Optimal Network Reconfiguration of Large-Scale Distribution System Using Harmony Search Algorithm

Rayapudi Srinivasa Rao, Sadhu Venkata Lakshmi Narasimham, Manyala Ramalinga Raju, and A. Srinivasa Rao

***Abstract*—Electrical distribution network reconfiguration is a complex combinatorial optimization process aimed at finding a radial operating structure that minimizes the system power loss while satisfying operating constraints. In this paper, a harmony search algorithm (HSA) is proposed to solve the network reconfiguration problem to get optimal switching combination in the network which results in minimum loss. The HSA is a recently developed algorithm which is conceptualized using the musical process of searching for a perfect state of harmony. It uses a stochastic random search instead of a gradient search which eliminates the need for derivative information. Simulations are carried out on 33- and 119-bus systems in order to validate the proposed algorithm. The results are compared with other approaches available in the literature. It is observed that the proposed method performed well compared to the other methods in terms of the quality of solution.**

***Index Terms*—Distribution system, harmony search algorithm, loss reduction, network reconfiguration.**

I. INTRODUCTION

FEEDER reconfiguration entails altering the topological structure of distribution feeders by changing the open/close status of the switches under both normal and abnormal operating conditions. Since many candidate-switching combinations are possible in a distribution system, finding the operating network reconfiguration becomes a complicated combinatorial, nondifferentiable constrained optimization problem. Distribution system reconfiguration for loss reduction was first proposed by Merlin and Back [1]. They employed a blend of optimization and heuristics to determine the minimal-loss operating configuration for the distribution system represented by a spanning tree structure at a specific load condition. The strength of the algorithm is that an optimal solution can be obtained which is independent of the initial switch status. But the shortcomings in the paper are: 1) contribution of only real component of current was considered while calculating power loss and assumed that the voltage angles are negligible; 2) the losses associated with line equipment are not considered; and 3) the solution proved to be very time consuming as the possible system configurations are 2^n, where n is line sections equipped with switches.

A branch and bound type heuristic algorithm was suggested by Civanlar *et al.* [2], where a simple formula was developed for determination of change in power loss due to a branch exchange. The advantages of this algorithm are rapid determination of a switching configuration which reduce losses and reduced number of switching combinations due to heuristic rules. The disadvantages are: 1) only one pair of switching operations is considered at a time and 2) the reconfiguration of network depends on the initial switch status.

Power flow method-based heuristic algorithm (PFBHA) is suggested by some authors [3]–[5] to determine the minimum loss configuration of radial distribution networks. Shirmohammadi and Hong [3] modeled the weakly meshed networks accurately by using a compensation-based power flow technique. The shortcomings of [3] are the inefficient search strategy which is time consuming and unbalanced multiphase distribution systems are not efficiently modeled. Wagner *et al.* [4] presented the reconfiguration problem as linear transportation problem and approximated the quadratic feeder line section losses as piecewise linear function. This method converges well and is efficient for small distribution systems. However, the analysis of larger networks (those in excess of 1000 buses) would result in an excessive computational burden for real-time implementation. Goswami and Basu [5] proposed a method, in which any switch closure is complemented by the opening of another switch to ensure a radial network. Although the method is suitable for smaller systems, it becomes prohibitive for larger networks as the solution involves a huge number of computations.

Simulated annealing (SA) method was proposed as a solution procedure by some authors [6]–[8] to search an acceptable non-inferior solution. Although mathematically rigorous, the algorithm is very time consuming for any practical problem. Nara *et al.* [9] presented a solution using a genetic algorithm (GA) to look for the minimum loss configuration. They formed strings, which represented switch status, a fitness function consisting of total system losses, and penalty values of voltage drop limit and current capacity limit. Sample results demonstrate that, although the minimal loss solutions were obtained, solution time was prohibitive for even the 97-bus sample system (in excess of

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15 min). Das [10] presents an algorithm based on the heuristic rules and fuzzy multi-objective approach for optimizing network configuration. The four objectives—load balancing among the feeders, real power loss, deviation of nodes voltage, and branch current constraint violation—are modeled and results obtained are encouraging, but criteria for selecting a membership function for each objective are not provided.

Although the methods mentioned above do not have good convergence property, most of them are used due to less computation time requirement for smaller systems. For larger systems, the computation time is prohibitively high and may not be suitable for real-time operation.

In this paper, harmony search algorithm (HSA) is proposed for the minimization of power loss in the distribution system. The proposed method is tested on 33- and 119-bus systems and results obtained are very encouraging. Further, the results converge to optimal solution very fast even for a large system.

The rest of this paper is organized as follows: Section II gives the problem formulation. Section III provides an overview of HSA and describes how this can be applied for the network reconfiguration problem. Section IV presents results of 33- and 119-bus systems and Section V outlines conclusions.

II. PROBLEM FORMULATION

The network reconfiguration problem in a distribution system is to find a best configuration of radial network that gives minimum power loss while the imposed operating constraints are satisfied, which are voltage profile of the system, current capacity of the feeder, and radial structure of the distribution system. The objective function for the minimization of power loss is described as

$$Minimize\ f = min.(P_{T,Loss}) \tag{1}$$

$$\left.\begin{array}{c} Subjected\ to\quad V_{\min} \le |V_i| \le V_{\max} \\ \text{and}\quad |I_j| \le |I_{j,\max}| \end{array}\right\} \tag{2}$$

$$\left.\begin{array}{c} det(A) = 1\ or\ -1\ (radial\ system) \\ det(A) = 0\ (not\ radial) \end{array}\right\} \tag{3}$$

where

$P_{T,Loss}$	total real power loss of the system;
$\lvert V_i\rvert$	voltage magnitude of bus i;
$V_{\min},\ V_{\max}$	bus minimum and maximum voltage limits, respectively; ($V_{\min} = 0.9$ p.u. and $V_{\max} = 1.0$ p.u.);
$I_j,\ I_{j,\max}$	current magnitude and maximum current limit of branch j, respectively;
A	bus incidence matrix;

The power flows are computed by the following set of simplified recursive equations [11] derived from the single-line diagram shown in Fig. 1:

$$\begin{aligned} P_{k+1} &= P_k - P_{Loss,k} - P_{Lk+1} \\ &= P_k - \frac{r_k}{|V_k|^2}\left\{P_k^2 + (Q_k + Y_k|V_k|^2)^2\right\} \\ &\quad - P_{Lk+1} \end{aligned} \tag{4}$$

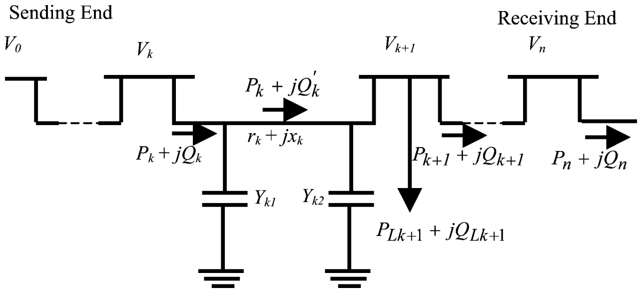

Fig. 1. Single-line diagram of a main feeder.

$$\begin{aligned} vQ_{k+1} &= Q_k - Q_{Loss,k} - Q_{Lk+1} \\ &= Q_k - \frac{x_k}{|V_k|^2}\left\{P_k^2 + (Q_k + Y_{k1}|V_k|^2)^2\right\} \\ &\quad - Y_{k1}|V_k|^2 - Y_{k2}|V_{k+1}|^2 - Q_{Lk+1} \end{aligned} \tag{5}$$

$$\begin{aligned} |V_{k+1}|^2 &= |V_k|^2 + \frac{r_k^2 + x_k^2}{|V_k|^2}\left(\mathrm{P}_k^2 + Q_k'^2\right) \\ &\quad - 2\left(r_k P_k + x_k Q_k'\right) \\ &= |V_k|^2 + \frac{r_k^2 + x_k^2}{|V_k|^2} \\ &\quad \times \left(\mathrm{P}_k^2 + (Q_k + Y_k|V_k|^2)^2\right) \\ &\quad - 2\left(r_k P_k + x_k(Q_k + Y_k|V_k|^2)\right) \end{aligned} \tag{6}$$

where P_k and Q_k are the real and reactive powers flowing out of bus k, and P_{Lk+1} and Q_{Lk+1} are the real and reactive load powers at bus $k+1$. The shunt admittance is denoted by Y_{kl} at any bus k to ground. The resistance and reactance of the line section between buses k and $k+1$ are denoted by r_k and x_k, respectively.

The power loss of the line section connecting buses k and $k+1$ can be computed as

$$P_{Loss}(k, k+1) = r_k.\frac{(P_k^2 + Q_k'^2)}{|V_k|^2}. \tag{7}$$

Total power loss of the feeder, $P_{T,Loss}$, may then be determined by summing up the losses of all line sections of the feeder, which is given as

$$P_{T,Loss} = \sum_{k=1}^{n} P_{Loss}(k, k+1) \tag{8}$$

where n is the total number of lines sections in the system.

III. OVERVIEW OF HARMONY SEARCH ALGORITHM

The HSA is a new metaheuristic population search algorithm proposed by Geem *et al.* [12]. 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 is simple in concept, less in parameters, and easy in implementation. It has been successfully applied to various benchmarking, and real-world problems like traveling salesman problem [13]. The main steps of HS are as follows [12].

Step 1) Initialize the problem and algorithm parameters.
Step 2) Initialize the harmony memory.
Step 3) Improvise a new harmony.
Step 4) Update the harmony memory.
Step 5) Check the termination criterion.

These steps are described in the next five subsections.

A. Initialization of Problem and Algorithm Parameters

The general optimization problem is specified as follows:

$$\begin{aligned} &Minimize && f(x) \\ &Subject\ to && x_i \in X, \quad i = 1, 2, \ldots N \end{aligned} \tag{9}$$

where $f(x)$ is an objective function; x is the set of each decision variable x_i; N is the number of decision variables; X_i is the set of the possible range of values for each decision variable, that is ${}_Lx_i \leq X_i \leq {}_Ux_i$ and ${}_Lx_i$ and ${}_Ux_i$ are the lower and upper bounds for each decision variable. The HS algorithm parameters are also specified in this step. These are the harmony memory size (HMS) , or the number of solution vectors in the harmony memory; harmony memory considering rate $(HMCR)$; pitch adjusting rate (PAR); and the number of improvisations (NI), or stopping criterion. The harmony memory (HM) is a memory location where all the solution vectors (sets of decision variables) are stored. Here, $HMCR$ and PAR are parameters that are used to improve the solution vector, which are defined in Step 3.

B. Initialize the Harmony Memory

In this step, the HM matrix is filled with as many randomly generated solution vectors as the HMS

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & .. & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & .. & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & .. & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & .. & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix}. \tag{10}$$

There is a possibility of infeasible solutions which violate the constraints. However, the algorithm forces the search towards feasible solution area. Static penalty functions are used to calculate the penalty cost for an infeasible solution. The total cost for each solution vector is evaluated using

$$fitness(\vec{X}) = f(\vec{X}) + \sum_{i=1}^{M} \alpha_i(\min[0, g_i(\vec{x})]^2 + \sum_{j=1}^{P} \beta_j(\min[0, h_j(\vec{x})]^2 \tag{11}$$

where α_i and β_j are the penalty coefficients. Generally, it is difficult to find a specific rule to determine the values of the penalty coefficients, and hence, these parameters remain problem dependent.

C. Improvise a New Harmony

A new harmony vector $\overrightarrow{x'} = (x_1', x_2', \ldots x_N')$ is generated based on three criteria: 1) memory consideration, 2) pitch adjustment, and 3) random selection. Generating a new harmony is called improvisation. According to memory consideration, ith variable $x_i^1 = (x_l^1 - x_1^{HMS})$. The $HMCR$, which varies between 0 and 1, is the rate of choosing one value from the historical values stored in the HM, while $(1 - HMCR)$ is the rate of randomly selecting one value from the possible range of values, as shown in (12):

$$\begin{aligned} &if\,(rand() < HMCR) \\ &x_i' \leftarrow x_i' \in \{x_i^1, x_i^2, \ldots x_1^{HMS}\} \\ &else \\ &x_i' \leftarrow x_i' \in X_i \\ &end \end{aligned} \tag{12}$$

where $rand()$ is a uniformly distributed random number between 0 and 1 and X_i is the set of the possible range of values for each decision variable, i.e., ${}_Lx_i \leq X_i \leq {}_Ux_i$. For example, an $HMCR$ of 0.85 indicates that HSA will choose decision variable value from historically stored values in HM with 85% probability or from the entire possible range with 15% probability. Every component obtained with memory consideration is examined to determine if pitch is to be adjusted. This operation uses the rate of pitch adjustment as a parameter as shown in the following:

$$\begin{aligned} &if\,(rand() < PAR) \\ &x_i' = x_i' \pm rand()*bw \\ &else \\ &x_i' = x_i' \\ &end \end{aligned} \tag{13}$$

where bw is an arbitrary distance bandwidth for the continuous design variable and $rand()$ is uniform distribution between -1 and 1. Since the problem is discrete in nature, bw is taken as 1 (or it can be totally eliminated from the equation).

D. Update Harmony Memory

If the new harmony vector $\overrightarrow{x'} = (x_1', x_2', \ldots x_N')$ has better fitness function than the worst harmony in the HM, the new harmony is included in the HM and the existing worst harmony is excluded from the HM.

E. Check Termination Criterion

The HSA is terminated when the termination criterion (e.g., maximum number of improvisations) has been met. Otherwise, steps 3 and 4 are repeated.

In order to demonstrate the convergence capability of harmony search, let us consider the harmony memory with the following parameters:

- size of $HM = M$;
- number of instruments (variables)$= N$;
- number of possible notes (values) of instruments $= L$;

- number of optimal note (value) of instrument i in $HM = H_i$;
- harmony memory considering rate $= H_r$;
- optimal harmony (optimal vector)$=$ (X, Y, Z).

The probability to find the optimal harmony, $Pr(H)$, is

$$\Pr(H) = \prod_{i=1}^{N} \left[H_r \frac{H_i}{M} + (1 - H_r) \frac{1}{L} \right] \tag{14}$$

where the pitch adjusting rate is not considered because it is an optional operator. Initially, the HM is stuffed with random harmonies. If there is no optimal note of all instruments in the HM

$$H_1 = H_2 = \cdots = H_N = 0$$
$$\text{and}$$
$$\Pr(H) = \left[(1 - H_r) \frac{1}{L} \right]^N .$$

This means that the probability $Pr(H)$ is very low. Consider a solution vector (X, Y, Z). If the schema of optimal harmony such as $(*, Y, Z)$, $(X, *, Z)$, $(X, Y, *)$ have better fitness (better evaluation) than other ones, the number of optimal notes of instrument i in the HM, H_i will be increased iteration by iteration. Consequently, the probability of finding the optimal harmony, $Pr(H)$, will increase.

It is observed that, by nature, the harmony search incorporates the structure of existing heuristic methods. It preserves the history of past vectors (harmony memory) similar to tabu search (TS), and is able to vary the adaptation rate (harmony memory considering rate) from the beginning to the end of computation resembling SA, and manages several vectors simultaneously in a manner similar to GAs. However, the major difference between GA and HS is that HS makes a new vector from all the existing vectors (all harmonies in the harmony memory), while GA makes the new vector only from two of the existing vectors (the parents). In addition, HS can independently consider each component variable in a vector while it generates a new vector, whereas GA cannot since it has to maintain the structure of a gene.

IV. APPLICATION OF HSA FOR RECONFIGURATION PROBLEM

The optimum distribution network is obtained by first generating all possible radial structures of the given network (without violating the constraints) and subsequently evaluating the objective function. However, real distribution systems contain many nodes, branches, and trees. Conventional optimization methods are ineffective and impractical, because of dimensionality. In this paper, HSA is proven to be an effective and useful approach for the network reconfiguration problem.

In general, the structure of solution vector [15] for a radial distribution system is expressed by "Arc No.(i)" and "SW. No.(i)" for each switch i. "Arc No.(i)" identifies the arc (branch) number that contains the ith open switch, and "SW. No.(i)" identifies the switch that is normally open on Arc No.(i). For large distribution networks, it is not efficient to represent every arc in the string, since its length will be very long. In fact, the number of open switch positions is identical to keep the system radial once the topology of the distribution networks is fixed, even if the open switch positions are changed. Therefore, to memorize the radial configuration, it is enough to number only the open switch positions. Fig. 2 shows a 33-bus [15] distribution network with five switches that are normally open.

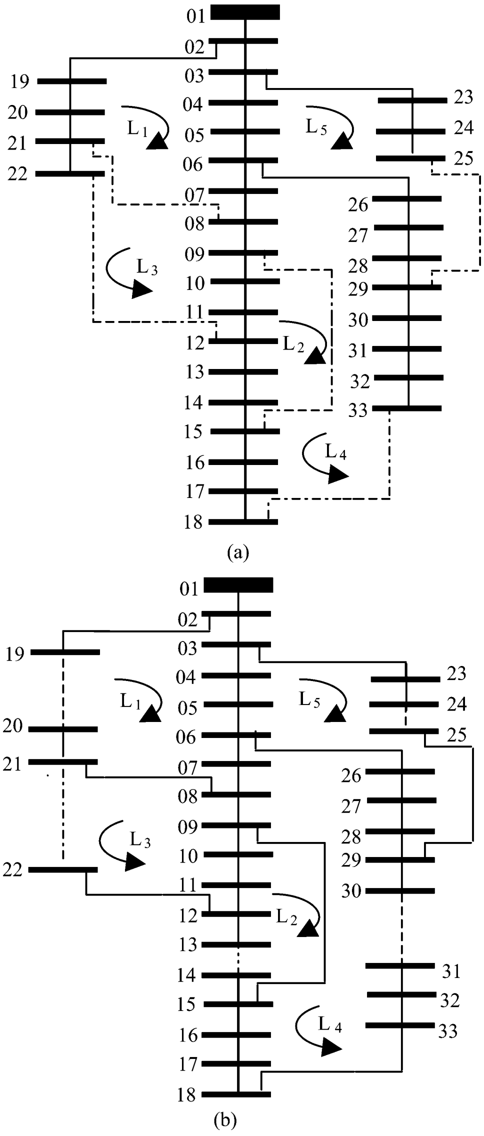

Fig. 2. A 33-bus radial distribution system.

The open switches in the loops L_1 to L_5 for the network given in Fig. 2(a) are given as 33, 34, 35, 36, and 37. Similarly, other radial topology is generated randomly with the open switches 19, 13, 21, 30, and 24 as shown in Fig. 2(b) and open status of these switches satisfy the radial topology without any isolated node in the system. In order to represent an optimum network topology, only positions of the open switches in the distribution network need to be known. Suppose the number of normally open switches (tie switches) is N; then the length of a solution vector is N.

The solution vectors for Fig. 2(a) and (b) are represented as follows:

The solution vector for Fig. 2(a):

$$HW^1 = [33 \quad 34 \quad 35 \quad 36 \quad 37].$$

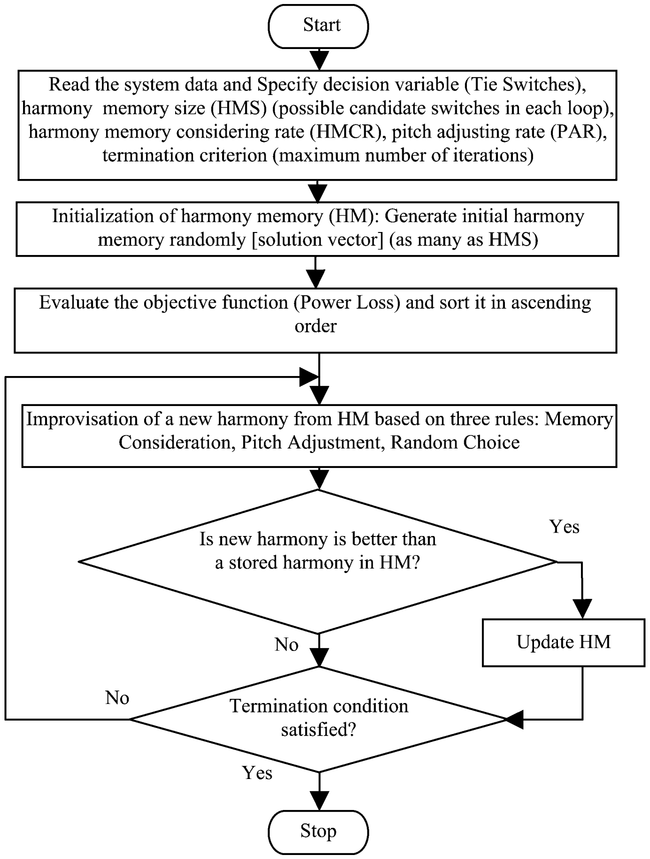

Fig. 3. Flow chart of harmony search algorithm.

The solution vector for Fig. 2(b):

$$HW^2 = [19 \quad 13 \quad 21 \quad 30 \quad 24].$$

Similarly, all other possible solution vectors of Fig. 2 are generated without violating the radial structure or isolating any load in the network. The total number of solution vectors (HMS) generated are less than or equal to the highest numbers of switches in any individual loop. The total harmony matrix generated randomly, with objective function values sorted in ascending order, is shown in (15):

$$HM = \begin{bmatrix} 7 & 10 & 14 & 28 & 32 & | & 138.54 \\ 7 & 11 & 34 & 26 & 36 & | & 141.32 \\ 6 & 35 & 14 & 37 & 16 & | & 145.11 \\ 6 & 21 & 34 & 25 & 16 & | & 152.23 \\ 7 & 35 & 13 & 37 & 30 & | & 155.75 \\ 7 & 9 & 13 & 24 & 30 & | & 157.31 \\ 20 & 9 & 14 & 25 & 16 & | & 170.57 \\ 20 & 10 & 14 & 27 & 17 & | & 178.41 \\ 19 & 11 & 14 & 26 & 16 & | & 182.13 \\ 19 & 21 & 34 & 26 & 17 & | & 192.37 \end{bmatrix}. \tag{15}$$

The new solution vectors are updated by using (12). Using the new solution vectors, the worst vectors of previous iteration will be replaced with a new random vector selected from the population that has less objective function value. This procedure is repeated until termination criteria are satisfied. The flow chart of the proposed algorithm is shown in Fig. 3.

TABLE I
PARAMETERS OF THE HSA

HMS	10
HMCR	0.85
PAR	0.3
Number of iterations	250

V. TEST RESULTS

The proposed method is tested on 33-bus [15] and 119-bus [19] radial distribution systems, and results are obtained to evaluate its effectiveness. For all these systems, the substation voltage is considered as 1 p.u., and all tie and sectionalizing switches are considered as candidate switches for reconfiguration problem. The algorithm was developed in MATLAB, and the simulations were done on a computer with Pentium IV, 3.0 GHz, 1GB RAM.

A. Test Case I

The first example system is a 33–bus, 12.66-kV, radial distribution system [15] as shown in Fig. 2. It consists of five tie lines and 32 sectionalize switches. The normally open switches are 33 to 37, and the normally closed switches are 1 to 32. The line and load data of the network are obtained from [15], and the total real and reactive power loads on the system are 3715 kW and 2300 kVAr, respectively. The initial power loss of this system is 202.771 kW. The lowest bus bar voltage is 0.9131 p.u., which occurs at node 18.

The parameters of HSA used in the simulation of the network are shown in Table I. The optimal configuration obtained by the proposed algorithm is 7, 10, 14, 37, 36, which has a real power loss of 138.067 kW. This amounts to a reduction of 31.89% in total power loss. The minimum node voltage of the system is improved to 0.9342 p.u. (node 33) after reconfiguration. The node voltages at each bus and their angles are shown in Table II.

The voltage profiles of the system before and after reconfiguration are shown in Fig. 4. The minimum voltage in the system after reconfiguration is improved by 2.6%.

The angles of voltages at various buses in the system are shown in Fig. 5. The improvement in angles after reconfiguration is an indication of relieving of overload on feeders of the system. From Fig. 5, it can be observed that the feeders in the middle of the system are relieved of higher loads than those feeders at ends.

The real power flows in each branch before and after reconfiguration are shown in Fig. 6. From Fig. 6, it is observed that the power flow in each branch is reduced after reconfiguration. This shows that feeders are relieved from the overloading and makes it possible to load the feeders further.

The power loss in each branch before and after reconfiguration is shown in Fig. 7. It is observed that the losses in almost every branch is reduced, except at 18, 19, 20, 21, 33, 34, and 35, where the losses are increased because of shifting of loads onto these feeders.

For the purpose of comparison, GA [9], refined GA (RGA) [17], and Improved TS (ITS) [18] are also applied to solve this problem. For the GA and RGA, population size, crossover rate,

TABLE II
NODE VOLTAGES AND ANGLES OF 33-BUS SYSTEM

Bus No:	Before Reconfiguration		After Reconfiguration	
	Voltage	Angle	Voltage	Angle
1	1.0000	0	1.0000	0
2	0.9970	-0.0148	0.9971	-0.0140
3	0.9829	-0.0967	0.9869	-0.0964
4	0.9754	-0.1614	0.9823	-0.1615
5	0.9680	-0.2263	0.9778	-0.2268
6	0.9496	-0.1364	0.9666	-0.2368
7	0.9461	0.0811	0.9659	-0.1999
8	0.9412	0.0470	0.9653	0.6421
9	0.9350	0.1150	0.9621	0.6970
10	0.9292	0.1724	0.9616	0.7054
11	0.9283	0.1656	0.9681	0.5072
12	0.9268	0.1546	0.9683	0.5093
13	0.9207	0.2377	0.9657	0.5224
14	0.9185	0.3092	0.9649	0.5375
15	0.9171	0.3433	0.9574	0.8273
16	0.9157	0.3641	0.9561	0.8466
17	0.9137	0.4341	0.9541	0.9126
18	**0.9131**	0.4426	0.9536	0.9205
19	0.9965	-0.0040	0.9953	0.0207
20	0.9929	0.0605	0.9802	0.2758
21	0.9922	0.0797	0.9760	0.3824
22	0.9916	00998	0.9733	0.4454
23	0.9793	-0.0660	0.9833	-0.0659
24	0.9727	0.0208	0.9767	0.0205
25	0.9693	0.0631	0.9734	0.0626
26	0.9477	-0.1735	0.9647	-0.2750
27	0.9451	-0.2259	0.9622	-0.3263
28	0.9338	-0.3007	0.9510	-0.3987
29	0.9256	-0.3704	0.9429	-0.4663
30	0.9220	-0.4660	0.9395	-0.5598
31	0.9178	-0.3865	0.9354	-0.4813
32	0.9169	-0.3649	0.9345	-0.4601
33	0.9166	-0.3578	**0.9342**	-0.4531

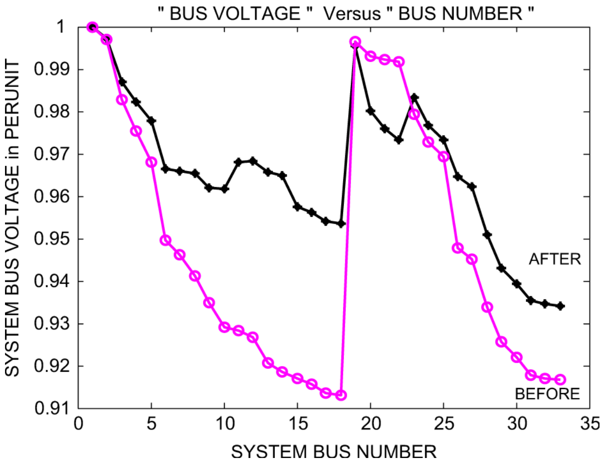

Fig. 4. Voltage profiles of 33-bus system.

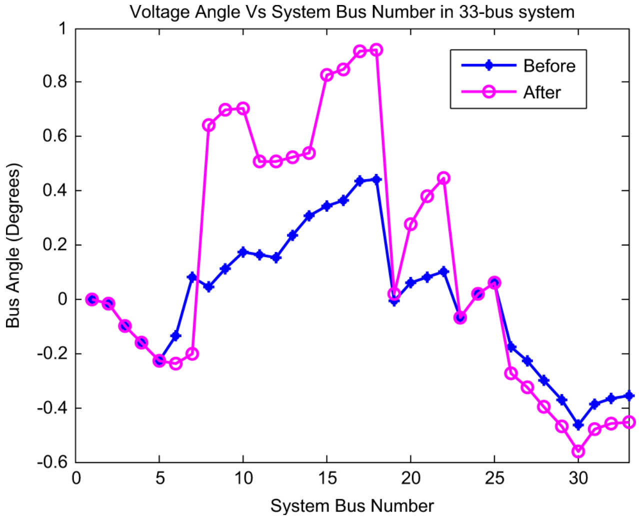

Fig. 5. Angles of voltages of at various buses in 33-bus system.

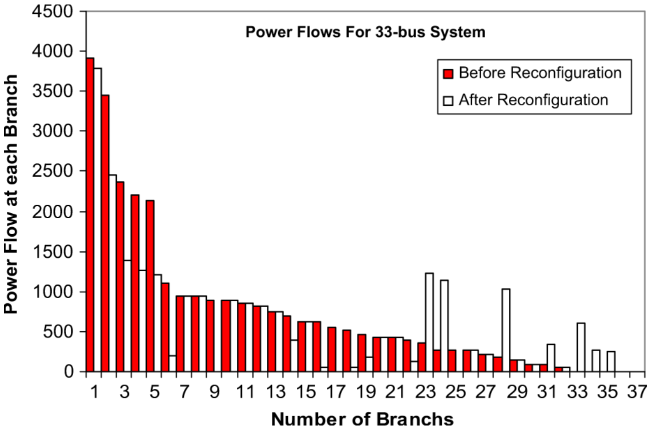

Fig. 6. Power flow in 33-bus system before and after reconfiguration.

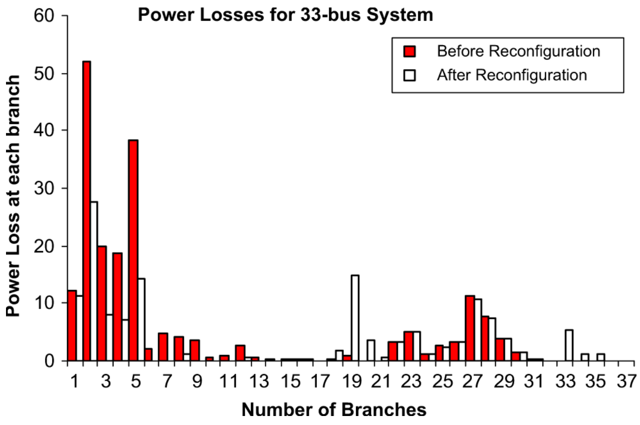

Fig. 7. Losses in 33-bus system before and after reconfiguration.

and mutation rate are chosen to be 85, 0.8, and 0.05, respectively, and for ITS, the parameters chosen are the same as in [18].

To verify the performance of the proposed algorithm, this case was repeatedly solved 200 times. The best and the worst values among the best solutions as well as the average value and standard deviation (STD) for the best solutions of these 200 runs are listed in Table III. A smaller standard deviation implies that most of the best solutions are close to the average. The best solutions for these 200 runs are compared with the best objective function values obtained by the GA, RGA, ITS, and HSA. The GA, RGA, and ITS got premature convergence so that their standard deviation is larger than that of the HSA method.

From Table III, it is also observed that the optimal power loss obtained by the proposed method is 5%, 3%, and 2% less than that of GA, RGA, and ITS, respectively. The convergence rate

TABLE III
SIMULATION RESULTS OF 33-BUS SYSTEM

Item	Initial Configuration	Final Configuration			
		GA [9]	RGA [17]	ITS [18]	Proposed Method HSA
Tie Switches	33,35,34, 37,36	7,9,14, 37, 32	7,9,14, 37, 32	7,9,14, 37, 36	7,10,14, 37,36
Loss (kW) (For 200 Runs) Best	202.71	141.6	139.5	139.28	138.06
Worst		202.7	198.4	196.3	195.10
Average		166.2	164.9	163.5	152.33
STD		14.53	13.34	12.11	11.28
Average Loss Reduction (%)	--	18.01	18.65	19.34	24.85
Loss Reduction (Best value) (%)	--	30.15	31.20	31.29	31.89
Minimum Voltage (p.u)	0.9131	0.9290	0.9315	0.9210	0.9342
CPU Time (s)	--	19.1	13.8	8.1	7.2

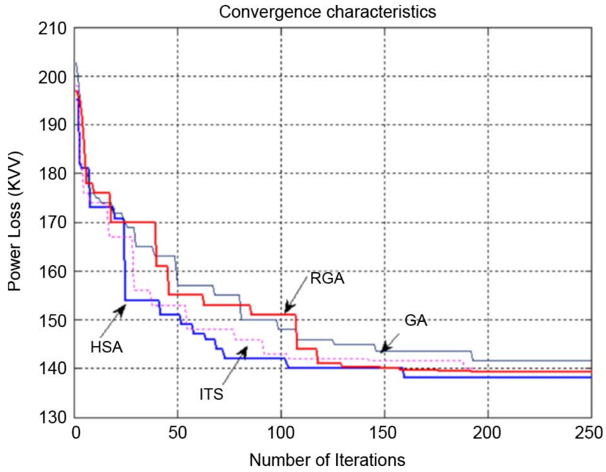

Fig. 8. Convergence characteristics of HSA for 33-bus system.

TABLE IV
RESULTS BASED ON DIFFERENT PARAMETERS
SETTING OF HSA FOR 33-BUS SYSTEM

Scenario	Paramter Setting			Power Loss (kW)
	HMCR	PAR	HMS	
1	0.95	0.3	10	146.73
	0.70	0.3	10	142.11
	0.60	0.3	10	143.28
	0.30	0.3	10	153.60
2	**0.85**	**0.3**	**10**	**138.06**
	0.85	0.4	10	138.31
	0.85	0.5	10	138.40
	0.85	0.6	10	138.45
3	0.85	0.3	2	158.38
	0.85	0.3	15	147.96
	0.85	0.3	20	160.87
	0.85	0.3	30	162.67

of the proposed HSA algorithm compared with that of the GA, RGA, and ITS methods for 33-bus system is depicted in Fig. 8. It can be seen that the proposed method has a relatively fast convergence performance compared to other methods.

Simulations are carried out for 250 iterations and optimum solution is obtained after 160 iterations. The average CPU time taken by the processor to carry out the simulations for 250 iterations is 7.2 s, which is less than all the other methods.

To determine the impacts of different parameters of the HS algorithm on the solution quality and convergence behavior, an empirical study is performed. To show the effects of single parameter changes, 12 different cases are tested as shown in Table IV. Each case is tested over 200 runs in three scenarios, and maximum number of iterations is fixed to 250 for all runs. In scenario 1, 2, and 3, HMCR, PAR, and HMS are varied, respectively, and other two parameters are kept constant.

The total power loss for 33-bus distribution by varying the parameters are summarized in Table IV. The HMCR determines the rate of choosing one value from the historical values stored in the HM. The larger the HMCR, the less exploration is achieved; the algorithm further relies on stored values in HM, and this potentially leads to the algorithm getting stuck in a local optimum. On the other hand, choosing the HMCR too small decreases the algorithm efficiency, and the HS algorithm behaves like a pure random search, with less assistance from the historical memory. As shown in Table IV, large and small HMCR values lead to a decrease in the solution quality. Large and small HMS values decrease the efficiency of the harmony memory as seen in Table IV. For most problems, an HMS between N and 2N is reasonable. It is observed that the algorithm has small sensitivity to PAR values.

B. *Test Case II*

To demonstrate the applicability of the proposed method in large-scale distribution systems, it was applied to a 119-bus system [18] as shown in Fig. 9. It consists of 118 sectionalizing switches (normally closed) and 15 tie switches (normally opened). The normally open switches are 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, and 133. The line and load data of the system can be found in [18]. The total power loads are 22709.7 kW and 17041.1 kVAr, and the initial real power loss is 1298.09 kW. The minimum node voltage of the system is 0.8783 p.u., which occurs at bus 116.

For this test case, HMS value and maximum number of iterations are taken as 25 and 600. The other parameters of the algorithm are the same as test case I. The optimal configuration obtained with proposed algorithm is 43, 27, 23, 53, 123, 62, 125, 126, 75, 72, 129, 130, 131, 132, and 33. The optimal power loss after reconfiguration is 854.205 kW. The optimal configuration is shown in Fig. 10. The percentage reduction in real power loss after reconfiguration is approximately 35%. The minimum voltage in the system is improved to 0.9323 p.u. after reconfiguration at the same bus. Similar to test case I, GA [9], RGA [17], and ITS [18] are applied to solve this problem for the purpose of comparison, and results are shown in Table V. From Table V, it is observed that the results obtained by the proposed method are encouraging and better than all other methods. The CPU time taken by the processor to carry out simulations for 600 iterations is 8.61 s. The optimal solution is obtained after 200 iterations.

The proposed algorithm and other methods (GA, RGA, and ITS) are repeatedly solved 200 times. The best and the worst values among the best solutions as well as the average value

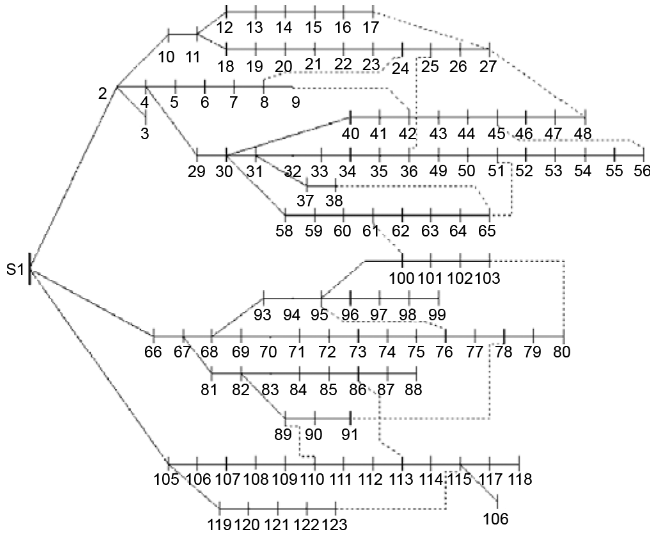

Fig. 9. Initial configuration of 119-bus test system.

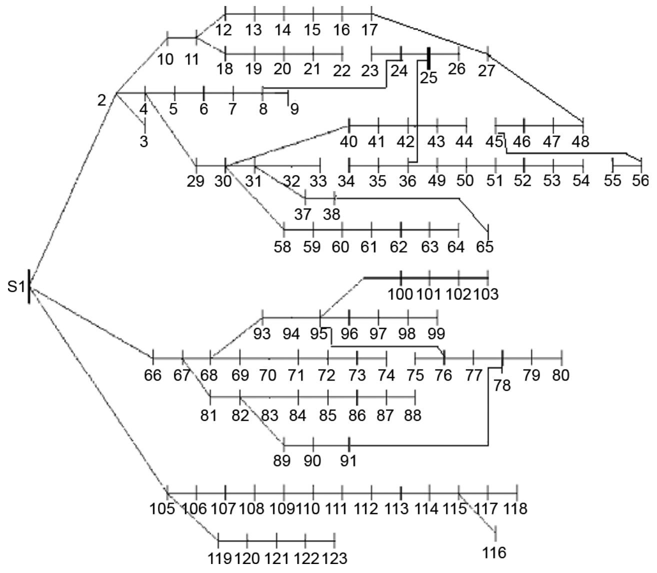

Fig. 10. Optimal configuration of 119-bus test system.

and standard deviation (STD) for the best solutions of these 200 runs are also listed in Table V. From the table, it can be seen that the performance of the proposed HSA method is better than GA, RGA, and ITS methods.

TABLE V
SIMULATION RESULTS OF 119-BUS SYSTEM

Item		Initial Configuration	Final Configuration			
			GA [9]	RGA [17]	ITS [18]	Proposed Method
Tie Switches		119,120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133	43,120, 24, 51, 49, 62, 40,126, 74, 73, 77, 83, 31,110, 35	43, 27, 23, 52, 49, 62, 40,126, 74, 73, 77,83, 131,110, 33	43, 27, 24, 52, 120, 59, 40, 96, 75, 72, 98,130, 131,110, 35	43, 27, 23, 53, 123, 62, 125,126, 75, 72, 129,130, 131,132, 33
Loss (kW)	Best	1301.9	885.56	883.13	865.86	854.21
	Worst		1301.90	1297.34	1288.17	1282.73
	Average		965.8	963.1	952.6	935.01
	STD		78.5	77.4	73.2	69.3
Average Loss Reduction (%)		--	25.81	26.02	26.83	28.10
Loss Reduction (Best Value) (%)		--	31.98	32.16	33.49	34.39
Minimum Voltage (p.u)		0.8783	0.9321	0.9321	0.9323	0.9323
CPU Time (s)		--	24.45	17.53	9.038	8.61

VI. CONCLUSIONS

In this paper, a recently developed meta-heuristic HSA is successfully applied to optimize radial distribution systems with objectives of improving the voltage profile and minimizing real loss. Simulations are carried on two test cases, comprising 33 and 119 buses, and results are compared with other methods GA, RGA, and ITS available in the literature. Results show that the proposed algorithm can converge to optimum solution quickly with better accuracy compared to other methods mentioned. Computational results of 33-bus system showed that proposed HSA method is better than GA, RGA, and ITS. It can be observed that 24.85% of average loss reduction is achieved by HSA comparing with 18.01% by the GA, 18.65% by the RGA, and 19.34% by the ITS as shown in Table III. For the large-scale system like 119-bus system, numerical results demonstrate that the advantage of HSA is more remarkable. In 119-bus system, 28.10% of average loss reduction can be achieved by the HSA comparing with 25.81% by the GA, 26.02% by the RGA, and 26.83% as shown in Table V. From Table IV, the results based on some different parameters setting for the HSA method show that the proposed method is effective in loss reduction for various parameters setting demonstrating a certain extent adaptive performance for the proposed method. The convergence rate curve confirms that the HSA method can more efficiently search the optimal or near-optimal solution for network reconfiguration problems. Moreover, it can be observed from results of 33-bus and 119-bus systems that the proposed method is the best in the solution as well as the CPU time. In the proposed method, the size of solution the vector is equal to the number of tie switches in the system. But in the conventional and other methods, the size of the solution vector is equal to the total number of switches in the system. As the size of the system increases, the size of the solution vector in the other methods is large compared to the proposed method. Thus, the computation time of the proposed method is less than the other methods. This method is useful for analyzing existing systems, helps in planning a future system, and is especially suitable for a large-scale practical system.

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