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A comprehensive technique for optimal allocation of distributed energy resources in radial distribution systems

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HIGHLIGHTS

- Presents a parameter independent intelligent optimization technique.
- Proposed technique is suitable for both continuous and discrete variables.
- Optimization technique is validated through mathematical benchmark functions.
- Proposed technique used to optimally place energy resources in distribution systems.
- Performance improvement of distribution systems with distributed energy resources.

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ABSTRACT

Distributed generation (DG) is a better alternative to meet power demand near the load centers than centralized power generation. Optimal placement and sizing of DGs plays a crucial role in improving the performance of distribution systems in terms of network loss reduction, voltage profile improvement, reliability of power supply and stability issues. This paper presents a comprehensive teaching learning-based optimization (CTLBO) technique for the optimal allocation of DGs in radial distribution systems to improve network loss reduction, voltage profile and annual energy savings. The proposed technique can handle mixed integer variables, is parameter independent and possesses immunity to local extrema trappings. The effectiveness of the proposed method is first validated on standard mathematical benchmark functions. It is observed to have better convergence characteristics than teaching learning-based optimization (TLBO) and quasi-oppositional teaching learning-based optimization (QOTLBO). Subsequently, it is applied to optimal DG allocation in IEEE 33-bus, 69-bus and 118-bus radial distribution test systems. Both single and multi-objective formulations are considered. In addition, the selection of the optimal number of DGs in the distribution networks is also investigated and case studies are carried out. Results demonstrate that optimal allocation of DGs using the proposed technique results in marked improvement in the performance of distribution systems over TLBO and QOTLBO. The applicability of the proposed technique for DG allocation in distribution systems with practical load profiles results in further improvement in annual energy loss reduction and cost savings.

1. Introduction

Currently, centralized power generation is unable to meet the continuously rising global energy demand. Around 16% of the global populations still live without electricity [1]. In this perspective, Distributed Generation (DG) has proved to be a viable option where electricity is generated near the load centers. Although DGs have several environmental and economical benefits, they impose several operational issues in distribution systems. These may include but are not limited to relay co-ordination problems caused by reverse power flow, voltage rise issues, power quality and voltage stability issues, etc. [2,3]. Proper DG allocation have severe impact on power loss, voltage profile, line loadability, operational cost, reliability of power supply, pollution and stability issues of distribution systems. Therefore optimal DG allocation has been a global challenge for both the academia and the industry.

Several research works have been reported on the optimal siting and sizing of DGs in distribution systems. In this context, some of the comprehensive research works for the placement of DGs using analytical methods to reduce network power loss and improvement of voltage profile considering several loading conditions, have been reported in [4–11]. However, complexities in the formulation of objective

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functions caused by multiple DGs, different type of resources and multi-objective analysis affect the computational time with analytical methods.

Advancements in soft computing techniques have led to the development of several evolutionary optimization algorithms for the optimal allocation of DGs in distribution systems. Some notable ones among these are genetic algorithms (GA), particle swarm optimization (PSO), artificial bee colony (ABC), ant colony optimization (ACO), bacterial foraging optimization (BFO) etc. Some comprehensive research works on the use of GA for optimal allocation of DGs in distribution networks reported in [12–19]. However, GA requires increased computational time while suffering from premature convergence than analytical approach [4].

Particle swarm optimization (PSO) is another intelligent technique which has been widely used for DG placement in distribution networks. Some comprehensive research works on the use of PSO for optimal DG allocation in distribution systems presented in [20–22]. In addition, several variants of PSO based optimization technique have also been used. Some notable ones include multi-objective evolutionary PSO (MEPSO) [23] and discrete PSO [24]. Although PSO possesses better search capability than GA, it may converge to strong local minima if optimization parameters are not properly tuned.

Artificial Bee Colony (ABC) has been used [25] for optimal placement of DGs to minimize overall investment cost. Apart from GA, PSO and ABC, several other nature-inspired algorithms have also been proposed by researchers for optimal allocation of DGs. These include the modified honey bee mating algorithm [26], cuckoo search algorithm [27], bacterial foraging optimization (BFO) [28], modified bacterial foraging optimization algorithm [29], Firefly algorithm [30], Hereford Ranch algorithm [31], Modified shuffled leaping algorithm [32], chaotic symbiotic organisms search (CSOS) algorithm [33], Kalman Filter Algorithm [34], harmony search algorithm [35] and Gravitational Search algorithm [36]. Even if evolutionary methods are spontaneous, easy to realize and simple to implement as compared to analytical ones, the nature of the optimization variable (continuous, discrete or mixed) and inappropriate selection of algorithm parameters can lead to premature convergence in the event of strong local extrema. To avoid a non-optimal solution, these algorithms require proper parameter tuning.

In this perspective, teaching learning-based optimization (TLBO), reported in [37], is a parameter independent intelligent algorithm which was developed and subsequently used for the optimal placement of energy resources in distribution systems. Although TLBO is parameter independent and has a very fast convergence rates, it is prone to local maxima/minima trappings. It is observed that TLBO often converges to local minima when the numbers of DGs and/or operating constraints in the distribution system increase. In this context, a modified-TLBO algorithm [38] for DG placement has been suggested. However, it requires an additional mutation phase to find the global solution. QOTLBO [39], which utilizes opposition–based learning to enhance the exploration of the search space, has been implemented for DG placement in radial distribution systems. An improved TLBO, in which a cross over rate and a cross over parameter have to be specified, has been reported in [40]. However, this additional phase adds complexity to the TLBO and increases the computational time. Moreover, they need to be proper parameter tunning to achieve a satisfactory convergence while placing DGs in the distribution network.

In addition, optimal DG allocation of DGs deals with mixed integer variables. While sizing of solar-based energy resources deals with continuous variables, those of wind-based generators involve discrete ones. It is observed that many of the soft computing techniques are not equally proficient at handling mixed integer variables.

This paper presents a comprehensive TLBO (CTLBO) technique for the optimal siting and sizing of DGs, which possesses more exploration and exploitation capabilities over TLBO and QOTLBO. While TLBO gives the better result with unconstrained problems, CTLBO can deal with constrained optimization problems. The proposed technique is capable of handling mixed integer variables, is parameter independent and possesses immunity to strong local extrema trappings. In order to avoid local extrema trappings, a modified teaching phase has been proposed which results in better exploration and exploitation of the solution search space to ensure a global solution. The algorithm is first validated on eight standard mathematical benchmark functions. Comparative results in the form of mean value and standard deviation validate the superiority of the proposed optimization technique over several existing PSO, ABC, and TLBO. Subsequently, to demonstrate the applicability of the proposed algorithm to a specific application, a deterministic problem of optimal DG sizing and placement in radial distribution systems is considered. Both single and multi-objective criterions are utilized for optimal allocation of distributed energy resources. For the multi-objective analysis, power loss, voltage deviation and voltage stability index were considered as reported in [33,37,39]. Unlike a manual weight factor estimation approach as presented in [20,27,41,42] for multi-objective formulations, the proposed technique presents a mathematical formulation based on the ε-constraint method [43], which is independent of penalty factors. Several case studies were carried out with multiple DGs on the IEEE 33-bus, 69-bus, and 118-bus radial distribution test systems. The results demonstrate that optimal allocation of DGs using the proposed technique results in improvement in the performance of the radial distribution systems as compared to TLBO and QOTLBO [39]. A comparison of the reduction in annual energy losses and costs without and with DGs in the 33 and 69-bus radial distribution systems show improvement, which has used analytical methods [44] for DG allocation. These reiterate the superiority of the proposed method in the perspective of computational speed, accuracy, parameter independence and immunity to local extrema trappings, over existing TLBOs and QOTLBO.

The contribution of the paper can be summarized as follows:

– Development of a CTLBO algorithm which is capable of handling mix integer variables and constrained optimization problems
– Modification in the teaching phase improves the exploitation and exploration capability of the proposed algorithm over several modification of TLBO [39,40,45–47], which improves immunity to local extrema trappings and ensures a global solution.
– Multi-objective optimization is based on the ε-constraint method which is independent of penalty factors unlike [20,27,41,42].
– Direct power flow method based on the BIBC/BCBV matrix is used for the power flow which does not require either the network admittance matrix or the forward/backward substitution of the Jacobian matrix. This reduces the computational time substantially less than Exact loss formulation [21,36,37,39].
– Multiple case studies were conducted with standard mathematical benchmark functions and optimal allocation of DGs in IEEE 33-bus, 69-bus and 118-bus radial distribution test systems.
– CTLBO algorithm is further validated by DG allocation with real load profile of distribution systems, which further enhance the annual energy loss reduction and cost savings over analytical method [44].
– Results demonstrate a marked improvement in the performance indices (network active power loss, voltage profile improvement, voltage stability, etc.) of the distribution test systems over TLBO and QOTLBO[39].

The rest of the paper is organized as follows: Section 2 deals with the problem formulation. Section 3 presents the introduction and the proposed modifications carried out in TLBO. Section 4 illustrates the flowchart of the proposed technique. Section 5 deals with the mathematical validation of the proposed algorithm and its implementation in several radial distribution systems. Section 6 presents the practical application of DG allocation for energy loss reduction and cost savings. Section 7 presents the conclusions.