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Review

A review of power distribution planning in the modern power systems era: Models, methods and future research

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ABSTRACT

In recent years, significant research efforts have been devoted to the optimal design of modern power distribution systems. The aim of power distribution planning (PDP) is to design the distribution system such as to timely meet the demand growth in the most economical, reliable, and safe manner possible. The gradual transformation of the distribution grid from passive to active imposes the need to also consider the effect of distributed generation and active demand during planning and the increased advantages of their control. Several models and methods have been proposed recently for the solution of the modern PDP problem. This paper presents an overview of the state of the art models and methods applied to the modern PDP problem, analyzing and classifying current and future research trends in this field.

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1. Introduction

The designer of the power distribution system, in the context of power distribution planning (PDP), has as a primary goal to design the distribution system such as to timely meet the demand growth in the most economical, reliable, and safe way. This is not straightforward, because of the very large extension of the power distribution system, as well as the fact that this system is responsible for most of the electrical energy losses and most of the interruptions due to faults. In general, the traditional PDP consists of finding the most economical solution (single objective function) with the optimal location and size (capacity) of future substations and/or feeders to meet the future demand. The objective of the traditional PDP is the minimization of an economic cost function (the investment cost to add, reinforce or replace substations and/or feeders, plus the energy loss cost), subject to a set of technical and operational constraints.

In the last years the distribution planning function is further complicated by the high penetration of distributed generation (DG) technologies, including storage, and the participation of the consumers in the form of active demand, encouraged by national and regional policies worldwide. This is the basic notion of the active distribution network (ADN) that incorporates DG, distributed storage, active demand, automation, communication, and advanced metering in its operational planning. It is now widely recognized that by exploiting the capacity and control capabilities of the distributed energy resources (DER) at distribution level instead of just connecting them to the network (the so-called "fit and forget" approach) can provide optimal planning solutions with significant cost savings. For example, the optimal placement of DG into *existing* power distribution systems has already attracted the interest of significant research efforts [1] in the last twenty years, with the first work published in 1994. An exhaustive review of PDP works has been provided in [2–4], published in 1997, 2000, and 2002, respectively. As will be shown later in Table 2, with respect to modern PDP of active distribution networks, the consideration of automatic switching actions appears in 2005; consideration of DER integration and control appears in 2007; and consideration of multiple controls (active and reactive power control of DG units, on-line network reconfiguration, demand side response, and generation curtailment) appears in 2008. This paper provides an overview of selected PDP works published after 2005 (when the first modern PDP appears) [5–81]. It should be noted that in [1], 83 state of the art publications on the optimal placement of DG into *existing* power distribution systems were reviewed, while in this paper, 77 completely different state of the art publications on modern PDP are reviewed. More specifically, this paper reviews 77 selected PDP articles, published after 2004, which optimize at least the feeders and/or the substations of the distribution network. As will be shown in this paper, the modern PDP models and methods are more integrated (e.g., simultaneously optimize the substations and feeders), more often multiobjective, more often consider the installation of DG simultaneously to the expansion of substations and feeders, and more often consider DG control, load control and automatic switching actions, in comparison to the traditional PDP models of the past [2–4].

This paper introduces a taxonomy of the state of the art PDP models and methods, offering a unifying description of a relatively large number of works devoted to the subject [5–81]. Moreover, this work analyzes and classifies current and future research trends in PDP. This review aims to serve as a guide to power system engineers and researchers on the available PDP models and methods in the modern power systems era.

The paper is organized as follows. Section 2 focuses on PDP models, defines the general problem statement, outlines and classifies the published models and presents the objectives, constraints, design variables, types of application, problem types, categories of planning period, characteristics of load models, and types of distributed generation studied in PDP. Section 3 outlines and classifies the published PDP methods. Section 4 discusses the contribution of the reviewed works. Section 5 suggests future research ideas and Section 6 concludes.

2. PDP models

2.1. General problem statement

The typical PDP consists of finding the most economical solution with the optimal location and size of future substations and/or feeders to meet the future demand. The objective of the typical PDP is the minimization of an economic cost function (e.g., the investment cost to add, reinforce or replace substations and/or feeders, plus the energy loss cost), subject to a set of technical and operational constraints. The PDP is a complex mixed integer nonlinear optimization problem.

2.2. Objective

This section is focused on the main objective functions of the PDP problem. The PDP can be formulated as a single-objective problem or a multiobjective problem. The main single-objective functions minimize the net present value of the following costs:

(1) investment cost (to add, reinforce or replace substations and feeders), plus energy loss cost; (2) investment and power loss cost; (3) investment, loss, and reliability cost; (4) total costs (fixed and variable): investment, loss, reliability, and operation and maintenance cost; or (5) total costs minus total revenues.

PDP multiobjective formulations can be classified as:

(1) multiobjective with weights, where the multiple objectives are in fact transformed into a single objective thanks to the user-defined fixed weights of the individual objectives; this formulation belongs to the methods with *a priori articulation of preferences*, which means that the user determines the relative importance of the objective functions before executing the optimization algorithm [82];
(2) multiobjective, which belongs to the methods with *a posteriori articulation of preferences*, which means that an algorithm is used to determine the Pareto optimal set (potential solutions), and then, the decision-maker imposes preferences directly on the Pareto optimal set, i.e., the decision-maker chooses a solution from the Pareto set [82].

2.3. Design variables

The following design variables (unknowns) are mainly computed: (1) feeders location (routing); (2) feeders location and size; (3) substations location and size, feeders location; (4) substations location and feeders location and size; (5) substations size and feeders location and size; (6) substations and feeders location and size; (7) substations location, feeders size, and load allocation (e.g., assignment of single-phase loads to the different phases, or load balancing among phases); (8) substations location and size, feeders size, and load allocation; (9) size of substations, distributed generation (DG) and feeders; (10) size of substations and DG, location and size of feeders; and (11) substations, DG, and feeders location and size.

2.4. Distribution

The PDP is applied to: (1) the primary (medium voltage – MV) distribution network, (2) the secondary (low voltage – LV) distribution network, and (3) the primary and the secondary distribution network.

2.5. Problem type

The optimization problem type can be: (1) design of new network that is based on the design of the whole network assuming there is no real existing network; (2) network expansion that is based on the optimal expansion of the existing network to serve the future growth of current and new forecasted loads and DER; or (3) application of PDP both for the design of new network and network expansion.

2.6. Planning period

According to the model, the optimization problem can be: (1) static that is also called single-stage, which determines the PDP requirements in only one stage (planning period); or (2) dynamic that is also called multistage, which determines the PDP requirements in successive expansion plans over several planning periods (stages), thus representing the natural course of progression. More useful results are offered by the dynamic approach, which is, however, more challenging because of the interdependency between stages.

2.7. Load models

The load profile is modelled in PDP as: (1) one load level; (2) multi-load level; (3) probabilistic; or (4) fuzzy.

The loads are modelled as: (1) balanced three-phase; (2) unbalanced three-phase; or (3) a mix of single-phase and three-phase loads.

In the active distribution networks, the loads are distinguished as critical or inflexible (non-elastic) and as controllable or flexible (elastic).

2.8. Distributed generation

The DGs can be owned: (1) by the utility, or (2) by private investors and they can be: (1) thermal (dispatchable), or (2) renewable (mostly non-dispatchable) DGs.

2.9. Constraints

The most common constraints in the PDP formulation are: (1) power flow equality constraints, (2) bus voltage or voltage drop limits, (3) substation and feeder capacity limits, (4) use of standard sizes for transformers and conductors, (5) radial operation of the network, and (6) full connectivity, i.e., the network must supply all buses. Moreover, the following constraints have been considered in some PDP models: (7) budget constraint, (8) layout of cables in urban areas according to the street map, (9) bus angle limits, (10) transformer taps limits, (11) tapering conductor constraints, i.e., the upstream conductors must have a cross-section greater than or equal to the downstream ones. In case of DG connection, the following constraints have been considered: (12) capacity limits of DGs, (13) total DG capacity penetration limit, (14) capacity reserve, (15) short-circuit current limit.

2.10. Taxonomy

Table 1 presents a unifying taxonomy of the reviewed PDP models.

3. PDP methods

3.1. Numerical methods

3.1.1. Mixed integer linear programming (MILP)

A multistage distribution expansion problem is formulated as a MILP problem that is solved by a branch-and-bound algorithm and/or standard commercial solvers [20,21,24,46]. An integral planning methodology of primary–secondary distribution systems is formulated and solved using MILP [6]. A spatial PDP is formulated and solved using MILP [52].

3.1.2. Nonlinear programming (NLP)

Continuous constrained NLP is applied for the solution of a generalized horizon planning (20+ years ahead) model with ten decision (design) variables [16,18]. A mixed-integer NLP (MINLP) based PDP is solved by Benders decomposition [31]. A dynamic PDP is formulated using two interrelated models, which are solved by MILP and NLP, respectively [34].

3.1.3. Dynamic programming (DP)

DP solves a multistage PDP [19,40] and a multiobjective PDP [65].

Table 1
Taxonomy of the reviewed power distribution planning models.

Reference	Distribution	Type	Period	Decisions (design variables)	Objective function
[5]	Secondary	Expansion	Static	Substations location, feeders size, load allocation	Min total costs (fixed + variable)
[6]	Prim. + Second.	Expansion	Static	Substations and feeders location & size	Min investment and energy loss cost
[7]	Secondary	Expansion	Static	Substations and feeders location & size	Min investment and energy loss cost
[8]	Primary	Expansion	Static	Feeders location & size	Min cost (investment + loss + reliability)
[9]	Primary	Expansion	Static	Substations location, feeders location & size	Min investment and energy loss cost
[10]	Primary	Expansion	Static	Substations size, feeders location & size	Min cost (investment + loss + reliability)
[11]	Primary	Expansion	Static	Substations and feeders location & size	Fuzzy multiobjective
[12]	Primary	New + Expan.	Static	Substations and feeders location & size	Multiobjective
[13]	Primary	Expansion	Static	Substations and feeders location & size	Multiobjective
[14]	Primary	Expansion	Static	Substations and feeders location & size	Min investment and energy loss cost
[15]	Primary	Expansion	Dynamic	Substations, DGs, and feeders size	Min total costs minus total revenues
[16]	Prim. + Second.	Expansion	Static	Substations and feeders size, primary voltage	Min cost (investment + loss + reliability)
[17]	Primary	Expansion	Static	Feeders location & size	Min total costs (fixed + variable)
[18]	Prim. + Second.	Expansion	Static	Substations and feeders size, primary voltage	Min cost (investment + loss + reliability)
[19]	Primary	Expansion	Dynamic	Substations, DGs, and feeders location & size	Min total costs (fixed + variable)
[20]	Primary	Expansion	Dynamic	Substations and DGs size, feeders location & size	Min total costs (fixed + variable)
[21]	Primary	Expansion	Dynamic	Substations and DGs size, feeders location & size	Min total costs (fixed + variable)
[22]	Primary	New	Static	Feeders location	Min cost (investment + loss + reliability)
[23]	Primary	Expansion	Dynamic	Feeders location & size	Min investment and energy loss cost
[24]	Primary	New	Dynamic	Substations location and size, feeders location	Multiobjective with weights
[25]	Primary	Expansion	Static	Substations, DGs, and feeders location & size	Min total costs (fixed + variable)
[26]	Primary	New	Static	Feeders location & size	Multiobjective
[27]	Primary	Expansion	Static	DGs and feeders location & size	Multiobjective
[28]	Primary	Expansion	Static	Substations location and size, feeders location	Min investment and energy loss cost
[29]	Secondary	New	Static	Substations and feeders location & size	Min investment and energy loss cost
[30]	Secondary	New	Static	Substations and feeders location & size	Min investment and energy loss cost
[31]	Primary	Expansion	Static	Substations and DGs size, feeders location & size	Min cost (investment + loss + reliability)
[32]	Primary	Expansion	Dynamic	Substations and feeders location & size	Multiobjective with weights
[33]	Secondary	New + Expan.	Static	Substations location & size, feeders size, load allocation	Min total costs (fixed + variable)
[34]	Primary	Expansion	Dynamic	Substations, DGs, and feeders location & size	Min total costs (fixed + variable)
[35]	Primary	Expansion	Static	DGs location & size, feeders location	Min total costs (fixed + variable)
[36]	Primary	New	Static	Substations size, feeders location & size	Multiobjective with weights
[37]	Primary	New	Static	Feeders location & size	Min investment and power loss cost
[38]	Primary	Expansion	Static	Substations, DGs, and feeders location & size	Multiobjective
[39]	Primary	Expansion	Static	Substations and feeders location & size	Min total costs (fixed + variable)
[40]	Primary	Expansion	Dynamic	Feeders location & size	Min cost (investment + loss + reliability)
[41]	Prim. + Second.	New + Expan.	Static	Substations and feeders location & size	Min total costs (fixed + variable)
[42]	Primary	Expansion	Static	Feeders location & size	Min total costs (fixed + variable)

Table 1 (*Continued*)

Reference	Distribution	Type	Period	Decisions (design variables)	Objective function
[43]	Primary	New	Dynamic	Feeders location	Min total costs (fixed + variable)
[44]	Primary	New	Static	Feeders location & size	Min investment and energy loss cost
[45]	Secondary	New	Static	Substations and feeders location & size	Min total costs (fixed + variable)
[46]	Primary	Expansion	Dynamic	Substations and feeders location & size	Min total costs (fixed + variable)
[47]	Primary	Expansion	Dynamic	Substations, DGs, and feeders location & size	Min total costs (fixed + variable)
[48]	Prim. + Second.	New	Static	Substations and feeders location & size	Min total costs (fixed + variable)
[49]	Primary	Expansion	Static	DGs and feeders location & size, switches status	Min total costs (fixed + variable)
[50]	Primary	New	Static	Feeders location	Min total costs (fixed + variable)
[51]	Primary	New	Static	Substations and feeders location	Min cost (investment + loss + reliability)
[52]	Primary	Expansion	Static	Feeders location	Min investment cost
[53]	Primary	New	Static	Feeders location	Min investment cost or max DG penetration
[54]	Primary	Expansion	Static	Substations and feeders location & size	Multiobjective
[55]	Primary	Expansion	Dynamic	Substations, DGs, and feeders location & size	Min total costs (fixed + variable)
[56]	Primary	New	Static	Substations and feeders location	Min investment and energy loss cost
[57]	Primary	Expansion	Dynamic	Substations, DGs, and feeders location & size	Min total costs (fixed + variable)
[58]	Primary	New	Static	Feeders location & size	Min investment and energy loss cost
[59]	Primary	Expansion	Static	Substations, DGs, and feeders location & size	Min total costs (fixed + variable)
[60]	Prim. + Second.	Expansion	Dynamic	Substations, DGs, and feeders location & size	Min total costs (fixed + variable)
[61]	Prim. + Second.	New + Expan.	Static	Substations and feeders location & size	Min total costs (fixed + variable)
[62]	Primary	New	Static	Feeders location & size	Min cost (investment + loss + reliability)
[63]	Primary	New + Expan.	Static	Feeders location & size	Min cost (investment + loss + reliability)
[64]	Primary	Expansion	Static	DGs location or size, feeders location	Multiobjective with weights
[65]	Primary	New + Expan.	Static	Feeders location & size	Multiobjective with weights
[66]	Primary	Expansion	Dynamic	Substations, DGs, and feeders location & size	Min total costs (fixed + variable)
[67]	Primary	Expansion	Dynamic	Substations, DGs, and feeders location & size	Min total costs (fixed + variable)
[68]	Primary	Expansion	Dynamic	Substations, DGs, and feeders location & size	Max a return-per-risk index
[69]	Primary	Expansion	Dynamic	Substations, DGs, and feeders location & size	Max a return-per-risk index
[70]	Secondary	New + Expan.	Static	Substations and feeders location & size	Min total costs (fixed + variable)
[71]	Primary	Expansion	Dynamic	Substations, DGs, and feeders location & size	Min total costs (fixed + variable)
[72]	Primary	Expansion	Dynamic	Substations, DGs, and feeders location & size	Min total costs (fixed + variable)
[73]	Primary	Expansion	Dynamic	DGs and feeders location & size	Multiobjective
[74]	Primary	Expansion	Dynamic	Substations and feeders location & size	Multiobjective
[75]	Primary	Expansion	Static	Feeders location & size	Min total costs (fixed + variable)
[76]	Primary	Expansion	Static	Feeders location	Min total costs (fixed + variable)
[77]	Primary	Expansion	Dynamic	DGs, feeders, and smart metering location & size	Min total costs (fixed + variable)
[78]	Primary	Expansion	Static	Substations, feeders, and charg. stat. location & size	Multiobjective
[79]	Primary	New	Static	Feeders location & size	Min total costs (fixed + variable)
[80]	Primary	New	Static	Feeders location & size, reclosers location	Multiobjective with weights
[81]	Primary	Expansion	Static	Substations, feeders, and charg. stat. location & size	Min total costs (fixed + variable)

3.1.4. Ordinal optimization (OO)

OO simultaneously optimizes PDP and electric vehicle charging stations planning [81].

3.1.5. Direct solution

The optimal feeder routing is solved by a direct approach that depends only on tracking radial paths and computing the cost of the paths [51,56].

3.2. Heuristic methods

3.2.1. Genetic algorithm (GA)

GA is applied for the solution of PDP problem [7,32,37,49,60,61,64,70]. The PDP is solved by GA in combination with quasi-Newton [9], optimal power flow (OPF) [47,57], and branch exchange [62]. A balanced GA in combination with data envelopment analysis solves multistage PDP under uncertainty [43]. GA is combined with graph theory to solve a PDP considering DG connection [35]. GA is applied to solve two problems: (1) the optimal MV substation problem, and (2) the optimal HV substations placement and feeders routing problem [28]. An interior point method embedded discrete GA co-optimizes DG and smart metering allocation simultaneously with network reinforcement [77]. A multiobjective GA is combined with geographic information systems to solve the PDP of open-loop MV networks [26]. A non-dominated sorting GA (NSGA) is applied for PDP [13,73]. NSGA-II, a variant of NSGA, is used to solve a multiobjective PDP [12,38]. A GA with problem-specific fix, crossover and mutation operators solves a multistage PDP [23]. A recombination-based evolutionary approach is used for finding the optimal distribution network topology [8]. The planning of secondary distribution networks is formulated as a MINLP problem that is solved by an evolutionary approach [5]. A strength Pareto evolutionary algorithm (SPEA) is applied for PDP [13,27].

3.2.2. Tabu search (TS)

A fuzzy model for the multiobjective PDP problem is solved by a TS method that computes the nondominated solutions corresponding to the simultaneous minimization of the fuzzy economic cost, the fuzzy expected nonsupplied energy, and the risk of overloading the feeders and/or substations [11]. The LV PDP of a real size distribution company is effectively solved by the method of [33] in combination with Voronoi diagrams and TS [30]. A constructive heuristic algorithm (CHA) in conjunction with TS solves the LV PDP [33]. A PDP considering DG and uncertainties is solved by TS with an embedded Monte Carlo simulation based probabilistic power flow model [79]. Multiobjective TS solves a dynamic PDP [74]. Multiobjective reactive TS in combination with CHA and GA solve a PDP [54]. TS and simulated annealing (SA) have been applied to solve the PDP and the conclusion is that TS is more efficient than SA [36].

3.2.3. Particle swarm optimization (PSO)

The MV and LV networks are simultaneously designed by a discrete PSO (DPSO) [48]. A modified DPSO solves a PDP considering DG and cross-connections [55,66]. A PDP considering DG and storage is solved by a modified PSO with local search [71]. An evolutionary PSO solves a PDP under uncertainty considering DG [68,69].

3.2.4. Evolutionary algorithms

A decomposition based multiobjective evolutionary algorithm seeks the Pareto front (non-dominated solutions) of a multiobjective PDP that also co-optimizes electric vehicle charging system planning [78]. A population-based evolutionary algorithm, the seeker optimization algorithm simultaneously optimizes PDP and automatic reclosers allocation [80].

3.2.5. Ant colony system (ACS)

A dynamic ACS algorithm solves a PDP that considers the installation of DG together with the reinforcement of feeders and substations [15].

3.2.6. Bacterial foraging (BF)

A BF technique solves the optimal feeder routing problem [50].

3.2.7. Simulated annealing (SA)

The PDP is solved by SA in combination with a steepest descent method [22] and in conjunction with MILP in [75].

3.2.8. Artificial immune system (AIS)

An AIS optimization method computes a set of nearly optimal solutions, which are next evaluated by a Monte Carlo simulation that considers load uncertainty, and, finally, the solutions are compared via a multiobjective analysis [17]. An immune system memetic algorithm, i.e., the AIS of [17] is combined with a network local search to solve the PDP under load uncertainty [42].

3.2.9. Artificial bee colony (ABC)

ABC computes the network reinforcements and the commitment schedule for the installed generating units [67].

3.2.10. Practical heuristic algorithms

A heuristic approach solves a value-based distribution system reliability planning problem [10]. The PDP is solved by a constructive heuristic algorithm [25,39,59,63]. A minimum spanning tree method solves feeder routing problem in distribution networks including DG [76]. A heuristic method solves a PDP in order to increase the penetration of DG [53]. A heuristic algorithm is developed to solve the PDP and a statistical approach is introduced to support network planers identify the best design strategy for given types of LV networks [45]. The PDP is solved by a branch-exchange technique in combination with minimum spanning tree [41] and DP [44,58]. The PDP is divided into the substation problem and the feeder problem; a pseudo-combinatorial algorithm solves the substation problem; next, the feeder problem is solved by two consecutive approaches: the node ordering and the node ordering directed branch exchange [14]. The geographic zone of a secondary distribution network is divided into small zones, and the LV PDP is solved independently in each zone combining heuristic algorithm and clustering technique [29]. A heuristic method for dynamic PDP is proposed based on back-propagation of the planning procedure starting from the final year [72].

3.3. Evaluation of PDP methods

The general PDP problem is nonlinear, non-differentiable, and combinatorial with a large number of binary, discrete and continuous variables. This section provides an evaluation of the methods used for PDP.

3.3.1. Evaluation of numerical methods

The numerical methods have the following advantages: the optimal solution is usually accurate and the time to compute the optimal solution is low. On the other hand, the numerical methods have the following disadvantages: it is difficult to manage power system equations into an optimization model; in order to insert a new constraint, the optimization model has to be rearranged and new equations have to be added.

Among the available numerical methods for PDP, the most efficient is the MINLP. In comparison to discrete numerical techniques, the continuous ones are much faster; however, they may not find the optimal solution due to the discretization of the continuous variables. The advantage of MILP is that it is fast, robust, and efficiently handles very large scale PDP problems; however, it may introduce errors due to the linearization of the nonlinear characteristics of PDP. The dynamic programming method is not suitable for large-scale PDP problems.

3.3.2. Evaluation of heuristic methods

Heuristic methods are easy to use and they do not require the conversion of the power system model into an optimization programming model. Moreover, heuristic optimization methods are usually robust and provide near-optimal solutions for complex, large-scale PDP problems; however, there is no guarantee that they will find a global optimum solution. Generally, they require high computational effort; however, this is not necessarily critical in PDP applications.

4. Contribution of the reviewed works

Table 2 describes, in a chronological order, the main contribution of the published PDP works reviewed. The parameter related to the active distribution network concept (if any) is also noted.

The material of Sections 2–4 and Tables 1–2 provides a guide to the reader about the approach to choose depending on the characteristics of the problem under consideration. The following examples are provided:

1. The method proposed in [6] is suitable for the simultaneous planning of primary and secondary distribution grids using MILP, as indicated in Section 3.1.1 and Table 1.
2. The approaches in [27,38] can be used for the investigation of the impacts of DG and ADN on PDP for different regulatory environments and tariff schemes, as shown in Table 2.
3. The method described in [25] is suitable for planning of ADNs with multiple controls (active and reactive power control of DG units, on-line network reconfiguration, demand side response, and generation curtailment), as shown in Table 2.
4. Efficient methods for planning active distribution networks with controlled distributed energy resources can be found in [19,27,32,34,38,59,60,63,64,66,68,69].
5. The approaches in [78,81] can be used for the simultaneous optimization of PDP and electric vehicle charging stations planning.
6. The method of [71] can be used for the simultaneous optimization of PDP and energy storage planning.

It is clearly beyond the scope of this paper to present to what extent and how power distribution utilities implement modern PDP approaches. It is well known however, that the majority of power distribution utilities still follow traditional PDP approaches without considering ADN concepts.

5. Future research

As already shown in the previous sections, a lot of research has been done in the area of power distribution planning in the modern power systems era. More specifically, Table 1 indicates that twenty different combinations of design variables and ten different types of objective functions have been studied in PDP, which has been applied to three types of distribution (Section 2.4), three types of problems (Section 2.5), and two different types of planning periods (Section 2.6). Moreover, Table 2 shows that nine different types of ADN components have been studied in PDP. The combination of these different types of modelling attributes creates a large number of PDP models. In addition, Section 3 indicates that fifteen types of optimization methods have been already proposed to solve PDP. Despite this large number of models and methods, there is clearly significant room for PDP research.

5.1. Evolution of PDP requirements

The shift that has started in the last decade towards modern PDP is expected to significantly increase in the years to come taking advantage of the innovations of modern power systems, under the terms of smart grids, distributed generation, microgrids, and active distribution networks.

1. Regulatory framework: modifications are needed to the regulatory framework so as to give the appropriate incentives to consider the costs and benefits of DER in the context of ADNs. More specifically, new market rules have to be implemented to remunerate: (1) the distribution system operators for their ADN service that allows increasing the DG revenue; and (2) the DER owners for the deferral of the investments their DERs can produce. The structure of tariffs is very important for the promotion of active distribution networks and their optimal planning. The PDP solutions have to improve the network operational performance and ensure power quality by fulfilling the regulation standards for signal conformity and service continuity, with the minimum impacts on the environment.
2. Coordinated planning: optimal location and sizing of capacitors, distributed generators, and distributed energy storage systems, and optimal planning of microgrids have to be simultaneously considered with substations and feeders' expansion or upgrade. It should be noted that the upgrade of equipment (substations and feeders) is the most commonly chosen alternative in heavy populated urban areas, where it is very difficult and costly to find space for new substations and to obtain rights of way for new power distribution lines.
3. Non-dispatchable DGs: the installation of non-dispatchable DGs (e.g., wind and photovoltaics) increases rapidly in various areas worldwide. However, existing PDP models consider only dispatchable DGs (e.g., diesel units, gas micro-turbines, and fuel cells). Future PDP models have to consider both types of DGs, taking also into account the DG owner (utility or private investor).
4. Uncertainties: various parameters of PDP are uncertain, e.g., future load growth, power of plug-in electric vehicles, market prices, future capital costs, wind power generation, and solar power generation. Consequently, appropriate PDP models and solution methods, e.g., stochastic optimization, risk analysis, or robust programming algorithms, are needed to handle these uncertainties. Given the uncertainty in long-term PDP, the distribution networks have to be designed as flexible as possible and DG is an alternative that offers enough flexibility.
5. Cost of reliability: successful PDP models have to quantify and take into account the cost of reliability. The service reliability has to include not only the service continuity but also the service quality. Multiobjective formulations, including as objective the reliability cost are possible. However, accurate quantification of the reliability cost is not easy, since it requires more accurate data both from the supplier and the customer sides.
6. Utility applications: advanced models and methods already exist for PDP. However, the majority of distribution utilities still use heuristic processes and empirical rules through expert judgement and practical analysis for PDP. The collaboration between researchers and utility planners provides great opportunities for the development of models and methods well fitted to the utility needs and applied for real-world PDP problems of distribution utilities.
7. New loads and storage: new components, such as heat pumps and energy storage systems, including plug in and hybrid plug in electric vehicles, have to be further studied in the context

Table 2
Contribution of the reviewed power distribution planning works.

Reference	Published	Contribution	ADN component
[5]	Jan. 2005	A PDP model that considers the unbalanced loads and the optimal balancing of loads to the three phases.	
[6]	May 2005	An optimization model is formulated for the simultaneous planning of primary and secondary distribution grids. The method is applied to a real case of a residential primary–secondary distribution grid with 75 buses.	
[7]	May 2005	A general mathematical model is developed for the planning of low voltage power distribution networks.	
[8]	Nov. 2005	The role of individual quality of service standards in PDP and corresponding quality is investigated. Results show how system optimal reliability and optimal quality change with the setting of individual quality standards.	Autom. switch.
[9]	Nov. 2005	The PDP is solved by a hybrid algorithm that combines a quasi-Newton and a GA in a sequential iteration.	
[10]	Nov. 2005	A value-based probabilistic approach is developed for the design of urban power distribution networks. The method is applied to a real urban distribution network and practical network design rules are derived.	
[11]	Feb. 2006	A fuzzy PDP model that simultaneously optimizes the economic cost, the reliability, and the risk of overloading. Results from the application of the method in real distribution networks show its practical usefulness.	
[12]	Apr. 2006	A GA with specific crossover and mutation operators specially-designed for PDP. The results in the form of Pareto optimal set are valuable to aid distribution companies to decide on the investment policy.	
[13]	Nov. 2006	NSGA and SPEA with a fuzzy c-means clustering algorithm solve a multiobjective PDP. The results indicate the flexibility and the practical application of the proposed method.	
[14]	Apr. 2007	Hybrid algorithms decouple the PDP into the substation and feeder sub-problems.	
[15]	May 2007	A PDP model that considers the reinforcement of feeders and substations as well as the integration of DG. The results show that it is better to plan together network reinforcement and DG instead of planning them separately.	DG integration
[16]	May 2007	A generalized horizon planning (20+ years ahead) for the simultaneous design of primary and secondary grids.	DG integration
[17]	May 2007	The PDP under load uncertainty is solved by AIS in conjunction with Monte Carlo simulation. Results indicate that the proposed approach provides robust network designs under load evolution uncertainties.	
[18]	May 2007	The planning model [16] is validated and applied for evaluating spatial forecast impacts on distribution design.	DG integration
[19]	May 2007	A novel multi-year optimization algorithm for planning active distribution networks with DER. Real world examples illustrate the effectiveness of the proposed methodology for planning active distribution networks.	DER control
[20]	Apr. 2008	A MILP PDP model is developed using dc power flow in combination with a linear disjunctive model.	Load control
[21]	Apr. 2008	Evaluation of the model [20], investigating the impact of DG, investment constraints, and load levels. A significant cost reduction is obtained when using dynamic (multistage) planning instead of static (sequential) planning.	DG integration
[22]	May 2008	A SA method solves the PDP, using as initial solution the one found by a steepest descent technique.	
[23]	May 2008	A multistage PDP is solved by dynamic programming GA with problem-specific fix, crossover and mutation operators. Results show that the proposed method works for problem sizes that exact DP is infeasible.	
[24]	Jun. 2008	A multistage multiobjective PDP model for distribution substation sitting, sizing, and timing.	
[25]	Jul. 2008	A novel PDP for ADN with multiple controls including active and reactive power control of DG units, on-line network reconfiguration, demand side response, and generation curtailment.	ADN with multiple controls
[26]	Feb. 2009	A multiobjective PDP model for open-loop MV networks using geographic information systems.	
[27]	Mar. 2009	A flexible PDP evaluates different regulatory environments and tariff schemes for DER integration. Results indicate the importance of tariff schemes in conjunction with optimal planning of DER and network reinforcement.	DER control
[28]	May 2009	Heuristic algorithms for locating HV substations, MV substations, and MV feeders. Results indicate the ability of the proposed method for application in large-scale power distribution planning problems.	
[29]	May 2009	The PDP is solved independently in each zone of the planning area considering street constraints. The method is applied for planning a large-scale low voltage distribution network over an area of 12.9 km^2 with 20 215 consumers.	
[30]	May 2009	The method of [29] in combination with Voronoi diagrams and TS solves the PDP of a distribution utility. The method is applied for planning a low voltage network over an area of 2118 km^2 with nearly 1 300 000 consumers.	
[31]	May 2009	A planning model that evaluates the remuneration of the fixed costs of distribution networks with DG. Results show that simultaneous planning of DG integration and network reinforcement can reduce reinforcement costs.	Load control
[32]	Jun. 2009	Investigation of the impact of energy carrier systems on PDP and the adequacy of system under contingencies.	DER control
[33]	Aug. 2009	An integrated model for the simultaneous planning and development of secondary distribution projects.	
[34]	Dec. 2009	A hierarchical dynamic optimization model for PDP considering interties and investor DG investments. Results show that capital investments in DG are barely justified by their energy cost savings over a 10-year planning period.	DER control

Table 2 (*Continued*)

Reference	Published	Contribution	ADN component
[35]	Mar. 2010	A PDP with DG connection as planning alternative, considering specific constraints related to DG connection.	DG integration
[36]	Apr. 2010	SA and TS are compared in solving nine PDP problems within 500–30 000 load points and 20 substations. Results show that the efficiency of SA decreases as the problem size increases, and TS is more efficient than SA.	
[37]	Jul. 2010	The PDP is separated by feeder areas based on an equitable distribution of loads among the feeder areas.	
[38]	Jul. 2010	The impacts of DG and ADN on PDP have been analyzed for six different regulatory environments. The obtained results can help regulators define a fairer asset and performance based distribution revenue.	DER control
[39]	Aug. 2010	The PDP is formulated as a mixed binary NLP problem and solved by a constructive heuristic algorithm.	
[40]	Oct. 2010	A graph theory formulation decomposes a dynamic PDP into a number of static PDP problems. Simulation results indicate the capability of the proposed method to improve the quality of the multistage PDP process.	
[41]	Feb. 2011	Simultaneous plan for high, medium, and low voltage networks, considering the street map for cables layout. Simulation results indicate that the incorporation of street maps significantly affects the solution of PDP.	DG integration
[42]	Feb. 2011	An immune system memetic algorithm solves more efficiently the PDP in comparison with the AIS of [17].	
[43]	May 2011	A balanced GA provides higher intensity searching and filtering of the PDP solutions.	
[44]	Jul. 2011	A special algorithm and the utilization of parallel computing allow the solution of large-scale PDP problems. Results show that the proposed method efficiently optimizes large distribution grids with thousands of loads.	
[45]	Jul. 2011	A statistical approach supports decision makers identify the best design strategy for LV distribution networks. Application results highlight the main features and the differences in the optimal planning of urban and rural areas.	
[46]	Oct. 2011	A PDP model finds a pool of solutions, assisting the decision maker to evaluate and select from that pool. Application results help compare the reliability cost for the electric utility and its customers.	Load control
[47]	Oct. 2011	DG integrated multistage PDP considering DG operating strategy, reliability improvement, and load variation. Results show that the integration of DG in PDP can reduce cost and increase reliability.	DG integration
[48]	Oct. 2011	Integrated planning of MV and LV grids applicable to consumption areas with uniform and non-uniform loads.	
[49]	Nov. 2011	Planning DG integration in combination with distribution network expansion considering DG and demand response uncertainties. Results show that better solutions are obtained when all scenarios are analyzed simultaneously.	DG integration + demand response
[50]	Jan. 2012	The optimal feeder routing is solved by a problem-specific BF technique requiring fewer parameters to be tuned. Results show that there is a good probability the solution, which is computed quickly, to be the global optimum.	
[51]	Jan. 2012	A direct solution method to optimal feeder routing problem of radial distribution systems. Results indicate that the proposed method reduces problem complexity without compromising solution optimality.	
[52]	Feb. 2012	Methodology for the spatial PDP considering variant environmental factors in the feeder routing formulation. Results show that more economical planning solution can be obtained by considering variant environmental factors.	
[53]	Feb. 2012	A method to optimize current French urban network architecture (secured feeder) to increase DG penetration.	Autom. switch.
[54]	Mar. 2012	The PDP is solved together with the placement of sectionalizing switches to reduce non-supplied energy costs.	Autom. switch.
[55]	Apr. 2012	An integrated PDP including DG and cross-connections is proposed to improve reliability and voltage profile. The results show that the lowest cost plan is obtained when all technologies are simultaneously optimized.	DG integration
[56]	Jun. 2012	A PDP model is proposed to determine the trade-off between minimum cost and higher reliability.	
[57]	Jul. 2012	A dynamic PDP model considering DG and the electricity market impact via a load-dependent electricity price.	DG integration
[58]	Jul. 2012	The PDP model [44] is validated and applied for solving large-scale PDP problems in reduced time.	
[59]	Aug. 2012	Investigation of the influence of the reliability of information and communication technology on ADN planning. Preliminary results show that WiMAX communication technology is reliable enough for application to ADNs.	DER control
[60]	Sep. 2012	A PDP considering the impact of wholesale and retail markets and the system adequacy under contingencies.	DER control
[61]	Oct. 2012	A PDP model simultaneously optimizes the quantity, location and size of MV/LV distribution transformers (DTs). Results show that the influence area of DT depends on network layout, loads, and size of the DT.	
[62]	Nov. 2012	Long term PDP considering urbanity uncertainties introducing the points with high accessibility.	
[63]	Dec. 2012	A PDP evaluates the impact of MV connected microgrids on grid topology, reliability, and expansion savings. Results show that the microgrids offer considerable cost savings in networks designed with optimal backup.	DER control
[64]	Feb. 2013	A PDP model considering DGs and upgrade of network from normally closed loop to a mesh arrangement.	DER control
[65]	Mar. 2013	Optimal feeder routes and branch conductor sizes obtained via simultaneous optimization of cost and reliability.	

Table 2 (*Continued*)

Reference	Published	Contribution	ADN component
[66]	May 2013	Integrated planning of DGs, capacitors, substations, and feeders using DPSO and time-segmentation. Results demonstrate that the main benefit of dispatchable DGs is to defer distribution network upgrade.	DER control
[67]	Jul. 2013	ABC solves dynamic PDP considering DG integration and demand variation. The proposed ABC is applied to systems with up to 45 buses and the results are compared with those obtained by comprehensive learning PSO.	DG integration + load control
[68]	Aug. 2013	Implementation of real options valuation to quantify the investment deferral benefit of DG in the context of PDP.	DER control
[69]	Aug. 2013	The PDP model [68] is applied for the evaluation of DGs as expansion options to defer network reinforcements.	DER control
[70]	Oct. 2013	PDP model for unbalanced LV distribution networks considering the impacts of micro DG and system reliability. Results highlight the impact of unbalanced loads on the optimal planning of low voltage distribution networks.	DG integration
[71]	Nov. 2013	Integrated planning of DGs, storage units, substations, and main and reserve feeders using modified PSO. Results show that the proposed integrated planning can reduce system cost and increase network reliability.	DG + storage
[72]	Dec. 2013	A back-propagation approach based on cost–benefit analysis solves the PDP considering DG integration.	DG integration
[73]	Dec. 2013	A multiobjective multi-year PDP simultaneously considering DG allocation and network reconfiguration. The results indicate the effectiveness of the proposed method in reducing significantly the costs and the gas emissions.	DG integration
[74]	Jan. 2014	A dynamic multistage PDP allows a comprehensive analysis of the investments made in the planning horizon. Results demonstrate that some investments can be avoided and others can be postponed, thus reducing the total cost.	Autom. switch.
[75]	Mar. 2014	A hybrid SA and MILP approach for expansion planning of radial distribution networks with DG units. Results indicate that failures at DGs may have considerable impact on the optimal expansion plan.	DG integration
[76]	May 2014	A graph theoretic approach including reliability assessment is proposed for feeder routing in distribution networks with DG. The proposed approach is compared with five other methods in power systems with up to 123 buses.	DG integration
[77]	May 2014	Results from joint planning of network reinforcement, renewable DG and demand response indicate increased environmental benefits (CO_2 reduction) than integrating renewable DG alone.	DG integration + demand response
[78]	Jul. 2014	Results show that the simultaneous power distribution planning and electric vehicles charging system planning can significantly improve investment efficiency.	Electric vehicles integration
[79]	Jul. 2014	PDP considering the uncertainties of renewable DG output, load evolution, and electricity price growth.	DG integration
[80]	Dec. 2014	Simultaneous co-optimization of PDP and automatic reclosers allocation by seeker optimization algorithm.	Autom. switch.
[81]	Dec. 2014	Results from the simultaneous planning of PDP and electric vehicle charging stations show that the vehicle-to-grid features can efficiently reduce the operational costs of the power distribution network.	Electric vehicles integration

of modern PDP. Energy storage units can offer peak shaving, reliability enhancement, and increased DG penetration. The simultaneous power distribution planning and electric vehicle charging system planning can reduce distribution system investment and operation cost, promote the use of electric vehicles, and reduce CO_2 emissions.

8. Planning of intelligent distribution management system (IDMS): the distribution systems of the future will face a huge penetration of distributed energy resources (DERs). IDMS with advanced metering infrastructure will allow real-time communication between utilities, service providers and customers to exchange useful price and energy information together with offer and command signals. The role of IDMS is to support the integration of DERs into distribution systems and improve the efficiency of DERs operation [83]. The impact of IDMS on modern PDP has to be studied.

5.2. *Evolution of PDP methods*

1. Advanced optimization methods: the PDP problem belongs to the class of facility location and network topology optimization (FLNTO) problem. Both problems involve continuous and discrete variables and share common characteristics. Since the FLNTO problem forms an active research area of optimization methods, the findings of FLNTO could be also useful for the PDP problem.
2. Decomposition: the PDP is a large-scale problem, because of the size of a typical distribution network and due to the fact that the best way to plan the system is through the multistage (dynamic) approach. To solve the large-scale PDP, decomposition methods are applied to the size of the network (spatial decomposition) or to the planning period (time decomposition). As the PDP becomes even more challenging nowadays, more efficient decomposition methods for the solution of PDP are needed.
3. Initial population in heuristic algorithms: the initial population, which is necessary in some heuristic algorithms, could be intelligently produced based on practical rules extracted from the experience of engineers from the planning division of electric utilities.
4. Parameters setting in heuristic methods: the optimal settings of the parameters of the heuristic methods (e.g., GA, PSO, ACS) are estimated in a trial and error fashion. It is proposed that these parameters are adaptively and automatically tuned to improve the efficiency of the heuristic PDP techniques.

6. Conclusions

This paper presents a thorough overview of the state of the art models and optimization methods applied to the PDP problem in the last decade, analyzing and classifying current and future research trends in this field. The most common PDP model of the last decade has the following characteristics: (1) it is applied for the static expansion of primary distribution system; (2) the design variables include the integrated optimization of the location and size of substations and feeders; and (3) the objective is the minimization of the total fixed and variable costs. It should be noted that: (1) 55% of the reviewed PDP papers cover at least one attribute of the active distribution network functionality, e.g., DER control, load control, automatic switching, and DG integration; (2) the simultaneous optimization of the location and size of substations, DGs and feeders holds the second position among all the design variables; and (3) the multiobjective formulation is in the third position among all different objective functions. Moreover, the majority of the papers published in the last two years deal with modern PDP issues. The above findings show the shift of modern PDP towards more integrated, multiobjective, and DG integrated solutions with control functionalities, in comparison to the traditional PDP models. The solution methodologies for the PDP problem are classified into two major categories: numerical and heuristic methods. The most frequently used techniques for the solution of the PDP problem are the *genetic algorithm* and various *practical heuristic algorithms*. Future research areas include evolution of PDP, planning of intelligent distribution management system, utility applications, coordinated planning, consideration of uncertainties, decomposition, and advanced optimization methods.

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