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Distribution Network Expansion Planning Considering DG - Penetration Limit Using a Metaheuristic Optimization Technique: A Case Study at Debre Markos Distribution Network

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Abstract: This paper presents an optimization model for the expansion planning of electrical distribution network in the selected 15-kV Debre Markos distribution network to evaluate the power loss and voltage deviation when installing distributed generation (DG) with proper penetration limit together with newly upgraded lines. For the aforementioned problems, the objective function is minimizing the total power loss and total voltage deviation for the expanded distribution network during the planning period and particle swarm optimization (PSO) is employed to solve the problem. Case studies are performed to demonstrate the validity of the proposed model and method.
To evaluate the capability of the existing Debre Markos distribution network and capability to supply reliable power considering future expansion, load demand forecast for the years 2016/17-2021/22-2026/27 is done using the least square method. The performance evaluation of the existing and the expanded network considering the existing and forecasted load demand for the years 2021/22 and 2026/27 is done using forward-backward sweep power flow method. To make the distribution network reliable, the expansion planning is carried out using PSO as a major task of the paper.

Keywords: Backward-forward load flow, DG penetration, Distribution network planning, least-square method, power loss, load forecasting, metaheuristic algorithm, PSO, voltage deviation

1. Introduction

The power distribution system, in the context of power distribution planning, has as a primary goal to design the distribution system to satisfying system load as well as the requirement of its customers by ensuring the acceptable continuity and quality of electricity supply to customers [1]. Electric power is supplied by power generation stations which usually consists of large-scale generation units (e.g. hundreds of megawatts) with the unidirectional power flow, and an extensive interconnected network that transmits and distributes electricity to a range of domestic, commercial and industrial consumers. On the other hand, a distributed generation system consists of small-scale generation units directly connected to the distribution network, with capacities ranging from a few kilowatts to a number of megawatts, resulting in bidirectional power flows. The optimal planning of distributed generation sizing and siting is critical to ensure the operational performance of distribution network in terms of power quality, voltage stability, reliability. The optimal DG planning problem has been addressed with regard to several technical and economic objectives, e.g. loss minimization, voltage profile improvement and cost-bene fit maximization [2].

In fact, expansion planning for the distribution system is a dynamic but knotty task. It raises the question of where, when and which facilities should be built. The planner has to plan the system expansion for the planning horizon and analyze the possible behavior of the system at each planning stage to guarantee an economic and reliable power supply as planned. Studies are performed, considering initial data which includes the available topology of the base network, a series of feasible generating plants, predicted load growth for each bus of the system, limits on the operation of all equipment in the electrical system and costs in terms of investment as well as operation [3].

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The Distribution Expansion Planning is carried out to provide a distribution infrastructure that meets the electricity customer requirements in terms of electrical power system profiles. Distribution planners must ensure that there is adequate distribution substation capacity and electrical feeder capacity to meet the forecasted load within the planning period [4]. The incorporation of DG with its optimal size and location plays an important role in the electrical power distribution network for minimizing the power losses and enhancing voltage stability in power systems [5], [6].

2. Problem Formulation

The problem is to determine DG penetration limit by allocating and sizing of DGs which minimizes the power losses and the voltage deviation for the expanded distribution network. An assumption is taken that One DG can be allocated for each feeder due to the complexity of the problem [7], [8].

A. Objective Function

The main objective is to minimize the real power loss and the voltage deviation subject to different constraints. This can be expressed mathematically as:

$$\boldsymbol{f = \omega_1 \sum_{i=1}^{m} I_i^2 * R_i + \omega_2 \sum_{i=1}^{m} (1 - V_i)^2} \quad (1)$$

Where,

i: Any feeder branch,

m: The number of network branches

R_i: The resistance of branch i and

I_i: is the current magnitude flows in branch i.

V_i: is the voltage of bus i.

Ω_1 and ω_2 : Weights of the real power loss and cumulative voltage deviation in the objective function respectively and their sum is equal to one.

B. Constraints

The objective function is subjected to the following constraints:

- *Node Voltage limits on each bus*

The bus voltage on each bus should be in the range of 0.95 to 1.05 pu with tolerance range of ±5% of the nominal value as per the standard [9].

$$\boldsymbol{V_i^{min} \le V_i \le V_i^{max}} \quad (2)$$

Where

V_i: bus voltage;

V_i^{min}: minimum bus voltage;

V_i^{max}: maximum bus voltage.

- *Branch Capacity Limits*

$$\boldsymbol{I_{(i,j)} \le I_{rated}} \quad (3)$$

Where

I_{rated}: Thermal Current carrying capacity of line section ij

- *DG power rating constraint*

The size of DG in the expanded network should not be less than or equal to one-tenth of the feeder load and not more than the feeder loading value.

$$\boldsymbol{10\%L \le DG_z \le 100\%L} \quad (4)$$

Where; L: Total feeder load

DG_Z: DG size

- *Active and Reactive Power Losses Constraint*

The losses after installing DG in the expanded network should be less than or equal to the losses before installing DG.

$$\begin{pmatrix} P_L withDG \leq P_L withoutDG \\ Q_L withDG \leq Q_L withoutDG \end{pmatrix} \quad (5)$$

3. Solution Method

The overall methodology of this study including the following main steps was illustrated using a flow chart as shown below:

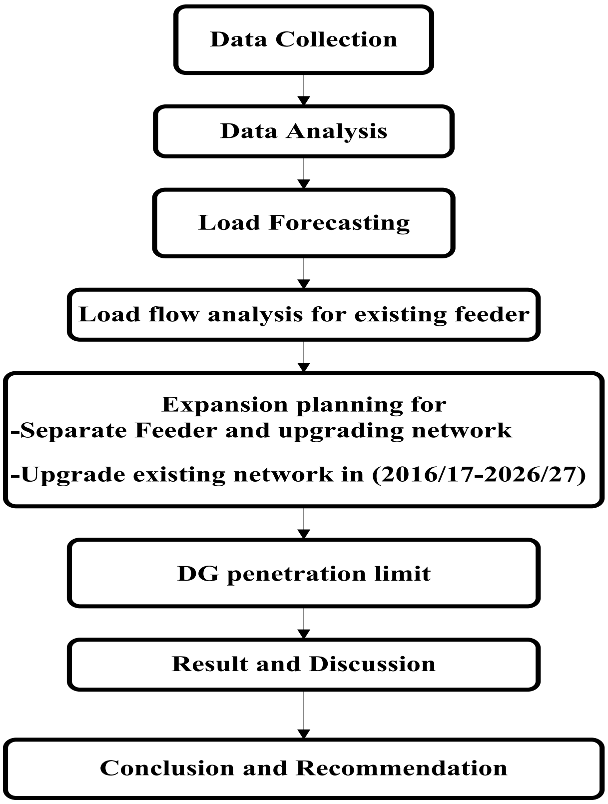

Figure 1. The Overall Methodology

A. Load Flow Method

For this study backward/forward sweep load flow method is implemented for its computational efficiencies and system accuracies due to its fast convergence since the radial distribution network has high R/X value that causes problems in the convergence in conventional methods [10], [11].

B. Constraints Handling

The PSO technique is employed to integrate the bus voltage limit, branch capacity limit, DG power rating and the active and reactive power loss constraints to the objective function and the schemes does not violet the limits.

C. DG penetration Limit Determination

In this work, a proposed methodology is tested on MATLAB software to find the effects of DG penetration limit in radial feeders in terms of power loss and voltage deviation minimization. Therefore; DG penetration is defined as the ratio of total peak DG power to peak load power on the feeder which is expressed as [12], [13]:

$$\boldsymbol{DGPenetration} = (\boldsymbol{PeakDGPower})/(\boldsymbol{PeakLoadPoweronfeeder}) \quad (6)$$

D. Separating and Upgrading Feeders

Since Debre Markos feeder 3 covers a large area of the city and feeds loads at a long distance which is about 27 KM from the source, it has high power loss and voltage deviation for existing and forecasted load demand.

So, this feeder is separated into two and the new feeder is added. These separated feeders are F3A and F3B. Feeder upgrading is performed based on the amount of current through the conductors resulted from the backward forward load flow, the appropriate conductor's size is selected for F3A and F3B and F4.

E. Incorporating DG in the Upgraded Separated Network

To find the optimal DG location and size with its penetration limit, the objective function explained in equation (1) is computed by satisfying the constraints for each expanded feeder using PSO based on the set parameters and it is tabulated in table 3.

4. Optimization Method

A. Genetic Algorithm

In [14]–[16], Gene tic Algorithm is an optimization technique based on Darwinian principle of selection and survival of fittest. It is a search algorithm that uses natural genetic operations for instance cross over and mutation. It is an artificial intelligence (AI) method used for solving the optimal DG placement problem for distribution systems. A simple genetic algorithm in most of practical problems consists of three operators: reproduction, crossover and mutation. In these papers, GA is required to calculate the active power losses and node voltages and find optimal location and sizing of DG.

B. Harmony Search Algorithm

In [16], [17], Harmony search (HS) is associated rule that simulates a phenomenon in computer science and operation research, and that is inspired by Zong Woo Geem's improvisation method of the 2001 improvisation method. Originally, the HS algorithm was based on the musician's improvisation method. Each musician corresponds to every variable of choice; the pitch range of the musical instrument corresponds to the value variable of choice; musical harmony refers to a vector solution for certain iteration at a certain moment and the aesthetics of the music instrument corresponds to the purpose function.

Like musical harmony, solution vector is enhanced by iteration moment after moment. In these papers, Optimal Location and sizing of Distributed Generation Sources for the Distribution Network to Reduce Losses and Improve Voltage Profile.

C. Particle swarm optimization

- Introduction

Particle swarm optimization is a meta-heuristic population-based stochastic optimization method which can easily optimize non-linear optimization problems proposed by Doctor Kennedy and E Berhart in 1995 and it is inspired by the social behavior of certain groups of animal's activity.

The PSO approach utilizes a population of individuals to search promising regions of the search space. In this context, the individual or each bird or fish is called a particle or agent and its flock is called "Particle Population or swarm". All the particles have own fitness or objective value which is calculated by the objective function.

This algorithm is based on a very simple idea like bird flocking and fish schooling which is an iterative search technique in which particle moves around the wide area of search space according to the objective function.

Each particle searches through the entire space by randomly moving in different directions and remembers the previous best solutions of that particle from their own experience and also positions of its neighbor particles or from other particles' experiences. Particles of a swarm adjust their position and velocity dynamically by communicating best positions of all the particles with each other. In this way, finally, all particles in the swarm try to move towards better positions until the swarm reaches an optimal solution.

This PSO optimization theory can be understood by the concept of simulating the movement of a group of individuals to find the optimum solution to a mathematical problem, as birds or fishes are searching the food in either scattered or go together before they locate the place where they can find the food in the wide area.

Therefore; the PSO technique is more popular due to its ability to obtain fast convergence, easy implementation and PSO uses only basic mathematics rather than involve any derivative or gradient information [18], [19].

- *Basic Model of PSO*

In PSO, all agents go through entire search space and update its position and velocity vector based on its personal influence as well as a social influence for optimizing the objective function. Consider a function of n dimension which is defined as:

$$f\ (X_1, X_2, X_3, X_4 \dots X_n) = f\ (X) \quad (7)$$

Where;

X_i is the optimizing variable, which represents the set of variables for a given function f(x). Here, the goal is to obtain an optimum value x* so that the function f(x*) can become either a maximum value or a minimum value.

The velocity of each agent can be modified by the equation:

$$V_i^{k+1} = \omega V_i^k + C_1 * rand * \left(Pbest_i - S_i^{\ k}\right) + C_2 * rand * \left(gbest_i - S_i^{\ k}\right) \quad (8)$$

Using equation (8), the velocity which gradually gets close to best and best can be calculated and the current position (searching point in the solution space) can be modified by the equation:

$$S_i^{\ k+1} = S_i^{\ k} + V_i^{\ k+1} \quad (9)$$

Where, $S_i^{\ k}$: is current searching point of agent i at iteration k,
$S_i^{\ k+1}$: is denotes the position of agent i at the next iteration k+1
V_i^k: is current velocity of agent i at iteration k,
$V_i^{\ k+1}$: New velocity of agent i at iteration k,
n: is number of particles in a group,
$Pbest_i$: is personal best of agent i,
$gbest_i$: is the global best of the population/ group,
ω: is weight function for velocity of the agent i,
$rand$: Random number between 0 and 1,
C_1: is adjustable cognitive acceleration constant (self-confidence),
C_2: is adjustable social acceleration constant (swarm confidence).

The updated velocities and positions of the particles are used as the present velocities and positions to the next iteration for the calculation of new value and these processes are repeated until stopping criteria (limitation of maximum iteration) is satisfied.

Fundamentally, there are two classes of PSO algorithms which are the Global Best (gbest) and Local Best (lbest) PSO algorithms and they differ in the size of their neighborhood particles, convergence of gbest PSO will be faster than lbest PSO because of the larger agent interconnectivity and lbest PSO is less susceptible of being trapped in local minima due to the larger diversity. In the gbest PSO technique, every agent gathers the information from the best agent in the entire swarm, whereas in the lbest PSO technique each agent gathers the information from only its immediate neighbors in the swarm. They are explained on C.2.1. and C.2.1. respectively.

✓ *Global Best PSO*

In the global best PSO (or gbest PSO) technique the position of each agent is influenced by best agent in the whole Particle Population and the information is shared in all agents to resemble as a star network topology. If an optimization problem is considered, the personal best position of a particle, which is adjusted from its position according to its own experience (Pbest), represents the position of particle "i" in search space with optimal fitness function value. Gbest is the position of particle which yields the optimal value among all personal best positions and it is expressed using the equation (10) below.

$$V_{ij}^{t+1} = V_{ij}^{t} + C_1 r_{1j}^{t} * \left(Pbest_i - x_{ij}^{t}\right) + C_2 r_{2j} * \left(gbest_i - x_{ij}^{t}\right) \quad (10)$$

Where,

V_{ij}^{t+1}: is the velocity of the agent at time t;

x_{ij}^{t}: is the position of agent at time t;

$Pbest_i$: is the personal best position of agent starting from initialization through time t;

$gbest_i$: is the global best position of agent starting from initialization through time t;

C_1 and C_2 are positive acceleration constants which are used to determine Contribution level of the cognitive and social components respectively;

r_{1j}^{t} and r_{2j} are random numbers generated at time t.

Therefore; personal best is the best position of each agent among all-time steps that each agent traversed and Global best is the best position of all agents in the entire swarm.

✓ Local Best PSO

In local best PSO (or lbest PSO) technique each agent will be influenced by the best agent among its immediate neighbor agents in the swarm and it resembles as a ring social topology. In this method, the social information which is local knowledge of the environment is exchanged within neighborhood of the particle.

With reference to the velocity equation, the social contribution to particle velocity is proportional to the distance between a particle and the best position found by the neighbourhood of particles. For this case, the velocity of the agent is computed by:

$$V_{ij}^{t+1} = V_{ij}^{t} + C_1 r_{1j}^{t} * \left(Pbest_i - x_{ij}^{t}\right) + C_2 r_{2j} * \left(Lbest_i - x_{ij}^{t}\right) \quad (11)$$

Where,

$Lbest_i$: is the best position that an agent has had in the neighborhood of particle i obtained from initialization through time t.

- PSO Parameters

PSO requires a number of parameters to be selected before optimization which may affect its performance for any given optimization problem. The values and choices of these parameters have large, small or no impact on the performance of the PSO method. These parameters are illustrated below.

✓ Swarm Size

The swarm size or population size is the number of individuals/particles/agents inside the population/swarm and is determined by the integer parameter 'P'. A large swarm generates larger particles and maximum of the search space to be covered per iteration. A larger population will increase the computation time requirements since a large number of particles may reduce the number of iterations and more time is needed to obtain a good optimization result.

✓ Iteration Numbers

Observing significant improvement in the solution based on computational experience, a number of iterations is usually sufficient which is dependent on the problem providing that the initial solutions are feasible. The proper number of iteration number should be taken since taking a small number of iterations may force to stop the search process prematurely and taking a large number of iterations may result in unnecessary additional computational complexity and more time.

- ✓ Velocity Components

  The velocity components play a vital role to limit the maximum jump that a particle can make in one step at every iteration. Therefore; a very large value will result in oscillations around a certain position while a very small value can cause the particle to become confined within local minima. The three terms in agent's velocity are inertia component, cognitive component, and social component.

  1. The term V_{ij}^{t} is called inertia component. It gives the information of the movement in the immediate past. This component is used to prevent sudden changes in the agents' direction and provides a tendency to move towards the current direction.

  2. The term $C_1 r_{1j}^{t} * \left(Pbest_i - {x_{ij}}^{t}\right)$is called cognitive component. It is used to measure the performance of the agents with respect to their past performances. It acts like an individual memory of the best position for an agent. The effect of this component is to make the agents to positions which satisfied them the most in past.

  3. The term $C_2 r_{2j} * \left(gbest_i - {x_{ij}}^{t}\right)$ for gbest PSO or $C_2 r_{2j} * \left(Lbest_i - {x_{ij}}^{t}\right)$for lbest PSO is called social component. It is used to measures the performance of the agents with respect to a group of agents. It makes each agent to move towards best position found by agent's neighborhood.

- ✓ Acceleration Coefficients

  The values for cognitive and social acceleration constants, together with the random values r_1 and r_2, have a significant impact on the dynamic performance of the PSO algorithm. The constant c_1 for cognitive expresses how much confidence a particle has in itself, while c_2 social acceleration expresses how much confidence a particle has in its neighbors.

  When $c_1 = c_2$, all particles are attracted towards the average of $Pbest_i$ and $gbest_i$

  When $c_1 >> c_2$, each particle is more strongly influenced by its personal best position, resulting in excessive wandering.

  When $c_1 << c_2$, then all particles are much more influenced by the global best position, which causes all particles to run prematurely to the optima.

- Implementation of PSO to Determine Optimal Location, Size, and Penetration Limit of DG

The PSO-based approach for solving the DG allocation and sizing problem for a specified DG penetration can be summarized as follows:

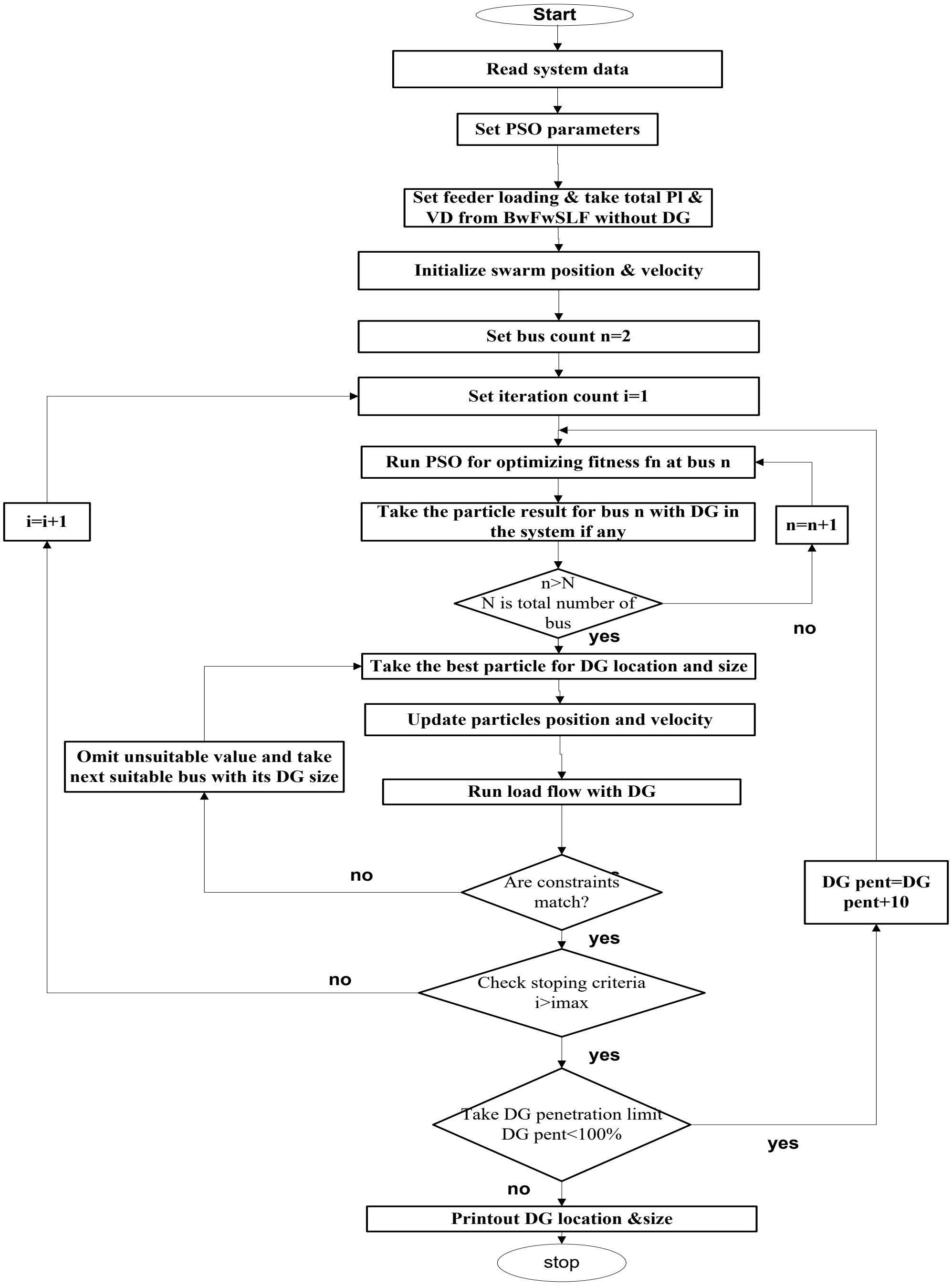

Figure 1. PSO algorithm for DG sizing and placement of DG penetration determination

5. Case Study and Simulation Results

The simulations have been carried out on the 59, 62, 71 and 129 node networks for the case study.

A. Load Flow Result Analysis of the Feeders

From load flow, total voltage deviations, overloading condition and power losses for the existing, separated, upgraded separated and upgraded separated feeders with DG are shown in the table from 1 to 5.

Table 1. Result Analysis for Feeder 3 for Load in 2016/17, 2021/22 and 2026/27

case	Feeder 3					
	line data@	bus data@	Power loss(kW)	Voltage deviation(p.u)	overloaded lines	overloaded Trs
existing/ base	2016/17	2016/17	519.39	15.61	YES	YES
	2016/17	2021/22	2040	31.02	YES	YES
	2016/17	2026/27	7430	58.7	YES	YES
Separate feeder	F3A 2016/17	2016/17	55.85	2.05	NO	NO
	F3A 2016/17	2021/22	170.4	3.59	YES	YES
	F3A 2016/17	2026/27	361.22	5.23	YES	YES
	F3B 2016/17	2016/17	93.1	4.04	NO	YES
	F3B 2016/17	2021/22	296.4	7.23	YES	YES
	F3B 2016/17	2026/27	665.11	10.84	YES	YES
	Total for	2026/27	1026.33	16.07		
Upgraded separated Feeder	upgraded A	2026/27	198.11	3.48	NO	YES
	upgraded B	2026/27	334.57	6.97	NO	YES
	Total		532.68	10.45		
Upgraded separated Feeder with DG	upgraded A	2026/27	38.96	0.25	NO	No
	upgraded B	2026/27	39.34	0.84	NO	NO
	Total		78.3	1.09		

Table 2. Result Analysis for Feeder 4 for Load in 2016/17, 2021/22 and 2026/27

case	Feeder 4					
	line data@	bus data@	Power loss(kW)	Voltage deviation(p.u)	overloaded lines	overloaded Trs
existing/base	2016/17	2016/17	102.6	3.01	NO	YES
	2016/17	2021/22	246	4.66	YES	YES
	2016/17	2026/27	471	6.44	YES	YES
Upgraded existing	Upgraded @2026/27	2026/27	216	4	NO	YES
Upgraded existing with DG	Upgraded @2026/27	2026/27	39.06	0.57	NO	NO

B. Determination of DG penetration limit, DG size and DG location using PSO

From table 3, it can be noted that the optimal values of DG penetration limit and DG size and location set by the PSO algorithm are the results which have minimum power loss and voltage deviation in the expanded feeders for the target year 2026/27.

Table 3. DG penetration limit, location and Size on the expanded feeders

No.	Feeder Name	Total Bus	DG penetration (%)	DG location	DG size (MVA)	Voltage deviation (p.u)	Active Power loss(kW)	Reactive Power loss(kVAR)
1	F3A	59	40	22	4.03430	0.25	38.96	61.04
2	F3B	71	60	39	3.44	0.84	39.34	60.65
3	F4	62	20	27	1.46	0.57	39.06	60.89

C. Result Analysis of Percentage Reduction

Table 4 shows that the percentage reduction of the power loss and voltage deviation between the upgraded separated feeders and upgraded separated feeders with DG.

Table 4. Result comparison based on percentage reduction in power loss and voltage deviation with DG and without DG

Case	Power loss (kW)				Voltage deviation (p.u)			
	F3AU	F3BU	Total	F4	F3AU	F3BU	Total	F4
Without DG	198.11	334.6	532.68	216	3.48	6.97	10.45	4
With DG	38.96	39.34	78.3	39.11	0.25	0.84	1.09	0.57
Reduction (%)	80.33	88.24	85.30	81.89	92.82	87.95	89.57	85.75

D. Voltage Profile for different cases For Expanded feeders

The voltage profile for different cases for the expanded feeders is shown in figure 1, figure 2 and figure 3 and it can be observed that the greatest improvement on voltage profile is achieved when the DG unit is integrated.

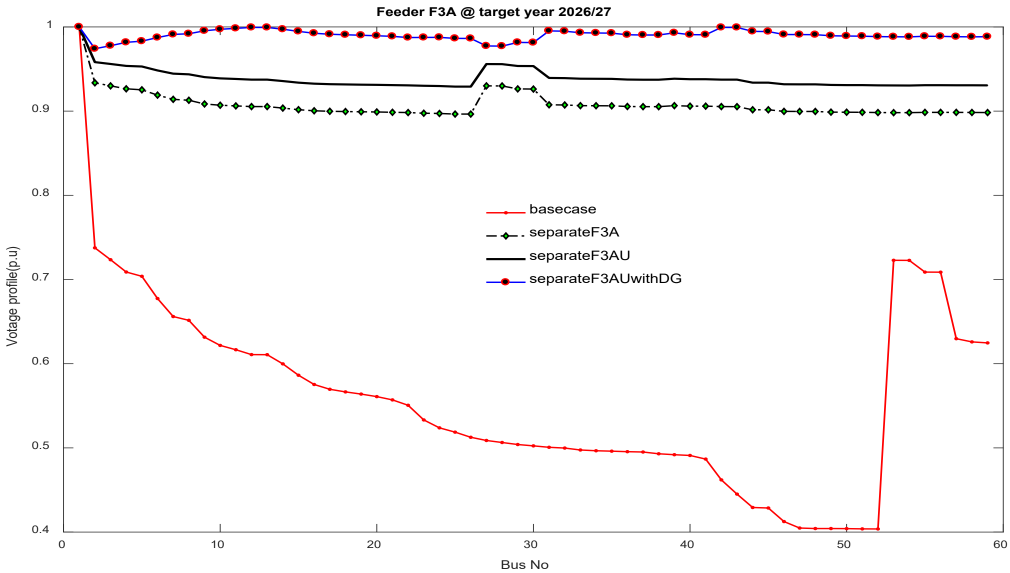

Figure 1. Voltage Profile of separated feeder F3A for different cases

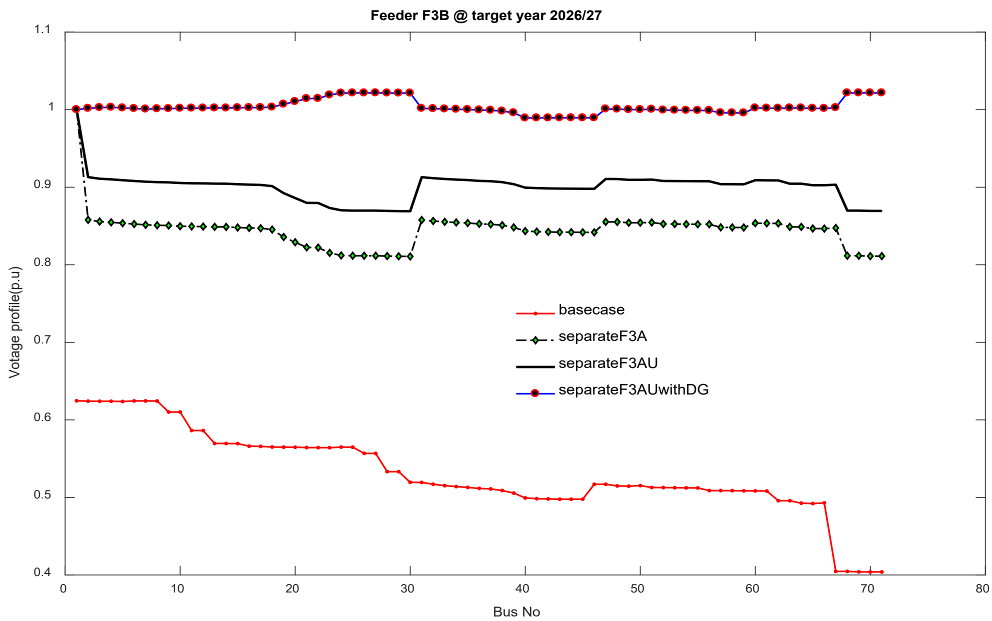

Figure 2. Voltage Profile of separated feeder F3B for different cases

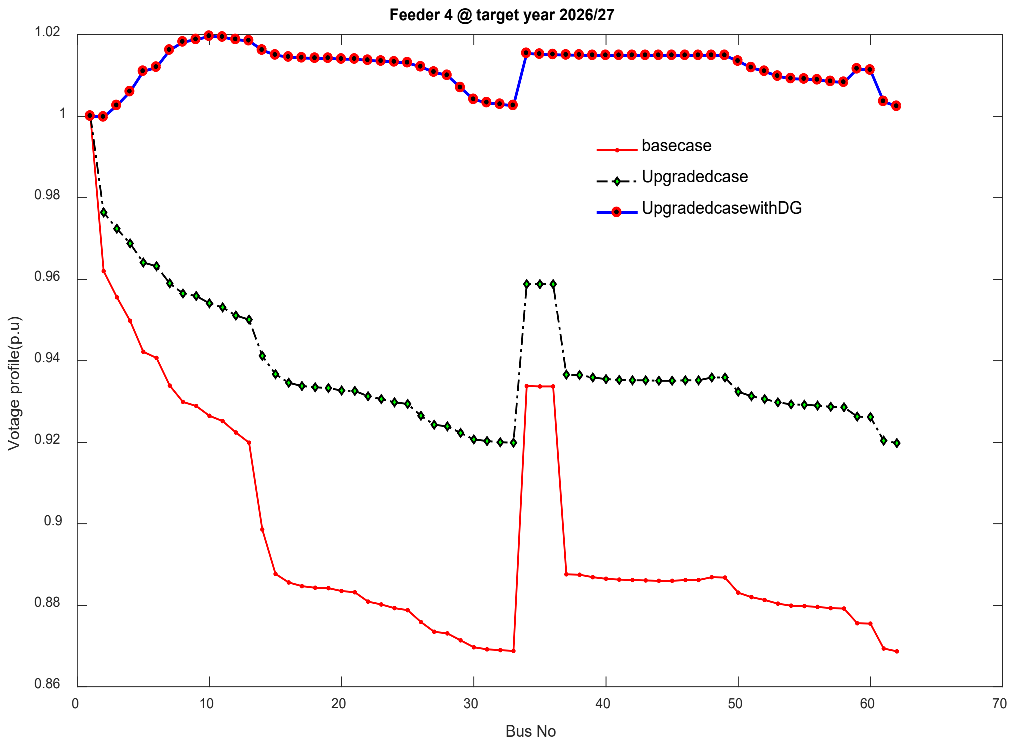

Figure 3. Voltage Profile of feeder F4 for different cases

E. Performance Comparison of PSO with GA and HSA

GA and HSA are selected for comparison since they are more popular in DG sizing and placement in electrical networks due to their ability to obtain fast convergence and easy implementation as PSO and the comparison of voltage profiles of separated upgraded feeders

F3A, F3B and F4 by utilizing these optimization techniques for DG sizing and placement with the appropriate penetration level is presented in the following figures.

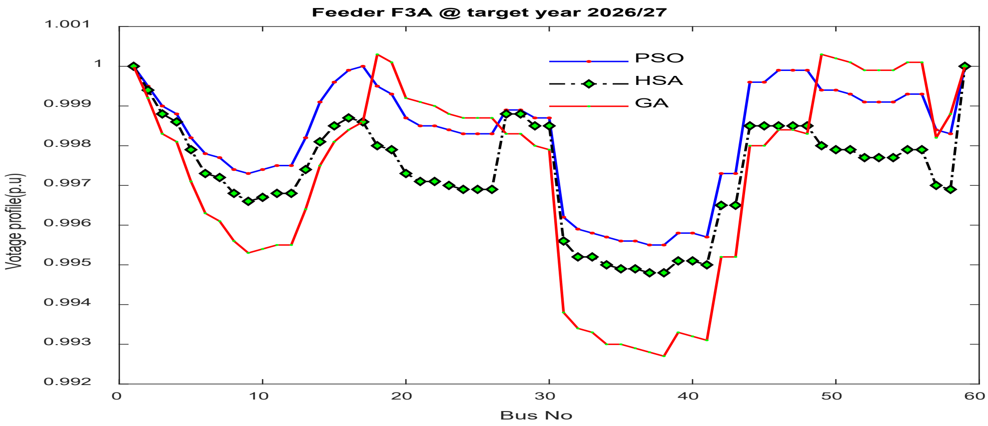

Figure 4. Voltage profile of separate upgraded feeder F3A for PSO, GA and HAS

As the result shown in figure 4, PSO optimization technique resulted the best voltage profile than GA and HSA for feeder F3A after the distribution network is expanded and incorporated with optimally sized and placed DG for the targeted year, 2026/27.

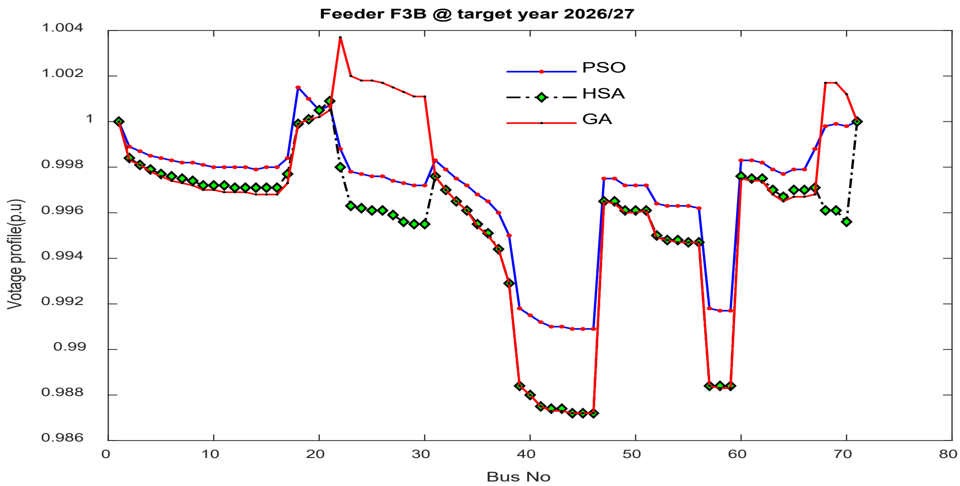

Figure 5. Voltage profile of separate upgraded feeder F3B for PSO, GA and HAS

Figure 5 presented the voltage profiles obtained by various optimization techniques for separate upgraded feeder F3B. As the result shown in figure 5, PSO optimization technique resulted the best voltage profile than GA and HSA for feeder F3B after the distribution network is expanded and incorporated with optimally sized and placed DG for the targeted year, 2026/27.

Figure 6. Voltage profile of separate upgraded feeder F4 for PSO, GA and HAS

As the result shown in figure 6, PSO optimization technique resulted the best voltage profile than GA and HSA for feeder F4 after the distribution network is expanded and incorporated with optimally sized and placed DG for the targeted year, 2026/27. The comparison of results indicated that the proposed PSO based optimization technique is effective for solving the problem of optimal placement and sizing with the proper penetration level of distributed generation than the above-mentioned optimization methods.

6. Conclusion

In this thesis, electrical load demand forecasting, backward-forward sweep load flow analysis, distribution network expansion planning, and optimal DG penetration level determination for the proper size and placement of DG using PSO to improve the power loss and voltage deviation of the radial Debre Markos distribution feeders have been conducted and the promising results are obtained. In this work, feeder separation, upgrading the components and incorporating DG with proper penetration level are conducted using PSO.

In this work, incorporation of DG unit in Debre Markos distribution feeders considering its penetration limit is prominent due to the benefits including reducing power losses, improving voltage profiles and improving power quality. The optimal selection of nodes for the placement and size of the DG with its optimal penetration level is obtained using PSO technique and voltage profile improvement and power loss reduction is analyzed in a detailed manner. The application of PSO for DG sizing, DG placement and DG penetration determination, efficiently minimize the total power loss and total voltage deviation of the objective function satisfying constraints.

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