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Improved Harmony Search Algorithm based Optimal Load Shedding for Radial Distribution Systems without and with Distributed Generations

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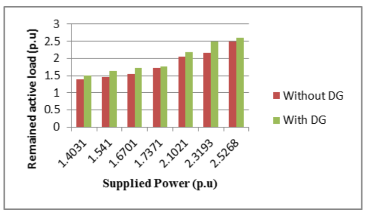
Graphical Abstract



Abstract

The main aim of the electric utilities is to provide a continuous and reliable supply without violating system constraints and operational limits. But during contingencies, system frequency and voltages get declined owing to real and reactive power deficiencies. These situations may lead to cascaded failures and complete blackout in the system. In order to reduce the risk of cascaded outage and blackout, load shedding has been considered as a preventive scheme. This paper presents a new music inspired harmony based optimization algorithm known as improved harmony search algorithm (IHSA) to find an optimal load shedding strategy for radial distribution systems during an overload contingency. The radial distribution systems are the final link of the interconnection between power systems and the consumers with unidirectional power flows. Overload contingency in the radial distribution systems without and with installed distributed generations (DGs) are the two cases considered in this paper. By the introduction of the distributed generations, the electrical distribution system has a locally looped system and bidirectional power flows. The main objective of the proposed algorithm is to minimize the sum of curtailed load based on their assigned degree of importance and system losses within the operational and security constraints of the system. The proposed method has been tested on IEEE 12-bus, 33-bus and 69-bus radial distribution systems. The feasibility of the proposed algorithm has been established and compared with genetic algorithm (GA) in terms of solution quality over realistic test systems considered.

Keywords: Optimal load shedding, improved harmony search algorithm, distributed generation, meta-heuristic

Nomenclature

N_b The total number of branches

R_k The resistance of the K^{th} branch

I_k Absolute value of current in the K^{th} branch

P_L Active power demand of customer L

W_L The importance degree of customer L

P_{gi}, P_{di} Active power generated and demand at bus i respectively

Q_{gi}, Q_{di} Reactive power generated and demand at bus i respectively

V_i, δ_i The magnitude and angle of voltage at bus i respectively

Y_{ij}, θ_{ij} The magnitude and the angle of (i, j) element of Y_{bus} admittance matrix respectively

N_{DG} Number of DGs installed in the system

$P_{gi}^{\min}, P_{gi}^{\max}$ The minimum and maximum limit for generating active power at bus i

$Q_{gi}^{\min}, Q_{gi}^{\max}$ The minimum and maximum limit for generating reactive power at bus i

$V_i^{\min}, V_i^{\max}$ The minimum and maximum limit for magnitude of voltage at bus i

$x_i = (x_{i1}, x_{i2}, ..., x_{id})$ The position of i^{th} particle in the *d* dimensional space

$v_i = (v_{i1}, v_{i2}, ..., v_{id})$ The velocity of i^{th} particle in the *d* dimensional space

x_i^k, $v_i^{(k)}$ The current position and velocity of a particle i at iteration k respectively

$pbest_i = (pbest_{i1}, pbest_{i2}, ..., pbest_{id})$ The previous best position of i^{th} particle

$gbest_d$ Index of the best particle among all the particles in the group

N_P The number of particles in a group

N_g The number of members in a particle

k The pointer of iterations

w The inertia weight factor

C_1, C_2 Acceleration constant

1.0 INTRODUCTION

The continuous growth of load demand both in developed and developing countries has been emerging as a potential challenge to the power system planners and operators. Past records show that the growth in load demand is always going to be ahead of the growth in generation. Unexpected transmission and electric supply failures can have solemn economic impacts on the power system consumers. The main objective of the electric power utilities is to provide a continuous and reliable power supply with an acceptable level of quality.

During a major disturbance caused by the transmission or generation failures due to natural calamities like lightning, severe storm etc., there could be over loading in certain tie lines or in certain generators. In that case the system frequency may have a great variation and the voltage profile may be far from flat which leads the system to enter extreme emergency state. This emergency situation may lead to cascade tripping which may result in a complete shutdown of a major portion of the system.

During these situations the system operators are forced to take load shedding decisions as a last line of defense to avoid the violation of system operational constraints and to regain the state of operating equilibrium of the system.

The radial distribution systems act as a final link of the connection between power systems and the consumers. If there is a necessity to increase the load in order to guarantee the safety limitations, usually the load curtailment occurs in the distribution system. Actually, in the operation of these systems the load curtailment originates due to the failure of generation and transmission system or due to overload contingency.

A new approach for solving the steady state load shedding problem using genetic algorithm (GA) in distribution system during generation deficiency without and with distributed generations (DGs) has been presented in [1]. The constriction factor particle swarm optimization (CPSO) technique has been implemented for solving the steady state load shedding problem in [2]. In [3] GA has been implemented for optimal load-shedding in distribution system with dispersed generation units. The relevant issues and aims at providing a general definition for distributed generation in competitive electricity markets has been provided in [4].

A survey of operational and economic benefits of implementing DGs in the distribution network has been presented in [5]. Here, the authors have made a comprehensive survey by adding new classifications to relate on types, technologies and applications.

Ref. [6] describes a selected set of conflicts that occurs in distribution systems due to the installation of distributed generation (DGs) in significant capacity. Impact of Ferro-resonance on the consumer loads or the service transformer is also discussed.

Ref. [7] has proposed a new algorithm to quickly restore the de-energised loads in a distribution system by using the sectionalising switches. Concept of dual effective gradient method is used for the improvement of computational burden and solution accuracy of the algorithm.

A methodology based on minimum number of switching operations, minimum losses and adherence to the voltage and current constraints, has been proposed in [8]. A best set of service restoration strategies for an affected load point due to a fault in the distribution network was determined in this work.

In [9] an optimum load shedding technique, aimed at reduction of total amount of load shed required and total system interruption cost that will improve the reliability of a local distribution system has been presented.

For a power system with distributed generation, optimal load shedding strategies has been presented in [10]. According to the role of distributed generation, during an emergency state of power system, the distributed generations are classified as the central type and storage type. The dynamic and static models of each type after perturbation are also developed.

In [11] genetic algorithm had been implemented to search for the supply restoration and optimal load shedding in distribution system. Line ampacity violation and voltage drop violation at the load points are considered for load-shedding in [12].

Planning and operation of active distribution network, with respect to placement and sizing of distributed generators are discussed in [13]. Fuzzy logic and analytical methods are used for the determination of distributed generation unit placement and sizing.

In [14] an optimization technique based on genetic algorithm (GA) and optimal power flow calculations are used for the determination of optimal location and size of DG units for distribution networks in order to minimize the cost of active and reactive power generation.

This paper presents a new approach for solving the steady state load-shedding problem in distribution system with distributed generation, during overload conditions. The main objective of the paper is to minimise the sum of curtailed load and also system losses. The minimization problem is subjected to equality and inequality constraints. HS algorithm has been implemented in this paper for solving the formulated optimization problem. The proposed algorithm has been tested on three different distribution test systems, IEEE 12-bus [15], 33-bus [16] and 69-bus [17] radial distribution systems respectively. In this paper two cases are studied and analysed for all the three test systems considered. The first case is without DGs and the second case is with DGs. Details about the DGs installed in the test systems are described in the sections 2 and 4 of this paper. The results obtained for 33-bus radial distribution system using IHSA are compared and validated with the results obtained using GA reported in [1]. The results obtained for the other test systems are presented and analysed. The efficiency and the effectiveness of IHSA applied to the proposed problem have been analysed and discussed in this paper.

2.0 FORMULATION OF OBJECTIVE FUNCTION

The steady state load shedding problem can be formulated as an optimization problem with the following objective functions and constraints.

2.1 Objective Function

The objective of the steady state load shedding problem is to minimize the sum of curtailed load based on their assigned degree of importance and system losses. This can be mathematically expressed as follows

$$Min\left(\sum_{k=1}^{N_b} R_k \times I_k^2\right) + W_L\, P_L \tag{1}$$

where R_K is the resistance of the K^{th} branch, N_b is the total number of branches, I_K is the absolute value of current in the K^{th} branch, W_L is the importance degree of consumer L and P_L is the active power demand of consumer L.

2.2 Constraints

The objective function given in Equation (1) is subject to the following equality and inequality constraints. The equality constraints are the power flow equations of the system and are given in Equations (2) and (3).

2.2.1 Equality Constraints

$$P_{gi} - P_{di} - V_i \sum_{j-1}^{Nb} V_j\, Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) = 0 \quad i = 1, 2 .... N_b \tag{2}$$

$$Q_{gi} - Q_{di} - V_i \sum_{j-1}^{Nb} V_j\, Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) = 0 \quad i = 1, 2 .... N_b \tag{3}$$

where P_{gi} and Q_{gi} are the active and reactive power generated at bus i respectively, P_{di} and Q_{di} are the active and reactive power demand at bus i respectively, V_i, δ_i are the magnitude and angle of voltage at bus i respectively, Y_{ij}, θ_{ij} are the magnitude and the angle of (i, j) element of Y_{bus} admittance matrix respectively.

2.2.2 Inequality Constraints

The inequality constraints are the limits of voltage magnitude and real and reactive power generations, which are expressed as

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad i = 1, 2.......N_b \tag{4}$$

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \qquad i = 1, 2.......N_{DG} \tag{5}$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \qquad i = 1, 2......N_{DG} \tag{6}$$

and

$$Q_{gi} = Q_{gi}^{\min} \text{ if } Q_{gi} \le Q_{gi}^{\min} \quad ; \quad Q_{gi} = Q_{gi}^{\max} \text{ if } Q_{gi} \ge Q_{gi}^{\max} \tag{7}$$

where $V_i^{\min}$ is the minimum limit for magnitude of voltage at bus i, $V_i^{\max}$ is the maximum limit for magnitude of voltage at bus i, $P_{gi}^{\min}$ is minimum limit for generating active power at bus i, $P_{gi}^{\max}$ is maximum limit for generating active power at bus i, $Q_{gi}^{\min}$ is minimum limit for generating reactive power at bus i , N_{DG} is the number of DGs installed in the system and $Q_{gi}^{\max}$ is maximum limit for generating reactive power at bus i.

The steady state model of DG is used in this paper. DGs such as gas turbine, combustion engines and hydro generation are suitable for this model. DGs are modeled as constant power factor units. Considering this the bus connected to the DG can be modeled as PQ bus [14]. It must be pointed out that minimum output of some distributed generation is an important constraint because of the cogeneration. They must generate certain power to ensure the heat supply [10]. These constraints are given in Equations (5), (6) and (7). Now the problem can be stated as minimization of the objective function satisfying all the system constraints stated above.

3.0 IMPROVED HARMONY SEARCH ALGORITHM

This section describes the proposed improved harmony search (IHS) algorithm. A brief overview of harmony search (HS) algorithm is given first and then the modification procedures of the proposed IHSA are stated.

3.1 Harmony Search Algorithm

In recent years for solving complex engineering optimization problems, the heuristic and/or meta-heuristic methods, also called non-traditional optimization methods, have emerged as a powerful and popular method to obtain better solutions. These methods are versatile in solving multidimensional and complex non-linear equations. This algorithm is inspired by the music improvisation process in which the musician seeks for harmony and continues to tune the pitches to obtain a better harmony [18]. The effort of musicians to find the harmony in music is analogous to the search for a best state (i.e., global optimum) in an optimization process. The HS algorithm has several advantages compared to the traditional optimization techniques and has been very successful in solving a wide variety of optimization problems [19, 20].

The design parameters of the HS algorithm are:

Harmony is the set of the values of all the variables of the objective function. Each harmony is a possible solution vector.
Harmony memory (HM) is the location where harmonies are stored.
Harmony memory size (HMS) is the number of solution vectors in the harmony memory.
Harmony memory considering rate ($HMCR$) is the probability of selecting a component of the solution vector in HM .
Pitch adjusting rate (PAR) determines the probability of mutating a component of the solution vector from the HM .

The HS algorithm consists of the following steps:

Step 1: Initialization of the optimization problem and algorithm parameters

The problem to be optimized is formulated in the structure of optimization problem, having an objective function and constraints as

$$\begin{aligned} &\textit{Minimise (or Maximise) } f(\vec{x}) \\ &\textit{subject to } x_i \in X_i, \qquad i = 1, ..., N \end{aligned} \tag{8}$$

where $f(\vec{x})$ is the objective function with $\vec{x}$ as the solution vector composed of decision variables x_i , and X_i is the set of feasible range of values for each decision variable $x_i \left({}_L x_i \le X_i \le {}_U x_i \right)$, where ${}_L x_i$ and ${}_U x_i$ are the respective lower and upper limits for each decision variable. N is the number of decision variables of the problem. The values of the various parameters of HS algorithm like HMS , $HMCR$, PAR and the maximum number of iterations are also specified in this step.

Step 2: Initialization of the Harmony Memory (HM)

The harmony memory is initialized by randomly generating HMS number of solution vectors for the formulated optimization problem. Each component of the solution vector in HM is initialized using the uniformly distributed random number between the lower and upper bounds of the corresponding decision variable $[{}_L x_i, {}_U x_i]$, for $1 \le i \le N$. The i^{th} component of the j^{th} solution vector is as follows

$$x_i^j = {}_L x_i + ({}_U x_i - {}_L x_i).rand[0,1] \qquad (9)$$

where $j = 1, 2, ..., HMS$ and $rand[0,1]$ is a uniformly distributed random number between 0 and 1.
The HM matrix with HMS number of solution vectors is expressed as

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \qquad (10)$$

The value of the objective function is calculated for each solution vector of this HM matrix

Step 3: Improvisation of new harmony from the HM

HM is improved by generating a new harmony vector $\vec{x}' = (x_1' \;\; x_2' \;\; x_3' \;\; \cdots \;\; \cdots \;\; \cdots \;\; \cdots \;\; x_N')$.
Each component of the this vector is generated using

$$x_i' \leftarrow \begin{cases} x_i' \in HM(i) & \text{with probability } HMCR \\ x_i' \in X_i & \text{with probability } (1-HMCR) \end{cases} \qquad (11)$$

where $HM(i)$ is the i^{th} column of the HM, $HMCR$ is already defined as the probability of selecting a component from the HM members and $(1-HMCR)$ is, therefore, the probability of randomly generating a component within the range of values. After the generation of x_i' from the HM it is further mutated (pitch adjustment) according to PAR which determines whether the generated component is to be adjusted or not. The pitch adjustment for a generated x_i' is given as

$$x_i' \leftarrow \begin{cases} x_i' \pm rand[0,1].bw & \text{with probability } PAR \\ x_i' & \text{with probability } (1-PAR) \end{cases} \qquad (12)$$

where bw is an arbitrary distance bandwidth for the continuous design variable.

Step 4: Updating the HM

For updating the HM, the value of the objective function is calculated using the newly generated harmony vector $\vec{x}_i'$. If this r

worst harmony in the HM, judged in terms of the objective function value, then the HM is updated by replacing the worst harmony by the new harmony.

The steps 3 and 4 are repeated until the maximum number of iterations is reached. Finally, the best solution is chosen from the final HM and it is considered as the optimal solution for the formulated optimization problem.

3.2 Proposed Improved Harmony Search Algorithm

The parameters $HMCR$, PAR and bw, given in Step 3, help the algorithm to find globally and locally improved solutions [18,19]. In HS algorithm PAR and bw are very important parameters in fine-tuning of the optimal solution vectors and adjusting the convergence rate of the algorithm effectively. So it is of great interest in the fine adjustment of these parameters. In HS algorithm the values of both PAR and bw are fixed in the initialization step (Step 1) and cannot be varied during new generations.

In order to improve the performance of the algorithm and to reduce the computational time needed to find the optimal solution, initially a large bw with small PAR must be considered to increase the diversification (or exploration) of the search. However in the final iterations the value of PAR must be large with small bw to improve the intensification (or exploitation) of the search. Therefore having fixed values of PAR and bw in HS algorithm will deteriorate the performance of the algorithm and also increase the computation time. This main drawback of HS algorithm can be eliminated by IHSA reported in [21]. In IHSA the values of PAR and bw are dynamically updated in each iterations.

IHSA consists of the same steps as those in HS algorithm except Step 3, where the value of parameter PAR is increased linearly and the value of parameter bw is decreased exponentially with the number of iterations. The mathematical expression for PAR and bw are given by Equations (13) and (14) respectively.

$$PAR(iter) = PAR_{\min} + (PAR_{\max} - PAR_{\max}).\left(\frac{iter}{Maxiter}\right) \qquad (13)$$

where $PAR_{\min}$ is the minimum pitch adjustment rate, $PAR_{\max}$ is the maximum pitch adjustment rate, $iter$ is the current iteration and $Maxiter$ is the maximum number of iterations.

$$bw(iter) = bw_{\max}.\exp\left[\left\{\ln\left(\frac{bw_{\min}}{bw_{\max}}\right)\right\}.\left(\frac{iter}{Maxiter}\right)\right] \quad (14)$$

where $bw_{\min}$ is the minimum bandwidth and $bw_{\max}$ is the maximum bandwidth. The value of $bw_{\min}$ and $bw_{\max}$ greatly influences the performance of the algorithm.

3.2.1 Implementation of Proposed IHSA to Optimal Load Shedding Problem

The implementation of the IHSA to the proposed problem can be explained in the following steps. The real and reactive power loads to be shed at each bus are considered as the variables of the optimal load shedding problem. Each harmony corresponds to a solution vector of these variables. These values of the variables are stored in a location called Harmony memory. The number of these solution vectors in the harmony memory is the harmony size.

Step 1: The solution vectors are randomly initialized. With the generated solutions the value of the objective function is calculated using Equation (1).

Step 2: The HM is improved by generating new solution vector using Equation (11).

Step 3: The generated solution are further mutated based on pitch adjustment rate using Equation (12). Here the values of PAR and bw are calculated using Equations (13) and (14) respectively.

Step 4: With the newly generated solution the objective function is calculated using Equation (1).

Step 5: The HM is updated by replacing the worst harmony by the new harmony.

Step 6: The steps 3 to 5 are repeated until maximum number of iterations are reached.

4.0 SIMULATION RESULTS

The proposed HS algorithm for the optimal load shedding has been implemented for IEEE 12 – bus, 33 – bus and 69 – bus radial distribution systems. Each of distribution systems is subjected to overload contingencies. The results obtained are presented and analysed in this section. The test systems without and with DGs are the two cases considered in the analysis. The HMS of the proposed HS algorithm applied to these test systems is assumed as 100.

4.1 Test system-1: IEEE 12-Bus Radial Distribution System

The single line diagram, line and load data of this test system are taken from [15]. Under normal operating condition the total real power and reactive power loads on this system are 0.435 pu and 0.405 pu The initial real and reactive power losses in the system are 0.015280197 pu and 0.005934202 pu respectively.

Overload contingencies without and with DGs

The proposed algorithm is implemented without and with DGs for the test system-1. A load increment factor of 4.5 times the normal load has been considered as overload contingency in both the cases. The percentage loss of the system under this contingency before load shedding is 0.0996. The minimum and maximum values of the bus voltages before load shedding are 0.8282 pu and 0.9805 pu respectively. Heavily loaded buses are considered for the optimal location of DGs. Here buses 2 and 4 are the heavily loaded buses and the DGs are installed at these buses.

The optimal value of the distributed generation obtained is 0.14237 pu Table 1 shows the optimal value of the objective function (ie., sum of load shed and system losses), total load shed and the corresponding loss percentage for this test system without DGs and with DGs. As observed from the table both the load shed and the system losses during the contingency with DGs is lower than those obtained without DGs. Table 2 shows the amount of load shed without and with DGs at the heavily loaded buses (where the DGs are installed). From the table it is observed that the amount of load shed at these buses with DGs are less than those obtained without DGs.

The convergence characteristic of IHSA without DGs is shown in Figure 1. The figure shows that the proposed algorithm has converged after 45 iterations. Figure 2 shows the convergence characteristic with DGs and this has almost converged after 15 iterations. The number of iterations here has reduced due to the fact that the search for the feasible solution is much easier since the constraints are more easily satisfied with the availability of DGs.

The load increment factor is reduced in steps of 0.5 from the initial overload contingency in both Table 3 and Table 4. The supplied power and the remained active load (connected load) after load shedding without DGs and with DGs are shown in Table 3. The Table shows that the increase in remained active load for the corresponding supplied power is higher for the system with DGs than without DGs. The values tabulated in Table 3 are represented graphically in Figure 3. From the figure also the improvement in the remained active load after load shedding can be observed.

The supplied power and the percentage losses without DGs and with DGs are shown in Table 4. The Table shows the decrease in percentage losses with the installation of DGs. The values given in Table 4 are represented graphically in Figure 4. The figure also shows the reduction of the percentage losses when DGs are installed.

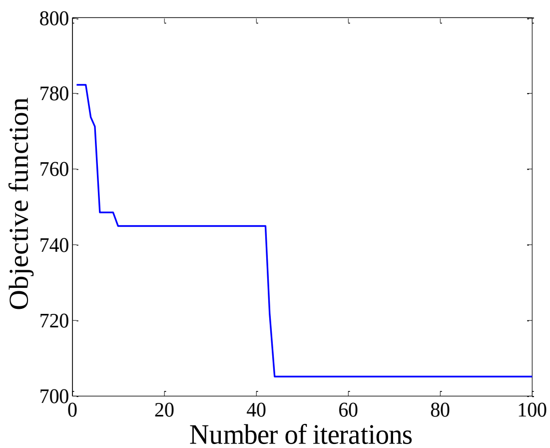


Figure 1 Convergence characteristics of IHSA for test system-1

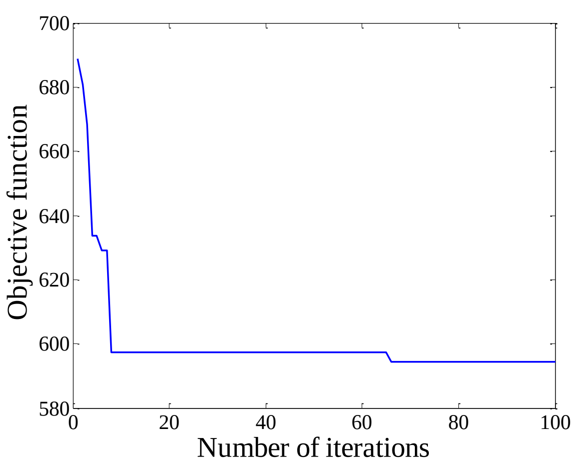


Figure 2 Convergence characteristics of IHSA for without DG test system-1 with DG

Table 1 Results obtained using IHSA for test system-1

Index	Without DGs (pu)	With DGs (pu)
Objective function	0.7051048	0.5943985
Toad load shed	0.6010627	0.4944958
Percentage losses	0.0463	0.03892

Table 2 Load shed at the heavily loaded buses of test system-1 without and with DGs

Bus	Load shed without DGs (pu)	Load shed with DGs (pu)
2	0.0865105	0.0683986
4	0.0723842	0.0517397

Table 3 Supplied power (Vs) Remained active load for test system-1

Supplied Power (pu)	Remained active load without DGs (pu)	Remained active load with DGs (pu)
1.4031	1.3843	1.5101
1.541	1.4576	1.6342
1.6701	1.5365	1.7242
1.7371	1.7172	1.7668
2.1021	2.0471	2.1782
2.3193	2.1722	2.4843
2.5268	2.4852	2.591

Table 4 Supplied power (Vs) Percentage losses for test system-1

Supplied Power (pu)	Percentage losses without DGs	Percentage losses with DGs
1.5421	0.0442	0.0389
1.6711	0.0469	0.041
1.7828	0.0558	0.05
1.8342	0.0719	0.0619
2.0443	0.0865	0.0705
2.2354	0.1067	0.088
2.5782	0.1118	0.1049

The minimum and maximum values of the bus voltages after load shedding (without DGs) are 0.9532 pu and 0.9972 pu respectively. Whereas with installed DGs the minimum and maximum values of the bus voltage are 0.9554 pu are 0.9990 pu respectively. The values of bus voltages before and after the load shedding for both the cases are shown in Figure 5. The figure shows that the voltage profile with DGs has improved when compared with the case without DGs.

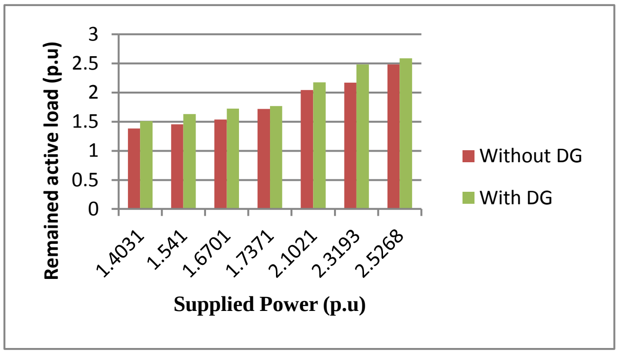


Figure 3 Supplied power (Vs) Remained active load for Test system-1 using IHSA

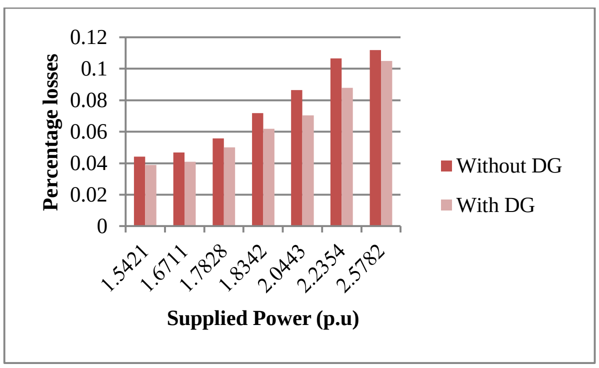


Figure 4 Supplied power (Vs) Percentage losses for test system-1 using IHSA

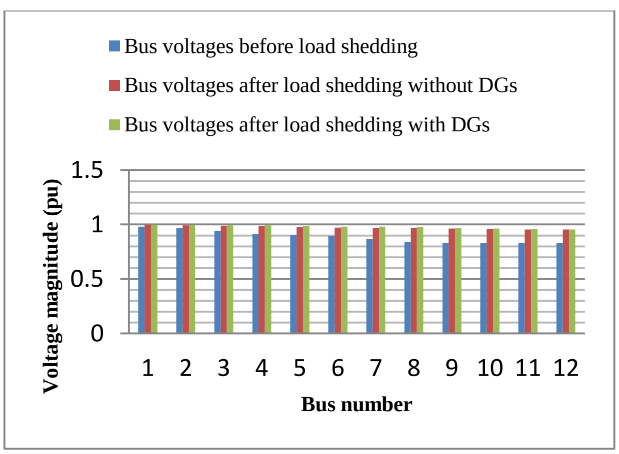


Figure 5 Bus voltages before and after load shedding (without and with DGs) for test system-1

4.2 Test system-2: IEEE 33-Bus Radial Distribution System

This test system is a hypothetical 12.66 kV system taken from Ref. [16]. The base value of real and reactive loads of this test system is 3.715 pu and 2.3 pu respectively. Under normal operating condition the real and reactive power losses in the system are 0.211 pu and 0.1431 pu respectively.

Overload contingencies without DGs and with DGs

A load increment factor of 3.5 is considered as contingency, which is equivalent to a decrease in power flows of the system to 1.5 pu as considered in [1]. The results obtained using IHSA for the two cases considered are compared with the results obtained using GA [1] in this section. The percentage loss of the system under this contingency before load shedding is 0.175. The minimum and maximum values of the bus voltages before load shedding are 0.6478 pu and 0.9893 pu respectively.

The proposed algorithm is implemented for this test system without DGs and with DGs. In order to validate the results obtained with those reported in [1], the buses considered for the optimal location of DGs are 4, 7, 25 and 30 as given in [1]. These buses are the heavily loaded buses of this test system. The optimal distributed generations obtained for this contingency with installed DGs is 2.2654 pu Table 5 shows the comparison of results obtained using the proposed algorithm for this test system with those reported in [1]. From the table it can be observed that the value of the objective function obtained using proposed method for both without and with DGs are less than those reported in [1].The percentage losses obtained here for both the case is also lower than those reported in [1].

Table 6 shows the comparison of total load shed at the heavily loaded buses of this system without and with DGs. From the Table 5 and 6 it can observed that the required amount of load shed and the system losses are reduced when the DGs are installed at the optimal buses of the test system.

The convergence characteristic of IHSA for the case without DGs is shown in Figure 6. The figure shows that the proposed algorithm has converged after 100 iterations. Figure 7 shows the convergence characteristic with DGs and this has converged after 49 iterations. The number of iterations here has reduced due to the fact that the search for the feasible solution is much easier since the constraints are more easily satisfied with the availability of DGs.

The load increment factor is reduced in steps of 0.5 from the initial overload contingency in both Table 7 and 8. The supplied power and the remained active load after load shedding without DGs and with DGs are shown in Table 7. The Table shows that the increase in remained active load for the corresponding supplied power is higher for the system with DGs than without DGs. The values tabulated in Table 7 are represented graphically in Figure 8. From the figure also the improvement in the remained active load after load shedding can be observed.

Table 5 Comparison of results obtained for test system-2 without and with DGs

Index	GA reported in [1]		Proposed IHSA	
	without DGs (pu)	with DGs (pu)	without DGs (pu)	with DGs (pu)
Objective function (pu)	6.189	4.12	5.3795	4.0642
Percentage losses	0.023	0.0225	0.02277	0.02199

Table 6 Load shed at the heavily loaded buses of test system-2 without and with DGs

Bus	Load shed without DGs (pu)	Load shed with DGs (pu)
4	0.17622	0.11265
7	0.317743	0.23652
25	0.540455	0.217949
30	0.3302514	0.15276

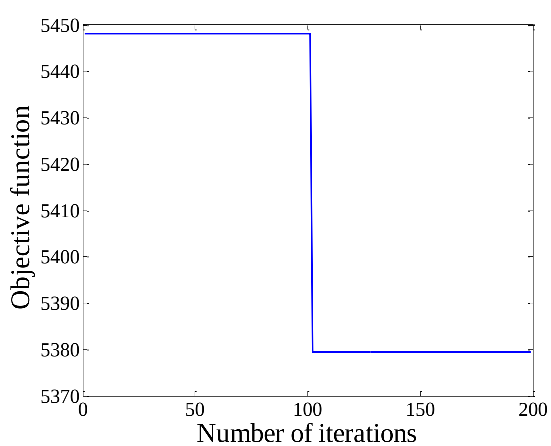


Figure 6 Convergence characteristics of IHSA for test system-2 without DG

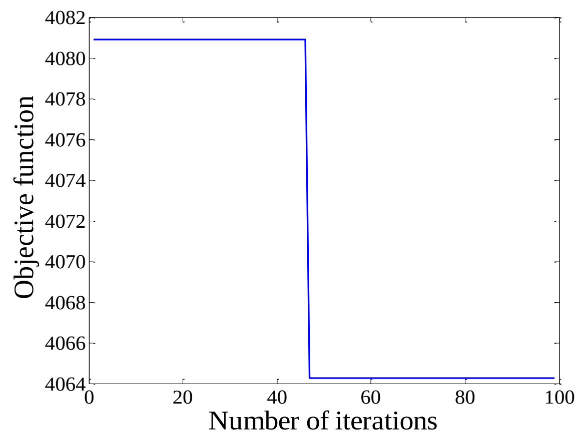


Figure 7 Convergence characteristics of IHSA for test system-2 with DG

Table 7 Supplied power (Vs) Remained active load for test system-2

Supplied Power (pu)	Remained active load without DGs (pu)	Remained active load with DGs (pu)
1.589	1.5268	2.1263
1.6867	1.6148	2.3614
1.8843	1.8126	2.4128
2.3315	2.2597	2.7112
2.5577	2.4754	2.9075
2.8749	2.7346	3.1264
2.9711	2.821	3.6612

Table 8 Supplied power (Vs) Percentage losses for test system-2

Supplied Power (pu)	Percentage losses without DGs (pu)	Percentage losses with DGs (pu)
1.6314	0.0142	0.0113
1.7887	0.01	0.0132
2.02	0.0162	0.0157
2.1548	0.0151	0.0168
2.3387	0.0178	0.0169
2.699	0.0188	0.0165
2.9311	0.018	0.0261

The supplied power and the percentage losses without DGs and with DGs are shown in Table 8. The Table shows the decrease in percentage losses with DGs. The values given in Table 8 are represented graphically in Figure 9. The figure also shows the reduction of the percentage losses when DGs are installed.

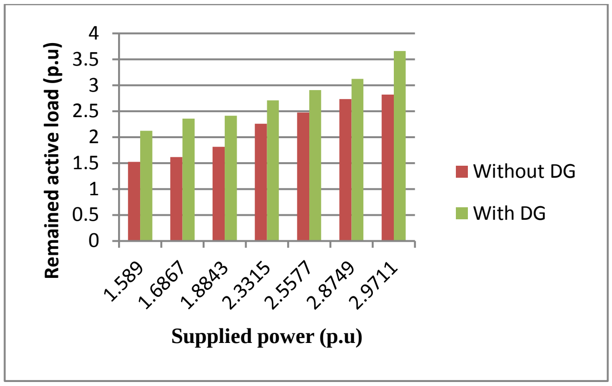


Figure 8 Supplied power (Vs) Remained active load for test system-2 using IHSA

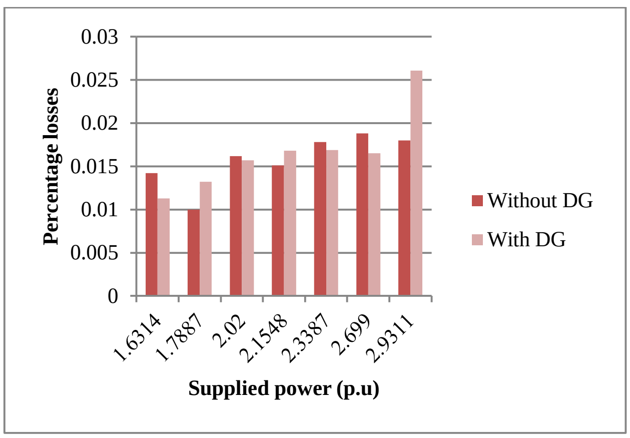


Figure 9 Supplied power (Vs) Percentage losses for test system -2 using IHSA

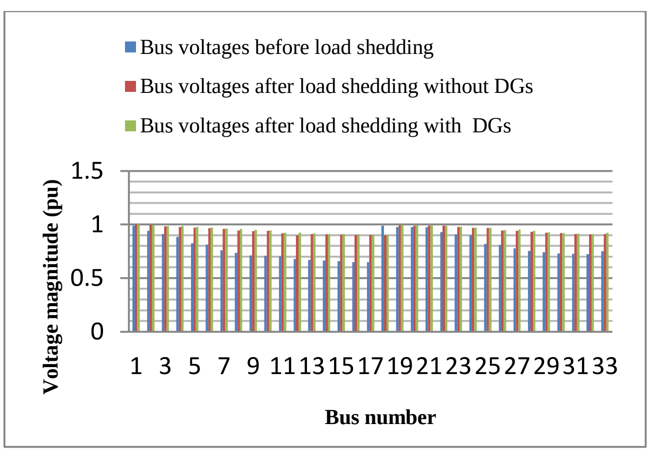


Figure 10 Bus voltages before and after load shedding (without and with DGs) for test system-2

The minimum and maximum values of the bus voltages after load shedding (without DGs) are 0.8998 pu and 0.9998 pu respectively. Whereas with installed DGs the minimum and maximum values of the bus voltages are 0.9024 pu are 0.9998 pu respectively. The values of bus voltages before and after the load shedding for both the cases are shown in Figure 10. The figure shows that the voltage profile with DGs has improved when compared with the case without DGs.

4.3 Test system-3: IEEE 69-Bus Radial Distribution System

The data for this test system is taken from Ref. [17]. The base values of real and reactive loads of this system are 3.8023 pu and 2.694 pu respectively.

The real and reactive power losses in the system under normal operating conditions are 0.2205 pu and 0.102 pu respectively.

Overload contingency without DGs and with DGs

Sudden increase in the load from base value to 2 times the normal load has been considered as the contingency for both the cases. . The percentage loss of the system under this contingency before load shedding is 0.09729. The minimum and maximum values of the bus voltages before load shedding are 0.825 pu and 0.99 pu respectively.

The results obtained using the proposed algorithm for this test system without and with DGs are analyzed in this section.

For this test system also, the heavily loaded buses: 10, 49, 60 and 63 are assumed as the optimal location for the installation of DGs. The optimal value of DGs obtained using the IHSA is 1.17694 pu Table 9 shows the optimal value of the objective function and the corresponding loss percentage for this test system without and with DGs. As observed from the table both the load shed and the system losses during the contingency with DGs is lower than those obtained without DGs.

Table 10 shows the comparison of total load shed at the heavily loaded buses of this system without and with DGs. From the Table 9 and 10 it can observed that the required amount of load shed and the percentage losses are reduced when the DGs are installed at the optimal buses of the test system when compared to those obtained without DGs.

The convergence characteristic of IHSA without DGs is shown in Figure 11. The figure shows that the proposed algorithm has converged after 50 iterations.

Figure12 shows the convergence characteristic with DGs and this has converged after 42 iterations. The number of iterations here too has reduced due to the fact that the search for the feasible solution is much easier since the constraints are more easily satisfied with the availability of DGs.

Table 9 Results obtained using IHSA for test system-3 without and with DGs

Index	Load shedding without DGs (pu)	Load shedding with DGs (pu)
Objective Function (pu)	2.0708	1.7091
Total load shed	1.8602	1.2885
Percentage losses	0.0449	0.0372

Table 10 Load shed at the heavily loaded buses of test system-3

Bus	Load shed without DGs (pu)	Load shed with DGs (pu)
10	0.160144	0.126523
49	0.1663277	0.164399
60	0.864321	0.754872
63	0.198726	0.197961

The load increment factor is reduced in steps of 0.5 from the initial overload contingency in both Table 11 and Table 12. The supplied power and the remained active load after load shedding without and with DGs are shown in Table 11. The Table shows that the increase in remained active load for the corresponding supplied power is higher for the system with DGs than without DGs. The values tabulated in Table 11 are represented graphically in Figure13. From the Figure also the improvement in the remained active load after load shedding can be observed.

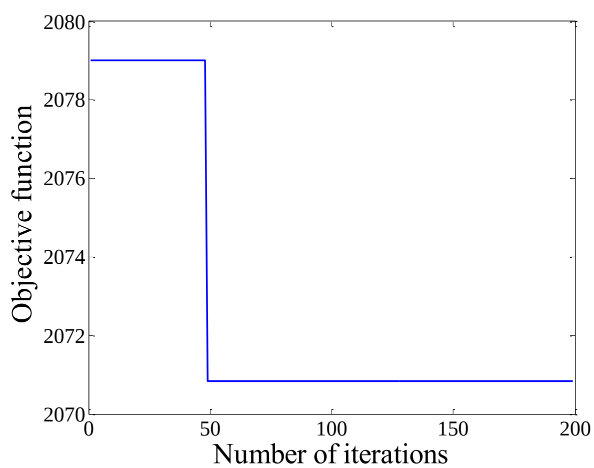


Figure 11 Convergence characteristics of IHSA for test system-3 without DG

The supplied power and the percentage losses without DGs and with DGs are shown in Table 12. The table shows the decrease in percentage losses with DGs. The values given in Table 12 are represented graphically in Figure 14. The Figure also shows the reduction of the percentage losses when DGs are installed.

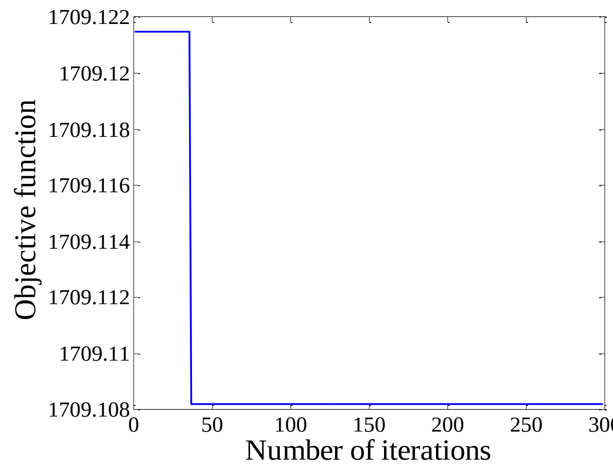


Figure 12 Convergence characteristics of IHSA for test system-3 with DG

The minimum and maximum values of the bus voltages after load shedding (without DGs) are 0.910 pu and 1.06 pu respectively. Whereas with installed DGs the minimum and maximum values of the bus voltages are 0.9127 pu are 1.1 pu respectively. The value of bus voltages before and after the load shedding for both the cases is shown in Figure 15. The Figure shows that the voltage profile with DGs has improved when compared with the case without DGs.

Table 11 Supplied power (Vs) Remained active load for test system-3

Supplied Power (pu)	Remained active load without DGs (pu)	Remained active load with DGs (pu)
1.4564	1.4323	1.5215
1.6827	1.5287	1.7221
1.8223	1.6911	1.9523
1.9241	1.8329	2.0861
2.1323	2.0336	2.2782
2.3934	2.1942	2.5798
2.6227	2.4911	2.891

Table 12 Supplied power (Vs) Percentage losses for test system 3

Supplied Power (pu)	Percentage losses without DGs (pu)	Percentage losses with DGs (pu)
1.4214	0.071	0.0162
1.5083	0.0187	0.0174
1.7898	0.0187	0.0171
1.9121	0.0199	0.0183
2.1638	0.0197	0.0209
2.3515	0.0212	0.0211
2.5733	0.0257	0.0243

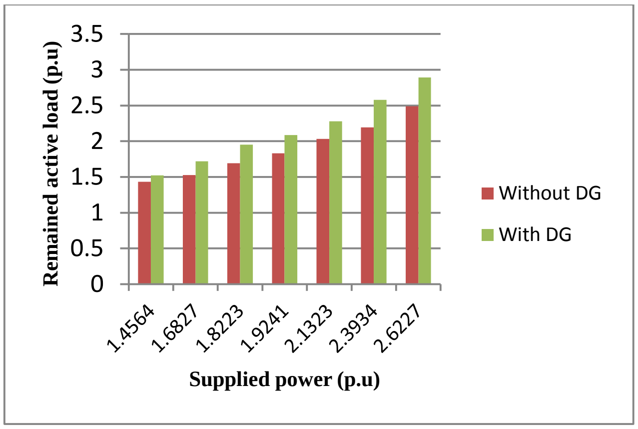


Figure 13 Supplied power (Vs) Remained active load for test system-3 using IHSA

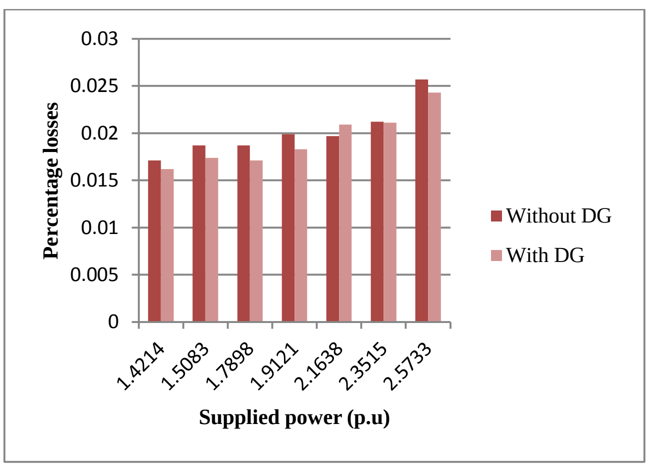


Figure 14 Supplied power (Vs) Percentage losses for test system-3 using IHSA

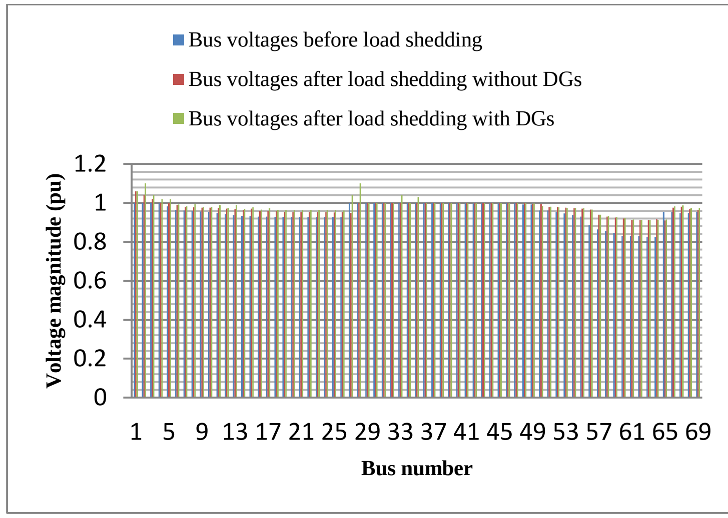


Figure 15 Bus voltages before and after load shedding (without and with DGs) for test system-3

5.0 CONCLUSION

In this paper improved harmony search algorithm has been implemented for the optimal load shedding in IEEE 12 - bus, 33 - bus and 69 - bus radial distribution systems without and with DGs. For the overload contingencies considered, the results obtained using IHSA for 33 – bus system without and with DGs are compared with GA presented by Malekpuour. The comparison done in terms of optimal load shed and total system losses show that the proposed method has provided better solutions. The simulation results indicate that, presence of DGs in the system has increased the remained active load by minimizing the load to be shed, improved the voltage profile and reduced the active power loss during overload contingencies. The proposed approach has better convergence characteristics. Based on these results, it is concluded that the proposed IHSA is an effective alternative approach for optimal load shedding.

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