shown in Fig. 1. The AHP is used to find the weight of the various objective function to use the concept of judgement matrix. The weight criteria are decided based on pair wise comparison of the two criteria and past experience or available data. This innovative concept proposes the planning of the optimal location of DG and its capacity to the

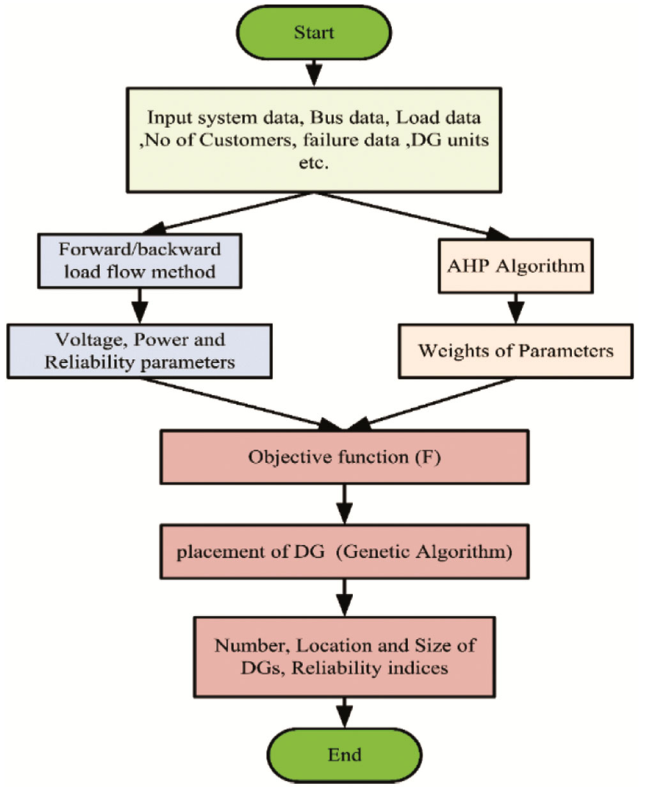

Fig. 1 — Flowchart of the proposed method

distribution network. The candidate position of DG decides where to place the DG to maximize capacity, so that reduced line losses and enhance reliability of the distribution network. System data are entered into the computer programme as system information, such as unit cost, branch length, average outage rate, line and load data, average outage duration, and the opinion of the decision maker. The active power losses and voltage are calculated by the computer program using the forward-backward load flow approach. The potential location of DG is identified based on this calculation. The decision-makers, or engineers derive the reliability parameter weights using the AHP method. The ideal position and capacity of DG are determined to minimize the objective function using the novel AHP-GA.

2.1 Load Flow

In general, we avoid to use of Newton-Raphson and other existing method to solve the DN power flow equations. The forward-backward method of load flow is used to determine the electrical parameters such as voltage magnitude, voltage angle, active power loss and reactive power loss etc. for radial distribution network[17]. The single line diagram of a radial distribution network having M load points, substation supply is coming to node 1 and corresponding nodes voltages are V_1, V_a, V_b…. V_M is shown in Fig. 2.

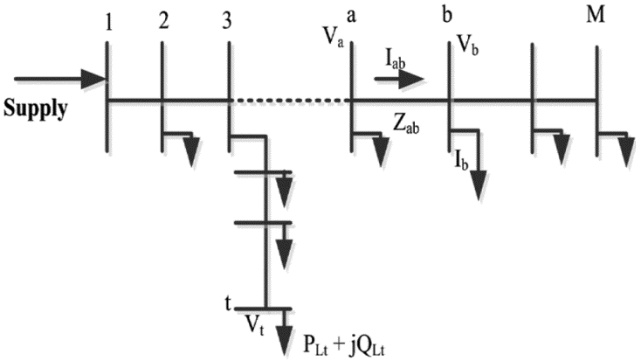

Fig. 2 — Single-line diagram of RDN

The steps to solve the forward-backward load flow method is explained below:

Step 1: Initialization of voltages at each node

$V_t^{(0)} = V_s\angle 0$ for t = 2,3,4….M

Step 2: The load current can be calculated using Eq. (1)

$$I_t^{(i)} = \left(\frac{P_{Lt}+jQ_{Lt}}{V_t^{(k-1)}}\right)^* \text{ for t= 2,3,4……M} \quad \text{… (1)}$$

where, P_{Lt} Q_{Lt} are loads at bus t, i is iteration, and V_t is voltage at bus t.

Step 3: backward sweep: In this step the branch currents from the last bus to the source bus can be evaluated the current flowing through the branch ab can be calculated using Eq. (2)

$$I_{ab}^{i} = I_b^{i} + \sum_{p\in N} I_p \quad \text{… (2)}$$

where, I_{ab} is the current through branch ab, I_b is current drawn by load connected to bus b and second term of right-hand side of Eq. (2) represents the sum of all the currents of branches entered from bus b.

Step 4: Forward sweep: in this step we update the bus voltage using Eq. (3) starting from source node to the last node as shown below:

$$V_b^{(i)} = V_a^{(i)} - Z_{ab} I_{ab}^{(i)} \quad \text{… (3)}$$

where, Z_{ab} is the branch impedance, V_a and V_b are the voltages at node a and b respectively.

3 Problem Formulation

A novel multi-objective technique is proposed, incorporating the minimization of two key performance indicators: the cost of system active power loss (C_p) and the cost of reliability loss (C_r). These indicators are formulated as optimization subobjectives within the framework. DG access location and capacity, demand, reliability indices and no of DGs unit locations are the decision variables, and the objective function can be expressed as shown in Eq. (4)

$$\begin{cases} f_1 = \min(C_r) \\ f_2 = \min(C_p) \end{cases} \quad \dots (4)$$

3.1 Reliability Loss Cost (C_r)

It is defined as:

$$C_r = \sum_{j=1}^{h} \sum_{i=1}^{hf} D_j A_j X_k \quad \dots (5)$$

$$X_k = \sum_{k=1}^{hf} f_k T_k \quad \dots (6)$$

where, h means load points; hf implies failure modes number. D_j is the load connected to node j; A_j is the cost of supply loss due to fault i with a duration of T_k causes the loss of customers connected to the load point j; X_k is the unavailability of supply due to fault k and f_k is the average failure rate of failure mode k.

3.2 System Active Power Loss Cost (C_p)

If any fault occurs in the system, then it is not possible to provide the electricity to the connected load until and unless fault is cleared or DG is connected properly. Thus, the reliability of the system becomes poor due to fault, so the main work of discom engineer is to clear the fault and resume the supply to the connected load. Minimizing the total active power loss is the primary objective of optimal placement of DG in the distribution network.

The power loss in each segment can be calculated as:

$$P_l = \sum_i^M (I_i)^2 . R_i = \sum_i^M R_i . \frac{P_i^2 + Q_i^2}{|V_M|^2} \quad \dots (7)$$

where, I_i, R_i, P_i and Q_i represent current, resistance, active power and reactive power of i^{th} branch respectively, M is the total number of buses. Now the cost of active power loss can be calculated as

$$C_p = P_l T_m \beta \quad \dots (8)$$

where, β is the per unit cost due to network power disconnected and T_m is the maximum time during which power disconnected.

The reduction in active power loss after DG installation can be calculated using Eq. (9) as shown below:

$$P_{reduction} = \frac{[P_l - P_{l,DG}]}{P_l} * 100 \quad \dots (9)$$

where, $P_l$is the active power loss without DG and $P_{l,DG}$ is the loss after installing DG.

3.3 Final Objective Function

In our problem related to the placement of DG and the reliability indices parameters, one objective is to minimize the cost of network loss, the second one is to minimize the cost of reliability loss. These objectives may not be directly comparable based on data size because they relate to different aspects of the process. To make these problems comparable and accessible for decision-making, they are usually transformed into a single objective function. In this method, the conversion from a multi-objective function to a single-objective function is accomplished using the judgment matrix approach[17]. The final objective function of this problem is written as:

$$F = \min(\omega_1 f_1 + \omega_2 f_2) \quad \dots (10)$$

where ω_1, and ω_2 are the normalized weights which are determined with the help of the judgment matrix idea as described in the next section.

3.4 Inequality Constraints

For the objective function as given in Eq. (10) have some limitations to solve so that objective function must be satisfied within given range, the limitations are given below in Eqs. (11-12)

$$\begin{cases} 2 \le DG_{loc} \le M \\ Q_{DG}^{min} \le Q_{DG} \le Q_{DG}^{max} \\ P_{DG}^{min} \le P_{DG} \le P_{DG}^{max} \end{cases} \quad \dots (11)$$

$$\text{And,} \begin{cases} V_{min} \le V \le V_{max} \\ I_i \le I_{rated} \\ M_{DG} \le M_{DGmax} \end{cases} \quad \dots (12)$$

where; Eq. (11) represents the active and reactive power limits of distributed generation as well as the DG location range from bus 2 to M. The M_{DG} is optimum number of DG; M_{DGmax} indicates maximum number of candidate location of DG; V_{max} and V_{min} are the voltage range of a particular bus; I_i = i^{th} branch current, I_{rated} = Maximum permissible branch current.

4 Analytic Hierarchy Process

T. L. Saaty developed AHP a framework for making decisions, in the 1970s. It offers a structured way for analyzing and prioritizing complex multicriteria problems by decomposing challenging multicriteria problems into hierarchical structures and measuring the relative weights of various criteria and alternatives. A judgment matrix is a tool used in decision-making that assesses and ranks several possibilities according to a number of criteria[38].

Table 1 briefly provides an idea of how to construct a judgment matrix.

Now after the formation of the judgment matrix, it is essential to solving to get the solution of weights as in equation 10. These are the following steps to solve a judgment matrix:

i Normalize the matrix: The matrix can be normalized by divide each element in a column by the sum of the column elements.

$$h_{st}^{-} = \frac{h_{st}}{\sum_{x}^{M} h_{xt}} \quad s,t = 1,2\ldots., M \qquad \ldots (13)$$

Here M is the number of factors.

ii Now each element of a normalized matrix of a row is added.

$$X_s = \sum_{t=1}^{M} h_{st} \quad s=1, 2,3,\ldots..M \qquad \ldots (14)$$

i Then the vector $\overline{X} = [\overline{X_1}, \overline{X_2}, \overline{X_3}, \ldots\ldots \overline{X_M}]^T$ is normalized as s = 1,2,3….., M

$$\omega = \frac{\overline{X_s}}{\sum_{k=1}^{M} X_k} \quad s= 1, 2, 3\ldots\ldots, M \qquad \ldots (15)$$

ii The final result $\omega = [\omega_1, \omega_2, \ldots\ldots, \omega_M]^T$ is the desired weight of the system.

Table 1 — Rule of building a Judgment Matrix

Scaling	Explanation
1	Two criteria have the same status
3	One criterion has a moderate status with respect to the second criteria
5	One criterion has strong significance with respect to the second criteria
7	One criterion has very strong position with respect to the second criteria
9	One criterion has extreme significance with respect to the second criteria
2,4,6,8	The intermediate status between adjacent decisions

where $\omega_h \geq 0$ and $\sum_{h=1}^{M} \omega_h = 1$

Now using above steps in MATLAB program, the judgement matrix, the normalized matrix and weight vector will be given by:

$$J = \begin{matrix} 1 & 5 \\ 1/5 & 1 \end{matrix} \quad J_N = \begin{matrix} 0.833 & 0.833 \\ 0.167 & 0.167 \end{matrix} \quad \omega = 0.833 \quad 0.167$$

4.1 Formation of DG Locations

The IEEE 69-node distribution network used in this research has a single feeder, and five distributors, and loads are connected to nodes as shown in Fig. 3. Integrating a huge number of DG into a distribution network faces a number of challenges, such as the limit of the network complexity because of the high node density, reverse power flow, voltage fluctuations, protection challenges etc. To address these challenges, this study proposes an efficient methodology for selecting optimal DG locations as well as DG capacity. The approach considers the impact of DG integration on the distribution network's performance, along with the network's load-carrying capacity, to ensure a balanced and efficient system.

4.2 Planning for Candidate Position for Distributed Generation

DG integration, relative to the load demand, is measured by the penetration rate, i.e. the ratio of total DG capacity to the network's maximum load. With higher penetration rates, the share of DG load met is higher, but also brings about grid stability problems, voltage regulations problems, reverse power flow, protection coordination problems, and increased network losses. This paper considers the impact of DG access location on distribution network active power loss, and voltage, and combines reliability

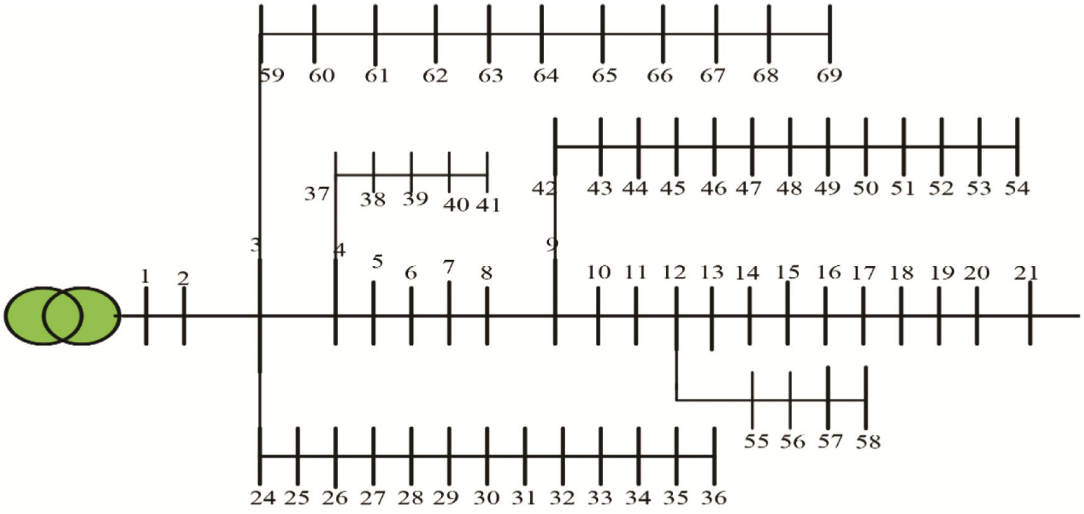

Fig 3 — IEEE 69- node system

requirements[13] and actual distribution network structure to determine DG candidate locations. In order to quantify the improvement degree of DG access to network loss [14], the system active power loss improvement rate χ is introduced, as shown in Eq. (16), which means it is the ratio of the active power loss after installing DG to the active power loss before installing DG.

$$\chi = \frac{P_a}{P_b} \qquad \ldots (16)$$

where P_a is the active power loss after installing DG and P_b is the active power loss before installing DG. The method utilized in this research involves estimating the ratio of the branch line load to the total system load. For the modified IEEE 69-bus system, 12 potential DG placement locations were identified, as illustrated in Fig. 4. According to the above analysis, combined with active power loss, voltage and reliability indicators and distribution network load distribution, a practical method for selecting DG candidate locations is proposed.

5 Method of DG Optimization Planning

The Genetic Algorithm (GA) plays a great role in solving DN planning problems due to its robust global search capabilities and adaptability to complex, nonlinear optimization tasks. Its ability to handle multiple objectives, such as to enhance reliability, and minimizing power losses makes it ideal for such applications. The elite retention planning further improves its efficiency by providing the best solutions across generations. Its stochastic nature also gives diverse exploration of the solution space, reducing the risk of being trapped in local optima. This combination of efficiency, versatility, and precision makes GA a powerful tool for optimizing DG siting and sizing problems in distribution network. The methodology is illustrated through the flowchart presented in Fig. 5.

5.1 Solution Algorithm for Integrated Coordination and DG Allocation

The steps of DG and distribution network comprehensive coordination planning are as follows:

Step 1: Input consumer data, load data, bus data failure rate, repair time, population size, mutation probability, crossover probability etc.

Step 2: Perform AHP Algorithm to calculate the weights for objective functions.

Step 3: Define criteria and construct pairwise comparison matrix, now determine weights.

Step 4: The forward-backward sweep method is utilized to perform power flow analysis.

Step 5: The candidate positions for DG placement are identified by analyzing the effects of DG integration on voltage profiles, active power losses, and compliance with the reliability criteria of the distribution network.

Step 6: The genetic chromosome adopts binary code, and each chromosome is divided into two parts: DG, and load point. Coding each decision variable. In this part, the number of DGs at each candidate position are represented by 3-bit binary numbers, meaning that each position has 8 possible capacities. When the code is 0, it indicates that the candidate

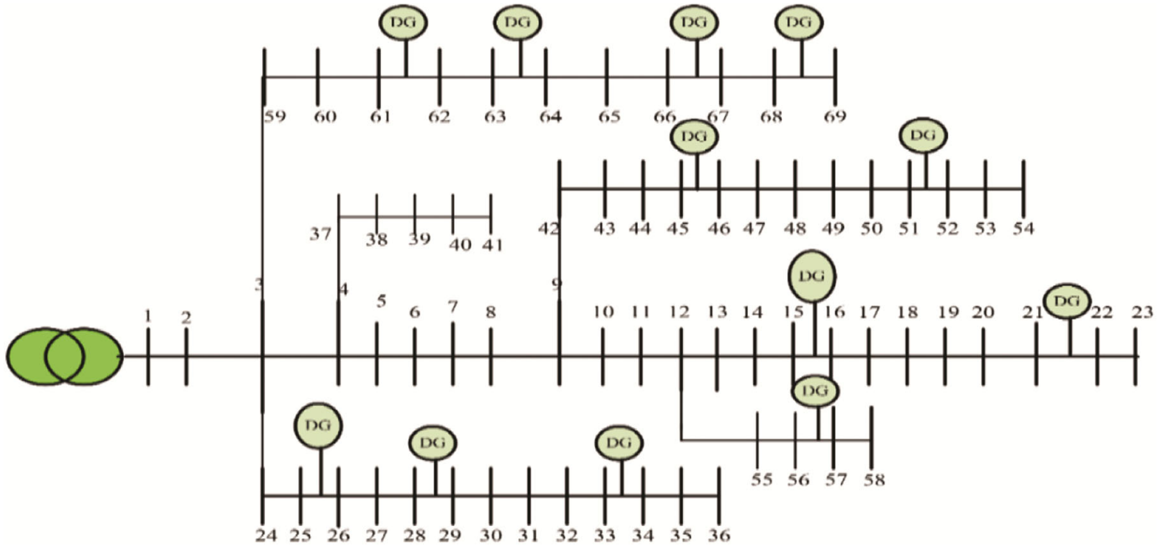

Fig. 4 — Candidate location for DG

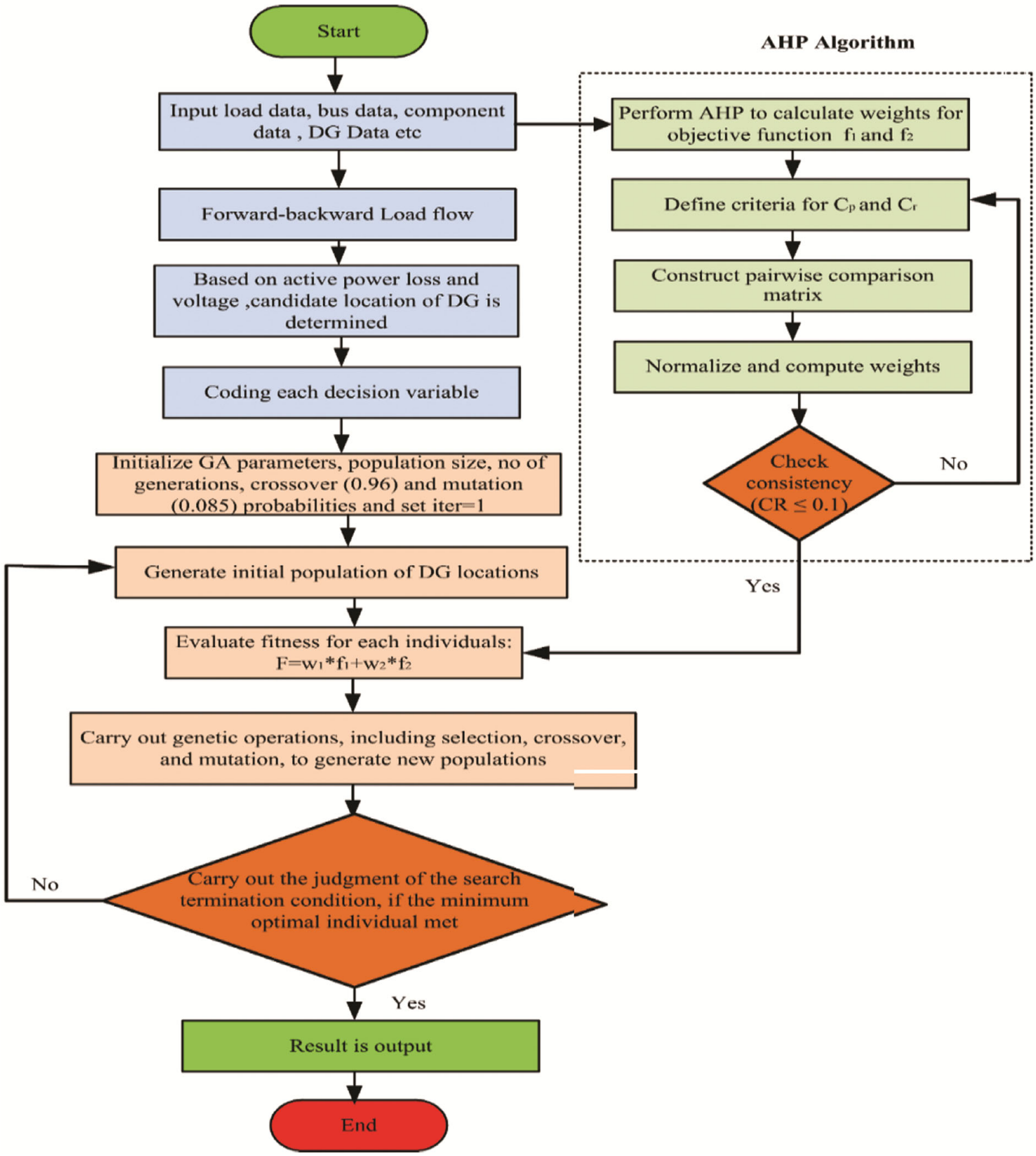

Fig. 5 — Flow chart of the proposed technique

position is not connected to DG; when the code is 1 -7 indicates that the corresponding number of DG units are connected to the candidate position.

Step 7: Initialize GA parameters.

Step 8: Generate initial population of DG locations

Step 9: Evaluate fitness for each individual from equation (9).

Step 10: Now perform selection, crossover and mutation to create new populations.

Step 11: Evaluate the termination condition of the search, If the optimal individual's minimum is obtained, then calculation ends and the result is output; otherwise, iter=iter+1, go to step 8.

6 Results and Discussion

To validate the approach presented in this research paper, two scenarios have been analyzed: distribution network planning considering 4 DG and 6 DG integration. The site selection, capacity setting, and network expansion planning of DG are carried out using this calculation example. The test line includes 69 nodes, single feeder, five distributors, and 68 branch, and 68 load points, the source reference voltage at node 1 is 12.66 kV, the connected demand is 4659.68 kVA (3801.9 kW, 2694.1 kVAR), the full installed size of DG does not exceed 35 % of the total load. The parameters of initialization are as follows: population size = 80, iteration count = 40, crossover probability = 0.96, mutation probability=0.085 load power factor=0.9 efficiency of DG = 0.95, and failure rate of line = 0.10 failure/year/km. now the proposed novel technique has implemented on IEEE 69- bus system considering 4 DG of total capacity 1620 kW to 466 kW variation in penetration rate from 35 % to 10 % as shown in Table 2. The relevant reference prices involved are as follows:

The price of electricity sold to the consumers is 8.0 per unit. The capital cost of DGs is 80,000.0 ₹ /kW for PV, 152,000.0 ₹/kW for vertical wind turbine, the operation and maintenance cost per year for DG is 1% of the capital investment amount and the cost of maintenance of feeder, is 700,000.0 ₹/km. The average outage per consumer per year is 98.5 min[26] and total number of consumers connected is 2947. “All of the pricing listed were obtained from Indian distributors and suppliers.”

Table 2 — Variation active power loss with DG capacity (kW)

Active power loss (kW)	Total DG capacity (kW)	Reduction in active power loss	DG location
224.960	--	--	---
52.005	1620	76.88 %	64 52 24 16
62.456	1398	72.24 %	64 59 52 24
65.182	1165	71.05 %	64 62 52 16
87.840	932	60.95 %	64 59 24 16
102.98	700	54.22 %	64 52 24 12
110.68	466	50.08 %	68 58 27 16

i Assuming the installation of four DGs within the distribution network

Relationship between DG capacity, Active power loss reduction and DG placement in distribution network are highlighted in Table 3. However, without DG the system loses 224.960 kW active power. By integrating DG, losses are integrated significantly and a maximum reduction of 76.88 % is observed at a total DG capacity of 1620 kW placed at location 64, 52, 24 and 16. On the other hand, at locations 68, 58, 27, and 16, losses are decreased by only 50.08% to a capacity of 466 kW. The best location for 35 % penetration rate (1620 kW) DG capacity are 16, 24, 52, and 64 respectively and DG capacities are 518 kw, 334 kW, 195 kW, and 573 kW. This shows that the minimization of losses depends not only on DG capacity, but also strategic placement. Reductions from the DG capacities are generally higher, but the higher DG capacities are even better if they are placed at key nodes to enhance voltage regulation and reduce line losses.

i Assuming the installation of six DGs within the distribution network

Now the technique has implemented on IEEE 69-bus system considering 6 DG of total capacity 1620 kW to 466 kW variation in penetration rate from 35 % to 10 % as shown in Table 4. From the table 3, we can

Table 3 — Variation of active power loss with DG capacity (kW)

Active power loss (kW)	reactive power loss (kVAR)	DG capacity (kW)	Reduction in active power loss	DG locations
224.960	102.15	--	---	--
45.596	23.66	1620	79.73 %	64 68 52 24 12 21
60.086	35.60	1398	73.30 %	6 15 52 59 64 68
64.681	40.28	1165	71.25 %	12 18 32 56 63 65
85.97	45.47	932	61.78 %	12 18 24 52 62 68
101.57	50.20	700	54.85 %	15 23 55 58 63 69
110.312	55.22	466	50.96 %	6 18 24 52 63 68

Table 4 — Comparison of the output with proposed and existing methods

Methods	No of buses with under voltage	Real power losses (kW)	Reactive power losses (kVAR)	DG capacity (kW)	No of DG	Reduction in active power loss
Without DG	22	224.96	102.15	---	---	---
Ref [33]	13	113.57	79.43	1000	01	43.75 %
Ref [35]	--	70.56	50.30	2736	03	59.65 %
Ref [36]	--	87.523	--	3130	03	49.95 %
Ref [37]	--	78.659	57.17	2910	03	55.01%
Proposed method	8	62.456	31.47	1398	04	72.24 %
		45.596	23.66	1620	06	79.73 %

observe that the reduction in both power losses (active and reactive) decline as the capacity of DG increases. The best location for 35 % penetration rate (1620 kW) DG capacity are 12, 21, 24 52 64 and 68 respectively and DG capacities are 195 kw, 310 kw, 272 kW, 155 kW, 472 kW and 216 kW.

From Table 2 and Table 3, it is observed that increasing the number of DG units and their total capacity leads to higher reductions in active power loss as well as reactive power loss. In the table 2, a maximum active power loss reduction of 76.88% is attained with four DGs of 1620 kW, while in the Table 3 achieves a higher reduction in active power loss of 79.73% by positioning the same capacity across a distribution network six number of DGs. This illustrates that allocating DG across more strategic locations enhances efficiency as well as voltage profile. Similarly, fewer DG capacities result in lower reduction in active power loss and reliability, but proper placement mitigates this impact. So, we can say that optimizing the location and number of DG placement is critical for minimizing overall losses.

The Table 4 shows the comparative analysis of proposed method and various existing method as per literatures. We can observe that the proposed method proves its efficacy as well as robust performance. The line losses, reactive power losses, and voltage profile also improves significantly. The proposed method provides 79.73 % reduction in line losses and 76.83 % reduction is reactive power losses. The penetration rate of proposed model is from 30% to 35 % which is suitable for distribution network configuration.

The cost analysis is given in Table 5 and the outage cost can be calculated as:

Outage cost (without DG) = outage duration* no of consumers*tariff* total load/60

= 98.5*2947*8*3801.9/60 = Rs. 147,148,484.14

From the Table 5, three cases have considered for cost analysis (i) without DG (ii) 4 DG of capacity 1398 kW and (iii) 6 DG of capacity 1620 kW. The C_P and C_r have obtained from proposed technique and it is observed that the total loss to the company without DG is 162.91 million ₹ which is very high. The total cost after DG placement in the DN are 84.13 and 60.71 million ₹ for 1398 kw DG, 1620 kW DG respectively. So, from Table 5, it is clear that the percentage reduction loss in costs is 48.36 and 62.73 for both the cases (ii, iii) respectively. The installation cost of DGs can be coverup by the company from two years, after that company will fully be benefitted i.e. about 102.2 million ₹ per year. Here the proposed method is very much suitable for practical distribution line and very easy to implement.

Figure 6 shows the system line losses with respect to branches under different penetration rate and it is observed that how placement of DG influences the line losses to each branch. The Table 6 shows the

Table 5 — DG planning cost analysis results

Cost in million ₹ per year

Case	DG Invest. Cost (₹)	Loss Cost (C_P)	outage cost (C_r)	Total cost (C_P+ C_r) (₹)	Percentage reduction
1	---	15.77	147.14	162.91	…..
2	140.5	4.21	79.92	84.13	48.36 %
3	159.9	3.20	57.51	60.71	62.73 %

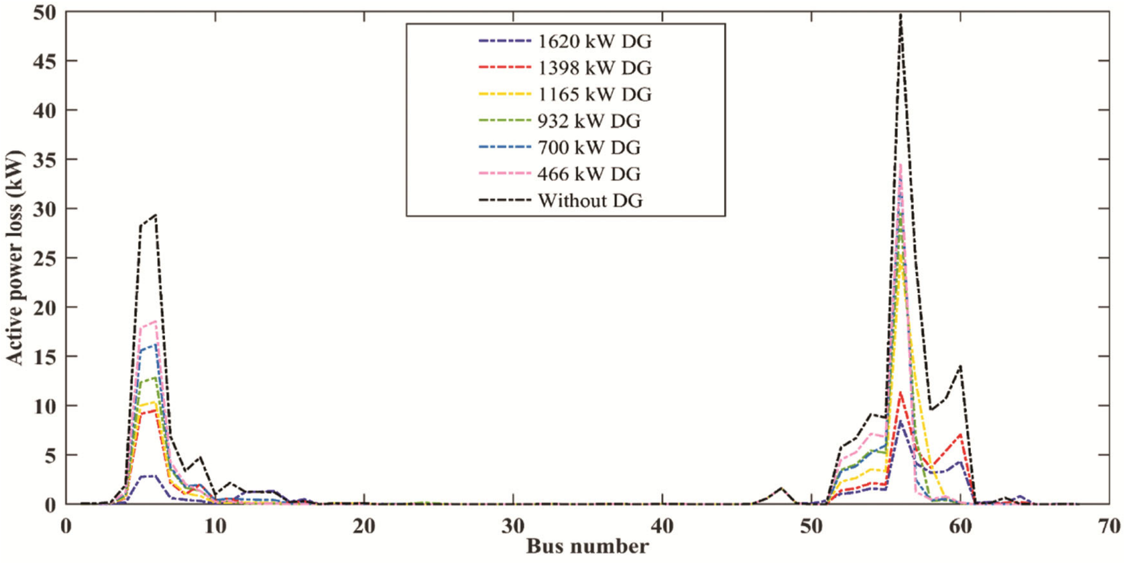

Fig. 6 — Variation of active power with DG capacity

variation of line losses with respect to branches for different penetration rate, it is observed that from Table 6, the maximum line losses occur across branches 5, 6, 56, 57, 58, 59 and 60 which is 28.23, 29.34, 49.68, 24.45, 9.5, 10.67 and 14.02 kW respectively. When DG is installed for various capacity then line losses reduced accordingly as shown in table. If we consider 1620 kW DG installation then line losses for the same branches are reduced to 2.76, 2.86, 8.45, 4.16, 3.20, 3.32 and 4.37 Kw, respectively.

Table 6 — Variation of line losses with branches for various penetration rate

Branch No	Line loss (kW), DG -1620 kW	Line loss (kW), DG -1398 kW	Line loss (kW), DG -1165 kW	Line loss (kW), DG -932 kW	Line loss (kW), DG -700 kW	Line loss (kW),DG -466 kW	Without DG
1	0.0176	0.02923	0.0320	0.038	0.0458	0.0545	0.075
2	0.0176	0.0356	0.0320	0.038	0.0458	0.0545	0.075
3	0.0393	0.0867	0.0920	0.106	0.1252	0.138	0.194
4	0.1894	0.6286	0.6866	0.8484	1.069	1.225	1.936
5	2.7625	9.167	10.012	12.37	15.591	17.868	28.235
6	2.8627	9.5133	10.392	12.844	16.192	18.56	29.343
7	0.6423	2.187	2.3945	3.566	3.766	4.328	6.893
8	0.4629	1.0003	1.1027	1.687	1.787	2.070	3.374
9	0.3343	2.0229	0.8469	1.355	1.988	1.361	4.772
10	0.0668	0.4134	0.1633	0.2702	0.405	0.271	1.013
11	0.2841	0.6115	0.1332	0.3055	0.591	0.306	2.189
12	1.2180	0.1157	0.1864	0.0587	0.488	0.105	1.284
13	1.2799	0.1033	0.1695	0.0604	0.461	0.097	1.245
14	1.3469	0.0918	0.1530	0.0639	0.433	0.083	1.20
15	0.2503	0.2150	0.0284	0.0118	0.08	0.015	0.223
16	0.4975	0.3077	0.02502	0.03605	0.094	0.014	0.320
17	0.0036	0.0025	9.80E-05	0.0009	0.0005	0.0001	0.002
18	0.0480	0.1000	0.099	0.115	0.007	0.0032	0.104
19	0.0310	0.0642	0.0640	0.002	0.005	0.002	0.067
20	0.0503	0.1031	0.1027	0.0034	0.008	0.025	0.107
21	0.0034	0.0005	0.0005	0.0019	0.0008	0.0001	0.0005
22	0.0391	0.0049	0.005	0.024	0.0103	0.0020	0.005
23	0.0009	0.0107	0.010	0.0531	0.010	0.0107	0.011
24	0.0005	0.0058	0.005	0.170	0.006	0.0058	0.006
25	0.0002	0.0023	0.0023	0.0703	0.002	0.002	0.0024
26	3.08E-05	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
27	0.0003	0.00034	0.0003	0.0003	9.60E-05	0.0003	0.0003
28	0.0025	0.0026	0.0025	0.0025	0.0009	0.002	0.002
29	0.0058	0.0058	0.0058	0.0058	0.009	0.005	0.005
30	0.0010	0.0010	0.001	0.001	8.83E-05	0.001	0.001
31	0.0051	0.0051	0.005	0.0051	0.0004	0.005	0.005
32	0.0122	0.0123	0.0122	0.012	0.002	0.0122	0.012
33	0.0104	0.0104	0.0104	0.010	0.0103	0.0104	0.0104
34	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
35	0.0014	0.0014	0.0014	4.91E-05	0.001	0.0014	0.0014
36	0.0150	0.0150	0.0150	0.0009	0.015	0.015	0.0150
37	0.0173	0.0173	0.0173	0.0173	0.017	0.017323	0.0173
38	0.0050	0.0050	0.0050	0.005	0.005	0.0050	0.005
39	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
40	0.0487	0.0487	0.0487	0.0486	0.0487	0.043	0.0487
41	0.0201	0.0201	0.0201	0.0201	0.0201	0.020	0.020

(*Contd.*)

Table 6 — Variation of line losses with branches for various penetration rate (*Contd.*)

Branch No	Line loss (kW), DG -1620 kW	Line loss (kW), DG -1398 kW	Line loss (kW), DG -1165 kW	Line loss (kW), DG -932 kW	Line loss (kW), DG -700 kW	Line loss (kW),DG -466 kW	Without DG
42	0.0026	0.0026	0.0026	0.0026	0.0026	0.002	0.002
43	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
44	0.0060	0.0060	0.006	0.0060	0.006	0.006	0.006
45	1.26E-05	1.26E-05	1.26E-05	1.26E-05	1.26E-05	1.26E-05	1.26E-05
46	0.0232	0.0232	0.0232	0.0232	0.023	0.023	0.023
47	0.5826	0.5827	0.5827	0.5827	0.582	0.582	0.582
48	1.6331	1.6333	1.633	1.6333	1.633	1.633	1.633
49	0.1158	0.1158	0.1158	0.1158	0.1158	0.115	0.115
50	0.0772	0.0017	0.0017	0.0017	0.0017	0.001	0.001
51	0.3533	4.30E-05	4.30E-05	4.32E-05	4.33E-05	4.34E-05	4.38E-05
52	1.0588	1.4051	2.2957	3.4896	3.323	4.541	5.781
53	1.222	1.6234	2.6578	4.0456	3.852	5.268	6.71
54	1.6047	2.1441	3.5538	5.455	5.190	7.137	9.124
55	1.4957	2.0097	3.3704	5.216	5.986	6.852	8.790
56	8.4543	11.3598	25.2651	29.482	33.83	34.62	49.684
57	4.1671	5.5991	12.4530	6.773	2.507	1.263	24.489
58	3.2090	3.7137	4.0451	0.323	0.409	0.506	9.505
59	3.3270	5.3771	0.5910	0.410	0.526	0.805	10.67
60	4.3732	7.0678	0.1175	0.138	0.160	0.182	14.023
61	0.1386	0.0133	0.0007	0.0001	2.72E-06	0.0002	0.113
62	0.2397	0.0300	0.0014	0.0024	0.002	0.0001	0.134
63	0.0603	0.1474	0.0070	0.0117	0.01	0.0008	0.661
64	0.8301	0.2328	0.0430	0.0007	0.0007	0.0007	0.0412
65	0.0025	0.0025	0.0025	0.0025	0.002	0.0025	0.0026
66	1.47E-05	1.50E-05	1.49E-05	1.50E-05	1.51E-05	1.51E-05	1.53E-05
67	0.0221	0.0227	0.0226	0.0227	0.0476	0.0095	0.0233
68	3.53E-05	3.61E-05	3.59E-05	3.62E-05	0.00054	3.63E-05	3.71E-05
Total line losses	45.56	70.08	83.68	91.97	101.57	110.31	224.96

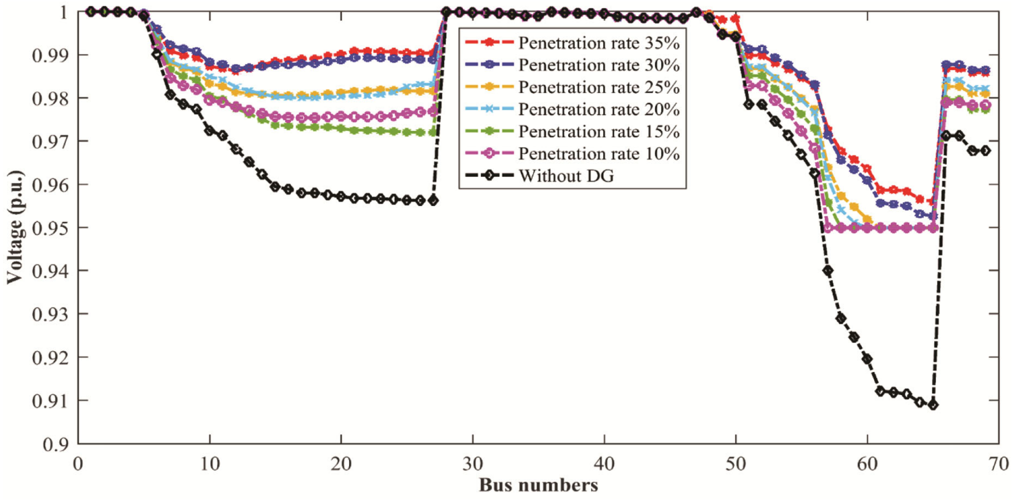

Fig. 7 — Variation of voltage profile with penetration rate of DG

Figure 7 shows the system voltage profile under different penetration rates 10%, 15%, 20%, 25%, 30%, and 35%. Comparing the influence of different locations of DG access on the total network loss of the system, it is found that the installation locations with better improvement rates are concentrated at the middle end of the entire network, especially when the long branch line is connected to the middle end

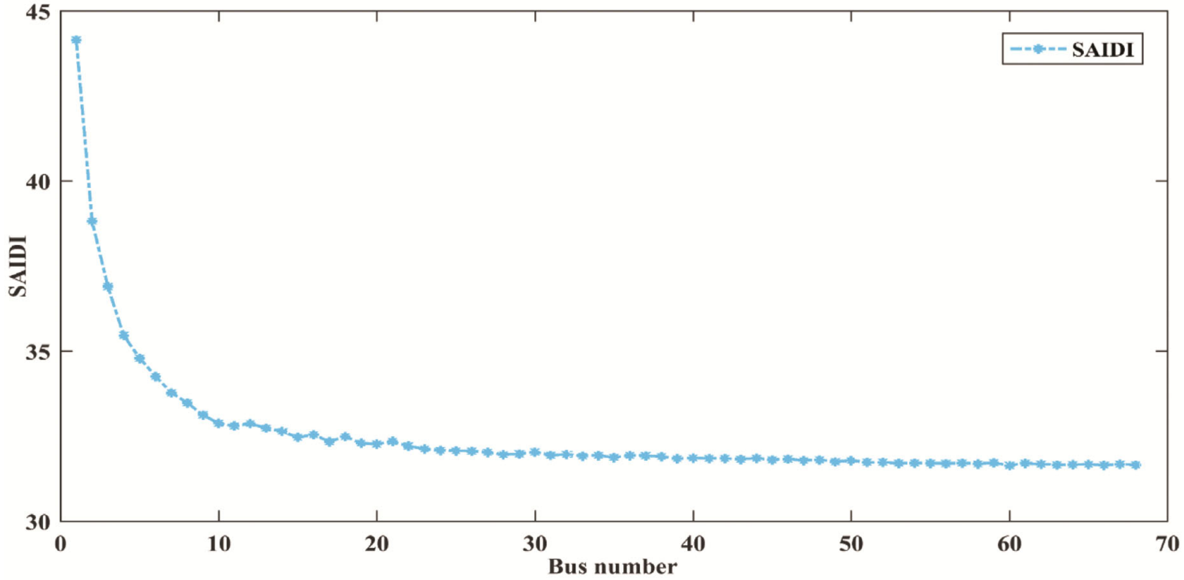

Fig. 8 — variation of SAIDI

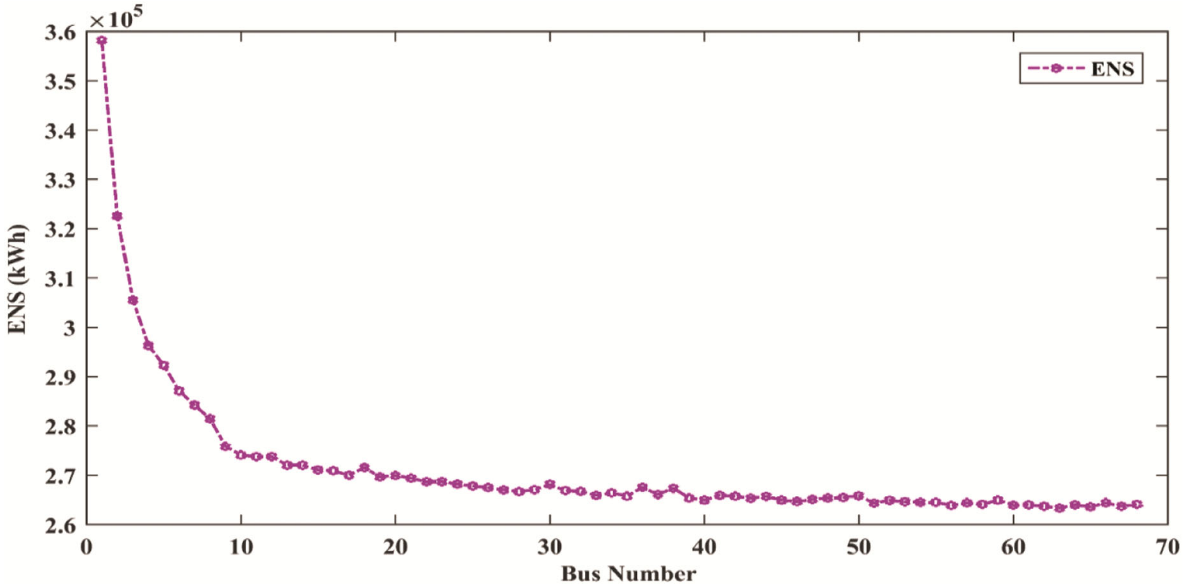

Fig. 9 — variation of ENS

position, the improvement effect is the best. From Fig. 7, it is detected that as penetration rate increases the voltage profile enhanced and also the penetration rate 35 % i.e. 1620 kW DG provides the best result among all.

Figures (8-9) shows the variation of reliability indicators (SAIDI, ENS) with respect to bus number, from these plots we can conclude that the introduction of DG in distribution network reduces these indicators significantly. Table 7 clearly shows the benefits of the proposed method, the reduction in SAIDI and ENS is more than 44 % which also shows the consumer satisfactions.

Table 7 — Analysis of SAIDI and ENS

	SAIDI	ENS	Reduction in SAIDI	Reduction in ENS
Without DG	57.3	481,320	---	----
Ref [31]	---	---	30.02 %	17.18 %
Proposed method	31.66	264118.87	44.74 %	45.12 %

The Fig. 10 shows the variation of DG capacity with respect to line losses, when there is no any DG in the system then line losses are very high 224.96 kW but when DGs are inserted in the distribution network then losses reduced for (466 kW DG, losses 110.3 kw), (700 kw DG, losses 101.6 kW), (932 kW DG, losses 98.0 kW), (1165 kw DG, losses 83.7), (1398 kW DG, losses 70.) and (1620 kW DG, losses 45.6). So, authors observed a sharp reduction in line losses because of reduction in line currents. The voltage profile is shown in Fig. 11, from this plot we can observed that the voltage of weakest buses enhances sharply from 0.91 p.u. to 0.97. The overall voltage throughout the system is between the desire limit set in Eq. (11), hence the placement of DG at appropriate location enhances the system voltage profile.

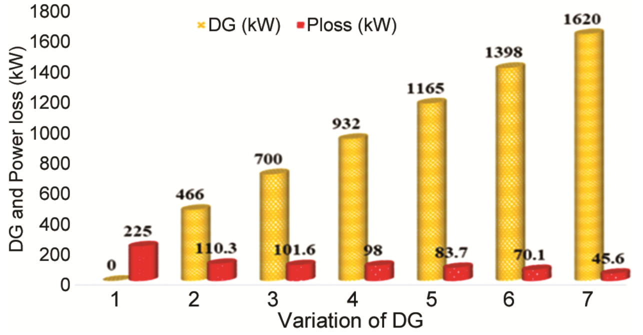

Fig. 10 — Comparison of DG and active power loss

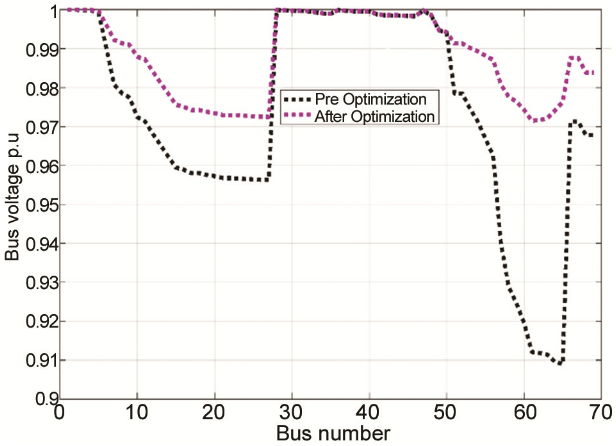

Fig. 11 — Voltage profile

The Figs. (12-13) show the line losses or active power losses and reactive power loss. The trends show how the impact of DG reduces these losses at significant level. In Fig. 12, the maximum line loss reduced across a branch 5 and 6 is about 89.65 % whereas across branch 56 it reduces to 83.67 %, which is very prominent output. In Fig. 13, the reduction in reactive power loss across branch 5 and 56 is about 86.66 % and 88.45 %, respectively. So, it can be dictated that after inserting the DG at proper location of optimal capacity the reactive power demand can also be controlled or minimized. The proposed algorithm is also compared with BFA to validate the importance of the GA-AHP technique. The Figs. 14 -15 show the comparative analysis of line losses and reactive power losses across each branches, respectively. The line losses and reactive power losses is minimum in proposed method whereas in BFA it is higher. The peaks of the GA curve is also very low so, low current is flowing through the particular branch after DG installation, hence cost of the conductor and protective devices are less.

The voltage profile is shown in Fig. 16, in which proposed technique (GA-AHP) provides better result

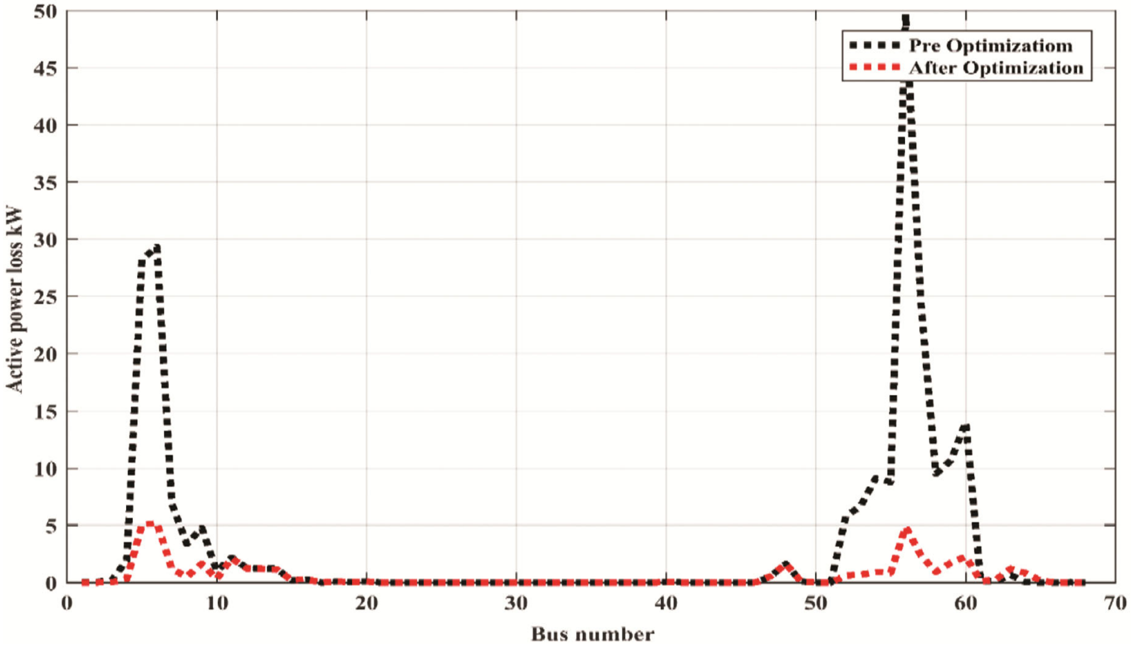

Fig. 12 — Variation of line loss

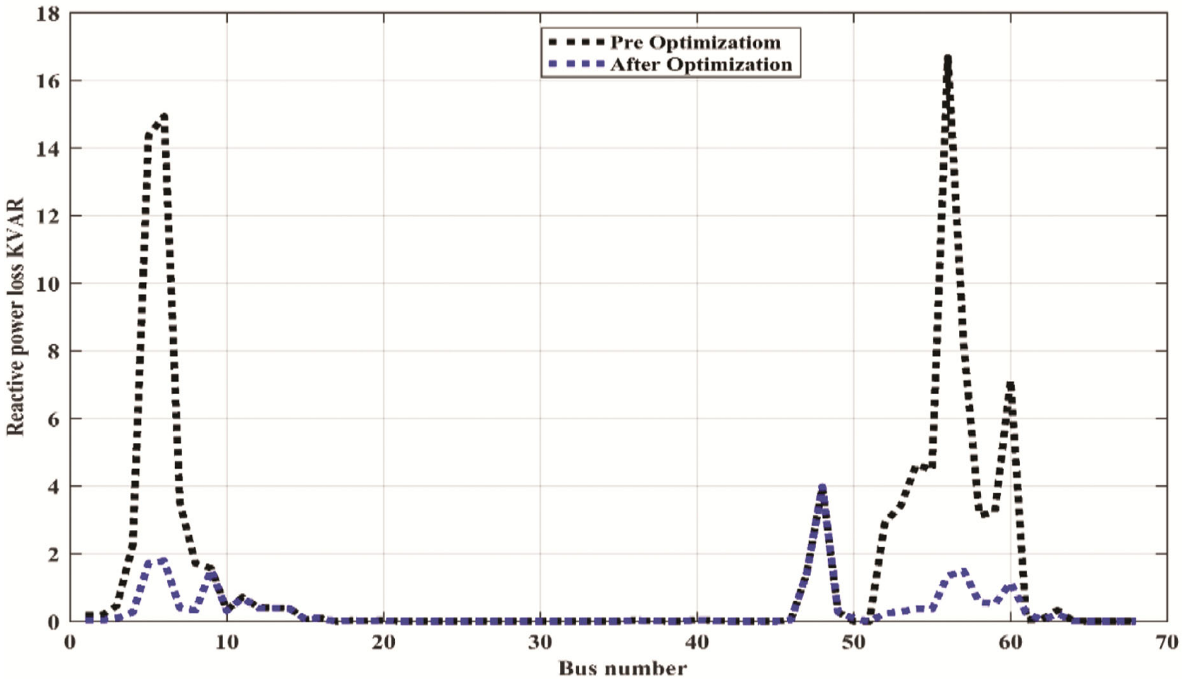

Fig. 13 — Variation of reactive power loss

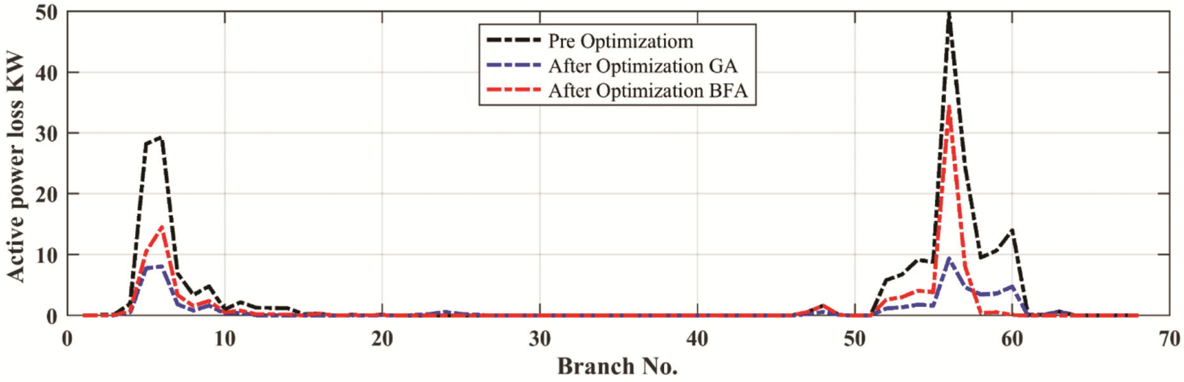

Fig. 14 — Comparison line losses for BFA and GA

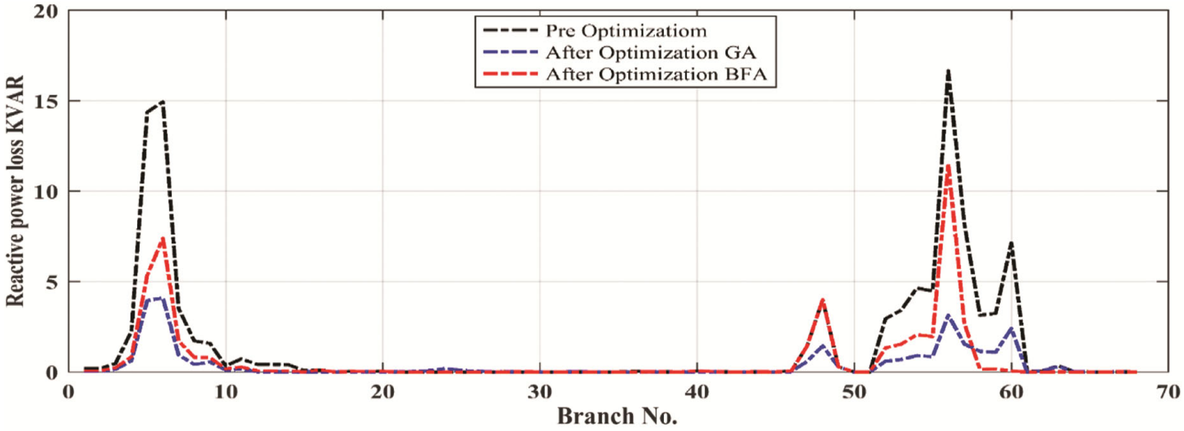

Fig. 15 — Comparison reactive power losses for BFA and GA

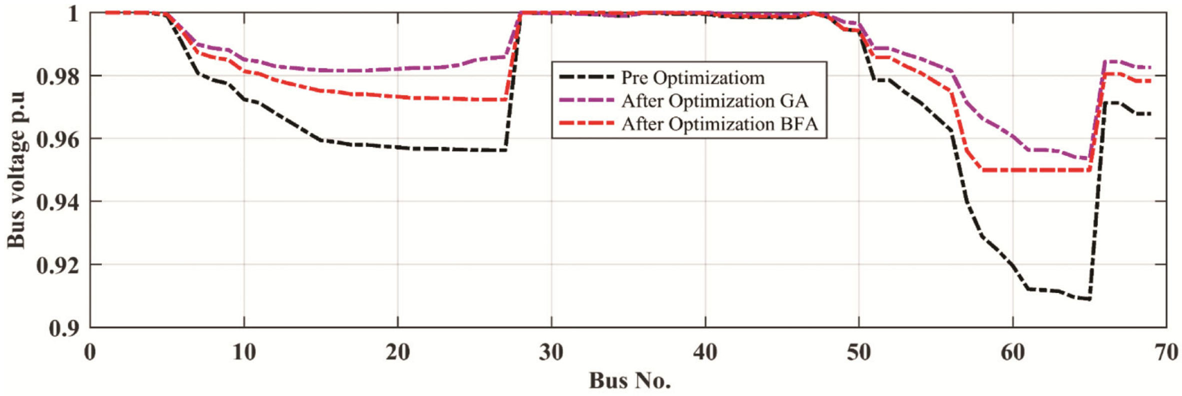

Fig. 16 — Comparison voltage profile for BFA and GA

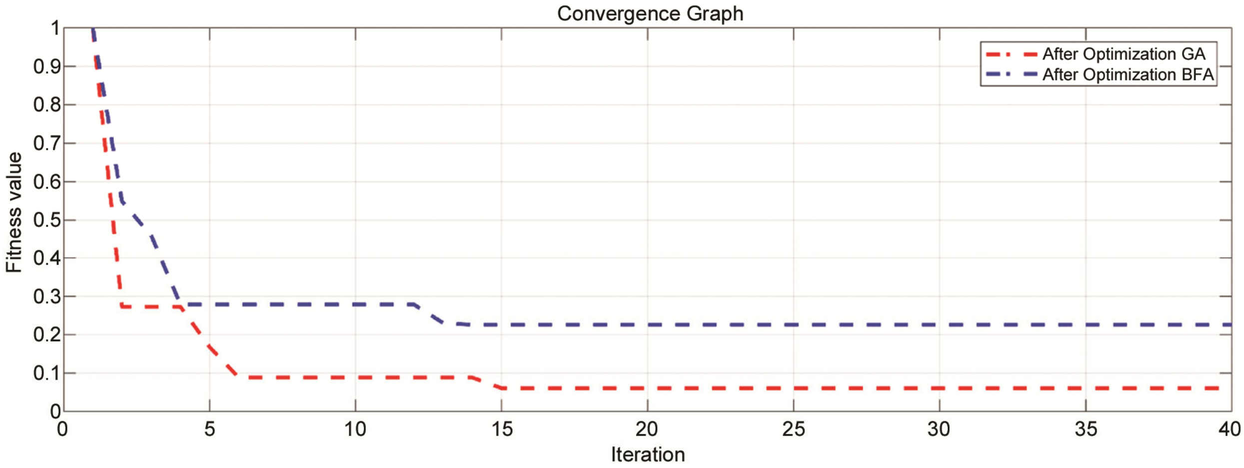

Fig. 17 — Convergence plot of BFA and GA

as compared to BFA. The minimum voltage is 0.957 p.u form GA whereas 0.951 p.u from BFA. The Fig. 17 shows the convergence plot, in which the fitness value from GA is lower than BFA.

7 Conclusion

The authors introduce an implementable method to select potential locations for distributed generation (DG) implementation. The decision about optimal DG placement sites arose from a detailed study which included active power loss evaluation with voltage profile and reliability metric assessment and reliability cost analysis. The chosen locations for 4 DG installations include sites 16, 24, 52, 64 followed by locations 12, 21, 24, 52, 64 and 68 for 6 DG installations. The planning model served as a multi-objective platform for incorporating distributed generation systems into distribution networks utilizing the evaluated characteristics. The implemented AHP-GA approach creates a complete system for optimizing DG placement and maximizing distribution network efficiency.

The presence of thorough DG unit planning in combination with distribution grid coordination enables effective reduction of distribution network expenses from losses and power outages. The developed model minimized active power loss expenses by 62.73% within the network. The combined implementation reduced the electrical distribution network failure indicators SAIDI and ENS annually by 45%. The addition of distributed generation units decreased active power loss by 79.73% when using six DG units and by 72.24% when using four DG units. Reactive power loss reached reductions of 76.8% for the 6 DG installation and 69.20% when only 4 DG units were used. A comparative study affirmed that the proposed approach was practical and superior based on its operational results.

The research has established that proper distribution generation system sizing together with placement represents a vital factor for achieving reduced power losses across distribution networks. The research evidences the effectiveness of proposed methodology for delivering major enhancements in network performance and reliability. The proposed approach can be extended to analyze larger and more complex distribution networks, including meshed systems, to assess scalability and adaptability to diverse grid configurations. This method can incorporate demand response strategies and load shifting techniques to evaluate their role in optimizing DG utilization while maintaining grid reliability and efficiency.

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