Probabilistic Multi-objective Microgrid Planning Methodology for Optimizing the Ancillary Services Provision

Sergio F. Contreras*†, Camilo A. Cortes†, Johanna M.A. Myrzik*,
* Institute of Automation Technology - IAT, University of Bremen, Bremen, Germany
{ContrerasS,MyrzikJ}@iat.uni-bremen.de
† Department of Electrical and Electronic Engineering, Universidad Nacional de Colombia, Bogota, Colombia
{sfcontrerasp,caacortesgu}@unal.edu.co

***Abstract*—Microgrids have attracted the attention of researchers and stakeholders because of their well-known impacts and related benefits. Especially the provision of ancillary services has drawn attention. However, traditional planning should be redefined to optimally achieve such promising advantages, which leads to a complex decision-making problem that should be progressively addressed with a more modern and comprehensive holistic approach. Hence, this paper proposes an enhanced version of the probabilistic multi-objective microgrid planning methodology (POMMP2) that includes a novel strategy to apply graph partitioning and metaheuristic optimization to consider simultaneously the planning of a cluster-based topology with the size and location of distributed energy resources under the paradigm of a microgrid with capacity for providing ancillary services. POMMP2 is tested in an adapted IEEE-37 node system, and NSGAII and AHP are used as optimization and decision-making algorithms respectively. Results show the benefits of a planning methodology viewed as a comprehensive problem and not a set of independent tasks.**

***Index Terms*—Networked microgrid, Multi-objective Optimization, Topology Planning, Probabilistic, Ancillary Services.**

I. Introduction

The microgrid (MG) is an emerging concept that can be defined as active distribution networks that interconnect loads and distributed energy resources (DER), and can operate in an autonomous controlled and coordinated way in either grid-connected or islanded modes [1], [2]. MGs have evolved as a powerful approach to boost the current transition from passive to active distribution networks, to manage the high penetration of DERs, and to satisfy the requirement of highly reliable, secure, efficient and sustainable electricity delivery. However, the implementation of the MG concept leads to diverse technical issues that must be tackled during the planning stage [3].

A complete compendium of key features, proposed models and optimization strategies for the optimal planning of active distribution networks are presented in [4]–[7], while a review of planning approaches with a focus on the transition to the MG implementation are presented in [3]. These reviews show the necessity of planning methodologies that include multi-objective and complex optimization approaches, high-level uncertainties and the incorporation of operational aspects into planning models. Furthermore, although the benefit for the provision of ancillary services (AS) was considered before [8]–[10], the influence of the planning stage on AS provision has not been deeply studied.

To tackle some of the issues mentioned above, authors in [8] propose an extension of the Mixed Integer Linear Programming-based Distributed Energy Resources Customer Adoption Model (DER-CAM) to include the revenue stream from the MG's provision in the MG resource sizing problem. Furthermore, authors in [1] propose a probabilistic multi-objective microgrid planning (POMMP) methodology to find the optimal size and location of DERs and maximize the available active power in grid-connected mode for AS provision, minimize the mismatch power in islanded mode and minimize the operating cost of the MG. Notwithstanding, both approaches consider a pre-defined MG topology, whose planning is traditionally done separately [4] even though they are mutually dependent in their planning.

In this vein, the planning of loop-based MG in active distributions networks is proposed in [11]. The iterative methodology applies graph partitioning and integer programming as part of an iterative strategy that improves the results of [12]. In a similar direction, [13] proposes a methodology for the optimal planning of an interconnected network of multi-microgrids based on clustering. The research above show the relevance of the MG's topology for enhancing its reliability. However, in these proposals the size and location of DERs are predetermined. On the other hand, authors in [14], [15] test two novel optimization algorithms to solve the topology design and DERs placement problem under a multi-objective approach. The proposals describe an effective strategy to solve the joint optimization problem. Notwithstanding, relevant issues in the MG planning such as uncertainties, time-depended energy storage systems, islanded operation and operational aspects are not considered.

In [16], a well-developed strategy to consider uncertainties for the planning of interconnected MGs is proposed. The authors present a stochastic multi-objective framework for the minimization of two cost functions. In a related work [16], a novel robust optimization procedure for contemplating uncertainties in the design of MGs is proposed. In this case, a single cost function is minimized. Results in the preceding literature show the advantages of the proposed strategies and effectively tackle relevant points in MG planning. However, significant issues for an attractive implementation of MG remain unattended, such as revenues from supplying AS, market trading participation and a capable continuous islanded operation. Furthermore, new strategies for optimal networked MG clustering and topology planning for new or expansion projects holistically offers plentiful research opportunities.

To fill the blanks, this paper is an extension of the authors' work in [1], where the purpose is to propose a second version of the probabilistic multi-objective microgrid planning methodology (POMMP2). Accordingly, the POMMP2 methodology is presented as a tool for accomplishing the decision-making associated with the expansion or transformation of existing distribution networks under the paradigm of a medium voltage networked MG with the capacity of providing AS to the main utility grid. POMMP2 enhances the proposal in [1] by modifying the methodology and optimization model in order to include a novel strategy to consider simultaneously the optimal planning of the MG topology with the size and location of DERs. Consequently, the main contributions of the paper are:

- A novel strategy to include a multilevel graph-partitioning technique for the optimal formation of clusters in the planning of networked MG.
- The networked MG topology, DERs size and DERs location are planned in the methodology considering a novel holistic approach with a flexible decision making to form full radial-based, loop-based, mesh-based or mixed topologies. The set of constraint functions is enhanced to consider topology-planning restrictions.
- The methodology proposes a strategy to consider the continuous operation in islanded mode of the networked MG from the planning process.
- The economic objective function to minimize the investment and operation cost of the MG is modified to include the lines installation cost per kilometer. Furthermore, minimization of the power losses is re-introduced as an objective function.

The remainder of the paper is organized as follows. In section II, the enhanced planning methodology is proposed, while section III and IV describe the optimization and mathematical model besides the changes in POMMP2. In section V, the test system IEEE37-bus, simulation framework, and the optimal planning results for two case studies are found and analyzed using the Non-dominated Sorting Genetic Algorithm (NSGAII) for the optimization task and Analytic Hierarchy Process (AHP) for decision-making. Finally, the conclusions of the work are presented in section VI.

II. The Probabilistic Multi-Objective Microgrid Planning Methodology - POMMP2

The POMMP2 methodology enhances the former version by including novel strategies for a holistic perspective of the

Symbol	Description
Subscripts	
mt, wt, pv	Microturbines, wind turbines, photovoltaics
ba	battery units
c	Continuous generation technologies: PV
g	Discrete generation technologies: WT y BM
j	Set of technologies $(g \cup c)$
b	Set of storage technologies
i	Set of technologies $(j \cup b)$
l, bus, br	load, Bus or branch (lines)
clu/mg	Cluster = MG
λ	Loop (cycle) in the network
m, d, h	Month 1, 2, ..., 12, day type 1, 2, 3, hour 1, 2, ..., 24
$t(m, d, h)$	Time segment along the horizon planning
Optimization problem	
$\vec{x}$	Variables vector
$\vec{z}$	Objective functions vector $\vec{F}(\vec{x})$
$\mathrm{f}_{1,2,3}$	Objective functions
M	Arbitrarily large number $[-]$
Graph partitioning and topology	
$\mathrm{G_{i/r}}$	Networked MG graph, i initial, r reduced
V	Vertices (buses) of the networked MG
E	Edges (lines) of the networked MG
k	Subset of vertices $\mathrm{k} \in \mathrm{V}$
Λ	Loop (cycle) in the network
Power data	
$\mathrm{P_{DG}}$	Active power generated [kW]
$\mathrm{P_{DS}}$	Power of storage systems [kW]
$\mathrm{P_{load}}$	Power demanded [kW]
$\mathrm{P_{loss}}$	Power losses [kW]
$\mathrm{PI_{DG}}$	Active power generated in islanded mode [kW]
$\mathrm{PI_{DS}}$	Power of storage systems in islanded mode[kW]
$\mathrm{PI_{load}}$	Power demanded in islanded mode [kW]
$\mathrm{PI_{loss}}$	Power losses in islanded mode [kW]
General system parameters	
n	Number of DG, DS, buses, lines or clusters
$\mathrm{I_{G_g}}$	Number of units of generation technology g installed $[-]$
Cap	Rated power capacity of generation [kW]
L	lenght of the lines $[km]$
GS	Energy generated to export [kW]
Cap	Nominal power capacity [kW]
N_{clu}	Maximum number of clusters
N_{λ}	Maximum number of loops; $mg = clu$ per cluster
$\min \lvert \mathrm{k}_{\lambda} \rvert$	Minimum number of buses per loop
System operation	
UL	Energy purchased [kW]
GT	Total power generated [kW]
P_g	Active power generated by the technology g [kW]
$\mathrm{G_S}$	Power generated to be exported [kW]
$\mathrm{b_{TEx}}$	Binary decision of selling electricity to the stock $[b]$
$\mathrm{b_S}$	Binary decision of sell spinnig reserve $[b]$
$\mathrm{b_{NS}}$	Binary decision of sell non-spinnig reserve $[b]$
$\mathrm{b_{RUp}}$	Binary decision of sell frequency up-regulation $[b]$
$\mathrm{b_{RDn}}$	Binary decision of sell frequency down-regulation $[b]$
Market data	
TF	Regulated tariff fixed charge for electricity in month m [$]
TE	Regulated tariff for electricity $[\$/kWh]$
$\mathrm{T_{Ex}}$	Regulated tariff for electricity export $[\$/kWh]$
$\mathrm{S_{MCP}}$	Regulated tariff for spinning reserve export $[\$/kWh]$
$\mathrm{NS_{MCP}}$	Regulated tariff for non-spinnig reserve export $[\$/kWh]$
$\mathrm{R_{UpMCP}}$	Regulated tariff for frequency up-regulation export $[\$/kWh]$
$\mathrm{R_{DnMCP}}$	Regulated tariff for frequency down-regulation export $[\$/kWh]$
Technology data	
$\mathrm{C_{VC}}$	Generation cost $[\$/kWh]$
$\mathrm{C_{OMV}}$	Variable annual operation and maintenance costs [$/kW]
$\mathrm{C_{CCD}}$	Turnkey capital cost of generation [$/kW]
$\mathrm{C_{OMF}}$	Fixed annual operation and maintenance costs
$\mathrm{C_{FCC}}$	Fixed capital cost of generation ($/kW)
$\mathrm{C_{CCB}}$	Turnkey capital cost of lines instalation $[\$/km]$
Other parameters	
$\mathrm{A}_{c,g,b,br}$	Annuity factor for investments in technologies and infraestructure $[-]$

planning of networked MG under the paradigm of MG with AS provision capacity. A comparison of the main highlights of POMMP2 compared with POMMP are shown in Table I

TABLE I
MAIN FEATURES POMMP AND POMMP2 METHODOLOGIES

Feature	**POMMP**	**POMMP2**
Probabilistic approach	✓	✓
Location and size of DERs	✓	✓
Topology definition		✓
Networked MG based on clusters		✓
Multilevel graph partitioning technique		✓
Heuristic optimization	✓	✓
Multi-objective (3 objectives)	✓	✓
Residual power maximization	✓	✓
Cost minimization	✓	✓
Power losses minimization		✓
Islanding operation	✓	✓

The POMMP2 methodology considers the size and location of DERs together with the topology planning. A set of dispatchable distributed generation (DG) (microturbines - MT), non-dispatchable units (Photovoltaic modules -PV and Wind turbines - WT), and distributed storage (DS) elements (batteries - BA) are considered. The AS provision is based on a fully available extra active power capacity to be exported back to the main grid or to provide spinning/non-spinning operating reserve, and up-/down-frequency regulation [1], [8]. The most remarkable steps of the proposal are presented in the methodology as follows in Fig. 1.

The methodology is composed of four stages: pre-planning, iterative heuristic optimization, iterative graph partitioning, and decision-making. Thus, the methodology starts with the pre-planning stage, where all the parameters, limits, PDFs, market characteristics and topology and optimization options are defined and loaded. The second stage (upper-level optimization) is executed by iterative population-based heuristic optimization. The optimization algorithm initializes the decision vector for all the individuals of the population. Afterward, the mathematical model is modified based on the values of the variables. The MG is then modeled as a graph $\mathrm{G_i(V, E)}$, where V represent the buses and E the connection lines. In POMMP2, V is always equal to the total number of buses, while the connections E are established by the decision variables as it is described in section III. Thus, the next step is to verify complete graph connectivity, since stand-alone buses are forbidden in the methodology. If the networked MG is not totally interconnected, objective functions are penalized as it is described in section III to stimulate convergence. On the other hand, for the fully connected graph, a multilevel graph partitioning stage (Lower-level optimization) is applied to find an optimal set of clusters (MG) that constitute the networked MG.

The adopted graph partitioning is a multilevel iterative approach with coarsening, partitioning, uncoarsening, refinement and selection parts whose output is an optimal clustered net-

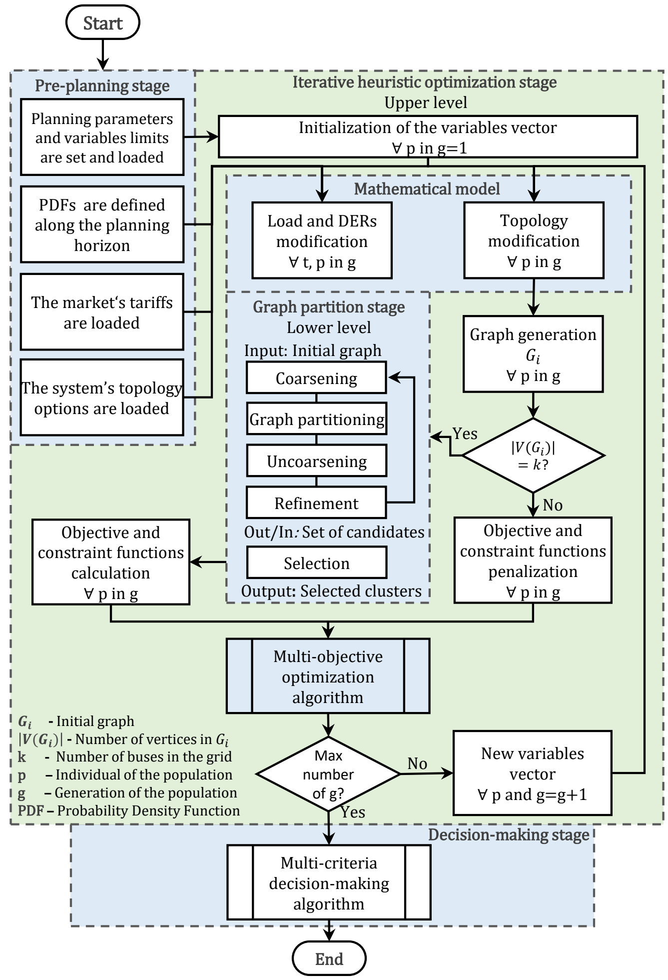

Fig. 1. Enhanced POMMP2 methodology

worked MG. Next, the objective and constraint functions are calculated for the decision variables set and defined clusters based on the outcomes of deterministic power flows. The power flows are run for four architectures based on the possible operation modes: a fully grid-connected networked MG with the feeder as slack bus; a complete disconnected networked MG with the strongest dispatchable DG as slack bus; and a islanded cluster with their individual dispatchable DG as slack bus.

The resulting objective functions and constraints are used by the optimization algorithm for the optimal exploration and exploitation of the feasible region to find the Pareto optimal solutions. In POMMP2, the well-known evolutionary algorithm NSGAII is used as a multi-objective optimization algorithm; however, the methodology can be adapted to any other population-based strategy. NSGAII is an evolutionary metaheuristic method based on a fast elitist non-sorting technique that has been extensively tested for the solution of constrained three-objective functions optimization problems and shown good results [17], and the outcome of the true-multi-objective technique is a set of planning solutions/alternatives with different trade-off. Hence, the last stage of the methodology is reserved to select a desired solution from the Pareto optimal solutions set. In this way, a multi-criteria decision-making strategy based on the AHP technique is used. In AHP, the problem is hierarchically organized, and different pairs of objectives and Pareto solutions are compared at each level to obtain their relative weights and a final ranking of the alternatives regarding decision maker's preferences [1], [18]. AHP supports decision-makers to establish priorities and select a single-solution based on the best compromise among solutions. AHP is chosen in this methodology, as in [1], due to its simplicity, ease of implementation and good flexibility [18].

The outcome of the methodology is a networked MG with an optimal selection of the DERs in terms of their capacity and location, as well as the optimal clustering and interconnection of the networked MG.

III. Optimization problem of the POMMP2 methodology

POMMP2 adopts the true-multi-objective approach based on three objective functions of POMMP [1]; however, the approach is strategically reformulated to enhance the methodology considering the topology planning. Thus, in this case, objective functions are calculated in two levels (1)

$$\text{minimize} \quad \vec{\mathrm{F}}(\vec{\mathrm{x}}) = \begin{cases} [\mathrm{f_{k1}}(\vec{\mathrm{x}}), \mathrm{f_{k2}}(\vec{\mathrm{x}}), \mathrm{f_{k3}}(\vec{\mathrm{x}})]^{\mathrm{T}} & \text{if} \quad |\mathrm{V(G)}| < \mathrm{k} \\ [\mathrm{f_1}(\vec{\mathrm{x}})\, \mathrm{f_2}(\vec{\mathrm{x}}), \mathrm{f_3}(\vec{\mathrm{x}})]^{\mathrm{T}} & \text{if} \quad |\mathrm{V(G)}| = \mathrm{k} \end{cases} \quad \text{subject to} \quad \vec{\mathrm{x}} \in \mathrm{S} \tag{1}$$

Where S is the feasible region formed by the constraints and decision variables limits, $\mathrm{G} = (\mathrm{V}, \mathrm{E})$ is the undirected graph that represent the distribution network with a fixed number of vertices ($|\mathrm{V}| = \mathrm{n}_{bus}$) and a number of edges ($|\mathrm{E}| = |\vec{\mathrm{x}}_{br}| \ \forall \ \mathrm{x} \neq 0$), $\mathrm{k} = \mathrm{n}_{bus}$ is a minimum number of vertices that should be connected and $|\mathrm{V(G)}|$ is the number of connected vertices for the graph G. Equation (1) means that the objective functions will be calculated depending on the resulting connected or disconnected graph from the decision variables set $\vec{\mathrm{x}}_{br}$. In this way, for a disconnected graph G, $\mathrm{f_{k1}}(\vec{\mathrm{x}}) = \mathrm{f_{k2}}(\vec{\mathrm{x}}) = \mathrm{f_{k3}}(\vec{\mathrm{x}}) = M \times (\mathrm{k} - |\mathrm{V(G)}|)$, where M is an arbitrary penalty value to guarantee that $\mathrm{f_{k1}} >> \mathrm{f_1}$, $\mathrm{f_{k2}} >> \mathrm{f_2}$ and $\mathrm{f_{k3}} >> \mathrm{f_3}$ (two orders of magnitude for this paper). The objective functions and decision variables are calculated as follows for a fully connected network.

A. Objective functions of the optimization problem

1) Maximization of the networked MG residual power for the AS provision: The fully available residual active power to be exported to the main grid is calculated in (2) [1].

$$\mathrm{f_1}(\vec{\mathrm{x}}) = -\frac{1}{\mathrm{n}_t}\left[\sum_{t=1}^{\mathrm{n}_t}\left(\sum_j \mathrm{P}_{\mathrm{DG}_{j,t}}(\vec{\mathrm{x}}) \pm \sum_b \mathrm{P}_{\mathrm{DS}_{b,t}}(\vec{\mathrm{x}}) - \right.\right.$$
$$\left.\left. - \sum_l \mathrm{P}_{\mathrm{load}_{l,t}}(\vec{\mathrm{x}}) - \mathrm{P}_{\mathrm{loss}_t}(\vec{\mathrm{x}})\right)\right], \ [\mathrm{MW}] \quad \forall \quad t \tag{2}$$

The function has a negative value since it is desirable to maximize the residual capacity of the MG

2) Minimization of the networked MG power losses: The power losses have been re-introduced in the optimization problems as a technical objective function based on the work in [19] and the planning objectives review in [4]. The objective function is given in (3), and the losses are found from the results of a probabilistic power flow simulations for each time-step in the methodology.

$$\mathrm{f_2}(\vec{\mathrm{x}}) = \frac{1}{\mathrm{n}_t}\left[\sum_{t=1}^{\mathrm{n}_t} \mathrm{P}_{\mathrm{loss}_t}(\vec{\mathrm{x}})\right], \ [\mathrm{MW}] \quad \forall \quad t \tag{3}$$

3) Minimization of the networked MG investment, maintenance and operating cost: The economic function in (4) considers the operating and investment costs of a MG in a typical year [1]. Furthermore, the objective function has been updated to include the capital costs for the installation of distribution lines per distance unit in order to optimize the MG topology planning (part g).

$$\begin{aligned}
\mathrm{f_3}(\vec{\mathrm{x}}) = [& \\
& \sum_m \mathrm{T}_{\mathrm{F}_m} \rightarrow \text{(a)} \quad + \sum_m \sum_d \sum_h \mathrm{U}_{\mathrm{L}_t} \cdot \mathrm{T}_{\mathrm{E}_{m,d,h}} \rightarrow \text{(b)} \\
& + \sum_j \sum_m \sum_d \sum_h (\mathrm{G}_{\mathrm{T}_{j,t}}) \cdot (\mathrm{C}_{\mathrm{VC}_{j,m}} + \mathrm{C}_{\mathrm{OMV}_j}) \rightarrow \text{(c)} \\
& + \sum_g \mathrm{I}_{\mathrm{G}_g} \cdot \max(\mathrm{P}_g) \cdot (\mathrm{C}_{\mathrm{CCD}_g} \cdot \mathrm{A}_g + \mathrm{C}_{\mathrm{OMF}_g}) \rightarrow \text{(d)} \\
& + \sum_c (\mathrm{C}_{\mathrm{FCC}_c} \cdot \mathrm{Cap}_c) \cdot \mathrm{A}_c + \mathrm{Cap}_c \cdot \mathrm{C}_{\mathrm{OMF}_c} \rightarrow \text{(e)} \\
& + \sum_b (\mathrm{C}_{\mathrm{FCC}_b} \cdot \mathrm{Cap}_b) \cdot \mathrm{A}_b + \mathrm{Cap}_b \cdot \mathrm{C}_{\mathrm{OMF}_b}) \rightarrow \text{(f)} \\
& + \sum_{br} \mathrm{L}_{br} \cdot (\mathrm{C}_{\mathrm{CCB}_{br}} \cdot \mathrm{A}_{br}) \rightarrow \text{(g)} \\
& - \sum_m \sum_d \sum_h \mathrm{G}_{\mathrm{S}_t} \cdot \mathrm{T}_{\mathrm{Ex}_{s,d,h}} \cdot \mathrm{b}_{\mathrm{TEx}_t} \rightarrow \text{(h)} \\
& - \sum_m \sum_d \sum_h \mathrm{G}_{\mathrm{S}_t} \cdot \mathrm{S}_{\mathrm{MCP}_t} \cdot \mathrm{b}_{\mathrm{S}_t} \rightarrow \text{(i)} \\
& - \sum_m \sum_d \sum_h \mathrm{G}_{\mathrm{S}_t} \cdot \mathrm{NS}_{\mathrm{MCP}_t} \cdot \mathrm{b}_{\mathrm{NS}_t} \rightarrow \text{(j)} \\
& - \sum_m \sum_d \sum_h \mathrm{G}_{\mathrm{S}_t} \cdot \mathrm{R}_{\mathrm{UpMCP}_t} \cdot \mathrm{b}_{\mathrm{RUp}_t} \rightarrow \text{(k)} \\
& - \sum_m \sum_d \sum_h \mathrm{G}_{\mathrm{S}_t} \cdot \mathrm{R}_{\mathrm{DnMCP}_t} \cdot \mathrm{b}_{\mathrm{RDn}_t} \rightarrow \text{(l)} \\
& \quad], \ [\$\mathrm{MUSD}] \qquad \forall \quad t(m,d,h)
\end{aligned} \tag{4}$$

In (4), the generation and installation costs are considered from part (a) to (f). The part (g) has been included to consider the investment cost due to the installation of lines per unit of distance (in this case km), which are annualized based on an interest rate and the lifespan of the connections. Furthermore, the generation revenues are considered from part (h) to (l). An extended description of (4) can be found in [1]

B. Decision variables for the optimization problem

The decision variables are organized in the vector $\vec{x}$. The vector has been modified to include a set of binary variables that represents the connected (1) or disconnected (0) state of a line in a set of possible connections. The decision variables vector model for the holistic planning perspective is shown in Fig. 2

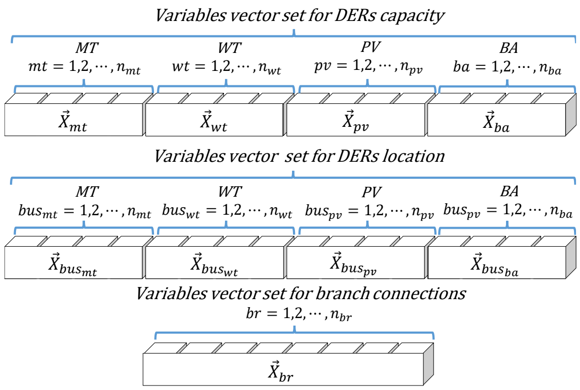

Fig. 2. Decision variables model for an holistic planning perspective

C. Constraints functions for the optimization problem

The optimization problem is defined with 35 constraints. The operation limits of the distributed generators, operation limits of storage systems, voltage limits at each node, export and import of energy from and to the MG and the AS supply to consider its dispatch and supplying time, power capacity and the minimum bid to participate in each energy market, were maintained from [1]. However, the power balance constraint was modified to consider a continuous operation in islanded operation mode; furthermore, constraints for the topology formation were introduced as it is described below

1) Energy balance in the MG in islanded mode: The energy balance in islanded mode includes generated and stored power, demanded power and power losses. For the islanded operation simulation, the slack bus is switched from the main feeder to the largest dispatchable unit of the fully connected networked MG or each cluster in the MG (Section IV-B). Thus, probabilistic power flow is used to calculate the mismatch power for each time-step. The constraint is given by (5)

$$\sum_{t=1}^{n_t}\sum_{j=1}\mathrm{PI}_{\mathrm{DG}_{j,mg,t}} = \sum_{t=1}^{\mathrm{n}_t}\left(\sum_{l}\mathrm{PI}_{\mathrm{load}_{l,mg,t}} + \mathrm{PI}_{\mathrm{loss}_{mg,t}} \pm \sum_{p}\mathrm{PI}_{\mathrm{DS}p,mg,t}\right), \quad \forall \quad mg,j,p,t \quad (5)$$

With this constraint, the rated capacity of the dispatchable units are optimally sized to avoid a power mismatch during a continuous islanded operation of the networked MG, as well as to limit the oversize of the DERs in the system due to the reserve capacity optimization goal.

2) Connectivity and topology formation: Five functions were included in POMMP2 in order to constrain the optimal formation of clusters and the topology. Thus, the constraint in (6) guarantees that all the buses of the distribution network are connected by at least one branch.

$$\left|\mathrm{V}(\mathrm{G}_{\mathrm{i}_p})\right| = \mathrm{k}_p \qquad \forall\, p \qquad (6)$$

Constraint (7) guarantees a number of clusters n_{clu} in the complete networked MG equal to a pre-defined number N_{clu}. Furthermore, the methodology can configure a full radial-based ($\mathrm{N}_{\lambda_{mg}} = 0$), loop-based ($\mathrm{N}_{\lambda_{mg}} = 1$), mesh-based ($\mathrm{N}_{mg} > 1$) or mixed topologies. Thus, the number of loops per each cluster $\mathrm{n}_{\lambda_{mg}}$ is constrained to $\mathrm{N}_{\lambda_{mg}}$ in (8). POMMP2 is proposed to have a cluster per each dispatchable MT ($\mathrm{N}_{clu} = \mathrm{n}_{mt}$), and a loop per each cluster MG ($\mathrm{N}_{\lambda_{mg}} = 1$).

$$\mathrm{n}_{clu,p} = \mathrm{N}_{clu,p} \qquad \forall\, p \qquad (7)$$

$$\mathrm{n}_{\lambda_{mg,p}} = \mathrm{N}_{\lambda_{mg,p}} \qquad \forall\, mg,p \qquad (8)$$

The number of buses (vertices) $|\mathrm{k}_\lambda|$ that belong to a loop Λ ($\mathrm{k}_\lambda \in \mathrm{V}_\lambda$) is constrained in (9) to a minimum number of buses $\min|\mathrm{k}_\lambda| = 5$ to avoid undesirable small loops.

$$|\mathrm{k}_{mp,\lambda,p}| \geq \min|\mathrm{k}_\lambda| \qquad \forall\, mg,\lambda,p \qquad (9)$$

Loops in graph theory are known as cycles and there are several algorithms available in literature that can be used to find the fundamental cycles in the clusters and networked MG.

IV. Mathematical Models of the POMMP2 Methodology

The mathematical model for the available power calculation of the dispatchable and non-dispatchable DG units, the charge/discharge strategy and operation management of the DS units, the MG operation modes, the network operator simulation for the AS supplying and the probabilistic approach for modeling the WT, PV and load demand uncertainties are based on the formulation in [1]. However, the most relevant key aspects and the proposed MG clustering definition based on a multilevel graph partitioning technique are described below.

A. Topology and clusters formation in the networked MG

One of the main contributions of the paper is the holistic planning of DERs and topology based on clusters. For that purpose, the graph partitioning technique in [11] is adapted to POMMP2. The strategy is described in Fig. 3.

First, the MG graph G_i is reduced iteratively in a coarsening procedure based on the shortest edge machine (SEM) method. Afterward, the coarsened graph G_r is then partitioned using the "greedy graph growing partitioning (GGGP)" technique [11] for the formation of the cluster. The partitioned graph is expanded back in an uncoarsening procedure. The uncoarsened graph is refined based on the mismatch power in the clusters and the storage resources distribution based on equations proposed in [11]. The iterative methodology evaluates a high number of clustering possibilities (1000 in this proposal) and

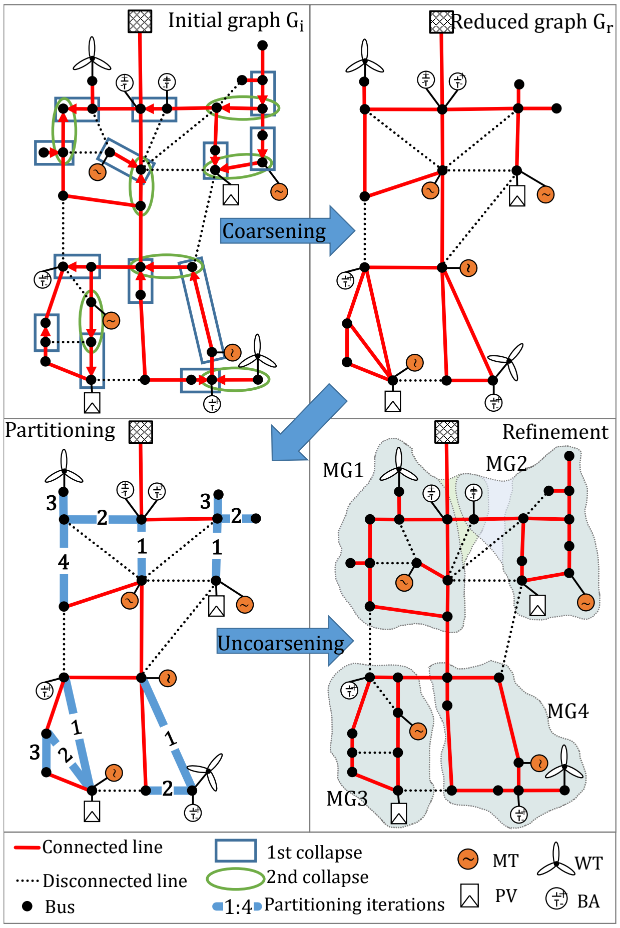

Fig. 3. Description of the multilevel graph partitioning strategy

finds a set of candidate clusters. For that purpose, problems regarding the collapsing of dispatchable units in the coarsening step, clusters disconnection after swaps in the refinement step and the influence of the storage magnitude are taken into account [11].

It is important to highlight that POMMP2 designates a cluster for at least one dispatchable unit. Thus, a partitioning cluster grows around a dispatchable DG bus based on GGGP, which selects an initial vertex and expands it to optimally find a larger part of the graph. However, each cluster can include additional distributed generation (e.g. WT, PV) and must include at least one DS unit. The refinement strategy evaluates the mismatch power balance between the installed capacity of the whole generation matrix and the load demand per each cluster and assesses the energy storage resources sharing. The iterative process is included as part of the POMMP2 methodology as it was described in section II.

B. Uncertainties, MG operation modes, and network operator simulation strategies

In POMMP2, the probabilistic operation of the MG is considered with hourly time-steps for three typical days (weekdays, weekends and peak days) per each month of the planning-horizon [1], [8]. The uncertainties from the stochastic WT and PV operation and the load demand are modeled based on their associated PDF during each time-step [1].

A novel strategy is proposed in POMMP2 to consider grid-connected and islanded operation modes. The grid-connected operation mode is modeled with a unique point of common coupling with the main utility grid, while two islanded operation conditions are contemplated for the planning.

1) The complete networked MG is disconnected at the point of common coupling and operates in islanded mode. Thus, the slack bus is switched from the main feeder to the dispatchable unit with the highest capacity.
2) An individual cluster MG inside of the networked MG may operate in islanded mode. In this case, the dispatchable unit in the cluster operates as slack bus.

In [1], the islanding operation was considered based on the mismatch power minimization in islanded mode operation.

V. Case Study, Results and Discussion

The test system IEEE 37-bus adapted in [11], [12] is used in this paper to prove the performance of POMMP2. The test system is a three-phase radial-based feeder with 4,8 kV operating voltage; underground line segments with a configuration 722 between bus 1-5, and 723 for all others; and all loads are spot loads with constant PQ, current and impedance whose value is the sum of the phase demand of the test system [20]. However, the set of connection options and distances are adopted from [11], [12]. The load demand is taken from the IEEE Reliability Test System [21], while the wind speed and solar irradiation from time-series data is available in [22]. The market data from the PJM Interconnection LLC territory was chosen to implement the model [8]. The tariff information used was based on data available in different sources [1], [8] and it can be consulted in [22]. The DER's capacity limits are described in Table II, while all the buses of the network are candidates for the DERs location and all the branches are candidates to define the topology.

TABLE II
Standard DG unit sizes and optimization boundaries

DG type / Case	**No. Units**	**Lower boundary**	**Upper boundary**
		P_{lb} **[kW]**	P_{ub} **[kW]**
Discrete variables			
MT Case 1	2	5×120	15×120
MT Case 2	4	5×120	15×120
WT	2	0×120	5×120
Continuous variables			
PV	2	0	180
BA	4	0	120

Two case studies are proposed for testing POMMP2: networked MG planning with two dispatchable units, and four dispatchable units. In both cases, a planning horizon of one year with time-steps of one hour and three typical days per month are embraced. A loop-based topology configuration with ($N_{\lambda_{clu}} = 2$) and ($N_{\lambda_{clu}} = 4$) respectively are adopted for both cases, and results are compared with two reference cases:

planning with POMMP for the loop-based topologies found in [11], and planning with POMMP for the IEEE37 radial-based topology of [20]. Simulations with 500 individuals and 100 generations were running 10 times for both cases to confirm the convergence and reliability of the methodology. The hypervolumen indicator was used to compare the resulting Pareto fronts. The hipervolumen media from the 10 case simulations is $\bar{\mathrm{HV}} = 869$ with a standard deviation of $\sigma = 51.9$ for the case 1, while it is $\bar{\mathrm{HV}} = 836$ with a standard deviation of $\sigma = 74.9$. The Pareto front with the highest hipervolumen indicator for each case was chosen for the analysis of the results. Furthermore AHP was applied, where the objective functions relevance order has been defined from more-relevant to less-relevant as: f_1,f_3 and f_2. The results are presented below.

A. Case 1: networked MG planning with two dispatchable units

The results of the planning with POMMP2 and POMMP (for a radial-based and loop-based reference topologies), are shown in Fig. 4

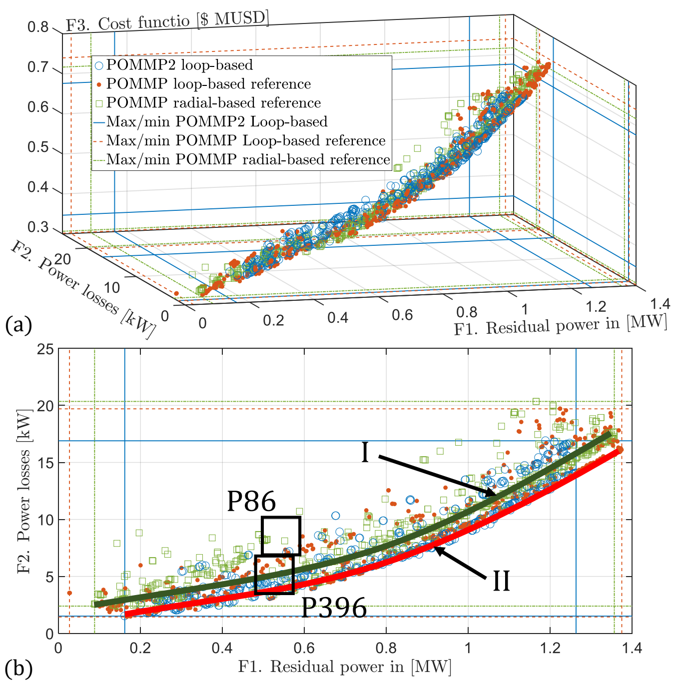

Fig. 4. Pareto front for the planning with POMMP2 and two dispatchable units

Fig. 4 shows that POMMP2 can get optimal results (Line II) in the same space area than the planning results with POMMP for the optimal loop-based topology of [11]. Furthermore, the Pareto front outcome shows features for the decision-making on networked MG planning. For example, the line I in Fig. 4(b) highlight the Pareto solutions from POMMP over the reference radial-based topology, while the line II describe the Pareto front for the planning with POMMP2. It can be seen that the topology planning with a loop-based condition gives rise to solutions with a reduction in power losses. However, also an increment was found in the MG cost as it is seen in Fig. 4(a).

The solution P396 from the POMMP2 planning and P86 from the POMMP over a radial-based topology were chosen with AHP. Thus, $f_1(\vec{x}) = 0.56\text{MW}$, $f_2(\vec{x}) = 7.18\text{kW}$ and $f_3(\vec{x}) = 0.4324$ for P369 and $f_1(\vec{x}) = 0.59\text{MW}$, $f_2(\vec{x}) = 10.71\text{kW}$ and $f_3(\vec{x}) = 0.4085$ for P86, and the decision variables results are shown in Fig. 5.

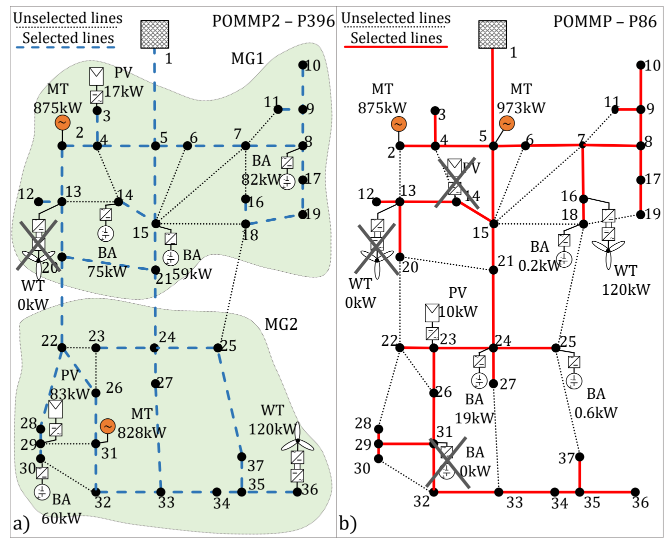

Fig. 5. a) Topology based on clusters; b) Radial-based topology

The results show that POMMP2 places the DERs with a wider distribution than POMMP, highlighting the location of the two MT and the WT in Fig 5. Furthermore, it can be seen that the initial generation portfolio limits with 2xMT, 2xWT, 2xPV and 4xBA was optimally adjusted to 2xMT, 1xWT, 2xPV and 4xBA in the solution P396, and 2xMT, 1xWT, 1xPV and 3xBA in the solution P86. Furthermore, the 29.1% and 29.8% of the installed DG's capacity for P396 and P86 respectively can be delivered as reserve power, while the losses are 0.37% and 0.54% respectively, that might represent a reduction up to 31MWh energy losses during a year; 0.6% of the exported energy from the reserve during the same period.

B. Case 2: networked MG planning with four dispatchable units

The results of the planning with POMMP2 and POMMP (for a radial-based and loop-based reference topologies) are shown in Fig. 6.

The line II highlights the solutions of POMMP2 and POMMP for the reference loop-based topology. This shows the capacity of POMMP2 to achieve an optimal set of Pareto solutions under the holistic perspective even for a higher number of decision variables and clusters. In this case, the separation in the power losses and cost of the Line II with the reference radial-based planning (Line I) is wider than in the Case 1, which can be understood as a consequence of the higher penetration of DERs with the extra two MT units. Furthermore, the residual power capacity to provide AS or

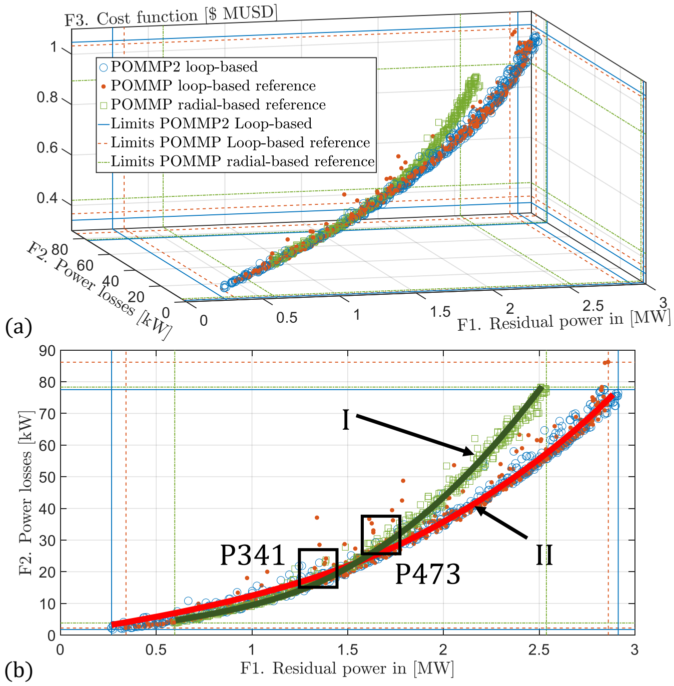

Fig. 6. Pareto front for four dispatchable units planning with POMMP and POMMP2

participate in open-markets can be almost two times higher than in Case 1 with two MT, which confirms the relevance of a posteriori analysis based on a multi-objective methodology.

AHP was used to select two optimal solutions from the Pareto fronts for POMMP2 and POMMP for the radial-based topology. The decision variables results for the solutions P341 (POMMP2) and P473 (POMMP) are shown in Fig. 7. The output objective functions in this case were $f_1(\vec{x}) = 1.35$MW, $f_2(\vec{x}) = 22.77$kW and $f_3(\vec{x}) = 0.5598$ for P341 and $f_1(\vec{x}) = 1.65$MW, $f_2(\vec{x}) = 31.49$kW and $f_3(\vec{x}) = 0.6731$ for P86.

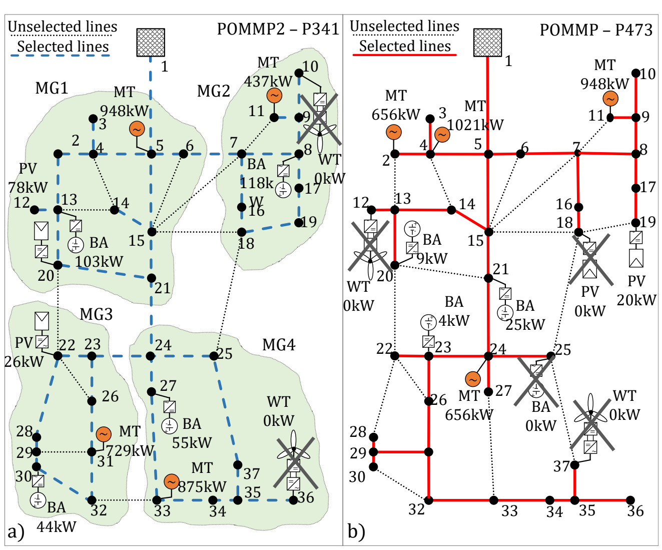

Fig. 7. a) Topology based on clusters; b) Radial-based topology

From results, it can be seen that the DERs placement is achieved with greater coverage with POMMP2. A second remark is related to the generation portfolio since it is optimally adjusted to 6xMT, 0xWT, 2xPV, and 4xBA in the P341 and 2xMT, 0xWT, 1xPV and 3xBA in P473. Furthermore, it can be mentioned that there is a trend to group the generation units close to the disconnected feeder when the planning of DERs is done without considering topology but contemplating a continuous islanding operation as in the planning with POMMP with radial-based topology. Hence, it can be claimed that the role of the dispatchable units will influence the planning to guarantee reliable operation in islanded mode, which is not visible with traditional planning methodologies. Additionally, results show that the losses in POMMP are 39% higher respect the value from POMMP2.

VI. Conclusion

The paper proposes an enhanced version of the probabilistic multi-objective Microgrid planning methodology (POMMP2). The methodology is formulated as a true-multi-objective optimization problem with a novel holistic perspective for considering simultaneously the topology and DERs definition. Thus, three objective functions have been chosen and a multilevel graph partitioning strategy is included in the methodology for the optimal definition of MGs as clusters inside the distribution network. It was found from the results that the strategy offers advantages regarding traditional separated approaches as with the former POMMP. For example, MG losses can be reduced with an optimal loop-based topology compared with a radial-based one for similar residual power capacity. Moreover, the available residual power can be increased by almost two times with the increase of the generation portfolio, where dispatchable units have a relevant role to benefit the islanded operation. Future research will comprise the assessment of the methodologies for different test systems and case studies, the evaluation of specific reliability and power quality objective functions and the expansion of the planning methodology with more comprehensive operational aspects.

Acknowledgment

We thank Colciencias and its program ”Becas para Doctorados Nacionales 2014 - 647” for funding the doctoral research that led to the results in this paper.

References

[1] S. F. Contreras, C. A. Cortes, and J. M. A. Myrzik, “Optimal microgrid planning for enhancing ancillary service provision,” *Journal of Modern Power Systems and Clean Energy*, vol. 7, no. 4, pp. 862–875, jul 2019.

[2] CIGRE WG C6.22 Microgrids Evolution Roadmap, “Microgrids 1 Engineering, Economics, & Experience,” CIGRE, Tech. Rep. 635, 2015.

[3] M. J. Ghadi, A. Rajabi, S. Ghavidel, A. Azizivahed, L. Li, and J. Zhang, “From active distribution systems to decentralized microgrids: A review on regulations and planning approaches based on operational factors,” *Applied Energy*, vol. 253, p. 113543, nov 2019.

[4] R. Li, W. Wang, Z. Chen, J. Jiang, and W. Zhang, “A review of optimal planning active distribution system: Models, methods, and future researches,” *Energies*, vol. 10, no. 11, 2017.

[5] Y. Xiang, J. Liu, F. Li, Y. Liu, Y. Liu, R. Xu, Y. Su, and L. Ding, "Optimal Active Distribution Network Planning: A Review," *Electric Power Components and Systems*, vol. 44, no. 10, pp. 1075–1094, jun 2016.
[6] P. S. Georgilakis and N. D. Hatziargyriou, "A review of power distribution planning in the modern power systems era: Models, methods and future research," *Electric Power Systems Research*, vol. 121, pp. 89–100, apr 2015.
[7] D. Emad, M. A. El-Hameed, M. T. Yousef, and A. A. El-Fergany, "Computational Methods for Optimal Planning of Hybrid Renewable Microgrids: A Comprehensive Review and Challenges," *Archives of Computational Methods in Engineering*, 2019.
[8] G. Cardoso, M. Stadler, S. Mashayekh, and E. Hartvigsson, "The impact of ancillary services in optimal DER investment decisions," *Energy*, vol. 130, pp. 99–112, jul 2017.
[9] A. Majzoobi and A. Khodaei, "Application of microgrids in providing ancillary services to the utility grid," *Energy*, vol. 123, pp. 555–563, mar 2017.
[10] M. Stadler, G. Cardoso, S. Mashayekh, T. Forget, N. DeForest, A. Agarwal, and A. Schönbein, "Value streams in microgrids: A literature review," *Applied Energy*, vol. 162, pp. 980–989, jan 2016.
[11] C. A. Cortes, S. F. Contreras, and M. Shahidehpour, "Microgrid Topology Planning for Enhancing the Reliability of Active Distribution Networks," *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 6369–6377, nov 2018.
[12] L. Che, X. Zhang, M. Shahidehpour, A. Alabdulwahab, and Y. Al-Turki, "Optimal Planning of Loop-Based Microgrid Topology," *IEEE Transactions on Smart Grid*, vol. 8, no. 4, pp. 1771–1781, jul 2017.
[13] L. Che, X. Zhang, M. Shahidehpour, A. Alabdulwahab, and A. Abusorrah, "Optimal Interconnection Planning of Community Microgrids With Renewable Energy Sources," *IEEE Transactions on Smart Grid*, vol. 8, no. 3, pp. 1054–1063, may 2017.
[14] S. Jiménez-Fernández, C. Camacho-Gómez, R. Mallol-Poyato, J. Fernández, J. Del Ser, A. Portilla-Figueras, and S. Salcedo-Sanz, "Optimal Microgrid Topology Design and Siting of Distributed Generation Sources Using a Multi-Objective Substrate Layer Coral Reefs Optimization Algorithm," *Sustainability*, vol. 11, no. 1, p. 169, dec 2018.
[15] C. Camacho-Gómez, S. Jiménez-Fernández, R. Mallol-Poyato, J. Del Ser, and S. Salcedo-Sanz, "Optimal design of Microgrid's network topology and location of the distributed renewable energy resources using the Harmony Search algorithm," *Soft Computing*, pp. 1–16, jun 2018.
[16] F. S. Gazijahani and J. Salehi, "Stochastic multi-objective framework for optimal dynamic planning of interconnected microgrids," *IET Renewable Power Generation*, vol. 11, no. 14, pp. 1749–1759, 2017.
[17] V. Khare, X. Yao, and K. Deb, "Performance scaling of multi-objective evolutionary algorithms," *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, vol. 2632, pp. 376–390, 2003, cited By 264.
[18] O. Ayadi, H. Felfel, and F. Masmoudi, "Analytic hierarchy process-based approach for selecting a Pareto-optimal solution of a multi-objective, multi-site supply-chain planning problem," *Engineering Optimization*, vol. 49, no. 7, pp. 1264–1280, jul 2017.
[19] S. F. Contreras, C. A. Cortes, and J. M. Myrzik, "Multi-Objective Probabilistic Power Resources Planning for Microgrids with Ancillary Services Capacity," in *2018 Power Systems Computation Conference (PSCC)*. IEEE, jun 2018, pp. 1–8.
[20] IEEE PES Distribution Systems Analysis Subcommittee Radial Test Feeders, "1992 Test Feeder Cases, 37-bus Feeder," [Online]. Available: http://sites.ieee.org/pes-testfeeders/, . Accessed: Aug 2019.
[21] Probability Methods Subcommittee, "IEEE Reliability Test System," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-98, no. 6, pp. 2047–2054, nov 1979.
[22] S. F. Contreras, C. A. Cortes, and J. M. Myrzik, "POMMP methodology economical parameters and markets description for the study cases," [Online]. Available: https://tinyurl.com/POMMP-Methodology, . Accessed: Aug 2019.