CHAPTER 1

INTRODUCTION

1.1 GENERAL

Electrical Power Distribution Systems (EPDS) form the main link between Generation, Transmission and End Electricity Users. Due to ever increasing demand of electric power, the size and complexity of the modern day power systems are also increasing rapidly. Because of this enhanced size and complexity of the systems, the likelihood of occurrence of fault and size of the area affected by faults have also enhanced significantly. The duration of fault and the size of the area affected by the fault directly affect the safety and satisfaction of the customers which, in turn, have a profound effect on the revenue earned by the electricity supply company. As a result, fastest restoration of supply to the maximum possible out-of-service area is one of the most important tasks for any power supply company. After the service restoration also, from the economic point of view, there should be minimum power loss in the system. Now, the topology of the distribution system changes because of service restoration operation.

The EPDS planner/ operator must consider all types of fault. The duration and the extent of blackout areas have to be evaluated by the operator. Since these blackouts are totally unwanted and are not tolerable, all possible operational planning studies are to be carried out to quantify the extent of blackouts. Further, possible restoration methods with minimum time of restoration need a detailed study. 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, 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. Due to 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 components such as transformer, feeder and line, it is important that the bus voltage and line current do not cross their respective operational limits. Further, it is important to consider the following aspects at the operational planning stage of the EPDS.

i) Pre-fault state (i.e., normal state, emergency state, serious emergency state, restorative state) of the power distribution network.

ii) The pre-fault and post-fault network connectivity of the EPDS.

iii) The loads that are lost during the process of restoration and their priority.

iv) The total number and location of the sectionalizing and tie switches in the power distribution network.

v) Minimal number of switch operations to minimize the frequency of interruption of power supply to the consumers.

vi) Possible increase/decrease of distribution system losses.

vii) Division of EPDS into different zones and possibility of zone wise restoration.

viii) Voltage limit violation and their minimization.

ix) The capacity margin of transformers and feeders.

x) Estimation of service restoration time and operating time of the associated protective devices.

Hence, for a distribution network, the issue in determining a restoration plan is combinatorial, non-differential, multi-objective and non-linear optimization problem with various operational and engineering constraints. These constraints are:

a) The resulting feeder configuration should remain radial.

b) Service should be restored to all the isolated branches downstream to the affected areas, so that minimum number of consumers will be without power supply.

c) The operators specify the limit for the number of switching operations.

d) Feeder and sub-feeder capacity limits are not violated.

The switching options will be determined by closing a tie line switch and opening a complementary normally closed sectional switches due to the constraints of the radial structure in the load transfer problem. Hence, the power supply restoration in EPDS requires a detailed operational planning study and the need for a quick service restoration of power supply is the major requirement for efficient operational planning problem of the EPDS.

Best configuration of the post-fault power distribution network and the optimal solution to the service restoration problem can be achieved by considering all the constraints simultaneously. Past researchers in service restoration as detailed in the literature survey do not consider all operational constraints simultaneously and do not provide any idea of estimation of the Service Restoration Time. Hence, in this research work efforts are made to develop a highly suitable fast service restoration algorithm for EPDS taking into account the following constraints:

i) Lost load minimization

ii) Power loss minimization

iii) Minimization of voltage limit violation

iv) Minimization of the number of switch operations

v) Transformer load balancing

vi) Feeder load balancing

vii) Consideration of loads in the order of their priority

The simultaneous consideration of all the above mentioned constraints in addition to service restoration time period estimation makes the proposed Multi-objective Multi-constraint Service Restoration problem for Electrical Power Distribution Systems and it is solved using Non-Dominated Sorting Genetic Algorithm

The developed Multi-objective Multi-constraint Fast Service Restoration Algorithm involves the following six steps.

Step 1: A new method for identifying the status of network connectivity of power distribution network.

Step 2: An improved power flow method for the analysis of single/three phase EPDS.

Step 3: A new algorithm using Preemptive Method for the consideration of loads in the order of their highest priority.

Step 4: Estimation of Service Restoration Time period

Step 5: A new method using Non-Dominated Sorting Genetic Algorithm for the search of optimal configuration of the power distribution network.

Step 6: Formulation of New Combined Objective Function and the development of overall solution algorithm.

The validity of this new algorithm has been tested on various EPDS. The fast and effective convergence of the results of this Multi-objective Multi-constraint Fast Service Restoration Algorithm showed that it is a highly efficient algorithm for use in service restoration procedures of distribution automation systems.

1.2 LITERATURE SURVEY

Past service restoration methods are briefly reviewed in this section. For a distribution network an efficient post fault supply restoration strategy plays an important role in improving service reliability and enhancing consumer satisfaction. There has been considerable research effort focused on this problem. Approaches available in the literature for distribution system service restoration problem have been roughly divided into three categories as given below:

1.2.1 Optimization Methods used in Service Restoration

The method of Service Restoration by network reconfiguration by Daurish Shirmohammadi (1992), suitable for optimization of planning of the EPDS, does not consider all the operational constraints. Real time service restoration in distribution networks - a practical approach by Sarma et al (1994a) and the new network configuration technique for service restoration in distribution networks approach by Sarma et al (1994b) consider the objectives of the problem separately and provide the solution, i.e. the service restoration strategy for each objective of the problem. But these methods need the operator’s decision in the selection of the best objective to achieve the restoration of power supply. Analytical approach for step by step restoration by Canbolt Ucak and Anil Pahwa (1994) is suitable for distribution systems extended outages. However, this method does not consider all the objectives which are suitable for efficient operational planning of the EPDS. In this thesis the formulation of the objective function with simultaneous consideration of operational constraints helps in achieving the best operating condition of the EPDS.

1.2.2 Heuristic Search Methods used in Service Restoration

The combinatorial problem can be solved using the heuristic search programming techniques; the solution normally involves the analysis of a large number of alternatives or possible combinations that may increase exponentially. A binary decision tree is used to solve this search problem.

These methods compare a number of candidate solutions with the specified performance criteria. Heuristic rules are employed during the search for solutions to reduce the search space. As a result, solutions can be reached within an acceptable time period. This approach is an efficient one and does not realy on the specific knowledge about system. Distribution system service restoration using a heuristic approach by Yuan-Yih Hsu et al (1992) provides a number of candidate solutions for the service restoration in EPDS. Development of restoration algorithm for a typical power distribution system to study the post-fault network topology by Das.J.K et al (2000) is a system dependent approach and this method needs modifications based on the size of the system. Comparative study of modern heuristic algorithms to service restoration by Sakae Toune et al (2002) gives effectiveness of the various methods for service restoration in EPDS. But the minimum number of constraint consideration does not give any suitability for quick service restoration in EPDS. Multi-tier service restoration through network reconfiguration and capacitor control for large scale radial distribution networks by Karen Nan Miu et al (2000) does not consider all the operational planning constraints. Moreover in this method analysis of service restoration time is not dealt with. A Reactive Tabu Search for service restoration in electric power distribution systems by Sakae Toune et al (1998) considers only two constraints. However, the number of possible solutions of these methods will be prohibitively large unless effective heuristic rules can be developed. In addition, when the load is transferred from feeder to feeder in multipart switching, there is no guarantee for optimal solution. Hence, these methods are not suitable for efficient operational planning of EPDS. In this thesis the generalization of the objective function formulation and minimizing the deviation of the objective function from the global minimum helps in quick service restoration of supply in EPDS.

1.2.3 Domain specific knowledge based methods for Service Restoration

These expert system-based methods attempt to capture the knowledge and heuristic rules used by the system operators to determine switching sequences for supply restoration under a range of fault conditions. This information is typically stored as a knowledge base in the form of rules. The resulting knowledge base is specific for a given system and its normal running configuration would have to be built for each network. System restoration plan development for a metropolitan electric system by Kafka (1981) is a system dependent method and this method cannot be used as a general tool for solving the service restoration problems. In addition there is no guarantee that, in a given case, the solution found will be close to the optimal solution under the prevailing conditions. In this thesis the effective formulation of objective function helps in achieving system dependency elimination and, hence the proposed Multi-objective Multi-constraint Fast Service Restoration Algorithm can be used as a general tool for solving the service restoration problems in EPDS.

Distribution system service restoration by Fuzzy Set theory by Elena Danilova (2003) is a system dependent method and this method needs modifications in the set of Fuzzy knowledge based rules for the different distribution systems. This Expert System based approach is dependent on the decision of the expert due to limitations in the set of formulation of the fuzzy rules.

A new approach for distribution feeder reconfiguration for loss reduction and service restoration by Whei-Min Lin and Hong-Chan Chin (1998) uses the voltage index. Ohmic index and decision index are used to determine the set of switches to be opened /closed. But the calculation of these indices under fault conditions for the various network configuration of the distribution network is a tedious procedure.

Distribution feeder reconfiguration for service restoration for load balancing by Qin Zhou et al (1996) considers only load balancing constraint, but the remaining operational planning constraints such as load priority, switch operations minimization etc., are not considered in this approach.

Development of knowledge-based algorithm for restoration of typical power systems by Das.J.K et al (2001) is a system dependent approach and the network reconfiguration of post fault power distribution network is totally dependent on stored network state knowledge. The rapid variations in the post fault state of distribution network leads to inaccurate results and hence, the optimal solution is not always guaranteed.

Most of the approaches developed so far, have concentrated only on some of the operational aspects in service restoration of the EPDS and the system dependency of these approaches fails to obtain optimal operating condition of the EPDS. Moreover, these previous approaches do not provide any idea of the estimation of service restoration time of the power supply. The complexity of these approaches will not help the electric power distribution engineers/distribution system substation operators in achieving the best configuration of the post-fault Power Distribution Network (PDN).

The Multi-objective Evolution Programming for feeder reconfiguration by Ying-Tung Hsaio (2004) with interactive fuzzy satisfying method considers only two constraints such as radial structure maintenance and maximizing the load served conditions. The remaining constraints such as load balancing, loss minimization, priority order consideration of the loads, switch operations, etc., are not included in this method. The proposed service restoration algorithm will become an efficient algorithm when the formulated objective function is solved with simultaneous consideration of all operational planning constraints of the EPDS.

Multi-objective Service Restoration in distribution networks using an Evolutionary approach and Fuzzy sets by Augugliaro et al (2000) are based on the power margin and power losses. This approach has set up a hybrid GA for service restoration problem in a multi-objective optimization formulation, but the solution strategy itself is not multi-objective optimization.

Service restoration in distribution systems using non-dominated sorting genetic algorithm by Yogendra Kumar et al (2006) considered only line current and bus voltage constraints, but the remaining operational planning constraints such as load priority, transformer load balancing, feeder load balancing etc., are not considered in this approach.

A new hybrid multi-objective quick service restoration technique for electric power distribution systems by Manjunath and Mohan (2007) proposed GA-based methods to overcome the limitations mentioned above, wherein using weighting factors multi-objective optimization problem is converted into a single optimization problem and the GA is used to solve the optimization problem. Weighting factors depend on the importance of the objective functions and constraints. Importance of objective functions does not change from network to network, but causes variation of weighting factor for different networks, therefore the weights have to be tuned.

Multi-objective, multi-constraints service restoration of electric power distribution systems with Priority Customers by Yogendra Kumar (2008) is suitable for service restoration, but does not discuss the estimation of service restoration time.

It has been observed from the above literature survey that there is a need to simplify and optimize service restoration in EPDS. Hence, an effort has been made in this thesis to develop a Multi-objective Multi-constraint Fast Service Restoration Algorithm with the consideration of various operational and engineering constraints. This new algorithm also helps in estimation of the service restoration time. The validity of this algorithm has been tested on various EPDS. The fast and effective convergences of the results of this Multi-objective Multi-constraint Fast Service Restoration Algorithm show that it is an efficient algorithm for use in the service restoration procedures of Distribution Automation Systems.

1.3 OBJECTIVE OF THE THESIS

A fast, simple and cost effective service restoration algorithm for an effective operational planning of EPDS is the need for the existing scenario of electric power distribution systems.

The main objective is to obtain the best configuration of post-fault power distribution network. The reconfigured post-fault power distribution network should satisfy all the operational and engineering constraints. Here an effort has been made to develop a quick service restoration algorithm for efficient operational planning of EPDS. The objectives of thesis are outlined below:

i) To develop a new network connectivity method for EPDS

A new mathematical model has been formulated to analyze the network connectivity of the post faulty PDN. The paper by Daurish Shirmohammadi et al (1988) on compensation based power flow method for weakly meshed distribution and transmission network and Fan Zhang and Carol Cheng (1997) on modified Newton method for radial distribution system load flow analysis use the tree order method for identifying the network configuration. The methods need renumbering of the nodes in the order of the lateral and sub-lateral connectivity to the root node. In this work we do not use the concept of renumbering, to develop the network connectivity. The newly formulated mathematical model helps in the identification of nodes beyond a particular node and hence it will provide the complete knowledge of the connectivity of the pre/post power distribution network. The node load identification of forward substitution method can be obtained easily by using the New Network Connectivity Method and greatly improving the computational efficiency.

ii) To obtain an improved power flow method for the analysis of Pre/Post -fault Distribution Networks

The knowledge of pre/post fault power distribution network status helps in the detailed analysis of operational planning of the EPDS. The efficient load flow method for Radial EPDS needs optimal operation of the EPDS. The load flow method should be simplified because of the higher R/X ratio of the EPDS. The short line length of distribution lines show negligible effect on shunt capacitance of the lines. The conventional load flow methods like Fast Decoupled load flow method, Newton–Raphson load flow method lead to divergence and hence there is a need to develop a generalized load flow method for EPDS. Forward Substitution method is used by Meseut and Felix (1989) in the optimal capacitor placement on radial distribution systems and Civanlar et al (1988) in distribution feeder reconfiguration for loss reduction in the load flow analysis. Though these two methods are simplified, they need more computational time. For the analysis of single/three phase power distribution network a new power flow method has been developed in this thesis. In this method the real and reactive power losses is calculated in addition to the power flow in all feeder sections and transformers of the EPDS. The method is highly suitable, fast and effective for the proper operational planning of the EPDS.

iii) To consider Loads in the order of their Priority and implementation using the Preemptive Method

Some transformers and feeders get disconnected due to the occurrence of fault. Due to faults, there is a reduction in the system power transmission capacity that needs disconnection of some of the loads in the EPDS to maintain the allowable voltage limit and hence to maintain the good quality of electric power supply. Important and unimportant loads are to be considered when disconnecting the loads. Preemptive Method (Hamdy 2002) is suitable for considering the loads in the order of their priority. This method helps to consider the highest priority order first and then to consider the next highest priority order load. The procedure is repeated until the capacity of feeder and transformer is reached.

iv) To develop a new method for Estimating Service Restoration Time in Power Distribution Systems

For planning the exact restoration schedule of power supply in EPDS, a prior knowledge of restoration time of electrical power supply is required for the electric power distribution engineers/distribution system substation operators.

The estimation of total restoration time needs the consideration of probability for exact operation of the protective/switching devices in the EPDS. By using Critical Path Method (CPM) and Program Evaluation Review Technique (PERT), the probability consideration (Yannis Viniotis 1998) and Estimation of Service Restoration Time is effectively implemented. This method helps in estimating the exact schedule of power supply restoration to the consumer localities.

v) To formulate a new Combined Objective Function with various Operational and Engineering Constraints

The EPDS gets completely perturbed from its normal state for a small change in the configuration of the power distribution network. Various operational and engineering constraints are considered for best Service Restoration Algorithm for the restoration of power supply in EPDS. The generalized approach helps in eliminating the draw back of system dependency in comparison to earlier service restoration methods. Best configuration of power distribution network is achieved by effectively formulating the objective function and hence obtaining a favourable operating condition of the EPDS.

vi) To develop an overall solution algorithm of the Service Restoration for the EPDS

In this thesis an attempt has been made to develop the overall solution algorithm to analyze fast service restoration of the power distribution network. To develop the overall solution algorithm the objectives mentioned through (i)-(vi) are used.

Here the Non-Dominated Sorting Genetic Algorithm (Deb 2001) is used to search for the best configuration of the post fault PDN. In this thesis work in contrast to conventional genetic algorithm based methods, the proposed method does not require weighting factors which was required for conversion of multi-objective function into an equivalent single objective function. The generalization in the selection of parameters for the Non-Dominated Sorting Genetic Algorithm (NSGA) helps to use this new multi objective quick service restoration algorithm as a generalized tool for solving the EPDS service restoration problems.

This also helps in achieving the best operating condition of the EPDS and simulating various faults in different feeder sections of the EPDS. The best configuration of the post fault PDN is searched using the Non-Dominated Sorting Genetic Algorithm (Deb 2001). Under various operating conditions the status of all the quantities like pre/post voltages, currents, real and reactive power losses, transformer and feeder loading are calculated in the overall solution algorithm. The non-dominated sorting genetic algorithm evolves towards the minimum of objective function. In the formulation of chromosome for the next generation the deviation of objective function from the minimum value has been observed. In the next generation, the status of switches is chosen based on the magnitude of this deviation. Hence the new algorithm effectively increases the speed of convergence.

The validity of this Multi-objective Multi-constraint Service Restoration Algorithm for Electrical Power Distribution Systems Using Non-Dominated Sorting Genetic Algorithm has been tested on various distribution systems Viz., 12-Bus, 16-Bus, 26-Bus, 29-Bus, 33-Bus, 69-Bus, 79-Bus and 133-Bus system. The results reveal that it is a highly suitable Fast Service Restoration Algorithm for the EPDS. The above mentioned objectives help in the exact analysis for the efficient operational planning of the EPDS.

1.4 OUTLINE OF THE THESIS

A brief outline of the various chapters of the thesis is presented in this section.

In chapter 2, the procedures employed for the network connectivity identification by the previous researchers with their drawbacks are presented. Network connectivity development and node load identification with examples are detailed with theory and algorithm. Feeder loading can be analyzed by the identification of nodes connected to particular feeder. The matrix horizontal concatenation and elimination of additional load node that is newly implemented is also discussed. In this chapter various power distribution systems are highlighted along with the merits of the new network connectivity method viz., simplicity, system dependency elimination, minimal data requirement, fast and effective convergence. This chapter presents an effective idea for electric power distribution engineers/distribution system substation operators in the analysis of operational planning of the EPDS and hence the switch status is useful in the reconfigured post-fault power distribution network

In chapter 3, an improved power flow method using forward substitution for the analysis of EPDS is presented. Considerably good results are obtained using the forward substitution method for power flow analysis. First the demerits of the conventional load flow methods like Newton-Raphson Method, Gauss Seidel method, Fast Decoupled load flow method over forward substitution method are presented. In the formation of mathematical model, the assumptions made for single/three phase power distribution network are discussed. For the analysis of power distribution network the generalized solution algorithm for power flow method using substitution is presented. For various test systems under pre/post-fault conditions power flow results and analysis in detail are presented. The merits of this improved power flow analysis and its fast, effective convergence are also presented.

In chapter 4, implementation of preemptive method for the consideration of loads in the order of their priority of post fault power distribution network is dealt. Transformer and feeder loading ratios calculation is presented. For various test systems under pre/post-fault condition the priority considered is discussed. Based on the transformer and feeder loading conditions in the reconfiguration of power distribution network the constraints in the selection of loads are presented.

In chapter 5, Estimation of Service Restoration Time is presented. Mathematical model formulation and analysis of relays/breakers operation based on probability are also presented. The calculation of fault current for a particular type of fault, determination of operating current of the relay and its related calculation for the various test systems viz., 12-Bus, 16-Bus, 26-Bus, 29-Bus, 33-Bus, 69-Bus, 79-Bus, and 133-Bus systems have been done and the results are presented for 12-Bus and 16-Bus systems in this Chapter.

In chapter 6, Electric Power Service Restoration using Non-Dominated Sorting Genetic Algorithm is presented. First, the modification in the implementation of Non-Dominated Sorting Genetic Algorithm is dealt and then the detailed solution algorithm is presented. For various test systems the modification in generation of chromosomes, selection of size of the population, selection of chromosomes, and choice of crossover and mutation probability are detailed. To solve the Electric Power Service Restoration Problem, the generalization of Non-Dominated Sorting Genetic Algorithm is also presented.

In chapter 7, the development of Multi-objective Multi-constraint Service Restoration for Electrical Power Distribution Systems Using Non-Dominated Sorting Genetic Algorithm is dealt. Formulation of the problem with objective function and the methods for consideration of various operational and engineering constraints are presented. For efficient operational planning of EPDS, the overall solution algorithm and generalization of this algorithm to solve the Electrical Power Service Restoration Problem are also presented.

The detailed service restoration analysis is carried out for the 12-Bus, 16-Bus, 26-Bus, 29-Bus, 33-Bus, 69-Bus, 79-Bus and 133-Bus distribution systems. Minimization of objective function considering the various constraints using the non-dominated sorting genetic algorithm to achieve the best post-fault reconfigured Power Distribution Network is presented. For different fault cases the Total Restoration Time is also presented. For illustration, 26-Bus and 33-Bus distribution system results are presented in this chapter and remaining system results including Line data, Bus data, total restoration time for different fault cases, voltage during the fault, line current during fault and summary of results for various EPDS compared with original GA are presented in Appendices 1 to 8.

In chapter 8, a review of the work carried out, major conclusions reached and contributions made are dealt with. The scope for further research work in the fast service restoration of power supply in the EPDS is also presented.