Power Loss Minimization in Distribution System Using Network Reconfiguration in the Presence of Distributed Generation

R. Srinivasa Rao, K. Ravindra, K. Satish, and S. V. L. Narasimham

***Abstract*—This paper presents a new method to solve the network reconfiguration problem in the presence of distributed generation (DG) with an objective of minimizing real power loss and improving voltage profile in distribution system. A meta heuristic Harmony Search Algorithm (HSA) is used to simultaneously reconfigure and identify the optimal locations for installation of DG units in a distribution network. Sensitivity analysis is used to identify optimal locations for installation of DG units. Different scenarios of DG placement and reconfiguration of network are considered to study the performance of the proposed method. The constraints of voltage and branch current carrying capacity are included in the evaluation of the objective function. The method has been tested on 33-bus and 69-bus radial distribution systems at three different load levels to demonstrate the performance and effectiveness of the proposed method. The results obtained are encouraging.**

***Index Terms*—Distributed generation, distribution system, Harmony Search Algorithm, real power loss, reconfiguration, voltage profile.**

NOMENCLATURE

P_k	Real power flowing out of bus k.
Q_k	Reactive power flowing out of bus k.
P'_k	Real power flowing out of bus k after reconfiguration.
Q'_k	Reactive power flowing out of bus k after reconfiguration.
P_{Lk+1}	Real load power at bus $k+1$.
Q_{Lk+1}	Reactive load power at bus $k+1$.
P_G	Real power supplied by DG.
Q_G	Reactive power supplied by DG.
$P_{Lk,,eff}$	Total effective active power supplied beyond the bus "k".
$Q_{Lk,,eff}$	Total effective reactive power supplied beyond the bus "k".
L	Total length of the feeder from source to bus k in km.
G	Distance from source to the DG location in km.
n	Total number of lines sections in the system.
Y_k	Shunt admittance at any bus K.
r_k	Resistance per km of the line section between buses k and $k+1$.
$R_k(=Lr_k)$	Resistance of the line section between buses k and $k+1$.
$X_k(=Lx_k)$	Reactance of the line section between buses k and $k+1$.
$P_{Loss}(k,k+1)$	Loss in the line section connecting buses k and $k+1$.
$P_{T,Loss}$	Total power loss of the feeder.
$P'_{T,Loss}$	Total power loss of the feeder after reconfiguration.
V_k	Voltage at bus K.
V'_k	Voltage at bus K after reconfiguration.
V_{max}	Maximum bus voltage.
V_{min}	Minimum bus voltage.
$I_{k,k+1}$	Current in line section between buses k and $k+1$.
$I_{k,k+1,max}$	Maximum current limit of line section between buses k and $k+1$.
A	Bus incidence matrix.

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I. INTRODUCTION

DUE to uncertainty of system loads on different feeders, which vary from time to time, the operation and control of distribution systems is more complex particularly in the areas where load density is high. Power loss in a distributed network will not be minimum for a fixed network configuration for all cases of varying loads. Hence, there is a need for reconfiguration of the network from time to time. Network reconfiguration is the process of altering the topological structure of feeders by changing open/closed status of sectionalizing and tie switches. In general, networks are reconfigured to reduce real power loss and to relieve overload in the network. However, due to dynamic nature of loads, total system load is more than its generation capacity that makes relieving of load on the feeders not possible and hence voltage profile of the system will not be improved to the required level. In order to meet required level of load demand, DG units are integrated in distribution network to improve voltage profile, to provide reliable and uninterrupted power supply and also to achieve economic benefits such as minimum power loss, energy efficiency and load leveling. To date, network reconfiguration and DG placement in distribution networks are considered independently. However, in the proposed method, network reconfiguration and DG installation are dealt simultaneously for improved loss minimization and voltage profile.

Since network reconfiguration is a complex combinatorial, non-differentiable constrained optimization problem, many algorithms are proposed in the past. Merlin and Back [1] first proposed network reconfiguration problem and they used a branch-and-bound-type optimization technique. The drawback with this technique is the solution proved to be very time consuming as the possible system configurations are 2^n, where n is line sections equipped with switches. Based on the method of Merlin and Back [1], a heuristic algorithm has been suggested by Shirmohammadi and Hong [2]. The drawback with this algorithm is simultaneous switching of the feeder reconfiguration is not considered. Civanlar *et al.* [3] suggested a heuristic algorithm, where a simple formula was developed to determine change in power loss due to a branch exchange. The disadvantage of this method is only one pair of switching operations is considered at a time and reconfiguration of network depends on the initial switch status. Das [4] presented an algorithm based on the heuristic rules and fuzzy multi-objective approach for optimizing network configuration. The disadvantage in this is criteria for selecting membership functions for objectives are not provided. Nara *et al.* [5] presented a solution using a genetic algorithm (GA) to look for the minimum loss configuration in distribution system. Zhu [6] presented a refined genetic algorithm (RGA) to reduce losses in the distribution system. In RGA, the conventional crossover and mutation schemes are refined by a competition mechanism. Rao *et al.*[7] proposed Harmony Search Algorithm (HSA) to solve the network reconfiguration problem to get optimal switching combinations simultaneously in the network to minimize real power losses in the distribution network.

Deregulation of electricity markets in many countries worldwide brings new perspectives for distributed generation of electrical energy using renewable energy sources with small capacity. Typically 5-kW to 10-MW capacities of DG units are installed nearer to the end-user to provide the electrical power. Since selection of the best locations and sizes of DG units is also a complex combinatorial optimization problem, many methods are proposed in this area in the recent past. Rosehart and Nowicki [8] presented a Lagrangian based approach to determine optimal locations for placing DG in distribution systems considering economic limits and stability limits. Celli *et al.* [9] presented a multi-objective algorithm using GA for sitting and sizing of DG in distribution system. Wang and Nehrir [10] proposed an analytical method to determine optimal location to place a DG in distribution system for power loss minimization. Agalgaonkar *et al.* [11] discussed placement and penetration level of the DGs under the SMD framework.

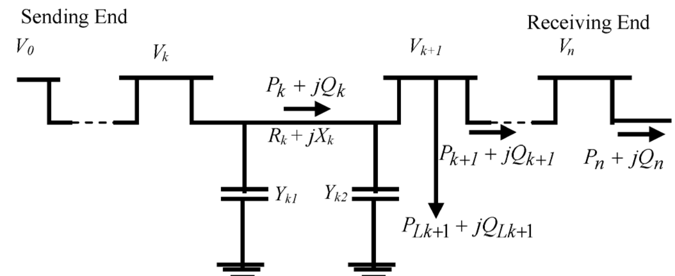


Fig. 1. Single-line diagram of a main feeder.

In this paper, HSA [12] has been proposed to solve the distribution system network reconfiguration problem in the presence of distributed generation. The algorithm is tested on 33- and 69-bus systems and results obtained are compared with other methods available in the literature.

The rest of this paper is organized as follows: Section II gives the problem formulation, Section III provides sensitivity analysis for DG allocation, Section IV gives the overview of proposed optimization algorithm, Section V explains the application of HSA to network reconfiguration problem in the presence of distributed generation, Section VI presents results, and Section VII outlines conclusions.

II. Problem Formulation

A. Power Flow Equations

Power flows in a distribution system are computed by the following set of simplified recursive equations [13] derived from the single-line diagram shown in Fig. 1:

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

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

$$\begin{aligned} |V_{k+1}|^2 &= |V_k|^2 + \frac{R_k^2 + X_k^2}{|V_k|^2}\left(\mathrm{P}_\mathrm{k}^2 + Q_k'^2\right) - 2(R_kP_k + X_kQ_k) \\ &= |V_k|^2 + \frac{R_k^2 + X_k^2}{|V_k|^2}\left(\mathrm{P}_\mathrm{k}^2 + \left(Q_k + Y_k|V_k|^2\right)^2\right) \\ &\quad - 2\left(R_kP_k + X_k\left(Q_k + Y_k|V_k|^2\right)\right). \end{aligned} \tag{3}$$

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

$$P_{Loss}(k, k+1) = R_k \cdot \frac{\left(P_k^2 + Q_k^2\right)}{|V_k|^2}. \tag{4}$$

The 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

$$P_{T,Loss} = \sum_{k=1}^{n} P_{Loss}(k, k+1). \tag{5}$$

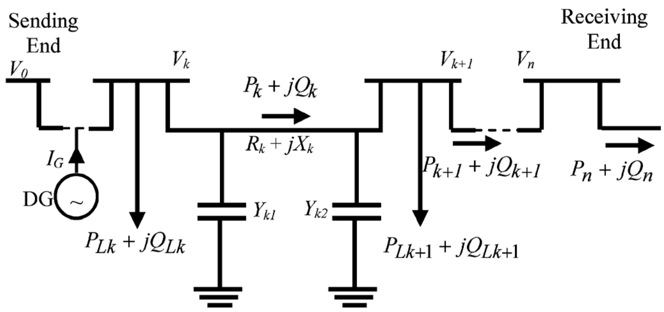


Fig. 2. Distribution system with DG installation at an arbitrary location.

B. Power Loss Using Network Reconfiguration

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 distribution system. The power loss of a line section connecting buses between k and $k+1$ after reconfiguration of network can be computed as

$$P'_{Loss}(k, k+1) = R_k . \frac{\left(P_k'^2 + Q_k'^2\right)}{|V_k'|^2}. \quad (6)$$

Total power loss in all the feeder sections, $P'_{T,Loss}$, may then be determined by summing up the losses in all line sections of network, which is written as

$$P'_{T,Loss} = \sum_{k=1}^{n} P'_{Loss}(k, k+1). \quad (7)$$

C. Loss Reduction Using Network Reconfiguration

Net power loss reduction, ΔP^R_{Loss}, in the system is the difference of power loss before and after reconfiguration, that is (5)–(7) and is given by

$$\Delta P^R_{Loss} = \sum_{k=1}^{n} P_{T,Loss}(k, k+1) - \sum_{k=1}^{n} P'_{T,Loss}(k, k+1). \quad (8)$$

D. Power Loss Reduction Using DG Installation

Installation of distribution generation units in optimal locations of a distribution system results in several benefits. These include reduction of line losses, improvement of voltage profile, peak demand shaving, relieving the overloading of distribution lines, reduced environmental impacts, increased overall energy efficiency, and deferred investments to upgrade existing generation, transmission, and distribution systems. The power loss when a DG is installed at an arbitrary location in the network as shown in Fig. 2, is given by

$$P_{DG,Loss} = \frac{R_k}{V_k^2}\left(P_k^2 + Q_k^2\right) + \frac{R_k}{V_k^2}\left(P_G^2 + Q_G^2 - 2P_kP_G - 2Q_kQ_G\right)\left(\frac{G}{L}\right). \quad (9)$$

Net power loss reduction, ΔP^{DG}_{Loss}, in the system is the difference of power loss before and after installation of DG unit, that is (9)–(14) and is given by

$$\Delta P^{DG}_{Loss} = \frac{R_k}{V_k^2}\left(P_G^2 + Q_G^2 - 2P_kP_G - 2Q_kQ_G\right)\left(\frac{G}{L}\right). \quad (10)$$

The positive sign of ΔP^{DG}_{Loss} indicates that the system loss reduces with the installation of DG. In contrast, the negative sign of ΔP^{DG}_{Loss} implies that DG causes the higher system loss.

E. Objective Function of the Problem

The objective function of the problem is formulated to maximize the power loss reduction in distributed system, which is given by

$$\text{Maximize } f = \max.\left(\Delta P^R_{Loss} + \Delta P^{DG}_{Loss}\right) \quad (11)$$

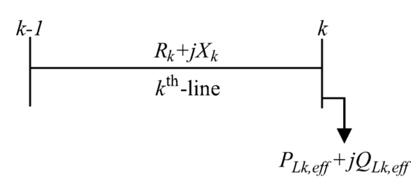
$$\left.\begin{array}{l} \text{Subjected to} \quad V_{\min} \le |V_k| \le V_{\max} \\ \text{and} \quad |I_{k,k+1}| \le |I_{k,k+1,\max}| \\ \sum_{k=1}^{n} \mathrm{P_{Gk}} \le \sum_{k=1}^{n} (P_k + P_{Loss,k}) \end{array}\right\} \quad (12)$$

$$\left.\begin{array}{l} \det(\mathrm{A}) = 1 \text{ or } -1 \text{ (radial system)} \\ \det(\mathrm{A}) = 0 \text{(not radial)} \end{array}\right\}. \quad (13)$$

III. Sensitivity Analysis for DG Installation

Sensitivity analysis is used to compute sensitivity factors [14] of candidate bus locations to install DG units in the system. Estimation of these candidate buses helps in reduction of the search space for the optimization procedure.

Consider a line section consisting an impedance of $R_k + jX_k$ and a load of $P_{Lk,eff} + jQ_{Lk,eff}$ connected between $k-1$ and k buses as given below.



Active power loss in the kth-line between $k-1$ and k buses is given by

$$P_{lineloss} = \frac{\left(P^2_{Lk,eff} + Q^2_{Lk,eff}\right) R_k}{V_k^2}. \quad (14)$$

Now, the loss sensitivity factor (LSF) can be obtained with the equation

$$\frac{\partial P_{lineloss}}{\partial P_{Lk,eff}} = \frac{2 * P_{Lk,eff} * R_k}{V_k^2}. \quad (15)$$

Using (15), LSFs are computed from load flows and values are arranged in descending order for all buses of the given system. It is worth to note that LSFs decide the sequence in which buses are to be considered for DG unit installation. The size of DG unit at candidate bus is calculated using HSA.

IV. Overview of Harmony Search Algorithm

The HSA is a new meta-heuristic population search algorithm proposed by Geem *et al.* [15]. Das *et al.* [16] proposed an explorative HS (EHS) algorithm to many benchmarks problems successfully. 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). HS algorithm is simple in concept, less in parameters, and easy in implementation. It has been successfully applied to various benchmark and real-world problems like traveling salesman problem [17]. The main steps of HS are as follows [15]:

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:

$$\begin{aligned} &Minimize\ f(x) \\ &\quad Subject\ to\ x_i \in X_i, \qquad i = 1,2,\ldots\ldots N \end{aligned} \tag{16}$$

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 ${}_L x_i \leq X_i \leq_U x_i$; and ${}_L x_i$ and ${}_U x_i$ 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

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \ldots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \ldots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \ldots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \ldots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix}. \tag{17}$$

C. Improvise a New Harmony

A New Harmony vector $\vec{x}' = (x_1', x_2', \ldots\ldots . x_N')$ is generated based on three criteria: 1) memory consideration, 2) pitch adjustment, and 3) random selection. Generating a new harmony is called improvisation. $HMCR$, 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 (18):

$$\begin{aligned} &if\ (rand() < HMCR) \\ &x_i' \leftarrow x_i' \in \{x_i^1, x_i^2, \ldots\ldots x_1^{HMS}\} \\ &else \\ &x_i' \leftarrow x_i' \in X_i \\ &end \end{aligned} \tag{18}$$

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., ${}_L x_i \leq X_i \leq_U x_i$. 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 follows:

$$\begin{aligned} &if\ (rand() < PAR) \\ &x_i' = x_i' \pm rand() * bw \\ &else \\ &x_i' = x_i' \\ &end \end{aligned} \tag{19}$$

where bw is an arbitrary distance bandwidth for the continuous design variable and $rand()$ is uniform distribution between 0 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 $\vec{x}' = (x_1', x_2', \ldots\ldots . x_N')$ 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.

V. Application of HSA for Power Loss Minimization

This section describes application of HSA in network reconfiguration and DG installation problems for real power loss minimization. Since both reconfiguration and DG installation problems are complex combinatorial optimization problems, many authors addressed these problems independently using different optimization techniques. In this paper, these two problems are dealt simultaneously using HSA.

To reconfigure the network, all possible radial structures of given network (without violating the constraints) are generated initially. The structure of solution vector (17) for a radial distribution system is expressed by "Arc No.(*i*)" and "SW. No.(*i*)" for each switch i. "Arc No.(*i*)" identifies arc (branch) number that contains ith open switch, and "SW. No.(*i*)" identifies switch that

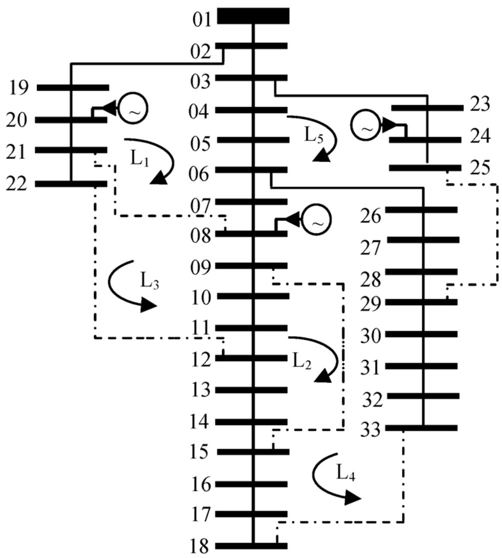


Fig. 3. 33-bus radial distribution system for HV^1.

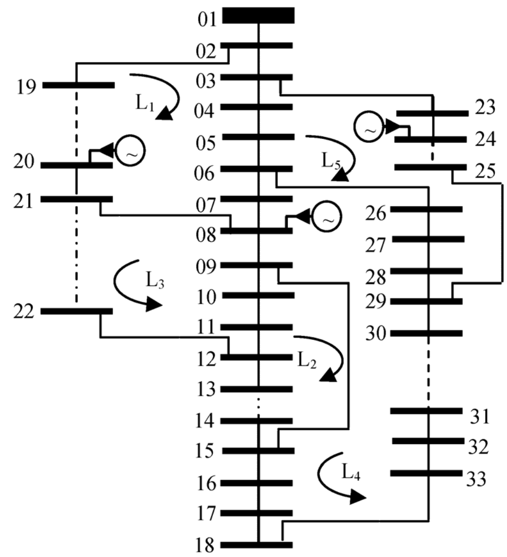


Fig. 4. 33-bus radial distribution system for HV^2.

is normally open on Arc No.(*i*). For large distribution networks, it is not efficient to represent every arc in the string, as its length will be very long. Therefore, to memorize the radial configuration, it is enough to number only open switch positions [6].

In order to simplify the selection of candidate buses for installation of DG units *a priori*, sensitiveness of buses to the change in active power loss with respect to change in active power injection at various buses are computed. Then buses are sorted according to their sensitivity factors and buses that are more sensitive are picked to install DG units.

Application of HSA for loss minimization problem with reconfiguration and DG installation is illustrated with the help of standard 33-bus radial distribution system. In 33-bus system, there are five open tie switches with branch numbers 33, 34, 35, 36, and 37, respectively, which forms five loops L_1 to L_5 (if formed) as shown in Fig. 3. Further, assume that candidate buses for optimal installation of DG units are 8, 20, and 24 as shown in Fig. 3. The ratings of units will vary in discrete steps at specified location during optimization process.

In order to represent an optimal network topology, only positions of open switches in the distribution network need to be known. Suppose the number of normally open switches (tie switches) is N, then length of a first part of solution vector for reconfiguration problem is N. Similarly, length of second part of solution vector is the number of candidate buses chosen for DG units installation. Thus, the solution vector HV^1 using reconfiguration and DG installation is formed as follows:

$$HV^1 = \left[\underbrace{os_1^1 \quad os_2^1 \quad os_3^1 \quad os_4^1 \quad os_5^1}_{reconfiguration}\underbrace{S_1^1 \quad S_2^1 \quad S_3^1}_{DG\ Sizes}\right]$$

where $os_1^1, os_2^1, os_3^1, os_4^1$, and os_5^1 are open switches in the loops L_1 to L_5 corresponding to tie switches 33, 34, 35, 36, and 37, S_1^1, S_2^1, and S_3^1 are sizes of DG units in kW installed at candidate buses 8, 20, and 24, respectively.

Second solution vector HV^2 is randomly generated with open switches 19, 13, 21, 30, and 24 in same loops and DG units at same locations with different ratings is formed as

$$HV^2 = \left[\underbrace{os_1^2 \quad os_2^2 \quad os_3^2 \quad os_4^2 \quad os_5^2}_{reconfiguration}\underbrace{S_1^2 \quad S_2^2 \quad S_3^2}_{DG\ Sizes}\right]$$

where os_1^2, os_2^2, os_3^2, os_4^2, and os_5^2 are open switches corresponding to tie switches 19, 13, 21, 30, and 24 in loops of Fig. 4, S_1^2, S_2^2, and S_3^2 are sizes of DG units in kW installed at candidate buses 8, 20, and 24, respectively.

Similarly, all other possible solution vectors are generated without violating radial structure or non-isolation of any load in the network. Total number of solution vectors (HMS) generated are less than or equal to the highest numbers of switches in any individual loop.

Total Harmony Matrix randomly generated is shown in (20). For each solution vector of HM, the objective function is evaluated and HM vector is sorted in descending order based on their corresponding objective function values:

$$HM = \begin{bmatrix} os_1^1 & os_2^1 & os_3^1 & os_4^1 & os_5^1 & S_1^1 & S_2^1 & S_3^1 \\ os_1^2 & os_2^2 & os_3^2 & os_4^2 & os_5^2 & S_1^2 & S_2^2 & S_3^2 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ os_1^H & os_2^H & os_3^H & os_4^H & os_5^H & S_1^H & S_2^H & S_3^H \end{bmatrix}. \tag{20}$$

The new solution vectors are generated and updated using (18). Using new solution vectors, inferior vectors of previous iteration will be replaced with a new randomly generated vector selected from the population that has lesser objective function value. This procedure is repeated until termination criteria is satisfied. The flow chart of proposed method is shown in Fig. 5.

VI. Test Results

In order to demonstrate the effectiveness of the proposed method (simultaneously reconfiguring the network and instal-

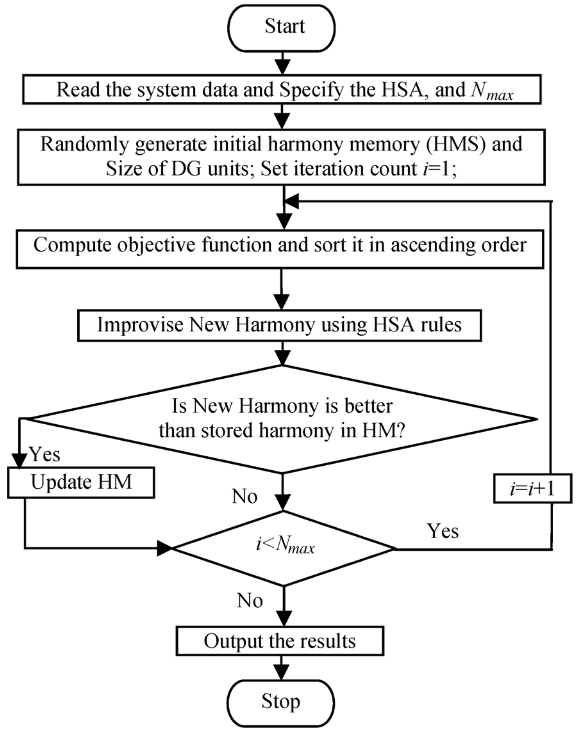


Fig. 5. Flow chart of the proposed method.

TABLE I
RESULTS OF 33-BUS SYSTEM

Scenario		Load Level		
		Light (0.5)	Nominal (1.0)	Heavy (1.6)
Base Case (Scenario I)	Switches Opened	33, 34, 35, 36, 37	33, 34, 35, 36, 37	33,34, 35,36, 37
	Power Loss (kW)	47.06	202.67	575.27
	Minimum Voltage (p.u)	0.9583	0.9131	0.8529
Only Reconfiguration (Scenario II)	Switches Opened	7, 14, 9, 32, 37	7, 14, 9, 32, 37	7, 14, 9, 32, 37
	Power Loss	33.27	138.06	380.43
	% Loss Reduction	**29.3**	**31.88**	**33.86**
	Minimum Voltage (p.u)	0.9698	0.9342	0.8967
Only DG Installation (Scenario III)	Switches Opened	33, 34, 35, 36, 37	33, 34, 35, 36, 37	33, 34, 35, 36, 37
	Size of DG in MW (Bus Number)	0.1303 (18) 0.1777 (17) 0.5029 (33)	0.1070 (18) 0.5724 (17) 1.0462 (33)	0.1939 (18) 0.9108 (17) 1.6115 (33)
	Power Loss (kW)	23.29	96.76	260.97
	% Loss Reduction	**50.5**	**52.26**	**54.63**
	Minimum Voltage (p.u)	0.9831	0.9670	0.9437
DG Installation after Reconfiguration (Scenario IV)	Switches Opened	7, 14, 9, 32, 37	7, 14, 9, 32, 37	7, 14, 9, 32, 37
	Size of DG in MW (Bus Number)	0.1015 (32) 0.1843 (31) 0.2568 (30)	0.2686 (32) 0.1611 (31) 0.6612 (30)	0.2443 (32) 0.3068 (31) 1.2185 (30)
	Power Loss (kW)	23.54	97.13	259.63
	% Loss Reduction	**49.98**	**52.07**	**54.87**
	Minimum Voltage (p.u)	0.9745	0.9479	0.9140
Reconfiguration with simultaneous DG Installation (Scenario V)	Switches Opened	7, 14, 11, 32, 27	7, 14, 10, 32, 28	7, 14, 10, 28, 32
	Size of DG in MW (Bus Number)	0.1954 (32) 0.4195 (31) 0.2749 (33)	0.5258 (32) 0.5586 (31) 0.5840 (33)	0.5724 (32) 1.2548 (31) 0.9257 (33)
	Power Loss (kW)	17.78	73.05	194.22
	% Loss Reduction	**62.22**	**63.95**	**66.23**
	Minimum Voltage (p.u)	0.9859	0.9700	0.9516

lation of DG units) using HSA, it is applied to two test systems consisting of 33 and 69 buses. In the simulation of network, five scenarios are considered to analyze the superiority of the proposed method.

Scenario I: The system is without reconfiguration and distributed generators (Base case);

Scenario II: same as Scenario I except that system is reconfigured by the available sectionalizing and tie switches;

Scenario III: same as Scenario I except that DG units are installed at candidate buses in the system;

Scenario IV: DG units are installed after reconfiguration of network;

Scenario V: System with simultaneous feeder reconfiguration and DG allocation.

All scenarios are programmed in MATLAB, and simulations are carried on a computer with Pentium IV, 3.0 GHz, 1 GB RAM.

A. Test System 1

This test system is a 33-bus radial distribution system [18] with five tie-switches and 32 sectionalizing switches. In the network, sectionalize switches (normally closed) are numbered from 1 to 32, and tie-switches (normally open) are numbered from 33 to 37. The line and load data of network are taken from [7], and the total real and reactive power loads on the system are 3715 kW and 2300 kVAR. The parameters of HSA algorithm used in the simulation of network are $HMS = 20$, $HMCR = 0.85$, $PAR = 0.3$ and Number of iterations, $N_{max} = 20$, Number of runs, N $=$ 9.

Using sensitivity analysis [14] sensitivity factors are computed to install the DG units at candidate bus locations for scenarios III, IV, and V. After computing sensitivity factors at all buses, they are sorted and ranked. Only top three locations are selected to install DG units in the system. The limits of DG unit sizes chosen for installation at candidate bus locations are 0 to 2 MW. The candidate locations for scenarios III, IV, and V are given in Table I. To assess the performance, the network is simulated at three load levels: 0.5 (light), 1.0 (nominal), and 1.6 (heavy) and simulation results are presented in Table I.

It is observed from Table I, at light load, base case power loss (in kW) in the system is 47.06 which is reduced to 33.27, 23.29, 23.54, and 17.78 using scenarios II, III, IV, and V, respectively. The percentage loss reduction for scenario II to V is 29.3, 50.5, 49.98, and 62.22, respectively. Similarly the percentage loss reduction for scenarios II to V at nominal and heavy load conditions is 31.88, 52.26, 52.07, and 63.96; 33.86, 54.63, 54.87, and 66.23, respectively. This shows that for all the three load levels, power loss reduction using scenario V (proposed method) is highest, which elicits the superiority of the proposed

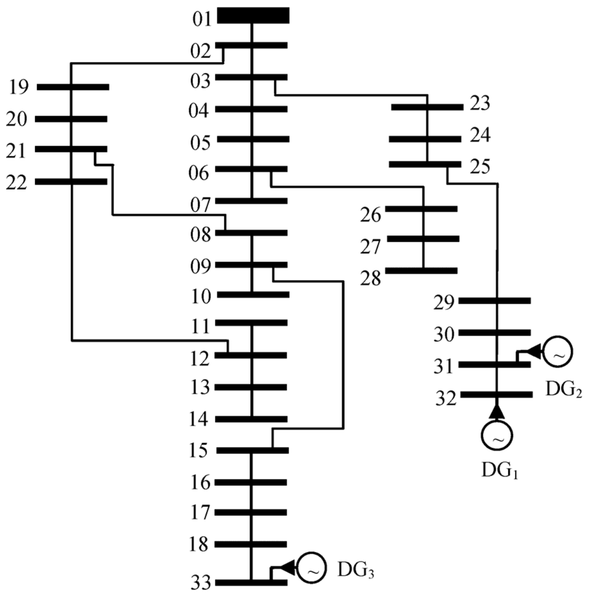


Fig. 6. Optimal network structure after simultaneous reconfiguration and DG installation.

method over the others. However, as load increases from light to heavy, improvement in percentage loss reduction in all scenarios is almost the same.

From Table I, it is seen that improvement in power loss reduction and voltage profile for scenario V are higher when compared to scenario IV. This implies that DG Installation after reconfiguration (scenario IV) does not yield desired results of maximizing power loss reduction and improved voltage profile.

The percentage improvement in minimum voltage of the system for scenario II to V at light, medium, and heavy load is {1.2, 2.52, 2.20, 3.33}, {2.23, 5.60, 3.67, 5.87}, and {4.88, 9.62, 6.68, 10.37}, respectively. From this, it is seen that improvement in minimum voltage of the system for scenario V is the highest. Further, it is also observed that fall in minimum voltage with increase of load from light to peak is least in case of scenario V.

The optimal structure of network after simultaneous reconfiguration and DG installation for scenario V is shown in Fig. 6.

The voltage profile curves of all scenarios at light, nominal, and heavy load conditions are shown in Fig. 7(a)–(c), respectively. The shapes of voltage profiles at all three load levels for five scenarios are almost the same except minor change in voltage magnitude.

To study the effect of number of DG installation locations on power loss for scenario V, DGs are installed at optimal candidate bus locations in sequence and results are presented in Table II. By sensitivity analysis, candidate bus locations considered for DG installations are 32, 31, 33, and 30. From the Table II, at light load, it is seen that the percentage power loss reduction improves as the number of DG installation locations are increasing from one to four, but rate of improvement is decreasing. Similar conclusions may be drawn from Table II with respect to other load levels. Though power loss is reduced when four DGs are installed, the impact of adding fourth DG on power loss is marginal. Thus, three DG installation gives near optimal power loss with near optimal size compared to other installations.

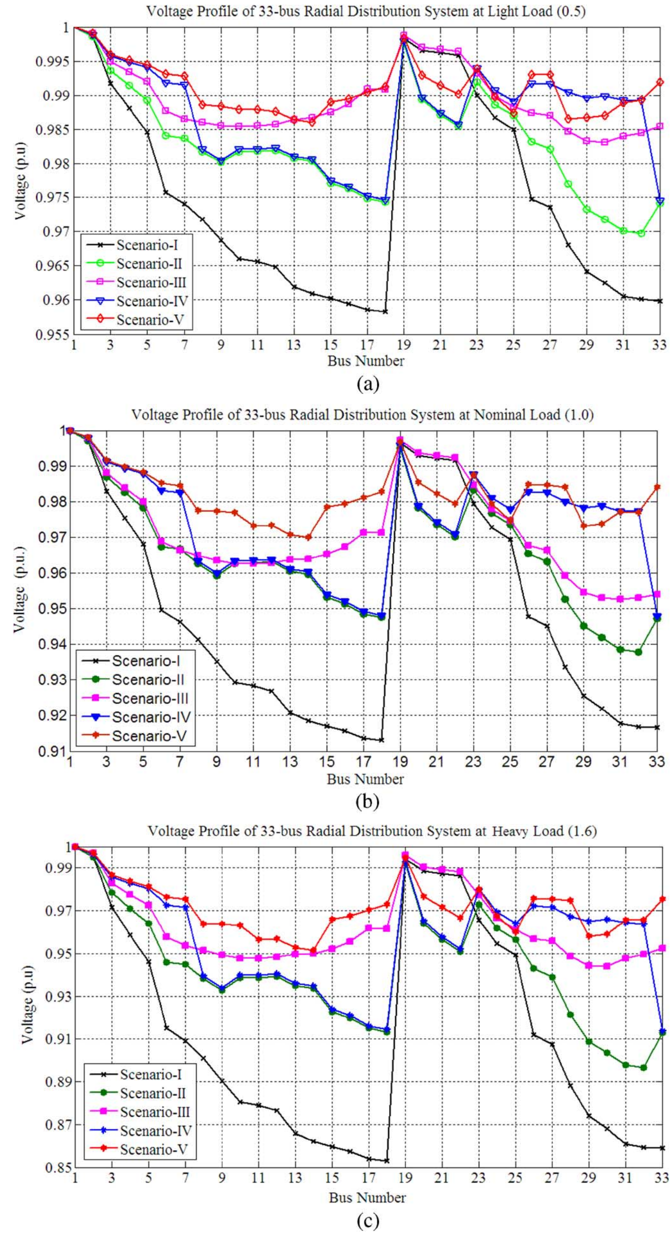


Fig. 7. Voltage profiles of 33-bus system at light, nominal, and heavy load conditions.

TABLE II
EFFECT OF NUMBER OF DG INSTALLATIONS ON POWER LOSS

Number of DG locations		1 DG	2 DGs	3 DGs	4 DGs
Light	Size (MW)	0.4493	0.9264	0.8898	0.9867
	Power Loss (kW)	22.25	18.25	17.78	16.74
	% Loss reduction	52.72	61.22	62.22	64.43
Nominal	Size (MW)	0.8727	1.7632	1.6684	1.9504
	Power Loss (kW)	92.21	74.75	73.05	69.00
	% Loss reduction	54.50	63.12	63.95	65.95
Heavy	Size (MW)	1.4074	2.8932	2.7529	3.2368
	Power Loss (kW)	247.11	200.75	194.22	179.24
	% Loss reduction	57.04	65.10	66.23	68.84

TABLE III
COMPARISON OF SIMULATION RESULTS OF 33-BUS SYSTEM

Method	Item	Scenario II	Scenario III	Scenario IV	Scenario V
HSA	Switches opened	7, 14, 9, 32, 37	--	7, 14, 9, 32, 37	7, 14, 10, 32, 28
	Power Loss (kW)	138.06	96.76	97.13	73.05
	% Power Loss	31.88	52.26	52.07	63.95
	Min. Voltage (p.u)	0.9342	0.9670	0.9479	0.9700
	DG Size (MW)	--	1.7256	1.0909	1.6684
GA	Switches opened	33,9,34, 28,36	--	33,9,34, 28,36	7,10,28, 32, 34
	Power Loss	141.60	100.1	98.36	75.13
	% Power Loss	30.15	50.60	51.46	62.92
	Min. Voltage (p.u)	0.9310	0.9605	0.9506	0.9766
	DG Size (MW)	--	1.6044	1.448	1.9633
RGA	Switches opened	7,9,14, 37, 32	--	7,9,14, 37, 32	7, 9,12 32, 27
	Power Loss	139.46	97.60	98.23	74.32
	% Power Loss	31.20	51.84	51.53	63.33
	Min. Voltage (p.u)	0.9315	0.9687	0.9479	0.9691
	DG Size (MW)	--	1.777	1.100	1.774

To compare the performance of HSA, all the scenarios are simulated with GA [5] and RGA [6] (only at nominal load) and results are provided in Table III.

The population size, crossover rate, and mutation rate are selected as 50, 0.8, and 0.05 for GA and an adaptive mutation rate is applied in the iterative process for RGA. From the table, it is observed that the performance of the HSA is better compared to GA and RGA in terms of the quality of solutions in all scenarios.

B. Test System 2

This is a 69-bus large-scale radial distribution system with 68 sectionalizing and five tie switches. Configuration, line, load, and tie line data are taken from [19].

Total system loads for base configuration are 3802.19 kW and 2694,06 kVAr. The sectionalizing switches are labeled from 1 to 68 and tie switches from 69 to 73, respectively. HSA parameters of the algorithm used to simulate this test system are same as test system 1.

Similar to test systems 1, this test system is also simulated for five scenarios at three load levels and results are presented in the Table IV. The limits of DG unit sizes chosen for installation at candidate bus locations are same as test case 1.

The base case power loss (in kW) at light, nominal, and heavy load conditions is 55.61, 225.00, and 655.23, respectively. From Table IV, it is observed that scenario V is more effective in improving minimum voltage and reducing power loss compared to other scenarios.

The effect of number of locations of DG installations on power loss at all three load levels is studied and results are provided in Table V.

The candidate bus locations considered for DG installations are 61, 60, 62, and 63. Similar to case I, it is seen that the reduction in power loss is minuscule for the fourth DG and hence only three DGs are enough which gives the near optimal power loss with near optimal size compared to other installations.

Scenarios II to V for nominal load condition are simulated using GA and RGA to compare with the results obtained by HSA. From Table VI, it is observed that the performance of the HSA is better compared to GA and RGA in terms of the quality of solutions in all scenarios.

TABLE IV
RESULTS OF 69-BUS SYSTEM

Scenario		Load Level		
		Light (0.5)	Nominal (1.0)	Heavy (1.6)
Base Case (Scenario I)	Switches Opened	69, 70, 71, 72, 72	69, 70, 71, 72, 72	69, 70, 71, 72, 72
	Power Loss (kW)	51.61	225.00	652.53
	Minimum Voltage (p.u)	0.9567	0.9092	0.8445
Only Reconfiguration (Scenario II)	Switches Opened	69, 70, 14, 57, 61	69, 18, 13, 56, 61	69, 18, 13, 55, 61
	Power Loss	23.72	99.35	271.42
	% Loss Reduction	54.03	55.85	58.40
	Minimum Voltage (p.u)	0.9722	0.9428	0.9048
Only DG Installation (Scenario III)	Switches Opened	69, 70, 71, 72, 72	69, 70, 71, 72, 72	69, 70, 71, 72, 72
	Size of DG in MW (Bus Number)	0.2579 (65) 0.1280 (64) 0.5857 (63)	0.1018 (65) 0.3690 (64) 1.3024 (63)	0.1589 (65) 0.8308 (64) 1.9710 (63)
	Power Loss (kW)	21.92	86.77	230.61
	% Loss Reduction	57.53	61.43	64.66
	Minimum Voltage (p.u)	0.9846	0.9677	0.9478
DG Installation after Reconfiguration (Scenario IV)	Switches Opened	69, 70, 14, 57, 61	69, 18, 13, 56, 61	69, 18, 13, 55, 61
	Size of DG in MW (Bus Number)	0.4462 (61) 0.1835 (60) 0.1052 (58)	1.0666 (61) 0.3525 (60) 0.4257 (58)	1.8208 (61) 0.3305 (60) 0.2703 (58)
	Power Loss (kW)	12.55	51.30	135.71
	% Loss Reduction	75.68	77.2	79.2
	Minimum Voltage (p.u)	0.9817	0.9619	0.9377
Reconfiguration with simultaneous DG Installation (Scenario V)	Switches Opened	10, 16, 14, 56, 62	69, 17, 13, 58, 61	10, 18, 13, 58, 61
	Size of DG in MW (Bus Number)	0.3143 (62) 0.3481 (61) 0.3397 (64)	1.0666 (61) 0.3525 (60) 0.4527 (62)	1.5935 (61) 0.8219 (60) 0.9674 (62)
	Power Loss (kW)	11.07	40.30	104.67
	% Loss Reduction	78.55	82.08	83.96
	Minimum Voltage (p.u)	0.9860	0.9736	0.9592

TABLE V
EFFECT OF NUMBER OF DG INSTALLATIONS ON POWER LOSS

Number of DG locations		1 DG	2 DGs	3 DGs	4 DGs
Light	Size (MW)	0.6776	1.3933	1.0021	1.6874
	Power Loss (kW)	12.51	11.01	11.07	10.10
	% Loss reduction	75.76	78.67	78.55	80.43
Nominal	Size (MW)	1.4624	2.0607	1.8718	2.1901
	Power Loss (kW)	51.01	44.10	40.30	43.39
	% Loss reduction	77.33	80.40	82.09	80.71
Heavy	Size (MW)	1.8253	2.7393	2.366	3.303
	Power Loss (kW)	138.10	120.65	104.67	105.80
	% Loss reduction	78.84	81.51	83.96	83.79

TABLE VI
COMPARISON OF SIMULATION RESULTS OF 69-BUS SYSTEM

Method	Item	Scenario II	Scenario III	Scenario IV	Scenario V
HSA	Switches opened	69,18,13, 56,61	--	69,18,13, 56,61	69,17,13, 58,61
	Power Loss	99.35	86.77	51.30	40.30
	% Power Loss	55.85	61.43	77.20	82.08
	Min. Voltage (p.u)	0.9428	0.9677	0.9619	0.9736
	DG Size (MW)	--	1.7732	1.8448	1.8718
GA	Switches opened	69,70,14 53,61	--	69,70,14 53,61	10,15,45, 55,62
	Power Loss	103.29	88.50	54.53	46.50
	% Power Loss	54.08	60.66	75.76	73.38
	Min. Voltage (p.u)	0.9411	0.9687	0.9401	0.9727
	DG Size (MW)	--	1.9471	1.7422	2.0292
RGA	Switches opened	69,17,13 55,61	--	69,17,13 55,61	10,16,14 55,62
	Power Loss	100.28	87.65	52.34	44.23
	% Power Loss	55.42	61.04	76.73	80.32
	Min. Voltage (p.u)	0.9428	0.9678	0.9611	0.9742
	DG Size (MW)	--	1.7868	1.6396	2.0654

VII. CONCLUSIONS

In this paper, a new approach has been proposed to reconfigure and install DG units simultaneously in distribution system. In addition, different loss reduction methods (only network reconfiguration, only DG installation, DG installation after reconfiguration) are also simulated to establish the superiority of the proposed method. An efficient meta heuristic HSA is used in the optimization process of the network reconfiguration and DG installation. The proposed and other methods are tested on 33- and 69-bus systems at three different load levels viz., light, nominal, and heavy. The results show that simultaneous network reconfiguration and DG installation method is more effective in reducing power loss and improving the voltage profile compared to other methods. The effect of number of DG installation locations on power loss reduction is studied at different load levels. The results show that the percentage power loss reduction is improving as the number of DG installation locations are increasing from one to four, but rate of improvement is decreasing when locations are increased from one to four at all load levels. However, the ratio of percentage loss reduction to DG size is highest when number of DG installation locations is three. The results obtained using HSA are compared with the results of genetic algorithm (GA) and refined genetic algorithm (RGA). The computational results showed that performance of the HSA is better than GA and RGA.

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