

A novel approach for the reconfiguration of distribution systems considering the voltage stability margin

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Abstract: In recent years, the problem of optimum reconfiguration in distribution systems (DSs) has been a task that must be solved in an optimal manner. This paper presents a new approach for the optimal reconfiguration of DSs based on a hierarchical 2-stage optimization problem to improve the power system voltage stability margin and reduce losses incorporating the constraints. The mentioned problem has been modeled as a nonlinear and multiobjective optimization problem. It uses the ability of the developed harmony search algorithm (HSA) as the first stage of the proposed optimization problem to reach the best network configuration. This reconfiguration algorithm starts with a radial topology by a theoretical approach that is based on the graph concept and matroid theory. These concepts are used in order to propose new intelligent HSAs to form a new harmony vector that is well dedicated to the DS reconfiguration problem. Thus, all of the resulting individuals after forming a new harmony vector are claimed to be feasible configurations. Moreover, the presented approach is valid and avoids tedious mesh checks for the topology constraint validation.

In the second stage of the proposed approach, the voltage stability index is calculated to evaluate the static voltage stability security margin for each reconfiguration pattern. Hence, a toolbox has been developed to recognize the loadability limit of DSs based on the Lagrangian optimization method.

Finally, the proposed method establishes a tradeoff between the security index and power losses to reach a coordinated reconfiguration pattern. To demonstrate the validity of the proposed method, the simulations are carried out on 33- and 69-bus IEEE DSs. The proposed method is finally compared to some previous techniques used by other authors. The results show a good enhancement in the security margin and smaller power losses with considerably less computation effort. To validate the proposed method, the results that were obtained from the HSA are compared with the particle swarm optimization algorithm to ascertain its effectiveness.

Key words: Reconfiguration, voltage stability, hierarchical optimization, graph theory, harmony search, matroid theory, loadability limit, distribution system

1. Introduction

With the development of national economies and the improvement of people's lives, load demands in distribution systems (DSs), especially in industrial areas, are sharply increasing and the operation conditions of DSs are closer and closer to the system boundaries. DSs experience a distinct change from low to high load levels every day. Under certain critical loading conditions, DSs may experience voltage collapse. Hence, voltage stability is

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considered to be one of the keen interests of industry and research sectors around the world.

Voltage stability is the ability of a system to maintain voltage and it is closely associated with power delivering capability. The voltage instability phenomenon, which can occur in DSs, may not be new to power system practicing engineers and researchers. The decline of the voltage stability level is one of the important factors that restrict the increase of loads served by distribution companies. Hence, it is necessary to consider voltage stability constraints for the planning and operation of DSs.

Moreover, the topological structure of the radial DS (RDS) is reconfigured to improve the operating conditions from time to time. Regarding these matters, reconfiguration is increasingly drawing great attention from engineers. There are many technical benefits of employing reconfiguration in existing DSs, such as an improvement in line losses, economics, reliability indicators, voltage control issues, and load balancing, which was investigated in previous works. The reconfiguration of DSs is usually done to minimize real power losses.

Until now, many studies have been done on reconfiguration scenarios to reach the optimum conditions in DSs. In this field, guaranteed convergence particle swarm optimization (GCPSO) and graph theory is used to improve voltage profile and loss [1]. Recently, minimizing the DS losses in the presence of a set of structural and operational constraints has been an objective that used the ant colony heuristic algorithm [2]. Moreover, use of the genetic algorithm based on the matroid theory was suggested in [3]. A simple and efficient 2-stage reconfiguration algorithm for the minimization of active power loss in balanced and unbalanced DSs was presented in [4]. Many reconfiguration methods based on heuristic optimization, artificial intelligence methods, and evolution programming can be found in the literature, as well. Sensitivity and heuristic methods based on loss minimization were used by Viswanasha et al. [5]. Sanjay et al. [6] suggested minimizing financial losses due to voltage sag as a new objective function. Saffer et al. presented a new combined method for optimal reconfiguration using a multiobjective function with fuzzy variables [7]. This method considered both load balancing and loss reduction in the feeders as an objective function. The authors in [8] used DSTATCOM allocation to mitigate losses and improve the voltage profile via reconfiguration in DSs. Furthermore, DS reconfiguration has the potential to improve the system voltage stability, as well. Kashem et al. [9] presented the relationship between voltage stability and loss minimization. It can be shown that voltage stability is maximized when power losses are minimized in the networks. In [10], a new method for optimal reconfiguration was suggested for RDSs. Several performance criteria were considered for optimal network reconfiguration, such as maximizing the loadability, which is an important one. Owing to the discrete nature of the solution space, a fuzzy adaptation of the evolutionary programming algorithm for optimal reconfiguration of RDSs to maximize loadability was proposed in [10]. In [11], the authors reported a reconfiguration algorithm based on Tabu search for maximizing the security margin to voltage collapse. Arun et al. [12] presented a new reconfiguration algorithm that enhances voltage stability and improves the voltage profile, aside from minimizing losses. A fuzzy genetic algorithm was reported by Sahoo et al. This algorithm was used for the reconfiguration of RDSs to improve the voltage stability security margin for a specific set of loads [13].

In this paper, a novel method for solving the DS reconfiguration problem is suggested. The proposed method establishes a tradeoff between the security index (voltage stability security margin) and power losses simultaneously for the reconfiguration problem as a multiobjective nonlinear optimization problem. This method uses the new voltage stability index for DS voltage stability analysis, P_{sys} (maximum loadability limit), which is the maximum loading of DSs under the feasibility of power flow equations. The proposed method uses the harmony search algorithm (HSA) to solve the mentioned optimization problem as the first layer of the optimization search. The HSA has emerged as a useful tool for engineering optimization that has been used in

complex optimization problems. Hence, the optimal situations for open switches are determined to obtain the best objective. Due to the discrete nature of the switching statue, the feasible topologies in the reconfiguration process are very important. To find them, the matroid theory based on the graph concept has been used.

In the second layer of the hierarchical optimization method and, respectively, to each feasible reconfiguration pattern, the voltage stability index is calculated based on nonlinear optimization. The analysis process is performed using a steady state voltage stability index, P_{sys} , which is the maximum loading under the feasibility of the power flow equations [14–19]. Hence, a toolbox has been developed to assess the power system voltage stability margin based on the Lagrangian method.

The IEEE-33 and IEEE-69 bus DS test systems are used to illustrate the performance of the proposed methodology and the results are compared with those of other studies.

2. Problem formulation

2.1. The objective function

Several aspects might be taken into consideration when defining the objective function of the network reconfiguration problem. The objectives that were considered in this study for finding the optimal reconfiguration of the DS are minimizing the total system power losses and maximizing the loadability limit.

One of most common adopted approaches refers to the minimization of power losses, but the maximization of the voltage stability security margin is also mentioned in this study. The objectives of this optimization problem are maximizing the static voltage stability as well as minimizing the DS loss. These objectives are described below in more detail.

2.1.1. Minimize the active power losses

One of the major potential benefits offered by reconfiguration is the reduction in electrical line losses. The utility is forced to pass the cost of electrical line losses on to all of the customers in terms of higher energy costs. With the inclusion of reconfiguration, line loss in the distribution system can be reduced. The proposed index for a bus is defined as follows:

$$P_{loss} = \sum_{l=1}^b R_l B_l^2 = \sum_{i,j=1,2,\dots,NB} [V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)] Y_{ij} \cos \phi_{ij}, \quad (1)$$

subject to:

$$\begin{aligned} g(x) &= 0 \\ V_i^{\min} &\leq V_i \leq V_i^{\max}, \\ B_l^{th} &\leq B_l^{th,\max} \end{aligned}$$

where b is the number of branches; R_l is the resistance of line l ; B_l is the current passing through line l ; NB is the number of buses; V_i, δ_i are the voltage magnitude and voltage angle of node i and Y_{ij}, ϕ_{ij} are the magnitude and angle of the $i - j$ line admittance; $g(x)$ are power flow equations; V_i^{\min} is the lower voltage limit (taken to be 0.9 p.u); V_i^{\max} is the upper voltage limit (taken to be 1 p.u); and $B_l^{th,\max}$ is the thermal current rating limit.

To reach the aim of active power losses in DSs, it is necessary to calculate the voltage magnitude and voltage angle of each node. For this calculation, a load flow model is presented. This model is based on graph theory and uses the graph topology of the system.

2.1.1.1. Formulation of load flow model

The relationship between the bus current injection and branch current (BIBC) matrix is obtained by applying Kirchhoff's current law to the distribution network. However, in the reconfiguration process, the network structure is continuously changing and the load flow algorithm generates the corresponding downstream nodes' vectors necessary for dynamic generation of the BIBC's matrices, securing the radiality of the network and the correct current flow direction. The load flow algorithm follows changes in the system structure by creating a directed graph for the distribution network in each switching iteration [20]. For an effective explanation, a 6-bus DS is suggested. This DS is shown in Figure 1. The relationship between the bus current injections and the branch current can be expressed as:

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix}. \quad (2)$$

This equation can be show in the following form:

$$[B] = [BIBC][I]. \quad (3)$$

The relationship between the branch currents and the bus voltage can be explained as:

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix}. \quad (4)$$

The general format is:

$$[\Delta V] = [BCBV][B]. \quad (5)$$

By the combination of Eqs. (3) and (5), the relationship between the bus current injection and the bus voltage can be shown as:

$$[\Delta V] = [BCBV][BIBC][I] = [DLF][I]. \quad (6)$$

To gain power flow convergence, the algorithm is repeated in Figure 2. At this step, the voltage magnitude and voltage angle of each node are detected. Hence, the active power losses are calculated by Eq. (1).

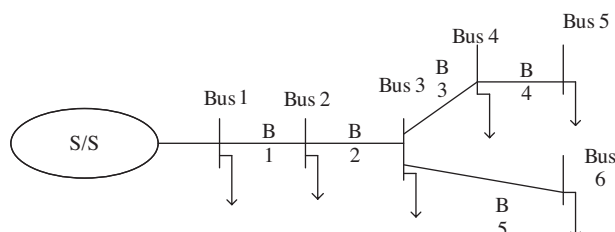


Figure 1. Test system.

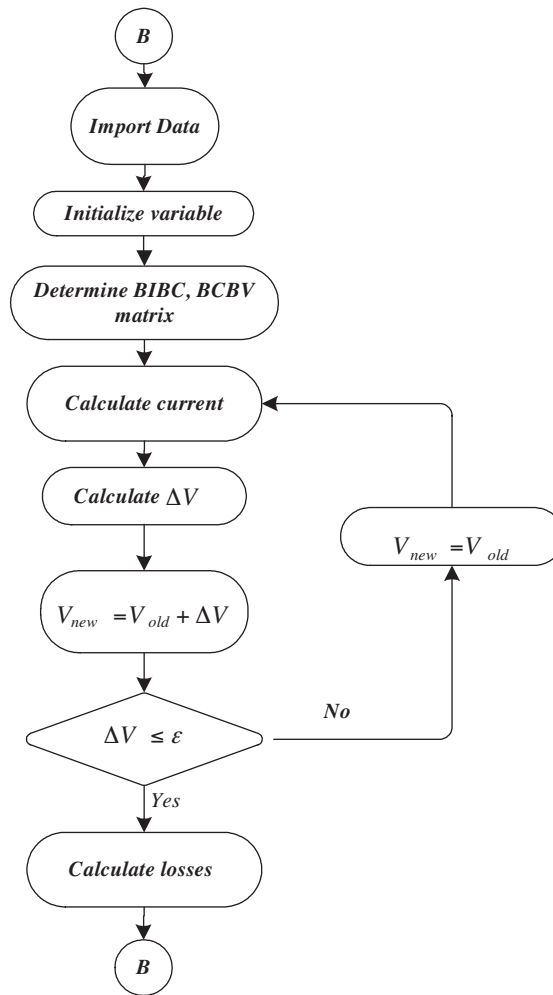


Figure 2. Flowchart of the loss calculation.

2.2. Maximizing loadability limit index

The loadability limit is a new index to determine the static voltage stability of DSs [16]. System loadability can be evaluated by means of nonlinear optimization, in which it tries to maximize system loading under the constraint of power flow equations. For this purpose, the problem can be formulated as follows [15–19]:

$$\begin{aligned}
 \text{Min} \quad & : -P_{sys} \\
 \text{s. t} \quad & : \begin{cases} P_{Gi} - P_{Di} - f_i(v, \delta) = 0 \\ Q_{Gi} - Q_{Di} - g_i(v, \delta) = 0 \end{cases}, \\
 & P_{Gi}^{Min} \leq P_{Gi} \leq P_{Gi}^{Max} \\
 & Q_{Gi}^{Min} \leq Q_{Gi} \leq Q_{Gi}^{Max}
 \end{aligned} \quad (7)$$

where P_{sys} is the system total active load, P_{Gi} and Q_{Gi} represent the vectors of the active and reactive generation, P_{Di} and Q_{Di} represent the vectors of the active and reactive load, and f_i and g_i are the active and reactive power flow equations, respectively.

The main constraint for voltage stability is the feasibility of the power flow solution. Therefore, the above equation tries to find the maximum loading under the feasibility of the power flow equation that corresponds to the system loadability limit. This nonlinear problem can be solved by the Lagrange method. For this purpose, the nonconstrained Lagrange function can be constructed as follows:

$$L = -P_{sys} + [\lambda]^T [P_G - P_D - f(V, \delta)] + [\gamma]^T [Q_G - Q_D - g(V, \delta)] \quad (8)$$

In this optimization problem, the increased pattern of loads at buses is one of the main factors that dominate the loadability limit. Hence, in order to include their effects, it can be modeled as follows [16]:

$$P_{Di} = \left[P_{Di}^{(0)} + \beta_i P f_i (P_{sys} - P_{sys}^{(0)}) \right] \left(\frac{V_i}{V_i^{(0)}} \right)^{kpvi}, Q_{Di} = \left[Q_{Di}^{(0)} + \beta_i Q f_i (P_{sys} - P_{sys}^{(0)}) \right] \left(\frac{V_i}{V_i^{(0)}} \right)^{kqvi}. \quad (9)$$

Hence, the Lagrange equation can be finalized as follows:

$$\begin{aligned} L : & - \sum_{i=2}^{NB} \left[P_{Di}^{(0)} + \beta_i P f_i (P_{sys} - P_{sys}^{(0)}) \right] \left(\frac{V_i}{V_i^{(0)}} \right)^{kpvi} + \\ & \sum_{i=2}^{NB} \lambda_i \left\{ \alpha_i P_{sys} - \left[P_{Di}^{(0)} + \beta_i P f_i (P_{sys} - P_{sys}^{(0)}) \right] \left(\frac{V_i}{V_i^{(0)}} \right)^{kpvi} - f_i(v, \delta) \right\} + \\ & \sum_{i=2}^{NB} \gamma_i \left\{ Q_{Gi} - \left[Q_{Di}^{(0)} + \beta_i Q f_i (P_{sys} - P_{sys}^{(0)}) \right] \left(\frac{V_i}{V_i^{(0)}} \right)^{kqvi} - g_i(v, \delta) \right\} \end{aligned} \quad (10)$$

where $P_{Di}^{(0)}$ and $Q_{Di}^{(0)}$ are the primary values of the active and reactive load powers, α_i is the generation contribution of each bus, β_i is the generation and load contributions for each bus, $P f_i$ and $Q f_i$ are the load factor coefficients, $V_i^{(0)}$ is the primary value of the bus voltage magnitude, V_i is the value of the bus voltage, $kpvi$ and $kqvi$ are the load active and reactive powers, $P_{sys}^{(0)}$ is the total primary active load of the system, and P_{sys} is the total active load of the system.

To solve the Lagrange equation, the Newton-Raphson method is employed. For this purpose, the first derivatives of the Lagrange equation are calculated as follows:

$$F_X = \frac{\partial L}{\partial X} = 0, X = [V, \delta, \lambda, \gamma, P_{sys}]. \quad (11)$$

For example, F_{λ_i} can be derived as:

$$F_{\lambda_i} = \alpha_i P_{sys} - \left[P_{Di}^{(0)} + \beta_i P f_i (P_{sys} - P_{sys}^{(0)}) \right] - V_i \sum_{m=1}^{nb} Y_{im} V_m \cos(\delta_i - \delta_m - \phi_{im}) = 0, \quad (12)$$

where nb is the system bus numbers. Other equations are also derived in the same manner. Next, the factors of every equation that contains ΔV , $\Delta \delta$, $\Delta \lambda$, $\Delta \gamma$, and ΔP_{sys} by a derivative of Eq. (10) with these factors

are calculated. For example, the other equations can be derived as:

$$\begin{aligned} \frac{\partial F_{\lambda j}}{\partial X} \Delta X &= \{-\alpha_j + \beta_j P f_j\} \Delta P_{Sys} + \left\{ V_j Y_{jj} \cos(\phi_{jj}) + \sum_{m=1}^{NB} Y_{jm} V_m \cos(\delta_j - \delta_m - \phi_{jm}) \right\} \Delta V_j \\ &+ \left\{ V_j \sum_{\substack{i=2 \\ i \neq j}}^{NB} Y_{ji} \cos(\delta_j - \delta_i - \phi_{ji}) \Delta V_i \right\} - \left\{ V_j \sum_{\substack{m=1 \\ m \neq j}}^{NB} Y_{jm} V_m \sin(\delta_j - \delta_m - \phi_{jm}) \right\} \Delta \delta_j \\ &+ \left\{ V_j \sum_{\substack{i=2 \\ i \neq j}}^{NB} Y_{ji} V_i \sin(\delta_j - \delta_i - \phi_{ji}) \Delta \delta_i \right\} \end{aligned} \quad (13)$$

In this study, the factors of every equation that contains ΔV , $\Delta \delta$, $\Delta \lambda$, $\Delta \gamma$, and ΔP_{Sys} are calculated. By a derivative of Eq. (4) with these factors, the following objective matrix would be earned:

$$\begin{bmatrix} F_V^{(0)} \\ F_\delta^{(0)} \\ F_\lambda^{(0)} \\ F_\gamma^{(0)} \\ F_{P_{Sys}}^{(0)} \end{bmatrix} = \begin{bmatrix} F_{VV} & F_{V\delta} & F_{V\lambda} & F_{V\gamma} & F_{VP_{Sys}} \\ F_{\delta V} & F_{\delta\delta} & F_{\delta\lambda} & F_{\delta\gamma} & F_{\delta P_{Sys}} \\ F_{\lambda V} & F_{\lambda\delta} & F_{\lambda\lambda} & F_{\lambda\gamma} & F_{\lambda P_{Sys}} \\ F_{\gamma V} & F_{\gamma\delta} & F_{\gamma\lambda} & F_{\gamma\gamma} & F_{\gamma P_{Sys}} \\ F_{P_{Sys}V} & F_{P_{Sys}\delta} & F_{P_{Sys}\lambda} & F_{P_{Sys}\gamma} & F_{P_{Sys}P_{Sys}} \end{bmatrix} \cdot \begin{bmatrix} \Delta V \\ \Delta \delta \\ \Delta \lambda \\ \Delta \gamma \\ \Delta P_{Sys} \end{bmatrix} \quad (14)$$

The proposed method is implemented using the MATLAB platform and FORTRAN 95. The flowchart of this proposed method is given in Figure 3.

The graphic process for finding the optimal reconfiguration for DSs is shown in Figure 4 and the flowchart of the mentioned process is described in Figure 5.

To find the best configuration for DSs, 3 different objective functions are employed. The first and second are based on a single objective function: how to minimize the active power losses and maximize the voltage stability margin.

The problem is considered as a multiobjective optimization in the third objective function, which is minimizing the active power losses as well as improving the voltage stability margin. The overall objective function can be expressed as the weighted sum of the objective function, as in Eq. (15).

The problem is solved with this objective function, subject to equality and inequality constraints. These constraints are contained in the power flow constraints (Section 2.1.1) and loadability limit constraint (Section 2.1.2).

$$\begin{aligned} \text{Min. Fitness} &= K_1 \cdot \overset{\Delta}{P}_{Loss} + K_2 \cdot \frac{1}{\overset{\Delta}{P}_{Sys}} \\ \overset{\Delta}{P}_{Loss} &= \frac{P_{loss}}{P_{loss-base}} \\ \overset{\Delta}{P}_{Sys} &= \frac{P_{Sys}}{P_{Sys-base}} \end{aligned} \quad (15)$$

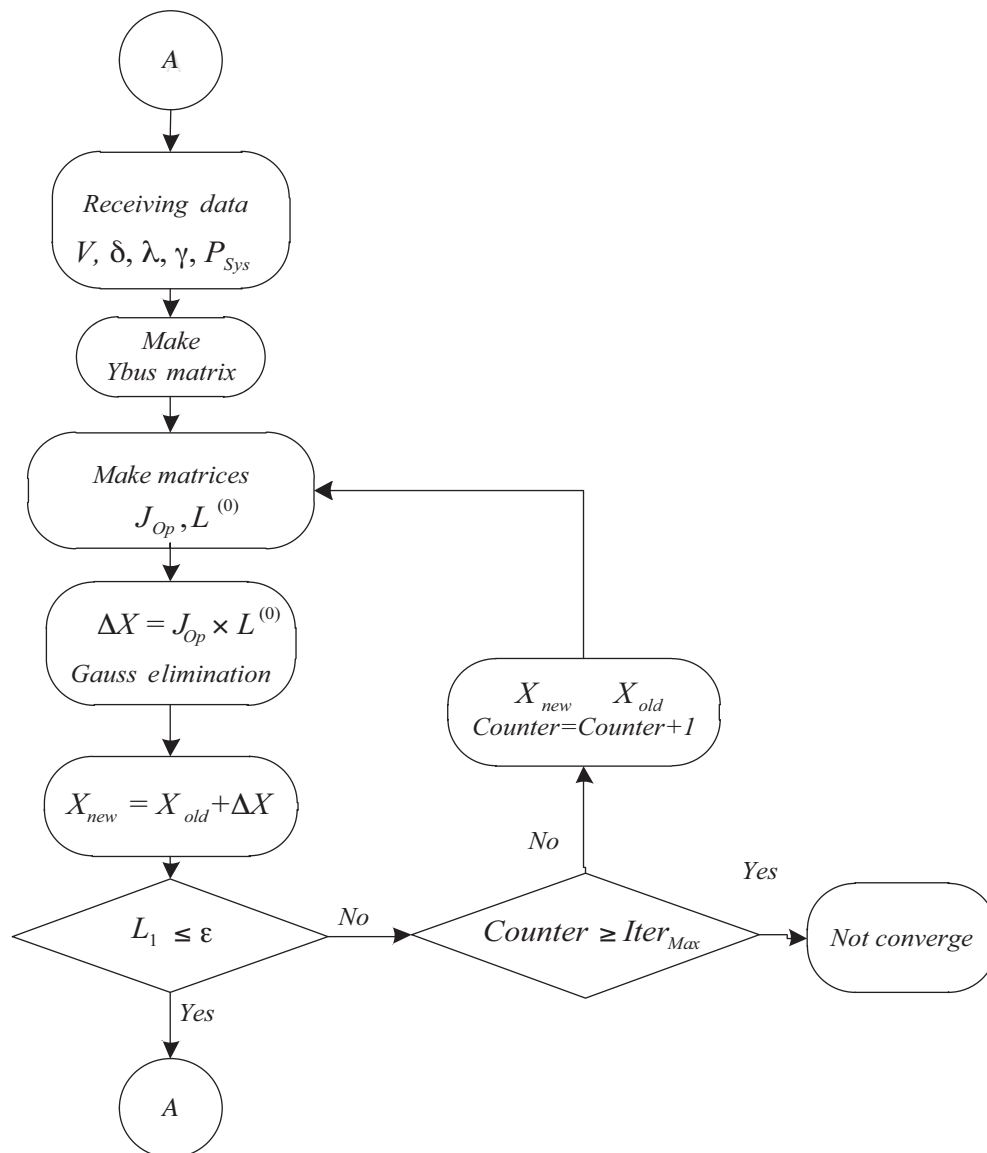


Figure 3. Flowchart of the loadability limit index calculation.

Here, P_{sys} and $P_{sys-base}$ are the total active load and the total active load of the network without the reconfiguration of the DS, and P_{loss} and $P_{loss-base}$ are the total active power loss and the primary value of the active load losses.

3. Harmony search algorithm

3.1. Brief survey

The HSA was derived from the natural phenomena of musicians' behavior when they collectively play their musical instruments (population members) to come up with a pleasing harmony (global optimal solution). This state is determined by an aesthetic standard (fitness function). The HSA, simple in concept with few parameters and easy in implementation, has been successfully applied to various benchmarking and real-world problems, like the traveling salesman [21,22].

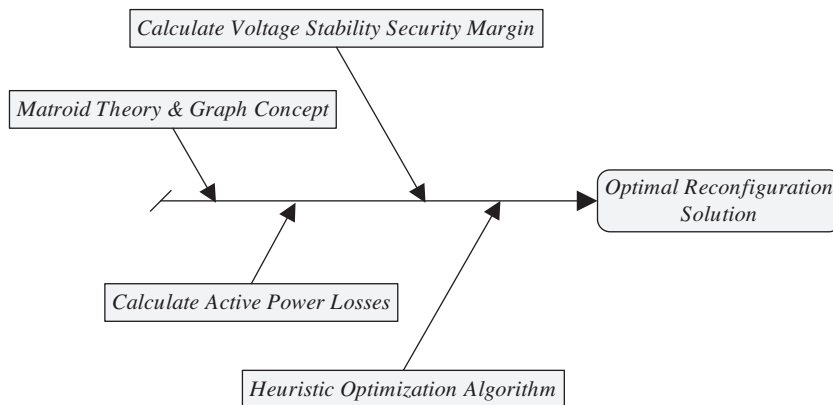


Figure 4. Graphic process to find the optimal configuration.

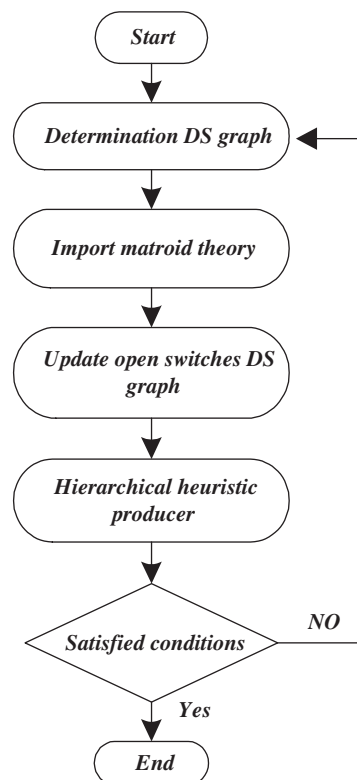


Figure 5. Proposed method's flowchart.

Despite the passage of more than a decade, this algorithm is still noted by many researchers. The debut of the PSO algorithm took place in 2001 by Geem et al. [23]. Kulluk et al. addressed the application of the self-adaptive global-best HSA (SGHSA) for the supervised training of feedforward neural networks. A structure suitable for the data representation of neural networks was adapted to the SGHSA [24]. In [25], a SGHSA for solving continuous optimization problems was presented. In the proposed SGHSA, a new improvisation scheme was developed so that the good information captured in the current global best solution could be well utilized to generate new harmonies [25]. The authors in [26] focused on the optimal scheduling of the generators to reduce the fuel consumption in an oil rig platform using the HSA. Pandi and Ketan presented a hybrid HSA with swarm intelligence to solve the dynamic economic load dispatch problem [27]. To maximize the degree of customer

satisfaction, benefit third-party logistics providers, and minimize transport costs simultaneously, fourth-party logistics need to design an optimal route from a supply node to a demand node. In [28], the mathematical model of the point-to-point single task path optimization in fourth-party logistics with soft time window was set up. To solve the model, harmony search was suggested. The authors in [29] presented a comparison of postoutage bus voltage magnitudes calculated by 2 metaheuristic approaches, namely differential evolution and

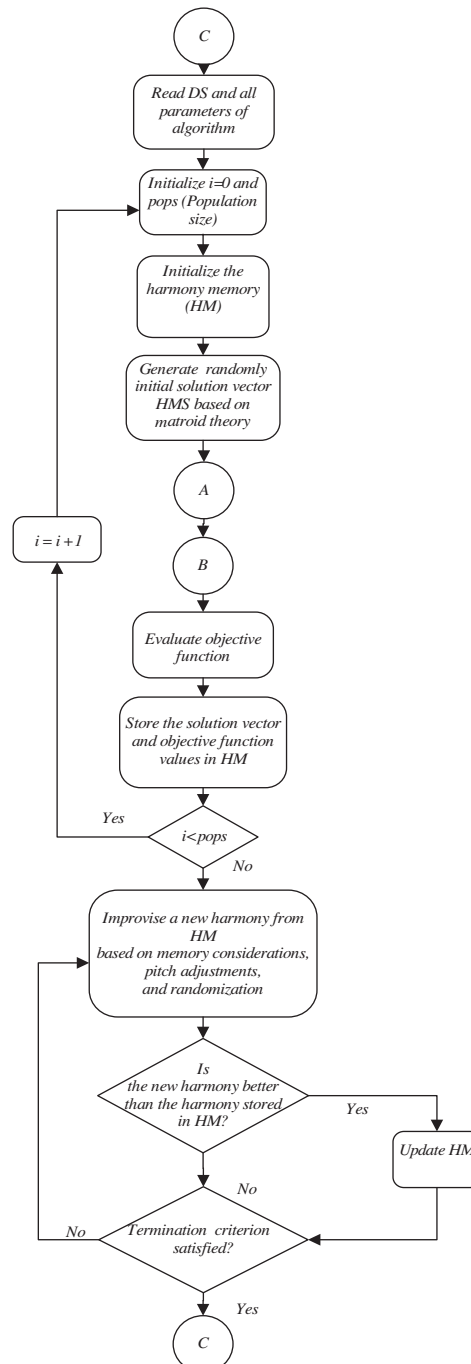


Figure 6. Flowchart of the HSA.

harmony search methods. Harrou and Zeblah combined the universal generating function with the harmony search metaheuristic optimization method to solve a preventive maintenance problem for a series parallel system [30].

3.2. Definition

The HSA optimization technique consists of several steps. The flowcharts are explained in detail. In each step, the related constraints are taken into account, while, finally, the objective function associated with all of the constraints is minimized with the HSA. Figure 6 introduces the main flowchart of the proposed algorithm.

The HSA is applied to solve the feeder configuration problem using the following steps:

Step1: Initialize the optimization problem and algorithm parameters.

These parameters are the harmony memory size (HMS), harmony memory considering rate (HMCR), pitch adjusting rate (PAR), number of improvisations (NI), and harmony memory (HM).

Step 2: Initialize the HM

The format of the solution vector in the HM matrix is given in Figure 7. In this problem, the HMS consists of configurations (suggested open switches with the matroid and graph theories) and the fitness value of the objective function for the suggested configuration.

Switch statuses (Number of open switches)					Fitness value
Open switch 1	Open switch 2	Open switch n -1	Open switch n	

Figure 7. Format of the solution vector.

In this step, the HM matrix is filled with the spanning tree theory. The spanning tree is a theory that has been explained by Kruskal [31]. The following is a definition of the spanning tree.

G is a graph with n vertices. A spanning tree is a connected subgraph that uses all of the vertices of G that have $n - 1$ edges. Two spanning trees of a sample G graph are shown in Figure 8.

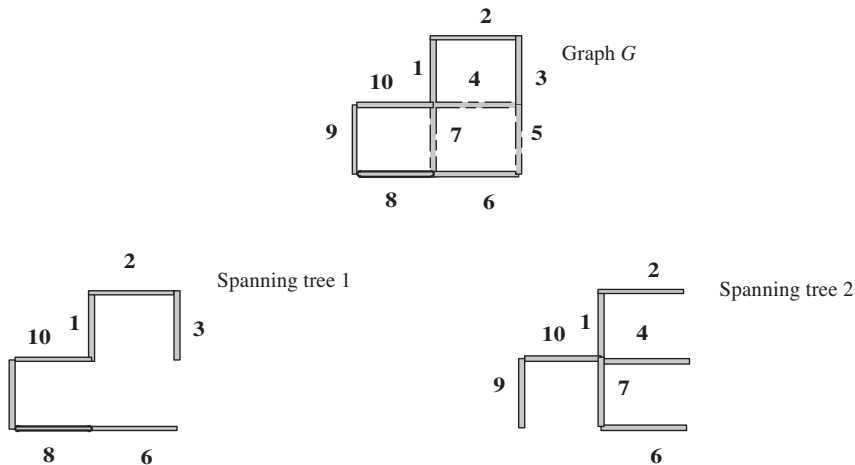


Figure 8. Two spanning trees of a sample graph.

Wilson explained the exchange axiom for spanning trees [32]. Let M and N be spanning trees of a connected graph G .

(i) If e is any edge of M , show that there exists an edge f of N , such that the graph $(T_1 - \{e\}) \cup \{f\}$ (obtained from M on replacing e by f) is also a spanning tree.

(ii) Deduce that M can be ‘transformed’ into N by replacing the edges of M one at a time with the edges of N in such a way that a spanning tree is obtained at each stage.

Because the spanning trees of a graph can be taken to be the bases of a matroid, it can be concluded that the bases of a matroid have the same number of elements, and by definition of a spanning tree it has $n - 1$ elements (if there are n vertices).

For more explanation of this step of the HSA, suppose that M and N are 2 spanning trees of the graph G , and $a \in M$, $a \notin N$, then $b \in N$. Moreover, $N - a + b$ is a spanning tree in the graph. To understand better, 2 spanning trees are shown in Figure 9. One edge that replaces $a = 6$ in M in order to form another spanning tree can be found. Edge b can be selected in the loop formed by $N \cup a$. In Figure 9, this loop is formed by $N \cup a$, the branches 4, 5, 6, and 7. Only the edges in 5 and 7 can replace the edge in 6. Finally, the edge in 5 is chosen to replace the edge in 6, and a new spanning tree is obtained (see the resulting tree in Figure 9).

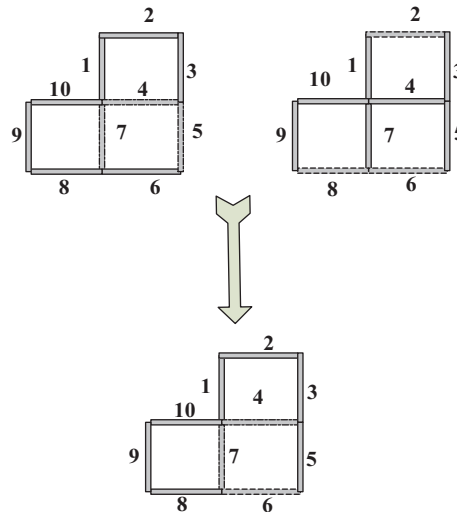


Figure 9. Branch exchange between 2 spanning trees.

Step 3: Improvise a new harmony: a new harmony vector $x'_i = \{x'_1, x'_2, \dots, x'_N\}$ is generated using 3 rules: memory considering, pitch adjustment, and random selection. In the 2 last rules, matroid theory is used to form a new harmony vector. The general algorithm of this step is:

For each $i \in [1, N]$ do

If $rand < HMCR$

Then $x'_i \in \{x_i^1, x_i^2, \dots, x_i^{HMS}\}$

Else if $rand < PAR$

Next, $x'_i = x_i \pm rand(bw)$ and bw is a switch selection via the matroid theory.

Step 4: Update the HM: if the new harmony vector has a better fitness function than the worst harmony in the HM, it replaces the worst harmony in the HM.

Step 5: Check stopping criterion: terminate when the stopping criterion has been met.

The PSO algorithm is applied to verify the result of the HSA. The typical PSO algorithm was described in detail in [33]. The flowchart of the PSO algorithm is shown in Figure 10.

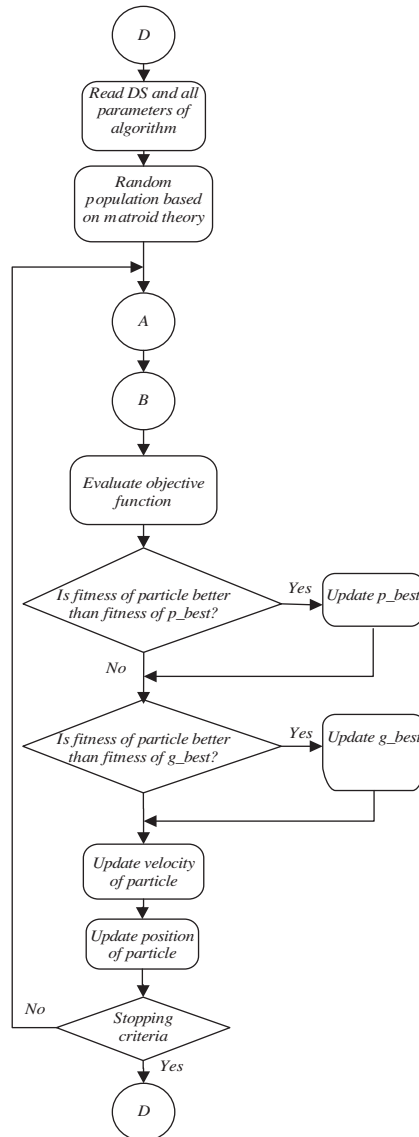


Figure 10. Flowchart of PSO.

4. Application of the matroid theory to the HSA and PSO

The matroid theory, initially developed by Whitney [34], abstracts the important characteristics of the matrix and graph theories. A definition and detail was given in [35].

A matroid M consists of a nonempty finite set E and a nonempty collection B of subsets of E , called bases, satisfying the following properties:

(i): no base properly contains another base;

(ii): if B_1 and B_2 are bases and if e is any element of B_1 , then there is an element of B_2 such that $(B_1 - \{e\}) \cup \{f\}$ is also a base.

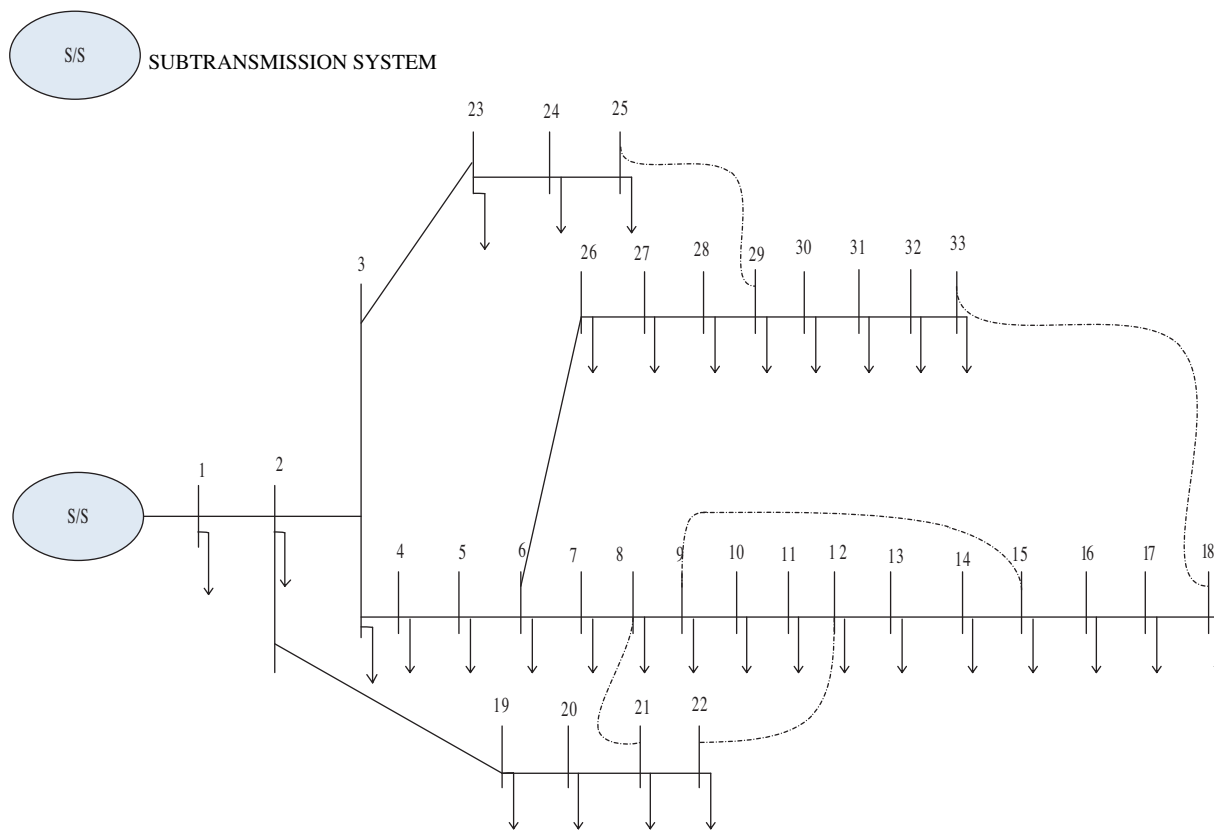


Figure 12. IEEE 33-bus test system.

Table 1. Executing program via the IEEE 33-bus via HSA.

Objective Function	Initial condition	Securest reconfiguration pattern	Reconfiguration pattern based on min. loss	Coordinated reconfiguration pattern
Switch status	33, 34, 35, 36, 37	7, 10, 14, 16, 37	5, 8, 13, 31, 37	5, 8, 13, 31, 24
Loadability limit (P_{sys} (MW))	15.19	27.11	20.17	24.28
P_{sys} growth in comparison with initial condition (%)	—	78.50	32.80	59.86
P_{loss} (KW)	210.99	139.92	97.17	118.73
P_{loss} reduction (%)	—	33.37	53.94	43.73

Table 2. Executing program via the IEEE 33-bus via PSO.

Objective Function	Initial condition	Securest reconfiguration pattern	Reconfiguration pattern based on min. loss	Coordinated reconfiguration pattern
Switch status	33, 34, 35, 36, 37	7, 9, 14, 15, 28	5, 8, 13, 31, 37	6, 8, 14, 17, 24
Loadability limit (P_{sys} (MW))	15.19	27.31	20.17	25.24
P_{sys} growth in comparison with initial condition (%)	—	79.77	32.80	66.14
P_{loss} (KW)	210.99	151.58	97.17	122.54
P_{loss} reduction (%)	—	28.16	53.94	41.92

Table 3. Comparison of the proposed method with other methods using the IEEE 33-bus system data.

Method	Final open switches	Total loss savings (%)
Proposed (HSA & PSO)	5, 8, 13, 31, 37	53.94
Abul'Wafa [20]	34, 37, 11, 31, 28	48.07
Assadian et al. [1]	7, 9, 14, 32, 37	31.39

In this paper, 2 objects are considered in the fitness function for reconfiguration, which is considered in the matroid theory. This means that all of the feasible patterns for the switching status are considered in this study. Hence, switching statuses via the matroid and graph theories affect the optimum reconfiguration.

The results for the initial condition (without reconfiguration) are shown as column 1 of Tables 1 and 2. The results for improving the voltage stability security index as an objective function are derived in column 2 of Tables 1 and 2. Five switches in the HSA (7, 10, 14, 16, and 37) and PSO (7, 9, 14, 15, and 28) are obtained for opening 5 bus ties in this case. These results show an improvement in the voltage stability margin (loadability limit) with these obtained switching statuses for the reconfiguration.

Column 3 of Tables 1 and 2 presents the results for the reduction power losses as an objective function. Switches 5, 8, 13, 31, and 37 are candidates for opening. Most authors have used reducing power losses as an objective function in previous works; these results are compared with the proposed method in Table 3. The best result was reported in [20], where the result of the reconfiguration with the proposed method has a better savings in the total active losses.

This result emphasizes the usefulness and robustness of mixing the matroid and graph theories via the heuristic algorithm for reconfiguration.

A trade-off between a security improvement and a loss reduction is another objective for reconfiguration in DSs, which are derived in column 4 of Tables 1 and 2. In the HSA, 5 switches (5, 8, 13, 31, and 24) are obtained for opening 5 bus ties, in this case for improving the voltage stability index and reducing power losses. In this case, the HSA has a 59.86% and 43.73% improvement in voltage stability and power losses, respectively. Using the PSO algorithm, 5 switches (6, 8, 14, 17, and 24) are candidates for opening. This DS configuration gives a 66.14% and 41.29% improvement in the voltage stability index and power losses, respectively.

5.2. Case study 2: IEEE 69-bus test system

The developed methodology is demonstrated by a RDS with 69 buses, 7 laterals, and 5 tie-lines, as shown in Figure 13 [37]. For this base case, the total loads at the feeder head-section are 3801.5 kW and 2694.6 kVAr. The base network losses are 20.89 kW. The results of running the HSA and PSO for different terms of the objective function are derived in Tables 4 and 5. The results of the proposed method are compared with other previous methods in Table 6. From the results of this case study, it can be seen from the 69-bus test system that mixing the matroid and graph theories via the heuristic algorithm for reconfiguration has the effect of a loss reduction improvement over feeders in this particular case, and the configuration structures of the optimum network with the proposed reconfiguration are different from those without reconfiguration. Based on the 69-bus system with the proposed reconfiguration, the proposed HSA and PSO method in this paper has a lower loss reduction than the method proposed in [37] (the best result was reported). Tables 4 and 5 show the results of the HSA and PSO, respectively. The HSA and PSO have a 52.03% and 55.24% improvement in the voltage stability and power losses, respectively.

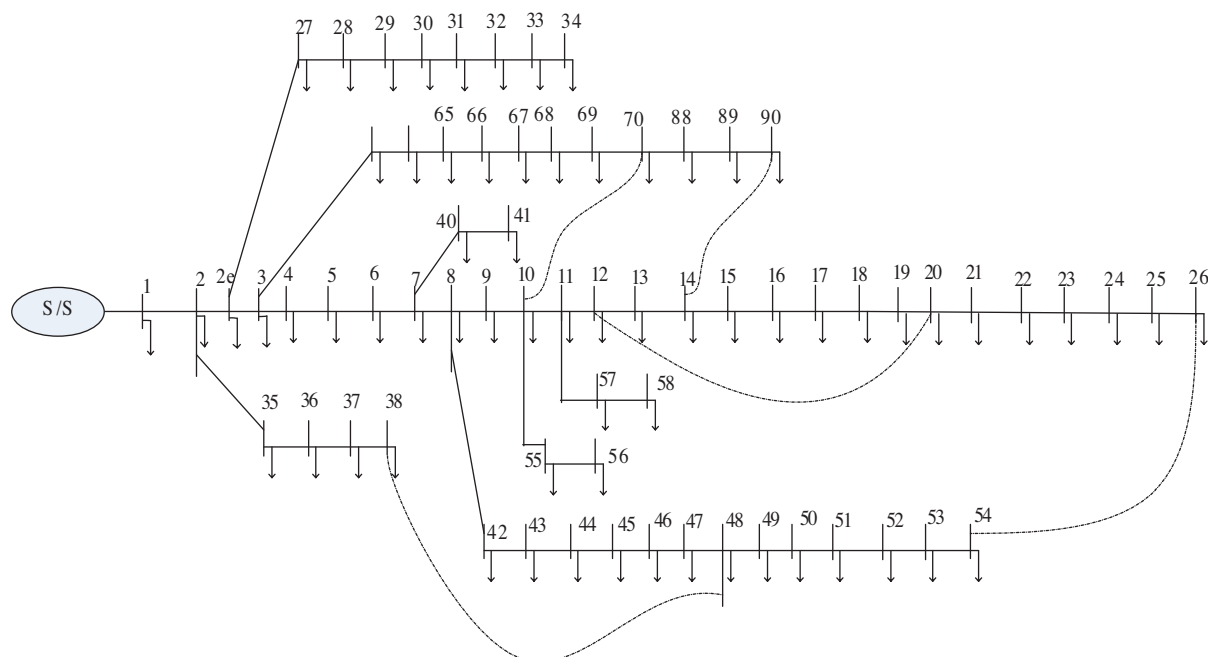


Figure 13. IEEE 69-bus test system.

Table 4. Executing program via the IEEE 69-bus via HSA.

Objective Function	Initial condition	Securest reconfiguration pattern	Reconfiguration pattern based on min. loss	Coordinated reconfiguration pattern
Switch status	69, 70, 71, 72, 73	17, 36, 44, 53, 62	16, 42, 43, 54, 62	16, 22, 42, 45, 53
Loadability limit (P_{sys} (MW))	12.66	19.48	18.81	19.25
P_{sys} growth in comparison with initial condition (%)	—	53.87	48.57	52.03
P_{loss} (KW)	20.89	13.03	9.19	9.35
P_{loss} reduction (%)	—	37.62	56.01	55.24

Table 5. Executing program via the IEEE 69-bus via PSO.

Objective Function	Initial condition	Securest reconfiguration pattern	Reconfiguration pattern based on min. loss	Coordinated reconfiguration pattern
Switch status	69, 70, 71, 72, 73	19, 42, 45, 56, 61	16, 42, 43, 54, 62	16, 22, 42, 45, 53
loadability limit (P_{sys} (MW))	12.66	19.48	18.81	19.25
P_{sys} growth in comparison with initial condition (%)	—	53.87	48.57	52.03
P_{loss} (KW)	20.89	12.22	9.19	9.35
P_{loss} reduction (%)	—	41.50	56.01	55.24

Table 6. Comparison of proposed method with other methods using the IEEE 69-bus system data.

Method	Final open switches	Total loss savings (%)
Proposed (HSA & PSO)	16, 42, 43, 54, 62	56.01
Abdelaziz et al. [37]	14, 44, 50, 65, 70	55

6. Conclusion

In this study, reliable and efficient methods used the heuristic technique for reconfiguration. On the other hand, a new approach to select the best harmony via the HSA and PSO has been presented, where the objective function in the HSA and PSO comprised power loss and voltage stability, and this yields a wide search area.

The proposed method has been successfully applied to standard IEEE 33- and 69-bus DSs. The satisfactory results were compared in 2 cases via the results of other authors. The results can also offer the usefulness of the proposed method, which can be considered as a practical technique. The results show that the proposed method has the following merits in both reconfiguration problems while considering loss and voltage stability improvement: efficient searching ability and robustness.

Symbols			
b	Number of branches	$P_{Gi}^{(0)}$	Primary value of the active generation
B	Current passing through the line	P_{sys}	Total active load of the system
BIBC	Relation matrix between the bus current injection and the branch current	$P_{sys-base}$	Total primary active load of the system
BCBV	Relation matrix between the branch current and the bus voltage	P_{loss}	Total active power loss
$B_l^{th,max}$	Thermal current rating limit	$P_{loss-base}$	Total primary active power loss
DLF	Relation matrix between the bus current injection and the bus voltage	Qf_i	Load factor coefficient
$F_V^{(0)}$	First derivative of the Lagrange function by the value of the bus voltage magnitude	Q_i	Reactive power flow
F_{VV}	Derivative of F_V by the value of the bus voltage magnitude	Q_{Di}	Reactive load
$g(x)$	Power flow equations	$Q_{Di}^{(0)}$	Primary value of the reactive load
If_{max}	Maximum limit of the generator exciting current	Q_{Gi}	Reactive generation
I_l	Current passing through the line	$Q_{Gi}^{(0)}$	Primary value of the reactive generation
kpv_i	Load active power	R_l	Resistance of line L
kqv_i	Load reactive power	V_i	Value of bus voltage magnitude
Pf_i	Load factor coefficient	V_i^{min}	Lower voltage limit
P_i	Active power flow	V_i^{max}	Upper voltage limit
P_{Di}	Active load	Y_{ij}	Magnitude of the i-j line admittance
$P_{Di}^{(0)}$	Primary value of the active load	Z_{ij}	Impedance of the line between bus i and j
P_{Gi}	Active generation	α_i	Generation contribution of each bus
		β_i	Load contribution of each bus
		γ	Lagrange multiplier
		λ	Lagrange multiplier
		δ_i	Bus voltage angle
		ϕ_{ij}	Angle of the i-j line admittance

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