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Multi-Objective Invasive Weed Optimization – An application to optimal network reconfiguration in radial distribution systems

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A B S T R A C T

Optimal Network Reconfiguration (ONR) is one of the technique utilized by distribution operators in normal and emergency condition for optimal operation of the distribution system. In this article, a Multi-Objective Invasive Weed Optimization (MOIWO) Algorithm is proposed to solve the Optimal Network Reconfiguration (ONR). While solving ONR of the radial distribution system, minimization of active power loss, maximum node voltage deviation, number of switching operations and the load balancing index are considered as the objectives simultaneously. For adopting Invasive Weed Optimization (IWO) Algorithm for solving this multi-objective problem, a non-dominated sorting technique and crowding distance are used to rank the weeds. To investigate the feasibility of the proposed algorithm, it is tested on standard IEEE 33-Bus Test Radial Distribution System and 84 Bus Taiwan Power Company (TPC) Practical Distribution Network. For an analysis of the load flows in a radial distribution system Backward/Forward sweep load flow algorithm is implemented. The performance of the proposed algorithm is compared with results available in recent literature and it is observed that the proposed method produces a high quality Pareto solution and finds a global optimum configuration.

Introduction

Power systems across the world have been recently deregulated, which resulted in competition among the power sellers. This resulted in increased complexity of distribution networks. Further the distribution system planner and operator are facing new challenges that put emphasis on optimal planning and operation of the distribution system. Reduction of power loss, improvement of power quality, cost minimization and load balance among the branches are important factors for better operation of the distribution system. These can be accomplished by Optimal Network Reconfiguration (ONR). Generally the distribution feeders are configured in radial manner to increase the effectiveness and coordination among the protection devices. Distribution feeders can be reconfigured by opening and closing the switches to sectionalize the part of the distribution system for better performance and to maintain radial configuration of feeders. Under normal operating conditions the distribution feeders are reconfigured with switching operations to enhance network reliability, maintain load balance and/or minimize line loss. One of the important constraint for ONR is after reconfiguration the distribution system must preserve radial structure and supply service to each and every load as needed. ONR is a complex combinatorial, non-differentiable constrained optimization process aimed at finding optimal operation of the distribution system.

Optimal feeder reconfiguration has been investigated over decades with heuristic and meta-heuristic techniques for single and multi-objectives in order to find optimal planning and operation of the distribution system. In this paper ONR is discussed with multi-objective optimization for optimal operation of the distribution system. A brief survey of contribution by authors in this area over a decade is presented below. Huang [1], presented enhanced genetic algorithm based fuzzy multi-objective algorithm to minimize power loss reduction, violation of voltage, current constraints and switching operations and a weighted sum multi-objective technique is used to form a single objective. Momoh et al. [2] implemented Integer Interior Point Programming technique for enhancement of reliability and load balancing. The authors considered one objective as fitness and another objective as constraints to convert the problem into a single objective problem. Prasad et al. [3] presented a fuzzy mutated genetic algorithm for optimal reconfigurations for the minimization of real power loss and to improve the power quality of radial distribution system. In this method, multi-objective is converted as a single objective by considering weights depending on the preference of the objectives. Hsu et al. [4] proposed Multi-objective evolutionary programming to minimize feeder loss and load balancing and the multi-objective

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Nomenclature

nl	number of lines	Vs	voltage of substation in per unit
nb	number of buses	I_i	current flows through the '*i*th' line
nt	number of tie-lines	I_i^{max}	current rating of the '*i*th' line
R_i	resistance of line '*i*'	P_{loss}	total system active power loss
V_{min}	minimum bus voltage	dV	system node voltage deviation
V_{max}	maximum bus voltage	itermax	maximum number of iterations
V_i	voltage of '*i*th' node	pop	number of initial population
LBI	load balancing index	$\sigma_{initial}$	initial value of standard deviation
A	incidence matrix	σ_{final}	final value of standard deviation
D	problem dimension	NSW	number of switching operations
S_{max}	maximum number of seeds	n	nonlinear modulation index
S_{min}	minimum number of seeds	$Rank_i$	rank of the 'ith' population
maxpop	number of maximum weeds (or population)	$Seed_i$	number of seeds generated by '*i*th' population
S_{oi}	original system status of the switches	Si	status of the switches after reconfiguration

problem is formed as single objective with normalized objectives. Das [5] proposed fuzzy multi-objective approach for reconfiguration and weighted sum multi-objective technique. Ahuja et al. [6] proposed a hybrid algorithm based on Artificial Immune Systems (AIS) and Ant Colony Optimization (ACO) for reconfiguration in order to minimize power loss, transformer load balancing and minimization of voltage deviation. Sahoo et al. [7] implemented a fuzzy-tuned genetic algorithm for optimal reconfigurations of the radial distribution network. Lakshminarayana and Mohan [8] used a genetic algorithm, multi-objective approach for the efficient operation planning technique of the distribution system with weighted sum technique. Niknam [9] proposed a new hybrid algorithm for Multi-Objective Distribution Feeder Reconfiguration with the combination of Discrete Particle Swarm Optimization (DPSO), ACO and fuzzy multi-objective approach. Olamaei et al. [10] used a hybrid algorithm formed by the combination of ACO and simulated annealing (SA) to minimize power loss, voltage deviation and switching operations with Distributed Generation and weighted sum technique is used to solve multi-objective problem. Swarnkar et al. [11] implemented fuzzy multi-objective approach using Adaptive PSO. Tsai and Hsu [12] applied gray correlation analysis in evolutionary programming for the distribution system feeder reconfiguration and a weighted sum approach is used to solve multi-objectives. Sun [13] used fuzzy preference, multi-objective approach for distribution reconfiguration for load balancing among feeders, to minimize power loss, voltage deviation and branch current constraint violation. Huang et al. [14] implemented multi-objective optimization via a fuzzy-evaluation method for the minimization of power loss, to increase system security and to improve power quality. In this paper, the multi-objective problem is converted to a single objective using fuzzy evolution.

Niknam et al. [15] proposed an efficient multi-objective modified shuffled frog leaping algorithm for distribution feeder reconfiguration problem. Sanches et al. [16] proposed Node-Depth Encoding with recombination for multi-objective evolutionary algorithm to solve loss reduction problem in large-scale distribution systems. Syahputra et al. [17] used fuzzy multi-objective method to solve reconfiguration and a heuristic technique is used to find the optimal configuration which generates a solution which depends upon the original configuration. Ahmad et al. [18] proposed multi-objective quantum-inspired Artificial Immune System (AIS) approach for ONR in the distribution system. Malekpour et al. [19] implemented Point Estimate Method to solve Distribution Feeder Reconfiguration. Andervazh et al. [20] proposed DPSO algorithm with graph theory to minimize real power loss, voltage deviation and switching operations. Ferdavani et al. [21] implemented Neighbor chain updating approach for the minimization of power loss and voltage deviation with weighted sum optimization technique. Sedighizadeh et al. [22] used an Efficient Hybrid Big Bang–Big Crunch Algorithm for multi-objective reconfiguration of balanced and unbalanced distribution systems in fuzzy framework. Hsu and Tsai [23] proposed a non-dominated sorting evolutionary programming algorithm for multi-objectives power distribution system feeder reconfiguration problems.

Dehnavi and Esmaeili [24] proposed fuzzy shuffle frog leaping algorithm for reconfiguration in the presence of reactive power compensators. Narimani et al. [25] proposed Enhanced gravitational search algorithm for multi-objective distribution feeder reconfiguration considering reliability, loss and operational cost. Shuaib et al. [26] implemented Gravitational Search Algorithm for minimization of loss reduction and to improve voltage deviation. Mazza et al. [27] implemented multi-objective for reconfiguration which enhanced genetic operators to minimize network loss and energy not supplied. Barbosa et al. [28] proposed an Interval Multi-Objective Evolutionary Algorithm to minimize power loss, average current index, average node voltage deviation and number of switching operations. Gupta et al. [29] proposed a Genetic Algorithm for improvement in power quality and reliability issues, the solution obtained by his approach depends upon the weights chosen. Mohamed Imran et al. [30] a proposed Fireworks algorithm for power loss minimization and voltage profile enhancement, the normalized objectives are simply added and formed as main objective which cannot obtain the best solution. Shareef et al. [31] implemented optimum network reconfiguration by using a quantum firefly algorithm. Mirhoseini et al. [32] proposed an improved adaptive imperialist competitive algorithm for the reduction of loss and improvement of voltage profile which are attempted individually.

Researchers concentrated on both heuristic and meta-heuristic techniques to solve feeder reconfiguration to achieve different objectives, and most of the researchers used traditional methods to solve multi-objective optimization which consisted of converting all objectives into a single objective function. The ultimate goal is to find a solution that minimizes this single objective while maintaining the constraints of the system. The optimized solution results in a single value that reflect a compromise between objectives. This simple optimization process no longer acceptable for a system with multiple conflicting objectives: the distribution system engineer or operator may desire to know all possible optimized solutions for all objectives simultaneously. It is known as trade-off analysis. Very few authors attempted to find the trade-off solutions for ONR with multiple objectives using Pareto optimality concept. In this article, a Multi-Objective Invasive

Weed Optimization (MOIWO) Technique is used to solve multi-objective optimal network reconfiguration. Invasive Weed Optimization (IWO), first designed and developed by Mehrabian and Lucas [33], is a relatively novel numerical stochastic optimization algorithm inspired from colonization of invasive weeds. A non-dominated sorting technique [34] is adopted to IWO Algorithm for sorting weeds to solve multi-objective optimization problem. Backward/Forward sweep load flow algorithm [35] is used for load flow analysis of radial distribution system. The proposed method is tested on standard IEEE 33-Bus Test Radial Distribution System and 84 Bus Practical Distribution Network Taiwan Power Company (TPC) and the result obtained by MOIWO Algorithm performed better in terms of quality of solution when it is compared with the results available in the literature.

Problem formulation

Objective functions

In this article, four objectives are considered for minimization, active power loss, maximum node voltage deviation, number of switching operations and load balancing index.

Active power loss

Minimization of active power loss is considered as one of the objectives to achieve economical operation of the distribution system.

The power loss of a distribution system is described as:

$$P_{loss} = \sum_{i=1}^{nl} I_i^2 R_i \tag{1}$$

Maximum node voltage deviation

Minimizing the maximum node voltage deviation is considered as another objective function for ONR in order to improve power quality of the distribution system. The maximum node voltage deviation is calculated as

$$dV = \max[(V_s - \min(V)), (V_s - \max(V))] \tag{2}$$

Number of switching operations

Minimization of switching operations is also considered as one of the objective function in order to reduce the operating cost of the distribution system.

$$\mathrm{NSW} = \sum_{i=1}^{nb+nt} |S_{oi} - S_i| \tag{3}$$

Load balancing index

Minimization of the load balancing index is considered as another objective function for ONR in order to achieve load balancing among the branches.

The Load Balancing Index is calculated as

$$\mathrm{LBI} = \mathrm{Var}\left[\frac{I_1}{I_1^{\max}} \quad \frac{I_2}{I_2^{\max}} \quad \cdots \quad \frac{I_i}{I_i^{\max}} \quad \cdots \quad \frac{I_n}{I_n^{\max}}\right] \tag{4}$$

$\frac{I_i}{I_i^{\max}}$ gives branch loading and it is called as line usage index [22].

Operational constraints

(a) The voltage magnitude at each bus must be within a permissible range.

$$V_{\min} \leqslant V \leqslant V_{\max} \tag{5}$$

(b) The current loading of distribution feeders must be within the rated current.

$$|I| \leqslant I^{\max} \tag{6}$$

(c) No feeder section must be left out of service and the radial network structure must be maintained.

(d) The radial constraint is verified by using an incidence matrix (A).

If $|A| = 1$ *or* -1, the system is radial and
$|A| = 0$, the system is not radial.

Invasive Weed Optimization (IWO) Algorithm

Mehrabian and Lucas [33] have developed a relatively novel numerical stochastic optimization algorithm inspired from colonization of invasive weeds named as Invasive weed optimization Algorithm.

The algorithm is simple and effective in finding the optimal solution by employing basic properties of a weed colony. The behavior of weeds are model and simulated as a novel optimization algorithm with some basic properties of the colonization process.

The modelling of the basic properties of proposed algorithm presents in detail with the following steps.

Initialization

For initialization of the population finite number of seeds are randomly dispread over the D-dimensional problem space.

Reproduction

Depending on their fitness, every seed grows into a flowering plant and produces seeds (reproduction): With the lowest and highest fitness values of the colony, a member of the colony of weeds is allowed to produce seeds. From a possible minimum to maximum, the number of seeds in each plant produced increases linearly. The search algorithm acquires significant property with this step. In most of the evolutionary algorithms, intuitively, reproduction is not allowed with the infeasible individuals (feasible individuals are the ones with better fitness values than infeasible individuals), although it is possible that more useful information is carried by some of the infeasible individuals than that of feasible individuals. So, survival and reproduce chance is given to infeasible individuals in the reproduction method during the evolution process.

Spatial dispersion

The delivered seeds are constantly randomly dispread over the search region and develop to new plants (spatial dispersal), the produced seeds are, no doubt arbitrarily circulated over the D-dimensional search space by typically dispersed randomly numbers with a mean equivalent to zero yet with a varying variance of σ_{iter}. Hence, seeds will be randomly disseminated such that they tolerate close to the parent plant. The standard deviation (SD) of the arbitrary function is decreased from an initial value $\sigma_{\mathrm{initial}}$ to a final value $\sigma_{\mathrm{final.}}$ In reproductions, a nonlinear adjustment has indicated satisfactory performance for spatial dispersion.

$$\sigma_{\mathrm{iter}} = \left(\frac{\mathrm{iter\,max} - iter}{\mathrm{iter\,max}}\right)^n * (\sigma_{\mathrm{initial}} - \sigma_{\mathrm{final}}) + \sigma_{\mathrm{final}} \tag{7}$$

This change guarantees that the probability of dropping a seed in a far off range diminishes nonlinearly at each one stage, which brings about gathering fitter plants and the disposal of inappropriate plants.

Table 1
Pseudo code of the Multi-Objective Invasive Weed Optimization (MOIWO).

1. Generate the initial weeds of 'pop' number of solutions randomly
2. Evaluate the objective functions for these initial weeds
3. Rank the weeds by using non-dominated sorting technique and crowding distance
4. Allow each weed to produce a number of seeds with better weed produce more number of seeds
   $\text{Seed}_i = \text{floor}(S_{\min} + S_{\max} - S_{\min}) * (\text{pop} - \text{rank}_i)/\text{pop})$
5. The generated seeds are distributed over the search space by normally distributed random numbers with mean equal to zero but varying variance. The standard deviation is reduced over successive generations, according to the given formula:
   $\sigma_{\text{iter}} = \left(\frac{\text{iter max}-\text{iter}}{\text{iter max}}\right)^n * (\sigma_{\text{initial}} - \sigma_{\text{final}}) + \sigma_{\text{final}}$
6. When the weeds exceeds the maximum number of weeds (maxpop), the weeds are sorted by using non-dominated sorting technique and the best maxpop weeds are allowed to survive
7. Continue until stopping criterion is met

Table 2
Loop vectors of IEEE 33 bus radial distribution system.

Loop1	**33**,7,6,5,4,3,2,18,19,20
Loop2	**34**,9,10,11,12,13,14
Loop3	**35**,11,10,9,8,33,21
Loop4	**36**,17,16,15,34,8,7,6,25,26,27,28,29,30,31,32
Loop5	**37**,24,23,22,3,4,5,25,26,27,28

Competitive-exclusion

After reaching the maximum number of seeds, each weed is allowed to produce seeds and spread them over the search area. Now find their position or rank together with their parents, only the plants with higher fitness can survive and lower fitness plants are eliminated in order to attain the maximum allowable population. The process continues until the maximum number of iterations is reached. After reaching the maximum number of iterations, the best fitted plant is considered as the optimal solution.

The algorithm proved to be a powerful tool to reach the global optimum value by mimicking the ecological process of weed colonization.

Multi-Objective Invasive Weed Optimization (MOIWO)

In order to adopt IWO algorithm for solving multi-objective optimization problems, a non-dominating sorting technique is used to find the strength of the weeds or for sorting the weeds. The sorting of weeds in MOIWO Algorithm is similar to the NSGA-II [34].

In this algorithm, the initial population of 'pop' weeds is generated randomly in a small region of the search space. The objective functions are evaluated for these initial weeds and are then ranked using non-dominated sorting technique. Each weed generates a number of seeds depends upon its rank. The seeds are then spread across the neighborhood of the parent weed and are added to the weed population. This procedure continues until the population exceeds a predefined maximum number of weeds. The population is again ranked, and depends upon the rank, the population is truncated to the maximum number of weeds. This procedure continues until it reaches the stopping criterion. The pseudo code for MOIWO is given in Table 1.

Methodology

Optimal Network Reconfiguration (ONR)

Generally in any distributed system, there are two types of switches, normally closed switches and normally open switches. All lines in the distribution system are considered to be switches to find the feasible solution. For optimal operation of the distribution system the status of the switches can be changed, i.e., an open switch can be closed and a closed switch can be opened to reconfigure the system without violating the constraint. The main constraints for optimal network reconfiguration are that the system must maintain the radial structure and service must be provided to all the loads. In order to reduce the size of the solution vector only switches to be open are generated as a solution and the remaining switches are assumed to be closed. The size of the solution vector is equal to the number of switches to be open which is equal to number of tie-lines in the system. Initially, it is assumed that all switches are closed and in order to maintain the radial structure and to avoid the generation of more infeasible solutions, each switch to be opened is selected for each loop without isolating any node and without forming any islands. Then the length of the solution vector or the dimension of the problem is equal to the number of tie-switches.

For example, consider IEEE 33-bus radial distribution system. The number of the tie-lines for this system is 5. So that the length of the solution vector for IEEE 33-bus radial distribution system is 5. The solution vector of the original configuration is [33–37]. Similarly, other possible solution vectors are generated by using MOIWO without violating the constraints. If the generated solution is feasible (the solution must obey all the constraints), evaluate the objective functions otherwise generate another solution. An

Table 3
Parameters values of MOIWO.

Symbol	Parameter definition	Parameter values	
		IEEE 33 Bus Test Distribution System	84 Bus Practical Distribution System
Pop	Number of initial population	10	20
Maxpop	Number of maximum weeds(or population)	40	80
Itermax	Maximum number of iterations	200	200
D	Problem dimension	5	13
$S_{\max}$	Maximum number of seeds	3	5
$S_{\min}$	Minimum number of seeds	0	0
N	Nonlinear modulation index	3	3
σ_{initial}	Initial value of standard deviation	2	2
σ_{final}	Final value of standard deviation	0.01	0.01

Table 4
Results of Case studies-1, 2 & 4 (System 1).

	Open switches	Active power loss (kW)	Maximum node voltage deviation (p.u.)	No. of switching operations	Load balancing index
Original system	33,34,35,36,37	202.66	0.086904	0	0.077089
Case-1					
Proposed method (IWO)	7,9,14,32,37	***139.55***	0.062192	8	0.040594
Taher Niknam-2011 [15]	7,9,14,32,37	*139.55*	0.062192	8	0.040594
Mostafa-2012 [22]	7,9,14,32,37	*139.55*	0.062192	8	0.040594
Andervazh-2013 [20]	7,9,14,32,37	*139.55*	0.062192	8	0.040594
Dehnavi-2013 [24]	7,9,14,28,32	*139.98*	0.058724	10	0.052779
Case-2					
Proposed method (IWO)	7,9,14,28,32	139.98	***0.058724***	10	0.052779
Taher Niknam-2011 [15]	7,9,14,28,32	139.98	*0.058724*	10	0.052779
Mostafa-2012 [22]	7,9,14,28,32	139.98	*0.058724*	10	0.052779
Andervazh-2013 [20]	7,10,14,28,32	140.71	*0.058724*	10	0.053654
Case-4					
Proposed Method (IWO)	7,9,14,31,37	142.60	0.076067	8	***0.037314***
Mostafa-2012 [22]	11,28,31,33,34	146.83	0.076748	6	*0.044899*

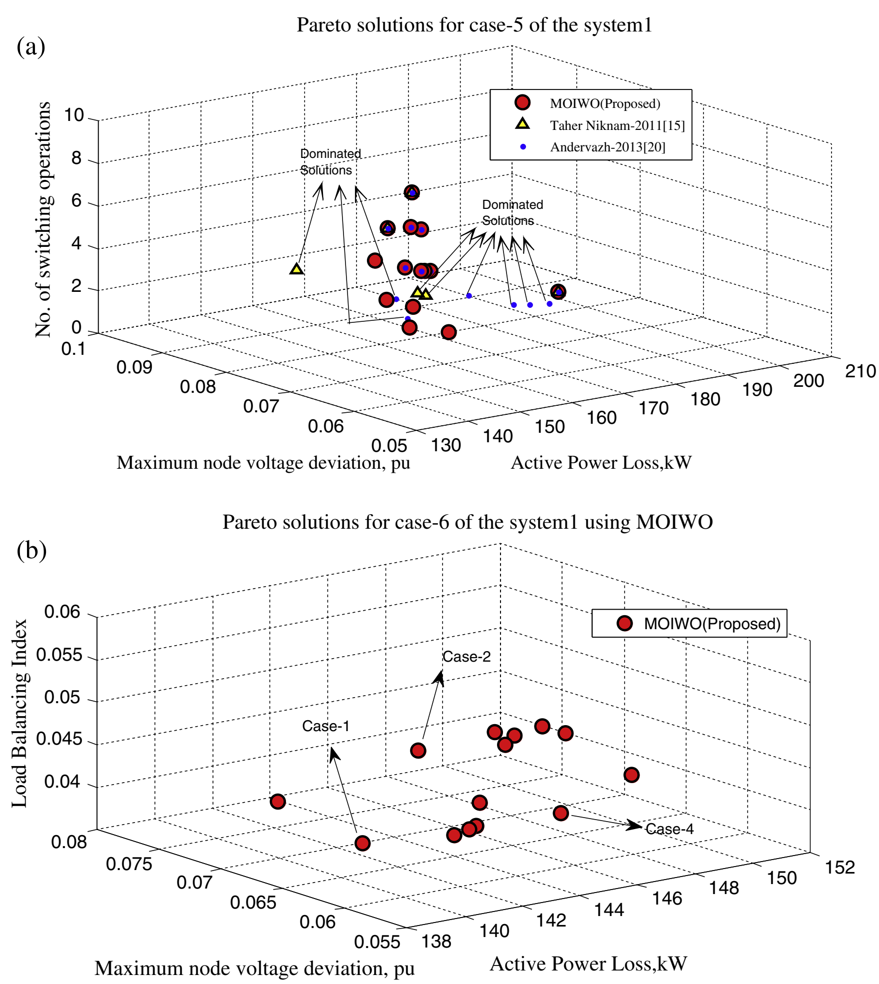

Fig. 1. Pareto solutions obtained by the proposed method of Case studies 5&6 for system1. (a) Pareto solutions of Case study-5 for system1. (b) Pareto solutions of Case study-6 for system1.

incidence matrix is formed for each solution in order to check the radial constraint. Loop vectors formed in IEEE 33 bus radial distribution system by closing each tie line are given in Table 2 and the tie lines are indicated as bold.

MOIWO Algorithm for ONR

In this article, a Multi-Objective Invasive Weed Optimization Algorithm is used for determining the optimal performance of

Table 5
Pareto solutions of Case study-7 obtained by MOIWO (system1).

Sl. no.	Open switches	Active power loss (kW)	Maximum node voltage deviation (p.u.)	No. of switching operations	Load balancing index
1	33,34,35,36,37	202.7	0.087	***0***	0.0771
2	33,34,11,32,28	143.7	0.06	6	0.0504
3	33,34,11,31,37	152.4	0.077	4	0.0396
4	33,34,10,32,28	143.9	0.06	6	0.0515
5	33,34,9,32,28	144.8	0.06	6	0.0522
6	33,34,8,36,37	153.5	0.07	2	0.0473
7	33,14,8,32,28	146	0.061	8	0.0502
8	7,34,35,36,37	158.4	0.07	2	0.0401
9	7,34,35,32,37	159.4	0.079	4	0.0382
10	7,34,11,36,37	144.5	0.066	4	0.0424
11	7,34,11,32,37	142.8	0.062	6	0.0396
12	7,34,11,32,28	143.2	0.06	8	0.0524
13	7,34,33,36,37	156.5	0.066	2	0.0428
14	7,14,9,36,37	142.2	0.066	6	0.0437
15	7,14,9,32,37	***139.6***	0.062	8	0.0406
16	7,14,9,32,28	140	***0.059***	10	0.0528
17	7,14,9,31,37	142.6	0.076	8	***0.0373***
18	6,34,11,36,37	145	0.063	4	0.0405
19	6,34,11,32,37	144.4	0.064	6	0.0386
20	6,14,9,32,37	142.8	0.061	8	0.0407
21	6,14,8,36,37	146.7	0.063	6	0.0394
22	6,14,8,32,37	146.7	0.069	8	0.0376
23	6,12,8,36,37	151.5	0.068	6	0.0384

the distribution system with Network Reconfiguration. Each weed is considered as a solution vector consisting of switches to be open. Generation of initial population is similar to all other optimization techniques. The objective function in MOIWO approach for ONR includes minimization of active power loss, maximum node voltage deviation, number of switching operations and a load balancing index, these are evaluated for each feasible solution. Next the population is ranked by using non-dominated sorting technique and generate other solutions by using IWO Algorithm. After generating each solution the feasibility of each solution is checked. For ONR, the main constraint is to maintain the radial structure and providing services for all the loads and the other constraints are voltage limits and current limits. If the solution obeys all these constraints, then it can be said that the solution is a feasible solution and otherwise the solution is an infeasible solution and it can be discarded. The parameter values of IWO used for ONR is given in Table 3.

All algorithms are implemented in MATLAB and are tested on Intel core i5-4200U CPU @ 1.60 GHz, 2.30 GHz processor, 8 GB RAM and 64-bit operating system.

Best Compromised Solution (BCS)

Based on the priority of the system operators, the solution is selected for the operation of the distribution system from available Pareto solutions. In this article, the best compromised solution is obtained by using max–min method [36].

The BCS is calculated as $\max\left\{\min_i\left\{\ldots,\frac{f_j^{\max}-f_{ij}}{f_j^{\max}-f_j^{\min}},\ldots\right\}\right\}$

Results and discussion

The proposed method is tested on both standard test and practical distribution systems and the results are compared with the results available in recent literature.

Table 6
Best compromised solutions of Case studies-5, 6 & 7 (system1).

Cases		Open switches	Active power loss (kW)	Maximum node voltage deviation (p.u.)	No. of switching operations	Load balancing index
	Original system	33,34,35,36,37	202.66	0.086904	0	0.077089
Case-5	Proposed method	6,11,34,36,37	***145.04***	***0.062679***	***4***	0.040505
	Andervazh-2013 [20]	9,28,33,34,36	*146.36*	*0.063311*	*4*	0.055542
Case-6	Proposed Method	7,9,14,32,37	***139.55***	***0.062192***	8	***0.040594***
	Mostafa-2012 [22]	7,9,14,28,32	*139.97*	*0.058724*	10	*0.052779*
	Dehnavi-2013 [24]	6,8,12,36,37	*151.49*	*0.068208*	6	*0.038395*
Case-7	Proposed Method	6,11,32,34,37	***144.41***	***0.064343***	***6***	***0.038574***

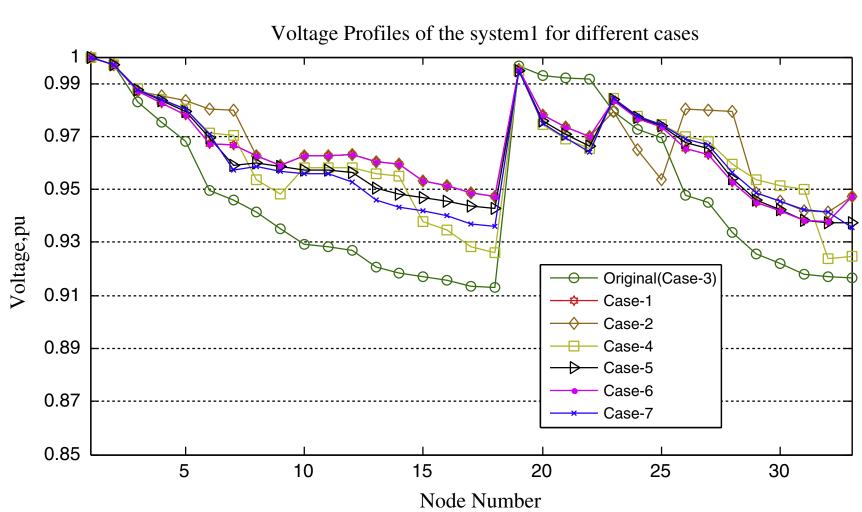

Fig. 2. Voltage profiles of system1 for all Case studies.

Table 7
Results of Case studies-1, 2 & 4 (system 2).

	Open switches	Active power loss (kW)	Maximum node voltage deviation (p.u.)	No. of switching operations	Load balancing index
Original system	84,85,86,87,88,89,90, 91,92,93,94,95,96	526.97	0.071481	0	0.057918
Case-1					
Proposed Method (IWO)	7,13,34,39,42,55,62, 72,83,86,89,90,92	***469.71***	0.046813	18	0.058378
Taher Niknam-2011[15]	7,14,34,39,42,55,62, 72,83,86,88,90,92	481.97	0.047124	18	0.067206
Mostafa-2012 [22]	7,13, 34,39,42,55,62, 72,83, 86,89,90,92	469.71	0.046813	18	0.058378
Dehnavi-2013 [24]	7,13,34,39,42,55,62, 72,83,86,89,90,92	469.71	0.046813	18	0.058378
Case-2					
Proposed Method (IWO)	7,13,34,39,42,55,62, 72,83,86,89,90,92	469.71	***0.046813***	18	0.058378
Taher Niknam-2011 [15]	7,13,14,34,37,42,55, 61,71,83,86,90,92	511.85	0.047124	20	0.083803
Mostafa-2012 [24]	7,39,43,55,61,72,76, 83,89,90,92,94,95	502.19	0.046813	16	0.067856
Case-4					
Proposed Method (IWO)	7,13,29,32,34,41,54, 61,72,86,89,90,91	482.31	0.052142	18	***0.046438***
Mostafa-2012 [22]	7,13,29,34,41,55,72, 86,89,90,91,92,96	489.57	0.061644	14	0.051398

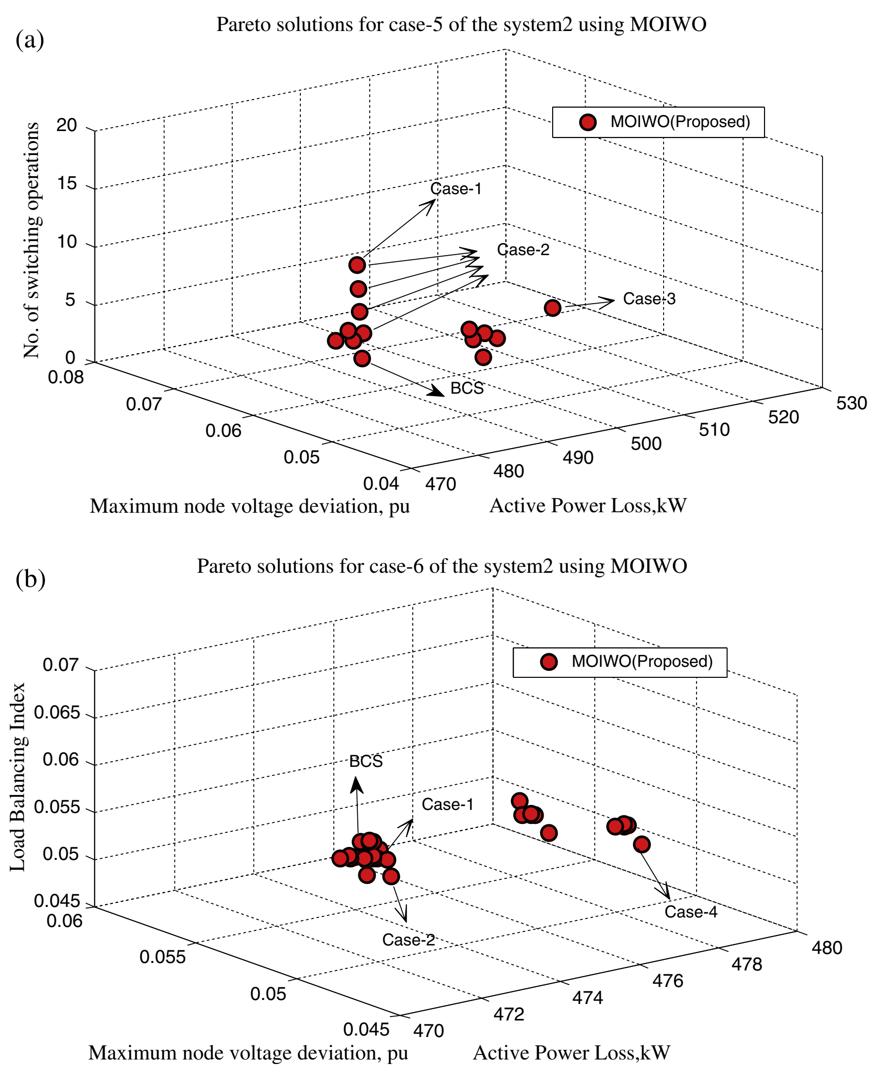

Fig. 3. Pareto Solutions obtained by the proposed method of Case studies 5 & 6 for system 2. (a) Pareto solutions of Case study-5 for system2. (b) Pareto solutions of Case study-6 for system1.

System 1: IEEE 33 Bus Test Radial Distribution System and System 2: 84 Bus Practical Distribution Network Taiwan Power Company (TPC)

For better illustration and comparison purpose, the ONR is solved for the following cases using the proposed method.

Case-1. Minimization of active power loss

Case-2. Minimization of maximum node voltage deviation
Case-3. Minimization of number of switching operations
Case-4. Minimization of load balancing index
Case-5. Minimization of active power loss, maximum node voltage deviation and number of switching operations simultaneously
Case-6. Minimization of active power loss, maximum node voltage deviation and load balancing index simultaneously
Case-7. Minimization of active power loss, maximum node voltage deviation, number of switching operations and load balancing index simultaneously

Table 8
Pareto solutions of Case study-7 obtained by MOIWO (system2).

Sl. no	Open switches	Active power loss (kW)	Maximum node voltage deviation (p.u.)	No. of switching operations	Load balancing index
1	84,85,86,87,88,89,90,91,92,93,94,95,96	526.9727	0.0715	***0***	0.0579
2	84,7,86,72,88,89,90,83,92,93,94,95,62	488.4932	***0.0468***	8	0.0665
3	55,7,86,72,88,89,90,83,92,39,34,42,62	***470.0153***	***0.0468***	16	0.0602
4	54,7,86,72,88,89,90,91,92,35,34,39,61	484.8698	0.0521	14	***0.0477***
5	84,85,86,87,88,89,90,91,92,93,34,42,96	509.357	0.0715	4	0.0536
6	55,7,86,72,88,89,90,83,92,36,34,39,63	473.6498	0.0483	16	0.0568
7	84,7,86,87,88,89,90,91,92,93,34,41,96	490.1911	0.0616	6	0.0552
8	84,7,86,87,88,89,90,91,92,93,94,95,96	507.3702	0.0616	2	0.0619
9	84,7,86,72,88,89,90,91,92,93,34,95,64	476.9111	0.0552	8	0.0562
10	55,7,86,72,88,89,90,91,92,93,34,41,64	478.2184	0.0552	12	0.0526
11	***84,7,86,87,88,89,90,83,92,93,34,41,63***	***474.8426***	***0.0512***	***10***	***0.059***
12	84,7,86,87,88,89,90,91,92,93,34,41,63	477.2865	0.0521	8	0.0555
13	55,7,86,7288,89,90,83,92,93,34,42,63	470.4211	0.0483	14	0.0587
14	84,85,86,72,88,89,90,91,92,9394,95,96	523.0153	0.0715	2	0.0573
15	84,7,86,72,88,89,90,83,92,93,94,95,63	488.0643	0.0483	8	0.0649
16	84,85,86,87,13,89,90,91,92,93,34,41,96	511.3075	0.0715	6	0.0497
17	84,7,86,72,88,89,90,91,92,93,34,41,63	473.3291	0.0521	10	0.0549
18	84,7,86,87,88,89,90,91,92,93,34,95,63	476.889	0.0521	6	0.058
19	54,7,86,72,88,89,90,91,92,93,34,42,61	479.2711	0.0521	12	0.0514
20	84,7,86,72,88,89,90,83,92,39,34,95,62	470.7812	***0.0468***	12	0.0625
21	84,7,86,87,88,89,90,83,92,93,94,95,63	492.0217	0.0512	6	0.0655
22	84,7,86,72,88,89,90,83,92,93,34,41,62	471.3141	***0.0468***	12	0.06
23	84,7,86,87,88,89,90,91,92,93,94,95,63	494.4657	0.0521	4	0.0621
24	54,7,86,87,88,89,90,91,92,93,94,95,61	500.8442	0.0521	6	0.0564
25	54,7,86,87,88,89,90,83,92,93,94,95,61	498.4003	0.0519	8	0.0598
26	84,85,86,72,13,89,90,91,92,39,34,95,96	504.9933	0.0715	8	0.0513
27	84,7,86,87,88,89,90,91,92,93,94,95,64	498.4451	0.0552	4	0.0609
28	54,7,86,87,88,89,90,91,92,93,34,41,61	483.6651	0.0521	10	0.0498
29	54,7,86,72,88,89,90,83,92,35,34,39,61	482.4259	0.0519	16	0.0512
30	54,7,86,87,88,89,90,83,92,35,34,39,61	486.3834	0.0519	14	0.0518
31	84,85,86,72,88,89,90,91,92,93,34,41,96	505.8361	0.0715	6	0.0507
32	55,7,86,87,88,89,90,83,92,36,34,39,63	477.6073	0.0512	14	0.0575
33	55,7,86,87,88,89,90,83,92,93,34,95,63	474.4176	0.0512	10	0.0596
34	84,7,86,87,88,89,90,91,92,93,34,41,64	481.266	0.0552	8	0.0543
35	84,85,86,87,88,89,90,91,92,39,34,95,96	509.2607	0.0715	4	0.0539
36	54,7,86,87,88,89,90,91,92,35,34,39,61	488.8273	0.0521	12	0.0484
37	54,7,86,72,88,89,90,83,92,93,34,42,61	476.8272	0.0519	14	0.0548
38	54,7,86,87,88,89,90,91,92,93,34,95,61	483.2676	0.0521	8	0.0523
39	55,7,86,87,88,89,90,83,92,35,34,39,63	479.9773	0.0512	14	0.0558
40	55,7,86,72,88,89,90,8392,39,34,95,62	470.1459	***0.0468***	14	0.0602
41	84,7,86,87,88,89,90,83,92,93,34,95,63	474.4451	0.0512	8	0.0614
42	54,7,86,72,88,89,90,91,92,93,34,41,61	479.7076	0.0521	12	0.0491
43	84,85,86,87,88,89,90,91,92,93,34,41,96	509.7935	0.0715	4	0.0513
44	84,7,86,72,88,89,90,83,92,93,34,95,63	470.4877	0.0483	10	0.0608
45	55,7,86,72,88,89,90,91,92,39,34,42,62	472.4592	0.0521	14	0.0567
46	55,7,86,72,88,89,90,91,92,93,34,41,62	473.1227	0.0521	12	0.0543
47	54,7,8687,88,89,90,83,92,93,34,41,61	481.2212	0.0519	12	0.0532
48	84,85,86,72,13,89,90,91,92,93,34,41,96	505.5261	0.0715	8	0.0487
49	54,7,86,87,88,89,90,83,92,93,34,95,61	480.8237	0.0519	10	0.0557
50	55,7,86,72,88,89,90,83,92,35,34,39,62	475.841	***0.0468***	16	0.0563
51	54,7,86,72,88,89,90,91,92,39,34,42,61	479.0441	0.0521	14	0.0516
52	84,85,86,72,88,89,90,91,92,93,34,42,96	505.3995	0.0715	6	0.0529
53	55,7,86,72,88,89,90,83,92,35,34,39,63	476.0198	0.0483	16	0.0551
54	84,7,86,72,88,89,90,83,92,93,34,4163	470.8851	0.0483	12	0.0583
55	84,85,86,72,13,89,90,91,92,93,34,42,96	505.0896	0.0715	8	0.051
56	54,7,86,72,88,89,90,91,92,93,34,95,61	479.3102	0.0521	10	0.0516
57	84,7,86,72,88,89,90,83,92,93,34,95,62	470.9166	***0.0468***	10	0.0625
58	55,7,86,87,88,89,90,83,92,35,34,39,62	479.7984	0.0512	14	0.057
59	54,7,86,72,88,89,90,83,92,9334,41,61	477.2637	0.0519	14	0.0526
60	55,7,86,72,88,89,90,83,92,93,34,41,62	470.6788	***0.0468***	14	0.0577
61	84,7,86,72,88,89,90,91,92,93,34,41,64	477.3085	0.0552	10	0.0537
62	55,7,86,72,8889,90,91,92,39,34,95,62	472.5898	0.0521	12	0.0568
63	55,7,86,72,88,89,90,91,9293,34,42,61	472.782	0.0521	12	0.0566

System1: IEEE 33 Bus Test Radial Distribution System

The IEEE 33 bus radial distribution system consists of 33 buses, 32 sectionalized switches and 5 tie-switches. The system substation voltage is 11 kV. The total active and reactive power loads on the system are 3715 kW and 2300 kVAr, respectively. The initial active and reactive power losses of this system are 202.67 kW and 135.24 kVAr. The lowest bus bar voltage is 0.913096 p.u., occurs at bus 18.

In order to find the extreme points of the Pareto front, each objective function has to be minimized individually which is defined in Cases-1 to 4. For Case-3, the solution is same as original configuration, i.e., the minimum number of switching operations is zero, which is achieved when the status of switches are same as the original system. The configuration for Case-3 of system1 is [33–37] and the solutions for the Cases-1, 2 & 4 are presented in Table 4, the shaded one is the solution obtained by proposed method and the bold one is objective value of the corresponding Case. From Table 4, the solution obtained by proposed method is more or less similar for Cases-1 & 2 and better for Case-4 when compared to other existing methods.

From the results shown in the Table 4, it is observed that the objectives are conflicting with each other so, to find the optimal solution different objectives have to be minimized simultaneously. To find the tradeoff solution with three or more objectives for optimal operation of distribution system Case-5 to 7 are studied. The tradeoff (Pareto) solutions obtained in Cases 5 & 6 of system 1 using the proposed method are shown in Fig. 1. For comparison purpose, in Fig. 1a, the Pareto solutions obtained by the methods of Taher Niknam-2011 [15] and Andervazh-2013 [20] for Case-5 of system1 are also shown and the dominated solutions of these methods by proposed method are marked. The number of Pareto solutions obtained by proposed a method for Case-5 of system1 are fourteen solution and these solutions are non-dominated. The Pareto solutions obtained in Case 6 of system 1 are pictured in Fig. 1b and the extreme points are noted along the plot.

The Pareto solutions obtained from Case-7 i.e., for minimization of all objectives considered in this article are given in Table 5 and the shaded solutions are the extreme points of the pareto front, the corresponding objective optimal values are indicated by bold. The BCS for Cases-5 to 7 are given in Table 6 and the corresponding objective values are indicated by bold. The voltage profiles of system1 for all Case studies are shown in Fig. 2.

From Table 6 for Case-5, the best compromised solution given by proposed method is better than the Andervazh-2013 [20]. The active power loss is reduced by 28.43%, minimum node voltage is improved from 0.9131 to 0.9373 and the number of switching operations is four. For Case-6, when compared to Mostafa-2012 [22] and Dehnavi-2013 [24], the proposed method given the most compromised solution. In Mostafa-2012 [22], the load balancing index is more and in dehnavi-2013 [24], the active power loss and voltage deviation are more when compared to proposed method. For Case-7, the active power loss is reduced by 28.74%, minimum node voltage is improved from 0.9131 to 0.9357, number of switching operations are six and the load balancing index is reduced from 0.077089 to 0.038574.

System2: 84 Bus Practical Distribution Network Taiwan Power Company (TPC)

This second system consists of 84 buses, 11.4 kV, and radial distribution system. It consists of 11 feeders, 2 substations, 83 sectional switches and 13 tie-lines. The total active and reactive power loads in the system are 28350 kW and 20700 kVAr. The

Table 9
Best compromised solutions of Case studies-5, 6 & 7 (system2).

Cases		Open switches	Active power loss (kW)	Maximum node voltage deviation (p.u.)	No. of switching operations	Load balancing index
Original system		84,85,86,87,88,89,90, 91,92,93,94,95,96	526.97	0.071481	0	0.057918
Case-5	Proposed method	**7,34,63,84,86,87, 88, 89, 90,91, 92,93,95**	**476.89**	**0.052100**	**6**	0.058000
Case-6	Proposed method	**7,34,39,55,63,72,86,88,89,90,91,92,93**	**473.30**	**0.052142**	12	**0.053068**
	Mostafa-2012 [22]	7,13,29,34,41,54,63,72,86,89,90,91,92	483.14	0.052142	16	0.046574
	Dehnavi-2013 [24]	7,13,34,39,54,62,86,87,89,90,91,92,95	484.70	0.052142	12	0.050945
Case-7	Proposed method	**7,34,41,63,83,84,86,87,88,89,90,92,93**	**474.84**	**0.051186**	**10**	**0.058965**

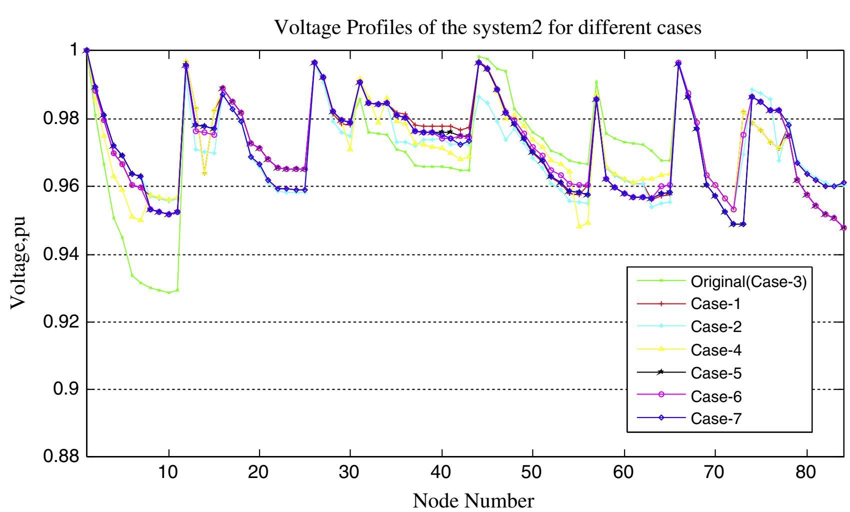

Fig. 4. Voltage profiles of the system2 for all case studies.

initial power loss of this system is 526.97 kW and the minimum bus voltage is 0.9285 p.u. which occurs at node 10.

The solution for Case-3 of system2 is [84,85,86,87,88,89,90,91,92,93,94,95,96] and the solutions for the Cases-1, 2 & 4 are presented in Table 7, the shaded ones are the solution obtained by the proposed method and the bold ones are the objective optimal values of corresponding Cases. From Table 7, the better optimal solutions are obtained by the proposed method for Cases 1, 2 & 4 when compared the other methods.

The tradeoff (Pareto) solutions obtained in Cases 5 & 6 of system2 using the proposed method are shown in Fig. 3 and the extreme points and BCS are marked on the plot. The Pareto solutions obtained from Case-7 i.e., for minimization of all objectives considered in this article are presented in Table 8 and the shaded solutions are the extreme points of the pareto front, the corresponding objective optimal values are indicated by bold. The Pareto solutions obtained in Cases-5 to 7 are validated with the extreme points presented in Table 7. The BCS for Cases-5 to 7 are given in Table 9 and the corresponding objective values are indicated by bold. The voltage profiles of system2 for all Case studies are shown in Fig. 4.

From Table 9 for Case-5, the active power loss is reduced by 9.50%, minimum node voltage is improved from 0.9285 to 0.9479 and the number of switching operations is six. For Case-6 the proposed algorithm given the best compromised solution when compared to other methods and the active power loss is reduced by 10.18%, minimum node voltage is improved to 0.9479 and the load balancing index is reduced to 0.053068 from 0.057918. Similarly for Case-7, the active power loss is reduced by 9.89%, the minimum node voltage is improved to 0.9488, number of switching operations are ten and the load balancing index is reduced to 0.058965.

Conclusion

A Pareto based MOIWO algorithm for optimal network reconfiguration with multiple objectives has been presented in this article. A non-dominating sorting technique and crowding distance method are employed to adopt IWO for solving multi-objective problem. Minimization of total active power losses, maximum node voltage deviation, number of switching operations and the load balancing index are considered as the parameters of the objective functions. The IWO algorithm is implemented for mono and multi-objective ONR to compare with the existing resolutions from the literature. The algorithm is tested on IEEE 33 bus test and 84 bus practical radial distribution systems. The max–min method is employed to determine the best compromised solution. The results illustrate that the proposed algorithm is highly efficient to find global optimum configurations and is able to produce a Pareto solution containing high quality results when compared to other methods. Because of its unique switch selection approach the obtained solution is independent of the initial configuration of the network.

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