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Review of Service Restoration for Distribution Networks

Feifan SHEN¹, Qiuwei WU¹*, Yusheng XUE²

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 require communication systems. They 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.

Keywords Distribution networks, Fault detection, Fault isolation, Service restoration, Self-healing schemes

1 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 to the faulty portion [3]. The statistics show that distribution networks contribute most to the unavailability of electricity supply [4]. Hence, it is important to enhance the resilience of distribution networks [5].

In case of emergencies, self-healing enables the distribution network to restore itself automatically and intelligently to the best possible status with a set of equipment, algorithms and communication technologies [2]. With the installation of the AMI and DA devices, such as remote terminal units (RTUs) and intelligent electronic devices (IEDs), the network is capable of detecting its operating 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 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 2 introduces concepts of fault location, isolation and service restoration of distribution networks. Section 3 presents an overview of service restoration approaches of distribution networks. Sections 4 and 5 review the service restoration approaches without and with communication systems. The approaches for online use and practical applications are presented in Section 6. Section 7 discusses future research areas of service restoration of distribution networks, followed by the conclusions.

2 Fault location, isolation and service restoration

2.1 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 single-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 are activated immediately to cut off fault currents with the zero-sequence over-current protection. However, the over-current protection is ineffective due to unobvious fault characteristics under high impedance fault conditions. In [8], [9], the zero-sequence inverse time over-current protection and third harmonic current based protection were proposed for the high impedance fault detection.

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. The authors in [10], [11] analyzed traveling waves generated by single-phase-ground faults and proposed a traveling waves based method for the single-phase-to-ground fault feeder selection. For temporary single-phase-to-ground faults, several fast arc extinguishing technologies were proposed to eliminate them. In [12], [13], a fast arc suppression system was 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) was 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 was 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.

2.2 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 micro-grids. The network has six zones and a DG unit with the black-start capability connected at zone 6.

![Fig. 1. Initial topology of the test network](image-url)
be respected, such as power balance constraints, voltage and current constraints and radial topology constraints.

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 operational policies [2], and switches S5 and S6 are opened 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 micro-grid shown in Fig. 2. During the micro-grid formation, the sudden load pick-up, cold load inrush and energizing unload lines may cause violations of frequency and voltage constraints [16]. Since there are usually not controllable synchronous generators in the micro-grid, at least one DG unit should have the ability to control frequency and voltage in the micro-grid. Therefore, additional constraints must be respected during the micro-grid formation, including frequency response rate constraints, spinning reserve constraints, maximum incremental load constraints, etc. Moreover, the formation and operation of the micro-grid should consider security criteria, e.g., the N-1 security criterion.

Generally, service restoration has the following three objectives.

- Objective 1: restore as many out-of-service loads as possible.
- Objective 2: minimize service restoration time.
- 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.

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

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

3) Distributed: there is not a central controller and each agent communicates with its neighbors to make decisions.

4) Hierarchical: 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 voltage-delay type sectionalizers [7].

4 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 for some cases, such as for a trunk with multiple short lengths.

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

5 Service restoration approaches with communication systems

5.1 Centralized approaches

Centralized approaches are based on the distribution automation system (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 computational capacity to process data and computations. Hence, the centralized approach has the single point failure risk, i.e., a failure of the CC would cause a collapse of service restoration, and may have heavy computation burdens. In this subsection, the centralized approaches are reviewed according to techniques used to obtain restoration solutions. In addition, the advantages and disadvantages of each technique are discussed.

5.1.1 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 used to match 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 the expert system.](image)

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 operational 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 operating 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 loads of zone 2 to feeder 2.

In [24], the knowledge base was developed based on 180 rules used by operators in restoration planning. The proposed system can restore the network with single zone or multi-zones restoration strategies. Moreover, rules of line loss reduction are incorporated into the system. In [25], the knowledge base was developed based on 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 was developed based on the Colored Petri Net (CPN) inference model. The components of distribution networks such as switches are modeled using the CPN and rules applied in a real distribution network are used to make restoration plans. Since the CPN has parallel-like inference characteristics, it can find restoration plans in 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 was developed in [27], in which rules are derived using the OOP technique. The feeder components and data is 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], [29], multiple knowledge bases or inference engines are used. In [28], an expert system was 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 rule processing. In [29], the proposed expert system has two functions, i.e., fault detection and service restoration, and three inference engines, i.e., the 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.

5.1.2 Heuristic algorithm

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

A heuristic restoration procedure was 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 load flow-based heuristic algorithm was developed in [31]. All available switches, except those switches opened 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 opened to eliminate one network loop such that the disturbance in the power flow pattern is minimized. Repeat this process until there is no network loop and a radial network with acceptable operating conditions is obtained. In [32], [33], multi-tier heuristic algorithms were developed, in which the switches and supporting feeders directly related to out-of-service portions, defined as tier 1, firstly attempt to restore all de-energized loads. 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 imprecise expressions of heuristic rules and uncertainties of loads, the fuzzy set theory was 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 uncertainties of loads based on historical load patterns of different customers and days. Then, the heuristic restoration procedures in [30] were 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.

5.1.3 Graph theory

a) Abstract graph of the distribution network

As shown in Fig. 1, a distribution network consists of substations (s/s) and interconnected load zones delimited by switches. If substations and load zones are viewed as vertexes and switches are viewed as edges (e1–e6), the network can be represented as a graph $G(V, E)$, where $V$ denotes vertexes and $E$ denotes edges. Therefore, service restoration is to find a spanning tree that represents a radial configuration of the network satisfying operational 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.

![Fig. 4. Abstract graph of the test network.](image)

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, and to find the best configuration according to certain criteria, such as the amount of de-energized load restored and the number of switching
operations. The author in [37] proposed an “interested tree” concept representing a tree in which all loads are supplied by substations. An algorithm was 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 was used to find multiple spanning trees, i.e., a forest, in order to deliver power to outage areas from multiple energized nodes.

The graph theory was used in [39], [40] to form micro-grids for service restoration. The fundamental loop concept-based method in [39] considers substations and micro-turbines (MTs) as root nodes and searches for a spanning tree representing a configuration with multiple islanded micro-grids. A cut set theory based spanning tree search algorithm was proposed in [40], in which each micro-grid is treated as a virtual feeder and 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 micro-grids is obtained.

b) Binary decision tree

Decision tree-based heuristic algorithms were 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 was used to search for desired solutions.

![Binary decision tree](image)

Fig. 5. Binary decision tree.

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. Through 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 was 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 was used in [43] to find the optimal decision tree solution.

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.

5.1.4 Mathematical programming

The mathematical programming technique has been used to solve service restoration problems. According to requirements on solutions, i.e., the optimality and computational 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.

- Loads are assumed to be three-phase balanced. The network is represented by equivalent single-phase circuits.
- Switches are considered as short-length circuits with negligible impedance.
- DG units and loads are controllable.

\[
\begin{align*}
\min & \quad \sum_{i \in \Omega_h} c^G P^G_i + \sum_{z \in \Omega} c^U (1 - x_z) + \sum_{y \in \Omega_h} c^I I^R_y \\
& \quad + \sum_{y \in \Omega_h} c^S (w_y - w^{oi}_y)^2 + \sum_{i \in \Omega_h} c^S r_i \quad \text{(1)} \\
\text{subject to} & \quad P^G_i + \sum_{y \in \Omega_h} P_y - \left( \sum_{y' \in \Omega_h} (P_{y'} + I^R_y) \right) = P^G_i (x_z - r_z); \quad \forall z \in \Omega, i \in b(z)
\end{align*}
\]
\[Q_i^p + \sum_{k=1}^{Q_x} \left( \sum_{j=1}^{Q_y} (Q_j^q + P_j^r X_j) \right) = Q_i^p (x_z - r); \forall z \in \Omega, i \in b(z)\]

\[0 \leq r_i \leq x_i; \forall z \in \Omega, i \in b(z)\]

\[V_i^r - V_{ij}^r = 2(P_{ij}^r R_{ij} + Q_{ij}^r X_{ij}) + P_{ij}^r (R_{ij}^2 + X_{ij}^2) + b_{ij}^r; \forall ij \in \Omega\]

\[-M(1-w_{ij}) \leq b_{ij} \leq M(1-w_{ij}); \forall ij \in \Omega\]

\[V_{ij}^r I_{ij}^r = \left( P_{ij}^r \right)^2 + \left( Q_{ij}^r \right)^2; \forall ij \in \Omega\]

\[x_i V_{ij}^{\text{min}} \leq V_{ij}^r \leq x_i V_{ij}^{\text{max}}; \forall z \in \Omega, i \in b(z)\]

\[0 \leq I_{ij} \leq w_{ij} I_{ij}^{\text{max}}; \forall ij \in \Omega\]

\[0 \leq I_{ij} \leq x_i I_{ij}^{\text{max}}; \forall z \in \Omega, ij \in \Omega \setminus \Omega_z, i, j \in b(z)\]

\[\sum_{i=1}^{Q_x} w_{ij} = n_c - 1\]

\[x_i, w_{ij} \in (0,1); \forall z \in \Omega, ij \in \Omega\]

The decision variables are status of switches \( w_{ij} = 1 \), if the corresponding switch is closed; otherwise, \( w_{ij} = 0 \), if the switch is open), status of zones \( x_i = 1 \), if the corresponding zone is energized; otherwise, \( x_i = 0 \), if the zone is de-energized) and the percentage of load shedding at each node \( r_i \). Variables \( P_{ij} \) and \( Q_{ij} \), representing the active and reactive power flow from node \( i \) to node \( j \). \( V_{ij}^r \) and \( I_{ij}^r \) represent the square voltage magnitude of node \( i \) and square current magnitude from node \( i \) to node \( j \), respectively. \( b_{ij} \) represents the auxiliary variable associated with circuit \( ij \). \( P_{ij}^G \) and \( Q_{ij}^G \) are active and reactive power generations at node \( i \), respectively. \( P_{ij}^P \) and \( Q_{ij}^P \) are the active and reactive demands at node \( i \), respectively. \( R_{ij} \) and \( X_{ij} \) are the resistance and reactance of circuit \( ij \), respectively. \( n_c \) is the number of total vertexes of the abstract graph of the network. \( c^G \) is the energy production cost, \( c^U \) is the cost of de-energizing a zone, \( c^{\text{loss}} \) is the cost of line losses, \( c^R \) is the cost of load shedding, and \( c^S \) is the cost of a switching action. \( w_{ij}^{\text{ini}} \) represents the initial status of switches. \( V_{ij}^{n, \text{min}} \) and \( V_{ij}^{n, \text{max}} \) are lower and upper bounds of square voltage magnitudes, respectively. \( I_{ij}^{n, \text{min}} \) and \( I_{ij}^{n, \text{max}} \) are lower and upper bounds of square current magnitudes, respectively. \( M \) 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. Constraints (2) and (3) represent the active and reactive power balance at each node, respectively. Constraint (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. Constraint (5) calculates the voltage drop for each circuit. Constraint (6) represents that constraint (5) is removed for circuits whose switches are open. Constraint (7) calculates current magnitudes of all circuits. Constraint (8) limits the voltage magnitudes: if a given zone is de-energized, voltage magnitudes of all nodes in the zone are forced to be zero. Constraint (9) limits square current magnitudes of all circuits. Constraints (2), (3) and (10) ensure a radial topology of the network. Constraint (11) defines the binary nature of \( w_{ij} \) and \( x_i \).
The model in (1)-(11) has been adapted to service restoration with islanded micro-grids. A comprehensive strategy considering the normal operating mode and self-healing mode was developed in [49]. In the normal operating 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 micro-grids. Moreover, the rolling horizon optimization technique is used to deal with 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 was proposed in [50], which provides a sequence of control actions to coordinate DG units and switches to form micro-grids 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 was proposed, in which the inter-temporal characteristics of energy storage systems (ESSs) and cold load pickup (CLPU) phenomenon are considered.

Two robust service restoration models have been formulated in [52], [53]. A two-stage robust optimization model considering uncertainties of DG outputs and load consumption was 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 solved iteratively by the column-and-constrained generation method. An information gap decision theory based robust restoration model was proposed in [53], in which uncertainties of DG units and load consumption are modeled by bounded uncertain sets. The solution obtained can guarantee that the amount of loads restored would not fall below a specified threshold. A fuzzy mixed-integer programming model considering uncertainties of load consumption and the payback effect was proposed in [54] to perform risk management for service restoration.

In addition, the dynamic programming (DP) technique was 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 dynamic programming method was used to reduce the number of states by grouping similar states and to select the best sequence of states. The Bender decomposition technique was used in [56] to solve the service restoration problem with micro-grids. The problem is decomposed into a master problem and a slave problem, which are solved iteratively to obtain solutions. The master problem formulated as a mixed integer programming (MIP) model determines the configuration of the network and minimizes the amount of load shedding. The slave problem formulated as a conic model minimizes 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 complexity of the network.

5.1.5 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 but 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.

1. **Step 1**: Representation of the problem.

The decision variables of the problem in (1)-(11) can be represented as a binary string, e.g., $1, 1, 0, \ldots 0, 0, 1, 0)$. The binary value in the string represents the status of the DG units, and “0” represents an open switch.

2. **Step 2**: Generation of an initial population of strings.

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

3. **Step 3**: 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 higher objective value has a higher probability to be selected to produce the next generation of strings.

4. **Step 4**: Update of each string.

The GA updates strings by crossover and mutation operations. An offspring string is generated from two parent strings by crossover operation denoting an exchange of part of numbers between two parent strings. In selected offspring springs, some of their numbers subject to changes, i.e., “1” replaces “0”, and “0” replaces “1”.
• Step 5: Iteration and convergence.
  Repeat evaluating and updating strings until the number of iterations reaches a preset maximum or other termination conditions are satisfied; otherwise, go to Step 3 and the iteration number increases by one.

In [61], four meta-heuristic algorithms (GA, TS, reactive TS, and PSA) were 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 computational time. A non-dominated sorting genetic algorithm-II (NSGA-II) was adopted in [62], which considers priorities of customers and remotely controlled switches without converting multiple objectives as a single objective via weighting coefficients. It was demonstrated that the NSGA-II algorithm outperforms the conventional GA algorithm. A multi-objective revolutionary algorithm considering the switching sequence was 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 was proposed in [64], in which multi-objective 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.

| Year          | References | Means¹ | Techniques² | Quality of SR results                      |
|--------------|------------|--------|-------------|--------------------------------------------|
|              |            | NR     | MG          | ES | HE | GT | MP | MH | unbalanced network | uncertainty |
|              |            |        |             |    |    |    |    |    |                    | DG  | 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    | [47], [45], [56] |         |             |    |    |    |    |    |                    |     |            |
|              | [52]       |         |             |    |    |    |    |    |                    |     |            |
5.1.6 Hybrid approaches

Many research efforts have been put on hybrid methods to leverage 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 a 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 a MIP model. A two-phase strategy was proposed in [67], in which the target configuration is found at the first phase through the GA algorithm while the optimal switching sequence is obtained using the DP in the second phase.

5.1.7 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 micro-grid, techniques, and quality of solutions. It is concluded that network reconfiguration is the most widely used means for service restoration while the formation of the micro-grid 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.

5.2 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 MAS and mathematical programming are used.

5.2.1 Multi-agent systems

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). A MAS based distributed control strategy for DG units in the EI was proposed in [68], in which a consensus algorithm is used to regulate voltages of DG units and power sharing among DG units and to minimize circulating currents in the EI. In [69], a MAS-based distributed control strategy for the optimal energy management of the EI was 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 requiring central negotiation agents in distributed MASs, whereas the central negotiation agent is needed to coordinate agents in hierarchical MASs.

The hierarchical MAS was used in [70]-[72]. In [70], the bus agent and facilitator agent were developed in the MAS. The bus agent controls loads connected to the bus and the facilitator agent as the negotiation agent coordinates all bus agents. A two-layer multi-agent system was designed in [71], in which zone agents were developed in the lower layer and feeder agents as negotiation agents were 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 with the communication with adjacent feeder agents. A similar two-layer MAS was 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 was proposed in [73]-[77]. In [73], switch agents, load agents, and generator agents communicate with each other to make decisions without requiring a negotiation agent. Four types of zone agents including faulty zone agents, down zone agents, zone tie agents and healthy zone agents were developed in the MAS in [74], in which each agent identifies its type based on the fault location and communicates with other agents to make decisions.

The MAS was used in [75], [76] for service restoration with micro-grids. In [75], switch agents and distributed energy storage (DES) agents were developed in the MAS, in which a “team” concept representing 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 micro-grids. In [76], load agents, EV aggregator agents, DG agents, and switch agents were developed in the MAS where these agents negotiate to determine the configuration of micro-grids and operating conditions of EVs and DG units. The MAS was improved in [77] by modelling uncertainties of loads and DERs with the Monte Carlo method.

How the MAS-based approach solves service restoration problems is illustrated with an example. The restoration procedures are explained with the MAS in [70] 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 BAGs negotiate 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 optimality of solutions.

| Year     | Ref. | Means | Technique | Agent types                                                                 | Negotiation agent |
|----------|------|-------|-----------|------------------------------------------------------------------------------|-------------------|
| 2000-2010| [70] | √     | MG MAS MP | 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 agents, aggregator agents, DG agents 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 agents, EV aggregator agents, DG agents and switch agents              | -                 |
|          | [79] | √     |           | feeder agents                                                               | -                 |
|          | [78] | √     |           | node agent                                                                  | -                 |
5.2.2 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 was proposed in [78], in which the service restoration problem formulated as a 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.

5.2.3 Hybrid methods

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

5.2.4 Summary of distributed and hierarchical approaches

The distributed and hierarchical approaches are summarized in Table 2 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 micro-grid. Moreover, it has a trend of combining the MAS with mathematical programming to obtain optimized restoration solutions.

6 Validation and practical applications

6.1 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.

The service restoration approaches without communication systems are available for online use because they can take actions immediately based on the predefined operational logics. For 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 was 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 was 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 seconds. In [59], the proposed TS-based meta-heuristic algorithm was 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 seconds.

6.2 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 type sectionalizers was invented by Japanese engineers and introduced to China by Hai and Chen. 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 was 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 restored 600 households and shops in the center of Rotterdam within 18 seconds after a fault occurrence. 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 was 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 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 was 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 minutes.

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.

7 Future research areas

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

7.1 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 computational resources. The distributed optimization algorithm is a promising tool because it can decompose a large-scale complex problem into smaller scale sub-problems 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 was used to solve security-constrained unit commitment problems [85] and optimal power flow (OPF) problems [86]. The optimality condition decomposition (OCD) technique was used to solve OPF problems [87]. The ADMM was 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 was proposed in [78]. However, the strategy is designed for specific service restoration scenarios and network reconfiguration as an important means for 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.

7.2 Micro-grids

The ever-increasing penetration of DERs brings benefits to service restoration. If 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 the micro-grid mode, which is a promising means for service restoration.

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

7.3 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 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 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.

8 Conclusions

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 feeder automation (FA) based on intelligent switches. These approaches can immediately restore outage customers based on the predefined operational 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 means for service restoration should be optimally integrated into the service restoration strategy; and 3) The uncertainties of DERs and loads should be carefully modeled in the service restoration problem.

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Feifan SHEN received the B.Eng. degree in electrical engineering and automation from Hohai University, Nanjing, China, in 2015, and the M.Eng. degree from the Department of Electrical Engineering, Wuhan University, Wuhan, China, in 2017. He is currently working toward the Ph.D. degree in the Department of Electrical Engineering, Centre of Electric Power and Energy, Technical University of Denmark, Kongens Lyngby, Denmark.

Qiuwei WU received the B.Eng. and M.Eng. in power system and its automation from Nanjing University of Science and Technology, Nanjing, China, in 2000 and 2003, respectively, and the Ph.D. in power system engineering from Nanyang Technological University, Singapore, in 2009. He has been associate professor since September 2013 in the Centre of Electric Power and Energy (CEE), Department of Electrical Engineering, Technical University of Denmark (DTU), Kongens Lyngby, Denmark. He is an Editor of IEEE Transactions on Smart Grid and IEEE Power Engineering Letters. He is also the Deputy Editor-In-Chief of International Journal of Electrical Power and Energy Systems. He is an Associate Editor of Journal of Modern Power Systems and Clean Energy, and the Regional Editor for Europe of IET Renewable Power Generation.

Yusheng XUE received the M.Sc. degree in electrical engineering from EPRI, China, in 1981, and the Ph.D. degree in electrical engineering from the University of Liege, Liege, Belgium, in 1987. He was elected as an Academician of the Chinese Academy of Engineering in 1995. He is now the Honorary President of State Grid Electric Power Research Institute (SGEPRI or NARI), China. He holds the positions of Adjunct Professor in many universities in China and is a Conjoint Professor with the University of Newcastle, Callaghan, NSW, Australia. He is also an Honorary Professor with the University of Queensland, Brisbane, Qld., Australia. He has been a member of the PSCC Council, and the Editor-in-Chief of Automation of Electric Power System since 1999, and a Member of Editorial Board of IET Generation, Transmission, and Distribution, and Chairman of Technical Committee of Chinese National Committee of CIGRE since 2005.