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Stud Krill herd Algorithm for multiple DG placement and sizing in a radial distribution system

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ABSTRACT

In this paper a new meta-heuristic technique, Stud Krill herd Algorithm (SKHA) is employed for the solution of optimal placement and sizing of Distributed Generation (DG) in radial distribution system. The main objective is to minimize the line losses considering various constraints like voltage limit, DG real power generation limit, power balance constraint and DG location constraint. Krill movement is based on the two factors – minimum distance of the Krill individual from food and highest density of the herd and for better performance adaptive genetic operators, stud selection and crossover (SSC) are included. The proposed algorithm is implemented on 33, 69 bus IEEE test system and 94 bus Portuguese radial distribution system. The results are compared with recently developed heuristic and analytical methods from the literature. The outcomes reveal the effectiveness of the algorithm.

1. Introduction

Distributed generation (DG) is a small scale generation otherwise called as embedded generation, dispersed or decentralized generation, which generates power in the range of 3–10,000 kW from wind, solar, bio-mass, fuel cells, micro turbines etc. DG units are connected closer to the customers and are used for industrial, commercial and domestic applications. The main advantages of using DG units are improving voltage stability, real power loss reduction, reliability, grid strengthening and reduction of SO_2, CO_2 gas emissions. Although DG has lots of advantages, the key problem in DG placement is the selection of optimal location and size of DG units. If DG units are improperly allocated and sized, the reverse power flow from larger DG units can lead to higher system losses, voltage fluctuations and increase in costs. Hence, to minimize losses, it is important to find the best location and size of DG units [1–4]. In recent years many researchers have proposed new analytical approaches based on power stability index (PSI) and power loss sensitivity (PLS) index to find the optimal location and sizing of DGs for obtaining an optimal solution of the power loss minimization problem in the radial distribution system [5–7].

The critical bus can be found out from PSI and the DG should be placed at the end of the line which is having highest PSI. The size of DG is determined based on real power loss minimization. Voltage profile, the real and reactive power intake by the grid, real and reactive power flow patterns, cost of energy losses, savings in the cost of energy loss and cost of power obtained from DGs have also been considered while solving the DG problem. Near optimal results are the main drawbacks in all the above methods. The method described in [6], though the convergence is achieved at few iteration, but the method is not applicable for unbalanced and meshed distribution system. Several artificial intelligence based techniques have been proposed for solving the DG optimization problem. In [8], the authors used firefly algorithm for solving DG placement and sizing in order to obtain minimum loss, voltage profile improvement and minimum generation cost. But the key

Abbreviations: DG, Distributed Generation; RDS, Radial Distribution System; ODGP, Optimal Distributed Generation Placement; KHA, Krill herd Algorithm; SKHA, Stud Krill herd Algorithm; SSC, Stud Selection and Crossover; PSI, Power Stability Index; PLS, Power Loss Sensitivity index; CVD, Cumulative Voltage Deviation; LSF, Loss Sensitivity Factor; MOPI, Multi Objective Performance Index; KCL, KVL, Kirchhoff's Current Law, Kirchhoff's Voltage Law; PSO, Particle Swarm Optimization; ACO, Ant Colony Optimization; GA, Genetic Algorithm; SA, Simulated Annealing; BFOA, Bacterial Foraging Optimization Algorithm; REPSO, Rank Evolutionary Particle Swarm Optimization; TLBO, Teaching Learning Based Optimization; CABC, Chaotic Artificial Bee Colony algorithm; QOTLBO, Quasi – Oppositional Teaching Learning Based Optimization; SOS, Symbiotic organism search algorithm; MOShBAT, Multi-objective Shuffled Bat algorithm; FPA, Flower Pollination Algorithm; OKHA, Oppositional Krill herd Algorithm.

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Nomenclature

S^a	specific apparent power injection at node a (kVA)
a	number of nodes, 1 to n
P_D^a	real power injected at node a (kW)
Q_D^a	reactive power injected at node a (kVAR)
$iter_{max}$	maximum number of iterations
$I^{iter,a}$	node current at node a at iterth iteration (amps)
$V^{(iter-1),a}$	voltage at node a at (iter-1)th iteration (volts)
$i^{iter,B}$	branch current at branch B at iterth iteration (amps)
$I^{iter,B2}$	current injection at node B2 at iterth iteration (amps)
$V^{iter,B1}$	updated voltage at node B1 at (iter)th iteration (volts)
Z^B	series impedance of branch B (ohms)
S^1_{inj}	injected apparent power at bus 1 (kVA)
V^1_{inj}	injected/input voltage at bus 1(volts)
I^1_{inj}	branch current at bus 1(amps)
P_{inj}	injected real power at bus 1 (kW)
Q_{inj}	injected reactive power at bus 1 (kVAR)

disadvantage is slow convergence. Bacterial foraging optimization algorithm (BFOA) and modified BFOA are used in [9] and [10] respectively for solving the optimal DG placement (ODGP) problem. The main drawback is complexity of the algorithm and hence the less convergence speed.

Invasive Weed Optimization algorithm is applied for reconfiguration and DG placement problem in [11] and [12]. But % power loss reduction is near optimal when compared to other optimization methods. In [13], Rank Evolutionary Particle Swarm Optimization (REPSO) is used for solving reconfiguration and DG placement problem. The main disadvantage is poor convergence speed. The authors of [14] improved the teaching learning based optimization (TLBO) with quasi-opposition based rules for obtaining the optimal solution for ODGP problem. The results are enhanced still the convergence time is slightly high. The authors considered power loss minimization and DG installation cost as two objectives using the weighted sum method and solved using sequence quadratic programming deterministic technique in [15]. The proposed technique in [16] is adjusted to attempt the deficit of loss sensitivity factors and to decide the final placement of the DGs. Initial DG locations are obtained by framing fuzzy rules based on sensitivity factors and bus voltages. Cumulative Voltage Deviation (CVD) is used to indicate the voltage profile improvement. The backtracking search optimization algorithm is also a population based iterative, evolutionary algorithm consists of initialization, selection, mutation, crossover and selection. The determination of optimal location and sizing of DG units using multi objective performance index (MOPI) for enhancing the voltage stability of the radial distribution system is presented in [17]. The different technical issues are combined using various weighting coefficients and solved under different operating constraints using a Chaotic Artificial Bee Colony (CABC) algorithm.

In [18], the authors utilized a new nature inspired approach intelligent water drop algorithm for sizing of DGs and loss sensitivity factor (LSF) is used to find the optimal location. The drawback of this method is the results are near optimal. The authors of [19] presented a two stage approach fuzzy set theory to find optimal location of DG and clonal selection algorithm to find the DG size. Time consumption for obtaining the solution is slightly high. In [20], the authors projected cuckoo search algorithm to find the optimal location of wind based distributed generators in order to reduce the power loss of the distribution system. The authors of [21], used Newton-Raphson extended method with Naplan software to find the power losses at each bus. The power losses at each DG connected bus are considered for the selection of optimal location of DG.

In [22], Particle Swarm Optimization (PSO) is proposed for multi DG placement for power loss reduction and voltage profile improvement. The authors of [23] used Symbiotic organism search (SOS) algorithm to DG placement problem. SOS algorithm is a nature inspired heuristic technique, based on the symbiotic relationship between different biological individual species. In [24], the authors proposed Grey Wolf Optimizer (GWO) to solve the multi objective function in terms of minimization of reactive power losses and voltage profile improvement. The authors [25] presented a hybrid approach with an analytical method used to find the size of DGs and PSO based technique is applied to determine the location. They have considered different types of DGs for analysis. The authors of [26] developed Multi-objective Shuffled Bat (MOShBAT) algorithm to determine the DG placement and sizing, in order to minimize the multi objective function considering the power losses, cost and voltage deviation. The method is based on the Shuffled frog leaping algorithm and Bat algorithm.

In [27], modified Firefly Algorithm is applied to determine the optimal size and location of DGs in unbalanced distribution system. The DG in this algorithm is framed with a flexibility to change the PV node to PQ node, when the reactive power limit is violated. The authors of [28] proposed flower pollination algorithm (FPA) to find the DG size and index vector method to determine the DG location. Index vector is framed with reactive component of current in the branches and reactive power load concentration at each node obtained from the base case load flow results. In [29], backtracking search algorithm is presented to find the optimal location and size of DG. The initial location of DGs is found out by framing fuzzy expert rules using loss sensitivity factor and bus voltages. The authors framed multi objective function which comprises minimization of power loss and maximization of voltage stability index. DG sources classified as four types. The authors applied the algorithm to first three types to validate the results.

i. Type-I: DG capable of injecting real power only
ii. Type-II: DG capable of injecting reactive power only
iii. Type-III: DG capable of injecting both real and reactive power
iv. Type-IV: DG capable of injecting real but consuming reactive power

The main drawbacks in all the above methods are poor convergence speed and obtaining near optimal solutions. In 2012, Gandomi and Alavi [30], proposed a biologically inspired swarm intelligence algorithm, known as Krill Herd Algorithm (KH). This method is based on the simulation of herding behavior of the large number of individual krills. The KH algorithm is capable to explore the search space globally, but it fails to select sometimes the global optimum solution in the search space. In [32], the authors have minimized annual energy losses by using different renewable energy resources like bio-mass, solar and wind DG units. The Oppositional Krill herd Algorithm (OKHA) is used to determine the optimal location and size of DG units. Later in 2014, Wang et al. [35], added updated genetic operators namely stud selection and crossover to KH method to avoid being trapped in local optima. In SKH, stud selection and crossover (SSC) operator is used, which accepts the newly generated better solutions only, rather than selecting all the other possible solutions.

This paper is aimed to overcome all the above drawbacks by implementing one of the new bio – inspired, heuristic technique, Krill herd algorithm with stud operators namely Stud Krill herd algorithm for solving the Distributed Generation optimization problem with active power loss minimization as objective function subjected to various constraints like Voltage limit constraint, Real power limits, DG location and DG capacity limit and an optimum solution is obtained using SKH algorithm. Both KH and SKHA are applied on 33, 69 bus IEEE standard test systems and 94 bus Portuguese radial distribution systems with multiple DG's at various load conditions. The results are compared with other recently developed methods like intelligent water drop algorithm, bacterial foraging optimization algorithm (BFOA), firefly algorithm, QOTLBO and analytical methods. The paper is organized as follows: Abstract, (1) Introduction (2) Problem formulation (2.1) Load flow equations (2.2) Objective function and Constraints (3) Krill herd algorithm (4) Stud Krill herd Algorithm (4.1) Flowchart for Stud Krill herd Algorithm application to DG placement problem (5) Test case and Results comparison (6) Conclusion (7) Acknowledgment and (8) References.

2. Problem formulation

2.1. Load flow equations

Due to high R/X value, the classical load flow techniques Newton – Raphson and Gauss – Seidal methods are not suited for solving RDS load flow problem. The forward – backward sweep algorithm [31], based on basic formulation of Kirchhoff's laws is used for finding out the power flow in the system.

RDS Load flow solution method steps:

1. Read system data.
2. Given the voltage to node 1 and assume a flat voltage profile for the initial voltages.
3. Calculate specified power injection at node a, $S^a = P_D^a + j\,Q_D^a$ for a = 1 to n (n – no. of nodes)
4. Set iteration count *iter* = 1 and $iter_{max}$ is the maximum number of iterations.
5. Calculate the nodal current (Bus current). The node current at node an and iteration = iter is

$$I^{iter,a} = \left[\frac{S^a}{V^{(iter-1),a}}\right]^* \tag{1}$$

where
S^a = injected power at node '*a*'
$V^{(iter-1),a}$ = Voltage at node '*a*' at (iter-1)th iteration

6. Backward Sweep: Calculate the branch currents.
Starting from the last layer and moving towards the first node, the current at branch B is obtained by applying KCL,

$$i^{iter,B} = -I^{iter,B2} + \sum \text{currents in branches originating from node B2.} \tag{2}$$

where $B = b, b-1, \ldots 1$

7. Forward Sweep: Calculate the node voltage.
Starting from the first layer and moving towards the last layer, for each branch B, the node voltage at B2 is calculated by applying KVL,

$$V^{iter,B2} = V^{iter,B1} - Z^B i^{iter,B} \tag{3}$$

where $B = 1, 2, \ldots b$ b – number of branches

$V^{iter,B1}$ – Updated voltage at node B1 at (iter)th iteration

Z^B – Series impedance of branch B

8. Increment the iteration count iter = iter + 1 until iter reaches itermax.
9. Calculate the power injection at bus 1.

$$S^1_{inj} = V^1_{inj}\left(I^1_{inj}\right)^* \tag{4}$$

where

V^1_{inj} – Injected/Input voltage at bus 1

I^1_{inj} – Branch current at bus 1

10. From Eq. (4), calculate the total real and reactive power injected,

$$P_{inj} = real(S_{inj}); \; Q_{inj} = imag(S_{inj}) \tag{5}$$

where, $P_{inj} = P_{Slack}$
Now, calculate the system power loss as

$$P_{loss} = P_{inj} - \sum P_D; \; Q_{loss} = Q_{inj} - \sum Q_D \tag{6}$$

11. Print the results.

2.2. Objective function and constraints

The main objective of determining the optimal placement and sizing of DG is to minimize the system power loss subjected to various equality and inequality constraints of a distribution network such as voltage limit, DG real power limit, power balance constraint and DG location limit.

Minimize $F = \min\,(P_L)$

$$P_L = P_{Slack} + \sum_{a=2}^{ndg} P^a_{DG} - \sum_{a=1}^{n} P^a_D \tag{7}$$

ndg – number of DG units connected
Subjected to constraints

1. Voltage limit

The voltage magnitude should be within the minimum and maximum limits.

$$V^a_{min} \leqslant V^a \leqslant V^a_{max} \tag{8}$$

where
V^a_{min} – Minimum voltage limit (0.95 p.u.)
V^a_{max} – Maximum voltage limit (1.05 p.u.)

2. DG Real power limit

P^a_{DG} is the real power generated from the DG and it should be within minimum and maximum limits.

$$P^a_{DG,min} \leqslant P^a_{DG} \leqslant P^a_{DG,max} \tag{9}$$

$P^a_{DG,min}$ – minimum permissible limit of DG generation (0 kW)
$P^a_{DG,max}$ – maximum permissible limit of DG generation ($\sum_1^n P_D/no.\ of\ DG\ units$)

3. Power balance constraint

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The total real power generated by the DGs should be less than the sum of total demand excluding the slack bus and real power loss.

$$\sum_{a=2}^{ndg} P_{DG}^{a} \leqslant \sum_{a=2}^{n} P_{D}^{a} + P_L \tag{10}$$

4. DG location
   DGs should be placed within the total number of nodes.

$$1 < \mathrm{DG_{loc}} < \mathrm{n}; \mathrm{n} = \text{number of nodes} \tag{11}$$

3. Krill herd Algorithm

Krill herd Algorithm is a biologically inspired swarm intelligence algorithm which is proposed by Gandomi and Alavi in [32]. In this population based algorithm, each krill individual has a fitness function which is defined by its distances from food and highest density of swarm. Each krill individuals modify its position using three processes namely movement induced by other krill individuals (local), foraging motion (global) and random physical diffusion. The fitness (imaginary distances) is the value of the objective function. In [33], the authors used the krill herd algorithm for the solution of economic load dispatch problem.

The n dimensional decision space is given by

$$\frac{dX_i}{dt} = N_i + F_i + D_i \quad i = 1 \text{ to } n_k \quad n_k - \text{number of krill individuals} \tag{12}$$

where
N_i – movement induced by other krill individuals
F_i – foraging activity
D_i – random diffusion

For each krill individual the movement is given by,

$$N_i^{new} = \left[N^{max} \left\{ \sum_{j=1}^{NN} \left[\frac{K_i - K_j}{K_{worst} - K_{best}} \right] \left[\frac{X_j - X_i}{|X_j - X_i| + \varepsilon} \right] \right\} \times \left\{ 2 \left(rand + \frac{I}{I_{max}} \right) \widehat{K_{i,best}} \widehat{X_{i,best}} \right\} \right] + \omega_n N_i^{old} \tag{13}$$

where
K_i – fitness value of the ith krill individual (i = 1 to nk)
K_j – fitness value of the neighbor (j = 1 to NN)
K_{worst}, K_{best} – worst and best fitness value of the krill individual
X – related position of the krill individual
ε – small positive number
N^{max} – maximum induced speed in ms^{-1}
I – actual iteration count
I_{max} – maximum iteration count
$\widehat{K_{i,best}}$ – best fitness value of ith krill
$\widehat{X_{i,best}}$ – position corresponds to $\widehat{K_{i,best}}$ of ith krill
ω_n – inertia weight of the motion induced, in the range of (0,1)
N_i^{old} – last motion induced
rand – random number between 0 and 1

The foraging motion depends on food location and previous experience about food location.

$$F_i = V_f \left\{ 2 \left(1 - \frac{I}{I_{max}} \right) \widehat{K_{i,food}} \widehat{X_{i,food}} + \widehat{K_{i,best}} \widehat{X_{i,best}} \right\} + \omega_f F_i^{old} \tag{14}$$

Sensing distance is given by the equation

$$d_{s,i} = \frac{1}{5N} \sum_{j=1}^{N} ||X_i - X_j||$$

If the distance between the krill individuals is less than the defined sensing distance, then they are neighbors.

where, N – number of krill individuals
V_f – foraging speed, ms^{-1}
ω_f – inertia weight of the foraging motion in the range (0, 1)
F_i^{old} – last foraging motion

The physical diffusion of the krill individual is a random process.

$$D_i = D^{max} \left(1 - \frac{I}{I_{max}} \right) \delta \tag{15}$$

where
D^{max} – maximum diffusion speed, $D^{max} \in [0.01, 0.02]$ ms^{-1}
δ – random directional vector [−1 &1]

3.1. Motion process of KHA

The position vector is given by

$$X_i(t + \Delta t) = X_i(t) + \Delta t \frac{dx_i}{dt} \tag{16}$$

where $\Delta t = C_t \sum_{j=1}^{NV} (UB_j - LB_j)$ $\frac{dX_i}{dt} = N_i + F_i + D_i$ from Eq. (12).
NV – total number of variables
C_t – constant between [0,2]
UB, LB– upper and lower bound of the variables

If the related fitness value of each of the above mentioned effective vector (K_i, K^{best}, K^{food} or K_i^{best}) is better than the fitness of the i^{th} krill it has an attractive effect else repulsive effect.

3.2. Genetic Operators

Crossover:

$$X_{i,m} = \begin{cases} X_{r,m} & rand_{i,m} < C_r \\ X_{i,m} & else \end{cases} \tag{17}$$

$$C_r = 0.2 \widehat{K_{i,best}}$$

$$r \in \{1, 2, \ldots i-1, i+1, \ldots N\}$$

Mutation:

$$X_{i,m} = \begin{cases} X_{gbest,m} + \mu(X_{p,m} - X_{q,m}) & rand_{i,m} < Mu \\ X_{i,m} & else \end{cases} \tag{18}$$

$$Mu = 0.05 / \widehat{K_{i,best}}$$

$p, q \in 1, 2, \ldots i-1, i+1, \ldots K$ and μ is between 0 and 1

4. Stud Krill herd Algorithm

In [35], the authors introduced a reorganized genetic reproduction schemes, called stud selection and crossover (SSC) operator, into the KH during the krill updating process. In regular KH algorithm, the search depends fully on randomness; therefore, it cannot always converge rapidly. The aim of SKH is to accelerate convergence speed. The SSC operator is applied to fine-tune the selected solution in order to improve its consistency and robustness for global optimization. In SKH, the SSC operator is employed only to take the newly generating better solutions for each krill individual; as in KH, it is tending to accept all the updated krill. The proposed SKH approach can search the whole space widely by basic KH method and take out useful information by SSC operator.

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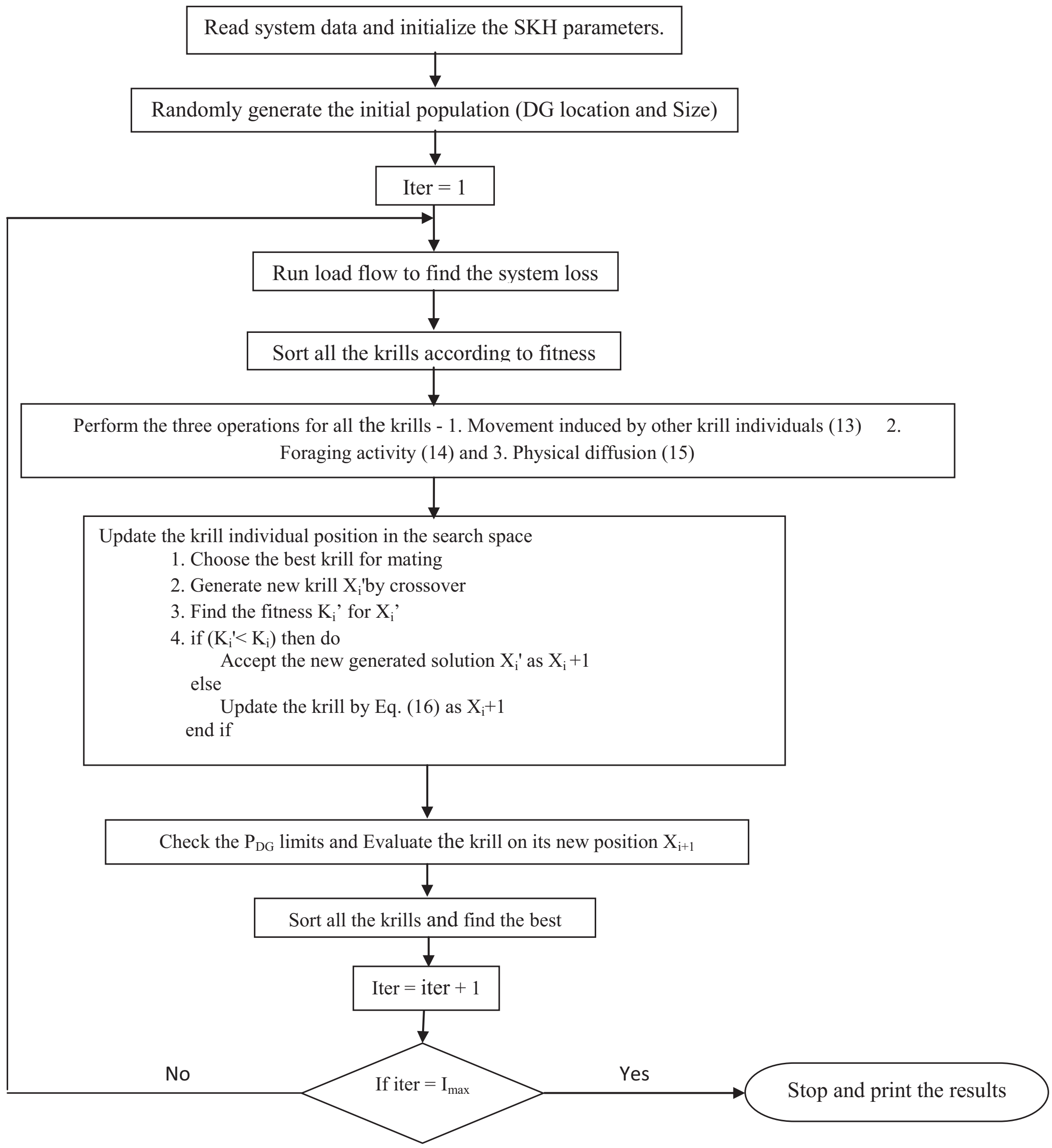
4.1. Flowchart for Stud Krill herd Algorithm application to DG placement problem



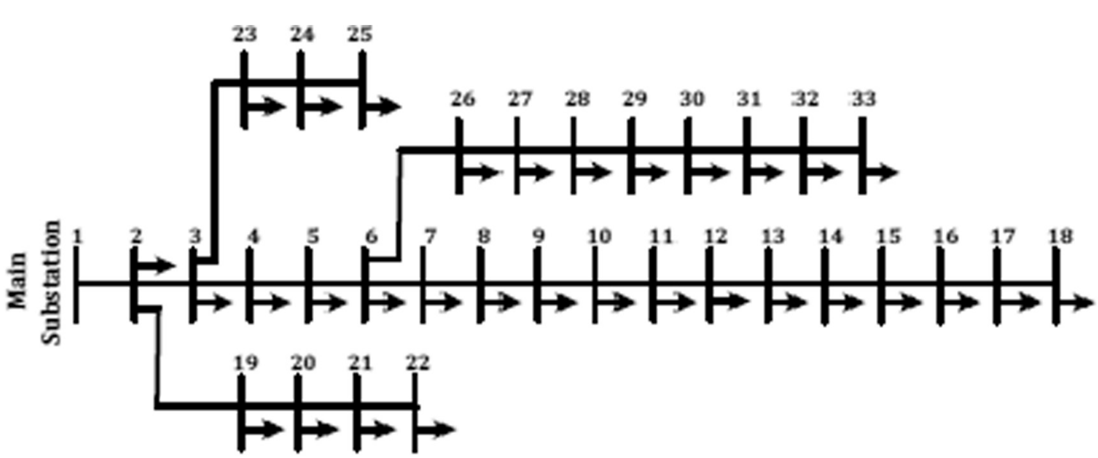


Fig. 1. Single line diagram of 33 bus system.

Stud Krill herd Algorithm

```
Begin
  Define the population size N and maximum iteration count
  Imax.
  Set The iteration Count I = 1;
  Initialize the population Xi of N krill individuals; Vf, Dmax,
  Nmax, Pc.
  Evaluate the krill population based on its position.
  While I < Imax
    Sort all the krill according to their fitness.
    for i = 1:N do
      Perform the three motions.
        1. Movement induced by other krill individuals 2.
  Foraging activity 3. Physical diffusion
      Apply mutation operator
      Update position for krill i by SSC operator as following
      Perform selection operator
      Choose the best krill (the Stud) for mating.
      Implement crossover operator
      Generate new krill X'i by crossover.
      Evaluate its quality/fitness K'i.
      if (K'i < Ki)
        Accept the new generated solution Xi' as Xi +1
      else
        Update the krill by Eq. (16) as Xi+1
      end if
        Evaluate each krill based on its new position Xi+1.
      end
    end
    Sort all the krill and find the current best.
    I = I + 1;
  end
  Output the best solutions.
End
```

5. Simulation results

The Krill herd and Stud Krill herd Algorithms are implemented on the 33 bus, 69 bus IEEE radial test system and 94 bus Portuguese radial distribution system. The software program is developed in MATLAB 2009a environment and executed on intel Core processor i3 – 2120 CPU with 3.30 GHz. The various control parameters applied for SKHA are given below and are common for all the test systems. The proposed technique can be implemented for any number of DGs, but for reliability the number of DG's are limited to three [9]. For all the test systems, bus 1 is taken as slack bus. The load is varied as light (0.5), nominal (1.0) and peak (1.6) at full load condition and results are tabulated for all the test systems. Control Parameters used in DG-SKHA problem are

Number of krill individuals n_k	10
Maximum number of iterations I_{max}	100
Maximum induced speed N_{max}	0.01
Inertia weight of motion induced ω_n	0.9
Foraging speed V_f	0.02
Inertia weight of foraging motion ω_f	0.9
Constant C_t	0.5
Small positive number e	0.001
Probability of crossover p_c	1

5.1. Case 1: 33 – bus system

This case study considers the 33 bus RDS test system with 32 branches. The total load is (3.715 + j 2.3) MVA with a base voltage of 12.66 kV. The single line diagram of 33 bus system is shown in Fig. 1. The total system losses of an uncompensated system is 210.9876 kW. In this paper, minimization of system losses is considered as objective function and is achieved by introducing DGs in the system. The optimal location and size of DGs are found out by KH and SKHA and the corresponding results are tabulated in

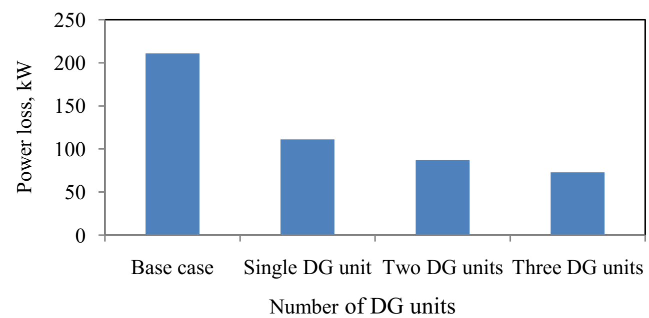


Fig. 2. Comparison of power loss for 33 bus system.

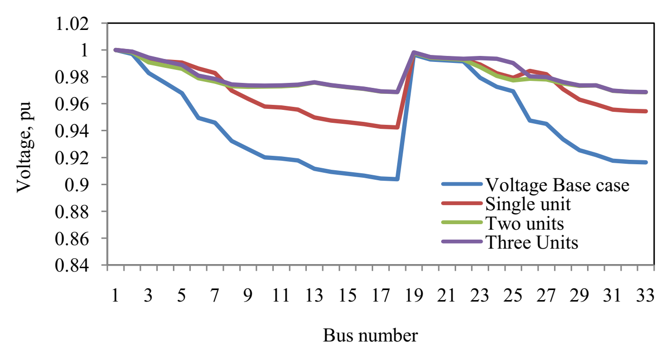


Fig. 3. Comparison of Bus voltages with respect to No. of DG units for 33 bus system.

Table 1
Summary of results after applying multiple DGs with KHA and SKHA for 33 bus system.

Item	Load flow Results	KHA			SKHA		
		Single DG unit	2 DG units	3 DG units	Single DG unit	2 DG units	3 DG units
Optimal Bus no./DG size in kW	_	6/2590.2126	29/1241.7140 13/824.4876	24/914.9803 14/750.1998 30/1142.4045	6/2590.215	13/851.6319 30/1157.5892	30/1053.6346 24/1091.3850 13/801.8118
V_{min} p.u./Bus no.	0.9038/18	0.9424/18	0.9667/33	0.9701/33	0.9424/18	0.9685/33	0.9687/33
V_{max} p.u./Bus no.	0.9970/2	0.9986/2	0.9983/2	0.9987/2	0.9986/2	0.9983/2	0.9988/2
P_{loss}, kW	210.9876	111.0188	87.426	73.2968	111.0188	87.1656	72.7853
Q_{loss}, kVAr	143.1284	81.7167	60.2091	51.016	81.7167	59.8129	50.6814
Elapsed time in sec*	–	4.2406	4.0925	4.092876	4.2406	4.2083	4.1333
% Loss reduction	–	47.3814	58.5634	65.2601	47.3814	58.6869	65.5026

* Elapsed time includes the time consumed in load flow runs.

Table 1. Number of DG's is varied from one unit to three units. The system loss is reduced by 65.26% for SKHA and 65.5% for KHA with three DG units included to the system. It is evident from the results that SKH algorithm gives better solution than KHA. Fig. 2 shows the effect of number of DG units in loss minimization and Fig. 3 illustrates the voltage profile improvement with respect to number of DG units. Fig. 4 shows the comparison of convergence characteristics of KHA and SKHA.

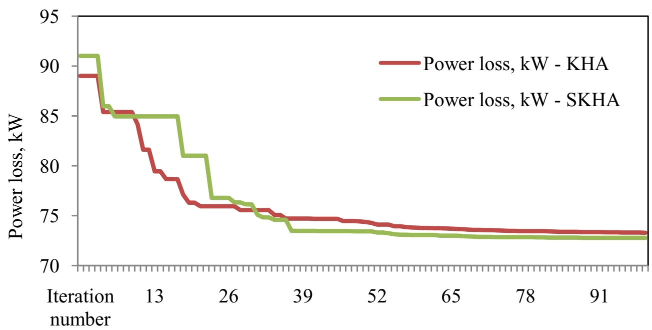


Fig. 4. Convergence characteristics of KHA and SKHA for 33 bus system.

To verify the efficiency of the algorithm, the optimal location of DGs is found for the system at different load levels – light (0.5), nominal (1.0) and peak (1.6) at full load and the corresponding results are tabulated in Table 2 and it is observed that the minimum voltage magnitude is improved at all load levels after the implementation of the algorithm. The attained results of KHA and SKHA are compared with various recently developed methods from the literature in Table 3. It is observed that SKHA gives optimal solution when compared to other methods.

5.2. Case 2: 69 – bus system

For the 69 bus RDS test system the base voltage is 12.66 kV and the total load is (3.80 + j 2.69) MVA [34]. The single line diagram of 69 bus system is shown in Fig. 5. The proposed method is employed on 69 bus system and the power loss of the system without DGs is 220.534 kW. The proposed SKHA is used to find the optimal DG locations and sizes; the acquired results are structured in Table 4. The graphical representation of network real power losses and voltage profile with single and multiple DGs

Table 2
Summary of results of 33 bus system after applying DG using KHA and SKHA with Load Variation.

Parameters		KHA			SKHA		
		Load Level					
		Light load (0.5)	Nominal load (1.0)	Peak load (1.6)	Light load (0.5)	Nominal load (1.0)	Peak load (1.6)
Load flow results	Ploss in KW	48.787	210.9876	603.4308	48.787	210.9876	603.4308
	Qloss in kVAr	33.0486	143.1284	410.2075	33.0486	143.1284	410.2075
	Vmin in pu/bus	0.954/18	0.9038/18	0.836/18	0.954/18	0.9038/18	0.836/18
	Vmax in pu/bus no	0.9986/2	0.997/2	0.995/2	0.9986/2	0.997/2	0.995/2
Optimal DG location/Size in kW		13/424.9912 30/529.2512 25/358.5569	24/914.9803 14/750.1998 30/1142.4045	30/1658.85 12/1457.7173 24/1746.446	30/517.5651 24/567.630914/381.2038	30/1053.6346 24/1091.3850 13/801.8118	30/1655.8742 24/1737.0977 13/1427.2515
Ploss/kW		**17.9082**	**73.2968**	**195.3122**	**17.643**	**72.7853**	**194.716**
Qloss/kVAr		12.3742	51.016	135.7373	12.2932	50.6814	135.2874
Vmin/bus no.		0.9845/33	0.9701/33	0.9496/33	0.9843/33	0.9687/33	0.9491/33
Vmax/bus no.		0.9993/2	0.9987/2	0.9981/2	0.9994/2	0.9988/2	0.9981/2

Bold values represent the reduction in loss.

Table 3
Comparison of results with other methods for 33 bus test system.

Method	Power loss without DG, kW	Single DG		Two DGs		Three DGs	
		Bus no./Size of DG, kW	Power loss, kW	Bus no./Size of DG, kW	Power loss, kW	Bus no./Size of DG, kW	Power loss, kW
Fuzzy + Clonal Alg. [19]	203.9088	32/1931	127.0919	32/383.6, 30/1150.6	117.3946	32/2071, 30/1113.8, 31/150.3	117.358
Golden section search [16]	211	6/2590.2	111				
Grid search alg. [16]	211	6/2600.5	111				
Analytical [16]	211.2	6/2490	111.24				
Backtracking search [16]	210.84	8/1857.5	118.12	13/880, 31/924	89.34	13/632, 28/487, 31/550	89.05
Int. water drop alg. [18]	211.27	6/2490	111.01			9/600.3, 16/300, 30/1011.2	85.78
Analytical [16]	211	6/3150	115.29				
Analytical [16]	211	6/2490	115.15				
BFOA [9]	210.98					14/652.1, 18/198.4, 32/1067.2	89.9
Invasive weed opt. [12]	202.771					14/624.7, 104.9/18, 1056/32	85.86
Firefly alg. [8]	227.7	30/1190.4	116.7	30/1013.1, 14/612.8	96.9		
Rank Evol. PSO(REPSO) [13]	202.7					6/1260.7, 12/609.6, 25/1579.2, 32/2059.7 with reconfiguration	98.8
QOTLBO [14]	210.998					13/1083.4, 26/1187.6, 30/1199.2	103.409
Craziness based PSO [37]	202	6/2575	103	29/1158, 12/846	86		
KHA	210.9876	6/ 2590	111.0188	29/1242, 13/825	87.426	24/915, 14/750, 30/1142	73.2968
SKHA	210.9876	6/2590	111.0188	13/851.6, 30/1157.6	87.1656	30/1054, 24/1091, 13/802	72.7853

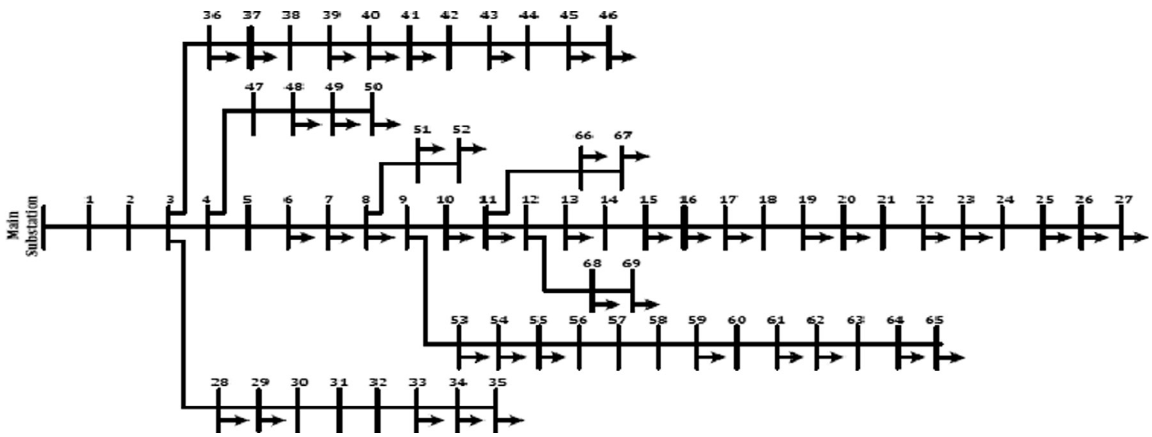


Fig. 5. Single line diagram of 69 bus system.

Table 4
Summary of results after applying multiple DGs with KHA and SKHA for 69 bus system.

Item	Load flow results	KHA			SKHA		
		Single DG unit	2 DG units	3 DG units	Single DG unit	2 DG units	3 DG units
Optimal Bus no./DG size in kW	_	61/1864.6446	51/972.1609 61/1726.9813	15/549.1027 61/1768.4752 49/1013.9691	61/1864.6376	17/522.9145 61/1778.9700	61/1719.0677 17/370.8802 11/527.1736
V_{min} p.u./Bus no.	0.9105/65	0.9689/26	0.973/26	0.979/65	0.9689/26	0.9792/65	0.9792/65
V_{max} p.u./Bus no.	1.00/2,28	1.0000/2,28	1.0000/2,3,28	1.0/2,3,28	1.0/2,28	1.0/2,3,28	1.0/2,3,28
P_{loss}, kW	220.534	81.6003	77.0354	69.1977	81.6003	70.4092	68.1523
Q_{loss}, kVAr	100.0281	39.8185	37.5038	31.9783	39.8185	35.342	34.3566
Elapsed time in sec	_	11.2187	11.1014	11.244116	11.302697	11.893807	11.931362
% Loss reduction	_	62.9988	65.0687	68.6227	62.9988	68.0733	69.0967

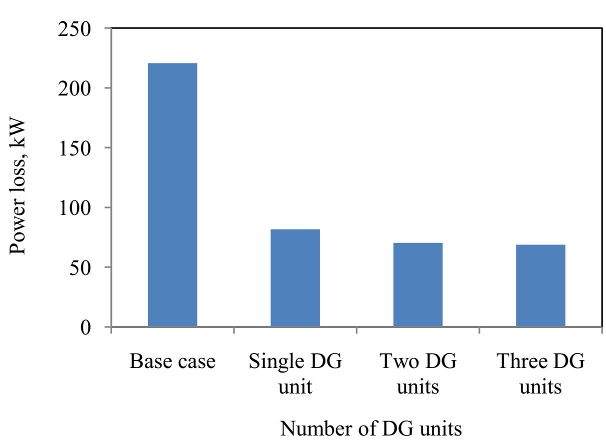


Fig. 6. Comparison of power loss for 69 bus system.

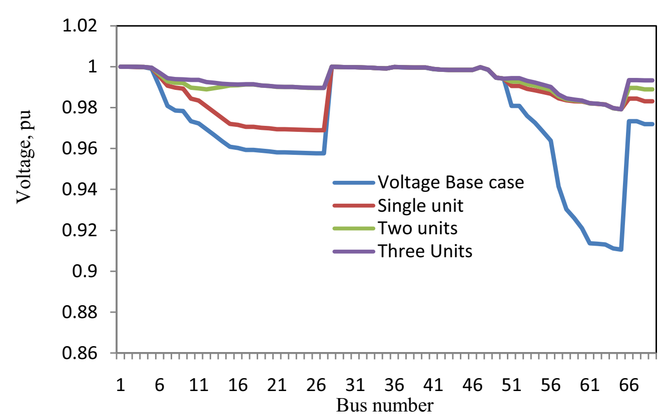


Fig. 7. Comparison of Bus voltages with respect to No. of DG units for 69 bus system.

are given in Figs. 6 and 7 respectively. After DG placement the real power loss is reduced to 68.1523 kW and the minimum voltage is 0.9792 at bus 65. The real power capacity of three units DG compensation is 1719.0677 kW at bus 61, 370.8802 W at bus 17 and 527.1736 kW at bus 11. At different load levels the performance of the system is given in Table 5. The results are compared with various methods from literature and are listed in Table 6 and convergence characteristics of KHA and SKHA is shown in Fig. 8. The results show the effectiveness of SKHA in the improvement of results.

5.3. Case 3: 94 – bus system

The base voltage of 94 bus Portuguese RDS test system is 15 kV [36] with a total load (4.797 + j2.324) MVA and the single line diagram is shown in Fig. 9. The power loss of the system without DGs is 362.8578 kW. The proposed SKHA is employed to find the optimal DG locations and sizes; the acquired results are structured in Table 7. The graphical representation of network real power losses and voltage profile with single and multiple DGs are given in Figs. 10 and 11 respectively. After DG placement the real power

Table 5
Summary of results of 69 bus system after applying DG using KHA and SKHA with Load Variation.

Parameters		KHA			SKHA		
		Load Level					
		Light load (0.5)	Nominal load (1.0)	Peak load (1.6)	Light load (0.5)	Nominal load (1.0)	Peak load (1.6)
Load flow results	Ploss in KW	50.6496	220.5340	638.0838	50.6496	220.5340	638.0838
	Qloss in kVAr	23.0904	100.0281	287.4235	23.0904	100.0281	287.4235
	Vmin in pu/bus	0.9573/65	0.9105/65	0.8469/65	0.9573/65	0.9105/65	0.8469/65
	Vmax in pu/bus no	1.0/2,3,28,36	1.0/2,28	0.9999/2,3,28,36	1.0/2,3,28,36	1.0/2,28	0.9999/2,3,28,36
Optimal DG location/ Size in kW		36/248.3250	15/549.1027	62/1205.1531	24/52.6136	61/1719.0677	20/553.175
		17/253.4436	61/1768.4752	17/853.8292	1/873.5822	17/370.8802	61/2814.583
		61/878.1729	49/1013.9691	61/1684.0163	16/218.796	11/527.1736	11/914.4973
Ploss/kW		**17.2574**	**69.1977**	**184.8825**	**17.2131**	**68.1523**	**178.4262**
Qloss/kVAr		8.6824	31.9783	92.5262	8.6632	34.3566	89.7021
Vmin/bus no.		0.9895/65	0.979/65	0.9677/65	0.9894/65	0.9792/65	0.9679/65
Vmax/bus no.		1.0/2,3,28,29,36	1.0/2,3,28	1.0/2	1.0/2,3,28,29,36	1.0/2,3,28	1.0/2,28

Bold values represent the reduction in loss.

Table 6
Comparison of results with other methods – 69 bus test system.

Method	Power loss without DG, kW	Single DG		Two DGs		Three DGs	
		Bus no./Size of DG, kW	Power loss, kW	Bus no./Size of DG, kW	Power loss, kW	Bus no./Size of DG, kW	Power loss, kW
Analytical [18]	225	61/1800	83.37				
Analytical [18]	224.88	61/1830	83.19				
Analytical [18]	219.28	61/1810	81.44				
MINLP [18]	225.27	61/1870	83.49				
Int. water drop alg.[18]	225	60/1820	80.12			17/2999, 60/1320, 63/438.8	73.55
GA [18]						21/929.7, 62/1075.2, 64/992.5	89
PSO [18]						61/1199.8, 63/796, 17/992.5	83.2
GA + PSO [18]						63/884.9, 61/1196, 21/910.5	81.1
BFOA[9]						27/295.4, 65/446, 61/1345.1	75.23
MBFOA[10]	225.4	61/1879.2	83.4				
QOTLBO [14]	224.7					15/811.4, 61/1.1470, 63/1.0022	80.585
Craziness based PSO[37]	317	61/1891.4	112	60/1786,13/610	97		
KHA	220.534	61/ 1865	81.6003	51/972.1609 61/1726.9813	77.0354	15/549.10, 61/1768.48, 49/1013.9697	69.1977
SKHA	220.534	61/1864.6	81.6003	17/5229.1 61/1778.9	70.4092	61/1719.0677, 17/370.8802, 11/527.1736	68.1523

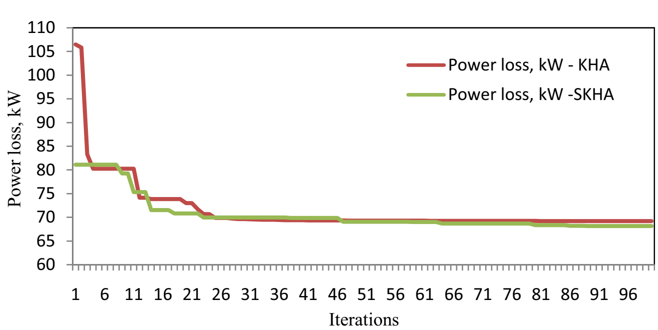


Fig. 8. Convergence characteristics of KHA and SKHA for 69 bus system.

loss is reduced to 73.1022 kW and the minimum voltage is 0.9437 at bus 91 and 92. The real power capacity of three units DG compensation is 498.7761 kW at bus 25, 1575.7066 kW at bus 19 and 1638.3085 kW at bus 58. At different load levels the performance of the system is given in Table 8. The results are compared with various methods from literature and are listed in Table 9 and convergence characteristics of KHA and SKHA is shown in Fig. 12.

The strength of the algorithm is established by various statistical measuring factors after 25 trials and exhibited in Table 10. Many independent trials have been carried out to verify the efficacy of the algorithm because of the randomness of the algorithm. The analysis is carried out for the system connected with three DGs at nominal load condition. The best solution is near to the average value.

6. Conclusion

In this paper, Stud Krill herd Algorithm is implemented to find the optimal location and capacities of DGs for power loss minimization in radial distribution system. The proposed method is applied on 33 bus, 69 bus and 94 bus Portuguese radial distribution systems at different load levels with single and multiple DGs and the results obtained show the effectiveness of the algorithm. The results illustrate that including DGs reduce the real and reactive power losses in the system and improve the voltage magnitude. From the results, it is concluded that Stud Krill herd Algorithm

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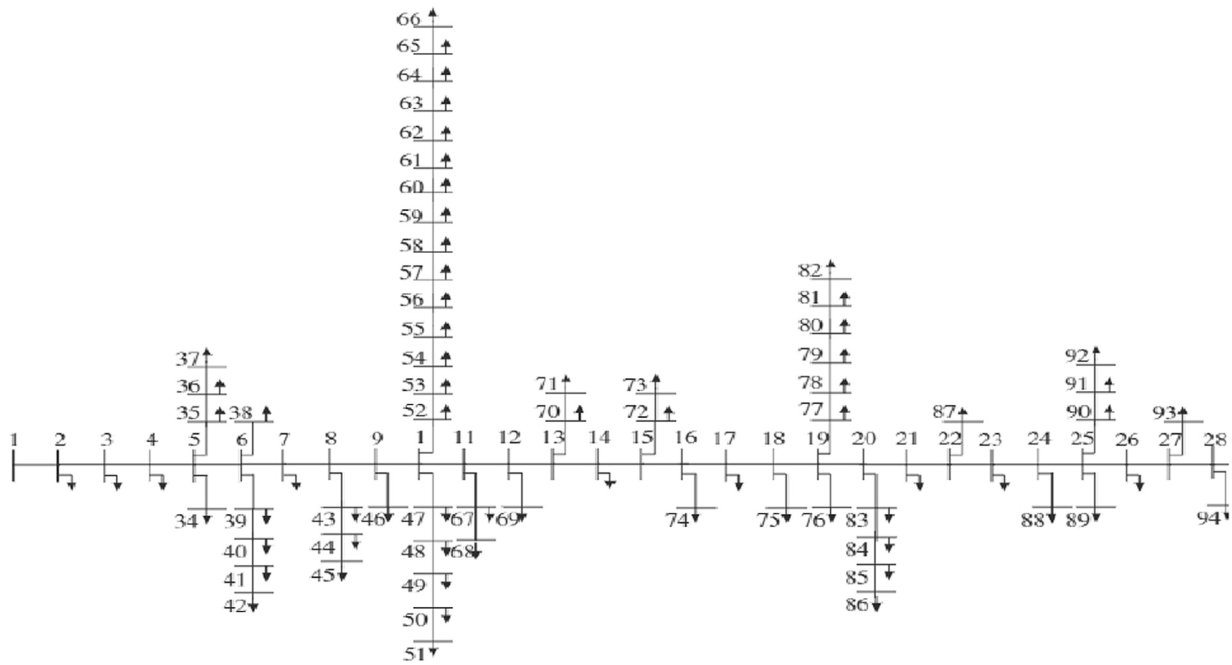

Fig. 9. Single line diagram of 94 bus system.

Table 7
Summary of results after applying multiple DGs with KHA and SKHA for 94 bus system.

Item	Load flow results	KHA			SKHA		
		Single DG unit	2 DG units	3 DG units	Single DG unit	2 DG units	3 DG units
Optimal Bus no./DG size in kW	_	19/2636.0175	56/1940.2177 83/1752.4332	10/955.1033 58/1285.2885 20/1833.7965	19/2636.018	58/1726.6598 20/1978.5448	25/498.7761 19/1575.7066 58/1638.3085
V_{min} p.u./Bus no.	0.8485/92	0.9301/66	0.9284/92	0.934/92	0.9301/66	0.9332/92	0.9437/91,92
V_{max} p.u./Bus no.	0.9951/2	0.9968/2	0.9974/2	0.9976/2	0.9968/2	0.9974/2	0.9974/2
P_{loss}, kW	**362.8578**	**132.3957**	**86.6475**	**74.4197**	**132.3957**	**79.2549**	**73.1022**
Q_{loss}, kVAr	504.042	164.7009	101.1686	90.9651	164.7009	97.0315	95.0521
Elapsed time in sec	_	22.5702	20.62681	19.24969	21.17227	20.29797	19.04671
% Loss reduction	_	**63.5131**	**76.1208**	**79.4907**	**63.5131**	**78.1581**	**79.8538**

Bold values represent the reduction in loss.

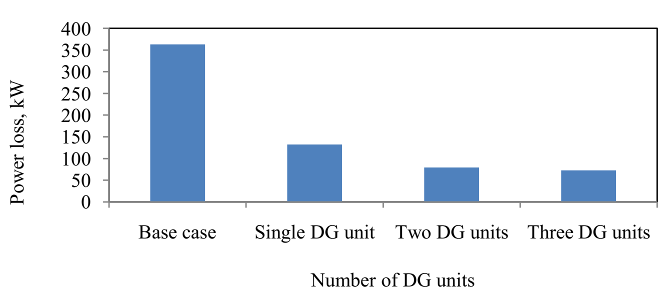

Fig. 10. Comparison of power loss for 94 bus system.

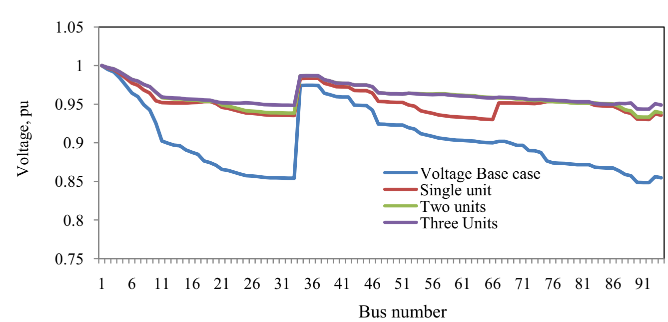

Fig. 11. Comparison of Bus voltages with respect to No. of DG units for 94 bus system.

can be employed for solving the optimal DG placement problem in radial distribution system. SKH noticeably advances the accuracy of the global optimality and the superiority of the solutions. The proposed algorithm can also be extended to find the optimal location and size of multiple DGs for loss reduction along with minimization of system cost and voltage deviation.

Table 8
Summary of results of 94 bus system after applying DG using KHA and SKHA with Load Variation.

Parameters		KHA			SKHA		
		Load Level					
		Light load (0.5)	Nominal load (1.0)	Peak load (1.6)	Light load (0.5)	Nominal load (1.0)	Peak load (1.6)
Load flow results	Ploss in KW	79.6036	362.8578	1150.2	79.6036	362.8578	1150.2
	Qloss in kVAr	110.9393	504.042	1587.3	110.9393	504.042	1587.3
	Vmin in pu/bus no.	0.9299/91	0.8585/92	0.725/92	0.9299/91	0.8585/92	0.725/92
	Vmax in pu/bus no.	0.9977/2	0.9951/2	0.9913/2	0.9977/2	0.9951/2	0.9913/2
Optimal DG location/Size in kW		83/525.124	10/955.1033	70/872.8886	19/770.8539	25/498.7761	25/1099.1851
		58/891.3638	58/1285.2885	20/2685.6479	57/858.2636	19/1575.7066	77/2103.2127
		24/382.6106	20/1833.7965	58/2706.7872	25/236.4532	58/1638.3085	58/2491.1535
Ploss/kW		**17.9095**	**74.4197**	**206.3811**	**17.4796**	**73.1022**	**204.5294**
Qloss/kVAr		23.0235	90.9651	250.0987	22.6679	95.0521	262.5157
Vmin/bus no.		0.972/92	0.934/92	0.8908/92	0.972/91	0.9437/91,92	0.909/92
Vmax/bus no.		0.9987/2	0.9976/2	0.9959/2	0.9987/2	0.9974/2	0.9956/2

Bold values represent the reduction in loss.

Table 9
Comparison of results with other methods – 94 bus test system.

Method	Power loss without DG	Single DG		Two DGs		Three DGs	
		Bus no./Size of DG	Power loss, kW	Bus no./ Size of DG	Power loss, kW	Bus no./ Size of DG	Power loss, kW
Backtracking search Algorithm [29,16]	362.86	21/2399	153.86				
KHA	362.8578	19/2636.0175	132.3957	56/1940.2177 83/1752.4332	86.6475	10/955.1033, 58/1285.2885 20/1833.7965	74.4197
SKHA	362.8578	19/2636.018	132.3957	58/1726.6598 20/1978.5448	79.2549	25/498.7761, 19/1575.7066 58/1638.3085	73.1022

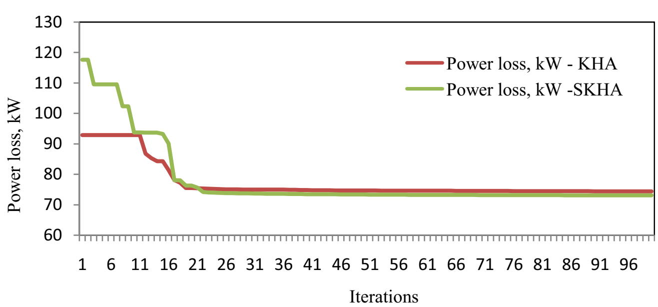

Fig. 12. Convergence characteristics of KHA and SKHA for 94 bus system.

Table 10
Statistical Performance Analysis of SKHA (After 25 trials).

Measuring factor	Test Systems		
	33 bus test System	69 bus test system	94 bus test system
Best (Ploss/kW)	**72.7853**	**68.1523**	**73.1022**
Worst(Ploss/kW)	84.4969	74.1872	84.9861
Average	76.61893	70.29724	77.76965
Median	74.6759	70.4146	76.833
Variance	12.01379	2.013929	11.39961
Standard deviation	3.466091	1.41913	3.376331

Bold values represent the reduction in loss.

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