A Multi-Objective Evaluation of the Impact of the Penetration of Distributed Generation

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Abstract — **This paper proposes a methodology to consider the effects of the integration of DG on planning. Since DG has potential to defer investments in networks, the impact of DG on grid capacity is evaluated. A multi-objective optimization tool based on the meta-heuristic MEPSO is used, supporting an alternative approach to exploiting the Pareto front features. Tests were performed in distinct conditions with two well-known distribution networks: IEEE-34 and IEEE-123. The results combined minimization and maximization in order to produce different Pareto fronts and determine the extent of the impact caused by DG. The analysis provides useful information, such as the identification of futures that should be considered in planning. A future means a set of realizations of all uncertainties. MEPSO also presented a satisfactory performance in obtaining the Pareto fronts.**

Index Terms **— Multi-objective optimization, Distributed Generation, Distribution planning, Multi-objective evolutionary particle swarm optimization.**

I. Introduction

The traditional planning of distribution networks is a difficult task that deals with a high number of variables, multiple constraints and objectives, huge investments and uncertainties. These challenges are intensified with the profound change in the traditional paradigm of the distribution network which is driven mainly by the increasing amount of Distributed Generation (DG) at the MV/LV distribution level, and also by new technologies, market structures and environmental concerns [1]. Hence, it is necessary to develop computational tools and methodologies that are able to efficiently deal with new features that emerge on the planning of distribution grids.

Multi-objective optimization (MO) methods based on meta-heuristics are being extensively investigated in terms of issues relating to evaluating the impact of DG or Distributed Energy Resources (DER) [2]. MO makes it possible to consider the objectives and its conflicts for a more realistic decision-making. It also supports studies on the relationship between objectives if the conflict behaviour is unknown or not well defined. The use of meta-heuristics makes the optimization of complex models possible and has been closely investigated, resulting in a number of efficient approaches.

Therefore, the main idea in this work is to evaluate the impact of the integration of DG on an existing network using an efficient MO meta-heuristic. The aim is to accommodate the main concerns regarding the impact of DG within a MO model of the problem, providing useful information for decision-makers during the planning stage.

Section II presents a review of the objectives, constraints and other relevant issues to evaluate the impact of DG. The conflict behaviour among the attributes and how they may be added to a MO model is emphasized. Section III focuses on an overview of MO concepts and presents the method used, MEPSO, which is a multi-objective approach for the Evolutionary Particle Swarm Optimization (EPSO) technique [3]. Section IV describes the problem modelling to evaluate and test the impact of the integration of DG. Section V presents and discusses the results and the conclusions are drawn in Section VI.

II. Evaluation of the Impact of DG

As previously mentioned, there are a number of technical, environmental, regulatory and commercial challenges for the integration of DG. This study focuses on the technical impact. A set of interdependent issues that will be considered in MO is presented as follows.

- **DG position:** the impact of DG is highly influenced by the connection node. Depending on where the generators are installed in the grid, the benefits and negative impact may also vary. The DG position is generally considered in the literature as the decision variable in the optimal allocation problem approach, in which the connection nodes that maximize benefits are defined. However, there are studies that evaluate the impact considering a predefined DG unit location, where the position is not the decision variable.
- **DG size/generation:** the impact of DG generation is defined by the operation regime and the amount of generation. The negative impact, for instance, of DG on voltage (voltage rise) in times of low demand for the network is explored in the literature. Furthermore, DG may provide an important contribution when it is able to deliver power in times of peak demand. The DG generation or size, as placement, is generally considered as a decision variable in optimal siting and

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sizing approaches, but it can also be predefined.

- **Impact on voltage:** the effects of DG penetration on voltage regulation are a basic concern. Voltage limits of operation are commonly considered as a constraint in modeling. Nevertheless, depending on the MO analysis performed, an objective may be added in order to explicitly observe the voltage behaviour.
- **Impact on capacity:** in general, this is indicated by the current limits on lines and by the power limit of the Substation (S/S) transformer. Gains in network capacity and the possibility of investment deferral provided by DG are related to be a decisive incentive for the integration of DG [4], [5]. As with voltage limits, they may be modelled as a constraint but also as an objective.
- **Loss levels:** loss level is largely used as objective function since it reflect efficiency and indirectly indicate the impact on capacity and voltage. There is also regulation over losses, defining penalization and rewards, these may also be included in the calculation of a fitness function [5].
- **Short-circuit level:** the integration of DG generally has a negative impact on operation of protection. This is because of the contribution of DG for short-circuit currents and reverse power flow, resulting in changes in protection equipment and strategies. In order to define the impact on fault schemes, it is important to take into account the amount of increased fault current and the percentage of change in short-circuit current from the original [6].
- **DG ownership:** regulation may define whether the utility is allowed to own and conveniently install DG units in a network. In Europe, for instance, distribution network operators are generally not permitted to own generator units. This is mainly due to the unbundling rules for electricity markets [4].

III. Multi-objective optimization and the MEPSO method

MO is different to single-objective optimization as there is a vector of objective functions (two or more) which must be optimized simultaneously and subject to a set of equality and inequality constraints. Consequently, there is no longer one single optimal solution but a set of optimal solutions called the Pareto optimal set or non-dominated solutions set. In order to choose a final solution, a human agent, called a decision-maker, is then needed to articulate the preferences with the search for the Pareto optimal set. The Pareto Front (PF) is the Pareto optimal set mapped in the objective function space. More details about basic concepts, methods and decision-making can be found in [7] and [8].

The ability of MO to permit a more complex and realistic analysis is being explored in depth in studies on the impact of DG, generally using Evolutionary Algorithms [2].

This work proposes the use of MEPSO [9], a method that exploits the performance gains obtained by EPSO in single-objective optimization [3] with the efficient procedures developed for MO proposed by NSGA-II [10]. In terms of the EPSO basic algorithm [11], the MEPSO method preserves the replication scheme, with the replicated particles having their strategic parameters mutated, and the reproduction based on the PSO movement equation. Nevertheless, the global and personal best assignment steps and the evaluation and selection steps were completely adapted for MO. MEPSO inherited the *Fast Non-dominated Sorting* procedure from NSGA-II, to rank and sort the swarm using dominance; the crowding distance metric, used to maintain diversity; and the elitist selection scheme. The global best assignment is also remodelled in order to guarantee convergence and diversity, taking advantage of the swarm dominance ranking.

The general algorithm for the MEPSO method is presented as follows [9]:

- Parameter initialization;
- <u>Do</u> iter = 0;
- <u>Do while</u> iter < IterMax:
    - Rank and sort the swarm using the *Fast Non-dominated Sorting* procedure from NSGA-II;
    - Update the Pareto List (PL), an external list that holds the optimal solution set;
    - Assign the Global Best (Gb) to each particle of the swarm;
    - <u>For</u> each particle of the swarm:
        - Replicate the particle;
        - Execute on the replicated particle:
            - Mutation of the strategic parameters;
        - Execute on both original and replicated particles:
            - Reproduction, based on the PSO movement equation;
            - Assign the Personal best (Pb);
        - Add the replicated particle to the Replica List (RL) that holds the whole set of replicated particles;
    - End <u>for</u>;
    - Combine the original swarm with the RL;
    - Perform Selection over the combined list of particles;
    - <u>Do</u> iter = iter + 1;
- End <u>do while;</u>
- <u>Print</u> PL.

During the PL update step the solutions in PL are compared with the non-dominated solutions obtained in the current iteration. Dominated and repeated solutions are not included in the PL. A fixed size of 100 solutions to PL is defined.

The proposed structure for the Gb assignment attempts to combine convergence with diversity. As the swarm is divided in different fronts based on the dominance rank, a particle belonging to the front f receives a solution as Gb randomly chosen from the front $(f-1)$. The Gb for front 1 solutions are randomly taken from a reduced set of the PL, called the Gb List.

The Pb of a particle is the last non-dominated position along its trajectory.

During the selection stage an elitist strategy [10] is applied to the combined set of the original swarm and the RL.

IV. Problem formulation and description of tests

This section proposes a methodology, based on MO, to consider the impact of the integration of DG in MV distribution networks at the planning stage. A problem formulation is proposed that defines criteria, attributes and decision variables based on the issues indicated in Section II. It is important to stress the difference between criteria and attributes [12], [13]: a criterion sets the limits within which a measure or variable is considered adequate; whereas the attributes are a measure of how good a plan or scenario is. While the criteria are fully satisfied if they are within their limits, the attribute may be optimized and the aim is for it to be maximized or minimized. [13].

The level of integration of DG was defined as an attribute through the index PEN given in (1). It reflects the percentage of the total real power generated related to the sum of load and losses of the original network at the rated power.

$$PEN = \left(\frac{\sum_{i=1}^{N_{grid}^{DG}} P_{Gi}}{P_D^0 + P_L^0} \right) \cdot 100 \qquad (1)$$

where N_{grid}^{DG} is the total number of DG units connected in the network; P_{Gi} is the three-phase real power of the DG unit i; P_D^0 is the three-phase total real power demand in the base case; P_L^0 is the three-phase real losses in the base case.

The second attribute proposed is based on the network capacity. The high costs involved are recognized for the rebuilding of the T&D systems to obtain a higher capacity and this currently represents one of the most noticeable opportunities for the integration of DG: the possibility of deferral investment in grid reinforcements [4], [13]. The investment deferment occurs when DG provide improvements in capacity, especially with generation support at times of peak load. However, generation may also cause an increase in congestion. Therefore, the impact of DG on deferring investment is analyzed through the attribute IC, given in (2) [14], which indicates the impact on the grid capacity, which is only represented here by the current limit of the wires. The positive values represent the current capacity available and the negative IC gives the percentage of current exceeded, both in the most loaded branch.

$$IC = \left[1 - \max_{k=1,\ldots,NB} \left(\frac{I\varphi_k}{I\varphi_k^{\max}} \right) \right] \cdot 100 \qquad (2)$$

where $I\varphi_k$ represents the current magnitude in phase φ for branch k; $I\varphi_k^{max}$ is the maximum current magnitude in phase φ for branch k; NB is the total number of branches.

The DG position and real power generated are considered decision variables. The codification is similar to the MOTS method in [15] with a DG unit being described by two positions in the decision variables vector: the discrete connection node and the continuous real power delivered.

It is assumed that the generators have a unitary power factor and a fixed set of DG units is defined.

Furthermore, although losses may also be seen as an attribute, IC indirectly provides information on losses since capacity improvements indicate a reduction in losses. Finally, voltage is considered a criterion. The problem formulation is presented in (3).

$$\begin{aligned} & FO_1 = PEN \\ & FO_2 = IC \\ & s.t. \begin{cases} P_i = \sum_{j \in NC_i} P_{ij}\left(V_i, V_j, \theta_i, \theta_j\right) & i = 1,\ldots NN \\ Q_i = \sum_{j \in NC_i} Q_{ij}\left(V_i, V_j, \theta_i, \theta_j\right) & \\ 0.95 \cdot V_N \le V_i^{DG} \le 1.05 \cdot V_N & \\ n_i^{DG} \le 1 & \\ N_{grid}^{DG} = N_{available}^{DG} & \\ P_{Gk}^{\min} \le P_{Gk} \le P_{Gk}^{\max} & k = 1,\ldots N_{grid}^{DG} \end{cases} \end{aligned} \qquad (3)$$

where NN is the number of nodes; P_i and Q_i are the net injection of real and reactive power respectively at node i; P_{ij} and Q_{ij} are the real and reactive power flow respectively at the $i-j$ branch; V_i and θ_i are respectively the voltage magnitude and angle at node i; NC_i is the set of nodes connected to node i; V_N is the nominal voltage; V_i^{DG} is the voltage magnitude at the node i for a given DG configuration; n_i^{DG} is the number of DG units connected in node i; $N_{available}^{DG}$ is the total number of DG units available; P_{Gk} is the real power generated by DG unit k; P_{Gk}^{min} is the minimum real power for DG unit k; and P_{Gk}^{max} is the maximum real power for DG unit k.

From the point of view of the MO methodology, using PEN and IC as attributes is permitted to explicitly investigate the conflict relationship between the integration of DG and network capacity. Depending on where the DG units are located, the elevation on real power injected in the grid initially improves capacity. Nevertheless, there is a limit for the level of integration of DG, beyond which more power injected by DG increases congestion and negatively affects IC. Therefore, the IC index is maximized since improvement in the capacity is aimed. The PEN index, however, is analyzed in both minimization and maximization in order to define the IC behaviour with minimum and maximum DG penetration.

The DG ownership issues define how the analysis of the Pareto front and the Pareto optimal set will support decision-making in planning. If utilities own generators, or want to evaluate this option, the results provide straightforward support since they provide the optimal site and generation level for DG units and permit a trade-off analysis that considers other attributes. However, if a distribution company deals with the impact of DG that is owned by other agents, which is the most common situation in many places, the proposed analysis is limited in terms of its importance for planning. In this case, significant information for planners is obtained by defining the full extent of the impact caused by DG in the planning horizon. This is not a trivial task. The Pareto front will then be defined considering minimizing IC with both the minimization and maximization of PEN. Obviously there is no technical interest in minimizing IC, however it will serve to show the worst impact on capacity caused by the integration of DG. As the PF is unique [12], four PFs will be determined to define the limits within which the attribute values will fall. The tests are also made without the voltage constraint since it can reveal more about the negative impact of the integration of DG.

V. Results

Two radial distribution networks are used: the rural and lightly loaded IEEE-34 and the urban and heavily loaded IEEE-123 [17]. Both networks were adapted to create a scenario where only DG is used to ensure the network adequacy. Nodes and equipments were removed and it was assumed that all the loads are connected in wye with the constant power model. A three-phase backward-forward sweep power flow routine was used [18].

The analysis of the results focuses on the situation when DG is not owned by the utility. How the methodology may be exploited in planning is presented and, its limitations are discussed along with possible improvements.

Table I shows the number of DG units used and the generation limits for each unit depending on the network. The original value of IC (IC_0) for each network is also presented.

Table I
Number of DG units, maximum and minimum generation allowed and IC value for both original networks

	DG units	Min. generation (kVA)	Max. generation (kVA)	IC_0
IEEE-34	2	0.0	1,000	72.2
IEEE-123	2	0.0	1,500	-26.7

Fig. 1 shows the PFs considering MinPEN-MaxIC, MaxPEN-MaxIC, MinPEN-MinIC and MaxPEN-MinIC for the distribution network IEEE-34. The four PFs obtained without the voltage constraint are plotted in yellow.

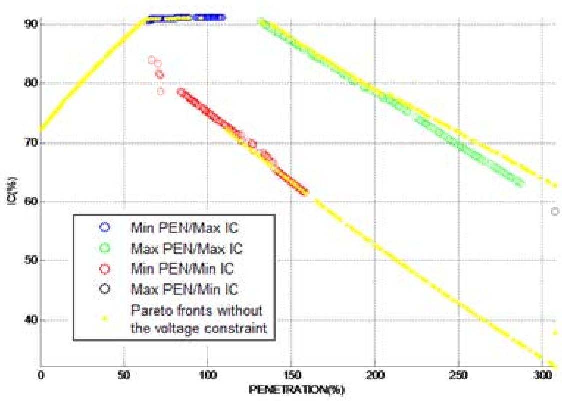

Fig. 1. Pareto fronts considering MinPEN-MaxIC, MaxPEN-MaxIC, MinPEN-MinIC and MaxPEN-MinIC, with and without voltage constraint for the IEEE-34 network.

In Fig. 1 it can be seen that the PFs determined with voltage constraint define the boundaries of a region containing all of the feasible solutions. It is then possible to know the limit of the positive and negative impact produced by DG in a given connection condition. With regard to the problem without the voltage constraints, the region illustrating the unfeasible solutions is defined. The approximated shape of the regions is depicted in Fig. 2. The areas filled with horizontal lines (A) and vertical lines (B) were obtained for the problem with and without the voltage constraints, respectively.

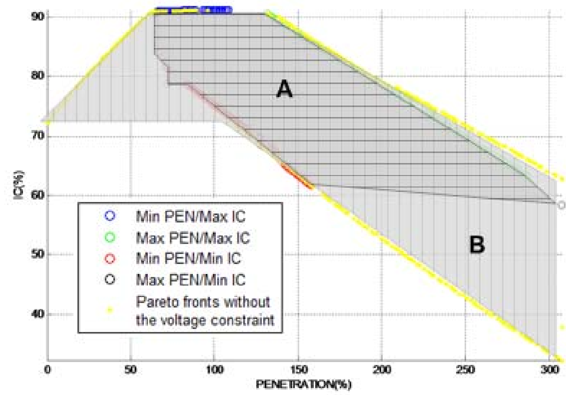

Fig. 2. Approximate regions defined by the Pareto fronts for the IEEE-34 network.

It is essential to stress that area A maintains all of the feasible solutions, however, as seen in Fig. 2, A is contained in B and unfeasible solutions may be encountered inside region A.

The lightly loaded IEEE-34 network does not present significant capacity problems: even with a penetration of 300% the IC is higher than 30% in the worst case. However, due to its long feeder and the fact that the load concentration is far from the S/S, a significant voltage drop along the feeder is observed. Therefore, in Fig. 1 and 2 it can be seen that the MinPEN-MaxIC Pareto front with voltage constraint starts at a penetration level close to 65%, this corresponds to the minimum DG support needed to guarantee voltage feasibility. From a level of 65% to almost 110% of penetration it is possible to obtain more than 90% in IC. This is obtained by combining the local generation at an optimal level with the reinforcements proposed for single-phase branches to accommodate DG. Additionally, the right side of region A demonstrates that it is possible to have high penetration levels for DG with an IC greater than 55%, in specific conditions and keep the voltage within the boundaries.

On the contrary to the IEEE-34, the IEEE-123 network is heavily loaded and presents, as seen in Table I, a current overload of almost 27% at the S/S branch, considering the rated load. First of all the Pareto fronts MinPEN-MaxIC and MaxPEN-MaxIC are shown in detail, considering the voltage constraint, for IEEE-123 in Fig. 3.

Over 35% of integration of DG is necessary to ensure voltage feasibility. This also results in an improvement in capacity, which may reach 10% considering a specific generation and location of DG units. Up to a penetration level of 100% the peak value of IC is verified at around 50%. The PF for the MinPEN-MaxIC problem generally corresponds to attempts to generate close to the most representative loads, indicated in Fig. 4.

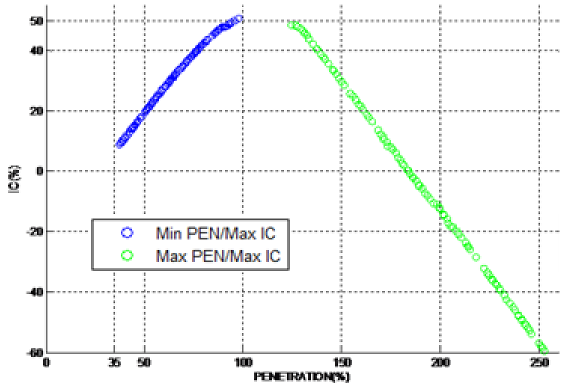

Fig. 3. Pareto fronts considering MinPEN-MaxIC and MaxPEN-MaxIC for the IEEE-123 network.

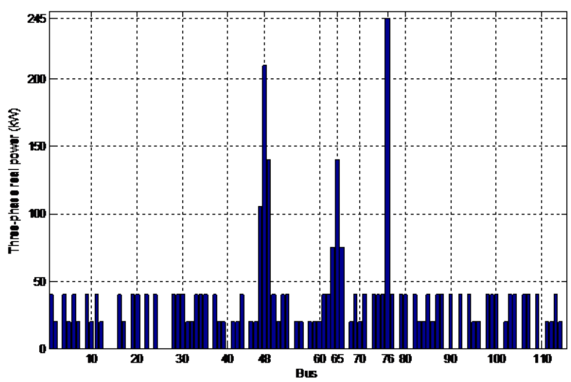

Fig. 4. Three-phase real power for each node of the IEEE-123 network.

Then, the generation close to nodes 48, 65 and 76, for instance, locally supplies the main loads and there is an improvement in the capacity with the level of penetration increasing. By analyzing the PF and considering MaxPEN-MaxIC, it can be seen that even in the most favourable DG configuration, the IEEE-123 network admits less integration of DG when compared to the IEEE-34 network. The IC index goes to zero when the penetration level achieves approximately 180%.

A similar analysis performed in Fig. 1 for IEEE-34 is presented in Fig. 5 for IEEE-123.

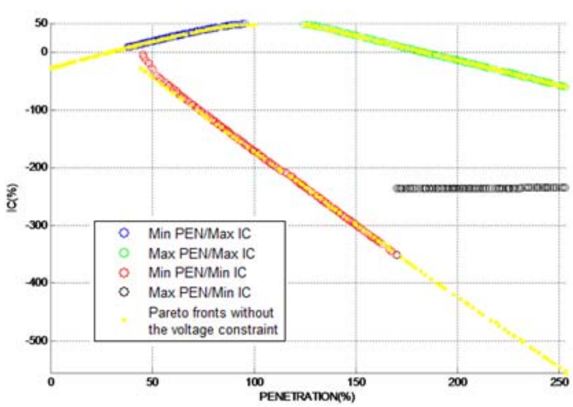

Fig. 5. Pareto fronts considering MinPEN-MaxIC, MaxPEN-MaxIC, MinPEN-MinIC and MaxPEN-MinIC, with and without voltage constraint for the IEEE-123 network.

Based on Fig. 5, considering the voltage constraint, the index IC is positive in any situation from a level of almost 35% to approximately 45% of DG penetration. However, for a penetration level over 45% there is an increasing risk of a negative impact on capacity: for instance, at a level of 100% penetration, DG may provide both the best benefit for capacity and a huge overload, more than 150%, depending on the connection node and the amount of generation. The result also makes it possible to deal with the negative impact represented by both red and black PFs in Fig. 5. All of these solutions correspond to connect generator units at the three phase underground section of the grid, from node 60 to 66, 465 m in length, with the lowest current capacity.

Fig. 6 shows an evaluation of the impact of the integration of DG, not allowing the connection of generators in the underground section of the network.

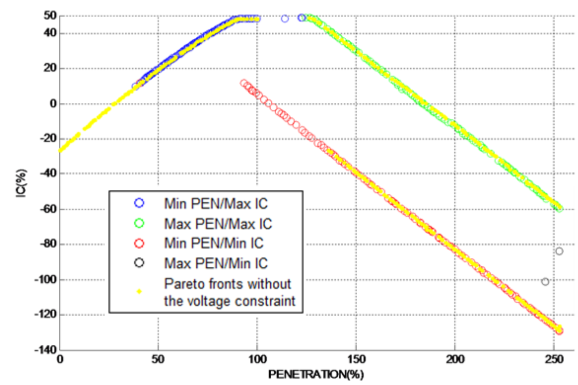

Fig. 6. Pareto fronts with and without voltage constraints for the IEEE-123 network, avoiding DG connection at the underground nodes.

Avoiding the DG access to the underground branches has a remarkable effect on minimizing the possible negative impact. All of the feasible solutions presented a positive IC until the penetration level reached approximately 105%. Therefore, permitting DG to be connected to the underground section of the network must be carefully evaluated: since there is a significant amount of load connected to the nodes 64, 65 and 66, as shown in Fig.4, it is possible to obtain high gains in capacity with generation supporting the local load. However, the generation is severely limited with the risk of overload.

In summary, the methodology provides relevant information for planning. Assuming the conditions exposed, the given peak load, amount and size of generators, as a future, it is not possible to have feasibility and a positive IC with less than approximately 35% of DG penetration, considering DG as the only alternative for voltage and capacity. Based on Fig. 6, from 35% to almost 105% integration of DG, the feasible solutions safely present a positive IC between 0 and 50%. Nevertheless, depending on the position and the level of generation, it is possible that situations with penetration between 35% and 105% present a negative IC. In these solutions it is perceived that at least one generator is connected to a node close to the S/S node. Then, if there is no DG connected at the underground nodes and at the buses between node 1 and node 14, with the penetration level between approximately 35% and 105% and two DG units for instance, there is a low probability of a current overload. There is also the possibility of seeing a gain in the capacity deferring investment. Furthermore, a planner may be interested in defining futures that will be evaluated using risk analysis for example [12], [19]. The methodology provides useful information on the extreme, positive or negative, impact that may be exploited in order to compose futures.

VI. Conclusion

This work proposes MO modelling to evaluate the impact of the integration of DG in terms of the capacity of distribution networks. This approach, based on MEPSO, had considered many relevant technical issues affected by the integration of DG, providing important information for decision-making. The analysis performed allows planners to identify the limits of the impact of DG, which may help to orientate investments and policies for efficient DG integration and also address the effect of the penetration of DG that is not owned by utilities, indicating possible benefits or bottlenecks.

Further improvements can be made to this approach. Attributes may be included to represent the impact of DG on other network aspects, such as fault currents or losses. In the current formulation, voltage may also be considered as a third attribute to explicitly observe the effect of DG on voltage regulation. However, the visual analysis of the PFs may become more complex with three attributes.

Finally, in this study the impact of DG on the capacity was evaluated, assuming that the generators are able to ensure a firm level of generation during the hours of peak load. A topic for further investigation is the evaluation of DG with intermittent generation and varying load pattern.

In summary, the main contributions of this work are: it offers a new approach to using MO techniques to deal with uncertainties related to the integration of DG. The proposed methodology provides important information for planners on the extent of the impact of DG on a network. The analysis is also strongly dependent on the performance of the MO technique. The MEPSO method, a MO approach for EPSO developed by the authors, demonstrated efficiency, especially in this work, dealing with a mix of continuous and discrete decision variables for the first time.

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VIII. Biographies

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