A Review on Self-healing in Modern Power Distribution Systems

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***Abstract*—The ever-increasing dependence on electrical power has posed more challenges to power system engineers to deliver secure, stable, and sustained energy to electricity consumers. Due to the increasing occurrence of short- and long-term power interruptions in the power system, the need for a systematic approach to mitigate the negative impacts of such events is further manifested. Self-healing and its control strategies are generally accepted as a solution for this concern. Due to the importance of self-healing subject in power distribution systems, this paper conducts a comprehensive literature review on self-healing from existing published papers. The concept of self-healing is briefly described, and the published papers in this area are categorized based on key factors such as self-healing optimization goals, available control actions, and solution methods. Some proficient techniques adopted for self-healing improvements are also classified to have a better comparison and selection of methods for new investigators. Moreover, future research directions that need to be explored to improve self-healing operations in modern power distribution systems are investigated and described at the end of this paper.**

***Index Terms*—Self-healing, distributed generator, renewable energy source, microgrid, optimization, reconfiguration, service restoration, automation system.**

I. Introduction

ELECTRICAL power is an inevitable part of our daily lives to the extent that the present world could not be imagined without it. Continuity of electrical power and its secure delivery is a significant concern and challenge for the utilities, as the world faces more unexpected events than before, especially in recent years [1], [2], causing enormous economic losses for countries' economies [3]. Researchers around the world are continuing to search and improve methods for minimizing the impacts of unexpected power failures. Advancements in energy generation/consumption units as well as in communication and control infrastructure have led the traditional power distribution systems towards a new structure called smart grid [4].

The smart grid concept provides more advanced options to manage and control the power system components and increases power system's reliability, resiliency, and efficiency. Self-healing is the key characteristic of a smart grid defined as the ability of power distribution systems to automatically restore themselves after faults, by the report from National Energy Technology Laboratory (NETL), USA [5]. Self-healing is an essential feature of smart distribution systems that minimizes the impacts of extreme events and restores the loads automatically and intelligently during such incidents [6]. The development of self-healing strategies is highly required to improve the power system's reliability, efficiency, resiliency, and security [7], [8]. A self-healing system uses various modern techniques to supply sustainable, reliable, and secure power in the consumer sites [9], [10]. However, it is a persisting challenge to implement self-healing control strategies and their corresponding effective operations [11], [12].

Self-healing in smart distribution systems follows specific algorithms to isolate the faulted area and restore the system entirely or partially during an extreme event for the regular operation [13], [14]. In self-healing operation, automation systems detect the location and type of faults as early as the fault happens in the system [15]. Then, control actions are performed instantly to isolate the faulted area and restore the maximum possible loads within the shortest possible time without any human intervention [16], [17]. The principle of operation of a self-healing system during a fault event includes fault location, isolation, and service restoration (FLISR).

FLISR provides the utilities with an intelligent automation operation during fault conditions by effective monitoring and decision-making without human intervention [18], [19]. According to the United States Department of Energy (DOE), FLISR has reduced the number of customer minutes of interruption by 51% for an outage event and reduced the number of customers interrupted by 45% [20].

Self-healing is expected to operate in real-time and quickly locate, isolate, and reconfigure the network to restore the maximum load. Restoration function is achieved by adopting advanced intelligent control systems that incorporate multiple available control actions in smart grids. For instance, service restoration is addressed by the network configuration technique based on the optimal switching actions on the

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feeders. Reference [21] proposes a graph theory-based distribution system restoration strategy using system reconfiguration techniques, while reducing the number of switching operations. Reference [22] proposes a multi-objective evolution algorithm to reconfigure the system and restore the loads within the stand-alone microgrid to minimize switching operations and interrupted loads. A multi-objective evolutionary algorithm based solution is proposed in [23] for service restoration problem in a real large-scale distribution system. An A*-based search algorithm is used in [6] to find a lower cost reconfiguration plan in a radial distribution system. The outage areas are optimally sectionalized in [24] and converted into networked microgrids, which can autonomously supply electric power to many affected customers by rescheduling the output power of distributed generators (DGs). The application of energy management systems and self-healing capabilities are discussed in [25] to control the existing microgrid DGs to improve the microgrid operational performance. The amount of energy from the DGs is determined by the SBB algorithm, discussed in [26]. In addition to the DGs, the energy storage and reactive sources also play a key role in self-healing control operations.

For instance, [13] presents a model for service restoration using energy storage that will support the system in grid-connected as well as islanded operation. Reference [6] proposes a systematic strategy for constructing self-sufficient microgrids, using energy storage units and reactive sources for performing optimum self-healing control actions. Reference [27] develops an analytical methodology and perform operations of reactive sources of renewable photovoltaic (PV) to improve the power stability index in a state grid. A power factor control and volt-var control strategy to control active and reactive current injection to the grid is discussed in [28]-[30]. Moreover, load management based on consumer load priority during extreme event periods can positively impact on self-healing operations. References [21] and [22] maximize the restored load and optimal switching operation within the shortest possible time by proposing a restoration plan in the distribution system. Reference [31] proposes a methodology to support self-healing in distribution systems to restore the maximum possible load while ensuring power quality.

Several research papers that have recently been published further illustrate the significant impact of self-healing on power system reliability and security. In this scenario, a comprehensive review paper is needed for a more in-depth understanding and organization of the existing literature. Some review papers have been published in the literature partially describing the self-healing subject in power distribution systems. Reference [32] summarizes network reconfiguration and load restoration strategies for power systems restoration from 2006 to 2016.

An overview of distributed multi-agent systems in self-healing is presented in detail in [33]. The principle of different multi-agent's techniques for the self-healing service restoration problem is briefly described in [34]. Reference [35] summarizes and addresses the reality of professionally designed failure with multiple models. The different approaches for self-healing restoration problems in the past 35 years are summarized in [36]. Reference [37] reviews and collects different self-healing techniques by focusing on different control architectures to face emergency states of the distribution network. Reference [38] performs a literature review of self-healing control strategies and the system's state by describing different stages of the self-healing process. In addition, [39] reviews other service restoration approaches in distribution networks renamed centralized, distributed, and hierarchical based on the communication structure of the network. In [40], self-healing algorithms and their application areas are surveyed using papers published between 2003 and 2017.

Although valuable papers have been published on self-healing reviews so far, the literature still lacks a comprehensive review on the subject of self-healing in power distribution systems, which organizes the research papers considering different aspects of self-healing. To fill the gap, this paper presents a complete up-to-date review on the self-healing research area by focusing on different features such as solution algorithms, optimization objective functions, and proficient techniques and methodologies adopted to address the implementation of self-healing. At the same time, several fundamental limitations and strengths are investigated for the reviewed papers. Finally, the challenges are identified, and future research works are proposed at the end of this paper. Thus, the main contributions of this paper are as follows.

1) A comprehensive and up-to-date literature review is conducted on self-healing in power distribution systems.

2) The self-healing operational procedures are summarized by describing different operating stages, including fault detection, fault understanding, fault isolating, and service restoration.

3) Up-to-date self-healing research papers are organized and key features such as self-healing control actions, objective functions, and solution algorithms are categorized.

4) Fundamental limitations on self-healing are addressed, major challenges in the present paper are identified, and some future research paths are recommended.

The rest of the paper is organized as follows. The self-healing concept is described in Section II. Section III presents motivation and paper analysis. Section IV discusses self-healing control actions while Section V discusses the self-healing goals. The optimization algorithms of self-healing are discussed in Section VI. The future works are presented in Section VII, and finally, conclusions are given in Section VIII.

II. Self-healing Concept

The primary concept of self-healing comes jointly from the United States Department of Defense (DOD) and the Electric Power Research Institute (EPRI) that enable extensive national infrastructure to self-heal in response to threat [41]. Due to the power grid modernizations, self-healing is gaining attention from researchers around the globe to ensure grid reliability during disturbance periods and improve the power quality in the distribution systems. Self-healing is the ability of power systems to automatically restore themselves after faults, while resilience is the measure of the ability to withstand disasters (low-frequency high-impact incidents). These two terms are related and the main difference is that self-healing usually refers to minimizing the impact of faults after an incident; however, resilience is an index to measure the ability of system to withstand an incident. In general, self-healing can improve the system resilience, and a self-healing system has higher resiliency. The self-healing process and its principle of operation during a fault event are shown in Fig. 1, where the normal mode, faulted mode, and restoration mode are illustrated in different parts of the figure. Different stages of self-healing are described in detail in the following subsections.

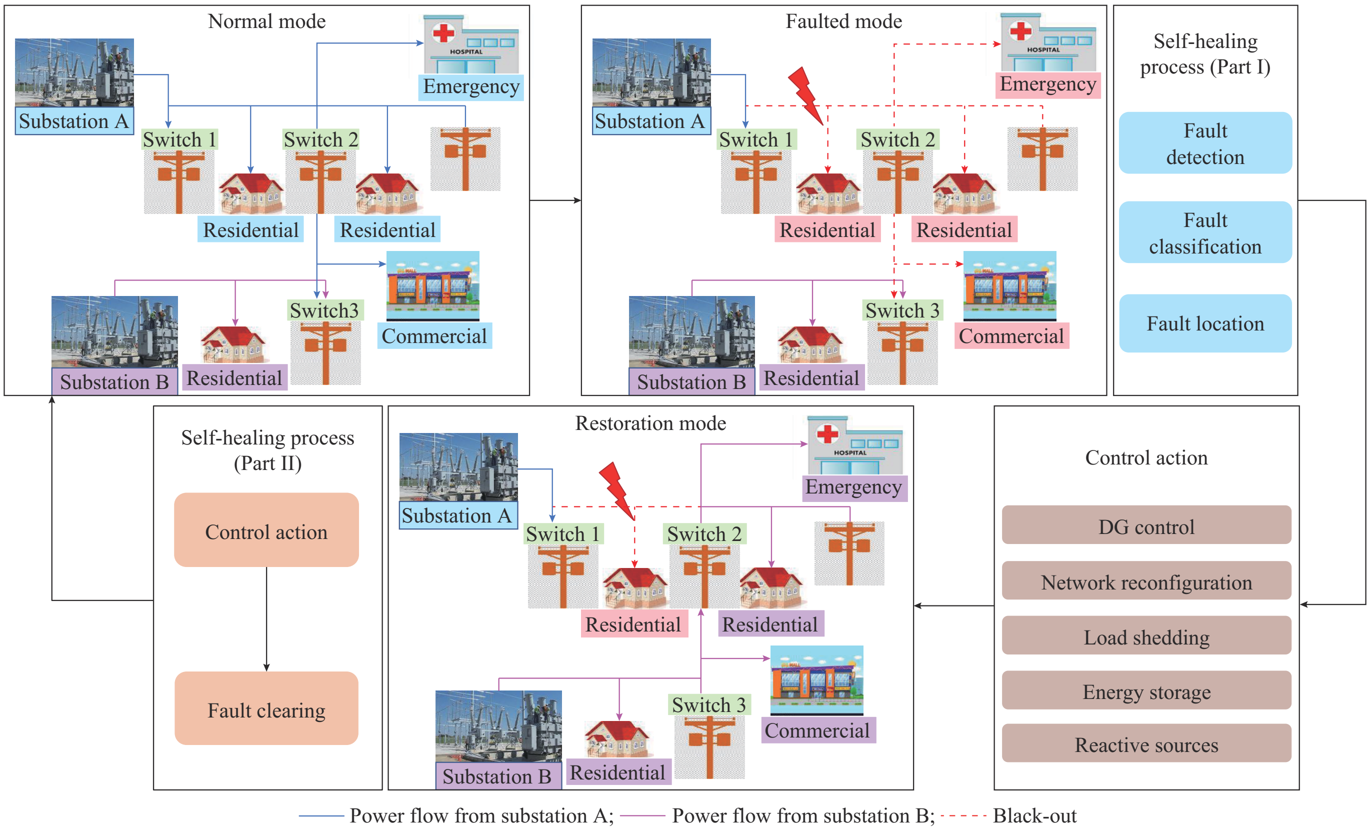

Fig. 1. Self-healing process and its principle of operation during a fault event.

A. Fault Detection

The first stage of self-healing operations is fault detection. A self-healing system should detect the fault in the distribution system as fast as possible to avoid adversarial impacts of abnormal events and reduce productivity loss.

In a simple protection system, the circuit breaker trips the equipment to prevent the fault from damaging the equipment and creating further losses. For a centralized supervisory and control approach, the supervisory control and data acquisition (SCADA) system executes the communication, collects information and measurements, and sends them to the control center. For a decentralized and distributed approach, the communication system implemented in a peer-to-peer format collects the information and measurements required for decision-making. Collecting the information about fault severity, fault locations, and fault types is the first step to perform the subsequent operations discussed in the following text. Although it may seem straightforward, there are always challenges for accurately and adequately detecting the faults in a power distribution system. Several research papers have been published on fault detection with different methods in [8], [13], [14], [18], [42]-[53].

B. Fault Understanding

One challenging task in the self-healing process is to analyze the type of fault. The faults in distribution systems are categorized as symmetrical and unsymmetrical. Symmetrical faults occur irregularly and cause extreme damage to the equipment. In unsymmetrical faults, the possibility of damage is less than that in symmetrical cases. This type of fault can be in line-to-ground and line-line-to-ground. Reference [46] reviews papers that survey the conceptual aspects, and recent developments in fault detection, isolation, and service restoration following an outage in a distribution system. Some extra relevant works to fault understanding in the literature can be found in [45], [54].

C. Fault Isolation

Fault isolation is the next stage of the self-healing process after a fault is detected. Fault isolation is executed by tripping the circuit breakers and disconnecting the faulted area from the rest of power system. During the isolation operation, it is necessary to identify the root cause of the fault and the location of the fault. An important task at this stage is to estimate the capability of the neighboring feeder to be selected for isolation. The fault should be cleared, load shedding should be performed if needed, and the grid should be divided into subsections, if possible. All these actions should be taken immediately to avoid significant impacts on power systems due to the fault. Some research related to fault isolation exists in [14], [18], [45], [48], [49], [53], [55].

D. Service Restoration

The self-healing process starts with fault detection and ends with the restoration process after a fault occurrence. When the power supply is interrupted, it is critical to rapidly restore power to the affected areas to avoid further customer interruptions. Therefore, the restoration strategy changes the power system outage state to normal stage using available energy resources. A self-healing system performs restoration process primarily using line switching operations within the faulty area. Restoration strategy needs an appropriate capable backup feeder and sources to transfer the load to another feeder. After restoring the power to the out of service areas, the system needs to perform corrective actions. There are more publications available in literature that address service restoration, including [13], [14], [16]-[18], [23], [47], [53], [56]-[76].

III. Motivation and Paper Analysis

Self-healing is one of the essential techniques in power systems to improve their reliability, efficiency, and quality of service. Due to its importance, researchers worldwide are working on enhancing the self-healing performance. Although there are review papers in other areas of power systems, to the authors' best knowledge, no complete review paper summarizes self-healing applications in power distribution systems. Thus, this paper will motivate the researchers to work in this area, especially the beginner researchers. This section describes the motivation behind the self-healing review papers and presents the paper selection strategy, frequency, and venue of publications.

Significant research on self-healing in power distribution systems has been conducted since a couple of decades ago, which is also flourishing nowadays. The first research paper with the term self-healing in power distribution systems was published in 2004; however, the power restoration and restoring service in power systems have been in the literature since 1981 [77]. Since then, papers on this subject have been published in different venues. Figure 2 shows the ratio of different publications (popular journals, conferences, reports from industries, and reports from online) on self-healing subjects in power distribution systems. It can be observed that 85% of research papers are published in different popular journals compared with other categories of publications.

IV. Self-healing Control Actions

After detecting a fault in a power distribution system, self-healing is usually performed through a set of control actions. This section discusses such control strategies and explains how the self-healing process is performed in a faulted system.

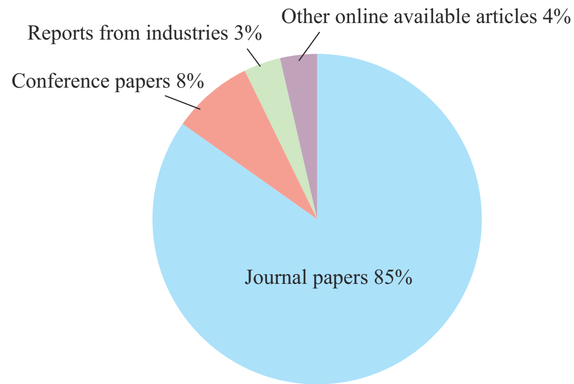

Fig. 2. Ratio of different publications on self-healing subjects in power distribution systems.

A. Grid Reconfiguration

In a self-healing power distribution system, the first control action could be grid reconfiguration after detecting contingencies. When a fault occurs in a power distribution system, grid reconfiguration is performed for two reasons. First, isolate the fault or faulted area to avoid supporting the fault current and minimize the fault impacts on other loads in the system. Second, reroute the power from available sources to the loads located downstream of the fault location. If operated instantly, efficiently, and strategically, the grid reconfiguration could reduce restoration time significantly. Reference [6] proposes an optimal informed search algorithm for finding optimal feeder configurations while ensuring the lowest switching costs. Reference [21] presents a model for system reconfiguration purpose that maximizes the restored load and minimizes the number of switching operations. Graph-theory based methods are usually used for grid reconfiguration to minimize interrupted load during faults. Several research papers in literature have discussed network reconfiguration as part of self-healing control actions, including [9], [14], [18], [19], [23], [64], [78]-[88].

B. Control of DG Output Power

Another control action as part of the self-healing process is the control of DG output power. If appropriately controlled, utility-owned or customer-owned DGs could partially or fully supply the existing loads in a distribution system during contingencies. For an efficient self-healing process, the available output power of all DGs and existing loads should be known to the self-healing decision-making system before performing any restorative actions. Therefore, forecasted load and generation data and potential fault impacts in different locations are crucial for optimum system restorative actions.

References [7] and [26] propose a decision-making method to determine the optimal restoration strategy by coordinating multiple DGs to serve critical loads after blackouts in distribution systems to enhance system resiliency. Reference [60] proposes a new restoration strategy for fully decentralized multi-agent service restoration system in the presence of large-scale DGs to restore the critical loads, reduce system energy losses, and accelerate the restoration process. The DG output power is usually modeled by a vector where its vertices are the power generation of each DG located at different buses. When an optimization problem is defined for self-healing, this vector will be one of decision variables. Controlling output power of DGs as part of the self-healing process is addressed in more research papers including [6], [9], [24], [62], [89]-[96].

C. Load Management

When disconnected from the grid, the power generated by the DGs may be insufficient to support all the loads in the system. In such cases, they should be disconnected from the grid, or their consumption should be adjusted to match the available supply. In this scenario, the priority of loads should be considered based on the customer's reliability requirements. A load management strategy has been presented in [7] to maximize the number of loads restored, weighted by their priority. Reference [10] presents a new mathematical model to solve the restoration problem in balanced distribution systems to minimize load curtailment in the restored system. Reference [21] presents a graph-theoretic distribution system restoration strategy to maximize the restored load by incorporating microgrids. Load management is also implemented by optimizing a vector of load values at different buses during self-healing optimization process. Other research papers published to address restoration service using load management include [6], [9], [97]-[101].

D. Control of Energy Storage Units

Energy storage systems (ESSs) are integrated into modern power distribution systems to improve the system performance. As part of self-healing restorative actions, while the DG support is not sufficient to supply all existing loads, the energy stored in such storage units could support the distribution system and energize the remaining loads. Since the capacity and output power of ESSs are limited, their available power and energy should be known to the self-healing decision-making system for performing an optimal task. Reference [13] presents an algorithm for service restoration with distributed energy storage support for load restoration. The role of energy storage by controlling them to enhance distribution system resiliency in terms of system mobility and flexibility has been discussed in [102]. Furthermore, service restoration using energy storage units has been addressed with different methods in several research papers including [6], [13], [84], [92].

E. Control of Reactive Power Sources

Reactive power sources exist in power distribution systems as fixed or controllable capacitors/reactors or provided by DGs. During the self-healing process in power distribution systems, controlling reactive power sources can improve the quality of restored service in terms of power factor, voltage profile and power losses. Reference [87] proposes an optimization method for voltage regulation by reactive power control based on a comprehensive architecture model that coordinates multiple PV distributed sources to support self-healing. Moreover, researchers have used reactive power sources as part of self-healing control actions in the past years [6], [29], [93].

The energy storage units and reactive power sources are modeled similarly to the DGs, where the former has only active power and the latter only reactive power.

V. Self-healing Goals

Self-healing in power distribution systems is performed by detecting, locating, and isolating faulty parts and restoring power as quickly as possible. An effective self-healing system performs such actions through an optimized strategy. An optimization problem is defined for this purpose, where different researchers have used different goals or objective functions to formulate the self-healing problem. The classifications of self-healing control actions, objective functions of self-healing, and optimization algorithms used for self-healing are summarized in Fig. 3.

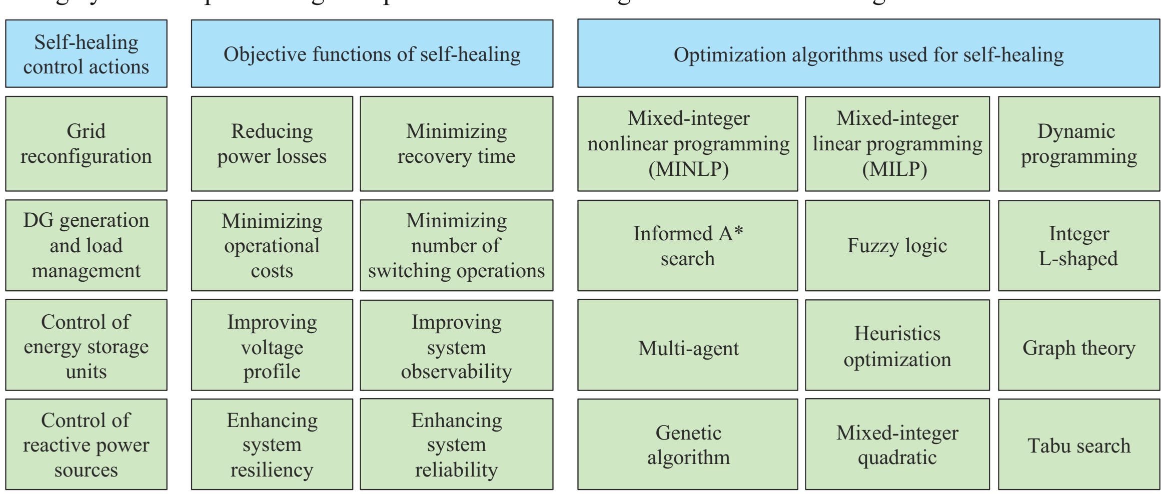

Fig. 3. Classifications of self-healing control actions, objective functions of self-healing, and optimization algorithms used for self-healing.

A. Reducing Power Losses

Reducing power losses is one of the goals for performing efficient self-healing in power distribution systems. Power losses have always been a concern in power distribution systems, and engineers have always tried to minimize them. High power losses in a system can cause operational issues, e.g., power quality issues, and increase the customer's electricity costs. Although it cannot be eliminated, the loss in a system can be controlled and minimized to improve the efficiency of the system's operation. An optimized self-healing strategy planner will try to minimize the losses during this process. Reference [31] presents a methodology to optimally restore the maximum loads to minimize system power and energy losses, while assuring power quality. The decision parameter considered in this research is the number of searching spaces in switching values. A binary particle swarm optimization technique is used in this paper to determine a scenario to restore load. Reference [66] presents a methodology that uses network reconfiguration with DGs as a real-time operating tool for loss reduction from the view of the distribution system operator. In this paper, the decision variables are reactance of branch, reactive power provided by a DG, and var compensators. A mixed-integer second-order cone programming method is used in their paper to better utilize the big-*M*, second-order cone relaxation, and piecewise linearization methods. Moreover, power and energy losses have been considered as part of objective function for self-healing in several other research papers [6], [63], [86].

B. Minimizing Recovery Time

One important aspect for performing an efficient self-healing is to speed up the process and minimize the affected consumers. Self-healing systems usually use advanced communication technologies such as software-defined networks, to locate and recover from faults. Reference [60] proposes a restoration strategy for power distribution systems with highly integrated DGs to restore the critical loads shortly by reducing energy losses. The output power of the DGs with uncertain characteristics has been considered as decision variables in their research. Reference [103] formulates an integer linear programming model by using a self-healing phasor measurement unit to minimize the overhead of the self-healing process. Phasor measurement units are considered as decision variables in different forms, and a greedy heuristic algorithm has been considered to solve this optimization problem. Reference [104] presents a service restoration model by concentrating on switch timing derivation and optimizing black start restoration of single master operation microgrids, while minimizing total restoration time and maximizing total loads restored. More papers are published in this area including [82], [105]-[107].

C. Minimizing Operational Costs

Minimizing operational costs has always been a challenge for power system engineers and yet is for performing self-healing.

The operational cost for a system during self-healing can be minimized in different aspects. For instance, a cost-efficient self-healing system could be achieved by using the minimum cost generators, minimizing the costly load shedding, minimizing power losses, and shortening the distance of power transfer in feeders. Reference [6] presents a class of algorithms for system reconfiguration plans to minimize system operational costs. Switching parameters have been considered as decision variables additive heuristic algorithm which can work in the large-scale system. Reference [108] proposes a comprehensive framework for optimal day-ahead operational planning of smart distribution systems to minimize operational costs and provide sustainability using the seamlessness index. The decision variables for this problem are the scheduling and dispatching statutes of the local generation units. Also, those parameters are used in the graph theory algorithm to solve this optimization problem. Moreover, [24], [62], [93], [95] present research to address this issue for power distribution systems.

D. Minimizing Number of Switching Operations

Minimizing the number of switching operations during self-healing can speed up the process and minimize the affected consumers. Using advanced communication and control technologies to locate the faulted area, the number of switches to recover the loads can be reduced. A service restoration strategy is presented in [109] to restore the maximum loads using reconfiguration by the minimum number of switching operations. Continuous and discrete decision variables considered for active and reactive power, which are applied in mixed-integer programing, significantly improves the training efficiency compared with exploration of dominant reinforcement learning methods. Reference [83] develops a self-healing strategy with multi-agent system in reconfiguration operations of power distribution systems to minimize switching operations. Other research papers have been published in this area including [23], [90], [100]-[111].

E. Improving Voltage Profile

Improving voltage profile in distribution systems is another consideration while performing self-healing. Different self-healing strategies have different impacts on the voltage profile of the system. Therefore, among the possible options for self-healing, the one that, besides addressing other concerns, improves the voltage profile should be selected. Volt-var functions of inverters to mitigate voltage violations and improve the voltage stability in distribution systems have been discussed by case studies in [27], where the decision variable is to find the locational value of solar PV generation. The role of controlling reactive power sources in the distribution system for minimizing voltage fluctuations is discussed in [112]. The same decision variable, i.e., the locational value of solar PV generation, is also considered in this research to minimize the voltage fluctuation simulated in ETAP and MATLAB. A comprehensive scheme based on decentralized multi-agent systems is presented in [113] for the voltage control of power systems, and [26] also uses voltage profiles as part of self-healing objectives.

F. Improving System Observability

Observability restoration during the self-healing process is another concern for distribution system operators. A series of synchronized phasor measurement units are usually required to achieve global observability in a power distribution system. Therefore, it is critical to consider the minimum number of phasor measurement units to complete the observation restoration while performing self-healing in a power distribution system. Reference [103] protects the power network by maximizing the observability in the transmission line where phasor measurement units are considered as decision variable and greedy heuristic algorithm is used to solve this optimization problem. Reference [114] presents a methodology for power system observability analysis using SCADA system and phasor measurement units. Reference [115] presents a methodology for the phasor measurement unit placement to achieve high observability of system dynamics to perform a reliable real-time dynamic vulnerability assessment. Phasor measurement units have been considered as decision variables while improving the system observability.

G. Enhancing System Resiliency

Climate changes could directly affect the modern world and cause many intensive unwanted natural disasters such as hurricanes and floods. The power system is one of the areas which is recurrently affected by such events. Almost 80% of all major power outages happen due to natural disasters in the United States and are expected to increase continuously [116]. The individual line switching status has played a key role in optimally placing the mobile emergency resources in this paper. A resilient power system can protect its infrastructure rapidly and effectively during extreme events. Self-healing in power distribution systems can be performed to increase system resiliency for subsequent events. Reference [117] proposes adaptive multi-microgrids as part of the critical service restoration strategy to enhance microgrid resilience and survivability. A two-stage coordinated power-sharing strategy among battery energy storages and coupled microgrids is proposed in [99] for overload management in autonomous microgrids for self-healing and resiliency improvement. The power capacity of battery energy storages has been used in two-stage coordinated overload management technique as a decision variable to make system more resilient. More research papers are available in the literature investigating the power system resiliency enhancements and are summarized in [118]-[124].

H. Enhancing System Reliability

To fill up the ever-increasing energy demand, the power system needs to accommodate large-scale DERs. This will create a new paradigm for the existing power system to face challenges during operation, especially for renewable energy sources (RESs). Although RESs can support the grid by providing economically and environmentally friendly clean energy, there are issues with managing their uncertain characteristics. In these scenarios, service interruption may be unavoidable, especially for large-scale integration of RESs. Self-healing can substantially improve the reliability of the power systems. Reference [18] constructs a self-healing framework to locate and isolate faults in smart distribution systems by implementing fewer switching operations to restore the out-of-service loads and increase reliability. Reference [101] proposes a methodology to improve the power supply reliability, and to avoid moving into an unstable operating state. Moreover, there are many papers published in the literature that address the system reliability such as [64], [72], [93].

VI. Optimization Algorithms of Self-healing

This section classifies the publications based on the optimization algorithms used for self-healing. A summary of papers for each algorithm is presented in each subsection. Moreover, Table I and Table II summarize different popular algorithms used for self-healing, before and after 2019, respectively, including the type of test feeders, goals, strengths, and limitations of each paper.

A. Multi-agent

The out-of-service area is usually energized by changing the distribution system configuration utilizing switching actions on the feeders. The multi-agent optimization is considered in [50] for switching actions and an agent-based approach is proposed for service restoration in distribution systems and control of distributed generations. The proposed control structure has four different types of agents: feeder agents, zone agents, switch agents, and DG agents [67]. Such agents cooperate with each other to solve restoration problem and to restore power supply to an outage area. Multi-agent algorithm has been used in literature for self-healing purposes [13], [18], [53], [56], [80], [125].

B. MILP

The MILP algorithm has been used in literature to optimize the service restoration in a self-healing system. MILP is a more direct approach to generating optimal solutions with high-speed processors. Most research papers using MILP algorithm have considered minimizing the number of switching operations and load shedding, maximizing load restoration, and minimizing the outage period. Reference [9] utilizes a linearized MILP model that can be used for computational optimization of restoration strategy. More recently, in [17], [57], [104], and [126], the integrated microgrid in a distribution system is used to prevent the unbalanced operation that trips the DGs. In [19], [61], [79], [98], [120], [127], and [128], self-healing has been implemented by using MILP algorithm.

C. MINLP

MINLP has been widely employed in solving service restoration problems in self-healing systems, as it can obtain globally optimal solutions. This trend has inspired researchers to apply MINLP to solve optimization problems in self-healing problems. The adopted new healer reinforcement approach in [129] can minimize a combination of system average interruption duration index and total cost of reliability. In this approach, parking lots participate in the service restoration as backup units and storage units. In [10], the optimal solution with high quality is provided, which can be achieved by maximizing load restoration, minimizing the number of switching operations, prioritizing the use of automatic switches, and prioritizing special loads. The proposal adopted in [130] presents a model based on exact power flow equations to implement a restoration strategy based on microgrids through distribution systems.

D. Heuristics Optimization

Many research papers have been presented to address distributed service restoration problems using heuristics algorithms. Reference [21] proposes heuristics search algorithm to identify a post outage in distribution system topology subject to several constraints such as minimizing the number of switching actions in distributed service restoration, integrating microgrids to ensure the generation limits of distribution system restoration. Reference [58] presents a solution through extensive simulation experiments for faulty areas and DGs besides the heuristic method.

TABLE I
SUMMARY OF DIFFERENT POPULAR ALGORITHMS USED FOR SELF-HEALING - BEFORE 2019

Type of test feeder	Optimization algorithm	Reference	Goal	Strength	Limitation	Year
16-, 33-, and 69-bus	MILP	[9]	Minimize restoration cost and maximize the number of supplied customers based on priority ratings	Optimal solution based on DG output and load shedding is obtained	Fault detection and clearing are not considered	2018
A 53-node case	MINLP	[10]	Maximize load restoration, minimize the number of switching operations, and prioritize special loads	Optimal solution with high quality is provided	Processing time is very long	2016
IEEE 13-node and 37-node	MINLP	[16]	Maximize load restoration	Optimal solution for voltages/currents in a system is provided	Optimal solution for a large-scale system is not provided	2007
69-bus	MILP	[47]	Minimize costs of switching actions and minimize load shedding	Fast response time is obtained with local control actions and supported with microgrids	No load shedding is considered	2017
38- and 119-bus	Multi-agent	[56]	Maximize a restoration index which considers the priority of loads and number of switching operations	It is capable of working with different type of test systems	Active power and reactive power are ignored	2018
IEEE 34- and 118-bus	MILP	[57]	Maximize load restoration	Recover a large scale of outage area	Fault detection stage is not analyzed	2018
53-bus	Heuristics	[58]	Maximize load restoration, minimize power loss, topology variation and power flow changes	Availability of DG is considered. The restoration is performed in parallel in multiple simultaneous faults	The priority of critical loads is not considered	2018
IEEE 34- and 8500-bus	MILP	[79]	Maximize restored power considering repair crew routing	Large scale problems can be solved	Limited type of complicated optimization problem is solved	2018
16 switches, 2 reclosers	Multi-agent	[87]	Maximize restored load considering efficient fault location and isolation	The number of messages is lower since each agent only sends single messages	Power losses need to be improved in distribution network	2016
IEEE 33-bus test	Fuzzy logic	[88]	Perform grid reconfiguration to eliminate feeders' congestion, correct voltage violations, and coordinate reactive power devices	Overstress of substation voltage regulator tap changer is avoided	The minimum number of switching operation needs to be considered to minimize the system operational cost	2015
44-node, radial	MINLP	[111]	Minimize the cost of de-energized zones, load-shedding in nodes, active power losses, after reconfiguring the system	High-quality optimal solutions are found	Computing time is high	2016
1069-bus unbalanced	MILP	[126]	Maximize the cumulative service time of microgrids to loads weighted by their priority	Microgrids are utilized to restore critical loads	The variety of DGs for restoring the power system efficiently needs to be focused on	2018
IEEE 123	MINLP	[127]	Maximize the restored energy over the time horizon considering weight factors for each load	Generate a sequence of control actions assigned to multiple time steps	Power losses and the number of switching operation are not considered	2018
IEEE 39- and 118-bus	MILP	[128]	Minimize the outage period	It is very simple and flexible	System parameters are very limited	2018
Roy Billinton test system (RBTS4)	MINLP	[129]	Minimize a combination of system average interruption duration index (SAIDI) and total cost of reliability	Parking lots participate in service restoration as backup units and storage units	Power flow analysis is not considered	2016

In [124], a hierarchical service restoration method is developed to address power restoration with microgrids to ensure resilience. This method considers the limitation of the service capacity of microgrids, and the emergency power supply vehicle as a backup feeder to restore the critical loads in case of an outage.

E. Graph Theory

Graph theory is widely used in self-healing optimization algorithms. Meanwhile, a set of studies are published for power restoration strategy considering the graph theory algorithms for the optimization approach.

TABLE II
SUMMARY OF DIFFERENT POPULAR ALGORITHMS USED FOR SELF-HEALING – AFTER 2019

Type of test feeder	Optimization algorithm	Reference	Goal	Strength	Limitation	Year
IEEE 13- and 123-node	Graph theory	[7]	Determine the optimal restoration strategy, coordinate multiple sources to serve critical loads	Multiple sources are integrated to obtain a better solution	The decision-making does not focus on critical load in an unbalanced distribution system	2019
IEEE 33- and 123-node	MILP	[17]	Maximize the restored load and minimize the voltage unbalance and power losses	The optimization algorithm is capable of avoiding a major fault	ESSs are not considered	2020
6-bus	Multi-agent	[50]	Efficient fault location and isolation	It is combined DG restoration with topology reconfiguration to restore the maximum load	The modeling analysis is complex	2019
70-bus	Fuzzy logic	[67]	Realize fast load restoration, predict the distributed generation, and consider different load scenarios	Power losses are reduced in emergency state	The data are locally collected; thus, the problem is not globally solved	2019
IEEE 2- and 90-bus	MINLP	[93]	Minimize investment costs and maximize system reliability	Reliability indexes are in a multi-objective and multi-period optimization	Initial investment cost of the capacitor's installation is not considered	2019
IEEE 123- and 8500-bus	MILP	[98]	Minimize unserved energy considering crew dispatch	An optimal solution based on switching sequence is obtained	Power flow is ignored	2019
IEEE 123-node	MILP	[104]	Maximize restored power and minimize restoration time	Dynamic modeling is considered	Operation costs are not considered	2020
IEEE 123-node	MILP	[120]	Maximize the restored energy over the time horizon, considering weight factors for each load	It is applicable to large-scale systems without computation complexity	Network reconfiguration is not considered	2019
IEEE 118- and 30-node	Heuristics	[124]	Find the optimal repair and activation schedule for damaged components	The solution method is computationally efficient	Restoration stages as a part of the system are not considered	2020
IEEE 33-bus and PE&G 69-bus	MINLP	[130]	Maximize restore load in microgrid	Load restoration is obtained with lower power loss than traditional methods	Priority of loads is not considered	2020
PG&E 69-node and IEEE 123-node	Graph theory	[132]	Maximize restored load	Emergency power supplies are considered to restore critical and non-critical loads	Mobile energy storage supports service restoration and performs a better solution	2019
11-bus and 39-bus	Graph theory	[133]	Maximize generating power and minimize restoration time	ESSs and microgrid are integrated for service restoration	Backup techniques is not considered	2019
IEEE 33-bus	Graph theory	[134]	Perform service restoration without violating system operation constraints	The system is efficiently and quickly restored	Unbalanced critical loads are not considered	2020

Reference [131] proposes a solution based on Prim's algorithm to restore the loads in the out-of-service area. The adopted solution can be computed in several seconds and handle complex cases such as multiple simultaneous faults. Reference [132] discusses a post-disaster restoration planning model to restore critical loads in out-of-service areas. Several papers have used graph theory in their optimization problem, including [7], [73], [133]-[135].

F. Genetic Algorithm

Genetic algorithms are being widely used to solve restoration problems in power distribution systems with the possibility of reaching the optimal global solution. Reference [71] proposes a multi-objective evolutionary algorithm using node-depth encoding to solve service restoration problems in large-scale power distribution networks. The idea is to minimize the number of switching operations to process the reconfiguration network with a minimum number of out-of-service loads. Reference [59] uses genetic algorithm for optimization that has been applied to find optimal solutions considering the maximum restoration zones and to minimize the distribution losses. Reference [136] presents an optimization model by considering multiple decision-making tools. The decision method incorporates the planning problem of backbone reconfiguration, sub-transmission power system restoration, and non-black start unit start-up.

G. Fuzzy Logic

The fuzzy logic optimization algorithm involves finding an optimal solution for service restoration with a minimum time and supplying maximum loads to the out-of-service areas after a fault. Reference [88] proposes a method that includes developing a quantitative measurement to be used for evaluating the priority of restoration plans. Reference [88] proposes a multi-agent control system for power distribution systems and distributed generation. The proposed method is a hybrid centralized and decentralized control system. The critical feature of the solution under consideration is to eliminate the feeder congestion, correct voltage violation, coordinate the operation of reactive power devices, and prevent over-stress on the transformers with under load tap changers. Reference [69] proposes smart fault current controllers to control fault current and ensure high reliability and healthy electric power infrastructure. The objective is to avoid any malfunction of the utilized protection devices and keep the system solid.

H. Dynamic Programming

This algorithm is applied for solving the power restoration problem with iterative schemes for finding the best solution, which is close to the global optimum solution. Reference [62] proposes a multi-agent system to solve service restoration with multiple DGs containing radial configurations that enable the system to be analyzed in a two-step process. The input feature of the solution under consideration is that it determines the maximum restoration loads by choosing the best arrangement of reconfigurations in power distribution network. The algorithm proposed in [137] is an automated optimization approach to restore the power supply after a fault in the distribution system. The procedure considers the priority ranking, which determines the feeders with priority loads that should be energized initially.

I. Tabu Search

Tabu search is a popular algorithm applied to solve several optimization problems as well as self-healing in power distribution systems. Reference [68] suggests a parallel hybrid genetic algorithm, i.e., Tabu search, to solve service restoration in the power grid. Near-optimal solutions for the models are achieved by formulating service restoration problems as multi-objective, minimizing switching operations and load balance. Reference [138] proposes a comprehensive design and operational planning framework to obtain optimal solutions for self-healing control actions in the electric power grid. The framework is based on dividing the DGs into microgrids based on distributed energy storage units and distributed reactive sources.

The strengths and limitations of the research papers presented in this section are also illustrated in Tables I and II.

VII. Future Work

This paper reviews the up-to-date research in self-healing in power distribution systems. The published papers are analyzed and categorized based on different factors, and their limitations and strengths are investigated. Based on the presented literature review, some research questions arise that need to be explored in further detail. This section categorizes such research paths and briefly explains them as future works.

A. Improvement of Observability

The phasor measure units are used for complete observability and measurement of the voltage and current phasors of all the nodes located in the power distribution system. The strategic allocation of the phasor measurement units is significant to achieve complete observability. Much research has been conducted regarding the optimal placement of phasor measurement units in power networks. Previous research can be extended in the reconfigurable power distribution system to consider enhancing of the self-healing operation in the network. More specifically, researchers can focus on new methodical developments that will effectively increase the observability in the power distribution system using phasor measurement units during the self-healing process and if the topology of the reconfigurable network is changed.

B. Accurate Forecasting

Smart technology has provided the economic scheduling of DGs in power distribution systems and has responded with an expanded self-healing capability to restore an efficient real-time service during the network's outage. A large proportion of these DGs are renewable types, and the output power of these non-dispatchable DGs is not always of a deterministic nature. The intermittency of non-dispatchable DGs, besides the probabilistic nature loads, introduces new challenges to the self-healing control actions. In this circumstance, accurate forecasting techniques are vital to predict RESs' generation and probabilistic loads to create the supply-demand balance during the self-healing process. Therefore, proper forecasting techniques are needed for optimal performance during system disturbances and the self-healing process.

C. Cyber Security

Self-healing control actions are scheduled based on the various information received from the system. The security and accuracy of such information will affect the accuracy of the self-healing process. In this scenario, any cyberattack on the self-healing software frameworks could impact the whole system reliability. Therefore, this paper encourages developing advanced cyber security techniques specifically for self-healing control actions as a future research direction. The secure operation of smart grids and their management require conducting various legitimate control actions quickly, and this would not be possible without adequate security of information.

D. Development of Event Prediction Model

Several factors must be considered during fault conditions in power distribution systems, including equipment's status and the affected areas. The self-healing prediction model performs accurate data analysis using advanced technology to predict critical events in real-time with locations. The event-based models can be developed based on several factors such as cascading technical failure, extreme natural events, cyber-physical attacks, and space weather events. The event-based models will give ideas to prevent or improve self-healing operations before any power failure incidents. This will also help planners know the limitations of understanding the system for the specific event with the corresponding event locations and the inadequate level of situational awareness. An advanced optimization algorithm can be implemented to analyze these data and predict the outage events to perform a better operation. The prediction model uses forecasted data for future events based on the available current data obtained from the system to formulate the model parameters. The model can be further implemented in future studies, increasing the reliability during the service restoration process.

E. Optimizing Centralized Approach

Centralized approaches for controlling power distribution systems are gaining the attention of power engineering researchers. In a centralized approach, intelligent electronic devices send all the system information through the SCADA system to the control center, where the self-healing strategy is planned. When a fault occurs in the system, the self-healing system starts operating to restore the loads as early as possible. Recently, researchers have focused on overcoming the limitations of this centralized approach to improve the performance and reliability of self-healing. In a centralized approach, the DGs support the grid by providing economical and environmentally friendly electrical energy, increasing the reliability and resiliency of the distribution system. In sharing electrical energy between utilities and DGs, there is a need for an optimization process to minimize power losses, environmental emissions, and system operational costs. These objective functions can be considered individually or collectively based on the design approach and the power requirements of DG owners or utilities.

F. Protection

Centralized approaches that are widely used for automated relay protection systems increase the reliability of the self-healing operation. The operational time delay measurements during protection relay operation are essential for self-healing performance improvements. In a centralized approach, the protection of the backup feeder is vital for the efficient operation of power networks. An extra line can be added to back up the existing feeder and controlled by a smart controller. In these scenarios, extensive and elaborative studies are needed to focus on the relay's integration with the terminal unit for processing multiple tasks. These tasks may include controlling and monitoring the system network, identifying the system state, and finding relevant data in the system.

G. Implement High-performance Computing (HPC)

In self-healing operations, real-time service restoration is a key step to run the system facility at any point. Service restoration performance can be improved during the self-healing operation by using advanced computational tools. For instance, HPC is being widely used for faster data processing and complex calculations in many applications that may be used in self-healing. HPC-applicable hardware can provide supercomputing functionality with high performance to accelerate the self-healing algorithms during the service restoration operation stage. An example tool used in this regard is general-purpose graphics processing unit (GPGPU) computing, commonly used for crunching big data. GPGPU can be applied to perform a faster self-healing operation by processing the data elements simultaneously during service restoration. HPC hardware computational tools can be extensively used in self-healing for optimal scheduling of the DGs during the restoration process, and thus, further extensive research is required in this area.

H. Construction of Networked Microgrids

One goal of performing self-healing is to minimize the number of switching operations within the shortest time interval. The fewer switching operations ensure restoring the maximum affected loads by a fault during a disturbance in the system, and preserve the limit of the operation at the same time. Moreover, the minimization of the switching operations reduces the risk related to the equipment and increases the switch's lifespan [21], [22], [24], [47]. Despite much research being conducted for self-healing improvements using a minimum number of switching operations, many need to be properly addressed, especially automated switching operations in networked microgrids. Automated switching operation reduces the risk of damaging the equipment, reduces the load shedding time, and improves the system performance. A healthy microgrid can contribute at the primary level to compensate for power shortages in the faulty area. Therefore, in networked microgrid, there is a need for a priority-based formation of microgrid, which should be explored in detail. Furthermore, multiple points of common coupling can be used within networked microgrid, for self-healing service restoration operations. In this regard, appropriate formulation of networked microgrids' formation, while considering uncertainties, is another avenue for prospective future work in this area.

VIII. Conclusion

Self-healing is potentially the most important feature of smart power distribution systems, which helps minimize the extreme events' impacts and automatically and intelligently restores the affected loads. However, a comprehensive study on the self-healing subjects in power distribution operations has not been carried out to this date. This review paper attempts to rectify this issue through a complete literature review of self-healing in distribution systems, which summarizes notes by using self-healing research papers available in the literature.

This paper presents and analyzes different self-healing optimization objective functions, control strategies, and proficient algorithms to improve the self-healing operations employed in the reviewed studies. It also surveys reviewed papers by their publication site and year of publication. Tables are provided by summarizing some research papers with proficient algorithms and applied bus-wise distribution systems for self-healing operations. The future research that needs to be accomplished is also described in detail at the end of this paper. The classified and organized research papers in the self-healing area presented here would help the researchers get familiar with the up-to-date research and make their research efforts more efficient and intelligent.

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