CHAPTER 2

REVIEW OF LITERATURE ON POWER SYSTEM RESTORATION

In the power system literature, there is a period of nearly forty years, extending from 1940 to the late 1970s, during which there were only a few papers on power system restoration. Following the major blackouts in the north-eastern United States in the mid-1960s and early 1970s, industry engineers and operators undertook serious reconsideration of system restoration problems as well as the need for developing and maintaining adequate restoration plans.

This chapter presents an overall view of restoration with background and introductory material for those who want to become familiar with the key aspects of restoration and various approaches used in planning, simulating, field testing and verifying different aspects of power system restoration. It also incorporates restoration training which covers a variety of tools used to develop and deliver effective system restoration training programmes and specific system restoration deals with restoration plans for various organisations. This chapter presents a brief review of the applications of SPF algorithm, comparison of algorithms, necessity for network reduction techniques and restoration using MAS.
2.1 OVERALL VIEW OF RESTORATION

Agrawal and Paul Erickson (2000) suggested the POWER GRID Corporation of India the ten sets of emergency restoration systems that were built in accordance with IEEE Standard 1070. When there was blackout because of natural disasters, it was estimated that the lost gross domestic product for India would be eighteen times the value of the power that was lost and also loss of income across India on account of loss of power was equivalent to 1% to 3.5% of the gross domestic product. A comprehensive discussion of the restoration plan was discussed by Adibi et al (1987). The requirements of database for generators, the importance of balancing the reactive power, voltage control during restoration, the philosophies of sequential versus parallel restoration in terms of backup power supply problems, black-start capability and sectionalizing subsystems were also discussed.

Adibi and Fink (1992) explained the use of computer in power system restoration. They included the strengths and weaknesses of restoration, key steps involved in developing and implementing an expert system and necessity for an operator training simulator in preparing the restoration plans. Ramon Nadira et al (1992) began with the argument that the use of general guidance for restoration lacked specificity. He proposed that these guidelines be framed more tightly in terms of multiple, albeit conflicting objectives, variables that can be controlled and constraints that need to be honoured. Felix F. Wu and Monticelli (1998) proposed a conceptual framework for computer-aided monitoring and assessment during restoration. He also discussed the effectiveness of knowledge-based or expert system-based restoration.

Shahnawaz et al (2003) illustrated a method to prevent the blackout in real time through controlled segregation of a system into several islands.
The nature and location of any fault that warrants such islanding can be ascertained in real time through monitoring the active power flows at both ends of the specified network. The blackout of June 20, 1998 in the Bangladesh Power Development Board system was taken as an example for the illustration.

Alexandre Assis Mota et al (2006) identified a methodology to separate the electrical network into an electrical island which was named as Restoration Building Block (RBB). This method was based on heuristic search and on the solution of a multi-stage decision problem. The electric network was modeled by a matrix with a nodal admittance type structure. Hence, it was possible to numerically analyze this matrix and rapidly infer about its topology connections, so determining the RBBs associated to an electric network. The methodology was tested with IEEE14 and IEEE30 systems and the obtained results had shown that the method was able to yield satisfactory RBBs configurations.

Arash Nezam Sarmadi et al (2011) described a novel sectionalizing method for the build-up strategy in power system restoration. One of the most important feature of the method was the build-up strategy that included the process of restoring separated parts (islands) in the power system and interconnecting them afterwards. This paper intended to develop a systematic algorithm for sectionalizing a power system considering various constraints such as black-start capability of generators, power supply-demand balance and independence of islands. Each island was fully observable using the Wide Area Measurement System (WAMS) which was a crucial requirement for the restoration process. The New England 39 bus power system was used to demonstrate the proposed algorithm and to prove its capability the algorithm was applied to IEEE 118 bus system.
Outage time after extensive blackouts depends very much on the power system restoration process. Olof Samuelsson et al (2008) proposed a simulation-based tool that determined a feasible sequence of operator actions that restored power system operation. The effect of each candidate switching operation or set point change was evaluated mainly in terms of restored load and the predicted steady state voltage and frequency. Application to the CIGRE NORDIC32 test system showed that operation was fully restored from complete blackout after about 750 actions including network switching and gradual connection of system loads. The main applications of the methodology were off-line use for surveying new restoration strategies and on-line use for suggesting the next action to the operator.

Yunhe Hou et al (2011) reported a practical methodology for the construction of system restoration strategies. The strategy followed by each power system differs, depending on system characteristics and policies. A new method based on the concept of “generic restoration milestones (GRMs)” was proposed. A specific restoration strategy can be synthesized by a combination of GRMs based on the actual system conditions. The decision support tool was expected to reduce the restoration time, thereby improving system reliability. The proposed decision support tool had been validated with cases based on a simplified Western Electricity Coordinating Council (WECC) 200-Bus system and Hawaiian Electric Company system.

Vaiman et al (2012) explained the challenges of cascading failure and summarized a variety of state-of-the-art analysis and simulation methods, including analyzing observed data, and simulations relying on various probabilistic, deterministic, approximate, and heuristic approaches. Limitations to the interpretation and application of analytical results were highlighted, and directions and challenges for future developments were included.
2.2 VARIOUS APPROACHES TO RESTORATION

In heuristics method of restoration, Kafka et al (1981) explained the importance of maintaining reactive power balance, continuous matching of load and generation, coordination of time frames for hot and cold restart of a variety of system generating units and constant awareness of the probable effects of each action on the rest of the system. Edward Simburger et al (1981) proposed a method to energize substantial portions of the transmission system from a location without picking up any load. A simulation of energizing the Los Angeles Department of Water and Power system from a set of under excited hydro units indicated that such a process was possible. Kafka et al (1982) explained the combined effort of operating personnel and system analysts and the usage of an interactive load flow programme.

In expert system of restoration, Sakaguchi and Matsumoto (1983) developed the first application of knowledge-based system technology to power system restoration. The knowledge-based systems were used for identification of fault locations, restoration strategies, power system representation and modelling, determination of switching sequence, and tie line assistance. Komai et al (1988) was the person who explained how to use the optimization for the restoration problem. This paper aimed at creating a bridge between numeric and knowledge methods through analysis and evaluation of the expert’s knowledge in solving a restoration problem.

Yokio Kojima et al (1989) identified a relationship between system components and the restoration policy. To make the expert system efficient, a black board software structure was used. The idea was implemented using an object oriented programming technique and was tested on prototype bulk power system with 36 power plants, 68 transmission lines and 48 substations. Shimakura et al (1992) proposed two modules for power system restoration. They were Load-feeding knowledge (LK) and Augmentation knowledge
(AK). The LK module included the sub-knowledge block “Load-Division” which divided and grouped outage area in terms of the availability of power supply and equipment. Using the LK block, the proposed system built a restoration plan to minimize the number of outage areas. If more power was required, then the AK block supported the restoration plan using equipment and generators outside the outage area. Nagata et al (1995) were the first to apply the optimization model in the field of restoration. This paper aimed to develop a suitable restoration method by a Mathematical programming approach. Under this devise, the optimal target system for restoration was formulated as an MP problem and solved efficiently by the decomposition-coordination strategy. The validity and effectiveness of the combined method was demonstrated by applying it to a practical size restoration problem.

Men-Shen Tsai (2008) developed an expert system by utilizing its fast reasoning mechanism and object-oriented features. The feeder component and configuration data were organized in a hierarchy way using the object-oriented programming paradigm. On the other hand, facts were used for representing the information during inference process. Service restoration procedure proposed in this paper took load variations into consideration. Another unique property of the proposed system was that it was capable of proposing multiple restoration plans.

In the field of soft computing, Seung-Jae Lee et al (1998) proposed a new restoration strategy in which the first step was Candidate Set Generation and Fuzzy Decision Making, which can generate the most preferable plan. The object-oriented paradigm was adopted in development of the system and the corresponding three models - object model, functional model, and dynamic model were designed. The test results showed the effectiveness of the proposed method.
Rahman (1993) provided a very extensive survey of AI for electric power systems in the Japanese industry and some of his comments deliberated on the difficulties of its application, especially in the system’s operating environment. Teo and Gooi (1998) presented the development of a PC-based integrated system, to illustrate the application of AI in the fault diagnosis and supply restoration for an interconnected distribution network. The intelligent process utilized the post-fault network status, a list of the tripped breakers, main protection alarm, and the conventional event log. By linking to a PC-based distribution simulator, it was demonstrated that the developed mechanisms enabled the correct detection of fault under different network configurations. Arturo Bretas and Arun Phadke (2003) discussed the limitations encountered in some currently used power system restoration techniques.

Petri nets (PNs) were developed in the early 1960s by Petri in his Ph.D. dissertation. Fountas et al (1997) exploited hierarchical time-extended Petri nets in order to support the restoration process. The proposed framework was applied to the black start of the Hellenic power system. Crucial issues pertaining to the restoration procedures were identified and the corresponding PNs models were presented. Zhang et al (2009) developed a novel hybrid intelligent method, which combined Petri Net (PN) model with Ant Colony Optimization (ACO) to solve target network reconfiguration strategy for power system restoration. Petri Net (PN) theory modeled the target network. In order to find the shortest restored energized path effectively, the transition rules of PN and the ACO algorithm were integrated elaborately. Finally, the case studies for IEEE 30-bus system as benchmark were applied to demonstrate the validity and effectiveness of the proposed model and method.

During the last 30 years, there has been a growing interest in problem-solving systems based on the principles of evolution and machine
learning. Route planning is an important problem for a car navigation system. Basabi Chakraborty et al (2005) proposed a GA-based algorithm to find out several alternate routes simultaneously depending on different criterion according to driver’s choice such as shortest path by distance, path which contains minimum number of turns, path passing through mountains or by the side of the river, etc. The proposed algorithm has been evaluated by simulation experiment using real road map compared to other existing GA based algorithms. Adelmo Cechin (2009) used GA for new initialization and crossover operators based on the electrical power network which was able to generate and maintain the plants feasible along GA runs. This method was tested on IEEE 14 bus, IEEE 30 bus and a large realistic system.

The ANT colony algorithm was a technique for combinatorial optimization borrowed from swarm intelligence. Real ants were capable of finding the shortest path from a food source to their nest without using visual cues by exploiting pheromone information. This was an algorithm in which a set of artificial ants cooperated to the solution of a problem by exchanging information via pheromone deposited on graph edges. Mohanty et al (2003) proposed two methods namely, Absolute Switch Position ANT Colony algorithm (ASP–ACO) and Relative Switch Position ANT colony algorithm (RSP–ACO). The difference between them was the manner in which the pheromone reinforcement was carried out. The convergence rate of RSP–ACO was better which was shown in the simulation result.

In the area of hybrid model, Fukuyama et al (1996) developed a hybrid system for solving a service restoration problem in distribution systems using ES and GA. The main objective in service restoration procedure was to restore as many loads as possible by transferring de-energized loads via network reconfigurations to other supporting distribution feeders without violating operating and engineering constraints.
The ES determined switching operations to expand the supply margin of power sources in a case where the total power source capacity was not enough to restore the whole out-of-service areas. The GA determined a part of out-of-service area for each power source. The feasibility of the developed algorithm for service restoration was demonstrated on a distribution network with promising results.

Ying-Tung and Ching-Yang (2000) presented a combination fuzzy-GA method to resolve the service restoration problem. The problem formulation proposed herein considered five different objective functions related to maximizing the amount of total load to be restored as well as minimizing the number of the switching operations, deviation of the bus voltage, the feeder’s current, and transformer’s loading. Meanwhile, the operational constraints, radial structure of the network configuration and sequence of the switching operations were included in the problem formulation. These objective functions were modeled with fuzzy sets to evaluate their imprecise nature. In the interactive method, the dispatcher provided his or her anticipated value (the degree of preference) of each objective, and then the optimization problem was solved by the GA. Analyzing the results from the former interactive and updating the expected value of each objective function via the interactive procedure allowed one to derive the compromised or satisfied solution efficiently. Simulation results obtained from the Taipower system demonstrated the effectiveness of the solution algorithm.

Yogendra Kumar et al (2008) presented a technique based on nondominated sorting genetic algorithm-II (NSGA-II) for solving the service restoration problem in an electric power distribution system. This approach did not require weighting factors for the conversion of such a multi-objective optimization problem into an equivalent single objective function
optimization problem. Various practical distribution system operation issues, such as the presence of priority customers, presence of remotely controlled, as well as manually controlled switches had been considered. Based on the simulation results on four different distribution systems, the performance of the NSGA-II-based scheme was found to be significantly better than that of a conventional GA-based method. Besides, to reduce the software runtime of the NSGA-II algorithm, a faster version of NSGA-II had also been implemented.

Tabu search was a powerful optimization procedure that had been successfully applied to a number of combinatorial optimization problems. It had the ability to avoid entrapment in local minima by employing a flexible memory system. Xiangzhen He et al (2008) designed a new distributed model for PSR and was proposed by combining Multi-agent Technology (MAT) with Tabu Search Method (TSM). The proposed model consisted of a number of Crunode Intelligent Agents (CIAGs) and a single Intelligent Control Agent (ICAG). These agents were co-operative and capable of interacting with each other dynamically to gain local optimal solutions. Based on that, TSM was utilized by ICAG to search for a global optimal solution. Through flexible interaction of agents and heuristic search of TSM, the optimal solution of PSR could be obtained and this was verified by simulation results.

Teo and Wei Shen (2000) presented a rule-based system to generate and implement a dynamic restoration plan for a partial or total blackout in a bulk power system. The governor response and ramp rate of each generator, system load regulation, pick-up characteristic of individual load and the transmission network were modeled and the rules for each component were framed. Based on these rules, a restoration plan was developed for a practical power system network and it was validated by conducting load flow calculation at every minute. Zhenzhi Lin and Fushuan Wen (2007) discussed
several important issues related to power system restoration in restructured power industry. They analyzed and compared the electricity market environment and identified the impacts of the restructuring efforts on power system restoration.

2.3 RESTORATION TRAINING

Restoration training covers a variety of tools used to develop and deliver effective system restoration training programmes. Susumago (1986) described a dispatcher training simulator for a large power system which included the model of generator, load, sub-station controllers and protective relays. The simulator was used for scenario building, training sessions, playback, and evaluation.

Chu (1991) described a restoration drill using a training simulator which was used to verify the restoration procedure and then to train the operator to restore part of the system in a simulated environment. Gary Miller et al (1993) Shared their thoughts and experiences gained in the area of operator training using a simulator. Since the power system operations were becoming increasingly complicated and critical too, there was a need to provide more directed power system operation training. The experiences of New York Power Pool had shown the dispatcher training simulator to be an effective tool in the training of power system operators and dispatchers, particularly in such areas such as voltage control, stability and system restoration. In this paper, detailed description had been provided regarding the simulator capabilities, training objectives and training environment.

Mehdi Rafian et al (1996) developed a knowledge based restoration tool along with the consolidated Edison (ConEd’s) Company of Newyork. This tool guided the operators through the execution of predefined procedures and also had the ability to adapt and modify these procedures if needed. This
tool had been developed and integrated with ConEd’s operator training simulator so that it could be used to train the operators in the restoration procedures.

### 2.4 SPECIFIC SYSTEM RESTORATION

Specific system restoration deals with restoration plans for various organisations. Mariani et al (1984) explained the procedures, guidelines, tests and experience of the National Authority for Electrical Energy – Italian system. Roger Kearsley (1987) discussed the basic philosophy for system restoration in Sweden. The structure of the Sweden network and the brief introduction for blackout were discussed. They emphasized the basic rules and the instructions for restoration. Huang et al (1991) described a semi-automated and mathematically optimal system to develop a system restoration plan. It was one of the first applications of interactive graphics for the development of the system restoration plan. It is applied to a sub-system of Hydro-Quebec system. Hain and Schweitzer (1997) presented a technical survey of the power failure which affected the Israel Electrical Network on June 8, 1995. As a result of the failure, about 70% of the consumers were disconnected from the energy supply. In this paper, restoration was organized in three parts. In the first part, the general systems characteristics and the condition of the network before the blackout were discussed. The second part, events during and after the failure were described. The third part, the lessons learn from the power blackout were summarized.

Stefano Barsali et al (2008) presented reports about the main results of a comprehensive international survey on behalf of the Italian independent
system operator. They also explained the main strategies, critical issues and practical experiences related to the restoration plans of a wide set of deregulated systems worldwide. The usage of HVDC links for restoration, the contribution of local networks to build up islands and specific demand side management techniques seemed to have improved the restoration plans in a deregulated environment. Taking the international survey as a starting point, this paper proposed and discussed possible innovative enhancements being studied for the Italian system, aimed at increasing the effectiveness of the restoration service.

2.5 APPLICATIONS OF SPF ALGORITHMS

Route selection for a given pair of origin and destination, offered many possible routes. But Yasushi Kambayashi et al. (2009) found that the classical Dijkstra’s algorithm could be used to find the most comfortable route subjectively by changing the data structure. The optimal driving route can be identified with the help of modified Dijkstra algorithm and concluded that the Dijkstra outperformed genetic algorithm in finding the optimal route selection in transportation industry.

Sudhakar et al. (2004) described a high speed switching algorithm for a distribution network that was developed with an aim of reducing the time of the restoration and maximizing the amount of power restored. The developed algorithm isolated only the fault section and restored the power supply to normal section after a fault took place. The determination of optimal configuration of the reduced network using Dijkstra’s algorithm was explained and was tested on a standard network. Sudhakar and Srinivas (2011) utilized the Prim’s algorithm for the identification of power flow path in the network since this was the complicated task of the power system operator. A computer was developed for planning and operation in service restoration of distribution network. The validity of this approach had been
tested on 16 bus IEEE power distribution system. The obtained results reduced the losses considerably without any optimization technique.

Chong Wang et al (2010) presented a power transfer distribution factor (PTDF)-based path selection approach for large-scale power systems. Two types of restoration performance indices were utilized considering all possible restoration paths, which were then ranked according to their expected performance characteristics as reflected by the restoration performance index. Based on PTDFs and weighting factors, the restoration paths were listed which can enable the load to be picked up by lightly loaded lines or relieve stress on heavily loaded lines. The algorithm was tested on the Western region of the Entergy system.

LiBao Shi et al (2012) suggested the Data Envelopment Analysis (DEA) method for incorporating preference information to identify the weight coefficient for each transmission line of the network during power system restoration. Some practical factors involving line charging reactive power, weather condition, equipment reliability, line operation time, and transmission capability were taken into account during the analysis.

2.6 COMPARISON OF ALGORITHMS

The choice of SPF algorithms for a particular problem will involve complex tradeoffs between flexibility, scalability, performance, and implementation complexity. The comparison provides a basis for evaluating these tradeoffs. Mawale and Gandole (2011) analysed the existing optimal route algorithms on a specific problem under constraint conditions with optimal factors based on the Dijkstra algorithm, Bellman Ford Algorithms and A* Algorithms.

2.7 NETWORK REDUCTION TECHNIQUES
The need for studying large scale power systems was increasing due to long distance power transfers, common power markets and planning of highly interconnected areas. Large systems were difficult to handle if not reduced. Also the SPF algorithms cannot be directly applied to a larger network hence the network size is reduced. Christian Rehtanz and Dirk Westermann (2003) concentrated on the modeling of the network environment. It was shown that the optimization process could be streamlined most effectively by avoiding the exchange of entire network data among the different parties involved during the design stage. To simplify the modelling of a network, a special modified Extended-Ward Algorithm for network reduction was introduced.

Antonis Papaemmanouil and Goran Andersson (2011) focused on reduction techniques applied on power system models. According to the purpose of the model, different inputs and outputs criteria were applied. In this paper, four methods were compared, two conventional, e.g. WARD, REI, and two market-based, according to their suitability for large scale reduction and development of economic models. Besides, the criteria of reducing the European electricity network were discussed and defined. Sahar Idwan and Wael Etaiwi (2011) explained the procedure of applying the Dijkstra’s algorithm to a larger network.

Power systems are, in general, very large systems; therefore, precise power system optimization is practically infeasible. HyungSeon Oh (2010) proposed a new network reduction algorithm for reducing the network into a small system, thereby the computational expenses could be reduced. Using the Power transfer distribution factor, network was reduced and tested on a simple system. The performance was compared with that of other methods observed in the references in terms of power flow. It obtained more precise representation of the reduced network than the conventional methods.
Another advantage was that the reduced network did not depend on the operation set point. As a result, it provided a precise representation of the transmission network for a power flow study. Therefore, it could be used in a large system OPF, national corridor, and renewable portfolio studies, among other things.

2.8 RESTORATION USING MULTI-AGENT SYSTEM

Nagata and Sasaki (2002) proposed a multi-agent approach to power system restoration. The proposed system consisted of several bus agents (BAGs) and a single facilitator agent (FAG). A BAG was developed to decide a sub-optimal target configuration after faults occurred by interacting with other BAGs, while a FAG was developed to act as a manager for the decision process. That is, a BAG was intended to conduct the local search, whereas the FAG was intended to proceed with the global search. It was shown from simulation results that this method was able to obtain sub-optimal target configurations which were the same as the ones obtained by an MP approach. Nagata et al (2004) also proposed a multi-agent simulator with four-level hierarchical architecture. In the first level, a single independent system operator agent was suggested to control the timing of the simulation process. Several local area management agents were fixed at the second level. Several load facilitator agents, generator facilitator agents and remote load facilitator agent were implemented in the third level. In the fourth level a number of load agents and generator agents were located.

Takeshi Nagata et al (2005) proposed a new decentralized multi-agent approach for the bulk power system restoration. The two-level architecture was constructed with several Local area management agents and Remote area management areas which were located in the upper level. Several load agents and generator agents were located in the lower level.
order to prove its capability, the system was applied to the bulk power system and the obtained results were effective and promising.

Dayong Ye et al (2011) presented a hybrid multi-agent framework with a Q-learning algorithm to support rapid restoration of power grid systems. This methodology integrated the advantages of both centralized and decentralized architectures which does not rely on a centralized controller, the single point of failure in power grid systems could be avoided. Further, the use of the Q-learning algorithm developed in conjunction with the restorative framework can help the agents to make accurate decisions to protect against cascading failures in a timely manner without requiring a global reward signal. Simulation results demonstrated the effectiveness of the proposed approach in comparison with the typical centralized and decentralized approaches based on several evaluation attributes.

MAS adopted a single central coordinator to control the whole system for system management, maintenance, and restoration purposes. Fenghui Ren et al (2012) introduced a conceptual MAS design in power system modeling. A novel dynamic team forming mechanism was proposed to dynamically manage agents in power system with a flexible coordination structure, so as to balance the effectiveness and efficiency of the introduced MAS. The results from simulations of case studies indicated the performance of the proposed multi-agent model.

Thillainathan Logenthiran et al (2012) proposed a MAS for real time operation of a microgrid. It mainly focused on generation scheduling and demand side management. The schedule coordinator agent executed a two-stage generator scheduling: day-ahead and real-time scheduling. A demand side management agent performed load shifting before the day-ahead scheduling. The MAS maximized the power production of local distributed generators, minimized the operational cost of the micro-grid, and
optimized the power exchange between the main power grid and the micro-grid subjected to system constraints and constraints of distributed energy resources. Results of simulation studies demonstrated the effectiveness multi-agent approach.

The literature review shows that the application of SPF algorithm for optimal path identification in power system network has not been carried out elaborately till now. The available restoration plans do not have the knowledge of optimal path to transmit the power. Hence an attempt is being made in this work to address this issue and propose a systematic methodology to overcome the existing drawbacks.