A Review of Multi-Objective Methods for Optimal Location and Capacity of Distributed Generations in Modern Power Systems

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Abstract**—**Penetration of distributed generation (DG) units in distribution system has increased rapidly stimulated by reduced network power loss, improved bus voltage profile and better power quality. Appropriate location and capacity of DG play significant role in maximizing beneficial effects. The aim of the optimal DG placement (ODGP) is to provide the best location and capacity of DGs to optimize electrical distribution network operation and planning taking into account DG capacity constraints. Different methods applied to the OPDG problem are reviewed in this paper. Future research trends in this field are also analyzed.

Keywords**—**Distributed Generation (DG), Optimal Distributed Generation Placement (ODGP), Optimal Site, Optimal Size.

I. INTRODUCTION

THE distributed generation, also termed as embedded generation or dispersed generation or decentralized generation, has been defined as electric power source connected directly to the distribution network or on the customer site of the meter [1]. The emergence of new technological alternatives allows the DG technologies in distribution network to achieve immense technical, economical and environmental benefits. In addition, the governments of the developing and under-development countries are supporting the DG for they can supply the required electrical energy of their increasing customers. Installing DGs at the network buses have a direct impact on the flowing power and the voltage of the network. This impact depends on many different factors and may be positive or negative [2]. The positive impacts of installing DG resources include increasing the power quality, improving the voltage profile, reducing the power loss, decreasing the requirements of installing new transmission lines and deferring the necessity of improving the capacity of substations[3], [4]. On the other hand, the main adverse impact of installing DG is the increase in short circuit level of the network [2]. The studies show that if the capacity and location of DGs are not identified appropriately, not only the network parameters are not improved, but also they are deteriorated [5], [6]. Some of the common distributed technologies are photovoltaic, wind energy, fuel cells, micro turbines and combined heating and power (CHP) generators.

To maximize on the benefits of DG penetration, the optimal location, size, number and type is fundamental. The two of the most important factors of DG plans are identifying the capacity and location of these resources [7]. The place and capacity of DGs can be decided according to the improvement of one or more parameter, in order to increase the efficiency and decrease the adverse effects of installing them.

II. TYPES OF DGS

DG can be classified into four major types based on their terminal characteristics in terms of real and reactive power delivering capability as follows:

1. Type 1: DG capable of injecting real power, P, only e.g. Photovoltaic, micro turbines, fuel cells, which are integrated to the main grid with the help of converters/inverters
2. Type 2: DG capable of injecting reactive power, Q, only e.g. synchronous compensators such as gas turbines.
3. Type 3: DG capable of injecting both P and Q e.g. DG units that are based on synchronous machine (cogeneration, gas turbine, etc.)
4. Type 4: DG capable of injecting P but consuming Q e.g. squirrel-cage induction generators that are used in wind farms.

III. LOCATION OF DG

The location of a DG is specified by the bus-bars the DG is connected. Effects of location of a DG are determined using load flow analysis. Proper location ensures among others improved voltage profile and minimized power losses.

IV. NUMBER OF DG

Installing and exploiting some DG resources with a small capacity is proven to be more effective than a single DG with a big capacity. On the other hand, increasing the number of installed DGs at the network will cause some extra costs due to the DGs installing and their service costs. Hence, there should be a balance between the imposed costs and the

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improvement of the considered parameters of the network. This balance can be created by deciding the optimal number of DGs.

V. SIZE OF DG

The size at most should be such that it is consumable within the distribution substation boundary. Any attempt to install high capacity DG with the purpose of exporting power beyond the substation (reverse flow of power though distribution substation), will lead to very high losses. So, the size of distribution system in terms of load (MW) will play important role is selecting the size of DG. The reason for higher losses and high capacity of DG can be explained by the fact that the distribution system was initially designed such that power flows from the sending end (source substation) to the load and conductor sizes are gradually decreased from the substation to consumer point. Thus without reinforcement of the system, the use of high capacity DG will lead to excessive power flow through small sized conductors and hence results in higher losses.[8].

VI. OBJECTIVES OF DG INSTALLATION

Some examples of objectives of DG installation are; Minimization of the total power loss of the system, Minimization of energy losses, Minimization of system average interruption duration index (SAIDI), Minimization of cost, Minimization of voltage deviations, Maximization of DG capacity, Maximization of profit, Maximization of a benefit/cost ratio and Maximization of system loadability limit.

VII. OBJECTIVE FUNCTION

The aim of the optimal DG placement (ODGP) is to provide the best location and capacity of DGs to optimize electrical distribution network operation and planning taking into account DG capacity constraints. To achieve this the objective function is formulated and then optimal solution obtained using different optimization techniques.

The objective function can be single-objective or multi-objective. However, sitting and sizing DGs, with the aim of improving a single parameter, enhances the considered parameter significantly, but may have negative impact on other parameters of the network. On the other hand, sitting and sizing DG with the purpose of enhancing some of the parameters of the network will result in improvement of the considered parameters. Hence in this review multi objective ODGP has been considered. This is unique from other review works where single objective ODGP dominated the review [9], [110].

For multi-objective functions we can have:

1. Multi-objective function with weights (also called weighted sum method), where the multi objective formulation is transformed into a single objective function using the weighted sum of individual objectives.
2. Goal Multi objective index, where the multi objective formulation is transformed into a single objective function using the goal programming method.
3. Multi objective formulation considering more than one often contrasting objectives and selecting the best compromise solution in a set of feasible solutions.

VIII. TAXONOMY

Table I presents taxonomy of the reviewed optimal DG placement works.

IX. METHODS

In this study the reviewed work is classified based on the three multi objective functions.

a. MULTI OBJECTIVE FUNCTION WITH WEIGHTS

It has been noted in this review that about 2/3 of the researchers have used multi objective functions with weights to transform them into single objective functions. Research has shown that the weighted multi objective index cannot accurately reflect the relationship between the various objectives, and the corresponding weights are difficult to determine due to lack of enough information about the problem.

Invasive weed optimization algorithm is proposed for optimally determining the location and sizing of multiple distributed generations (DG) units in the distribution network with different load models in [11]. In [12], [13], [14], [15], [16], and [17] PSO and its improved version have been used for optimization. Weight-Improved Particle Swarm Optimization Algorithm (WIPSO) for optimal location and size of distribution generation and compensating devices is suggested in [12] to reduce the losses and will also maintain the required voltage profile within limits. A Butterfly-PSO methodology is implemented to optimally allocate multiple DG units to improve voltage profile, increment in the economy, reduction in losses in [13]. DAPSO which is an improved version of PSO is used in [14] for multi objective optimization placement of DG problem for different load levels on distribution systems for reduction of loss, cost and improving voltage profile. PSO is presented in [15] for sizing and sitting of DG in Institute of Electrical and Electronics Engineers (IEEE) 33 bus test system. The proposed objective function is the multi objective function (MOF) that considers active and reactive power losses of the system and the voltage profile in nominal load of system. The study in [16] proposes a multi-objective index-based approach for optimally determining the size and location of multi-distributed generation units in distribution systems with different load models using PSO. In [17] Particle Swarm Optimization approach (PSO) for the placement of Distributed Generators (DG) in the radial distribution systems to reduce the real power losses and to improve the system reliability. Power loss

TABLE I
TAXONOMY OF THE REVIEWED OPTIMAL DG PLACEMENT

Ref.	year	No. of DGs	Design Variables	Objectives	Optimization Method
[11]	2016	Multiple	Location + Size	Multi objective with weights	Invasive weed optimization Algorithm
[12]	2016	Single	Location + Size	Multi objective with weights	Weight-Improved Particle Swarm Optimization Algorithm
[13]	2015	Multiple	Location + Size	Multi-objective function based on the indices	Butterfly- Particle Swarm Optimization Algorithm
[14]	2013	Multiple	Location + Size	Multi objective with weights	Dynamic Adaptive Particle Swarm Optimization Algorithm
[15]	2013	Multiple	Location + Size	Multi objective with weights	Particle Swarm Optimization Algorithm
[16]	2011	Multiple	Location + Size	Multi objective with weights	Particle Swarm Optimization Algorithm
[17]	2011	Single	Location + Size	Multi objective with weights	Particle Swarm Optimization Algorithm
[18]	2015	Multiple	Type + Location + Size	Multi objective with weights	Genetic algorithm
[19]	2014	Multiple	Type + Location + Size	Multi objective with weights	An improved adaptive genetic algorithm
[20]	2014	Single	Location + Size	Multi objective with weights	Genetic Algorithm
[21]	2011	Multiple	Number + Location + Size	Multi objective with weights	Genetic Algorithm
[22]	2011	Multiple	Location + Size	Multi objective with weights	Genetic Algorithm
[23]	2011	Multiple	Location + Size	Multi objective with weights	Genetic Algorithm
[24]	2011	Multiple	Type + Location + Size	Multi objective with weights	Genetic Algorithm
[25]	2010	Single	Location + Size	Multi objective with weights	Genetic Algorithm
[26]	2009	Single	Location + Size	Multi objective with weights	Genetic Algorithm
[27]	2008	Single	Location	Multi objective with weights	Hybrid Genetic Algorithm and power flow technique
[28]	2013	Multiple	Location + Size	Multi objective with weights	Point Estimate Method Embedded Genetic Algorithm
[29]	2016	Multiple	Location + Size	Multi objective with weights	PSO, GSA, and hybrid PSOGSA algorithms
[30]	2013	Multiple	Location + Size	Multi-objective index-based approach	Hybrid (PSO & Gravitational Search Algorithm)
[31]	2012	Multiple	Location + Size	Multi objective with weights	Hybrid (GA &PSO)
[32]	2016	Multiple	Location + Size	Multi objective with weights	Bat Algorithm
[33]	2015	Single	Location + Size	Multi objective with weights	Modified Shuffled frog Leaping Algorithm
[34]	2013	Multiple	Location + Size	Multi objective with weights	Modified Shuffled frog Leaping Algorithm (MSFLA)
[35]	2012	Multiple	Location + Size	Multi objective with weights	shuffled frog leaping algorithm
[36]	2015	Single	Location + Size	Multi objective with weights	Supervised Big Bang-Big Crunch method
[37]	2014	Multiple	Location + Size	Multi objective with weights	Harmony Search Algorithm with Differential Operator
[38]	2012	Multiple	Location + Size	Multi objective with weights	heuristic iterative method (clustering techniques and exhaustive search)
[39]	2011	Multiple	Location + Size	Multi objective with weights	Mixed integer nonlinear programming (MINLP) Technique
[40]	2010	Single	Location + Size	Multi objective with weights	Heuristic iterative search technique
[41]	2008	Multiple	Location	Multi objective with weights	Ant Colony Optimization

TABLE I (CONTINUED)
TAXONOMY OF THE REVIEWED OPTIMAL DG PLACEMENT

Ref.	year	No. of DGs	Design Variables	Objectives	Optimization Method
[42]	2015	Multiple	Location	Multi objective	NSGA-II Algorithm
[43]	2013	Multiple	Location + Size	Multi objective	Non-dominated Sorting Genetic Algorithms II
[44]	2008	Multiple	Location + Size	Multi objective	Genetic Algorithm
[45]	2008	Multiple	Location	Multi objective	Genetic Algorithm
[46]	2013	Multiple	Location + Size	Multi objective	Strength Pareto Evolutionary Algorithm
[47]	2011	Multiple	Location + Size	Multi objective	Strength Pareto Evolutionary Algorithm
[48]	2010	Single	Location + Size	Multi objective	Strength Pareto Evolutionary Algorithm
[49]	2016	Multiple	Location + Size	Multi objective	Advanced Pareto Front Non-Dominated Sorting Multi-Objective Particle Swarm Optimization
[50]	2013	Multiple	Location + Size	Multi-objective	Hybrid (PSO & Evolutionary Programming
[51]	2012	Multiple	Location + Size	Multi-objective	Hybrid (Binary PSO-based & Fuzzy)
[52]	2011	Single	Location + Size	Multi objective	GA and an ϵ-constrained method
[53]	2012	Multiple	Number + Location + Size	Goal Multi objective index	Genetic Algorithm
[54]	2008	Multiple	Location + Size	Multi objective- goal programming	Genetic Algorithm

reduction Index and Reliability Improvement Index are used. In [18], [19], [20], [21] [22], [23] [24], [25], [26] and [27] GA and its improved version have been used for optimization. Optimization of distributed generation with voltage step constraint using GA is presented in [18]. An improved adaptive genetic algorithm is suggested in [19] for ODGP of distributed generation considering timing characteristics and environmental benefits. GA methodology for ODGP is proposed in [20] for loss minimization and tail end node voltage improvement during peak load. In [21] GA is proposed to find the optimal place and capacity of DG resources, in order to improve the technical parameters of network, including power losses, voltage profile and short-circuit level. In [22] GA is presented working together with a fuzzy controller which is used to dynamically adjust the crossover and mutation rates to maintain the proper population diversity during GA's operation. A novel methodology that employs fuzzy set theory and the genetic algorithm for formulation and evaluation of a multi-objective function, respectively, for optimal planning of distributed generator units is proposed in [23]. A Monte Carlo simulation embedded GA is suggested to solve an ODGP with uncertainties represented by probability distribution function in [24]. An optimal proposed approach (OPA) to determine the optimal sitting and sizing of DG with multi-system constraints to achieve a single or multi-objectives using genetic algorithm (GA) is presented in [25]. In [26] GA is proposed to study the effects of load models on the optimal location and sizing of DG resources in distribution systems. A hybrid method employing genetic algorithms and optimal power flow is proposed to search a network for the best sites and capacities available to strategically connect a defined number of DGs among a large number of potential combinations in [27]. A probabilistic power flow embedded genetic algorithm based approach is proposed in [28] in order to solve the optimization problem that is modeled mathematically under a chance constrained programming framework.

In [29], [30] and [31] hybrid of PSO, GSA and GA was used for optimization. Combined nature inspired algorithms PSO, GSA, and hybrid PSOGSA algorithms are proposed in [29] for ODGP. PSO & Gravitational Search Algorithm are suggested in [30] for ODGP to improve total real power losses, voltage profile, MVA intake by the grid and greenhouse gases emission. In [31] a novel combined genetic algorithm (GA)/particle swarm optimization (PSO) is presented for optimal location and sizing of DG on distribution systems. In [32] Bat Algorithm (BA) is presented to exploit the benefits of DG by selecting optimal location and size of DGs in the distribution network. The multi-objective function (MOF) considered in this work is to minimize the total real power (Ploss) losses and maximize voltage stability index (VSI), within the range of voltage constraint.

In [33], [34] and [35], Shuffled frog Leaping Algorithm and its modified versions are used. In [33] a comparison is done between modified shuffled frog leaping algorithm (MSFLA) and shuffled frog leaping algorithm (SFLA). The allocation of DGs is done to reduce losses and improve voltage profile in power networks. Modified Shuffled Frog Leaping Algorithm (MSFLA) is proposed in [34] multi objective multiple DGs allocation and sizing to improve Interruption Duration Index (SAIDI) and Average Energy

Not Supplied (AENS) per customer index at the lowest cost. Shuffled frog leaping algorithm (SFLA) is represented in [35] for ODGP to minimize the total real power loss and to improve the voltage profile. In [36] the study presents an efficient multi-objective optimization approach based on the supervised big bang–big crunch method for optimal planning of dispatchable distributed generator. In [37] the study proposes a novel method that employs harmony search algorithm with differential operator to install multiple DG units optimally in distribution system with an objective of minimizing active power loss and improving voltage profile. In [38] a heuristic iterative method (clustering techniques and exhaustive search) is used exploiting information on the time varying voltage magnitude and loss sensitivity factor at each node. Optimal allocation of distributed generation using a two-stage multi-objective mixed-integer-nonlinear programming is proposed in [39]. In [40] a simple conventional iterative search technique along with Newton Raphson method of load flow study is implemented with objective to lower down both cost and loss very effectively. The weighting factors are also optimized. In [41] an ant colony system algorithm is used to derive the optimal recloser and DG placement scheme for radial distribution networks.

b. MULTI OBJECTIVE FOR SET OF FEASIBLE SOLUTIONS

Many studies have come up with set of optimum solutions, each one with its own features, especially for non-commensurable objectives. The choice of optimum solution is dependent on planner's interest.

Weighted sum method can be used to get a set of Pareto-optimal solutions by varying the weights. Unfortunately, this requires multiple runs as many times as the number of desired Pareto-optimal solutions. Furthermore, this method cannot be used to find Pareto-optimal solutions in problems having a non-convex Pareto-optimal front. In addition, there is no rational basis of determining adequate weights and the objective function so formed may lose significance due to combining non-commensurable objectives. To avoid this difficulty, the ε-constraint method for multi-objective optimization has been used. This method is based on optimization of the most preferred objective and considering the other objectives as constraints bounded by some allowable levels. These levels are then altered to generate the entire Pareto-optimal set. The most obvious weaknesses of this approach are that it is time-consuming and tends to find weakly non-dominated solutions. Better approaches, adopted is to Pareto rank candidate solutions, and keep an archive of all non-dominated search. In this way it's possible to explore the entire Pareto front without any a priori knowledge about the problem.

Data Clustering and NSGA-II algorithm are proposed in [42] to investigate optimal placement of wind turbines for reducing losses and improving load ability and voltage profile in distribution networks. In [43] Non-dominated Sorting Genetic Algorithms II (NSGA-II) is proposed is used to obtain the set of Pareto optimal solutions, which form a numerous set of non-dominated solutions and will be employed by the Decision Maker (power system operator) to select the best compromise solution. In [44] true Pareto-optimal solutions are found with a multi-objective genetic algorithm and the final solution is found using a max–min approach. A multi objective programming approach based on the non dominated sorting genetic algorithm (NSGA) is proposed in order to find configurations that maximize the integration of distributed wind power generation (DWPG) while satisfying voltage and thermal limits in [45].

In [46], [47] and [48] Strength Pareto Evolutionary Algorithm is used. A novel Strength Pareto Evolutionary Algorithm (SPEA) is represented in [46] for optimal location and sizing of DG on distribution systems. The objective is minimizing network power losses, better voltage regulation and improves the voltage stability within the security constraints in radial distribution systems. Pareto based Multi-objective Optimization Algorithm (MOA) called Strength Pareto Evolutionary Algorithm (SPEA) is suggested in [47] for Distributed Generation planning in distribution networks considering reliability, cost of energy and power loss. The weighting factors are also optimized. Strength Pareto Multi-Objective Optimization Approach is presented in [48] to generate Pareto front from which a designer can select from.

In [49], [50] and [51] multi objective PSO and its varieties are used. . In [49] Advanced Pareto Front Non-Dominated Sorting Multi-Objective Particle Swarm Optimization is presented to get Pareto front considering power loss reduction and voltage stability improvements with voltage profile and power balance as constraints. A combination of Evolutionary Programming (EP) and PSO methodology is proposed in [50] for distributed generation (DG) placement and sizing using multi-objective optimization concept. A stochastic dynamic multi-objective model for integration of distributed generations in distribution networks is proposed in [51] .The Pareto optimal solutions of the problem are found using a binary particle swarm optimization (PSO) algorithm and finally a fuzzy satisfying method is applied to select the optimal solution considering the desires of the planner.

The ε-constraint method [52] where GA is used for Multi objective ODGP considering voltage rise issue and voltage dependent loads is solved by interactive trade off method.

c. GOAL PROGRAMMING METHOD

Goal attainment or goal programming is becoming a practical method for handling multiple criteria or objectives [7]. In this method, all objectives are assigned target levels for achievement, and these targets are treated as aspirational goals. After the goals have been formed, the deviations of the objective function values from the target values are minimized so as to find an optimal solution.

A novel methodology that employs a goal programming technique and genetic algorithm for formulation and evaluation of a multi-objective function, respectively, is proposed in [53] for optimal planning of distributed generator units in the distribution system. Multi objective function with fuzzy sets is searched by Genetic Algorithm (GA) to determine optimal size and size of DGs in [54].

X. FUTURE WORK

A lot of research has been done on optimal location and size of distributed generation to a system for more than one and half a decade. With assumption now that power system networks exists with DGs optimally introduced, it is necessary to carry out research to determine introduction of new DGs to such systems. The research results should show whether there is a trend for introduction of new DGs or the optimization procedure has always to be repeated afresh.
A number of scenarios can be considered as listed below:

1. Introduction of DGs to system which already contains other DGs which had been optimally introduced.
2. Introduction of DGs to system which already contains other DGs which were not optimally introduced.
3. Introduction of a given type of DG of a given capacity to a system which already contains other DGs.
4. Introduction of DGs to a system which already contains other DGs and has also experienced a given percentage of load growth.

XI. CONCLUSION

This study has presented a critical review of various existing optimization methods applied to the OPDG problem. It has also identified that most common objective is the minimization of the total power loss and improvement of system voltage. Also it is found that multi objective problems are solved mainly by genetic algorithms and particle swarm optimization techniques. Future research areas are in the effects of introduction of new DGs in a network with already existing optimally placed and sized DGs.

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