

A new algorithm is employed for the efficient allocation of distributed generation resources

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ABSTRACT

The bat algorithm (BA) has emerged as a promising meta-heuristic approach, demonstrating its efficiency in tackling diverse optimization problems across the areas such as engineering design, issues with economic load dispatch, power and energy systems, image processing, and medicinal applications. Due to its potential to increase grid resilience, decrease greenhouse gas emissions, and increase energy efficiency, the incorporation of distributed generation (DG) into contemporary power systems has drawn a lot of interest. This paper presents technique for the optimal allocation of DG units, aiming to address existing challenges and improve the overall performance of the power system. The proposed BA technique combines advanced optimization algorithms with comprehensive power system modelling to identify the optimal locations and capacities for DG installation. Key factors are taken into account to formulate a multi-objective optimization problem that includes minimizing power losses, enhancing voltage stability, and minimizing the environmental impact while considering economic feasibility. The algorithm is applied on standard IEEE 33 and 69 bus systems as test cases and a result has been discussed.

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1. INTRODUCTION

With the ever-increasing demand for electricity and the growing concerns about environmental sustainability, the integration of distributed generation (DG) has emerged as a promising solution for modern power systems. DG refers to small-scale power generation units, often based on renewable energy sources that are connected to the distribution network. These decentralized generators offer numerous benefits, including enhanced grid resiliency, reduced transmission losses, and lowered greenhouse gas emissions. However, to harness the full potential of DG and ensure its seamless integration into the existing power infrastructure, an efficient and optimal allocation strategy is imperative. Traditionally, the allocation of DG units in power distribution networks has been approached using conventional methodologies that rely on simplified assumptions and pre-defined heuristics. While these methods may yield satisfactory results under certain conditions, they often fail to address the complex and dynamic nature of today's power systems. Factors such as variable energy demands, uncertain renewable energy resources, and evolving load patterns necessitate innovative approaches that can adapt and optimize DG allocation in real-time.

DG is the processes of producing electricity at the distribution end utilizing sources that emit little or no carbon dioxide [1]. Although DG as a concept is not new, some users have used their own generating systems for years. However, due to a number of worrying circumstances, DG has gained momentum recently

to fulfil the rising electricity demands [2]. These include concerns with network reliability, escalating power quality disturbances, rising technical and commercial losses, and environmental degradation. The efficiency, dependability, and cost-effectiveness of DG have increased because to advancing technical knowledge, a competitive electric market, the use of power electronics devices, and the advent of novel distributed power technologies like fuel cells and micro-turbines. Finding the ideal placement and size for DGs is the main goal of research on DG installation in the distribution system. This optimization seeks to better voltage profiles of crucial buses, save costs, and increase overall system reliability [3]. The genetic algorithm [4], particle swarm optimization (PSO) [5], ant colony optimization [6], analytical methods [7], and simulated annealing [8] are only a few of the algorithms that have been suggested to solve the DG allocation problem. These algorithms are still developing, but they have produced encouraging results. Multi-objective functions have been used to address the concerns around cost, dependability, and power quality that are becoming increasingly complicated [9], [10]. Nature-inspired algorithms have shown greater promise in resolving challenging issues. This led to the development of various bio-inspired heuristic algorithms, such as PSO [5], artificial bee colony [11], and cuckoo search algorithm [12]. The bat-inspired algorithm, a new population-based, gradient-free, meta-heuristic algorithm, is introduced in this paper [13]. This program, which takes its cues from the echolocation technique used by microbats, has showed promise in effectively resolving challenging issues.

The bat-inspired algorithm is used in the paper to evaluate the ideal placement and size of DGs on an IEEE 33 and IEEE 69 bus systems. Simulation findings show that the bat algorithm offers better-quality solutions with greater precision. Six sections make up the organization of the paper: i) The analytical modelling is formulated in section 2; ii) Section 3 that provides a detailed description of the bat-inspired algorithm for optimal DG placement and sizing; iii) Section 4 that presents the IEEE 33 and IEEE 69 bus radial system as a base case and presents the simulated results; and iv) Section 5 brings the study to a close.

2. ANALYTICAL METHOD

The primary objective of this paper is to determine the most suitable location and capacity of distributed generation, taking into account multiple objectives and constraints. In this section, we present the mathematical formulation of the objective function. The minimization of real power loss and the maximization of the voltage stability index in a radial distribution system include the mathematical representation of the goal function in this study. In order to ensure the stability of the system, the voltage restrictions of the system are also taken into account. The weight approach is used to reduce multi-objective functions (MOF) into a single objective function. The following is how the objective function is stated:

- Minimize: Weighted sum = $\alpha * \text{Real power loss} + \beta * \text{Voltage stability index}$
- Subject to: Voltage limits constraints
- Minimum,

$$f = w_1 f_1 + w_2 f_2 \quad (1)$$

Where f_1 represents the total real power losses and f_2 represents the voltage stability index. While w_1 and w_2 are weight factors assigned to the objective function.

$$\min f = w_1 f_1 + w_2 f_2 \\ \sum_{k=1}^n (w_k) \text{ and } 0 < w_k < 1 \quad (2)$$

Selection of weighting factors values vary from utility to utility. The utility assigns varying weighting factors to each objective function based on its importance, taking into account factors such as fuel cost, technology used, environmental concerns. In this particular scenario, real power losses are deemed more critical and are given a higher weighting factor of 0.7, while the voltage stability index (VSI) is considered relatively less crucial and assigned a weighting factor of 0.3.

Power losses: The objective function for calculating the total real power losses at all nodes in the distribution network due to circulating currents caused by the substation and DGs is expressed as (3). Objective Function 1 (f_1):

$$f_1 = p_{L(DG)} / P_L \quad (3)$$

Where: P_L represents the total real power losses in the distribution network before the connection of DGs. P_L represents the total real power losses in the distribution network after the connection of DGs. Power losses after DG connection are expressed as (4).

$$PL(DG) = \sum I_m R_m \quad (4)$$

Where I_m is the magnitude of current which is calculated by load flow analysis and R_m is line resistance.

Voltage stability index: Buses in the distribution system that are farther removed from the substation are assessed for vulnerability using the voltage stability index (VSI). These remote buses are more vulnerable to suffering considerable voltage drop since the distribution system has a radial structure, making them susceptible to voltage collapse. The VSI approach suggested by Chakravorty and Das [14] is used to locate and rank these buses.

$$I_{ri} = \frac{V_{si} - V_{ri}}{R_{ri} + jX_{ri}} \quad (5)$$

$$P_{ri}(ri) - jQ_{ri}(ri) = V_{ri} * I_{ri} \quad (6)$$

$$VSI(ri) = |V_{si}|^4 - 4[P_{ri}(ri)R_{ri} + Q_{ri}(ri)X_{ri}][V_{si}|^2 - 4[P_{ri}(ri)R_{ri} - Q_{ri}(ri)X_{ri}]^2 \quad (7)$$

V_{si} is the voltage of sending end node whereas V_{ri} , P_{ri} , Q_{ri} , R_{ri} , and X_{ri} are receiving end node voltage, reactive power, resistance and impedance respectively.

The enhancement of the voltage stability index (VSI) concerning the given objective function can be expressed as (8). Maximize: VSI improvement.

$$f_2 = \frac{1}{\min(VSI(ri))}; r_i = 2, 3, \dots, r_r \quad (8)$$

Constraints: The integration of DG into the distribution network can lead to reverse power flow and inrush currents, resulting in voltage rise at various buses [15]. To ensure the voltage magnitude remains within acceptable limits for all scenarios and with each algorithm used, the voltage constraints must be maintained. Therefore, the voltage magnitude constraints at each bus can be expressed as (9). For each bus 'i' in the distribution network, the voltage magnitude (V_i) should satisfy the following conditions.

$$|V_i|^{min_i^{max}} \quad (9)$$

Where: V_{min} is the minimum allowable voltage magnitude at bus 'i'; V_{max} is the maximum allowable voltage magnitude at bus 'i'; These constraints are essential to prevent over voltage or under voltage conditions and maintain a reliable and stable distribution system after the integration of DG.

In this scenario, the voltage magnitude constraints are set to ensure the power system equipment operates within allowable variations of $\pm 5\%$ to $\pm 10\%$ of the rated voltage. Therefore, the minimum and maximum allowable voltage magnitudes (V_{min} and V_{max}) are specified as: $V_{min} = 0.95$ pu and $V_{max} = 1.05$ pu. In this simulation, the DG units are discrete in nature, meaning they are available in specific capacity levels with 100 KW increments [16]. The capacity of DG units is dependent on various factors, including the availability of the energy source, technology employed, and the local conditions at the installation site. As a result, DGs are considered to have discrete values, and their capacity is represented in steps of 100 KW during the simulation.

The solutions for all the DG units are constrained by minimum and maximum limits for real and reactive power [17], expressed as (10). For real power (P_{DG}).

$$P_{DG}^{min_{DG}} \leq P_{DG} \leq P_{DG}^{max_{DG}} \quad (10)$$

Where: P_{DG}^{min} is the minimum allowable real power output for the DG unit; P_{DG}^{max} is the maximum allowable real power output for the DG unit.

The real power output (P_{DG}) of each DG is limited to the range of 0 to 5 MW. For reactive power (Q_{DG}), expressed as (11).

$$Q_{DG}^{min_{DG}} \leq Q_{DG} \leq Q_{DG}^{var_{max}} \quad (11)$$

Where: Q_{DG}^{min} is the minimum allowable reactive power output for the DG unit; Q_{DG}^{max} is the maximum allowable reactive power output for the DG unit.

The reactive power output (Q_{DG}) of each DG is restricted to the range of 0 to 1 Mva. Explaining research chronological, including research design, research procedure (in the form of algorithms and

pseudocode), how to test and data acquisition [18], [19]. The description of the course of research should be supported references, so the explanation can be accepted scientifically.

3. PROCEDURE FOR PROPOSED ALGORITHM

Based on how bats use echolocation for navigation, the bat (bat method) is an optimization method inspired by nature. It is frequently employed to resolve optimization issues, such as deciding how to best distribute DG units in power distribution networks [20]. The BA for the best DG allocation is implemented in the following steps:

- Step 1: Initialization
Define the problem variables: Determine the decision variables that represent the allocation of DG units. These variables include the location, capacity, and type (e.g., solar and wind) of DG units. Set algorithm parameters: Initialize the algorithm parameters, such as the population size (number of bats), maximum generation, pulse rate, loudness, and wavelength.
- Step 2: Create initial population
Generate an initial population of bats: Randomly create a set of solutions (bat positions) for the decision variables, representing the initial allocation of DG units.
- Step 3: Evaluate fitness function
Calculate each bat's fitness value based on an objective function to determine their level of fitness. Combining minimising power losses, enhancing voltage stability, maximising renewable energy integration, and taking economic factors into account might be the aim function.
- Step 4: Update bat positions
Update bat positions: Update the positions of each bat based on their current position and the best position found so far. The new position represents a potential solution for the allocation of DG units.

$$f_i = f_{minmax_{min}} \quad (12)$$

$$v_i^t = v_i^{t-1} + (x^t - x_*) * f_i \quad (13)$$

$$x_i^t = x_i^{t-1} + v_i^t \quad (14)$$

- Step 5: Explore and exploit
Explore: With a certain probability (epsilon), allow some bats to explore new solutions by random exploration of the search space. Exploit: With a certain probability (alpha), encourage some bats to focus on the best solutions found so far and refine their positions accordingly.
- Step 6: Loudness and pulse rate update
Update the loudness and pulse rate of each bat based on their fitness and iteration number. The loudness and pulse rate control the magnitude and rate of the bat's echolocation behavior, respectively.
- Step 7: Evaluate new solutions
Evaluate the fitness of the new bat positions: Calculate the fitness of the updated bat positions using the objective function.
- Step 8: Update best solution
Update the best solution: Keep track of the bat with the best fitness value (optimal allocation) found so far.
- Step 9: Termination criteria
Check termination criteria: Decide whether to stop the algorithm based on a predefined stopping criterion, such as reaching a maximum number of iterations or achieving a satisfactory solution.
- Step 10: Output the optimal allocation
Output the best solution: Once the termination criteria are met, output the best allocation of DG units that was found during the optimization process.
- Step 11: Post-processing and analysis
Analyse the results: Perform post-processing and sensitivity analysis to assess the impact of the DG allocation on the power system's performance and make any necessary adjustments.
- Step 12: Fine-tuning (optional)
If required, fine-tune the algorithm parameters to improve convergence and solution quality. By following this procedure, the bat algorithm can efficiently explore the search space and identify an optimal allocation of DG units that satisfies multiple objectives and constraints for the power distribution network [21].

4. RESULTS AND DISCUSSION

4.1. Test case-1: Standard IEEE 33 bus system

We are considering the information of the standard IEEE 33 bus system. The major goals of the objective function are to reduce actual power loss and enhance the system's voltage profile. The impact of type-1 and type-3 DG [22], [23] placement on the actual power loss of the 33-bus system is shown in Table 1. It can be seen from Table 1 that type-3 DGs have a large real power loss. When using type-1 DGs and type-3 DGs, the BA achieves a loss reduction success rate of 64.7% and 92.94%, respectively. For all algorithms, the minimum voltage with type-1 DGs is the same, or around 0.972 per unit, while the minimum voltage with type-3 DGs is about 0.9943 per unit. Correction of the voltage profile for the 33-bus using type-1 and type-3 DGs presented in Figures 1 and 2.

Table 1. Results of 33 bus system with type-1 DGs and type 3 DGs

Method	Optimal locations	Optimal DG size	P _{loss} without DG	P _{loss} with DG	Loss reduction in %	V _{min} in P.U	Simulated time
BA (type 1 DG)	24	1.3966	210.78 KW	74.387 KW	64.7	0.9719	9.643
	13	0.8192					
	30	1.1333					
BA (type 3 DG)	24	0.8558	210.78 KW	16.0933 KW	92.3	0.9880	8.238
	15	1.200					
	30	0.6442					

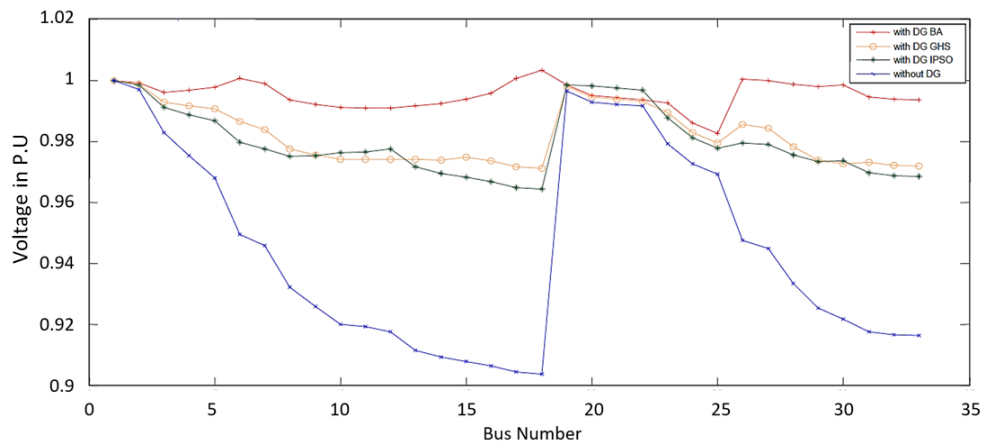


Figure 1. Voltage profile correction of 33 bus system with type-1 DGs

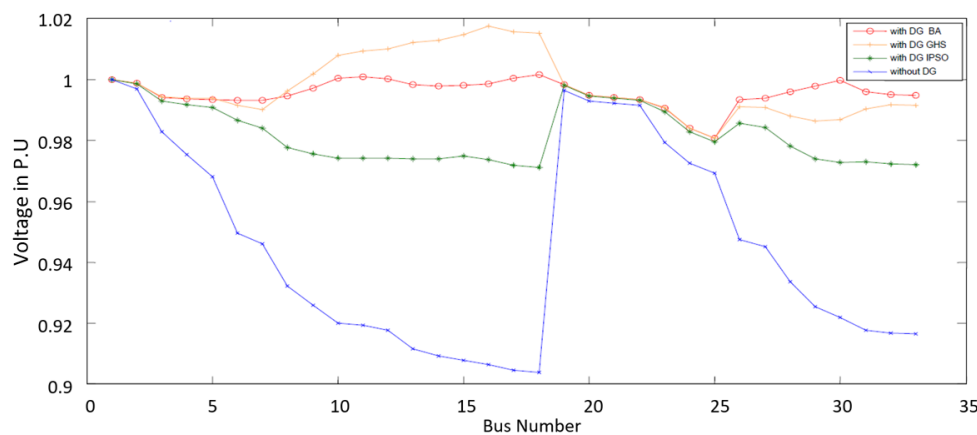


Figure 2. Voltage profile correction of 33 bus system with type-3 DGs

It is clear from Figure 2 that type-3 DGs have allowed for the maximization of voltage profiles. The solution provided by the BA algorithm has resulted in the largest voltage profile improvement feasible. It is

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clear from the convergence characteristics [24] of the BA algorithm shown in Figures 3 and 4 that the algorithm was successful in minimizing the objective function. Compared to other methods, the BA algorithm found the best solution after a very small number of iterations. That is how the BA algorithm, using type-1 DGs, reached the better answer at the sixth generation. At the fifth generation, BA found the best solution using Type-3 DGs.

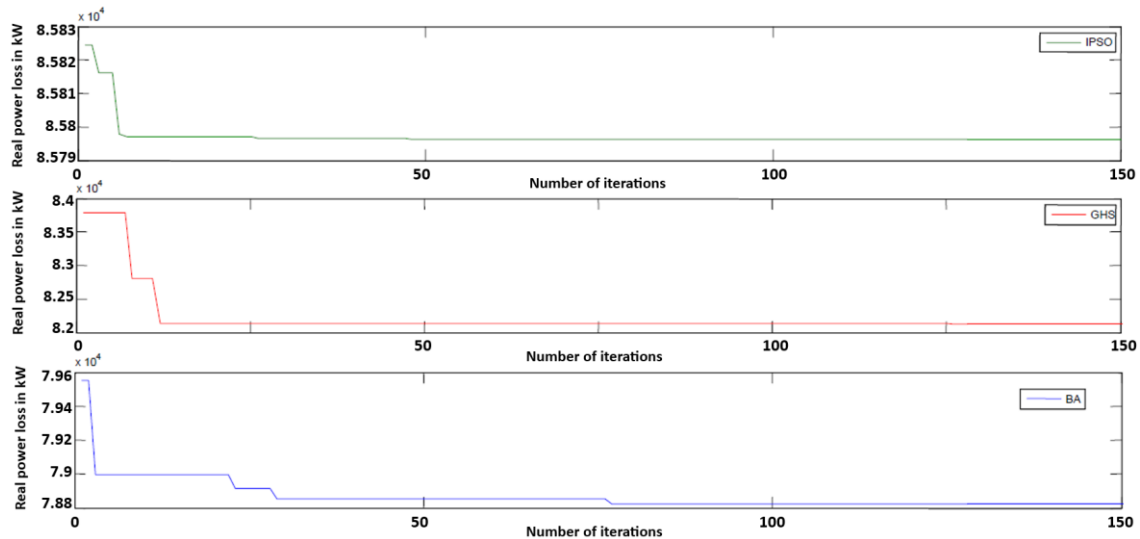


Figure 3. Convergence characteristics for 33 bus system with type-1 DGs

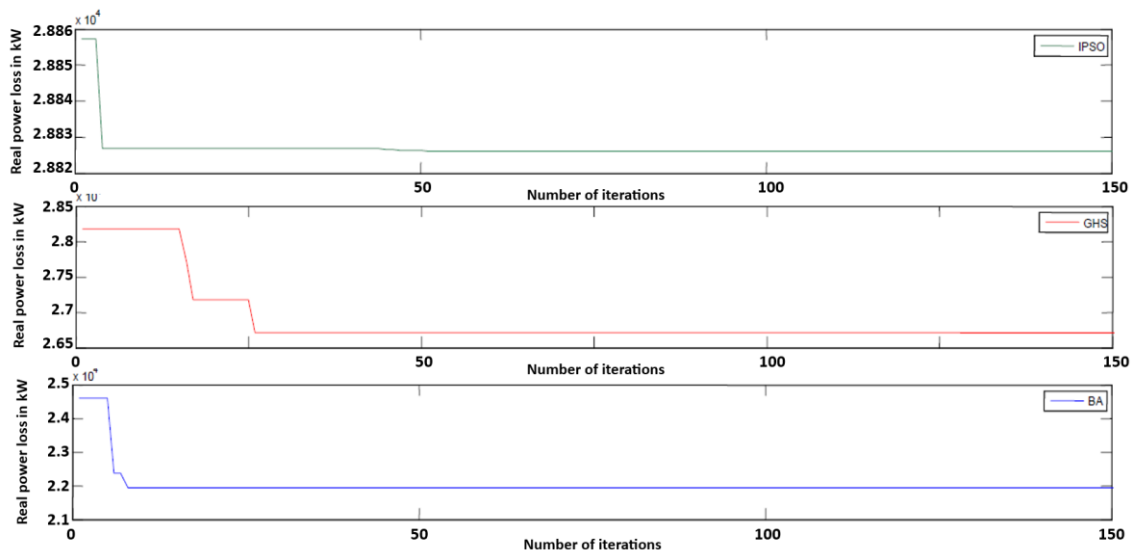


Figure 4. Convergence characteristics for 33 bus system with type-3 DGs

4.2. Test case-2: Standard IEEE 69 bus system

From the case-1 results that type-3 DGs are the only ones capable of maximizing voltage profile and minimizing real power loss. Additionally, it has been observed that giving the voltage deviation index top priority in a multi-objective function results in a superior voltage profile than when a single target is regarded as the actual power loss minimization. Therefore, for case-2, the simulation only takes into account type-3 DGs. Table 2 lists the ideal locations [25] and sizes for DGs, real power loss, loss reduction percentage [26], and simulation duration for the suggested approach.

Table 2. Results of 66 bus system with Type-1 DGs and type 3 DGs

Method	Optimal locations	Optimal DG size	P_{loss} without DG	P_{loss} with DG	Loss reduction in %	V_{min} in P.U	Simulated time
Bat (type3 DG)	61	1.7994 MW, 1.1152 MVAR	224.719 KW	6.5672 KW	97.07	0.9943	20.94
	68	0.3508 MW, 0.2174 MVAR					
	18	0.4998 MW, 0.3098 MVAR					

Table 2 shows that in this instance, the BA algorithm was successful in attaining the intended purpose. With the suggested algorithm, there is a large real power loss decrease, or about 97%. With the suggested algorithm, an improvement in the voltage profile has been made [27]. This means that the type-3 DGs' minimum voltage is 0.9943 p.u. It is clear from the findings that BA algorithm performed well, and it took 20.26 sec to arrive at a better answer. Figure 5 shows the convergence characteristics of the BA and algorithm for the radial distribution system of 69 buses, and Figure 6 shows the correction of the voltage profile using type-3 DGs for the same system. Figure 6 shows that BA is convergent at the sixth generation.

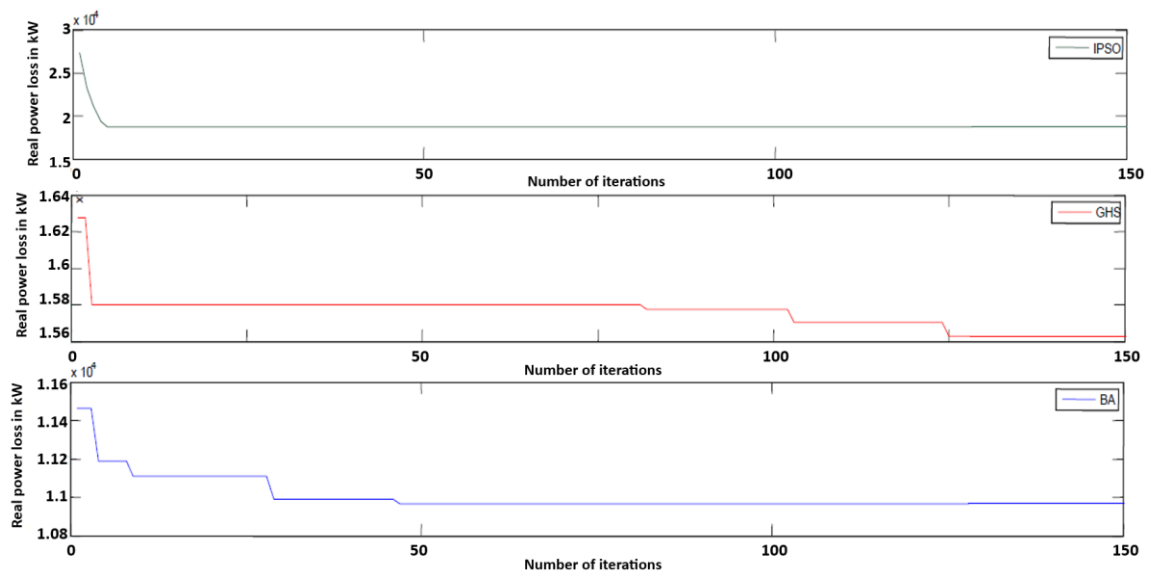


Figure 5. Convergence characteristics for 69 bus system with type-3 DGs

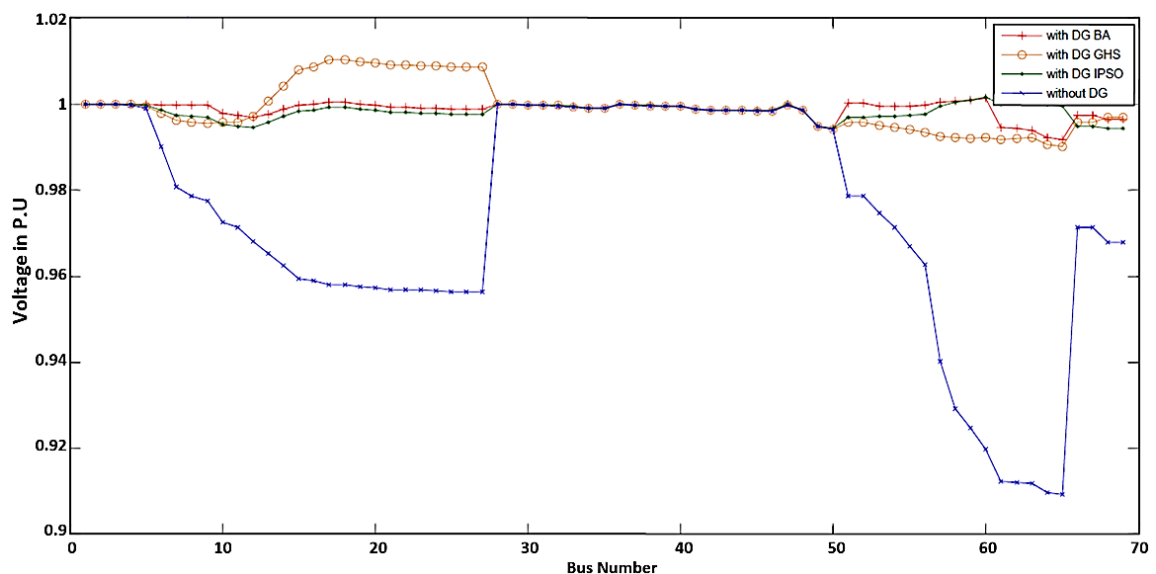


Figure 6. Voltage profile correction of 69 bus system with type-3 DGs

5. CONCLUSION

BA offer powerful optimization technique for addressing the complex problem of optimal allocation of DG units in power distribution networks. Each algorithm brings its unique strengths and characteristics, making them valuable tools for different scenarios and problem settings. The bat algorithm, inspired by the echolocation behavior of bats, demonstrate an efficient and adaptive nature for global optimization. Its ability to balance exploration and exploitation through echo loudness and pulse rate makes it particularly effective in dealing with dynamic and uncertain environments. BA's random exploration capability allows it to escape local optima and discover promising solutions, while the exploitation component helps it converge towards the optimal solution over successive iterations. Furthermore, the bat algorithm's simplicity and fewer algorithm parameters make it easier to implement and fine-tune.




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