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REVIEW

Optimal allocation of protection and control devices in smart distribution systems: Models, methods, and future research

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Abstract

The fundamental goal of the distribution system operator (DSO) is to serve its customers with reliable and low-cost electricity. Failures in power distribution systems are responsible for 80% of customer service interruptions. The emergence of smart distribution system (SDS) with advanced distribution automation (DA) and communication infrastructure offers a great opportunity to improve reliability, through the automation of fault location, isolation, and service restoration (FLISR) process. DA includes the installation of protection and control devices (PCD). The use of PCD makes fault management more efficient, reduces average outage duration per customer in case of faults, reduces costs due to unsupplied energy, and improves distribution system reliability. Although the use of PCD remarkably enhances distribution system reliability, it is neither economical nor affordable to install them in all potential locations. To obtain the optimal allocation of PCD (OAPCD), an optimisation problem has to be formulated and solved. Several models and methods have been suggested for the OAPCD in SDSs. Herein, an overview of the state-of-the-art models and methods applied to the OAPCD in SDSs are introduced, identifying the contributions of reviewed works, identifying advantages and disadvantages, classifying and analysing current and future research directions in this area.

1 | INTRODUCTION

The fundamental goal of the distribution system operator (DSO) remains always the same—to serve its customers with a reliable and low cost electricity. However, DSOs are continuously concerned with meeting contradictory objectives: satisfy customer demands for high power quality and increased energy consumption, fulfil regulatory targets for reliability, and improve distribution network availability and performance without increasing electricity cost. The deregulation of electricity sector and the increased competition exerts more pressure to DSOs to further reduce costs and increase reliability.

The power distribution system has several components that are subject to failures, including poles, cables, overhead conductors, switches, breakers, voltage regulators, capacitors, and transformers [1]. Power interruptions in distribution systems are caused by several reasons, including faulty equipment, bad weather conditions, unpredictable accidents (e.g. kites), animals (e.g. birds), and contact with trees. These events reduce distribution system reliability because they represent non-scheduled power interruptions for the affected customers. It has been found that 80% of customer service interruptions is due to failures in power distribution systems. Moreover, about 70% of the total interruption duration in power systems is due to failures in primary distribution systems.

Regulatory authorities and DSOs use reliability indices to evaluate the reliability and performance of distribution systems. There are two categories of reliability indices: customer oriented and load oriented indices. Customer oriented reliability indices include system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI), and momentary average interruption frequency index (MAIFI). Load oriented reliability indices include average system interruption frequency index (ASIFI) and average system interruption duration index (ASIDI) [2].

To improve reliability, a distribution automation (DA) is developed within the power distribution systems. DA includes installation of protection and control devices (PCD), for example, circuit breakers, reclosers, fuses, fault indicators, and sectionalisers [3,4]. DA uses digital sensors and switches with advanced control and communication technologies to automate several functions, including outage management, voltage control, feeder switching, and reactive power management. The use of PCD makes fault management more efficient, reduces average outage duration per customer in case of faults, reduces costs due to unsupplied energy, and improves distribution system reliability. Although the use of PCD remarkably enhances distribution system reliability, it is neither economical nor affordable to install them in all potential locations. To obtain the optimal allocation of PCD (OAPCD), an optimisation problem has to be formulated and solved. The OAPCD improves distribution system's resilience to fault events, and reduces operation costs by making more efficient use of repair personnel and by implementing more effective monitoring and maintenance of equipment. Thus, OAPCD helps increase the income of DSOs and increase service reliability to customers. The development of OAPCD differentiates by several factors, including number of customers and their importance, load density, network type (overhead or underground), and available budget.

The power distribution system is changing quickly in recent years, forming the smart distribution system (SDS) of the new era [3,5]. One of the major reasons of the changes is the large penetration of distributed energy resources that include distributed generation (DG) units, demand response, and energy storage systems [6,7]. The optimal allocation of renewable and non-renewable DG units into SDSs has a lot of benefits, including environmental advantages, reliability improvement, deferral of network upgrades, lower losses, and lower costs [8].

Recent review works have analysed the optimal operation and planning of SDSs. More specifically, the work [1] reviews the reliability of power distribution system components and provides relevant data including failure rates and the change of failure rates due to aging. The work [9] reviews big data analytics for smart grids. The works [8,10] review the optimal allocation of DG units and charging stations for electric vehicles, respectively, at SDSs. The work [11] reviews islanding detection methods of DG units at SDSs. The work [12] reviews the optimal planning models and methods of SDSs.

The integration of DG units creates challenges associated with the protection of SDSs. More specifically, problems that may arise due to DG units include feeder false tripping, DG unit false tripping, protection blinding, short circuit level increase or decrease, undesirable network islanding, and prevention of asynchronous automatic reclosing [13]. To avoid these problems, the protection system of the SDS has to be redesigned [14]. In this context, the work [15] reviews protection systems for power distribution networks with renewable DG units, and the work [16] reviews protection in DC microgrids.

Another feature of the SDS is the automation of the outage management process that includes fault location, isolation, and service restoration (FLISR). The objective of automatic FLISR is to increase reliability and decrease operation and maintenance costs, leading the SDS to a self-healing condition [17]. Many efforts have been devoted to design automatic FLISR mechanisms by developing appropriate hardware and software. Hardware includes PCD, and communication infrastructure, which automate FLISR [18,19]. Software includes methods and computer algorithms for the automation of FLISR [20].

Additional DA solutions for SDSs have been proposed in the bibliography. The work [21] reviews the challenges associated with the implementation of DA in SDSs. The work [22] reviews control issues of distribution system automation in SDSs. The work [23] reviews distribution network reconfiguration for reliability improvement and power loss reduction.

The above bibliography review shows that there is no review paper which focused on the OAPCD in SDSs. This study covers this bibliography gap and introduces a taxonomy of models and methods for the allocation of PCD in SDSs, offering a unified presentation of a relatively large number of selected high quality research works [24–121], published in high quality international journals.

The contributions are manifold:

- It is the only review paper of the bibliography that is focused on the OAPCD in SDSs.
- It is the first paper that reviews models for the OAPCD in SDSs, identifies their contributions, and introduces various well-designed classifications.
- It provides future research directions and sets the future research goals of coordinated distribution system planning, enhanced reliability assessment, advanced protection, consideration of communication infrastructure, increased penetration of variable DG, detailed fault management, focused objectives, consideration of network operational constraints, consideration of uncertainties, and advanced optimisation methods for the OAPCD in SDSs.
- It serves as a guide to aid engineers and researchers on the available models and methods as well as the future research trends in the OAPCD of SDSs.

The structure of the study is as follows. Section 2 analyses and classifies the models for the OAPCD in SDSs. Section 3 reviews the optimisation methods for the OAPCD in SDSs and identifies the core contribution of the reviewed works. Section 4 provides future research directions. Section 5 summarizes the main findings and concludes the paper.

2 | MODELS FOR OPTIMAL ALLOCATION OF PROTECTION AND CONTROL DEVICES

In the reviewed papers [24–121], different models are considered for the OAPCD in SDSs. In the following, the OAPCD models are classified according to types of devices, design variables, consideration of DG, objectives, and consideration of power flow constraints.

2.1 | Types of devices

The most commonly investigated PCD are the following:

2.1.1 | Sectionaliser

The counter sectionaliser is a protection device that automatically isolates a de-energized faulted line section from a power distribution network. The sectionaliser is a self-contained circuit opening device, which is typically used in conjunction with reclosers or reclosing relays associated with circuit breakers. During a fault, the reclosing device performs a predetermined number of circuit interruptions. The sectionaliser senses and responds to the predefined number of successive electric circuit impulses of a predefined magnitude, caused by the reclosing device operation. The sectionalizing switch is another type of sectionaliser, which can operate manually or automatically to enable network reconfiguration in both normal and abnormal conditions. The automatic sectionalizing switch is called remote controlled switch (RCS) or load break switch. Its operation can be controlled from a remote control centre via a motorised mechanism and telecontrol equipment. The allocation of sectionaliser is considered in the following reviewed works [24–26,28,30,32–38,40–42,44,45,47,48,50,52,54–60,62,64,65,67–69,71–83,85–87,89–96,98–100,102–108,110–118,120,121].

2.1.2 | Recloser

The recloser automatically interrupts and recloses an electrical circuit with a predefined sequence of opening and reclosing. Typically, in case of a temporary fault, the recloser clears the fault and next quickly restores service. In case of a permanent fault, the recloser disconnects the faulted circuit or lets other protection equipment (e.g. lateral fuses) clear the fault. The allocation of the recloser is considered in the following reviewed works [27,29,31,35,39,41,43,45,46,48–50,54,64,69,74,77,78,83,84,87,89,90,94,100,104,105,113].

2.1.3 | Fuse

A fuse provides overcurrent protection of electric circuits. In case an overcurrent passes through the fuse, it is heated and, depending on time, it may melt. The allocation of fuse is considered in the following reviewed works [27,29,31,35,41,45,48–50,63,64,77,85,89,94,98–100,104,108,110,113], and [117].

2.1.4 | Circuit breaker

A circuit breaker is a device for making or interrupting an electrical circuit under load or fault conditions. Its basic protection function is to interrupt current flow after the detection of a fault. The trip order for the interruption is given either from the circuit breaker itself or by an associated protection relay. The allocation of circuit breaker is considered in the following reviewed works [44,54,66,85,86,99,104,117].

2.1.5 | Fault indicator

The fault indicator enables visual or remote indication of faults on the power distribution network. The fault indicator picks-up when it senses an inrush current or short circuit in the distribution line on which it is placed. When a fault takes place downstream the fault indicator, it sends a signal to the control centre. The allocation of fault indicator is considered in the following reviewed works [51,53,54,61,70,87–91,97,101,105,106,108–110,118–120].

2.2 | Design variables

In the reviewed papers [24–121], the following design variables are investigated:

1. Location. In this case, the model for OAPCD finds the optimal location for the installation of PCD. With the exception of [88], all other 97 reviewed papers consider location as a design variable.
2. Number. In this case, the model for OAPCD finds the optimal number of PCD to be installed.
3. Type. In this case, the model for OAPCD finds the optimal type (e.g. sectionaliser, recloser, fuse, circuit breaker, or fault indicator) of PCD to be installed at each optimal location.
4. Time. In this case, the model for OAPCD finds the optimal time (usually year) each PCD has to be installed during a multiyear planning horizon. Only the works [86,88,89], and [110] consider time as a design variable.

2.3 | Distributed generation

Among the reviewed papers, the following OAPCD works consider DG units: [34,39,43,46,47,56,57,62,66,67,75,77–79,81,82,84,85,87,90,92,93,100,104,107,115,119].

2.4 | Objectives

There are three cases depending on the number of investigated objectives and the objective function form:

1. Single objective. The most common single objective is the minimisation of the total cost, which is the objective function of the OAPCD problems of the works [24–26,28,30,36,40–42,45,50,51,56–58,69,71,72,75,76,82,85,87,90,91,97–99,101–107,112,113,115–118,120], and [121]. The objective is to minimise the total cost, which is the sum of

the cost for the installation and maintenance of PCD and the service interruption cost.

2. Multiple objectives with weights [31,47,62], and [111]. In this case, the DSO selects fixed weights for the individual objectives, and as a result, the objective function, which is the weighted sum of the multiple objectives, reduces to a single objective function.
3. Multiple objectives [29,34,48,52,54,55,59,60,67,70,73,74, 77,78,80,84,86,93,95,100,108,109], and [119]. In this case, there are multiple objectives for the OAPCD problem, and the proposed multi-objective optimisation method first calculates the set of Pareto optimal solutions, and, then, it calculates the best compromise solution among the set of Pareto optimal solutions.

2.5 | Power flow constraints

Out of 98 papers, 37 works consider the power flow constraints at their optimisation models [26,28,32–34,39,44,45,47,48,50,52,54-57,59,62,65–68,71,76,79,81,82,90,92,93,96,99,100,107,108,110, 115], and [117].

2.6 | Taxonomies

Tables 1 and 2 classify the reviewed models and optimisation problems, respectively, for OAPCD in SDSs.

3 | METHODS FOR OPTIMAL ALLOCATION OF PROTECTION AND CONTROL DEVICES

The optimisation methods that have been developed to solve the models for the OAPCD of the reviewed works are classified into analytical, numerical, and computational intelligence based optimisation methods.

3.1 | Analytical methods

The following analytical methods have been used for the solution of the OAPCD problem:

- Exhaustive search [28,66];
- An analytical method, by setting the partial derivatives of energy not supplied (ENS) equal to zero [37];
- Analytic hierarchy process [55].

The main advantage of analytical optimisation methods is that they can be easily implemented. The main disadvantage of analytical optimisation methods is that their results are only indicative, since they make simplified assumptions including the consideration of only one type of protection device [28,37,55].

The main advantage of the exhaustive search method is that it guarantees the finding of the optimal solution. However, the main disadvantage of the exhaustive search is that it needs prohibitively high computing time for large-scale OAPCD problems.

3.2 | Numerical optimisation methods

The following numerical optimisation methods have been used for the solution of the OAPCD problem:

- Dynamic programming [30,114];
- Goal programming [31];
- Mixed integer linear programming (MILP) [27,29,41, 58,72,75,87,90,92,96,97,101–106,109,111–113,115,118,120, 121];
- Mixed integer non-linear programming (MINLP) [49,64,83, 85,94,98,107].

The main advantage of MINLP is that it solves the original nonlinear OAPCD problem, without the need to convert the optimisation problem to a linear one. This means that the solution of MINLP is the solution of the original OAPCD problem. However, the main disadvantage of MINLP is that it needs very high computation time for large-scale OAPCD problems. Dynamic programming is also not suitable for large-scale problems, because it suffers from the curse of dimensionality problem.

The main advantage of MILP for OAPCD is that using available commercial optimisation solvers, the MILP formulation guarantees the finding of the global optimum solution very fast even for large-scale OAPCD problems. However, the main disadvantage of MILP is that the original nonlinear OAPCD problem has to be converted to a linear optimisation problem, which may have a slightly different optimal solution in comparison with the original nonlinear optimisation problem.

3.3 | Computational intelligence based optimisation methods

The following computational intelligence based optimisation methods (also called metaheuristic optimisation methods) have been used for the solution of the OAPCD problem:

- Alliance algorithm [62];
- Ant colony system (ACS) [33,46–48];
- Artificial bee colony (ABC) [76,81,93];
- Differential evolution (DE) [84];
- Differential search [80];
- Genetic algorithm (GA) [24,25,35,36,39,43,53,56,57,61, 78,86,88,89,91,95,99,100,108,110,116,117,119];
- Greedy randomized adaptive search procedure [82];
- Immune algorithm [42,51];
- Memetic algorithm [71,74];

TABLE 1 Taxonomy of the reviewed models for OAPCD

References	Types of Devices	Design Variables	Includes DG
[25,32,33,52,55,65,114]	Sectionaliser	Location	No
[56,57,81,92]	Sectionaliser	Location	Yes
[24,26,28,30,36–38,40,42,58,59,68,71–73,76,80,95,96,102,103,111,112,116,121]	Sectionaliser	Number + location	No
[34,47,62,67,75,79,82,93,107,115]	Sectionaliser	Number + location	Yes
[60]	Sectionaliser	Number + type + location	No
[39,43,46]	Recloser	Location	Yes
[84]	Recloser	Number + location	Yes
[63]	Fuse	Number + location	No
[66]	Circuit breaker	Number + location	Yes
[53,61]	Fault indicator	Location	No
[119]	Fault indicator	Location	Yes
[51,70,97,101,109]	Fault indicator	Number + location	No
[88]	Fault indicator	Time	No
[69]	Sectionaliser + recloser	Location	No
[74,83]	Sectionaliser + recloser	Number + type + location	No
[78]	Sectionaliser + recloser	Number + type + location	Yes
[94]	Sectionaliser + recloser + fuse	Number + location	No
[77]	Sectionaliser + recloser + fuse	Number + location	Yes
[35,41]	Sectionaliser + recloser + fuse	Type + location	No
[45,48,50,64,113]	Sectionaliser + recloser + fuse	Number + type + location	No
[100]	Sectionaliser + recloser + fuse	Number + type + location	Yes
[104]	Sectionaliser + recloser + fuse + circuit breaker	Number + type + location	Yes
[89]	Sectionaliser + recloser + fuse + fault indicator	Type + location + time	No
[54]	Sectionaliser + recloser + circuit breaker + fault indicator	Number + type + location	No
[105]	Sectionaliser + recloser + fault indicator	Number + type + location	No
[87,90]	Sectionaliser + recloser + fault indicator	Number + type + location	Yes
[98]	Sectionaliser + fuse	Number + type + location	No
[99,117]	Sectionaliser + fuse + circuit breaker	Number + type + location	No
[85]	Sectionaliser + fuse + circuit breaker	Number + type + location	Yes
[108]	Sectionaliser + fuse + fault indicator	Number + location	No
[110]	Sectionaliser + fuse + fault indicator	Type + location + time	No
[44]	Sectionaliser + circuit breaker	Number + location	No
[86]	Sectionaliser + circuit breaker	Number + type + location + time	No
[91,106]	Sectionaliser + fault indicator	Number + location	No
[118,120]	Sectionaliser + fault indicator	Number + type + location	No
[27,29,31,49]	Recloser + fuse	Type + location	No

TABLE 2 Taxonomy of the reviewed optimisation problems

Reference	Objective	Objective Function	Power Flow Constraints
[79]	Single	Minimisation of the total number of switches	Yes
[24,25,30,36,40–42,51,58,69,72, 75,85,87,91,97,98,101–106,112,113,116,118,120,121]	Single	Minimisation of the total cost for the installation and maintenance of protective devices and the service interruption cost	No
[26,28,45,50,56,57,71,76, 82,90,99,107,115,117]	Single	Minimisation of the total cost for installation and maintenance of protective devices and the service interruption cost	Yes
[89]	Single	Maximisation of the power distribution company profit during the planning period	No
[110]	Single	Maximisation of the power distribution company profit during the planning period	Yes
[38]	Single	Minimisation of reliability cost	No
[83,94]	Single	Maximisation of the power distribution company revenue earning	No
[81]	Single	Maximisation of distribution system loadability	Yes
[32,33,44]	Single	Minimisation of customer interruption cost	Yes
[39]	Single	Minimisation of a composite reliability index	Yes
[43,46]	Single	Minimisation of a composite reliability index	No
[68]	Single	Minimisation of load dispersion among feeders	Yes
[53]	Single	Minimisation of the distance among the locations that are suspected to be location of the fault	No
[65]	Single	Minimisation of the expected energy not supplied (ENS)	Yes
[37]	Single	Minimisation of the ENS	No
[88]	Single	Minimisation of the investment financed externally	No
[92]	Single	Optimisation of an index for the resilience of the distribution network	Yes
[66]	Single	Minimisation of the risk to network faults	Yes
[96]	Single	Minimisation of SAIDI	Yes
[27,35,49]	Single	Minimisation of SAIFI	No
[64]	Single	Minimisation of SAIDI or SAIFI	No
[114]	Single	Minimisation of SAIDI or SAIFI or average energy not supplied	No
[31,111]	Multiple	Multi-objective with weights	No
[47,62]	Multiple	Multi-objective with weights	Yes
[29,48,60,70,73,74, 77,78,80,84,86,95,109,119]	Multiple	Multi-objective	No
[34,52,54,55,59,67,93,100,108]	Multiple	Multi-objective	Yes

- Particle swarm optimisation (PSO) [44], [59,67,69,70,73,77];
- Practical heuristic optimisation algorithm [32,34,38,40,52,54, 63,65,68,79];
- Simulated annealing (SA) [26];
- Shuffled frog leaping algorithm [60];
- Tabu search [45,50].

These optimisation algorithms are generally nature-inspired methods. For example, GA is a nature-inspired optimisation method, based on the mechanisms of natural genetics and evolution. Another example is ABC, which is a nature-inspired optimisation algorithm that solves complex optimisation problems by simulating the food search of bee swarm.

The main advantages of computational intelligence based optimisation methods are that they are usually robust, they have broad applicability, they provide near-optimal solutions for large and complex OAPCD problems, they can use knowledge and they can be hybridised with other optimisation methods. The main disadvantages of these methods are that they usually require high computational time, they may provide different solutions in repeated runs, and they do not guarantee the finding of the optimal solution. Another disadvantage of computational intelligence based optimisation methods is that they usually necessitate the tuning of several input parameters, which is usually done by trial and error. It has been shown that in OAPCD problems, there are no general rules on how to optimally tune these input parameters to find the global optimal solution.

3.4 | Contribution

Table 3 highlights the core contribution of the published works reviewed in this article in a chronological order.

4 | COMPARISON OF METHODS

Sections 2 and 3 have described models and methods for OAPCD in SDSs. It is not realistic to implement all the 98 methods of [24–121] to make a comparison of their performance. Each method has its own merit. The choice of which method to apply depends on the OAPCD problem to be solved, the complexity of the problem, and the desirable accuracy of results.

4.1 | Problem

Various OAPCD problems are solved in the reviewed works [24–121]. These OAPCD problems can be classified according to the following five features:

1. Types of devices. Five different PCD are considered: sectionaliser, recloser, fuse, circuit breaker, and fault indicator.
2. Design variables. In OAPCD, four different design variables are considered: a) optimal location for the installation of PCD, b) optimal number of PCD to be installed, c) optimal type of PCD to be installed, and d) optimal time each PCD has to be installed during a multiyear planning horizon.
3. Distributed generation. Only some models consider DG units.
4. Objectives. In OAPCD, three different types of objectives are considered: a) single objective, b) multiple objectives with weights, and c) multiple objectives. The objectives include: a) minimisation of the total cost (which is the sum of the cost for the installation and maintenance of PCD and the service interruption cost), b) minimisation of SAIDI, c) minimisation of SAIFI, d) minimisation of ENS, and e) maximisation of the power distribution company profit during the planning period.
5. Power flow constraints. Only some works consider power flow constraints at their optimisation models.

Table 1 classifies the OAPCD problems according to the above first three features (types of devices, design variables, and DG), and Table 2 classifies the OAPCD problems according to the rest two features (objectives, and power flow constraints). The information herein in combination with the information of Tables 1 and 2 can help the reader appreciate the features of the methods and guide the reader through the literature. Two such examples are the following:

- If the reader is interested to find OAPCD problems with the following features: a) the PCD are the sectionaliser, recloser, and fault indicator, b) the design variables are the number, type, and location of PCD, and c) DG is considered, then, as can be seen in Table 1, the reader has to study the works [87,90].
- If the reader is interested to find OAPCD problems with the following features: a) single objective that minimises customer interruption cost, and b) power flow constraints are considered at the optimisation models, then, as can be seen in Table 2, the reader has to study the works [32,33], and [44].

4.2 | Complexity

When formulating the OAPCD problem, it is very important to decide which features to include into the optimisation process. For example, among the five different types of PCD (sectionaliser, recloser, fuse, circuit breaker, and fault indicator), one can decide to optimise some and not all of them. It is also important to decide which of the four design variables (location, number, type, and time) to optimise. It is also important to decide if it is needed to optimise a single objective or multiple objectives, and, then to select the single or multiple objectives from a list of possible objectives (third column of Table 2). Moreover, it has to be decided if DG and power flow constraints will be included in the optimisation model.

As can be seen in Tables 1 and 2, there is not any formulation that includes all the different options for the five problem features of Section 4.1. The OAPCD formulations that consider most of the different options for the problem features (e.g. all five different PCD, namely sectionaliser, recloser, fuse, circuit breaker, and fault indicator) require more detailed distribution system data, and are more difficult to implement.

In general, the more the problem features are considered, the more complex is the optimisation problem. For the same problem feature, the different options add different complexity to the OAPCD problem. For example, among the five options of the design variables, the time adds the higher complexity because the OAPCD problem has to be optimized during a multiyear planning horizon. The information here in combination with the information of Tables 1 and 2 can help the reader identify the complexity of the optimisation problem. e.g.:

- The works [25,32,33,52,55,65,114] have a rather low complexity, since: a) they optimise only one PCD (sectionaliser) from the list of five possible PCD, b) they optimise only one design variable (location) from the list of four possible design variables, and c) they do not consider DG units.
- The work [89] has a high complexity, since: a) it optimises four PCD (sectionaliser, recloser, fuse, and fault indicator)

TABLE 3 Contribution of the reviewed works

Reference	Published	Contribution
[24]	Nov 1994	A GA method is proposed to optimise the number and location of sectionalisers considering the effect of sectionaliser failure.
[25]	Dec 1995	A GA method optimises location of sectionalisers considering alternative supply by network reconfiguration.
[26]	Jul 1996	SA is proposed to find the optimal number and location of sectionalisers in radial distribution systems.
[27]	Jan 1998	To minimise the computational time, engineering heuristics is incorporated into a binary programming model to optimally allocate reclosers and fuses to minimise SAIFI.
[28]	Sep 1998	An exhaustive search and a bisection method are proposed for optimal allocation of sectionalisers.
[29]	Jun 1999	Binary programming is proposed to find the optimal type and location of reclosers and fuses.
[30]	Jul 1999	A new method, based on dynamic programming, is proposed to optimally allocate sectionalisers for both radial and meshed distribution networks.
[31]	Apr 2001	It introduces goal programming to find the Pareto optimal solution, i.e. the solution that minimises SAIFI and ASIFI, by computing the optimal types and locations of reclosers and fuses.
[32]	Jan 2002	A heuristic approach is proposed for optimal relocation of sectionalisers, i.e. to find the optimal new locations of already installed sectionalisers.
[33]	Feb 2003	An ACS algorithm is proposed to solve the combinatorial optimisation problem of switch relocation to minimise customer interruption cost.
[34]	Nov 2003	A heuristic optimisation method optimally allocates sectionalisers, considering islanding operation of DG units, and priority loads.
[35]	Apr 2004	A GA method is proposed to optimally allocate sectionalisers, reclosers, and fuses in the feeder and all laterals considering protection device coordination.
[36]	Apr 2004	A GA method is proposed to find the optimal number and location of sectionalisers considering the importance of loads using fuzzy membership functions.
[37]	Nov 2004	An analytical method computes the optimum number and location of disconnectors, by setting the partial derivatives of ENS equal to zero.
[38]	Apr 2005	A two-stage decomposition method is proposed to find the optimal number and location of RCSs.
[39]	Jun 2005	A GA is proposed to simultaneously allocate reclosers and DG units to increase distribution network reliability and security.
[40]	Mar 2006	A three-stage rule-based method is proposed to compute the optimal number and location of sectionalisers.
[41]	May 2006	A MILP method, based on contingency analysis of several components, is introduced to optimally allocate sectionalisers, reclosers, and fuses.
[42]	Aug 2006	An immune algorithm is proposed to find the optimal number and location of manual and automatic sectionalisers.
[43]	Aug 2006	A GA is proposed to concurrently allocate reclosers and DG units in a feeder with capacity constrained DG units.
[44]	Jan 2008	A novel three-state discrete PSO is proposed to find the optimal number and location of sectionalisers and circuit breakers.
[45]	Mar 2008	Reactive tabu search is proposed to find the optimal type, number and location of sectionalisers, reclosers and fuses.
[46]	Nov 2008	ACS is proposed to solve the discrete optimisation problem of optimal location of reclosers considering DG units.
[47]	Jan 2009	Ant colony optimisation is proposed to solve a fuzzy multi-objective model to optimally allocate sectionalisers in the presence of DG units.

TABLE 3 (Continued)

Reference	Published	Contribution
[48]	Jul 2009	A multi-objective ACS is proposed to optimally allocate sectionalisers, reclosers, and fuses considering protection coordination and feeder topology.
[49]	Oct 2009	A MINLP model is proposed to identify the optimal type and location of reclosers and fuses considering the relation between failures and protection device actions.
[50]	Jan 2010	Reactive tabu search is proposed to find the optimal type, number and location of sectionalisers, reclosers and fuses.
[51]	Feb 2011	An immune algorithm is proposed to find the optimal number and location of fault indicators with communication capability.
[52]	Feb 2011	A fuzzy multi-objective algorithm for optimal allocation of a pair of one normally open and one normally closed remote controlled switch.
[53]	Feb 2011	A GA is proposed to optimally locate fault indicators to minimise the distance among locations that are suspected to be the actual fault locations.
[54]	Mar 2011	A heuristic combinatorial search algorithm is proposed to optimally allocate sectionalisers, reclosers, fuses, and circuit breakers.
[55]	Jul 2011	A new methodology is proposed to compute the impact of RCS on reliability. Moreover, an analytic hierarchy process optimally allocates RCS.
[56]	Oct 2011	A GA simultaneously allocates RCSs and DG units in distribution networks considering a quantized yearly multilevel load model.
[57]	Oct 2011	A GA is proposed to optimally allocate RCSs and DG units considering the impact of the annual optimal operation strategy of DG units.
[58]	Jan 2012	A new MILP model for sectionaliser allocation is proposed that explicitly incorporates sectionaliser investment, operation, and maintenance costs, plus customer outage costs.
[59]	Apr 2012	A multi-objective PSO is proposed to simultaneously find the optimal number and location of sectionalisers and the optimal number and routing of feeders.
[60]	Jun 2012	A shuffled frog leaping algorithm is proposed to find the optimal type, number and location of manual and automatic sectionalisers.
[61]	Nov 2012	A GA method optimises the location of fault indicators on the main feeder of an actual power distribution system.
[62]	Nov 2012	The optimal allocation of sectionalisers in the presence of DG units is solved by an improved alliance algorithm that adjusts the derivation of alliances and the formation of a new tribe.
[63]	Nov 2012	A heuristic method is proposed to find the optimal number and location of fuses, considering the hidden failures of fuses.
[64]	Dec 2012	For allocation and relocation of sectionalisers, reclosers, and fuses, a MINLP model is proposed, which accurately models the response of the protection system to faults and restoration actions.
[65]	Jan 2013	An iterated sample construction with path relinking is proposed to optimally locate sectionalisers in distribution networks.
[66]	Jan 2013	A new methodology is proposed for the protection of distribution networks with DG units by dividing the network into zones, each capable for islanding operation. Moreover, exhaustive search optimises the protection zones by optimal allocation of circuit breakers.
[67]	Feb 2013	A multi-objective PSO is proposed to simultaneously find the optimal number and location of sectionalisers, the optimal number and routing of feeders, and the optimal network structure (radial or meshed).
[68]	Jul 2013	A heuristic method is proposed to find the optimal number and location of automatic switches in existing and new distribution networks.
[69]	Feb 2014	PSO is proposed to find the optimal location of sectionalisers and reclosers in distribution networks considering the impact of load types.
[70]	Sep 2014	A multi-objective PSO is proposed to find the optimal number and location of fault indicators considering operational uncertainties.

(Continues)

TABLE 3 (Continued)

Reference	Published	Contribution
[71]	Jan 2015	A memetic algorithm is proposed to find the optimal number and location of manual and automatic sectionalisers.
[72]	Mar 2015	The impact of Earth faults is considered in the optimal allocation of remotely controlled sectionalisers.
[73]	Apr 2015	A multi-objective PSO is proposed to find the optimal number and location of sectionalisers. The method does not require the failure rates of the distribution system, which are often unavailable.
[74]	Apr 2015	A memetic algorithm is proposed to find the optimal type, number, and location of sectionalisers and reclosers.
[75]	Jun 2015	An accurate assessment of reliability cost is introduced and a sectionaliser allocation method is proposed considering DG islanding operation as well as permanent and temporary faults.
[76]	Nov 2015	An ABC method optimally allocates manual and automatic sectionalisers taking into account the operational probabilities of all feasible control sequences under network contingencies.
[77]	Nov 2015	A binary multi-objective PSO is proposed to find the optimal number and location of sectionalisers, reclosers, and fuses.
[78]	Jan 2016	A multi-objective GA optimally allocates sectionalisers and reclosers in distribution grids with DG units, considering no island operation.
[79]	Mar 2016	A greedy rule-based heuristic algorithm optimally allocates RCSs with a polynomial time computational complexity.
[80]	Mar 2016	A multi-objective direct search method is proposed to optimise the number and location of RCSs in radial distribution systems.
[81]	Jul 2016	A discrete ABC method is proposed for simultaneous allocation of tie switches and DG units with the objective to maximise system loadability.
[82]	Aug 2016	Greedy randomized adaptive search procedure optimally allocates sectionalisers, considering controllable and uncontrollable DG units.
[83]	Nov 2016	A MINLP model optimally allocates sectionalisers and reclosers taking into account uncertainties of loads, failure rates, and repair rates.
[84]	Dec 2016	A multi-objective DE is proposed for optimal allocation of reclosers considering DG units and short circuit constraints.
[85]	Jan 2017	A MINLP model is proposed to optimally allocate sectionalisers, fuses, and circuit breakers considering the presence of DG units.
[86]	May 2017	A multi-objective non-dominated sorting genetic algorithm II (NSGA-II) is proposed to find the optimal time, type, number, and location of sectionalisers and circuit breakers.
[87]	Jul 2017	It concurrently computes the optimal type, number, and location of PCD, as well as the optimal relocation of existing PCD.
[88]	Sep 2017	A GA finds the optimal time to install fault indicators within a planning period in order the investment cost for fault indicators to be partially financed by exploiting the periodical savings due to the installation of fault indicators.
[89]	Sep 2017	A GA is proposed for optimal multi-year planning of different protection and control devices to maximise the profit of DSO.
[90]	Jan 2018	Simultaneous allocation of new devices and relocation of existing automation devices considering island operation of DG and the possibility of load shedding in the creation of islands.
[91]	Mar 2018	A GA method optimally allocates sectionalisers and fault indicators considering the impact of cyber-enabled distribution network reliability.
[92]	Mar 2018	Optimal allocation of switches with the objective to improve the resilience of distribution system against major faults caused by hurricanes.
[93]	Mar 2018	A multi-objective ABC method is proposed for simultaneous allocation of RCSs and wind turbines.
[94]	Apr 2018	A MINLP model optimally allocates sectionalisers, reclosers, and fuses considering uncertainties as well as momentary and sustained interruptions.

TABLE 3 (Continued)

Reference	Published	Contribution
[95]	Apr 2018	A GA is proposed for optimal allocation of RCSs, incorporating the financial risk resulting from the stochastic nature of contingencies.
[96]	May 2018	A new transformation method, based on practical candidate restoration strategies, is proposed to solve the MILP model for RCS allocation.
[97]	May 2018	A new fault indicator allocation is formulated as a mixed integer programming (MIP) model, including a more accurate calculation of customer outage time.
[98]	May 2018	A MINLP model is proposed to calculate the optimal type, number, and location of sectionalisers and fuses.
[99]	May 2018	A GA method optimally allocates sectionalisers, circuit breakers, and fuses in the presence of emergency demand response programs.
[100]	Nov 2018	A GA method optimally allocates sectionalisers, reclosers, and fuses, considering coordination and selectivity of the protection devices.
[101]	Dec 2018	The fault indicator allocation problem is solved by a new MILP formulation, which guarantees the finding of the global optimum solution.
[102]	Jan 2019	A new MILP model for sectionaliser allocation is proposed that incorporates sectionalisers malfunction probability.
[103]	Jan 2019	It is found that switch failure has significant impact on switch allocation, because ignoring switch failure overestimates the number of allocated switches.
[104]	Jan 2019	A new MILP model is proposed for protection device allocation considering device interactions, DG islanding, and the compromise between sustained and momentary interruptions.
[105]	Jan 2019	A risk-based method is introduced for optimal protection device allocation in the presence of uncertainties and performance-based regulation for the continuity of supply.
[106]	Mar 2019	A MILP model is proposed that simultaneously optimises the number and location of sectionalisers and fault indicators.
[107]	Mar 2019	A MINLP model is proposed to find the optimal number and location of manual sectionalisers to be upgraded to RCSs.
[108]	Jun 2019	GA optimally allocates RCSs, fuses, and fault indicators, considering the importance of candidate locations for installation of protection devices.
[109]	Jul 2019	A new multi-scenario, multi-objective, accurate, and scalable MILP model for optimal allocation of fault indicators.
[110]	Jul 2019	A GA is proposed to solve the integrated planning for protection device allocation and network capacity expansion.
[111]	Jul 2019	Through conditional value-at-risk, uncertainties are translated to financial risk and incorporated into a MIP model for optimal allocation of RCSs.
[112]	Aug 2019	A new MILP model is developed that considers the potential location of RCSs not only on main feeder but also on laterals.
[113]	Aug 2019	A MIP model is proposed that simultaneously allocates reclosers, fuses, RCSs, and manual switches, considering permanent and temporary faults.
[114]	Nov 2019	Taking advantage from the tree structure of the distribution network, a fast algorithm is introduced to optimally allocate sectionalisers.
[115]	Nov 2019	A stochastic MILP model is proposed for optimal allocation of RCSs considering renewable DG units, ESSs, and active reconfiguration.
[116]	Nov 2019	GA in combination with mixed integer quadratically constrained programming solves sectionaliser and tie line allocation problem.
[117]	Dec 2019	A GA is proposed to allocate sectionalisers, fuses, and circuit breakers, considering uncertainties in load profile and electricity price.
[118]	Jan 2020	A MILP model is proposed for the simultaneous allocation of sectionalisers and fault indicators considering the coordination between fault indicators and sectionalisers.

(Continues)

TABLE 3 (Continued)

Reference	Published	Contribution
[119]	Feb 2020	NSGA-II optimally allocates conventional and directional fault indicators, considering the real distance among the suspect fault locations.
[120]	Feb 2020	Three new metrics are proposed for the computation of the available locations for installing sectionalisers and fault indicators.
[121]	Jul 2020	A MILP model is proposed for sectionaliser allocation considering switch malfunction probability using discrete Markov chain model.

from the list of five possible PCD, and b) they optimise three design variables (type, location, and time) from the list of four possible design variables.

4.3 | Accuracy

The accuracy of the results depends on the problem formulation, the optimization method, and the accuracy and availability of data. Recent methods (e.g. [100]) with detailed and accurate modelling of coordination and selectivity of the protection devices provide better results than the earlier OAPCD techniques.

Among the various analytical, numerical, and computational intelligence based optimisation methods for OAPCD, only the exhaustive search ([28,66]) analytical optimisation method and the MILP ([27,29,41,58,72,75,87,90,92,96,97,101–106,109,111–113,115,118,120,121]) numerical optimisation method can guarantee the finding of the optimal solution. The results of analytical optimisation methods are only indicative, since they make simplified assumptions. The accuracy of the results of MILP may be impacted by the fact that the original nonlinear OAPCD problem is converted to a linear optimisation problem. Although the computational intelligence based optimisation methods for OAPCD are usually robust and rather easy to implement, their accuracy is a challenge, since they may provide different solutions in repeated runs, and they do not guarantee the finding of the optimal solution.

5 | FUTURE RESEARCH

As has been shown in the previous sections, significant work has been done in the area of OAPCD at SDSs [24–121]. However, there are still promising domains for future research that need further examination as described in the following.

5.1 | Coordinated distribution system planning

The OAPCD is part of the distribution system planning. It is proposed to include the OAPCD within the distribution system planning, because the coordinated multi-year planning of the distribution system will bring the highest benefits for the DSO. The coordinated distribution system planning has to include the planning of substations, distribution lines, capacitors, distributed generators, and PCD. The planning model has to be able to optimise the design of a new distribution system as well as to optimally expand an existing distribution system. Especially for the OAPCD, it is important to simultaneously consider multiple PCD, for example, sectionaliser, recloser, fuse, circuit breaker, and fault indicator. Additionally, for the expansion planning problem, the effect of redundant PCD has to be investigated. Moreover, the models for OAPCD have to simultaneously optimise the time (year of installation), type, number, and location of PCD. The DSO has to customize the models for OAPCD to follow regulations, standards, and operational strategies of the studied power distribution system.

5.2 | Enhanced reliability assessment

The models for OAPCD have to include reliability indicators based on both loads and customers. Moreover, the OAPCD methods have to increase reliability worth for the DSO by reducing the costs of power failures. The failures and the malfunction of PCD have to be considered in OAPCD. Appropriate methods, for example, the point estimate method or the Monte Carlo simulation, can be used for reliability evaluation considering uncertainties. The impact on reliability of the unavailability of DG units during islanding operation can be also studied.

5.3 | Advanced protection

The effects on OAPCD of the various types of PCD (e.g. sectionaliser, recloser, fuse, circuit breaker, and fault indicator) have to be explicitly considered. The OAPCD models have to consider coordination, selectivity, and specification of the various types of PCD. Advanced protection schemes in the presence of DG units need to be developed. Adaptive protection is another challenging research field. The actual technical characteristics of the PCD have to be considered, including the investigation of unidirectional and bidirectional PCD. Smart PCD, already available on the market, also need to be investigated. The hardening of PCD towards resilient SDSs to natural disasters has to be researched.

5.4 | Consideration of communication infrastructure

To make SDS a reality, more research is necessary to improve the controllability and observability of distribution systems by installing and using smart meters, communication and control devices, and smart distribution management systems. The models for OAPCD have to consider the complexity and the cost of the communication system that is needed in SDSs. The models have also to include the limitations and the reliability of the communication infrastructure. Another interesting area is to study the resilience of the distribution system considering the behaviour of the communication network during natural disasters.

5.5 | Increased penetration of variable distributed generation

The penetration of variable, renewable DG (e.g. wind power, solar photovoltaic power) increases rapidly in recent years. The models for OAPCD have to consider the time varying characteristics, the uncertainties, and the online and offline (islanding) operation of DG units. A DG power forecasting system is needed. The OAPCD models also study the bidirectional power flow due to DG and the possible distribution line overloads and the node voltage violations due to DG uncertainties. Moreover, the unavailability of DG units must also be considered, because during outages (permanent faults), the availability of DG is not guaranteed and is difficult to measure. The technical characteristics of various types of DG units have also to be considered, for example, a) the limited short circuit current of the inverter-based DG units, and b) some DG units do not have black-start capability.

5.6 | Detailed fault managment

The models for OAPCD have to consider both permanent and temporary faults. Moreover, the detailed fault management process has to be incorporated into OAPCD. The investigation of the impact on OAPCD of the different fault location techniques is also a promising research area. The OAPCD models to enhance distribution system resilience have to take into account multiple faults and failures that can simultaneously take place during natural disasters.

5.7 | Focused objectives

It is important to develop multi-objective problems for the OAPCD and to select the best compromise solution from the set of Pareto optimal solutions. In the context of the deregulated electricity market, the ultimate objective for the DSO is to maximise its profit. As a result, one objective for the OAPCD has to be the profit maximisation for the DSO during the planning horizon, considering all the expected profits and costs for the DSO during the planning horizon, where the expected costs include the cost for the installation of PCD and communication infrastructure, the customer reliability cost, the operational cost, and the cost of power losses. Other objectives can include the optimisation of reliability indicators to fulfil regulatory targets for reliability.

5.8 | Consideration of network operational constraints

The models for OAPCD have to consider power flow constraints and network operational constraints, e.g. line capacity limitations, and node voltage constraints.

5.9 | Consideration of uncertainties

The models for OAPCD have to consider several uncertainties during the planning horizon, including uncertainties in load, electricity price, variable renewable DG power output, interest rate, inflation rate, and available loans. The uncertainties can be modelled using methods including Monte Carlo simulation or point estimate method. The OAPCD can be solved using methods including stochastic optimisation or robust optimisation. Due to the uncertainty in several parameters, a sensitivity analysis is necessary when solving the multi-year OAPCD problem. The sensitivity analysis is also useful when considering parameters that are fully controlled by the DSO, for example, the number of years of the planning horizon that has a big impact on the optimal results of the OAPCD problem.

5.10 | Advanced optimisation methods

The development of advanced optimisation algorithms for OAPCD is proposed as a future research field. This is due to two main reasons: model complexity and size of the distribution network. Indeed, the proposed future research fields for coordinated distribution system planning, enhanced reliability assessment, advanced protection, consideration of communication infrastructure, increased penetration of variable DG, detailed fault management, focused objectives, consideration of network operational constraints, and consideration of uncertainties, make the OAPCD a very hard optimisation problem to solve. Moreover, the large size of practical, real-world distribution feeders further complicates the optimisation problem. As a result, big data analytics and advanced optimisation methods with scalability will be needed to solve the OAPCD problem. The advanced optimisation methods can be hybrid optimisation methods that exploit the advantages of analytical, numerical, and computational intelligence based optimisation techniques. In the case of computational intelligence-based optimisation techniques, a very important research field is the development of methods to automatically and adaptively tune their input parameters.

6 | CONCLUSIONS

Herein, a comprehensive description of the state-of-the-art of models and methods for the OAPCD in SDSs are introduced, apart from classifying and analysing the current and future research directions in this area. The most common model for the OAPCD has the following characteristics: 1) the sectionaliser is the most commonly allocated type of device, 2) the simultaneous optimisation of the number and location is the most common design variable, 3) the optimisation model does not consider DG units, 4) the most common objective is the minimisation of the total cost for the installation and maintenance of protective devices and the service interruption cost, and 5) power flow constraints are not included in the optimisation model. The most commonly adopted methods for OAPCD are MILP, GA, and practical heuristic optimisation algorithms. Future research areas include coordinated distribution system planning, enhanced reliability assessment, advanced protection, consideration of communication infrastructure, increased penetration of variable DG, detailed fault management, focused objectives, consideration of network operational constraints, consideration of uncertainties, and advanced optimisation methods.

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