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# Optimization in the planning of electrical distribution networks with the incorporation of distributed generation

Optimización en la planificación de redes eléctricas de distribución con la incorporación de generación distribuida

Otimização no planejamento de redes de distribuição elétrica com a incorporação da geração distribuída

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**ABSTRACT**

This article presents the search, organization and analysis of the documentation, articles from magazines and conferences related to the optimization techniques applied in the planning of electrical distribution networks. The objective of this research is to review the state of the art of the significant aspects of the insertion of DG in the distribution system, the objectives and restrictions and how these affect the state of electrical networks. The information was acquired from available and recognized sources in the field of electrical engineering. The analysis of the publications was made chronologically from the beginnings to the current trends in the planning of electrical distribution networks; In addition, technical aspects were considered to classify the content, which allowed the information to be better extracted. The most relevant result was obtained that the most used techniques for solving the ODGP problem are the genetic algorithm and various heuristic algorithms.

**Keywords:** distributed energy resources, optimization techniques, electrical distribution systems.

**RESUMO**

Este artigo apresenta a busca, organização e análise da documentação, artigos de revistas e congressos relacionados às técnicas de otimização aplicadas no planejamento de redes elétricas de distribuição. O objetivo desta pesquisa é revisar o estado da arte dos aspectos significativos da inserção da GD no sistema de distribuição, os objetivos e restrições e como estes afetam o estado das redes elétricas. As informações foram adquiridas de fontes disponíveis e reconhecidas na área de engenharia elétrica. A análise das publicações foi feita cronologicamente desde os primórdios até as tendências atuais no planejamento de redes elétricas de distribuição; Além disso, aspectos técnicos foram considerados para classificar o conteúdo, o que permitiu uma melhor extração das informações. O resultado mais relevante obtido foi que as técnicas mais utilizadas para a resolução do problema ODGP são o algoritmo genético e diversos algoritmos heurísticos.

**Palabras clave:** recursos energéticos distribuídos, técnicas de otimização, sistemas de distribuição elétrica.

**RESUMEN**

En este artículo se presenta la búsqueda, organización y análisis de la documentación artículos de revistas y conferencias relacionados con las técnicas de optimización aplicadas en la planificación de redes eléctricas de distribución. El objetivo de esta investigación es revisar el estado del arte de los aspectos significativos de la inserción de GD en el sistema de distribución, los objetivos y las restricciones y como estas afectan al estado de las redes eléctricas. La información fue adquirida de fuentes disponibles y reconocidas en el campo de la ingeniería eléctrica. El análisis de las publicaciones fue hecho en forma cronológica desde los inicios hasta las tendencias actuales de la planificación de redes eléctricas de distribución; además, se consideraron aspectos técnicos para clasificar el contenido, lo que permitió extraer de mejor manera la información. Se obtuvo como resultado más relevante que, las técnicas más utilizadas para la solución del problema ODGP son el algoritmo genético y varios algoritmos heurísticos.

**Palavras-chave:** recursos energéticos distribuidos, técnicas de optimización, sistemas eléctricos de distribución.

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**Originality/value:**
It guides professionals how and what are the essential topics to understand the insertion of distributed generation in electrical networks.

## INTRODUCTION

The planning of electrical distribution networks is a complex task and in general, it can be stated as an optimization problem, so that for a given region with a set of loads, the characteristics of the network are determined, including the location of the transformation centers required for power supply, minimizing the total costs of both installation and operation, subject to the technical requirements for proper system operation, such as voltage profile and capacities of the system elements, all within a time horizon. (Khodr et al., 2009).

The constant population growth and the trend towards a greater use of electricity in industrial and productive processes have made it necessary to take advantage of different energy sources in order to satisfy the energy demand. In this sense, the electricity generation sector has had to transform with respect to the needs and technologies of the present time.

Renewable energy sources are directly related to distributed generation (DG) which is defined as systems to produce small or medium scale electrical energy, connected to a power electrical system (SEP) through a common point of connection, located close to consumers and operating in conjunction with energy storage systems takes the name of distributed energy resources (DER) (IEEE, 2018).

The non-linear nature of the system makes it necessary to consider a large number of scenarios, hence, the value of the analysis of electric distribution systems in the face of the incorporation of distributed generation becomes relevant, which consists of studying a given system within the planning stage, considering all the variables that allow an adequate operation, obtaining results that will contribute to outline strategies with the objective of maintaining a resilient system that delivers energy in a continuous, reliable and safe manner and at the lowest possible cost.

Investments in EDS constitute a significant part of the expenses of electric service distribution companies, and for this reason it is necessary to have efficient planning tools to reduce costs. Given this, in recent years, several mathematical models and algorithms have been developed for the design of distribution networks taking into account DG (Miguez et al., 2002).

In this context, it is necessary to review the state of the art of optimization applied to the planning of distribution networks in order to know and analyze the evolution in search of achieving the resilient operation of a SED at the lowest possible cost.

## METHODS

Articles from both academic journals and conferences related to applied optimization in the planning of distribution power grids, powered by conventional or renewable generation, were reviewed chronologically. These have been developed in the period from the years 2012 to 2020. The process is described below:

### Sources of information

The search for scientific articles was carried out in the main bibliographic databases related to electrical engineering available on the web, namely: ieeexplore.ieee.org/ and sciencedirect.com/.

The following keywords were used for the search: planning electrical networks, optimal distribution system planning, distributed generation, optimal location and sizing of DG and review of distribution network planning.

### Organization of information

The documents were systematically ordered by means of a bibliographic reference manager software that allows easy organization of the information by type of article, title, author, journal, year of publication and others; in addition, it easily generates the bibliography for the final report.

### Inclusion criteria

From the bibliographic references resulting from the keyword search, we selected for the analysis those that contain traditional planning topics or by means of current optimization techniques, also those that consider DER input, load curve modeling, storage systems and the use of software to deal with the electrical planning problem.

### Aspects studied

For the analysis of the selected articles, we have focused on the following aspects: problem statement, methodology developed, optimization technique applied, objective function and constraints specific to the nature of the DER and SED.

### A. General approach to the problem

Optimal distributed generation placement (ODGP) is a mixed integer nonlinear optimization problem. Generally, it is to obtain the best size and location of DG to be introduced into an existing distribution network. To obtain the results, several system constraints are considered, such as power grid operational constraints, DG operational constraints, and investment and operating cost constraints.

### B. Objective function

The objective function of the ODGP can be single or multi-objective. The main mono-objective functions used are: minimization of power and energy losses; improvement of voltage profile; minimization of load supply cost; improvement of reliability; minimization of DG installation cost; mitigation of voltage dips; reduction of total harmonic distortion (THD); improvement of power factor; and minimization of cost caused by power generation and emissions (Niazi and Lalwani, 2017)..

Multi-objective formulations can be classified into:1) weighted multi-objective function, where the multi-objective formulation is transformed into a single objective function using the weighted sum of the individual objectives; 2) metamulti-objective index, here the multi-objective formulation is transformed into a single objective function using the goal programming method; and 3) multi-objective formulation considering more than one often contrasted objective and selecting the best compromise solution from a set of feasible solutions.

### C. Restrictions

To limit the search space to feasible solutions it is necessary to apply constraints. These can be system constraints such as: voltage drop limit, equal power flow, overload on lines or equipment; imposed by the planner according to his needs, such as: discrete size and number of DG units and economic constraints.

## BIBLIOGRAPHIC REVIEW

(Arritt et al., 2012) describe load estimation methods for SED analysis and compare the results of load allocations using Advanced Measurement Infrastructure (AMI) data with traditional load allocation methods. AMI provides the ability to record and store load data individually over a long period of time, which is essential to produce more accurate real load curves, models and simulations, and to understand the behavior of a circuit. For the analysis, they use a real 13.2 kV distribution network in which AMI-based load allocation, substation allocation, monthly billing and load shape allocation are performed.

They conclude, based on the case analyzed, that some traditional methods do not accurately predict overloads in SED equipment and networks. In addition, these methods are not very reliable for estimating voltages, losses and operation of certain system components such as capacitor banks. They emphasize that as AMI data becomes available, better modeling of loads will be possible, which will allow more accurate results to be obtained.

In the article by (Georgilakis and Hatziargyriou, 2013) a state of the art review of models and methods for optimal DG location planning in existing distribution networks is made. As for the mathematical formulation, the problem is stated, here both locations and sizes are conditioned by SED operational, DG operation and investment constraints.

Regarding the objective function, they describe its classification as single objective and multi-objective, the latter can be modeled as multi-objective with weights, where the multi-objective formulation is transformed into a single objective function using the weighted sum of individual objectives, considering constraints such as: equal power flow, voltage drop limits and line or transformer overload. Analytical, numerical and heuristic methods of resolution are mentioned.

At (de Souza et al., 2014) study the impact of DG on the operational planning and design of medium voltage SEDs. They indicate that the SED planning problem is characterized as a combinatorial optimization problem, where there are several physical and budgetary constraints. Within the methodology they propose, firstly, they define the objective function where they consider minimizing voltage drop, losses and operating costs (cable replacement, phase load balancing, capacitor location and sizing and DG).

The constraints used were voltage and capacity limits on lines and equipment. The Genetic Algorithm model was coded in C# and the power flow (back/forward sweep method) in C++, it was evaluated on a feeder having 302 nodes and providing power to 3400 residential and 991 commercial consumers.

In the article by (Arritt and Dugan, 2014) highlights the importance of sequential time simulation for SED planning with the incorporation of DER. They indicate that simulations should perform power flow solutions considering as input variables the load curves, generation profiles and voltage control elements such as LTC, regulators and capacitors.

In addition, it should be taken into account that solar production varies seasonally, therefore, with software that considers these aspects, information on daily, monthly and annual response can be obtained as needed. This consideration contributes to the reduction of inaccuracies associated with the approximate methods used for power and energy loss calculations. The simulations helped to determine the necessary storage capacity and its distribution along a feeder adapting to operational constraints.

The work of (Arritt et al., 2015) makes an analysis on the determination of the loss factor using load allocation methods that consider either the measurement at the substation made by the SCADA or according to the type of customer (residential, commercial and industrial). Within the analysis they find that, individual load variation can produce a significant impact on the predicted loss results. In addition, losses can be underestimated if annual simulations are performed using substation allocation to predict power losses by running a maximum demand power flow.

They conclude that annual simulations allow consideration of the effects of capacitor switching and voltage regulation schemes. However, the load allocation method used in most SED analysis software does not consider the temporal composition of the load, leading to inaccurate results.

They also mention that the closer the load allocation is to actual measurements at the customer, the more reliable these estimates become and that as AMI becomes available each load can be represented by its actual annual load shape. They also highlight the importance of annual sequential time simulations in understanding the impact of DG on feeder losses.

At (Prakash and Khatod, 2016) a review and comparison of optimization techniques used to determine the sizing and location of DG in SEDs with the objective of maximizing their benefits is made. The articles reviewed and that considered the location and sizing of DG units in the distribution network proved that it reduced system losses (between 10 and 20%), improved system voltage profile, load capacity, reliability, stability, power quality and power factor of the system, etc.; demonstrating that, they are essential technical factors both the location and sizing of DG units in SEDs to maximize their benefits, both for distribution companies and consumers.

The general procedure is detailed for: determining the optimal size and location of the DG units in the distribution network, elaborating the objective function considering the fulfillment of all constraints and indices. For the power flow, the backward and forward sweep method is used, the location and size is solved by means of a generalized algorithm. Emphasis is made on the Genetic Algorithm technique that requires minimum computational capacity in terms of memory and speed and is able to obtain efficient, accurate and optimal solutions in an intelligent way.

In the work of (Lalitha and Adivesh, 2016) a method based on the symbiotic organism search (SOS) algorithm is presented to find optimal DG location and size focused on minimizing the active power losses associated with the active component of the currents. The constraints considered were reverse power flow and bus voltage limit. The programming of both the power flow and the algorithm is performed in MATLAB and the study is performed on two IEEE test systems, one with 33 busbars and the other with 69 busbars, both at a voltage level of 12.66 kV. As a result of the optimal placement and sizing of DG on the 33 and 69 bus networks, a reduction of total power losses of 67.42% and 69.33% respectively is achieved.

The study by (Hongxia Zhan et al., 2016) presents a method for optimal DG placement and sizing based on Genetic Algorithm, the objective function seeks to maximize the DG penetration level in SED without changing the original protection relay schemes. The constraints used were short-circuit current limit, total DG capacity and individual capacity of each DG unit.

It is tested on a 14-node distribution network and a 33-bar IEEE system. For the population, 10000 location/size combinations were randomly generated, from these the best 300 in terms of fitness are selected which are used as initial population for the following steps of the GA (selection, crossover and mutation), the algorithm ends when verifying that the solution satisfies the constraint and if it has met the stopping criterion corresponding to the limit of 100 generations.

In the article by (Mahmoud et al., 2016) an efficient analytical method (EA) is proposed to determine the optimal DG locations and capacity (multiple technologies), maximize DG penetration and minimize SED losses, furthermore, it is integrated with the optimal power flow (OPF) algorithm to develop a new EA-OPF method. The optimal DG locations are obtained using the EA method, then the OPF calculates the optimal DG sizes for the defined locations. The OPF algorithm considers the SED constraints, such as voltage, penetration and DG size limits, as well as the maximum line flows.

DG penetration is defined as the ratio of the total size of DG units to the total load. The algorithm is developed in C++ and tested on two radial distribution systems of 33 and 69 busbars. Their results indicate that DG power factors are of great importance in loss reduction, especially when multiple DG units are assigned.

(Shreya Mahajan and Shelly Vadhera, 2016) use the particle swarm optimization (PSO) technique for optimal DG location and sizing, the objective function considers factors by weight in order to minimize losses and improve the voltage profile. While the constraint present in the problem was the voltage limit on the busbars.

The proposed method is analyzed in IEEE test systems of 14, 30 and 57 busbars. First, the Newton Raphson model is designed for power flow calculation, then the optimal size and location of the DG unit are determined by the algorithm, both of which were developed in MATLAB. For the simulations, 100 particles and 20 maximum iterations were considered.

At (Tyagi and Verma, 2016) a comparison between two metaheuristic algorithms, Improved Harmony Search (IHS) and Bacterial Feed Forward Differential Evolution (BF-DE) is performed to determine the optimal DG location furthermore the effects of penetration level on SED is studied. The objective function seeks to minimize the power losses of the system. The constraints used were voltage limit and maximum capacity of DG incorporation.

The studies are performed on a standard radial SED of 10, 15, 33 and 69 bars. Based on the results, the importance of optimal DG localization and penetration is highlighted, it is also indicated that the IHS algorithm presents a better convergence characteristic compared to the BF-DE algorithm, same that can be suitable for DG localization problems in more complex and large-scale systems.

At (Roger C. Dugan et al., 2017) describes the modeling of storage systems to evaluate their impact on the capacity, reliability and power quality of SEDs. They propose these systems as the solution to various operational and reliability problems in distribution systems, mainly due to the variable and uncertain behavior of both solar and wind generation.

Regarding simulations. They emphasize the use of sequential time for a more accurate analysis, since this way the time dimension is added to the planning analysis, which is very useful when time-varying resources are available within an EDS. The modeling and simulation was performed in OpenDSS using Loadshape Following mode.

(Kazeem et al., 2017) proposes to use a hybrid algorithm to solve the optimal DG location and control problem in radial distribution networks. This algorithm is the combination of an artificial neural network (ANN) and a Genetic Algorithm (GA). The objective function seeks to minimize the active power losses, under power balance and voltage limit constraints.

The code for the proposed neurogenetic algorithm was developed in MATLAB, while the power flow solution was carried out using MATLAB's Power System Analysis Toolbox (PSAT). For the evaluation of the technique, the 60-bus distribution system at 33 kV SouthEast was used. The results validated the technique as there was a reduction in power losses and improvement in the voltage profile compared to the initial scenario data.

In the paper by (Cruz et al., 2017) a modified Genetic Algorithm is employed to solve DG reconfiguration and allocation problems in distribution systems. The objective function was to minimize the total operating cost of energy production in the system.

Regarding the constraints, we have considered maintaining the radiality of the network, avoiding the formation of islands, voltage limits, power generation limits (active and reactive) and flow limits. The analysis is performed using optimal power flow with the MatPower tool, while the optimization algorithm was developed within MATLAB. A 16-bus radial distribution test system was used.

(Chowdhury and Matlokotsi, 2017) shows a methodology to find the optimal DG (photovoltaic and doubly fed induction generators) locations and sizes in subtransmission and distribution networks. A comparative analysis of voltage profiles and active power losses before and after optimal DG location is performed.

The multi-objective function of the problem seeks to improve the voltage profile and minimize the total active power losses. The constraints considered were the DG incorporation capacity and the voltage limit at the busbars.

For the resolution of the power flow by the Newton Raphson method and the Genetic Algorithm, MATLAB has been used. While the networks used as test systems are the IEEE 9 and 33 bus systems. The IEEE 33 bus system is used to represent the SED. A comparative analysis of voltage profiles and active power losses before and after optimal DG placement is performed.

At (Gidd et al., 2018) a methodology to optimize the optimal DG location and sizing in distribution networks is presented. The technique used is the Genetic Algorithm and for the power flow the Newton Raphson method has been used, both have been developed in MATLAB.

The objective function seeks to minimize system power losses, voltage profile constraints and DG incorporation capacity. The IEEE 14-bus, 37-bus and 50-bus systems were used for the tests. They conclude that, adding DG to the distribution system contributes to reduce the active and reactive power loss and improves the system voltage.

(Suresh and Edward, 2020) propose a hybrid algorithm that combines Grasshopper Optimization Algorithm (GOA) and Cuckoo Search (CS) techniques to determine the optimal DG location and size in distribution power systems.

The power flow is developed in Simulink while the optimization algorithm is executed in MATLAB. The methodology is evaluated on IEEE 33 and 69 bar test systems.

The objective function was modeled to reduce power losses, voltage deviation index and generation costs. The constraints used were power flow equation, voltage limit, thermal limit of conductors and equipment, and DG input capacity.

In the study of (Saini and Gidwani, 2020) a methodology using a Genetic Algorithm is proposed for the allocation of PV generation and storage systems in radial distribution systems.

The objective function seeks to minimize the annual energy losses. The constraints are: power flow balance, inverse power flow, bus voltage limit, nominal power limit, load/discharge state, and BESS storage capacity limit.

The power flow and optimization algorithm was developed in MATLAB. The methodology was evaluated in IEEE 69 bars test system. As a particularity and for a better estimation of losses, three types of time-varying load models (commercial, residential and industrial) were considered.

In the article by (Moloi et al., 2021) the incorporation of photovoltaic and wind generation is evaluated. The technique presented uses Newton Raphson for power flow analysis and Genetic Algorithm (GA) to solve the optimization problem. Photovoltaic generation is modeled as an asynchronous generator and wind as a synchronous generator.

The objective function sought to minimize the active power losses of the system. As for the constraints, voltage limit and DG penetration level were considered. The GA technique was implemented in MATLAB to determine the optimal size, location and technology for power system integration.The results show that the voltage profile is improved and power losses are minimized by optimally integrating PV and wind units.

The study by (Dhivya and Arul, 2021) proposes the location and sizing of DG (photovoltaic and wind), using the optimization technique Improved Flower Pollination Algorithm (IFPA).

The objective function seeks to minimize the power losses of the electrical system. As for the restrictions, the power balance equation, voltage limit, DG penetration and equipment thermal limit are used.

The proposed methodology is evaluated on the Indian 52-bus radial distribution test system. Which consists of 3 main feeders, 51 branches and 52 busbars. It feeds a total load of 4184 kW and 2025 kVAr.

In the work of (Hemeida et al., 2021) the coupling of photovoltaic, wind and fuel cell generation in distribution networks is analyzed. The technique used includes the Genetic Algorithm and Satin Bowerbird Optimization forming a hybrid algorithm. It was evaluated in 2 IEEE systems of 33 and 69 bars.

The problem is approached with a multi-objective function, which seeks to minimize energy losses, voltage deviation index, total emissions and investment cost. The constraints considered were power balance, voltage limit and thermal limit of the network equipment.

## RESEARCH RESULTS AND DISCUSSION

### Problem statement

The incorporation of distributed generation in distribution power grids has been approached by the authors as an optimization problem. The following have been considered as input variables: 1) location; 2) size; 3) location and size; 4) type, location and size; 5) number of DG units, location and size; and 6) number of DG units, type, location and size. DG type refers to the DG technology, e.g., wind, solar, biomass, fuel cell, and diesel.

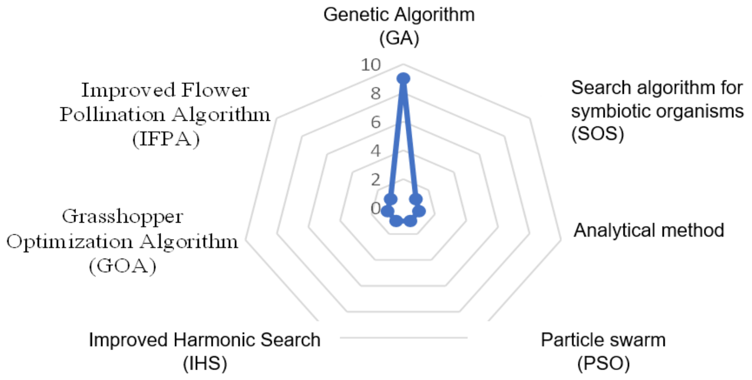
### Optimization technique

Several optimization techniques are applied in the reviewed works. Heuristic methods were the most used because they are robust and provide near-optimal solutions for large and complex DG optimal location problems. In general, they require a high computational effort but given the current technological characteristics of computers this limitation is not necessarily critical in DG location and sizing applications.

Analytical methods have also been used because of their ease of implementation and speed of execution. However, their results are based on estimates of a snapshot of the power system load.

Figure 1 shows the trend of the researchers in the reviewed papers, where the majority of them used the Genetic Algorithm to solve the OGDP problem.

**Figure 1** Types of optimization techniques



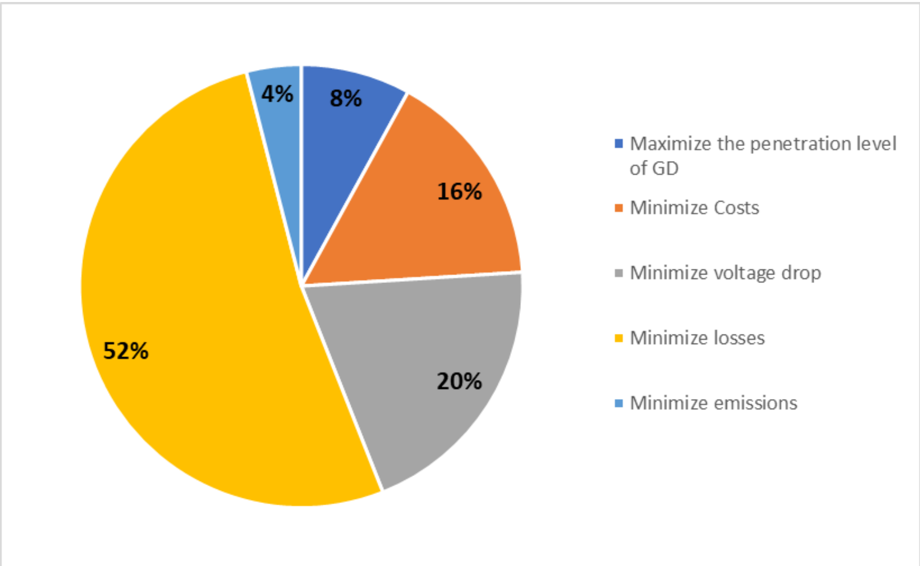

Note: Prepared by authors with research data

### Target function

Among the objective functions used by the authors were mono-objective, multi-objective and weight factor. First, they decided whether the objective function should be minimized or maximized, and then formulated the objective function considering the parameters associated with it.

The most commonly implemented objective function was to minimize losses, followed by minimizing voltage drop and finally minimizing costs as detailed in Figure 2. One factor in deciding these objectives is that the analyses have been done with a view to correcting short-term problems in existing distribution networks and thus deferring investments.

**Figure 2** Target functions

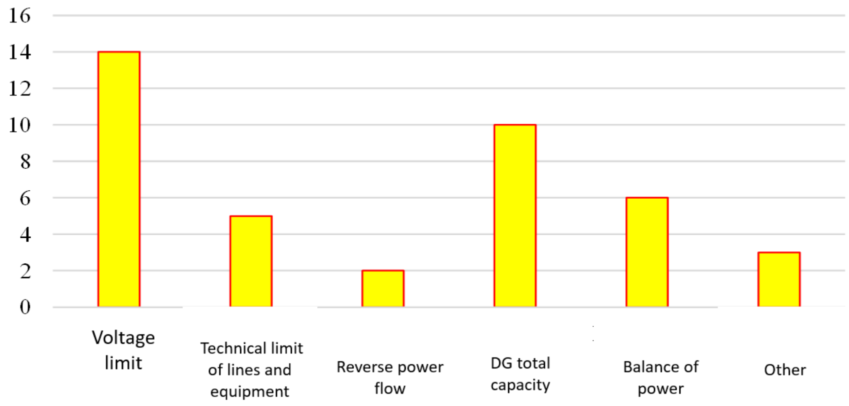



Note: Prepared by authors with research data

### Restrictions

Constraints are very important parameters. The selected objective function must satisfy all the given constraints otherwise, the obtained location and sizing could not fulfill the purpose and may lead to a malfunction of the system. Figure 4 shows the most commonly used constraints in the reviewed articles.

**Figure 3** Main restrictions




Note: Prepared by authors with research data

As main constraints we have the voltage limit at the busbars followed by the total DG incorporation capacity. As with the objective function, the selection of these constraints generally occurs because the optimization problem is focused on solving problems of existing distribution networks, where it is required to use existing lines and equipment, thus postponing investments

## FINAL CONSIDERATIONS

This paper reviews the state of the art of the significant aspects of DG insertion into the distribution system, the objectives and constraints and how these affect the state of the power grids .

The most common mathematical models for ODGP have the following characteristics: 1) installation of multiple DGs; 2) the design variables are location and size; and 3) the objective is to minimize the total power loss of the system.

The ODGP solution methodologies used were analytical, numerical and heuristic methods. The most used techniques for the solution of the ODGP problem are the genetic algorithm and several heuristic algorithms.

Metaheuristic optimization techniques are currently being applied for the location, sizing and installation of DG in the distribution network, with the aim of improving the reliability of the power system.

The objective function can be composed of a single objective or multiple objectives. A single-valued objective function can also be formed by combining multiple objectives to achieve this, the most appropriate technique is weight factors. The literature reveals that the incorporation of DG advances in the distribution system due to its technical and economic characteristics, but it is necessary to be demanding and precise in the technical criteria, such as suitable capacity and location for DG installation, limit of DG units, operating power factor, technology, in order to avoid undesired effects on the SEDs.

In terms of the research reviewed, it is recommended that planning consider the uncertainties associated with generation from non-dispatchable DG units, such as wind and solar, for long-term expansion planning. Planning should also provide dynamic models of consumers and electric vehicles for demand forecasting, thus providing time-dependent results.

Analyze DG integration in conjunction with energy storage systems to determine the effects on reliability and power quality of distribution networks.

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**Contribution of each author to the manuscript:**

| Task | % of contribution of each author | |
|---|---|---|
| | A1 | A2 |
| A. theoretical and conceptual foundations and problematization: | 50% | 50% |
| B. data research and statistical analysis: | 50% | 50% |
| C. elaboration of figures and tables: | 50% | 50% |
| D. drafting, reviewing and writing of the text: | 50% | 50% |
| E. selection of bibliographical references | 50% | 50% |
| F. Other (please indicate) | - | - |

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