Review of Service Restoration for Distribution Networks

Feifan Shen, Qiuwei Wu, and Yusheng Xue

***Abstract*—With the rapid deployment of the advanced metering infrastructure (AMI) and distribution automation (DA), self-healing has become a key factor to enhance the resilience of distribution networks. Following a permanent fault occurrence, the distribution network operator (DNO) implements the self-healing scheme to locate and isolate the fault and to restore power supply to out-of-service portions. As an essential component of self-healing, service restoration has attracted considerable attention. This paper mainly reviews the service restoration approaches of distribution networks, which requires communication systems. The service restoration approaches can be classified as centralized, distributed, and hierarchical approaches according to the communication architecture. In these approaches, different techniques are used to obtain service restoration solutions, including heuristic rules, expert systems, meta-heuristic algorithms, graph theory, mathematical programming, and multi-agent systems. Moreover, future research areas of service restoration for distribution networks are discussed.**

***Index Terms*—Distribution networks, fault detection, fault isolation, service restoration, self-healing scheme.**

I. Introduction

CONTINUITY of electricity supply is a major concern of system operators following the privatization and deregulation of the power industry [1]. As the final link between end-users and utilities, distribution networks must have reliable and efficient electricity supply to customers. However, since the distribution network operates with a radial topology [2], any fault of the network will cause supply interruption to downstream customers with the faulty portion [3]. The statistics show that distribution networks mostly contribute to the unavailability of electricity supply [4]. Hence, it is important to enhance the resilience of distribution networks [5].

In the case of emergencies, self-healing enables the distribution network to restore itself automatically and intelligently for the best possible status with a set of equipment, algorithms and communication technologies [2]. With the installation of the advanced metering infrastructure (AMI) and distribution automation (DA) devices such as remote terminal units (RTUs) and intelligent electronic devices (IEDs), the network is capable of detecting its operation status and making corrective actions. In the presence of a permanent fault, the self-healing scheme is able to detect the fault location and isolate the faulty portions. Then, it starts to restore out-of-service portions by controlling DA devices, e.g., opening or closing remote controllable switches (RCSs) and dispatching distributed generation (DG) units.

The applications of self-healing provide distribution networks with functional and monetary benefits [6]. For functional benefits, the self-healing scheme can significantly improve the reliability indexes of the network such as system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI). For the monetary benefits, the self-healing scheme enhances the continuity of electricity supply and consequently reduces the loss of unsupplied demands. Moreover, it has labor and vehicle saving due to the fast and accurate fault location.

The successful implementation of self-healing depends on the comprehensive deployment of fault location, isolation and service restoration. As an essential aspect of self-healing, service restoration has drawn considerable attention. Therefore, this paper reviews the existing service restoration approaches of distribution networks.

The rest of the paper is organized as follows. Section II introduces the concepts of fault location, isolation and service restoration of distribution networks. Section III presents an overview of service restoration approaches for distribution networks. Sections IV and V review the service restoration approaches without and with communication systems. The approaches for online use and practical applications are presented in Section VI. Section VII discusses the future research areas of service restoration in distribution networks, followed by the conclusion in Section VIII.

II. Fault Location, Isolation and Service Restoration

A. Fault Location and Isolation

Various types of faults happen in distribution networks. According to statistics, more than 80% of faults on distribution lines are single-phase-to-ground faults. Depending on the neutral grounding type of distribution networks, the sin-

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gle-phase-to-ground fault has different characteristics and needs different detection technologies [7].

For effectively neutral grounded networks, a short-circuit path is established when a single-phase-to-ground fault occurs. Therefore, there is a high fault current passing through the faulty feeder and protection devices which are activated immediately to cut off fault currents with the zero-sequence over-current protection. However, the over-current protection is ineffective due to the unobvious fault characteristics under the condition of high impedance fault. In [8] and [9], the zero-sequence inverse-time over-current protection and the protection based on the third harmonic current are proposed for the detection of high impedance fault.

For non-effectively neutral grounded networks, after a single-phase-to-ground fault occurs, the network can operate for a short period because the fault current is small. As a result, the fault is difficult to detect due to the small zero-sequence current. For permanent single-phase-to-ground faults, the network should locate the faulty feeder and trip it in a short time. References [10] and [11] analyze the traveling waves generated by single-phase-ground faults and propose a method based on traveling waves for the selection of single-phase-to-ground fault feeder. For temporary single-phase-to-ground faults, several fast arc extinguishing technologies are proposed to eliminate them. In [12] and [13], a fast arc-suppression system is developed based on the transformer with high short-circuit impedance, which automatically compensates faulty currents with a high response speed. In [14], a two-phase current injection method based on the cascaded H-bridge static var generator (SVG) is proposed, in which the SVG works in the reactive power compensation mode under the normal condition and injects arc-suppression currents into the network when a single-phase-to-ground fault occurs. In [15], an active arc-suppression method based on the double loop control is proposed, in which inverters inject zero-sequence currents into the neutral point to extinguish fault arcs caused by single-phase-to-ground faults.

After detecting and tripping the faulty feeder, the fault should be located and the smallest faulty portion of the network is isolated by opening switches connected to the faulty portion.

B. Service Restoration

Once the faulty portion is isolated, the out-of-service areas upstream to the faulty portion are restored immediately by closing the feeder output circuit breaker. The out-of-service areas downstream to the faulty portion are restored using service restoration strategies. A test network in Fig. 1 is used to briefly illustrate service restoration procedures based on network reconfiguration and islanded microgrids. The network has six zones and a DG unit with the black-start capability connected at Zone 6.

Suppose that a permanent fault occurs in Zone 1. As a result, switches S1 and S2 are open to isolate Zone 1. Then, the distribution network operator (DNO) reconfigures the network topology to restore the out-of-service Zone 2 by closing tie-switch 1 (TS1), as shown in Fig. 2. During the reconfiguration, operation constraints must be satisfied such as power balance, voltage, current, and radial topology.

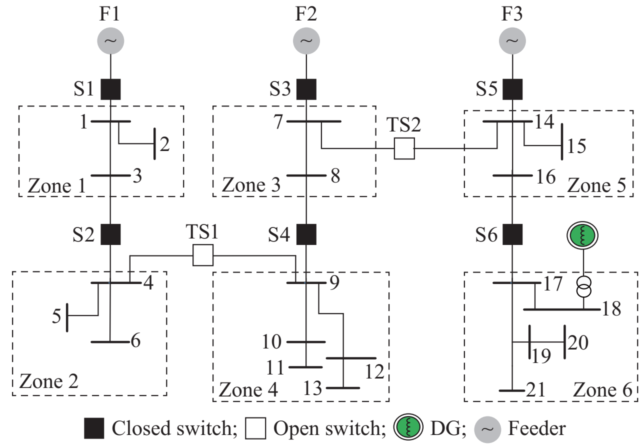

Fig. 1. Initial topology of test network.

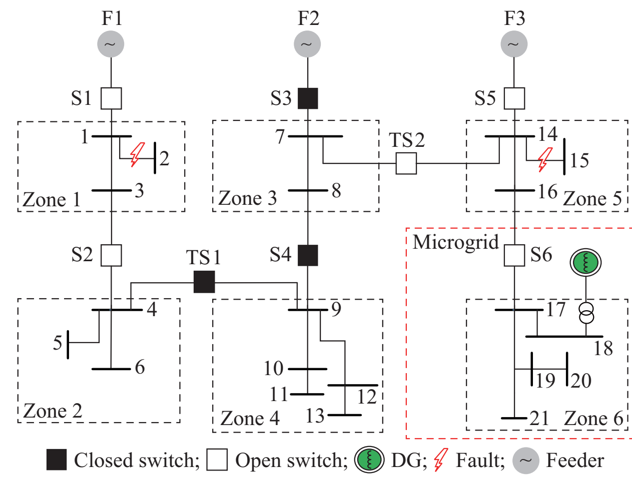

Fig. 2. Illustration of service restoration procedures.

Suppose that a permanent fault occurs in Zone 5. After the fault occurrence, the DG unit is disconnected immediately to avoid adverse impacts according to the current operation policies [2], and switches S5 and S6 are open to isolate the faulty Zone 5. In such a case, restoration paths to Zone 5 are unavailable. Therefore, the DG unit restarts and is dispatched to supply outage loads locally and to form a microgrid shown in Fig. 2. During the microgrid formation, the sudden load pick-up, cold load inrush and energizing unload lines may cause the violations of frequency and voltage constraints [16]. Since there are usually no controllable synchronous generators in the microgrid, at least one DG unit should have the ability to control frequency and voltage in the microgrid. Therefore, additional constraints must be respected during the microgrid formation, including frequency response rate constraints, spinning reserve constraints, maximum incremental load constraints, etc. Moreover, the formation and operation of the microgrid should consider security criteria, e.g., the N–1 security criterion.

Generally, service restoration has the following three objectives.

1) Objective 1: restore as many out-of-service loads as possible.

2) Objective 2: minimize service restoration time.

3) Objective 3: minimize line losses of network with the new topology.

The above-mentioned objectives have different priorities. It is the top priority to maximize out-of-service loads restored especially for critical customers such as hospitals and government sectors. To avoid posing too much discomfort to customers, service restoration time should be minimized, e.g., by minimizing the number of switching operations, and has the second priority. Since the newly configured network would not last for a long period, loss reduction would not provide a significant benefit and has the last priority. In summary, service restoration is a complex problem since it is: ① combinatorial due to discrete switching actions; ② constrained; ③ non-linear due to non-linear constraints; ④ multi-objective.

III. Overview of Service Restoration Approaches

In general, service restoration approaches can be categorized into centralized, decentralized, distributed and hierarchical approaches, which are defined as follows [17].

1) Centralized approach: each local agent communicates with a central controller where the decision is made based on overall system information.

2) Decentralized approach: each local agent makes the decision based on local information without communications among agents.

3) Distributed approach: there is no central controller and each agent communicates with its neighbors to make decisions.

4) Hierarchical approach: the decision is made by agents that communicate in a hierarchical structure.

This paper mainly focuses on the service restoration approaches with communication systems, i.e., centralized, distributed, and hierarchical approaches. They use different techniques to obtain restoration solutions, including expert systems, heuristic algorithms, meta-heuristic algorithms, graph theory, mathematical programming, and multi-agent systems. The service restoration approaches without communication systems, i.e., decentralized approaches, use local intelligence to obtain restoration solutions with automatic reclosing control, backup automatic switching control and feeder automation (FA) based on intelligent switches such as sectionalizers in voltage-delay type [7].

IV. Service Restoration Approaches Without Communication Systems

The service restoration approaches without communication systems use local intelligence to obtain restoration solutions. Although they provide solutions rapidly, it is difficult to coordinate different types of local control units in some cases such as for a trunk with multiple short lengths.

In [7], the over-current protection is coordinated with an FA based on reclosers and voltage-delay type sectionalizers to restore power supply. A coordination strategy between the relay protection, automatic backup switching and the distribution automation system (DAS) is proposed in [18]. A hierarchical model of the distribution network is developed in [19] to study the parameter setting of an FA system considering the coordination between reclosers and sectionalizers with voltage-delay type. A novel FA system for rural distribution systems is designed in [20], in which the instantaneous protection during reclosing is used. This FA system is improved in [21] by adding a time delay to sectionalizers and introducing an out-of-voltage lock mechanism into the control of sectionalizers and loop switchers, which can significantly reduce restoration time and outage areas. An FA system based on reclosers and voltage-current-mode pole-mounted switches (RVC) is proposed in [22], which has quick restoration for temporary faults and needs less time for permanent faults.

V. Service Restoration Approaches with Communication Systems

A. Centralized Approaches

Centralized approaches are based on DAS consisting of a master station, substations, DA devices, and a communication system. With global information, centralized approaches can obtain optimized restoration solutions. However, centralized approaches require the transmission of large amounts of filed data and a powerful control center (CC) with expensive computation capacity to process data and computations. Hence, the centralized approach has the single point failure risk, i.e., a failure of CC would cause a collapse of service restoration, and may have heavy computation burdens. In this subsection, the centralized approaches are reviewed according to the techniques used to obtain restoration solutions. In addition, the advantages and disadvantages of each technique are discussed.

1) Expert System

An expert system shown in Fig. 3 has three principal parts [23]: the knowledge base, database, and inference engine. The knowledge base consists of the domain knowledge used for problem solving. The domain knowledge is translated into rules, e.g., IF (condition)-THEN (action) rules. The database includes a set of facts to match the rules in the knowledge base. The inference engine links the facts with rules and conducts the reasoning process to obtain solutions.

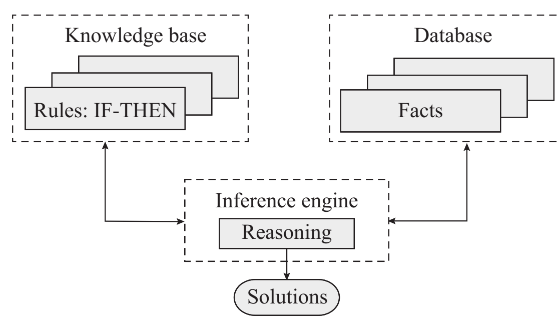

Fig. 3. Structure of expert system.

A set of typical IF-THEN rules in [24] are listed as follows.

Rule 1: if a de-energized zone has one candidate feeder and the feeder can pick up the zone without violating operation constraints, then assign the zone to this feeder.

Rule 2: if a de-energized zone has more than one candidate feeders, then select the feeder with the highest operation margin as the most suitable candidate feeder.

Rule 3: if there is a de-energized zone unrestored, then attempt to restore it.

It is assumed that a fault occurs in Zone 1 in Fig. 1, then Zone 2 is de-energized and Rule 1 is activated. Consequently, the tie-switch TS1 is closed to transfer the loads of Zone 2 to Feeder 2.

In [24], the knowledge base is developed based on 180 rules used by operators in restoration planning. The proposed system can restore the network with single-zone or multi-zone restoration strategies. Moreover, the rules of line loss reduction are incorporated into the system. In [25], the knowledge base is developed based on the control and situation rules. The former rules determine restoration steps and the latter ones describe detailed actions in each step. The proposed expert system uses single-group, multi-groups and, if necessary, group modification to restore the network. In [26], an expert system is developed based on the colored Petri net (CPN) inference model. The components of distribution networks such as switches are modeled by the CPN and rules which are applied in a real distribution network, and used to make restoration plans. Since the CPN has parallel-like inference characteristics, it can find restoration plans in the case of multiple contingencies. In addition, the proposed system considers load shedding during peak periods and the priorities of loads. An object-oriented programming (OOP) technique based expert system is developed in [27], in which rules are derived using the OOP technique. The feeder components and data are organized in a hierarchy way, which can improve inference performance and find multiple restoration plans. In addition, load variation is also taken into account in the restoration procedure.

In [28] and [29], multiple knowledge bases or inference engines are used. In [28], an expert system is developed for fault restoration, over-load management, and emergency operation. The proposed system has six knowledge base blocks, in each of which the rules are organized in a hierarchical manner, making it easier to add new rules and speed up the rule processing. In [29], the proposed expert system has two functions, i. e., fault detection and service restoration, and three inference engines, i.e., faulty detection, restoration planning, and restorative operation engines, which can improve the reasoning speed.

The expert system can obtain feasible restoration plans quickly. However, it is difficult to construct a large knowledge base and it is costly to maintain a large-scale expert system. In addition, the optimality of solutions cannot be guaranteed.

2) *Heuristic Algorithm*

The approach based on heuristic algorithm also uses heuristics or rules to obtain solutions. In these approaches, heuristics are transformed into algorithms to guide solution searching.

A heuristic restoration procedure is translated into a heuristic algorithm in [30], in which de-energized loads are restored firstly by supporting feeders followed by corresponding supporting laterals in order to reduce switching actions. A heuristic algorithm based on load flow is developed in [31]. All available switches, except those switches open to isolate the fault, are closed to create a meshed network. All closed switches are regarded as modifiable fictitious current sources and an optimal power flow study is conducted. Then, the switch carrying the least current is open to eliminate one network loop so that the disturbance in the power flow pattern is minimized. This process is repeated until there is no network loop and a radial network with acceptable operation conditions is obtained. In [32] and [33], multi-tier heuristic algorithms are developed. In these algorithms, the switches and supporting feeders in tier 1, which are directly related to out-of-service portions, are used to restore all de-energized loads firstly. Once it fails, the outer switches and feeders related to tier 1 are used afterward. Moreover, load curtailment is taken into account in the algorithm.

To deal with the imprecise expressions of heuristic rules and uncertainties of loads, the fuzzy set theory is used. In [34], the heuristic restoration procedures in [30] are expressed using a fuzzy cause-effect (FCE) network. In the FCE network, each feasible solution is evaluated using a fuzzy objective function based on the membership function. In [35], fuzzy variables are used to model the uncertainties of loads based on the historical load patterns of different customers and days. Then, the heuristic restoration procedures in [30] are used to find solutions.

The advantage of heuristic algorithms is that feasible solutions can be obtained quickly. However, they require problem-dependent knowledge, i.e., heuristics, to search for solutions. Moreover, the optimality of solutions cannot be guaranteed.

3) *Graph Theory*

1) Abstract graph of the distribution network

As shown in Fig. 1, a distribution network consists of substations and interconnected load zones delimited by the switches. If substations and load zones are viewed as vertexes and the switches are viewed as edges (e_1-e_6), the network can be represented as a graph $G(\upsilon, \varepsilon)$, where υ denotes vertexes and ε denotes edges. Therefore, service restoration is to find a spanning tree that represents a radial configuration of the network satisfying operation constraints. Suppose that a permanent fault occurs in Zone 1 in the test network. After the fault isolation, the abstract graph of the network is shown in Fig. 4.

Graph theory-based approaches in [36]-[40] use different techniques to find spanning trees. In [36], according to the fundamental loop concept, a spanning tree can be obtained by removing one edge from each fundamental loop. As shown in Fig. 4, a spanning tree can be generated by removing e_1. After obtaining all configurations, the power flow study is conducted to check the feasibility of each configuration, i. e., constraints are not violated if the configuration is applied. It is also conducted to find the best configuration according to the certain criteria such as the amount of de-energized loads restored and the number of switching operations. Reference [37] proposes an "interested tree" concept representing a tree in which all loads are supplied by substations. An algorithm is developed to extract all "interested trees" from feasible spanning trees and evaluate them. As a result, only the full service restoration plan is obtained. In the above-mentioned literature, only substations are considered as root nodes. In [38], nodes in energized portions connecting outage portions are treated as root nodes as well. Then, the modified Prim's algorithm is used to find multiple spanning trees, i.e., a forest, in order to deliver power to outage areas from multiple energized nodes.

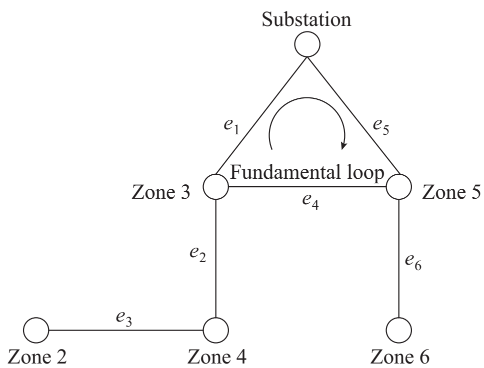

Fig. 4. Abstract graph of test network.

The graph theory is used in [39], [40] to form microgrids for service restoration. The fundamental loop concept-based method in [39] considers substations and microturbines (MTs) as root nodes and searches for a spanning tree representing a configuration with multiple islanded microgrids. A spanning tree search algorithm based on cut set theory is proposed in [40], in which each microgrid is treated as a virtual feeder and distributed energy resources (DERs) are treated as root nodes. By applying the cut set theory, a spanning tree is generated by switching a normally closed switch and a normally open switch. Then, a radial network incorporating microgrids is obtained.

2) Binary decision tree

Heuristic algorithms based on decision tree are proposed in [41]-[43], which construct the solution space as a decision tree and use different search techniques to search the tree. A binary decision tree in [41] is shown in Fig. 5. Starting from the root node, each of its successor nodes is assigned with a binary value, representing the status of a switch, e. g., the switch is closed if $x_1 = 1$; otherwise, the switch is open if $x_1 = 0$. Any path between the root node and a node in the m^{th} level (leaves of the tree) represents a combination of status of m switches, namely a restoration solution. Hence, through the exhaustive search of the tree, all restoration solutions can be obtained and evaluated. With the domain-specific knowledge, only a part of the tree needs to be evaluated to reduce searching burdens. In [41], the depth-first search technique is used to search for desired solutions.

A node in the binary tree can also represent a configuration of the network [42], [43]. The transition from one parent node to one of its successor nodes represents a switch pair operation, e.g., open one sectionalizing switch and close one tie-switch. By searching the tree from the root node (initial post-fault configuration), a combination of switching actions is obtained to reach a target configuration. The breadth-first search algorithm is used in [42] to find a decision tree solution with the minimum number of switching operations because the breadth-first search algorithm can obtain the shortest path from the root nodes to leaf nodes. The A* search algorithm guarantees solution optimality and is used in [43] to find the optimal decision tree solution.

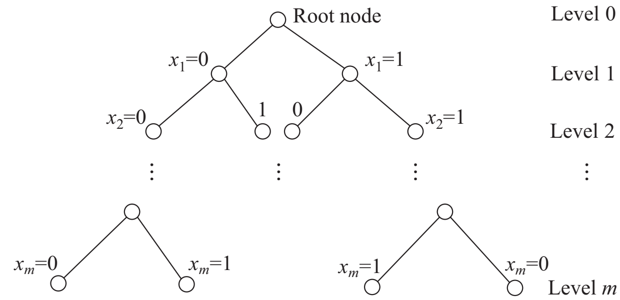

Fig. 5. Binary decision tree.

In the graph theory-based approaches, feasible solutions can be obtained rapidly. Although the optimal solution can be obtained through an exhaustive search, the number of trees may be very high for large-scale systems, which makes the above methods costly and unattractive.

4) Mathematical Programming

The mathematical programming technique has been used to solve service restoration problems. According to the requirements on solutions, i.e., the optimality and computation time, the service restoration problem can be formulated as the mixed integer non-linear programming (MINLP) model [44]-[47], mixed integer linear programming (MILP) model [45], [46] and mixed integer second-order cone programming (MISOCP) model [47].

An MINLP model based on the branch flow formulation in [45] is shown in (1)-(11) to illustrate the service restoration problem. The assumptions of the MINLP model are summarized as follows.

1) Loads are assumed to be three-phase balanced. The network is represented by equivalent single-phase circuits.

2) Switches are considered as short-length circuits with negligible impedance.

3) DG units and loads are controllable.

$$\min \Bigg[c_{\mathrm{G}} P_{\mathrm{G},i} + \sum_{z \in \Omega_z} c_{\mathrm{U}} \left(1 - x_z\right) + \sum_{ij \in \Omega_l} c_{\mathrm{lss}} I_{\mathrm{s},ij} R_{ij} + \sum_{ij \in \Omega_b} c_{\mathrm{S}} \left(w_{ij} - w_{\mathrm{ini},ij}\right)^2 + \sum_{i \in \Omega_d} c_{\mathrm{R}} r_i \Bigg] \tag{1}$$

s.t.

$$P_{\mathrm{G},i} + \sum_{ki \in \Omega_l} P_{ki} - \sum_{ij \in \Omega_l} \left(P_{ij} + I_{\mathrm{s},ij} R_{ij}\right) = P_{\mathrm{D},i} \left(x_z - r_i\right) \quad \forall z \in \Omega_z, i \in b(z) \tag{2}$$

$$Q_{\mathrm{G},i} + \sum_{ki \in \Omega_l} Q_{ki} - \sum_{ij \in \Omega_l} \left(Q_{ij} + I_{\mathrm{s},ij} X_{ij}\right) = Q_{\mathrm{D},i} \left(x_z - r_i\right) \quad \forall z \in \Omega_z, i \in b(z) \tag{3}$$

$$0 \le r_i \le x_z \qquad \forall z \in \Omega_z, i \in b(z) \tag{4}$$

$$V_{s,i}-V_{s,j}=2\left(P_{ij}R_{ij}+Q_{ij}X_{ij}\right)+I_{s,ij}\left(R_{ij}^2+X_{ij}^2\right)+b_{ij} \qquad \forall ij\in\Omega_l \tag{5}$$

$$-M(1-w_{ij})\leq b_{ij}\leq M(1-w_{ij}) \qquad \forall ij\in\Omega_b \tag{6}$$

$$V_{s,j}I_{s,ij}=P_{ij}^2+Q_{ij}^2 \qquad \forall ij\in\Omega_l \tag{7}$$

$$x_zV_{s,i}^{\min}\leq V_{s,i}\leq x_zV_{s,i}^{\max} \qquad \forall z\in\Omega_z, i\in b(z) \tag{8}$$

$$\begin{cases}0\leq I_{ij}\leq w_{ij}I_{s,ij}^{\max} & \forall ij\in\Omega_b\\ 0\leq I_{ij}\leq x_zI_{s,ij}^{\max} & \forall z\in\Omega_z, ij\in\Omega_l\backslash\Omega_b, i,j\in b(z)\end{cases} \tag{9}$$

$$\sum_{ij\in\Omega_b}w_{ij}=n_v-1 \tag{10}$$

$$x_z, w_{ij}\in\{0,1\} \qquad \forall z\in\Omega_z, ij\in\Omega_b \tag{11}$$

where Ω_z and Ω_d are the sets of zones and nodes, respectively; Ω_l and Ω_b are the sets of all circuits and circuits with switches, respectively; c_G is the energy production cost; c_U is the cost of de-energizing a zone; c_{lss} is the cost of line losses; c_R is the cost of load shedding; c_S is the cost of a switching action; $P_{G,i}$ and $Q_{G,i}$ are the active and reactive power generations at node i, respectively; $V_{s,i}$ and $I_{s,ij}$ are the square voltage magnitude of node i and square current magnitude from node i to node j, respectively; R_{ij} and X_{ij} are the resistance and reactance of circuit ij, respectively; $w_{ini,ij}$ is the initial status of the switches; $b(z)$ is the set of nodes that belong to zone z; the decision variables are the status of switches w_{ij} (w_{ij} = 1, if the corresponding switch is closed; otherwise, w_{ij} = 0, if the switch is open), the status of zones x_z (x_z = 1, if the corresponding zone is energized; otherwise, x_z = 0, if the zone is de-energized) and the percentage of load shedding at each node r_i; P_{ij} and Q_{ij} are the active and reactive power flows from node i to node j, respectively; b_{ij} represents the auxiliary variable associated with circuit ij; $P_{D,i}$ and $Q_{D,i}$ are the active and reactive demands at node i, respectively; n_v is the number of total vertexes of the abstract graph in the network; $V_{s,i}^{\min}$ and $V_{s,i}^{\max}$ are the lower and upper bounds of square voltage magnitudes, respectively; $I_{s,ij}^{\min}$ and $I_{s,ij}^{\max}$ are the lower and upper bounds of square current magnitudes, respectively; and M is a very big number.

The objective function in (1) consists of five terms: the energy production cost, the number of de-energized zones, the cost of line losses, the number of switching actions and the cost of load shedding. Formulas (2) and (3) represent the active and reactive power balance at each node, respectively. Formula (4) limits the percentage of load shedding at each node: if a given zone is de-energized, the amount of load shedding of all nodes in the zone is set to be zero. Formula (5) calculates the voltage drop for each circuit. Formula (6) represents that (5) is removed for circuits whose switches are open. Formula (7) calculates the current magnitudes of all circuits. Formula (8) limits the voltage magnitudes: if a given zone is de-energized, the voltage magnitudes of all nodes in the zone are forced to be zero. Formula (9) limits the square current magnitudes of all circuits. Formulas (2), (3) and (10) ensure a radial topology of the network. Formula (11) defines the binary nature of w_{ij} and x_z.

The MINLP model in (1)-(11) provides a relatively detailed representation of service restoration problems. In the model, controllable DG units and load shedding are modeled. The model can be solved using the non-linear solvers such as BARON and the optimal or near-optimal solutions can be obtained. However, it is computationally expensive because the problem is combinatorial and non-convex due to the non-linear constraint (7) and binary variables.

Besides the MINLP model based on branch flow formulation, an MINLP model based on the bus injection formulation for unbalanced distribution networks is proposed in [44]. To efficiently solve service restoration problems, linearization and convex relaxation techniques have been applied. A two-stage service restoration strategy is proposed in [45], [47]. In the first stage, the piecewise linearization technique is used to linearize the non-linear expression (7) and obtain an MILP model. Then, with binary variables obtained from the MILP model, a non-linear programming (NLP) problem is solved in the second stage to obtain solutions of continuous variables, i. e., the steady-state operation point. Meanwhile, the switching sequence is considered in [47] by incorporating time steps in the model formulation.

The convex relaxation technique is used in [44] to transform the MINLP model into an MISOCP model by relaxing (7) as a second-order cone constraint in (12). The MISOCP model can be solved efficiently using commercial solvers based on the convex optimization techniques such as branch and bound (B&B) [48].

$$V_{s,j}I_{s,ij}\geq P_{ij}^2+Q_{ij}^2 \qquad \forall ij\in\Omega_l \tag{12}$$

The model in (1)-(11) has been adapted to service restoration for islanded microgrids. A comprehensive strategy considering the normal operation mode and self-healing mode is developed in [49]. In the normal operation mode, DGs are dispatched to minimize the total generation cost of the network. In the self-healing mode, an MINLP model is solved to adjust DG outputs and optimally sectionalize the network into multiple microgrids. Moreover, the rolling horizon optimization technique is used to deal with the uncertainties of DG outputs and load consumption. However, the strategy does not consider the switching sequence. A sequential service restoration strategy based on an MILP model is proposed in [50], which provides a sequence of control actions for coordinating DG units and switches to form microgrids sequentially to restore outage areas. Moreover, network components such as ZLP loads, voltage regulators, and capacitor banks, are carefully modeled. In [51], a similar sequential service restoration strategy is proposed, in which the intertemporal characteristics of energy storage systems (ESSs) and cold load pickup (CLPU) phenomena are considered.

Two robust service restoration models are formulated in [52], [53]. A two-stage robust optimization model considering the uncertainties of DG outputs and load consumption is proposed in [52], in which the robust solution is obtained at the second stage with respect to the worst-case scenario extracted from a set of scenarios at the first stage. The model is iteratively solved by the column-and-constraint generation method. An robust restoration model based on information gap decision theory is proposed in [53], in which the uncertainties of DG units and load consumption are modeled by bounded uncertain sets. The solution obtained can guarantee that the amount of restored loads would not fall below a specified threshold. A fuzzy mixed integer programming (MIP) model considering the uncertainties of load consumption and the payback effect is proposed in [54] to perform the risk management for service restoration.

In addition, the dynamic programming (DP) technique is applied in [55] to decompose the decision-making process into a sequence of decision steps over time. In [55], the energized sequence of feeders is represented by a sequence of states and an enhanced DP method is used to reduce the number of states by grouping similar states and to select the best sequence of states. The bender decomposition technique is used in [56] to solve the service restoration problem with microgrids. The problem is decomposed into a master problem and a slave problem, which is solved iteratively to obtain solutions. The master problem formulated as an MIP model determines the configuration of the network and minimizes the amount of load shedding. The slave problem formulated as a conic model minimizes the power losses of the network.

The mathematical programming-based approaches can provide a detailed representation of the service restoration problem, e. g., by modeling network components and renewable energy sources in detail. As a result, optimal or near-optimal solutions can be obtained. However, mathematical programming-based approaches may have heavy computation burdens due to the increasing size and the complexity of the network.

5) Meta-heuristic Algorithms

The mathematical models can also be solved by meta-heuristic algorithms, which use intelligence observed from natural phenomenon to derive solutions. Meta-heuristic algorithms have similar procedures with different searching and encoding strategies. The widely used meta-heuristic algorithms include the genetic algorithm (GA) [57], [58], tube search (TS) algorithm [59], particle swarm optimization (PSO) algorithm [60] and parallel-simulated annealing (PSA) algorithm [61]. The encoding and searching strategies of the GA are described as follows.

Step 1: the representation of the problem.

The decision variables of the problem in (1)-(11) can be represented as a binary string, e.g., (1, 1, 0, …, 0, 0, 1, 0). The binary value in the string represents the status of the corresponding binary variable, i. e., "1" represents a closed switch and "0" represents an open switch.

Step 2: the generation of an initial population of strings.

In general, the initial population of strings is produced randomly. To improve the efficiency of the algorithm, problem-dependent heuristics can be used to generate the initial population of strings.

Step 3: the evaluation and selection of each string.

Each string is evaluated by a fitness function denoting the quality of the string. A good candidate for the fitness function is the objective function of the problem. For a string denoting a network configuration, it is evaluated by conducting an optimal flow study with the objective function (1). The string with a better objective value has a higher probability to be selected to produce the next generation of strings.

Step 4: the updating of each string.

The GA updates the strings by crossover and mutation operations. An offspring string is generated from two parent strings by crossover operation denoting an exchange of a part of numbers between two parent strings. In selected offsprings, some of their numbers subject to changes, i. e., "1" replaces "0" and "0" replaces "1".

Step 5: the iteration and convergence.

The evaluating and updating process of strings are repeated until the number of iterations reaches a preset maximum or other termination conditions are satisfied. If none of the termination conditions is satisfied, go back to *Step 3* and the iteration number increases by one.

In [61], four meta-heuristic algorithms (GA, TS, reactive TS, and PSA) are compared with respect to the average calculation time and quality of solutions. It is concluded that reactive TS algorithm is the best algorithm among them since it generates the best solution with less computation time. A non-dominated sorting genetic algorithm-II (NSGA-II) is adopted in [62], which considers the priorities of customers and remotely controlled switches without converting multiple objectives as a single objective via weighting coefficients. It is demonstrated that the NSGA-II outperforms the conventional GA. A multi-objective revolutionary algorithm considering the switching sequence is proposed in [63], in which the node-depth encoding method is used to ensure a radial topology of the network during solution searching.

The fuzzy set theory has been incorporated into the meta-heuristic algorithms to optimize solutions. An interactive fuzzy satisfying method combining the fuzzy set and GA is proposed in [64]. Multi-objective functions are modeled by fuzzy sets to evaluate their imprecise nature and the GA algorithm is used to solve the problem. Moreover, the switching sequence is included in the problem formulation.

The advantage of the meta-heuristic algorithms is that they do not require problem dependent heuristics and can be used for a number of types of problems. However, the optimality of solutions cannot be guaranteed.

6) Hybrid Approaches

Many research efforts have been put on hybrid methods to leverage the advantages of different techniques. In [65], the expert system is used firstly to divide the whole network into several sub-networks, each of which is finally formulated as an MILP model. In [66], the heuristic algorithm is used firstly to find all restoration plans. If none of the restoration plans is feasible, the restoration problem is formulated as an MIP model. A two-phase strategy is proposed in [67], in which the target configuration is found at the first phase through the GA while the optimal switching sequence is obtained using the DP at the second phase.

7) Summary of Centralized Approaches

All the above-mentioned centralized approaches are compared in Table I with respect to the means, i.e., network reconfiguration and the formation of the microgrid, techniques, and quality of service restoration results. It is concluded that network reconfiguration is the most widely used means for service restoration while the formation of the microgrid is attracting more and more attention in recent years. For techniques, most of the early approaches use rule-based techniques, i. e., the expert systems and heuristic algorithms, whereas, recently, more elaborate techniques such as mathematical programming are used to obtain optimized solutions. In addition, the quality of solutions is getting better by considering the switching sequence, detailed network component models such as the three-phase unbalanced circuits, and uncertainties of DERs and loads.

TABLE I
SUMMARY OF CENTRALIZED APPROACHES

Year	Reference	Means		Technique					Quality of SR results			
		NR	MG	ES	HE	GT	MP	MH	Switching sequence	Unbalanced network	Uncertainty: DG	Uncertainty: Load
1989-2000	[24], [25], [28], [29]	√		√								
	[42]	√			√					√		
	[30]-[32]	√			√							
	[35]	√			√							√
	[38], [41]	√				√						
	[57], [59]	√						√				
	[65]	√		√			√					
	[64]	√						√	√			
	[66]				√		√					
2001-2005	[26]	√		√								
	[34]	√			√							
	[54]	√					√					√
	[58], [61]	√						√				
2006-2010	[27]	√		√								√
	[44]	√					√			√		
	[55]	√					√					
	[62]	√						√				
	[67]						√	√	√			
2011-2015	[33]	√			√							
	[60]	√						√				
	[40]		√			√						
	[37], [43]	√				√						
	[53]	√					√				√	√
	[49]		√				√				√	√
2016-2019	[45], [47], [56]	√					√					
	[52]	√					√				√	√
	[39]		√			√		√				
	[36]	√				√						
	[46]	√					√		√	√		
	[51]		√				√		√	√		
	[50]		√				√		√			
	[63]	√						√	√			

Note: NR stands for network reconfiguration; MG stands for microgrid; ES stands for expert system; HE stands for heuristic algorithm; GT stands for graph theory; MP stands for mathematical programming; MH stands for meta-heuristic algorithm; SR stands for service restoration; and the symbol "√" means that the listed item is considered in the literature.

B. Distributed and Hierarchical Approaches

Distributed and hierarchical approaches use distributed intelligence to solve service restoration problems. The distribution network is divided into sub-networks, each of which is controlled by a local agent. In the existing approaches, only the multi-agent system (MAS) and mathematical programming are used.

1) MAS

In the MAS, agents communicate and coordinate to solve problems according to specified heuristic rules. Each agent can perceive and react changes in its environment autonomously. Besides the applications of MASs to service restoration, the MAS has been widely used in other power system applications such as the distributed coordinated control of the Energy Internet (EI). An MAS-based distributed control strategy for DG units in the EI is proposed in [68], in which a consensus algorithm is used to regulate the voltages of DG units and power sharing among DG units and to minimize circulating currents in the EI. In [69], an MAS-based distributed control strategy for the optimal energy management of the EI is proposed in [69], which can realize the maximum utilization of renewable energy sources.

The MAS-based service restoration approaches can be characterized by types of agents and communication architecture. Agents communicate with neighbors without central negotiation agents in distributed MASs, whereas the central negotiation agent is needed to coordinate agents in hierarchical MASs.

The hierarchical MAS is used in [70] - [72]. In [70], the bust agent and facilitator agent are developed in the MAS. The bus agent controls the loads connected to the bus and the facilitator agent as the negotiation agent coordinates all bus agents. A two-layer multi-agent system is designed in [71], in which zone agents are developed in the lower layer and feeder agents as negotiation agents are developed in the upper layer. A feeder is divided into several zones separated by switches and each zone has a zone agent detecting the zone status and communicating with its feeder agent. The feeder agent coordinates affiliated zone agents communicating with adjacent feeder agents. A similar two-layer MAS is proposed in [72] with the zone agent replaced by the load agent and an inclusion of a regulator agent that controls voltage regulator to improve voltage profile.

The distributed MAS is proposed in [73] - [77]. In [73], switch agents, load agents, and generator agents communicate with each other to make decisions without a negotiation agent. Four types of zone agents including faulty zone agents, down zone agents, zone tie agents and healthy zone agents are developed in the MAS [74], in which each agent identifies its type based on the fault location and communicates with other agents to make decisions.

The MAS is used in [75], [76] for service restoration with microgrids. In [75], switch agents and distributed energy storage (DES) agents are developed in the MAS, in which a “team” represents a group of segments bounded by switches is proposed. The agents within a team communicate with each other and, as a whole, communicate with other teams next to it to determine the configuration of the network and adjust distributed energy storages to form microgrids. In [76], load agents, EV aggregator agents, DG agents, and switch agents are developed in the MAS where these agents negotiate to determine the configuration of microgrids and operation conditions of EVs and DG units. The MAS is improved in [77] by modelling the uncertainties of loads and DERs with the Monte Carlo method.

It is illustrated with an example in [70] how the MAS-based approach solves service restoration problems. The restoration procedures are explained with the MAS and test system shown in Fig. 1. Suppose that a fault occurs in zone 1. As a result, loads at Buses 4, 5 and 6 need to be restored and Bus 9 has power available for restoration. In the MAS, each bus is controlled by a bus agent (BAG) and the BAG negotiates under the supervision of a facilitate agent (FAG). Firstly, BAGs 4, 5 and 6 send restoration requests to the FAG. Then, the FAG puts these BAGs in a de-energized agent (DEA) list and selects BAG 4 as the starting agent for restoration because it has the highest voltage level. The detailed negotiation process is described as follows.

Firstly, BAG 4 negotiates with its neighboring agents who have available power for restoration, i.e., BAG 9. Since the available power (2.0 MW) from BAG 9 is greater than the loads of BAG 4 (0.5 MW), Bus 4 is energized. Then, BAG 4 negotiates with its neighboring de-energized BAGs, i.e., BAGs 5 and 6. Since BAG 5 has more loads than BAG 6, BAG 4 negotiates with BAG 5 first, and Bus 5 is energized because power available (1.5 MW) is larger than loads of Bus 5 (1.2 MW). Since BAG 5 has no neighboring BAGs, BAG 5 sends a termination message to the FAG and the FAG removes BAG 5 from the DEA list. Then, BAG 4 tries to negotiate with BAG 6, but BAG 6 rejects the request since the current available power (0.3 MW) is insufficient to supply loads of BAG 6 (1.0 MW). Hence, Bus 6 remains de-energized and sends a terminal message to the FAG. After the negotiation process is completed, a target configuration of the network is obtained, as shown in Fig. 2.

The MAS-based approaches can realize distributed or hierarchical implementation and obtain feasible solutions quickly, whereas the heuristic-based decision-making process cannot ensure the optimality of solutions.

2) Mathematical Programming

The alternating direction method of multipliers (ADMM) has been used to solve the service restoration problem in a distributed manner. An ADMM-based distributed service restoration strategy is proposed in [78], in which the service restoration problem formulated as an MISOCP model is decomposed using the ADMM and solved by agents at each node in parallel. However, the strategy is designed for black-start service restoration when the whole distribution network is out-of-service and network configuration is not considered.

3) Hybrid Methods

The mathematical programming is combined with the MAS [79]. In the MAS, feeder agents negotiate with each other to obtain a reduced model of the portion in the network involved in service restoration. Then, an MISOCP model is solved to obtain restoration solutions.

4) Summary of Distributed and Hierarchical Approaches

The distributed and hierarchical approaches are summarized in Table II with respect to means, techniques and types of agents. It is concluded that most of the MAS-based approaches solve service restoration problems through network reconfiguration. Recently, more and more research applies MASs to service restoration with the microgrid. Moreover, it has a trend of combining the MAS with mathematical programming to obtain optimized restoration solutions.

VI. Validation and Practical Applications

A. Validation of Online Use

The service restoration solution should be obtained rapidly once the fault is detected and isolated. Therefore, it is necessary to validate if the proposed approach is feasible for online use.

TABLE II
SUMMARY OF DISTRIBUTED AND HIERARCHICAL APPROACHES

Year	Reference	Means		Technique		Agent type	Negotiation agent
		NR	MG	MAS	MP		
2000-2010	[70]	√		√		Bus and facilitator agents	Facilitator agent
	[73]	√		√		Switch, load and generator agents	
2010-2015	[71]	√		√		Zone and feeder agents	Feeder agents
	[75]		√	√		Switch and DES agents	
	[76]		√	√		Load, aggregator, DG and switch agents	
	[72]	√		√		Load, feeder and regulator agents	Feeder agents
2016-2019	[74]	√		√		Faulty zone, down zone, zone tie and healthy zone agents	
	[77]		√	√		Load, EV aggregator, DG and switch agents	
	[79]			√	√	Feeder agents	
	[78]		√		√	Node agent	

The service restoration approaches without communication systems are available for online use because they can take actions immediately based on the predefined operation logics. For the approaches with communication systems, it takes time to transmit and process data and to compute. A few of them have been validated for online use by providing real system simulations and computation time. In [45], the proposed mathematical programming-based method is tested on a real Brazilian distribution system with 964 nodes, 855 branches, 136 switches and 106 load zones. The results show that the proposed algorithm can obtain optimal solutions with a few minutes. In [29], the proposed expert system is tested on a real distribution system in Japan with 120 substations and 80 branches. It is concluded that the proposed system can obtain an effective restoration solution with approximately 50 s. In [59], the proposed TS-based meta-heuristic algorithm is demonstrated on a real distribution system in Korea with 7 substations, 100 feeders and 2558 load zones. The results show that the algorithm can obtain the optimal solution within 45 s.

B. Practical Applications

The service restoration approaches without communication systems are the earliest technologies for service restoration and are still used in the industry. Hybrid schemes of three-section over-current protection and time-delay over-current protection coordination are widely used in Chinese utilities [7]. The FA system based on reclosers and voltage-delay sectionalizers is invented by Japanese engineers and introduced to China. This technology has been used in Asia for decades [7].

For the approaches with communication systems, several pilot projects have been conducted for real applications. In the Stedin Project [80], a distributed scheme is designed, in which each feeder is divided into multiple segments and each segment is equipped with a self-healing controller and DA devices such as fault passage indicators (FPIs) and voltage presence detectors (VPDs). Each controller communicates with its neighbors and controls its controllable switches based on a number of practical principles acquired from the field crew. This project has been successfully deployed in a medium voltage distribution network in Netherlands [81]. In a real case, the proposed scheme restores 600 households and shops in the center of Rotterdam within 18 s after a fault occurs. In addition, the Greenly project based on the framework proposed in the Stedin project has been deployed in France [81], Vietnam and Cuba [82]. In the UHENPAL project in the Brazil [83], a centralized scheme is proposed. A self-healing software module integrated into the supervisory control and data acquisition (SCADA) system evaluates available service restoration plans based on a rule-based algorithm and multi-criteria analyses. The best restoration plan is carried out by operating remote controlled switches according to the commands from the centralized controller. The project has been deployed in a distribution network in Brazil. The statistics results show that the proposed scheme can significantly improve the SAIDA and SAIFI reliability indices. In a pilot project in Guangdong, China [84], a comprehensive scheme is developed to combine the centralized scheme with the distributed scheme. The centralized scheme acts as a backup tool for the distributed scheme. In the distributed scheme, each controllable switch is equipped with a local controller that communicates with its neighbors to make decisions based on predefined rules. If unexpected situations happen, e. g., overloading after reconfiguration, the centralized scheme is activated to make corrective actions. This project has been deployed in a distribution network in Guangdong. The field tests show that the scheme shortens the average intervention duration of the network from 8.76 hours to 5.2 min.

In practical applications, the approaches using rule-based algorithms are preferred because they can obtain qualified solutions quickly, which is in line with the DSOs' main goal to restore as many affected customers as possible in a short time. With the rapid development and deployment of the DA devices and high-speed communication systems, it is expected that the rule-based approaches will be replaced by the approaches with more elaborated decision-making processes, which can provide optimized solutions with a high computation speed.

VII. FUTURE RESEARCH AREAS

To achieve effective service restoration under complicated operation conditions in the future, the following research areas deserve more attention.

A. Distributed Optimization Algorithms

The growing size and complexity of the distribution network will put more burdens on the DNO to obtain desired solutions with limited computation resources. The distributed optimization algorithm is a promising tool because it can decompose a large-scale complex problem into sub-problems with smaller scale while obtaining solutions almost the same as the ones obtained with centralized algorithms.

So far, distributed optimization algorithms have been widely used in power system applications [17]. The analytical target cascading (ATC) technique is used to solve security-constrained unit commitment problems [85] and optimal power flow (OPF) problems [86]. The optimality condition decomposition (OCD) technique is used to solve OPF problems [87]. The ADMM is used to solve OPF problems [88], unit commitment problems [89], voltage control problems [90] and load forecasting problems [91]. However, the applications of distributed optimization algorithms to service restoration are limited. An ADMM-based distributed service restoration strategy is proposed in [78]. However, the strategy is designed for specific service restoration scenarios and network reconfiguration as an important means because service restoration is not considered in the model formulation. Therefore, distributed optimization algorithms should be further studied for more service restoration scenarios in the future.

B. Microgrids

The ever-increasing penetration of DERs brings benefits to service restoration. If the restoration paths of utility power supply are unavailable, the DERs can supply de-energized loads locally [31]. Therefore, the whole or a portion of the distribution network can operate in microgrid mode, which is a promising means for service restoration.

In [49], the distribution network is rearranged as networked microgrids to serve outage customers. However, it does not consider network reconfiguration. In [50], a sequence of control actions is provided to form multiple microgrids by reconfiguring the network and coordinating DERs. However, it does not study the optimal coordinated operation of microgrids for optimal service restoration. A two-layer framework is designed in [92] to coordinate operation of microgrids in the case of one or multiple faults. However, it does not consider network reconfiguration. In summary, network reconfiguration and coordinated operations of microgrids are two important factors for optimal service restoration. Therefore, it is necessary to investigate comprehensive strategies considering both network reconfiguration and optimal coordinated operation of microgrids.

C. Uncertainties of DERs and Loads

The DERs and loads introduce uncertainties to the service restoration process [36]. In practice, it takes time to complete the whole restoration procedure due to time-consuming switching operations. During restoration, DG outputs and load consumption will fluctuate, which may make the restoration solution not be optimal or even become infeasible. Robust optimization techniques, e. g., the min-max robust optimization [52], rolling horizon optimization [49] and information gap decision theory (IGDT) [53], have been used to design robust service restoration strategies. In the rolling horizon optimization, the probability distribution is needed to extract scenarios of uncertain variables. The min-max robust methods and IGDT-based methods model the uncertainties by uncertainty sets without requiring the probability distribution. However, they usually provide conservative solutions. To overcome these drawbacks, it is necessary to investigate more advanced robust optimization techniques to design robust strategies, e. g., distributionally robust optimization [93], [94].

Additionally, forecasting techniques are alternatives to alleviate the effects of uncertainties on service restoration. Although many forecasting techniques have been proposed to predict the load consumption [95]-[97] and renewable energy generation [98], [99], they should be further studied to have better prediction accuracy.

VIII. Conclusion

This paper reviews the existing service restoration approaches of distribution networks. The service restoration approaches without communication systems include relay protection, automatic reclosing control, backup automatic switching control, and FA based on intelligent switches. These approaches can immediately restore outage customers based on the predefined operation logic of local control units. However, it is difficult to coordinate local units in complicated situations.

The service restoration approaches with communication systems can be categorized as centralized, distributed and hierarchical approaches according to the communication architecture. Among them, different techniques are used to obtain restoration solutions, including expert systems, heuristic algorithms, meta-heuristic algorithms, graph theory, mathematical programming, and multi-agent systems. Using different techniques, each approach has different advantages and disadvantages.

A few research areas deserve more attention in the future: ① the distributed optimization algorithms should be further studied to obtain a high-quality restoration solution with reduced computation complexity; ② the network reconfiguration and microgrid operation as two important factors for service restoration should be optimally integrated into the service restoration strategy; ③ the uncertainties of DERs and loads should be carefully modeled in the service restoration problem.

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