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Review

Fault Detection, Isolation and Service Restoration in Modern Power Distribution Systems: A Review

Ishan Srivastava [1], Sunil Bhat [1], B. V. Surya Vardhan [1] and Neeraj Dhanraj Bokde [2,3,*]

[1] Department of Electrical Engineering, Visvesvaraya National Institute of Technology, Nagpur 440010, India
[2] Center for Quantitative Genetics and Genomics, Aarhus University, 8000 Aarhus, Denmark
[3] iCLIMATE Aarhus University Interdisciplinary Centre for Climate Change, Foulum, 8830 Tjele, Denmark
* Correspondence: neerajdhanraj@qgg.au.dk

Abstract: This study examines the conceptual features of Fault Detection, Isolation, and Restoration (FDIR) following an outage in an electric distribution system.This paper starts with a discussion of the premise for distribution automation, including its features and the different challenges associated with its implementation in a smart grid paradigm. Then, this article explores various concepts, control schemes, and approaches related to FDIR. Service restoration is one of the main strategies for such distribution automation, through which the healthy section of the power distribution network is re-energized by changing the topology of the network. In a smart grid paradigm, the presence of intelligent electronic devices can facilitate the automatic implementation of the service restoration scheme. The concepts of service restoration and various approaches are thoroughly presented in this article. A comparison is made among various significant approaches reported for distribution automation. The outcome of our literature survey and scope for future research concludes this review.

Keywords: distribution automation; reliability; service restoration; smart grid; multi-agent system

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1. Introduction

The year 2020 has seen the largest decline in global energy demand since World War II and the highest absolute decline ever. The effects of the COVID-19 pandemic on global energy use are shown by the recent statistics on energy usage in 2021 [1]. In 2021, electricity demand is anticipated to rise by 4.5%. With a forecast GDP growth of 9% in China and 12% in India in 2021, energy demand in both nations is likely to increase by about 8% over 2020 [1].

From the installation of the first electrical grid on 4 September 1882, in Manhattan, supplying power to 85 customers and 400 lamps, to the present grid today, many aspects of electrical power have changed. These include the deregulation of the energy market, changes in metering, changes in power generation, distributed energy decentralization, and the rise in micro-generation and isolated micro-grids, including renewable sources of energy and electric vehicles in the grid. The complexity of the current grid is growing, along with the number of consumers and loads. To effectively manage this extremely complex power network, the idea of the Smart Grid (SG) has been introduced. The SG is defined by NIST, USA [2] as "a modernized grid that enables bidirectional flows of energy and uses two-way communication and control capabilities that will lead to an array of new functionalities and applications". Power electronics, communication engineering, and material science advancements have all contributed to the development of SG. The following requirements must be met by the modern grid's design, expansion, and operation.

1. Energy distribution and transmission must be cost-effective.
2. The cost of electricity for consumers must be lower.
3. The security of the system must be ensured.
4. In the event of a fault event, service restoration must be rapid.

5. By connecting more Renewable Energy Sources (RES) to the grid, the environmental implications must be properly monitored.
6. RES management and integration must be improved.

The conventional grid differs from an SG in numerous ways, as noted in [3]. In comparison to an SG infrastructure, the conventional grid has fewer sensors. These sensors are responsible for providing the grid's real-time data for monitoring and control of the system. The SG's communication network needs to be set up for two-way communication between customers and control centres. Additionally, the introduction of SG Advanced Metering Infrastructure (AMI) depends on this two-way connection. A standard power grid's electro-mechanical metering method precludes the use of real-time data transfer in this setup. Consequently, a digital metering system is a crucial necessity for SG in order to adopt automation solutions such as Automatic Meter Reading (AMR) or AMI. Energy meter data collection and secure transmission to the control station for billing, troubleshooting, and analysis are the tasks of AMR or AMI. SG consists of various domains or operational units, as shown in Figure 1. Each unit's functionality is directly or indirectly dependent on every other unit in the grid. The operation under this scenario is known as interoperability; to have this feature in SG, a proper two-way communication infrastructure is required.

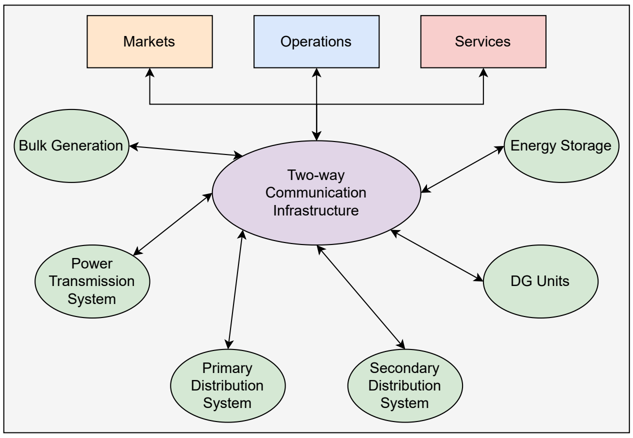

Figure 1. Smart grid building blocks.

Along with fault detection and isolation strategies, service restoration forms one the key feature of distribution automation. Most previous review articles focus on individual strategies rather than presenting the problems and solutions of FDIR as a single strategy.

In [4], a review is presented for different techniques used to solve service restoration problems. The methodologies for fault isolation and detection are not covered in this article. Similarly, Ref. [5] covers various conventional and artificial intelligence-based methods for fault location and detection techniques in a power distribution system. In review [6], the authors have presented various centralized and distributed strategies for fault localization and service restoration. Multi-agent strategies have been highlighted by the authors as well. However, the features of distribution automation and novel Fault Detection, Isolation, and Restoration (FDIR) approaches such as IoT-based FDIR were not discussed. In [7], various features of smart distribution systems are mentioned, including smart metering systems, security and outage management aspects, and of service restoration solutions. However, the discussion is restricted to the performance of smart distribution system under different scenarios, and the details of FDIR are not presented by the authors.

The principles of distribution automation are discussed in this paper, along with the associated advantages and challenges. The communication infrastructure required to implement various distribution automation strategies is discussed as well. The explanation of FDIR concepts and their background research work is presented in the following section of this paper. Various aspects of FDIR problem, as well as centralized and decentralized approaches to solving them, are discussed. The evolution of various service restoration algorithms is addressed, along with their benefits and drawbacks.

2. Distribution Automation

Any automatic process is defined as a process that performs a task in an automated manner to achieve a faster rate of operation. The concept of distribution automation was proposed for the first time in the 1970s [8], when the goal was to enhance the operating performance of the power distribution system. However, due to high implementation costs and immature communications technology, the concept was not fully adopted by the electric utilities. In recent years, with the advancement of communications technology, data acquisition systems, data analysis tools and power electronics, distribution automation is again becoming the focus of research and improvement. The Institute of Electrical and Electronics Engineers (IEEE) has defined Distribution Automation Systems (DAS) as systems that enable an electric utility to monitor, coordinate, and operate distribution components in real time from remote locations [9]. Distribution automation enables more flexible network control operations. As a result, the power supply is more reliable, efficient, and of higher quality. The speed, cost, and accuracy of multiple key distribution processes can be improved with distribution automation. These include failure detection, feeder switching, outage management, voltage monitoring and control, reactive power management, feeder line equipment maintenance, and grid integration of distributed energy resources. In the SG paradigm, the management of power flow can be carried out by automatically monitoring the grid and controlling switching operations through intelligent devices.

2.1. Benefits of Distribution Automation

There are several benefits of implementing distribution automation strategies.

1. Operational and maintenance benefits
    - Increased reliability by lowering outage time through the use of an automated restoration strategy
    - Reduced man-hours and manpower costs
    - Improved fault detection and diagnostics
    - Improved system and component loading management
2. Financial benefits
    - Quick restoration results in increased revenue
    - Improved usage of system capacity
    - Customer retention to boost supplier quality
    - Improved service reliability
    - For industrial and commercial users, lower interruption costs

2.2. Features of Distribution Automation

(a) Automation Devices: The automation device must be able to perform multiple tasks. For example, the device deployed in the field to control various equipment must gather the information and perform local decision-making when required. In the modern grid, this multi-task is carried out by Intelligent Electronic Devices (IEDs).

(b) Data Analysis Tools: Automation requires processing the large amount of data collected by different sensors in the network. These data are required in order to (i) estimate the current state of the grid, (ii) predict its load patterns, and (iii) identify vulnerable buses in the network. Therefore, data processing tools must be present in substations and central control stations. Data availability, integrity, and security must be maintained in order to carry out proper data analysis.

(c) Real Time Implementation: High-speed data transfer communication infrastructure and computational resources are required for the real time implementation of a distribution automation strategy. The current state of the network is determined by the different parameters of the components, topology of the network, status of various switches/breakers, and measured data from nodes in the network. Subsequently, based on the type of contingency, the optimal control plan is deployed through distributed or centralized control schemes.

(d) Sensors: In the contemporary era, the advancement of sensor technology is reducing the cost of sensors. In a complex grid, more sensors are required to collect all of the information relevant to the current state of the grid. Therefore, it is economically possible to place the required number of sensors at critical locations throughout the grid.

(e) Asset Management: Distribution automation can play a vital role in asset management for the utility. Advanced sensors can regularly monitor the condition of various equipment present in the network, which is useful for the utility in preparing a proper maintenance schedule. Real time analysis of the grid can provide the loading details of different types of equipment. Based on this information, proper utilization of these assets is possible.

(f) Communication Infrastructure: Recent advances in communications technology are key to the evolution of smart grids. A two-way communication channel ensures the proper exchange of information among various components of the grid. All the domains of the SG are interconnected through the internet via various Local Area Network (LAN), Wide Area Network (WAN), Home Area Network (HAN), Building Area Network (BAN), Industry Area Network (IAN), etc. The efficiency of DAS is mostly dependent on the performance of the implicit communication network. With advanced communications technology, protocols such as IEC61850, which were proposed originally for substation automation can be implemented for feeder automation and service restoration. In the SG, various sensors and IEDs are deployed to gather information, which then needs to be transferred as quickly as possible through a low-latency communication network. This information is essential for decision-making processes in DAS. A typical architecture of a Wireless Mesh Network (WMN) used in SG communication is shown in Figure 2.

Improvements in grid management and monitoring are possible with the deployment of Information and Communication Technology (ICT) in the electricity distribution system. This infrastructure is highly interconnected, and is responsible for the exchange of information among substations, control centers, power markets, and various measurement devices [10]. The merits of an ICT-enabled network are shown in Figure 3.

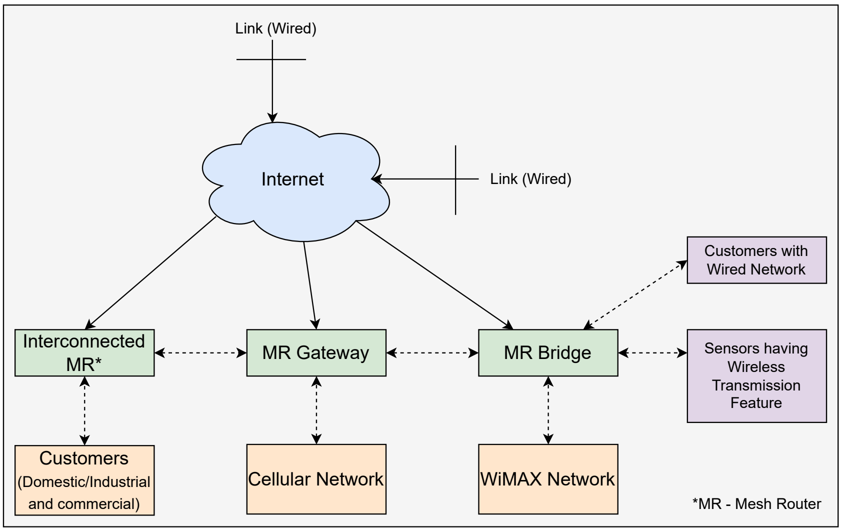

Figure 2. Architecture of wireless mesh network.

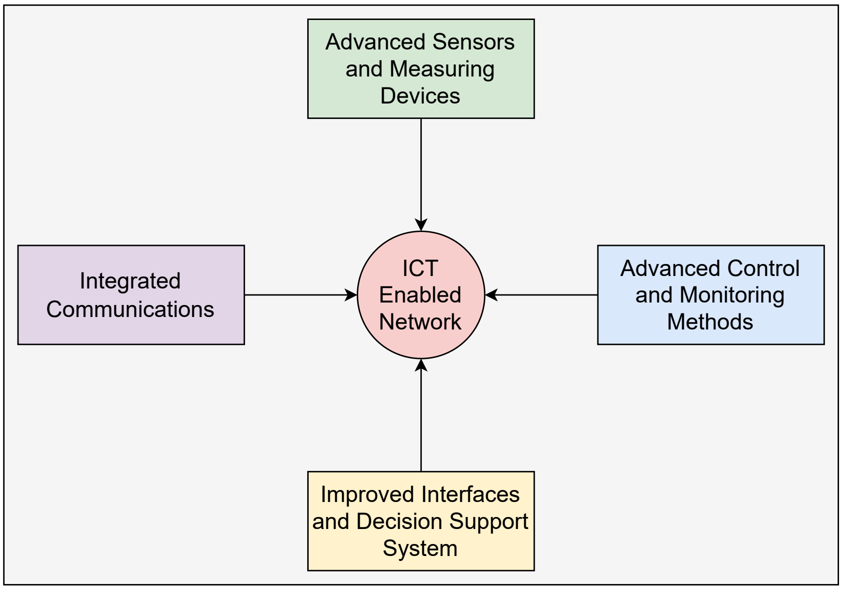

Figure 3. Merits of ICT-enabled network.

2.3. Technical Challenges for Distribution Automation Systems

There are several challenges for a distribution automation system, including the following:

- High penetration of DER
- Common protocols for the communication system
- Data loss, data security, and data integrity issues
- Estimation of real-time pricing of electricity in a market-driven framework
- Requirement of high-speed computational resources

One of the features of the modern power distribution system is the presence of Distributed Generation (DG) units. As the complexity of the network increases, the placement and control of DG units becomes challenging with respect to the deployment of distribution automation strategies. Additionally, the dynamic load variations in the case of modern distribution systems need to be considered. In most of the reported works, the daily load variation in case distribution automation has not been considered.

To examine the dynamic behaviour of automated distribution systems, the authors in [11] included daily load variations in the analysis. In this work, a methodology based on the Manta Ray Foraging Optimization (MRFO) algorithm has been proposed to control and allocate distributed generators and capacitor banks in the system and to deploy the network reconfiguration strategy.

In another recently reported work [12], a novel Improved Heap-Based Optimizer (IHBO) was proposed to solve the network reconfiguration problem and ensure optimal sizing and placement of DG units. Minimization of power loss and maximization of voltage stability was the objectives considered for network reconfiguration. This problem of integrating network reconfiguration with DG sizing and placement was solved by another variant of heap-based optimizer, the Heap-Based Optimizer with Deeper Exploitative Improvement (HODEI), in [13]. In this case, the authors considered different loading conditions for analysis.

3. Fault Detection, Isolation, and Service Restoration (FDIR)

In order to retain consumers in a deregulated market, power providers must enhance their service quality. As a result, several electric utilities have introduced DAS as a smart method to improve distribution system reliability and efficiency. FDIR is regarded as the most crucial of all distribution automation functions. The goal of FDIR is to minimize service restoration time for a permanent fault event of distribution feeders from an average of 58 min to less than 5 min [14]. When a fault occurs in the distribution side, different intelligent components such as IEDs that are linked via a communication network transmit fault information across the affected network segment. In addition to protection, IEDs perform functions such as control, measurement, disturbance recording, and condition monitoring. The data transfer rate through IEDs is much faster than with conventional methods [15]. When these IEDs are networked together, they can provide almost all of the necessary information to the system operators. In case of fault, IEDs associated with circuit breakers send control messages to the other network IEDs. Based on this information exchange, necessary steps are taken to clear the fault and restore the power as quickly as possible.

The communication network plays a critical role in identifying the fault and restoring power. Substation protocols such as IEC61850 can be used in modern power systems to exchange information. The advent of the IEC61850 standard enables a range of protection and control capabilities and benefits, including peer to peer communication through Generic Object Oriented Substation Event (GOOSE) messaging [15]. GOOSE wireless communication can be used to improve current Medium Voltage (MV) substation automation applications. GOOSE enables more extensive monitoring of the system. All GOOSE connections are checked continually and if any abnormalities are found, they are reported to the operator. Fast and reliable data transfer is crucial for the implementation of the FDIR strategy.

In FDIR strategies, the following steps are implemented sequentially:

A. Fault Detection: Different types of faults can affect distribution networks. Fault detection is the process of determining whether or not a fault has occurred. High currents and/or low voltages reported by the sensors or any other measurement device can automatically trigger alarms, which can traced to identify the fault's location. Feeder Circuit Breakers (FCBs) and Fault Passage Indicators (FPIs) can operate in case of a fault event. The primary role of a fault passage indication system is to identify faults in the section downstream of the site of their occurrence. When a current exceeds a preset value, FCBs are tripped, triggering a temporal reaction that is dependent on the measured current value [16]. The DAS is promptly notified by these devices.
B. Fault Isolation: After the DAS has detected the faulty section, the next step is to isolate the faulted portion by operating the relevant upstream and downstream sectionalizing switches. In this step, the DAS tries to isolate the smallest section of the network.
C. Fault Classification: The DAS attempts to identify the type of fault that occurred in the distribution network during this step. The fault classification details can be useful in assessing the required fault clearing time, which can help the operator to choose a suitable restoration plan.
D. Estimation of Capacity: The ampacity of a conductor is determined by the physical and electrical properties of the conductor's material and construction, its insulation and ambient temperature, and the environmental conditions proximal to the conductor. Before restoring power, the capacity of adjacent feeders are calculated. This can be achieved by performing load flow analysis. The restoration solutions which exceed the feeder capacity are discarded.
E. Service Restoration: Following fault isolation, the distribution network operator's goal is to restore as many out-of-service loads as possible with the minimum of switching operations. Service restoration is the process of finding suitable backup feeders and laterals (branches of the network) to re-energize the out-of-service area by changing the topology of the network [17]. After estimating the feeder capacity, the distribution network operator decides whether the adjacent healthy feeders are capable of supplying total or partial out-of-service loads.

Control Schemes for FDIR

The desirable characteristic of a modern power system is the self-healing capability of the network. By following self-healing methods and protocols, the network is able to perform corrective action on its own when an abnormality occurs in the system. To alter the distribution system state to a better one, control actions are key parts of self-healing. The available control strategies can be categorized as centralized control or distributed (de-centralized) control.

1. Centralized Control Scheme:
   In this scheme, all data are routed to a centralized control station and the control strategy is determined depending on the requirements. In the modern grid, a huge amount of data are collected by various sensors and measurement devices. All these data are transferred to the centralized control station through a two-way communication channel. As a centralized controller frequently requires a low-latency system in order for large amounts of data to be transferred between various power system components and control centers. This kind of control scheme is very efficient in the case of a small system. However, in the case of a network with a large number of nodes there are various disadvantages associated with this kind of control. The deployment of a centralized control strategy can be time-consuming for to various reasons, including high computational burden, lack of automation throughout the system, human error, etc. Furthermore, the inclusion of distributed energy resources and electric vehicles in the power grid results in more complexity, thus requiring more complex network management. The risk of single points of failure is a major issue associated with centralized control schemes [18].
2. Distributed Control Scheme:
   Decentralized methods rely on direct peer-to-peer communication between monitoring and control devices present in the network [19]. Data are collected by various sensors and IEDs, and data processing is performed by IEDs locally. Decentralized approaches primarily focus on simultaneously resolving a problem. Control/protection measures that govern the overall system response are made in each distribution or primary substation depending on the contingency. This scheme requires distributed agents able to perform different tasks and an efficient communication system through which information exchange is carried out among these agents [20]. Agents can conduct fault detection, isolation, classification, and service restoration independently, and all are connected via a single platform. Distributed strategies can substantially increase the reliability of power monitoring and control and improve the flexibility and efficiency of the system [21]. In a centralized control scheme, data must be transferred from all nodes to the central control station regardless of how far apart they are in the network. These long communication links require significant investment, and the failure of one of these communication links can lead to a considerable delay in data collection at control stations, increasing the deployment time of the control strategy. Therefore, the presence of a well-structured two-way communication network in the distributed control scheme makes it more economically efficient than a centralized control scheme.

From the above discussion, it can be concluded that one of the main aspects of DAS is to enhance the reliability of the power supply by introducing self-healing features to the grid. FDIR is the basis of this self-healing characteristic. Fault detection and isolation is based on efficient information exchange between different power system components. The optimal service restoration strategy, on the other hand, is a combination of several factors, which are addressed in the next portion of this chapter.

4. Literature Review

This section provides a comprehensive review of the literature on various FDIR and service restoration optimization approaches. This section is divided into multiple subsections based on the type of approach and the computational techniques used to address the restoration problem.

4.1. FDIR Methods for Distribution System

A fully automated distribution automation system that includes all customers, substations, and generating stations was proposed by the US Department of Energy in its "Grid 2030" vision [20]. The key feature of this smart distribution network is the two-way flow of information and electricity. The ability to respond to disturbances, reduce their impact, and restore power quickly is required to achieve the goal of this smart distribution network. Its establishment is expected to result in better system stability during disturbances and be the indicator for the self-healing capability of the grid [20,22]. Reducing outage times and raising system reliability as a whole are the main goals of the FDIR algorithm. The system reliability is measured by indicators such as the System Average Interruption Duration Index (SAIDI), the System Average Interruption Frequency Index (SAIFI), and the Customer Average Interruption Duration Index (CAIDI). These indicators are utilised to assess the distribution automation performance during outages that are sustained and extend for five minutes or more [23]. ENMAX Power Corporation in Calgary, Alberta, Canada has deployed an FDIR strategy to part of its network; the benefits obtained are reported in [24]. The authors reported that from 2004–2010, the total estimated customer savings were approximately $ 7,500,000. The FDIR strategy was applied to 73 circuits out of 160 in the network. It has been shown that through FDIR, the annual customer benefits ($ 10,067,000) are more than the annual cost of automation ($ 3,100,000).

As mentioned earlier, there are various benefits to using a distributed control strategy over centralized control in the deployment of an FDIR scheme. The main features of this distributed control scheme are mentioned in [25] and are given below.

1. All processing units are linked together through a communications network.
2. Processing units such as IEDs can make the control decisions based on the local information available to them.
3. Single points of failure or malfunctioning of one control unit is not a major issue, as control can be managed by an adjacent unit.
4. Information transfer among different units occurs rapidly, making proper communication links of the utmost importance.
5. Data security measures are required, as the data network is widely dispersed and vulnerable to cyberattacks.

Different communication protocols have been enacted to communicate information among devices at different levels, including the central controller level, I/O level, bay level, and station level. IEC61850 is a contemporary communications protocol utilized for substation automation as well as distribution automation. In contrast to traditional protocols, it is able to exchange information among various devices through peer-to-peer communication via GOOSE messages. GOOSE signals are received by IEDs and take action accordingly without the help of a central controller [26].

Three FDIR approaches are outlined in [27]: loop control, peer-to-peer schemes, and decentralized scheme. These schemes are implemented through IEDs using IEC61850 communication protocol. The measured data are transmitted as GOOSE signal and used to develop the logic for fault isolation and service restoration. Another peer-to-peer GOOSE messaging scheme for FDIR using IEC61850 and DNP3 protocols is proposed in [28]. The authors devised a way to update information in Remote Terminal Units (RTUs) utilising programmable automation controllers, on which they based the logic for fault detection and isolation.

In [29], the authors presented a "close-before-opening" method, in which the idea is to close the tie-switches before opening the corresponding sectionalizing switches, thereby causing the elimination of power blinks or momentary power outages during switching operations. According to the findings of this study, the proposed strategy improves the overall reliability of the distribution power supply. In the fiber optic-based communication technology used by the authors, each recloser can communicate with an adjacent one through a fiber optic link [29]. The SCADA system is integrated in the same way.

4.1.1. Multi-Agent Systems for FDIR

A multi-agent system is one of the most prominent ways of applying decentralized power systems management; it is applicable to multiple areas, including fault diagnosis, voltage stability, electricity pricing, coordination of protection schemes, and restructuring and restoration of the power system. Distributed control schemes are increasingly popular at present thanks to their more efficient performance for large and complex systems. As the system size increases, the computational burden of solving the problem of distribution automation is substantial. Researchers have proposed various agent-based schemes or multi-agent systems to implement distributed (decentralized) control for the FDIR problem. By performing many tasks simultaneously via defined agents, this multi-agent system can alleviate the computational burden. The multi-agent system is subject to change, and acts as a decision-making support system that includes all decision-making components within the system.

The authors of [30] proposed a multi-agent approach for service restoration. They first defined the load agents that collect local information; the feeder agents, which are the decision-making entities, are connected to the load agents via communications link. The local information guides the multi-agent system to build a logic for service restoration and implement it through the feeder agents. The proposed framework works well for medium and large system sizes. However, the authors did not include the logic for fault detection and isolation in the scheme or discuss the protocols required for communication. To address this issue, subsequent research works have incorporated fault detection and isolation logic and proposed the necessary communication connections.

In 2009, Lin et al. [14] presented a multi-agent system to deploy a distribution automation strategy for the 43 feeders of the Taipower distribution system. This multi-agent architecture uses four agents for FDIR, namely, a Main Transformer Agent (MTR), Remote Terminal Unit Agent (RTU), Feeder Circuit Breaker Agent (FCB), and Feeder Terminal Unit Agent (FTU). FTUs and FCBs are similar to the load agents and feeder agents used in [30], and information exchange among these agents happens locally. The MTR and RTU agents are used in decision-making. All of these agents are integrated through a Java-based JADE platform. A multi-agent approach using feeder agents and bus agents based on the JADE platform is reported in [31].

4.1.2. FDIR with DG Penetration

In subsequent analyses of the FDIR problem utilizing a multi-agent paradigm, researchers have considered the penetration of Distributed Generation (DG) in the distribution network. It has been reported in [32] that the total processing time required by the centralized controller is more than that of the distributed controller with or without DG in the network. In [33], Khamphanchai et al. incorporated a DG agent to efficiently control the use of DGs in the network in both regular and emergency situations. During restoration, the FDIR approach is able to re-energize critical loads while performing load-shedding for non-critical loads. The authors used JADE to design the multi-agent environment, and the simulation model was developed in MATLAB/Simulink, with communication between these platforms carried out via MACSimJX [33].

In [34], the authors suggested a hybrid control architecture in which both centralized and decentralized control techniques are incorporated. The agents in this work were split into two levels. Load agents and feeder agents at the lower level acquire information and send it to agents at the higher level. Decisions regarding service restoration are then made by higher-level agents, which communicate with one another during the decision-making process. The DG security and voltage quality issues are addressed in this work, and parallel simulation MATLAB/PSAT-JADE platforms are integrated together. The work reported by Ghorbani et al. [35] presents a new learning-based approach for higher level agents.

The service restoration scheme is obtained using the information provided by the lower level agents and the knowledge acquired by learning (termed as Q-learning). Due to this learning capability, fewer messages are required by the agents for decision-making, which reduces the overall computational burden, cost of computation, and the processing time required to obtain the restoration scheme. The authors in [36] proposed a decentralized multi-agent control scheme that uses a controlled DG islanding methodology as additional input for the service restoration strategy. Integration of electric vehicles is considered and the corresponding vehicle-to-grid facility is studied from the perspective of service restoration.

In [37], a service restoration scheme for an active distribution system was suggested. This scheme introduces a "region agent" that is integrated with the feeder agent and is responsible for performing restoration using local information. The load priority is considered as one of the constraints for service restoration. The restoration scheme was tested for an IEEE-14 bus test system modeled in DIGSILENT.

The authors in [38] described a microgrid-based FDIR scheme that makes use of a multi-agent framework. The fault is identified by comparing current phasors recorded by two agents stationed at the extremities of the network section under study. To deploy a fault detection and isolation strategy, they reported that the data transfer between local agents is sufficient. Furthermore, the service restoration agent and generator agent are decision-making entities for the purpose of restoring power to the network's healthy section.

In recent research work [39], a multi-agent based service restoration scheme was proposed which integrates static and mobile (movable) energy storage systems for service restoration planning. To manage the mobile energy storage device, an additional transportation layer is included along with the existing two-layer multi-agent schemes. The proposed method was tested for single fault conditions as well as multiple fault conditions on an IEEE-33 bus test system. A comparison of different agent-based methods is shown in Table 1.

Table 1. A comparison of several agent-based distribution automation techniques.

Articles	Tools/Software Incorporated	Merits of Proposed Method	Limitations of Proposed Method
[30]	JAVA	(1) Multi-agent method for restoration is presented. (2) Local and global search operation are performed by agents.	(1) Intelligence and decision making feature at local level is missing. (2) Failure of facilitator agent can cause single point failure.
[32]	NS-2	(1) Comparison is made between centraized and distributed MAS. (2) DG penetration taken into account.	(1) Decision making agent is present at a fixed loacation. (2) Voltage limit is not considered.
[34]	MATLAB, JADE, PSAT	(1) Hybrid centralized-decentralized control scheme is presented. (2) Load priority, Voltage quality and load priority is considered.	(1) Membership function and fuzzy logic rules are difficult to formulate. (2) Time requirement is more. (3) Difficult to implement in real time application.
[40]	dNetSim, JADE	(1) Distributed energy storage is considered for restoration of power. (2) FDIR scheme has the feature of islanding coordination.	(1) Communication solutions not disclosed.
[35]	MATLAB, CYME	(1) Easy communication among agents. (2) Local agent can do decision making.	(1) Problem formulation is difficult.

Table 1. *Cont.*

Articles	Tools/Software Incorporated	Merits of Proposed Method	Limitations of Proposed Method
[41]	MATLAB, Opal-RT	(1) IoT based FDIR approach presented. (2) Approach compatible with various protocols.	(1) Data loss aspect is not discussed. (2) FDIR agent working is not disclosed.
[14]	JADE	(1) MAS scheme applied to Taipower network.	(1) Not suitable for complex system.
[33]	JADE, MATLAB, MACSimJX	(1) Load shedding technique is considered with service restoration scheme. (2) Less time requirement.	(1) Communication delay not mentioned. (2) Small test system size.

4.1.3. IoT-Based FDIR Approach

The development of the Energy Internet (EI), Internet of Things (IoT), and data-driven analysis has aided in the development of smart distribution network communications infrastructure [42]. The most crucial and challenging duty in a smart distribution system is energy management [43–45]. A suitable communication infrastructure is necessary for EI applications [46]. There are additional challenges with SGs or cyber-enabled networks, such as the lack of an acceptable technique to calculate the rate of return on SG capital investments [47]. Additionally, the grid's data flow is susceptible to a variety of dangers. Data from smart metres (SM) is essential for effective power network monitoring [48], which can be altered by a potential hacker for various reasons. Li et al. [49] covered several grid-related cyberthreats. The correct operation of the grid can be seriously hampered by data loss through the communication link. In a wireless communications network, factors including hardware breakdown, radio interference, and data congestion can cause data loss [50]. Weather issues, incorrect antenna alignment, and long transmission distances are other causes of data loss via wireless networks [51]. In addition, unlike a wired network, a wireless network's link capacity, which defines the continuation of the communications link, may not remain constant due to interference [52].

Outage management schemes are becoming more reliable and flexible in the SG paradigm thanks to interoperability among the various components of the grid. IoT has wide applications in SG systems. Interoperability refers to communication ability among the various devices present in all the domains and sub-domains of the SG. The three layers of information collection, transmission, and processing in an IoT-based SG are shown in Figure 4 [53]. For FDIR, Estebsari et al. [41] have proposed an IoT-based framework. For modelling of physical components of the grid, they used Opal-RT integrated with MATLAB to develop a service restoration logic. A Message Queuing Telemetry Transport (MQTT)-based communication link emulates real-time communications delays based on type of the IEDs used, bandwidth, amount of traffic in the network, type of protocol, etc. This IoT-based technology can be implemented along with the application of grid computing. FDIR requires distributed computational resources; therefore, grid computing which facilitates distributed parallel computing can play a major role in reducing overall FDIR time requirements [54]. The self-healing capability, observability, and controllability of the network have all been reported to be enhanced in an IoT-based SG [55]. A study using a multi-agent framework for power restoration using an IoT-based system has been reported in [55].

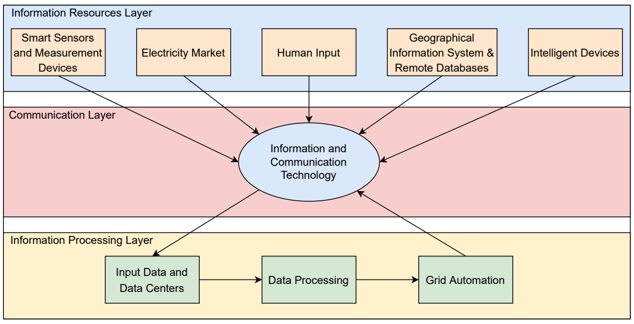

Figure 4. Three layers of information exchange and processing for grid automation.

4.2. Methods to Solve the Service Restoration Problem

Service restoration is a combinatorial optimization problem with multiple objectives and constraints. Each discrete member in the set that makes up the possible solutions corresponds to a switching sequence. Different methods have been suggested in the literature to identify an optimum switching sequence that must be implemented in the network for power restoration. The restoration process starts after a fault is detected in the system; see Figure 5. In the case of a permanent fault condition, part of the network remains in outage condition, and is recovered only when the fault is cleared. In the next scenario, where the fault clearing time is relatively low, the power utility tries to implement a restoration strategy to supply power to the healthy section of the network. On failure of implementation of the service restoration strategy, the number of disconnected loads is higher compared to the condition in which service restoration is properly implemented [56]. Two network segments can be joined or disconnected for service restoration using sectionalizing switches. These switches are normally closed. The distribution network includes tie-switches, which are typically left open, to regulate the use of tie lines for power transfer between two nodes. During a fault, a tie line can provide electricity to loads in nearby areas based on its capacity. The problem of service restoration can be expressed as a multi-objective constrained optimization problem. The total out-of-service area is provided as follows:

$$f_1 \quad = \min \frac{\beta_{\text{int}}(n1)}{\beta_{total}(n2)} \tag{1}$$

where $\beta_{int}(n2)$ denotes the total number of interrupted customers in the healthy section of the network or the out-of-service area and $\beta_{total}(n2)$ represents the total load which is connected in the network obtained after restoration.

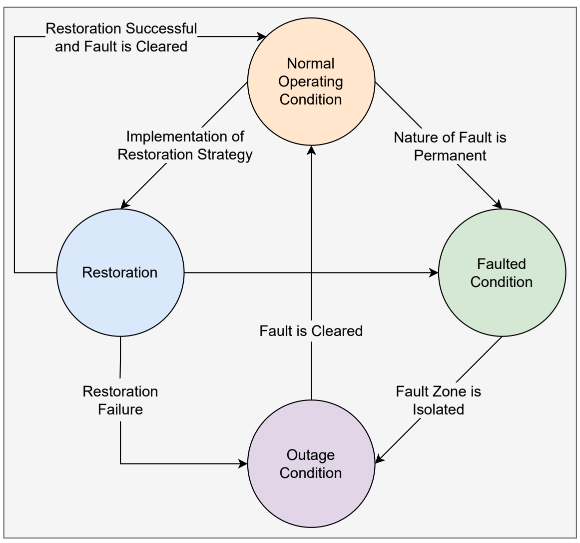

Figure 5. System operating conditions during restoration process.

Tie switches and sectionalizing switches can be operated manually or remotely. The time-consuming procedure of operating manually-operated switches can delay the restoration process. Remotely Controlled Switching (RCS) operation, on the other hand, is rapid, although it requires sufficient communication infrastructure in the network and is significantly more expensive than manually controlled switches.

Minimizing the number of switching operations is the other main objective considered by researchers. The problem can be written as

$$f_2 = \min \frac{\alpha_{mcs}(n1, n2)}{\alpha_{mt}} \tag{2}$$

The network topology is changed from $(n1)$ to $(n2)$ during the restoration process; the corresponding total manual switching operations is represented by α_{mcs}. For normalization, α_{mt} (representing the total number of manually controlled switches in the network) is taken into consideration as follows:

$$f_3 = \min \frac{\alpha_{rcs}(n1, n2)}{\alpha_{rt}} \tag{3}$$

Here, α_{rcs} is the total number of remotely controlled switching operations required for service restoration and α_{rt} denotes the total number of RCS present in the network.

4.2.1. Expert System Approach

Expert systems are developed based on the knowledge of a particular system acquired by the operator over a period of time. This knowledge is utilized to create the rules that guide the decision-making process. Various researchers have used an expert system method to identify the best switching sequence for service restoration.

The rules of the expert system may change for different types of systems. In [57], the suggested expert system comprised generic rules for service restoration which are independent of the system type.

Zhang et al. [58] developed an expert system on the PROLOG platform for the general task of network re-organization; for validation, an optimal switching sequence is obtained in the electric substation. The work in [57] was further expanded in [59], where the knowledge base for service restoration was strengthened by the addition of certain new relevant rules. The authors of [60] proposed a methodology for maintaining an online rule-based expert system. The proposed work was tested for a real-time expert system.

In [61], the formation of two knowledge bases was suggested by the authors for an expert system to solve the service restoration problem. These knowledge bases were (1) a network state knowledge base and (2) a restoration knowledge base. These two knowledge bases were integrated in order to provide a solution for total and partial service restoration. A best search technique-based expert system strategy employing heuristic rules for power restoration was presented by the authors of [62].

In [63], Tsai et al. presented an expert system which takes load variations into account; they suggested a multiple service restoration solution for the same fault instance, allowing the operator to choose the most suitable plan for real-time implementation.

The development of an expert system's knowledge base is a tedious task because the information gathering process takes a long time and necessarily requires the expertise of a system operator. Furthermore, expert system rules may not be generalized for the majority of scenarios, and it is difficult to formulate them for complex systems such as power distribution systems. Therefore, expert systems can be substituted by alternative ways to more quickly address service restoration issues.

4.2.2. Fuzzy Logic Approach

In this approach, various parameters of the distribution network are formulated as fuzzy variables. These variables include the number of disconnected loads in the network, bus voltages, line currents, the total number of switching operations, etc.

Before solving the restoration problem, earlier studies required load estimation techniques. This step is required when the operator does not know the exact loading at various nodes in the network due to the lack of sensors and other measuring devices in the network. The authors of [64] proposed a load estimation method as the initial step and afterwards presented a heuristic-based service restoration method to obtain the optimal switching scheme.

Huang et al. in [65] used an analytical hierarchy process to obtain the weights for each service restoration objective. Consequently, the multi-objective problem is formulated as a single-objective problem using the weighted sum approach. In the same work, the authors used a fuzzy cause–effect network to obtain the optimal switching sequence for service restoration. The proposed method was tested on a real distribution network of the Taiwan Power Company. In [66], the multi-objective restoration problem was solved using fuzzy evaluation of feasible candidates through the application of different restoration schemes. The concept of a local network was introduced by the authors of [67] as a way to reduce the dimensionality of the problem, and the fuzzy logic method was used to solve the service restoration problem.

4.2.3. Artificial Neural Network Approach

Artificial neural networks (ANNs) are best suited for solving complicated, ambiguous, highly nonlinear, multi-faceted, and stochastic issues. The goal of an ANN is to simulate the behaviour of biological neural networks. Over the years, numerous ANN models and network-related learning methods have been created. In neural networks, the complicated nonlinear link between the load levels of the zone and system topologies can be mapped, which is an important task that needs to be done before deploying the service restoration scheme for the network.

Load level estimation using ANN was presented in [68]. Network reconfiguration to reduce power losses was performed with varying load patterns. The ANN was trained using different inputs from each zone and system topology.

The researchers in [69] proposed an ANN and pattern recognition-based approach for service restoration. The developed approach was tested for a typical Taiwan-based distribution system. In further studies, Bretas and Phadke [70] developed a back-propagation learning-based ANN method for service restoration. The authors tested the proposed method on a 162-bus system and obtained feasible solutions for various fault scenarios in a short time.

Although the ANN approach is generalized and offers high processing speed, there are several drawbacks, and training the algorithm for the various loading conditions present in a complex modern power distribution network becomes tedious and difficult.

4.2.4. Heuristic Methods

Heuristic methods are relatively fast compared to conventional optimization methods. A heuristic approach is governed by the rules derived for a particular system based on the system characteristics. In combination with conventional computational methods, these rules can solve a system-specific problem. The heuristic rules are framed from the knowledge of the distribution system operator, similar to the case of the expert system knowledge base formation method. Consequently, these approaches are likewise subject to the same constraints as the expert system approach. For large networks, these approaches are not very effective. In the case of service restoration, the problem is a multi-objective combinatorial one. The goal is to find a switching sequence for the changing network topology such that all the objectives are met and all the constraints are satisfied. The conventional way of solving this problem (uninformed search algorithms) is to check every feasible switching sequence. Practically, the deployment of a service restoration strategy is time-sensitive, and the conventional approach fails in the case of real-time scenarios. Therefore, heuristic methods (informed search algorithms) are used to guide the search process. Heuristic algorithms are more efficient, as they employ data feedback to guide the search direction. With the help of a good heuristic algorithm, an informed search can significantly outperform any uninformed search. Although heuristic algorithms do not always guarantee the best feasible solution, such strategies aid in identifying a solution in an acceptable amount of time and computation.

Heuristic search approaches determine the operators based on domain knowledge. In the search process, the algorithm moves through the search space using these operators. The transition from one point in search space to another depends on the fitness value of objectives at these two points. When compared to a point far from the optimal situation, the one closer to it has better fitness.

In the case of the service restoration problem, the starting point of all algorithms is to assume an initial condition, such as a feasible arbitrary switching sequence. The goal is to find the switching sequence with the best fitness value corresponding to the objectives. Based on the heuristic algorithm, the search space is explored; instead of checking all feasible solutions in the search space, the search process is guided from diversification to intensification through the heuristic algorithm to find the global optimal solution. During the search process, the fitness value corresponding to each visited point is calculated. For example, if the objective is to minimize the out-of-service area, then the total number of disconnected loads in the healthy section of the network corresponding to each switching sequence (each point in the search space) is determined. In the case of multi-objective optimization formulation, the concepts of dominance and Pareto optimality of the solution are used. In [71], a heuristic method using a depth-first search method along with practical rules was proposed for service restoration. This study conducted research to determine the relationship between the rules of the proposed approach and the optimality of the solution. The rules governing the heuristic method were acquired by researchers in [72] from an experienced operator at the Taiwan Power Company, and service restoration was conducted after the faulty zone was isolated.

Nahman and St′rbac [73] performed minimization of total interruption costs during service restoration. The number of switching operations was minimized using MV busbars to facilitate load transfer among transformers.

A search technique for service restoration based on heuristic rules was reported in [68]. The objective of this study was to minimize the number of switching operations required to re-energize the interrupted loads. This study is primarily relevant for developing countries, as most of the switching was manual and components such as transformers and feeders were operated near the rated values.

In [74], a heuristic method to minimize the number of switching operations during service restoration was developed by Shirmohammadi. In this approach, the isolated section is first connected to the adjacent feeders by closing the corresponding tie-switch, thus making the system weakly meshed. Afterwards, load flow analysis is performed to determine the current through each branch. Finally, the switching status is changed from ON to OFF for the branch with minimum current. The same procedure is repeated for the complete network until the configuration of the network becomes radial.

The authors of [75] developed a ranking-based search algorithm to perform service restoration of a large-scale distribution network. Serving a maximum number of priority customers was the additional objective for the restoration problem in this work. Other heuristic based restoration methods have been suggested by researchers in [76,77].

4.2.5. Meta-Heuristic Optimization Methods

What exactly are meta-heuristics? In essence, the phrase heuristic refers to a resource that assists in discovering ‘something.’ The word ‘meta’ is often used to highlight the presence of a higher-level strategy that guides the search process [78]. The meta-heuristics may differ depending on the problem [79]. Many meta-heuristics are centered on converting natural events or physical processes into computing tools [80]. Large-scale complex nonlinear optimization problems with a large number of variables and multiple local optima can be solved using meta-heuristics.

Service restoration is a complex optimization problem and requires fast computation to detect the switching scheme after the fault event. The obtained scheme must be implemented by the operator to quickly re-energize the interrupted loads. Reliability indicators such as SAIDI and CAIDI are directly related to outage duration. Therefore, quick implementation of the service restoration scheme is needed in order to reduce the total outage duration. Although heuristic methods are faster than conventional methods, they are governed by system-dependent rules. Therefore, the generalized framework of meta-heuristic methods have been implemented by researchers to solve the service restoration problem.

Tabu-Search Method

In this approach, local search is carried out to obtain the optimal solution. Local search techniques are usually entrapped in sub-optimal areas, in other words, the algorithm reports the local optimal solution. However, the Tabu search technique solves this problem by forbidding local search methods from returning to the same solution more than once. As a result, there is a high likelihood of obtaining the global optimum solution.

The authors of [81] devised a reactive Tabu search technique for the service restoration problem, which was framed as a single objective problem using the weighted sum method. The suggested technique outperforms the standard Tabu search algorithm, Genetic Algorithm (GA), and Parallel Simulated Annealing methods.

In [82], the researchers presented a parallel Tabu search method combined with ordinal optimization for service restoration. Parallel Tabu search has a lower computational time compared to the conventional Tabu-search method. The time was further decreased by the use of the ordinal optimization approach in the selection of solution candidates.

Genetic Algorithm

GA can simulate genetic evolution by expressing individual traits through genotypes. The major driving operators of a GA are selection, which represents the "survival of the fittest”, and recombination via the use of a crossover operator, which models reproduction. Both GA and its updated form, Non-Dominated Sorting Genetic Algorithm (NSGA), are highly effective for solving combinatorial optimization problem. The parent and offspring population is expressed in the form of strings. Therefore, formulating the service restoration problem through GA and its variant is relatively simple. The status of all the switches (either 0 or 1) can form one single string for a particular network topology. These strings can be changed through crossover and mutations. The conventional GA has the disadvantage of slow response. As a result, various fast variants of GA have been developed by researchers.

Generally, a GA-based approach has input strings coded in binary form. The authors of [83] adopted an integer permutation encoding method to reduce the computational burden. In this encoding method, each chromosome is a list of indices of switches present in the distribution network.

A parallel GA method which is capable of providing a trade-off solution between computational time and hardware cost for service restoration problem was reported in [84].

A hybrid approach combining GA and tabu search techniques to solve the service restoration problem was proposed by the authors of [85]. Cost minimization was taken as the primary objective for the restoration problem. A comparative analysis between the reactive tabu search method, parallel simulated annealing, and GA for service restoration optimization was performed by authors of [86]. To address the multi-objective nature of the service restoration challenge, the traditional GA has been modified to provide a faster and more efficient solution. The concepts of dominance, front formation, and selection have been included in newer GA versions such as NSGA, NSGA-II, and NSGA-III.

In [87,88], Kumar et al. have reported an NSGA-II optimization method for service restoration. The problem is solved as a multi-objective optimization problem using the concepts of dominance and Pareto optimality. This approach alleviates the problem of determining weights for each objective of the restoration problem. Both articles present an approximate trade-off solution for service restoration. The downside of employing

NSGA-II is that the method is stochastic, which means that it does not always provide the global optimal solution.

The work reported in [89] included DG penetration in the distribution network and presented a solution to the service restoration problem using the NSGA-II algorithm. An improved multi-objective evolutionary algorithm based on NSGA-II was proposed in [90] for service restoration. Through Remotely Controlled Switches (RCS), the switching operations are prioritized in order to obtain a faster and more economical solution.

Particle Swarm Optimization

Particle Swarm Intelligence is a swarm intelligence-based method in which an initial random population of particles proceeds through guided search in the search space. Similar to GA, in Particle Swarm Optimization (PSO) a random starting population is created for service restoration after encoding the particle's position in binary or integer forms. A PSO algorithm can provide faster and more efficient solutions to both continuous and discrete optimization problems.

The authors of [91] developed a PSO-based decision support tool to help system operators decide on a suitable restoration plan after a fault event. The developed tool provides the optimal switching scheme which requires minimum number of switching operations and can re-energize the maximum number of loads.

In their research work [92], Wu and Tsai have used binary coded PSO to solve the feeder reconfiguration problem. This work has been extended by the same authors, who reported an Enhanced Integer Coded Particle Swarm Optimization (EICPSO) method to deal with service restoration problem in [93]. In this approach, the *pbest* variable in the PSO velocity update equation is substituted with a local optimum list. This list is generated by picking the optimal particle position in successive iterations. This improves the probability of finding the global optimal solution. In [94], a modified PSO approach was reported for obtaining the optimal switching sequence after a fault event. The authors of [95] used binary coded PSO to solve the service restoration problem with the objectives of maximizing the supplied load and voltage regulation while minimizing power loss and switching operations.

PSO–ANN-based optimization is well suited for optimization problems with large system size. Therefore, the authors of [96] proposed a restoration plan for a large-scale distribution network using a PSO–ANN algorithm.

In 2020, a Boolean PSO method developed by integrating Boolean algebra and a PSO algorithm in binary space was reported in [97] for solving the service restoration problem for an islanded section of a network. This work investigated the effect of restoration schemes and the use of distributed energy resources and capacitor banks on the stability and reliability of power distribution system.

Ant Colony Optimization

This approach is based on the natural of behavior ants, which locate the shortest path from their colony to their food source. While travelling, ants leave a chemical substance called a pheromone along the route. Other ants are guided in their path choices by the intensity of this pheromone. This kind of search methodology is utilized by researchers to find the optimal solution for combinatorial problems such as the service restoration problem.

The research proposed in [98] discusses two Ant Colony Optimization (ACO) methods for solving the service restoration problem, namely, Absolute Switch Position-ACO (ASP-ACO) and Relative Switch Position-ACO (RSP-ACO). These algorithms were applied for restoration in a scenario involving cold load pickup conditions, which occur due to long-duration interruptions.

A hyper-cube framework-based ACO for service restoration was proposed by the authors of [99]. The "energy not supplied" value was minimized in order to ensure a lower number of interrupted loads in the restored network. The same objective was considered by the authors in [100] along with the additional goals of providing electricity to priority consumers, loss minimization, and distinct formulation for both manually controlled switching operations and remotely controlled switching operations.

The research presented by the authors of [101] discusses an ACO method combined with stochastic a spanning tree algorithm to improve search efficiency in restoration optimization. The authors used three IEEE test systems to test their proposed method.

4.2.6. Hybrid Methods

These methods are developed to improve efficiency and reduce the required computational time of an algorithm. A hybrid algorithm is obtained when two or more algorithms are combined together in order to utilize the merits of all the integrated algorithms. Several hybrid techniques for service restoration optimization have been suggested by researchers in recent years.

A hybrid method combining GA and an expert system was reported in [102]. When the total power source capacity is insufficient to restore all out-of-service regions, the expert system calculates switch operations to increase the supply margin of power sources. For each power source, the GA calculates a portion of the out-of-service area.

The authors of [103] proposed a fuzzy GA approach for service restoration with multiple objectives, viz., maximization of load supplied, minimization of number of switching operations, voltage deviation, loading of the transformer, and feeder current. These objectives were formulated as fuzzy sets. A membership function was associated with each objective, the value of which determines the satisfaction level of that objective in the restoration plan obtained by the GA.

A technique involving chaotic optimization and an immune algorithm for service restoration was discussed in [104]. The suggested method uses a global search method known as a thick search to boost convergence speed by first initialising the immune algorithm's antibodies via chaotic optimization. In order to increase population variation and avoid the algorithm becoming stuck in local minima, local search then uses the artificial immune method to finish a thin search for chaotic optimization. A non-dominated sorting fuzzy evolution strategy as a new multi-objective method was presented by the authors of [105] to solve the service restoration problem.

The combination of Evolutionary Programming (EP) with ACO was suggested in [106]. The goal was to reduce system actual power loss with the least number of switching operations by considering the changes in load currents. EP was used to identify a collection of acceptable solutions using a specially constructed mutation operator. The authors suggested employing the grey correlation grade instead of constant values for the desirability of state transitions during the ACO search process.

4.2.7. Mathematical Programming Methods

Mathematical programming refers to mathematical models that are used to solve problems such as decision problems. In contrast to computer programming, which uses algorithms designed for specific problems to tackle complex optimization problems, mathematical programming employs declarative techniques. This indicates that a distinction is made between the representation of a problem via a mathematical model and its solution.

Khushalani et al. [107] formulated the multi-objective service restoration problem as a mixed-integer nonlinear programming problem. They proposed an unbalanced distribution network and tested it for the IEEE-13 bus and IEEE-37 bus test systems. The main characteristics of this formulation are that a separate computation of the unbalanced power flow in three phases is not required, the equations are not linearized, and mutually coupled cables are considered.

In [108], a two-stage technique to restore power in electrical distribution network was proposed. In the first stage, the original problem is expressed as a mixed integer linear programming problem using linearization. This mixed integer linear programming model results in an optimal solution with the use of a conventional optimization tool. In the second stage, a nonlinear programming model is obtained by fixing the decision binary variables obtained in the first stage, resulting in a steady-state operating point of the solution.

The authors of [109] used a mixed-integer nonlinear programming model to find the best switching scheme for restoring service in an unbalanced distribution network. The suggested mixed-integer nonlinear programming model determines the state of RCS and dispatchable DG units, which are utilized to de-energize the faulted section of the network and try to supply the maximum number of interrupted customers in the healthy section of the network.

In [110], Romero et al. proposed a detailed mathematical model for solving the restoration problem in balanced radial distribution systems. The restoration problem is presented as a mixed integer second-order cone programming problem that can be solved effectively utilizing a variety of commercial solvers.

To increase the self-healing capabilities of advanced distribution networks, the authors of [111] proposed a mixed-integer second order cone programming approach for obtaining the optimal coordination of multiple soft open points.

4.2.8. Miscellaneous Methods

A service restoration plan after the occurrence of substation outages due to extreme events was developed by the authors of [112]. In this technique, the DERs are regulated such that the maximum load pickup is realized while the constraints are satisfied. The network is described with a linearized optimal power flow and the restoration problem is expressed as model predictive control. In another work [113], island partitioning as a restoration technique after extreme events was proposed. For this objective, a graph theory-based island partitioning system and optimal load shedding were studied. To rejoin the nodes on the island with main grid after fault clearance, an optimal multi-step reconnection technique is used.

A Machine Learning (ML)-based approach was proposed by Kalysh et al. in [114] to obtain an optimal restoration plan for a smart distribution system.

The authors of [115] tested a fault location, isolation, and service restoration algorithm using an advanced distribution management system tool. In [116], an adaptive restoration plan employing a modified sequential opening branches was reported. This approach searches the system's loop configuration for the optimal tie-switch or sectionalize switch for operation. In [117], the authors proposed a hybrid ML framework integrating four meta-heuristic algorithms for service restoration. The reported accuracy of this ML framework is promising. A comparison of various methods proposed for solving the service restoration problem is shown in Table 2. A block diagram representing various methods for solving the service restoration problem is shown in Figure 6.

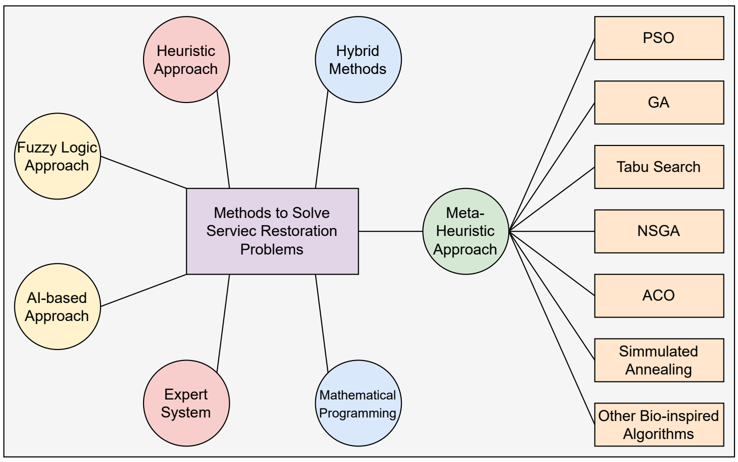

Figure 6. Various methods of solving the service restoration problem.

Table 2. Merits and demerits of various methods proposed for solving the service restoration problem.

Method	Advantages	Drawbacks	Articles
Expert system	1. System attributes are taken into account while finding the solution	1. Knowledge base formation is difficult. 2. Not generalized.	[57–63]
Fuzzy logic approach	1. Can provide solution to complex problem like service restoration. 2. Logic system construction is simple	1. Depends on human expertise. 2. Fails in case of inaccurate data input.	[64–67]
ANN	1. Method efficiency is independent of system size. 2. High reliability.	1. Weight assignment for layers is complex.	[68–70]
Heuristic approach	1. Less computational burden. 2. Fast execution.	1. Optimal solution not guaranteed. 2. System specific	[71–77]
Tabu search	1. Can be used for multi-objective optimization. 2. The final solution obtained is either optimal or close to optimal solution.	1. As the system size increases, the time for obtaining the solution also increases.	[81,82]
Genetic algorithm	1. Very effective for combinatorial problems.	1. Weight factor calculation is difficult for multi-objective optimization problem. 2. Computational time depends upon system size.	[83–86]
NSGA-II	1. Suitable for multi-objective optimization. 2. No convergence issue.	1. Global optimal solution not guaranteed.	[87–90]
PSO	1. Suitable for multi-objective optimization. 2. Easy formulation.	1. Needs modifications for various search strategies.	[91–97]
ACO	1. Global search efficiency is good. 2. Robust	1. Convergence time depends on system size.	[98–101]
Mathematical Optimization	1. Captures all the key features like objectives, constraints and decision variables. 2. No algorithm update required. 3.Highly accurate	1. High computational burden.	[107–111]

5. Conclusions

The management of a smart distribution grid is a challenging task and requires a great deal of computational resources. Distribution automation uses smart sensors and two-way communication technologies to automate the feeder switching process, monitor various grid parameters at various locations, monitor the health of installed equipment, and manage the reactive power at various buses. In this paper, different strategies related to the outage management aspect of distribution automation have been discussed.

The following are the main observations derived from previous research work on solveing the FDIR and service restoration optimization problems:

- For proper deployment of an FDIR scheme in modern power distribution systems, a decentralized control architecture is required.
- Enabling the grid to handle two-way flow of power and information is of the utmost importance in a modern grid.
- The issues of data availability, data integrity, data loss, and data security may arise during information exchange in modern distribution systems. These issues must be addressed by utilities to ensure smooth operation of any smart grid.
- Protecting the grid from cyberattacks is one of the key future challenges associated with power grids.
- High penetration of renewable energy sources and inclusion of micro-grids results in a more complex control strategy for the grid.
- A better solution for service restoration can be obtained through a multi-objective approach using the concept of Pareto optimality.
- The use of machine learning and artificial intelligence methods for planning and management of contemporary power grids represents a viable option in future research work.
- Deterministic methods are very accurate compared to stochastic methods. Although there is no guarantee that a stochastic or probabilistic technique will always result in a global optimal solution, these methods are nonetheless popular because they yield approximate solutions most of the time without requiring many processing resources.

Based on the study carried out in this review, the following areas can be identified as promising future aspects of research:

- Load variations in DAS must be considered during problem formulation, as this can make an impact in the real-time implementation of proposed methodologies.
- The systems taken into consideration in most extant research works are of a radial type, whereas in the present SG paradigm the distribution grids can be either radial or weakly meshed in nature. Therefore, previously proposed methods can be extended to address weakly meshed system configurations.
- There are various challenges present related to communication aspects in smart grids, including issues pertaining to data availability, data integrity, and data security. These problems can be addressed in the multi-agent framework by including proper agents.
- Proposed multi-agent frameworks by the researchers can be tested using the IEC61850 protocol to ensure better suitability in practical smart grid systems.

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Nomenclature

SG	smart grid
RES	renewable energy sources
AMI	advanced metering infrastructure
FDIR	fault detection, isolation, and service restoration
DAS	distribution automation system
IED	intelligent electronic device
DG	distributed generation
FCB	feeder circuit breaker
f_n	n_{th} objective of service restoration
α_{rcs}	number of remotely controlled switching operations
α_{mcs}	number of manually controlled switching operations
α_{rt}	number of remotely controlled switches
α_{mt}	number of manually controlled switches
β	out-of-service area

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