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ORIGINAL ARTICLE

Designing a Smart Distribution Network for Voltage Stability and Loss Minimization Using AI Algorithms

Moaiad Mohseni[a*], Abbas Hakimnezhad[b]

[a] Instructor, Khuzestan Regional Electric Company, Ahvaz, Iran.
[b] MSc, Khuzestan Regional Electric Company, Ahvaz, Iran.

[*]Corresponding Author E-mail Address: moaiadmohsenii@gmail.com

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Abstract

Due to the vast scale of power systems and the complexity of classical optimization methods, these types of approaches generally lack the necessary efficiency in power system analysis and fail to deliver satisfactory performance. The shortcomings of classical methods have, in recent years, pushed planners to investigate and explore metaheuristic methods. These algorithms have demonstrated greater efficiency in determining optimal structures compared to classical methods, thus attracting the attention of many researchers. In this paper, the Harmony Search Algorithm (HSA) is employed to develop the distribution network in a 9-bus system. Various scenarios, such as different generation and consumption states, energy price fluctuations, load consumption variations, and uncertainties, are examined, and in each case, the optimal development plan is obtained using the proposed algorithm. To assess the efficiency of the proposed algorithm, the results obtained from the simulation are compared with the Particle Swarm Optimization (PSO) algorithm. The simulation results demonstrate the capability and effectiveness of the proposed planning approach in addressing uncertainties within the electricity market environment.

Keywords: Harmony Search Algorithm, Particle Swarm Optimization Algorithm, Distributed Generation, Distribution Network Development Plan.

1. Introduction

In recent decades, significant changes have occurred in the management and ownership of power systems, driven by increased efficiency and investor incentives. To create a competitive market, different segments of the power system, including generation, transmission, and distribution, have been decentralized and restructured. In these restructured power systems, all participants aim to maximize their profits, and in doing so, they utilize various planning methods and components. One of the most important components in restructured systems is Distributed Generation (DG). DGs can address issues related to network development, loss reduction, reliability enhancement, voltage profile improvement, and more. Therefore, power system operators are inclined to install DG units within the network. Distributed generation technologies are typically flexible in terms of operation, size, and scalability. Moreover, their application in power systems leads to greater flexibility in electricity pricing and system performance (Ackermann et al., 2001). Regarding DGs, the primary issue lies in the modeling of DGs in conventional power flow formulation. This issue has been addressed in (Eminoglu & Hocaoglu, 2005), where a useful list of DG models and an unbalanced three-phase power flow algorithm for radial distribution networks with DGs is presented. In addition, DGs have been examined from various perspectives, such as their impact on the energy market (Vahl et al., 2013), their effects on stability, losses, and voltage (Esmaili et al., 2014), network reconfiguration with DG integration (Bernardon et al., 2014), DGs and islanding issues (Khamis et al., 2013), and their impact on system reliability (Borges, 2012). DGs have also been extensively studied

in conjunction with distribution network development planning. Distribution network development planning is defined as the process of determining the location and type of new lines, as well as the size and location of new transformers (Ravadanegh & Roshanagh, 2014; Sedghi et al., 2013). A review of the methods developed for distribution network development planning is presented in (El-Khattam et al., 2005; Zamora et al., 2012), where various approaches are compared. Reference (Mikic, 1986) provides a static model for distribution network development planning in the presence of DGs, including the location and type of lines, protective devices, and relays. Multi-level distribution network development planning, considering DG units, is presented in (Haffner et al., 2008). Planning for distribution network development, taking into account DGs for peak shaving, is presented in (Ouyang et al., 2010), where the goal is to minimize the total cost of new lines, DGs, and losses. The impact of DG uncertainty on distribution network planning is discussed in (Zeng et al., 2012). Multi-level development planning and unit commitment (UC) for distribution networks using the Artificial Bee Colony (ABC) algorithm is provided in (El-Zonkoly, 2013). Distribution system development planning using dynamic programming and genetic algorithms is solved in (Carrano et al., 2008).

In this paper, the Harmony Search Algorithm (HSA) is employed to develop the distribution network in a 9-bus system. Various scenarios, such as different generation and consumption states, energy price fluctuations, load consumption variations, and uncertainties, are examined, and in each case, the optimal development plan is obtained using the proposed algorithm. The simulation results demonstrate the capability and effectiveness of the proposed planning approach in addressing uncertainties within the electricity market environment.

The remainder of the paper is organized as follows: Section 2 formulates the problem, Section 3 explains the Harmony Search Algorithm, Section 4 presents the proposed development planning, Section 5 provides simulation results, and finally, Section 6 concludes the paper.

2. PROBLEM FORMULATION

Distribution network development planning can be formulated as follows:

$$\min v = IC + OC \quad (1)$$

$$V_{\min} \le V \le V_{\max} \quad (2)$$

$$0 \le S_i^{ss} \le S_{i-cap}^{ss} \quad (3)$$

$$S_j^{FD} \le S_{j-cap}^{FD} \quad (4)$$

$$S_k^{DG} \le S_{k-cap}^{DG} \quad (5)$$

$$radial \quad structure = 1 \quad (6)$$

Equation (1) represents the objective function of the planning process in terms of dollars per year. The proposed objective function consists of two terms: IC and OC. The first term, IC, represents the annual cost of the installed or upgraded components and is defined as follows:

$$IC = C_{RF}\left(\sum_{i\in s} IC_i^{ss} + \sum_{j\in F} IC_j^{FD} + \sum_{k\in G} IC_i^{DG} \times S_{k-cap}^{DG}\right) \quad (7)$$

Where C_{RF} represents the discount factor used to convert all costs to the same year, IC_i^{ss} indicates the fixed cost of distribution substation j in dollars, IC_j^{FD} represents the investment cost for feeder j in dollars, IC_j^{DG} represents the investment cost for DG j in dollars per MVA, and S_{k-cap}^{DG} is the total capacity of DG k in MVA. The second term, OC, represents the annual operating cost of the system, depending on power purchases from the grid and the power generated by the DG units. This term is expressed as follows:

$$OC = \sum_{t\in T} T_t\left(\sum_{k\in G} OC_k^{DG} \times P_{k-t}^{DG} + \sum_{i\in s} EC_{i-t}^{ss} \times P_{i-t}^{ss}\right) \quad (8)$$

Where T_t indicates the duration of the load level in hours, OC_k^{DG} represents the operating cost of DG k in dollars per MWh, P_{k-t}^{DG} indicates the power generated by DG k at load level t in MW, EC_{i-t}^{ss} represents the base market price of electricity at the substation during load level t in dollars per MWh, and P_{i-t}^{ss} represents the real power dispatched from substation j at load level t in MW.

The planning constraints are also shown in equations (2) to (6). Equation (2) represents the voltage limits, (3) shows the apparent power limits, and the maximum feeder capacities are defined by (4) and (5),

specifying the DG capacities. Constraint (6) ensures the radial structure of the network expansion is maintained. In this context, the radial constraint must be satisfied for each development plan; otherwise, the proposed plan will be discarded.

It should be noted that in this paper, it is assumed that the ownership of DGs belongs to the utility company and is not dependent on independent power producers. In other words, the network operator aims to minimize the cost of investing in new lines and DG units while simultaneously owning both the DGs and the network components.

3. HARMONY SEARCH ALGORITHM

The Harmony Search Algorithm (HSA) is a population-based metaheuristic search algorithm introduced in (Geem et al., 2001; M'zoughi et al., 2018; Mohsin et al., 2018). In (Das et al., 2011), the Exploratory Harmony Search (EHS) algorithm was proposed for benchmarking, which has been successful in many problems. HSA is inspired by the natural phenomenon of musicians striving to achieve a harmonious sound (optimal solution) when they play together with their instruments (population members). This state is represented by a subtle standard (fitness function). The HS algorithm is simple in concept, has fewer parameters, and is easy to implement. It has also been applied to real-world problems, such as the traveling salesman problem (Geem et al., 2005). The main steps of HS are described in (Geem et al., 2001).

- Step 1: Initialize the problem and algorithm parameters
- Step 2: Initialize the harmony memory
- Step 3: Create a new harmony
- Step 4: Update the harmony memory
- Step 5: Check the termination criterion

These steps are explained in the following five subsections:

3.1. Initialization of the problem and algorithm parameters

The main optimization problem is given as follows:

$$\begin{aligned} &Minimize\ F(x) \\ &\text{Subject to } x_i \in X_i, i = 1,2,\dots,N \end{aligned} \quad (9)$$

Here, F(x) is the objective function, xi is the set of decision variables, N is the number of decision variables, and xi is the set of possible values for each decision variable, which is represented as, $lx_i \le X_i \le ux_i$ where lx_i and ux_i are the lower and upper bounds of each decision variable, respectively.

In this step, the HS parameters are specified, including the harmony memory size (HMS), the number of solution vectors in the harmony memory, the harmony memory considering rate (HMCR), the pitch adjustment rate (PAR), the number of improvisations (NI), and the stopping criterion. The harmony memory (HM) is a memory location where all solution vectors are stored. Here, HMCR and PAR are parameters used to improve the solution vector, as defined in Step 3.

3.2. Initialization of the Harmony Memory

In this step, the harmony memory (HM) matrix is filled with solution vectors randomly generated, similar to the harmony memory size (HMS).

$$HM = \begin{bmatrix} x^1{}_1 & x^1{}_2 & \dots & x^1{}_{N-1} & x^1{}_N \\ x_1{}^2 & x_2{}^2 & \dots & x^2{}_{N-1} & x^2{}_N \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1{}^{HMS-1} & x_2{}^{HMS-1} & \dots & x_{N-1}{}^{HMS-1} & x_N{}^{HMS-1} \\ x_1{}^{HMS} & x_2{}^{HMS} & \dots & x_{N-1}{}^{HMS} & x_N{}^{HMS} \end{bmatrix} \quad (10)$$

3.3. Creating a New Harmony

A new harmony vector is created as $\overrightarrow{x} = (x'_1, x'_2, \dots, x'_N)$ and is generated based on three rules:

1- Memory consideration
2- Pitch adjustment
3- Random selection

The process of generating a new harmony is called improvisation. HMCR is a variable between 0 and 1, which defines the rate of selecting a value from the historical values stored in HM, while (1−HMCR) represents the rate of randomly selecting a value from the possible range, as shown in equation (11).

$$\begin{aligned} &if\ (rand() < HMCR) \\ &x_i^{'} \in \{x_i^{1}, x_i^{2}, \dots, x_i^{HMS}\} \rightarrow x_i^{'} \\ &else\ x_i^{'} \in X_i \rightarrow x_i^{'} \end{aligned} \quad (11)$$

Here, rand() represents random numbers uniformly distributed between 0 and 1, and x_i is the set of possible values for each decision variable, represented as $lx_i \le X_i \le ux_i$. For example, an HMCR value of 0.85 indicates that the Harmony Search Algorithm (HSA) will select the decision variable from the historical values stored in HM with an 85% probability, and from the entire possible range with a 15% probability. Each component

obtained is evaluated by considering the memory. To indicate that the pitch has been adjusted, this action is applied at the pitch adjustment rate as follows:

$$if\ (rand() < PAR)$$
$$x_i^{'} = x_i^{'} \pm rand() * b\omega \qquad (12)$$
$$else\ x_i^{'} \in X_i \rightarrow x_i^{'}$$

Here, bw is a bandwidth parameter used for continuous variable adjustment, and rand() is a uniformly distributed random number between 0 and 1. Since the problem is inherently discrete, bw is taken as 1.

3.4. Updating the Harmony Memory

If the new harmony $\vec{x} = (x_1', x_2', \dots, x_N')$ ، has a better fitness function compared to the worst harmony in the HM, the new harmony is included in the HM, and the worst existing harmony is removed from the HM.

3.5. Checking the Termination Criterion

The HSA terminates when the termination criterion (the maximum number of improvisations) is met. In other words, steps 3 and 4 are repeated.

4. Proposed Development Planning

In this paper, the Harmony Search Algorithm (HSA) is used for optimization, and the optimization results are compared with the Particle Swarm Optimization (PSO) algorithm. It is worth mentioning that distributed generation (DG) sources are modeled as negative loads in the network, and the capacity of the generation sources is considered as an integer value between 1 and 4 MW. The load flow method used is the efficient and fast forward-backward method. To search for the optimal configuration of the distribution network, it is necessary to consider several harmony memories. The size of the harmony memory depends on the designer's and consultant’s needs and equals the required number of DG sources and the candidate lines for network development. Using the Harmony Search Algorithm, we identify the optimal configuration for the network expansion. Additionally, analyzing and considering uncertainties has become essential. Without considering and analyzing these uncertainties, the occurrence of undesirable situations that may challenge the project’s objectives is not unexpected. The Monte Carlo simulation method is used as a tool for the comprehensive and simultaneous analysis of various combinations of uncertainties. In the Monte Carlo method, uncertainty evaluation is performed based on the system's mathematical model, but it is done using the Probability Density Function (PDF) propagation. In this paper, considering a long-term annual load growth rate of 10%, the uncertainty in the distribution network's power consumption and the cost of purchasing electrical power is modeled using normal probability density functions with a variance of 15% for power consumption and energy price, proportional to inflation and bank interest rates. The flowchart of the proposed development plan algorithm is shown in Figure 1.

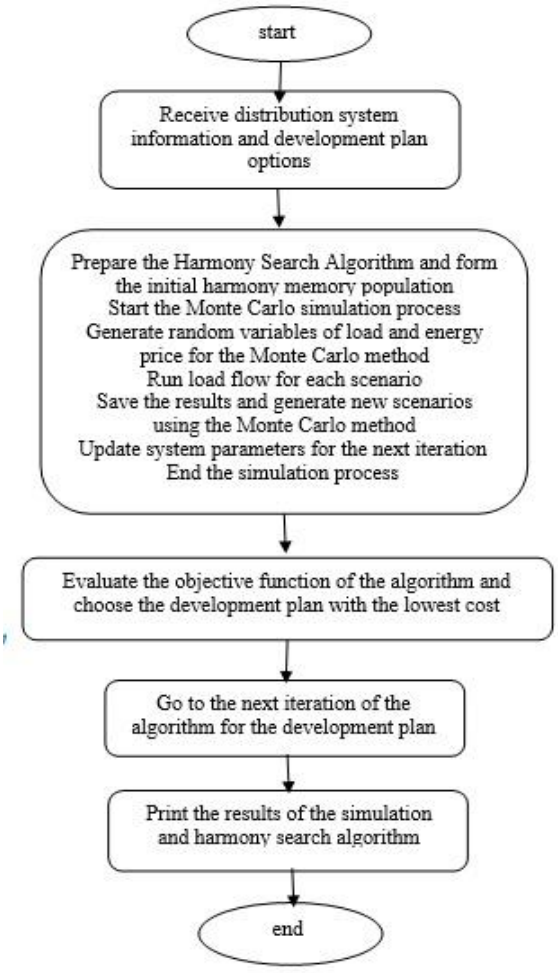


Fig. 1. Flowchart of the Proposed Development Plan Algorithm.

As a result, it can be expected that the optimal configuration of the developed distribution network can be obtained using the Harmony Search Algorithm. To achieve this, by defining scenarios for power and probable energy costs for the network loads with up to 1000 iterations, it is possible to identify

critical load consumption events and network probability indices. Additionally, the load flow results of the network under such probabilistic conditions can be analyzed, thereby improving the reliability of the distribution network development in supplying the optimal load.

5. Simulation Results

Figure 2 shows the linear schematic of the 9-bus network, which consists of 8 distribution buses with a nominal voltage of 33 kV and one sub-transmission bus connected to the distribution network through a distribution substation with a 40 MVA step-down transformer. The network has six power transmission lines, and due to the increased load consumption and the addition of new consumer load points at buses 5 and 7, there is a need for the expansion of distribution lines and additional candidate transformers to supply the load. Accordingly, 12 candidate lines (shown as dashed lines in the figure) and a 40 MVA transformer at bus 10 have been defined to supply the network's load. The network development plan has a time horizon of 10 years with an annual load growth rate of 10%. Considering the variations in the load profile throughout the year, the hourly load and the cost of power purchase are divided into three levels (nominal load, 70% of nominal load, and 50% of nominal load during low demand). The power and cost information for the loads and lines are provided in (Ackermann et al., 2001).

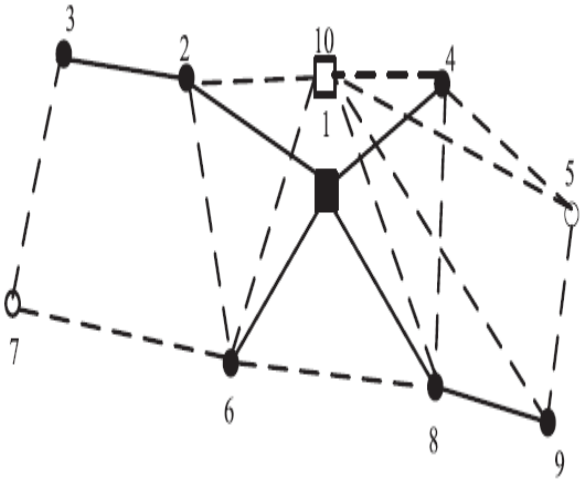


Fig. 2. Schematic of the distribution network under study.

Given the role of distributed generation (DG) in reducing losses and improving the voltage profile, as well as the uncertainty in consumer demand in the distribution network, it is necessary to consider both factors in distribution network development plans. To better evaluate the performance of the proposed algorithm, we will consider the network development plan in two general stages:

Development of the distribution network to supply the load located at bus number 7

Development of the distribution network to supply the load located at bus number 5

We will examine the distribution network development for each of these two cases under conditions of using or not using DG resources, and with or without considering load and cost uncertainties. To assess the performance of the proposed algorithm, we will also carry out optimization using the PSO algorithm and numerically compare and analyze the results of both algorithms.

It is worth noting that the number of optimization variables for the network under study is equal to the total number of existing load buses (for DG capacity) and the number of candidate lines. The population size for both algorithms has been set to 50.

5.1. Distribution Network Development Without Considering Uncertainty and Distributed Generation (Case One)

In the first part of the simulation, we assume that load and cost uncertainties are not considered, and the objective of the optimization is the development of the distribution network to supply the load at bus number 7.

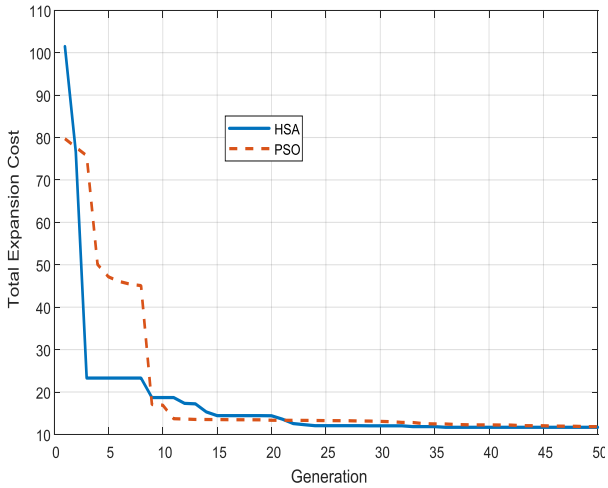


Fig. 3. Convergence graph of the HSA and PSO algorithms (Case One).

TABLE 1. Results of the Distribution Network Development Plan (Case 1)

Development Sources		Development Lines		Development Plan Costs		
HS	PSO	HS	PSO	HS	PSO	
		L_{45}=1	L_{45}=1	4.636	5.044	Feeder Investment Cost
		L_{12}=2	L_{12}=2	0.76	0.888	Substation Investment Cost
		L_{16}=2	L_{16}=3	0	0	DG Investment Cost
		L_{18}=2	L_{18}=3	0	0	Annual Operating Cost of Distributed Generation
				0	0	Annual Power Purchase Cost
				11.2195	16.583	Annual Network Losses Cost
				0.4655	0.507	Total Development Cost
				17.081	23.021	Total Development Plan Cost

We aim to supply the load without adding any distributed generation (DG) sources. The convergence results of the two algorithms, HSA and PSO, are shown in Figure 3. Based on this, the HSA algorithm was able to identify the required transmission line for development faster than the PSO algorithm, achieving this by the 23rd iteration. Both algorithms suggested adding one optimal direct line at a cost of 10.66 million dollars to supply power to bus 7 over a 10-year period with a gradual 10% annual load growth. The majority of this cost was allocated to power purchases. The table of investment cost calculations and power purchase costs is presented as Table 1.

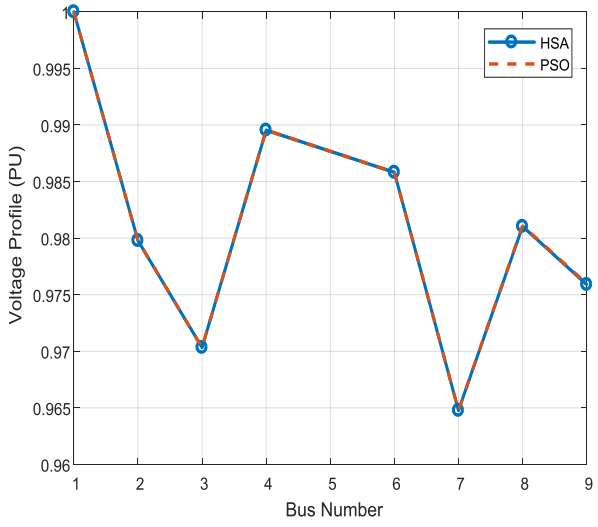


Fig. 4. Voltage Profile Convergence Graph (Case 1).

Based on this, the average voltage profile of the distribution network is shown in Figure 4, where the network voltage decreases by up to 3.5% at bus 7 during the period. This voltage drop is within the permissible standard range.

5.2. Distribution Network Development Without Considering Uncertainty and Generation Sources (Case 2)

In this section, we assume that load and cost uncertainties are not considered, and the optimization goal is the development of the distribution network to supply the load at bus number 5 without considering distributed generation (DG) sources. The convergence results of the two algorithms, HSA and PSO, are shown in Figure 5. Based on this, the HSA algorithm was able to identify the required transmission line for development faster than the PSO algorithm by the 21st iteration. The proposed algorithm suggested adding 7 optimal direct lines at a cost of $17.68 million to supply power to bus 5 over a 10-year period with a gradual 10% annual load growth. The PSO algorithm, however, failed to identify the global minimum and got stuck in a local minimum development cost by the 42nd iteration, remaining trapped until the 50th iteration. As a result, the PSO algorithm proposed a higher total cost compared to the proposed algorithm.

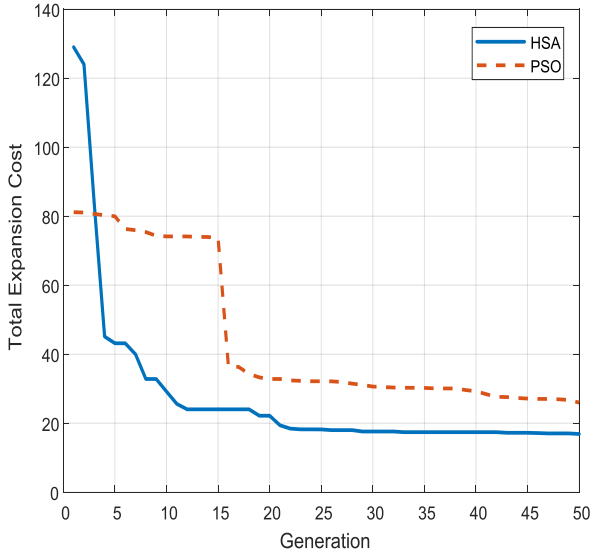


Fig. 5. Convergence graph of the HSA and PSO algorithms (Case 2).

The development plan costs for the two algorithms are presented in Table 2. Based on this, the PSO algorithm has suggested adding 7 parallel lines to connect the network buses in order to balance the line currents within permissible limits under heavy load conditions.

TABLE 2. Results of the Distribution Network Development Plan (Case 2)

Development Sources		Development Lines		Development Plan Costs		
HS	PSO	HS	PSO	HS	PSO	
		L_{45}=1	L_{45}=1	4.636	5.044	Feeder Investment Cost
		L_{12}=2	L_{12}=2	0.76	0.888	Substation Investment Cost
		L_{16}=2	L_{16}=3	0	0	DG Investment Cost
		L_{18}=2	L_{18}=3	0	0	Annual Operating Cost of Distributed Generation
				11.2195	16.583	Annual Power Purchase Cost
				0.4655	0.507	Annual Network Losses Cost
				17.081	23.021	Total Development Plan Cost

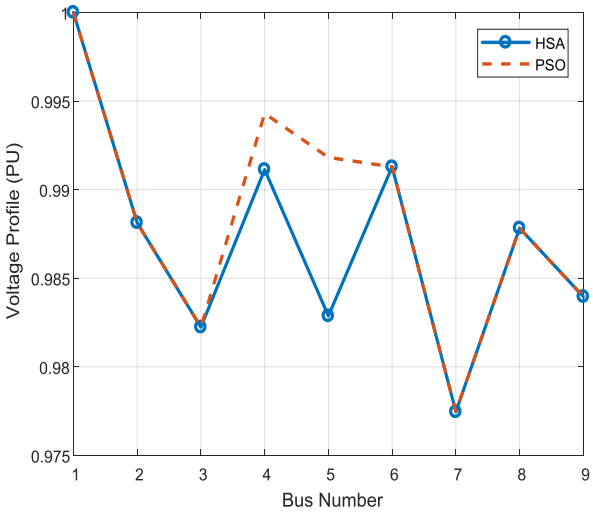


Fig. 6. Voltage Profile Convergence Graph (Case 2).

Based on this, the average voltage profile of the distribution network is shown in Figure 6, where the network voltage decreases by up to 2.5% at bus 7 during the period. This voltage drop is within the permissible standard range. Due to the creation of additional parallel lines in the PSO algorithm, the voltage profile in some buses has improved compared to the Harmony Search Algorithm, despite the annual load increase. As a result, the network development cost has increased significantly.

5.3. Distribution Network Development Considering Uncertainty and Generation Sources (Case 3).

In this section, we assume that load and cost uncertainties are considered, and the optimization goal is the development of the distribution network to supply the load at bus number 7 while taking into account distributed generation (DG) sources. The convergence results of the two algorithms, HSA and PSO, are shown in Figure 7. Based on this, the HSA algorithm was able to identify the required transmission line for development faster than the PSO algorithm by the 13th iteration. The proposed algorithm suggests adding one optimal direct line and a total of 8 MW of distributed generation capacity at a cost of $12.7 million to supply power to bus 7 over a 10-year period with a gradual 10% annual load increase. Compared to the case without uncertainty, more power generation was assigned to distributed generation sources.

The PSO algorithm, however, failed to identify the global minimum and got stuck in a local minimum development cost by the 11th iteration. It remained trapped until the 50th iteration and proposed a higher total cost than the proposed algorithm.

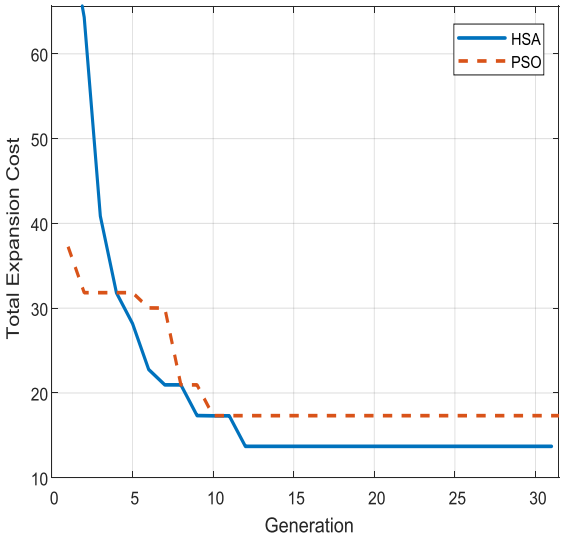


Fig. 7. Convergence graph of the HSA and PSO algorithms (Case 3).

The development plan costs for the two algorithms are presented in Table 3. Based on this, the PSO algorithm has proposed adding one parallel line to connect bus 6 to bus 7. However, the Harmony Search Algorithm, due to optimal location selection and combined optimal capacity at buses 3, 7, and 9, has reduced the current passing through the lines to within the nominal permissible limits. As a result, the total development cost has been reduced.

TABLE 3. Results of the Network Development Plan (Case 3)

Development Sources		Development Lines		Development Plan Costs		
HS	PSO	HS	PSO	HS	PSO	
4MW B3	2MW B3	L_{67}=1	L_{67}=1	1.14	1.660	Feeder Investment Cost
2MW B7	1MW B7			0	0	Substation Investment Cost
2MW B9	4MW B9			2.109	2.405	DG Investment Cost
	3MW B6			1.7195	1.830	Annual Operating Cost of Distributed Generation
				7.3815	9.876	Annual Power Purchase Cost
				0.38	0.564	Annual Network Losses Cost
				12.73	16.334	Total Development Plan Cost

Based on this, the average voltage profile of the distribution network is shown in Figure 8, where the network voltage decreases by up to 3.5% at bus 7 during the period. This voltage drop is within the permissible standard range.

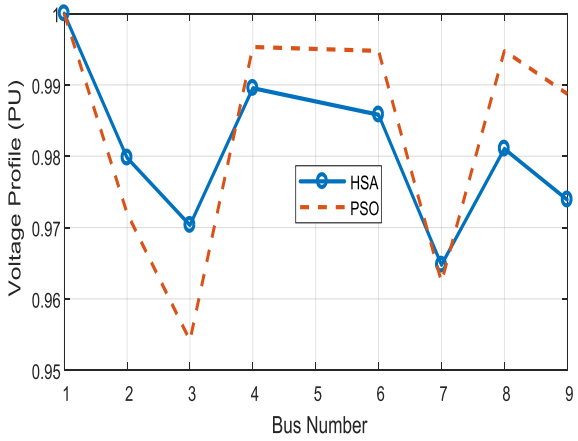


Fig. 8. Voltage Profile Convergence Graph (Case 3).

5.4. Distribution Network Development Considering Uncertainty and Generation Sources (Case 4).

In this section, we assume that load and cost uncertainties are considered, and the optimization goal is the development of the distribution network to supply the load at bus number 5 while taking into account distributed generation (DG) sources. The convergence results of the two algorithms, HSA and PSO, are shown in Figure 9. Based on this, the HSA algorithm was able to identify the required transmission line for development faster than the PSO algorithm by the 25th iteration. The proposed algorithm suggests adding 5 optimal lines at a cost of $17.38 million to supply power to bus 5 over a 10-year period with a gradual 10% annual load increase.

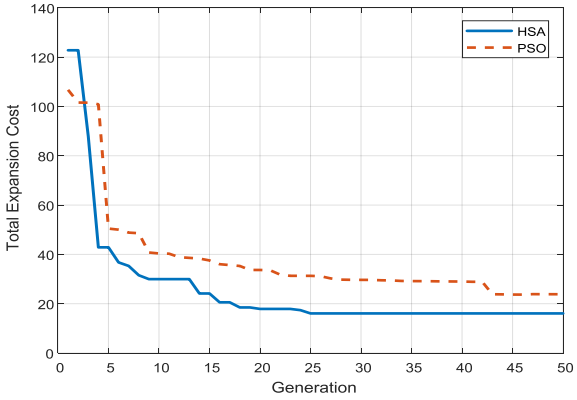


Fig. 9. Convergence graph of the HSA and PSO algorithms (Case 4).

TABLE 4. Results of the Network Development Plan (Case 4)

Development Sources		Development Lines		Development Plan Costs		
HS	PSO	HS	PSO	HS	PSO	
3MW B2 B5 B8 B9	3MW B2 B5 B9	L_{45}=2	L_{45}=1	3.04	4.392	Feeder Investment Cost
2MW B4 B6 B7 B9	2MW B4 B6	L_{12}=1	L_{12}=2	0	0	Substation Investment Cost
1MW B3 B7	4MW B3 B8	L_{14}=2	L_{14}=3	3.924	5.195	DG Investment Cost
	1MW B1			4.389	4.671	Annual Operating Cost of Distributed Generation
				5.928	7.544	Annual Power Purchase Cost
				0.467	0.618	Annual Network Losses Cost
				17.737	22.42	Total Development Plan Cost

The PSO algorithm, however, failed to identify the global minimum and got stuck in a local minimum development cost by the 43rd iteration. It remained trapped until the 50th iteration, and as a result, proposed a higher total cost compared to the proposed algorithm.

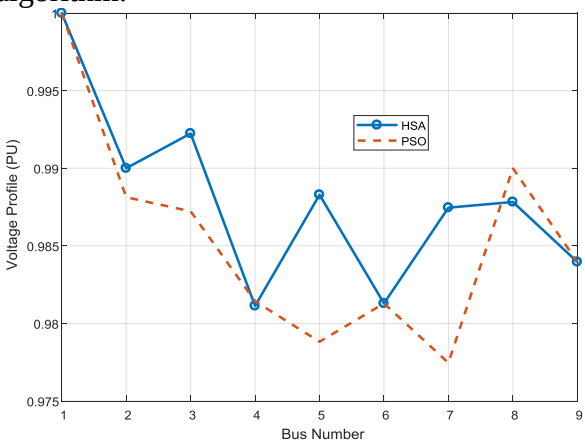


Fig. 10. Voltage Profile Convergence Graph (Case 4).

The development plan costs for the two algorithms are presented in Table 4. Based on this, due to the beneficial role of distributed generation (DG) sources, the investment cost for the auxiliary substation has been reduced to zero. Based on this, the average voltage profile of the distribution network is shown in Figure 10, where the network voltage decreases by up to 2% at buses 4 and 6 during the period. This voltage drop is within the permissible standard range. Power system planning is an optimization problem that aims to determine the type, location, and installation schedule of new equipment in an optimal way under a set of specific constraints. Given the role of distributed generation (DG) in reducing losses and improving the voltage profile, as well as the uncertainty in consumer demand in the distribution network, it is necessary to consider these two factors in distribution network development plans. In this paper, the Harmony Search Algorithm (HSA) has been used for the development of a 9-bus distribution system. Various scenarios of generation and consumption, energy price fluctuations, load consumption variations, and uncertainties were examined. In each case, the optimal development plan was obtained using the proposed algorithm. The simulation results demonstrate the capability and effectiveness of the proposed planning approach in dealing with uncertainties in the electricity market environment. The voltage profile has improved, and both planning costs and losses have been reduced.

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