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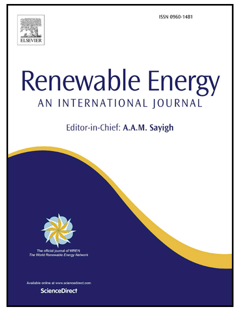

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Review of Optimization Techniques Applied for the Integration of Distributed Generation from Renewable Energy Sources

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Abstract

Several potential benefits to the quality and reliability of delivered power can be attained with the installation of distributed generation units. To take full advantage of these benefits, it is essential to place optimally sized distributed generation units at appropriate locations. Otherwise, their installation could provoke negative effects to power quality and system operation. Over the years, various powerful optimization tools were developed for optimal integration of distributed generation. Therefore, optimization techniques are continuously evolving and have been recently the focus of many new studies. This paper reviews recent optimization methods applied to solve the problem of placement and sizing of distributed generation units from renewable energy sources based on a classification of the most recent and highly cited papers. In addition, this paper analyses the environmental, economic, technological, technical, and regulatory drivers that have led to the growing interest on distributed generation integration in combination with an overview about the challenges to overcome. Finally, it examines all significant methods applying optimization techniques of the integration of distributed generation from renewable energy sources. A summary of common heuristic optimization algorithms with Pro-Con lists are discussed in order to raise new potential tracks of hybrid methods that haven't been explored yet.

Keywords: Distributed Generation (DG); Optimization methods; Renewable Energy Sources (RES); Heuristic Methods; Power System Losses

GLOSSARY OF TERMS	
ACROMYMS	**DEFINITION**
ABCA	Artificial Bee Colony Algorithm
ACO	Ant Colony Optimization
AGA	Adaptive Genetic Algorithm
BBO	Biogeography Based Optimization
BPSO	Binary Particle Swarm Optimization
CHP	Combined Heat and Power
CIGRE	International Council on Large Electric Systems
CO_2	Carbon dioxide
COP	COnférence des Parties
CSA	Cuckoo Search Algorithm
DER	Distributed Energy Resource
DG	Distributed Generation
DSI	DG Suitability Index
DSM	Demand Side Management
DSO	Distribution System Operator
EPRI	Electric Power Research Institute
FA	Firefly Algorithm
FL	Fuzzy Logic
GA	Genetic Algorithm
GHG	Greenhouse Gas
HS	Harmony Search
ICA	Imperialist Competitive Algorithm
IEA	International Energy Agency
IPSO	Improved Particle Swarm Optimization
LP	Linear Programming
MADM	Multi-Attribute Decision Making
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Nonlinear Programming
NDC	Nationally Determined Contribution
OPF	Optimal Power Flow
PGSA	Plant Growth Simulation Algorithm
PSI	Power Stability Index
PSO	Particle Swarm Optimization
PSO-CF	PSO with Constriction Factor
PSO-IW	PSO with Inertia Weight
PV	Photovoltaic
R&D	Research & Development

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RE	Renewable Energy
RES	Renewable Energy Source
SA	Simulated Annealing
SBA	Shuffled Bat Algorithm
SFLA	Shuffled Frog Leaping Algorithm
SLPSO	Social Learning Particle Swarm Optimization
T&D	Transmission and Distribution
THD	Total Harmonic Distortion
TS	Tabu Search

Contents

1. Introduction

For the first time in more than two decades, the international community agreed in the Paris COP21 on a joint goal for lowering Greenhouse Gas (GHG) emissions and defined a roadmap to give an end to the dominance of fossil fuels that lasted for more than two centuries. This global deal gave not only a hope to world citizens from developed and developing countries, but also a powerful signal for investors to ease the shift toward low-carbon economies. The most important outcomes of COP21 agreement can be summarized in the following two points [1]:

- Legal obligations for countries to set official targets, called also Nationally Determined Contributions (NDCs), and prepare policies to achieve them.
- Countries can voluntarily use “cooperative approaches” to trade emissions obligation, in a decentralized, bilateral way. This might encourage existing national and regional carbon markets to link together, expand and grow.

This agreement will create a long-lasting framework to tackle environmental problems effectively and pave the way for even more ambitious targets over the years. Therefore, implementing energy efficiency measures and clean sources of energy such as Renewable Energy Sources (RES) would highly shorten the time to achieve the objective of net zero GHGs emissions. However, RES when they were first introduced created new challenges. On the one hand, the intermittence problem of renewables formed additional technical and economic issues, which limited their penetration level. On the other hand, unlike conventional power plants, RE power plants require specific locations, which usually resources' potential is high but the distance from load demand is far. This situation urged the need for mathematical optimization tools that help in the planning and decision making process, especially when it comes to the selection of RE plants' sizes and locations. To encourage more the deployment of RES and reduce the cost of large scale investments, utilities have recently developed Distributed Generations (DGs) in order to facilitate investments and create competiveness in the RE market. In fact, in a liberalized electricity market, opportunities for connected generation at distribution levels will increase, especially when the size and location of DGs from RES are optimized giving their big impact in reducing the technical challenges associated with RE integration such as energy losses. It has been indicated that inadequate determination of DG location and size, may lead to an increase in system losses [2][3]. By optimum allocation and sizing of DGs, not only losses in the power system are reduced, but also network voltage and reliability are improved. As a result, the determination of the maximum level of DGs from RES that can be incorporated in the system while reducing the losses can be considerate as one of the main objectives for power utilities when it comes to planning of new power generation sources. Although small distributed and renewable generation might increase the costs due to the complexity of monitoring and running the network, it would however provide a more efficient and secure electricity network. But with the continuous technological advancement in materials and power system control, the cost of DGs from RES is expected to be reduced. Thus, DG modular and small size will shorten the installation time compared to large conventional power plants. In addition, DGs can be also utilized as a backup solution in case of contingencies giving the islanding capabilities given by decentralized power generation units. In a context of increased uncertainty in electricity demand and supply, DGs present the advantage of being installed with lower risk and change in the existing infrastructure, which will transform power systems from centralized to decentralized systems. That is why there is a need to develop tools that are able to maximize these benefits while accommodating multiple conflicting objectives.

The development of DGs throughout the world is presented in two levels, with Research & Development (R&D) advancements and the expansion of DG projects. On the research side, Figure 1 shows the rapid increase witnessed during the last decade in the number of research papers that use optimization methods in the DGs deployment from RES using Scopus database[2]. Accompanying the evolution in research papers, there has been also a growth in DG installations. For instance, the liberalization of power market in Europe fostered the development of DGs with about 40% penetration in Denmark and Netherlands [4].

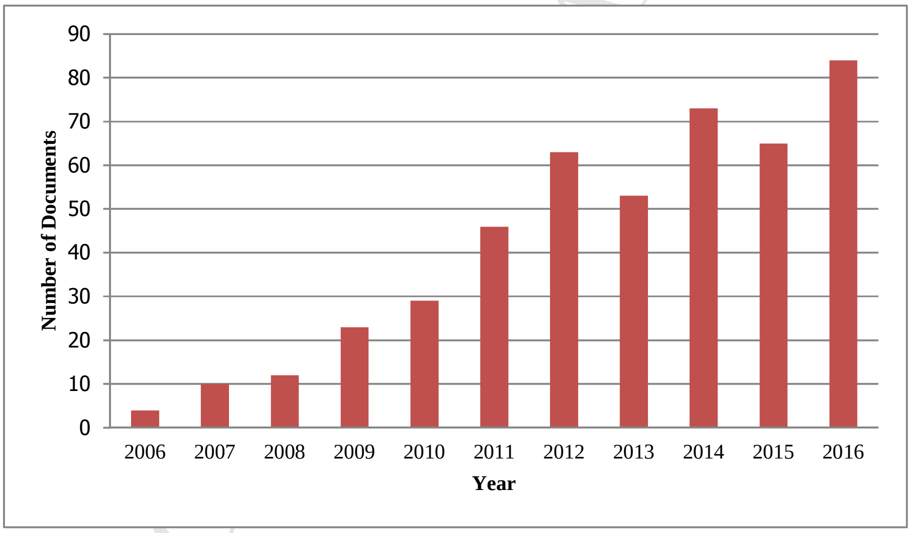

Figure 1 Number of articles using optimization methods applied in the deployment of DGs from RES in the past 10 years

This rising interest in the use of optimization methods applied for the deployment of DGs from RES is expanded all over the world with more than half of the total research papers produced from developed countries such as European countries (Italy represents ¼ of the total European countries), USA, and Japan. However, about 30 % of the total research papers are produced by emerging developing economies such as China, Iran and India. Figure 2 illustrates the relative distribution by country of the published articles during the last decade. The interest in the developed countries and the highest emerging developing countries can be explained by the international pressure on the reduction of CO_2 emissions and the encouraging policies and incentives regarding the use of RES. In addition, it is noticeable that more interest is starting to grow even in countries rich in fossil fuels, such as Saudi Arabia and UAE. This is manifested with their decision to consider RES as a viable alternative to conventional sources of energy in order to meet their fast-growing domestic demand, ensure national security, and diversify their economies.

[2] Scopus is the largest abstract and citation database of peer-reviewed literature: scientific journals, books and conference proceedings. Delivering a comprehensive overview of the world's research output in the fields of science, technology, medicine, social sciences, and arts and humanities, Scopus features smart tools to track, analyze and visualize research [5].

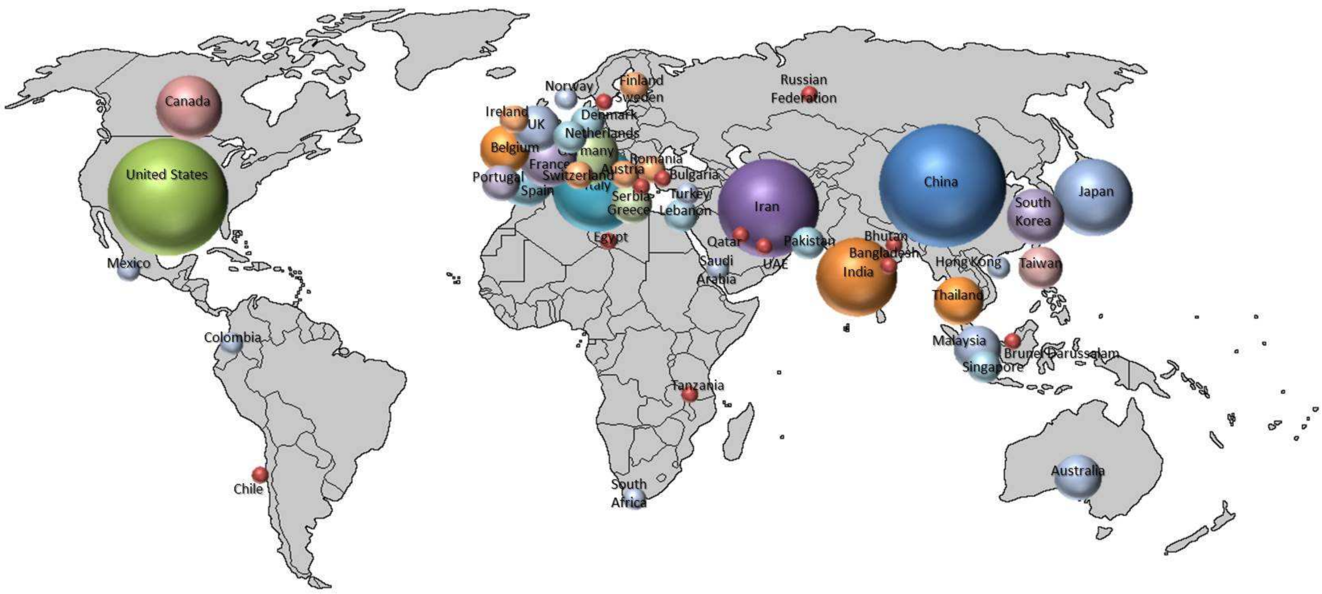

Figure 2 Distribution map of research papers about optimization methods applied in the deployment of DGs from RES

Despite the various benefits resulting from the deployment of DGs from RES, studies have indicated that utilities may face new challenges of increased system losses caused mainly by inappropriate selection of location and size of DGs [6] [2]. By including optimization techniques, utilities will be able to address the problems of losses, reliability and quality of the supplied electricity. Additionally, optimal placement of DGs can further reduce the need for new time-consuming and costly investments, and save investments related to the Transmission and Distribution (T&D) systems [7]. In fact, T&D cost represents the biggest part of the capital budget for utilities (almost two thirds). Recently, the T&D cost has raised from 25% to around 150% of the generation cost [2]. Due to the recent concerns on environmental and increased cost of T&D, large central power plants become often ineffective.

This paper shed light on the diverse existing optimization methods applied to the planning and integration of DG from RES. The focus is on solving the problem of placement and sizing of DG units. A summary grouping all the discussed optimization methods provided at the end will help to choose the most effective technique to model a similar problem and solve it.

2. Drivers and challenges of DG growth

In this section, a synopsis of the diversified drivers that have led to the growing interest on DG integration is provided while focusing on DGs from RES. This analysis will emphasize on the actual context of the transition into a more active management of power systems and smart grid application. An overview about the challenges to overcome will be presented as well.

2.1. Definitions

DG is defined as a small-scale generation source of electricity connected usually to the distribution level. The definition of DG might be different from one agency to another. For instance, the International Energy Agency (IEA) [8] defines DG as a generation plant serving a customer on-site or providing support to a distribution network, connected to the grid at distribution-level voltages. Alternatively, International Council on Large Electric Systems (CIGRE) defines DG as a decentralized generation that is smaller than 50-100 MW, and usually connected to the distribution network [4]. Other organizations like Electric Power Research Institute (EPRI) outlines the capacity of DG from few kilowatts up to 50 MW [9].

For a wider concept, Distributed Energy Resource (DER) is considered to be any generation or storage technology located near the load center and has a modular aspect, such as, mini-hydro, wind generator, photovoltaic (PV) or in the form of diesel, fuel cells, batteries, and also Demand Side Management (DSM) measures.

2.2. Drivers

The main drivers behind the expansion of DGs from RES can be categorized into five main classes: environmental, economic, technological, technical and regulatory drivers.

2.2.1. Environmental drivers

There is no doubt that during the last decade, concerns about climate change raised considerably due to the noticed negative impacts on the environment. This alarming situation urged policy makers to establish policies in order to enforce the environment preservation. Therefore, environmental policies aiming at promoting RE and reducing CO_2 emissions are major drivers for the development of DG coming from RES. In fact, in Europe, regulations have enforced electricity providers to consider cleaner energy sources [10]. In this context, DGs were perceived as an excellent solution to meet the increasing demand on electricity while optimizing the energy consumption, due to the decentralized nature of DGs and their ability to be used for co-generation by heat generating industries.

2.2.2. Economic drivers

One of the objectives behind the liberation of the electricity market was to reduce electricity prices by establishing a competitive market. In this context, DGs presented favorable incentives in order to compete with large scale power generation projects. In fact, large scale projects require the construction of new transmission lines in order to transport electricity to the load centers, which can be considered as an economic constraint. Unlike DGs, which are usually installed right next to the load, the financial risk is reduced. Therefore, DG could relieve power companies from additional investments in T&D capacity. According to the IEA, cost savings in T&D can reach 30% of electricity costs thanks to on-site production [8]. Besides that, the closeness of DGs to load centers presents another economic advantage which is the enhancement of power quality and reliability, especially in case of outages. In fact, DGs make possible the operation in islanding mode when a failure of one power station will have a partial effect on the overall system. This will help to prevent major economic losses in case of contingencies [11].

2.2.3. Technological drivers

Recent advancements in technologies related to REs and energy storage allowed the expansion of small-scale generation of electricity such as DG technologies. In fact, thanks to technological developments in generators, small and medium size generation technologies used for home application are cost effective and available in the market, such as micro-CHP (Combined Heat and Power). These micro-CHP are very popular especially in Europe since the electricity is mostly needed for heating in winter [11].

2.2.4. Technical drivers

There are many technical drivers for the growth of DGs giving their numerous benefits to the power system. In fact, to reduce losses, it is possible to apply several techniques, such as feeder reconfiguration, cable grading, capacitor placement, and DG unit placement. However, DG unit placement is the only non-passive element where loss reduction almost double than with capacitors [12]. In fact, DG has a direct effect on power flow and voltage quality, which is generally described as "system support benefits", and includes [9] [13]-[15]:

- Voltage support and power quality enhancement;
- Loss decrease;
- Capacity relief at T&D levels;
- System reliability;
- Peak load shaving and reliability enhancement;
- Flexibility to track load variation;
- Backup supply in case of sudden contingencies.

For instance, in USA, using DG for peak load (peak shaving) was the major driver behind DG growth [16]. DG primarily ensures the supply of electricity, but can also play a role in grid stabilization due to its capability to generate active power. This helps improving the network frequency which may drop during under supply or over demand conditions.

The second major driver for DGs development is ensuring good power quality. In fact, reliability issues refer to continued interruptions caused by voltage drops in electricity supply. For instance, big electricity consumers such as industries may face some problems with insufficient supplied electricity. Thus, investing in DG generation units can help them strengthen the reliability of the supplied electricity [10].

2.2.5. Regulatory drivers

Particular attention is being paid around the world especially within Europe towards climate change and regulatory schemes that promote the variation of energy sources for energy security purposes. This has resulted into the employment of incentive regulation to the development of the distributed network through DGs especially from RES [17]. Moreover, the high support for policies encouraging active management has enlarged the access from transmission networks to distribution networks by enabling competition through small-scale generation.

2.3. Challenges

Despite the numerous benefits and drivers behind the expansion of DGs, economic and technical challenges can result from the aggressive integration of DGs. Some of the major problems facing DGs are outlined here. First of all, with DGs power flow has changed from unidirectional into bidirectional flow within a certain voltage level. Thus, an aggressive integration of DG units may affect the grid stability and power system quality. Accordingly, the choice of the installed DG capacity will not only depend on the cost and benefits of each technology, but also will depend on the optimal location and size that enable high loss reduction in the overall system [11]. In addition, the structure of the electricity market is one of the challenges facing DGs installation. In fact, in a traditional non-liberalized power system, the market is usually characterized by a vertically integrated monopoly. However, in a liberalized market, risk investments in DGs are leveled through the competitiveness created by new opportunities.

3. Review of optimization approaches for DGs placing and sizing

Uncertainties and variability are the main challenges associated with RES, especially with non-continuous availability of wind, solar and hydro resources. To accommodate the integration of large share of RES, it is important to have appropriate planning tools able to optimize the integration of variable RES. Many optimization techniques related to energy problems in general exist in the literature, such as conventional and intelligent search methods. In principal, searching for the optimal site and capacity of DG is usually modelled as a non-linear mathematical optimization problem. Various constraints and objective functions are first set. The optimization technique help in decision-making by generating one optimal or a set of optimal solutions or output variable from a reduced set of initial input variables. Broadly, there are two approaches to solve a problem, by exact methods such as Mixed-Integer Linear Programming (MILP) which is usually very effective but necessitate excessive computing time and hard to implement on real size problems, and heuristic methods which is based on simplifying the problem and offering satisfying solutions. In this section, a simple formulation of the most common problem is presented, which is to find the optimal DG size and bus location that minimize the network total losses. The resulting objective function is minimized in the presence of suitable equality and inequality constraints. Prior to introducing the mathematical model, some notation is provided.

Parameters:

N: total branches number

r_{ij}: resistance between bus *i* and bus *j*

Vi, V_j: voltage magnitude at bus *i* and bus *j* respectively

δ_i, δ_j: voltage angle at bus *i* and bus *j* respectively

Decision variables:

$P_{i,}\, Q_i$: active and reactive power injection at bus *i*

$P_{j,}\, Q_j$: active and reactive power injection at bus *j*

Based on the exact formula of total losses developed by Elgerd [18], the objective function requires the minimization of the total power losses. That is,

$$Minimize(P_{loss}\{DG(i,size)\}) \tag{1}$$

$$P_{Loss} = \sum_{i=1}^{N}\sum_{j=1}^{N}[\alpha_{ij}\left(P_i P_j + Q_i Q_j\right) + \beta_{ij}(Q_i P_j - P_i Q_j)] \tag{2}$$

Where, the coefficients α_{ij} and β_{ij} are determined as

$$\alpha_{ij} = \frac{r_{ij}}{V_i V_j}\cos(\delta_i - \delta_j)\,, \beta_{ij} = \frac{r_{ij}}{V_i V_j}\sin\left(\delta_i - \delta_j\right) \tag{3}$$

Where $r_{ij} + jx_{ij} = Z_{ij}$ is the ij^{th} element of $[Zbus]$ matrix with $[Zbus] = [Ybus]^{-1}$.

Subject to:

- Power balance constraint

$$H(x,u) = 0 \tag{4}$$

Where

- *x* is the vector of power system optimization variables.
- *u* is the control vector of the independent variables.

- Voltage limits constraint as follows:

$$V^{min} \le V_i \le V^{max} \tag{5}$$

Where V^{min} and V^{max} are the minimum and maximum values of voltage at bus *i* ; normally the bus voltage lies between $0.95 \le V_i \le 1.05\ PU$.

- DG real power output constraint is as follows:

$$P_{DG}^{min} \le P_{DG} \le P_{DG}^{max} \tag{6}$$

Where P_{DG}^{min} and P_{DG}^{max} are the minimum and maximum active power output of DG.

To solve these models, a large variety of optimization techniques were proposed in the literature so far. As illustrated in Figure 3, these methods can be generally classified as heuristic methods, analytical-based techniques, gradient and second order methods, and iterative methods. Heuristic methods may include Genetic Algorithms (GAs), Artificial Bee Colony Algorithm (ABCA), Tabu Search (TS) and Particle Swarm Optimization (PSO). These optimization methods have given acceptable results over the years, in addition to mathematical programming such as Linear Programming (LP) and Optimal Power Flow (OPF), are also widely presented in the literature.

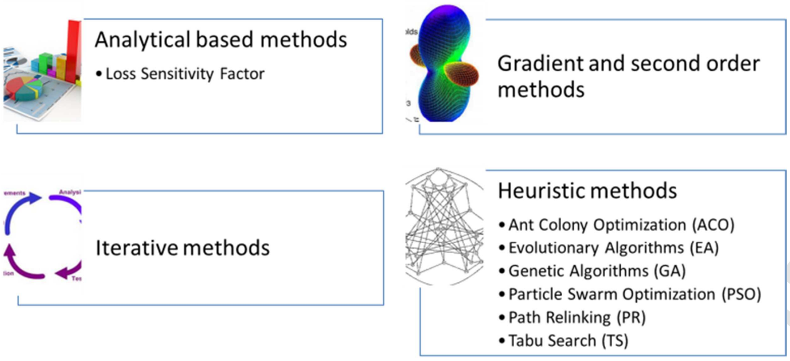

Figure 3 Classification of different methodologies to solve DGs placement and sizing problem

Considering the objective function, two categories of optimization methods can be presented, which are single-objective and multi-objectives approaches. The most common objective found in this review is the minimization of the power system losses. In addition, other approaches focus on saving the total cost, which can be evaluated from different perspectives. In fact, the problem can be formulated from the perspective of a DER developer, or the perspective of Distribution System Operator (DSO) that want or refuse to invest in DER [19].

Actually, multiple objectives of an optimization problem create naturally a certain conflict, where no single solution is able to satisfy all the different perspectives. For example, in a DG placement and sizing problem, the objective function of maximizing DG capacity can create a conflict with not only the increase of line losses, but also with the potential increase in investments cost as well as society's interest to reduce CO_2 emissions [20]. In general, multi-objective optimization problems contain various objective functions that need to be simultaneously minimized or maximized [21].

One of the most common available approaches to solve multi-objective optimization problems is the so-called weighted sum approach which consists in converting the multi-objective problem into a single-objective problem using pre-specified weights. Despite the simplicity of the weighted sum approach, there are some disadvantages associated with it. On one hand, weighted sum approach cannot be applicable to non-convex problems [22] and dissimilar objectives cannot be added together. On the other hand, the proposed solution is only applicable for the set of weights (priorities) chosen for the objective functions.

Figure 4 summarizes the above discussed elements forming a general mathematical optimization model. It enumerates all possible types of constraints and objective functions related to the allocation and sizing problem of DGs.

3.1. Conventional methods

In this section, some conventional optimization methods are reviewed to solve the problem of DGs allocation and sizing. In fact, during the recent years the interest in using analytical approaches to handle optimization problem has grown greatly [12] [23][34]in addition to traditional methods such as methods based on Linear Programming.

3.1.1. Analytical approaches

Analytical approaches usually produce a numerical equation that can be examined for optimization. The accuracy of the method highly depends on the model developed. It might also be applied in combination with another model based on the simulation results of the system. However, they are mostly based on theoretical, calculations, and mathematical analysis. They offer the advantage of short computing time and easiness in implementation while ensuring convergence of the problem. Nevertheless, the assumptions used for simplifying the problem may threaten the accuracy of the solution when the problem becomes complex. For instance in [26], the applied analytical method was based on the analysis of continuous power flow calculations and identification of the buses that are most susceptible to voltage drop. This approach proved to be successful in improving voltage profile and reducing power losses while increasing power transfer capacity.

Moreover, some new analytical approaches were based on Power Stability Index (PSI) in order to illustrate the impact of DG on the power system. PSI analytical approach was tested in [27] on several types of buses in radial distribution networks.

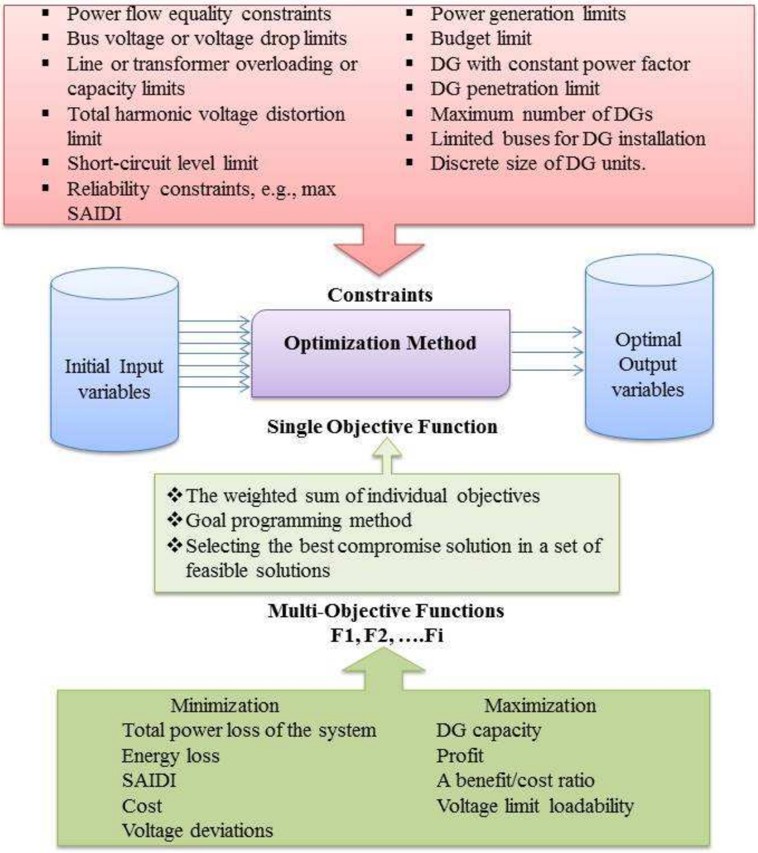

Figure 4 Elements of a general mathematical optimization model related to the allocation and sizing problem of DGs

3.1.1.1. 2/3 rule

The 2/3 rule consists on applying a simple intuitive rule for only approximate placement of capacitors in distribution systems based on graphical display of the power flow. This analytical method suggests that if we consider the size of the DG unit to be 2/3 of the uniform load, and the location is set at 2/3 of the distance from the feeder, total VAR-miles of flow can be minimized. For multiple units (N units), it can also be generalized to “2/(2N+1) Rule”. In [28][29] this rule was applied in a case where the load is distributed in a uniform way on a radial feeder. In fact, 2/3 of the incoming generation was chosen as the capacity of the DG to be placed at 2/3 of the line length in order to minimize the losses and voltage impacts.

3.1.1.2. Loss Sensitivity Factor and Sensitivity Analysis

Loss sensitivity factor method is essentially utilized to reduce the number of all feasible solutions forming the search space by linearizing the original non-linear equation around the initial operating point. This approach has been extensively applied to determine the size and location of DGs using the exact loss formula developed by Elgerd [18], such as it was applied in [12][29]. The use of analytical methods in combination with loss sensitivity factor is highly common in the literature due to the simplicity of implementation [24][25][31][32].

Sensitivity analysis method consists on changing some parameters in order to see their impact on the final results [35]. The methodologies that use sensitivity analysis help to reduce the computational time which can be critical especially with large real case systems. In fact, sensitivity analysis method is highly effective in assessing uncertainties such as the ones resulting from RE intermittent nature. In fact, the different results in the output variables are dependent on the different sources of uncertainty associated with the inputs where this impact is assessed through sensitivity analysis. The uncertainty in the output of the modelled system can be apportioned to different sources of uncertainty in its inputs. In [33][34] the authors studied the real and reactive power losses sensitivity taking into consideration the size of DG. The search space and computational time were considerably minimized.

3.1.2. Linear and Non-Linear Programming (LP & NLP)

LP is a type of mathematical programming utilized to solve a mathematical model where the requirements are represented by linear relationships for maximizing or minimizing the objective function. One of the methods to solve LP problems is the simplex method that it is based on polytope edges of the visualization solid to determine the optimal solution [36]. LP is widely used in power system optimization problem as it gives the exact solution, such as finding the optimal size of DG units. In [37]-[39] LP was implemented to improve the effect of DG reactive power demand on the system voltages and increase the number of connected DGs while respecting the distribution voltage limits.

However, the mathematical model to solve is called Mixed Integer Nonlinear Programming (MINLP) when the variables are continuous and discrete and the objective function and constraints are non-linear (such as with power balance and cost equations. In the context of finding the optimal location and size of DGs in the power system, MINLP has been used in several papers [40][42], where the optimal locations of DGs were determined economically and operationally based on power loss sensitivity index. However, the very large number of decision variables and the long computation time are the major drawbacks of MINLP.

There are many computing tools to solve LP and MILP problems, some of them are open source tools (like, COIN-OR) or commercial solvers (including CPLEX, GUROBI, XPRESS, LINDO, MATLAB to quote just a few).

3.1.3. Optimal Power Flow (OPF)

The goal of an OPF is to define the optimum economic operating cost to instantaneously operate a power system while considering the impact of the transmission and distribution systems. OPF was widely employed in the literature for solving DGs allocation and sizing problem since it considers already the economic aspect in the optimization problem [43][46]. For example “reverse load-ability” approach was considered with OPF to maximize the size of DG and find available locations in the system considering the obligatory constraints underlined by the voltage and harmonics. In addition in [47] to solve the capacity allocation problem, switchgear was also considered as an additional fault level constraint imposed to protect equipment using an OPF model within limited numbers of contingencies (line outages).

3.1.4. Fuzzy Logic (FL)

Firstly, FL was introduced in 1979 as a generalization of classical set concept to solve problems related to power system. In fact, it consists on the identification of a membership function containing the level of association of each component by indicating a number between 0 and 1. This function measures the resemblance level of any element to a fuzzy subgroup [48]. The most commonly utilized membership functions are the triangular, trapezoidal, piecewise-linear, and Gaussian functions. The number of memberships allowed is infinite [49].

FL is highly used in the allocation and sizing problem of DGs. For instance, in [50] FL was implemented to solve the optimal location problem of DGs aiming to minimize real power losses and enhance voltage profile.

3.2. Intelligent search methods

Artificial Intelligence is generally described as the exhibition of intelligence within machines [51]. Heuristic methods are considered as intelligent search methods, which consist on algorithms that speed up the process of finding a satisfactory or near optimal solution [52]. The major advantage of heuristic approach comparing to analytical approach is its simplicity. However, it sacrifices accuracy and precision. A meta-heuristic is an iterative process that can help to find near optimal solutions in a more efficient way [53]. The objective of meta-heuristics is to enlarge the aptitudes of heuristics by joining one or more heuristic methods [54]. The following sections present some of the most popular approaches, such as Genetic Algorithm (GA), Simulated Annealing (SA), Tabu Search (TS), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and Harmony Search (HS).

Figure 5 presents the historical evolution of these heuristic methods. Genetic algorithm was the first proposed method. Other methods that are based on natural evolution and animal social behaviors followed the GA. New methods such as HS were recently suggested which are based on different areas such as musical harmony.

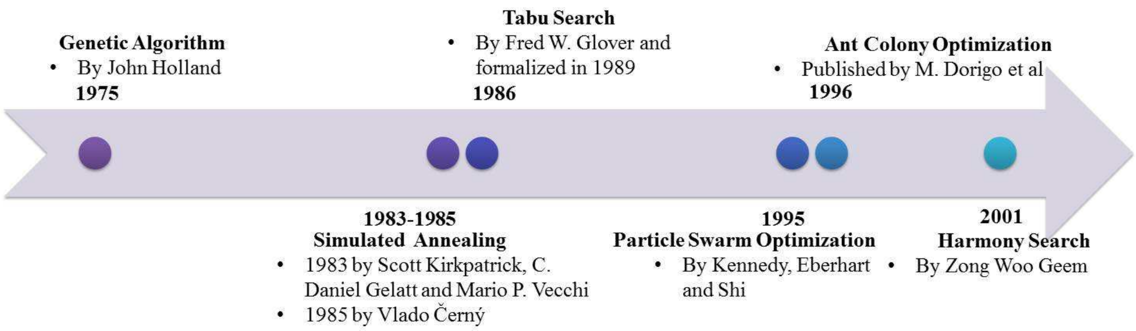

Figure 5 Historical developments of some heuristic optimization methods

3.2.1. Genetic Algorithm (GA)

GA is among the first developed heuristic methods since 1975 by Holland. It can be defined as a search technique based on the principles of genetics and natural selection, such as, selection, crossover, mutation, and inheritance [55]. Under a specified selection rules, GA permits for a population to evolve into a state that maximizes the “fitness” in contrast to other search techniques that work on a single solution.

In fact, the population of elements is assimilated to chromosomes, which encrypts potential candidates, to evolve toward better state. Conventionally, solutions are represented in binary code. The first population is randomly generated and through evolution of generations, the suitability of every candidate is evaluated. The selected candidates are modified through mutation to form a new population. This will be repeated until the algorithm reaches a satisfactory level or maximum level of iterations.

In the literature, GA is considered to be the most applied optimization techniques in solving the problem of DGs placing and sizing [56][63]. In [64][65] GA was applied in the aim to save the system expansion costs and increase the system reliability. As these two objectives are conflicting pareto-optimum models were used in order to determine the dominant solution at a single run.

New enhanced methods are being proposed in the DG locating and sizing problem, such as in [66] where GA was combined with Multi-Attribute Decision Making (MADM) method considering different parameters of power system. Other enhanced methods of GAs can be listed such as Adaptive Genetic Algorithm (AGA) which has proved in [67] to be more robust and has greater search ability level, as well as Quantum Genetic Algorithm [68].

Table 1 compares the major disadvantages and advantages that GAs face.

Table 1 Advantages and disadvantages of Genetic Algorithm (GA)

Advantages	▪ Have greater success at finding the global optimal to a wide variety of functions ▪ Do not require derivatives ▪ Can be applied with both discrete and continuous parameters ▪ Can be applied for complex and not well defined problems ▪ Bad solutions do not negatively affect the end solution
Disadvantages	▪ Can be time consuming for large and complex problems due to repeated fitness function evaluation ▪ Can suggest bad solutions ▪ Can be trapped into local optima ▪ Can be inaccurate

3.2.2. Simulated Annealing (SA)

SA is an iterative algorithm used to solve combinatorial optimization problems that exploits crystallization process in a physical system usually when the search space is discrete [69]. Originally, it was defined by S. Kirkpatrick, C. D. Gelatt and M. P. Vecchi in 1983, then by V. Černý in 1985. The cooling criterion is the core point of SA optimization method. In fact, SA depends on three variables: initial temperature (T), cooling rate (β), and final temperature (T_{min}). The process is initiated with a feasible solution point. After system perturbation, new possible solutions will be determined based on a probabilistic acceptance criterion. In the literature, SA was used in [70][71] to locate and define the capacity of DGs while reducing computing time comparing to GA and TS methods. In addition, SA method is suitable for optimization problems which are based on stipulated reliability criteria. For example, in [72] power system planning based on reliability resulted into optimal size and location of DGs while meeting the consumer requirements with minimum system upgrade.

Table 2 presents the general advantages and disadvantages of SA method.

Table 2 Advantages and disadvantages of Simulated Annealing (SA)

Advantages	▪ Can be simply implemented ▪ Can provide good solutions for many combinatorial problems ▪ Can be robust
Disadvantages	▪ May terminate in a local minimum ▪ Have large computing time ▪ Cannot provide information about the amount by which the local minimum deviates from the global minimum ▪ Local minimum can depend on the initial configuration (generally no guideline is available for the choice) ▪ Cannot give an upper bound for the computation time

3.2.3. Tabu Search (TS)

TS is a meta-heuristic approach that was firstly suggested by F. Glover in 1986 to solve optimization problems [73][74]. The approach is based on the principle of adaptive memory and responsive exploration that enable searching the solution space in an economic and effective way until no improvement is reached.

TS was highly identified in solving the locating and sizing of DGs problem. For example in [75][76], Golshan et al. focused on DG optimal planning with the objective to minimize both losses and line loadings. However, TS has the disadvantage of large number of iterations and parameters to be determined.

Table 3 summarizes the main identified advantages and disadvantages of TS.

Table 3 Advantages and disadvantages of Tabu Search (TS)

Advantages	▪ Can be used for complex problems ▪ Have explicit memory ▪ Can be applied to discrete and continuous variables ▪ Can be used for large problems
Disadvantages	▪ Can depend on the strategy for Tabu list manipulation ▪ Can get stuck in local minima ▪ Should determine many parameters ▪ Have many iterations ▪ Can depend on parameter settings to find global optimum

3.2.4. Particle Swarm Optimization (PSO)

PSO is an optimization approach developed by Eberhart and Kennedy in 1995. It is principally inspired from the social behavior of bird flocking and fish schooling (the particles are moving in a multidimensional search space, where single intersection of all dimensions forms a particle) [77]. The system is firstly adjusted with a set of arbitrary solutions and the optimization search is ensured through updating generations. At each iteration, the particles assess their positions considering their fitness level, while the neighboring particles show the history of their “best” positions in order to refine the final solution [78].

In DGs locating and sizing problem, PSO was extremely used in the literature [79]-[81]. For instance, in [82] PSO is used to select the optimal location, type, and size of DG units to achieve the optimal integration of DGs taking into consideration harmonic limits and protection constraints. In addition, a PSO was employed in [83][84] to not only reduce Total Harmonic Distortion (THD), losses, and costs, but also improve the voltage profile. The results proved that PSO gave better solution quality and less number of iterations compared to GA method. In fact, PSO presents a shorter computational time in comparison with GA and can be adapted to real cases for power networks.

Table 4 lists the main advantages and disadvantages of PSO method.

Table 4 Advantages and disadvantages of Particle Swarm Optimization (PSO)

Advantages	▪ Can be simple to implement ▪ Have few parameters to adjust ▪ Able to run parallel computation ▪ Can be robust ▪ Have higher probability and efficiency in finding the global optima ▪ Can converge fast ▪ Do not overlap and mutate ▪ Have short computational time ▪ Can be efficient for solving problems presenting difficulty to find accurate mathematical models
Disadvantages	▪ Can be difficult to define initial design parameters ▪ Cannot work out the problems of scattering ▪ Can converge prematurely and be trapped into a local minimum especially with complex problems

New enhanced PSO methods are being proposed in the DG locating and sizing problem, such as Improved PSO (IPSO) [85], Binary PSO (BPSO) [86], Social Learning PSO (SLPSO) [87], PSO with Inertia Weight (PSO-IW), and PSO with Constriction Factor (PSO-CF) [88].

3.2.5. Ant Colony Optimization (ACO)

ACO algorithms were first published by Dorigo et al in 1996, which are principally inspired from the social behavior of insects (such as ants) in finding the shortest paths to get their food [89]. Physically, researcher discovered the existence of pheromone trails left by ants. This substance is used by other aunts in order to share the information about their path. Like other meta-heuristics, the process is initialized by random solutions which are assimilated to random searches performed by ants and the trails resulting from ants' movement. Consequently, the shorter the path, the more trails density increases. This information will be considered in the following searches. In [90][91] ACO is proposed to solve the location and size problem of DGs from RES in radial distribution systems while minimizing total system losses. The objective function used in [91] was based on a reliability index, where ACO algorithm was applied to solve discrete optimization problems. The results showed that ACO gave better soltion quality and less computational time compared to GA. However, ACO presents longer time to converge since the solution space to be evaluated is larger, but still shorter than with analytical methods.

Table 5 lists more details about the advantages and disadvantages of ACO method.

Table 5 Advantages and disadvantages of Ant Colony Optimization (ACO)

Advantages	▪ Can search among a population in parallel ▪ Can give rapid discovery of good solutions ▪ Can adapt to changes such as new distances ▪ Have guaranteed convergence
Disadvantages	▪ Probability distribution can change for each iteration ▪ Have a difficult theoretical analysis ▪ Have dependant sequences of random decisions ▪ Have more experimental than theoretical research ▪ Have uncertain time to convergence

3.2.6. Harmony Search (HS)

HS approach is a meta-heuristic optimization method which was developed relatively recently in 2001. Principally, HS is inspired by the technique used by musicians in order to improve the harmony of their instruments. Unlike other existing algorithms based on natural observed behaviors, HS is characterized by the musical performance process looking for a better harmony [92].

HS was applied in [93][94] to find the optimal DG location in combination with loss sensitivity factor approach. In [94] it was concluded that deploying HS algorithm was more acceptable than PSO for DG allocation to ameliorate voltage stability.

Table 6 displays some of the advantages of HS method.

Table 6 Advantages of Harmony Search (HS)

Advantages	▪ No Initial value settings are required ▪ Can use discrete and continuous variables ▪ Cannot diverge ▪ may escape local optima
Disadvantages	▪ Ability to search for local is weak ▪ Can reach a high number of iterations ▪ May encounter unproductive iterations without improving the solution ▪ Have high dimensional multimodal problem

3.2.7. Further Heuristic Methods

Some authors implemented further heuristic methods efficient for solving the DGs locating and sizing problem appeared in recent years, such as:

- **Artificial Bee Colony (ABC)** which is an optimization algorithm inspired by the searching behavior of honey bee swarm. ABC algorithm was applied in [95][96], where the comparison of the method with PSO approach showed that ABC offered better quality of the solution and faster convergence.
- **Cuckoo Search Algorithm (CSA)** which is based on the obligate brood parasitism of some cuckoo species that is characterized by placing their eggs in the nests of other host species [97]. CSA was implemented in [98] to enhance voltage profile and minimize power losses for DG biomass and solar-thermal DG units.
- **Shuffled Frog Leaping Algorithm (SFLA)** which is based on the behavior of frogs while they are searching for their food [99]. SFLA has been successfully applied to DG allocation and sizing problem. For example, in [100] SFLA was applied in order to maximize the system voltage profile and reduces line losses. SFLA has the advantage to associate between the benefits of GA and PSO algorithms.

- **Shuffled Bat Algorithm (SBA)** which is inspired by the echolocation behavior of micro-bats. This proposed algorithm was tested in [101] on a radial distribution systems to demonstrate its effectiveness With 100% base load conditions at a first stage , then with 120%.
- **Plant Growth Simulation Algorithm (PGSA)** which mimics the growing process of plant phototropism. The principle of PGSA is based on the search of the feasible region as the plant grows in a certain environment. At each change of the objective function, the algorithm looks for the possibilities to grow a new branch on different nodes and then forms the complete model [102]. In [103] PGSA was efficiently applied where the objective function was to decrease the losses and improve the voltage profile. The major advantage of PGSA is the capability to function without the need for external parameters.
- **Biogeography Based Optimization (BBO)** which is based on the mathematical models of biogeography. It describes several behaviors related to species like animals, fish, birds, or insects, such as their evolution, their migration between regions, and their extinction [104]. This new approach was employed in [105] for the optimal allocation and sizing of capacitor banks and DGs under the objective of improving power quality and THD.
- **Firefly Algorithm (FA)** which is based on the signal transfer used between fireflies in a courtship system. In fact, the firefly's flash aims to act as a signal system to seduce other fireflies [106]. In [107] the optimal allocation of DG was ensured by FA with the objective of minimizing real and reactive power losses and line loading.
- **Imperialist Competitive Algorithm (ICA)** which is a search strategy method based on socio-political science in order to solve optimization problems. Firstly, ICA starts with an initial random set of individuals of P countries. The selected best countries are named the imperialists and the rest are considered colonies of these imperialists. Then, based on each imperialist's power colonies are divided among imperialists in order to build initial empires [108]. In [109] the determination of DG location and size was ensured by ICA while including sensitive loads through islanding mode of a distribution network.

3.3. Hybrid Heuristic Methods

Researchers are continuously adopting new techniques and combining existing methods with the aim of improving certain factors such as the quality of the solution and the simplicity of implementation. The new combined method is usually called a hybrid technique. Several types of hybrid algorithms were proposed in the literature to solve the optimal location and size of DGs. Through this survey it was possible to raise the existing new hybrid approaches and combinations. The matrix displayed in Figure 6 shows clearly the areas for potential new combinations in hybrid optimization methods and enables researchers to identify new combinations that were not previously considered and might lead to better solutions and improvements. In addition, the matrix shows that GA has the highest number of orange cells, which refers to a high number of highly published papers combining GA with other commonly used methods such as PSO to solve the sizing and placement problem of DGs. The matrix was based on published articles during the last decade.

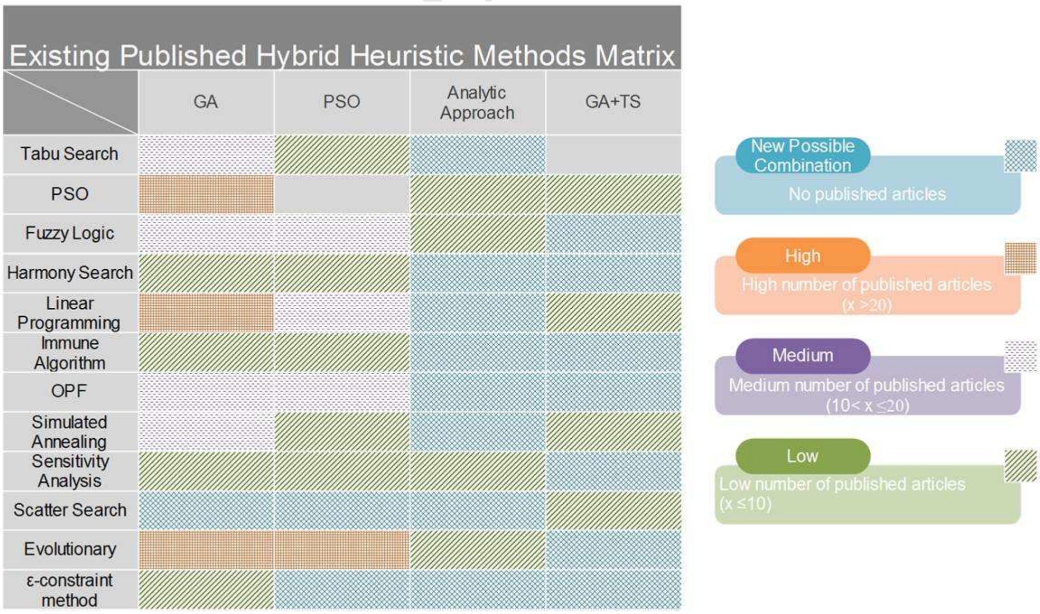

Figure 6 Matrix of existing published hybrid methods to solve the location and size problem of DGs

4. Synthesis of optimization approaches for DGs placing and sizing

In this section a synthesis of optimization techniques used to solve the DGs placement and sizing problem is presented. The methods are classified into three main categories, intelligent search methods, hybrid methods, and conventional methods. The major references are listed based on the different objective functions and constraints employed by the authors. The most common objective function is the power loss minimization. As for the constraint, voltage constraints are the most common ones. To summarize, analytical methods are considered simple and rapid to implement. However, due to the simplifying assumptions, their results can be less accurate. Among the available conventional methods, the most efficient methods are the LP and MILNP. The main advantage of the exhaustive search method is that it guarantees to find the global optima, unlike heuristic methods where the resulting point can be trapped in local optima. But they present some limitations with real and large-scale systems. Heuristic methods are usually very efficient in finding near-optimal solutions especially with complex problems. Even though, heuristic methods necessitate high computational effort, it does not affect their extensive application in solving DG placement and sizing problem.

A summary grouping all the discussed optimization methods is presented at Table 7. It could be used as a guide for selecting the most effective technique to model a similar problem and solve it by looking at the high number of verified research using these methods. But it also opens opportunities for potential original areas where further investigations are still needed such as with heuristic and hybrid methods. The effectiveness of an optimization method will depend on the most prioritized factor between the efficiency, quality of the solution, simplicity, and speed.

Table 7 Summary of optimization techniques used to solve the placement and sizing problem of DGs

Category	Optimization Technique	Objective Function	Constraints	References
Intelligent Search Methods	GA	Minimize the total real power losses	• Capacity limits • Voltage constraints • Three-phase short circuit current	[6][56], [57], [59]-[68], [110][124]
	Evolutionary Programming	• Maximize the network performance (voltage quality and harmonic distortion) • Minimize the network costs	Voltage constraints	[130][131]
	SA	Minimize total system cost per year (deployment costs + heat compensation costs)	• Network constraints • Stipulated reliability criteria	[70]-[72], [152]
	Differential Evolution	Minimize the losses	Voltage constraints	[114], [125]-[129], [141]
	ACO			[90], [91], [114], [132]
	ABC			[95], [96], [133], [134]
	CSA			[98], [135]
	FA			[107], [136]
	ICA			[109], [137][139]
	SFLA			[100]
	SBA			[101]
	PGSA			[103]
	BBO			[105]
	PSO			[79]-[88], [114], [140][148]
	Hereford Ranch Algorithm (HRA)			[149]
	TS			[75], [76], [114], [150], [151]
	HS			[93][94]
Hybrid Methods	GA and FL	Reduce power loss and costs of distribution systems	Technical constraints: • Capacity limits • Voltage • Three-phase short circuit currents • Number and size of DGs	[153]-[155]
	Primal Dual Interior-Point PDIP and OPF	Minimize the losses	Individual generation capacity limits	[156][157]

Category	Optimization Technique	Objective Function	Constraints	References
	GA and OPF	Reduce the cost of active and reactive power generation	Technical constraints	[161]-[164]
	Sensitivity Analysis and GA	Minimize the losses	• Loading conditions • Generation penetration level • Power factor	[58]
	Evolutionary Programming with Sensitivity Analysis	Minimize active energy loss	• Voltage • Line loadings • Number of DGs	[34]
	OPF with Second Order Algorithm Method (Gradient Method)	Minimize the losses, VAR losses, and loadings in selected lines	Voltage constraints	[29]
	GA and TS	Minimize the losses	Voltage constraints	[165]
	GA and PSO			[166]
	GA and an ε-Constrained Method			[158]
	PSO and FL			[159][160]
	GA and SA			[167]
	TS and FL			[168]
	PSO and OPF			[169]
	Analytical Technique and 2/3 Rule			[28]
Conventional Methods	LP	Maximize the revenue of the rural system	Number of energy and non-energy related relevant constraints	[37][39], [110], [170]
	OPF	Maximize social welfare and maximize profit	Voltage constraints	[43]-[47] ,[174]-[180]
	Analytical Techniques	Minimize total power loss	Voltage constraints	[12], [24], [27], [31][33], [171]-[173]
	Iterative Search Technique	Lower down both cost and loss	Voltage constraints	[26], [183]
	MILP	Minimize total system planning: • Costs of DG investment • DG operation & maintenance • Purchase of power from the existing TRANSCOs	• Voltage constraints • Capacity limits	[40]-[42], [181], [182], [19]
	Analytical Techniques (Not iterative algorithms)	Minimize power loss	Voltage constraints	[23]
	Analytical approach (Sensitivity Analysis)			[26], [33], [184][185]
	FL			[50]

5. Conclusion and future challenges

This paper explains the need for optimization techniques applied for efficient integration of DGs especially from RES. It presents the global context that encouraged both the development of RES and the decentralization of generation units through DGs. The exponential increase of research papers using optimization techniques to solve DGs placement and sizing problem shows the great interest towards this topic among power system researchers. This paper offers a review of the recent published works about the application of different optimization techniques to solve the optimal location and size of DG problem in power systems. It summarizes the several conventional and heuristic optimization techniques used to address the problem, and classifies them taking into consideration their main advantages and limitations. The review provides also a survey of most recent works as essential guidelines for the future research and enhancement on optimal DG placement and sizing. It shows the variety of the existing optimization techniques especially with heuristic and metaheuristic methods. It shed light on various existing optimization methods applied to the planning and integration of DGs from RES. Solving this problem consists on determining the objective function to model the problem and set system constraints I order to reduce the space of potential solutions (for example the buses where to locate DGs at the distribution level. Despite the efficiency of exact methods to solve this problem, the limited hardware capabilities especially with large size problems make exact deterministic methods not a viable option. Heuristic methods offer more flexibility to solve the problem, especially with multi-objective optimization. However, most of the heuristic methods despite being in general simple to implement present some common disadvantages such as being trapped in a local minimum. It has been noticed that GA and PSO are among the most promising optimization techniques to solve the DGs planning optimization problem. However, analytical approaches are still being used in recent research giving their advantage of explaining the physics and mechanisms behind the mathematical models. It is also suitable when it comes to validation of numerical methods.

Since most of the reviewed papers addressing optimal placement and sizing of DGs have utilized static existing distribution network, dynamic models are needed to address long-term future planning of DGs. In addition, future planning of DGs from RES will show the presence of uncertainties in several parameters, such as the generation of wind and solar, fluctuant oil prices, load forecast, electric vehicles …etc. Accordingly, these uncertainties should be taken into consideration in the optimal placement and sizing of DGs from RES.

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Highlights

- Thorough review of the recent works about optimization techniques applied to solve the problem of placement and sizing of DGs from RES.
- Drivers that have led to the growing interest on DGs integration and the challenges to overcome are analyzed.
- A summary of common heuristic optimization algorithms with their Pro-Cons are discussed.
- New possible hybrid optimization methods that haven't been yet considered were identified which might lead to better solutions and improvements.
- This survey is an essential guideline for the future research and enhancement on optimal DG placement and sizing.