RESTORATION OF ELECTRIC SUPPLY IN DISTRIBUTION NETWORKS

A THESIS

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **RESTORATION OF ELECTRIC SUPPLY IN DISTRIBUTION NETWORKS** in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Department of Electrical Engineering of Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period from July 2002 to February 2006 under the supervision of **Dr. Jaydev Sharma**, Professor and **Dr. Biswarup Das,** Associate Professor, Department of Electrical Engineering of Indian Institute of Technology Roorkee, Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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ABSTRACT

Due to ever increasing demand of electric power, the size and complexity of modern day power distribution system have increased significantly, which, in turn, have enhanced the likelihood of occurrence of fault and size of the area affected by the fault in the electric power distribution system significantly. Hence, to maintain the customer satisfaction and the consequent revenue earned by the power distribution company, fast restoration of power supply to the healthy out-of-service area is of profound importance. However, in the course of service restoration, several related issues must also be considered as described below.

a) The power supply must be restored to the maximum possible healthy out-of-service area.

b) From economic point of view, there should be minimum loss in the system after the service restoration is accomplished.

c) The topology of the distribution systems changes because of service restoration operation. However, due to various reasons such as ease of fault location, fault isolation and protective device co-ordination etc., power distribution systems are often required to operate in a radial fashion. Hence, it is important to maintain this radiality of the systems, even when the topology of the systems is undergoing changes during the service restoration process.

d) Because of the varying topology and the connected loads, the bus voltages and line currents do also change during the service restoration process. To maintain the safety and security of different power system components (such as transformers and lines etc.), it is important that the bus voltages and line currents should not cross their respective operational limits.

e) Service restoration is essentially accomplished by transferring the loads in the out-of-service area to the neighboring supporting feeders via 'ON-OFF' control of different switches in the distribution systems. As the time taken by the restoration process depends on the number of switching operations, it follows from the above requirement

that the number of switching operations should be kept as minimum as possible. In the early days, only manually controlled switches (MCS) were used in a distribution system. Recently, these MCS are being replaced by remote, automatic control switches (ACS). As MCS have not been completely replaced by ACS in most part of the world, both these types of switches exist in almost all the power distribution systems in the world. However, the operating times of MCS and ACS are different. Therefore, both these types of switches should be considered separately in the service restoration study.

f) In any distribution system, there are always some loads, which are of highest priority (e.g. hospital). In the event of partial service restoration, the supply must be restored to highest priority customers and this fact should be reflected in the final solution of service restoration problem.

g) The software run time required by the service restoration algorithm should be minimum for speedier solution.

From the above discussion, it is apparent that the service restoration task is a multi-objective, multi-constraint optimization problem and therefore, following objective functions and constraints have been considered for service restoration problem in this thesis.

Objective functions:

1. Minimization of out-of-service area
2. Minimization of manually controlled switches
3. Minimization of remotely controlled switches
4. Minimization of losses

Constraints:

1. Radiality of the network should be maintained
2. Voltage constraint should not be violated
3. Current constraint should not be violated
4. Priority customers should always be supplied

Generally, in any distribution system operation, all these objective functions are not of equally important. Depending upon the broader perspective of system operation, generally the relative importance of the objective functions is known in the power distribution systems. As a result, in this work also it is assumed that the preferential knowledge of the objective functions considered herein is known a priori. As the customer's satisfaction is mostly affected by the availability of supply, the first objective function (minimization of out-of-service area) has been kept at the first preference. Moreover, to enhance the customer's satisfaction, the time taken for service restoration (which essentially depends on the operational times of manually controlled and remotely controlled switches) should also be minimum. Generally, the time taken for operating a manually controlled switch is significantly more than that of a remote controlled switch. Therefore, between any two solutions, the solution which requires fewer number of manual switch operations would need lesser time to complete the service restoration task as compared to the other solution. As a result, the objective function of minimization of manually controlled switch operations has been given the second preference and that of minimization of remotely controlled switch operations has been kept at the third preference. Finally the objective function of minimization of losses has been kept at the fourth preference.

In the literature, different techniques such as heuristic rule-base, expert system, mathematical programming algorithms, fuzzy logic, genetic algorithm (GA) etc. have been used to solve this complex problem. However, all these methods have some or other limitations. Both the heuristic rule based approach and expert system based approach essentially attempt to capture the knowledge base of the operators which they use to determine the switching sequences for supply restoration under fault conditions. This knowledge base is typically stored in the form of 'rules', and these rules are used by these two approaches for arriving at the appropriate solution. However, acquisition of the knowledge base of the operators for this purpose is often a very difficult task. Mathematical programming approaches have been proved to be computationally very costly for large systems. In Fuzzy set approaches, out of service load, number of switching operation, bus voltage, line current, loading of transformer etc. are taken as fuzzy variables and the solution is found on the basis of maximum membership function. But it also does not guarantee the optimal solution. Off late, GA based techniques have been proposed in the literature to solve these limitations. In this approach, initially the multi-objective optimization problem is converted into a single objective optimization by using weighting factors and subsequently, GA is used to solve this single objective optimization problem. The values of the weighting factors depend on the importance of the objective functions as well as on the scaling of the objective functions and constraints. Although the importance of the objective functions does not generally vary from network to network, the values of the objective functions and constraints vary from network to network. As a result, the scaling factors vary from network to network which, in turn, causes the variation of weighting factors for different networks. Hence, for every network, the weights are to be tuned.

To alleviate the above problems, in this thesis, a Non-Dominated Sorting genetic Algorithm-II (NSGA-II) based approach is proposed for solving the service restoration problem. In this technique, the multi-objective nature of the service restoration problem is retained without using any tunable weights or parameters. As a result, the proposed methodology is generalized enough to be applicable to any power distribution network. In NSGA-II, the final solution is found out based on the rank of the solutions in the population, which is obtained by non-dominated sorting concept. In this concept, initially the dominated solutions, dominating solutions and non-dominated solutions are found from a set of solutions and subsequently, based on these solutions; a rank is given to each and every solution in the population. After each solution is given its rank, it is assigned to its corresponding front, i.e., the solution with rank 1 is assigned to front 1, the solution with rank 2 is assigned to second front and so on. After all the fronts are formed, the final solution is chosen from the first front using the preferential knowledge of the objective functions.

For reducing the software run time of NSGA-II, two efficient algorithms, one for checking the radiality of the system and another for fast load flow computation of the distribution system with changing configuration have been developed, which are described below.

For checking the radiality of the system, a breadth-first-search (BFS) based algorithm has been used in this work. For this purpose, the original distribution network is first mapped to a graph involving nodes and branches. The nodes of the graph represent the various zones of the original distribution system. A zone is defined by a partial network of the distribution system that does not contain any switch. The branches of the graph represent only the "ON" switches. Inside any zone (i.e. the partial network), the structure is radial and all the relevant network data like load data, feeder data etc. are known from the given distribution system data. As a result, the structure, whether radial or meshed, of the original distribution system network is completely determined by the structure of the graph, i.e. if the structure of the graph is radial, the original distribution system network also operates radially, whereas, if the structure of the graph is meshed, the original distribution system also operates in a meshed fashion. To check the radiality of the system, the traversal of the graph starts from the node containing the substation and if, during the traversal, any node is reached twice, the system is meshed, otherwise it is radial.

For fast power flow computation of the distribution system with changing configuration, an efficient, two-way linked list based dynamic load flow technique has been developed. Because of the use of two-way linked list, the change in the configuration of the distribution system is taken care of very easily. The two way linked list stores the information regarding the configuration of the system quite effectively. After the configuration of the system is known, two matrices, which represent the topological characteristics of distribution systems, are used. The first matrix, denoted BIBC, shows the relationship between bus current injections and branch currents, and the second matrix, denoted BCBV, represents the relationship between branch currents and bus voltages. Subsequently, these two matrices are combined to form a direct approach for solving the load flow problem. As already reported in the literature, this direct method of load flow is quite fast and also, many limitations of the existing methods are avoided in this direct approach. Because of the combination of the two-way linked list and direct computation approach, the developed dynamic load flow method is both robust (takes care of the change in system configuration quite easily) and efficient (computes the power flow solution quickly).

With the help of the above two algorithms, the performance of NSGA-II has been validated with a large number of simulation studies on a number of distribution systems and its performance has also been compared with that of the conventional GA. Based on these simulation results, the performance of the NSGA-II technique has been found to be better than that of the conventional GA. Moreover it has also been observed that the NSGA-II reaches the best solution quite quickly as compared to conventional GA. Also from these large simulation studies, two distinct characteristics of NSGA-II have been noticed. It has been observed that in many (in fact almost all) instances, often a drastic improvement in the solution takes place (because of the utilization of crossover, mutation operators etc.) and therefore, the best solution is reached quite quickly. However, even after the best solution is achieved, the simulation runs are still continued to attain the convergence criterion. Thus, in almost all occasions, the time needed to reach the best solution (TBS) is significantly less than the time needed for convergence (TC). Hence, in all the cases, the software continues the execution even after it reaches the best solution, which in turn, increases the time for service restoration. Hence, for enhancing the speed of service restoration further, this gap between TBS and TC must be reduced (ideally should be made zero).

Because of the above observed limitation of NSGA-II, another heuristic search technique, namely Reactive Tabu Search (RTS) has been investigated for application to solve the service restoration problem. However, in a traditional RTS method, any multi-objective optimization problem first needs to be converted into a single objective optimization problem by using suitable weights. To retain the original multi-objective nature of the problem (and thereby eliminating any need of weights), in this work, the traditional RTS method has been suitably modified. In this modified version, henceforth named Multi Objective Reactive Tabu Search (MORTS) technique, the main structure of original RTS is retained. However, in MORTS, the best candidate among the neighborhood of a given solution is calculated using the non-dominated sorting concept.

Upon a large number of simulation studies, two salient features of MORTS have also been observed. In contrast to NSGA-II, the drastic improvement in the solution does not take place in MORTS and as a result, the value of TBS is generally more than that achieved by NSGA-II. However, after the best solution is obtained, the MORTS algorithm reaches the convergence criterion also quite quickly. Therefore, in MORTS, the difference between TBS and TC is quite less as compared to NSGA-II.

From the above discussions, it is observed that NSGA-II and MORTS are, in some sense, complimentary to each other. The advantage (limitation) of NSGA-II is manifested as limitation (advantage) in MORTS. Therefore, if NSGA-II and MORTS are combined, then it would be possible to retain the advantages (and avoid the disadvantages) of both these techniques. With this objective, a combined NSGA-II/MORTS technique has been developed. In this combined method, NSGA-II is first run for three iterations and subsequently MORTS is run for single iteration. This combination of three runs of NSGA-II followed by one run of MORTS is called a cycle. This cycle is repeated till the algorithm converges and the best solution is obtained. Comparison of the results of this combined technique with those of NSGA-II and MORTS shows that both the TBS as well as the difference between TBS and TC are lower than those obtained by NSGA-II or MORTS individually.

The above developed methods in this thesis to solve the service restoration problem in distribution system are fast enough. But, in a fully automatic system, it would be useful to reduce the solution time further. With that objective, in this thesis, an artificial neural network (ANN) is trained that gives service restoration solution quickly enough necessary for real time application. In this BPNN, the number of input nodes (N) is chosen to be N = 2Z+1, where Z is the number of zones in the distribution system under study. In the first 2Z nodes, the total real and reactive power loading of the zones are given. Thus, nodes 1 & 2 represent the total real and reactive power loading of zone 1, nodes 3 & 4 represent the total real and reactive power loading of zone 2 and so on. At the last node of the BPNN, the information regarding the faulted zone is given as input. The number of output nodes of the BPNN has been chosen to be equal to the number of switches in the distribution network under study. In this work, only one hidden layer has been used for the BPNN. For generating training and testing patterns, initially the loading (both real and reactive) at each bus of the distribution system under study has been varied randomly. In this process, a large number of loading patterns in the distribution network has been generated. For each of the loading patterns, a faulted bus also has been assumed randomly. Subsequently, at each of the loading patterns with its associated faulted zone, the service restoration problem is solved using the combined NSGA-II/MORTS technique thereby obtaining the corresponding status of the distribution network switches. In this process, a large number of training and testing patterns have been generated. Upon training and testing of the BPNN on a number of distribution systems, the performance of the BPNN has been found to be quite acceptable.

In conclusion, following works have been carried out in this dissertation:

- A BFS based algorithm for network traversing has been developed.
- A robust and efficient dynamic load flow technique has been developed to compute the load flow solution quickly under changing configuration of the distribution network.
- A NSGA-II based approach has been developed for solving the service restoration problem.
- Another approach, based on MORTS has also been developed to solve the service restoration problem.
- A combined NSGA-II/MORTS based approach has been developed to exploit the advantages of both these methods.
- For on line implementation of service restoration methodology, an ANN based approach has been developed.

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LIST OF SYMBOLS

The symbols used in the text have been defined at appropriate places, however, for easy reference the list of principal symbols is given below.

r	Resistance
x	reactance
I_{Ei}^{r}	Real part of current injection of bus i
I_{Ei}^{im}	Imaginary part of current injection of bus i
I_{Ei}	Bus injection current at i^{th} bus
I_{Bi}	Current flowing in branch i
S_i	Complex load at i^{th} bus
P_i	Real and power injection at bus 'i'
Q_i	Reactive power injection at bus 'i'
V_i	Voltage at i^{th} bus
I_{Ei}^{k}	Current injection of bus i in k^{th} iteration
V_i^k	Voltage at i^{th} bus in k^{th} iteration
V^{k+1}	Updated voltage for $(k + 1)^{th}$ iteration
V^o	Vector containing N terms, each equal to bus voltage connected with substation.
ΔV^{k+1}	voltage drop in k^{th} iteration
L_i	Load on i^{th} bus.
B	Set of energized buses in the restored network.
$\overline{X}$	Switch state vector of network under consideration for service restoration
SW_j	Status of j^{th} switch

N_S	Total number of switches in the network
b_1	No. of energized buses in the network before fault
N_m	Number of manually controlled switches
SWM_j	Status of j^{th} manually controlled switch in network just after fault
$SWMR_j$	Status of j^{th} manually controlled switch in the restored network
N_a	Number of remotely controlled switches
SWA_j	Status of j^{th} remotely controlled switch in network just after fault
$SWAR_j$	Status of j^{th} remotely controlled switch in the restored network
V_{max}	Maximum acceptable bus voltage
V_{min}	Minimum acceptable bus voltage
I_{max}	Maximum acceptable line current
I_{min}	Minimum acceptable line current
P_t	parent population in t^{th} iteration
P_o	Initial parent population
Q_t	Offspring population in t^{th} iteration
Q_o	Initial offspring population
F_i	i^{th} front

LIST OF ABBREVIATIONS

GA	Genetic algorithm
FCE	Fuzzy cause effect
NSGA	Non-dominated sorting of genetic algorithm
BFS	Breadth first search
TC	Time of convergence
TBS	Time to reach at best solution
RTS	Reactive tabu search
MORTS	Mult-objective reactive tabu search
ANN	Artificial neural network
BPNN	Back propagation neural network
CTSO	Crowded tournament selection operator
kW	Kilowatts
PFC	Pre-fault configuration
CS	Candidate solution
TS	Tabu search
TL	Tabu list
BNS	Best neighborhood solution

Chapter 1

INTRODUCTION

1.1 BACKGROUND

Due to increasing urbanization, the demand of electricity is ever-growing. To keep pace with this increasing urbanization, the reach of the power distribution system has also spread over a large geographical area. Moreover, to satisfy the increased demand of electricity, the amount of electrical power carried by the distribution system has also increased significantly in recent times. Therefore, the sizes, complexity as well as the stress in the distribution system have increased substantially nowadays compared to the scenario even a decade ago. A direct adverse consequence of the stressed system operation of any distribution grid is the increasing probability and frequency of faults (the faults can also take place due to different natural hazards such as storm, lightning, flood etc). Because of size and complexity of the grid, the number of consumers affected by the fault is also quite significant nowadays, thereby having a direct and profound adverse effect on the reliability of the supply and the revenue earned by the electricity supply company. Therefore, it is imperative for any power distribution company to enhance the reliability of supply. Hence, many approaches have been suggested and adopted throughout the world to improve the electricity service reliability [1-16] and fast restoration of supply to the maximum possible "out-of service" area due to occurrence of the fault is one of the most important tasks for any power supply company.

Essentially, the service restoration task is accomplished by transferring the loads in the "out-of-service" area to the neighboring supporting feeders via "ON-OFF" control of different switches installed in the distribution system. Basically, there are two different types of switches installed in a distribution system. The switches which are generally kept open in the normal running condition of the distribution system are called the "tie-line switches" and usually, these switches are provided between the neighboring feeders. On the other hand, the switches which are usually kept closed in the normal running condition are called the "sectionalizing switches" and generally, these switches are placed between different sections of a feeder. As the service restoration task is accomplished by "ON-OFF" control of these tie-line and sectionalizing switches, the service restoration problem is basically a combinatorial optimization problem. For illustration, consider a typical distribution system with two substations (denoted by SS1 and SS2) and several switching devices (denoted as SW1, SW2, ……SW12) as shown in Fig. 1.1. There are altogether four feeders in the system supplying a total of 22 buses (denoted as B1, B2, ….. B22) and these feeders are supplied from the two substations via two circuit breakers (CB1 and CB2). In this system, the switches SW6, SW12 and SW13 are tie-line switches and all the other remaining switches are sectionalizing switches. After occurrence of a fault at any location between switches SW4 and SW5, these switches would be made open to isolate the fault and as a result, bus B8 and bus B9 between these two switches would be de-energized. Along with bus B8 and bus B9 the healthy buses i.e. bus B10, B11, B16, B17, B18, B20, B21 and B22 would also be de-energized. In this case, the supply can be restored to the healthy de-energized buses by transferring the load from de-energized area to energized area by means of reconfiguration of the distribution system. This can be achieved by either closing switch SW6 or switch SW12 or switch SW7. Similarly, there can be many other combinations of switching operations which can accomplish this task. In fact the maximum number of these combinations in this distribution system is 2^{12} and the most suitable combination out of these 2^{12} options should be chosen.

Similarly, in a distribution system having 'n' switches, the possible number is 2^n. Since in a distribution system the number of switches (n) can be quite high [17], a complete enumerative analysis of all the possible 2^n combinations can take too long a time, thereby making this approach impractical. Thus, it is imperative that any analysis technique of service restoration problem should be able to handle this large number of combinations in a reasonable time. Also, in the course of service restoration, several related issues need also to be considered, which are described below.

a) The power supply must be restored to the maximum possible healthy out-of-service area.

b) From economic point of view, there should be minimum power loss in the system after the service restoration is accomplished.

c) The topology of the distribution system changes because of service restoration operation. However, due to various reasons such as ease of fault location, fault isolation and protective device co-ordination etc., power distribution systems are often required to operate in a radial fashion. Hence, it is important to maintain this radiality of the systems, even when the topology of the systems is undergoing changes during the service restoration process.

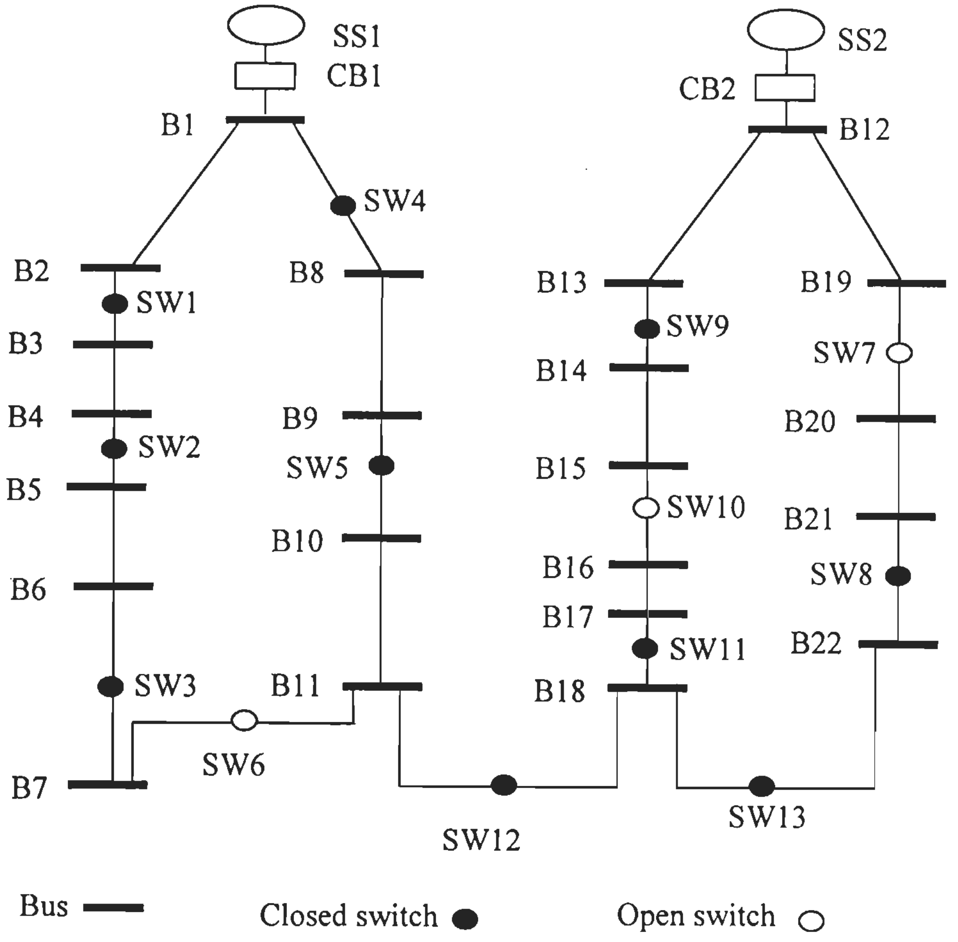


Figure 1.1 - A simple distribution system

d) Because of the varying topology and the connected loads, the bus voltages and line currents do also change during the service restoration process. To maintain the safety and security of different power system components (such as transformer and lines etc.), it is important that the bus voltage and line current should not cross their respective operational limits.

e) As describe earlier, service restoration is essentially accomplished by 'ON-OFF' control of different switches in the distribution system. As the time taken by the restoration process depends on the number of switching operations, it follows from the above requirement that the number of switching operations should be kept as minimum as possible. In the early days, only manually controlled switches (MCS) were used in the distribution systems. Recently, these MCS are being be replaced by remote, automatic control switches (ACS). As MCS have not been completely replaced by ACS in most part of the world, both of these types of switches exist in almost all the power distribution systems in the world. However, the operating times of MCS and ACS are different. Therefore, both of these types of switches should be considered in the service restoration study.

f) In any distribution system, there are always some loads, which are of highest priority (e.g. hospital). In the event of partial service restoration, the supply must be restored to highest priority customers and this fact should be reflected in the final solution of service restoration problem.

g) The software run time required by the service restoration algorithm should be minimum for finding speedier solution.

From the above discussion, it can be seen that the service restoration problem is essentially a multi-objective, multi-constraint optimization problem. To handle this problem, several approaches have been suggested in the literature as discussed below.

1.2 LITERATURE REVIEW

Because of the importance of the service restoration problem, there has been considerable interest in the past in developing suitable methods for service restoration in distribution systems [18 - 66]. Various methods, which have been suggested in the literature, can be broadly grouped in the categories of expert systems, heuristic approach, genetic algorithms, tabu search, mathematical programming, minimal path and search technique and other methods.

1) Expert system [18 - 26]

In expert system based approach, essentially the knowledge base of the operators, which they use to determine the switching sequences for supply restoration under fault conditions is captured and subsequently this knowledge base is stored in the form of 'rules'. These rules are in turn used by the expert systems for arriving at the appropriate solution. These approaches give the solutions very efficiently and also in these techniques, weighting factors are not required. However, acquisition of the knowledge base of the operators for this purpose is often a very difficult task. As a result, there is no guarantee of getting optimal solution. Moreover, for every new network a new expert system is required to be developed and therefore, this approach is not a generalized method.

Different versions of expert system have been proposed in the literature. In the method developed by C. C. Liu et al [18], some general rules for group restoration, zone restoration and load transfer are developed. Zhang et al [19] presented a knowledge-based approach for general task of network reorganization in which they have used Best-First search (BFS) method. In the method developed by C. Y. Teo [20], the proposed restoration algorithm searches for all possible links to connect the out-of-service area in the network. A step-by-step partial restoration algorithm is given which will restore supply subject to the maximum capacity of the distribution system. S. S. Ahmed et al in method[21] suggested an expert system with a rule base for service restoration in which the authors have enhanced and expanded the rule base suggested by Liu et al [18] by adding significant number of rules. In reference [22], T. K. Ma and R. Rogers proposed an on-line expert system for service restoration problem. In the method developed by K. Okuda et al [23], the experience of the skilled operators and the cases of restoration plans obtained in the past are used. For specific fault, reference is made to the restoration plan of a similar case in the past and the restoration strategy is produced quickly. In the method developed by H. Schwarzjirg and H. Brugger [24] also some knowledge-based/rule-based method for service restoration is suggested. In the work of C. Y. Teo and H. B. Gooi [25], different restoration algorithms based on a network state knowledge base and a restoration knowledge base are developed. These algorithms are; i) direct restoration algorithm (which attempts to restore the entire load) and ii) partial restoration algorithm (which attempts to restore the partial load using branch restoration algorithm). Branch restoration algorithm attempts to restore supply to as many branches in the dead islands using priority restoration algorithm (this is concerned with the load shedding of low priority loads). Kim et al [26] developed the expert system using best first search method. The heuristic rules obtained from system operator are also incorporated in this technique to improve the solution procedure.

2) Heuristic approach [27 - 37]

The heuristic approach combines the heuristic rules and conventional programming methods to achieve an adequate scheme. As in the expert system based approach, the heuristic rules are framed from the knowledge base of the operators of the distribution systems. Therefore, the same limitations, as those of the expert system based approach, are equally applicable to these methods also. These methods are not efficient for large system.

In the reference [27], Y. Xue, J. jhu, J. liu and H. Sasaki suggested a rule-base heuristic search approach for service restoration problem. The authors in [28] solved the problem by using depth-first search strategy supported by some practical rules to guide the search. Hsu et al [29] compiled the heuristic rules used by experienced dispatcher in conducting restoration of supply. In method developed by J. Nahman and G. Strbac [30], an algorithm is suggested for service restoration with an objective of minimizing the total supply interruption cost to the customers. A separate switching sequence synthesis algorithm is proposed to minimize the number of switching operations needed to realize the optimal solution. In the reference [31], Devi et al provided a heuristic search based methodology for solving the optimal electric power supply restoration policy. Among the various search methods, they recommend breadth-first search with pruning for solving the problem of service restoration for large distribution system to get the solution efficiently. Castro et al [32] presented an algorithm based on tree searching techniques utilizing switch tables and network maps. The switch table contains information about the network such as status of switches. In the work developed by Akoi et al in [33] presented an algorithm for load transfer by automatic sectionalizing switch operations in distribution systems on a fault occurrence satisfying transformer and line capacity constraints. Akoi et. al. [34] developed another restoration strategy in which priority customers are considered. In the method described by D. Shirmohammadi [35], the faulty component is first isolated and the remaining switches are kept closed at starting, thereby making the network weakly meshed. Subsequently, the switch which carries the minimum current is identified with the help of load flow analysis of this meshed network and thereafter this particular switch is opened. After each switch opening, the load flow analysis is solved again till the system is rendered completely radial. In the reference [36], Miu et al developed the algorithm for service restoration problem incorporating multi-tier or system-wide switching and capacitor control action for large-scale radial distribution systems. The solution algorithm is designed to consider networks with predominantly manual switches. In the work [37], Miu et al developed a method to restore the supply for large-scale distribution network with priority customers. A ranking-based search method employing analytical information obtained from three-phase power flow simulation is designed to restore service to as many priority customers as possible.

3) Genetic algorithm [38 - 48]

GA is one the stochastic search algorithm based on the mechanics of natural genes. It is a powerful technique for combinatorial optimization technique and as a result it has been used to solve different types of problems in distribution systems [38 - 48]. It utilizes string operations such as crossover and mutation for generation of the candidates for next state. In service restoration problems, the string contains status of switches while crossover operation performs partial exchange of network configuration between two different configurations. However, GA optimization technique has some drawbacks also. It takes relatively longer time to evaluate the modified search points. Moreover, it revisits the already searched states many times and also optimality is not guaranteed in this technique. To solve the service restoration problem in distribution systems, many methods based on GA [42 - 48] have been developed. In all these methods, the multi-objective service restoration problem has been first converted to single objective optimization problem using suitable weighting factors. In the method developed by Laun et al [42] instead of the standard 'binary' coding method, an 'integer permutation' coding scheme is adopted. In the method developed by Fukuyama et al [43], the authors developed parallel genetic algorithm for solving service restoration problem in distribution systems. The work developed in [43] belongs to coarse gain parallel genetic algorithm, which achieves the trade-off between computational speed and hardware cost. In the method developed by Augugliaro et al [44] a hybrid genetic algorithm is presented for the service restoration problem to eliminate the difficulties in the conventional GA. In the method developed by Y. T. Hsiao and C. Y. Chien [45], a combination of fuzzy logic and GA is used. In the method [46], Shin et. al developed the algorithm to solve the restoration problem using the combination of genetic algorithm and tabu-search. This method minimizes a cost function while keeping constraints such as line power capacity, voltage drop at load point etc. In the method developed by Toune et al [47], a comparison of three approaches based on GA, reactive tabu search (RTS) and simulated annealing has been made.

4) Tabu search [48 - 49]

In this class of methods to solve service restoration problem, the past histories are used to avoid the entrapment in local optima and obtain the global solution. In these methods also, the multi-objective optimization problem is first converted into a single objective optimization problem with the help of weighting factors. In the method developed by Toune et al [48], reactive tabu search is proposed for service restoration in distribution systems. A problem-dependent heuristic method is presented to generate an initial sub-optimal state in the solution space. The method generates neighboring states in a solution space by exchange of the direction of power source at a certain load. The search states are stored in a tabu list using a hash function. Therefore, fast storing and retrieving data are realized. The tabu-list is modified using reaction mechanism. Mori et al in their work [49] integrated parallel tabu search and ordinal optimization to solve the service restoration problem. Parallel tabu search has better performance than simple tabu search in terms of solution quality and computational time. Ordinal optimization is based on the probabilistic optimization method that speeds up computational time by reducing the number of solution candidates to be evaluated in a probabilistic way under guarantee of solution quality. None of these two methods considered the issues of loss minimization, priority customers as well as manual & automatic switches separately.

5) Mathematical programming [50 - 52]

These methods formulate the supply restoration problem as an optimization problem and subsequently, the optimization problem is solved by one of the standard mathematical programming techniques like mix-integer programming. Such methods can be applied to any network configuration and can find the optimal solution provided the optimization problem is adequately formulated. However, they have been proved to be computationally very costly for large systems. These techniques do not consider the key customers and remotely and manually controlled switches separately. In the reference [50], Akoi et al employed an approximate method, which uses effective gradient technique. Akoi et al [51] transfere the loads of the de-energized feeders to the other feeders in stages using effective gradient technique and give accurate solution. First all the de-energized loads are transferred to adjacent feeders, called main support feeders. A multistage solution strategy is then implemented if required, especially to satisfy the various constraints. In method [52], Ciric et al solved the service restoration problem using the combination of heuristic and mix-integer programming method.

6) Fuzzy approach [53 - 56]

In this method, different parameters of the distribution system such as out of service load, number of switching operation, bus voltage, line current, loading of transformer etc. are taken as fuzzy variables. In the method developed by Kuo et al [53], an approach based on fuzzy set theory to estimate the loads in a distribution system and to devise a proper service restoration plan following a fault is developed. The load of a branching point is estimated through fuzzy set operations. With the estimated load at hand, a heuristic search method is used to arrive at a restoration plan. Huang et al [54] developed an alternative approach using fuzzy cause effect networks to solve the problem of service restoration of distribution systems. In this method, the multi-objective optimization problem is converted into single objective optimization problem by employing weighting factors and the heuristic rules obtained by interacting with the operators of distribution scheme are transformed into a fuzzy cause-effect (FCE) network. Subsequently, the FCE network is used to evaluate the single objective optimization problem and arrive at the optimal solution. In the reference Lee et al [55] solved the restoration problem in distribution systems by applying the fuzzy logic technique in dealing with various practical criteria. It first constructs the candidate set of feasible restoration plans obtained by applying a series of basic restoration schemes and evaluates them based on four fuzzy criteria - contingency preparedness, feeder margin, number of switching operations and number and amount of live load transfer considering their relative weight. Subsequently the solution with the highest preference index is selected. D. S. Popovic and Z. N. Popovic [56] proposed a procedure for supply restoration based on fuzzy logic, as well as on the concept of the local network. By introduction of the local network concept, the dimensions of the problem are reduced.

7) Minimal path and search technique [57 - 58]

In these techniques the minimal path is searched to transfer the loads of the de-energized feeders to the other feeders. However, this method is also impractical, as for a practical distribution system, the search space becomes quite large. As a result, certain rules are introduced to prune the solution space efficiently, thereby sacrificing the optimality of the solution. Dialynas and Michos [57] suggested a graph theory based method which requires the knowledge of all minimal paths from the system service points to the load points. In the method developed by Sarma et al [58], the service restoration problem is solved with help of interested trees.

8) Other methods [59 - 66]

Broadwater et al [59] have explored the relationship between distribution system reliability and restoration analysis. Dialynas and Mochos [60] extended the techniques given in [57] by describing the modeling and evaluating techniques that permit an efficient and practical interactive probabilistic assessment of service restoration. They evaluated the probabilistic indices for quantifying the impact of component reliability parameter and system operational practices on the restoration capability of the distribution system. Y. Y. Hsu and H. M. Huang [61] suggested the use of neural network to solve the restoration problem. Neural networks have been applied to recognize a load pattern from feeder measurements and other data, and then select a pre-analyzed topology and switching strategy to reconfigure the network for service restoration. The neural network serves as a state estimator but does not analyze the topologies. It may suggest more than one solutions for a given service restoration problem. The work [62], I. Mohanty, J. Kalita, S. Das, A. Pahwa and E. Buehler proposed ant colony algorithm to compute the optimal order of restoring sections in a power distribution system. The restoration of distribution feeders after long interruptions creates cold load pickup conditions due to loss of diversity among the loads. The distribution system load is restored step-by-step using sectionalizing switches with cold load pickup. W. Lin and H. Chin [63] developed a method to solve distribution feeder reconfiguration problem for loss reduction and service restoration for distribution system. They used three switching indices for this purpose. Y. Ke [64] solved the service restoration problem in distribution systems by using G-net inference mechanism. G-net is a powerful tool for knowledge representation and reasoning process [65]. For distribution contingencies, such as feeder overloading and/or short circuit fault etc., the G-net inference mechanism with operation rules is applied to derive the optimal switching operation decision for service restoration to perform the optimal load transfer among distribution feeders. C. Ucak and A. Pahawa [66] developed an approach for step-by-step restoration of distribution systems following extended outages considering the cold load pick up problem.

Looking closely at all the categories of the methods to solve the service restoration problem in distribution systems discussed above, the main observations are as follows.

- In none of the reviewed methods, the manually controlled switches and remotely controlled switches have been considered separately.
- In the expert systems based approaches to solve the service restoration problem, some methods have considered priority customers and loss minimization but the voltage constraint is not considered.

- In heuristic approach, voltage constraints and current constraints has been considered. Some of the methods based on heuristic approach considered loss minimization but did not considered priority customers. Other methods of this category did not considered loss minimization.
- In genetic algorithm based approaches, voltage constraints and current constraints have been considered but priority customers are not considered. In some methods of genetic algorithm approach, the issue of loss minimization has not been considered.
- In the methods based on tabu search, the issues of loss minimization and priority customers have not been considered.
- In all methods based on mathematical programming, voltage constraints and current constraints are considered. But no method based on mathematical programming considered priority customers and the issue of loss minimization has been considered only in some other methods.
- In fuzzy approach, no method considered priority customers and the objective of loss minimization has not been taken into account in some other methods.
- In minimal path and search approach, loss of minimization has not been considered. Priority customers have not been considered in some methods of this category. But the voltage constraints and current constraints have been considered.
- In all other methods of service restoration kept in the last category namely 'other methods', the voltage constraints and current constraints have been considered. In some of the methods of this category, loss minimization has been considered but priority customers have not been considered. While, in some other methods of this approach, priority customers, voltage constraints and current constraints has been considered but loss minimization has not been considered.
- From the above observation, it can be said easily that some issues are not considered at all and other issues are not considered together in any method.

1.3 OBJECTIVES AND CONTRIBUTION OF THE AUTHOR

As described earlier, service restoration problem is a multi-objective, multi-constraint combinatorial optimization problem and based on the various issues involved in this problem discussed earlier, following objective functions and constraints have been considered in this thesis.

Objective functions:

1. Minimization of out-of-service area
2. Minimization of manually controlled switches
3. Minimization of remotely controlled switches
4. Minimization of losses

Constraints:

1. Radiality of the network should remain maintained
2. Voltage constraint should not be violated
3. Current constraint should not be violated
4. Priority customers should be always supplied

From the literature review, it is observed that there exists no single technique in the literature, which takes into account the above mentioned objective functions and constraints into consideration. Moreover, quite a few of the techniques reported in the literature first convert this multi-objective problem to a single objective optimization problem by using weighting factors. The values of the weighting factors depend on the importance of the objective functions as well as on the scaling of the objective functions and constraints. Although the importance of the objective functions does not generally vary from network to network, the values of the objective functions and constraints vary from network to network. As a result, the scaling factors vary from network to network which, in turn, causes the variation of weighting factors for different networks. Hence, for every network, the weights are to be tuned.

To bridge these two above mentioned gaps, in this thesis, a Non-Dominated Sorting genetic Algorithm-II (NSGA-II) based approach is proposed for solving the service restoration problem. In this technique, the multi-objective nature of the service restoration problem is retained and no tunable weights or parameters are required. In NSGA-II, the final solution is found out based on the rank of the solutions. To find the rank of solutions, non-dominated sorting concept is adopted. In this concept, initially the dominated solutions, dominating solutions and non-dominated solutions are found from a set of solutions and subsequently, based on these dominated, dominating and non-dominated solutions, a rank is given to each and every solution in the set. After each solution is given its rank, it is assigned to its corresponding front, i.e., the solution with rank 1 is assigned to front 1, the solution with rank 2 is assigned to second front and so on. After all the fronts are formed, the final solution is chosen from the first front using the preferential knowledge of the objective functions.

For reducing the software run-time of NSGA-II, two efficient algorithms, one for checking the radiality of the system and another for fast load flow computation of the distribution system with changing configuration have been developed, which are described below.

The radiality of the distribution systems is checked by traversing the distribution systems. To traverse the distribution system, a breadth-first-search (BFS) based algorithm has been used in this work. During the traversing of the distribution system, if any component of the system is traversed twice, it means the system is not radial otherwise it is radial.

For fast power flow computation of the distribution system with changing configuration, an efficient, two-way linked list based dynamic load flow technique has been developed. Because of the use of two-way linked list, the change in the configuration of the distribution system is taken care of very easily. The two way linked list stores the information regarding the configuration of the system quite effectively. The accuracy of the dynamic load flow is maintained by using the already efficient existing method with higher accuracy but this existing method can not sense any change in the configuration of the distribution system if any. Because of the combination of the two-way linked list and the efficient method with higher accuracy, the developed dynamic load flow method is both robust (takes care of the change in system configuration quite easily) and efficient (computes the power flow solution quickly).

With the help of the above two algorithms, the performance of NSGA-II has been validated with a large number of simulation studies on a number of distribution systems and its performance has also been compared with that of the conventional GA. Based on these simulation results, the performance of the NSGA-II technique has been found to be better than that of the conventional GA. Moreover it has also been observed that the

NSGA-II reaches the best solution quite quickly as compared to conventional GA. Also from these large simulation studies, two distinct characteristics of NSGA-II have been noticed. It has been observed that in many (in fact almost all) instances, often a drastic improvement in the solution takes place (because of the utilization of crossover, mutation operators etc.) and therefore, the best solution is reached quite quickly. However, even after the best solution is achieved, the simulation runs are still continued to attain the convergence criterion. Thus, in almost all occasions, the time needed to reach the best solution (TBS) is significantly less than the time needed for convergence (TC). Hence, in all the cases, the software continues the execution even after it reaches the best solution, which in turn, increases the time for service restoration. Hence, for enhancing the speed of service restoration further, this gap between TBS and TC must be reduced (ideally should be made zero).

Because of the above observed limitation of NSGA-II, another heuristic search technique, namely Reactive Tabu Search (RTS) has been investigated for application to solve the service restoration problem. However, in a traditional RTS method, any multi-objective optimization problem first needs to be converted into a single objective optimization problem by using suitable weights. To retain the original multi-objective nature of the problem (and thereby eliminating any need of weights), in this work, the traditional RTS method has been suitably modified. In this modified version, henceforth named Multi Objective Reactive Tabu Search (MORTS) technique, the main structure of original RTS is retained. However, in MORTS, the best candidate among the neighborhood of a given solution is calculated using the non-dominated sorting concept.

Upon a large number of simulation studies, it is observed that NSGA-II and MORTS are, in some sense, complimentary to each other. The advantage (limitation) of NSGA-II is manifested as limitation (advantage) in MORTS. Therefore, if NSGA-II and MORTS are combined, then it would be possible to retain the advantages (and avoid the disadvantages) of both these techniques. With this objective, the combination of NSGA-II and MORTS technique has been developed. In this combined method, NSGA-II is first run for three iterations and subsequently MORTS is run for one iteration. This combination of three runs of NSGA-II followed by one run of MORTS is called a cycle. This cycle is repeated till the algorithm converges and the best solution is obtained.

Comparison of the results of this combined technique with those of NSGA-II and MORTS shows that both the TBS as well as the difference between TBS and TC are lower than those obtained by NSGA-II or MORTS individually.

The above developed methods in this thesis to solve the service restoration problem in distribution system are fast enough. But, in a fully automatic system, it would be useful to reduce the solution time further. With that objective, in this thesis, the artificial neural network approach is proposed that gives service restoration solution quickly and accurately, which is necessary for real time application. In the ANN, the number of input nodes (N) is chosen to be N = 2Z+1, where Z is the number of zones in the distribution system under study. In the first 2Z nodes, the total real and reactive power loading of the zones are given. At the last node of the ANNs, the information regarding the faulted zone is given as input. The number of output nodes of the ANNs has been chosen to be equal to the number of switches in the distribution network under study. In this work, only hidden layer has been used for the ANN. To get the output for each input of ANN, the service restoration problem is solved using the technique based combination of NSGA-II and MORTS thereby obtaining the corresponding status of the distribution network switches. In this process, a large number of training and testing patterns have been generated. Upon training and testing of the ANN on a number of distribution systems, the performance of the ANN has been found to be quite acceptable.

In short, following works have been carried out in this dissertation:

- A BFS based algorithm for network traversing has been developed.
- A robust and efficient dynamic load flow technique has been developed to compute the load flow solution quickly under changing configuration of the distribution network.
- A NSGA-II based approach has been developed for solving the service restoration problem.
- Another approach, based on MORTS has also been developed solve the service restoration problem.
- A combined NSGA-II/MORTS based approach has been developed to exploit the advantages of both these methods to solve the service restoration problem.

- For on line implementation of service restoration methodology, an ANN based approach has been developed.

1.4 ORGANIZATION OF THE THESIS

The aim of this thesis is to develop comprehensive methods for service restoration in distribution system after the occurrence of fault. The organization of the thesis is as follows.

The present **chapter 1** introduces the service restoration problem in distribution systems, presents a brief state of art survey on the subjects and author's contribution in this thesis.

Chapter 2 presents the methods of network traversing and dynamic load flow.

Chapter 3 presents the mathematical formulations of the objective functions and the constraints. Subsequently, GA and NSGA-II are applied to solve the service restoration problem. Advantages and disadvantages of GA and NSGA-II are also discussed in this chapter.

In **Chapter 4** application of RTS, MORTS and combination of NSGA-II and MORTS are presented to solve the service restoration problem with the formulation already discussed in chapter 3. A comparative assessment of all the methodologies for service restoration developed in this thesis is also presented in this chapter.

Chapter 5 presents the application of artificial neural network to achieve the real-time solution of service restoration.

Chapter 6 concludes the work contained in the main body of the thesis and presents the suggestions for future work.

Chapter 2

DYNAMIC LOAD FLOW METHOD FOR DISTRIBUTION SYSTEMS

2.1 INTRODUCTION

Load flow is the most fundamental numerical algorithm required for power system analysis. As a result, a voluminous amount of work has been carried out on this topic. In 1967, the classical Newton based load flow solution method was developed by Tinny and Hart [67]. Subsequently, the Fast Decoupled Newton method was developed by Scott and Alsac [68] and these methods became de facto standard in power flow analysis problem, especially for transmission system analysis. Even though these methods work quite well for transmission systems, their convergence property is poor when applied to most distribution system due to the radial structure and high r/x ratio of the distribution grids. For this reason, suitable modifications of the basic Newton-Raphson algorithm have been suggested in [69-71] to take into account the specific characteristics of the distribution systems. Distribution load flow methods based on ladder theory have been developed in [72-73]. In these works, the basic ladder network theory has been applied to the solution of radial load flow problems. Stevens et al. [74] have shown that although the ladder technique is found to be the fastest but it did not always converge. Shirmohammadi et al. [75] have proposed a method for solving radial distribution system based on direct application of Kirchhofff's voltage and current laws. They have developed a branch-numbering scheme to enhance the numerical performance of the solution method. They also have extended their method for the solution of weakly meshed networks. Baran and Wu [76] have obtained load flow solution for a distribution system by the iterative solution of three recursive equations describing the real & reactive power flow over the feeders and the voltage magnitudes of the buses. Chaing [77] has also proposed three different algorithms for solving radial distribution networks based on method proposed by Baran and Wu [76]. He has proposed decoupled, fast decoupled and very fast-decoupled distribution load flow algorithms. In fact, decoupled and fast-decoupled distribution load flow algorithms proposed by Chaing are similar to that of Baran and Wu [76]. However, the very fast distribution load flow algorithm proposed by Chaing [77] is very attractive because it does not require any Jacobian matrix construction and factorization. Reneto [78] has proposed another method for obtaining the load flow solution of radial distribution systems. In this method, during the 'upstream iteration', an electrical equivalent of each node of the distribution network is made by summing all the loads as well as losses fed through that particular node and subsequently in the 'downstream iteration', the node voltages are calculated. Goswami and Basu [79] have presented a direct method for solving radial and meshed distribution networks. Jasmon and Lee [80, 81] have proposed a new load flow method for obtaining the power flow solution of radial distribution systems. In this technique, initially the whole distribution network is reduced to a single line equivalent network and subsequently, the recursive equations developed in [76] have been used to compute the power flow solution of the single line equivalent network. Das et al. [82] has proposed a load flow technique for solving radial distribution networks by calculating the total real and reactive power fed through any node. They have proposed a unique node, branch and lateral numbering scheme which help to evaluate exact real and reactive power loads fed through any node and also the receiving end voltages.

Now, after occurrence of a fault in distribution systems, a configuration is searched that can restore as maximum supply as possible from the big search space. The searching process should be efficient enough to restore the supply quickly. To find the network configuration that can restore as maximum supply as possible, a lot of network configurations are tested. For testing of the network configuration, load flow analysis is required. Thus, the speed at which the load flow analysis is carried out is often a determining factor in getting service restoration solution quickly. The speed of load flow analysis can be increased by reducing the computational time (number of calculations required to find the different parameters like losses etc.) and also by reducing the time needed for storing and retrieving the distribution system data. To address this issue, Venkatesh and Ranjan [83] developed a data structure to speed up the load flow analysis for on line implementation of the distribution load flow by reducing the time for storing and retrieving system data. The data structure developed in method [83] works well and is also capable to take care of the change in configuration under the umbrella of SCADA. Now, during reconfiguration of the distribution system, the direction of current flow in some feeder may get reversed. However, this proposed method does not take care of the change in the direction of current flow and moreover, in the absence of SCADA, it faces some difficulty in getting the information of network configuration. As in the process of service restoration many alternative network configurations need to be checked before arriving at the final solution, the input from SCADA are not available during the service restoration study. Therefore, this technique [83] is not very much helpful for carrying out the service restoration exercise. Jen-Hao Teng [84] has developed a direct approach for distribution system load flow solutions to speed up the distribution load flow by reducing the computation time. Now, the methodology developed in [83] is not computationally as efficient as in [84] while the technique suggested in [84] does not employ any advanced data structure to take care of the reversal of direction of current flow in the feeders, if any, resulting from the change in the distribution system configuration.

From the above discussion, it can be observed that in the literature, still no comprehensive technique exists for load flow analysis of distribution system, which on one hand is computationally efficient, while on the other hand is capable of taking care of reversal of direction of current flow in the feeders dynamically. To address this issue, in this chapter, a comprehensive load flow technique is developed for distribution systems. The proposed technique essentially uses the method of [84] for basic power flow calculation. However, it uses "two way linked list" for correct book keeping of the reversal of direction of current flow in the feeders. As it combines the method of [84] and "two way linked list", the proposed method is both computationally efficient as well as capable of tracking the direction of current flow in the feeders dynamically. Thus, henceforth in this thesis, the proposed method is termed as "dynamic load flow method". In the following sections of this chapter, the "dynamic load flow technique" is described in detail.

2.2 DYNAMIC LOAD FLOW

For carrying out the load flow solution of any distribution system network, the data (both the feeder data and the bus load data) of the distributed network must be given as input to the load flow software. Usually, only the data of the energized feeders and buses in the given distribution system are required for load flow analysis. As an example, the data of the energized feeders and buses of the sample distribution system shown in Fig. 2.1, are shown in Table 2.1. Now, if the topology of the distribution system does not change, the data shown in Table 2.1 can easily be represented by any suitable data structure inside the load flow software. However, in the course of service restoration study, the topology of the distribution study changes which, in turn, changes the energized feeders and buses in the distribution system. An example of a changed topology of the system in Fig. 2.1 is shown in Fig. 2.2. Comparison of Figs. 2.1 and 2.2 reveals that three distinct changes have taken place in the topology of Fig. 2.1 to result into the topology of Fig. 2.2. These changes are:

- In Fig. 2.2, the feeder between bus 9 and bus 10 (feeder number 6 in Table 2.1) is switched 'OFF'.
- In Fig. 2.2, the feeder between bus number 7 and 11 is now switched 'ON' (this feeder is not energized in Fig. 2.1).
- In Fig. 2.2, the direction of current flow in feeder number 7 is opposite to that in Fig. 2.1.

The system data with all these three changes are shown in Table 2.2. Now, in the new topology of Fig. 2.2, the total number of energized feeders and buses are the same as in Fig. 2.1. However, depending upon the status of the switches, the total number of energized feeders and buses in the distribution system under study may also change. For example, if switch s8 is 'OFF' in Fig. 2.1, then bus number 12 and 13 as well as feeder number 8 and 9 (as shown in Table 2.1) are not energized. Therefore, the data structure used for implementation of the load flow algorithm should be able to take into account all these changes mentioned above and also any other changes which might occur in the system topology during the service restoration study dynamically.

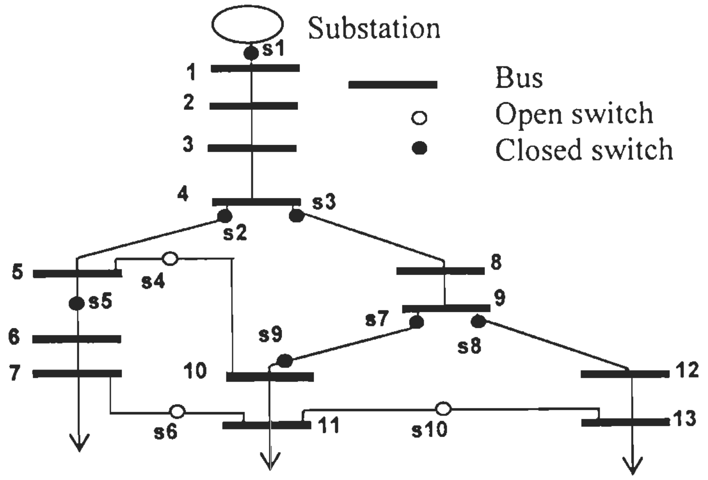


Figure 2.1 : A sample distribution system network

Table 2.1 : System data of Fig. 2.1

Feeder data				Bus load data		
Feeder no.	From (bus)	To (bus)	Feeder parameters (r,	Bus No.	P load (kW)	Q load (KVAR)
1	1	2	r and x values	1	P	Q value
2	2	3	do	2	Do	do
3	3	4	do	3	Do	do
4	4	8	do	4	Do	do
5	8	9	do	5	Do	do
6	9	10	do	6	Do	do
7	10	11	do	7	Do	do
8	9	12	do	8	Do	do
9	12	13	do	9	Do	do
10	4	5	do	10	Do	do
11	5	6	do	11	Do	do
12	6	7	do	12	Do	do
-	-	-	-	13	Do	do

It is to be noted that the detection of the changes in the system topology, if any, can only be accomplished after traversing the distribution network. The strategy adopted in this thesis to accomplish this task of network traversal is described next.

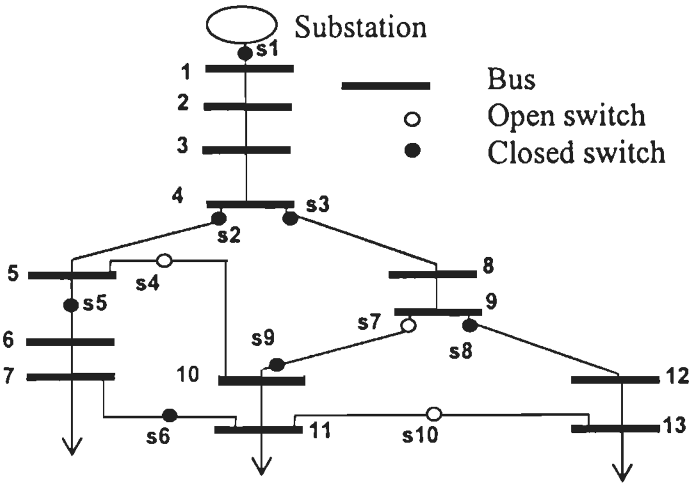


Figure 2.2 : Alternative configuration of the distribution network of Fig. 2.1

Table 2.2 : System data of Fig. 2.2

Feeder data				Bus load data		
Feeder no.	From (bus)	To (bus)	Feeder parameters (r, x)	Bus No.	P load (kW)	Q load (KVAR)
1	1	2	r and x	1	P	Q value
2	2	3	Do	2	do	do
3	3	4	Do	3	do	do
4	4	8	Do	4	do	do
5	8	9	Do	5	do	do
6	9	10	-	6	do	do
7	10	11	Do	7	do	do
8	9	12	Do	8	do	do
9	12	13	Do	9	do	do
10	4	5	Do	10	do	do
11	5	6	Do	11	do	do
12	6	7	Do	12	do	do
13	7	11	Do	13	do	do

Line does not exist

new line

2.2.1 Traversal of the distribution network

In this work, the breadth-first-search (BFS) [85] strategy has been adopted for the network traversal. For this purpose, the original distribution network is first mapped to a graph involving nodes and branches. The nodes of the graph represent the various zones of the original distribution system. A zone is defined by a partial network of the distribution system that does not contain any switch. The branches of the graph represent the 'ON' or 'OFF' switches of the original distribution system. Inside any zone (i.e. the partial network), the structure is radial and all the relevant network data like load data, feeder data etc. are known from the given distribution system data. As a result, the structure, whether radial or meshed, of the original distribution system network is completely determined by the structure of the graph, i.e. if the structure of the graph is radial, the original distribution system network also operates radially, whereas, if the structure of the graph is meshed, the original distribution system also operates in a meshed fashion. The illustration of the zones is shown in Fig. 2.3. In this figure, the shaded areas z1, z2, ….. z7 represent the various zones of the distribution system. The breadth-first-search traversal of the distribution network commences from the root switch and proceeds towards the downstream side of the distribution system. The switch at which the traversal starts (i.e. the root switch) is called the first-level switch. If any switch under consideration is closed ('ON'), the zones connected at the downstream side of this switch can be reached and hence is marked 'visited'. On the other hand, if this switch is open ('OFF'), the zones connected at the downstream side cannot be reached and these zones are marked 'unvisited'. After all the first level switches are considered, zones marked 'visited' are admitted in a list L. The switches connected at downstream side of the zones currently admitted in list L are called second level switches. After considering the second level switches in same manner as just described, the list L is updated. The switches connected at the downstream side of the zones most recently admitted in the list L are called 'third level switches'. This process is repeated till there is no switch left in the next level (i.e. all the switches are covered). The illustration of this above procedure is given below for the network shown in Fig. 2.3, in which s1 is the root switch.

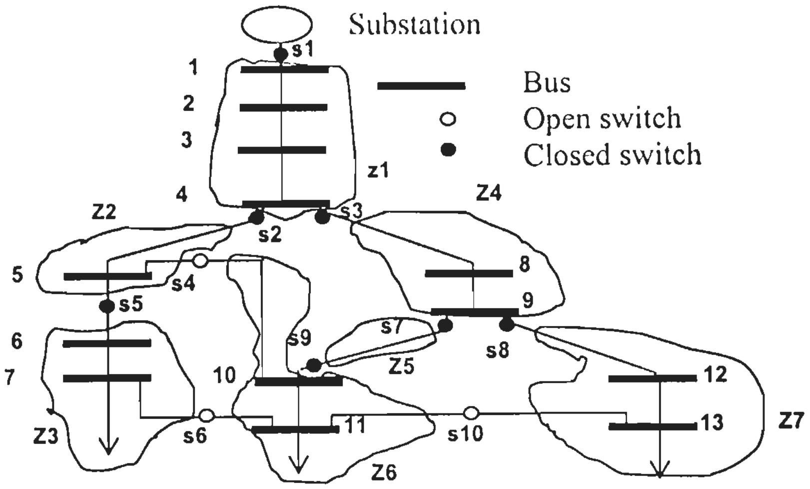


Figure 2.3 : The zones of the distribution system shown in Fig. 2.1

First level switch: s1

Zones visited, connected with first level switch: z1

Second level switches: s2, s3

Zones visited, connected with second level switches: z2, z4

Third level switches: s4, s5, s7, s8

Zones visited, connected with third level switches: z3, z5, z7

Fourth level switches: s6, s9, s10

Zones visited, connected with fourth level switches: z6

Fifth level switches: nil i.e. all zones have been visited

As mentioned in Chapter 1, for various reasons, any distribution system is generally operated radially. Now, during this traversal, if any of the zones is 'visited' more than once, the presence of a loop (mesh) is detected. To maintain the radiality of the system, the switch currently under consideration is made 'OFF' immediately. After the network traversal is complete (i.e. all the network switches are considered), all the zones marked 'visited' are put in a list EZ called "existing zones". It is to be noted that only the "existing zones" are actually energized zones (i.e. each of these zones is connected to the substation via some combination of 'closed' switches). Now, in the master database, the details of the buses contained in any particular zone are incorporated. Therefore, from the knowledge of the existing zones, the 'energized buses' in the distribution system can be identified with the help of the master database. It is to be noted that in any distribution system, all the zones need not contain equal number of buses. For example, in the distribution system shown in Fig. 2.3, there are four buses in zone z1 whereas zone z2 contains only one bus and zone z5 does not have any bus at all. Thus, a suitable data structure is needed which can store and represent this variability of number of buses in the zones adequately. In the next section, the description of the data structure adopted in this thesis to accomplish this task is described in detail.

2.3 Data Structure for radial distribution system load flow analysis

For any data structure to be used in the power flow analysis of a radial distribution system, the following attributes will be necessary.

- The data structure must be dynamic in nature such that it may be created and altered in the course of the execution of the software.
- The data structure required for holding the information of a zone must be compact and addressable from any function.
- It must be flexible enough to accommodate any number of buses within a zone.
- It should be simple and easy to program.

Among different, commonly used data structures available [85] with the above features, a 'simple linked list' can be used for the load flow solution of a distribution system. Basically, a 'simple linked list' is a linearly ordered sequence of memory cells called 'nodes' where the linear order is given by means of link. Each node is divided into two parts. The first part contains data of the node and second part called 'link' contains the address of next data in the list. Because of this feature, it is quite easy to insert and delete the elements ('nodes') in the list. The schematic diagram of a simple linked list with 5 nodes is shown in Fig. 2.4 where each node consists of two parts as described above. The left part of each node (called the 'data part') contains its data while the right part of the node (called a 'link') contains the address of the data part of the next node in the link. For example, in node 2, the left part contains data of node 2 and right part contains the address of the data part of node 3. In Fig. 2.4, this is indicated by an arrow which extends from the 'link' of a node to the 'data part' of the next node. The link of last node contains invalid address denoted by "0". The invalid address indicates the end of the list. The linked list contains a "pointer" also, which contains the address of first data in the list. The traversing through the list starts from the "pointer".

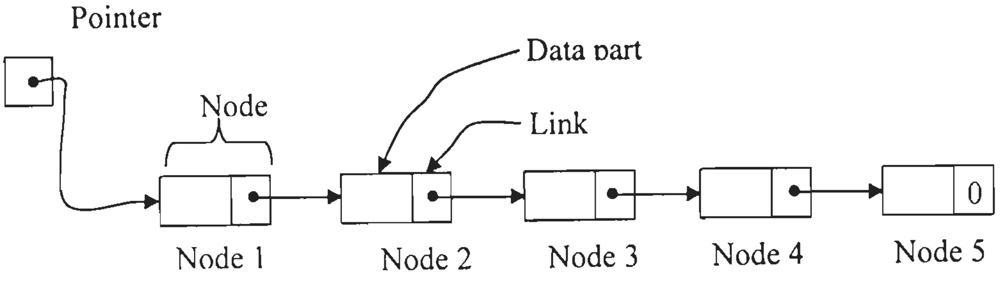


Figure 2.4 : Schematic diagram of a linked list

It is to be noted that in 'simple linked list', the traversal of the list can be accomplished only in one direction, i.e., from the starting pointer to the end of the list. Therefore, the buses contained in any particular zone of the distribution system should be inserted into the linked list in the same order in which these buses are encountered during traversal of the distribution network starting from the root switch. However, depending on the 'ON/OFF' status of the network switches, this order may also reverse. For example, in Fig. 2.3, let the switches s1, s2, s3, s7, s8 are 'ON' and the switches s9, s10 are 'OFF'. Under this condition, when the switches s4, s5 and s6 are 'ON', 'ON' and 'OFF' respectively, then in zone z6, bus 10 is encountered first during network traversal followed by bus 11. On the other hand, if the switches s4, s5 and s6 are 'OFF', 'ON' and 'ON' respectively, then in zone z6 these two buses are encountered in the reverse order. Now, in the linked list, if bus 10 is inserted first followed by bus 11, the first case (switches s4, s5 and s6 are 'ON', 'ON' and 'OFF' respectively) would be adequately represented by the linked list, whereas the second case (switches s4, s5 and s6 are 'OFF', 'ON' and 'ON' respectively) would not be properly represented at all. Again, if in the linked list bus 11 is inserted first followed by bus 10, then although the second case would be adequately represented, the representation of the first case would be completely wrong. Therefore, in this case, it is impossible to insert these two buses into the linked list in an appropriate order which would be able to represent properly all possible 'ON/OFF' combinations of the network switches. Generalizing this case, it can be seen that in a distribution network, it is impossible to decide the proper order of insertion of the buses of any particular zone into the linked list so that all possible combinations of the network switches encountered during service restoration study can be properly represented.

From the above discussion, it can be concluded that a simple linked list is inadequate for use in the service restoration study of a distribution network due to its property of unidirectional traversal. Therefore, for service restoration study, a linked list is required that has the facility of traversing of the list in both the directions. Such a linked list, having the facility of traversal in both forward and reverse directions, is called a 'two way linked list'. The schematic diagram of a 'two way linked list' is shown in Fig. 2.5. In this "two way linked list", for traversing of list, two links and two pointers are taken. These two links are called forward link (required for forward traversing) and backward link (required for backward traversing). Similarly, the two pointers are called forward pointer (required for forward traversing) and backward pointer (required for backward traversing). The reverse traversing of the list starts from the backward pointer.

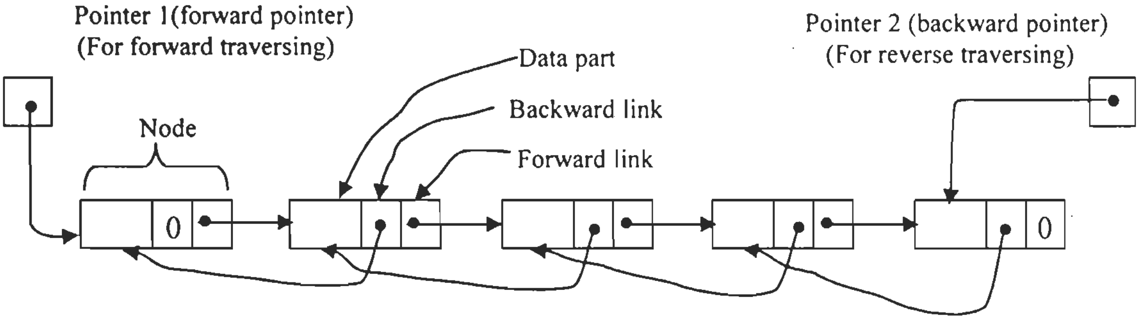


Figure 2.5 : Schematic diagram of two way linked list

Using the 'two way linked list', to appropriately capture the necessary data of the distribution system under study, 'n' "two way linked lists" are constructed, where 'n' is the total number of zones in the distribution grid. The procedure for construction of the 'two way linked list' for any particular zone starts from any one of the terminal buses of the zone under consideration. In the data part of the first node of the list, the data of the chosen terminal bus (let it be denoted as 't') is stored. In the forward link and the backward link of the first node, the address of the next bus connected to 't' (let it be denoted as 'u') and the null address ('0') are stored respectively. In the data part, forward link and backward link of the second node of the list, the data of the bus 'u', the address of the next bus connected to 'u' (let it be denoted as 'v') and the address of the bus 't' are stored respectively. Similarly, in the data part, forward link and backward link of the third node of the list, the data of the bus 'v', the address of the next bus connected to 'v' (let it be denoted as 'w') and the address of the bus 'u' are stored respectively. This process is repeated and a new node is inserted into the list for each of all the subsequent buses in the zone under consideration. In the last node of the list (corresponding to the other terminal bus of the zone under consideration), the forward link contains the null ('0') address as the zone does not have any more bus to be added in the list and the backward link contains the address of the bus immediately preceding the terminal bus.

The above procedure is illustrated below with reference to the system in Fig. 2.3. In this system, there are altogether seven zones and therefore 7 "two-way linked lists" are used to capture the data of this system. For illustration of various linked list of this system, let the different bus data of this system are stored at the memory addresses as shown in Table 2.1.

Table 2.3 : The memory addresses of buses of the system shown in Fig. 2.3

Bus no.	1	2	3	4	5	6	7	8	9	10	11	12	13
Memory address	a	b	c	d	e	h	i	f	g	m	n	j	k

With the above memory addresses as shown in Table 2.3, the detail of the "two – way linked list" corresponding to the zone z1 is shown in Fig. 2.6. Similarly, for all the other 6 zones "two-way linked list" have also been constructed and the detail of the entire seven 'two-way linked list' are shown in a tabular form in Fig. 2.7. It is to be noted that if any zone does not have any bus, there is no 'two way linked list' corresponding to this zone.

The algorithm of construction of "two-way linked list" following the above procedure is given below. Also the flow chart of the above procedure is shown in Fig. 2.8.

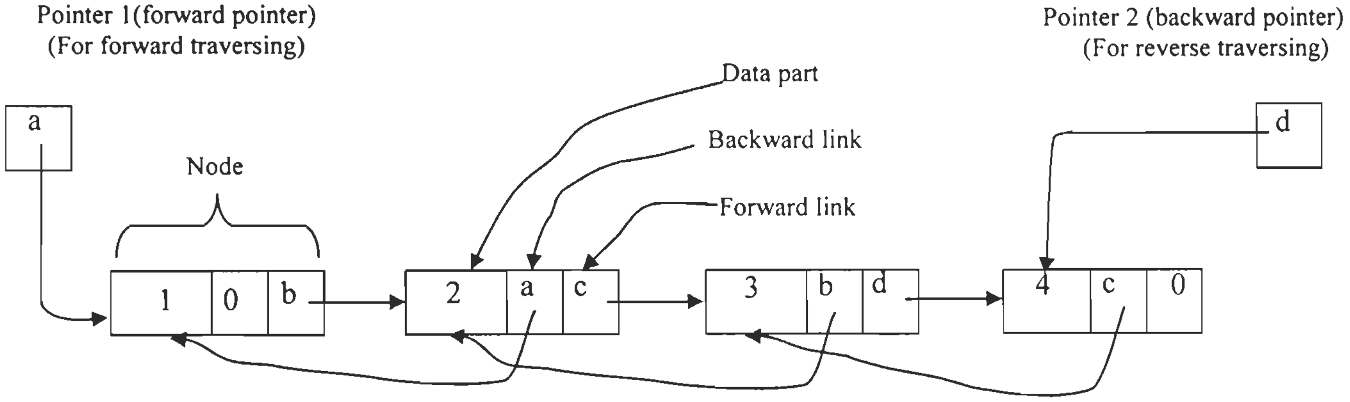


Figure 2.6 : Two way linked list of zone z1 of the distribution system shown in Fig. 2.3

Allocated memory	BUS	FORWARD_ LINK	BACKWARD_ LINK
a	1	b	0
b	2	c	a
c	3	d	b
d	4	0	c
e	5	0	0
f	8	g	0
g	9	0	f
h	6	i	0
i	7	0	h
j	12	k	0
k	13	0	j
m	10	n	0
n	11	0	m

Figure 2.7 : Complete details of the two-way linked lists of the system shown in Fig. 2.3

Algorithm for construction of 'two way linked list':

Steps:

1. Input: lists of buses of all zones, number of zones, number of total buses. Initialize i =1 and j =1.
2. Repeat step 3 to 13 while j <= nz. Where nz is a number of zones.
3. Temp_list = list of buses of j^{th} zone according their connectivity. Extra = an empty array.
4. Allocate memory for Temp_list [i] and store in extra[i].
5. Take a random integer number rnd, between 0 and tnb where tnb is total number of buses in the system.
6. Keep Temp_list [i] in BUS [rnd].
7. Repeat step 8 to 11 while i <= nb-1. Where nb is the number of buses in j^{th} zone.
8. Allocate memory for Temp_list [i+1] and store memory in FORWARD_LINK[rnd] and in extra [i+1]. If i => 2, set BACKWARD_LINK[rnd] = extra [i-1], else set BACKWARD_LINK [rnd] = 0.
9. Take a random integer number rnd other than taken so far between 0 and tnb.
10. Increment i = i + 1.
11. Keep Temp_list [i] in BUS [rnd] and go to step 8.
12. Set FORWARD_LINK [rnd]= 0 and BACKWARD_LINK [rnd]= extra [i-1]
13. Increment j = j + 1, set i = 1, empty extra and go to step 3.

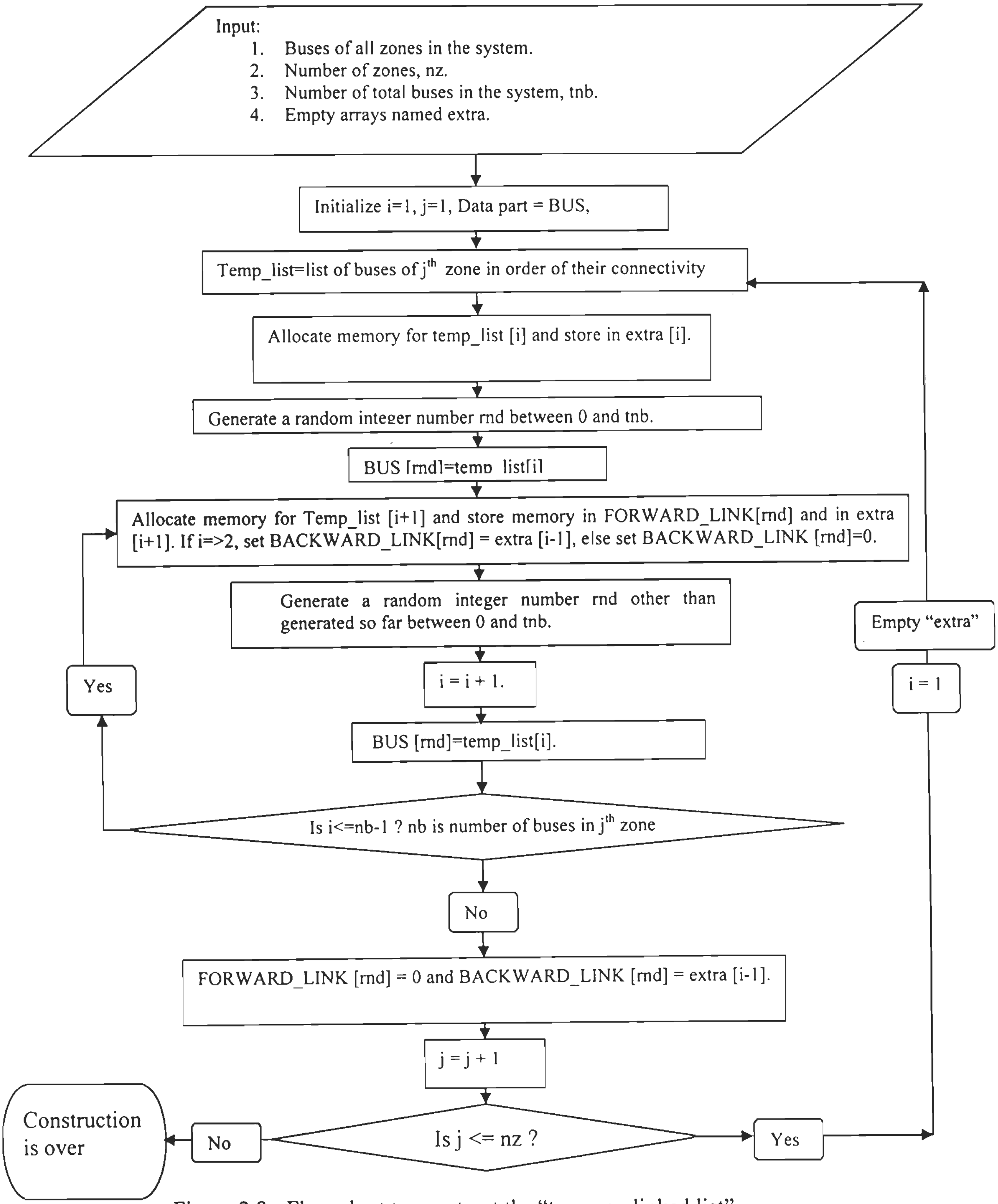


Figure 2.8 : Flow chart to construct the "two way linked list"

It is to be noted that the "two-way linked lists" capture only the connectivity of the buses inside the various zones of the distribution system. However, to determine the topology of the distribution network corresponding to any particular 'ON/OFF' combination of the network switches, the information regarding the inter-connections of the zones (via the network switches) is also required. This information of the inter-connectivity of the zones is prepared from the basic database of the distribution system. An illustrative example of this information prepared from the basic database of the system, shown in Fig. 2.3, is shown in Table 2.4. In this table, for example, switch s2 is connecting the zones z1 and z2 with the terminal buses of zones z1 and z2 being 4 and 5 respectively which are in fact connected physically with each other through switch s2.

Table 2.4: Inter-connectivity of the zones of the system of Fig. 2.3

switch	zones at both side of the switch	Terminal buses corresponding to zone
s1	substation	Null
	z1	1
s2	z1	4
	z2	5
s3	z1	4
	z4	8
s4	z2	5
	z6	10
s5	z2	5
	z3	6
s6	z3	7
	z6	11
s7	z4	9
	z5	0
s8	z4	9
	z5	12
s9	z5	0
	z6	10
s10	z6	11
	z7	13

With the help of Tables 2.3 and 2.4 and the two way linked lists as shown in Fig. 2.7, the basic procedure of obtaining the feeder data and the bus load data (required for performing the load flow analysis) corresponding to any combination of switch ON/OFF positions is illustrated below with examples with reference to Fig. 2.3.

Case 1

Let the switches s1, s2, s3, s5, s7, s8, s9 are closed and the rest of the switches are open.

Switch s1 = ON

Zone corresponding to s1 = z1 (from Table 2.4)

Bus corresponding to zone z1 = 1 (from Table 2.4)

Memory address of bus 1 = 'a' (from Table 2.3)

Starting point of two-way linked list of zone z1 = 'a'

Feeder data obtained from traversing the two-way linked list of z1

Feeder_Data = [1-2, 2-3, 3-4]

Existing_bus = [1 2 3 4]

Switch s2 = ON

Zone corresponding to s2 = z1, z2 (from Table 2.4)

As the zone z1 is already visited, it need not be traversed again.

Buses connected with switch s2 = 4 & 5 (from Table 2.4)

Hence, Feeder_Data = [1-2, 2-3, 3-4, 4-5]

Bus corresponding to z2 = 5 (from Table 2.4)

Memory address of bus 5 = 'e' (from Table 2.3)

Starting point of two-way linked list of z2 = 'e'

As there is only single bus (bus 5) in zone 2 (obtained after traversing the two way linked list of zone z2 from the starting address 'e'), there is no new addition to the feeder data.

Existing_bus = [1 2 3 4 5]

Switch s3 = ON

Zone corresponding to s3 = z1, z4 (from Table 2.4)

As the zone z1 is already visited, it need not be traversed again.

Buses connected with switch s3 = 4 & 8 (from Table 2.4)

Hence, Feeder_Data = [1-2, 2-3, 3-4, 4-5, 4-8]

Bus corresponding to zone z4 = 8 (from Table 2.4)

Existing_bus = [1 2 3 4 5 8]

Memory address of bus 8 = 'f' (from Table 2.3)

Starting point of two-way linked list of zone z4 = 'f'

Feeder data obtained from traversing the two-way linked list of z4 = [8-9]

Hence, Feeder_Data = [1-2, 2-3, 3-4, 4-5, 4-8, 8-9]

Existing_bus = [1 2 3 4 5 8 9]

Proceeding similarly for all the other switches, the final feeder data and bus data are obtained as below:

Feeder_Data = [1-2, 2-3, 3-4, 4-5, 4-8, 8-9, 5-6, 6-7, 9-10, 9-12, 12-13, 10-11]

Existing_bus = [1 2 3 4 5 8 9 6 7 10 12 13 11]

Case 2

Let the switches s1, s2, s3, s5, s6, s7 are closed and the rest of the switches are open.

Following the same procedure as illustrated in case 1, the final feeder data and bus data for this switch combination are obtained as below:

Feeder_Data = [1-2, 2-3, 3-4, 4-5, 4-8, 8-9, 5-6, 6-7, 7-11, 11-10]

Existing_bus = [1 2 3 4 5 8 9 6 7 11 10]

For the above two cases, the feeder data and the bus load data are obtained using the "two-way linked list". From these data, it is observed that in case 1 the direction of current between buses 10 and 11 is from 10 to 11 while in case 2 the direction of current flow between buses 10 and 11 is from bus 11 to bus 10. Moreover, in case 2, buses 12 and 13 do not exist and also the feeder between buses 12 and 13 does not exist. Therefore, the 'two way linked list' developed in this chapter takes care of any non-existing buses as well as feeders and also takes care of the change in the direction of the current through the feeders, if any, due to change in the configuration.

2.4 DIRECT APPROACH FOR DISTRIBUTION SYSTEM LOAD FLOW SOLUTIONS

As described in the last section 2.3, with the help of the 'two way linked list' based on data structure, the feeder data and the bus data can be easily retrieved for the present configuration of the distribution system under study. Now, for fast computation of the load flow solution with these feeder and bus data, the direct load flow technique as described in [84] has been adopted in this work. In the next subsection, the basic method of [84] is described in detail.

2.4.1 Description of the direct approach for distribution system load flow solutions

In this method, the load flow solution is found with help two matrices which describe the connectivity the distribution system. The first matrix represents the relationship between the bus injection currents and the branch currents (henceforth denoted as matrix BIBC) while the second matrix defines the relationship between the branch currents and the bus voltages (henceforth denoted as matrix BVBC). With reference to the sample distribution system shown in Fig. 2.9, the matrix inter-relationship between the bus injection currents and the branch currents can be written as shown in eqn. (2.1) below [84].

$$\begin{bmatrix} I_{B1} \\ I_{B2} \\ I_{B3} \\ I_{B4} \\ I_{B5} \\ I_{B6} \\ I_{B7} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_{E2} \\ I_{E3} \\ I_{E4} \\ I_{E5} \\ I_{E6} \\ I_{E7} \\ I_{E8} \end{bmatrix} \qquad (2.1)$$

In eqn. (2.1), the currents I_{B1}, ….., I_{B7} denote the branch currents while the currents I_{E2}, ……., I_{E8} represent the bus injection currents. These currents are also shown in Fig. 2.9. Eqn. (2.1) can be expressed in general form as

$$[I_B] = [BIBC][I_E] \tag{2.2}$$

where BIBC is the bus-injection to branch-current matrix.

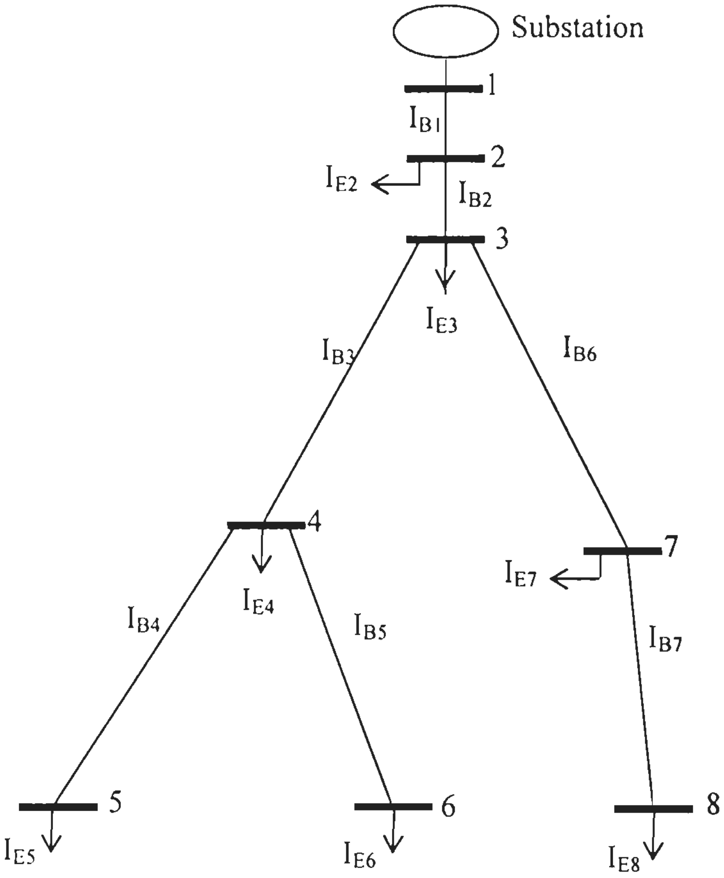


Figure 2.9 : A sample distribution system

The relationship between the branch currents and the bus voltages can be expressed as in eqn. (2.3) for the system shown in Fig. 2.9 [84].

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \\ V_7 \\ V_8 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & Z_{46} & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 & Z_{37} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 & Z_{37} & Z_{78} \end{bmatrix} \begin{bmatrix} I_{B1} \\ I_{B2} \\ I_{B3} \\ I_{B4} \\ I_{B5} \\ I_{B6} \\ I_{B7} \end{bmatrix} \qquad (2.3)$$

In eqn. (2.3), V_1, ..., V_8 represent the bus voltages and Z_{ij} denotes the impedance of the feeder (branch) between bus 'i' and bus 'j'.

Eqn. (2.3) can be rewritten in general form as

$$[\Delta V] = [BVBC][I_B] \qquad (2.4)$$

Where BCBV is the branch current to bus voltage matrix.

From eqns. (2.2) and (2.4) one can get,

$$\begin{aligned} [\Delta V] &= [BIBC][BVBC][I_E] \\ &= [DLF][I_E] \end{aligned} \qquad (2.5)$$

Now, in any power system, the complex load S_i for bus i is expressed as

$$S_i = (P_i + jQ_i) \qquad i = 1.....N \qquad (2.6)$$

where, P_i and Q_i are the real and reactive power injection at bus 'i' respectively while 'N' is the total number of buses in the system. The corresponding equivalent bus current injection at bus 'i' can be expressed as,

$$I_{Ei} = I_{Ei}^{r}(V_i) + jI_{Ei}^{im}(V_i) = \left(\frac{P_i + jQ_i}{V_i}\right)^{*} \qquad (2.7)$$

I_{Ei}^{r} and I_{Ei}^{im} are real and imaginary part of current injection of bus i respectively.

Eqns. (2.7) and (2.5) constitute the basic load flow equations. At any iteration 'k', using the most updated bus voltages, initially the bus injection currents are calculated using eqn. (2.7) and subsequently the correction in the bus voltages are found using eqn. (2.5). Finally, using the correction in the bus voltages, the bus voltages are updated for iteration 'k+1' and the procedure starts again from eqn. (2.7) till the procedure converges. The complete set of load flow equations are shown below in eqns. (2.8)-(2.10). In these equations, the subscripts 'k' and 'k+1' denote the kth and (k+1)th iteration respectively.

$$I_{Ei}^{k} = I_{Ei}^{r}(V_i^k) + jI_{Ei}^{im}(V_i^k) = \left(\frac{P_i + jQ_i}{V_i^k}\right)^{*} \tag{2.8}$$

$$[\Delta V^{k+1}] = [DLF][I_E^k] \tag{2.9}$$

$$[V^{k+1}] = \left[V^o\right] - \left[\Delta V^{k+1}\right] \tag{2.10}$$

In eqn. (2.10), the vector V^o contains N-terms, each equal to V_1. Now, the complete load flow algorithm developed in this thesis (combination of 'two way linked list' based data structure and the method of [84]) is described in next subsection.

2.5 ALGORITHM FOR DYNAMIC LOAD FLOW

Step:

1. Read the system data.
2. Construct the two way linked list of distribution system.
3. Find the connectivity of the distribution system as explained Section 2.3.
4. Construct the matrices BIBC, BVBC and DLF with help of connectivity of the distribution system.
5. Calculate equivalent current injection at each bus using eq. (2.8) retrieving the data from the two-way linked lists.
6. Calculate ΔV^{k+1} using eqn. (2.9).
7. Calculate V^{k+1} using eqn. (2.10).
8. Check for convergence. If satisfied then stop, else $k = k+1$ and go to step 5.

2.6 CASE STUDIES

To test the validity of the dynamic load flow solution for distribution systems, simulation studies have been carried out in four different radial distribution systems. The details of these four systems are given in Appendix A. The accuracy and speed of execution of the developed method is compared with other methods [75, 83, 84] and the results are shown in Table 2.5 and Table 2.6 respectively. In Table 2.5, the accuracy of the developed method vis-à-vis the accuracies obtained by other reported methods are shown for the 10-bus system. From this table it is observed that the accuracy of the developed method is quite close to those obtained by other reported methods. Similar results have also been obtained for other three distribution systems and hence these results are not repeated here. In Table 2.6, the speed of execution of the developed method is compared with the speed of execution obtained by other reported methods in the literature. From this table it is observed that because of the combination of 'two way linked list' and the direct method of load flow solution, the speed of execution of the developed method is more than the speeds obtained by other reported methods in all the distribution systems under study.

Table 2.5 : comparison of accuracy of proposed method with other known methods (10-bus system)

Bus number	Developed method	Method [83]	Method [84]	Method [75]
1	1.000000	1.000000	1.000000	1.000000
2	0.929275	0.929275	0.929271	0.929264
3	0.921887	0.921887	0.921880	0.921845
4	0.932615	0.932615	0.932595	0.932582
5	0.893918	0.893918	0.8938894	0.893881
6	0.863569	0.863569	0.863534	0.863516
7	0.844915	0.844915	0.844896	0.844875
8	0.887183	0.887183	0.887167	0.887156
9	0.846995	0.846995	0.846985	0.846972
10	0.916703	0.916703	0.916691	0.916782

Table 2.6 : Comparison of convergence time of the developed method

	10-bus system time in seconds	13-bus system time in seconds	33-bus system time in seconds	173-bus system time in seconds
Developed method	0.009	0.011	0.026	0.155
Venkatesh et. al. [83]	0.010	0.011	0.025	0.161
Jen-Hao [84]	0.015	0.018	0.036	0.276
Shirmohammadi et. al. [75]	0.080	0.095	0.215	0.927

2.7 CONCLUSION

In this chapter a dynamic load flow method for radial distribution system has been developed. The developed method is the combination of "two way linked list" and "a direct approach for distribution system load flow solution" proposed in [84]. The developed method is able to take care of the changes in the configuration of the distribution system under study quite efficiently. Based on the simulation studies on four distribution systems, it is found that the accuracy of the developed technique is quite close with those obtained by the other methods reported in the literature while the speed of execution of it is more than those obtained by the other reported methods. Therefore the developed technique is quite suitable for the use in the service restoration study.

Chapter 3

SERVICE RESTORATION IN DISTRIBUTION SYSTEMS USING NON-DOMINATED SORTING GENETIC ALGORITHM-II

3.1 INTRODUCTION

As discussed in Chapter 1, the service restoration problem is essentially a multi-objective, multi-constraint combinatorial optimization problem. To solve this multi-objective problem, many approaches reported in the literature first have converted this multi-objective problem into a single objective problem by using suitable weighting factors. However, as already pointed out in Chapter 1, there is no unique procedure for choosing these weighting factors and therefore, for every distribution network, the weighting factors need to be tuned (mostly by trial and error method). On the other hand, the non-dominated sorting genetic algorithm (NSGA-II) [86] does not require any weighting factors and retains the multi-objective nature of the problem at hand. Hence, in this chapter, use of NSGA-II is proposed for solving the service restoration problem. As no weighting factors are required, the proposed methodology is generalized enough to be applicable to any power distribution network. NSGA-II is essentially a modified form of conventional GA. Like conventional GA, NSGA-II also uses initialization of population, selection, crossover and mutation operator to create mating pool and offspring population. In this method, to improve the performance, the elite-preserving operator, which favors the elites of a population by giving them the opportunity to be directly carried over to the next generation, is used. Rudolph [87] has proved that GAs get convergence to the global optimal solution in the presence of elitism. Along with convergence, it is also desired that GA maintains a good spread of solutions in the obtained set of solutions (called diversity). The diversity, in this method, is achieved with the help of the crowded tournament selection operator (CTSO) that does not require any tuning parameter. CTSO has lower computational complexity and hence the run time is saved.

3.2 OBJECTIVE FUNCTIONS AND PROBLEM FORMULATION

In Chapter 1, the objective functions and the constraints considered in this work have been described in detail. In this section, the mathematical representation of the objective functions and the constraints are described as below.

Objective Functions:

1) Minimization of out-of-service area:

$$\text{Min } f_1(\overline{X}) = \sum_{i=1}^{b1} L_i - \sum_{i \in B} L_i \tag{3.1}$$

$\overline{X}$ is switch state vector of network under consideration for service restoration, i.e. $\overline{X} = [SW_1, SW_2, \ldots\ldots\ldots\ldots SW_{N_S}]$

SW_j = Status of j^{th} switch. A closed switch is represented by 1 and an open switch is represented by 0.

N_S = Total number of switches in the network.

$b1$ = No. of energized buses in the network before fault.

L_i = load on i^{th} bus.

B : Set of energized buses in the restored network.

In eqn. (3.1), it is assumed that in a power distribution system having 'n' buses, the buses are numbered from 1 to n and in the pre-fault case, all the buses in the network are energized. Therefore 'b1' is equal to 'n'. However, in the post fault scenario, all the buses would not be necessarily energized. Hence, 'B' would contain only the energized buses. For example, in a 5 bus system, b1 = 5 and if, in the post-fault case, bus 3 can not be energized, then B = (1, 2, 4, 5).

2) Minimization of number of manually controlled switch operation:

$$\min f_2(\overline{X}) = \sum_{j=1}^{N_m} \left| SWM_j - SWMR_j \right| \tag{3.2}$$

Where, N_m is number of manually controlled switches.

SWM_j = Status of j^{th} manually controlled switch in network just after fault.

$SWMR_j$ = Status of j^{th} manually controlled switch in the restored network.

3) Minimization of number of remotely controlled switch operation:

$$\min f_3(\bar{X}) = \sum_{j=1}^{N_a} \left| SWA_j - SWAR_j \right| \tag{3.3}$$

Where, N_a is number of remotely controlled switches.

SWA_j = Status of j^{th} remotely controlled switch in network just after fault.

$SWAR_j$ = Status of j^{th} remotely controlled switch in the restored network.

4) Minimize the losses:

$\min f_4(\bar{X})$ = Power loss in the restored network which can be calculated with help of load flow analysis. (3.4)

Constraints:

1) Radial network structure should be maintained.

2) Bus voltage limits should not be violated.

$$V_{min} < V_j < V_{max} \tag{3.5}$$

V_{min} = Minimum acceptable bus voltage.

V_j = Voltage at j^{th} bus.

V_{max} = Maximum acceptable bus voltage.

3) Feeder line current limits should not be violated.

$$I_{min} < I_j < I_{max} \tag{3.6}$$

I_{min} = minimum acceptable line current.

I_j = current in j^{th} line.

I_{max} = maximum acceptable line current.

4) Higher priority customers should always be supplied.

In this work, it is assumed that the preferential knowledge of the objective functions considered herein is known. As the customers' satisfaction is mostly affected by the availability of supply, the first objective function (minimization of out-of-service area) has been kept at the first preference. Moreover, to enhance the customers' satisfaction, the time taken for service restoration (which essentially depends on the operational times of manually controlled and remotely controlled switches) should also be minimum. Now, generally, the time taken for operating a manually controlled switch is significantly more than that of a remote controlled switch. Therefore, between any two solutions, the solution which requires fewer number of manual switch operations would need lesser time to complete the service restoration task as compared to the other solution. As a result, the objective function of minimization of manually controlled switch operations has been kept at the second preference and that of minimization of remotely controlled switch operations has been kept at the third preference. Finally the objective function of minimization of losses has been kept at the fourth preference.

3.3 NON-DOMINATED SORTING GENETIC ALGORITHM-II

The detail philosophy and technique of NSGA-II is already described in full detail in [86] and hence is not repeated here. However, the step-by-step procedure of NSGA-II for one generation is described here for ready reference and completeness of the chapter. The basic algorithm of NSGA-II is as follows.

Step 1: Initially a random parent population P_0 of size N is created (i.e. N is the number of strings or solutions in P_0). The length of each string is LS (i.e. LS is the number of bits in each string).

Step 2: Create offspring population Q_0 of size N by applying usual GA operators (i.e. selection, crossover, mutation) on P_0.

Step 3: Assign $P_t = P_0$ and $Q_t = Q_0$, where P_t and Q_t denote the parent and offspring population at any general t^{th} generation respectively.

Step 4: Create a combined population $R_t = P_t \cup Q_t$. Thus, the size of R_t is 2N.

Step 5: Perform non-dominated sorting on R_t. Non-dominated sorting divides the population in different fronts. The solutions in R_t, which do not constrained-dominate each other but constrained-dominate all the other solutions of R_t, are kept in the first front or best front (called set F_1). Among the solutions not in $F = F_1$, the solutions which do not constrained-dominate each other but constrained-dominate all the other solutions, are kept in the second front (called set F_2). Similarly, among the solutions not belonging to $F = F_1 \cup F_2$, the solutions which do not constrained-dominate each other but constrained-dominate all the other solutions, are kept in the third front (called set F_3). This process is repeated until there is no solution in R_t without having its own front. Subsequently, these generated fronts are assigned their corresponding ranks. Thus, F_1 is assigned rank 1, F_2 is assigned rank 2 and so on.

Step 6: To create P_{t+1}, i.e. the parent population in the next or '$(t + 1)^{th}$ generation, the following procedure is adopted. Initially, the solutions belonging to the set F_1 are considered. If size of F_1 is smaller than N, then all the solutions in F_1 are included in P_{t+1}. The remaining solutions in P_{t+1} are filled up from the rest of the non-dominated fronts in order of their ranks. Thus, if after including all the solutions in F_1, the size of P_{t+1} (let it be denoted by 'n') is less than N, the solutions belonging to F_2 are included in P_{t+1}. If the size of P_{t+1} is still less than N, the solutions belonging to F_3 are included in P_{t+1}. This process is repeated till the total number of solutions (i.e. n) in P_{t+1} is greater than N. To make the size of P_{t+1} exactly equal to N, (n - N) solutions from the last included non-dominated front are discarded from P_{t+1}. To choose the solutions to be discarded, initially the solutions of the last included non-dominated front are sorted according to their crowding distances and subsequently, the solutions having least (n - N) crowding distances are discarded from P_{t+1}.

Step 7: Create the offspring population Q_{t+1} by the application of crowded tournament selection, crossover and mutation operator on P_{t+1}.

Step 8: Test for convergence. If the algorithm has converged then stop, else, t = (t+1), and go back to step 4.

Illustrative examples of non-dominance, constraint domination, front formation, crowding distance and creation of P_{t+1} are given in Appendix B.

3.4 IMPLEMENTATION OF NSGA-II IN SERVICE RESTORATION PROBLEM

In this work, before NSGA-II is implemented for solving the service restoration problem, the original distribution network is mapped to a graph involving nodes and branches. As already described in detail in Chapter 2, the nodes of the graph represent the various zones of the original distribution system and the branches of the graph represent the switches of the original distribution system. Now, various issues of implementation of NSGA-II in this work are discussed below.

3.4.1 String representation

As the configuration of a network is represented by status of all the switches in the network, the string used in NSGA-II implementation of the service restoration problem represents the status of all the switches in the system. The length of each string (i.e. the number of bits in a string) is equal to the number of switches in the system. The status of the 'closed' and 'open' switch in the system is represented by the binary digit '1' and '0' respectively. For instance, in the sample network of Fig. 3.1, switches s1, s2, s3, s5, s7, s8, s9 are closed and rest are open. Therefore, the corresponding string for this configuration is s = [1 1 1 0 1 0 1 1 1 0], where the indices of this string represent the switch number.

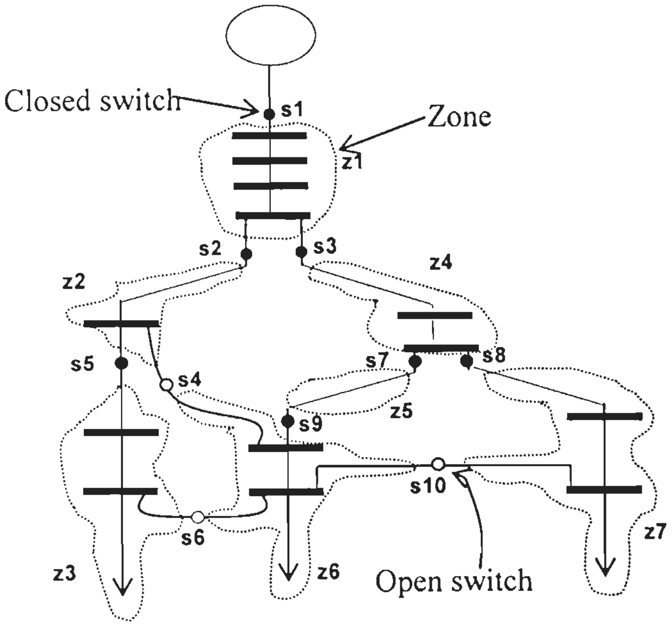


Figure 3.1 : A sample distribution system

3.4.2 Generation of initial strings

As discussed in step 1 of Section 3.3, generally the initial population P_o is generated randomly. This is the simplest method, in which no knowledge about the network is required. However, if the pre-fault network is well behaved (i.e. all loads are properly served, various constraints are satisfied etc.), it is reasonable to expect that the final solution would be found near the original configuration. In that case, if one of the randomly generated strings is replaced by the string representing the original, pre-fault configuration (PFC), then the spread of the solution in the initial population reaches closer to the optimal solution and hence the chance of reaching the final solution in shorter time enhances. Even if the optimal solution is quite far from the original configuration, keeping the original configuration in P_o gives at least a good spread of solutions (called diversity), which is helpful to prevent the premature convergence of NSGA-II. Moreover, to keep the faulted zone always isolated, if any of the elements (i.e. bits) corresponding to the switches around the faulted zone is '1', it is made '0' before proceeding further. Also, if any of these randomly generated strings, the bit corresponding to the root switch (i.e. the switch directly connected to the substation) is '0', it is immediately made '1' (if the root switch is 'OFF', the substation is isolated, which means no power can be supplied to the rest of the distribution system).

As the bit corresponding to the root switch must always be maintained as '1' to ensure supply to the rest of the system, another alternative methodology for generation of initial strings can also be adopted. In this alternative methodology, the bit corresponding to the root switch would always be fixed as '1' and a string of 'n-1' bits (where 'n' is the number of switches in the system) would be generated randomly. However, it is to be noted that for evaluation of all the objective functions and constraints, all the 'n' bits would be necessary. Therefore, a little extra bit of book keeping is necessary to concatenate the 'root switch bit' and the string comprising of 'n-1' bits before evaluation of the objective functions & constraints. On the other hand, no such concatenation is necessary in the first approach (described in the previous paragraph). However, it is to be observed that there is a very minor difference between these two approaches and as a result, there will be virtually no difference of performance of the NSGA-II algorithm using either of these two approaches. In this work, the first approach has been adopted due to which book keeping is not required.

3.4.3 Radiality checking

The procedure to check the radiality of the system during service restoration is adopted as explained in Chapter 2 (subsection 2.2.1).

3.4.4 String evaluation

After checking the radiality, all strings give radial configuration, and their corresponding existing zones are recorded. With the help of the existing zones, existing buses and existing lines are found. With the knowledge of the existing buses, the out-of-service area in terms of the disconnected load is calculated using equation ~~(1)~~ 3.1. Using equations ~~(2)~~ 3.2 and ~~(3)~~ 3.3, the number of switch operations is calculated. To calculate system loss, bus voltage violations and line current violations, dynamic load flow developed in Chapter 2 is used.

3.4.5 String operation

To generate the offspring population, single point crossover method is used. Moreover, the mutation operator is applied randomly in any string. After the offspring population is created, the radiality of all offspring configurations is checked. If any of the offspring configurations is found to be non-radial, it is made radial following the procedure described in subsection 3.4.3. Subsequently, with the help of crowded tournament selection operator (CTSO) [86], the mating pool is created for the next generation. An example of CTSO is shown in Appendix B. This operator maintains: (i) convergence as the solution having better front is selected and (ii) diversity as the solution having higher crowding distance within the same front is selected.

3.4.6 Front formation

Following step 5 of Section 3.3, the combination of parent and offspring population having length 2N is divided in various ranked non-dominated fronts. Because of the front formation from the combination of a parent and an offspring population, chance is given to the current best solution in parents to compete with the offspring solutions. If no better solution is generated in offspring, the current best solution in the parent population becomes the winner again. In this way, the elitism is maintained and due to the presence of elitism, convergence is improved [87].

3.4.7 Selection of n strings

N strings for parent population of the next generation from R_t (which has 2N strings) of current generation are selected following the procedure described in step 6 of section 3.3.

3.4.8 Convergence

To check for convergence, at each generation, the candidate configurations in parent P_t and offspring Q_t are compared after they are made radial. If both populations are same, the convergence is considered to be achieved, otherwise not.

3.4.9 Selection of final solution after convergence

After the convergence is achieved, the best solutions are contained in the first front of R_t. If the first front has only one solution, then obviously it is the final solution of the service restoration problem. On the other hand, if the first front has more than one solution, the final solution is chosen following a M stage (where M is the number of objective functions) procedure which uses the knowledge of preference of different objective functions. In the first stage, those solutions (from the first front of R_t) are picked up which have minimum value of the most preferred objective function and put them in a set FS. If FS contains only one solution, this is declared to be the final solution. If not, then in the second stage, those solutions from FS are picked up which have minimum value of the 2^{nd} preferred objective function and FS is updated with these solutions (i.e. FS now contains the solutions obtained after the second stage). Again, if FS now contains only one solution, it is declared to be the final solution. If not, the above procedure is repeated. In general, at any mth stage, those solutions from FS are picked up which have minimum value for the mth preferred objective function and the set FS is updated with these solutions. If FS contains only one solution at any stage, this is declared to be the final solution and the algorithm terminates. Otherwise the algorithm proceeds for the next stage. If, even after all the M objective functions are considered, FS still contains more than one solution, any solution in FS is equally good and hence can be declared as the final solution.

3.4.10 Steps of algorithm for service restoration

Step 1: The information available to the algorithm are, i) system data, ii) PFC and iii) post fault configuration.

Step 2: Generate P_o following the procedure described in subsection 3.4.2.

Step 3: Check the radiality of the solutions in P_o and modify them, if necessary, following the procedure described in subsection 2.2.1.

Step 4: Evaluate the strings in P_o as described in subsection 3.4.4 and assign $P_t = P_o$.

Step 5: Generate the offspring population Q_o as described in subsection 3.4.5. Moreover, in all the solutions of Q_o, the faulted zone is isolated and the root switch is always made 'closed' as described in subsection 3.4.2.

Step 6: Evaluate the strings in Q_o as described in subsection 3.4.4 and assign $Q_t = Q_o$.

Step 7: Follow steps 4-7 of NSGA-II as described in Section 3.3 to obtain P_{t+1} and Q_{t+1}.

Step 8: In all the solutions of Q_{t+1}, the faulted zone is isolated and the root switch is always made 'closed' as described in subsection 3.4.2.

Step 9: Check the radiality of the solutions in Q_{t+1} and modify them, if necessary, following the procedure described in subsection 2.2.1 in chapter 2.

Step 10: Check for convergence as described in subsection 3.4.8. If the algorithm has converged, find the final solution as discussed in subsection 3.4.9. Otherwise go to step 11.

Step 11: Evaluate the strings in Q_{t+1} as described in subsection 3.4.4.

Step 12: Update t = t + 1 and go back to step 7.

3.4.11 Reduced run-time NSGA-II

In this thesis, the algorithm for reducing the run time complexity of NSGA-II as described in the method developed by M. T. Jensen [88] has also been implemented to solve the service restoration problem in distribution systems. Basically, these two techniques (NSGA-II and NSGA-II with reduced run time complexity) are conceptually same. The only difference between these two techniques is in the superior methodology for storing and retrieving the data (data structures and algorithm) adopted in [88]. Because of this, the method described in [88] becomes faster than the standard NSGA-II described in [86].

3.5 RESULTS AND DISCUSSION

The effectiveness of the NSGA-II algorithm for service restoration has been studied on four different distribution systems. The details of these systems are given in Appendix A. As mentioned in subsection 3.4.11, in this work, both the basic NSGA-II technique and the advanced NSGA-II technique with reduced run time complexity have been implemented to solve service restoration problem. The performance of these two techniques has also been compared with that of the conventional GA technique for service restoration developed by Laun et al [42] and an another existing technique developed by Miu et al [36]. It is to be noted that, for any particular distribution system, the values of the crossover probability, mutation probability and the population size have been kept same in all three GA based methods (two proposed methods and one Laun et al [42]). However, their values are different for different distribution systems. These values are shown in Table B.5 in Appendix B. Here, the results corresponding to the 14 switch system (system-2) are only illustrated in this chapter, whereas, for other systems, the summary of the important results are given.

Fig. 3.2 shows the schematic diagram of the 14-switch system. In this system, it has been assumed that the fault has taken place at point A (Fig. 3.2) and due to this fault, the switch s4 trips for isolating the fault. As a result, the area shown inside the closed curve is left without electric power. The supply to this "out-of-service" area can be restored either by closing switch s14 (let it be called option A) or by closing switch s12 (let it be called option B). Now, it has been assumed that switch s12 is an automatic, remote controlled switch with a typical operating time of 50 seconds whereas, switch s14 is a manually controlled switch with operating time typically in the range of 1200-1500 seconds. It is to be noted that the operating time of a manually controlled switch depends on its distance from the nearest manned substation (from which an operator has to travel to operate the switch). Now, by both these options, the entire "out-of-service" area can be supplied. Therefore, from the considerations of the objective function kept at first preference, both these options are equally preferable. However, as option B takes considerably less time as compared to option A to accomplish the service restoration task, this option is chosen and the final configuration is shown in Fig. 3.3.

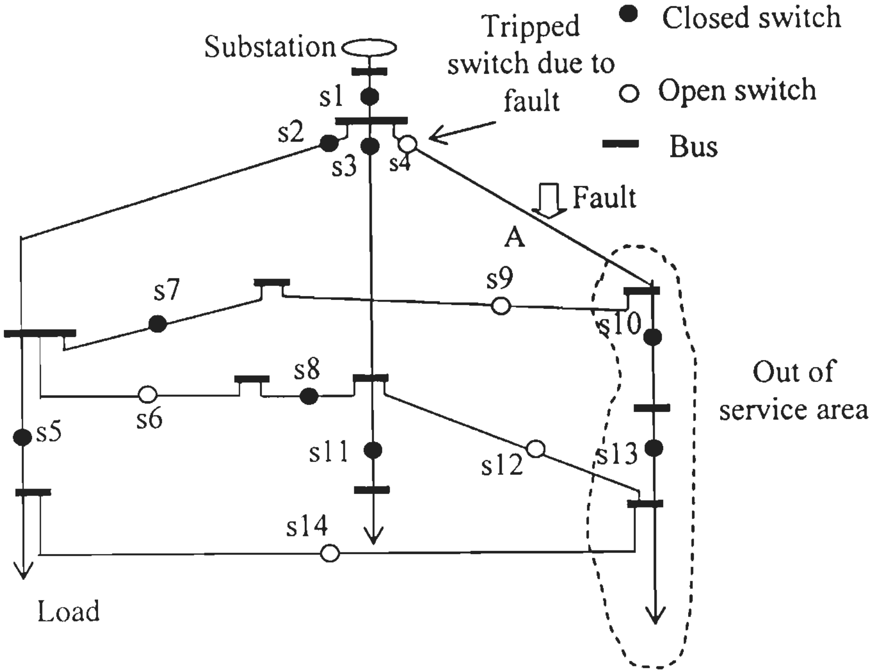


Figure 3.2 - Network before service restoration

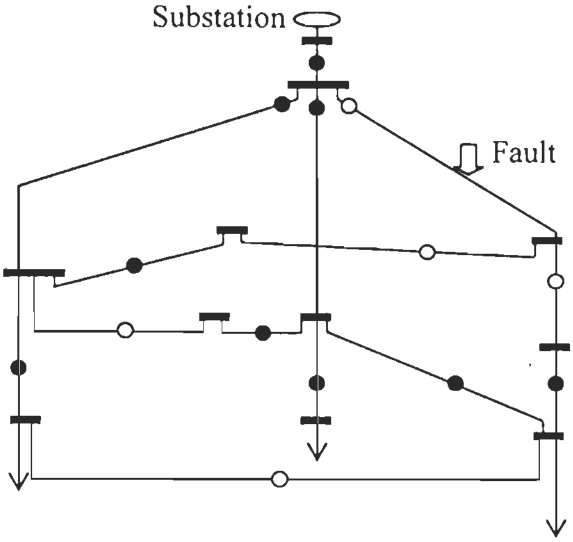


Figure 3.3 - Network after service restoration

Similar kind of studies for different faults has also been carried out for all the other systems. Both single fault and multiple faults have been considered in this thesis. The details of the single faults considered are shown in Table 3.1 and those of multiple faults considered are shown in Table 3.2. The zones, which contain the priority customers in all the four systems, are also indicated in Table 3.1. The results corresponding to the single fault cases are shown in Tables 3.3 and 3.4. For the results shown in Table 3.3, the real and reactive power loading of the four systems have taken same as given in Appendix A. For subsequent discussions in this thesis, the loading of the four systems as shown in Appendix A are termed as 'base loading condition'. In Table 3.3 and the other subsequent tables, methods 'm1', 'm2', 'm3' and 'm4' denote the proposed method based on advanced NSGA-II technique developed by Jensen [88], proposed method based on the basic NSGA-II technique developed by Deb et al [86], the existing method of service restoration developed by by Laun et al [42] and another existing method of service restoration developed by Miu et al [36] respectively. In these tables, 'y' stands for higher priority customer constraint is satisfied and 'n' stands for higher priority constraint is not satisfied. It is also to be noted that in Table 3.3 and the other subsequent tables, the entries corresponding to the "out-of-service" area have been given in terms of the total amount of load (in kW) left unsupplied. For example, from Table 3.3, it can be concluded that 600 kW of total load is always left unsupplied in system-1, by all four methods as the faulted zone z4 having 600 kW load is isolated following a fault and this load cannot be restored by any technique. Similarly, the faulted zones in system-2 and-3 contain 100 kW and 120 kW of load respectively and as a result, these loads can also not be restored by any of the methods. System-4, however, does not contain any load in the considered faulted zone.

Table 3.1: Various single fault location considered and priority customers in all four systems

System	System-1	System-2	System-3	System-4
Fault location zones	z4 (between bus 4 and 8)	z6 (between bus 1 and 4)	z4 (between bus 3 and 4)	z52 (between bus 104 and 105)
Priority customer zones	z6	z3	z21	z62

Table 3.2: Various multiple fault location considered in all four systems

System	System-1	System-2	System-3	System-4
1st Fault location	z3 (between bus 6 and 7)	Z2 (between bus 1 and 2)	z4 (between bus 3 and 4)	z52 (between bus 104 and 105)
2nd Fault location	z4 (between bus 8 and 9)	Z6 (between bus 1 and 4)	z15 (between bus 15 and 16)	z18 (between bus 40 and 41)
3rd Fault location	-	Z8 (between bus 3 and 7)	z9 (between bus 9 and 10)	z47 (between bus 90 and 92)
4th Fault location	-	-	z26 (between bus 26 and 27)	z62 (between bus 161 and 163)

Table 3.3: Single fault full service restoration by NSGA-II

System		System-1	System-2	System-3	System-4
Out-of-service area (kW)	m1	600	100	120	0.0
	m2	600	100	120	0.0
	m3	600	100	120	3134.0
	m4	600	100	120	0.0
No. of manual Switch operations	m1	2 S6 S10	1 S10	1 S6	0
	m2	2 S6 S10	1 S10	1 S6	0
	m3	3 S8, 6, 10	2 S10, 14	2 S10, 7	2 S53, 75
	m4	3 S8, 6, 10	2 S10, 14	2 S10, 7	2 S53, 60
No. of automatic Switch operations	m1	2 S4 S10	1 S12	1 S10	2 S52, 74
	m2	2 S4, S10	1 S12	1 S10	2 S52, 74
	m3	1 S7	0	0	0
	m4	1 S7	0	0	0
Losses (kW)	m1	104.50	582.40	210.00	15181.3
	m2	104.50	582.40	210.00	15181.3
	m3	106.86	579.00	216.0	14052.4
	m4	106.86	579.00	216.0	15181.3
Run-time of the algorithm (sec.)	m1	15.765	18.774	36.273	61.53
	m2	22.538	30.121	75.812	168.800
	m3	43.807	64.910	195.30	435.402
	m4	13.2040	15.180	32.770	60.060
Status of priority customer	m1	y	y	y	y
	m2	y	y	y	y
	m3	y	y	y	y
	m4	y	y	y	y

Table 3.3 shows the results for service restoration where the entire loads in the "out-of-service" could be restored, thereby making it a case of full service restoration. Closer observation of Table 3.3 reveals that for all the four systems considered, both the methods 'm1' and 'm2' produce identical results. However, because of using the faster methodology for storing and retrieving the data, the run-time taken by 'm1' is less than

that taken by ‘m2’ to achieve the results. On the other hand, method ‘m3’ can be observed to be inferior to both ‘m1’ and ‘m2’ for each system because ‘m3’ is giving the poor solution in comparison to ‘m1’ and ‘m2’. For example, in system-4, methods ‘m1’ and ‘m2’ are able to restore the entire ‘out-of-service’ area, whereas, method ‘m3’ suggests 3134.0 kW of load to be left unsupplied. Similarly, for all the systems, the number of manual switch operations suggested by ‘m3’ is more than that suggested by ‘m1’ or ‘m2’. Also, the run-time needed by the algorithm ‘m3’ is always more than that needed by ‘m1’ and ‘m2’. Method ‘m4’ also restores the entire ‘out-of-service’ area but it is inferior to ‘m1’ and ‘m2’ because it requires higher number of manual switch operations than both methods ‘m1’ and ‘m2’. Therefore, from the observation of Table 3.3, it can be concluded that methods ‘m3’ and ‘m4’ are inferior to methods ‘m1’ and ‘m2’ for this case and method ‘m1’ is the most preferred choice as the time taken by this method to achieve the solution is less as compared to method ‘m2’ and the objective functions are also minimum.

Table 3.4 shows the results for fault cases in which the restoration of supply to the entire ‘out-of-service’ area was not possible. In these cases, the faults which have been considered are same as those shown in Table 3.1. However, the real and reactive power loading at all buses of the four distribution systems under study have been uniformly increased from the ‘base loading conditions’ given in Appendix A. The percentage increase of the loading (expressed with respect to the base loading condition) which have been considered in this case are as follows: system -1: 128%, system -2: 130%, system -3: 125% and system-4: 122%. As in these fault studies the power supply could only be restored partially, these fault studies represent cases of ‘partial service restoration’. From Table 3.4 it is observed that for system-1 and system-3, the “out-of-service areas suggested by all the four methods are same. However, for these two systems, methods ‘m1’ and ‘m2’ are able to supply the priority customers, whereas, the methods ‘m3’ and ‘m4’ are unable to do so. Therefore, methods ‘m1’ and ‘m2’ are clearly superior to methods ‘m3’ and ‘m4’ for service restoration task corresponding to these two systems and as method ‘m1’ takes the least time of execution, it is the most suitable method for these two systems. For system-2 and system-4, the total “out-of-service” area suggested by methods ‘m1’ and ‘m2’ are less than those suggested by methods ‘m3’ and ‘m4’. As minimization of "out-of-service" area has been considered to be the top most priority of the service restoration task, methods 'm1' and 'm2' are superior to methods 'm3' and 'm4'. Moreover, method 'm1' is the most preferred choice between 'm1' and 'm2' as it needs least time of execution. Therefore, even for the case of partial service restoration, for all the systems under study, method 'm1' has been found to be the most preferred choice.

To evaluate the performance of the proposed algorithm for multiple faults in a distribution system, several studies involving simultaneous multiple faults have been carried out and some representative results for the faults shown in Table 3.2 are shown in Tables 3.5 and 3.6. As shown in Table 3.2, two, three, four and four simultaneous faults have been considered for system-1, system-2, system-3 and system-4 respectively. Results corresponding to complete service restoration are shown in Table 3.5 while Table 3.6 presents the results corresponding to partial service restoration. For result presented in Table 3.5, the loading level of the four systems under study have been kept at the 'base loading condition' and for the results shown in Table 3.6, the actual loading at all the buses of the four systems under study have been uniformly enhanced from the 'base loading condition'. The percentage increase of the loading (expressed with respect to the base loading condition) which have been considered for the results shown in Table 3.6 are as follows: system -1: 128%, system -2: 130%, system -3: 125% and system-4: 122%. From Table 3.5 it can be observed that all the four methods are able to supply the priority customers in all these four systems. It is to be noted again that the "out-of-service" area shown in Table 3.5 correspond to the sum total of all the loads (in kW) in the faulted zones and as a result, these loads can not be restored by any of the algorithm. Moreover, the values of all the four objective functions obtained by all the four methods are same for system-1 and system-4. Therefore, for these two systems, all the four methods give the same solution. However, as among these four methods, method 'm1' takes the least time, it can be considered to be the best method among these two systems. For system-2 and system-3, the "out-of-service" area obtained by all the four methods are same, but the number of manual switch operations are more in methods 'm3' and 'm4' than with 'm1' and 'm2'. As the number of manual switch operation is the second most preferred objective, methods 'm1' and 'm2' are better than the methods 'm3' and 'm4'. Again, because of least time of execution, method 'm1' is better among these two methods ('m1' and 'm2'). Thus, in this case also, for all the four systems under study, method 'm1' is found to be the best among all the four methods.

As mentioned above, Table 3.6 shows the results for partial service restoration with multiple faults. From this table it is observed that, for system-2, system-3 and system-4, the "out-of-service" area suggested by methods 'm3' and 'm4' are more than that suggested by methods 'm1' and 'm2'. Moreover, in contrast to the methods 'm1' and 'm2', methods 'm3' and 'm4' are not able to supply the priority customers. Therefore, on these two counts, methods 'm1' and 'm2' are significantly better than methods 'm3' and 'm4' for these three systems. For system-1, the "out-of-service" area suggested by all the methods is same and also all the four methods are able to supply the priority customers. However, as the number of manual switch operations required by methods 'm3' and 'm4' are more than that required by methods 'm1' and 'm2', methods 'm1' and 'm2' are preferable to methods 'm3' and 'm4' for this system also. Again, as method 'm1' takes the least time of execution between methods 'm1' and 'm2', this method is again the most preferred method for this case also.

From the above discussions, it can be concluded that method 'm1' (advanced NSGA-II) is the most suitable method for the service restoration task. However, from the simulation studies carried out in this work, two distinct characteristics of NSGA-II have been noticed. It has been observed that in many (in fact almost all) instances, often a drastic improvement in the solution takes place (because of the utilization of crossover, mutation operators etc.) and therefore, the best solution is reached quite quickly. But, even after the best solution is achieved, the simulation runs are still continued to attain the convergence criterion. Thus, in almost all occasions, the time needed to reach the best solution (TBS) is significantly less than the time needed for convergence (TC). The results of TBS and TC obtained by the method 'm1' for all the four systems are shown in Table 3.7. As pointed out in subsection 3.4.2, in this work, the pre-fault configuration (PFC) of the system under study has been included in the initial population of the strings. Therefore, the results of TBS and TC of 'm1' with PFC in initial population are shown in Table 3.7 for all the four systems. From these results it can be observed that there is perceptible gap between TBS and TC for all the systems and as a result, the proposed method continues the execution even after it reaches the best solution to get convergence,

Table 3.4: Single fault partial service restoration by NSGA-II

System		System-1	Syteme-2	System-3	System-4
Out-of-service area (kW)	m1	1344	260	240	4242.0
	m2	1344	260	240	4242.0
	m3	1344	650	240	4975.0
	m4	1344	650	240	4975.0
No. of manual Switch operations	m1	3	3	3	1
	m2	3	3	3	1
	m3	4	2	3	2
	m4	4	2	3	2
No. of automatic Switch operations	m1	2	1	2	2
	m2	2	1	2	2
	m3	0	0	2	1
	m4	0	0	2	1
Losses (kW)	m1	99.834	578.37	191.40	14287.6
	m2	99.834	578.37	191.40	14287.6
	m3	98.654	538.37	199.30	13652.2
	m4	98.797	533.14	199.30	13652.2
Run-time of the algorithm (sec.)	m1	15.714	18.762	36.556	60.375
	m2	21.976	29.789	75.291	169.375
	m3	43.782	65.117	195.64	432.262
	m4	14.783	17.239	36.770	63.065
Status of priority customer	m1	y	y	y	y
	m2	y	y	y	y
	m3	n	y	n	n
	m4	n	y	n	n

Table 3.5: Multi-fault full service restoration by NSGA-II

System		System-1	System-2	System-3	System-4
Number of fault		2	3	4	4
Out of service area (kW)	m1	853.0	2000	300	8642.0
	m2	853.0	2000	300	8642.0
	m3	853.0	2000	300	8642.0
	m4	853.0	2000	300	8642.0
No. of manual Switch operations	m1	4	3	5	2
	m2	4	3	5	2
	m3	4	4	6	2
	m4	4	4	6	2
No. of automatic Switch operations	m1	0	1	3	2
	m2	0	1	3	2
	m3	0	1	2	2
	m4	0	1	2	2
Losses (kW)	m1	95.300	187.30	148.11	12337.2
	m2	95.300	187.30	148.11	12337.2
	m3	96.100	198.30	157.00	12665.1
	m4	96.100	198.30	157.00	12665.1
Run-time of the algorithm (sec.)	m1	14.764	16.273	30.395	51.078
	m2	19.673	25.874	69.194	160.828
	m3	61.882	60.598	189.352	426.982
	m4	26.255	45.739	126.265	242.773
Status of priority customer	m1	y	y	y	y
	m2	y	y	y	y
	m3	y	y	y	y
	m4	y	y	y	y

Table 3.6: Multi-fault partial service restoration by NSGA-II

System		System-1	System-2	System-3	System-4
Number of fault		2	3	4	4
Out of service area (kW)	m1	1626.44	2730	750	11775.0
	m2	1626.44	2730	750	11775.0
	m3	1626.44	2825	950	13616.0
	m4	1626.44	2825	750	13616.0
No. of manual Switch operations	m1	2	4	6	3
	m2	2	4	6	3
	m3	3	3	7	4
	m4	3	3	7	4
No. of automatic Switch operations	m1	2	2	3	2
	m2	2	2	3	2
	m3	1	2	0	0
	m4	1	2	0	0
Losses (kW)	m1	158.4	244.2	139.8	12125.8
	m2	158.4	244.2	139.8	12125.8
	m3	168.9	208.32	108.7	11801.3
	m4	168.9	208.32	112.9	11801.3
Run-time of the algorithm (sec.)	m1	14.823	16.179	30.259	50.757
	m2	19.603	26.138	68.208	160.185
	m3	61.734	59.992	187.825	423.539
	m4	27.329	47.388	130.183	248.656
Status of priority customer	m1	y	y	y	y
	m2	y	y	y	y
	m3	y	n	n	n
	m4	y	n	n	n

which in turn, increases the run-time for service restoration method. The results of TBS and TC are also shown in Table 3.7 when PFC is not included in the initial population in method 'm1'. From these results, it can be observed that inclusion of PFC in the initial population reduces the TBS as well as TC significantly, thereby reducing the run-time of the methodology considerably.

Before concluding this chapter, an important issue regarding the proposed method to service restoration problem needs to be examined, that is related to some exceptional cases which might occur in some rare occasions. As described in subsection 3.4.9, the solution in the first front with lowest value of "out-of-service" area would be chosen as the final solution. However, if in some exceptional cases, this solution results very high values of objective functions f_2, f_3 and f_4, than from practical point of view, it may not be an acceptable solution. Indeed, it would be desirable to prevent this solution from being included in the first front. In the proposed technique, this can easily be achieved by imposing three more constraints in the service restoration problem. The first and second constraints would specify a maximum allowable limit of number of manual switch operations and automatic switch operations respectively while the third constraint would specify a maximum allowable limit of losses in the system. Thus, in this case, total number of constraints would be seven (instead of four as described in Section 3.2). For any solution having exceptionally high value of either f_2, f_3 or f_4, at least one of its constraints (out of seven) would be violated and therefore, it would be constraint-dominated by some other solution. As a result, following the step 5 of Section 3.3, this solution would automatically be relegated to lower fronts. However, for the case studies carried out in this work, no such cases has been observed and hence, in this thesis, these three additional constraints have not been imposed on the service restoration problem.

Table 3.7 : Comparison of TBS and TC for all the systems taken by NSGA-II

System	Method used	Single fault case (full service restoration)			Multiple fault case (full service restoration)		
		TBS (sec.)	TC (sec.)	Gap (sec.)	TBS (sec.)	TC (sec.)	Gap (sec.)
System-1	Proposed method without PFC	34.2785	62.3835	28.105	32.9358	45.6322	12.6964
	Proposed method with PFC	10.7835	15.765	4.9815	9.0352	14.764	5.7288
System-2	Proposed method without PFC	34.2785	62.3835	28.105	45.6322	12.6964	12.6964
	Proposed method with PFC	12.6453	18.774	6.1287	9.0398	16.273	7.2332
System-3	Proposed method without PFC	75.7303	96.1823	20.452	54.9383	60.0384	5.1001
	Proposed method with PFC	28.8574	36.273	7.4156	23.8576	30.395	6.5374
System-4	Proposed method without PFC	58.2399	95.8374	37.5975	61.9381	83.2837	21.3456
	Proposed method with PFC	37.0384	61.53	24.4916	43.0239	51.078	8.0541

3.6 CONCLUSION

In this chapter, a method based on NSGA-II is developed for solving the service restoration problem in electric power distribution systems. In this study, various practical issues of distribution system operation such as presence of priority customers, presence of remotely controlled as well as manually controlled switches etc. have also been considered. The advantage of the proposed NSGA-II based technique is that it does not require any weighting factor (as needed in a conventional GA based technique). Based on a large number of simulation studies it has been found that this approach performs better than the conventional GA based approach in solving the service restoration problem. It has also been shown that inclusion of PFC in the initial population reduces the execution time of the algorithm developed in this chapter considerably. Due to the presence of elitism, the proposed method gets convergence to the global optimal solution. The drastic improvement in the solution is found because the proposed method utilizes the crossover operator (a kind of global search procedure). For getting the mating pool (a set of solutions on which crossover and mutation operator are to be applied) for next generation, crowded tournament selection operator is used. In the crowed selection operator, the solutions having the highest crowding distance are included in the mating pool from the last front considered by crowded tournament selection operator during the execution of its process. Due to presence of the solutions having highest crowding distance in the mating pool, the diversity of the solution in the mating pool increases, due to which the premature convergence of the methodology developed is prevented.

Chapter 4

SERVICE RESTORATION USING MULTI OBJECTIVE REACTIVE TABU SEARCH (MORTS) AND COMBINATION OF MORTS & NSGA-II

4.1 INTRODUCTION

In chapter 3, a method based on NSGA-II has been presented for solving the service restoration problem and it has been demonstrated that this method offers significant advantages over methods based on GA and other methods. However, from the studies carried out in chapter 3, two significant limitations of the presented have been identified. These limitations are: a) large gap between TBC and TC which ultimately increases the computation time for service restoration and b) no improvement in the objective functions for long time during computation process which also ultimately increases the computation time of service restoration. Therefore, it is necessary to search for other evolutionary algorithm(s) which can mitigate these two limitations. Towards this goal, in this chapter, reactive tabu search has been considered. However, the basic reactive tabu search method is capable to handle only a single objective function optimization problem effectively. Therefore, to enable it to tackle the multi-objective, multi-constraint problem of service restoration, the basic reactive tabu search technique has been modified suitably in this work resulting into a new multi-objective reactive tabu search (MORTS) technique. In this chapter, initially the basic RTS technique is described followed by the newly developed MORTS method. Subsequently, the application of the developed MORTS technique to solve the service restoration problem is discussed. The proposed method based on NSGA-II developed by Jensen [88] to solve the service restoration problem in chapter 3 is represented by proposed NSGA in the henceforth part of this thesis.

4.2 BASIC REACTIVE TABU SEARCH (RTS) METHOD

Tabu search (TS) [89, 90] is the modified form of hill climbing optimization methods. TS has the ability to prevent the convergence to local optima whereas hill climbing methods get trapped in local optima. TS as well as hill climbing methods start with an initial current candidate solution (CS) generated randomly (or the specific solution if available). Subsequently, the neighborhood solutions of this initial current CS are found and the best among these neighborhood solutions is chosen. In hill climbing methods, if this best neighborhood solution (BNS) is better than the CS, then the BNS is chosen as the new CS for the next iteration and the algorithms (both hill climbing and TS) proceed. However, if in an iteration, no neighborhood solution is better than the candidate solution, hill-climbing methods converge at local optimum point (the current CS) and the algorithm stops. But TS still accepts the BNS as the new CS and drives the search process to different part of the search space instead of being trapped at the local optimum point.

The procedure adopted in TS for selecting the new CS from the neighborhood solutions might bring the search procedure at some of the already visited search points (in some previous iterations) before reaching the global optimal solution. In this case, the search procedure repeats a sequence of search points endlessly. This endless repetition of sequence of search points is called a cycle. To avoid this occurrence of cycles, the selection of previously visited search point as new CS is prohibited in TS. These prohibited search points (which had been already visited) are called 'tabu'. For preventing the search procedure to reach any of the already visited search points, these already visited search points are kept in a list called 'tabu list (TL)'. Best solution among the neighborhood solutions which are not in tabu list is selected as new CS. Taking this new candidate as current CS, the neighborhoods are generated and the procedure for selection of new CS is repeated. The procedure of generation of neighborhood and selection of new CS is repeated until the optimal solution is found. If all the already visited search points are made 'tabu' during TS, then this type of TS is called 'strict tabu search'. In 'strict tabu search', the TL becomes very lengthy because it keeps on adding each and every visited point to the list. Due to lengthy tabu list, the optimal point may be surrounded by already visited point. In that case, the optimal point may become unreachable because of the creation of barriers consisting of already visited points.

To avoid the problems of 'strict tabu search', the size of TL list may be kept fixed and in this case, the TS is called 'fixed tabu search'. The proper size of TL in 'fixed tabu search' is quite problem dependent. As in 'fixed tabu search' all the previously visited search points are not prohibited, the possibility of occurrence of cycles remains in this case. Generally, with increasing size of the TL, the possibility of occurrence of cycles reduces. However, as the search procedure needs to check a lengthy list, the efficiency (in terms of speed) of TS reduces with increasing size of TL. On the other hand, with decreasing size of TL, the efficiency of the TS increases although the possibility of occurrence of cycles increases. The proper choice of size of TL (long enough to avoid the occurrence of cycles but short enough to make efficient search) is critical to the success of the algorithm. In another version of TS, the search procedure is made more robust by varying the length of TL, although one must prescribe maximum and minimum allowable limits of its size. For any given problem, the actual size of the TL is varied within these two limits. Again, the suitable and proper values of these two limits are problem dependent. In addition to the size of TL, another important issue of TS is 'aspiration criteria'. The 'aspiration criteria' are essentially a set of rules to override the tabu restriction, i.e., a neighborhood solution with 'tabu' status is accepted as new CS if the 'aspiration criteria' are satisfied.

The problems associated with TS discussed above, have been overcome in the reactive tabu search developed by R. Battiti [91]. In RTS, the robustness of the basic TS is enhanced by adopting a simple reaction and escape mechanism for adapting the length of TL to the properties of the optimization problem under study. For implementation of simple reaction and escape mechanism, RTS maintains the memory in addition to TL. In memory, the already visited search points along with their corresponding iteration numbers and number of their repetition are stored so that, the repetition of a solution under consideration to be selected as new CS can be checked and subsequently the interval between two visits (in case of repetition) of the repeated solution can be calculated. In the case of low value of this interval (frequent repetitions), the basic 'fast reaction mechanism' is invoked, in which, when the search points are repeated, the size of TL is increased to discourage additional repetitions. Under this condition, a continuous sequence of repetition rapidly increases the length of TL. To initiate the 'escape mechanism', if the solution under consideration to be selected is found repeated, the number of repetition of this solution is counted. If this count is greater than a threshold value, the search procedure is said to be trapped in 'chaotic attractor'. In 'chaotic attractor', the search procedure repeats the search points within a certain zone of the search space. Therefore, if the optimal solution is not within this certain zone, it can never be found. To avoid the situation of 'chaotic attractor', the 'escape mechanism' is enforced. The escape mechanism helps to make the search out of this zone. In 'escape mechanism', some of the solutions among the neighborhood solutions of the current CS are randomly selected and the best among these selected solutions is accepted as a new CS. If the repetitions are infrequent, the large size of the TL is not required. Under this condition, the size of the TL is reduced by invoking the 'slower reaction mechanism', in which the oldest members of the list are removed. In addition to the basic 'fast reaction mechanism and 'slower reaction mechanism', there can be a third situation in which the length of the TL is modified. In this third situation, the size of the TL may become so large that all the neighborhood solutions of the current CS have 'tabu status' and also simultaneously none of the neighborhood solutions satisfies the aspiration criteria. In this situation, the size of TL is reduced by removing the oldest members from the TL. As a result, these members (which have now been removed from TL) would lose their 'tabu' status and subsequently, the best of these solutions can be again accepted as new CS. If the solution under consideration is not repeated, the new CS selected according the procedure of convention TS.

4.3 MULTI-OBJECTIVE REACTIVE TABU SEARCH (MORTS)

The RTS technique described in the last section works quite well for single objective optimization problems. For multi-objective optimization problems, initially suitable weighting factors must be used to convert the multi-objective problem into a single objective problem before application of RTS for its solution. Because of the difficulties involved in the choice of suitable weighting factors (as already discussed in Chapter 1, subsection 1.3), it is preferred to retain the multi-objective nature of the problem under study. Therefore, for successful application of RTS for finding the solution of a multi-objective optimization problem such as service restoration, in this work, the basic RTS technique has been suitably modified resulting into a new multi-objective reactive tabu search (MORTS) technique.

The basic difference between the RTS and the developed MORTS lies in the methodology of comparison of two solutions. In RTS, in which every solution essentially has only one associated objective function, the superiority of any particular solution over any other solution can be easily judged by just comparing the objective function values of these two solutions. However, for multi-objective optimization problem, the comparison of any two solutions is not trivial [86]. To compare between any two solutions of the service restoration problem, in this work, the developed MORTS uses the constraint domination principle [86]. Basically, MORTS works similarly as RTS does except for the fact that in these two techniques, the comparison of two solutions is made in different ways. Because of the use of constraint domination principle, MORTS does not face the difficulty of choosing proper weighting factors as RTS thereby making it more generalized technique to be applicable to a wide range of multi-objective optimization problems. The basic principles of constraint domination as well as of choice of the final solution from a set of solutions have already been explained in detail in Chapter 3 and Appendix B and therefore, these concepts are not repeated here.

4.4 PROPOSED METHODOLOGY BASED ON MORTS FOR SERVICE RESTORATION

For implementation of MORTS in service restoration problem, the distribution system under study is first mapped to a graph in the same manner as described in Chapter 2, subsection 2.2.1. Also any solution used in the MORTS of this work is represented by a string of bits and this string, in turn, represents the switch positions of the distribution system under study as described in Chapter 3, subsection 3.4.1. Now, to find the neighborhood solutions of current CS, the bits of the current CS are complemented one by one [92]. For example, if the current CS is [1 0 1 0], then its neighborhood solutions are: [0 0 1 0], [1 1 1 0], [1 0 0 1] and [1 0 1 1]. Therefore, the total number of neighborhood solutions of any CS is equal to the number of bits in the string, or in other words, equal to the number of switches in the distribution system under study. The implementation of MORTS in service restoration problem is given in detail in the pseudo code in next section. The proposed method based on MORTS to solve the service restoration problem in distribution systems, in this chapter is represented by proposed MORTS in the henceforth part of this thesis.

4.5 PSEUDO CODE OF PROPOSED METHODOLOGY

Steps:

1) Assign : i_t = 0; Maximum number of iterations = it_max; string variables best_configuration = null and best_so_far_configuration = null; best_neighborhood = null; Temp_best = null; Repetition_counter = 0: Chaotic_counter = 0; Size of tabu list: L = 1; Threshold value of chaotic attractor to invoke the 'escape mechanism' : CHAOS = 2; Threshold value of repetition of solution in memory structure to ensure the presence of chaotic attractor: REP = 2; CYCLE_MAX = 2(sw-1), where sw is number of switches; INCREASE = 1.1, DECREASE = 0.9; moving_average = 0.
2) Take the PFC as candidate solution (CS). Evaluate the objective functions and constraints of CS as described in subsection 3.4.4.
3) Assign best_configuration = CS, best_so_far_configuration = CS, best_so_far_objective_functions = objective functions of CS.
4) Include CS in the tabu list.
5) Generate neighborhood of CS. In all these neighborhood solutions faulted zone is isolated and root switch is always made closed as described in subsection 3.4.2.
6) Check if i_t > it_max. If yes, the solution is best_so_far_configuration and stop. Else i_t = i_t + 1 and proceed.
7) Evaluate the objective functions and constraints of each of the neighborhood solutions as described in subsection 3.4.4.
8) Assign the rank of each neighborhood solutions by following the procedure as described in step 5 of section 3.3 in chapter 3.
9) Find the best solution among the neighborhood solutions following the procedure described in subsection 3.4.9 in chapter 3 and let us call it 'best_neighborhood'.
10) If 'best_neighborhood' is not in tabu list then assign best_configuration =

'best_neighborhood' irrespective of aspiration criteria and go the step 15.

11) If 'best_neighborhood' is in tabu list then compare it with 'best_so_far_configuration' using the concept of 'constraint domination' (as described in Appendix B). As a result of this, any of three following scenario might emerge.
    a) The solution 'best_neighborhood' is found to be better than the solution 'best_so_far_configuration'. In this case, the aspiration criterio is satisfied. Set 'temp_best' = 'best_neighborhood' and go to step 12.
    b) The solution 'best_so_far_configuration' is found to be better than 'best_neighborhood'. In this case, the aspiration criteria is not satisfied and hence go to step 13.
    c) These solutions do not constraint dominate each other. In this case, both these solutions are assigned rank 1 (as described in step 5 of section 3.3) and subsequently, the better solution (between these two solutions) is found following the procedure described in section 3.4.9. If 'best_neighborhood' is found to be better then aspiration criteria is satisfied as set 'temp_best' = 'best_configuration' and go to step 12. On the other hand, if 'best_so_far_configuration' is found to be better one, then the aspiration criteria is not satisfied and hence proceed to step 13.
12) Set 'best_configuration' = 'temp_best' and go to step 15.
13) From the neighborhood solutions of CS (as described in step 8), find out best solution which is not already in the tabu list and assign this solution to 'best_configuration, and go to step 15. To find the best solution the procedure described in subsection 3.4.9 in chapter 3 is applied repeatedly if necessary. If all neighborhood solutions of CS are found to be in tabu list, go to step 14.
14) Pick up the best solution as found in step 9, assign it to 'best_configuration', discard the oldest member of the tabu list from the tabu list and go to step 15.
15) Check for repetition of 'best_configuration, in memory structure.
16) If repetition of 'best_configuration, is found, go to next step. Else assign 'best_configuration' to CS and go to step 24.
17) Update 'repetition_counter' of 'best_configuration' i.e. 'repetition_counter' =

'repetition_counter' +1.

18) If 'repetition_counter' > REP, update the 'chaotic_counter' i.e. 'chaotic_counter' = 'chaotic_counter' +1.
19) If 'repetition_counter' > REP and 'chaotic_counter' > CHAOS (this is the evidence of falling in chaotic attractor), go to next step to execute the escape function. Else go to step 22.
20) Pick up some solutions from neighborhoods of CS randomly. The number of these randomly picked up solutions should be equal to min(1+ moving everage/2, number of total neighborhoods)
21) Assign best of randomly picked up solutions to 'best_configuration'.
22) Find out the difference between current iteration and the iteration number in which 'best_configuration' was included in tabu list last time. i.e. difference = current iteration – last iteration.
23) If difference < CYCLE_MAX then a) Increase the size of tabu list to discourage the further repetition i.e. list_size = list size x INCREASE. b) moving_average = 0.1 x difference + 0.9 x moving_average. c) iteration_since_last_size_changed = 0 and go to step 24. Else go to next step without making any change in size of tabu list, moving_average and iteration_since_last_size_changed.
24) If iteration_since_last_size_changed > moving_average (it indicates that the size is not increased since long time hence there is no need of long size of tabu list. Therefore, it may be decreased), decrease the size of tabu list i.e. list_size = max (list_size x DECREASE, 1) and iteration_since_last_size_changed = 0.
25) Assign 'best_configuration' to CS. Include it in tabu list and go to next step.
26) If CS is better than 'best_so_far_configuration', replace 'best_so_far_configuration' by CS.
27) Update iteration_since_last_size_changed i.e. iteration_since_last_size_changed = iteration_since_last_size_changed +1. Go to step 4.

The concepts of chaotic attractor, repetition_counter, REP, chaotic_counter, CHAOS, moving average, increment factor, decrement factor and CYCLE_MAX, are described in detail in Appendix C.

4.6 RESULTS AND DISCUSSION

The proposed MORTS has been applied for service restoration in all the four distribution systems used in chapter 3. As in chapter 3, both single-fault and multiple-faults cases have been considered for all the four systems. The same fault cases described in Table 3.1 and 3.2 have been considered in this chapter also. The results obtained by proposed MORTS have also been compared with the results obtained by the proposed NSGA presented in chapter 3 and the existing technique based on RTS developed by Toune et al [48]. The results corresponding to full and partial service restoration for single fault cases as well as multiple faults cases are shown in Tables 4.1, 4.2, 4.3 and 4.4 for all the four systems considered in this thesis. It is to be noted that the conditions for

Table 4.1: Single fault full service restoration by proposed MORTS

System		System-1	System-2	System-3	System-4
Out-of-service area (kW)	Proposed MORTS	600	100	120	0.0
	Proposed	600	100	120	0.0
	Toune [48]	600	100	120	3134.0
No. of manual Switch operations	Proposed MORTS	2 S6,10	1 S10	1 S6	0
	Proposed NSGA	2 S6,10	1 S10	1 S6	0
	Toune [48]	3 S6,10,8	2 S10,14	2 S6,10	1 S5
No. of automatic Switch operations	Proposed MORTS	2 S4,70	1 S12	1 S10	2 S52,74
	Proposed NSGA	2 S4,70	1 S12	1 S10	2 S52,74
	Toune [48]	1 S7	0	0	1 S2
Losses (kW)	Proposed MORTS	104.50	582.40	210.00	15181.3
	Proposed NSGA	104.50	582.40	210.00	15181.3
	Toune [48]	10.6.86	580.900	216.0	14088.7
Run-time of the algorithm (sec.)	Proposed MORTS	26.8392	33.1023	68.9284	130.8572
	Proposed NSGA	15.765	18.774	36.273	61.530
	Toune [48]	33.9587	41.8374	86.7363	196.9384
Status of priority customer	Proposed MORTS	y	y	y	y
	Proposed NSGA	y	y	y	y
	Toune [48]	y	y	y	y

Table 4.2: Single fault partial service restoration by proposed MORTS

System		System-1	Syteme-2	System-3	System-4
Out-of-service area (kW)	Proposed MORTS	1344	260	240	4242.0
	Proposed NSGA	1344	260	240	4242.0
	Toune [48]	1344	500	240	4975.0
No. of manual Switch operations	Proposed MORTS	3	3	3	1
	Proposed NSGA	3	3	3	1
	Toune [48]	3	2	3	2
No. of automatic Switch operations	Proposed MORTS	2	1	2	2
	Proposed NSGA	2	1	2	2
	Toune [48]	1	2	2	1
Losses (kW)	Proposed MORTS	99.834	578.37	191.40	14287.6
	Proposed NSGA	99.834	578.37	191.40	14287.6
	Toune [48]	99.7654	537.34	199.30	13653.1
Run-time of the algorithm (sec.)	Proposed MORTS	26.9472	33.6477	68.7364	130.6473
	Proposed NSGA	15.714	18.762	36.556	60.375
	Toune [48]	35.8493	47.7563	96.8573	203.1823
Status of priority customer	Proposed MORTS	y	y	y	y
	Proposed NSGA	y	y	y	y
	Toune [48]	n	y	n	n

partial service restoration cases are same as those already described in Chapter 3. From these tables it is observed that in all the cases, the solution obtained by proposed NSGA and proposed MORTS are same while in many instances, the solution obtained by RTS [48] is quite inferior (as compared proposed NSGA). Closer observation also reveals that among all these three techniques, the run-time required by proposed NSGA is least whereas the run time required by RTS [48] is maximum. It is to be noted that to obtain the results in Tables 4.1 to 4.4, the values of the different parameters used in proposed MORTS are as follows: INCREASE = 1.1, DECREASE ~~DECERASE~~ = 0.9, CHAOS = 2 and REP = 2.

Table 4.3: Multi-fault full service restoration by proposed MORTS

System		System-1	System-2	System-3	System-4
Number of fault		2	3	4	4
Out of service area (kW)	Proposed MORTS	853.0	2000	300	8642.0
	Proposed NSGA	853.0	2000	300	8642.0
	Toune [48]	853.0	2000	300	8642.0
No. of manual Switch operations	Proposed MORTS	4	3	5	2
	Proposed NSGA	4	3	5	2
	Toune [48]	4	4	6	3
No. of automatic Switch operations	Proposed MORTS	0	1	3	2
	Proposed NSGA	0	1	3	2
	Toune [48]	0	1	2	1
Losses (kW)	Proposed MORTS	95.300	187.30	148.11	12337.2
	Proposed NSGA	95.300	187.30	148.11	12337.2
	Toune [48]	96.100	188.830	157.00	12583.9
Run-time of the algorithm (sec.)	Proposed MORTS	24.2039	27.03821	53.7483	95.2874
	Proposed NSGA	14.764	16.273	30.395	51.078
	Toune [48]	67.8472	128.8573	221.7364	689.7274
Status of priority customer	Proposed MORTS	y	y	y	y
	Proposed NSGA	y	y	y	y
	Toune [48]	y	y	y	y

Table 4.4: Multi-fault partial service restoration by proposed MORTS

System		System-1	System-2	System-3	System-4
Number of fault		2	3	4	4
Out of service area (kW)	Proposed MORTS	1626.44	2730	750	11775.0
	Proposed NSGA	1626.44	2730	750	11775.0
	Toune [48]	1626.44	2730	750	11775.0
No. of manual switch operations	Proposed MORTS	2	4	6	3
	Proposed NSGA	2	4	6	3
	Toune [48]	3	3	7	4
No. of automatic switch operations	Proposed MORTS	2	2	3	2
	Proposed NSGA	2	2	3	2
	Toune [48]	1	2	0	0
Losses (kW)	Proposed MORTS	158.4	244.2	139.8	12125.8
	Proposed NSGA	158.4	244.2	139.8	12125.8
	Toune [48]	157.289	242.832	135.87	11801.6
Run-time of the algorithm (sec.)	Proposed MORTS	25.8491	28.1672	53.9843	96.5367
	Proposed NSGA	14.823	16.179	30.259	50.757
	Toune [48]	69.02933	131.83921	228.7323	725.9283
Status of priority customer	Proposed MORTS	y	y	y	y
	Proposed NSGA	y	y	y	y
	Toune [48]	y	n	n	n

To investigate the effect of the values of the different parameters (i.e. increase factor, decrease factor, REP and CHAOS) on the final solution obtained proposed MORTS, a large number of simulation studies have been carried out with different values of the parameters. Some representative results corresponding to system-4 (for single fault, full service restoration case with fault in zone z52) are shown in Table 4.5. From this table it is observed that the best solution is obtained in minimum time for the following values: INCREASE = 1.1, ~~DECERASE~~ DECREASE = 0.9, CHAOS = 2 and REP = 2 (this combination is also highlighted in Table 4.5). From this table it is also observed that when the values of either REP or CHAOS is less than 2, the total execution time is less than what is needed for obtaining the best solution but the quality of the solutions is quite inferior to the best solution. On the other hand, when the values of either REP or CHAOS is greater than 2, the solutions obtained are not at all better than the best solution

(solution obtained with REP = 2 and CHAOS = 2) but the total execution time is significantly more than the time needed to arrive at the best solution. Therefore, the values of both the parameters REP and CHAOS have been chosen to be equal to 2 for this system. With the values of these two parameters fixed, it is also found from Table 4.5 that when the value of the factor INCREMENT is other than 1.1 or that of the factor DECREMENT is other than 0.9, the solution obtained is inferior to the best solution. The same observation has also been noted in the other three distribution systems under study and as a result, in this thesis, this combination of parameters (INCREASE = 1.1, ~~DECERASE~~ DECREASE = 0.9, CHAOS = 2 and REP = 2) has been used for all the studies involving MORTS.

Table 4.5: Effect of parameter values on the solution obtained by proposed MORTS

Out-of-service area (kW)	Manual Switch operation	Automatic Switch operation	Losses Obtained (kW)	TC (seconds)	INCREASE	DECREASE	CHAOS	REP
0.0	**0.0**	**2**	**15181.3**	**130.8572**	**1.1**	**0.9**	**2**	**2**
500	0	3	14837.2	130.8572	1.2	0.8	2	2
4242.0	1	3	14177.5	130.8572	1.3	0.7	2	2
5970.0	3	2	14333.7	106.9384	1.1	0.9	1	2
0.0	0	2	15181.3	160.8475	1.1	0.9	3	2
0.0	0	2	15181.3	198.7463	1.1	0.9	4	2
4975.0	3	4	13233.5	106.9384	1.1	0.9	2	1
0.0	0	2	15181.3	160.8475	1.1	0.9	2	3
0.0	0	2	15181.3	198.7463	1.1	0.9	2	4

Now, after performing a large number of simulation studies in all the four distribution systems, two salient features of proposed MORTS have been observed. In contrast to proposed NSGA, the drastic improvement in the solution does not take place in proposed MORTS and as a result, the value of TBS is generally more than that achieved by proposed NSGA. However, after the best solution is obtained, the proposed MORTS algorithm reaches the convergence criterion also quite quickly. Therefore, in proposed MORTS, the difference between TBS and TC is quite less as compared to proposed NSGA. This fact is also corroborated with the results shown in Table 4.6. Moreover it has been observed that the computational time per iteration needed for proposed MORTS is greater than that needed by proposed NSGA and due to this, the TC of proposed MORTS is higher than the TC of proposed NSGA.

Table 4.6: Comparison of TBS and TC of proposed MORTS

System	Method used	Single fault case (full service restoration)			Multiple fault case (full service restoration)		
		TBS (sec.)	TC (sec.)	Gap (sec.)	TBS (sec.)	TC (sec.)	Gap (sec.)
System-1	Proposed MORTS	24.9384	26.8392	1.9008	22.7263	24.2039	1.4776
	Proposed NSGA	10.7835	15.765	4.9815	9.0352	14.764	5.7288
	Toune [48]	31.6464	33.9587	2.3123	64.8746	67.8472	2.9726
System-2	Proposed MORTS	29.8374	33.1023	3.2649	23.9384	27.0382	3.0998
	Proposed NSGA	12.6453	18.774	6.1287	9.0398	16.273	7.2332
	Toune [48]	37.8476	41.8374	3.9898	122.645	128.857	6.212
System-3	Proposed MORTS	62.0293	68.9284	6.8991	49.7236	53.7483	4.0247
	Proposed NSGA	28.8574	36.273	7.4156	23.8576	30.395	6.5374
	Toune [48]	79.8394	86.7363	6.8969	202.847	221.736	18.889
System-4	Proposed MORTS	119.738	130.857	11.118	89.9134	95.2874	5.374
	Proposed NSGA	37.0384	61.530	24.491	43.0239	51.078	8.0541
	Toune [48]	185.098	196.938	11.839	684.847	689.727	5.120

Because of the characteristics of that of proposed NSGA-II and proposed MORTS, these two techniques can be considered as complimentary to each other in some sense. The advantage (limitation) of proposed NSGA is manifested as limitation (advantage) in proposed MORTS. Therefore, if proposed NSGA and proposed MORTS are combined, then it would be possible to retain the advantages (and avoid the disadvantages) of both these techniques. With this objective, proposed NSGA and proposed MORTS are combined to solve the service restoration problem in distribution systems. In the combination of proposed NSGA and proposed MORTS, proposed NSGA is first run for three iterations and subsequently proposed MORTS is run for iteration one only. This combination of three runs of proposed NSGA followed by one run of proposed

MORTS is called a cycle. This cycle is repeated till the algorithm converges and the best solution is obtained. The combination of proposed NSGA and proposed MORTS to solve the service restoration problem is represented by 'proposed NSGA/MORTS' in the henceforth part of the thesis. The description of the proposed NSGA/MORTS technique is given in next subsection.

4.7 PROPOSED NSGA/MORTS FOR SERVICE RESTORATION

In the proposed NSGA/MORTS, initially proposed NSGA is executed for three iterations. The best solution obtained after three iterations of proposed NSGA is chosen as the candidate solution for proposed MORTS and with this candidate solution proposed MORTS is executed only for single iteration. This completes one cycle of execution of the proposed NSGA/MORTS technique. By large number of simulation studies, it has been found that with this combination of three iterations of proposed NSGA and one iteration of proposed MORTS, the solution is obtained in minimum time. If proposed NSGA is executed for more than three iterations, then the combined technique would be rich in the property of proposed NSGA, thereby increasing the gap between TBS and TC. On the other hand, if the number of proposed NSGA execution is less than three or the number of proposed MORTS execution is more than one, then the attributes of the combined technique would be dominated by the attributes of proposed MORTS. As the computation time per iteration of proposed MORTS is greater than that of proposed NSGA, the value of TC in either of these two cases also increases.

Now, starting from the second cycle, at each iteration of proposed NSGA, some of the randomly generated initial strings are replaced by the best solution (CS) found by proposed MORTS (of the last cycle) as well as by some of the randomly chosen neighborhood solutions of the CS. By injecting new strings obtained by proposed MORTS in each generation of proposed NSGA, the chance of escaping the local minimum is increased as well as the tendency of proposed NSGA towards premature convergence is also reduced [93]. Typically 1-10% string of population can be replaced [93]. In this work 6% of the strings of proposed NSGA have been replaced by the solutions obtained by proposed MORTS. Again, by a large number of simulation studies, it has been found that with replacement of 6% strings, the final solution is obtained in minimum time. If more than 6% strings are replaced, the diversity of the population increases quite substantially. In such a situation, the attainment of convergence may take quite a prolonged time or convergence may even never be achieved.

Algorithm of proposed NSGA/MORTS technique

Steps

1. Run proposed NSGA for three iterations.
2. Find best solution in parent population and offspring.
3. Take best solution from parent population and offspring as candidate solution for proposed MORTS.
4. Run proposed MORTS for one iteration.
5. Replace, typically 1-10% (in this present study 6%) of parent population of proposed NSGA by best neighborhood and other randomly selected neighborhoods generated in proposed MORTS and go to step 1.

4.8 SIMULATION RESULTS WITH PROPOSED NSGA/MORTS TECHNIQUE

The simulation studies have been carried out for the same fault cases considered earlier in all the four distribution systems under study and the results are shown in Tables 4.7 - 4.10. For direct comparison, the results already obtained with proposed NSGA and proposed MORTS are also reproduced in these tables. As already discussed in the last subsection, in the proposed NSGA/MORTS technique, three iterations of proposed NSGA are executed followed by one iteration of proposed MORTS. In this combined technique, the different parameters chosen for proposed MORTS execution are as follows: INCREASE = 1.1, DECERASE = 0.9, CHAOS = 2 and REP = 2.

From the Tables 4.7 - 4.10 it is observed that in all the fault cases considered, the proposed NSGA/MORTS method produces the same results as those obtained by proposed NSGA alone. However, the execution time needed by the proposed NSGA/MORTS is less than needed by proposed NSGA alone. It is also observed that the proposed MORTS produced same results as produced by the other two techniques (proposed NSGA and proposed NSGA/MORTS) and in all the cases, the run time needed by proposed MORTS is significantly more than that needed by either of these two techniques. Therefore, among these three techniques, the performance of the proposed NSGA/MORTS technique can be considered to be the best.

The results for TBS & TC obtained with the proposed NSGA/MORTS technique for all the distribution systems under study are given in Table 4.11. From this table, it is observed that as expected, the gap between the TBS & TC is least with the combined technique, thereby reducing the execution run-time to the maximum extent possible.

Table 4.7: Single fault full service restoration by proposed NSGA/MORTS technique

System		System-1	System-2	System-3	System-4
Out-of-service area (kW)	Proposed MORTS/NSGA	600	100	120	0.0
	Proposed NSGA	600	100	120	0.0
	Proposed MORTS	600	100	120	0.0
No. of manual Switch operations	Proposed MORTS/NSGA	$2^{S6,10}$	1^{S10}	1^{S6}	0
	Proposed NSGA	$2^{S6,10}$	1^{S10}	1^{S6}	0
	Proposed MORTS	$2^{S6,10}$	1^{S10}	1^{S6}	0
No. of automatic Switch operations	Proposed MORTS/NSGA	$2^{S4,10}$	1^{S12}	1^{S10}	$2^{S52,74}$
	Proposed NSGA	$2^{S4,10}$	1^{S12}	1^{S10}	$2^{S52,74}$
	Proposed MORTS	$2^{S4,10}$	1^{S12}	1^{S10}	$2^{S52,74}$
Losses (kW)	Proposed MORTS/NSGA	104.50	582.40	210.00	15181.3
	Proposed NSGA	104.50	582.40	210.00	15181.3
	Proposed MORTS	104.50	582.40	210.00	15181.3
Run-time of the algorithm (sec.)	Proposed MORTS/NSGA	10.1328	12.7463	25.8373	46.8473
	Proposed NSGA	15.7650	18.7740	36.2730	61.5300
	Proposed MORTS	33.9587	41.8374	86.7363	196.9384
Status of priority customer	Proposed MORTS/NSGA	y	y	y	y
	Proposed NSGA	y	y	y	y
	Proposed MORTS	y	y	y	y

Table 4.8: Single fault partial service restoration by proposed NSGA/MORTS technique

System		System-1	Syteme-2	System-3	System-4
Out-of-service area (kW)	Proposed MORTS/NSGA	1344	260	240	4242.0
	Proposed NSGA	1344	260	240	4242.0
	Proposed MORTS	1344	260	240	4242.0
No. of manual Switch operations	Proposed MORTS/NSGA	3	3	3	1
	Proposed NSGA	3	3	3	1
	Proposed MORTS	3	3	3	1
No. of automatic Switch operations	Proposed MORTS/NSGA	2	1	2	2
	Proposed NSGA	2	1	2	2
	Proposed MORTS	2	1	2	2
Losses (kW)	Proposed MORTS/NSGA	99.834	578.37	191.40	14287.6
	Proposed NSGA	99.834	578.37	191.40	14287.6
	Proposed MORTS	99.834	578.37	191.40	14287.6
Run-time of the algorithm (sec.)	Proposed MORTS/NSGA	10.2837	12.5983	26.0289	46.7367
	Proposed NSGA	15.714	18.762	36.556	60.375
	Proposed MORTS	32.8493	42.7563	89.8573	203.1823
Status of priority customer	Proposed MORTS/NSGA	y	y	y	y
	Proposed NSGA	y	y	y	y
	Proposed MORTS	y	y	y	y

Table 4.9: Multi-fault full service restoration by proposed NSGA/MORTS technique

System		System-1	System-2	System-3	System-4
Number of fault		2	3	4	4
Out of service area (kW)	Proposed MORTS/NSGA	853.0	2000	300	8642.0
	Proposed NSGA	853.0	2000	300	8642.0
	Proposed MORTS	853.0	2000	300	8642.0
No. of manual Switch operations	Proposed MORTS/NSGA	4	3	5	2
	Proposed NSGA	4	3	5	2
	Proposed MORTS	4	4	5	2
No. of automatic Switch operations	Proposed MORTS/NSGA	0	1	3	2
	Proposed NSGA	0	1	3	2
	Proposed MORTS	0	1	3	2
Losses (kW)	Proposed MORTS/NSGA	95.300	187.30	148.11	12337.2
	Proposed NSGA	95.300	187.30	148.11	12337.2
	Proposed MORTS	95.300	187.30	148.11	12337.2
Run-time of the algorithm (sec.)	Proposed MORTS/NSGA	9.9282	11.3283	23.8292	42.8273
	Proposed NSGA	14.764	16.273	30.395	51.078
	Proposed MORTS	25.8472	36.8573	78.7364	183.7274
Status of priority customer	Proposed MORTS/NSGA	y	y	y	y
	Proposed NSGA	y	y	y	y
	Proposed MORTS	y	y	y	y

Table 4.10: Multi-fault partial service restoration by proposed NSGA/MORTS technique

System		System-1	System-2	System-3	System-4
Number of fault		2	3	4	4
Out-of-service area (kW)	Proposed MORTS/NSGA	1626.44	2730	750	11775.0
	Proposed NSGA	1626.44	2730	750	11775.0
	Proposed MORTS	1626.44	2730	750	11775.0
No. of manual Switch operations	Proposed MORTS/NSGA	2	4	6	3
	Proposed NSGA	2	4	6	3
	Proposed MORTS	2	4	6	3
No. of automatic Switch operations	Proposed MORTS/NSGA	2	2	3	2
	Proposed NSGA	2	2	3	2
	Proposed MORTS	2	2	3	2
Losses (kW)	Proposed MORTS/NSGA	158.4	244.2	139.8	12125.8
	Proposed NSGA	158.4	244.2	139.8	12125.8
	Proposed MORTS	158.4	244.2	139.8	12125.8
Run-time of the algorithm (sec.)	Proposed MORTS/NSGA	9.7738	12.4958	23.7364	43.1837
	Proposed NSGA	14.823	16.179	30.259	50.757
	Proposed MORTS	25.02933	36.83921	79.4323	183.9283
Status of priority customer	Proposed MORTS/NSGA	y	y	y	y
	Proposed NSGA	y	y	y	y
	Proposed MORTS	y	y	y	y

Table 4.11: Comparison of TBS and TC of proposed NSGA/MORTS technique

System	Method used	Single fault case (full service restoration)			Multiple fault case (full service restoration)		
		TBS (sec.)	TC (sec.)	Gap (sec.)	TBS (sec.)	TC (sec.)	Gap (sec.)
System-1	Proposed NSGA/ MORTS	8.8743	10.1328	1.2585	8.7865	9.9282	1.1417
	Proposed MORTS	24.9384	26.8392	1.9008	22.7263	24.2039	1.4776
	Proposed NSGA	10.7835	15.765	4.9815	9.0352	14.764	5.7288
System-2	Proposed NSGA/ MORTS	10.3492	12.7463	2.3971	9.7563	11.3283	1.572
	Proposed MORTS	29.8374	33.1023	3.2649	23.9384	27.0382	3.0998
	Proposed NSGA	12.6453	18.774	6.1287	9.0398	16.273	7.2332
System-3	Proposed NSGA/ MORTS	22.6583	25.8373	3.179	19.7363	23.8292	4.0929
	Proposed MORTS	62.0293	68.9284	6.8991	49.7236	53.7483	4.0247
	Proposed NSGA	28.8574	36.273	7.4156	23.8576	30.395	6.5374
System-4	Proposed NSGA/ MORTS	40.8372	46.8473	6.0101	39.8272	42.8273	3.0001
	Proposed MORTS	125.8574	130.857	4.9996	89.9134	95.2874	5.374
	Proposed NSGA	37.0384	61.530	24.4916	43.0239	51.078	8.0541

To investigate the effect of different number of iterations of either proposed NSGA or proposed MORTS in the proposed NSGA/MORTS on the speed of the overall solution, simulation studies have been carried out with different number of executions of proposed NSGA and proposed MORTS (in the proposed NSGA/MORTS technique). The results of different number of executions of proposed NSGA and proposed MORTS on the value of TC are shown in Tables 4.12 and 4.13 respectively. In all these studies, the different parameters chosen for proposed MORTS execution are as follows: INCREASE = 1.1, DECERASE = 0.9, CHAOS = 2 and REP = 2. In these two tables, a single fault full service restoration case in zone z52 in system-4 has been considered. For the results shown in Table 4.12, the number of execution of proposed MORTS has been kept fixed as one whereas for the results of Table 4.13, the number of proposed NSGA executions has been chosen as three. From these two tables, it is observed that variation of number of iterations of either proposed NSGA or proposed MORTS does not have any effect on the quality of the overall solution although this has a profound effect on the speed of the solution obtained. Specifically, it can be observed from these two tables that with a combination of three iterations of proposed NSGA and one iteration of proposed MORTS, the solution is obtained in minimum time.

Table 4.12: Effect of number of runs of proposed NSGA on the performance of proposed NSGA/MORTS technique

Number of runs proposed NSGA	1	2	3	4	5
Out-of-service area in kW	0.0	0.0	0.0	0.0	0.0
Number of manually switch operations	2	2	2	2	2
Number of automatic switch operations	2	2	2	2	2
Losses in kW	15181.3	15181.3	15181.3	15181.3	15181.3
TC in seconds	102.7262	65.4532	46.8473	83.7687	127.2341

Table 4.13: Effect of number of runs of proposed MORTS on the performance of proposed NSGA/MORTS technique

Number of runs of proposed MORTS	1	2	3	4	5
Out-of-service area in kW	0.0	0.0	0.0	0.0	0.0
Number of manually switch operations	2	2	2	2	2
Number of automatic switch operations	2	2	2	2	2
Losses in kW	15181.3	15181.3	15181.3	15181.3	15181.3
TC in seconds	46.8473	84.82736	154.8473	226.8373	273.3847

4.9 CONCLUSION

In this chapter, a multi-objective reactive tabu search (MORTS) technique has been developed for solving the service restoration problem in the distribution systems. The various practical issues of service restoration problem as considered in the previous chapter have also been taken into account in this chapter. The advantage of the proposed MORTS technique is that in contrast to the reactive tabu search (RTS) technique developed by Toune et al [48], the developed method does not require any weighting factors for solving a multi-objective optimization problem. From a large number of simulation studies, it has been found that the performance of the developed technique is significantly better that the RTS technique. Comparison of the performance of the proposed MORTS technique with that of the proposed NSGA method (discussed in Chapter 3) reveals that these two methods are somewhat complementary to each other. Therefore, to retain the advantages of these techniques, the combination of proposed NSGA and proposed MORTS (named proposed NSGA/MORTS) is made to solve the service restoration problem in distribution systems in this chapter. The detail studies conducted on all the four distribution systems considered in this thesis show that the proposed NSGA/MORTS outperforms both the proposed NSGA and proposed MORTS techniques. It (the proposed NSGA/ MORTS method) is better than the proposed MORTS method in terms of speed of the solution whereas, it is superior to the proposed NSGA technique in terms of the speed of the solution. The proposed NSGA technique has been already proved better than the techniques developed by Laun et al [42] and by

Miu et al [36]. Therefore, from the consideration of both the quality and speed of solutions, the proposed NSGA/ MORTS technique has been found to be the best.

Now, even though the speed of the combined technique is quite attractive, for on line solution of service restoration problem, the total software run time should be reduced further. A strategy for further reducing the run time of the service restoration software is described in the next chapter.

Chapter 5

ARTIFICIAL NEURAL NETWORK FOR SERVICE RESTORATION IN DISTRIBUTION SYSTEMS

5.1 INTRODUCTION

In previous chapters III and IV, the methodologies to solve the service restoration problem in distribution systems using non-dominated sorting genetic algorithm-II, multi-objective reactive tabu search and combination of non-dominated sorting genetic algorithm-II & multi-objective reactive tabu search have been developed. In All these three methods, the main emphasis has been given on both the accuracy of solution and the run-time needed by the algorithms and it has been found that in comparison to other existing methods, the developed methods give the restoration solution with high accuracy in less time. Among the developed methods in the last two chapters, the combined method has been found to be the best both in terms of accuracy and speed of execution. However, as it has been mentioned earlier that the solution of service restoration problem should be obtained as quickly as possible, the search for an appropriate technique for reducing the time taken to obtain the service restoration plan after a fault in distribution systems continues.

The techniques based on artificial intelligence such as artificial neural network and expert system offer such a possibility of obtaining the solution within a very short duration. However, the limitations of the expert system approach (knowledge of history of the systems and poor accuracy etc.) have already been enumerated in Chapter 1. The other alternative, the artificial neural networks (ANN) are computation tools, which operate on the principle of parallel processing while trying to mimic the human brain. As a result, once trained they are quite fast, especially while dealing with large volume of data which do not have any inherent mathematical correlation. Hence, any service restoration strategy based on artificial neural network technique is also expected to be quite fast and thus, it is expected that they will be quite suitable in modern distribution automation system to get service restoration plan after the fault. Guided by this philosophy, in the literature also ANN based service restoration technique in the distribution system has been suggested by Hsu et al [61]. However, in this method, all the objective functions and the constraints considered in this thesis have not been considered. Moreover, in the input of the ANN developed by Hsu et al [61], the fault location on which also service restoration plan depends, is not considered. To address these limitations and for further reduction in the time to find the service restoration plan, in this chapter, an ANN based methodology for service restoration in distribution systems is developed. Essentially, the development of the methodology comprises of two steps.

(1) A suitable chosen artificial neural network structure is to be trained first with a set of training data (input: loading pattern in the system under study and fault location, output: optimal switch ON/OFF status), with the help of a suitable training algorithm. The input patterns of the training data is obtained from the knowledge of the load pattern and fault location in the system while the output patterns of the training data would be obtained by using an appropriate methodology of service restoration.

(2) Once the artificial neural network is trained, with sufficiently large number of training data, the ANN learns the implicit correlation between the input patterns and the output patterns. In the next stage, new input patterns, which have not been used to train the ANN, would be fed to it to obtain the output of ANN within very short time. With these output, the performance of the designed ANN is verified.

In this work, the feed-forward multi-layer neural network with only one hidden layer has been used to solve the service restoration problem. For training of this ANN, the Levenberg-Marquardt algorithm has been used. As the detail of this algorithm is described in [94], the steps of the training algorithm are not described in this chapter. In the following sections, the different issues involved in the application of ANN to service restoration problem are discussed.

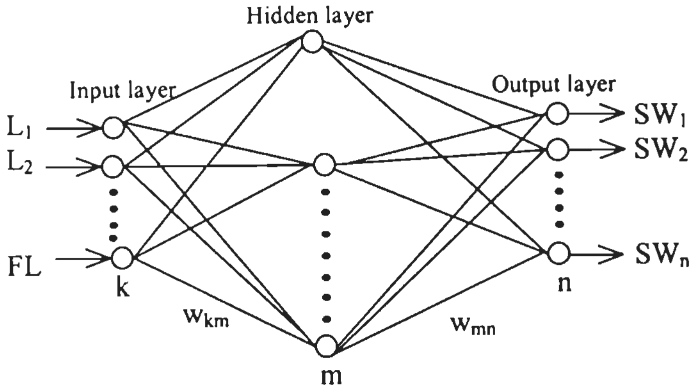
5.2 GENERATION OF INPUT AND OUTPUT PATTERNS

In this chapter, the load of zones (instead of bus load) and fault location are taken as input of the ANNs. It has been described in Chapter 2 (Section 2.2.1) that before service restoration study is commenced, the original network is mapped into a graph where the nodes represent the various zones of the distribution system. The load (real and reactive) of any particular zone is the sum of the loads (real and reactive) of the buses constituting that particular zone. The advantage of this approach (use of load of zone instead of load of buses) is much reduced dimension of the input space of the ANNs. For example, in system-4 described in Appendix 'A', there are altogether 173 buses distributed into 70 zones. Assuming that all the buses contain real and reactive power loads, a total of 173x2 = 346 loads need to be used at the ANN input in case the individual bus load pattern is utilized. On the other hand, if the zonal loading pattern is used, only 70x2 = 140 load values need to be given at the input of the ANN. In general, in any distribution system having 'M' zones, only '2M' load values need to be used in the ANN input. As the time needed to train any ANN increases with higher dimension of the input space, reduced number of nodes in input layer (achieved by load of zones) help to decrease the training time of the ANN significantly.

Apart from the load of different zones, the location of the fault also needs to be considered in the input of the ANN. This is due to the fact that for same loading of the zones, the fault in different zones results in different service restoration solution. Therefore, for the ANN to arrive at the appropriate service restoration solution, both the load of zones and the fault location (faulted zone) need to be given in the input of ANN. Thus, the total number of input values required the ANN input is '2M+1' where 'M' is the total number of zones in the distribution system under study.

To obtain the different loading patterns for any distribution system, a large number of random numbers have been generated within a specified range and subsequently, the kW and kVAR loads at all the buses of the distribution system corresponding to the 'base loading condition' (given in Appendix A) have been multiplied by these random numbers. With the new bus loading values, the load of zones is calculated. To generate the fault location, an integer number between 1 and M is generated randomly. A particular number generated randomly represents the fault in a particular zone. The combination of the randomly generated zonal loading pattern and the fault location constitutes the input pattern required by the ANN. To generate the output pattern (the service restoration solution represented in terms of the 'ON/OFF' status of the switches) corresponding to the input pattern, the proposed NSGA/MORTS algorithm in Chapter 4 has been used. As the output patterns represents the 'ON/OFF' status of the switches, the total number of output values of the ANN is 'SW', where 'SW' is the number of the switches in the distribution system under study. Fig. 5.1 shows the schematic diagram of the neural networks used in this chapter. Where, L_1, L_2

...... upto L_{k-1} are loads on the zones and SW_1, SW_2 ...... SW_n are status of switches. K -1 is the number of zones and n is the number of switches in the distribution system.



L_1, L_2 ...... upto L_{k-1} are loads on the zones.

FL is fault location.

SW_1, SW_2 ...... SW_n are status of switches.

K -1 is the number of zones.

n is the number of switches in the distribution system.

Figure 5.1. Multi-layer feed forward neural network

5.3 RESULTS AND DISCUSSION

The philosophy of the ANN described above have been applied to all the four distribution systems described in Appendix A. The systems system-1, system-2, system-3 and system-4 are divided into 7, 10, 32 and 70 zones respectively. Hence the total number of real and reactive loads in system-1, system-2, system-3 and system-4 are 14, 20, 64 and 140 respectively. As a result, the number of inputs (the number of nodes in the input layer of ANNs) of the ANN corresponding to system-1, system-2, system-3 and system-4 are 15, 21, 65 and 141 respectively. The number of switches in system-1, system-2, system-3 and system-4 are 10, 14, 37 and 75 respectively. Therefore, the number of nodes in the output layer of the ANN for system-1, system-2, system-3 and system-4 are 10, 14, 37 and 75 respectively. For generating the input-output patterns necessary for training (and testing) of the ANN, in this thesis, the real and reactive power loads at all the buses of the distribution system under study have been varied within a range of 45%-100% with respect to the 'base loading condition' and in this process, a total number of 1500 input-output patterns have been generated. Out of these 1500 patterns, 500 patterns have been used for training the ANN and the rest 1000 patterns (which had not been used for training), have been used to test the performance of the ANN.

To evaluate the performance of the ANN, in this study, two indices for testing errors have been formulated. These indices are called 'percentage error of pattern mismatch (PEPM)' and 'percentage error of status of switch mismatch (PESSM)' respectively. The first index, PEPM, is the percentage of output patterns given by ANN which are not exactly matching with the desired output patterns. The expression to find PEPM is given in eqn. (5.1).

$$\text{PEPM} = \frac{\text{No. of mismatch output patterns} \times 100}{\text{No. of testing patterns}} \tag{5.1}$$

The second measurement, PESSM, is the percentage of status of switches computed by ANN, which are not matching with the corresponding desired status of the switches. The expression used to compute PESSM is shown in eqn. (5.2).

$$\text{PESSM} = \frac{\text{No. of mismatch status of switches} \times 100}{\text{No. of switches} \times \text{No. of testing patterns}} \tag{5.2}$$

Regarding the computation of PESSM and PEPM, it is to be noted that, the status of an 'ON' switch and an 'OFF' switch are represented by the integer numbers 1 and 0 respectively. Therefore, ideally, the ANN should also produce these two integer numbers (1 and 0) at its output nodes corresponding to 'ON' and 'OFF' switches. However, actually, when an input pattern is given to the ANN, it produces continuous values (between 0 and 1) at its output nodes. To map these continuous values to the status of the switches, a threshold value has been chosen, i.e. any value less than or equal to the threshold value is taken to be 0 (denoting 'OFF' status of the switch) whereas any value greater than the threshold value is taken to be 1 (denoting 'OFF' status of the switch). In this work, a threshold value of 0.5 has been chosen. For the training of the ANN, a training performance goal of 1.0e-12 has been chosen and the values of different relevant parameters are given in Table 5.1. It is to be noted that the values indicated in Table 5.1 have been obtained by trail and error for satisfactory performance of the ANNs. The results are shown in Table 5.2.

Table 5.1: Different parameters of ANNs

System	Learning coefficient	Momentum factor	No. of hidden nodes
System-1	0.15	0.85	6
System-2	0.20	0.82	10
System-3	0.20	0.73	12
System-4	0.22	0.76	15

Table 5.2: Performance of the ANNs in all the four test systems

System	Test performance of ANN		Run time to give the restoration plan (sec.)	
	PEPM	PSSPM	ANN	Proposed NSGA/MORTS
System-1	0.9	0.8	0.163	10.1328
System-2	0.9	0.9	0.1765	12.7463
System-3	1.3	1.0	0.235	25.8373
System-4	3.8	2.9	0.286	46.8473

Table 5.2 shows that for all the four systems under study, the values of both PEPM and PSSPM are quite satisfactory (the error is within 4%). However, with increasing size of the distribution system, the testing errors also increase. As the size of the distribution system increases, the dimensions of both the input space (number of load zones) and the output space (number of switches) increase. With increasing dimension of input and output space, the generalization capability of the ANN becomes poorer thereby increasing the testing errors. Moreover, this table also shows that the run-time of the ANN is significantly less than the run-time needed by the Proposed NSGA/MORTS to give the restoration solution thereby making it more suitable for on-line application.

5.3.1 EFFECT OF MEASUREMENT ERROR

In the results shown in Table 5.1, it has been assumed that the available measurements (the loading patterns) are free of any measurement error. However, in practical life, no measurement is absolutely error free; it always contains some amount of measurement noise. Therefore, to get the accurate service restoration plan in the presence of these measurement errors, these measurement noises should also be taken into account on the performance of artificial neural network. To evaluate the performance of the ANN in the presence of noisy data, the input parts of all the testing patterns have been considered to be containing errors. The noisy measurement data have been simulated by adding a Gaussian noise (with appropriate mean and variance) to the ideal, error free load data. Although typical maximum level of measurement noise is around ±3%, in this thesis, a more stringent evaluation of the ANN has been done by assuming an error level of ±10%. The performances of the ANNs are shown in Table 5.3.

Table 5.3: Performance of the ANNs tested with noisy input data (ANNs have been trained with noiseless input data)

System	Test performance of ANN		Run-time to give the restoration plan (sec.)	
	PEPM	PSSPM	ANN	Proposed NSGA/MORTS
System-1	8.7	5.2	0.171	10.1328
System-2	10.6	6.2	0.179	12.7463
System-3	15.8	7.3	0.283	25.8373
System-4	28.2	10.1	0.311	46.8473

Comparison of Tables 5.2 and 5.3 shows that the when the ANNs are trained with noiseless data and tested with noisy data, their performance degrades significantly. As a result, the ANNs need also to be trained with noisy data to improve their generalization capabilities and prediction error. Towards, this goal, the input data parts of the training patterns have also been considered to be contaminated with ±10% noise. In this case also, a training performance goal of 1.0e-12 has been chosen. The testing errors of the ANNs are shown in Table 5.4. Comparison of Tables 5.3 and 5.4 shows that when the ANNs are trained with noisy data, their generalization performances improve significantly, although the performances are not as good as obtained in the ideal case (no noise in either training or testing data).

Table 5.4: Performance of the ANNs tested with noisy input data (ANNs have been trained with noisy input data)

System	Test performance of ANN		Run time to give the restoration plan (sec.)	
	PEPM	PSSPM	ANN	Proposed NSGA/MORTS
System-1	0.9	0.9	0.1736	10.1328
System-2	1.1	0.9	0.187	12.7463
System-3	1.6	1.1	0.291	25.8373
System-4	5.5	4.2	0.357	46.8473

5.4 CONCLUSION

- The feedback multilayer neural networks are designed and trained with satisfactory performance to find the service restoration solution for four distribution systems under study.
- The fault location and loading patterns of the distribution (on which the service restoration solution depends) are considered.
- The knowledge of the history (like operators experience etc.) of the distribution systems is not required.
- The artificial neural networks can be used quite effectively for reducing the run-time of the service restoration study thereby making them suitable for on-line application.
- For obtaining the accurate service restoration solution under practical condition, the neural network should be trained by noisy input data.

Chapter 6

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

6.1 GENERAL

In this thesis, an attempt has been made to solve the service restoration problem in power distribution systems. In order to take into account various practical operating constraints, service restoration problem is essentially a multi-objective, multi-constraint optimization problem. Specifically, the following practical issues of service restoration problem have been considered in this thesis.

- The electric supply should be restored as much as possible.
- The electric supply should be restored as quickly as possible.
- The remotely controlled switch operations should be as minimum as possible.
- The manually controlled switch operations should be as minimum as possible.
- The losses in the distribution systems after restoration of supply should be as minimum as possible.
- The radiality of the distribution systems should be maintained.
- The priority customers should be always supplied.
- The current constraints and voltage constraints should not be violated.

To solve this important task of service restoration, considerable work has been already done in the literature. However, to the best of the knowledge of the author of this thesis, not all the issues listed above have been considered together in any single paper or publication.

In this thesis, different methods have been developed to solve the service restoration problem in electric distribution systems and those developed methods have been tested on four distribution systems. The results obtained in various test systems show the effectiveness of the developed methods.

6.2 SUMMARY OF THE IMPORTANT FINDINGS

In Chapter 2, the dynamic load flow is developed. In a service restoration study, load flow solution needs to be computed repeatedly to compute the value of the objective functions as well as to check the violations of the constraints, if any. As a result, the load flow solution should be computed quite fast. Moreover, during the course of the service restoration study, many different configurations of the distribution system also need to be considered and therefore, the algorithm of the load flow should be generalized enough to be able to handle any configuration of the system. To address these two issues, a 'two-way-linked-list' based dynamic load flow method has been developed in this chapter and it is found from the simulation study that the developed method achieves the same accuracy of solution in a reduced time as compared to some of the existing methods.

In Chapter 3, a NSGA-II based method has been developed for solving the multi-objective, multi-constraint service restoration problem. The advantage of the proposed NSGA-II based technique over the traditional GA based technique is that the developed technique does not need any weighting factors (to convert the multi-objective optimization problem into a single objective optimization problem) as GA does. To speed up the solution process, a faster version, namely proposed NSGA-II technique, has also been implemented in this thesis. The main findings of this chapter are:

- The accuracy of the solutions obtained by developed methods is better than other existing methods.
- By including the PFC in the initial population, the run-time of the developed methods is considerably reduced.
- There is a considerable gap between TBS and TC of the developed methodologies.

Chapter 4 presents a technique based on Reactive Tabu Search (RTS) method. However, as the traditional RTS method is able to handle only a single objective function optimization problem, the RTS has been modified so as to enable it to handle multi-objective optimization problems, resulting into a new Multi-objective Reactive Tabu Search (MORTS) method. MORTS developed is implemented to solve the service restoration problem. The main conclusions of this chapter are:

- The accuracy of the developed method is satisfactory and same as that of the accuracy obtained by the NSGA-II based technique.

- The gap between TBS and TC is less in comparison to the NSGA-II based method.
- The total run-time of MORTS based technique is more than that of NSGA-II based technique.

To retain the advantage and to eliminate the disadvantage of both methods, both methods are combined. The main observations regarding the performance of the combined method are:

- The accuracy of the combined method is same as that of the NSGA-II based method and MORTS based technique.
- The run-time and gap between TBS and TC of the combined method is least in comparison to other (NSGA-II and MORTS based) methods.

To reduce the run time of the service restoration algorithm further, in Chapter 5, the service restoration problem is solved using multi-layer feed-forward neural network The Levenberg-Marquardt algorithm is used to train the ANNs. The input patterns required for ANN consists of zonal loading and fault location. The dimension space of the input of ANN is reduced, if zonal loading pattern and fault location is taken instead of bus loading pattern and fault location. As a result, the training time of the ANN is reduced. The effect of noise and error in the input of ANN is also considered. It is found that for achieving satisfactory performance of the ANN under practical load data (containing measurement errors), the ANN should be trained with practical field data (not with simulated data). Also the run-time of the ANN is significantly lower than that obtained with the combined technique (proposed NSGA/MORTS) of chapter 4.

6.3 SUGGESTIONS FOR FUTURE WORK

- Three important issues of Multi-objective evolutionary algorithms (MOEAs) are convergence, diversity in Pareto Optimal solutions and computational time. MOEAs should be well converged, the diversity in the Pareto Optimal solutions should be good which is helpful to prevent premature convergence, and computational time should be low. Therefore, the service restoration problem in distribution systems can be solved by such a MOEA which has good trade-off among these three issues to get the accurate service restoration plan in minimum time.

- In this work, as the outcome of the service restoration study, only the 'ON/OFF' statuses of the switches have been obtained. However, for practical implementation, the proper switching sequence (of the switches following the service restoration solution) should be decided taking into account different operational constraints including cold load pick up.

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LIST OF PAPERS PUBLISHED FROM THE WORK

Based on the work carried out, following papers are published/ communicated for publication in various journal and conferences.

1. "Dynamic load flow for radial distribution system" National conference on Power Electronics and Power Systems, St. Joseph's College of Engineering Chennai (India), January 28-29, 2005, pp. 471-479.
2. "Fast service restoration in distribution system using Genetic Algorithm" National conference on Power Engineering Practices & Energy Management, Thaper Institute of Engineering & Technology, Patiala, Punjab (India), January 28-29, 2005, pp. 317-321.
3. "Service restoration in distribution system using non-dominated sorting genetic algorithm" Electric Power System Research. **In press**
4. "Artificial neural network for service restoration in distribution systems" International conference on "Systematics, Cybernetics and Informatics" Pentagram Research Centre, Hyderabad, January 04-08, 2006, pp. 295-298.
5. "Multi-objective, multi-constraint service restoration of electric power distribution system with priority customers" IEEE Transaction on Power Delivery. **Under review**
6. "Genetic algorithm for supply restoration in distribution system with priority customers" 9th International conference on Probabilistic Methods Applied to Power System, Sweden, 11-15 June, 2006. **Under review**

APPENDIX A

In this appendix, the data of four test systems namely system-1, system-2, system-3 and system-4 used in the present thesis for research work is given. The brief summary of each system is given in table A-1. The single line diagram, feeder data and bus load data of all the four systems follow after table A-1.

Table - A.1: Brief summary of the test systems

SL. No.	Description	No. of buses	No. of switches	Systems nominal voltage (KV)	Total system Load	
					KW	KVAR
1	System-1	13	10	11	2652	866
2	System-2	10	14	13.8	5600	4080
3	System-3	33	37	12.66	3715	2300
4	System-4	173	75	33	169476	16421

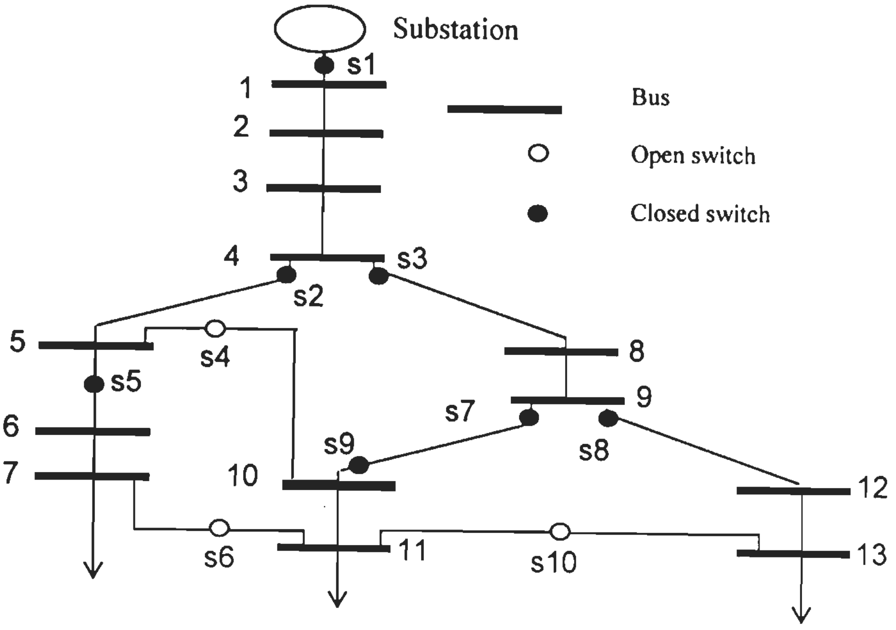


Figure A.1 – Single line diagram of system-1

In System-1, the switches s1, s4 and s7 are remote controlled automatic switches while the rest of the switches are manually controlled.

Table – A.2: Feeder data of system-1

Line no.	From bus	To bus	Resistance in ohm	Reactance in ohm
1	1	2	0.148	0.287
2	2	3	0.044	0.124
3	3	4	0.028	0.078
4	4	8	0.160	0.310
5	8	9	0.029	0.083
6	9	10	0.053	0.151
7	10	11	0.059	0.166
8	9	12	0.038	0.107
9	12	13	0.037	0.104
10	4	5	0.060	0.167
11	5	6	0.034	0.097
12	6	7	0.032	0.092
13	7	11	0.047	0.101
14	5	10	0.042	0.083
15	11	13	0.056	0.114

Table – A.3: Bus load data of system-1

Bus no.	Real power in KW	Reactive power in KVAR
1	0.000000	0.000000
2	473.0000	155.0000
3	127.0000	41.0000
4	35.0000	11.0000
5	438.0000	144.0000
6	211.0000	69.0000
7	42.0000	13.0000
8	473.0000	155.0000
9	127.0000	41.0000
10	35.0000	11.0000
11	438.0000	144.0000
12	211.0000	69.0000
13	42.0000	13.0000

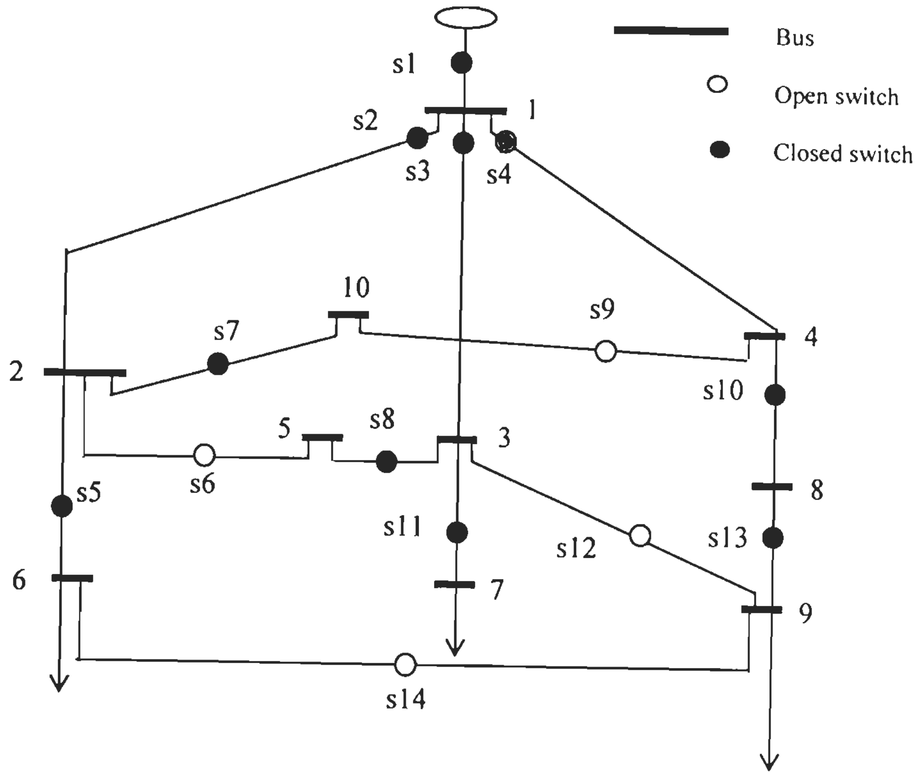


Figure A.2 – Single line diagram of system-2

In System-2, the switches s1, s2, s3, s7 and s12 are remote controlled automatic switches while the rest of the switches are manually controlled.

Table A.4: Feeder data of system-2

Line no.	From bus	To bus	Resistance in ohm	Reactance in ohm
1	1	2	0.7820	0.2120
2	1	3	0.7820	0.2120
3	1	4	1.5640	0.4240
4	3	5	1.1730	0.3180
5	2	6	1.1730	0.3180
6	3	7	1.3685	0.3710
7	4	8	1.1730	0.3180
8	8	9	1.1730	0.3180
9	2	10	1.1730	0.3180
10	2	5	0.7820	0.3180
11	4	10	1.1730	0.3180
12	3	9	0.7820	0.2120
13	6	9	0.7820	0.2120

Table A.5: Bus load data of system-2

Bus no.	Real power in KW	Reactive power in KVAR
1	00	000
2	600	400
3	500	300
4	100	90
5	600	400
6	1300	1100
7	1300	1000
8	100	90
9	800	600
10	300	100

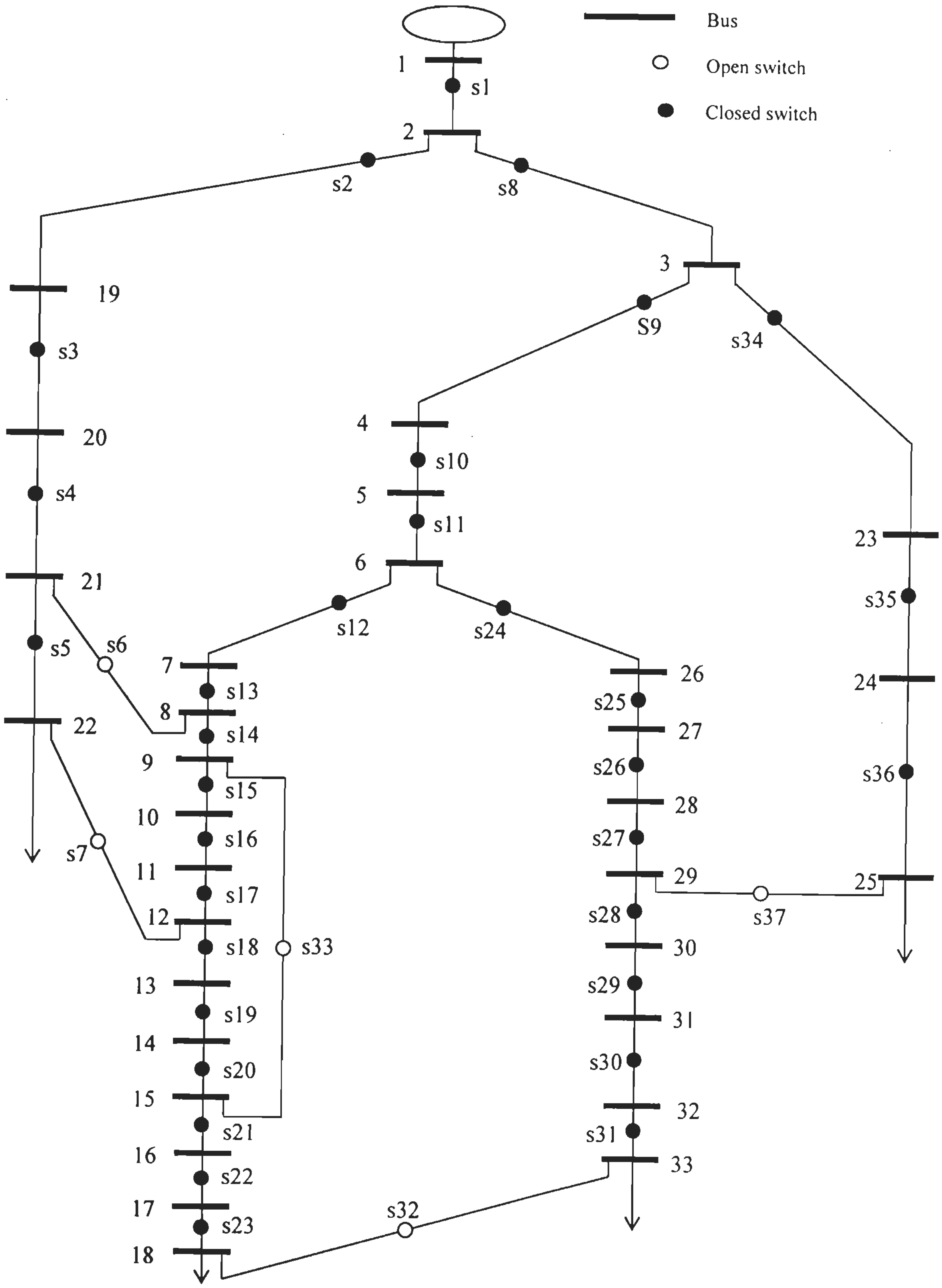


Figure A.3 – Single line diagram of system-3

In System-3, the switches s2, s3, s6, s8, s11, s24 and s34 are remote controlled automatic switches while the rest of the switches are manually controlled.

Table – A.6: Feeder data of system-3

Line no.	From bus	To bus	Resistance in ohm	Reactance in ohm
1	1	2	0.0922	0.0470
2	2	3	0.4930	0.2511
3	3	4	0.3660	0.1864
4	4	5	0.3811	0.1941
5	5	6	0.8190	0.7070
6	6	7	0.1872	0.6188
7	7	8	0.7114	0.2351
8	8	9	1.0300	0.7400
9	9	10	1.0440	0.7400
10	10	11	0.1966	0.0650
11	11	12	0.3744	0.1238
12	12	13	1.4680	1.1550
13	13	14	0.5416	0.7129
14	14	15	0.5910	0.5260
15	15	16	0.7463	0.5450
16	16	17	1.2890	1.7210
17	17	18	0.7320	0.5740
18	2	19	0.1640	0.1565
19	19	20	1.5042	1.3554
20	20	21	0.4095	0.4784
21	21	22	0.7089	0.9373
22	3	23	0.4512	0.3083
23	23	24	0.8980	0.7091
24	24	25	0.8960	0.7011
25	6	26	0.2030	0.1034
26	26	27	0.2842	0.1447
27	27	28	1.0590	0.9337
28	28	29	0.8042	0.7006
29	29	30	0.5075	0.2585
30	30	31	0.9744	0.9630
31	31	32	0.3105	0.3619
32	32	33	0.3410	0.5302
33	8	21	2.0000	2.0000
34	12	22	2.0000	2.0000
35	9	15	2.0000	2.0000
36	18	33	0.5000	0.5000
37	25	29	0.5000	0.5000

Table - A.7: Bus data of system-3

Bus no.	Real power in KW	Reactive power in KVAR
1	00	000
2	100.0	60.0
3	90.0	40.0
4	120.0	80.0
5	60.0	30.0
6	60.0	20.0
7	200.0	100.0
8	200.0	100.0
9	60.0	20.0
10	60.0	20.0
11	45.0	30.0
12	60.0	35.0
13	60.0	35.0
14	120.0	80.0
15	60.0	10.0
16	60.0	20.0
17	60.0	20.0
18	90.0	40.0
19	90.0	40.0
20	90.0	40.0
21	90.0	40.0
22	90.0	40.0
23	90.0	50.0
24	420.0	200.0
25	420.0	200.0
26	60.0	25.0
27	60.0	25.0
28	60.0	20.0
29	120.0	70.0
30	200.0	600.0
31	150.0	70.0
32	210.0	100.0
33	60.0	40.0

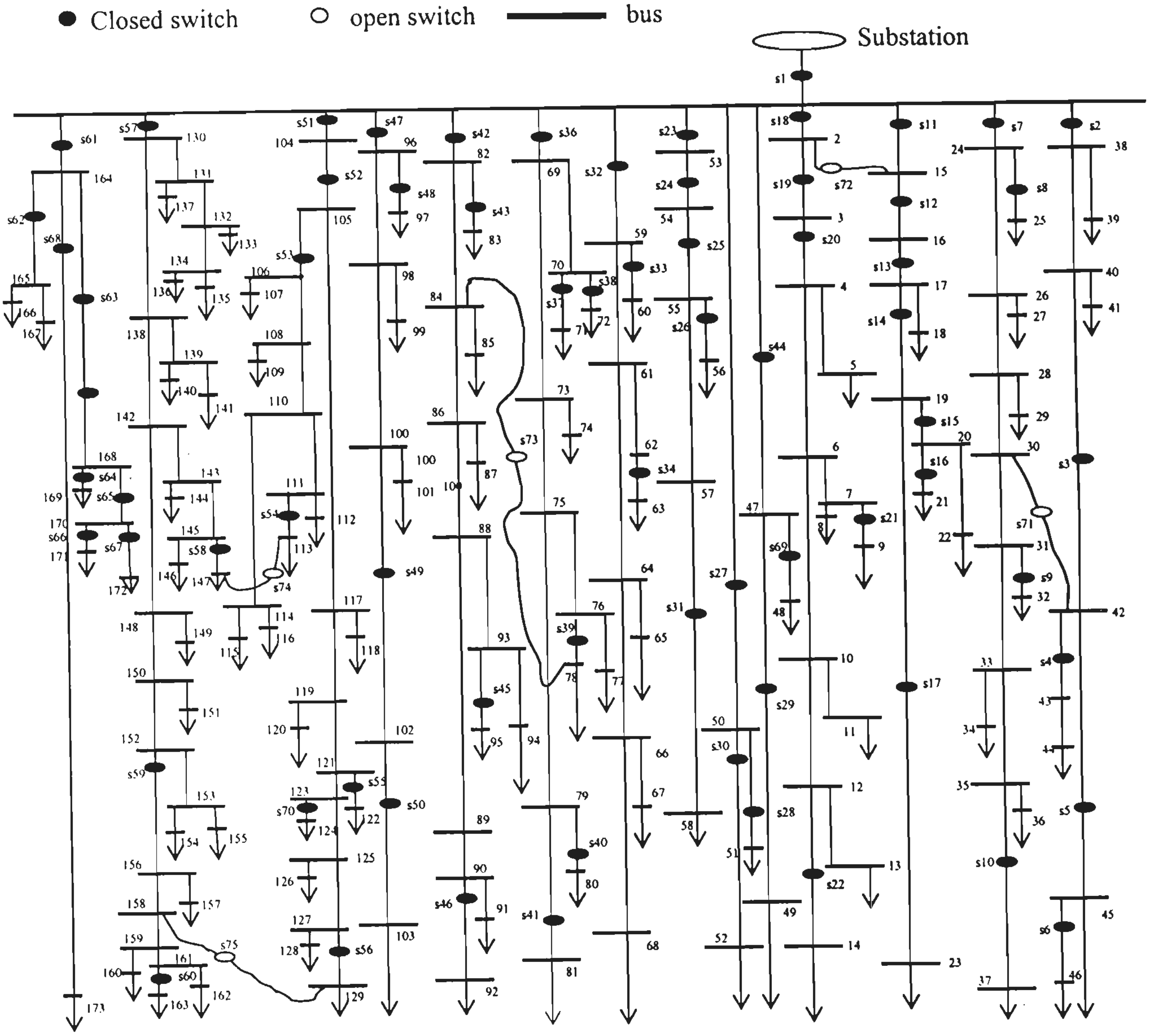


Figure A.4 - Single line diagram of system-4

In System-4, the switches s7, s71, s13, s20, s32, s42, s49, s52, s74 and s63 are remote controlled automatic switches while the rest of the switches are manually controlled.

Table - A.8: Feeder data of system-4

Line no.	From bus	To bus	Resistance in ohm	Reactance in ohm
1	1	2	0.1833	0.1940
2	2	3	1.0851	1.1487
3	3	4	0.8212	0.8693
4	4	6	0.1760	0.1863
5	4	5	0.7039	0.7451
6	6	7	0.0220	0.0233
7	6	10	0.2053	0.2173
8	7	8	0.0880	0.0931
9	7	9	0.2933	0.3105
10	10	11	0.1466	0.1552
11	10	12	0.8212	0.8693
12	12	13	0.3483	0.3687
13	12	14	0.1466	0.1552
14	1	15	0.1833	0.1940
15	15	16	1.0851	1.1487
16	16	17	0.8505	0.9003
17	17	18	0.3519	0.3725
18	17	19	0.3813	0.4036
19	19	20	0.1760	0.1863
20	19	23	2.2949	2.4293
21	20	21	0.0367	0.0388
22	20	22	0.0880	0.0931
23	1	24	0.7845	0.8305
24	24	25	0.6965	0.7373
25	24	26	0.0770	0.0815
26	26	27	0.0550	0.0582
27	26	28	0.0770	0.0815
28	28	29	0.1283	0.1358
29	28	30	0.2236	0.2367
30	31	32	0.1833	0.1940
31	31	33	0.1540	0.1630
32	33	34	0.3666	0.3881
33	33	35	0.1283	0.1358
34	35	36	0.1283	0.1358
35	35	37	0.0953	0.1009
36	30	31	0.1100	0.1164
37	1	38	0.6965	0.7373
38	38	39	0.1540	0.1630
39	38	40	0.1833	0.1940
40	40	41	0.0110	0.0116
41	40	42	0.2053	0.2173
42	42	45	0.3666	0.3881
43	42	43	0.3666	0.3881
44	43	44	0.0073	0.0078

45	45	46	1.2831	1.3582
46	1	47	2.3462	2.4836
47	47	48	0.0367	0.0388
48	48	49	0.1466	0.1552
49	1	50	1.2611	1.3349
50	50	51	0.2053	0.2173
51	50	52	0.2346	0.2484
52	1	53	1.2611	1.2611
53	53	54	0.5866	0.6209
54	54	55	0.1833	0.1940
55	55	56	0.5646	0.5976
56	55	57	0.6232	0.6597
57	57	58	0.7332	0.7761
58	1	59	0.4766	0.5045
59	59	60	0.6599	0.6985
60	59	61	0.8432	0.8926
61	61	62	0.2346	0.2484
62	61	64	0.3666	0.3881
63	62	63	1.4297	1.5135
64	64	65	0.0183	0.0194
65	64	66	0.2053	0.2173
66	66	67	0.0073	0.0078
67	66	68	0.4399	0.4657
68	1	69	0.1833	0.1940
69	69	70	0.4766	0.5045
70	69	73	0.2530	0.2678
71	70	71	0.2200	0.2328
72	70	72	1.1548	1.2224
73	73	74	0.0183	0.0194
74	73	75	0.2200	0.2328
75	75	76	0.7332	0.7761
76	75	79	0.3299	0.3493
77	76	77	0.0220	0.0233
78	76	78	1.8330	1.9403
79	79	80	0.0733	0.0776
80	79	81	1.6864	1.7851
81	1	82	0.5279	0.5588
82	82	83	0.0367	0.0388
83	82	84	0.9678	1.0245
84	84	85	0.0293	0.0310
85	84	86	0.3886	0.4114
86	86	87	0.1466	0.1552
87	86	88	0.2933	0.3105
88	88	89	0.1980	0.2096
89	88	93	0.0880	0.0931
90	89	90	0.2200	0.2328
91	90	91	0.0513	0.0543
92	90	92	0.7332	0.7761

93	93	94	0.0183	0.0194
94	93	95	0.5132	0.5433
95	1	96	0.5279	0.5588
96	96	97	0.0367	0.0388
97	96	98	0.2640	0.2794
98	98	99	0.0183	0.0194
99	98	100	0.0880	0.0931
100	100	101	0.0587	0.0621
101	100	102	1.3857	1.4669
102	102	103	0.9532	1.0090
103	1	104	0.1650	0.1746
104	104	105	0.3299	0.3493
105	105	106	0.1100	0.1164
106	105	117	0.0587	0.0621
107	106	107	0.0110	0.0116
108	106	108	0.3226	0.3415
109	108	109	0.0183	0.0194
110	108	110	0.0587	0.0621
111	110	111	0.0880	0.0931
112	110	114	0.1100	0.1164
113	111	112	0.0110	0.0116
114	111	113	0.0587	0.0621
115	114	115	0.0183	0.0194
116	114	116	0.0293	0.0310
117	117	118	0.0367	0.0388
118	117	119	0.1173	0.1242
119	119	120	0.0367	0.0388
120	119	121	0.1100	0.1164
121	121	122	1.4664	1.5523
122	121	123	0.1210	0.1281
123	123	124	0.0183	0.0194
124	123	125	0.1173	0.1242
125	125	126	0.0147	0.0155
126	125	127	0.2200	0.2328
127	127	128	0.1063	0.1125
128	127	129	0.4106	0.4346
129	1	130	0.4766	0.5045
130	130	131	0.0880	0.0931
131	130	138	0.0880	0.0931
132	131	132	0.0293	0.0310
133	131	137	0.0293	0.0310
134	132	133	0.1466	0.1552
135	132	134	0.0880	0.0931
136	134	135	0.0293	0.0310
137	134	136	0.0293	0.0310
138	138	139	0.0880	0.0931
139	138	142	0.0293	0.0310
140	139	140	0.0293	0.0310

141	139	141	0.0587	0.0621
142	142	143	0.0587	0.0621
143	142	148	0.1100	0.1164
144	143	144	0.0183	0.0194
145	143	145	0.1100	0.1164
146	145	146	0.0587	0.0621
147	145	147	0.0587	0.0621
148	148	149	0.0183	0.0194
149	148	150	0.0880	0.0931
150	150	151	0.0183	0.0194
151	150	152	0.0587	0.0621
152	152	153	0.1466	0.1552
153	152	156	0.1466	0.1552
154	153	154	0.1100	0.1164
155	153	155	0.1833	0.1940
156	156	157	0.0587	0.0621
157	156	158	0.0880	0.0931
158	158	159	0.1100	0.1164
159	159	160	0.1173	0.1242
160	159	161	0.3519	0.3725
161	161	162	0.0293	0.0310
162	161	163	0.5866	0.6209
163	1	164	4.5825	4.8508
164	164	165	0.0183	0.0194
165	164	168	0.6416	0.6791
166	164	173	3.2994	3.4926
167	165	166	0.0147	0.0155
168	165	167	0.5499	0.5821
169	168	169	0.1100	0.1164
170	168	170	0.7992	0.8460
171	170	171	0.2090	0.2212
172	170	172	0.4399	0.4657
173	2	15	0.2090	0.2212
174	38	42	0.5499	0.5821
175	78	84	0.5499	0.5821
176	113	147	0.2090	0.2212
177	129	158	0.6416	0.6791

Table – A.9: Bus load data of system-4

Bus no.	Real power in KW	Reactive power in KVAR
1	0	0
2	0	0
3	3134	313
4	0	0
5	0	0
6	0	0
7	0	0
8	5970	60
9	3134	313
10	0	0
11	117	12
12	0	0
13	100	10
14	0	0
15	0	0
16	4975	498
17	0	0
18	249	25
19	0	0
20	0	0
21	3134	313
22	289	29
23	4975	498
24	0	0
25	4975	498
26	0	0
27	503	50
28	0	0
29	351	35
30	0	0
31	0	0
32	4975	498
33	0	0
34	784	78
35	0	0
36	131	13
37	3134	313
38	0	0
39	386	39
40	0	0
41	146	15
42	0	0
43	0	0
44	103	10

45	4975	498
46	4975	498
47	0	0
48	4975	498
49	0	0
50	4975	498
51	1512	151
52	1170	117
53	4975	498
54	4975	498
55	0	0
56	4975	498
57	0	0
58	4975	498
59	0	0
60	746	75
61	0	0
62	597	60
63	4975	498
64	0	0
65	100	10
66	0	0
67	182	18
68	0	0
69	100	10
70	0	0
71	4975	498
72	3134	313
73	0	0
74	498	50
75	0	0
76	0	0
77	1756	176
78	0	0
79	0	0
80	4975	498
81	3134	313
82	0	0
83	4975	498
84	0	0
85	199	20
86	0	0
87	622	62
88	0	0
89	3134	313
90	0	0
91	448	45
92	4975	498

93	0	0
94	0	0
95	0	0
96	0	0
97	4975	498
98	0	0
99	80	8
100	0	0
101	174	17
102	3134	313
103	4975	498
104	0	0
105	0	0
106	0	0
107	995	100
108	0	0
109	143	14
110	0	0
111	0	0
112	147	15
113	0	0
114	0	0
115	149	15
116	0	0
117	0	0
118	179	18
119	0	0
120	149	15
121	0	0
122	3134	313
123	0	0
124	4975	498
125	0	0
126	199	20
127	0	0
128	219	22
129	0	0
130	0	0
131	0	0
132	0	0
133	498	50
134	0	0
135	498	50
136	246	25
137	572	57
138	0	0
139	0	0
140	249	25

141	165	17
142	0	0
143	0	0
144	100	10
145	0	0
146	100	10
147	0	0
148	0	0
149	249	25
150	0	0
151	80	8
152	0	0
153	0	0
154	154	15
155	199	20
156	0	0
157	907	91
158	0	0
159	0	0
160	100	10
161	0	0
162	101	10
163	3134	313
164	0	0
165	0	0
166	0	0
167	0	0
168	0	0
169	4975	498
170	0	0
171	4975	498
172	4975	498
173	0	0

APPENDIX B

Domination: A solution $x^{(i)}$ is said to dominate the other solution $x^{(j)}$, if $x^{(j)}$ is not better than $x^{(i)}$ in any objective function and $x^{(i)}$ is strictly better than $x^{(j)}$ in at least one objective function.

Example of Domination: Let us consider a minimization problem with two conflicting objective functions. Let the population size be 4 and the values of the objective functions of the parent population (comprising the solutions A, B, C and D) and the offspring population (comprising the solutions E, F, G and H) are as given in Table B.1 below.

Table – B.1 Solutions and their objective functions

Solution	First objective function (F_1)	Second objective function (F_2)
A	2.5	6.9
B	1.6	0.8
C	0.5	4
D	3.8	2.6
E	5.2	5.6
F	3.1	4.2
G	6.1	4.9
H	6.3	7

In the above table, the values of both the objective functions of solution C are less than the values of both the objective functions of the solution A, E, F, G and H. Therefore, solution C is dominating the solutions A, E, F, G and H or in other words, solutions A, E, F, G and H are dominated by solution C. The solution B and C are not dominated by any solution. Such solutions are called non-dominated solutions and set of such solutions is called the non-dominated set. Therefore, in this case, the non-dominated set = {B C}.

Constraint domination: Domination in the presence of constraints is called constraint domination. It is found as follows. If any constraint is violated by a solution j and is not violated by other solution i, the solution j is constraint dominated by solution i irrespective of the values of the objective functions. If both solutions violate the constraints, the solution which has higher value of constraint violation is constraint dominated by the solution having smaller value of constraint violation. If both solutions do not violate any constraint, constraint domination will be decided by the definition of "domination".

Example of constraint Domination: Let us revisit the minimization problem as shown in Table B.1 and let us assume that one constraint is now incorporated in this problem. The values of the objective functions and the constraint corresponding to all the solutions are given in Table B.2 below. Let the maximum and minimum limits on the constraint are +2 and -2 respectively.

Table – B.2 Solutions, their objective functions and constraints

Solution (S)	First objective function (F_1)	Second objective function (F_2)	Constraint
A	2.5	6.9	1.2
B	1.6	0.8	2.4
C	0.5	4	-1.1
D	3.8	2.6	2.4
E	5.2	5.6	1.8
F	3.1	4.2	-0.7
G	6.1	4.9	0.5
H	6.3	7	- 4.5

In the above table, the constraint is not violated in the solutions A, C, E, F and G while in the remaining solutions B, D and H the constraint is violated. Therefore the solutions A, C, E, F and G are constraint dominating the solutions B, D and H. Among the solutions A, C, E, F and G which are not violating the constraint, C has better solutions than A, E, F, and G, therefore, C is dominating A, E, F, and G according to definition of dominations. Among the solutions B, D and H which are violating the constraint, solution H has higher value of constraint violation than solutions B and D, therefore, solution H is constraint dominated by solutions B and D.

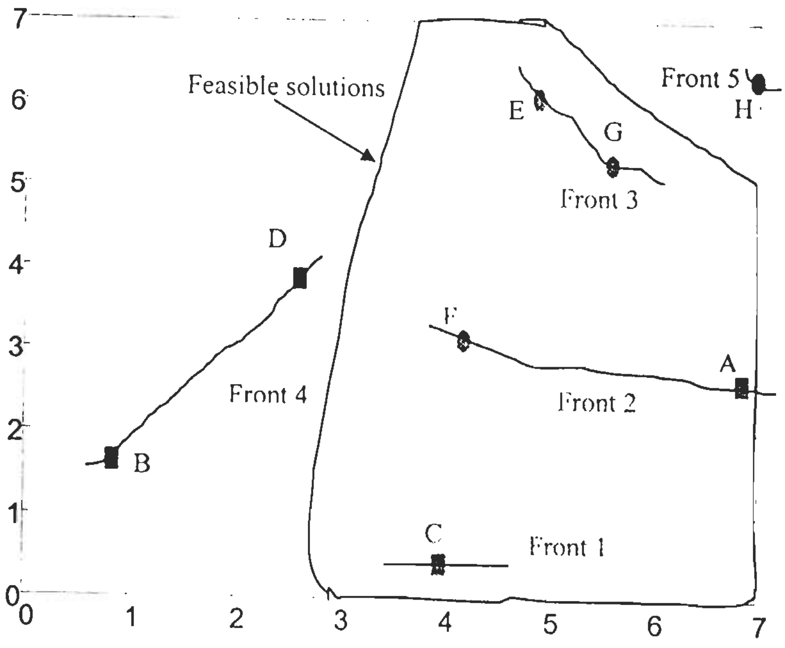
Front formation: The basic procedure for front formation has already been described in step 5 of Section 3.3 and therefore it is not repeated here. However, the procedure is illustrated with an example as described below.

Example of front formation: Let us revisit the set of solutions shown in table B.2. From the set of solutions in table B.2, i.e., {A B C D E F G H}, the non-dominated set is = {C} which is not dominated by any member of {A B C D E F G H}. Therefore, first rank is allotted to the solution C.

In the set of remaining solutions = {A B D E F G H}, the non-dominated set is = {F A} and these are not dominated by any member of {A B D E F G H}. Therefore, second rank is allotted to the solutions F and A.

In the set of remaining solutions = {B D E G H}, the non-dominated set is = {E G} which are not dominated by any member of {B D E G H}. Therefore, third rank is allotted to the solutions E and G.

In the set of remaining solutions = {B D H}, the non-dominated set is = {B D} which are not dominated by any other member of {B D H}. Therefore, fourth rank is allotted to the solutions B and D.



● : The solution belonging to offspring population.

■ : The solution belonging to parent population.

Figure B.1: Pictorial representation of fronts

Fifth rank is allotted to the only remaining solution H. The different fronts allotted are shown pictorially in the following figure B.1.

Crowding distance: The crowding distance of a solution tells the crowd ness of other solutions around it in search space. Higher crowding distance means lesser crowdness. Lesser crowding distance means higher crowdness.

Calculation of crowding distance: Let us take N solutions of a multi-objective problem which has M objective functions. Store m^{th} objective function of all solutions in an array "F^m". m=1..........M. Store all elements of array "F^m" in another array "ordered_F^m" in descending order (in case of minimization of objective function). Sort N solutions in worse order (descending order) of F^m and store in I^m . Initially, assign the crowding distance $\text{dist}=0$, for all objectives of each solution except boundary solutions. Assign a large crowding distance to boundary solutions

$\text{dist}_{I^m(1)} = \text{dist}_{I^m(N)} = \infty$. For all other solutions, the crowding distance of m^{th} objective function of $I^m(n)$ solution:

$$\text{dist}_{I^m(n)} = \text{dist}_{I^m(n)} + \frac{\text{ordered\_F}^m(n-1) - \text{ordered\_F}^m(n+1)}{F^m_{max} - F^m_{min}}$$

Where

n=2, 3............N-1

F^m_{max} and F^m_{min} are population-maximum and population-minimum value of the m^{th} objective function respectively.

Worked out example of crowding distance:- To find the crowding distances of S =[A B C D E F G H] given in table 1:

N=8, M=2, m=1,2.

$F^1 = [2.5\ 1.6\ 0.5\ 3.8\ 5.2\ 3.1\ 6.1\ 6.3]$,

ordered_$F^1 = [6.3\ 6.1\ 5.2\ 3.8\ 3.1\ 2.5\ 1.6\ 0.5]$,

$I^1 = [\text{H G E D F A B C}]$,

$F^2 = [6.9\ 0.8\ 4\ 2.6\ 5.6\ 4.2\ 4.9\ 7]$,

ordered_$F^2 = [7\ 6.9\ 5.6\ 4.9\ 4.2\ 4\ 2.6\ 0.8]$,

$I^2 = [\text{H A E G F C D B}]$.

Boundary solutions are H, C and B from I^1 and I^2. Therefore, $dist_H = dist_B = dist_C =$ infinity.

To find crowding distance of F^1 objective function of solution A, m=1, $F^1_{max}=6.3$, $F^1_{min} = 0.5$, n = 6, ordered_F^m(n+1)=1.6, ordered_F^m(n-1) = 2.5, initial $dist_A = 0$.

Crowding distance of 1st objective function of solution A

$$dist_A = 0 + \frac{2.5-1.6}{6.3-0.5} = 0.155.$$

Now to find $dist_A$ considering F^2, initial $dist_A = 0.155$, m=2, $F^2_{max}=7$, $F^2_{min} = 0.8$, n = 2. ordered_F^m(n+1) = 5.6, ordered_F^m(n-1) = 7,

$$dist_A = 0.155 + \frac{7-5.6}{7-0.8} = 0.381.$$

Similarily, $dist_D = 1.326$ $dist_E = 0.72$ $dist_F = 0.337$ $dist_G = 0.416$

The following table B.3 shows the crowding distance of the solution with their objective functions and rank.

Table – B.3 Solutions, their objective functions, crowding distance and rank

solution	First objective function (F_1)	Second objective function (F_2)	Crowding distance	Rank
A	2.5	6.9	0.381	2
B	1.6	0.8	∞	4
C	0.5	4	∞	1
D	3.8	2.6	1.326	4
E	5.2	5.6	0.72	3
F	3.1	4.2	0.337	2
G	6.1	4.9	0.416	3
H	6.3	7	∞	5

Creation of P_{t+1} : The rank wise division of solution in R_t (combination of parent population P_t and offspring Q_t =S here) is shown below in table B.4.

Table – B.4 Solutions and their rank

Rank	Solution
1	C
2	A, F
3	E, G
4	B, D
5	H

Length of P_{t+1} required is 4. With help of table 4 P_{t+1} is created as follow-

1. Initially P_{t+1} =[]
2. In this step $P_{t+1} = P_{t+1}$ U solutions having rank 1

$$P_{t+1} = [C]$$

The length of P_{t+1} is neither equal to nor greater than required length i. e. 4

3. $P_{t+1} = P_{t+1}$ U solutions having rank 2

$$P_{t+1} = [C] \text{ U } [A\ F] = [C\ A\ F]$$

The length of P_{t+1} is neither equal to nor greater than required length i. e. 4.

4. $P_{t+1} = P_{t+1}$ U solutions having rank 3

$$P_{t+1} = [C\ A\ F] \text{ U } [E\ G] = [C\ A\ F\ E\ G]$$

Now the length of P_{t+1} is greater than required length by 1. Therefore, one solution among solutions included in step 4 (last time included) i. e. E and G, is to be discarded from P_{t+1}.

The solution having lesser crowding distance among E and G is discarded. Solution G has lesser crowding distance. Therefore G should be discarded from P_{t+1}.

The final P_{t+1} = [C A F E G] – [G] = [[C A F E].

Crowded tournament selection operator (CTSO): Two solutions, based on rank and local crowding distance, are compared. The solution which has better rank is declared winner. If the rank is same then the solution having higher crowding distance is declared winner.

Worked out example of crowded tournament selection operator: The working of crowded tournament selection operator is explained for two cases with help of tournament between two solutions.

First case: The tournament between C and A: Rank of A = 1 and rank of C = 2. Therefore, A is winner.

Second case: The tournament between E and G: Rank of E = 3 and rank of G = 3. The winner can not be declared based on rank because the rank of both solutions is same. Therefore, winner is decided based on crowding distance. The crowding distance of E = 0.75 and of G = 0.416. E has higher crowding distance than G, Therefore E is declared winner.

Table B.5 : GA parameters for different system

	System-1	System-2	System-3	System-4
Population size	14	18	26	38
Crossover probability	0.6	0.6	0.68	0.7
Mutation probability	0.04	0.04	0.04	0.03
Single point crossover location	Center	Center	Center	Center

APPENDIX C

Chaotic attractor : The tabu search is a optimization technique. In tabu search, even in absence of the problem of reversal movement of search path and limit cycle, the third problem is that the search path might not visit out of the limited portion of the search space even after staring the search with different points in that area. If this part does not contain the desired solution, the desired solution will never be found in presence of chaotic attractor. The presence of chaotic attracter is confirmed, if number of repetition of the search point is greater than a threshold value of the repetition of the search point. The number if repetition of the solution is stored in the variable 'repetition_counter' and the threshold value of the repetition is stored in constant 'REP'.

CHAOS : The escape mechanism is invoked if the number of presence of chaotic attractor is found greater than a threshold value. The number of presence of chaotic counter is stored in a variable 'chaotic_counter' and the threshold value of chaotic_counter is stored in a constant 'CHAOS'.

Moving average : Moving average in the reactive tabu search is a parameter which is used to control the size of tabu list in reactive tabu search optimization technique. Its value depends on the repetition of a move (best_configuration found from neighborhoods of candidate solution) in the memory structure constructed for keeping the history of search The value of moving average is stored in variable moving_average.

Increment factor and Decrement factor : Increase factor and Decrease factor is used to decide the length of the step by which the size of tabu list can be increased or decreased at a time whenever required The value of increase factor and decrease factor are stored in constants INCREASE and DECREASE .

CYCLE_MAX : In the reactive tabu search optimization technique, if a solution is repeated for consideration for selection as new CS, the size of the tabu list is increased. But if a solution is repeated after a long period then the size of tabu list is not increased. The long period is stored in a constant 'CYCLE_MAX' in terms of iteration. In this thesis, to solve the service restoration problem, the value of 'CYCLE_MAX' depends on number of switches.