CHAPTER 6

A NEW METHOD TO SOLVE THE SERVICE
RESTORATION PROBLEM IN EPDS USING NON-
DOMINATED SORTING GENETIC ALGORITHM

6.1 INTRODUCTION

To solve service restoration problems in Electrical Power Distribution Systems (EPDS), in this chapter Non-Dominated Sorting Genetic Algorithm (NSGA) has been implemented. This optimization technique is suitable for solving the service restoration problems, because it is very easy to change constraints or objectives. In contrast to conventional Genetic Algorithm based methods, the NSGA does not require weighting factors required for conversion of multi-objective function into an equivalent single objective function.

To search for the optimal supply restoration strategy of EPDS, NSGA is employed. Electric distribution feeders have a number of switches that are normally closed (sectionalizing switches) and, switches that are normally open (tie switches). The status of these sectionalizing and tie switches of a configuration of the Power Distribution Network (PDN) has been taken as chromosome. Corresponding to open or closed position of the switch, each switch state takes a one bit value ‘0’ and ‘1’. The status of these switches is decided according to the optimal configuration of pre/post-fault PDN. Each chromosome maps to a feasible network topology. The modifications in generation of chromosome, selection of chromosomes,
choosing the size of populations and choice of crossover and mutation probability are presented in this chapter. The generalization of implementation of NSGA to solve the Electric Power Service Restoration Problem helps in the elimination of system dependency drawback of the Service Restoration analysis of the EPDS.

6.2 OPTIMAL SWITCHING IN ELECTRIC POWER DISTRIBUTION NETWORKS

Using the three/single phase switches, optimal switching analysis allows the electric power distribution engineers/ distribution system substation operators to find the best possible switching configuration for the electric power distribution system. For optimal switching substation Operators can select any combination of feeders and /or substations. The optimal switching provides a variety of powerful options for customizing the analysis and also helps the electric power distribution engineers to:

- Select the optimization objective, such as to reduce losses, or may be to raise the lowest voltage at the tail end of the feeder in the EPDS.
- Set voltage and loading constraints, so that switching operations do not violate distribution system standards.
- Save the suggested switching plan as an external switch position file, which electric power distribution engineers can load into customer’s model at a later time for a more detailed study.

In addition to the above aspects, the optimal switching provides realistic switching plans because it relies on a local optimization technique rather than a global approach. Depending upon the operational planning
requirements of the EPDS, the electric power distribution engineers may find that objectives such as ‘minimize substation transformer loading’ and ‘equate loading’ are particularly useful to balance the loading among feeders and Transformers. In this thesis the NSGA is used to find optimal configuration of the power distribution networks.

6.3 NON-DOMINATED SORTING GENETIC ALGORITHMS

NSGA is a well-known search algorithm for the operational planning of the EPDS. NSGA application helps in obtaining the optimal configuration of the PDN in fast Service Restoration of power supply in the EPDS. NSGA is a computerized search and optimization algorithm based on the natural selection and non-dominance. The ability of NSGA is found to give the global optimal solutions for large-scale combinatorial optimization problems. Also it has been found to be the efficient method for solving the power system problems, including the supply restoration problems. NSGA is highly suitable for solving the supply restoration problems because it is very easy to change the constraints or objectives.

6.3.1 Basic Function of NSGA

A modified form of conventional GA is essentially the non-dominated sorting genetic algorithm. The basic idea behind NSGA is the ranking process executed before the selection operation. This process identifies non-dominated solutions in the population, at each generation to form non-dominated fronts, based on the concept of non-dominance criterion. After this, the selection, crossover, mutation operator to create mating pool and offspring population usual operators are performed. NSGA and its application are discussed by Kalyanmoy Deb (2005). In this NSGA, the multi-objective nature of the service restoration problem is retained without the need of any tunable weights or parameters. As a result, the proposed
methodology is generalized enough to be applicable to any power distribution network. To improve the performance, in this method, the elite-preserving operator, which favours the elites of a population by giving them the opportunity to be directly carried over to the next generation, is used. Rudolph (1996) has proved that GAs converge 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. In this thesis work CTSO is used, which lowers computational complexity and hence the run time is reduced. Some of the concepts of NSGA are (a) crowded tournament selection operator, (b) domination and (c) crowding distance.

6.3.1.1 Crowded Tournament Selection Operator (CTSO)

A solution ‘i’ wins a tournament with another solution ‘j’ if any of the following conditions are true:

1. If solution ‘i’ has a better rank, that is \( r_i < r_j \).

2. If they have the same rank but solution ‘i’ has a better crowding distance than solution ‘j’, that is, \( r_i = r_j \) and \( d_i > d_j \).

The first condition makes sure that the chosen solution lies on a better non-dominated front. The second condition resolves the tie of both solutions being on the same non-dominated front by deciding on their crowded distance. The one residing in a less crowded area (with a larger crowding distance \( d_i \)) wins.
6.3.1.2 Domination

A solution $x^{(1)}$ is said to dominate the other solution $x^{(2)}$, if both conditions 1 and 2 are true:

1. The solution $x^{(1)}$ is no worse than $x^{(2)}$ in all objectives
2. The solution $x^{(1)}$ is strictly better than $x^{(2)}$, in at least one objective.

6.3.1.3 Crowding Distance

To get an estimate of the density of solutions surrounding a particular solution ‘i’ in the population, we take the average distance of two solutions on either side of solution ‘i’ along each of the objectives. This quantity ‘$d_i$’ serves as an estimate of the perimeter of the cuboid formed by using the nearest neighbors as the vertices (we call this the crowding distance). The following algorithm is used to calculate the crowding distance of each point in the set ‘F’.

6.3.1.3.1 Crowding distance Assignment Procedure: Crowding-sort

**Step C1:** call the number of solutions ($l$) in F as $l=|F|$. For each ‘i’ in the set, first assign $d_i=0$.

**Step C2:** For each objective function $m=1,2,...M$, sort the set in worse order of $f_m$ or, find the sorted indices vector: $I_m^m = \text{sort}(f_m, >)$.

**Step C3:** For $m=1,2..M$, assign a large distance to the boundary solutions, or $d I_{\ell}^m = d I_{\ell}^m = \infty$, for all other solutions $j=2$ to $\ell - 1$, assign:

$$d I_{j}^m = d I_{j}^m + \frac{f_m^{(i_{j-1})} - f_m^{(i_{j-1})}}{f_m^{(i_{j-1})} - f_m^{(i_{j-1})}}$$
The index $I_j$ denotes the solution index of the $j$-th member in the sorted list. Thus, for any objective, $I_l$ and $I_h$ denote the lowest and highest objective function values, respectively. The second term on the right side of the last equation is the difference in objective function values between two neighboring solutions on either side of the solution $I_j$.

### 6.3.2 The Basic Algorithm of NSGA is as follows:

**Figure 6.1 Schematic of the NSGA Procedure**

The step-by-step procedure of NSGA for one generation is described here for ready reference. The basic algorithm of NSGA is as follows:

**Step 1.** Initially a random parent population $P_o$ of size $N$ is created (i.e. $N$ is the number of strings or solutions in $P_o$).

**Step 2.** Create offspring population $Q_o$ of size $N$ by applying usual GA operators (i.e. selection, crossover and mutation) on $P_o$.

**Step 3.** Assign $P_t = P_o$ and $Q_t = Q_o$, 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 dominate each other but 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 dominate each other but 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 dominate each other but 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 the 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 application of CTSO, crossover and mutation operator on \(P_{t+1}\). In CTSO, the winner (better) solution is selected by comparing two solutions based on their rank and crowding distance. The solution having lower rank is declared winner. If two solutions have the same rank, the solution having higher crowding distance is declared winner. Now, to create offspring, two solutions are picked up randomly from the parents’ population, and subsequently the winner of these two solutions is collected. This process is repeated till the number of solutions collected is less than the size of population. After collecting required number of solutions, crossover and mutation operators are applied on collected solutions.

**Step 8.** Test for convergence. If the algorithm has converged, then stop and report the results. Else, \(t = (t + 1)\), \(P_t = P_{t+1}\), \(Q_t = Q_{t+1}\) and go back to step 4.

6.4 SOLUTION TO THE SERVICE RESTORATION PROBLEM USING NON-DOMINATED SORTING GENETIC ALGORITHM

Based on the different configurations of the PDN, the new NSGA gives a number of solutions to a service restoration problem, that is encoded as a string of status of the sectionalizing and tie switches. The status of all the available switches defines the topology of the PDN uniquely. A solution to the supply restoration problem can be encoded as a function of the controllable switch states of the network. The switch status ‘1’ is considered as close position and switch status ‘0’ is considered as open position. The set
of configurations of the PDN are termed as population. In the configuration of the PDN, ‘Chromosome’ is the string that encodes each set of sectionalizing and tie switches.

For selecting the parameters of NSGA the new implementation helps the Electric Power Distribution Engineers to use this method as a general tool to solve the EPDS Service Restoration problems:

- The Population Size has been taken as the total number of buses of the EPDS.
- The length of the chromosome will be equal to the total number of branches, that is, the total number of sectionalizing switches and tie switches in EPDS.
- Initially status of Tie Switches will be ‘0’ (open) and status of Sectionalizing Switches will be ‘1’ (closed).
- The NSGA goes through the number of steps in which the population at the beginning of each step is replaced with another population, by considering its deviation from the global minimum. These details have already been discussed in Section 6.3.2.
- The NSGA assigns a fitness value to each chromosome based on the value of objective function. The evolution objective function ‘f’ guides the NSGA to evolve towards better solutions.
- The fittest chromosome will have the higher probability that is, it will be retained and selected to generate a new candidate solution.
In this new method mutation probability and crossover probability have been taken as follows:

Crossover probability $P_c = 0.70$

Mutation probability $P_m = \frac{P_c}{\text{Total number of sectionalizing and tie switches}}$

The power flow analysis, for the post-fault reconfigured power distribution network has been performed, only after checking the radiality constraint of the EPDS.

### 6.4.1 String Representation for Service Restoration in EPDS

As the configuration of a network is represented by the status of all switches in the network, the string used in the NSGA implementation of service restoration problem presents the status of all switches in the system. The length of each string is equal to the number of switches (sum of the total number of sectionalizing and tie switches) in the system. In this work, the binary coding system has been adopted. Thus, the status of the “closed” and “open” switch in the system is represented by the binary digits “1” and “0”, respectively. Initially all the switches are assumed to be open, and starting with the first gene in the chromosome, its corresponding switch is closed. This process is repeated until the end of chromosome is reached. The radiality constraint violation and status of the switch in the faulty branch is checked for each configuration of the PDN by applying the new network connectivity method, which is explained in the Chapter 2.
6.4.2 Load Shedding by Preemptive Method

After performing the power flow analysis using forward substitution method, the load shedding of low priority order loads is done by using the preemptive method, these details are already mentioned in Chapter 4. The main advantage of the preemptive method is that it will never degrade the highest priority order loads in restoration of power supply to the consumer localities. The load shedding of low priority order loads has been done by setting their real and reactive power demands to zero, and then again the power flow analysis has been carried out to check the violation of operating constraints. If violations persist, then again the load shedding is done and this procedure repeated until the violation of feeder overloading and also transformer overloading in the post fault PDN is eliminated. The main advantage of this new method is that the use of Preemptive Method to consider loads in the order of their priority which helps in speeding up the service restoration process in EPDS. This improved priority based load switching helps in the minimization of duration of the power supply interruption to high priority loads.

6.4.3 Fitness Function for the solution of Service Restoration problem in EPDS

The individuals evolve according to their fitness to the environment. Fitness is defined as a non-negative figure of merit associated with a set of decision variables. If the objective function is smaller, it implies a larger fitness, for minimization problem. In this new method the service restoration problem has been formulated as a minimization problem. The objective function formulation considers all the objectives such as loss minimization, lost load minimization, load balancing of the feeders and transformers, priority order based load switching and quick restoration of power supply to high priority loads, in addition to the minimization of the number of switch
operations in the objective function formulation. The formulation of the objective function with various operational constraints is presented in Chapter 7.

6.4.4 String Operation for Service Restoration in EPDS

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 non-radial, it is made radial following the procedure described in Chapter 2. Subsequently, with help of a crowded tournament selection operator (CTSO), the mating pool is created for the next generation. This operator maintains: (1) convergence as the solution having a better front selected and (2) diversity as the solution having a higher crowding distance within the same front selected.

6.4.5 Front Formation for Service Restoration in EPDS

Following Step 5 of Section 6.3.2, the combination of parent and offspring population having length 2N is divided into various ranked non-dominated fronts. Due to the front formation from the combination of the parent and offspring population, chance is given to the current best solution in the parents to compete with offspring solutions. If no better solution is generated in offspring, the current best solution in the parent becomes a winner again. In this way, the elitism is maintained and due to the presence of elitism, convergence is improved. 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 the same, the convergence is considered to be achieved; otherwise, it is not.
6.5 SELECTION OF PARAMETERS OF THE NON-DOMINATED SORTING GENETIC ALGORITHM FOR VARIOUS EPDS

The NSGA has been used to search for the optimal configuration of PDN. NSGA parameters such as length of chromosome, population size, crossover probability and mutation probability for various EPDS are presented in Table 6.1.

Table 6.1 NSGA parameters for the various EPDS

<table>
<thead>
<tr>
<th>Type of the EPDS</th>
<th>Total Number of Branches</th>
<th>Length of the Chromosome</th>
<th>Population Size</th>
<th>Crossover Probability $P_c$</th>
<th>Mutation Probability $P_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-Bus</td>
<td>11</td>
<td>11</td>
<td>12</td>
<td>0.70</td>
<td>0.06363</td>
</tr>
<tr>
<td>14-Bus</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>0.70</td>
<td>0.05000</td>
</tr>
<tr>
<td>16-Bus</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>0.70</td>
<td>0.04375</td>
</tr>
<tr>
<td>26-Bus</td>
<td>27</td>
<td>27</td>
<td>26</td>
<td>0.70</td>
<td>0.02592</td>
</tr>
<tr>
<td>29-Bus</td>
<td>28</td>
<td>28</td>
<td>29</td>
<td>0.70</td>
<td>0.02500</td>
</tr>
<tr>
<td>33-Bus</td>
<td>37</td>
<td>37</td>
<td>33</td>
<td>0.70</td>
<td>0.01891</td>
</tr>
<tr>
<td>69-Bus</td>
<td>70</td>
<td>70</td>
<td>69</td>
<td>0.70</td>
<td>0.01000</td>
</tr>
<tr>
<td>79-Bus</td>
<td>78</td>
<td>78</td>
<td>79</td>
<td>0.70</td>
<td>0.00897</td>
</tr>
<tr>
<td>133-Bus</td>
<td>132</td>
<td>132</td>
<td>133</td>
<td>0.70</td>
<td>0.00530</td>
</tr>
</tbody>
</table>

The population size and the length of the chromosome increase linearly with the size of the EPDS and this can be observed from Table 6.1. The increase in size of population with the size of EPDS provides greater flexibility in the selection of the optimal chromosomes in each generation. This helps in reaching the global minimum value of the objective function at the earliest. The formulation of the objective function with consideration of various operational constraints is explained in Chapter 7.
6.6 SUMMARY

A new NSGA based approach to solve the service restoration problem in EPDS is presented. In this technique, the multi-objective nature of the service restoration problem is retained without the need for any tunable weights or parameters. As a result, the proposed methodology is generalized enough to be applicable to any PDN. The diversity, in this method, is achieved with the help of the crowded tournament selection operator (CTSO) that does not require any tuning parameter. The CTSO used in this research has lower computational complexity and hence the run time is reduced. The NSGA is an efficient optimization technique for solving the service restoration problems, because it is very easy to change constraints or objectives.