OPTIMAL PLACEMENT OF PROTECTIVE DEVICES IN DISTRIBUTION SYSTEM

Ph.D. THESIS

by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"OPTIMAL PLACEMENT OF PROTECTIVE DEVICES IN DISTRIBUTION SYSTEM"** 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 the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period from July, 2013 to November, 2017 under the supervision of Dr. Vinay Pant, Assistant Professor, Department of Electrical Engineering, 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.

(AFROZ ALAM)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

(Vinay Pant)
Supervisor

Date:

Abstract

Faults are more frequent in distribution system, as compared to other parts of the power system, leading to supply interruptions to the customers. For maximizing the customer satisfaction and retention, improvement of service reliability is a major concern for electric utilities. The main goal of the power distribution system reliability evaluation is the prediction of the service security of the customers. Service reliability can be improved by placing switches and reclosers at appropriate locations in the distribution system, so that supply from the main substation to the healthy load points can be maintained uninterrupted after isolating the faulted feeder section of the distribution system. Therefore, a strategy for optimal placement of the switches and reclosers needs to be evolved for improving the distribution system reliability. Proper locations of the protective devices (switches and reclosers) must be carefully chosen in order to maximize the benefits of placing these devices in a distribution system. To address this issue, in this thesis, a formulation for optimal placement of switches and reclosers in a distribution system for maximizing distribution system reliability, while minimizing the associated investment and outage costs has been proposed. The proposed formulation has been tested on 13-bus, 58-bus and IEEE 123-bus test systems using evolutionary programming (EP), genetic algorithm (GA), differential evolution (DE) and mixed-integer nonlinear programming (MINLP) methods. The obtained results establish the superiority of the MINLP method over the other optimization methods for the said purpose. However, the initial formulated optimization problem has considered only deterministic values of loads and system data.

The input parameters used for reliability evaluation may contain errors as they are derived from historical records. Hence, in order to achieve more realistic reliability indices, system components' data uncertainties need to be taken into account. To address this issue, Monte-Carlo simulation (MCS) method is used to model the load variation, failure rate (λ) and repair rate (μ) of the system components. The main demerit of MCS is the time consuming iterations making MCS unsuitable for most of the case studies, especially for large systems. Application of point estimate method (PEM) for probabilistic calculations, incorporating uncertainty of parameters, can provide similar results of acceptable accuracy but with less numerical efforts as compared to MCS. The uncertainty associated with the failure rate, outage time (r) and load (L) may be expressed in terms of the expected value (mean) and standard deviation of these quantities with an assumption that they are normally distributed. The PEM, used to calculate the statistical moments of a random quantity which, in turn, is a function of one or several random variables, has three prevalent versions, namely 3-point

estimate method (3PEM), 5-point estimate method (5PEM) and 7-point estimate method (7PEM). It is well established that while for calculating lower order statistics only (mean and variance), 3PEM is sufficient, for calculating higher order statistics (skewness and kurtosis) along with the lower order statistics, 5PEM and 7PEM are more useful.

This thesis presents a formulation for an optimal placement of switches and reclosers in a distribution system for maximizing the distribution system reliability considering uncertainties in load data, system failure and repair rates. The uncertainties have been incorporated in the formulation using 3PEM. The proposed formulation has been tested on 13-bus, 58-bus and IEEE 123-bus test systems using DE and MINLP methods. The obtained results establish the effectiveness of the consideration of data uncertainties in maximizing utilities' profits as also in improving the distribution system reliability by providing the bounds of profit. However, the formulation considered sustained interruptions (caused by permanent faults) only, and hence the scope for inclusion of momentary interruptions (due to temporary faults) has been explored next.

In a distribution system, momentary interruptions are more frequent than the sustained interruptions. Till recently, sustained interruptions were the main concern of the utilities and, hence, the protective devices were placed to limit the impact of these. However, these days, loads are more sensitive to momentary interruptions due to proliferation of electronic devices. Due to the increased use of electronic and precision devices, damages due to short-duration voltage disturbances have increased. The utilities employ fuse-save and fuse-blow schemes to decrease the impact of sustained and momentary interruptions, respectively. In the fuse-save scheme, an upstream recloser or circuit breaker operates, before a fuse can trip, to isolate a fault downstream of the fuse. Fuse-save scheme is used with an instantaneous relay or with the fast curve of a recloser associated with a circuit breaker. For temporary faults, service to the customers can be restored immediately by re-energizing the line, resulting in decreased sustained interruptions. The main drawback of fuse-save scheme is that all customers downstream of a recloser or circuit breaker experience momentary interruptions even for permanent faults downstream of the fuse. Because of this, many utilities prefer to use the fuse-blow scheme over the fuse-save scheme. In fuse-blow scheme, the fuse operates for all the downstream faults (temporary and permanent), resulting in sustained interruption for all the customers downstream of the fuse while rest of the system remains uninterrupted.

To address the above issue, the effect of temporary faults has also been incorporated next in the optimal placement problem of protective devices in the distribution system. Three different scenarios, for optimal placement of protective devices (switches, reclosers, fuses) in a distribution system, considering uncertainties in loads, temporary and permanent failure rates and repair rates have been formulated. The three versions of the formulated problem have been solved for 58-bus and IEEE 123-bus distribution networks using MINLP optimization technique.

Apart from the above three scenarios of protective devices' placement in distribution system, other scenarios pertaining to different combinations of protective devices are also feasible. Each scenario will give a different optimal profit value for a given system, hence, the best scenario needs to be identified. Thus, it becomes necessary to develop a generalized formulation which can simulate any desired scenario and help a utility in deciding the best possible combination and optimal placement of protective devices for profit and reliability maximization. In this thesis, a generalized model has been developed to address the difficulties pertaining to placement of various combinations of protective devices (recloser, switch, fuse-blow fuse and fuse-save fuse) in a distribution network for increasing the profit of the utility through reliability improvement. The uncertainties in temporary failure rates, permanent failure rates, repair rates and load data have been considered in the formulation using 3PEM. The developed objective function is capable of simulating different combinations of the protective devices. The formulated problems have been solved for 58-bus and IEEE 123-bus distribution networks using MINLP optimization technique. After analyzing the test results of the various scenarios for the two test systems, it is concluded that maximum profit to the utility is accrued by using the one involving a combination of all the four protective devices viz. reclosers, switches, fuse-blow fuses and fuse-save fuses.

Optimal placement of protective devices in distribution system increases the system reliability by isolating the faulty feeder section of the system and supplying uninterrupted power to healthy feeder sections (upstream of the faulty feeder section). However, the healthy feeder sections downstream of the faulty feeder section remain de-energized until the faulty feeder section is repaired and re-energized. If a distributed generation (DG) is present in the downstream isolated healthy part of the system, it can further improve the system reliability by operating in an islanded mode. For the formation of an island, the DG capacity should be sufficient to avoid load shedding or load prioritization. Thus, integration of DG in distribution networks has added advantages: additional reduction in customer interruption duration and increase in service restoration speed. However, the presence of DG in distribution system increases the complexity of the optimal placement problem of protective devices which has been addressed next.

In this thesis, the effect of DG has also been incorporated in the formulation of optimal placement problem of protective devices' (recloser, switch, fuse-blow fuse and fuse-save fuse) in the distribution system. A model has been developed to solve the problem of the protective devices placement in various zones of a distribution system with DG. The uncertainties in temporary failure rates, permanent failure rates, repair rates and load data have been considered in the problem formulation using 3PEM. The formulated problem has been solved for 69-bus and 118-bus distribution systems using MINLP optimization technique. After analyzing the results of the two test systems, it can be concluded that the profit to the utility can be increased if the protective devices are placed optimally in the zones formed due to DGs connected in the system.

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In the name of Almighty, the most beneficial and merciful

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Afroz Alam

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List of Abbreviations

3PEM 3 Point Estimate Method.

5PEM 5 Point Estimate Method.

7PEM 7 Point Estimate Method.

DE Differential Evolution.

DG Distributed Generation.

EP Evolutionary Programming.

Eq. Equation.

Eqs. Equations.

Fig. Figure.

GA Genetic Algorithm.

MCS Monte Carlo Simulation.

MINLP Mixed-Integer Non Linear Programming.

NLP Non-Linear Programming.

PEM Point Estimate Method.

Chapter 1

Introduction

Abstract

This chapter presents an overview of placement of protective devices in a distribution system for reliability improvement. It comprises need and challenges of protective devices' placement problems, research objectives and contributions. Finally, the organization of the thesis is presented.

1.1 Overview

IN power systems, faults are more frequent in distribution system as compared to other parts of the system leading to supply interruptions to the customers [1]. For maximizing the customer satisfaction and hence their retention, improvement of service reliability, while simultaneously minimizing the associated cost, is a major concern for electric utilities. In distribution systems, switches and reclosers are primarily used for the isolation of the faulted feeder section, network reconfiguration and reliability improvement [2]. Service reliability can be improved by placing switches and reclosers at appropriate locations in the distribution system so that the healthy parts of the system can be energised after isolating the faulted section of the system. Therefore, for improving the service reliability, a strategy for optimal placement of the switches and reclosers needs to be evolved. For maximizing the benefits of the protective devices, proper locations (of these devices) must be carefully identified. Recognizing the importance of this problem, considerable research efforts have been devoted to address this issue.

The parameters used for distribution system reliability evaluation may contain errors as they are derived from historical records. Hence, in order to achieve more realistic reliability indices, system components' data uncertainties need to be taken into account. To address this issue, Monte-Carlo simulation (MCS) method can be used to model the load variation, failure rate (λ) and repair rate (μ) of the system components. The main demerit of MCS is the huge computational time requirement which makes it unsuitable in most of the case studies, especially for large systems [3, 4]. For probabilistic calculations taking uncertainty of parameters into account, point estimate method (PEM) could provide similar results of acceptable accuracy but with less numerical effort as compared to MCS [5]. The uncertainty associated with the failure rate, outage time (r) and load (L) may be expressed in terms of the expected value (mean) and standard deviation of these quantities with an assumption that they are normally distributed. The PEM can be used to calculate the statistical moments of a random quantity which, in turn, is a function of one or several random variables [6]. In the literature, three different versions of PEM, namely 3-point estimate method (3PEM), 5-point estimate method (5PEM) and 7-point estimate method (7PEM) are generally used for handling data uncertainty. It is well established that for calculating lower order statistics (mean and variance), 3PEM is sufficient, while for calculating higher order statistics (skewness and kurtosis) along with the lower order statistics, 5PEM and 7PEM are more useful [7].

In distribution system, momentary interruptions are more frequent than sustained interruptions. Till recent past, sustained interruptions were the main concern of utilities and, hence, the protective devices were placed to limit their impact. Today, due to proliferation of electronic devices, loads are sensitive to momentary interruptions as well [8]. Due to the increased use of electronic and precision devices, damages due to the short-duration voltage disturbances have increased [9]. To reduce the damage to the electronic and precision devices due to momentary interruptions, Fuse-blow scheme is used which in turn increases sustained interruption. Utilities having more concern to the sustained interruptions prefer to use Fuse-save scheme over Fuse-blow scheme. Fuse-save and Fuse-blow schemes are used mainly to decrease the impact of sustained and momentary interruptions, respectively [10].

In the Fuse-save scheme, an upstream recloser or circuit breaker operates before a fuse can trip to isolate a fault downstream of the fuse. Fuse-save scheme is used with an instantaneous relay or with the fast current-time curve of a recloser associated with a circuit breaker. For temporary faults, service to the customers can be restored immediately by re-energizing the line, resulting in decreased sustained interruptions [10].

The main drawback of the Fuse-save scheme is that all customers downstream of a recloser or circuit breaker experience momentary interruptions even for permanent faults downstream of a fuse. As a result, many utilities prefer to use the Fuse-blow scheme over the Fuse-save scheme. The Fuse-blow scheme is also known by several other names such as (i) trip saving, (ii) breaker saving, (iii) fault clearing, and (iv) instantaneous relay blocking [10]. In Fuse-blow scheme, the fuse operates for all the faults (temporary and permanent) downstream of it, resulting in sustained interruption for all the customers downstream of the fuse while the rest of the system is uninterrupted [10]. Thus, Fuse-blow scheme results in reduced momentary interruptions but increased sustained interruptions.

Optimal placement of various types of protective devices in distribution system improves system reliability by isolating the faulty feeder section and supplying uninterrupted power to healthy feeder sections of the system. However, the healthy feeder sections downstream of the faulty feeder section remain de-energized until the faulty feeder section is repaired and re-energized. If a distributed generation (DG) present in the downstream isolated healthy part of the distribution system is capable of supplying all the downstream isolated healthy loads, the system reliability can further be improved by operating the DG in islanding mode.

Recently, integration of DG in distribution networks has brought in many added advantages [11–18]. One of the several advantages of integration of DG units in distribution networks is the improvement in system reliability [19, 20]. Due to presence of the DG, the distribution system reliability is increased due to further reduction in customer interruption duration and increase in restoration speed [21]. This requires the DG to be operated in islanded mode. For the formation of an island, the DG capacity should be sufficient to avoid load shedding or load prioritization [22]. However, presence of the DG in the distribution system increases the complexity of the optimal placement problem of protective devices. In this case, a faulted feeder section of a DG enhanced feeder is energized from both the ends which requires that the conventional protection system be modified [23].

1.2 Literature review

In the literature, many studies have been devoted to the investigation of optimal placement of switching devices in a distribution system. In [2], the problem of sectionalizing switch placement has been solved using simulated annealing (SA) method to find the optimal number and locations for the switches. An immune algorithm (IA) based approach is proposed in [24] for optimal switch placement in a distribution system to minimize the investment and outage cost considering different customer classes. A particle swarm optimization (PSO) based three-state approach is presented in [25] to simultaneously find the optimal number and locations of sectionalizing and breaker switches in a distribution system. An ant colony optimization (ACO) based multi-objective optimization approach is presented in [26] for placement of switches and protective devices in distribution system for reliability improvement. A mixed-integer linear programming (MILP) based approach is proposed in [27] for placement of sectionalising switches in a distribution system considering customer outage cost and the costs associated with switch installation, operation and maintenance. In [28], a PSO based multi-objective approach for distribution system planning incorporating tie-lines and sectinalizing switches is presented. Another PSO based multi-objective optimization problem is proposed in [29], for placement of switches in radial distribution system for minimizing the number of customers not supplied. The developed algorithm requires only the number of customers per load point and network topology. However, this work does not incorporate failure rates and repair rates of the system components, which are integrally associated with the outage costs. In [30], a method, quantifying the uncertainties in input and output data by introducing a criterion for assessing the grade of uncertainty, has been proposed for distribution system performance analysis. In [31], [32] and [33], a MCS method is used to model the load variation, failure rate of the system components, and the random output of the renewable sources over a specified period of time. In [34], a fuzzy MCS method, considering data uncertainty in failure rate and repair time of all lines, is proposed to calculate observability reliability and loss of data expectation indices in power system. A binary programming model is presented in [8], for evaluating system average interruption frequency index ($SAIFI$) and momentary average interruption frequency index ($MAIFI$) as a function of locations of reclosers, fuse-blow fuses and fuse-save fuses in a radial distribution system. In this model, the fuse-clearing scheme has been defined at the fuse level instead of at the recloser level. A binary formulation for system average interruption duration index ($SAIDI$) of a radial distribution system is presented in [35], considering locations of reclosers, fuses (fuse-blow and fuse-save), switches and tie lines as design variables. A binary programming model is proposed in [36] to identify the locations and types of protective devices to be placed in a power distribution system while minimizing the outage cost, life cycle cost and investment cost. In [37], a methodology is proposed for optimal placement of sectionalizing and tie switches (with automatic and manual operation schemes) in a radial distribution network for reliability improvement. A binary programming optimization technique is proposed in [38] to identify types and locations of protective devices on a radial distribution network for minimizing $SAIFI$. A non-dominated sorting genetic algorithm ($NSGA$-II) based optimization technique is proposed in [39] for minimizing $SAIFI$, $SAIDI$ and momentary average interruption event frequency index ($MAIFI_E$) by optimal allocation of reclosers, sectionalizers, switches, fuse-blow fuses and fuse-save fuses in a 51-bus radial distribution system. A mixed-integer linear programming ($MILP$) model is formulated in [40] for optimal placement of automated and remotely controlled sectionalizing switches in distribution system. In this work, minimization of the total cost for achieving a certain level of reliability is the primary objective for determining the optimal locations and number of sectionalizing switches. In [41], a mixed-integer non-linear programming ($MINLP$) problem is formulated for planning of distribution system. The proposed multi-objective model considers the expansion and operational investment cost of the network as well as outage costs caused by energy not supplied due to the switching and repairing operations carried out in the affected sections of the distribution network by permanent faults. Another $MINLP$ problem is formulated in [42] for solving the multistage planning problem (including allocation of sectionalizing switches) of a distribution network using Tabu search algorithm. The objective functions of the multi-objective problem considered system reliability as well as investment and operational costs. A fuzzy multi-objective model is presented in [43] to identify the locations and number of sectionalizing switches in distribution network for reliability improvement and for minimizing purchasing and maintenance cost of the switches as well as the customer interruption cost. In [44], a method is presented for determining the set of manual switches required to be upgraded to remote-controlled switches (RCS_S) for the existing distribution network for service restoration enhancement by minimizing customer interruption. However, RCS_S are not fully reliable and, hence, result in delayed service restoration in case the RCS_S malfunction [45]. An analytical reliability model is proposed in [46] for optimal allocation of protective devices and fault detectors in smart distribution network to improve system reliability. The proposed objective function considered the customer interruption cost and the investment cost.

To solve the problem of optimal placement of protective devices in distribution system with DG, considerable research efforts have been devoted. In [47], a graph-based switch placement scheme is proposed to support the priority customers by single or multiple DGs in the event of faults. A dynamic modeling of λ is proposed in [48] for reliability analysis of a distribution system with and without DG. An ant colony optimization (ACO) based methodology is proposed in [49] for optimal placement of sectionalizing switches in a distribution system with DG to improve system reliability while minimizing the cost of switches. Another ACO based optimization algorithm is proposed in [23] to determine the optimal locations of reclosers and DGs for distribution system reliability maximization by minimizing an index consisting of weighted sum of SAIFI and SAIDI. Another method to determine the optimal number and locations of sectionalizing switches using MILP approach has been proposed in [22]. In this work, the problem of switch placement in distribution network in the presence of DG has been considered, for minimizing the total associated cost in order to achieve a specified level of reliability. A multi-objective switching device placement problem has been solved in [50] using NSGA-II considering DG unavailability, equipment cost and network reliability without islanding operation. In [51], a reliability worth analysis is carried out to evaluate the effect of integration of DG units in distribution system by developing two customer interruption cost models viz. aggregate or average cost model (AAM) and probability distribution cost model

(PDM) using cascade correlation neural network. Reliability evaluation of a test distribution system employing these models showed that PDM is more realistic than AAM.

1.3 Motivation

In all of the above studies, the failure rates, repair rates and loading conditions are assumed to be fixed. However, during the lifetime of the protective devices, these quantities are likely to vary. Therefore, for deciding the locations of protective devices in a radial distribution system, the uncertainties associated with failure rates, repair rates and loading conditions need to be incorporated.

Further, most of the reliability studies discussed above do not include the effect of momentary interruptions (due to temporary faults) hence, neglect the effect of damages due to the increased short duration voltage disturbances to the electronic and precision devices. Consequently, authenticity of the distribution system reliability calculation is affected due to omission of the effect of momentary interruptions. This advocates the inclusion of momentary interruptions in the formulation of the protective devices placement problems as these contribute to high interruption costs on industrial feeders.

Various scenarios of protective devices' placement in a distribution system pertaining to different combinations of protective devices are feasible. Each scenario will give a different optimal profit value for a given system, hence, the best scenario needs to be identified. Thus, it becomes necessary to develop a generalized formulation which can simulate any desired scenario and help a utility in deciding the best possible combination and optimal placement of protective devices for profit and reliability maximization.

Further more, in all of the reliability studies of the DG enhanced distribution systems, discussed above, the location of DGs are assumed to be at the end of the feeder. However, more often than not, the location of DG in the distribution system may not always be at the end of the feeder. Hence, there is a need for development of a model to investigate placement of protective devices in a distribution system with DGs connected at any position in the feeder.

This thesis tries to address the various gaps stated above and presents a systematic evolution of the problem and the corresponding solutions for increasing distribution system reliability.

1.4 Author contribution

Following the discussion in the previous section, the major contributions of this thesis are as follows:

- A formulation for optimal placement of switches and reclosers in a distribution system for maximizing distribution system reliability while minimizing the associated investment and outage costs over the life time of the system has been proposed.

- For considering the uncertainty in load data, system failure rates and repair rates, 3PEM based problem has been formulated for optimal placement of switches and reclosers in a distribution system.

- Effect of momentary interruptions due to temporary faults has been incorporated in the optimal placement problem of reclosers, switches and fuses in the distribution system for reliability improvement.

- A generalized model has been developed to solve the problems incorporating placement of various combinations of protective devices (recloser, switch, fuse-blow fuse and fuse-save fuse) in a distribution network for increasing the profit of the utility by enhancing the reliability.

- For improving reliability of the distribution system, an analytical model considering bi-directional power flow has been developed to solve the problem of the protective devices' placement in various zones/islands of a distribution system with DG(s) connected at any location(s) of the feeder.

1.5 Thesis organization

Apart from this chapter, there are six more chapters in this thesis. The organization of the thesis is as follows:

In **Chapter 2**, a formulation for optimal placement of switches and reclosers in a distribution system has been proposed for maximizing distribution system reliability while minimizing the associated investment and outage costs. The proposed formulation has been tested on 13-bus, 58-bus and IEEE 123-bus test systems using evolutionary programming (EP), genetic algorithm (GA), differential evolution (DE) and mixed-integer nonlinear programming (MINLP) method.

The uncertainties in load data, system failure and repair rates are considered in **Chapter 3**. Hence, a formulation for optimal placement of switches and reclosers in a distribution system for maximizing the distribution system reliability considering uncertainties in load data, system failure and repair rates has been presented. The uncertainties have been incorporated in the formulation using 3PEM. The proposed formulation has been tested on 13-bus, 58-bus and IEEE 123-bus test systems using DE and MINLP method.

Next, in **Chapter 4**, the effect of temporary faults has been incorporated in the problem of optimal placement of protective devices in the distribution system. Three different models for optimal placement of protective devices (switches, reclosers, fuses) in a distribution system, considering uncertainties in loads, temporary and permanent failure rates and repair rates, have been developed. The formulated problems have been solved for 58-bus and IEEE 123-bus distribution networks using MINLP optimization technique and 3PEM.

In **Chapter 5**, a generalized model capable of simulating different combinations of the protective devices has been developed. The model can solve the problems incorporating placement of various combinations of protective devices (recloser, switch, fuse-blow fuse and fuse-save fuse) in a distribution network for increasing the profit of the utility by reliability improvement. The uncertainties in temporary failure rates, permanent failure rates, repair rates and load data have been considered in the problem formulation using 3PEM. The formulated problems have been solved for 58-bus and IEEE 123-bus distribution networks using MINLP optimization technique.

Next, in **Chapter 6**, the effect of DG(s) connected in the system has been incorporated in the formulation of optimal placement problem of protective devices (recloser, switch, fuse-blow fuse and fuse-save fuse) in the distribution system. A model has been developed to solve the problem of the protective devices placement in various zones/islands of a distribution system with DG. The model is capable of solving the problem irrespective of the location of DG in the system. The formulated problem has been solved for 69-bus and 118-bus distribution systems using MINLP optimization technique.

Finally, **Chapter 7** lists the major conclusions as well as future scope of the work.

In the next chapter, a procedure for optimal placement of switches and reclosers in a distribution system for maximizing distribution system reliability has been presented.

Chapter 2

Switch and recloser placement in a radial distribution system

Abstract

This chapter presents a formulation for an optimal placement of switches and reclosers in a distribution system for maximizing distribution system reliability while minimizing the associated investment and outage costs. The proposed formulation has been tested on 13-bus, 58-bus and IEEE 123-bus test systems using evolutionary programming (EP), genetic algorithm (GA), differential evolution (DE) and mixed-integer nonlinear programming (MINLP) method. The obtained results establish the effectiveness of the MINLP method among above algorithms in improving the distribution system reliability and maximizing utilities' profit.

2.1 Introduction

For maximizing the customer satisfaction and retention, improvement of service reliability is a major concern for electric utilities. Service reliability can be improved by placing switches and reclosers at appropriate locations in the distribution system so that supply from the main substation to the healthy load points can be maintained after isolating the faulted section. In this chapter, a formulation has been presented for an optimal placement of switches and reclosers in a distribution system for maximizing distribution system reliability while minimizing the associated investment and outage costs. The main aim of this exercise is to maximize utilities' profit. For solving this optimization problem, heuristic as well as analytical methods can be used. For selecting the most suitable optimization method, a comparison of performances of heuristic methods and an analytical method has been carried out.

In this chapter, a formulation for optimal placement of switches and reclosers in a distribution system considering failure rates and repair rates of the system components has been presented. Further, the proposed formulated problem has been tested on three different test systems using evolutionary programming (EP), genetic algorithm (GA), differential evolution (DE) and mixed-integer nonlinear programming (MINLP) method. The relevant details of these optimization methods have been given in Appendix A.

This chapter is organized as follows: The basic concept of reliability calculation in the presence of switches and reclosers is explained in Section 2.2. The proposed problem formulation is explained in Section 2.3. Section 2.4 presents the main results of this chapter. The final conclusions of this chapter are drawn in Section 2.5.

2.2 Distribution system reliability calculation with switches and reclosers

The reliability of a distribution system is assessed by evaluating the adequacy of supply at the customer load point. In practice the basic indices used are [52, 53] : (a) average failure rate (λ) f/yr, (b) average outage duration (r) hr/failure and, (c) average annual outage time (U) hr/yr.

The procedure for calculating the average load point reliability indices in the presence of reclosers and switches in a distribution system is explained next.

Consider the case of a distribution system protected by a circuit breaker (CB) at the feed point, a recloser in the i^{th} feeder section and a switch in the j^{th} feeder section. For a fault in the i^{th} feeder section and other downstream feeder sections, the recloser will open instead of the circuit breaker (CB) to interrupt the fault current. As a consequence, all the loads upstream to i^{th} feeder section will not experience any interruption. Hence, interruption rate (λ) for these loads is set equal to 0 and for all the loads downstream to i^{th} faulted feeder section, the interruption rate is set equal to 'λ_i' (the failure rate of i^{th} feeder section). For faults in the j^{th} feeder section and other downstream feeder sections, all feeder sections upstream to j^{th} feeder section will have an interruption time equal to the isolation time corresponding to the faulted feeder section, while the loads downstream to j^{th} switch will have an interruption time equal to the repair time of the faulted feeder section.

For example, in Fig. 2.1, for faults in feeder section F_2 and F_3, load L_1 will not experience any supply interruption as the fault will be cleared by opening of the recloser and 'λ' will be zero for L_1. For faults in F_2 and F_3, loads L_2 and L_3 will have an interruption rate equal to the interruption rate of the faulted feeder section. Further, for a fault in F_3, recloser will open to interrupt the fault and switch SW will be opened afterwards to isolate the faulted feeder section. Recloser will then be closed to resume supply to L_2. The interruption time of L_2 will now be equal to the isolation time of switch SW ($r_{iso,3}$). Supply to L_3 will be resumed only after the repairs are completed, i.e. after 'r_3' hours.

Let $X_{R,i}$ and $X_{S,i}$ be the binary variables representing recloser and switch respectively in line i.

Also, let

$$\begin{aligned} X_{R,i}/X_{S,i} &= 0, \quad \text{if a recloser/switch is connected in line i} \\ &= 1, \quad \text{if a recloser/switch is not connected in line i} \end{aligned} \tag{2.1}$$

For the system shown in Fig. 2.1, for calculation of the equivalent 'λ' and 'r', first bus-injection to branch-current (BIBC) matrix is formed following the procedure given in [54]. The $[\mathbf{BIBC}]$ matrix contains values of 0 and 1 only.

If $bibc(i,j) = 1$, it implies that j^{th} load is downstream of i^{th} feeder section, where, $bibc(i,j)$ denotes the $(i,j)^{th}$ element of the $[\mathbf{BIBC}]$ matrix. Therefore, failure of i^{th} feeder section will result in outage of j^{th} load and the supply can be resumed only after the feeder section is repaired. Hence, the failure rate ($\lambda_{i,j}$) and repair time ($r_{i,j}$) of j^{th} load due to failure of i^{th} feeder section can be written as,

$$\begin{aligned} \lambda i,j &= \lambda_i \\ r_{i,j} &= r_i \end{aligned} \tag{2.2}$$

If $bibc(i,j) = 0$, it implies that j^{th} load is upstream of i^{th} feeder section. Therefore, placement of reclosers/switches will help in isolating the faulted i^{th} feeder section, thereby improving the availability of supply at j^{th} load. Hence, the failure rate ($\lambda_{i,j}$) and repair time ($r_{i,j}$) of j^{th} load due to failure of i^{th} feeder section can be written as,

$$\begin{aligned} \lambda i,j &= \lambda_i \prod_{k \epsilon F(i,j)} X_{R,k} \\ r_{i,j} &= r_i \prod_{k \epsilon F(i,j)} X_{S,k} + r_{iso,i}(1 - \prod_{k \epsilon F(i,j)} X_{S,k}) \end{aligned} \tag{2.3}$$

Where,

$$F(i,j) = P_{ath}(1,i) \cap P_{ath}(j,i) \tag{2.4}$$

Further, $P_{ath}(1,i)$ is the path from root node to i^{th} feeder section (including i^{th} feeder section) and $P_{ath}(j,i)$ is the path from j^{th} node to i^{th} feeder section (including i^{th} feeder section). $F(i,j)$ is the feeder sections common to paths $P_{ath}(1,i)$ and $P_{ath}(j,i)$.

Following the above procedure, the calculated values of equivalent 'λ' and 'r' for the network shown in Fig. 2.1 are given in Table 2.1. In this system, feeder section F_2 has a recloser and feeder section F_3 has a switch. Hence,

$$X_{R,1} = X_{R,3} = 1, \quad X_{R,2} = 0$$

$$X_{S,1} = X_{S,2} = 1, \quad X_{S,3} = 0$$

The $[\mathbf{BIBC}]$ matrix for this network is given below,

$$BIBC = \begin{array}{c} \\ F_1 \\ F_2 \\ F_3 \end{array}\begin{array}{c} \begin{array}{ccc} L_1 & L_2 & L_3 \end{array} \\ \begin{pmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix} \end{array} \tag{2.5}$$

Using the elements of $[\mathbf{BIBC}]$ matrix, Eq. (2.3) and the values of $X_{R,i}$ and $X_{S,i}$, the values of 'λ' and 'r' for the system are given in Table 2.2.

Thus the equivalent failure rate ($\lambda_j^{'}$) and equivalent outage time ($U_j^{'}$) of j^{th} load can be written as,

$$\lambda_j^{'} = \sum_{i=1}^{n} \lambda_{i,j} \tag{2.6}$$

$$U_j^{'} = \sum_{i=1}^{n} U_{i,j} \tag{2.7}$$

where,

$$U_{i,j} = \lambda_{i,j} r_{i,j} \tag{2.8}$$

and 'nbr' is the number of branches whose outage can cause failure at load point j. Eq. (2.8) is an approximation for the condition when $\lambda_i r_i$<<1.

Thus, the total energy not supplied (ENS) and the total customer interruption cost (TIC) can be calculated as follows [2]:

$$ENS = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_{i,j} r_{i,j}) L_j \quad kWhr/year \tag{2.9}$$

$$TIC = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_{i,j} ICP_{i,j}) L_j \tag{2.10}$$

Where, L_j is the average load connected to the j^{th} load point, nl is the total number of load points and $ICP_{i,j}$ is the sustained interruption cost of the load connected at j^{th} node due to the permanent fault in i^{th} feeder section for an outage duration of $r_{i,j}$.

2.3 Problem formulation

In this chapter, the switch and recloser placement problem has been formulated as an optimization problem for determining their optimal number and locations in a distribution system that minimizes the total customer interruption and outage costs. The optimization problem is constrained by the

Table 2.1: Values of 'λ' and 'r' as functions of X_S and X_R for Fig. 2.1

	Load 1 (L_1)		Load 2 (L_2)		Load 3 (L_3)	
Fault ↓	**λ**	**r**	**λ**	**r**	**λ**	**r**
F_1	λ_1	r_1	λ_1	r_1	λ_1	r_1
F_2	$\lambda_2 X_{R,2}$	$r_2 X_{S,2} + r_{iso,2}(1 - X_{S,2})$	λ_2	r_2	λ_2	r_2
F_3	$\lambda_3 X_{R,2} X_{R,3}$	$r_3 X_{S,2} X_{S,3} + r_{iso,3}(1 - X_{S,2} X_{S,3})$	$\lambda_3 X_{R,3}$	$r_3 X_{S,3} + r_{iso,3}(1 - X_{S,3})$	λ_3	r_3

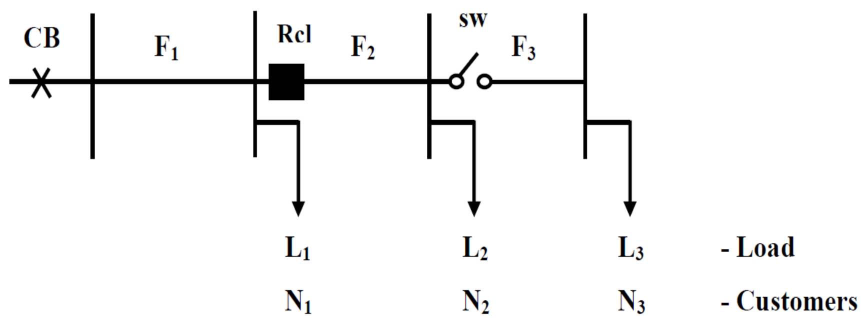

Figure 2.1: Radial distribution system with 3 feeder sections and 3 load points with one switch and one recloser

Table 2.2: Calculation of equivalent 'λ' and 'r' for a switch and a recloser case

	L_1		L_2		L_3	
Fault ↓	**λ**	**r**	**λ**	**r**	**λ**	**r**
F_1	λ_1	r_1	λ_1	r_1	λ_1	r_1
F_2	**0**	$\mathbf{r_2}$	λ_2	r_2	λ_2	r_2
F_3	**0**	$\mathbf{r_{iso,3}}$	$\boldsymbol{\lambda_3}$	$\mathbf{r_{iso,3}}$	λ_3	r_3

number of available switches and reclosers that can be placed in the distribution system as well as restriction on placement of at most one recloser or one switch in any feeder section. The optimization variables include number of switches, position of switches, number of reclosers and position of reclosers to be placed in the distribution system.

2.3.1 Objective function

The objective function for optimal placement of the switches and reclosers in a distribution system for reliability improvement involves maximization of the revenue earning due to increase in energy supplied to the customers and due to reduction in cost of interruption while minimizing the expenditure due to installation, operation and maintenance of reclosers and switches. Thus, the objective function can be expressed by the following equation:

$$\begin{aligned} Maximize \quad f &= (R_E + R_I) - (C_{SR} + T_{MC}) \\ &= Revenue - Expenditure \end{aligned} \tag{2.11}$$

Various terms in Eq. (2.11) are now explained below.

1. R_E is the net present worth of revenue earned, over the useful life of reclosers and switches (n_s years), due to increase in energy supplied to the customers. If ENS_{UP} is the expected energy not served by the unprotected system (when no switches and reclosers are placed) and ENS_P is the expected energy not served for protected system (with switches and reclosers), then $(ENS_{UP} - ENS_P)$ is the additional energy that can be supplied by the protected system in the base year which in turn will increase the revenue collection of the distribution system. Therefore,

$$R_E = (ENS_{UP} - ENS_P)C_E F_1 \tag{2.12}$$

Where,

$$F_1 = \frac{1 - a_1^{n_s}}{1 - a_1} \quad and \quad a_1 = \frac{(1 + \frac{L_c}{100})(1 + \frac{r_E}{100})}{(1 + \frac{i_r}{100})}$$

L_C = annual rate of load growth in percentage.

r_E = annual percentage increase in the cost of energy.

C_E = present cost of one unit of energy.

i_r = annual rate of interest in percentage.

n_s = lifetime of the switches and reclosers in years.

2. R_I is the increase in revenue due to the reduction in cost of interruption. This is also calculated for n_s years. Distribution companies have to compensate their customers for the damage caused due to supply interruption. The representative values of the interruption costs for three sectors namely, residential, commercial and industrial are given in Table 2.3 [55].

Table 2.3: Interruption cost for three types of customers

Time (min)	Residential ($)	Commercial ($)	Industrial ($)
1	0.001	0.0381	1.625
20	0.093	2.969	3.868
60	0.482	8.552	9.085
240	4.914	31.32	25.16
480	15.69	83.01	55.81

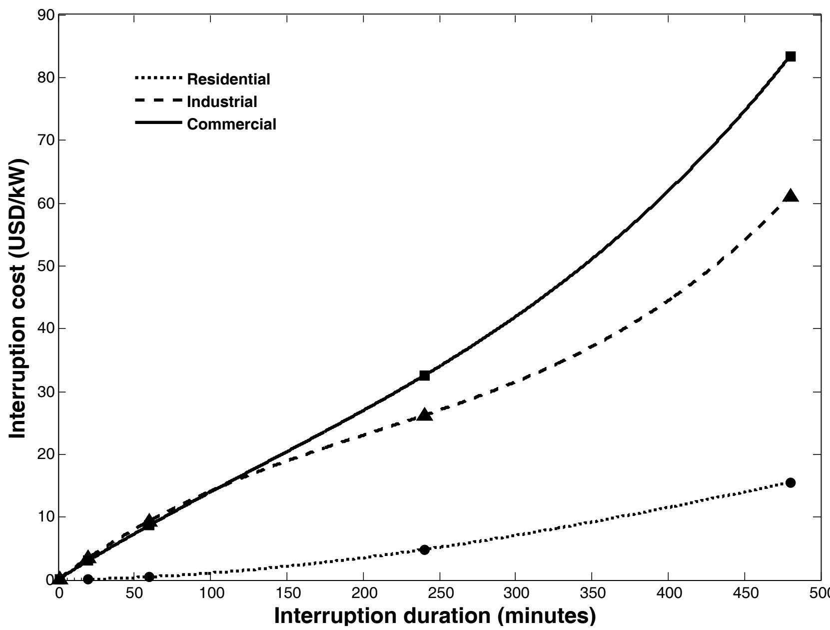

Figure 2.2: Interruption costs for different customers

Typical interruption cost characteristics for different types of customers are shown in Fig. 2.2. These characteristics have been drawn based on the numerical data given in [55]. For the purpose of utilising these characteristics in this work, polynomial equations have been fitted on each of these three characteristics. The obtained polynomial relations are:

(a) Residential customer:

$$IC_R(t) = -0.00000004 * t^3 + 0.00008 * t^2 + 0.0032 * t \tag{2.13}$$

(b) Industrial customer:

$$IC_I(t) = 0.0000008 * t^3 - 0.0005 * t^2 + 0.183 * t \tag{2.14}$$

(c) Commercial customer:

$$IC_C(t) = 0.0000005 * t^3 - 0.0002 * t^2 + 0.1545 * t \tag{2.15}$$

In the above expressions, t is the interruption duration in minutes and $IC_R(t)$, $IC_I(t)$ and $IC_C(t)$ are the interruption costs in US dollars (USD) for residential, industrial and commercial customers respectively. These values have been converted to equivalent amount of Indian rupees (Rs.) (at the rate of Rs. 60 per USD) in this chapter.

The customer interruption cost of i^{th} load for fault in j^{th} feeder section (CIC_{ij}) can be written as [53],

$$CIC_{ij} = \lambda_{ij} IC_{ij} L_i \tag{2.16}$$

Where, 'λ_{ij}'= failure rate of i^{th} load due to fault in j^{th} feeder section.
IC_{ij} = interruption cost at i^{th} load point due to outage duration r_{ij} for fault in j^{th} feeder section.
L_i = average load connected at i^{th} load point.

This is calculated using the appropriate interruption cost function with t set equal to r_{ij}.
The total interruption cost (TIC) can therefore be written as [53],

$$TIC = \sum_{i=1}^{nl} \sum_{j=1}^{nbr} CIC_{ij} \tag{2.17}$$

where,
nl = number of loads .
nbr = number of branches in the system.
The net present worth of saving in interruption cost 'R_I' is given by the following expression:

$$R_I = (TIC_{UP} - TIC_P)F_2 \tag{2.18}$$

Where,

$$F_2 = \frac{1 - a_2^{n_s}}{1 - a_2} \quad and \quad a_2 = \frac{(1 + \frac{L_c}{100})(1 + \frac{i_c}{100})}{(1 + \frac{i_r}{100})}$$

TIC_{UP} = Total interruption cost of unprotected system with no switches and reclosers.
TIC_P = Total interruption cost of protected system with switches and reclosers.
i_c = percentage annual rate of change in the interruption cost .

3. C_{SR} is the cost of switches and reclosers, given by

$$C_{SR} = N_{SW} * Cost_{SW} + N_{Rec} * Cost_{Rec}$$

Where,

N_{SW} = number of switches placed in the distribution system.

$Cost_{SW}$ = cost of a switch.

N_{Rec}= number of reclosers placed in the distribution system.

$Cost_{Rec}$ = cost of a recloser.

4. T_{MC} is the total cost of maintenance of the switches and reclosers over their useful lives. For this, the cost of maintenance (C_m) is assumed to be a given fraction of the total switch and recloser cost. Further, an annual rate of increase of maintenance cost over the lifetime of the components has also been assumed. The net present worth of the life time maintenance cost is finally calculated as:

$$T_{MC} = C_{SR} \frac{C_m}{100} F_3 \tag{2.19}$$

Where,

$$F_3 = \frac{1 - a_3^{n_s}}{1 - a_3} \quad and \quad a_3 = \frac{(1 + \frac{r_m}{100})}{(1 + \frac{r_i}{100})}$$

and,

r_m = percentage annual rate of increase in the maintenance cost,

2.3.2 Constraints

The model of switch and recloser placement in distribution system described in previous section consists of the following constraints.

1. The numbers of switches and reclosers to be installed in the distribution system should not exceed the number specified by the utility [22]. These constraints are given by the following equations.

$$\sum_{i=1}^{nbr} (1 - X_{R,i}) \leq N_{ar} \tag{2.20}$$

$$\sum_{i=1}^{nbr}(1 - X_{S,i}) \leq N_{as} \quad (2.21)$$

Where,

$X_{R,i}$ = 0, if recloser is present in i^{th} branch, else 1.

$X_{S,i}$ = 0, if switch is present in i^{th} branch, else 1.

N_{ar} = Number of available reclosers.

N_{as} = Number of available switches.

2. Recloser and switch should not be placed in the same branch.

$$X_{R,i} \neq X_{S,i} \quad i = 1, 2, ..., nbr \quad (2.22)$$

2.4 Case studies

The optimal placement of switches and reclosers have been carried out in the 13-bus, 58-bus and IEEE 123-bus test systems using EP [56], GA [57, 58], DE [59] and MINLP [60] for maximizing the objective function value (profit) defined in Eq. (2.11). MINLP considered in the work utilizes sequential quadratic programming through $fmincon$ function available in MATLAB optimization toolbox. Each method has been executed 100 times with the same convergence criterion for evaluating the reproducibility of the results. Subsequently, from these obtained results corresponding to 100 runs, various statistical parameters have been obtained for the purpose of comparison. The comprehensive flow-chart of the overall calculation procedure is shown in Fig. 2.3. The single line diagrams of 13-bus, 58-bus and IEEE 123-bus test systems are given in Figs. 2.4-2.6 respectively. System cost data is given in Table 2.4. Other system data such as bus data for 13-bus, 58-bus and IEEE 123-bus systems are given in Table 2.5, Table 2.6 and in [61] respectively while failure data are given in Table 2.7, Table 2.8 and Table 2.9 respectively. It is to be noted that in Table 2.5 and 2.6, P_{load} denotes real power load. Further, customer types '1', '2' and '3' denote residential, commercial and industrial customers respectively. In this paper, the IEEE 123-bus test system has been modified as given in [29] having residential customers only with a load of 1 kW per customer. Other necessary data used in the simulation studies are given in [61].

The various assumptions adopted in this work are listed below:

1. The lifetime of the switches and reclosers is taken as 20 years.

2. The values of real power given in Table 2.5 and Table 2.6 are taken as mean values.

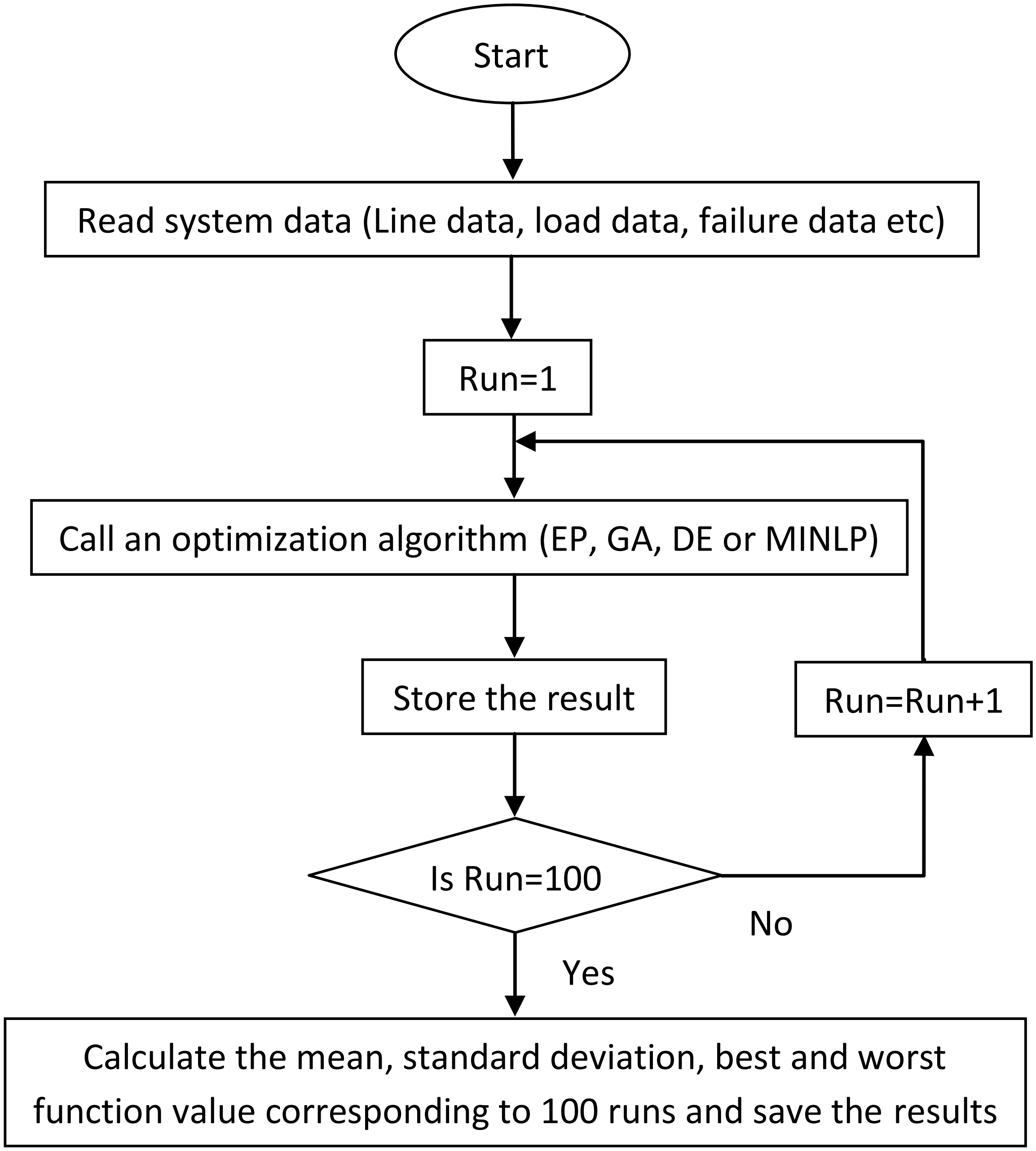

Figure 2.3: Flow-chart of the general optimization procedure

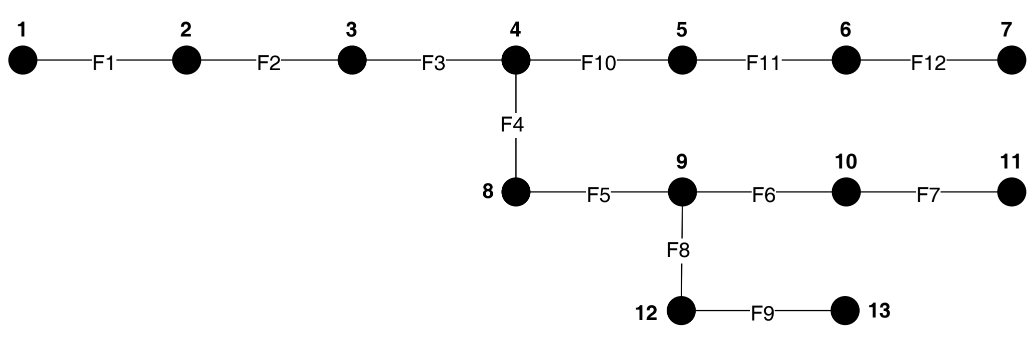

Figure 2.4: Single line diagram of 13-bus test system

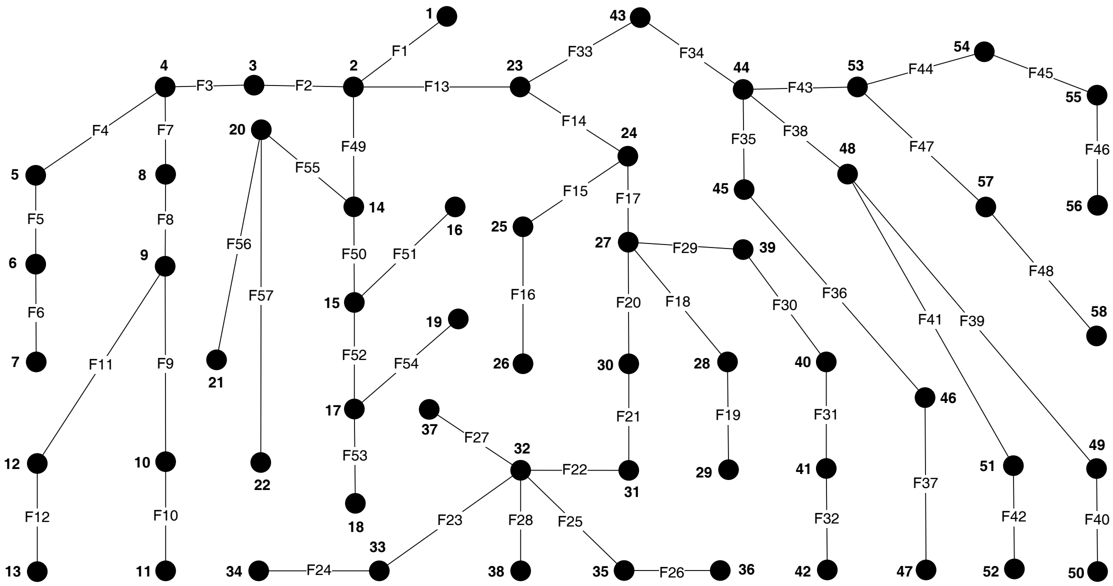

Figure 2.5: Single line diagram of 58-bus test system

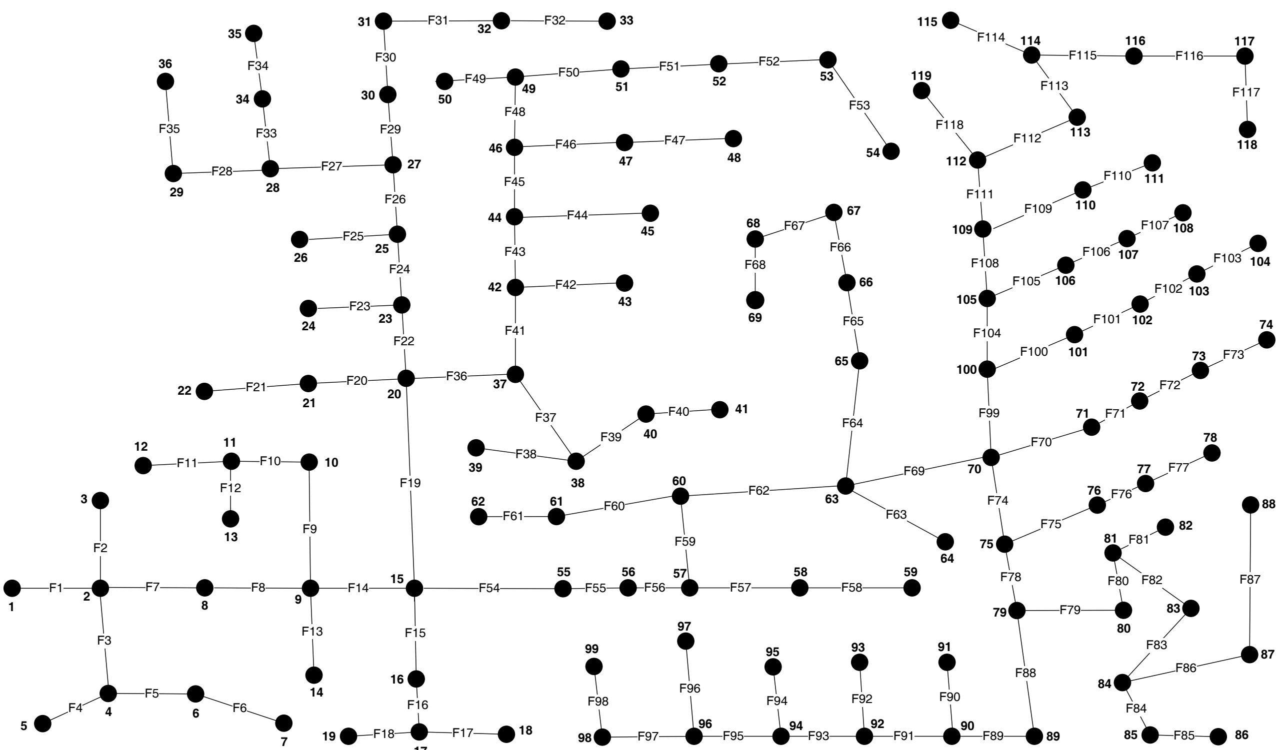

Figure 2.6: Single line diagram of IEEE 123-bus test system

Table 2.4: System cost data

Switch Cost	Rs. 1,50,000
Recloser Cost	Rs. 4,50,000
Cost of Energy	Rs. 7/kWh
Rate of load growth/year	5%
Rate of interest	10%
Rate of change of Energy cost/year	2%
Rate of change of interruption cost/year	2%
Maintenance cost of switches and reclosers	5% of the cost
Rate of change of maintenance cost/year	2%

3. The values of failure rate (λ) and repair time (r) given in Tables 2.7, 2.8 and 2.9 are taken as mean values.

4. The fault isolation time of the switches (r_{iso}) is taken as 0.5 hrs.

5. The crossover factor and the mutation factor for GA have been taken as 0.8 and 0.01, respectively [62].

6. The mutation factor and crossover rate for DE have been taken as 0.5 and 0.4 respectively [62].

7. The mutation scale β_m, for EP has been taken as 0.98 . β_m is a positive number slightly less than unity, that could be adaptively decreased during generations [56].

8. Population size and maximum number of iterations for EP and DE are 40 and 500 respectively, while for GA, population size and maximum number of iterations are 200 and 500 respectively. It is to be noted that with small population size (40), the optimum value obtained with GA was quite low, indicating that it was getting stuck to some local minimum point. As a result, the population size for GA was increased to 200.

9. No restriction has been placed on the numbers of reclosers and switches for the present study. However, the number of reclosers and switches can be limited through Eqs. (2.20) and (2.21).

10. For all the methods, for convergence, the difference in the function value between the current iteration and the previous iteration is checked. If this difference goes below a certain threshold

Table 2.5: Bus data for 13-bus test system

Bus No.	P_{load} (pu)	Customer type	Bus No.	P_{load} (pu)	Customer type	Bus No.	P_{load} (pu)	Customer type	Bus No.	P_{load} (pu)	Customer type
2	8.73	3	5	2.11	2	8	4.73	3	11	1.27	1
3	3.38	3	6	2.11	2	9	0.35	1	12	0.35	1
4	3.38	3	7	1.27	2	10	0.42	1	13	0.42	1

Table 2.6: Bus data for 58-bus test system

Bus No.	P_{load} (pu)	Customer type	Bus No.	P_{load} (pu)	Customer type	Bus No.	P_{load} (pu)	Customer type	Bus No.	P_{load} (pu)	Customer type
2	0	1	17	1.7	3	32	0	1	47	2.35	3
3	0.2	1	18	1.27	2	33	1.31	2	48	0.001	1
4	0	1	19	0.35	1	34	0.42	1	49	1.21	2
5	0.4	1	20	1.9	3	35	0.68	1	50	0.42	1
6	0.8	1	21	2.4	3	36	1.21	2	51	1.38	2
7	0.42	1	22	0.425	1	37	1.425	2	52	1.81	3
8	1.5	2	23	0	1	38	0.73	1	53	1.42	2
9	0	1	24	1.27	2	39	1.27	2	54	1.73	3
10	0.35	1	25	0.3	1	40	0.35	1	55	1.27	2
11	1.6	2	26	1.5	2	41	1.68	2	56	0.35	1
12	1.1	2	27	0	1	42	1.41	2	57	1.58	2
13	0.42	1	28	0.425	1	43	0.42	1	58	2.31	3
14	0	1	29	0.73	1	44	0	1			
15	1.3	2	30	1.27	2	45	1.73	3			
16	0.42	1	31	2.35	3	46	1.27	2			

(in this work, the threshold is 10^{-12}), then the algorithm is considered to have converged, otherwise not.

The parameters of the three evolutionary techniques (EP, GA and DE) given in assumptions above will be referred to as the set of standard parameters.

2.4.1 Results for 13-bus test system

Table 2.10 shows the mean and standard deviation of the results for 13-bus test system corresponding to 100 runs with standard parameter (crossover rate, mutation factor etc) values for each of the four techniques along with the best and worst objective function values and average run time per run for

Table 2.7: System failure data for 13-bus test system

Feeder section	λ (f/yr)	r (hrs)	Feeder section	λ (f/yr)	r (hrs)	Feeder section	λ (f/yr)	r (hrs)	Feeder section	λ (f/yr)	r (hrs)
F1	0.1	4	F4	0.25	3	F7	0.1	4	F10	0.25	3
F2	0.15	5	F5	0.15	2	F8	0.15	5	F11	0.15	2
F3	0.2	6	F6	0.1	2	F9	0.2	6	F12	0.1	2

Table 2.8: System failure data for 58-bus test system

Feeder section	λ (f/yr)	r (hrs)	Feeder section	λ (f/yr)	r (hrs)	Feeder section	λ (f/yr)	r (hrs)	Feeder section	λ (f/yr)	r (hrs)
F1	0.1	4	F16	0.25	3	F31	0.1	4	F46	0.1	4
F2	0.15	5	F17	0.1	2	F32	0.2	6	F47	0.1	2
F3	0.25	3	F18	0.1	4	F33	0.25	3	F48	0.1	4
F4	0.1	4	F19	0.15	5	F34	0.15	2	F49	0.2	6
F5	0.2	6	F20	0.2	6	F35	0.1	4	F50	0.15	2
F6	0.25	3	F21	0.15	2	F36	0.2	6	F51	0.25	3
F7	0.1	4	F22	0.1	2	F37	0.25	3	F52	0.1	2
F8	0.15	2	F23	0.15	5	F38	0.1	2	F53	0.15	5
F9	0.1	2	F24	0.2	6	F39	0.15	5	F54	0.15	2
F10	0.15	5	F25	0.2	6	F40	0.1	2	F55	0.2	6
F11	0.2	6	F26	0.15	2	F41	0.1	4	F56	0.25	3
F12	0.15	2	F27	0.25	3	F42	0.15	5	F57	0.1	2
F13	0.25	3	F28	0.1	2	F43	0.25	3			
F14	0.1	2	F29	0.15	5	F44	0.15	2			
F15	0.15	2	F30	0.15	2	F45	0.15	5			

each of these methods. It can be observed from Table 2.10 that all these four techniques give the same best objective function value for 13-bus test system. Corresponding to best objective function value, the optimal location of reclosers are in feeder sections F4 and F10 whereas, the optimal location of switches are in feeder sections F2, F3, F5 and F8. From this table, it is evident that EP gives the best mean value of the function and the least value of standard deviation. However, MINLP requires least amount of computational time among all the four methods. The optimal locations of switches and reclosers for this system are also shown in Fig. 2.7.

Table 2.11 shows the mean and standard deviation of the results for 13-bus test system corre-

Table 2.9: System failure data for IEEE 123-bus test system

λ (f/yr)	Feeder section
0.10	F1 F6 F7 F12 F13 F18 F19 F24 F25 F30 F31 F36 F37 F42 F43 F48 F51 F52 F57 F58 F63 F64 F69
	F70 F75 F76 F81 F82 F87 F88 F93 F94 F99 F100 F105 F108 F109 F114 F115
0.15	F2 F5 F8 F11 F14 F17 F20 F23 F26 F29 F32 F35 F38 F41 F44 F47 F50 F53 F56 F59 F62 F65 F68
	F71 F74 F77 F80 F83 F86 F89 F92 F95 F98 F101 F104 F107 F110 F113 F116
0.20	F3 F9 F15 F21 F27 F33 F39 F45 F54 F60 F66 F72 F78 F84 F90 F96 F102 F111 F117
0.25	F4 F10 F16 F22 F28 F34 F40 F46 F49 F55 F61 F67 F73 F79 F85 F91 F97 F103 F106 F112 F118

r (hrs)	Feeder section
2	F5 F6 F11 F12 F17 F18 F23 F24 F29 F30 F35 F36 F41 F42 F47 F48 F50 F51 F56 F57 F62 F63
	F68 F69 F74 F75 F80 F81 F86 F87 F92 F93 F98 F99 F104 F105 F107 F108 F113 F114
3	F4 F10 F16 F22 F28 F34 F40 F46 F49 F55 F61 F67 F73 F79 F85 F91 F97 F103 F106 F112 F118
4	F1 F7 F13 F19 F25 F31 F37 F43 F52 F58 F64 F70 F76 F82 F88 F94 F100 F109 F115
5	F2 F8 F14 F20 F26 F32 F38 F44 F53 F59 F65 F71 F77 F83 F89 F95 F101 F110 F116
6	F3 F9 F15 F21 F27 F33 F39 F45 F54 F60 F66 F72 F78 F84 F90 F96 F102 F111 F117

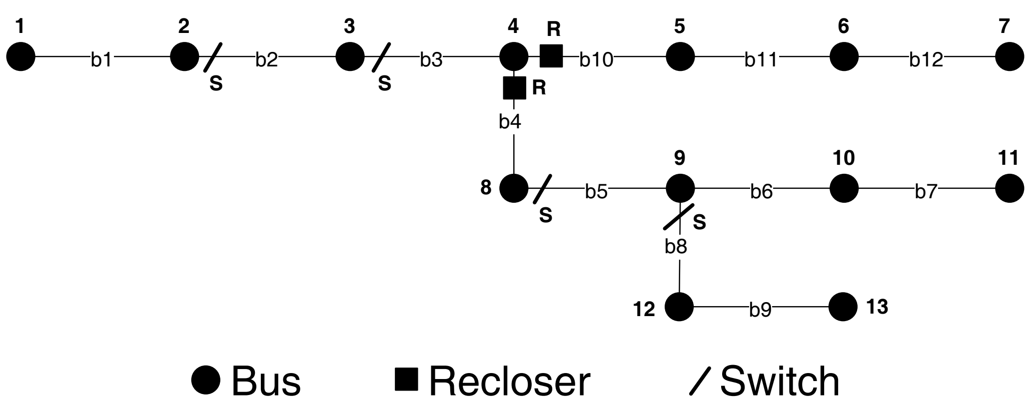

Figure 2.7: 13-bus test system protected by EP/GA/DE/MINLP techniques

Table 2.10: Summary of results of 100 runs with standard parameter values for 13-bus test system

Parameters	EP	GA	DE	MINLP
Best function value (Rs.)	30013919.52	30013919.52	30013919.52	30013919.52
Mean function value (Rs.)	29959334.75	29792166.28	29798332.27	29922195.81
Worst function value (Rs.)	29809829.11	29188630.61	28462904.24	29219402.37
Standard deviation (% of mean)	0.20	0.60	0.94	0.39
Average run time (s)	0.77	0.57	0.44	0.06

Table 2.11: Summary of results of 100 runs with perturbed parameter values for 13-bus test system

Parameters	EP	GA	DE
Best function value (Rs.)	30013919.52	30013919.52	30013919.52
Mean function value (Rs.)	29941688.88	29737876.29	29726109.82
Worst function value (Rs.)	29624292.45	29098164.71	28376856.22
Standard deviation (% of mean)	0.27	0.65	0.96

sponding to 100 runs, with perturbed parameter values of each of the evolutionary techniques viz. EP, GA and DE ($\pm$20% random variation in parameter values) along with the best and worst objective function values. From Table 2.10 and 2.11, it can be observed that the best objective function value remains unchanged for the perturbed and standard parameter values. However, the standard deviation and worst function values obtained with standard parameter values are better than those obtained with perturbed parameter values. Hence, the standard parameter values can be considered to be the most appropriate and therefore, all further studies have been carried out using the set of standard parameters.

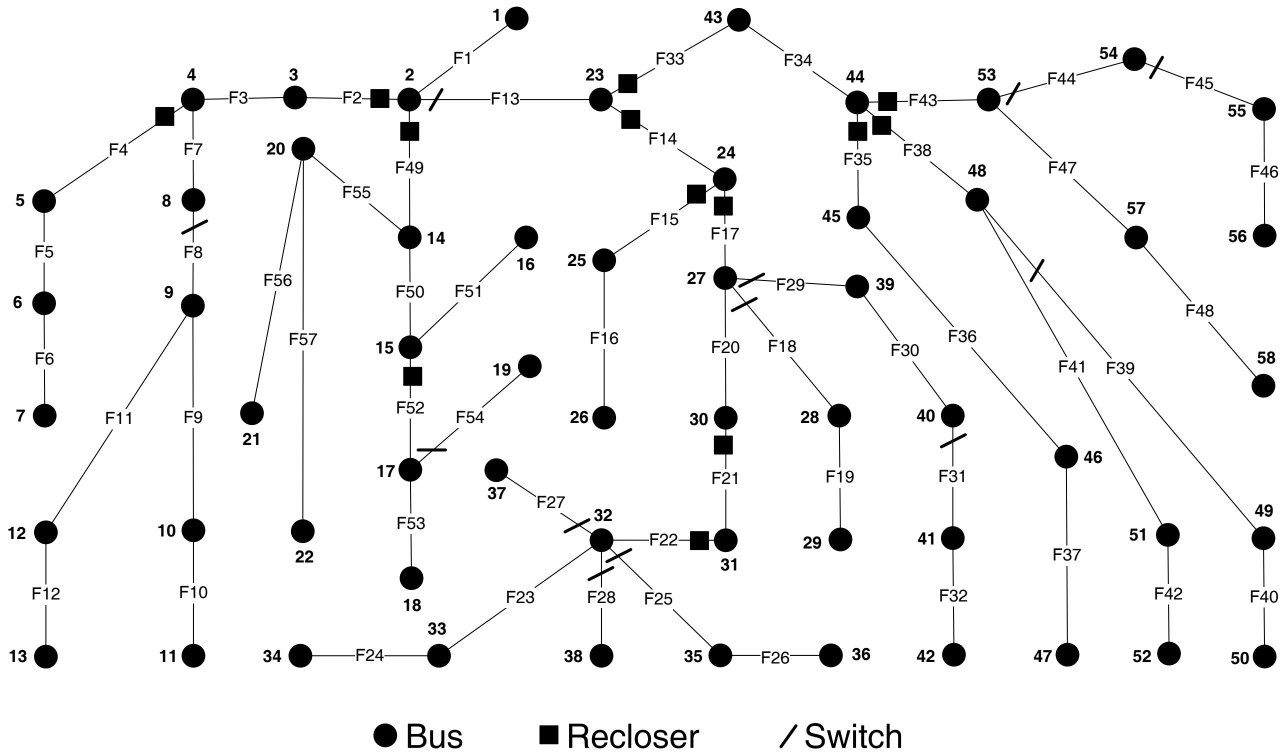

Figure 2.8: 58-bus test system protected by EP optimization technique

2.4.2 Results for 58-bus test system

The results for 58-bus test system corresponding to the four methods with standard parameter values are given in Table 2.12. From the results it can be observe that standard deviation, worst function value and best function value obtained with MINLP are better than the corresponding values obtained with other three evolutionary algorithms. Further, MINLP approach takes least amount of computational time. Therefore the locations of reclosers and switches corresponding to the best solution of MINLP are chosen as the final solution for 58-bus test system. These locations are : switches are placed in feeder sections F4, F8, F9, F13, F18, F20, F21, F23, F25, F27, F28, F32, F37, F39, F44, F45, F47, F50, F53, F54 and F55 while reclosers are placed in feeder sections F2, F14, F15, F22, F29, F33, F35, F38, F43 and F49. The optimal locations of switches and reclosers for this system corresponding to EP, GA, DE and MINLP optimization techniques are also shown in Figs. 2.8-2.11 respectively.

2.4.3 Results for IEEE 123-bus test system

The results for IEEE 123-bus test system for the four methods with standard parameter values are given in Table 2.13. From this table, it is observed that, among all the four methods, MINLP gives the

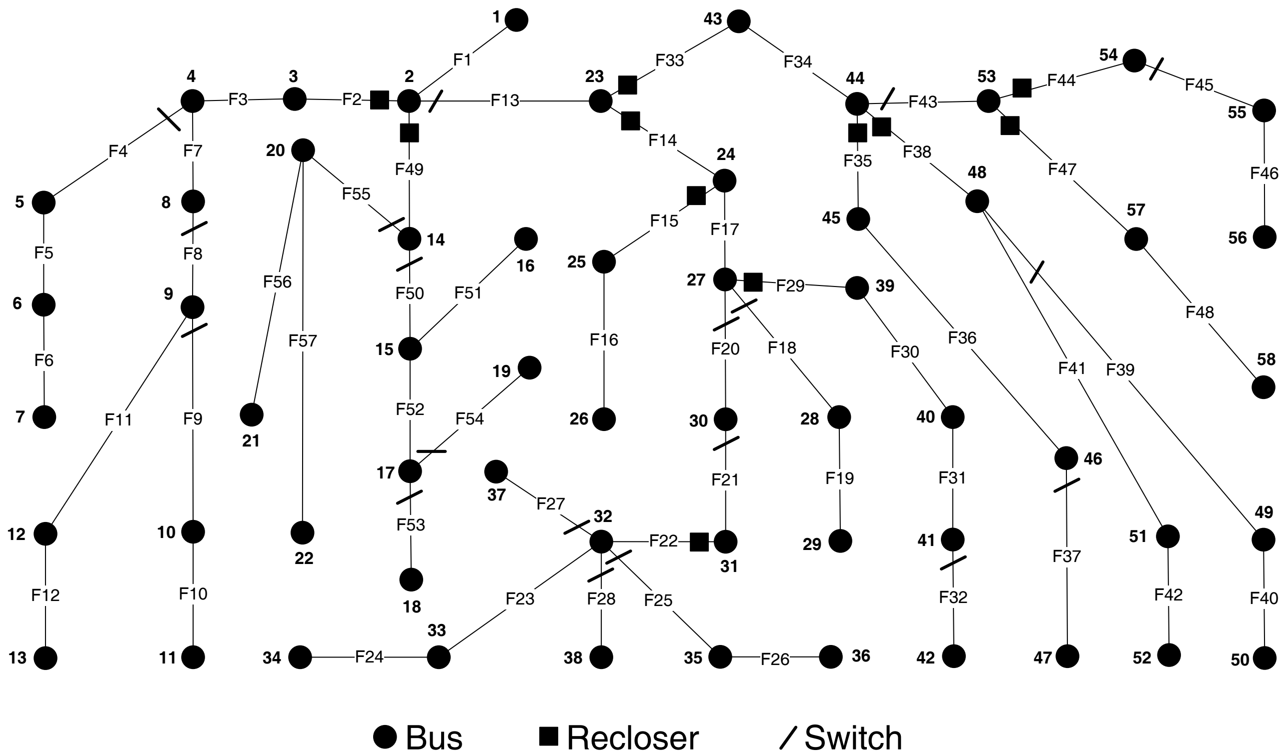

Figure 2.9: 58-bus test system protected by GA optimization technique

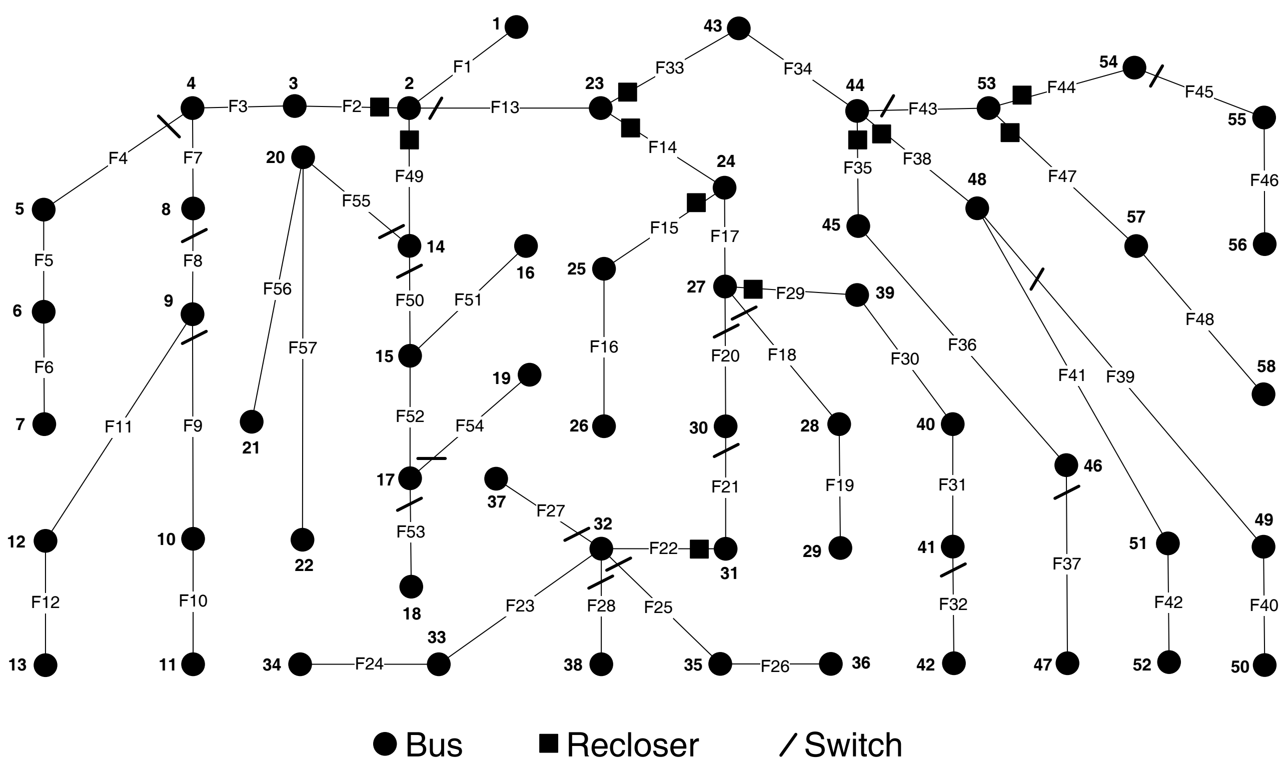

Figure 2.10: 58-bus test system protected by DE optimization technique

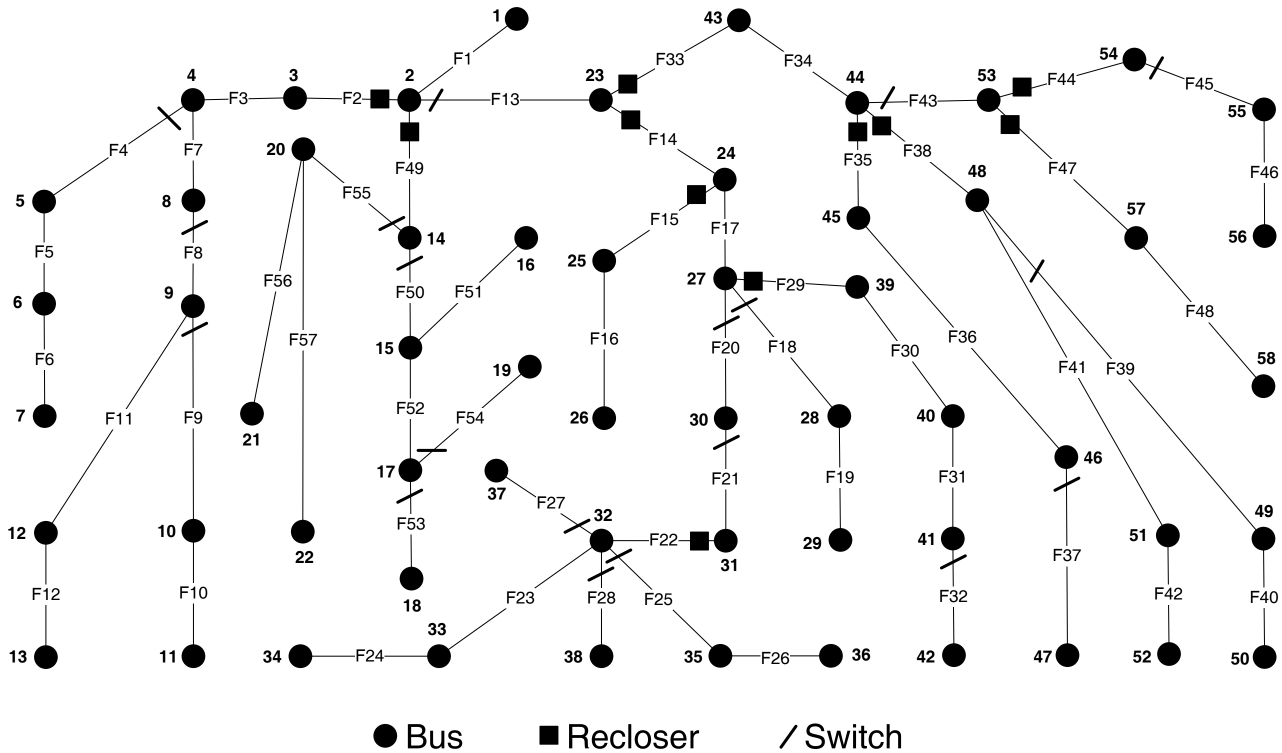

Figure 2.11: 58-bus test system protected by MINLP optimization technique

Table 2.12: Summary of results of 100 runs with standard parameter values for 58-bus test system

Parameters	EP	GA	DE	MINLP
Best function value (Rs.)	324931322.28	328101608.25	328182689.72	328185967.86
Mean function value (Rs.)	322772386.44	327410365.06	327687115.15	328048108.87
Worst function value (Rs.)	320529212.46	326289584.71	326815828.83	327091566.07
Standard deviation (% of mean)	0.27	0.11	0.09	0.05
Average run time (s)	9.60	16.91	6.88	1.24

Table 2.13: Summary of results of 100 runs with standard parameter values for IEEE 123-bus test system

Parameters	EP	GA	DE	MINLP
Best function value (Rs.)	32840327.27	34481884.92	34573820.45	34573820.45
Mean function value (Rs.)	31570775.07	33658638.45	34384077.22	34368000.67
Worst function value (Rs.)	29919438.22	32399928.35	33896104.89	33942413.82
Standard deviation (% of mean)	2.04	1.22	0.43	0.39
Average run time (s)	39.60	77.20	44.83	13.19

maximum best function value and mean function value with the smallest standard deviation. Further, the average run time is least for MINLP. Therefore again, the solution obtained by MINLP is taken as the final solution for the 123-bus test system. Using MINLP optimization technique, the obtained optimal locations of switches are in feeder sections F2, F3, F9, F13, F15, F20, F22, F37, F41, F60, F64, F70, F74, F79, F88, F99 and F111 while optimal location for reclosers are in feeder sections F19 and F54. The optimal locations of switches and reclosers for this system corresponding to EP, GA, DE and MINLP optimization techniques are also shown in Figs. 2.12-2.15 respectively.

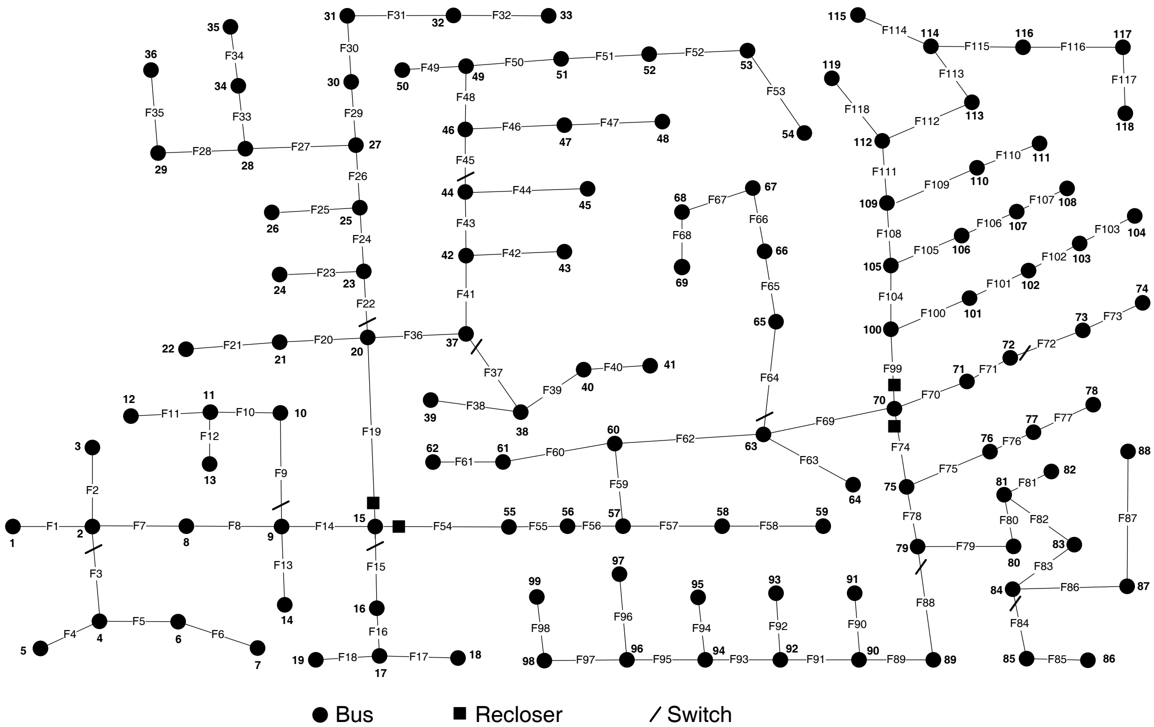

Figure 2.12: IEEE 123-bus test system protected by EP technique

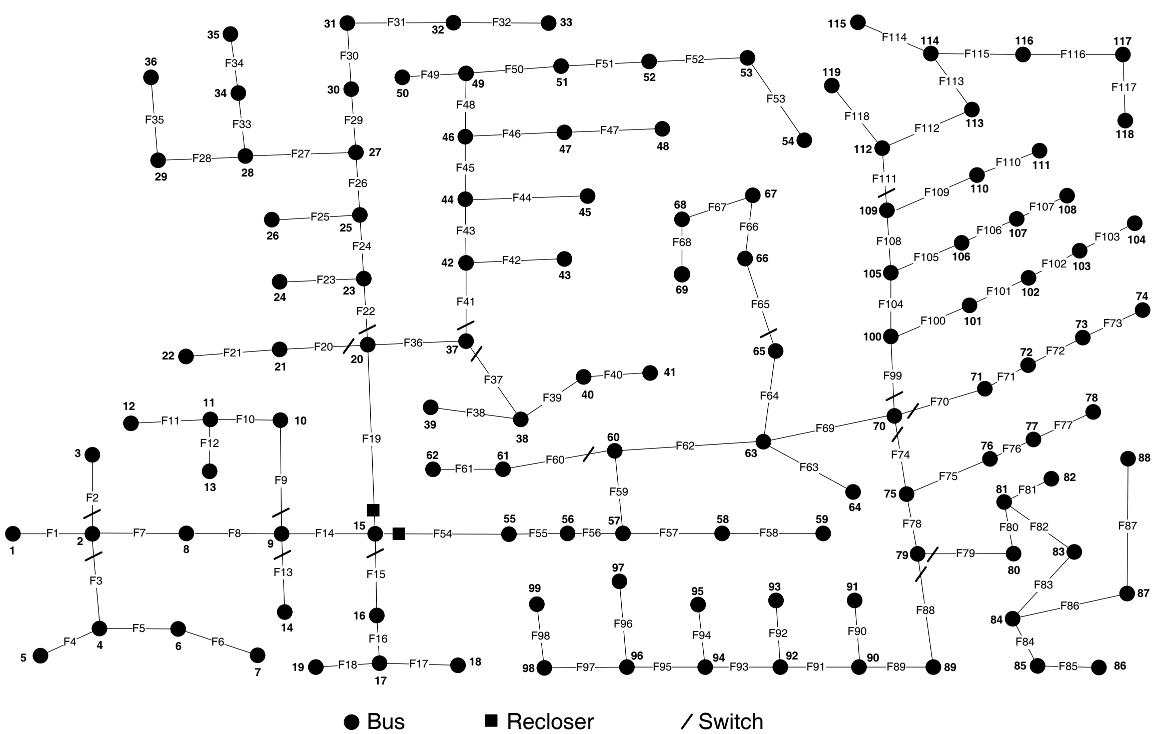

Figure 2.13: IEEE 123-bus test system protected by GA technique

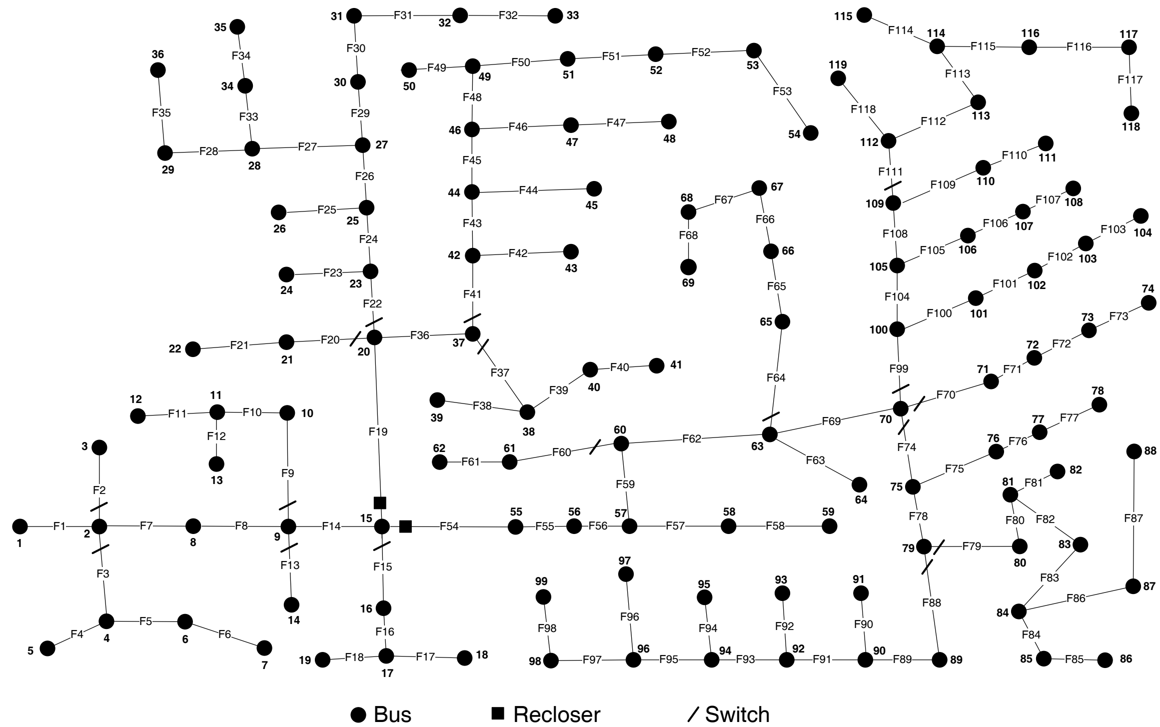

Figure 2.14: IEEE 123-bus test system protected by DE technique

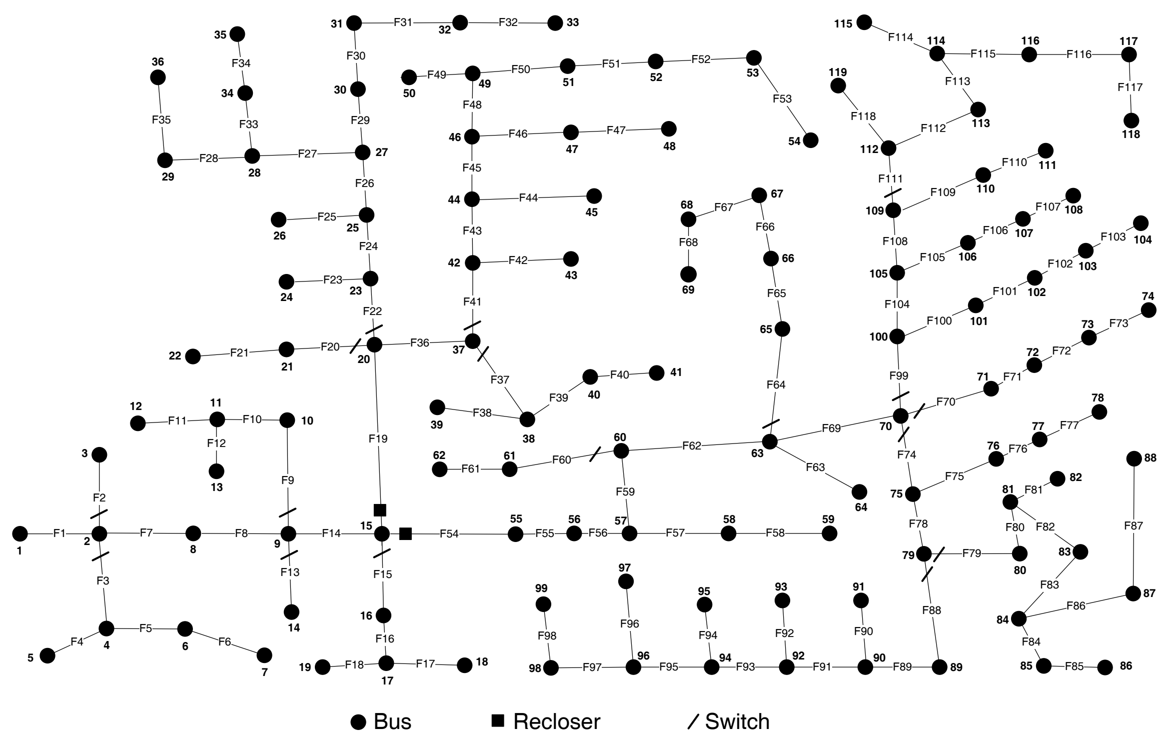

Figure 2.15: IEEE 123-bus test system protected by MINLP technique

2.5 Conclusion

In this chapter, a formulation for optimal placement of switches and reclosers in a distribution system for reliability improvement and maximizing utilities' revenues has been presented. MINLP method along with three evolutionary algorithms viz. EP, GA and DE (with same initial population and equivalent convergence criteria) have been used to evaluate the optimal location of switches and reclosers in the distribution system. Each of the four techniques have been evaluated for 100 independent runs for 13-bus, 58-bus and IEEE 123-bus test systems and various statistical parameters such as mean, standard deviation, average run time etc. have been calculated for the purpose of performance analysis. After comparative analysis of the obtained results, it is concluded that out of the four optimization methods considered, MINLP invariably produces best results with least computational efforts for all the test systems studied, closely followed by DE.

In the next chapter, a procedure for taking into account the uncertainties in the system loading conditions, failure rates and repair rates for the optimal placement of switches and reclosers in a distribution system is described.

Chapter 3

Switch and recloser placement in a distribution system considering uncertainties in loads, failure rates and repair rates

Abstract

Chapter 2 presents a formulation for optimal placement of switches and reclosers in a distribution system considering deterministic values of the load, failure rates and repair rates. However, the loading condition of the system, failure rates and repair rates of the switches and reclosers are likely to vary over a long period of operation. This chapter presents a formulation for an optimal placement of switches and reclosers in a distribution system for maximizing system reliability while minimizing the associated investment and outage costs considering uncertainties in load data, system failure and repair rates. The uncertainties have been incorporated in the formulation using three point estimate method (3PEM). The proposed formulation has been tested on 13-bus, 58-bus and IEEE 123-bus test systems using differential evolution (DE) and mixed-integer nonlinear programming (MINLP) method. This study also helps the utilities in taking a realistic decision based on the calculated values of robust profit (RP_β) and conditional robust profit (CRP_β).

3.1 Introduction

THE input parameters required for reliability evaluation methods may contain errors as they are derived from historical records. Generally, utilities have historical data in the form of system reliability indices instead of component reliability data [63]. Hence, in order to achieve more realistic reliability indices, component data uncertainties are needed to be taken into account.

The uncertainty associated with the failure rate (λ), the repair time (r) and load (L) may be expressed in terms of the expected value (mean) and standard deviation of these quantities with an assumption that they are normally distributed. The effect of data uncertainty in reliability calculations has been incorporated in this chapter by using the point estimate method (PEM). The PEM can be used to calculate the statistical moments of a random quantity which, in turn, is a function of one or several random variables [6]. It is well established that for calculating lower statistics (mean and variance), the point estimate method (3PEM) is sufficient, while for calculating higher order statistics (skewness and kurtosis) along with the lower order statistics, five point estimate method (5PEM) and seven point estimate method (7PEM) are more useful [7]. The values of mean and variance are sufficient to describe a normal distribution function, hence 3PEM is most suitable for the work described in this chapter.

In this chapter, a formulation for optimal placement of switches and reclosers in a distribution system considering uncertainties in load data, system failure and repair rates has been presented. The uncertainties have been incorporated in the formulation using three point estimate method (3PEM). Further, the proposed formulated problem has been tested on three different test systems using differential evolution (DE) and mixed-integer nonlinear programming (MINLP) method, the two most suitable optimization methods as established in the previous chapter.

This chapter is organized as follows: The proposed problem formulation is explained in Section 3.2. Procedure for incorporating the uncertainties using 3PEM is presented in Section 3.3. Section 3.4 presents the main results of this chapter. The final conclusions of this chapter are drawn in Section 3.5.

3.2 Problem formulation

In this chapter, uncertainties in load data, system failure rates and repair rates have been incorporated in the model for optimal placement of switches and reclosers in a radial distribution system.

3.2.1 Objective function

The model (objective function) corresponding to the optimal placement of the switches and reclosers in a distribution system considering uncertainties in load data, system failure rates and repair rates are aimed at revenue earning maximization of the utility due to reduction in customer interruption cost (CIC) and increase in extra energy supplied (due to decrease in ENS) to the customers while minimizing the associated investment cost such as cost of installation, operation and maintenance of switches and reclosers.

Presence of a recloser in a feeder section saves all the upstream loads for all the permanent and temporary faults in the feeder section and its downstream feeder sections. Similarly, the presence of a switch in a feeder section reduces the outage time of all the upstream loads for all the permanent faults in the feeder section and its downstream feeder sections.

As discussed in Chapter 2, the binary variables $X_{R,k}$ and $X_{S,k}$ represent recloser and switch in k^{th} feeder section respectively. Also,

$$\begin{aligned} X_{S,k}/X_{R,k} &= 0, \quad \text{if a switch/recloser is placed in } k^{th} \text{ feeder section} \\ &= 1, \quad \text{if a switch/recloser is not placed in } k^{th} \text{ feeder section} \end{aligned} \tag{3.1}$$

Using the procedures given in Chapter 2, the permanent failure rate ($\lambda_{i,j}$) and outage time ($r_{i,j}$) of j^{th} load due to the permanent fault in i^{th} feeder section can be represented as,

$$\lambda_{i,j} = bibc(i,j)\lambda_i + (1 - bibc(i,j))\lambda_i(\prod_{k \epsilon F(i,j)} X_{R,k}) \tag{3.2}$$

$$\begin{aligned} r_{i,j} = \quad & bibc(i,j)r_i + (1 - bibc(i,j))\{r_i(\prod_{k \epsilon F(i,j)} X_{S,k}) \\ + \quad & r_{iso}(1 - (\prod_{k \epsilon F(i,j)} X_{S,k}))\}(\prod_{k \epsilon F(i,j)} X_{R,k}) \end{aligned} \tag{3.3}$$

Using the procedure discussed in the previous chapter, we can calculate the savings (due to reduction in ENS and TIC) of the system protected by reclosers and switches. When no recloser or a switch is placed in the distribution system, then the term $\prod_{k \epsilon F(i,j)} X_{R,k}$ of Eq. (3.2) becomes unity. As a result, $\lambda_{i,j}$ becomes equal to λ_i. Similarly, in Eq. (3.3), the term $\prod_{k \epsilon F(i,j)} X_{S,k}$ also becomes unity, resulting in $r_{i,j} = r_i$. Therefore, using Eqs. (2.9) and (2.10), the ENS and TIC of an unprotected system (represented by ENS_U and TIC_U respectively) can be written as,

$$ENS_U = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} (\lambda_i r_i) L_j \quad kWhr/year \tag{3.4}$$

$$TIC_U = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} (\lambda_i ICP_{i,j}) L_j \tag{3.5}$$

When reclosers and switches are placed in the distribution system, then from Eqs. (2.9) and (2.10), the ENS and TIC of this protected system (represented by ENS_P and TIC_P respectively) can be written as,

$$ENS_P = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} (\lambda_{i,j} r_{i,j}) L_j \tag{3.6}$$

$$TIC_P = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} (\lambda_{i,j} ICP_{i,j}) L_j \tag{3.7}$$

Therefore, reduction in ENS (i.e. ENS_U-ENS_P) due to placement of reclosers and switches in the distribution system can be written as,

$$\sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_i r_i - \lambda_{i,j} r_{i,j})L_j \tag{3.8}$$

Similarly, reduction in TIC (i.e. TIC_U-TIC_P) due to placement of reclosers and switches in the distribution system can be written as,

$$\sum_{j=1}^{nl}\sum_{i=1}^{nbr}((\lambda_i - \lambda_{i,j})ICP_{i,j})L_j \tag{3.9}$$

Therefore, the objective function (f) is defined as follows:

$$\begin{aligned} Maximize \quad f = &\{\sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_i r_i - \lambda_{i,j} r_{i,j})L_j\}C_E F_1 + \{\sum_{j=1}^{nl}\sum_{i=1}^{nbr}((\lambda_i - \lambda_{i,j})ICP_{i,j})L_j\}F_2 \\ &- \{(\sum_{i=1}^{nbr}(1 - X_{R,i}))C_R + (\sum_{i=1}^{nbr}(1 - X_{S,i}))C_S\}(1 + \frac{C_m}{100}F_3) \end{aligned} \tag{3.10}$$

where,

$$F_1 = \frac{1 - a_1^{N_s}}{1 - a_1}, \quad a_1 = \frac{(1 + \frac{L_c}{100})(1 + \frac{r_E}{100})}{(1 + \frac{i_r}{100})} \tag{3.11}$$

$$F_2 = \frac{1 - a_2^{N_s}}{1 - a_2}, \quad a_2 = \frac{(1 + \frac{L_c}{100})(1 + \frac{i_c}{100})}{(1 + \frac{i_r}{100})} \tag{3.12}$$

$$F_3 = \frac{1 - a_3^{N_s}}{1 - a_3}, \quad a_3 = \frac{(1 + \frac{r_m}{100})}{(1 + \frac{i_r}{100})} \tag{3.13}$$

C_E = per unit energy cost,

N_s = life span of the protective devices (in years),

L_C = rate of annual load growth (in percent),

i_r = annual interest rate (in percent),

r_E = annual incremental rate of energy cost (in percent),

$ICP_{i,j}$ = sustained interruption cost of the load connected at j^{th} node due to the permanent fault in i^{th} feeder section for an outage duration of $r_{i,j}$

r_m = annual incremental rate of maintenance cost (in percent),

i_c = annual incremental rate of interruption cost (in percent),

C_m = maintenance cost of switching devices (in percent),

C_R = cost of a recloser,

C_S = cost of a switch.

'$\lambda_{i,j}$' and '$r_{i,j}$' used in Eq. (3.10) are calculated using Eqs. (3.2) and (3.3) respectively.

The first term of Eq. (3.10) accounts for the net present worth (NPW) of the earned revenue due to increased energy supplied to the customers corresponding to the useful life span of the switches and reclosers (N_s years). It is to be noted that optimal placement of switches and reclosers in distribution system results in reduction of 'ENS'. Thus, the protected system supplying additional energy to the customers increases the revenue collection of the distribution system.

The second term of Eq. (3.10) accounts for the 'NPW' of the earned revenue due to reduced customer interruption cost. The damages caused due to supply interruptions to the customers are compensated by the distribution companies. Typical values of the customer interruption costs for different types of customers considered in this chapter are give in Table 2.3 of chapter 2.

The third and fourth terms of Eq. (3.10) accounts for the 'NPW' of the installation and lifetime maintenance costs of reclosers and switches respectively.

3.2.2 Constraints

The model of switch and recloser placement in distribution system considering uncertainties in load data, system failure rates and repair rates described in previous section consists of the following constraints.

1. The numbers of switches and reclosers to be installed in the distribution system should not exceed the number specified by the utility [22]. These constraints are given by the following equations.

$$\sum_{k=1}^{nbr}(1 - X_{R,k}) \leq N_{ar} \tag{3.14}$$

$$\sum_{k=1}^{nbr}(1 - X_{S,k}) \leq N_{as} \tag{3.15}$$

   Where,

   $X_{R,k}$ = 0, if recloser is present in k^{th} feeder section, otherwise 1.

   $X_{S,k}$ = 0, if switch is present in k^{th} feeder section, otherwise 1.

   N_{ar} = Number of available reclosers.

   N_{as} = Number of available switches.

2. A recloser and a switch should not be placed in the same feeder section.

$$X_{R,k} \neq X_{S,k} \quad k = 1, 2, ..., nbr \tag{3.16}$$

3.3 Uncertainty calculations

For the purpose of consideration of uncertainties in failure rates, repair rates and loading conditions, three point estimate method (3PEM) has been used. In this method, h points on a probability distribution function (PDF) are first estimated and subsequently using these estimated points, the complete statistical information (such as mean, variance etc) of the function of interest is obtained. The general theory of h point estimation method is given in [64].

3.3.1 Brief description of 3PEM

The three random variables associated with the system are load, failure rate (λ) and outage time (r). λ and r are associated with the system branch. It has been assumed that in a distribution system for reliability calculations, n numbers of random input variables are required. For instance, if a distribution system has nbr branches (the random variables associated with each branch are λ and r) and $nl - 1$ load buses with randomly varying real power loads (bus 1 is the substation bus), then the number of random input variables required (n) can be written as,

$$n = 2nbr + nl - 1 \tag{3.17}$$

Let the l^{th} random variable x_l (l=1,2,...,n) having PDF f_l be considered [65]. The PEM uses two, three or h estimated points of x_l i.e. x_{l1}, x_{l2} or x_{lh} as defined in Eq. (3.18) to replace f_l by matching the first $h + 1$ moments of f_l.

$$x_{l,k} = \mu_{xl} + \xi_{l,k}\sigma_{xl} \quad \forall k = 1, 2, ..., h \tag{3.18}$$

In Eq. (3.18), μ_{xl} and σ_{xl} are the mean and standard deviation of x_l respectively. For 3PEM, k = 1, 2. The variable $\xi_{l,k}$ for 3PEM can be obtained as explained in the following steps.

1. Find the coefficients of skewness and kurtosis of x_l using Eqs. (3.19)-(3.20) respectively [65].

$$\lambda_{l,3} = \frac{E[(x_l - \mu_{xl})^3]}{\sigma_{xl}^3} \tag{3.19}$$

$$\lambda_{l,4} = \frac{E[(x_l - \mu_{xl})^4]}{\sigma_{xl}^4} \tag{3.20}$$

Where, the p^{th} moment about mean is given as

$$E[(x_l - \mu_{xl})^p] = \sum_{t=1}^{N} (x_l(t) - \mu_{xl})^p * P_r(x_l(t))$$

and p = 3,4. N is the number of observations for x_l, $x_l(t)$ is the t^{th} observation of x_l and $P_r(x_l(t))$ is the probability of $x_l(t)$.

2. Calculate $\xi_{l,1}$ and $\xi_{l,2}$ by using Eq. (3.21). Also set $\xi_{l,3}$=0.

$$\xi_{l,k} = \frac{\lambda_{l,3}}{2} + (-1)^{3-k}\sqrt{\lambda_{l,4} - \frac{3}{4}\lambda_{l,3}^2} \quad \forall k = 1,2 \tag{3.21}$$

3. Obtain the three point estimates of PDF (denoted as $x_{l,1}$, $x_{l,2}$ and $x_{l,3}$, respectively) from Eq. (3.18). Further, obtain the corresponding weighting factors $\omega_{l,1}$, $\omega_{l,2}$ and $\omega_{l,3}$ from Eqs. (3.22) and (3.23).

$$\omega_{l,k} = \frac{(-1)^{3-k}}{\xi_{l,k}(\xi_{l,1} - \xi_{l,2})} \quad \forall k = 1,2 \tag{3.22}$$

$$\omega_{l,3} = \frac{1}{n} - \frac{1}{\lambda_{l,4} - \lambda_{l,3}^2} \tag{3.23}$$

3.3.2 Estimation of the expected value of the objective function using 3PEM

Once the points and weights corresponding to system connected loads, failure rates and outage durations are estimated, the following procedure is adopted for the evaluation of the objective function:

1. Form the input matrices X_1 and X_2 as:

$$X_k = \begin{bmatrix} x_{1,k} & \mu_{x2} & . & . & . & \mu_{xn} \\ \mu_{x1} & x_{2,k} & . & . & . & \mu_{xn} \\ . & . & . & & & . \\ . & . & & . & & . \\ . & . & & & . & . \\ \mu_{x1} & \mu_{x2} & . & . & . & x_{n,k} \end{bmatrix} \tag{3.24}$$

where, k = 1,2.

2. For each row of X_k, objective function (Eq. (3.10)) is evaluated. As a result, a total of '2n' computations would be carried out.

3. For each output variable of interest $y_{i,lk}$, set the j^{th} moment as,

$$E(y_{i,lk}^{j}) = \sum_{i=1}^{n}\sum_{k=1}^{m} \omega_{l,k} y_{i,lk}^{j}, \quad \forall j = 1, 2, ...4 \tag{3.25}$$

   $y_{i,lk}$ denotes the value of the i^{th} variable of interest corresponding to $(lk)^{th}$ computation where, l = 1,2,...n and k = 1,2, and m = 2 for 3PEM.

4. Now, the objective function (Eq. (3.10)) is evaluated with a vector $X_{mean} = [\mu_{x1}, \mu_{x2}, ..., \mu_{xi}, ...\mu_{xn}]$, and let $y_{i,\mu}$ denotes the value of i^{th} output variable of interest corresponding to this computation. Then the j^{th} moment $E(y_{i,lk}^{j})$ is updated as:

$$E(y_{i,lk}^{j}) = E(y_{i,lk}^{j}) + \omega_{\mu} y_{i,\mu} \tag{3.26}$$

   Where, X_{mean} is the vector containing average values of connected load at buses, failure rates and outage durations of various feeder sections of the distribution system. Further,

$$\omega_{\mu} = \sum_{k=1}^{n} \omega_{k,3} \tag{3.27}$$

   where, ω_{μ} is the weight corresponding to the mean values of the random variables. For calculating the expected value of the function, the value of j in Eq. 3.26 is set equal to one.

3.4 Case studies

The optimal placement of switches and reclosers (considering uncertainties in failure rates, repaire rates and loading conditions) have been carried out in the 13-bus, 58-bus and IEEE 123-bus test systems using DE and MINLP (the two techniques giving best results in chapter 2) for maximizing the objective function value (profit) defined in Eq. (3.10). MINLP considered in the work utilizes sequential quadratic programming through $fmincon$ function available in MATLAB optimization toolbox. Each method has been executed 100 times with the same convergence criterion for evaluating the reproducibility of the results. Subsequently, from these obtained results corresponding to 100 runs, various statistical parameters have been obtained for the purpose of comparison. The comprehensive flow-chart of the overall calculation procedure is shown in Fig. 3.1. The single line diagrams of 13-bus, 58-bus and IEEE 123-bus test systems are given in Figs. 2.4-2.6 of chapter 2 respectively. System cost data is given in Table 2.4 of chapter 2. Other system data such as bus data for 13-bus, 58-bus and IEEE 123-bus are given in Table 2.5, Table 2.6 of chapter 2 and in [61] respectively while failure data are given in Table 2.7, Table 2.8 and Table 2.9 of chapter 2 respectively. Other necessary data used in the simulation studies are same as used in Chapter 2.

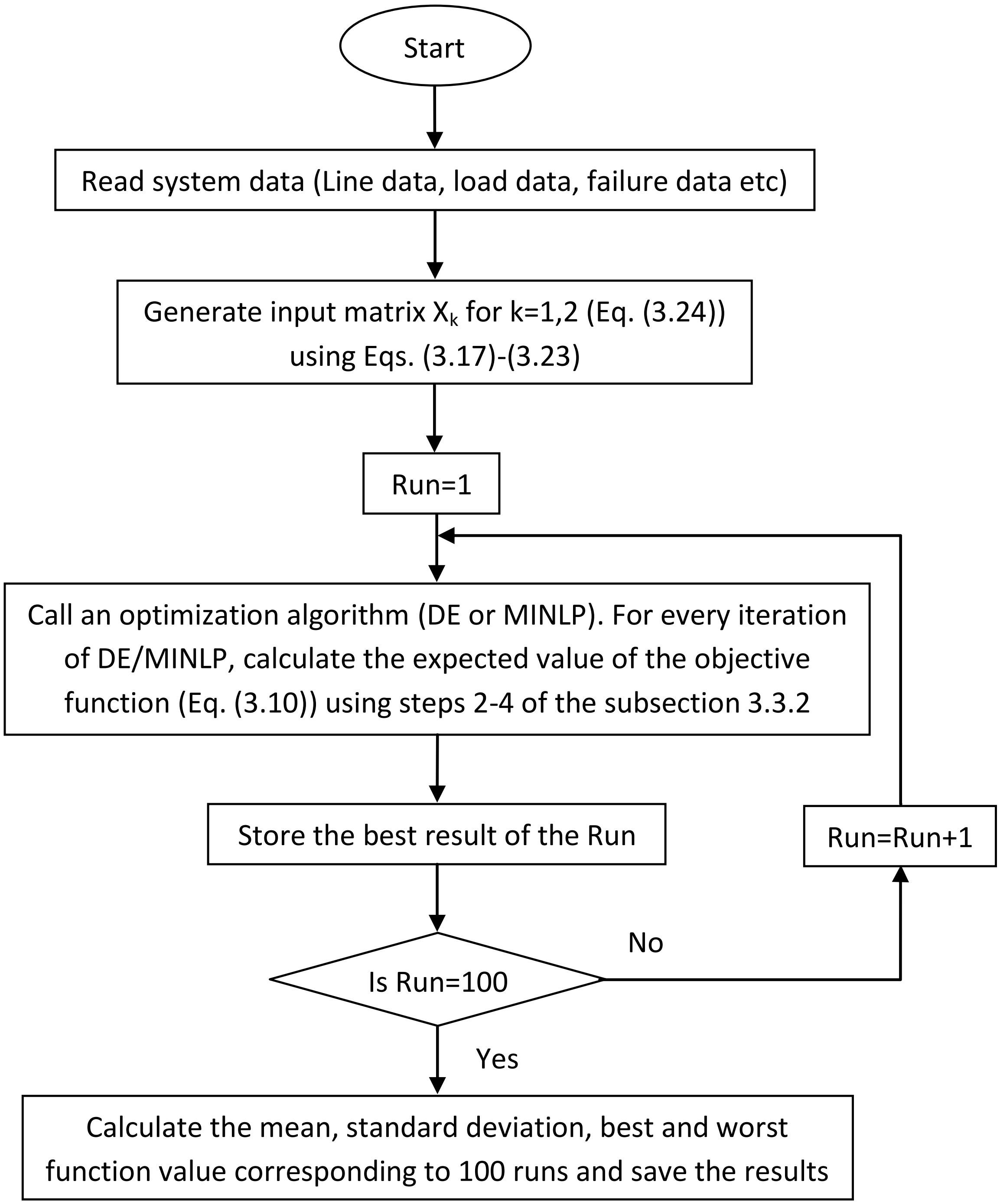

Figure 3.1: Flow-chart of the general optimization procedure

In order to investigate the possibility of any further improvement in DE results, comprehensive tuning of DE parameters has been done to find the best values of these parameters. Table 3.1 shows the tuning of the parameters of DE (mutation factor (F) and crossover rate (CR)) for each of the three test systems. The appropriate parameter set has been selected based on the 'best function value' with minimum number of iterations required. From the table, it is clear that for evaluating the objective function using DE, the parameters (F and CR) for 13-bus, 58-bus and IEEE 123-bus test systems can be selected as (0.1 and 0.5), (0.6 and 0.5) and (0.7 and 0.4) respectively as they give best results with minimum number of iterations. Maximum number of iterations for DE has been taken as 500. For both the techniques, the threshold value for convergence criterion is taken as 10^{-12}.

Table 3.1: Parameter tuning for DE

F	CR	13-bus test system		58-bus test system		IEEE 123-bus test system	
		Best function value	No. of iterations	Best function value	No. of iterations	Best function value	No. of iterations
0.1	0.1	29589520.45	14	325316989.9	86	29946159.71	100
0.1	0.2	29593364.12	16	324180319.9	56	33345351.15	131
0.1	**0.3**	**30033037.56**	**27**	327881952.1	113	32377498.28	84
0.1	**0.4**	**30033037.56**	**31**	326800306.3	91	31834478.3	80
0.1	0.5	**30033037.56**	**16**	327693166.4	98	31712324.19	71
0.1	0.6	29981371.1	9	327058895.3	59	29012626.63	71
0.1	0.7	29802690.46	15	325500421.7	49	28258944.7	58
0.1	0.8	29683882.55	10	322590241.1	38	22490888.09	60
0.1	0.9	29546933.59	10	322154422.9	32	6951924.908	15
0.2	0.1	28917462.47	6	322646324.3	46	32593047.28	139
0.2	0.2	29256774.04	8	327644606	107	33438966.91	118
0.2	0.3	29947745.59	23	327890997.6	95	32999975.59	107
0.2	0.4	29724292.45	11	327976692.6	65	32414275.52	81
0.2	0.5	29628146.21	9	327028607.2	59	31391242.88	73
0.2	0.6	29589520.45	13	326722316.9	66	28341449.74	66

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Table 3.1 : Continued from previous page

0.2	0.7	29483728.03	8	325531172.2	51	27825229.12	56
0.2	0.8	29787329.03	12	323223168.8	37	23741759.92	59
0.2	0.9	29871860.77	8	315395032	6	15740556.84	35
0.3	0.1	29440489.74	8	323937358.2	75	32745922.01	138
0.3	**0.2**	**30033037.56**	**27**	327633372.6	135	33381896.22	154
0.3	**0.3**	**30033037.56**	**19**	327827985	96	32647858.38	89
0.3	0.4	29981371.1	17	326975875.9	86	32215641.79	92
0.3	0.5	29713554.83	14	327003906.8	76	30515121.78	80
0.3	**0.6**	**30033037.56**	**18**	326512697.1	65	28875886.74	72
0.3	0.7	29246551.98	7	326054682.4	54	24813712.22	54
0.3	0.8	29981371.1	18	321775839	21	19891971.41	40
0.3	0.9	28101134.46	1	318975794.1	18	12992229.46	34
0.4	0.1	28624977.75	3	325817612.2	86	31008884.6	119
0.4	0.2	28587610.49	3	322942588.8	44	32640654.21	112
0.4	0.3	29945634.97	17	326986058.5	130	32178738.91	86
0.4	**0.4**	**30033037.56**	**21**	326967313.3	91	33246820.6	89
0.4	0.5	29656121.47	12	326340426.1	74	31578369.66	75
0.4	0.6	29625099.04	12	326540023.3	58	30960945.45	71
0.4	0.7	29934940.57	22	325605329.8	61	28154724.14	49
0.4	0.8	29063359.48	5	318125585.1	17	17792257.93	48
0.4	0.9	29440489.74	6	319873890.2	20	10458257.05	26
0.5	0.1	28675352.5	2	325096209.4	142	31575814.05	393
0.5	0.2	28625152.78	3	328105060.7	308	32983518.27	485
0.5	0.3	29828947.16	22	325523761.4	187	29809187.44	539
0.5	0.4	29719618.68	20	327610343.6	279	27002146.8	552
0.5	**0.5**	**30033037.56**	**20**	327137171.7	310	24473233.37	595

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Table 3.1 : Continued from previous page

0.5	0.6	29815891.97	11	325754924	228	19623993.42	683
0.5	0.7	29954639.55	16	325163727.6	291	18522456.9	536
0.5	0.8	29901183.94	6	322619918.4	193	11119219.41	333
0.5	0.9	29310287.28	6	319066251.1	171	227743.5041	114
0.6	0.1	29029878.46	6	327237227.4	229	31421714.56	243
0.6	0.2	29168974.95	4	327871624.6	243	34488464.33	416
0.6	0.3	29999412.06	47	328207911.8	354	34428218.26	321
0.6	**0.4**	**30033037.56**	**30**	328300476.9	377	34010864.32	386
0.6	**0.5**	**30033037.56**	**34**	**328371302.8**	**286**	33958880.24	357
0.6	0.6	29871860.77	36	327968344.6	244	34249326.89	284
0.6	**0.7**	**30033037.56**	**29**	328161256.8	334	34108893.87	293
0.6	0.8	29828301.1	26	327760989.9	218	31367803.44	196
0.6	0.9	29874731.63	25	325720290.3	100	25956043.39	136
0.7	0.1	28101134.46	1	325844622.5	132	33372560.41	292
0.7	0.2	29947745.59	25	327951182.4	300	34209159.12	312
0.7	0.3	29908209.02	24	328326876.2	306	33701160.08	336
0.7	**0.4**	29486724.64	27	328201862.4	315	**34582844.74**	**403**
0.7	0.5	29665405.28	16	328288773.8	408	34229530.11	333
0.7	0.6	29981371.1	31	328371302.8	294	33764135.71	376
0.7	0.7	29901183.94	33	328038809.8	218	33739743.25	281
0.7	0.8	29770154.17	19	328259595.8	225	32359624.5	186
0.7	0.9	29777280.69	17	327486697.6	182	26877197.82	161
0.8	0.1	28101134.46	1	325673425.1	149	32318588.06	252
0.8	0.2	28859318.57	5	327838600	310	33151874.91	292
0.8	0.3	29100618.54	9	328241487.2	318	34247642.9	384
0.8	0.4	29954639.55	34	328111235.1	321	34472455.56	414

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Table 3.1 : Continued from previous page

0.8	**0.5**	**30033037.56**	**36**	**328371302.8**	**322**	34381484.7	431
0.8	0.6	29986607.04	27	328084603.8	300	33558846.11	325
0.8	**0.7**	**30033037.56**	**33**	328231716.7	293	32612875.29	257
0.8	0.8	29823065.16	20	327824142.3	204	32868582.55	209
0.8	0.9	29785806.09	21	327587601.7	183	23386652.27	120
0.9	0.1	28101134.46	1	326571977.1	151	32498798.65	257
0.9	0.2	29704593.48	15	328035528.7	345	33586129.14	366
0.9	0.3	29288221.4	16	328191589.6	300	34442355.56	391
0.9	0.4	29715287.87	25	328330197.5	315	33462130.61	346
0.9	0.5	29999412.06	32	328256273.7	313	34392394.4	313
0.9	**0.6**	**30033037.56**	**36**	328183231.7	285	33939468.99	257
0.9	**0.7**	**30033037.56**	**30**	**328371302.8**	**325**	33021273.48	253
0.9	0.8	29854753.42	31	327456999.4	252	32711569.64	244
0.9	0.9	29815891.97	28	325412981.9	127	26764952.5	161

Table 3.2 shows the results for 13-bus, 58-bus and IEEE 123-bus test systems corresponding to 100 runs using DE and MINLP techniques. While using DE technique, the initial population remains same and the convergence was reached before reaching the maximum number of iterations for each of the 100 runs. From the table, it can be observed that these two techniques give the same best objective function value (profit) for all the three test systems. The standard deviation for 58-bus test system is nearly same for DE and MINLP while for 13-bus and IEEE 123-bus test systems, the standard deviation is lesser for MINLP as compared with DE. The average run time for all the three test systems are smaller for MINLP as compared with DE.

The optimal location of reclosers and switches corresponding to the best objective function value are chosen as the final solution. For 13-bus test system, the optimal location of reclosers are in branches F4 and F10 whereas, the optimal location of switches are in branches F2, F3, F5 and F8. For 58-bus test system, the optimal location of reclosers are in feeder sections F2, F14, F15, F22, F29, F33, F35, F38, F43 and F49 whereas, the optimal location of switches are in feeder sections

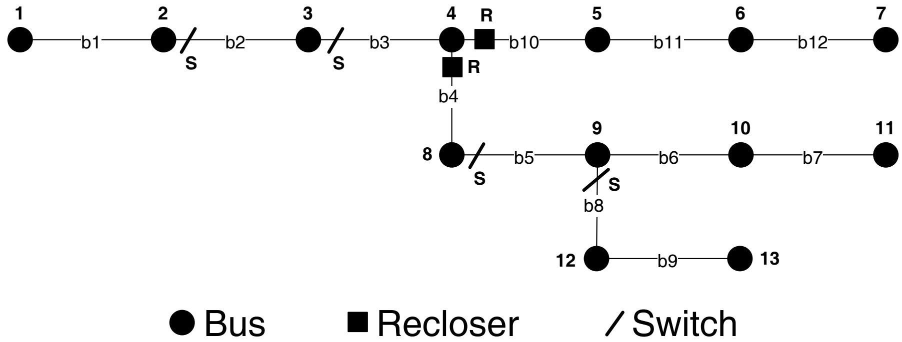

Figure 3.2: 13-bus test system protected by DE/MINLP techniques

Table 3.2: Summary of results of 100 runs for 13-bus, 58-bus and IEEE 123-bus test systems

Test systems	DE			MINLP		
	Best function value (Rs.)	Standard deviation (% of mean)	Average run time (s)	Best function value (Rs.)	Standard deviation (% of mean)	Average run time (s)
13-bus	30033037.56	0.82	1.33	30033037.56	0.31	0.30
58-bus	328371302.78	0.04	392.64	328371302.78	0.09	75.75
IEEE 123-bus	34582844.74	0.49	3430.48	34582844.74	0.34	770.35

F4, F8, F9, F13, F18, F20, F21, F23, F25, F27, F28, F32, F37, F39, F44, F45, F47, F50, F53, F54 and F55. For IEEE 123-bus test system, the optimal location of reclosers are in feeder sections F19 and F54 whereas, the optimal location of switches are in feeder sections F2, F3, F9, F13, F15, F20, F22, F37, F41, F60, F64, F70, F74, F79, F88, F99 and F111. The optimal locations of switches and reclosers for 13-bus, 58-bus and IEEE 123-bus test systems are also shown in Figs. 3.2-3.4 respectively.

The results obtained with PEM, at the selected level of uncertainty in parameters, have also been compared with the results obtained without considering parameter uncertainty for the three test systems, and are given in Table 3.3. As can be observed, the two approaches give identical locations of the switches and reclosers with slight variations in final function values. However, the PEM based method is useful in estimating the function value (profit) under varying uncertainty in parameters as explained below.

The effect of variations in the standard deviations of load, 'λ' and 'r' on profit values are shown in Figs. 3.6-3.7 respectively (σ_λ, σ_{load} and σ_r are standard deviation of failure rate, load and outage time respectively). These figures show the cumulative distribution function (CDF) of profit for different

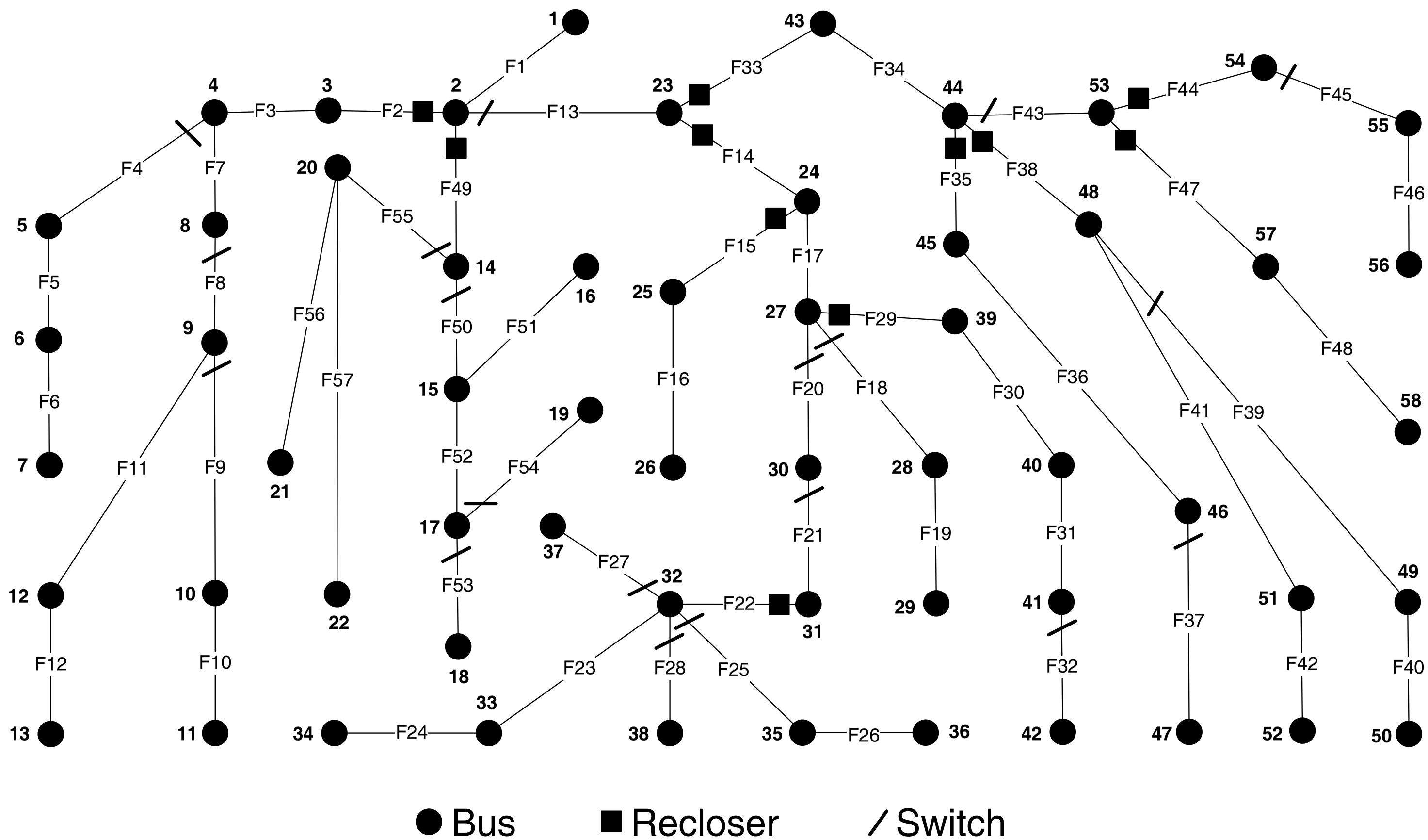

Figure 3.3: 58-bus test system protected by DE/MINLP techniques

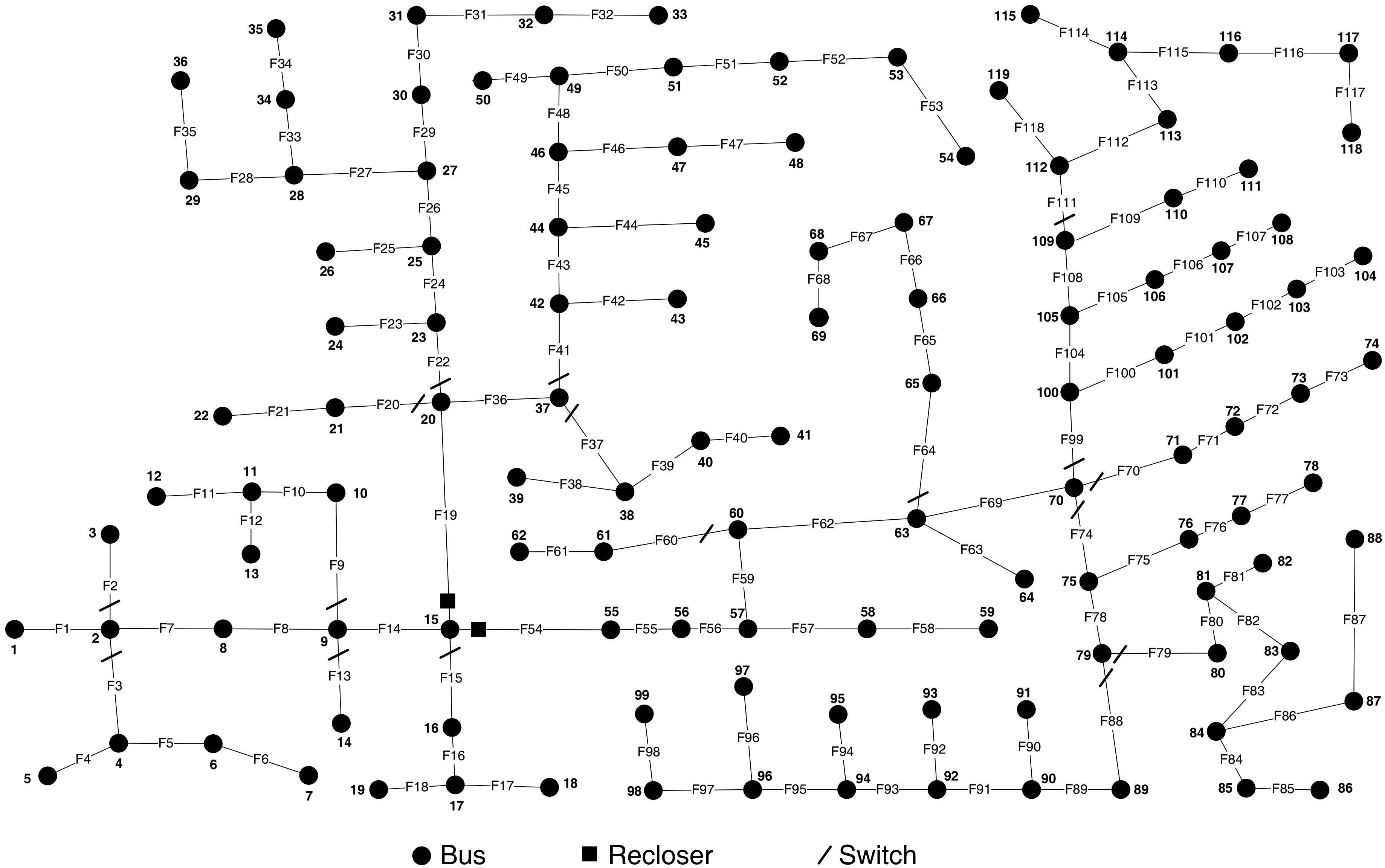

Figure 3.4: IEEE 123-bus test system protected by DE/MINLP techniques

Table 3.3: Results for all the three test systems without considering uncertainty in parameters

Test system	Function Value (Rs.)	Location of Switches	Location of Reclosers
13-bus	30013919.52	F2 F3 F5 F8	F4 F10
58-bus	328185967.86	F4 F8 F9 F13 F18 F20 F21 F23 F25 F27 F28 F32 F37 F39 F44 F45 F47 F50 F53 F54 F55	F2 F14 F15 F22 F29 F33 F35 F38 F43 F49
IEEE 123-bus	34573820.45	F2 F3 F9 F13 F15 F20 F22 F37 F41 F60 F64 F70 F74 F79 F88 F99 F111	F19 F54

values of standard deviations (σ) for IEEE 123-bus test system as a representative case.

From these figures, the spread of CDF can be observed to increase as the standard deviation increases. Further, it can also be seen that the expected value of profit does not change with the variations in load and failure rate uncertainty. This is due to the fact that when only one parameter (load or 'λ') changes, the change (increase or decrease) in ENS (Eq. (2.9)) and CIC (Eq. (2.16)) has a linear relationship with the change in load or 'λ'. Consequently, it can be easily shown analytically that with PEM, same expected values of ENS and CIC will be obtained when either load or 'λ' varies, leading to the same expected value of profit. However, when the repair time (r) varies, from Fig. 3.7, a small change in the expected value of profit (corresponding to cumulative probability of 0.5) can be observed. This is due to the non-linear IC(t) relations (Eqs. (2.13)-(2.15)) that creates a non-linear relation between change in CIC and change in repair time. As a result, following the basic steps of PEM, it can be easily shown analytically that the expected value of CIC will change. However, as change in ENS again enjoys a linear relationship with change in 'r', there is no change in the value of ENS calculated through PEM. Thus, only the change in CIC is responsible for change in the function value (profit).

Now, for taking a final financial decision under uncertain environment, usually, the expected value of profit and the CDF of profit are considered [66]. The variation in the profit with variation in parameter uncertainty can be quantified in terms of robust profit (RP_β) as shown in Fig 3.8 [66]. The values of RP_β is calculated at a probability value β, called confidence level. The common values of β are 90%, 95% and 99%, with 95% being the preferred confidence level [66]. It can be interpreted that for β=0.95, the probability of profit falling below RP_β is 1-β=0.05.

An extension of RP_β is CRP_β, the conditional robust profit. CRP_β gives a more conservative

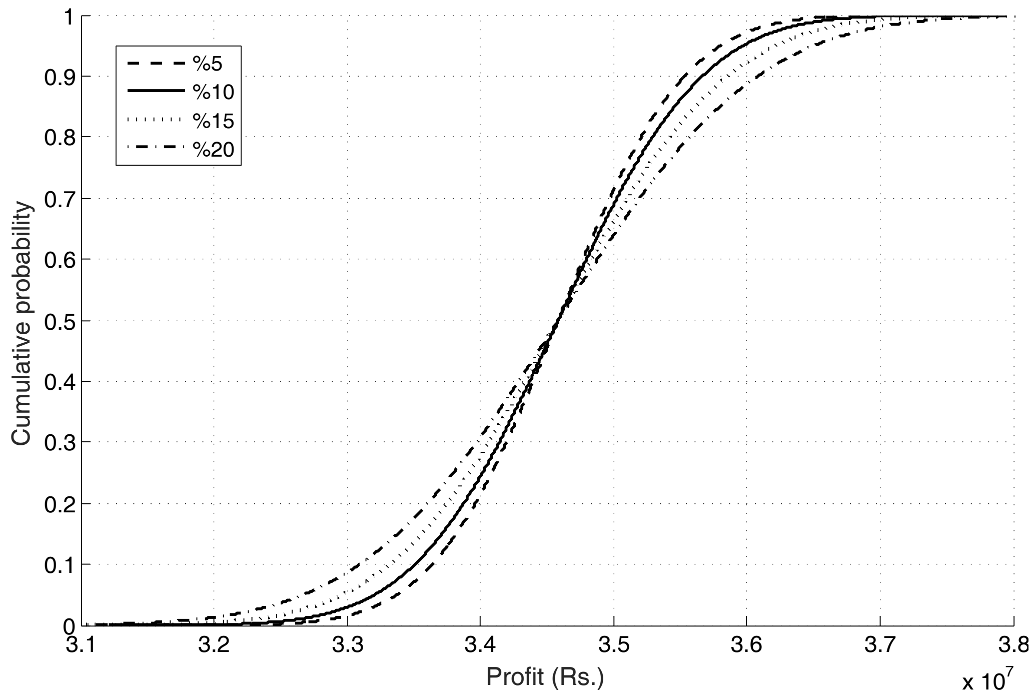

Figure 3.5: Sensitivity of function value w.r.t. σ_λ for IEEE 123-bus test system

but more assured value of profit. It is defined as the conditional expectation of the profit associated with system variables given that the profit is equal to or less than RP_β.

$$CRP_\beta = \frac{1}{1-\beta}\int_{-\infty}^{RP_\beta} xf(x)dx \tag{3.28}$$

Where, x is the random system variable and $f(x)$ is the associated probability density function of x.

As a representative example, for 58-bus test system, the variation of RP_β and CRP_β, with variations of uncertainty in the load, 'λ' and 'r' are shown in Figs. 3.9-3.11 for β=90%, 95% and 99% respectively. From these figures, it can be seen that with increase in parameter uncertainties, the robust and conditional robust profit decrease significantly. Therefore, for final financial decision, one must not rely on the expected value of profit only. As the conditional robust profit varies significantly with uncertainty, one must consider the data uncertainties before taking any financial decision, which can be accomplished using PEM.

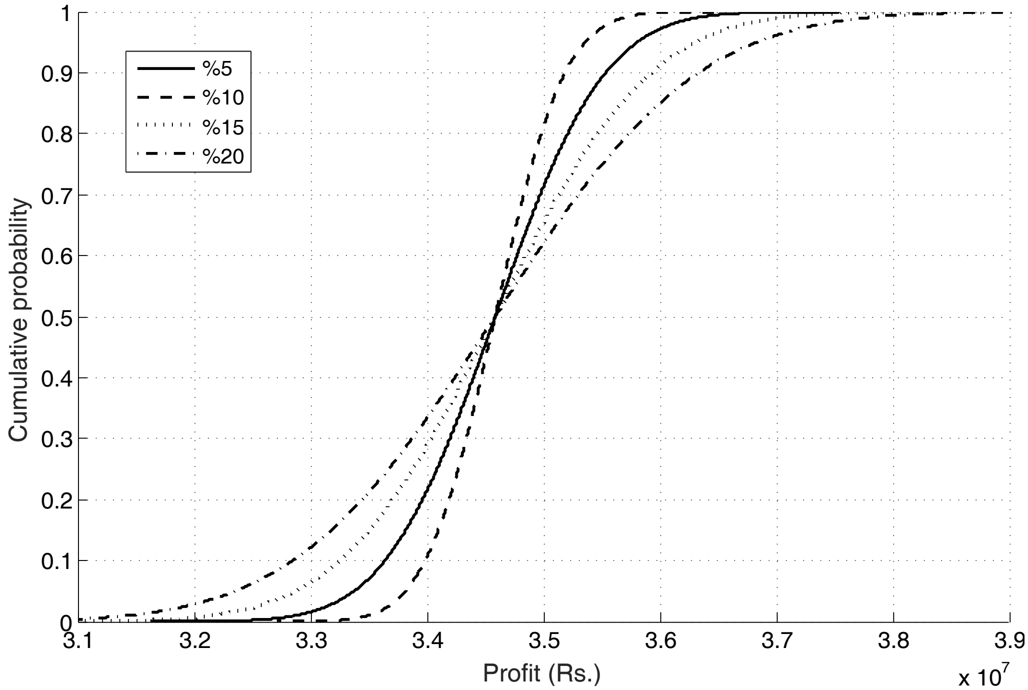

Figure 3.6: Sensitivity of function value w.r.t. σ_{load} for IEEE 123-bus test system

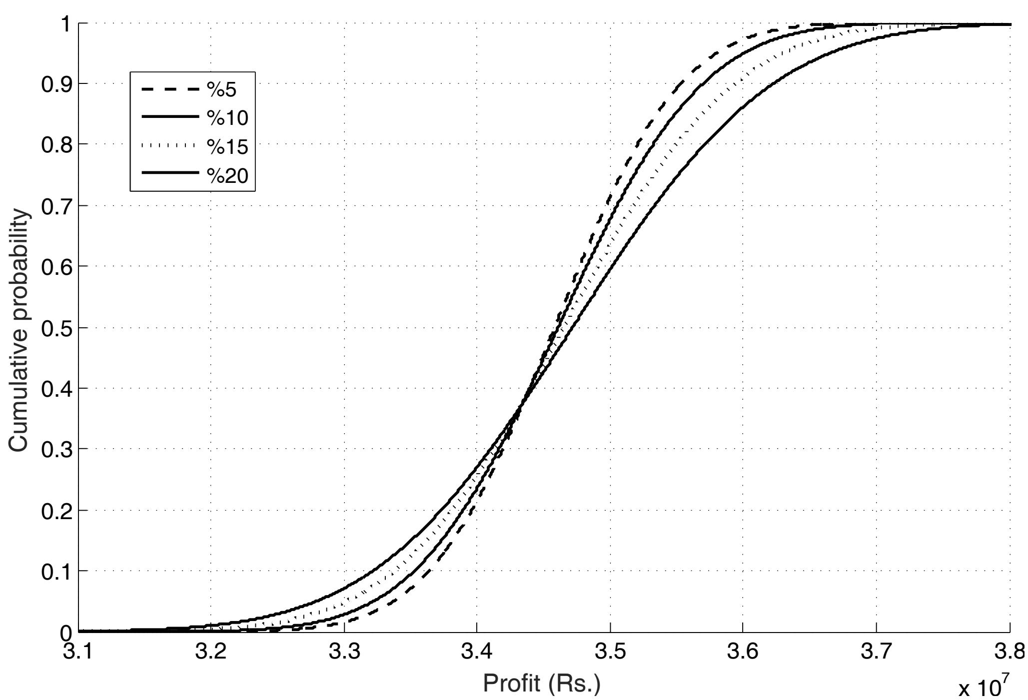

Figure 3.7: Sensitivity of function value w.r.t. σ_r for IEEE 123-bus test system

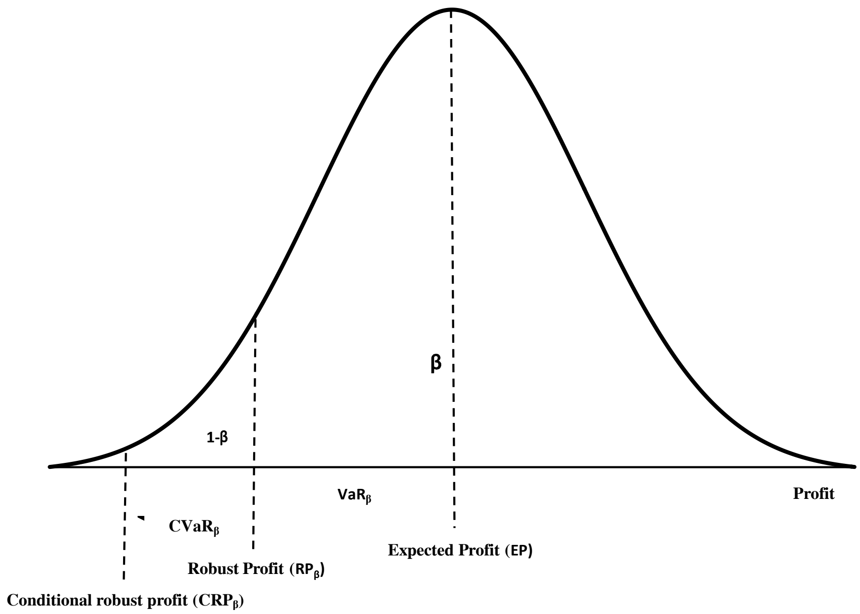

Figure 3.8: Graphical representation of β-VaR (Gaussian distribution)

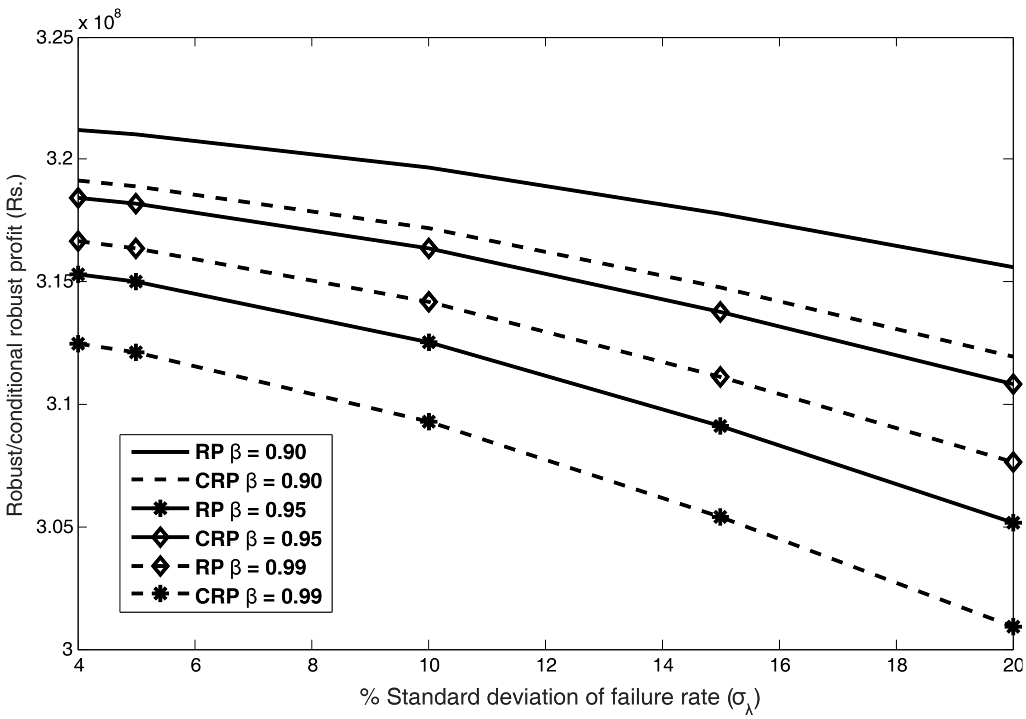

Figure 3.9: Variation of RP_β and CRP_β for variation in σ_λ for 58-bus test system

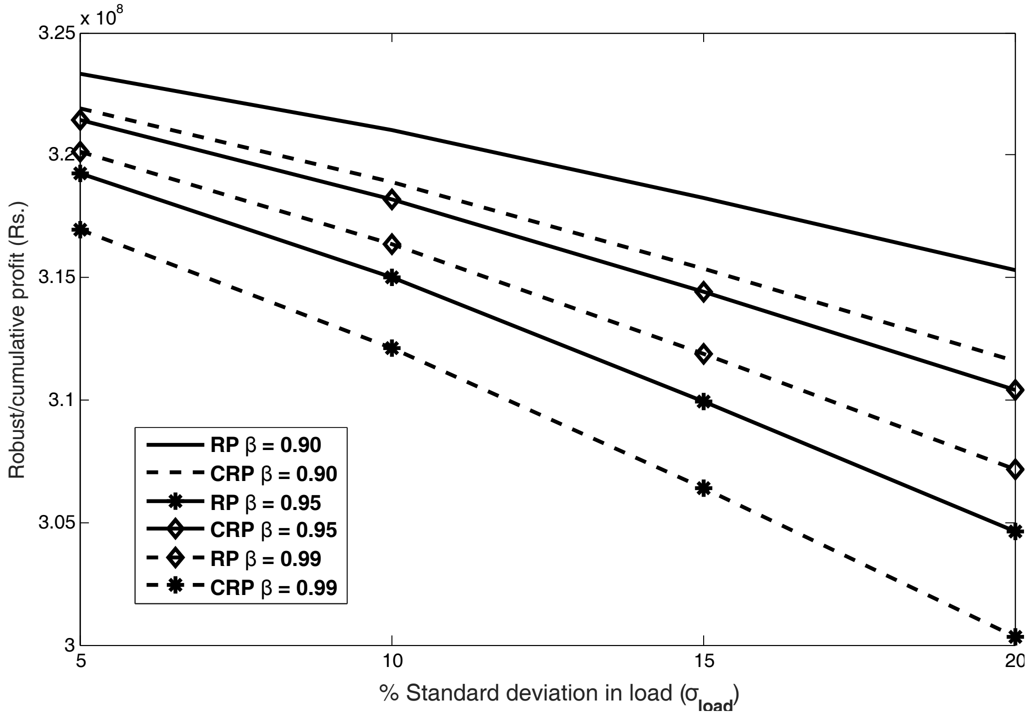

Figure 3.10: Variation of RP_β and CRP_β for variation in σ_{load} for 58-bus test system

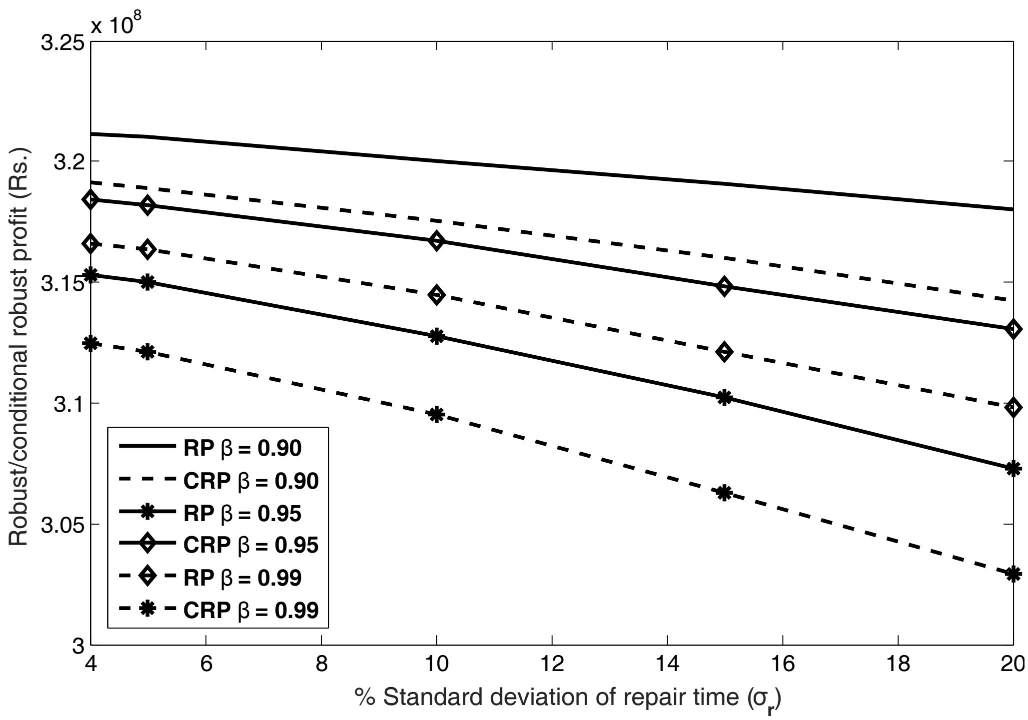

Figure 3.11: Variation of RP_β and CRP_β for variation in σ_r for 58-bus test system

3.5 Conclusion

Over a period of time, the system loading conditions, failure rates and repair rates are likely to vary. Therefore uncertainties in these quantities need to be considered for estimating the profit in the optimal placement of switches and reclosers for reliability improvement in distribution system. In this chapter, 3PEM has been used to incorporate the data uncertainty in reliability calculations. DE and MINLP techniques have been used to evaluate the optimal location of switches and reclosers in distribution system for reliability improvement and maximizing utilities' revenues under data uncertainty. The two techniques have been evaluated for 100 independent runs for 13-bus, 58-bus and IEEE 123-bus test systems and various statistical parameters such as mean, standard deviation, average run time etc have been calculated for the purpose of performance analysis. It is concluded that MINLP invariably produces best results with least computational efforts for all the test systems studied, without relying on heuristic parameters which are difficult to tune for each of the test system separately. Further, for all the three test systems, results obtained with uncertainty in parameters have also been compared with the results obtained without considering uncertainty. From the comparison of results obtained, it can be concluded that though the two cases give identical locations of switches and reclosers, the function value (profit) varies with variation in uncertainty level of parameters. The PEM based reliability evaluation method can thus be a very useful tool in estimating the bounds of profits expected from planned switch and recloser placement project. This study also helps the utilities in taking a realistic decision based on the calculated values of RP_β and CRP_β.

In the next chapter, methodologies for optimal placement of three different scenarios of protective devices viz. simultaneous placement of reclosers and switches, simultaneous placement of reclosers, switches and fuse-blow fuses and simultaneous placement of reclosers, switches and fuse-save fuses taking the uncertainties in loading conditions, permanent failure rates, temporary failure rates and repair rates into account, have been developed.

Chapter 4

Placement of protective devices in distribution system considering uncertainties in loads, temporary and permanent failure rates and repair rates

Abstract

The problem formulation in Chapter 3 considered sustained interruptions (caused by permanent faults) only. However, the effect of temporary fault also needs to be incorporated in the formulation for the loads sensitive to momentary interruptions (due to temporary faults). In this chapter, three different models for optimal placement of protective devices in a distribution system considering uncertainties in loads, temporary and permanent failure rates and repair rates have been developed. The uncertainties in temporary failure rates, permanent failure rates, repair rates and load data have been considered in the problem formulation using three point estimate method (3PEM). The three formulated problems have been solved for 58-bus and IEEE 123-bus distribution networks using mixed-integer nonlinear programming (MINLP) optimization technique.

4.1 Introduction

IN distribution system, momentary interruptions are more frequent then the sustained interruptions. In the past, sustained interruptions were the main concern of utilities and hence, the protective devices were placed to limit their impact. Now a days, loads are even more sensitive to momentary interruptions due to proliferation of electronic devices [8]. Due to the increased use of electronic and precision devices, damages due to the short duration voltage disturbances have increased [9]. Utilities use Fuse-save and Fuse-blow schemes to decrease the impact of sustained and momentary interruptions, respectively.

In the Fuse-save scheme, an upstream recloser or circuit breaker operates before a fuse can trip to isolate a fault downstream of the fuse. Fuse-save scheme is used with an instantaneous relay or with the fast curve of a recloser associated with a circuit breaker. For temporary faults (self clearing faults), service to the customers can be restored immediately by re-energizing the line, resulting in decreased sustained interruptions [10].

The main drawback of Fuse-save scheme is that all customers downstream of a recloser or circuit breaker experience momentary interruptions even for permanent faults downstream of a fuse. Because of this, many utilities prefer to use Fuse-blow scheme over Fuse-save scheme. The Fuse-blow scheme is also known by several other names such as (i) trip saving, (ii) breaker saving, (iii) fault clearing, and (iv) instantaneous relay blocking. In Fuse-blow scheme, the fuse operates for all the faults (temporary and permanent) downstream of it, resulting in sustained interruption of all the customers downstream of the fuse while supply to the rest of the system continues uninterrupted [10]. Thus, Fuse-blow scheme results in a reduction in momentary interruptions and an increase in sustained interruptions.

In this chapter, the effect of sustained and momentary interruptions as well as the uncertainties in temporary and permanent failure rates, repair rates and loading conditions have been considered for deciding the optimal locations of the protective devices. For placing the protective devices, three different scenarios have been considered; (i) Simultaneous placement of reclosers and switches (ii) Simultaneous placement of reclosers, switches and fuse-blow fuses and (iii) Simultaneous placement of reclosers, switches and fuse-save fuses.

This chapter is organized as follows: In Section 4.2, the procedure for reliability calculation in a distribution system for three different scenarios of protective devices is discussed. Section 4.3 discusses the formulated problem in detail. In Section 4.4, the main results of this work have been presented. Finally, the conclusions drawn have been discussed in Section 4.5.

4.2 Calculation of distribution system reliability for different scenarios of protective devices considering permanent and temporary faults

This section describes the procedure for distribution system reliability calculation for the following three scenarios:

4.2.1 Placement of reclosers and switches only (RS scheme)

A 7-bus radial distribution network having 6 feeder sections and 6 load points is shown in Fig. 4.1. Consider the scenario when the system is protected by a switch 'S' at feeder section'$F3$', a recloser 'R' at feeder section '$F2$' (apart from a circuit breaker 'CB' at the source end) as shown in Fig. 4.2. For a fault (permanent or temporary) in '$F2$' and its downstream feeder sections, the upstream recloser at '$F2$' will operate instead of 'CB' to isolate the fault current. Consequently, load '$L1$'

(upstream of '$F2$') will not experience any interruption. Hence, permanent failure rate (λ) and temporary failure rate (γ) for '$L1$' are set to zero for all permanent and temporary faults in '$F2$' and its downstream feeder sections. In general, 'λ' and 'γ' for all the loads upstream of a feeder section having a recloser are set to zero for all the permanent and temporary faults in the feeder section and its downstream feeder sections, respectively. Further, 'λ' and 'γ' for all the loads downstream of '$F2$' (feeder section having a recloser) are set equal to 'λ_f' (the permanent failure rate of faulted feeder section) and 'γ_f' (the temporary failure rate of faulted feeder section), respectively. For permanent faults in '$F3$' (having a switch) and its downstream feeder sections, all the loads upstream of '$F3$' will experience an outage time of switch isolation time (r_{iso}) while all the loads downstream of '$F3$' will experience an outage time equal to 'r_f' (time required to repair the faulted feeder section).

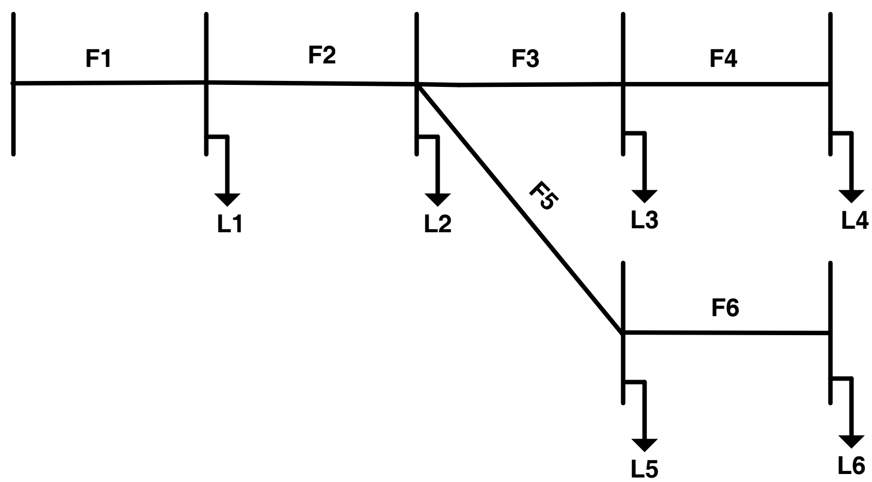

Figure 4.1: A 7-bus distribution system having 6 feeder sections and 6 load points

Let the binary variables $X_{R,k}$ and $X_{S,k}$ represent recloser and switch in k^{th} feeder section, respectively. Also, let

$$X_{S,k}/X_{R,k} = 0, \quad \text{if a switch/recloser is placed in } k^{th} \text{ feeder section} \\ = 1, \quad \text{if a switch/recloser is not placed in } k^{th} \text{ feeder section} \tag{4.1}$$

Using the procedures given in chapter 2, the permanent failure rate ($\lambda_{i,j}$) and outage time ($r_{i,j}$) of j^{th} load due to the permanent fault in i^{th} feeder section can be written as,

$$\lambda_{i,j} = bibc(i,j)\lambda_i + (1 - bibc(i,j))\lambda_i(\prod_{k \epsilon Fd(i,j)} X_{R,k}) \tag{4.2}$$

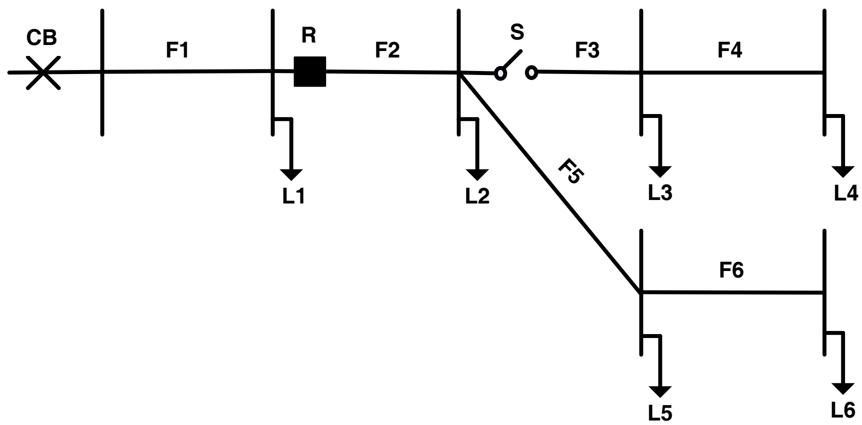

Figure 4.2: A 7-bus distribution system protected by a recloser and a switch

$$\begin{aligned} r_{i,j} = \quad & bibc(i,j)r_i + (1 - bibc(i,j))\{r_i(\prod_{k\epsilon Fd(i,j)} X_{S,k}) \\ + \quad & r_{iso}(1 - (\prod_{k\epsilon Fd(i,j)} X_{S,k}))\}(\prod_{k\epsilon Fd(i,j)} X_{R,k}) \end{aligned} \tag{4.3}$$

Similarly, the temporary failure rate ($\gamma_{i,j}$) of j^{th} load due to the temporary fault in i^{th} feeder section can be written as,

$$\gamma_{i,j} = bibc(i,j)\gamma_i + (1 - bibc(i,j))\gamma_i(\prod_{k\epsilon Fd(i,j)} X_{R,k}) \tag{4.4}$$

where,

$bibc(i,j)$ = element corresponding to the i^{th} row and j^{th} column of the $[\mathbf{BIBC}]$ matrix [67],

λ_i = permanent failure rate of i^{th} feeder section,

γ_i = temporary failure rate of i^{th} feeder section,

r_i = outage time of i^{th} feeder section,

and

$$Fd(i,j) = F_{Sec}(1,i) \cap F_{Sec}(j,i) \tag{4.5}$$

$F_{Sec}(1,i)$ is the set of feeder sections between source node and i^{th} feeder section (including i^{th} feeder section) and $F_{Sec}(j,i)$ is the set of feeder sections between j^{th} node and i^{th} feeder (including i^{th} feeder section). $Fd(i,j)$ represents feeder sections common to $F_{Sec}(1,i)$ and $F_{Sec}(j,i)$.

For the network shown in Fig.4.2, feeder section F_2 has a recloser and feeder section F_3 has a switch. Hence,

$$\begin{aligned} X_{R,1} = X_{R,3} = X_{R,4} = X_{R,5} = X_{R,6} = 1, \quad X_{R,2} = 0 \\ X_{S,1} = X_{S,2} = X_{S,4} = X_{S,5} = X_{S,6} = 1, \quad X_{S,3} = 0 \end{aligned} \tag{4.6}$$

The $[\mathbf{BIBC}]$ matrix for this network is given below,

$$BIBC = \begin{array}{c} \\ F1 \\ F2 \\ F3 \\ F4 \\ F5 \\ F6 \end{array} \begin{array}{c} \begin{array}{cccccc} L1 & L2 & L3 & L4 & L5 & L6 \end{array} \\ \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \end{array} \tag{4.7}$$

Using the elements of $[\mathbf{BIBC}]$ matrix (Eq. (4.7), expressions for $\lambda_{i,j}$ (Eq. (4.2)), $r_{i,j}$ (Eq. (4.3)), $\gamma_{i,j}$ (Eq. (4.4)) and the values of $X_{R,i}$ and $X_{S,i}$ (Eq. (4.6)), the calculated values of 'λ', 'r' and 'γ' for the system of Fig.4.2 are given in Tables 4.1, 4.2 and 4.3, respectively.

Table 4.1: Values of 'λ' for the system of Fig.4.2

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	λ_1	λ_1	λ_1	λ_1	λ_1	λ_1
$F2$	0	λ_2	λ_2	λ_2	λ_2	λ_2
$F3$	0	λ_3	λ_3	λ_3	λ_3	λ_3
$F4$	0	λ_4	λ_4	λ_4	λ_4	λ_4
$F5$	0	λ_5	λ_5	λ_5	λ_5	λ_5
$F6$	0	λ_6	λ_6	λ_6	λ_6	λ_6

Table 4.2: Values of 'r' for the system of Fig.4.2

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	r_1	r_1	r_1	r_1	r_1	r_1
$F2$	0	r_2	r_2	r_2	r_2	r_2
$F3$	0	$r_{iso,3}$	r_3	r_3	$r_{iso,3}$	$r_{iso,3}$
$F4$	0	$r_{iso,3}$	r_4	r_4	$r_{iso,3}$	$r_{iso,3}$
$F5$	0	r_5	r_5	r_5	r_5	r_5
$F6$	0	r_6	r_6	r_6	r_6	r_6

Table 4.3: Values of 'γ' for the system of Fig.4.2

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	γ_1	γ_1	γ_1	γ_1	γ_1	γ_1
$F2$	0	γ_2	γ_2	γ_2	γ_2	γ_2
$F3$	0	γ_3	γ_3	γ_3	γ_3	γ_3
$F4$	0	γ_4	γ_4	γ_4	γ_4	γ_4
$F5$	0	γ_5	γ_5	γ_5	γ_5	γ_5
$F6$	0	γ_6	γ_6	γ_6	γ_6	γ_6

After evaluating '$\lambda_{i,j}$', '$r_{i,j}$' and '$\gamma_{i,j}$', using Eqs. (4.2)-(4.4), respectively, the sustained interruption cost due to permanent fault (IC_λ) and momentary interruption cost due to temporary fault (IC_γ) can be evaluated as,

$$IC_\lambda = \sum_{j=1}^{nl}\sum_{i=1}^{nbr} \lambda_{i,j} ICP_{i,j} L_j$$
$$IC_\gamma = \sum_{j=1}^{nl}\sum_{i=1}^{nbr} \gamma_{i,j} ICT_{i,j} L_j$$

where,

nl = total number of connected loads,

nbr = total number of feeder sections,

L_j = mean value of the load connected at j^{th} node,

$ICP_{i,j}$ = sustained interruption cost of the load connected at j^{th} node due to the permanent fault in i^{th} feeder section for an outage duration of $r_{i,j}$,

$ICT_{i,j}$ = momentary interruption cost at j^{th} load point due to temporary fault in i^{th} feeder section.

Thus, the total customer interruption cost (TIC) for this scenario can be calculated as follows:

$$\begin{aligned} TIC &= IC_\lambda + IC_\gamma \\ &= \sum_{j=1}^{nl}\sum_{i=1}^{nbr} (\lambda_{i,j} ICP_{i,j} + \gamma_{i,j} ICT_{i,j}) L_j \end{aligned} \tag{4.8}$$

Further, the total energy not supplied (ENS) is given by,

$$ENS = \sum_{j=1}^{nl}\sum_{i=1}^{nbr} \lambda_{i,j} r_{i,j} L_j \quad kWhr/year \tag{4.9}$$

4.2.2 Placement of reclosers, switches and fuse-blow fuses (Fuse-blow scheme)

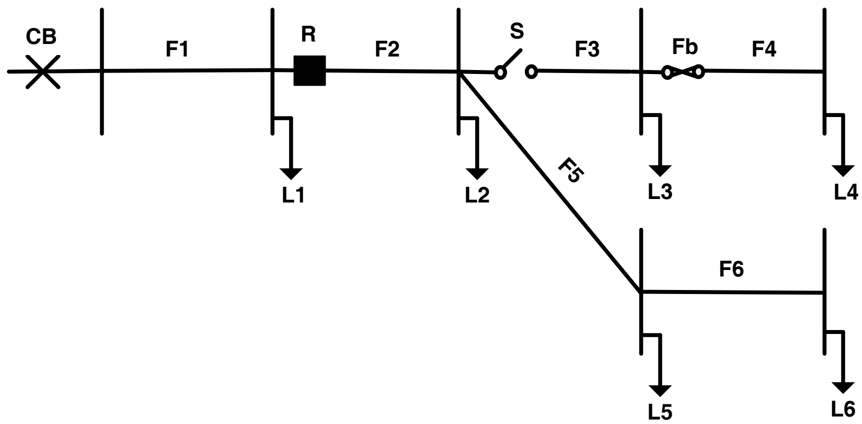

Figure 4.3: A 7-bus distribution system protected by a recloser, a switch and a fuse-blow fuse

Consider the scenario when the system is additionally protected by a fuse-blow fuse 'Fb' placed at feeder section '$F4$' apart from a switch 'S' at '$F3$', a recloser 'R' at '$F2$' and a circuit breaker 'CB' at the source point as shown in Fig. 4.3. For a fault (permanent or temporary) in '$F4$', the fuse-blow fuse 'Fb' at '$F4$' will trip before the upstream recloser 'R' at '$F2$' can operate (to interrupt the fault current). This results in sustained interruption ($\lambda^{'}$) of the customers downstream of the fuse-blow fuse, even for temporary faults in the feeder sections downstream of the fuse-blow fuse while the rest of the system operates uninterrupted. Thus, the placement of fuse-blow fuses in a distribution system results in a reduction of momentary interruptions and an increase in sustained interruptions.

Let a binary variable $X_{Fb,i}$ represents a fuse-blow fuse in i^{th} feeder section. Also, let

$$\begin{aligned} X_{Fb,i} &= 0, \quad \text{if a fuse-blow fuse is placed in } i^{th} \text{ feeder section} \\ &= 1, \quad \text{if a fuse-blow fuse is not placed in } i^{th} \text{ feeder section} \end{aligned} \tag{4.10}$$

For this case, the permanent failure rate ($\lambda_{i,j}$) and outage time ($r_{i,j}$) of j^{th} load due to the permanent fault in i^{th} feeder section, the temporary failure rate ($\gamma_{i,j}$) of j^{th} load due to the temporary fault in i^{th} feeder section and the permanent failure rate ($\lambda^{'}_{i,j}$) of j^{th} load due to a temporary fault in i^{th} feeder section can be represented as,

$$\lambda_{i,j} = bibc(i,j)\lambda_i + (1 - bibc(i,j))\lambda_i(\prod_{k \epsilon Fd(i,j)} X_{R,k}X_{Fb,k}) \tag{4.11}$$

$$\lambda'_{i,j} = bibc(i,j)\gamma_i(1-(\prod_{k\epsilon F_{Sec}(1,i)} X_{Fb,k})) + (1-bibc(i,j)) \\ \gamma_i(\prod_{k\epsilon Fd(i,j)} X_{R,k}X_{Fb,k})(1-(\prod_{k\epsilon G(i,j))} X_{Fb,k})) \tag{4.12}$$

$$\gamma_{i,j} = bibc(i,j)\gamma_i(\prod_{k\epsilon F_{Sec}(1,i)} X_{Fb,k}) + (1-bibc(i,j)) \\ \gamma_i(\prod_{k\epsilon Fd(i,j)} X_{R,k})(\prod_{k\epsilon F_{Sec}(1,i)} X_{Fb,k}) \tag{4.13}$$

$$r_{i,j} = bibc(i,j)r_i + (1-bibc(i,j))\{r_i(\prod_{k\epsilon Fd(i,j)} X_{S,k}) + \\ r_{iso}(1-(\prod_{k\epsilon Fd(i,j)} X_{S,k}))\}(\prod_{k\epsilon Fd(i,j)} X_{R,k}X_{Fb,k}) \tag{4.14}$$

$Fd(i,j)$ is evaluated using Eq. (4.5). $G(i,j)$ is the common feeder sections between $F_{Sec}(1,i)$ and $F_{Sec}(j,1)$. Therefore, $G(i,j)$ is given by,

$$G(i,j) = F_{Sec}(1,i) \cap F_{Sec}(j,1) \tag{4.15}$$

For the network shown in Fig.4.3, feeder section F_2 has a recloser, feeder section F_3 has a switch and feeder section F_4 has a fuse-blow fuse. Hence,

$$X_{R,1} = X_{R,3} = X_{R,4} = X_{R,5} = X_{R,6} = 1, \quad X_{R,2} = 0 \\ X_{S,1} = X_{S,2} = X_{S,4} = X_{S,5} = X_{S,6} = 1, \quad X_{S,3} = 0 \\ X_{Fb,1} = X_{Fb,2} = X_{Fb,3} = X_{Fb,5} = X_{Fb,6} = 1, \quad X_{Fb,4} = 0 \tag{4.16}$$

Using the elements of $[\mathbf{BIBC}]$ matrix (Eq. (4.7), expressions for $\lambda_{i,j}$ (Eq. (4.11)), $\lambda'_{i,j}$ (Eq. (4.12)), $\gamma_{i,j}$ (Eq. (4.13)), $r_{i,j}$ (Eq. (4.14)) and the values of $X_{R,i}$, $X_{S,i}$ and $X_{Fb,i}$ (Eq. (4.16)), the calculated values of 'λ', 'λ'', 'γ' and 'r' for the system of Fig.4.3 are given in Tables 4.4, 4.5, 4.6 and 4.7, respectively.

For a temporary or permanent fault in feeder section F_4, fuse-blow fuse Fb will blow and the load L_4 will experience a sustained interruption. Hence, $\lambda'_{4,4}$ = γ_4 (refer to Table 4.5). Since, the temporary faults in feeder section F_4 lead to permanent fault, hence, all the elements of the 4^{th} row of Table 4.6) are zero.

Table 4.4: Values of 'λ' for the system of Fig.4.3

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	λ_1	λ_1	λ_1	λ_1	λ_1	λ_1
$F2$	0	λ_2	λ_2	λ_2	λ_2	λ_2
$F3$	0	λ_3	λ_3	λ_3	λ_3	λ_3
$F4$	0	0	0	λ_4	0	0
$F5$	0	λ_5	λ_5	λ_5	λ_5	λ_5
$F6$	0	λ_6	λ_6	λ_6	λ_6	λ_6

Table 4.5: Values of 'λ'' for the system of Fig.4.3

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	0	0	0	0	0	0
$F2$	0	0	0	0	0	0
$F3$	0	0	0	0	0	0
$F4$	0	0	0	γ_4	0	0
$F5$	0	0	0	0	0	0
$F6$	0	0	0	0	0	0

Table 4.6: Values of 'γ' for the system of Fig.4.3

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	γ_1	γ_1	γ_1	γ_1	γ_1	γ_1
$F2$	0	γ_2	γ_2	γ_2	γ_2	γ_2
$F3$	0	γ_3	γ_3	γ_3	γ_3	γ_3
$F4$	0	0	0	0	0	0
$F5$	0	γ_5	γ_5	γ_5	γ_5	γ_5
$F6$	0	γ_6	γ_6	γ_6	γ_6	γ_6

After evaluating '$\lambda_{i,j}$', '$\lambda'_{i,j}$', '$\gamma_{i,j}$' and '$r_{i,j}$' using Eqs. (4.11)-(4.14), respectively, the sustained interruption cost due to permanent fault (IC_λ), sustained interruption cost due to temporary fault

Table 4.7: Values of 'r' for the system of Fig. 4.3

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	r_1	r_1	r_1	r_1	r_1	r_1
$F2$	0	r_2	r_2	r_2	r_2	r_2
$F3$	0	$r_{iso,3}$	r_3	r_3	$r_{iso,3}$	$r_{iso,3}$
$F4$	0	0	0	r_4	0	0
$F5$	0	r_5	r_5	r_5	r_5	r_5
$F6$	0	r_6	r_6	r_6	r_6	r_6

($IC_{\lambda'}$) and momentary interruption cost due to temporary fault (IC_γ) can be evaluated as,

$$IC_\lambda = \sum_{j=1}^{nl}\sum_{i=1}^{nbr} \lambda_{i,j} ICP_{i,j} L_j$$
$$IC_{\lambda'} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr} \lambda'_{i,j} ICPT_{i,j} L_j$$
$$IC_\gamma = \sum_{j=1}^{nl}\sum_{i=1}^{nbr} \gamma_{i,j} ICT_{i,j} L_j$$

where,

$ICPT_{i,j}$ = sustained interruption cost of the load connected at j^{th} load point due to the temporary fault in i^{th} feeder section for an outage duration of r'_i (For all the calculations, r'_i is assumed to be 30 minutes).

Thus, the total customer interruption cost (TIC) for this scenario can be calculated as,

$$\begin{aligned} TIC &= IC_\lambda + IC_{\lambda'} + IC_\gamma \\ &= \sum_{j=1}^{nl}\sum_{i=1}^{nbr} (\lambda_{i,j} ICP_{i,j} + \lambda'_{i,j} ICPT_{i,j} + \gamma_{i,j} ICT_{i,j}) L_j \end{aligned} \tag{4.17}$$

Further, ENS due to permanent fault (ENS_{λ_E}) and ENS due to temporary fault ($ENS_{\lambda_E{}'}$) can be written as,

$$\begin{aligned} ENS_{\lambda_E} &= \sum_{j=1}^{nl}\sum_{i=1}^{nbr} \lambda_{i,j} r_{i,j} L_j \\ ENS_{\lambda_E{}'} &= \sum_{j=1}^{nl}\sum_{i=1}^{nbr} \lambda'_{i,j} r'_i L_j \end{aligned} \tag{4.18}$$

Therefore, the total energy not supplied (ENS) for this scenario can be calculated as,

$$\begin{aligned} ENS &= ENS_{\lambda_E} + ENS_{\lambda_E}{}' \\ &= \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_{i,j}r_{i,j} + \lambda^{'}_{i,j}r^{'}_{i})L_j \quad kWhr/year \end{aligned} \tag{4.19}$$

where, $r^{'}_{i}$ is the fuse repair time of fuse-blow fuse placed at i^{th} feeder section.

4.2.3 Placement of reclosers, switches and fuse-save fuses (Fuse-save scheme)

Consider the scenario when the system is protected by a fuse-save fuse 'Fs' placed at feeder section '$F6$' apart from a switch 'S' at '$F3$', a recloser 'R' at '$F2$' and a circuit breaker 'CB' at the source point as shown in Fig. 4.4. For a fault (permanent or temporary) in '$F6$', the upstream recloser 'R' at '$F2$' will operate before the fuse-save fuse 'Fs' at '$F6$' can trip to interrupt the fault current. This results in momentary interruption to all the customers downstream of the recloser (even for permanent faults in the feeder sections downstream of the fuse-save fuse). On the other hand, for all the temporary faults downstream of the fuse-save fuse, service to the customers can be restored immediately by re-energizing the line, resulting in decreased sustained interruptions. Thus, placement of fuse-save fuse in the system results in reduced sustained interruptions and increased momentary interruptions.

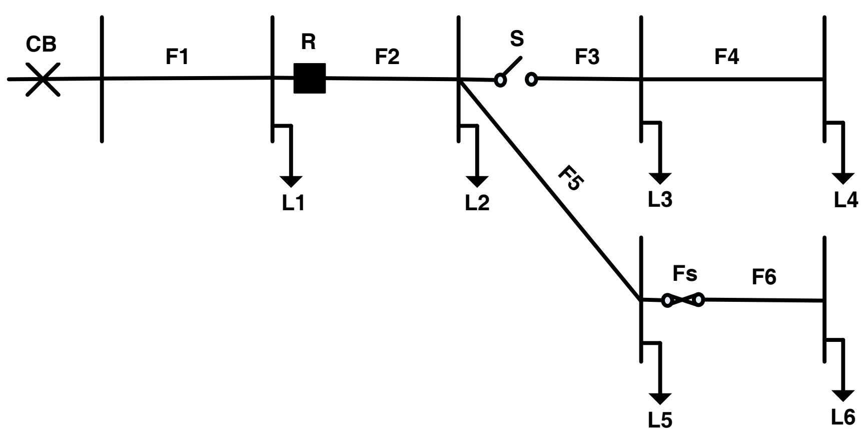

Figure 4.4: A 7-bus distribution system protected by a recloser, a switch and a fuse-save fuse

Let the binary variable $X_{Fs,i}$ represents fuse-save fuse in i^{th} feeder section. Also, let

$$\begin{aligned} X_{Fs,i} &= 0, \quad \text{if a fuse-save fuse is placed in } i^{th} \text{ feeder section} \\ &= 1, \quad \text{if a fuse-save fuse is not placed in } i^{th} \text{ feeder section} \end{aligned}$$

For this scenario, the permanent failure rate ($\lambda_{i,j}$) and outage time ($r_{i,j}$) of j^{th} load due to the permanent fault in i^{th} feeder section, the temporary failure rate ($\gamma_{i,j}$) of j^{th} load due to the temporary fault in i^{th} feeder section and the temporary failure rate ($\gamma^{'}_{i,j}$) of j^{th} load due to the permanent fault in i^{th} feeder section can be represented as,

$$\lambda_{i,j} = bibc(i,j)\lambda_i + (1 - bibc(i,j))\lambda_i(\prod_{k \epsilon Fd(i,j)} X_{R,k}X_{Fs,k}) \tag{4.20}$$

$$\gamma_{i,j} = bibc(i,j)\gamma_i + (1 - bibc(i,j))\gamma_i(\prod_{k \epsilon Fd(i,j)} X_{R,k}) \tag{4.21}$$

$$\gamma^{'}_{i,j} = (1 - bibc(i,j))\lambda_i(\prod_{k \epsilon Fd(i,j)} X_{R,k})(1 - (\prod_{k \epsilon Fd(i,j)} X_{Fs,k})) \tag{4.22}$$

$$\begin{aligned} r_{i,j} = \quad & bibc(i,j)r_i + (1 - bibc(i,j))\{r_i(\prod_{k \epsilon Fd(i,j)} X_{S,k}) \quad + \\ & r_{iso}(1 - (\prod_{k \epsilon Fd(i,j)} X_{S,k}))\}(\prod_{k \epsilon Fd(i,j)} X_{R,k}X_{Fs,k}) \end{aligned} \tag{4.23}$$

For the network shown in Fig. 4.4, feeder section F_2 has a recloser, feeder section F_3 has a switch and feeder section F_6 has a fuse-save fuse. Hence,

$$\begin{aligned} X_{R,1} = X_{R,3} = X_{R,4} = X_{R,5} = X_{R,6} = 1, \quad X_{R,2} = 0 \\ X_{S,1} = X_{S,2} = X_{S,4} = X_{S,5} = X_{S,6} = 1, \quad X_{S,3} = 0 \\ X_{Fs,1} = X_{Fs,2} = X_{Fs,3} = X_{Fs,4} = X_{Fs,5} = 1, \quad X_{Fs,6} = 0 \end{aligned} \tag{4.24}$$

Using the elements of $[\mathbf{BIBC}]$ matrix (Eq. (4.7), expressions for $\lambda_{i,j}$ (Eq. (4.20)), $\gamma_{i,j}$ (Eq. (4.21)), $\gamma^{'}_{i,j}$ (Eq. (4.22)), $r_{i,j}$ (Eq. (4.23)) and the values of $X_{R,i}$, $X_{S,i}$ and $X_{Fs,i}$ (Eq. (4.24)), the calculated values of 'λ', 'γ', '$\gamma^{'}$' and 'r' for the system of Fig. 4.4 are given in Tables 4.8, 4.9, 4.10 and 4.11, respectively.

Table 4.8: Values of 'λ' for the system of Fig.4.4

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	λ_1	λ_1	λ_1	λ_1	λ_1	λ_1
$F2$	0	λ_2	λ_2	λ_2	λ_2	λ_2
$F3$	0	λ_3	λ_3	λ_3	λ_3	λ_3
$F4$	0	λ_4	λ_4	λ_4	λ_4	λ_4
$F5$	0	λ_5	λ_5	λ_5	λ_5	λ_5
$F6$	0	0	0	0	0	λ_6

Table 4.9: Values of 'γ' for the system of Fig. 4.4

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	γ_1	γ_1	γ_1	γ_1	γ_1	γ_1
$F2$	0	γ_2	γ_2	γ_2	γ_2	γ_2
$F3$	0	γ_3	γ_3	γ_3	γ_3	γ_3
$F4$	0	γ_4	γ_4	γ_4	γ_4	γ_4
$F5$	0	γ_5	γ_5	γ_5	γ_5	γ_5
$F6$	0	γ_6	γ_6	γ_6	γ_6	γ_6

Table 4.10: Values of '$\gamma^{'}$' for the system of Fig. 4.4

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	0	0	0	0	0	0
$F2$	0	0	0	0	0	0
$F3$	0	0	0	0	0	0
$F4$	0	0	0	0	0	0
$F5$	0	0	0	0	0	0
$F6$	0	λ_6	λ_6	λ_6	λ_6	0

Table 4.11: Values of 'r' for the system of Fig. 4.4

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	r_1	r_1	r_1	r_1	r_1	r_1
$F2$	0	r_2	r_2	r_2	r_2	r_2
$F3$	0	$r_{iso,3}$	r_3	r_3	$r_{iso,3}$	$r_{iso,3}$
$F4$	0	$r_{iso,3}$	r_4	r_4	$r_{iso,3}$	$r_{iso,3}$
$F5$	0	r_5	r_5	r_5	r_5	r_5
$F6$	0	0	0	0	0	r_6

After evaluating '$\lambda_{i,j}$', '$\gamma_{i,j}$', '$\gamma^{'}_{i,j}$' and '$r_{i,j}$' using Eqs. (4.20)-(4.23) respectively, the sustained interruption cost due to permanent fault (IC_λ), momentary interruption cost due to temporary fault (IC_γ) and momentary interruption cost due to permanent fault ($IC_{\gamma'}$) are given by,

$$IC_\lambda = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} \lambda_{i,j} ICP_{i,j} L_j$$

$$IC_\gamma = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} \gamma_{i,j} ICT_{i,j} L_j$$

$$IC_{\gamma'} = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} \gamma^{'}_{i,j} ICT_{i,j} L_j$$

Thus, the total customer interruption cost (TIC) for this scenario can be calculated as,

$$\begin{aligned} TIC &= IC_\lambda + IC_\gamma + IC_{\gamma'} \\ &= \sum_{j=1}^{nl} \sum_{i=1}^{nbr} (\lambda_{i,j} ICP_{i,j} + (\gamma_{i,j} + \gamma^{'}_{i,j}) ICT_{i,j}) L_j \end{aligned} \tag{4.25}$$

and the total energy not supplied (ENS) for this scenario is given by,

$$ENS = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} \lambda_{i,j} r_{i,j} L_j \quad kWhr/year \tag{4.26}$$

4.3 Problem Formulation

In this section, three different models corresponding to the three scenarios of protective devices placement in a distribution network (discussed in the previous section) have been developed for maximizing the profit of the utility by reliability improvement while reducing the outage and investment costs.

4.3.1 Objective function

The objective functions corresponding to the three scenarios (RS scheme, Fuse-blow scheme and Fuse-save scheme) of protective devices placement in distribution system are aimed at revenue earning maximization of the utility due to reduction in CIC and increase in extra energy supplied (due to decrease in ENS) to the customers while minimizing the associated investment cost such as cost of installation, operation and maintenance of protective devices.

Consider the scenario when only reclosers and switches are to be placed in the distribution system (RS scheme). As discussed in the previous section, presence of a recloser in a feeder section saves all the upstream loads for all the permanent and temporary faults in the feeder section and its downstream feeder sections. In other words, all the loads upstream of a feeder section having a recloser will not experience any interruption for any fault in the feeder section (having a recloser) and its downstream feeder sections.

Similarly, presence of a switch in a feeder section reduces the outage time of all the upstream loads for all the permanent faults in the feeder section and its downstream feeder sections. In other words, for a permanent fault in the feeder section (having a switch) and its downstream feeder sections, all the loads upstream of the feeder section will experience a reduced outage time equal to the 'switch isolation time' of the feeder section.

Using the procedure discussed in the previous section, we can calculate the savings (due to reduction in ENS and TIC) of the system protected by reclosers and switches. When no reclosers and switches are placed in the distribution system, the expressions $\prod_{k\epsilon Fd(i,j)} X_{R,k}$ of Eqs. (4.2)-(4.3) and $\prod_{k\epsilon Fd(i,j)} X_{S,k}$ of Eqs. (4.3) become unity. As a result, $\lambda_{i,j}$ becomes equal to λ_i, $\gamma_{i,j}$ becomes equal to γ_i and $r_{i,j}$ becomes equal to r_i. Therefore, from Eqs. (4.8) and (4.9), the TIC and ENS of the unprotected system (represented by TIC^U_{RS} and ENS^U_{RS}, respectively) can be written as,

$$TIC^U_{RS} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_i ICP'_{i,j} + \gamma_i ICT_{i,j})L_j \tag{4.27}$$

$$ENS^U_{RS} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_i r_i)L_j \quad kWhr/year \tag{4.28}$$

where,

$ICP'_{i,j}$ = sustained interruption cost of the load at j^{th} bus due to outage duration of 'r_i' for the permanent fault in i^{th} feeder section.

Now consider the case when the distribution system is protected by reclosers and switches (RS scheme). Using Eqs. (4.8) and (4.9), the TIC and ENS of this protected system (represented by TIC_P and ENS_P, respectively) can be written as,

$$TIC_{RS}^{P} = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} (\lambda_{i,j} ICP_{i,j} + \gamma_{i,j} ICT_{i,j}) L_j \tag{4.29}$$

$$ENS_{RS}^{P} = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} (\lambda_{i,j} r_{i,j}) L_j \tag{4.30}$$

Therefore, reduction in TIC (i.e. TIC_{RS}^{U}-TIC_{RS}^{P}) due to placement of reclosers and switches in the distribution system can be written as,

$$TIC_{RS}^{U} - TIC_{RS}^{P} = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} ((\lambda_i ICP_{i,j}^{'} + \gamma_i ICT_{i,j}) - (\lambda_{i,j} ICP_{i,j} + \gamma_{i,j} ICT_{i,j})) L_j \tag{4.31}$$

Similarly, reduction in ENS (i.e. ENS_{RS}^{U}-ENS_{RS}^{P}) due to placement of reclosers and switches in the distribution system can be written as,

$$ENS_{RS}^{U} - ENS_{RS}^{P} = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} (\lambda_i r_i - \lambda_{i,j} r_{i,j}) L_j \tag{4.32}$$

Therefore, for this scenario (RS scheme), the objective function (f_{RS}) is defined as follows:

$$\begin{aligned} Maximize \quad f_{RS} = \{ & \sum_{j=1}^{nl} \sum_{i=1}^{nbr} (\lambda_i r_i - \lambda_{i,j} r_{i,j}) L_j \} C_E F_1 + \{ \sum_{j=1}^{nl} \sum_{i=1}^{nbr} ((\lambda_i ICP_{i,j}^{'} + \gamma_i ICT_{i,j}) \\ & - (\lambda_{i,j} ICP_{i,j} + \gamma_{i,j} ICT_{i,j})) L_j \} F_2 - \{ (\sum_{i=1}^{nbr} (1 - X_{R,i})) C_R \\ & + (\sum_{i=1}^{nbr} (1 - X_{S,i})) C_S \} (1 + \frac{C_m}{100} F_3) \end{aligned} \tag{4.33}$$

where,

C_E = per unit energy cost,

N_s = life span of the protective devices (in years),

L_C = rate of annual load growth (in percent),

i_r = annual interest rate (in percent),

r_E = annual incremental rate of energy cost (in percent),

$ICP_{i,j}^{'}$ = sustained interruption cost of the load at j^{th} bus due to outage duration of 'r_i' for the permanent fault in i^{th} feeder section,

r_m = annual incremental rate of maintenance cost (in percent),

i_c = annual incremental rate of interruption cost (in percent),

C_m = maintenance cost of switching devices (in percent),

C_R = cost of a recloser,

C_S = cost of a switch.

F_1, F_2, and F_3 are given by Eqs. (3.11)-(3.13) respectively. '$\lambda_{i,j}$', '$r_{i,j}$' and '$\gamma_{i,j}$', used in Eq. (4.33) are calculated using Eqs. (4.2)-(4.4), respectively.

Now consider the scenario when the distribution system is to be protected with reclosers, switches and fuse-blow fuses (Fuse-blow scheme). For any fault downstream of a fuse-blow fuse, first the fuse-blow fuse will trip before the recloser upstream of the fuse-blow fuse can operate to interrupt the fault current. This results in sustained interruption to all the customers downstream of the fuse-blow fuse even for a temporary fault in any of the feeder sections downstream of the fuse-blow fuse, while the rest part of the system is uninterrupted. It may be noted that, all the customers between nearest upstream recloser and the fuse-blow fuse never experience momentary interruption for a temporary fault in any of the feeder sections downstream of the fuse-blow fuse.

When no protective devices (for this scenario, reclosers, switches or fuse-blow fuses) are placed in the distribution system, the expression $\prod_{k\epsilon Fd(i,j)} X_{R,k}X_{Fb,k}$ of Eq. (4.11) become unity (as can be observed from Eqs. (4.1) and (4.10)). As a result, $\lambda_{i,j}$ becomes equal to λ_i. Similarly, in Eq. (4.12), $\prod_{k\epsilon F_{Sec}(1,i)} X_{Fb,k}$, $\prod_{k\epsilon Fd(i,j)} X_{R,k}X_{Fb,k}$ and $\prod_{k\epsilon G(i,j)} X_{Fb,k}$ all become unity. Hence, $\lambda^{'}_{i,j}$ becomes zero. Further, in Eq. (4.13), $\prod_{k\epsilon Fd(i,j)} X_{R,k}$ also becomes unity, hence $\gamma_{i,j}$ = γ_i. Finally, in Eq. (4.14), $\prod_{k\epsilon Fd(i,j)} X_{S,k}$ also becomes unity (as can be observed from Eq. (4.1)), hence $r_{i,j}$ = r_i. Therefore, from Eqs. (4.17) and (4.19), the TIC and ENS of the unprotected system (represented by TIC^U_{FB} and ENS^U_{FB}, respectively) can be written as,

$$TIC^U_{FB} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_i ICP^{'}_{i,j} + \gamma_i ICT_{i,j})L_j \tag{4.34}$$

$$ENS^U_{FB} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_i r_i)L_j \tag{4.35}$$

Now consider the case when the distribution system is protected by reclosers, switches and fuse-blow fuses (Fuse-blow scheme). Using Eqs. (4.17) and (4.19), the TIC and ENS of this protected system (represented by TIC_{FB}^{P} and ENS_{FB}^{P}, respectively) can be written as,

$$TIC_{FB}^{P} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_{i,j}ICP_{i,j} + \lambda_{i,j}^{'}ICPT_{i,j} + \gamma_{i,j}ICT_{i,j})L_j \tag{4.36}$$

$$ENS_{FB}^{P} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_{i,j}r_{i,j} + \lambda_{i,j}^{'}r_{i}^{'})L_j \tag{4.37}$$

Therefore, reduction in TIC (i.e. TIC_{FB}^{U}-TIC_{FB}^{P}) due to placement of reclosers, switches and fuse-blow fuses in the distribution system can be written as,

$$TIC_{FB}^{U} - TIC_{FB}^{P} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}((\lambda_{i}ICP_{i,j}^{'} + \gamma_{i}ICT_{i,j}) - (\lambda_{i,j}ICP_{i,j} + \lambda_{i,j}^{'}ICPT_{i,j} + \gamma_{i,j}ICT_{i,j}))L_j \tag{4.38}$$

Similarly, reduction in ENS (i.e. ENS_{FB}^{U}-ENS_{FB}^{P}) due to placement of reclosers, switches and fuse-blow fuses in the distribution system can be written as,

$$ENS_{FB}^{U} - ENS_{FB}^{P} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_{i}r_{i} - (\lambda_{i,j}r_{i,j} + \lambda_{i,j}^{'}r_{i}^{'}))L_j \tag{4.39}$$

Therefore, for this scenario (Fuse-blow scheme), the objective function (f_{FB}) is defined as follows:

$$\begin{aligned} Maximize \quad f_{FB} = \{&\sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_{i}r_{i} - (\lambda_{i,j}r_{i,j} + \lambda_{i,j}^{'}r_{i}^{'}))L_j\}C_E F_1 + \{\sum_{j=1}^{nl}\sum_{i=1}^{nbr}((\lambda_{i}ICP_{i,j}^{'} + \gamma_{i}ICT_{i,j}) \\ &- (\lambda_{i,j}ICP_{i,j} + \lambda_{i,j}^{'}ICPT_{i,j} + \gamma_{i,j}ICT_{i,j}))L_j\}F_2 - \{(\sum_{i=1}^{nbr}(1 - X_{R,i}))C_R \\ &+ (\sum_{i=1}^{nbr}(1 - X_{S,i}))C_S + (\sum_{i=1}^{nbr}(1 - X_{Fb,i}))C_{Fb}\}(1 + \frac{C_m}{100}F_3) \end{aligned} \tag{4.40}$$

'$\lambda_{i,j}$', '$\lambda_{i,j}^{'}$', '$\gamma_{i,j}$' and '$r_{i,j}$' used in Eq. (4.40) are calculated using Eqs. (4.11)-(4.14), respectively. C_{Fb} is the cost of a fuse-blow fuse.

Now consider the scenario when reclosers, switches and fuse-save fuses are to be placed in the distribution system (Fuse-save scheme). For any fault downstream of a fuse-save fuse, the recloser upstream of the fuse-save fuse will operate before the fuse-save fuse can trip to interrupt the fault current. This results in the momentary interruption to all the customers between the fuse-save fuse and the upstream recloser even for permanent faults in any of the feeder sections downstream of the fuse-save fuse. However, for all the temporary faults downstream of the fuse-save fuse, service to all the customers can be restored immediately by re-energizing the line, resulting in decreased sustained interruptions. Thus, placement of protective devices in distribution system using this scheme results in decrease in sustained interruptions and increase in momentary interruptions.

When no protective devices (for this scenario, reclosers, switches or fuse-save fuses) are placed in the distribution system, the expression $\prod_{k\epsilon Fd(i,j)} X_{R,k}X_{Fs,k}$ of Eq. (4.20) become unity (as can be observed from Eqs. (4.1) and (4.10)). As a result, $\lambda_{i,j}$ becomes equal to λ_i. Similarly, in Eq. (4.21), $\prod_{k\epsilon Fd(i,j)} X_{R,k}$ also becomes unity, hence $\gamma_{i,j}$ = γ_i. Further, in Eq. (4.22), $\prod_{k\epsilon Fd(i,j)} X_{R,k}$ and $\prod_{k\epsilon Fd(i,j)} X_{Fs,k}$ also becomes unity (as can be observed from Eq. (4.1) and (4.10)), therefore $\gamma^{'}_{i,j}$ becomes equal to zero. Finally, in Eq. (4.23), $\prod_{k\epsilon Fd(i,j)} X_{S,k}$ also becomes unity (as can be observed from Eq. (4.1)), hence $r_{i,j}$ = r_i. Therefore, from Eqs. (4.25) and (4.26), the TIC and ENS of the unprotected system (represented by TIC^U_{FS} and ENS^U_{FS}, respectively) can be written as,

$$TIC^U_{FS} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_i ICP^{'}_{i,j} + \gamma_i ICT_{i,j})L_j \tag{4.41}$$

$$ENS^U_{FS} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_i r_i)L_j \tag{4.42}$$

Now consider the case when the distribution system is protected by reclosers, switches and fuse-save fuses (Fuse-save scheme). Using Eqs. (4.25) and (4.26), the TIC and ENS of this protected system, (represented by TIC^P_{FS} and ENS^P_{FS} respectively) can be written as,

$$TIC^P_{FS} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_{i,j} ICP_{i,j} + (\gamma_{i,j} + \gamma^{'}_{i,j})ICT_{i,j})L_j \tag{4.43}$$

$$ENS^P_{FS} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}\lambda_{i,j} r_{i,j} L_j \tag{4.44}$$

Therefore, reduction in TIC (i.e. TIC^U_{FS}-TIC^P_{FS}) due to placement of reclosers, switches and fuse-blow fuses in the distribution system can be written as,

$$TIC^U_{FS} - TIC^P_{FS} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}((\lambda_i ICP^{'}_{i,j} + \gamma_i ICT_{i,j}) - (\lambda_{i,j} ICP_{i,j} + \lambda_{i,j} ICP_{i,j} + (\gamma_{i,j} + \gamma^{'}_{i,j})ICT_{i,j}))L_j \tag{4.45}$$

Similarly, reduction in ENS (i.e. ENS^U_{FS}-ENS^P_{FS}) due to placement of reclosers, switches and fuse-blow fuses in the distribution system can be written as,

$$ENS^U_{FS} - ENS^P_{FS} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_i r_i - \lambda_{i,j} r_{i,j})L_j \tag{4.46}$$

Therefore, for this scenario (Fuse-save scheme), the objective function (f_{FS}) is defined as follows:

$$
\begin{aligned}
Maximize \quad f_{FS} = &\{\sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_i r_i - \lambda_{i,j} r_{i,j})L_j\}C_E F_1 + \{\sum_{j=1}^{nl}\sum_{i=1}^{nbr}((\lambda_i ICP^{'}_{i,j} + \gamma_i ICT_{i,j}) \\
&- (\lambda_{i,j} ICP_{i,j} + (\gamma_{i,j} + \gamma^{'}_{i,j})ICT_{i,j}))L_j\}F_2 - \{(\sum_{i=1}^{nbr}(1 - X_{R,i}))C_R \\
&+ (\sum_{i=1}^{nbr}(1 - X_{S,i}))C_S + (\sum_{i=1}^{nbr}(1 - X_{Fs,i}))C_{Fs}\}(1 + \frac{C_m}{100}F_3)
\end{aligned} \tag{4.47}
$$

'$\lambda_{i,j}$', '$\gamma_{i,j}$', '$\gamma^{'}_{i,j}$' and '$r_{i,j}$' used in Eq. (4.47) are calculated using Eqs. (4.20)-(4.23), respectively. C_{Fs} is the cost of a fuse-save fuse.

The first term in Eqs. (4.33), (4.40) and (4.47) accounts for the net present worth (NPW) of the earned revenue due to increased energy supplied to the customers corresponding to the useful life span of the protective devices (N_s years). It is to be noted that optimal placement of switching devices such as reclosers, switches, fuses etc. in distribution system results in reduction of 'ENS'. Thus, the protected system supplying additional energy to the customers increases the revenue collection of the distribution system.

The second term in Eqs. (4.33), (4.40) and (4.47) accounts for the 'NPW' of the earned revenue due to reduced customer interruption cost. The damages caused due to supply interruptions to the customers have to be compensated by the distribution companies. Typical values of the customer interruption costs for different types of customers considered in this chapter are give in Table 2.3 of chapter 2.

The third term in Eqs. (4.33), (4.40) and (4.47) accounts for the 'NPW' of the cost of protective devices and their lifetime maintenance cost.

4.3.2 Constraints

The models of placement of various combinations of protective devices in distribution system described in previous section consists of the following constraints:

1. The number of switching devices (such as reclosers, switches, fuse-blow fuses or fuse-save fuses) to be placed in the distribution system should be within the specified numbers given by the utility. From Eq. (4.1), it can be observed that if a recloser is placed in the i^{th} feeder section of the distribution system, than $X_{R,i}$ = 0, otherwise $X_{R,i}$ = 1. In other words, if a recloser is placed in the i^{th} feeder section of the distribution system, than (1-$X_{R,i}$) = 1, otherwise (1-$X_{R,i}$)

= 0. The total number of reclosers to be placed among nbr branches of the distribution system should be less than or equal to the number of available reclosers (N_{AvR}). This constraint is modelled by the following inequality constraint:

$$\sum_{i=1}^{nbr}(1 - X_{R,i}) \leq N_{AvR} \tag{4.48}$$

Similarly, if a switch is placed in the i^{th} feeder section of the distribution system, than (1-$X_{S,i}$) = 1, otherwise (1-$X_{S,i}$) = 0. The total number of switches to be placed among nbr branches of the distribution system should be less than or equal to the number of available switches (N_{AvS}). This constraint is modelled by the following inequality constraint:

$$\sum_{i=1}^{nbr}(1 - X_{S,i}) \leq N_{AvS} \tag{4.49}$$

The other constraints corresponding to the maximum number of fuse-blow fuses and fuse-save fuses that can be placed in the distribution system are given by the following inequalities.

$$\sum_{i=1}^{nbr}(1 - X_{Fb,i}) \leq N_{AvFb} \tag{4.50}$$

$$\sum_{i=1}^{nbr}(1 - X_{Fs,i}) \leq N_{AvFs} \tag{4.51}$$

where,

N_{AvFb} = Number of available fuse-blow fuses,

N_{AvFs} = Number of available fuse-save fuses.

2. In RS scheme, reclosers and switches should not be installed simultaneously in the same feeder section. In other words, a recloser and a switch can not be simultaneously placed on the same feeder section. This constraint is modelled by the following inequality constraint.

$$X_{R,i} + X_{S,i} \geq 1 \quad i = 1, 2, ..., nbr \tag{4.52}$$

3. In Fuse-blow scheme, two or more than two protective devices (reclosers, switches and fuse-blow fuses) can not be simultaneously placed on the same feeder section. This constraint is modelled by the following inequality constraint:

$$X_{R,i} + X_{S,i} + X_{Fb,i} \geq 2 \quad i = 1, 2, ..., nbr \tag{4.53}$$

4. In Fuse-save scheme also, two or more than two protective devices (reclosers, switches and fuse-save fuses) can not be simultaneously placed on the same feeder section. This constraint is modelled by the following inequality constraint:

$$X_{R,i} + X_{S,i} + X_{Fs,i} \geq 2 \quad i = 1, 2, ..., nbr \tag{4.54}$$

5. Reclosers and switches may not be installed downstream of a fuse-blow fuse (in Fuse-blow scheme) or fuse-save fuse (in Fuse-blow scheme) [35]. This constraint is modelled in only Fuse-blow scheme and Fuse-save scheme which include fuse-blow fuses and fuse-save fuses, respectively.

4.4 Case studies

The optimal placement of protective devices corresponding to the three scenarios viz. RS scheme, Fuse-blow scheme and Fuse-save scheme has been carried out in the two test systems (58-bus and IEEE 123-bus) by solving the optimization problems described in the previous section using MINLP technique. The MINLP technique used for evaluating the objective functions (f_{RS}, f_{FB} and f_{FS}) utilizes the sequential quadratic programming (SQP) through the MATLAB function 'fmincon' of the MATLAB optimization toolbox. In this chapter, the various assumptions adopted and load data, failure data for the two test systems and the system cost data are same as given in [67]. Further, the temporary failure rates are assumed to be three times of the permanent failure rate of the corresponding feeder section in all the calculations. Cost of a fuse and its annual maintenance cost (including replacement cost) are assumed to be Rs. 30,000 and 40% (of the fuse cost), respectively. Uncertainties in loading conditions, temporary failure rates, permanent failure rates and repair rates of the system have been considered using the procedures given in Chapter 3.

To check the suitability of 3PEM method for calculating the expected value of total cost, the expected cost values (of unprotected system) obtained from 3PEM method were compared with the corresponding values obtained using sufficiently large number (50,000) of Monte Carlo simulations (MC). The results are tabulated in Table 4.12. The 58-bus system has 57 feeder sections and 57 load buses with a total load of 54.14 MW (with an average load of 0.95 MW/bus). The IEEE 123-bus system has 118 feeder sections and 118 load buses with a total load of 5.41 MW (with an average load of 0.046 MW/bus). Hence, using Eq. (3.17), total number of random variables associated with 58-bus system can be calculated as,

$$n_{rv58} = 3 * 57 + 57 = 228$$

Table 4.12: Comparison of cost values using 3PEM and MC

Test system →	58-bus		IEEE 123-bus	
Evaluation method →	3PEM	MC	3PEM	MC
No. of function evaluations	457	50,000	945	50,000
Total cost (CIC+ENS) (Rs.)	16537709.08	16540747.81	874218.34	873516.99
Time (s)	5.83	81.15	38.51	392.89

From Eqs. (3.24)-(3.26), it can be observed that for using 3PEM, the total number of function evaluations required for 58-bus system = 2*n_{rv58}+1 = 457. Similarly, the total number of function evaluations required for IEEE 123-bus system is calculated as 945.

From Table 4.12, it can be observed that the 3PEM method is able to calculate the expected value of total cost with an appreciable degree of accuracy (with errors of 0.018% and 0.080% for 58-bus and IEEE 123-bus, respectively) within a reasonably shorter time as compared to MC. Therefore, 3PEM method has been used in this work to calculate the expected value of utility profit under an uncertain environment.

The results for optimized placement of protective devices obtained for the three objective functions (f_{RS}, f_{FB} and f_{FS}) for 58-bus system are given in Table 4.13. From this table, it can be observed that the function values (profits) corresponding to the objective functions 'f_{RS}', 'f_{FB}' and 'f_{FS}' are Rs. 367284312.64, Rs. 371360333.30 and Rs. 369064817.37, respectively. The details of the locations of the protective devices obtained by all the three schemes are also given in Table 4.13. Further, the optimal locations of the protective devices obtained by RS scheme, Fuse-blow scheme and Fuse-save scheme are also shown in Figs. 4.5-4.7, respectively.

Table 4.14 shows the results for optimized placement of protective devices for the three objective functions (f_{RS}, f_{FB} and f_{FS}) for IEEE 123-bus system. From this table, it can be observed that the objective function values for IEEE 123-bus test system corresponding to the objective functions 'f_{RS}', 'f_{FB}' and 'f_{FS}' are Rs.34570048.40, Rs. 36208509.62 and Rs. 36291793.39, respectively. The details of the locations of the protective devices obtained by all the three schemes are also given in Table 4.14. The optimal locations of protective devices for this system corresponding to RS scheme, Fuse-blow scheme and Fuse-save scheme are also shown in Figs. 4.8-4.10, respectively.

As can be observed from Tables 4.13 and 4.14, for 58-bus system (heavily loaded system) the maximum profit is obtained for Fuse-blow scheme (corresponding to objective f_{FB}) while for IEEE

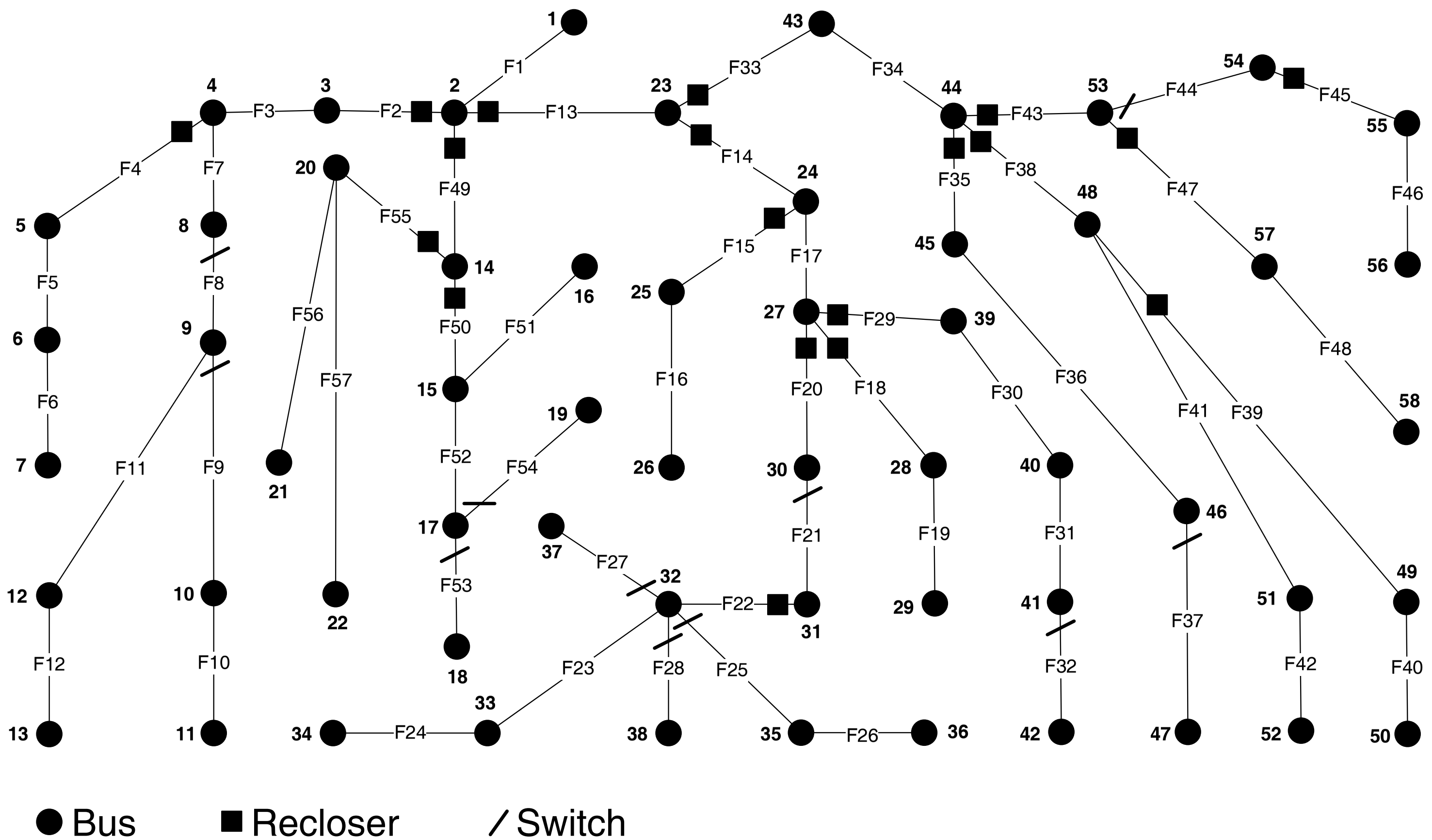

Figure 4.5: 58-bus system protected by RS scheme

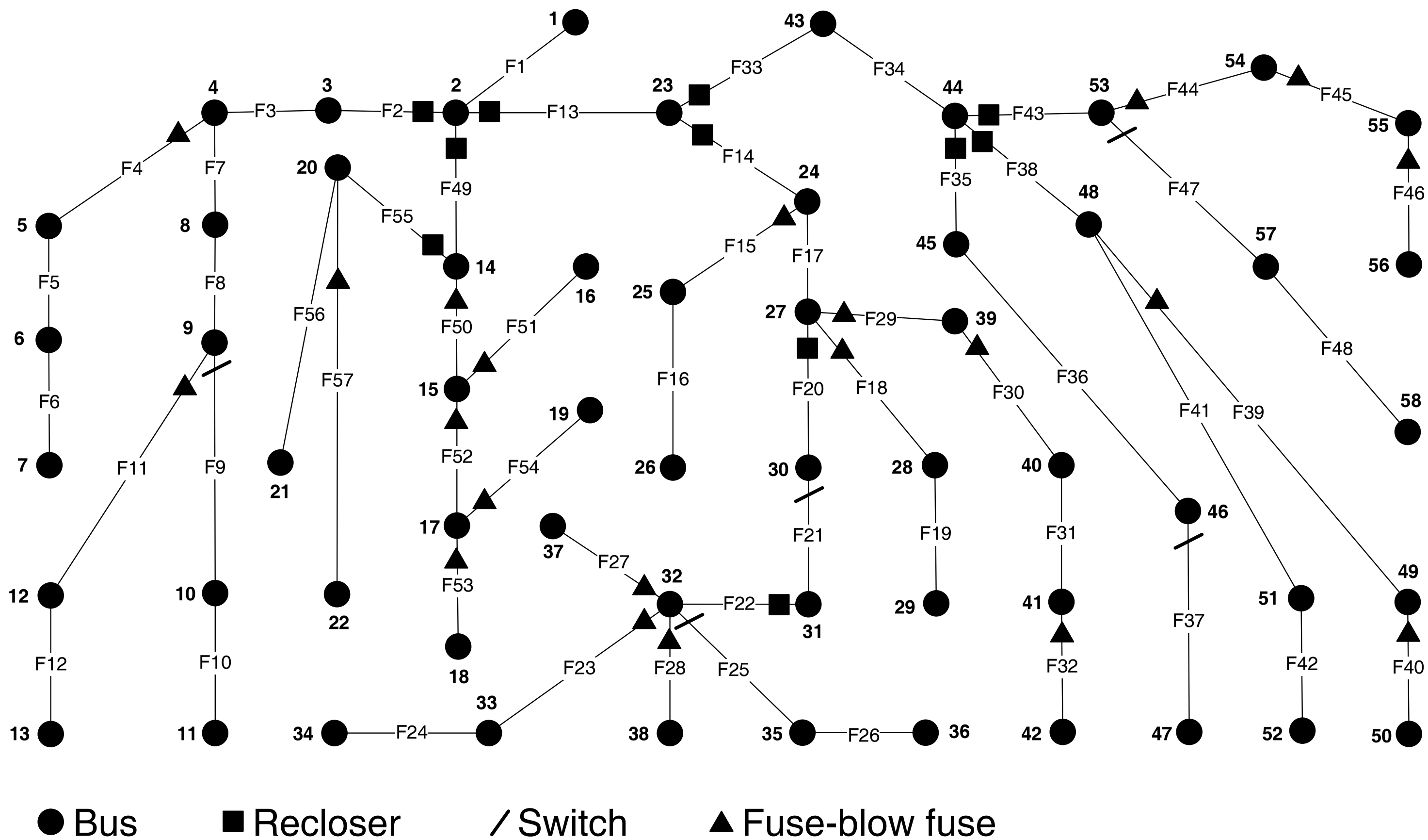

Figure 4.6: 58-bus system protected by Fuse-blow scheme

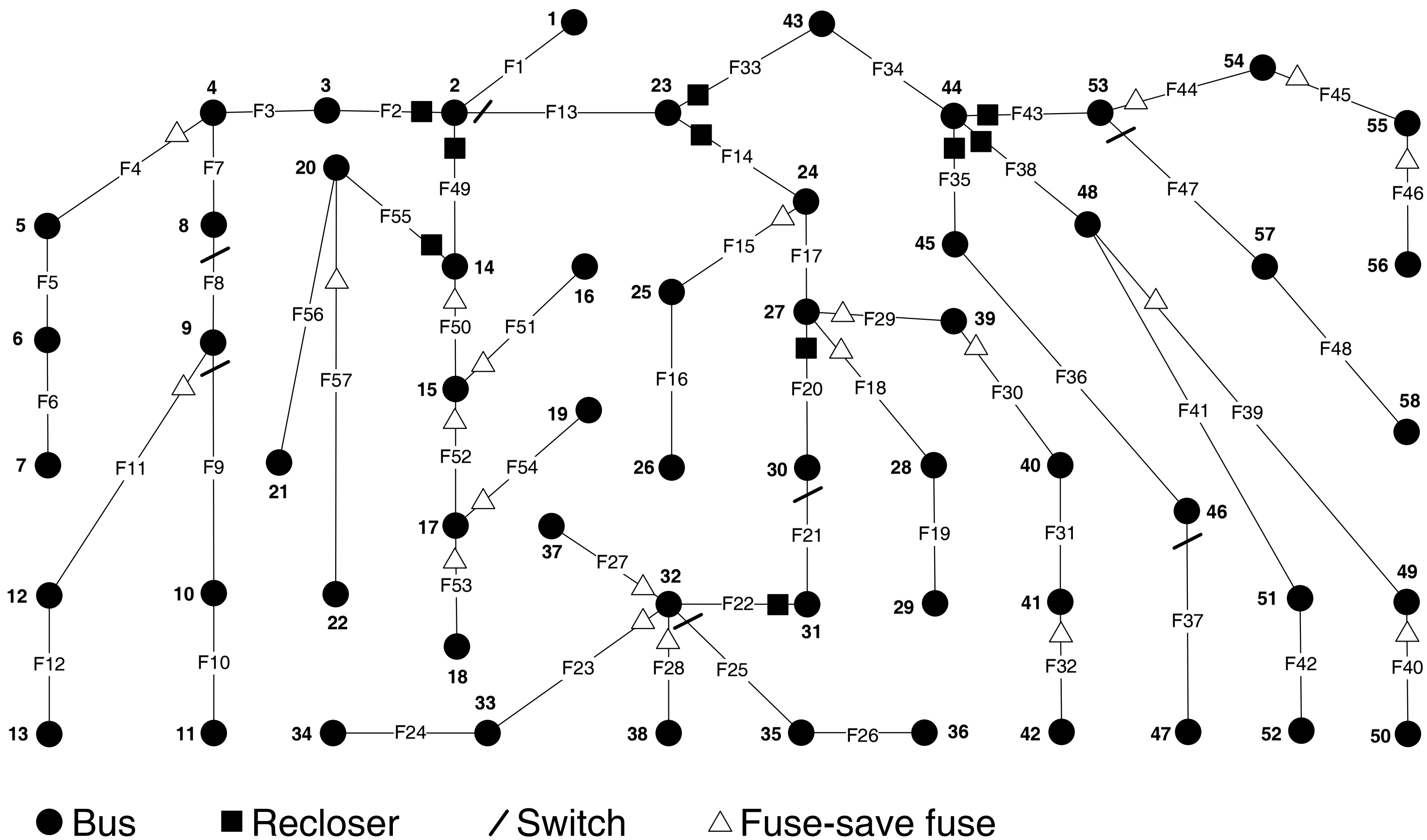

Figure 4.7: 58-bus system protected by Fuse-save scheme

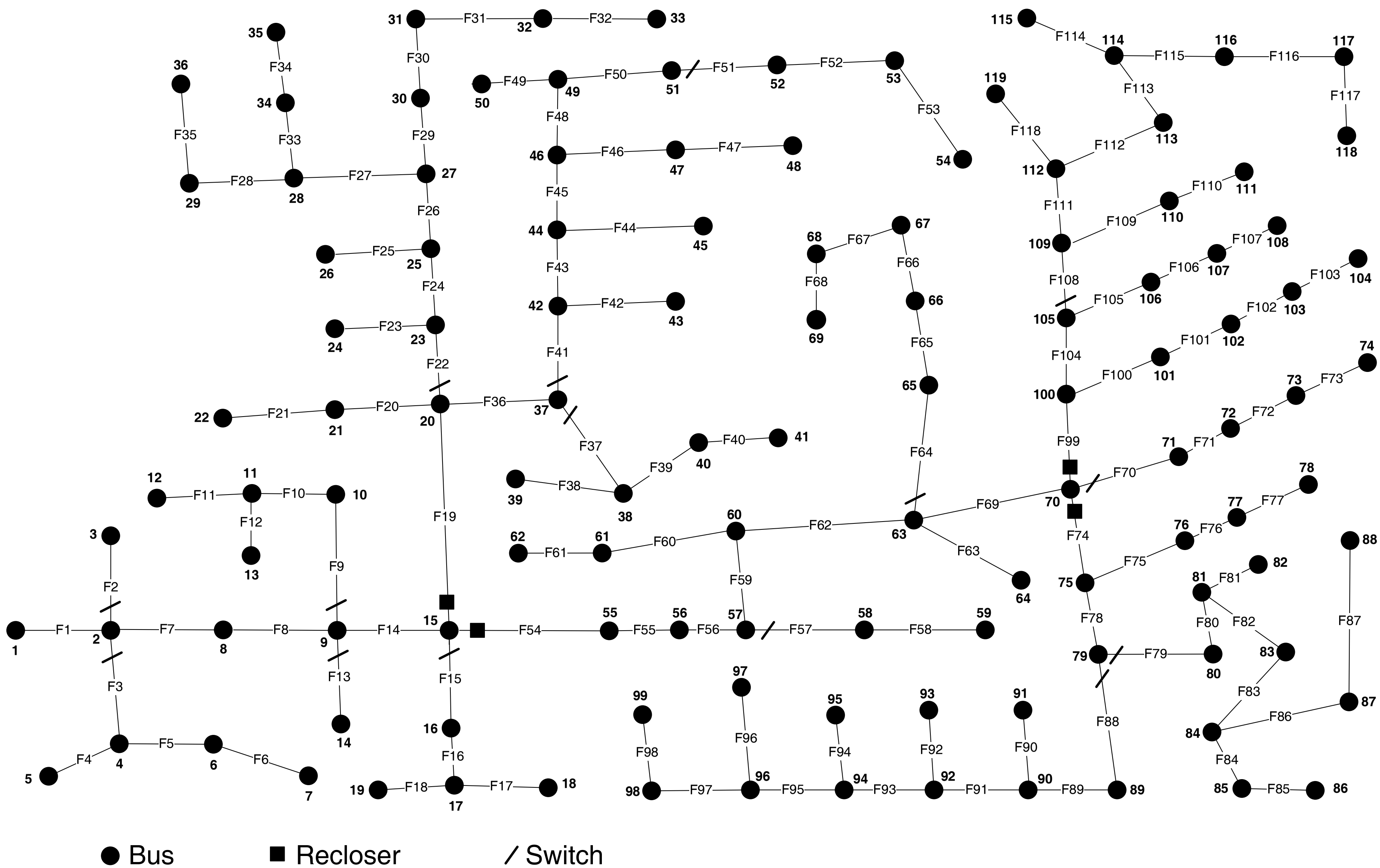

Figure 4.8: 123-bus system protected by RS scheme

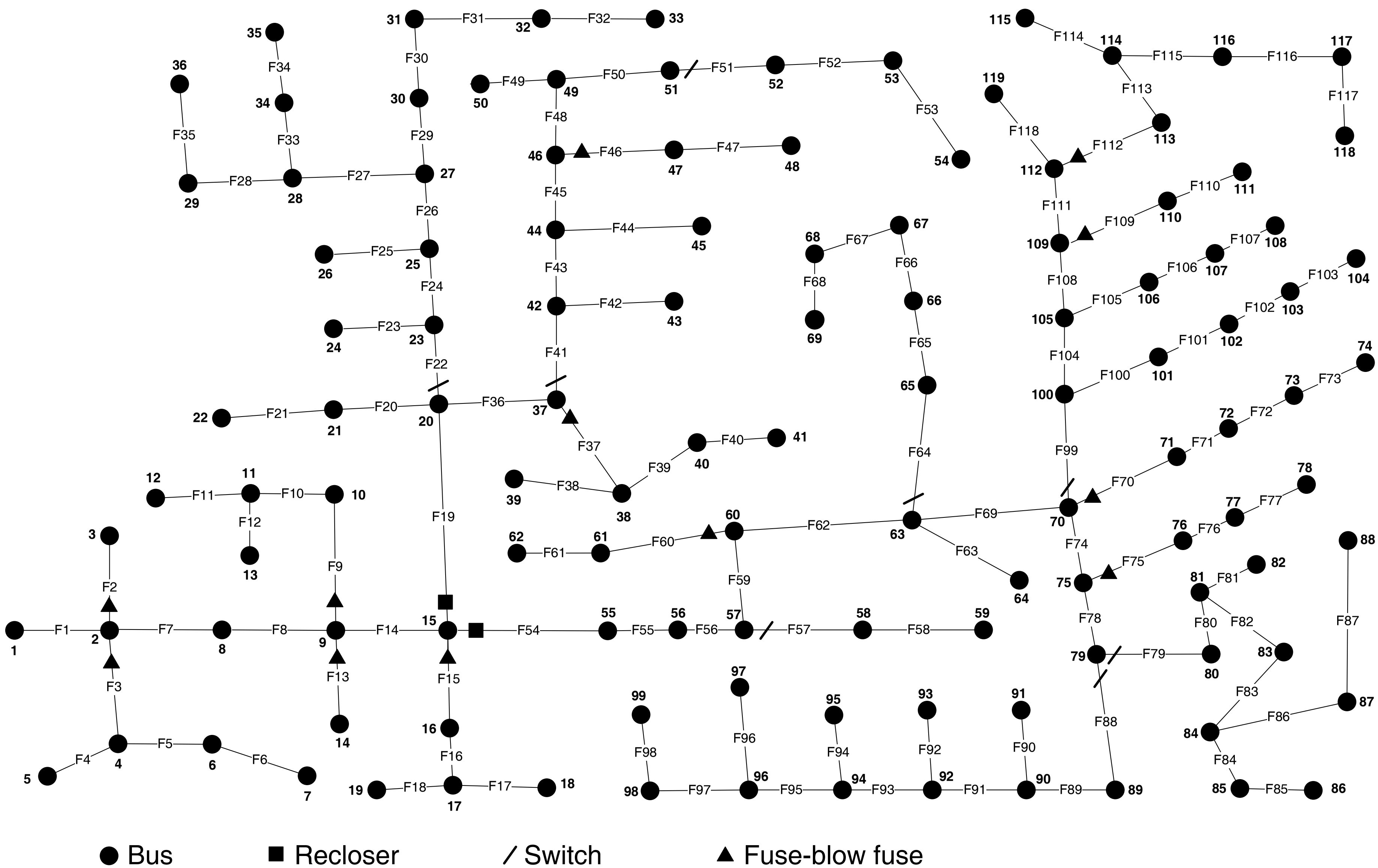

Figure 4.9: 123-bus system protected by Fuse-blow scheme

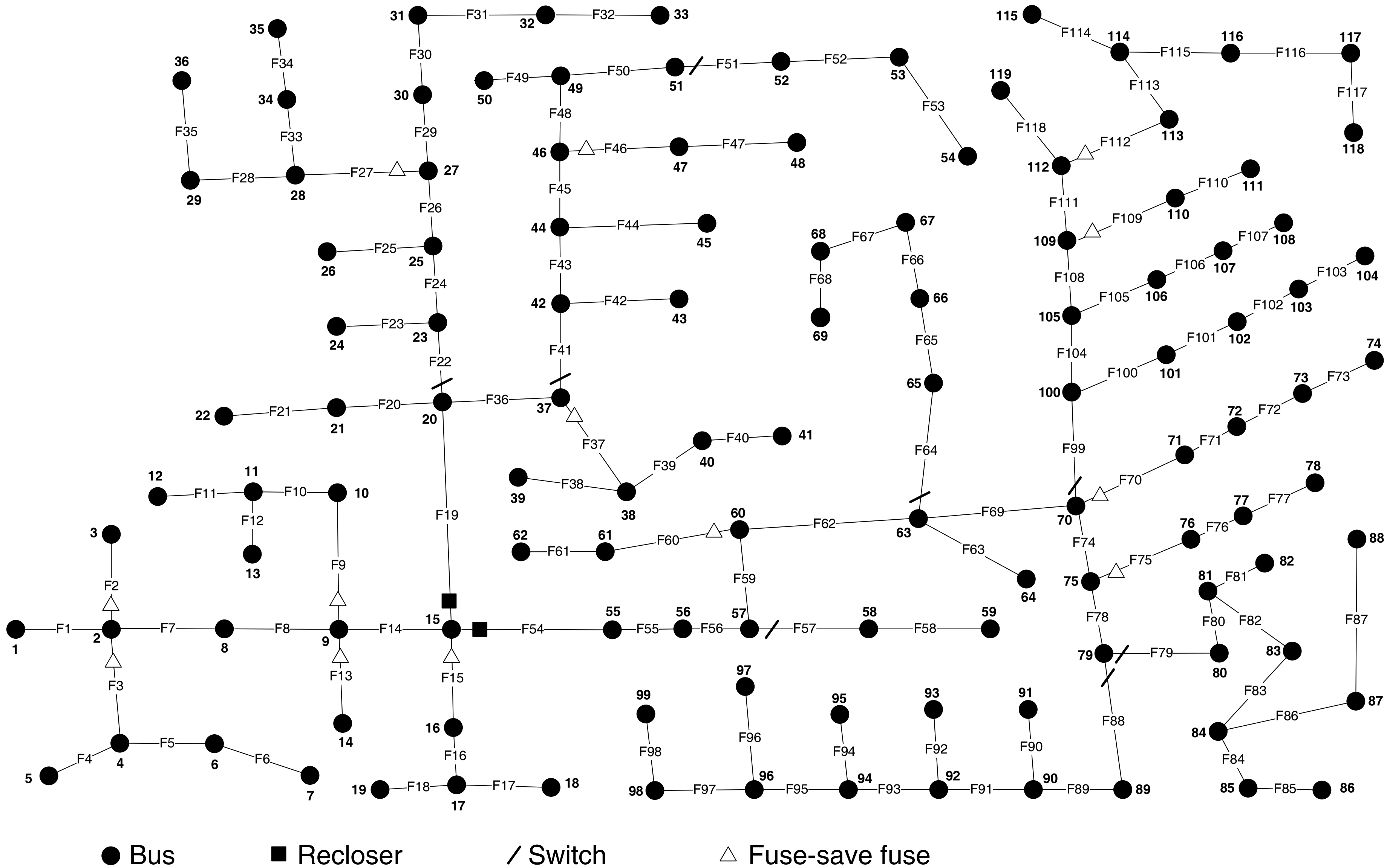

Figure 4.10: 123-bus system protected by Fuse-save scheme

Table 4.13: Results of the three objective functions for 58-bus distribution system

f_{RS}	Function value (Rs.)	367284312.64
	Reclosers	F2 F4 F13 F14 F15 F18 F20 F22 F29 F33 F35 F38 F39 F43 F45 F47 F49 F50 F55
	Switches	F8 F9 F21 F25 F27 F28 F32 F37 F44 F53 F54
f_{FB}	Function value (Rs.)	**371360333.30**
	Reclosers	F2 F13 F14 F20 F22 F33 F35 F38 F43 F49 F55
	Switches	F9 F21 F25 F37 F47
	Fuse-blow fuses	F4 F11 F15 F18 F23 F27 F28 F29 F30 F32 F39 F40 F44 F45 F46 F50 F51 F52 F53 F54 F57
f_{FS}	Function value (Rs.)	369064817.37
	Reclosers	F2 F14 F20 F22 F33 F35 F38 F43 F49 F55
	Switches	F8 F9 F13 F21 F25 F37
	Fuse-save fuses	F4 F11 F15 F18 F23 F27 F28 F29 F30 F32 F39 F40 F44 F45 F46 F50 F51 F52 F53 F54 F57

Table 4.14: Results of the three objective functions for IEEE 123-bus distribution system

f_{RS}	Function value (Rs.)	34570048.40
	Reclosers	F19 F54 F74 F99
	Switches	F2 F3 F9 F13 F15 F22 F37 F41 F51 F57 F64 F70 F79 F88 F108
f_{FB}	Function value (Rs.)	36208509.62
	Reclosers	F19 F54
	Switches	F22 F41 F51 F57 F64 F79 F88 F99
	Fuse-blow fuses	F2 F3 F9 F13 F15 F37 F46 F60 F70 F75 F109 F112
f_{FS}	Function value (Rs.)	**36291793.39**
	Reclosers	F19 F54
	Switches	F22 F41 F51 F57 F64 F79 F88 F99
	Fuse-save fuses	F2 F3 F9 F13 F15 F27 F37 F46 F60 F70 F75 F109 F112

123-bus system (lightly loaded system) the maximum profit is obtained for Fuse-save scheme (corresponding to objective f_{FS}). Protecting a system with only reclosers and switches (RS scheme corresponding to objective f_{RS}) is least profitable for both the systems as the cost of protective devices used is highest for this scheme with no tangible reduction in interruption and ENS costs.

The cost components for 58-bus and IEEE 123-bus radial distribution systems are shown in Tables 4.15 and 4.16, respectively and the extreme (minimum or maximum) values of cost components are shown in boldface font. From these tables, it can be observed that the total interruption cost is least in Fuse-blow scheme (corresponding to the objective function f_{FB}). This is because, in Fuse-blow scheme, on occurrence of permanent faults, fuses blow instantly and hence prevent momentary interruptions (i.e. $\gamma' = 0$) of the customers between nearest upstream recloser and the fuse resulting

Table 4.15: Cost components for 58-bus system

Cost components (Rs.)	f_{RS}	f_{FB}	f_{FS}
1. Total interruption cost	25744291.99	**24903889.09**	28857793.82
2. Total ENS cost	22592897.72	22938030.39	**21740335.80**
3. Total cost (1+2)	48337189.71	**47841919.49**	50598129.62
4. Protective devices cost	15663602.76	12082852.32	**11622158.12**
5. Total cost of protected system (3+4)	64000792.47	**59924771.81**	62220287.74
6. Total cost of unprotected system	431285105.11	431285105.11	431285105.11
7. Profit (6-5)	367284312.64	**371360333.30**	369064817.37

in reduced total interruption cost. Further, total ENS cost is least in Fuse-save scheme (corresponding to the objective function f_{FS}). This is because, in Fuse-save scheme, fuses do not blow due to momentary interruptions and hence prevent sustained interruptions due to momentary faults (i.e. $\lambda^{'}$= 0) resulting in zero contribution to the total ENS cost. However, in Fuse-save scheme, the customers between the fuse-save fuse and nearest upstream recloser, additionally suffer with momentary interruptions due to permanent faults ($\gamma^{'}$) in any of the feeder sections downstream of the fuse-save fuse. This effect is more pronounced in heavily loaded system (here, 58-bus system). Thus, for 58-bus system, Fuse-blow scheme gives minimum total combined interruption and ENS cost whereas for lightly loaded system (here, IEEE 123-bus system), Fuse-save scheme gives minimum total combined interruption and ENS cost. The cost of protective equipments may vary for either scheme (Fuse-blow or Fuse-save) depending upon the optimal numbers of protective devices used for these two schemes. For the heavily loaded 58-bus system, the total cost of protected system (sum total of total interruption cost, total ENS cost and protective devices cost) is minimum for Fuse-blow scheme whereas, for lightly loaded IEEE 123-bus system, the total cost of protected system is minimum for Fuse-save scheme. Thus, for the 58-bus system, use of Fuse-blow scheme gives maximum profit to the utility. Similarly, for lightly loaded IEEE 123-bus system, maximum profit to the utility is obtained by employing Fuse-save scheme.

Table 4.16: Cost components for IEEE 123-bus system

Cost components (Rs.)	f_{RS}	f_{FB}	f_{FS}
1. Total interruption cost	1219310.03	**1160905.44**	1197318.45
2. Total ENS cost	7598620.39	7110411.74	**6832159.60**
3. Total cost (1+2)	8817930.42	8271317.18	**8029478.05**
4. Protective devices cost	6219371.68	**5127523.70**	5286079.06
5. Total cost of protected system (3+4)	15037302.10	13398840.88	**13315557.11**
6. Total cost of unprotected system	49607350.50	49607350.50	49607350.50
7. Profit (6-5)	34570048.40	36208509.62	**36291793.39**

4.5 Conclusion

In distribution system, temporary faults are more frequent than permanent faults. Due to the increased use of electronic and precision devices, damages due to momentary interruptions have increased. To decrease the impact of momentary interruptions, Fuse-blow scheme is used by many utilities. The main drawback of Fuse-blow scheme is that it increases sustained interruptions in the system. Some utilities prefer Fuse-save scheme over Fuse-blow scheme as it decreases sustained interruptions at the cost of increased momentary interruptions.

In this chapter, three different scenarios have been presented for placing the protective devices in a radial distribution system for improving system reliability while reducing the outage and investment costs; (i) simultaneous placement of reclosers and switches (RS scheme) (ii) simultaneous placement of reclosers, switches and fuse-blow fuses (Fuse-blow scheme) and (iii) simultaneous placement of reclosers, switches and fuse-save fuses (Fuse-save scheme).

Three point estimate method (3PEM) has been used for incorporating the uncertainties in temporary failure rates, permanent failure rates, repair rates and loading conditions of the system. All the three objective functions have been evaluated for 58-bus and IEEE 123-bus radial distributions systems using MINLP optimization technique. From the test results, it can be concluded that for heavily loaded system, maximum profit is obtained when Fuse-blow scheme is used while for lightly loaded system, maximum profit is obtained when Fuse-save scheme is adopted.

In the next chapter, a methodology for optimal placement of various combinations of protective devices viz. reclosers, switches, fuse-blow fuses and fuse-save fuses, taking the uncertainties in loading conditions, permanent failure rates, temporary failure rates and repair rates into account, is described.

Chapter 5

Development of a generalized model for placement of various combinations of protective devices in a distribution system considering system data uncertainties

Abstract

In this chapter, a generalized model has been developed to solve the problems incorporating placement of various combinations of protective devices (recloser, switch, fuse-blow fuse and fuse-save fuse) in a distribution network. The uncertainties in temporary failure rates, permanent failure rates, repair rates and load data have been considered in the problem formulation using three point estimate method (3PEM). Various formulated problems developed from the generalized model have been solved for 58-bus and IEEE 123-bus distribution networks using mixed-integer nonlinear programming (MINLP) optimization technique. After analyzing the test results of the various scenarios for the two test systems, it is concluded that maximum profit for the utility is obtained by using the scenario corresponding to the combination of the four protective devices viz. reclosers, switches, fuse-blow fuses and fuse-save fuses.

5.1 Introduction

IN order to enhance the service security of the customers, distribution system reliability improvement is the main aim of the power distribution utilities. Distribution system reliability is improved by the optimal placement of various types of protective devices at optimal locations of the distribution system. Utilities prefer to use a particular combination of available protective devices for optimal placement in the distribution system for increasing their profit by improving system reliability while reducing the outage and investment costs.

In this chapter, a generalized model has been presented for optimal placement of various combination of protective devices (recloser, switch, fuse-blow fuse and fuse-save fuse) in a distribution system. From this generalized model, different objective functions corresponding to various feasible combinations of the protective devices have been developed for optimal placement of these devices. The effect of sustained and momentary interruptions as well as the uncertainties in loads, temporary and permanent failure rates and repair rates have also been considered for deciding the optimal locations of the protective devices. Further, for placing the protective devices in the distribution system, ten different scenarios have been considered.

This chapter is organized as follows: In Section 5.2, the procedure for reliability calculation in a distribution system with different combination of protective devices is discussed. Section 5.3 discusses the formulated problem in detail. Section 5.4 gives the main results of this work followed by the conclusion in Section 5.5.

5.2 Procedure for calculation of distribution system reliability for the generalized case (with reclosers, switches, fuse-blow fuses and fuse-save fuses)

Placement of various types of protective devices at different locations of the distribution system affects the system reliability. Fig. 5.1 shows a 7-bus radial distribution network having 6 feeder sections and 6 load points.

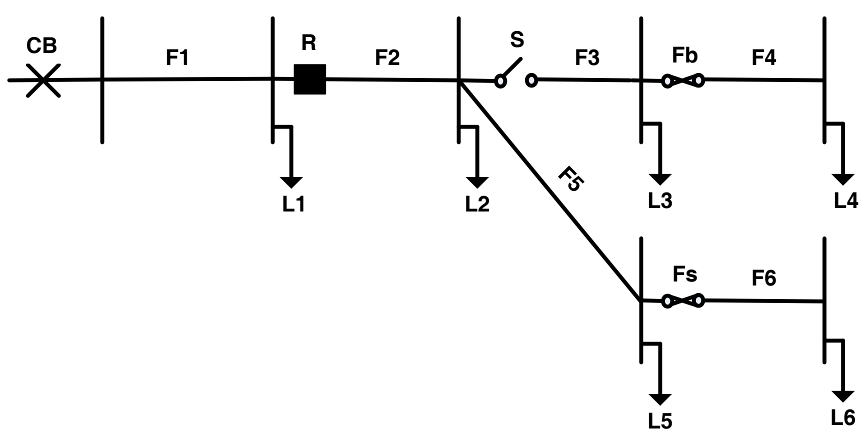

Figure 5.1: A 7-bus distribution system protected by a recloser, a switch, a fuse-blow fuse and a fuse-save fuse

Consider the scenario when the system is protected by a recloser 'R' at feeder section '$F2$', a switch 'S' at feeder section '$F3$', a fuse-blow fuse 'Fb' at feeder section '$F4$', a fuse-save fuse 'Fs' at feeder section '$F6$' and a circuit breaker 'CB' at the source end as shown in Fig. 5.1. For a fault (permanent or temporary) in '$F2$' and its downstream feeder sections, the upstream recloser at '$F2$'

will operate instead of 'CB' to isolate the fault current. Consequently, load '$L1$' (upstream of '$F2$') will not experience any interruption. Hence, permanent failure rate (λ) and temporary failure rate (γ) for '$L1$' are set to zero for all permanent and temporary faults in '$F2$' and its downstream feeder sections, respectively. In general, 'λ' and 'γ' for all the loads upstream of a feeder section having a recloser are set to zero for all the permanent and temporary faults in the feeder section and its downstream feeder sections, respectively. Further, 'λ' and 'γ' for all the loads downstream of '$F2$' (feeder section having a recloser) are set equal to 'λ_f' (the permanent failure rate of faulted feeder section) and 'γ_f' (the temporary failure rate of faulted feeder section), respectively. For permanent faults in '$F3$' (having a switch) and its downstream feeder sections, all the loads upstream of '$F3$' will experience an outage time of switch isolation time (r_{iso}) while all the loads downstream of '$F3$' will experience an outage time equal to 'r_f' (time required to repair the faulted feeder section). For any fault (permanent or temporary) downstream of fuse-blow fuse 'Fb' at '$F4$', first the fuse-blow fuse will trip before the upstream recloser 'R' at '$F2$' can operate to interrupt the fault current. This results in sustained interruption to all the downstream customers even for temporary faults, while the rest of the system is uninterrupted. For any fault (permanent or temporary) downstream of fuse-save fuse 'Fs' at '$F6$', the upstream recloser 'R' at '$F2$' will operate before the fuse-save fuse can trip to interrupt the fault current. This results in momentary interruption to all the customers downstream of the recloser even for permanent faults in the feeder sections downstream of the fuse-save fuse. However, for all the temporary faults downstream of the fuse-save fuse, service to the customers can be restored immediately by re-energizing the line, resulting in decreased sustained interruptions. Thus, presence of fuse-blow fuse in the system contributes in reduction of momentary interruptions and increase in sustained interruptions. On the other hand, presence of fuse-save fuse in the system contributes in increase in momentary interruptions and reduction in sustained interruptions.

Let the binary variables $X_{R,k}$, $X_{S,k}$, $X_{Fb,i}$ and $X_{Fs,i}$ represent recloser, switch, fuse-blow fuse and fuse-save fuse in k^{th} feeder section, respectively. Also, let

$$\begin{aligned} X_{S,k}/X_{R,k} &= 0, \quad \text{if a switch/recloser is placed in } k^{th} \text{ feeder section} \\ &= 1, \quad \text{if a switch/recloser is not placed in } k^{th} \text{ feeder section} \end{aligned} \tag{5.1}$$

$$\begin{aligned} X_{Fb,k}/X_{Fs,k} &= 0, \quad \text{if a fuse-blow fuse/fuse-save fuse is placed in } k^{th} \text{ feeder section} \\ &= 1, \quad \text{if a fuse-blow fuse/fuse-save fuse is not placed in } k^{th} \text{ feeder section} \end{aligned} \tag{5.2}$$

Using the procedures given in Chapter 4, the permanent failure rate of j^{th} load due to the permanent fault in i^{th} feeder section ($\lambda_{i,j}$), the permanent failure rate of j^{th} load due to the temporary fault in i^{th} feeder section ($\lambda'_{i,j}$), the temporary failure rate of j^{th} load due to the temporary fault in i^{th} feeder section ($\gamma_{i,j}$), the temporary failure rate of j^{th} load due to the permanent fault in i^{th} feeder section ($\gamma'_{i,j}$) and the outage time of j^{th} load due to the permanent fault in i^{th} feeder section ($r_{i,j}$) can be written as,

$$\lambda_{i,j} = bibc(i,j)\lambda_i + (1 - bibc(i,j))\lambda_i(\prod_{k\epsilon Fd(i,j)} X_{R,k}X_{Fb,k}X_{Fs,k}) \tag{5.3}$$

$$\lambda'_{i,j} = bibc(i,j)\gamma_i(1-(\prod_{k\epsilon F_{Sec}(1,i)} X_{Fb,k}))+(1-bibc(i,j))\gamma_i(\prod_{k\epsilon Fd(i,j)} X_{R,k}X_{Fb,k})(1-(\prod_{k\epsilon G(i,j))} X_{Fb,k})) \tag{5.4}$$

$$\gamma_{i,j} = bibc(i,j)\gamma_i(\prod_{k\epsilon F_{Sec}(1,i)} X_{Fb,k}) + (1 - bibc(i,j))\gamma_i(\prod_{k\epsilon Fd(i,j)} X_{R,k})(\prod_{k\epsilon F_{Sec}(1,i)} X_{Fb,k}) \tag{5.5}$$

$$\gamma'_{i,j} = (1 - bibc(i,j))\lambda_i(\prod_{k\epsilon Fd(i,j)} X_{R,k}X_{Fb,k})(1 - (\prod_{k\epsilon Fd(i,j)} X_{Fs,k})) \tag{5.6}$$

$$r_{i,j} = bibc(i,j)r_i + (1 - bibc(i,j))\{r_i(\prod_{k\epsilon Fd(i,j)} X_{S,k}) \quad + (r_{iso}(1 - (\prod_{k\epsilon Fd(i,j)} X_{S,k}))\} \\ (\prod_{k\epsilon Fd(i,j)} X_{R,k}X_{Fb,k}X_{Fs,k}) \tag{5.7}$$

where, $bibc(i,j)$ = element corresponding to the i^{th} row and j^{th} column of the $[\mathbf{BIBC}]$ matrix [67],
λ_i = permanent failure rate of i^{th} feeder section,
γ_i = temporary failure rate of i^{th} feeder section,
r_i = outage time of i^{th} feeder section,
and

$$Fd(i,j) = F_{Sec}(1,i) \cap F_{Sec}(j,i) \tag{5.8}$$

$F_{Sec}(1,i)$ is the feeder sections between source node and i^{th} feeder section (including i^{th} feeder section) and $F_{Sec}(j,i)$ is the feeder sections between j^{th} node and i^{th} feeder (including i^{th} feeder section). $Fd(i,j)$ represents feeder sections common to $F_{Sec}(1,i)$ and $F_{Sec}(j,i)$. $G(i,j)$ is the common feeder sections between $F_{Sec}(1,i)$ and $F_{Sec}(j,1)$. $G(i,j)$ is given by,

$$G(i,j) = F_{Sec}(1,i) \cap F_{Sec}(j,1) \tag{5.9}$$

For the network shown in Fig. 5.1, feeder section F_2 has a recloser, feeder section F_3 has a switch, feeder section F_4 has a fuse-blow fuse and feeder section F_6 has a fuse-save fuse. Hence,

$$\begin{aligned} X_{R,1} = X_{R,3} = X_{R,4} = X_{R,5} = X_{R,6} = 1, \quad X_{R,2} = 0 \\ X_{S,1} = X_{S,2} = X_{S,4} = X_{S,5} = X_{S,6} = 1, \quad X_{S,3} = 0 \\ X_{Fb,1} = X_{Fb,2} = X_{Fb,3} = X_{Fb,5} = X_{Fb,6} = 1, \quad X_{Fb,4} = 0 \\ X_{Fs,1} = X_{Fs,2} = X_{Fs,3} = X_{Fs,4} = X_{Fs,5} = 1, \quad X_{Fs,6} = 0 \end{aligned} \tag{5.10}$$

The $[\mathbf{BIBC}]$ matrix for this network is given below,

$$BIBC = \begin{array}{c} \\ F1 \\ F2 \\ F3 \\ F4 \\ F5 \\ F6 \end{array} \begin{array}{c} \begin{array}{cccccc} L1 & L2 & L3 & L4 & L5 & L6 \end{array} \\ \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \end{array} \tag{5.11}$$

Using the elements of $[\mathbf{BIBC}]$ matrix (Eq. (5.11), expressions for $\lambda_{i,j}$ (Eq. (5.3)), $\lambda^{'}_{i,j}$ (Eq. (5.4)) $\gamma_{i,j}$ (Eq. (5.5)), $\gamma^{'}_{i,j}$ (Eq. (5.6)), $r_{i,j}$ (Eq. (5.7)) and the values of $X_{R,i}$, $X_{S,i}$, $X_{Fb,i}$ and $X_{Fs,i}$ (Eq. (5.10)), the calculated values of 'λ', '$\lambda^{'}$' 'γ', '$\gamma^{'}$' and 'r' for the system of Fig. 5.1 are given in Tables 5.1, 5.2 5.3, 5.4 and 5.5, respectively.

Table 5.1: Values of 'λ' for the system of Fig. 5.1

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	λ_1	λ_1	λ_1	λ_1	λ_1	λ_1
$F2$	0	λ_2	λ_2	λ_2	λ_2	λ_2
$F3$	0	λ_3	λ_3	λ_3	λ_3	λ_3
$F4$	0	0	0	λ_4	0	0
$F5$	0	λ_5	λ_5	λ_5	λ_5	λ_5
$F6$	0	0	0	0	0	λ_6

After evaluating '$\lambda_{i,j}$', '$\lambda^{'}_{i,j}$', '$\gamma_{i,j}$', '$\gamma^{'}_{i,j}$' and '$r_{i,j}$', the sustained interruption cost due to permanent fault (IC_{λ}), sustained interruption cost due to temporary fault ($IC_{\lambda^{'}}$), momentary interruption

Table 5.2: Values of '$\lambda^{'}$' for the system of Fig. 5.1

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	0	0	0	0	0	0
$F2$	0	0	0	0	0	0
$F3$	0	0	0	0	0	0
$F4$	0	0	0	γ_4	0	0
$F5$	0	0	0	0	0	0
$F6$	0	0	0	0	0	0

Table 5.3: Values of 'γ' for the system of Fig. 5.1

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	γ_1	γ_1	γ_1	γ_1	γ_1	γ_1
$F2$	0	γ_2	γ_2	γ_2	γ_2	γ_2
$F3$	0	γ_3	γ_3	γ_3	γ_3	γ_3
$F4$	0	0	0	0	0	0
$F5$	0	γ_5	γ_5	γ_5	γ_5	γ_5
$F6$	0	γ_6	γ_6	γ_6	γ_6	γ_6

Table 5.4: Values of '$\gamma^{'}$' for the system of Fig. 5.1

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	0	0	0	0	0	0
$F2$	0	0	0	0	0	0
$F3$	0	0	0	0	0	0
$F4$	0	0	0	0	0	0
$F5$	0	0	0	0	0	0
$F6$	0	λ_6	λ_6	λ_6	λ_6	0

cost due to temporary fault (IC_{γ}), momentary interruption cost due to permanent fault ($IC_{\gamma'}$), ENS

Table 5.5: Values of 'r' for the system of Fig. 5.1

Fault ↓	$L1$	$L2$	$L3$	$L4$	$L5$	$L6$
$F1$	r_1	r_1	r_1	r_1	r_1	r_1
$F2$	0	r_2	r_2	r_2	r_2	r_2
$F3$	0	$r_{iso,3}$	r_3	r_3	$r_{iso,3}$	$r_{iso,3}$
$F4$	0	0	0	r_4	0	0
$F5$	0	r_5	r_5	r_5	r_5	r_5
$F6$	0	0	0	0	0	r_6

due to permanent fault (ENS_{λ_E}) and ENS due to temporary fault ($ENS_{{\lambda_E}'}$) can be evaluated as,

$$IC_\lambda = \sum_{j=1}^{nl}\sum_{i=1}^{nbr} \lambda_{i,j} ICP_{i,j} L_j, \quad IC_{\lambda'} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr} \lambda_{i,j}^{'} ICPT_{i,j} L_j$$
$$IC_\gamma = \sum_{j=1}^{nl}\sum_{i=1}^{nbr} \gamma_{i,j} ICT_{i,j} L_j, \quad IC_{\gamma'} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr} \gamma_{i,j}^{'} ICT_{i,j} L_j$$
$$ENS_{\lambda_E} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr} \lambda_{i,j} r_{i,j} L_j, \quad ENS_{{\lambda_E}'} = \sum_{j=1}^{nl}\sum_{i=1}^{nbr} \lambda_{i,j}^{'} r_i^{'} L_j$$

where,

nl = total number of connected loads,

nbr = total number of feeder sections,

$r_i^{'}$ = fuse repair time of fuse-blow fuse placed at i^{th} feeder section,

L_j = mean value of the load connected at j^{th} node,

$ICP_{i,j}$ = sustained interruption cost of the load connected at j^{th} node due to the permanent fault in i^{th} feeder section for an outage duration of $r_{i,j}$,

$ICPT_{i,j}$ = sustained interruption cost of the load connected at j^{th} load point due to the temporary fault in i^{th} feeder section for an outage duration of $r_i^{'}$ (For all the calculations, $r_i^{'}$ is assumed to be 30 minutes),

$ICT_{i,j}$ = momentary interruption cost at j^{th} load point due to temporary fault in i^{th} feeder section.

Thus, the total energy not supplied (ENS) and the total customer interruption cost (TIC) for this scenario can be calculated as follows:

$$\begin{aligned} ENS &= ENS_{\lambda_E} + ENS_{\lambda_E{}'} \\ &= \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_{i,j}r_{i,j} + \lambda^{'}_{i,j}r^{'}_{i})L_j \quad kWhr/year \end{aligned} \tag{5.12}$$

$$\begin{aligned} TIC &= IC_{\lambda} + IC_{\lambda'} + IC_{\gamma} + IC_{\gamma'} \\ &= \sum_{j=1}^{nl}\sum_{i=1}^{nbr}[\lambda_{i,j}ICP_{i,j} + \lambda^{'}_{i,j}ICPT_{i,j} + (\gamma_{i,j} + \gamma^{'}_{i,j})ICT_{i,j}]L_j \end{aligned} \tag{5.13}$$

5.3 Problem Formulation

In this section, a generalized model has been developed to solve the optimization problems incorporating placement of various combinations of protective devices (recloser, switch, fuse-blow fuse and fuse-save fuse) in a distribution network for increasing the profit of the utility by reliability improvement while reducing the outage and investment costs.

5.3.1 Objective Function

The objective functions corresponding to the different scenarios of protective devices (different combinations of reclosers, switches, fuse-blow fuses and fuse-save fuses) placement in distribution system are aimed at revenue earning maximization of the utility due to reduction in CIC and increase in extra energy supplied (due to decrease in ENS) to the customers while minimizing the associated investment cost such as cost of installation, operation and maintenance of protective devices.

Consider the generalized case when all the four types of protective devices viz. reclosers, switches, fuse-blow fuses and fuse-save fuses are to be placed in the distribution system. As discussed in the previous section, presence of a recloser in a feeder section saves all the upstream loads for all the permanent and temporary faults in the feeder section and its downstream feeder sections. In other words, all the loads upstream of a feeder section having a recloser will not experience any interruption for any fault in the feeder section (having a recloser) and its downstream feeder sections. Similarly, presence of a switch in a feeder section reduces the outage time of all the upstream loads for all the permanent faults in the feeder section and its downstream feeder sections. In other words, for a permanent fault in the feeder section (having a switch) and its downstream feeder sections, all the loads upstream of the feeder section will experience a reduced outage time equal to the 'switch isolation time' of the feeder section. For any fault downstream of a fuse-blow fuse, first the fuse-blow fuse will trip before the recloser upstream of the fuse-blow fuse can operate to interrupt the fault current. This results in sustained interruption to all the customers downstream of the fuse-blow fuse even for a temporary fault in any of the feeder sections downstream of the fuse-blow fuse, while the rest part of the system is uninterrupted. On the other hand, for any fault downstream of a fuse-save fuse, the recloser upstream of the fuse-save fuse will operate before the fuse-save fuse can trip to interrupt the fault current. This results in the momentary interruption to all the customers between the fuse-save fuse and the upstream recloser even for permanent faults in any of the feeder sections downstream of the fuse-save fuse. However, for all the temporary faults downstream of the fuse-save fuse, service to all the customers can be restored immediately by re-energizing the line, resulting in decreased sustained interruptions. Thus, placement of protective devices in distribution system using this scheme results in trade-off between sustained interruptions and momentary interruptions.

Using the procedure discussed in the previous section, we can calculate the savings (due to reduction in ENS and TIC) of the system protected by reclosers, switches, fuse-blow fuses and fuse-save fuses. When no reclosers, switches, fuse-blow fuses and fuse-save fuses are placed in the distribution system, the expression $\prod_{k \epsilon Fd(i,j)} X_{R,k} X_{Fb,k} X_{Fs,k}$ of Eq. (5.3) becomes to unity. As a result, $\lambda_{i,j}$ becomes equal to λ_i. Similarly, in Eq. (5.4), $\prod_{k \epsilon F_{Sec}(1,i)} X_{Fb,k}$, $\prod_{k \epsilon Fd(i,j)} X_{R,k} X_{Fb,k}$ and $\prod_{k \epsilon G(i,j)} X_{Fb,k}$ all become unity. Hence, $\lambda^{'}_{i,j} = 0$. Further, in Eq. (5.5), $\prod_{k \epsilon Fd(i,j)} X_{R,k}$ also reduces to unity, hence $\gamma_{i,j} = \gamma_i$, and in Eq. (5.6), as all product terms are unity, $\gamma^{'}_{i,j}$ becomes zero. Finally, in Eq. (5.7), $\prod_{k \epsilon Fd(i,j)} X_{S,k}$ also becomes unity, hence $r_{i,j} = r_i$. Therefore, from Eqs. (5.12) and (5.13), the ENS and TIC of an unprotected system (represented by ENS_U and TIC_U, respectively) can be written as,

$$ENS_U = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} (\lambda_i r_i) L_j \quad kWhr/year \tag{5.14}$$

$$TIC_U = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} (\lambda_i ICP^{'}_{i,j} + \gamma_i ICT_{i,j}) L_j \tag{5.15}$$

When reclosers, switches, fuse-blow fuses and fuse-save fuses are placed in the distribution system, then from Eqs. (5.12) and (5.13), the ENS and TIC of this protected system (represented by ENS_P and TIC_P, respectively) can be written as,

$$ENS_P = \sum_{j=1}^{nl} \sum_{i=1}^{nbr} (\lambda_{i,j} r_{i,j} + \lambda^{'}_{i,j} r^{'}_i) L_j \tag{5.16}$$

$$TIC_P = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}[\lambda_{i,j}ICP_{i,j} + \lambda^{'}_{i,j}ICPT_{i,j} + (\gamma_{i,j} + \gamma^{'}_{i,j})ICT_{i,j}]L_j \tag{5.17}$$

Therefore, reduction in ENS (i.e. ENS_U-ENS_P) due to placement of reclosers and switches in the distribution system can be written as,

$$ENS_U - ENS_P = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_i r_i - (\lambda_{i,j}r_{i,j} + \lambda^{'}_{i,j}r^{'}_i))L_j \tag{5.18}$$

Similarly, reduction in TIC (i.e. TIC_U-TIC_P) due to placement of reclosers and switches in the distribution system can be written as,

$$TIC_U - TIC_P = \sum_{j=1}^{nl}\sum_{i=1}^{nbr}((\lambda_i ICP^{'}_{i,j} + \gamma_i ICT_{i,j}) - (\lambda_{i,j}ICP_{i,j} + \lambda^{'}_{i,j}ICPT_{i,j} + (\gamma_{i,j} + \gamma^{'}_{i,j})ICT_{i,j}))L_j \tag{5.19}$$

Therefore, using above equations, the objective function (f_{gen}) for the generalized case is defind as follows:

$$\begin{aligned} Maximize \quad f_{gen} = &\{\sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_i r_i - (\lambda_{i,j}r_{i,j} + \lambda^{'}_{i,j}r^{'}_i))L_j\}C_E F_1 + \{\sum_{j=1}^{nl}\sum_{i=1}^{nbr}((\lambda_i ICP^{'}_{i,j} \\ &+ \gamma_i ICT_{i,j}) - (\lambda_{i,j}ICP_{i,j} + \lambda^{'}_{i,j}ICPT_{i,j} + (\gamma_{i,j} + \gamma^{'}_{i,j})ICT_{i,j}))L_j\}F_2 \\ &- \{(\sum_{i=1}^{nbr}(1 - X_{R,i}))C_R + (\sum_{i=1}^{nbr}(1 - X_{S,i}))C_S + (\sum_{i=1}^{nbr}(1 - X_{Fb,i}))C_{Fb} \\ &+ (\sum_{i=1}^{nbr}(1 - X_{Fs,i}))C_{Fs}\}(1 + \frac{C_m}{100}F_3) \end{aligned} \tag{5.20}$$

where,

N_s = life span of the protective devices (in years),

L_C = rate of annual load growth (in percent),

i_r = annual interest rate (in percent),

r_E = annual incremental rate of energy cost (in percent),

C_E = per unit energy cost,

$ICP^{'}_{i,j}$ = sustained interruption cost of the load j^{th} bus due to outage duration of 'r_i' for the permanent fault in i^{th} feeder section,

r_m = annual incremental rate of maintenance cost (in percent),

i_c = annual incremental rate of interruption cost (in percent),

C_m = maintenance cost of switching devices (in percent),

C_R = cost of a recloser,

C_S = cost of a switch,

C_{Fb} = cost of a fuse-blow fuse,

C_{Fs} = cost of a fuse-save fuse.

F_1, F_2, and F_3 are given by Eqs. (3.11)-(3.13), respectively. '$\lambda_{i,j}$', '$\lambda'_{i,j}$', '$\gamma_{i,j}$', '$\gamma'_{i,j}$' and '$r_{i,j}$' used in Eq. (5.20) are calculated using Eqs. (5.3)-(5.7), respectively. The first term in Eq. (5.20) accounts for the net present worth (NPW) of the earned revenue due to increased energy supplied to the customers corresponding to the useful life span of the protective devices (N_s years). It is to be noted that optimal placement of switching devices such as reclosers, switches, fuses etc. in distribution system results in reduction of 'ENS'. Thus, the protected system supplying additional energy to the customers increases the revenue collection of the distribution system. The second term in Eq. (5.20) accounts for the 'NPW' of the earned revenue due to reduced customer interruption cost. The damages caused due to supply interruptions to the customers are compensated by the distribution companies. The values of the customer interruption costs for different types of customers of the two test systems considered in this chapter are same as given in chapter 3. The third term in Eq. (5.20) accounts for the 'NPW' of the cost of protective devices and their lifetime maintenance cost.

The various possible scenarios corresponding to the different combinations of reclosers and/or switches in conjunction with other protective devices (fuse-blow fuses and/or fuse-save fuses) are listed in Table 5.6. From Eqs.(5.1) and (5.2), it can be observed that the presence of at least one recloser or a switch or a fuse-blow fuse or a fuse-save fuse in the distribution system, respectively makes the expressions $(\prod_{k \epsilon nbr} X_{R,k})$, $(\prod_{k \epsilon nbr} X_{S,k})$, $(\prod_{k \epsilon nbr} X_{Fb,k})$ and $(\prod_{k \epsilon nbr} X_{Fs,k})$ as zero. Similarly, absence of a recloser or a switch or a fuse-blow fuse or a fuse-save fuse in the distribution system, respectively makes the expressions $(\prod_{k \epsilon nbr} X_{R,k})$, $(\prod_{k \epsilon nbr} X_{S,k})$, $(\prod_{k \epsilon nbr} X_{Fb,k})$ and $(\prod_{k \epsilon nbr} X_{Fs,k})$ as unity.

The objective function f_{gen} (Eq. (5.20)) is the generalised equation for all the ten different scenarios of the protective devices placement depicted in Table 5.6. This generalised objective function enables one to simulate any scenario of protective device placement. For example, if one needs to simulate the scenario of placement of reclosers and switches only (objective function f_1 from the generalised equation, then one can modify '$\lambda_{i,j}$', '$\lambda'_{i,j}$', '$\gamma_{i,j}$', '$\gamma'_{i,j}$' and '$r_{i,j}$' of Eq. (5.20) by substituting ($\prod_{k\epsilon nbr} X_{Fb,k}$) = 1 and ($\prod_{k\epsilon nbr} X_{Fs,k}$) = 1 in Eqs. (5.3)-(5.7) (as the scenario corresponding to objective function f_1 does not has either fuse-blow fuses or fuse-save fuses). Thus, '$\lambda_{i,j}$', '$\lambda'_{i,j}$', '$\gamma_{i,j}$', '$\gamma'_{i,j}$' and '$r_{i,j}$' are modified as follows:

$$\lambda^{f_1}_{i,j} = bibc(i,j)\lambda_i + (1 - bibc(i,j))\lambda_i(\prod_{k\epsilon Fd(i,j)} X_{R,k}) \tag{5.21}$$

$$\lambda'^{f_1}_{i,j} = 0 \tag{5.22}$$

$$\gamma^{f_1}_{i,j} = bibc(i,j)\gamma_i + (1 - bibc(i,j))\gamma_i(\prod_{k\epsilon Fd(i,j)} X_{R,k}) \tag{5.23}$$

$$\gamma'^{f_1}_{i,j} = 0 \tag{5.24}$$

$$\begin{aligned} r^{f_1}_{i,j} = \quad & bibc(i,j)r_i + (1 - bibc(i,j))\{r_i(\prod_{k\epsilon Fd(i,j)} X_{S,k}) \\ + \quad & r_{iso}(1 - (\prod_{k\epsilon Fd(i,j)} X_{S,k}))\}(\prod_{k\epsilon Fd(i,j)} X_{R,k}) \end{aligned} \tag{5.25}$$

Further, it can be noted that for the scenario of placement of only reclosers and switches in a distribution system (objective function f_1), there will not be any fuse-blow fuse or fuse-save fuse in the system. Hence the sum of all the fuse-blow fuses and fuse-save fuses in the system will be zero, i.e.

$$\sum_{i=1}^{nbr}(1 - X_{Fb,i}) = 0 \quad , \sum_{i=1}^{nbr}(1 - X_{Fs,i}) = 0 \tag{5.26}$$

Now substituting all these modified values '$\lambda^{f_1}_{i,j}$', '$\lambda'^{f_1}_{i,j}$', '$\gamma^{f_1}_{i,j}$', '$\gamma'^{f_1}_{i,j}$' and '$r^{f_1}_{i,j}$' (from Eqs. (5.21)-(5.26)) into the generalised model (Eq. (5.20)), the objective function f_1 is given by,

$$\begin{aligned} Maximize \quad f_1 = \{&\sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_i r_i - \lambda^{f_1}_{i,j} r^{f_1}_{i,j})L_j\}C_E F_1 + \{\sum_{j=1}^{nl}\sum_{i=1}^{nbr}((\lambda_i ICP'_{i,j} + \gamma_i ICT_{i,j}) \\ &- (\lambda^{f_1}_{i,j} ICP_{i,j} + \gamma^{f_1}_{i,j} ICT_{i,j}))L_j\}F_2 - \{(\sum_{i=1}^{nbr}(1 - X_{R,i}))C_R \\ &+ (\sum_{i=1}^{nbr}(1 - X_{S,i}))C_S\}(1 + \frac{C_m}{100}F_3) \end{aligned} \tag{5.27}$$

The same procedure can be adopted to get the objective function (corresponding to any of the scenarios listed in Table 5.6) from the Eq. (5.20) (the generalised objective function f_{gen}).

Table 5.6: Different scenarios of placement of protective devices

Scenarios	Objective function	$\prod_{k \epsilon nbr} X_{R,k}$	$\prod_{k \epsilon nbr} X_{S,k}$	$\prod_{k \epsilon nbr} X_{Fb,k}$	$\prod_{k \epsilon nbr} X_{Fs,k}$
Reclosers and Switches (RS Scheme)	f_1	0	0	1	1
Reclosers, Switches and Fuse-blow fuses (RSFB Scheme)	f_2	0	0	0	1
Reclosers, Switches and Fuse-save fuses (RSFS Scheme)	f_3	0	0	1	0
Reclosers, Switches, Fuse-blow fuses and Fuse-save fuses (RSFBFS Scheme)	f_4	0	0	0	0
Reclosers and Fuse-blow fuses (RFB Scheme)	f_5	0	1	0	1
Reclosers and Fuse-save fuses (RFS Scheme)	f_6	0	1	1	0
Switches and Fuse-blow fuses (SFB Scheme)	f_7	1	0	0	1
Switches and Fuse-save fuses (SFS Scheme)	f_8	1	0	1	0
Reclosers, Fuse-blow fuses and Fuse-save fuses (RFBFS Scheme)	f_9	0	1	0	0
Switches, Fuse-blow fuses and Fuse-save fuses (SFBFS Scheme)	f_{10}	1	0	0	0

5.3.2 Constraints

The models of placement of various combinations of protective devices in distribution system described in previous section consists of the following constraints.

1. The number of switching devices (such as reclosers, switches, fuse-blow fuses or fuse-save fuses) to be placed in the distribution system should be within the specified numbers given by the utility. From Eq. (5.1), it can be observed that if a recloser is placed in the i^{th} feeder section of the distribution system, than $X_{R,i}$ = 0, otherwise $X_{R,i}$ = 1. In other words, if a recloser is placed in the i^{th} feeder section of the distribution system, than (1-$X_{R,i}$) = 1, otherwise (1-$X_{R,i}$) = 0. The total number of reclosers to be placed among nbr branches of the distribution system should be less than or equal to the number of available reclosers (N_{AvR}). This constraint is modelled by the following inequality constraint.

$$\sum_{i=1}^{nbr}(1 - X_{R,i}) \leq N_{AvR} \tag{5.28}$$

Similarly, if a switch is placed in the i^{th} feeder section of the distribution system, than (1-$X_{S,i}$) = 1, otherwise (1-$X_{S,i}$) = 0. The total number of switches to be placed among nbr branches of the distribution system should be less than or equal to the number of available switches (N_{AvS}). This constraint is modelled by the following inequality constraint.

$$\sum_{i=1}^{nbr}(1 - X_{S,i}) \leq N_{AvS} \tag{5.29}$$

The other constraints corresponding to the maximum number of fuse-blow fuses and fuse-save fuses that can be placed in the distribution system are given by the following inequalities.

$$\sum_{i=1}^{nbr}(1 - X_{Fb,i}) \leq N_{AvFb} \tag{5.30}$$

$$\sum_{i=1}^{nbr}(1 - X_{Fs,i}) \leq N_{AvFs} \tag{5.31}$$

where,

N_{AvFb} = Number of available fuse-blow fuses,

N_{AvFs} = Number of available fuse-save fuses.

2. Reclosers, switches, fuse-blow fuses and fuse-save fuses should not be installed simultaneously in the same feeder section. In other words, two or more than two protective devices can not be simultaneously placed on the same feeder section. This constraint is modelled by the following inequality constraint.

$$X_{R,i} + X_{S,i} + X_{Fb,i} + X_{Fs,i} \geq 3 \quad i = 1, 2, ..., nbr \tag{5.32}$$

   For example, if a recloser is present in the i^{th} feeder section, then $X_{R,i}$= 0. For this case, each of $X_{S,i}$, $X_{Fb,i}$ and $X_{Fs,i}$ must be unity.

3. Reclosers and switches may not be installed downstream of a fuse-blow fuse or fuse-save fuse [35]. This constraint is modelled in only those scenarios of protective devices placement which include either fuse-blow fuses or fuse-save fuses or both.

4. A fuse-save fuse may not be installed downstream of a fuse-blow fuse [35]. This constraint is modelled in only those scenarios of protective devices placement which include both fuse-blow fuses and fuse-save fuses.

5.4 Case studies

The optimal placement of protective devices corresponding to all the ten scenarios listed in Table 5.6 has been carried out for the two test systems (58-bus and IEEE 123-bus) by solving the optimization problems described in the previous section using MINLP technique. The MINLP technique used for evaluating the objective functions (f_1, f_2, ...f_{10}), utilizes the sequential quadratic programming (SQP) through the MATLAB function 'fmincon' of the MATLAB optimization toolbox. In this chapter, the various assumptions adopted and load data, failure data for the two test systems and the system cost data are same as given in [67]. Further, the temporary failure rates are assumed to be three times of the permanent failure rate of the corresponding feeder section in all the calculations. Cost of a fuse and its annual maintenance cost (including replacement cost) are assumed to be Rs. 30,000 and 40% (of the fuse cost), respectively. Uncertainties in loading conditions, temporary failure rates, permanent failure rates and repair rates of the system have been considered using the procedures given in Chapter 3. To calculate the expected value of utility profit under an uncertain environment, 3PEM method has been used.

The results for optimized placement of protective devices obtained for the ten objective functions (f_1, f_2, ...f_{10}) for 58-bus system are given in Table 5.8. The details of the locations of the protective

Table 5.7: Individual effect of different protective devices on various components of interruption and ENS costs

Protective devices	IC_λ	$IC_{\lambda'}$	IC_γ	$IC_{\gamma'}$	ENS_λ	$ENS_{\lambda'}$
Recloser	Decreases	No effect	Decreases	No effect	Decreases	No effect
Switch	Decreases	No effect	No effect	No effect	Decreases	No effect
Fuse-blow fuse	Decreases	Increases	Decreases	No effect	Decreases	Increases
Fuse-save fuse	Decreases	No effect	No effect	Increases	Decreases	No effect

devices obtained by all the ten schemes are also given in Table 5.8. Further, the optimal locations of the protective devices for this system corresponding to some representative schemes are shown in Figs. 5.2-5.5, respectively for ready reference.

Table 5.9 shows the results for optimized placement of protective devices for the ten objective functions (f_1, f_2, ...f_{10}) for IEEE 123-bus system. The details of the locations of the protective devices obtained by all the ten schemes are also given in Table 5.9. The optimal locations of protective devices for this system corresponding to some representative schemes are shown in Figs. 5.6-5.9, respectively for ready reference.

From Tables 5.8 and 5.9, it can be observed that, the objective function value (profit) is maximum for RSFBFS scheme for both the test systems (58-bus and IEEE 123-bus systems).

Table 5.7 shows the individual effect of different protective devices in a distribution system on various components of interruption and ENS costs. As explained in Section 5.2, presence of a recloser in a feeder section results in reduction of sustained interruptions (λ) and momentary interruptions (γ) of all the upstream loads, thereby decreasing sustained interruption cost due to permanent fault (IC_λ), momentary interruption cost due to temporary fault (IC_γ) and ENS cost due to permanent fault (ENS_λ). However, it does not have any effect on sustained interruption cost due to temporary fault ($IC_{\lambda'}$), momentary interruption cost due to permanent fault ($IC_{\gamma'}$) and ENS cost due to temporary fault ($ENS_{\lambda'}$). This is because, it prevents sustained interruptions due to temporary faults and momentary interruptions due to permanent faults. Similarly, the presence of a switch in a feeder section results in reduction of outage time (r) of the upstream loads, which reduces ENS_λ. This reduction in r also results in decrease in IC_λ due to a reduction in interruption costs given in Eqs. (2.13)-(2.15). It however, has no effect on λ, λ', γ and γ' of upstream feeder sections and

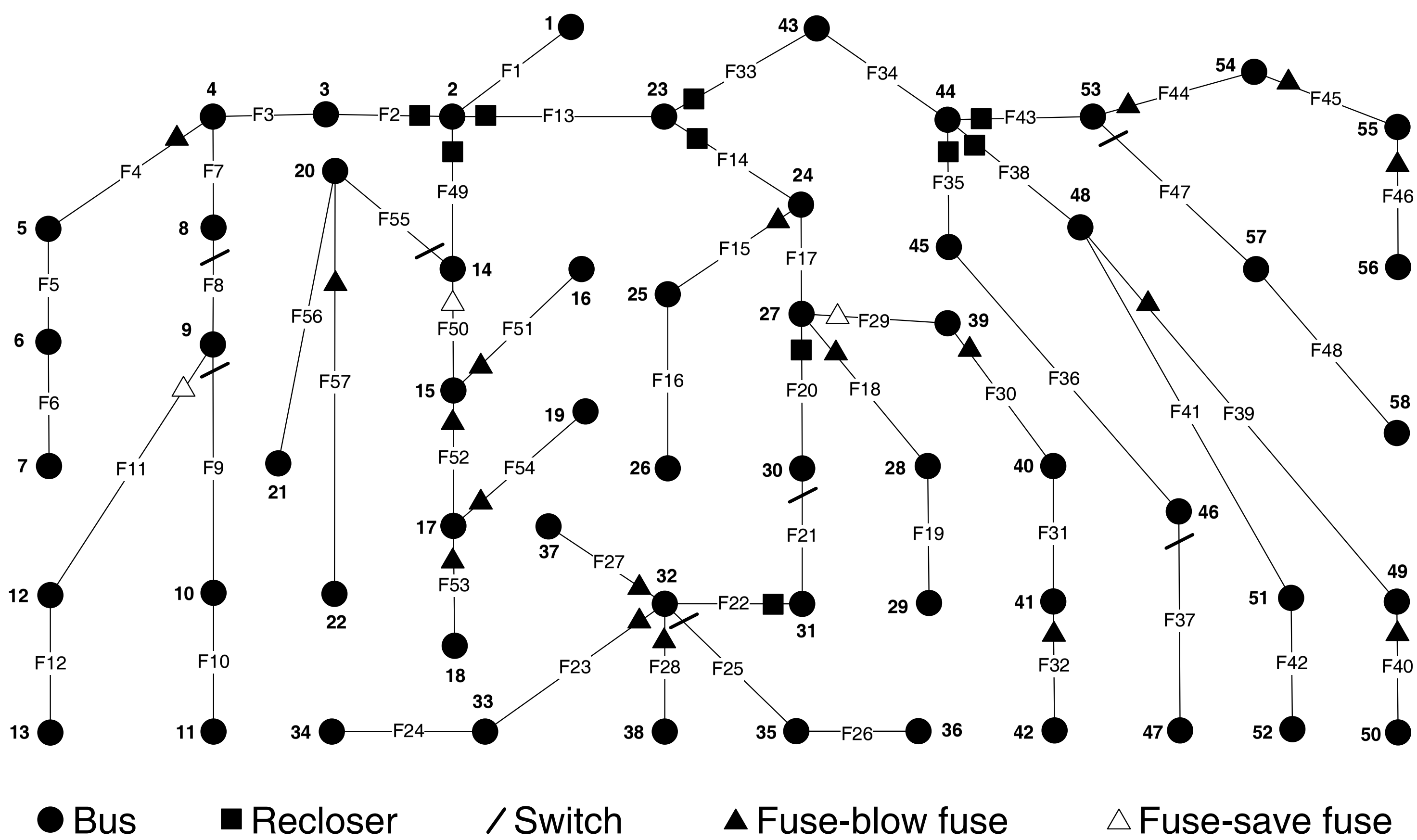

Figure 5.2: 58-bus system protected by RSFBFS scheme

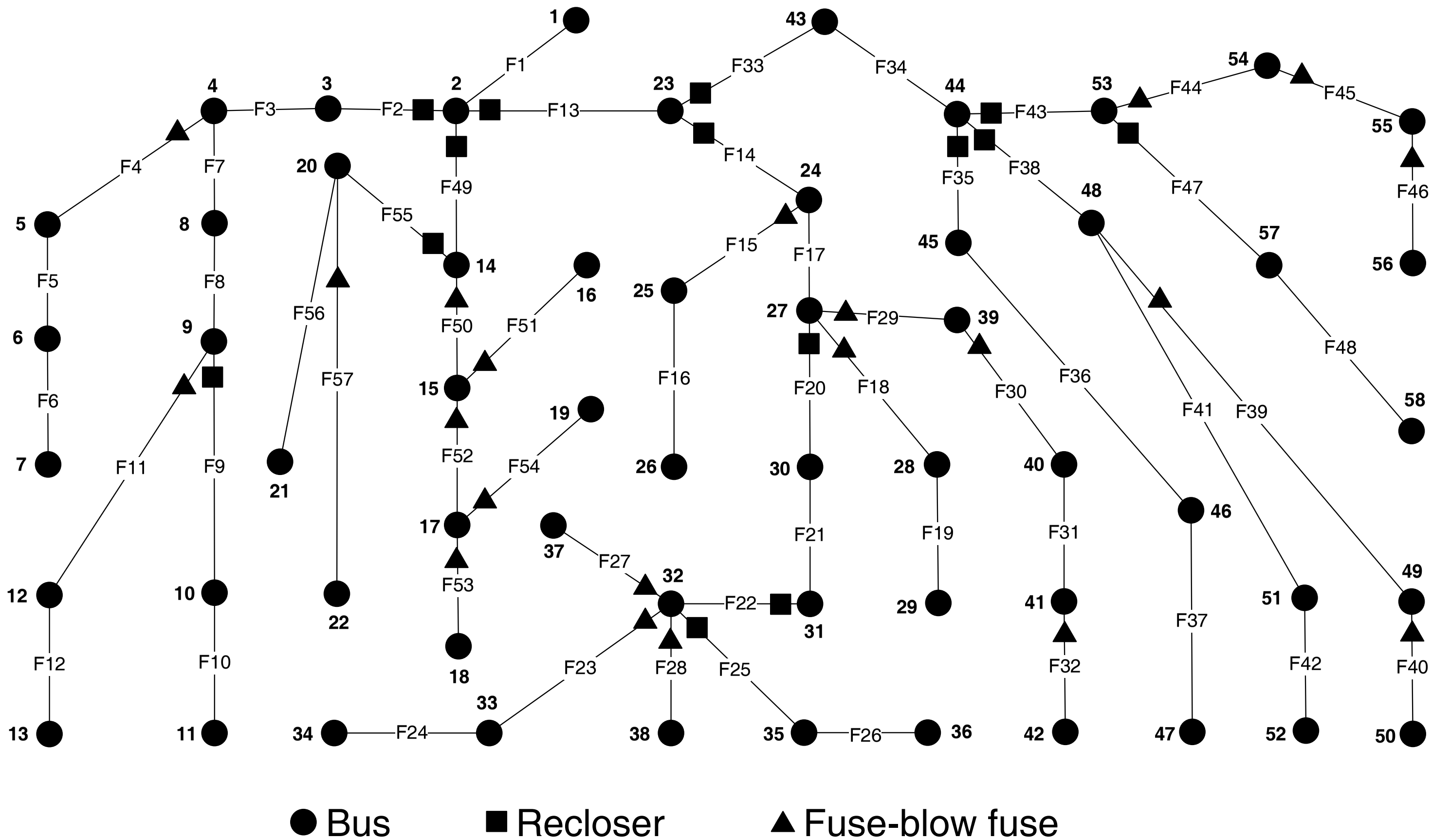

Figure 5.3: 58-bus system protected by RFB scheme

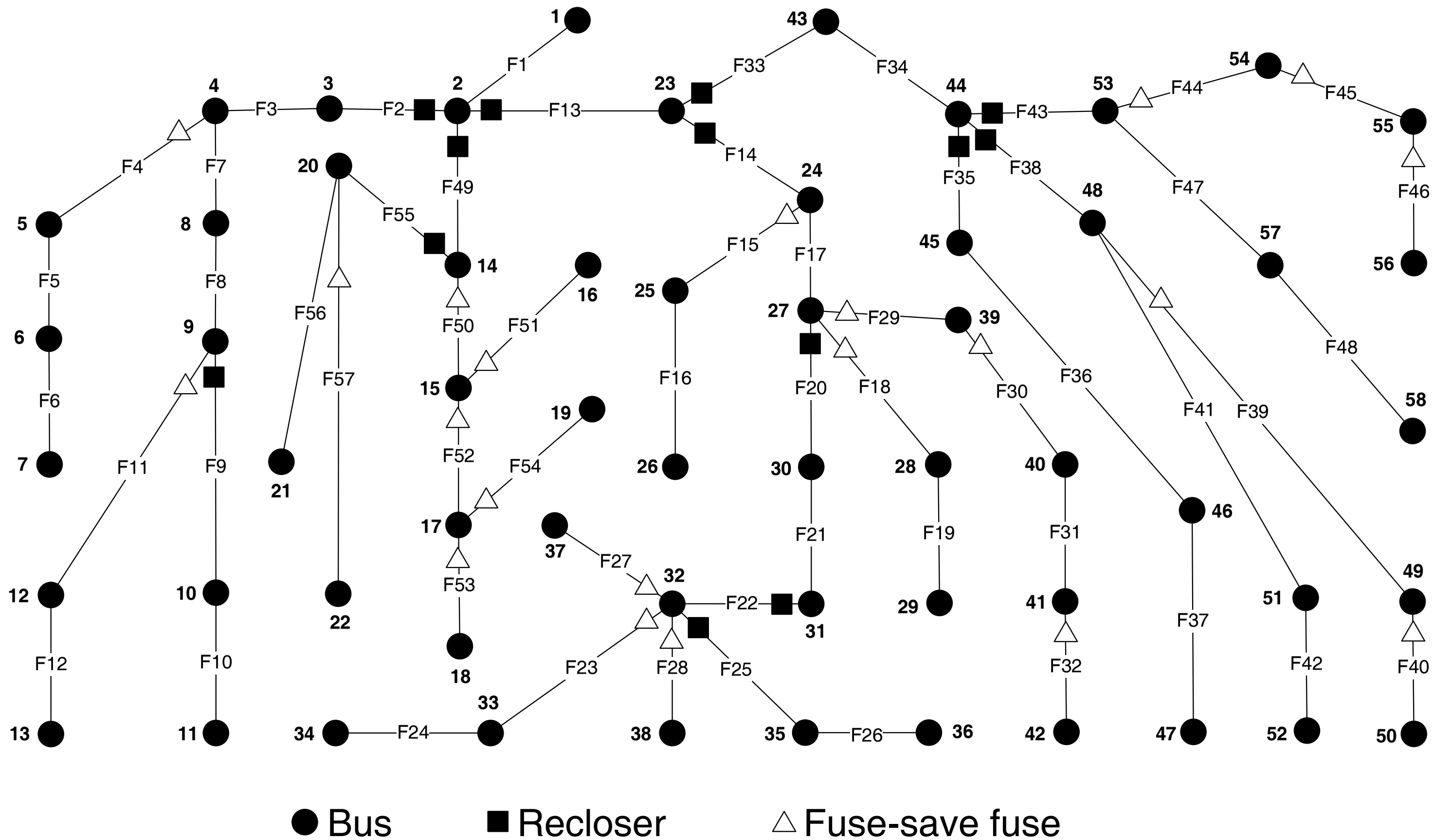

Figure 5.4: 58-bus system protected by RFS scheme

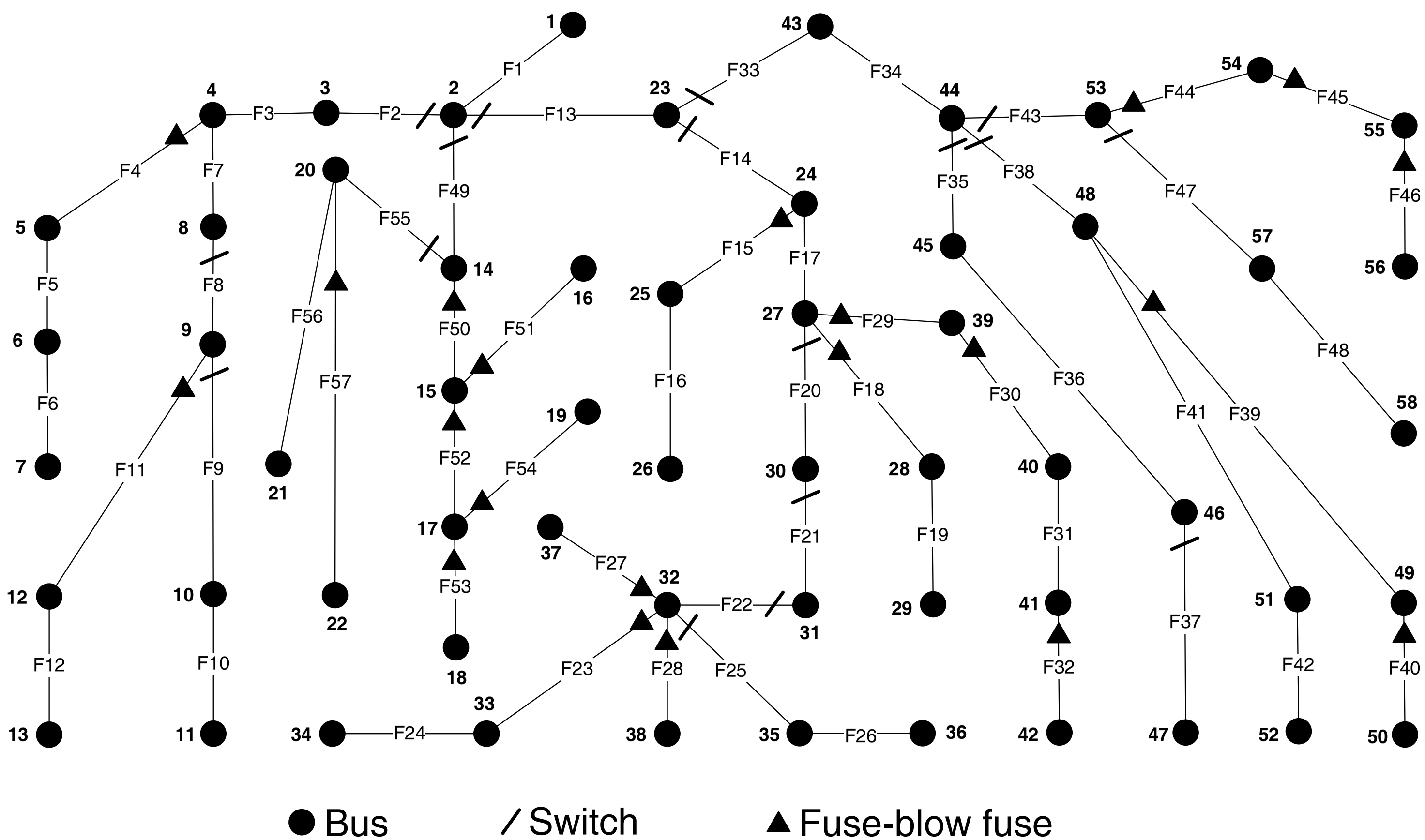

Figure 5.5: 58-bus system protected by SFB scheme

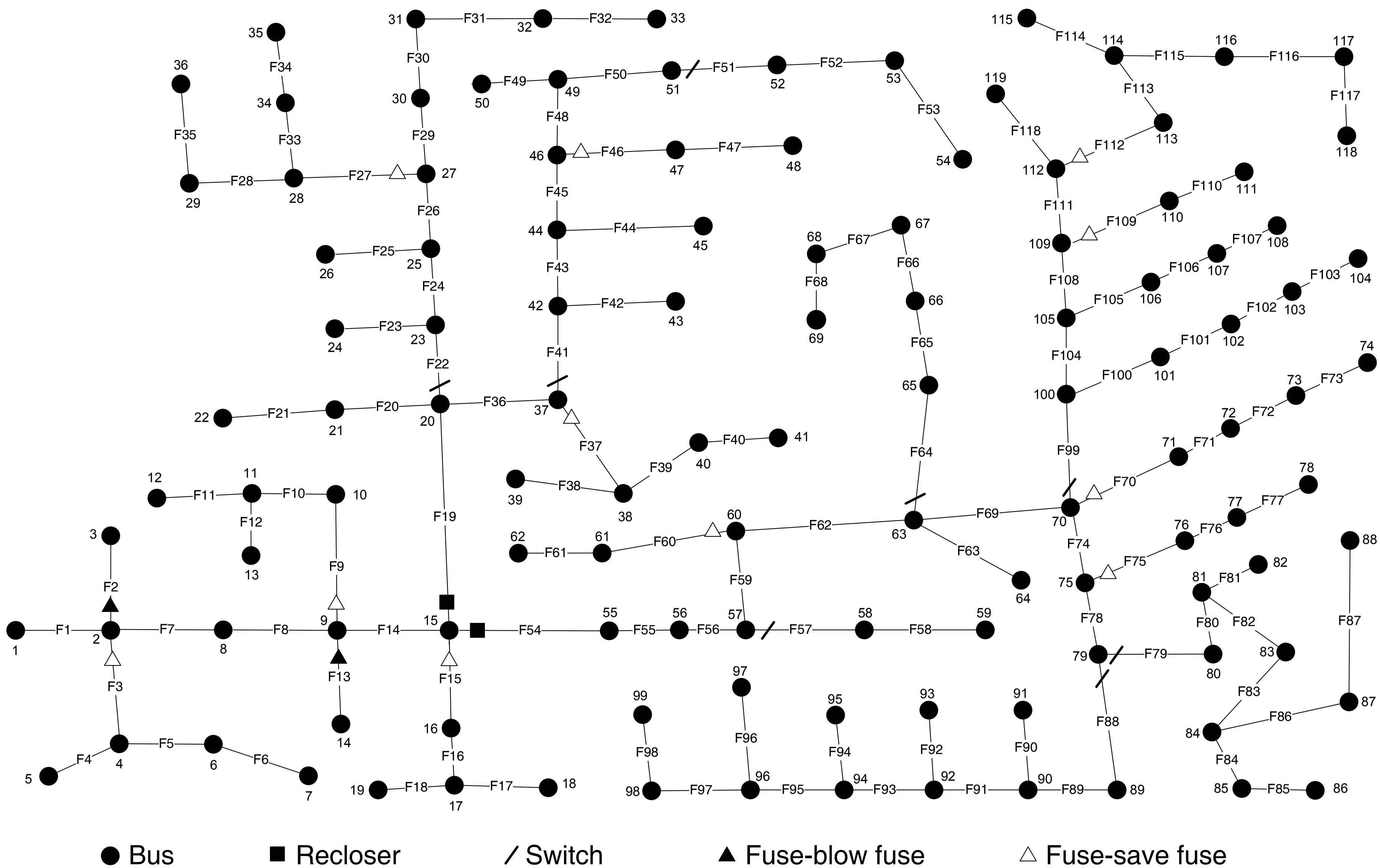

Figure 5.6: IEEE 123-bus system protected by RSFBFS scheme

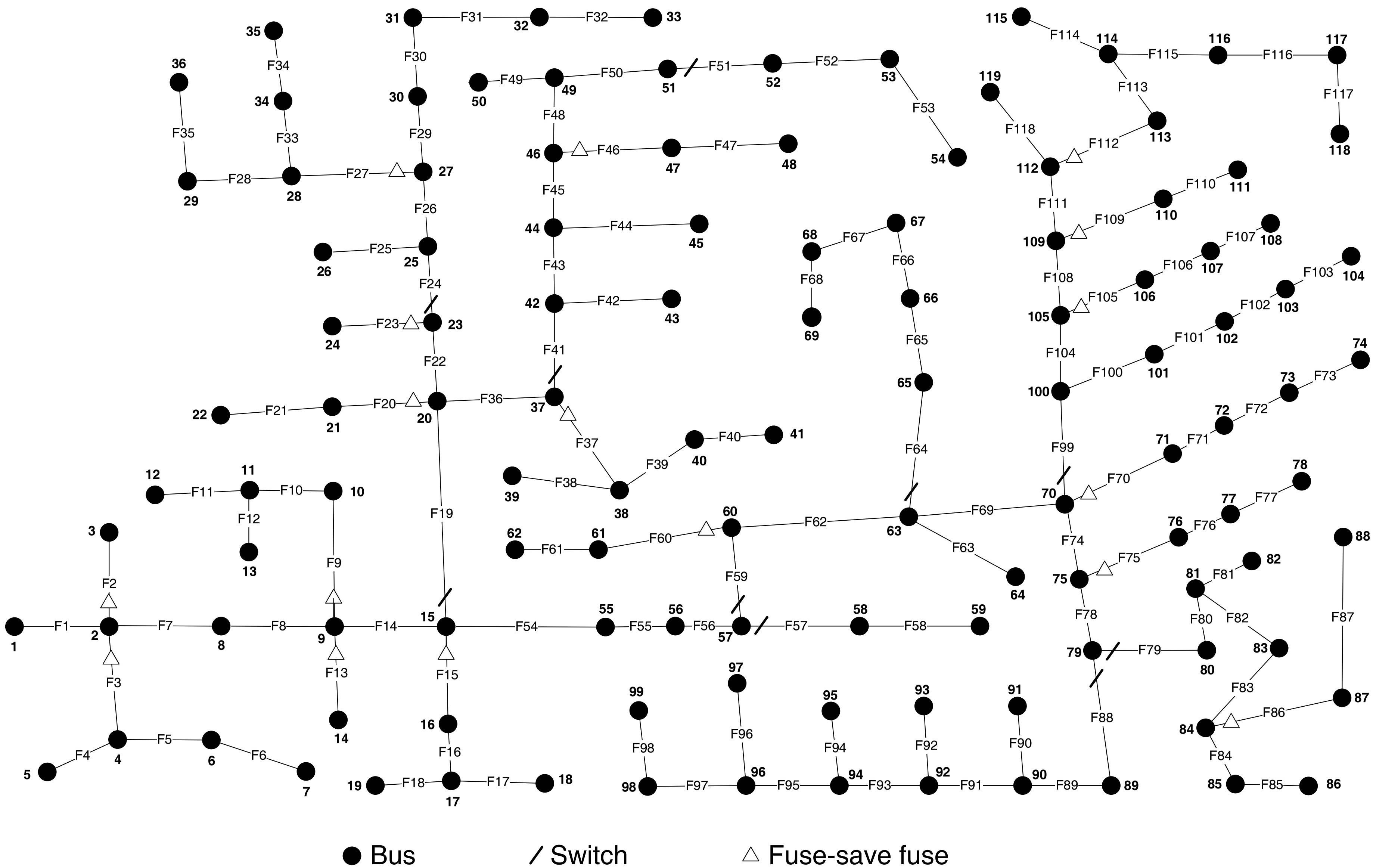

Figure 5.7: IEEE 123-bus system protected by SFS scheme

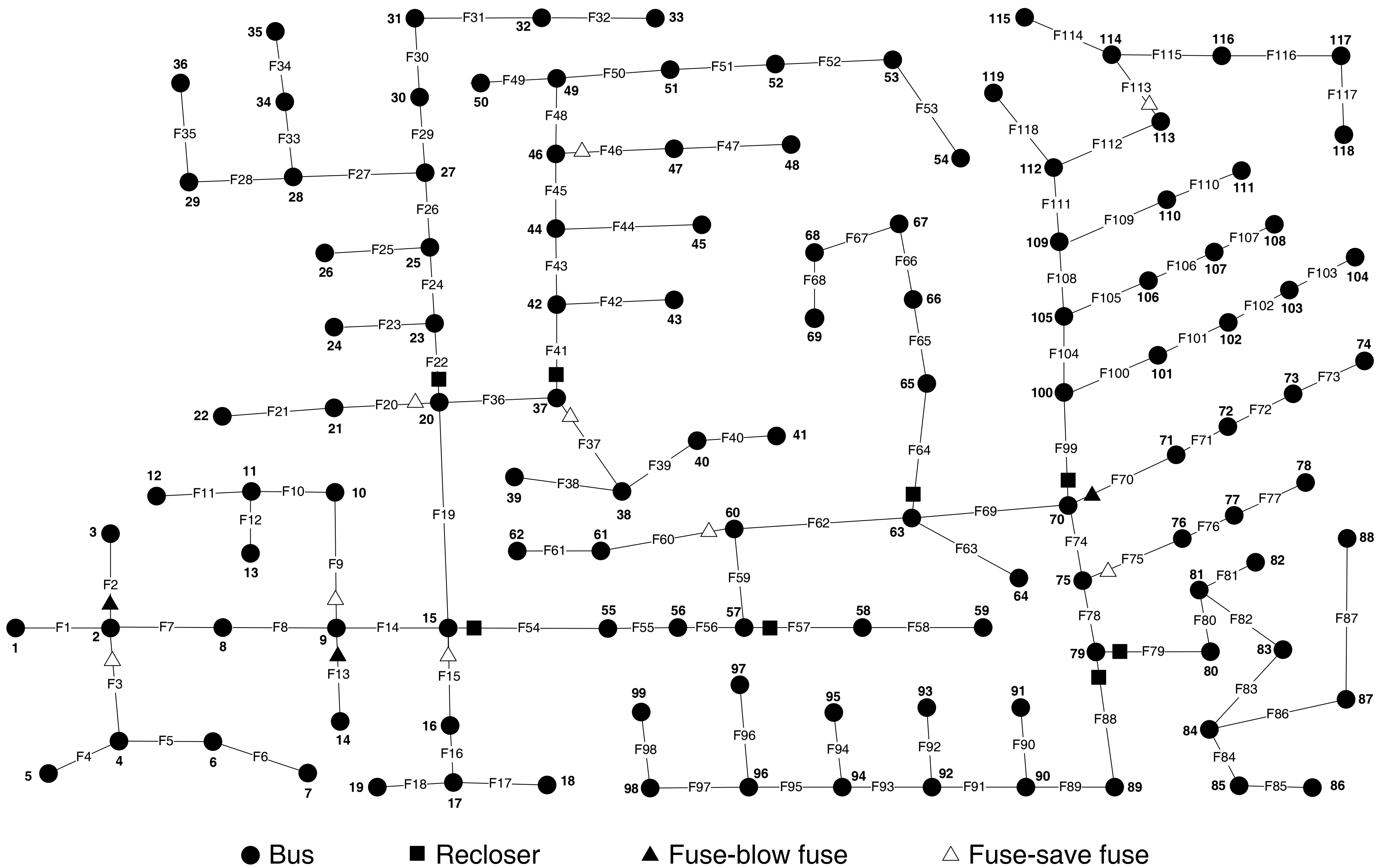

Figure 5.8: IEEE 123-bus system protected by RFBFS scheme

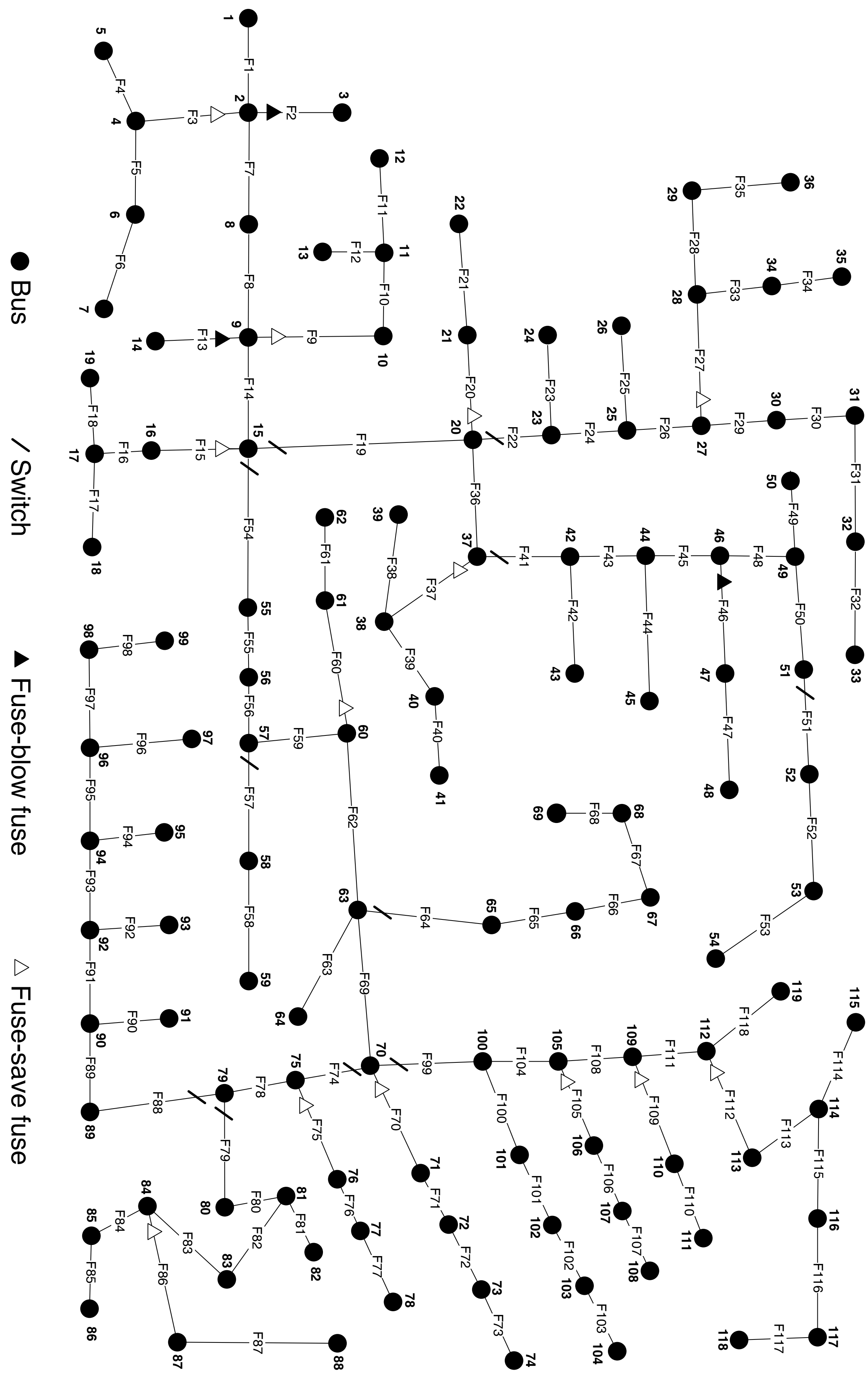

Figure 5.9: IEEE 123-bus system protected by SFBFS scheme

hence has no impact on $IC_{\lambda'}$, IC_{γ}, $IC_{\gamma'}$ and $ENS_{\lambda'}$. When a fuse-blow fuse is present in a feeder section, it decreases λ and γ of upstream loads, but increases λ' of downstream loads due to its operation even under temporary faults. Hence, it decreases IC_{λ}, IC_{γ} and ENS_{λ} but at the same time it increases $IC_{\lambda'}$ and $ENS_{\lambda'}$. However, it does not have any effect on $IC_{\gamma'}$. When a permanent fault occurs downstream of a fuse-save fuse, then the nearest upstream recloser tries to clear the fault till the fuse-save fuse blows. This results in the loads between the upstream recloser and fuse-save fuse experiencing momentary interruptions γ'. Thus, it decreases IC_{λ} and ENS_{λ} but at the same time it increases $IC_{\gamma'}$. However, it does not have any effect on $IC_{\lambda'}$, IC_{γ} and $ENS_{\lambda'}$. The overall impact of a combination of protective devices will be an amalgamation of the effects of individual devices and will depend on their locations, numbers and placement with respect to each other as can be observed in Tables 5.10 and 5.11.

The various cost components of all the objective functions (f_1, f_2, ...f_{10}) for 58-bus and IEEE 123-bus radial distribution systems are shown in Tables 5.10 and 5.11, respectively. The values (Rs.) of IC_{λ}, $IC_{\lambda'}$, IC_{γ}, $IC_{\gamma'}$, ENS_{λ} and $ENS_{\lambda'}$ for 58-bus unprotected system are 185177487.86, 0, 45886274.61, 0, 200221342.64 and 0, respectively whereas for IEEE 123-bus unprotected system, these values are 7550933.40, 0, 195468.88, 0, 41860948.21 and 0, respectively. From the tables, it can be observed that the cost components $IC_{\lambda'}$ and $ENS_{\lambda'}$ are zero for objective functions f_1, f_3, f_6 and f_8 as these scenarios do not include fuse-blow fuses. Presence of fuse-blow fuses in objective functions f_2, f_4, f_5, f_7, f_9 and f_{10} results in increase in $IC_{\lambda'}$ and $ENS_{\lambda'}$ but decrease in IC_{λ}, IC_{γ} and ENS_{λ}. Similarly, $IC_{\gamma'}$ for objective functions f_1, f_2, f_5 and f_7 is zero as these functions do not include fuse-save fuses. Presence of fuse-save fuses in objective functions f_3, f_4, f_6, f_8, f_9 and f_{10} results in increase in $IC_{\gamma'}$ but decrease in IC_{λ} and ENS_{λ}. Presence of switches in objective functions f_1, f_2, f_3, f_4, f_7, f_8 and f_{10} results in reduction of IC_{λ} and ENS_{λ}. Presence of reclosers in objective functions f_1, f_2, f_3, f_4, f_5, f_6 and f_9 results in reduction of IC_{λ}, IC_{γ} and ENS_{λ}.

From these tables, the combined effects of the various combinations of the protective devices on total reduction of interruption and ENS costs can be observed. It can be seen that for both the test systems, the combined effect of all the four protective devices (RSFBFS scheme) results in the maximum profit to the utility.

Table 5.8: Results of the ten objective functions for 58-bus distribution system

f_1	Function value (Rs.)	367284312.64
	Reclosers	F2 F4 F13 F14 F15 F18 F20 F22 F29 F33 F35 F38 F39 F43 F45 F47 F49 F50 F55
	Switches	F8 F9 F21 F25 F27 F28 F32 F37 F44 F53 F54
f_2	Function value (Rs.)	371360333.30
	Reclosers	F2 F13 F14 F20 F22 F33 F35 F38 F43 F49 F55
	Switches	F9 F21 F25 F37 F47
	Fuse-blow fuses	F4 F11 F15 F18 F23 F27 F28 F29 F30 F32 F39 F40 F44 F45 F46 F50 F51 F52 F53 F54 F57
f_3	Function value (Rs.)	369064817.37
	Reclosers	F2 F14 F20 F22 F33 F35 F38 F43 F49 F55
	Switches	F8 F9 F13 F21 F25 F37
	Fuse-save fuses	F4 F11 F15 F18 F23 F27 F28 F29 F30 F32 F39 F40 F44 F45 F46 F50 F51 F52 F53 F54 F57
f_4	Function value (Rs.)	**371629767.62**
	Reclosers	F2 F13 F14 F20 F22 F33 F35 F38 F43 F49
	Switches	F8 F9 F21 F25 F37 F47 F55
	Fuse-blow fuses	F4 F15 F18 F23 F27 F28 F30 F32 F39 F40 F44 F45 F46 F51 F52 F53 F54 F57
	Fuse-save fuses	F11 F29 F50
f_5	Function value (Rs.)	370669780.20
	Reclosers	F2 F9 F13 F14 F20 F22 F25 F33 F35 F38 F43 F47 F49 F55
	Fuse-blow fuses	F4 F11 F15 F18 F23 F27 F28 F29 F30 F32 F39 F40 F44 F45 F46 F50 F51 F52 F53 F54 F57
f_6	Function value (Rs.)	368299918.44
	Reclosers	F2 F9 F13 F14 F20 F22 F25 F33 F35 F38 F43 F49 F55
	Fuse-save fuses	F4 F11 F15 F18 F23 F27 F28 F29 F30 F32 F39 F40 F44 F45 F46 F50 F51 F52 F53 F54 F57
f_7	Function value (Rs.)	333681252.35
	Switches	F2 F8 F9 F13 F14 F20 F21 F22 F25 F33 F35 F37 F38 F43 F47 F49 F55
	Fuse-blow fuses	F4 F11 F15 F18 F23 F27 F28 F29 F30 F32 F39 F40 F44 F45 F46 F50 F51 F52 F53 F54 F57
f_8	Function value (Rs.)	306245700.40
	Switches	F2 F8 F9 F13 F14 F20 F21 F22 F25 F33 F35 F37 F38 F43 F47 F49 F55
	Fuse-save fuses	F4 F11 F15 F18 F23 F27 F28 F29 F30 F32 F39 F40 F44 F45 F46 F50 F51 F53 F54 F57
f_9	Function value (Rs.)	370853984.82
	Reclosers	F2 F9 F13 F14 F20 F22 F25 F33 F35 F38 F43 F47 F49 F55
	Fuse-blow fuses	F4 F15 F18 F28 F30 F32 F39 F40 F44 F45 F46 F51 F52 F53 F54 F57
	Fuse-save fuses	F11 F23 F27 F29 F50
f_{10}	Function value (Rs.)	333681252.35
	Switches	F2 F8 F9 F13 F14 F20 F21 F22 F25 F33 F35 F37 F38 F43 F47 F49 F55
	Fuse-blow fuses	F4 F11 F15 F18 F23 F27 F28 F29 F30 F32 F39 F40 F44 F45 F46 F50 F51 F52 F53 F54 F57
	Fuse-save fuses	Nil

Table 5.9: Results of the ten objective functions for IEEE 123-bus distribution system

f_1	Function value (Rs.)	34570048.40
	Reclosers	F19 F54 F74 F99
	Switches	F2 F3 F9 F13 F15 F22 F37 F41 F51 F57 F64 F70 F79 F88 F108
f_2	Function value (Rs.)	36208509.62
	Reclosers	F19 F54
	Switches	F22 F41 F51 F57 F64 F79 F88 F99
	Fuse-blow fuses	F2 F3 F9 F13 F15 F37 F46 F60 F70 F75 F109 F112
f_3	Function value (Rs.)	36291793.39
	Reclosers	F19 F54
	Switches	F22 F41 F51 F57 F64 F79 F88 F99
	Fuse-save fuses	F2 F3 F9 F13 F15 F27 F37 F46 F60 F70 F75 F109 F112
f_4	Function value (Rs.)	**36294825.08**
	Reclosers	F19 F54
	Switches	F22 F41 F51 F57 F64 F79 F88 F99
	Fuse-blow fuses	F2 F13
	Fuse-save fuses	F3 F9 F15 F27 F37 F46 F60 F70 F75 F109 F112
f_5	Function value (Rs.)	34515010.89
	Reclosers	F22 F41 F54 F57 F64 F79 F88 F99
	Fuse-blow fuses	F2 F3 F9 F13 F15 F20 F37 F46 F60 F70 F75 F113
f_6	Function value (Rs.)	34590054.77
	Reclosers	F22 F41 F54 F57 F64 F79 F88 F99
	Fuse-save fuses	F2 F3 F9 F13 F15 F20 F37 F46 F60 F70 F75 F113
f_7	Function value (Rs.)	35293106.25
	Switches	F19 F22 F41 F51 F54 F57 F64 F74 F79 F88 F99
	Fuse-blow fuses	F2 F3 F9 F13 F15 F20 F27 F37 F46 F60 F70 F75 F86 F105 F109 F112
f_8	Function value (Rs.)	35131692.03
	Switches	F19 F24 F41 F51 F57 F59 F64 F79 F88 F99
	Fuse-save fuses	F2 F3 F9 F13 F15 F20 F23 F27 F37 F46 F60 F70 F75 F86 F105 F109 F112
f_9	Function value (Rs.)	34576703.89
	Reclosers	F22 F41 F54 F57 F64 F79 F88 F99
	Fuse-blow fuses	F2 F13 F70
	Fuse-save fuses	F3 F9 F15 F20 F37 F46 F60 F75 F113
f_{10}	Function value (Rs.)	35374981.81
	Switches	F19 F22 F41 F51 F54 F57 F64 F74 F79 F88 F99
	Fuse-blow fuses	F2 F13 F46
	Fuse-save fuses	F3 F9 F15 F20 F27 F37 F60 F70 F75 F86 F105 F109 F112

Table 5.10: Cost components of objective functions for different scenarios of placement of protective devices (58-bus system)

Cost components (Rs.)	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}
1. Sustained interruption cost due to permanent fault (IC_λ)	20247271.21	19260108.75	19434326.02	19267073.39	19277077.39	19561675.03	32064429.69	32121074.35	19277077.39	32064429.69
2. Sustained interruption cost due to temporary fault ($IC_{\lambda'}$)	0	1220439.24	0	851210.19	1220439.24	0	1220439.24	0	704349.80	1220439.24
3. Momentary interruption cost due to temporary fault (IC_γ)	5497020.78	4423341.10	8329800.64	5079749.11	4145188.15	8025095.11	23323410.30	45886274.61	4760497.41	23323410.30
4. Momentary interruption cost due to permanent fault ($IC_{\gamma'}$)	0	0	1093667.16	106053.93	0	1093667.16	0	7358385.14	138631.79	0
5. Energy not supplied cost due to permanent fault (ENS_λ)	22592897.72	21699064.41	21740335.80	21563544.78	21729413.45	21991549.96	32511044.33	32586662.74	21729413.45	32511044.33
6. Energy not supplied cost due to temporary fault ($ENS_{\lambda'}$)	0	1238965.98	0	935200.87	1238965.98	0	1238965.98	0	816909.70	1238965.98
7. Decrease in IC_λ ($IC_{\lambda_{Unprotected}}$ - $IC_{\lambda_{Protected}}$)	164930216.65	165917379.11	165743161.84	165910414.47	165900410.48	165615812.83	153113058.17	153056413.51	165900410.48	153113058.17
8. Increase in $IC_{\lambda'}$ ($IC_{\lambda'_{Protected}}$ - $IC_{\lambda'_{Unprotected}}$)	0	1220439.24	0	851210.19	1220439.24	0	1220439.24	0	704349.8	1220439.24
9. Total reduction in SIC (7-8)	164930216.65	164696939.87	165743161.84	165059204.28	164679971.24	165615812.83	151892618.93	153056413.51	165196060.64	151892618.93
10. Decrease in IC_γ ($IC_{\gamma_{Unprotected}}$ - $IC_{\gamma_{Protected}}$)	40389253.83	41462933.51	37556473.97	40806525.50	41741086.46	37861179.50	22562864.31	0	41125777.19	22562864.31
11. Increase in $IC_{\gamma'}$ ($IC_{\gamma'_{Protected}}$ - $IC_{\gamma'_{Unprotected}}$)	0	0	1093667.16	106053.93	0	1093667.16	0	7358385.14	138631.79	0
12. Total reduction in MIC (10-11)	40389253.83	41462933.51	36462806.81	40700471.57	41741086.46	36767512.34	22562864.31	-7358385.14	40987145.41	22562864.31
13. Decrease in ENS_λ ($ENS_{\lambda_{Unprotected}}$ - $ENS_{\lambda_{Protected}}$)	177628444.92	178522278.23	178481006.84	178657797.86	178491929.19	178229792.68	167710298.31	167634679.90	178491929.19	167710298.31
14. Increase in $ENS_{\lambda'}$ ($ENS_{\lambda'_{Protected}}$ - $ENS_{\lambda'_{Unprotected}}$)	0	1238965.98	0	935200.87	1238965.98	0	1238965.98	0	816909.70	1238965.98
15. Total reduction in ENS cost (13-14)	177628444.92	177283312.25	178481006.84	177722596.99	177252963.22	178229792.68	166471332.33	167634679.90	177675019.49	166471332.33
16. Total savings (9+12+15)	382947915.40	383443185.62	380686975.49	383482272.84	383674020.92	380613117.86	340926815.58	313332708.27	383858225.53	340926815.58
17. Recloser installation cost	8550000.00	4950000.00	4500000.00	4500000.00	6300000.00	5850000.00	0	0	6300000.00	0
18. Switch installation cost	1650000.00	750000.00	900000.00	1050000.00	0	0	2550000.00	2550000.00	0	2550000.00
19. Fuse-blow fuse installation cost	0	630000.00	0	540000.00	630000.00	0	630000.00	0	480000.00	630000.00
20. Fuse-save fuse installation cost	0	0	630000.00	90000.00	0	630000.00	0	600000.00	150000.00	0
21. Maintenance cost of protective devices	5463602.76	5752852.32	5592158.12	5672505.22	6074240.71	5833199.42	4065563.23	3937007.87	6074240.71	4065563.23
22. Total protective devices cost (17+18+19+20+21)	15663602.76	12082852.32	11622158.12	11852505.22	13004240.71	12313199.42	7245563.23	7087007.87	13004240.71	7245563.23
23. Profit (16-22)	367284312.64	371360333.30	369064817.37	**371629767.62**	370669780.21	368299918.44	333681252.35	306245700.40	370853984.82	333681252.35

Table 5.11: Cost components of objective functions for different scenarios of placement of protective devices (IEEE 123-bus system)

Cost components (Rs.)	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}
1. Sustained interruption cost due to permanent fault (IC_λ)	1136738.61	1087666.66	1072546.27	1072546.27	1132254.21	1132254.21	1060846.47	1111504.73	1132254.21	1060846.47
2. Sustained interruption cost due to temporary fault($IC_{\lambda'}$)	0	6852.33	0	82.56	5991.36	0	8409.14	0	1073.26	294.85
3. Momentary interruption cost due to temporary fault (IC_γ)	82571.42	66386.45	110001.70	106362.65	28680.93	71478.42	114370.09	195468.88	63742.92	187151.06
4. Momentary interruption cost due to permanent fault ($IC_{\gamma'}$)	0	0	14770.48	13564.19	0	13777.68	0	26861.88	11286.62	23599.20
5. Energy not supplied cost due to permanent fault (ENS_λ)	7598620.39	6966731.26	6832159.60	6832159.60	6368790.72	6368790.72	7883590.81	8142910.87	6368790.72	7883590.81
6. Energy not supplied cost due to temporary fault ($ENS_{\lambda'}$)	0	143680.49	0	1731.09	125627.69	0	176323.90	0	22504.17	6182.46
7. Decrease in IC_λ ($IC_{\lambda_{Unprotected}}$ - $IC_{\lambda_{Protected}}$)	6414194.79	6463266.74	6478387.13	6478387.13	6418679.19	6418679.19	6490086.93	6439428.67	6418679.19	6490086.93
8. Increase in $IC_{\lambda'}$ ($IC_{\lambda'_{Protected}}$ - $IC_{\lambda'_{Unprotected}}$)	0	6852.33	0	82.56	5991.36	0	8409.14	0	1073.26	294.85
9. Total reduction in SIC (7-8)	6414194.79	6456414.41	6478387.13	6478304.57	6412687.82	6418679.19	6481677.80	6439428.67	6417605.93	6489792.08
10. Decrease in IC_γ ($IC_{\gamma_{Unprotected}}$ - $IC_{\gamma_{Protected}}$)	112897.46	129082.43	85467.19	89106.24	166787.95	123990.46	81098.79	0	131725.96	8317.82
11. Increase in $IC_{\gamma'}$ ($IC_{\gamma'_{Protected}}$ - $IC_{\gamma'_{Unprotected}}$)	0	0	14770.48	13564.19	0	13777.68	0	26861.88	11286.62	23599.20
12. Total reduction in MIC (10-11)	112897.46	129082.43	70696.71	75542.04	166787.95	110212.78	81098.79	-26861.88	120439.34	-15281.38
13. Decrease in ENS_λ ($ENS_{\lambda_{Unprotected}}$ - $ENS_{\lambda_{Protected}}$)	34262327.82	34894216.96	35028788.61	35028788.61	35492157.49	35492157.49	33977357.4	33718037.35	35492157.49	33977357.40
14. Increase in $ENS_{\lambda'}$ ($ENS_{\lambda'_{Protected}}$ - $ENS_{\lambda'_{Unprotected}}$)	0	143680.49	0	1731.09	125627.69	0	176323.90	0	22504.17	6182.46
15. Total reduction in ENS cost (13-14)	34262327.82	34750536.47	35028788.61	35027057.52	35366529.80	35492157.49	33801033.50	33718037.35	35469653.32	33971174.94
16. Total savings (9+12+15)	40789420.08	41336033.32	41577872.45	41580904.14	41946005.58	42021049.46	40363810.09	40130604.13	42007698.59	40445685.65
17. Recloser installation cost	1800000.00	900000.00	900000.00	900000.00	3600000.00	3600000.00	0	0	3600000.00	0
18. Switch installation cost	2250000.00	1200000.00	1200000.00	1200000.00	0	0	1650000.00	1500000.00	0	1650000.00
19. Fuse-blow fuse installation cost	0	360000.00	0	60000.00	360000.00	0	480000.00	0	90000.00	90000.00
20. Fuse-save fuse installation cost	0	0	390000.00	330000.00	0	360000.00	0	510000.00	270000.00	390000.00
21. Maintenance cost of protective devices	2169371.68	2667523.70	2796079.06	2796079.06	3470994.69	3470994.69	2940703.84	2988912.10	3470994.69	2940703.84
22. Total protective devices cost (17+18+19+20+21)	6219371.68	5127523.70	5286079.06	5286079.06	7430994.69	7430994.69	5070703.84	4998912.10	7430994.69	5070703.84
23. Profit (16-22)	34570048.40	36208509.62	36291793.39	**36294825.08**	34515010.89	34590054.77	35293106.25	35131692.03	34576703.90	35374981.81

5.5 Conclusion

In this chapter, a generalised objective function for calculating the utility profit for any combination of protective devices has been developed. A detailed analysis of various cost components of interruption and ENS costs has also been carried out to investigate the contribution of different protective devices under the scenarios studied.

The performance of ten different combinations of protective devices has been evaluated for 58-bus and IEEE 123-bus radial distribution systems using MINLP optimization technique. Three point estimate method (3PEM) has been used for incorporating the uncertainties in temporary failure rates, permanent failure rates, repair rates and loading conditions of the system. From the study carried out on the two test systems, it can be concluded that maximum profit is obtained when simultaneous placement of reclosers, switches, fuse-blow fuses and fuse-save fuses is adopted.

In the next chapter, a model has been developed to solve the problem of optimal placement of protective devices (recloser, switch, fuse-blow fuse and fuse-save fuse) in various zones of a distribution system with distributed generation (DG).

Chapter 6

Placement of protective devices in distribution system with distributed generation considering system data uncertainties

Abstract

In this chapter, a model has been developed to solve the problem of optimal placement of protective devices (recloser, switch, fuse-blow fuse and fuse-save fuse) in various zones of a distribution system with distributed generation (DG). The uncertainties in temporary failure rates, permanent failure rates, repair rates and load data have been considered in the problem formulation using three point estimate method (3PEM). The formulated problem has been solved for 69-bus and 118-bus distribution systems using mixed-integer nonlinear programming (MINLP) optimization technique. After analyzing the test results of the two test systems, it is concluded that considerable profit for the utility is obtained by optimal placement of protective devices in various zones of the distribution system with DG.

6.1 Introduction

THE major aim of distribution network planners and utilities is to provide electrical power to the customers with high efficiency and reliability. Placement of protective devices in distribution system reduces the frequency and duration of customer interruptions at the cost of increased investment. Optimal placement of protective devices in distribution system increases the system reliability by isolating the faulty feeder section of the system and supplying power to healthy feeder sections of the system (upstream of the faulty feeder section). However, in the absence of an alternate supply, the healthy feeder sections downstream of the faulty feeder section remain de-energized until the faulty feeder section is repaired and re-energized.

DG can further improve the system reliability by supplying power to the downstream isolated healthy part of the protected system in case of a fault in the system. This necessitates the DG to be operated in an islanding mode. For the formation of island, the DG capacity should be sufficient to avoid load shedding or load prioritization [22]. However, the presence of DG in distribution system makes the problem of optimal placement of protective devices in distribution system more complex.

In this chapter, various zones have been formed for the operation of DGs (present in the system) in islanding mode. Further, a model has been developed to solve the problem of placement of protective devices (recloser, switch, fuse-blow fuse and fuse-save fuse) in various zones of a distribution system with DG for increasing the profit of the utility through reliability improvement while reducing the outage and investment costs. The uncertainties in temporary failure rates, permanent failure rates, repair rates and load data have been considered in the problem formulation using three point estimate method (3PEM). The formulated problem has been solved for 69-bus and 118-bus distribution systems using mixed-integer nonlinear programming (MINLP) optimization technique.

This chapter is organized as follows: In Section 6.2, the procedure for reliability calculation of an islanded portion of a distribution system with reclosers, switches, fuse-blow fuses and fuse-save fuses is discussed. Section 6.3 discusses the formulated problem. Section 6.4 gives the main results of this work followed by the conclusion in Section 6.5.

6.2 Reliability calculation of an islanded portion of a distribution system with reclosers, switches, fuse-blow fuses and fuse-save fuses

Fig. 6.1 shows an islanded portion of a distribution system. The island has 13 buses, 12 feeder sections and 13 load points with a DG connected at node 1 and an alternate supply at node 7. The DG is capable of supplying all the loads connected at all the 13 load points. A recloser at alternate supply point isolates the island from alternate supply for any external fault to the island.

Consider the scenario when the island has to be protected by reclosers, switches, fuse-blow fuses and fuse-save fuses for reliability improvement. It is assumed that the protective devices in any feeder section can be placed at the beginning of the feeder section (from DG side). For instance, a fault in any of the feeder sections (within the island), supply from the DG and alternate supply is tripped with the help of reclosers present at these two sources (DG and alternate supply) [23]. As soon as the fault is cleared (or the faulty feeder section is removed with the help of protective devices present at various feeder sections), the healthy feeder sections are energized with the DG or alternate supply as applicable.

Using Eqs. (3.1) and (5.2), the permanent failure rate of j^{th} load due to the permanent fault in i^{th}

feeder section ($\lambda_{i,j}$) can be written as,

$$\lambda_{i,j} = bibc(i,j)\lambda_i(\prod_{k\epsilon DFd(i,j)} X_{R,k}X_{Fb,k}X_{Fs,k}) + (1 - bibc(i,j))\lambda_i(\prod_{k\epsilon Fd(i,j)} X_{R,k}X_{Fb,k}X_{Fs,k}) (\prod_{k\epsilon DFd(i,j)} X_{R,k}X_{Fb,k}X_{Fs,k}) \tag{6.1}$$

where,

$bibc(i,j)$ = element corresponding to the i^{th} row and j^{th} column of the $[\mathbf{BIBC}]$ matrix [67]. If j^{th} load is downstream of i^{th} feeder (from DG side) then $bibc(i,j)$ = 1 otherwise $bibc(i,j)$ = 0. The $[\mathbf{BIBC}]$ matrix for the system shown in Fig 6.1 is given by Eq. (6.2).

$$BIBC = \begin{array}{c} \\ F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \\ F_7 \\ F_8 \\ F_9 \\ F_{10} \\ F_{11} \\ F_{12} \end{array} \begin{array}{c} \begin{array}{ccccccccccccc} L_1 & L_2 & L_3 & L_4 & L_5 & L_6 & L_7 & L_8 & L_9 & L_{10} & L_{11} & L_{12} & L_{13} \end{array} \\ \begin{pmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \end{array} \tag{6.2}$$

$$DFd(i,j) = DF_{Sec}(S_n, i) \cap DF_{Sec}(j, i) \tag{6.3}$$

$DF_{Sec}(S_n, i)$ is the set of feeder sections between alternate supply node and the end node of i^{th} feeder section. $DF_{Sec}(j, i)$ is the set of feeder sections between j^{th} node and end node of i^{th} feeder section. $DFd(i,j)$ represents feeder sections common to $DF_{Sec}(S_n, i)$ and $DF_{Sec}(j, i)$.

$$Fd(i,j) = F_{Sec}(1, i) \cap F_{Sec}(j, i) \tag{6.4}$$

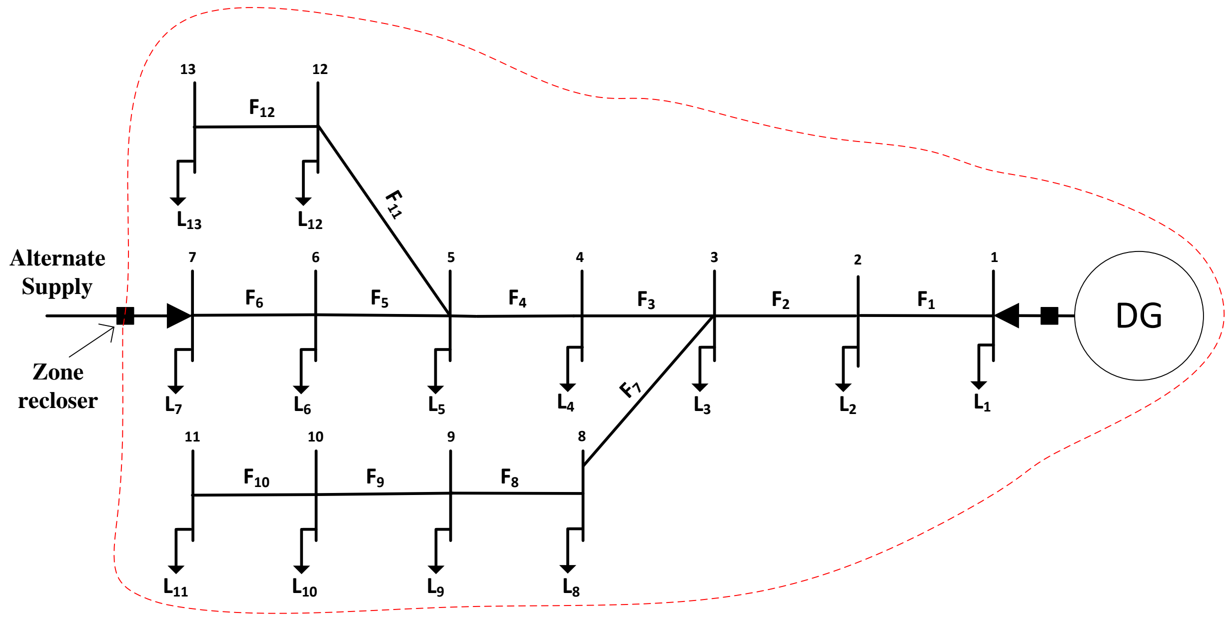

Figure 6.1: An islanded portion of a distribution system having 13 buses, and 13 load points

$F_{Sec}(1, i)$ is the set of feeder sections between DG node and i^{th} feeder section (including i^{th} feeder section) and $F_{Sec}(j, i)$ is the set of feeder sections between j^{th} node and i^{th} feeder section (including i^{th} feeder section). $Fd(i, j)$ represents feeder sections common to $F_{Sec}(1, i)$ and $F_{Sec}(j, i)$. The permanent failure rate of i^{th} feeder section is λ_i.

The failure rate of a load point due to fault in a feeder section depends on its location vis-a-vis the feeder section location. The load point can be either downstream or upstream to the feeder section. The failure rate for the two cases can be evaluated as follows:

(i) Load downstream to faulted feeder:

For evaluating $\lambda_{3,13}$, the permanent failure rate of load L_{13} due to the permanent fault in feeder section F_3, it can be observed from Eq. (6.2) that $bibc(3, 13) = 1$ because load L_{13} is downstream of feeder section F_3 (from DG side).

After substituting the value of $bibc(3, 13)$ in Eq. (6.1), $\lambda_{3,13}$ can be written as,

$$\lambda_{3,13} = \lambda_3 (\prod_{k \epsilon DFd(3,13)} X_{R,k} X_{Fb,k} X_{Fs,k}) \tag{6.5}$$

The set of feeder sections between alternate supply node and the end node of the F_3 feeder section, $DF_{Sec}(S_n, 3)$ is given by,

$$DF_{Sec}(S_n, 3) = \{F_4, F_5, F_6\}$$

Similarly, the set of feeder sections between 13^{th} node and the end node of the F_3 feeder section, $DF_{Sec}(13,3)$ is given by,

$$DF_{Sec}(13,3) = \{F_4, F_{11}, F_{12}\}$$

Therefore, feeder sections common to $DF_{Sec}(S_n,3)$ and $DF_{Sec}(13,3)$ i.e. $DFd(3,13)$ can be written as,

$$DFd(3,13) = DF_{Sec}(S_n,3) \cap DF_{Sec}(13,3) = \{F_4\} \tag{6.6}$$

From Eqs. (6.5) and (6.6), it can be concluded that, if a recloser or a fuse (fuse-blow fuse or fuse save fuse) is present in feeder section F_4 i.e. if any of the $X_{R,4}$, $X_{Fb,4}$ or $X_{Fs,4}$ is zero, then, $X_{R,4}X_{Fb,4}X_{Fs,4} = 0$ and hence, $\lambda_{3,13} = 0$. This implies that the fault (in feeder section F_3) is cleared by either a recloser or a fuse present in feeder section F_4 and supply to the load L_{13} is maintained through the alternate supply.

Further, if a recloser or a fuse (fuse-blow or fuse save) is not present in feeder section F_4 i.e. $X_{R,4}X_{Fb,4}X_{Fs,4} = 1$ then, $\lambda_{3,13} = \lambda_3$ (permanent failure rate of feeder section F_3). In this case, supply to the load L_{13} can be resumed only after the faulted feeder section F_3 is repaired.

(ii) Load upstream to faulted feeder:

Further, for calculating $\lambda_{12,4}$, the permanent failure rate of load L_4 due to the permanent fault in feeder section F_{12}, it can be observed from Eq. (6.2) that $bibc(12,4) = 0$ because load L_4 is upstream of feeder section F_{12} (from DG side).

After substituting the value of $bibc(12,4)$ in Eq. (6.1), $\lambda_{12,4}$ can be written as,

$$\lambda_{12,4} = \lambda_{12}\Big(\prod_{k \epsilon Fd(12,4)} X_{R,k}X_{Fb,k}X_{Fs,k}\Big)\Big(\prod_{k \epsilon DFd(12,4)} X_{R,k}X_{Fb,k}X_{Fs,k}\Big) \tag{6.7}$$

Further,

$$F_{Sec}(1,12) = \{F_1, F_2, F_3, F_4, F_{11}, F_{12}\}$$

$$F_{Sec}(4,12) = \{F_4, F_{11}, F_{12}\}$$

Therefore,

$$Fd(12,4) = F_{Sec}(1,12) \cap F_{Sec}(4,12) = \{F_4, F_{11}, F_{12}\} \tag{6.8}$$

From Eqs. (6.7) and (6.8), it can be concluded that, if a recloser or a fuse (fuse-blow or fuse save) is present in any of the feeder sections F_4, F_{11} or F_{12} then, $\lambda_{12,4} = 0$, as in this case, the fault (in feeder section F_{12}) is cleared by the recloser or fuse present in any of the feeder sections F_4, F_{11} or F_{12} and the supply to the load L_4 is continued through the DG source.

On the other hand, if a recloser or a fuse (fuse-blow or fuse save) is not present in any of the feeder sections F_4, F_{11} or F_{12} then, $\lambda_{12,4} = \lambda_{12}$ (permanent failure rate of feeder section F_{12}). In this case, supply to the load L_4 can be resumed only after the repair of faulted feeder section F_{12} is completed.

The permanent failure rate of j^{th} load due to the temporary fault in i^{th} feeder section ($\lambda^{'}_{i,j}$) can be written as,

$$\begin{aligned}\lambda^{'}_{i,j} = \; & bibc(i,j)\gamma_i(1-(\prod_{k\epsilon F_{sec}(1,i)} X_{Fb,k}))(\prod_{k\epsilon DFd(i,j)} X_{R,k}X_{Fb,k})(1-(\prod_{k\epsilon G^{'}(i,j))} X_{Fb,k})) \; + \\ & (1-bibc(i,j))\gamma_i(\prod_{k\epsilon Fd(i,j)} X_{R,k}X_{Fb,k})(1-(\prod_{k\epsilon G(i,j))} X_{Fb,k}))(\prod_{k\epsilon DFd(i,j)} X_{R,k}X_{Fb,k}) \\ & (1-(\prod_{k\epsilon G^{'}(i,j))} X_{Fb,k}))\end{aligned} \tag{6.9}$$

where,

γ_i = temporary failure rate of i^{th} feeder section.

$G(i,j)$ = common feeder sections between $F_{Sec}(1,i)$ and $F_{Sec}(j,1)$.

$G^{'}(i,j)$ = common feeder sections between $DF_{Sec}(S_n,i)$ and $DF^{'}_{Sec}(j,S_n)$.

$DF^{'}_{Sec}(j,S_n)$ = feeder sections between j^{th} node and alternate supply node.

Therefore, $G(i,j)$ and $G^{'}(i,j)$ can be written as,

$$G(i,j) = F_{Sec}(1,i) \cap F_{Sec}(j,1) \tag{6.10}$$

$$G^{'}(i,j) = DF_{Sec}(S_n,i) \cap DF^{'}_{Sec}(j,S_n) \tag{6.11}$$

For evaluating ($\lambda^{'}_{5,8}$), the permanent failure rate of load L_8 due to the temporary fault in feeder section F_5, it can be observed from Eq. (6.2) that $bibc(5,8)$ = 0 because load L_8 is upstream of feeder section F_5 (from DG side).

After substituting the value of $bibc(5,8)$ in Eq. (6.9), $\lambda_{5,8}$ can be written as,

$$\lambda^{'}_{5,8} = \gamma_5(\prod_{k\epsilon Fd(5,8)} X_{R,k}X_{Fb,k})(1-(\prod_{k\epsilon G(5,8))} X_{Fb,k}))(\prod_{k\epsilon DFd(5,8)} X_{R,k}X_{Fb,k})(1-(\prod_{k\epsilon G^{'}(5,8))} X_{Fb,k})) \tag{6.12}$$

The set of feeder sections between DG node and F_5 feeder section including F_5 feeder section ($F_{Sec}(1,5)$) can be written as,

$$F_{Sec}(1,5) = \{F_1, F_2, F_3, F_4, F_5\}$$

and the set of feeder sections between 8^{th} node and F_5 feeder section including F_5 feeder section ($F_{Sec}(8,5)$) can be written as,

$$F_{Sec}(8,5) = \{F_3, F_4, F_5, F_7\}$$

therefore, feeder sections common to $F_{Sec}(1,5)$ and $F_{Sec}(8,5)$ can be written as,

$$Fd(5,8) = F_{Sec}(1,5) \cap F_{Sec}(8,5) = \{F_3, F_4, F_5\} \tag{6.13}$$

Also, the set of feeder sections between 8^{th} node and F_1 feeder section including F_1 feeder section ($F_{Sec}(8,1)$) can be written as,

$$F_{Sec}(8,1) = \{F_1, F_2, F_7\}$$

therefore, the common feeder sections between $F_{Sec}(1,5)$ and $F_{Sec}(8,1)$ can be written as,

$$G(5,8) = F_{Sec}(1,5) \cap F_{Sec}(8,1) = \{F_1, F_2\} \tag{6.14}$$

For this system, 7^{th} node is the alternate supply node (S_n). The set of feeder sections between alternate supply node (7^{th} node) and the end node of F_5 feeder section is given by,

$$DF_{Sec}(S_n,5) = DF_{Sec}(7,5) = \{F_6\}$$

also, the set of feeder sections between 8^{th} node and the end node of F_5 feeder section ($DF_{Sec}(8,5)$) can be written as,

$$DF_{Sec}(8,5) = \{F_3, F_4, F_5, F_7\}$$

hence, feeder sections common to $DF_{Sec}(S_n,5)$ and $DF_{Sec}(8,5)$ is given by,

$$DFd(5,8) = DF_{Sec}(S_n,5) \cap DF_{Sec}(8,5) = \{\} = Nil \tag{6.15}$$

Finally, feeder sections between 8^{th} node and the alternate supply node ($DF^{'}_{Sec}(8, S_n)$) can be written as,

$$DF_{Sec}{}^{'}(8,S_n) = \{F_3, F_4, F_5, F_6, F_7\}$$

hence, the common feeder sections between $DF_{Sec}(S_n, 5)$ and $F^{'}_{Sec}(8,S_n)$ is given by,

$$G^{'}(5,8) = F_{Sec}(S_n,5) \cap F^{'}_{Sec}(8,S_n) = \{F_6\} \tag{6.16}$$

From Eqs. (6.12) and (6.13), it can be concluded that, if a recloser or a fuse-blow fuse is present in any of the feeder sections F_3, F_4 or F_5 i.e. if any of the $X_{R,3}$, $X_{R,4}$, $X_{R,5}$, $X_{Fb,3}$, $X_{Fb,4}$ or $X_{Fb,5}$ is zero then, $\lambda'_{5,8}$ = 0. This implies that the load L_8 is safe for any fault in feeder section F_5 due to presence of recloser(s) or fuse-blow fuse(s) in any of the feeder sections F_3, F_4 or F_5.

From Eqs. (6.12), (6.14) and (6.16), it can be concluded that, if a fuse-blow fuse is present in feeder section F_6 as well as in any of the feeder sections F_1 or F_2 then, $\lambda'_{5,8} = \gamma_5$, otherwise, $\lambda'_{5,8}$ = 0.

Now, the temporary failure rate of j^{th} load due to the temporary fault in i^{th} feeder section ($\gamma_{i,j}$) can be written as,

$$\begin{aligned}\gamma_{i,j} = \quad & bibc(i,j)\gamma_i[1-(1-(\prod_{k\epsilon F_{sec}(1,i)} X_{Fb,k}))(1-(\prod_{k\epsilon G'(i,j)} X_{Fb,k}))](\prod_{k\epsilon DFd(i,j)} X_{R,k}X_{Fb,k}) \\ + \quad & (1-bibc(i,j))\gamma_i(\prod_{k\epsilon Fd(i,j)} X_{R,k}X_{Fb,k})[1-(1-(\prod_{k\epsilon G(i,j)} X_{Fb,k}))(1-(\prod_{k\epsilon G'(i,j)} X_{Fb,k}))] \\ & (\prod_{k\epsilon DFd(i,j)} X_{R,k}X_{Fb,k})\end{aligned} \tag{6.17}$$

For calculating $\gamma_{11,10}$, the temporary failure rate of load L_{10} due to the temporary fault in feeder section F_{11}, it can be observed from Eq. (6.2) that $bibc(11,10)$ = 0 because load L_{10} is upstream of feeder section F_{11} (from DG side).

After substituting the value of $bibc(11,10)$ in Eq. (6.17), $\gamma_{11,10}$ can be written as,

$$\begin{aligned}\gamma_{11,10} = \gamma_{11}(\prod_{k\epsilon Fd(11,10)} X_{R,k}X_{Fb,k})[1-(1-(\prod_{k\epsilon G(11,10)} X_{Fb,k}))(1-(\prod_{k\epsilon G'(11,10)} X_{Fb,k}))] \\ (\prod_{k\epsilon DFd(11,10)} X_{R,k}X_{Fb,k})\end{aligned} \tag{6.18}$$

Further,

$$F_{Sec}(1,11) = \{F_1, F_2, F_3, F_4, F_{11}\}$$

$$F_{Sec}(10,11) = \{F_3, F_4, F_7, F_8, F_9, F_{11}\}$$

$$F_{Sec}(10,1) = \{F_1, F_2, F_7, F_8, F_9\}$$

$$DF_{Sec}(S_n,11) = \{F_5, F_6, F_{11}\}$$

$$DF_{Sec}(10,11) = \{F_3, F_4, F_7, F_8, F_9, F_{11}\}$$

$$DF'_{Sec}(10,S_n) = \{F_3, F_4, F_5, F_6, F_7, F_8, F_9\}$$

Therefore,

$$Fd(11,10) = F_{Sec}(1,11) \cap F_{Sec}(10,11) = \{F_3, F_4, F_{11}\} \tag{6.19}$$

$$G(11,10) = F_{Sec}(1,11) \cap F_{Sec}(10,1) = \{F_1, F_2\} \tag{6.20}$$

$$G^{'}(11,10) = DF_{Sec}(S_n,11) \cap DF^{'}_{Sec}(10,S_n) = \{F_5, F_6\} \tag{6.21}$$

$$DFd(11,10) = DF_{Sec}(S_n,11) \cap DF_{Sec}(10,11) = \{F_{11}\} \tag{6.22}$$

From Eqs. (6.18), (6.19) and (6.22), it can be concluded that, if a recloser or a fuse-blow fuse is present in any of the feeder sections F_3, F_4 or F_{11} then, $\gamma_{11,10}$ = 0. This implies that the load L_{10} is safe for any fault in feeder section F_{11}. Further, from Eqs. (6.18), (6.20) and (6.21), it can be concluded that, if a fuse-blow fuse is present in any of the feeder sections F_1 or F_2 as well as in (any of the feeder sections) F_5 or F_6 then, $\gamma_{11,10}$ = 0, as in this case, for a temporary fault in feeder section F_{11}, load L_{10} experiences a sustained interruption instead of momentary interruption.

Now, the temporary failure rate of j^{th} load due to the permanent fault in i^{th} feeder section ($\gamma^{'}_{i,j}$) can be written as,

$$\begin{aligned}\gamma^{'}_{i,j} = \quad & bibc(i,j)\lambda_i(\prod_{k\epsilon DFd(i,j)} X_{R,k}X_{Fb,k})(1-(\prod_{k\epsilon DFd(i,j)} X_{Fs,k}))(\prod_{k\epsilon G^{'}(i,j)} X_{Fb,k}) + (1-bibc(i,j)) \\ & \lambda_i(\prod_{k\epsilon Fd(i,j)} X_{R,k}X_{Fb,k})(1-(\prod_{k\epsilon Fd(i,j)} X_{Fs,k}))(\prod_{k\epsilon DFd(i,j)} X_{R,k}X_{Fb,k})(1-(\prod_{k\epsilon DFd(i,j)} X_{Fs,k}))\end{aligned} \tag{6.23}$$

For evaluating $\gamma^{'}_{2,6}$, the temporary failure rate of load L_6 due to the permanent fault in feeder section F_2, it can be observed from Eq. (6.2) that $bibc(2,6)$ = 1 because load L_6 is downstream of feeder section F_2 (from DG side).

After substituting the value of $bibc(2,6)$ in Eq. (6.23), $\gamma^{'}_{2,6}$ can be written as,

$$\gamma^{'}_{2,6} = \lambda_2(\prod_{k\epsilon DFd(2,6)} X_{R,k}X_{Fb,k})(1-(\prod_{k\epsilon DFd(2,6)} X_{Fs,k}))(\prod_{k\epsilon G^{'}(2,6)} X_{Fb,k}) \tag{6.24}$$

Further,

$$DF_{Sec}(S_n,2) = \{F_3, F_4, F_5, F_6\}$$

$$DF_{Sec}(6,2) = \{F_3, F_4, F_5\}$$

$$DF^{'}_{Sec}(6,S_n) = \{F_6\}$$

Therefore,

$$DFd(2,6) = DF_{Sec}(S_n,2) \cap DF_{Sec}(6,2) = \{F_3, F_4, F_5\} \tag{6.25}$$

$$G^{'}(2,6) = DF_{Sec}(S_n,2) \cap DF^{'}_{Sec}(6,S_n) = \{F_6\} \tag{6.26}$$

From Eqs. (6.24) and (6.25), it can be concluded that, if a recloser or a fuse-blow fuse is present in any of the feeder sections F_3, F_4 or F_5 then, $\gamma^{'}_{2,6} = 0$. This implies that the load L_6 is safe for any fault in feeder section F_2 and uninterrupted supply to load L_6 is continued from the alternate supply. Further, if a fuse-save fuse is present in any of the feeder sections F_3, F_4 or F_5 then, $\gamma^{'}_{2,6} = \gamma_2$ otherwise $\gamma^{'}_{2,6} = 0$.

From Eqs. (6.24) and (6.26), it can be concluded that, if a fuse-blow fuse is present in feeder section F_6 then, $\gamma^{'}_{2,6} = 0$. This is because, if a fuse-blow fuse is present in feeder section F_6 then load L_6 experiences a sustained interruption for a permanent fault in feeder section F_2.

Now, the outage time of j^{th} load due to the permanent fault in i^{th} feeder section ($r_{i,j}$) can be written as,

$$\begin{aligned} r_{i,j} = \; & bibc(i,j)\{r_i(\prod_{k\epsilon DFd(i,j)} X_{S,k}) + (r_{iso}(1-(\prod_{k\epsilon DFd(i,j)} X_{S,k}))\}(\prod_{k\epsilon DFd(i,j)} X_{R,k}X_{Fb,k}X_{Fs,k})+ \\ & (1-bibc(i,j))\{r_i(\prod_{k\epsilon Fd(i,j)} X_{S,k})(\prod_{k\epsilon DFd(i,j)} X_{S,k}) + (r_{iso}(1-(\prod_{k\epsilon Fd(i,j)} X_{S,k}) \\ & (\prod_{k\epsilon DFd(i,j)} X_{S,k}))\}(\prod_{k\epsilon Fd(i,j)} X_{R,k}X_{Fb,k}X_{Fs,k})(\prod_{k\epsilon DFd(i,j)} X_{R,k}X_{Fb,k}X_{Fs,k}) \end{aligned} \tag{6.27}$$

Where,

r_i = outage time of i^{th} feeder section.

r_{iso} = switch isolation time.

For evaluating $r_{3,12}$, the outage time of load L_{12} due to the permanent fault in feeder section F_3, it can be observed from Eq. (6.2) that $bibc(3,12)$ = 1 because load L_{12} is downstream of feeder section F_3 (from DG side).

After substituting the value of $bibc(3,12)$ in Eq. (6.27), $r_{3,12}$ can be written as,

$$r_{3,12} = \{r_3(\prod_{k\epsilon DFd(3,12)} X_{S,k}) + (r_{iso}(1-(\prod_{k\epsilon DFd(3,12)} X_{S,k}))\}(\prod_{k\epsilon DFd(3,12)} X_{R,k}X_{Fb,k}X_{Fs,k}) \tag{6.28}$$

Further,

$$DF_{Sec}(S_n,3) = \{F_4, F_5, F_6\}$$

$$DF_{Sec}(12,3) = \{F_4, F_{11}\}$$

Therefore,

$$DFd(3,12) = DF_{Sec}(S_n,3) \cap DF_{Sec}(12,3) = \{F_4\} \tag{6.29}$$

From Eqs. (6.28) and (6.29), it can be concluded that, if a recloser or a fuse (fuse-blow fuse or fuse save fuse) is present in feeder section F_4 then, $r_{3,12}$ = 0 (as in this case, the permanent fault in feeder section F_3 is cleared by the recloser or fuse present in feeder section F_4 and supply to the load L_{12} is continued through the alternate source), else if a switch is present in feeder section F_4 then, $r_{3,12}$ = r_{iso}. If none of the protective devices viz recloser, switch, fuse-blow fuse or fuse-save fuse is present in feeder section F_4, then $r_{3,12}$ = r_3.

6.3 Problem Formulation

In this chapter, a model has been developed for optimal placement of reclosers, switches, fuse-blow fuses and fuse-save fuses in an islanded zone of a distribution network for increasing the profit of the utility by reliability improvement of the zone while reducing the outage and investment costs.

6.3.1 Objective Function

The objective function for optimal placement of reclosers, switches, fuse-blow fuses and fuse-save fuses in an islanded zone of a distribution network is given by,

$$\begin{aligned} Maximize \quad f = &\{\sum_{j=1}^{nl}\sum_{i=1}^{nbr}(\lambda_i r_i - (\lambda_{i,j} r_{i,j} + \lambda'_{i,j} r'_i))L_j\}C_E F_1 + \{\sum_{j=1}^{nl}\sum_{i=1}^{nbr}((\lambda_i ICP'_{i,j} + \gamma_i ICT_{i,j}) \\ &- (\lambda_{i,j} ICP_{i,j} + \lambda'_{i,j} ICPT_{i,j} + (\gamma_{i,j} + \gamma'_{i,j}) ICT_{i,j}))L_j\}F_2 - \{(\sum_{i=1}^{nbr}(1 - X_{R,i}))C_R \\ &+ (\sum_{i=1}^{nbr}(1 - X_{S,i}))C_S + (\sum_{i=1}^{nbr}(1 - X_{Fb,i}))C_{Fb} + (\sum_{i=1}^{nbr}(1 - X_{Fs,i}))C_{Fs}\}(1 + \frac{C_m}{100}F_3) \end{aligned} \tag{6.30}$$

The values of the parameters '$\lambda_{i,j}$', '$\lambda'_{i,j}$', '$\gamma_{i,j}$', '$\gamma'_{i,j}$' and '$r_{i,j}$' used in Eq. (6.30) are calculated using Eqs. (6.1), (6.9), (6.17), (6.23) and (6.27), respectively. Values of factors F_1, F_2, and F_3 are calculated using Eqs. (3.11)-(3.13), respectively. The procedure for calculation of these parameters are explained in the previous section.

6.3.2 Constraints

The objective function f (Eq. (6.30)) consists of the following constraints:

1. The number of reclosers, switches, fuse-blow fuses or fuse-save fuses to be placed in the distribution system should be within the specified numbers given by the utility. The total number of reclosers to be placed among nbr branches of the distribution system should be less than or equal to the number of available reclosers (N_R). This constraint is modelled by the following inequality constraint.

$$\sum_{i=1}^{nbr}(1 - X_{R,i}) \leq N_R \tag{6.31}$$

   Similarly, The total number of switches to be placed among nbr branches of the distribution system should be less than or equal to the number of available switches (N_S). This constraint is modelled by the following inequality constraint.

$$\sum_{i=1}^{nbr}(1 - X_{S,i}) \leq N_S \tag{6.32}$$

   The other constraints corresponding to the maximum number of fuse-blow fuses and fuse-save fuses that can be placed in the distribution system are given by the following inequalities.

$$\sum_{i=1}^{nbr}(1 - X_{Fb,i}) \leq N_{Fb} \tag{6.33}$$

$$\sum_{i=1}^{nbr}(1 - X_{Fs,i}) \leq N_{Fs} \tag{6.34}$$

   where,
   N_{Fb} = Number of available fuse-blow fuses,
   N_{Fs} = Number of available fuse-save fuses.

2. Reclosers, switches, fuse-blow fuses and fuse-save fuses should not be installed simultaneously in the same feeder section. In other words, two or more than two protective devices can not be simultaneously placed on the same feeder section. This constraint is modelled by the following inequality constraint.

$$(1 - X_{R,i}) + (1 - X_{S,i}) + (1 - X_{Fb,i}) + (1 - X_{Fs,i}) \leq 1 \quad i = 1, 2, ..., nbr \tag{6.35}$$

3. Reclosers and switches may not be installed downstream of a fuse-blow fuse or fuse-save fuse [35].

4. A fuse-save fuse may not be installed downstream of a fuse-blow fuse [35].

6.4 Case study

Fig. 6.2 shows a 69-bus radial distribution system with total loads of 3.80 MW and 2.69 MVAr, respectively [68]. The bus data and line data of this system are adopted from [69] and are given in Appendix B. The system failure data for this system is also given in Appendix B. Further, the temporary failure rates are assumed to be three times of the permanent failure rate of the corresponding feeder section in all the calculations. Cost of a fuse and its annual maintenance cost (including replacement cost) are assumed to be Rs. 30,000 and 40% (of the fuse cost), respectively. Uncertainties in loading conditions, temporary failure rates, permanent failure rates and repair rates of the system have been considered using the procedures given in Chapter 3. To calculate the expected value of utility profit under an uncertain environment, 3PEM method has been used.

In [70], an improved multi-objective harmony search (IMOHS) technique is proposed for optimal allocation and sizing of DGs in a radial distribution system for power loss minimization and voltage profile improvement. Using this technique, the optimal sizes and locations of 3 DGs (DG_1, DG_2 and DG_3 at 0.85 lagging power factor) in 69-bus radial distribution system (shown in Fig. 6.2) for power loss minimization and voltage profile improvement have been determined as 0.4769 MW, 0.3124 MW and 1.4552 MW at buses 11, 21 and 61, respectively [70].

The first step towards the placement of protective devices in presence of DGs is to form islands or zones for each DG. An island or zone is the region in the vicinity a of DG in which the sum of total loads can be easily supplied by the DG alone. For this, a load flow analysis of the system is carried out to identify the zones for each DG.

The load flow result of the 69-bus system of Fig. 6.2 considering average values of DG generations and loads, is shown in Table 6.2. From this table, the direction of power flow in various feeder sections can be observed. Negative power flow (highlighted by boldface font) indicates the upstream power (or reverse power) flow (due to presence of DGs) in the system.

From the analysis of direction of power flow in various feeder sections and sum of loads in the vicinity of DG_1, it is concluded that DG_1 is capable of supplying all the loads present at buses 10, 11, 12, 13, 14, 15, 16, 66, 67, 68 and 69, thus forming 'Zone 1' as shown in Fig. 6.3. Similarly, DG_2 is capable of supplying all the loads present at buses 17, 18, 19, 20, 21, 22, 23, 24, 25, 26 and 27, thus forming 'Zone 2'. It may be noted that DG_3 can not form any zone due to its low capacity. Remaining loads (outside 'Zone 1' and 'Zone 2') of the system form 'Zone 0', which can only be supplied by the substation and DG_3. Any two zones are separated by a recloser (known as zone recloser) so that the healthy zones can be isolated from the faulty zone as soon as a fault occurs in any of the zones and the DG of the faulty zone is also disconnected immediately. Using this philosophy, two zone reclosers have been placed in feeder sections $F9$ and $F16$ towards the load buses 10 and 17, respectively (as shown in Fig. 6.3). This will ensure that for faults in feeder section $F9$ (or any other upstream feeder section), Zone 1 will be disconnected from Zone 0 and will continue to operate in islanded mode. Similarly, for faults in feeder section $F16$ (or any other upstream feeder section), Zone 2 will be disconnected from Zone 1 and will continue operating in islanded mode. After the isolation of the faulty feeder section(s), the remaining healthy feeder sections of the faulty zone are supplied by the DG of that zone operating in islanding mode [71].

To be able to operate in the islanding mode, DGs have to be capable of serving loads within the island and therefore, keep both the voltage and frequency within acceptable ranges. With islanding operation, the sequence of events after occurrence of a fault in the islanded zone are as follows:

1. DG is tripped and the fault is detected and isolated by one or more protection devices.
2. DG reconnects to serve the healthy feeder sections of the zone.
3. After the fault is cleared, zone recloser synchronizes its reclosing operation with DG.

After forming these zones, the optimal placement of protective devices in each zone is carried out by solving the objective function (Eq. (6.30)) using MINLP technique. The MINLP technique used for evaluating the objective function, utilizes the sequential quadratic programming (SQP) through the MATLAB function 'fmincon' of the MATLAB optimization toolbox. The results of optimized placement of protective devices in three zones of 69-bus system of Fig. 6.3 are given in Table 6.5. From this table, it can be observed that in Zone 0, the optimal locations of switches are in feeder sections $F4$ & $F61$, the optimal locations of fuse-blow fuses are in feeder sections $F27$, $F35$ & $F50$ and the optimal location of fuse-save fuse is in feeder section $F46$. However, no recloser can optimally be placed in Zone 0 since the high cost of a recloser makes it economically unviable for placing it in this zone. Further, in Zone 1, no protective devices can be placed optimally. This is because, the profit to the utility obtained by placing any protective device in this zone is lesser than the expenditure due to installation and maintenance of the protective device(s) for the given loads and customer types (Residential, Commercial, Industrial) of the zone. Further, no recloser or a switch or a fuse-save fuse can be optimally placed in Zone 2 for the similar reason. However, the optimal location of fuse-blow fuse in Zone 2 is in feeder section $F20$. The costs of the protected

Table 6.1: Cost components for optimized placement of protective devices in three zones of the 69-bus system of Fig. 6.3

1. Cost of original unprotected system without zoning (Rs.)	27026816.41
2. Cost of the system with protected zones (Rs.)	6901682.91
3. Cost of the 2 zone reclosers (Rs.)	900000.00
4. Total profit in Rs. (1-2-3)	19225133.50

zones (interruption and outage costs) for Z0, Z1 and Z2 are Rs. 5903811.62, Rs. 621861.78 and Rs. 376009.51, respectively. Therefore, the total cost of the system with protected zones (sum of the costs of three protected zones) is Rs. 6901682.91. The cost of original unprotected 69-bus system of Fig. 6.2 is Rs. 27026816.41. The cost of two zone reclosers at feeder sections $F9$ and $F17$ of the 69-bus system of Fig. 6.3 is Rs. 900000. The various cost components of 69-bus system of Fig. 6.3 is given in Table 6.1. From this table, it can be observed that the total profit to the utility corresponding to the optimal placement of protective devices in three zones of 69-bus system of Fig. 6.3 is determined as Rs. 19,225,133.50.

Now, for taking into account the uncertainty of DG generations and loads, consider the worst condition when generation from DGs are at lowest levels and the loading conditions are at highest levels. For this purpose, the lowest values of DG generation is taken as ($\mu_{DG} - 3\sigma_{DG}$) and highest possible values of loads is selected as ($\mu_{Load} + 3\sigma_{Load}$), where μ_{DG} and σ_{DG} are the mean and standard deviation of DG generation, respectively, whereas μ_{Load} and σ_{Load} are the mean and standard deviation of loads, respectively. For calculation purpose, σ_{DG} and σ_{Load} are assumed to be 10% of their mean value. For this worst combination of DG generation and load levels, the load flow result of the 69-bus system of Fig. 6.2 is shown in Table 6.4. From this table, the direction of power flow in various feeder sections can be observed.

From the analysis of direction of power flow in various feeder sections and the worst (highest possible) capacity of loads in the vicinity of DG_2, it is concluded that DG_2 is capable of supplying all the loads present at buses 19, 20, 21, 22, 23, 24, 25, 26 and 27, thus forming 'Zone 1' as shown in Fig. 6.4. It may be noted that for the present scenario, DG_1 and DG_3 can not form any zone due to their low capacities. The remaining loads (outside 'Zone 1') of the system form 'Zone 0', which can only be supplied by the substation, DG_1 and DG_3. The two zones ('Zone 0' and 'Zone 1') are separated by a zone recloser so that the healthy zone can be isolated from the faulty zone as soon as a fault occurs in any of the zones. The zone recloser has been placed in feeder sections $F18$ towards

Table 6.2: Power flow of 69-bus system with average values of DG generations and loads

Feeder Number	Power flow (MW)	Feeder Number	Power flow (MW)
1	1.630215809	35	0.185765635
2	1.630215809	36	0.159764251
3	1.352907876	37	0.133760476
4	0.502058434	38	0.133760476
5	0.502058434	39	0.109752994
6	0.499439308	40	0.085745469
7	0.458495629	41	0.084544474
8	0.337638207	42	0.084544474
9	**-0.012343989**	43	0.078537641
10	**-0.040844349**	44	0.078537641
11	0.25618987	45	0.039268827
12	0.050820447	46	0.850849442
13	0.042636159	47	0.850849442
14	0.034437679	48	0.771784167
15	0.034437679	49	0.38594987
16	**-0.012259186**	50	0.044747552
17	**-0.073773655**	51	0.003654441
18	**-0.135288277**	52	0.319511669
19	**-0.135288277**	53	0.315081684
20	**-0.13631386**	54	0.288161683
21	0.063031846	55	0.26361675
22	0.057589592	56	0.26361675
23	0.057589592	57	0.26361675
24	0.028799061	58	0.26361675
25	0.028799061	59	0.158537031
26	0.014399698	60	0.158537031
27	0.091542298	61	0.337492105
28	0.065541009	62	0.303601763
29	0.039538701	63	0.303601763
30	0.039538701	64	0.062657794
31	0.039538701	65	0.036686906
32	0.039538701	66	0.018343461
33	0.025528836	67	0.057232044
34	0.006007105	68	0.02861604

the load bus 19 (as shown in Fig. 6.4). This will ensure that for faults in feeder section $F18$ (or any other upstream feeder section), Zone 1 will be disconnected from Zone 0 and will continue operating in islanded mode.

Table 6.3: Cost components for optimized placement of protective devices in two zones of the 69-bus system of Fig. 6.4

1. Cost of original unprotected system without zoning (Rs.)	27026816.41
2. Cost of the system with protected zones (Rs.)	8232901.43
3. Cost of the zone recloser (Rs.)	450000.00
4. Total profit in Rs. (1-2-3)	18343914.98

After forming these zones, the optimal placement of protective devices in each zone is carried out by solving the objective function (Eq. (6.30)) using MINLP technique. The results of optimized placement of protective devices in the two zones of 69-bus system of Fig. 6.4 are given in Table 6.6. From this table, it can be observed that in Zone 0, the optimal location of recloser is in feeder section $F9$, the optimal locations of switches are in feeder sections $F4$ & $F12$, the optimal locations of fuse-blow fuses are in feeder sections $F27$, $F35$, $F50$, $F61$ & $F65$ and the optimal locations of fuse-save fuses are in feeder sections $F46$ & $F52$. However, in Zone 1, no protective device can be optimally placed as the profit to the utility obtained by placing any of the protective devices in this zone is lesser than the expenditure due to installation and maintenance of the protective device(s) for the given loads and customer types of the zone. The costs of the protected zones for Z0 and Z1 are Rs. 8024897.46 and Rs. 208003.97, respectively. Therefore, the total cost of the system with protected zones of Fig. 6.4 (sum of the costs of two protected zones) is Rs. 8232901.43. The cost of original unprotected 69-bus system of Fig. 6.2 is Rs. 27026816.41. The cost of one zone recloser at feeder section $F18$ of the 69-bus system of Fig. 6.4 is Rs. 450000. The various cost components of 69-bus system of Fig. 6.4 are given in Table 6.3. From this table, it can be observed that the total profit to the utility corresponding to the optimal placement of protective devices in the two zones of 69-bus system of Fig. 6.4 is determined as Rs. 18,343,914.98.

From Tables 6.5 and 6.6, it can be observed that there is a considerable reduction in the total cost (interruption and outage costs) of the system (with protected zones) with the increase in number of zones. Further, from Tables 6.1 and 6.3, it can be observed that the profit to the utility is more with more number of zones. This is because, as number of islands increases, more and more loads can be served by DGs or substation in case of a fault in the system.

Fig. 6.5 shows a 118-bus radial distribution system with total loads of 22.709 MW and 17.041 MVAr, respectively [72]. The bus data and line data of this system are adopted from [70] and are given in Appendix B. The system failure data for this system is also given in Appendix B.

Table 6.4: Power flow of 69-bus system with 3 DGs considering uncertainties in DG generations and loads

Feeder Number	Power flow (MW)	Feeder Number	Power flow (MW)
1	3.510680755	35	0.241541847
2	3.510680755	36	0.207739893
3	3.150118738	37	0.173933894
4	2.043077619	38	0.173933894
5	2.043077619	39	0.142721596
6	2.039662197	40	0.111509225
7	1.98608566	41	0.109947564
8	1.827798695	42	0.109947564
9	0.446770643	43	0.102136094
10	0.409326388	44	0.102136094
11	0.508706327	45	0.051068058
12	0.238344071	46	1.10704112
13	0.227553062	47	1.10704112
14	0.216727071	48	1.004233377
15	0.216727071	49	0.502214601
16	0.154950373	50	0.058608063
17	0.073517984	51	0.004785803
18	**-0.007915024**	52	1.341106645
19	**-0.007915024**	53	1.335298595
20	**-0.009273301**	54	1.299955895
21	0.083495859	55	1.267681739
22	0.076286893	56	1.267681739
23	0.076286893	57	1.267681739
24	0.038151104	58	1.267681739
25	0.038151104	59	1.126959768
26	0.019075853	60	1.126959768
27	0.119020169	61	0.454895942
28	0.085218377	62	0.409261942
29	0.05141486	63	0.409261942
30	0.05141486	64	0.084482285
31	0.05141486	65	0.048223193
32	0.05141486	66	0.02411161
33	0.033198389	67	0.07535193
34	0.007811934	68	0.037675997

In [73], an efficient technique is proposed for optimal allocation and sizing of DGs in a radial distribution system for power loss minimization and voltage stability improvement. Using this technique, the optimal sizes and locations of 5 DGs (DG_1, DG_2, DG_3, DG_4 and DG_5 at unity power

Table 6.5: Optimized placement of protective devices in three zones of 69-bus distribution system of Fig. 6.3

Zones	Location of reclosers	Location of switches	Location of fuse-blow fuses	Location of fuse-save fuses	Cost of protected zone (Rs.)
Zone 0	Nil	F4 F61	F27 F35 F50	F46	5903811.62
Zone 1	Nil	Nil	Nil	Nil	621861.78
Zone 2	Nil	Nil	F20	Nil	376009.51
Total cost of the system with protected zones (Rs.) = 6901682.91					

Table 6.6: Optimized placement of protective devices in two zones of 69-bus distribution system of Fig. 6.4

Zones	Location of reclosers	Location of switches	Location of fuse-blow fuses	Location of fuse-save fuses	Cost of protected zone (Rs.)
Zone 0	F9	F4 F12	F27 F35 F50 F61 F65	F46 F52	8024897.46
Zone 1	Nil	Nil	Nil	Nil	208003.97
Total cost of the system with protected zones (Rs.) = 8232901.43					

factor) in a 118-bus radial distribution system shown in Fig. 6.5 have been determined as 4.5353 MW, 1.1329 MW, 2.1318 MW, 4.9452 MW and 0.7501 MW at buses 35, 43, 72, 88 and 118, respectively [73]. The load flow result of this 118-bus system with optimal placement of the 5 DGs (with average values of DG generations and loads) is shown in Table 6.9. From this table, the direction of power flow in various feeder sections can be observed.

From the analysis of direction of power flow in various feeder sections and capacity of loads in the vicinity of DG_1, it is concluded that DG_1 is capable of supplying all the loads present at buses 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 61 and 62, thus forming 'Zone 1' as shown in Fig. 6.6. Similarly, 'Zone 2', 'Zone 3' and 'Zone 4' are formed with DG_2, DG_3 and DG_4, respectively. DG_5 can not form any zone due to its low capacity. Remaining loads (other than 'Zone 1', 'Zone 2', 'Zone 3' and 'Zone 4') of the system form 'Zone 0', which can only be supplied by the substation and DG_5.

After forming these zones, the optimal placement of protective devices in each zone of Fig. 6.6 is carried out by solving the objective function (Eq. (6.30)) using MINLP technique. The results of optimized placement of protective devices in five zones of 118-bus system of Fig. 6.6 are given in Table 6.10. From this table, it can be observed that in Zone 0, the optimal locations of reclosers are in feeder sections $F3$, $F9$, $F20$, $F48$, $F63$ & $F99$, the optimal locations of switches are in feeder

Table 6.7: Cost components for optimized placement of protective devices in the five zones of the 118-bus system of Fig. 6.6

1. Cost of original unprotected system without zoning (Rs.)	259268632.09
2. Cost of the system with protected zones (Rs.)	25462557.30
3. Cost of the 4 zone reclosers (Rs.)	1800000.00
4. Total profit in Rs. (1-2-3)	232006074.79

sections $F2$, $F43$, $F62$, $F93$, $F101$, $F104$ & $F110$, the optimal locations of fuse-blow fuses are in feeder sections $F4$, $F11$, $F52$ & $F56$ and the optimal locations of fuse-save fuses are in feeder sections $F96$, $F112$ and $F117$. In Zone 1, the optimal locations of recloser and switch are in feeder sections $F32$ and $F30$, respectively. However, no fuse-blow fuse or fuse-save fuse can be optimally placed in Zone 1 because, the profit to the utility obtained by placing any of these protective devices in this zone is lesser than the expenditure due to their installation and maintenance for the given loads and customer types of the zone. In Zone 2 and Zone 3, no protective device can be optimally placed for the similar reason. Similarly, in Zone 4, no recloser or a switch or a fuse-blow fuse can be optimally placed. However, the optimal location of fuse-save fuse in Zone 4 is in the feeder section $F80$. The costs of the protected zones for Z0, Z1, Z2, Z3 and Z4 are Rs. 19790134.26, Rs. 2714355.79, Rs. 120506.70, Rs. 910781.08 and Rs. 1926779.46, respectively. Therefore, the total cost of the system with protected zones (sum of the costs of five protected zones) is Rs. 25462557.30. The cost of original unprotected 118-bus system of Fig. 6.5 is Rs. 259268632.09. The cost of the four zone reclosers at feeder sections $F29$, $F39$, $F64$ and $F70$ of the 118-bus system of Fig. 6.6 is Rs. 1800000. The various cost components of 118-bus system of Fig. 6.6 are given in Table 6.7. From this table, it can be observed that the total profit to the utility corresponding to the optimal placement of protective devices in the five zones of 118-bus system of Fig. 6.6 is determined as Rs. 232,006,074.79.

Now, for taking into account the uncertainty in DG generations and loads for the 118-bus system of Fig. 6.5, consider the worst condition when generations from the 5 DGs are at lowest levels ($\mu_{DG} - 3\sigma_{DG}$) and the loading conditions are at highest levels ($\mu_{Load} + 3\sigma_{Load}$). For this case, the load flow result of the 118-bus system of Fig. 6.5 is shown in Table 6.12. From this table, the direction of power flow in various feeder sections can be observed.

From the analysis of direction of power flow in various feeder sections and the worst (highest possible) capacity of loads in the vicinity of DG_1, it is concluded that DG_1 is capable of supplying all the loads present at buses 32, 33, 34, 35, 36, 37, 38, 39 and 40, thus forming 'Zone 1' as shown in Fig. 6.7. Similarly, 'Zone 2' and 'Zone 3' are formed with DG_2 and DG_4, respectively. In this scenario, DG_3 and DG_5 can not form any zone due to their low capacities. Remaining loads (outside 'Zone 1', 'Zone 2' and 'Zone 3') of the system form 'Zone 0', which can only be supplied by the substation, DG_3 and DG_5.

Again, after forming these zones, the optimal placement of protective devices in each zone of Fig. 6.7 is carried out by solving the objective function (Eq. (6.30)) using MINLP technique. The results of optimized placement of protective devices in the four zones of the 118-bus system of Fig. 6.7 are shown in Table 6.11. From this table, it can be observed that in Zone 0, the optimal locations of reclosers are in feeder sections $F3$, $F9$, $F43$, $F62$, $F88$ & $F99$, the optimal locations of switches are in feeder sections $F2$, $F20$, $F93$, $F101$, $F108$ & $F110$, the optimal locations of fuse-blow fuses are in feeder sections $F4$, $F11$, $F52$, $F56$, $F60$ & $F74$ and the optimal locations of fuse-save fuses are in feeder sections $F29$, $F64$, $F66$, $F71$, $F96$ and $F112$. In Zone 1, the optimal locations of fuse-blow fuse and fuse-save fuse are in feeder sections $F32$ and $F34$, respectively. However, no recloser or switch can be optimally placed in Zone 1 because, the profit to the utility obtained by placing any of these protective devices in this zone is lesser than the expenditure due to their installation and maintenance for the given loads and customer types of the zone. In Zone 2, no protective device can be optimally placed for the similar reason. Similarly, in Zone 3, no recloser or a fuse-blow fuse or a fuse-save fuse can be optimally placed as they are economically unviable. However, the optimal location of switch in Zone 3 is in the feeder section $F84$. The costs of the protected zones for Z0, Z1, Z2 and Z3 are Rs. 25358781.33, Rs. 1349663.06, Rs. 46855.44 and Rs. 679244.52, respectively. Therefore, the total cost of the system with protected zones (sum of the costs of four protected zones) is Rs. 27434544.35. The cost of original unprotected 118-bus system of Fig. 6.5 is Rs. 259268632.09. The cost of the three zone reclosers at feeder sections $F31$, $F40$ and $F77$ of the 118-bus system of Fig. 6.7 is Rs. 1350000. The various cost components of 118-bus system of Fig. 6.7 are given in Table 6.8. From this table, it can be observed that the total profit to the utility corresponding to the optimal placement of protective devices in the four zones of 118-bus system of Fig. 6.7 is determined as Rs. 230,484,087.74.

From Tables 6.10 and 6.11, it can be observed that for this system also, there is considerable reduction in the total cost (interruption and outage costs) of the system (with protected zones) with the increase in number of zones. Further, from Tables 6.7 and 6.8, it can also be observed that the

Table 6.8: Cost components for optimized placement of protective devices in the four zones of the 118-bus system of Fig. 6.7

1. Cost of original unprotected system without zoning (Rs.)	259268632.09
2. Cost of the system with protected zones (Rs.)	27434544.35
3. Cost of the 3 zone reclosers (Rs.)	1350000.00
4. Total profit in Rs. (1-2-3)	230484087.74

profit to the utility is more with more number of zones. This is because, as the number of islands increases, more and more loads can be served by DGs or substation in case of a fault in the system.

6.5 Conclusion

In this chapter, a formulation for calculation of distribution system reliability in the presence of DG has been developed. The formulated problem has been applied to 69-bus and 118-bus test distribution systems considering uncertainties in loads, temporary failure rates, permanent failure rates and repair rates. Zoning of the test systems has been done in order to ensure successful operation of DGs in islanded mode. Zone boundaries have been determined considering (i) mean values of both loads and DG generations and (ii) worst case loading conditions ($\mu_{Load}+3\sigma_{Load}$) and minimum DG generations ($\mu_{DG} - 3\sigma_{DG}$). From the analysis of the test results, it is concluded that profit to the utility can be increased by optimal placement of protective devices in various zones of the test systems which enables the DGs of corresponding zones to operate in islanding mode and supply loads in the island, in case a fault occurs in any part of the system. The profit to the utility increases as the number of zones increase. This is because, as the number of islands increases, more and more loads can be served by DGs or substation in case of a fault in the system.

In the next chapter, the major contributions made in this thesis and suggestions for futute work are presented.

Table 6.9: Power flow of 118-bus system with average values of DG generations and loads

Feeder Number	Power flow (MW)	Feeder Number	Power flow (MW)	Feeder Number	Power flow (MW)
1	0.000000000	**40**	**-0.00574912**	**79**	**-0.0330419**
2	0.049077066	**41**	**-0.006466603**	80	0.002644881
3	0.026472642	**42**	**-0.006923422**	81	0.001490417
4	0.004407621	43	0.016864504	82	0.000667601
5	0.003671747	44	0.015720346	83	0.000350121
6	0.002220608	45	0.015167731	**84**	**-0.03632458**
7	0.001168794	46	0.011130415	**85**	**-0.041603256**
8	0.000881576	47	0.007761896	**86**	**-0.046700314**
9	0.021098182	48	0.002186377	**87**	**-0.046960573**
10	0.019100818	49	0.001391686	88	0.022535411
11	0.003116123	50	0.000833815	89	0.02007517
12	0.002852716	51	0.000413238	90	0.012297449
13	0.002325561	52	0.008722954	91	0.007240929
14	0.000888345	53	0.008093323	92	0.004701121
15	0.000666664	54	0.007148369	93	0.002158746
16	0.000328579	55	0.006276241	94	0.000754781
17	0.014501419	56	0.00270826	95	0.000516608
18	0.014296101	57	0.002475924	96	0.00472773
19	0.012699813	58	0.001644302	97	0.000747039
20	0.007129285	59	0.000650965	98	0.000232923
21	0.005289633	60	0.009131734	99	0.045619298
22	0.004337464	61	0.004524941	100	0.039331789
23	0.003459658	62	0.007149198	101	0.034703362
24	0.001725071	63	0.002346716	102	0.029366476
25	0.000434101	**64**	**-0.021413815**	103	0.025152901
26	0.000268703	65	0.009261509	104	0.023662749
27	0.021719526	66	0.005267548	105	0.022559095
28	0.015714859	67	0.004980233	106	0.021520125
29	**-0.011090701**	68	0.004433823	107	0.016188108
30	**-0.021273617**	69	0.003735581	108	0.013740596
31	**-0.026569523**	**70**	**-0.001295014**	109	0.008166788
32	**-0.031517883**	**71**	**-0.00758234**	110	0.00396211
33	**-0.033105166**	72	0.013096078	111	0.000600193
34	**-0.035227214**	73	0.012535945	112	0.005277085
35	0.009305591	74	0.003133835	113	0.003147498
36	0.008609365	75	0.002790639	114	0.002471354
37	0.007827368	76	0.00071225	115	0.00083517
38	0.006621948	**77**	**-0.032092133**	116	0.000342433
39	**-0.003506907**	**78**	**-0.032728175**	117	0.002116902

Table 6.10: Optimized placement of protective devices in five zones of 118-bus distribution system of Fig. 6.6

Zones	Location of reclosers	Location of switches	Location of fuse-blow fuses	Location of fuse-save fuses	Cost of protected zone (Rs.)
Zone 0	F3 F9 F20 F48 F63 F99	F2 F43 F62 F93 F101 F104 F110	F4 F11 F52 F56	F96 F112 F117	19790134.26
Zone 1	F32	F30	Nil	Nil	2714355.79
Zone 2	Nil	Nil	Nil	Nil	120506.70
Zone 3	Nil	Nil	Nil	Nil	910781.08
Zone 4	Nil	Nil	Nil	F80	1926779.46
Total cost of the system with protected zones (Rs.) = 25462557.30					

Table 6.11: Optimized placement of protective devices in four zones of 118-bus distribution system of Fig. 6.7

Zones	Location of reclosers	Location of switches	Location of fuse-blow fuses	Location of fuse-save fuses	Cost of protected zone (Rs.)
Zone 0	F3 F9 F43 F62 F88 F99	F2 F20 F93 F101 F108 F110	F4 F11 F52 F56 F60 F74	F29 F64 F66 F71 F96 F112	25358781.33
Zone 1	Nil	Nil	F32	F34	1349663.06
Zone 2	Nil	Nil	Nil	Nil	46855.44
Zone 3	Nil	F84	Nil	Nil	679244.52
Total cost of the system with protected zones (Rs.) = 27434544.35					

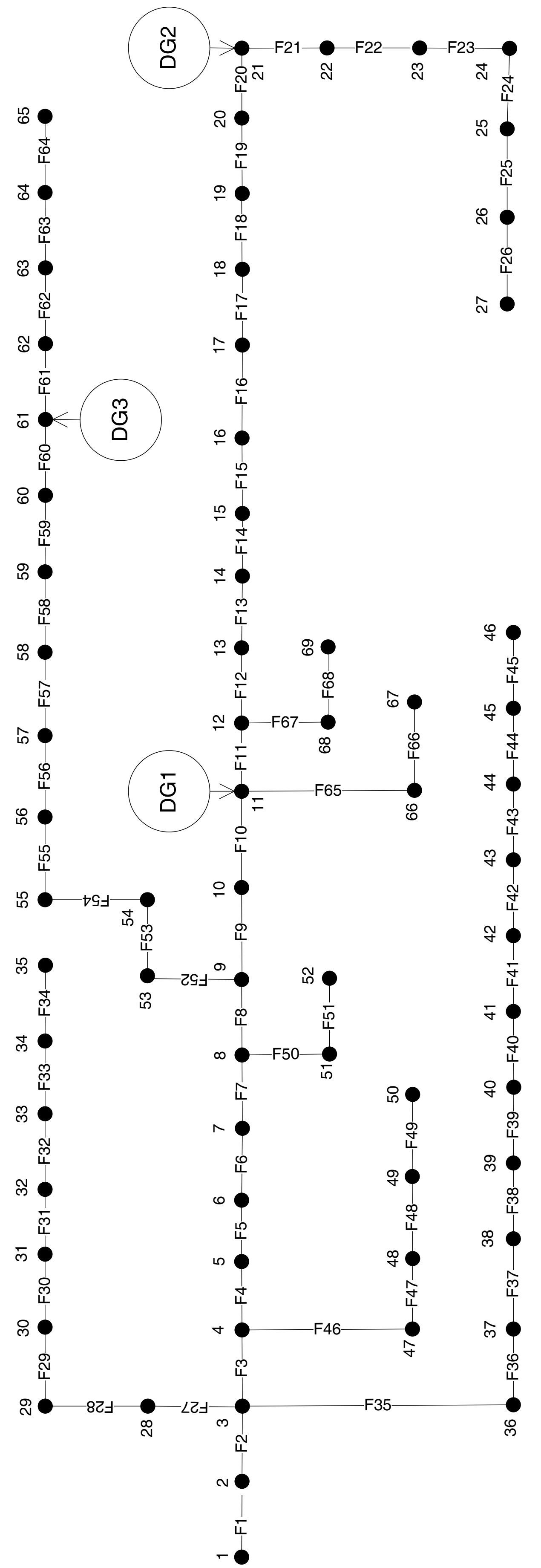

Figure 6.2: 69-bus radial distribution system

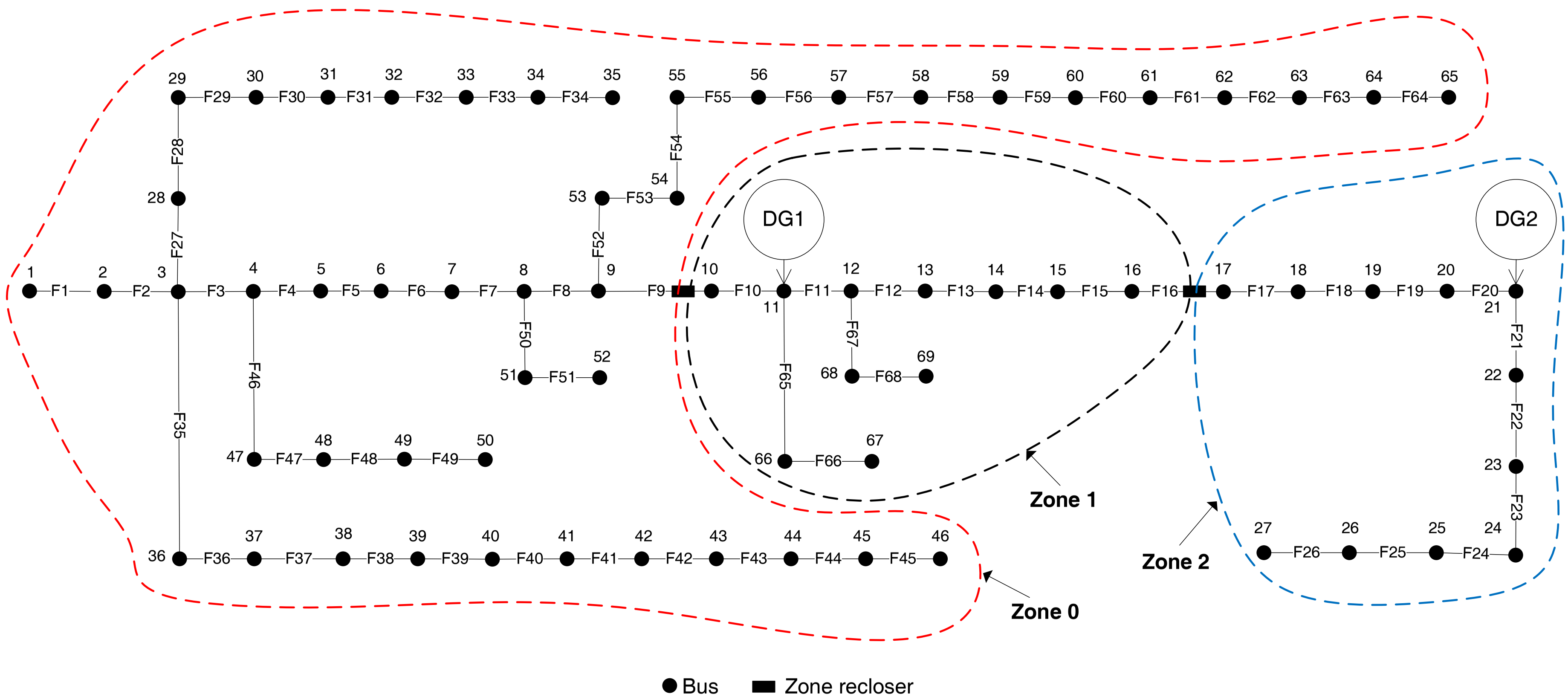

Figure 6.3: Zones of 69-bus distribution system with average values of DG generations and loads

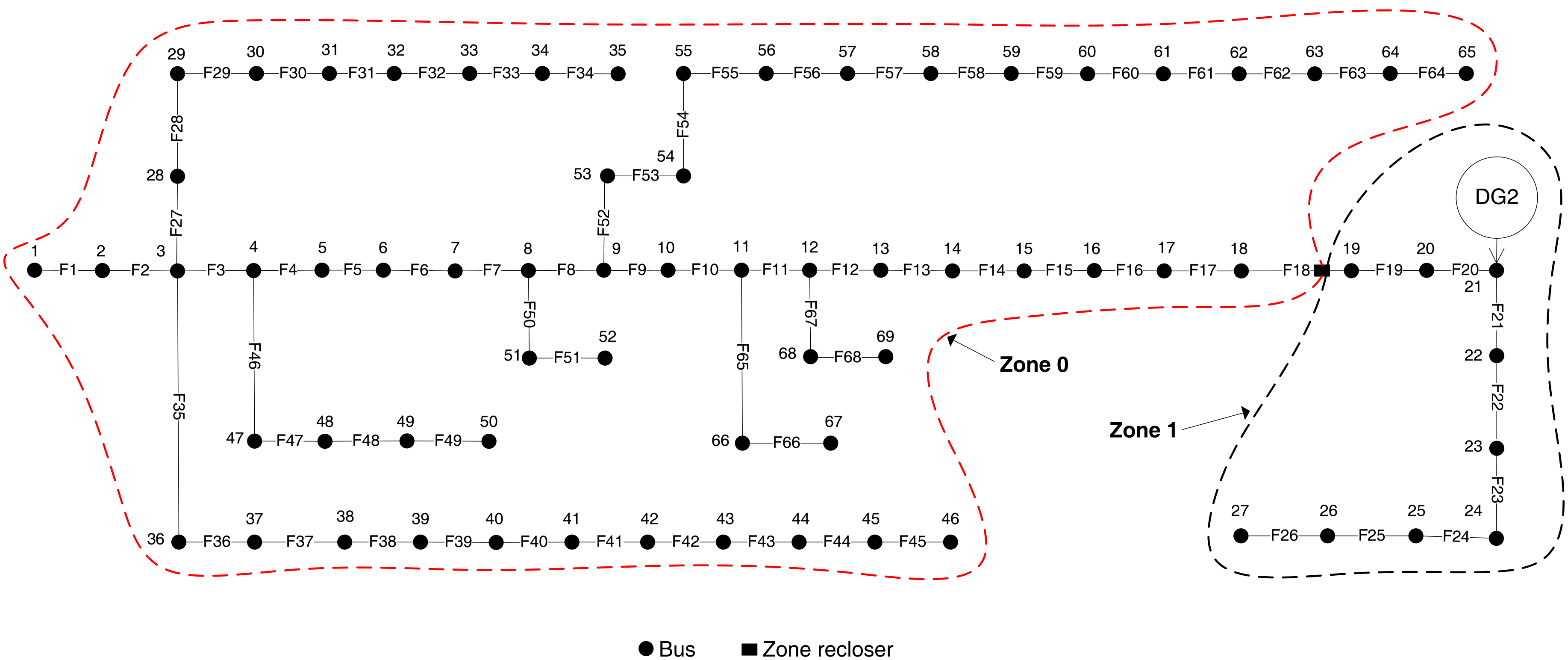

Figure 6.4: Zones of 69-bus distribution system considering uncertainties in DG generations and loads

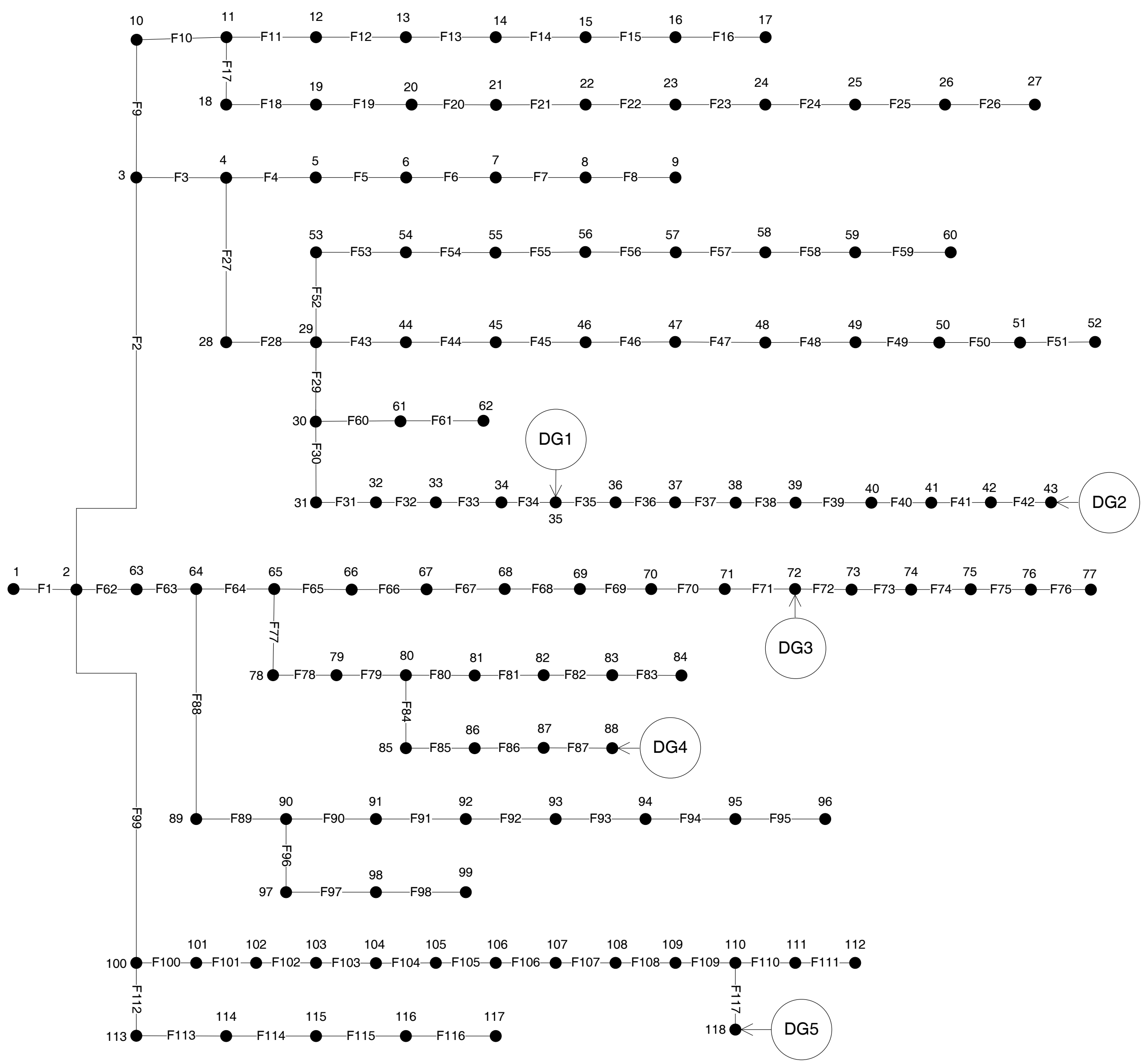

Figure 6.5: 118-bus radial distribution system

Table 6.12: Power flow of 118-bus system with five DGs considering uncertainties in DG generations and loads

Feeder Number	Power flow (MW)	Feeder Number	Power flow (MW)	Feeder Number	Power flow (MW)
1	0	40	**-0.0007498**	79	**-0.015421305**
2	0.098297669	41	**-0.001708084**	80	0.003528168
3	0.068722636	42	**-0.002317775**	81	0.001985852
4	0.005751771	43	0.022183733	82	0.000887668
5	0.004791429	44	0.020685979	83	0.000462366
6	0.002897817	45	0.019961309	84	**-0.019797784**
7	0.001525235	46	0.014663783	85	**-0.026886027**
8	0.00115044	47	0.010238179	86	**-0.033711019**
9	0.027613268	48	0.002883976	87	**-0.034061469**
10	0.025008416	49	0.001836095	88	0.029622933
11	0.004069703	50	0.001100202	89	0.026400912
12	0.003725802	51	0.000545392	90	0.016173423
13	0.003037419	52	0.011456622	91	0.009530976
14	0.001160341	53	0.010633025	92	0.006188397
15	0.000870802	54	0.009395496	93	0.002841273
16	0.000429197	55	0.008251775	94	0.000994037
17	0.019002683	56	0.003562398	95	0.000681307
18	0.018734337	57	0.003256931	96	0.006216266
19	0.016646371	58	0.002163201	97	0.000983508
20	0.009354577	59	0.000856385	98	0.0003065
21	0.006946313	60	0.01194664	99	0.065363967
22	0.005698992	61	0.005922634	100	0.05716868
23	0.004545895	62	0.051534373	101	0.051130134
24	0.00226643	63	0.045288348	102	0.044153109
25	0.000570367	64	0.014064348	103	0.038618252
26	0.000353102	65	0.026363454	104	0.036650311
27	0.062520021	66	0.021084906	105	0.035188294
28	0.054681471	67	0.020704144	106	0.033805819
29	0.019450044	68	0.019971574	107	0.026694864
30	0.00613129	69	0.019030016	108	0.02341532
31	**-0.00082874**	70	0.012164593	109	0.015934931
32	**-0.007325425**	71	0.003514118	110	0.005336091
33	**-0.009414642**	72	0.018088489	111	0.000808344
34	**-0.012238793**	73	0.017313704	112	0.006880019
35	0.019227631	74	0.004333454	113	0.004104165
36	0.018300008	75	0.003860838	114	0.003222693
37	0.017257746	76	0.000984962	115	0.001089185
38	0.015641765	77	**-0.014161584**	116	0.000446595
39	0.002253096	78	**-0.015005585**	117	0.007788974

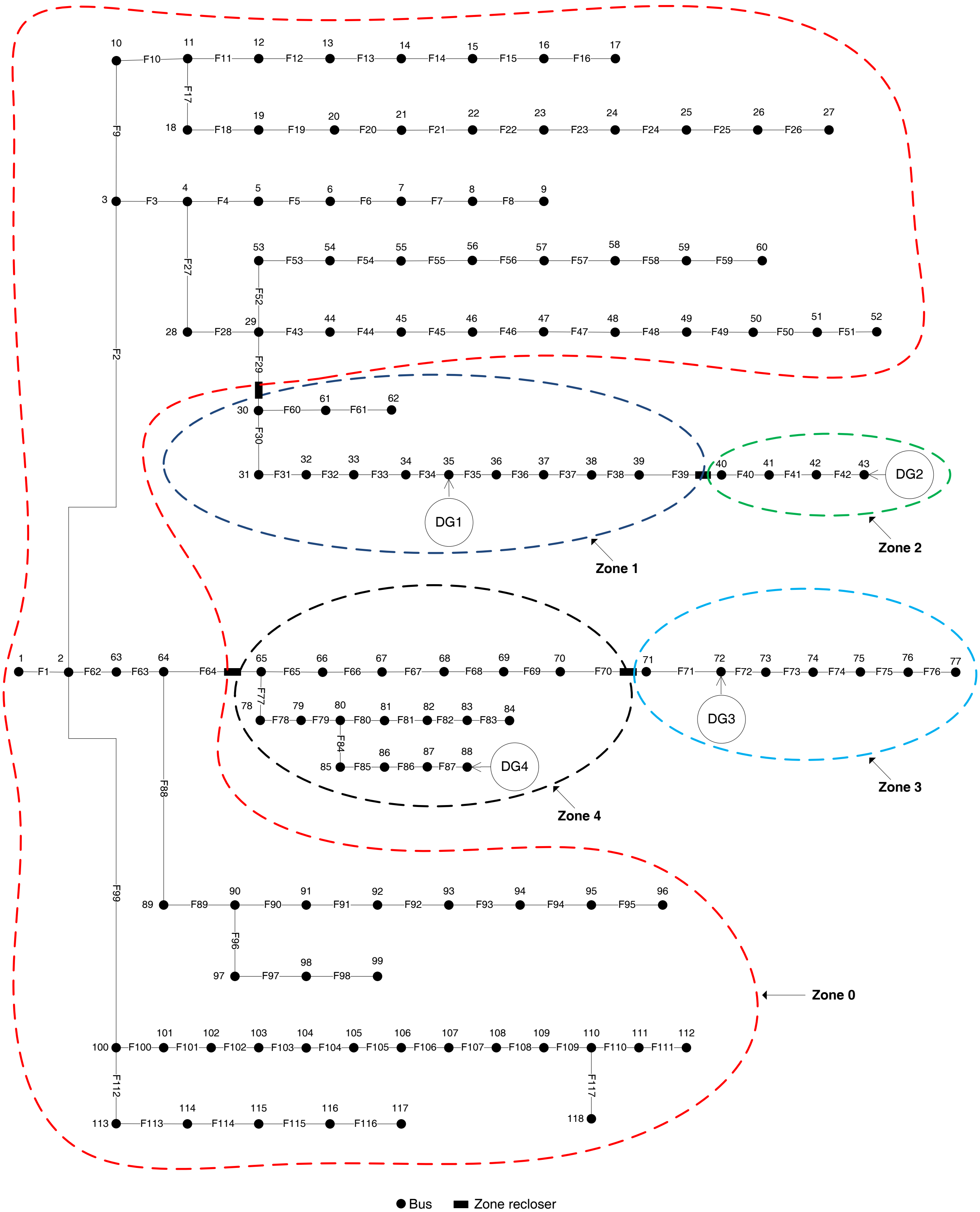

Figure 6.6: Zones of 118-bus distribution system with average values of DG generations and loads

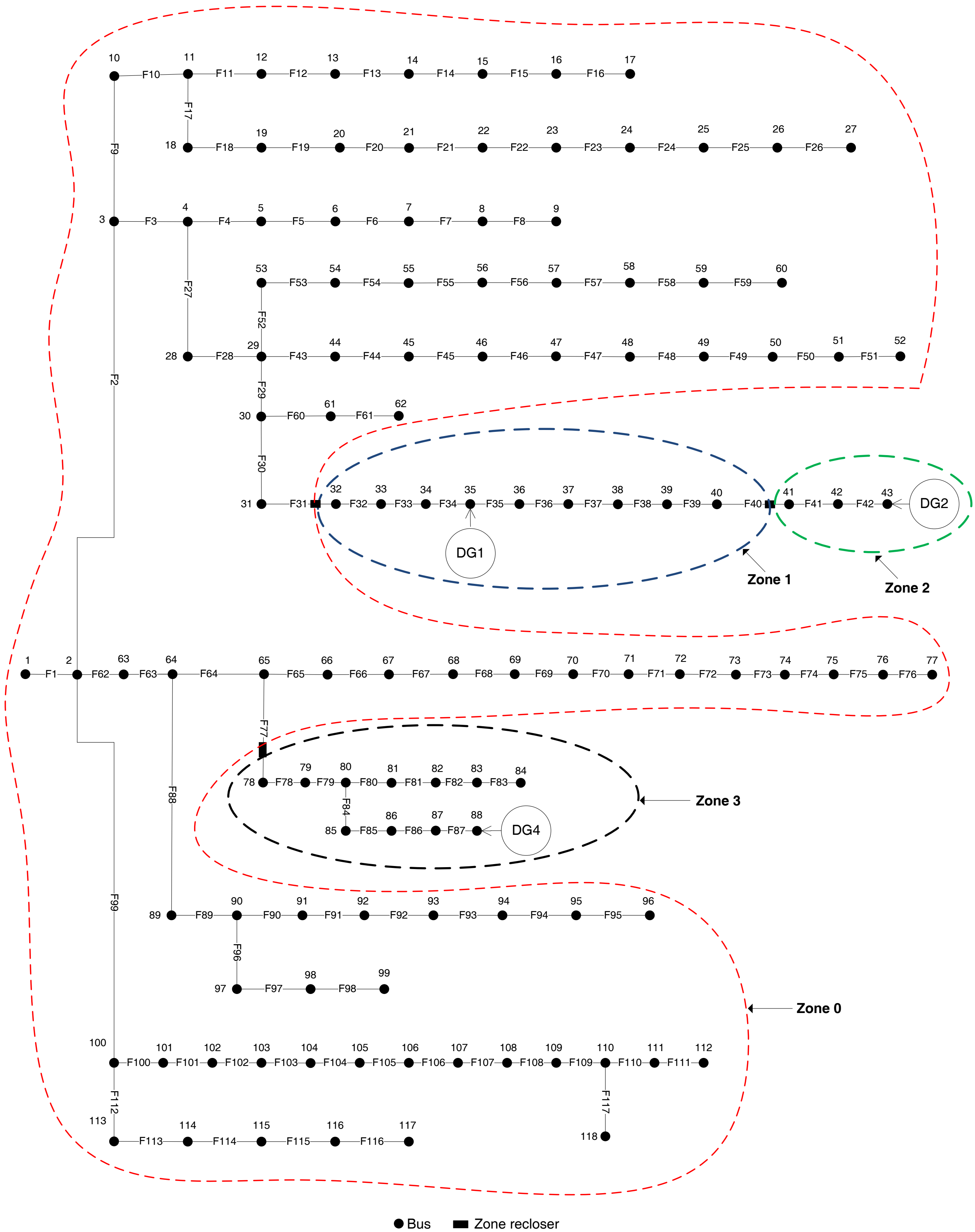

Figure 6.7: Zones of 118-bus distribution system considering uncertainties in DG generations and loads

Chapter 7

Conclusion and scope for future work

This chapter highlights the major findings of the work included in this thesis and suggests directions for future works in the area of protective devices' placement in distribution systems.

To begin with, a formulation for optimal placement of switches and reclosers in a distribution system has been proposed in Chapter 2, for maximizing distribution system reliability, while minimizing the associated investment and outage costs. The proposed formulation has been tested on 13-bus, 58-bus and IEEE 123-bus test systems using evolutionary programming (EP), genetic algorithm (GA), differential evolution (DE) and mixed-integer nonlinear programming (MINLP) methods. The results obtained establish the superiority of MINLP method over the other optimization methods for the said purpose. Further, it has been observed that the [BIBC] matrix is extremely effective in simplifying the identification of loads upstream and downstream of a feeder section.

The basic optimization problem, formulated in Chapter 2, considers only deterministic values of loads and system data. However, in order to carry out more realistic reliability calculations, uncertainties associated with system components' data need to be taken into account. To address this issue, a formulation for an optimal placement of switches and reclosers in a distribution system for maximizing the distribution system reliability considering uncertainties in load data, system failure and repair rates, has been presented in Chapter 3. The uncertainties have been incorporated in the formulation using 3PEM. The proposed formulation has been tested on 13-bus, 58-bus and IEEE 123-bus test systems using DE and MINLP methods. The results so obtained establish the effectiveness of inclusion of the data uncertainties in maximizing utilities' profits by providing the bounds of profit, and also in improving the distribution system reliability.

The formulation presented in Chapter 3, considered sustained interruptions (caused by permanent faults) only. However, due to the increased use of electronic and precision devices, damages due to the momentary interruptions have become a cause of concern. To address this issue, the effect of temporary faults has been incorporated, in Chapter 4, for optimizing the placement of protective devices in the distribution system. Three different scenarios, for optimal placement of protective devices (switches, reclosers, fuses) in a distribution system, considering uncertainties in loads, temporary and permanent failure rates and repair rates have been formulated. The three versions of the formulated problem (RS scheme, Fuse-blow scheme and Fuse-save scheme) have been solved for 58-bus and IEEE 123-bus distribution networks using MINLP optimization technique. To decrease the impact of momentary interruptions, Fuse-blow scheme is employed, while for reducing the impact of sustained interruptions, Fuse-save scheme is used. From the analysis of results for the test systems considered, it is concluded that for heavily loaded system (58-bus system), maximum profit is earned by the utility when Fuse-blow scheme is used, while for lightly loaded system (IEEE 123-bus system), maximum profit is obtained when Fuse-save scheme is adopted.

Apart from the above three scenarios of protective devices' placement in distribution system, other scenarios involving different combinations of protective devices are also feasible. Each scenario will yield a different optimal profit value for a given system. Hence, in order to identify the best scenario, a generalized model has been developed in Chapter 5. This model facilitates the placement of various combinations of protective devices (recloser, switch, fuse-blow fuse and fuse-save fuse) in a distribution network for maximizing utilities' profit. The formulated problems have been solved for 58-bus and IEEE 123-bus distribution networks using MINLP optimization technique. The results indicate that maximum profit is earned by the utility when the scenario employing the combination of the four protective devices viz. reclosers, switches, fuse-blow fuses and fuse-save fuses is used.

Distribution system reliability can be improved by connecting DGs to the system. It can be further enhanced through optimal placement of protective devices in various zones/islands of a distribution system with DGs. This enables the DGs of corresponding zones to operate in islanded mode in case a fault occurs in any part of the system. Chapter 6 incorporates the effect of DGs in the formulation of optimal placement problem of protective devices (recloser, switch, fuse-blow fuse and fuse-save fuse) in the distribution system. A model has been developed first to ascertain the system reliability in the presence of DGs and protective devices. Thereafter, optimal placement of the protective devices in various zones of a distribution system with DGs has been carried out. The uncertainties in temporary failure rates, permanent failure rates, repair rates and load data have been considered in the problem formulation using 3PEM. The formulated problem has been solved for 69-bus and 118-bus distribution systems using MINLP optimization technique. Analysis of the results for the two test systems, leads to the conclusion that the profit to the utility can be increased by the optimal placement of the protective devices in the zones associated with the DGs connected in the system. As the number of islands increases, more and more loads can be served by DGs or substation in case a fault occurs in the system. Therefore, profit to the utility increases as the number of zones increases.

7.1 Conclusions

Based on the work reported in this thesis, the major contributions in the area of placement of protective devices in the distribution system can be summarized as follows:

- For improving the distribution system reliability, switches and reclosers are to be optimally placed in the distribution system. The presence of switches/reclosers in the distribution system reduces the duration/frequency of interruptions. Comparison of the results obtained using EP, GA, DE and MINLP optimization methods establishes the effectiveness of the MINLP method in maximizing utilities' profit and improving the distribution system reliability. Further, it has been observed that the [BIBC] matrix is extremely effective in simplifying the identification of loads upstream and downstream of a feeder section.

- The uncertainties in load data, system failure rates and repair rates also need to be taken into account in order to perform more realistic reliability calculations. PEM based distribution system reliability evaluation method can efficiently incorporate these uncertainties in system parameters. Further, the calculated statistical parameters (mean and variance) of the objective function can be very useful in estimating the bounds of profit expected from planned switch and recloser placement project. This method can also help the utilities in taking a realistic investment decision based on the calculated values of robust profit (RP_β) and conditional robust profit (CRP_β).

- Momentary interruptions (due to temporary faults) should also be included in the formulation for the optimal placement of protective devices as they increase outage costs. To reduce the impact of momentary interruptions, Fuse-blow scheme is used, while for reducing the impact of sustained interruptions, Fuse-save scheme is preferred. From the analysis of results for the test systems considered, it is concluded that for heavily loaded system, maximum profit for the utility is obtained when Fuse-blow scheme is used. On the other hand, adoption of Fuse-save scheme for lightly loaded system, results in maximum profit.

- Various scenarios for placement of protective devices (recloser, switch, fuse-blow fuse, fuse-save fuse), in different combinations, in the distribution system are possible. For a given system, each scenario will give different optimal profit value to the utility. The results indicate that maximum profit to the utility is achieved by using the combination of all the four protective devices viz. reclosers, switches, fuse-blow fuses and fuse-save fuses.

- Reliability of distribution system can be improved further by optimal placement of protective devices in various zones of the system with DGs operating in islanding mode. The profit to the utility increases with the number of zones since as the number of zones increases, more and more loads can be served by DGs or substation in case of a fault in the system.

7.2 Scope for future work

- The optimal placement problem of protective devices in distribution system can be extended to include non-normal loads as well.
- The formulation of the problem of placement of protective devices can be modified to evaluate the reliability of the system having correlated normal/ non-normal loads.
- For finding the optimal locations and number of the protective devices in distribution system with DGs, the probability distribution function (p.d.f.) of DG can be considered along with p.d.f. of non-normal loads.

Publications from the research work

- A. Alam, V. Pant, and B. Das, ”Switch and recloser placement in distribution system considering uncertainties in loads, failure rates and repair rates,” *Electric Power Systems Research*, vol. 140, pp. 619 - 630, May 2016.

- A. Alam, M. Alam, V. Pant, and B. Das, ”Placement of protective devices in distribution system considering uncertainties in loads, temporary and permanent failure rates and repair rates”, *IET Generation Transmission & Distribution*. (DOI: 10.1049/iet-gtd.2017.0075 , Print ISSN 1751-8687, Online ISSN 1751-8695, Available online: 27 September 2017)

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Appendix A

Optimization Techniques

A.1 Evolutionary Programming (EP)

In this section of appendix, a brief overview of evolutionary algorithms (EAs) has been presented and then, evolutionary programming (EP) approach has been discussed. EAs are artificial intelligence methods, which mimic the natural evolutionary principles to constitute search and optimization problems. EAs have gained much popularity for solving different optimization problems due to their abilities of finding global optima efficiently at a rapid and robust convergence rate, regardless of nature/complexity level of the problem. EAs have following advantages over the existing classical optimization techniques [56]:

- EAs use multiple point search instead of single point search, thereby identifying more hills and valleys, and reducing the probability of getting stuck in local optima.
- EAs use payoff (fitness) functions directly for the search direction and do not require derivatives or any other auxiliary knowledge. Therefore, EAs can efficiently deal with non-smooth, non-continuous, and non-differentiable functions.
- EAs do not require any approximation in the optimization problems, which are quite often required in traditional optimization methods
- EAs uses probabilistic transition rules to select generations instead of deterministic rules, and hence, can search a complicated and uncertain area to find the global optima.
- Computation of each individual in the population is independent of others, and hence, EAs have inherent computational ability.
- EAs are more flexible and robust than the conventional optimization methods.

The EAs are based on the mechanics of natural selection such as: mutation, recombination, reproduction, selection, etc. Mutation randomly perturbs a candidate solution; recombination randomly mixes their parts so as to produce a novel solution; reproduction replicates the most optimal solution found in a population; and selection purges the poor solutions form a population. Starting form an initial generation of candidate solutions, EAs produce advanced generations with candidates, which are successively better suited to their environment.

EP is one type of EAs like Genetic Algorithm, Evolutionary Strategy, etc. EP algorithms use vectors, which contain a specified number of solutions. The solution vector is termed as population; number of solutions in a population represents population size; and each solution in a population is referred to as an individual, which contains the values of different variables for the problem under consideration. The various computational steps, involved in minimizing the optimization problems using an EP algorithm, are as following:

Step I. Initialization : An EP algorithm is initiated by generating a population of individuals and each variable of an individual is selected randomly from a uniform random number distribution within its feasible range. For example, if any variable j is bounded by its minimum value and maximum value, then this variable can be initialized using the following expression:

$$IP_{ij} = X_j^{Min} + U_{(0,1)} * (X_j^{Max} - X_j^{Min}) \tag{A.1}$$

where,
IP_{ij} = j^{th} variable in i^{th} individual of the initial population,
X_j^{Min} = Minimum value of j^{th} variable,
X_j^{Max} = Maximum value of j^{th} variable,
$U_{(0,1)}$ = A uniformly distributed random number between 0 and 1.

Step II. Calculation of fitness for initial population : In this step, the value of fitness function is calculated for each individual of the initial population, as generated in step I. The fitness function represents the desired objective function. Sometimes, the penalty terms reflecting the constraints, are also added to the objective function so as to develop the fitness function.

Step III. Creation of offspring population : The offspring population of solutions is created from the existing population through a mutation operator. Mutation operator randomly perturbs a candidate solution by adding a normally distributed noise. The degree of imposed random perturbation on any variable of an individual depends on the associated fitness of individual. Mathematically, it can be written as:

$$OP_{ij} = IP_{ij} + \mathit{NORM}(0, \sigma_{ij}^2) \tag{A.2}$$

where,

OP_{ij} = j^{th} variable in i^{th} individual of the offspring population,

$NORM(0, \sigma_{ij}^2)$ = A normally distributed random number with a mean value of zero and a standard deviation of σ_{ij}.

The value of σ_{ij} can be calculated as:

$$\sigma_{ij} = (X_j^{Max} - X_j^{Min})\{\frac{f_i - f^{Min}}{f^{Max} - f^{Min}} + a^r\} \tag{A.3}$$

where,

f_i = Value of fitness function corresponding to i^{th} individual of the existing population,

f^{Min} = Minimum value of fitness function within the existing population,

f^{Max} = Maximum value of fitness function within the existing population,

a = A positive number slightly less than unity,

r = Iteration number.

Step IV. Competition and selection : After generating the offspring population, the fitness is calculated for each individual in the offspring population in a similar manner as discussed in step II. The next stage in an EP based technique is the competition stage. In this stage, a new population is created from two existing (initial and offspring) populations by tournament scheme. In this scheme, each individual from initial population as well as offspring population undergoes a series of tournament with randomly selected opponents and gets a score. The score for an individual is calculated as:

$$S_i = \sum_{j=1}^{N_{Tour}} \alpha_j \tag{A.4}$$

where,

S_i = Score for i^{th} individual,

N_{Tour} = Number of tournaments faced by an individual,

The value of α_j is given as:

$$\begin{aligned} \alpha_j &= 1, \quad \text{if} f_i < f_k \\ &= 0, \quad \text{otherwise} \end{aligned} \tag{A.5}$$

where,

f_k = Fitness value for k^{th} individual, which is chosen randomly from initial and offspring populations.

After competition, the different individuals from initial and offspring populations are arranged according to the descending order of their scores and best individuals, equal to population size in count, are selected as parent for the next generation along with their fitness values. This completes one iteration of an EP based technique.

Step V. **Checking the stopping criterion** : At the end of each iteration, the difference between minimum and maximum values of parent population is calculated. If the difference is found to be lesser than a pre-specified tolerance, then the algorithm terminates, otherwise, steps III to V are repeated. EP algorithm can also be terminated when the optimal solution is not obviously improved or the number of iterations exceeds a pre-defined value.

The main stages of an EP based approach are illustrated in Fig. A.1 with the help of a flow chart.

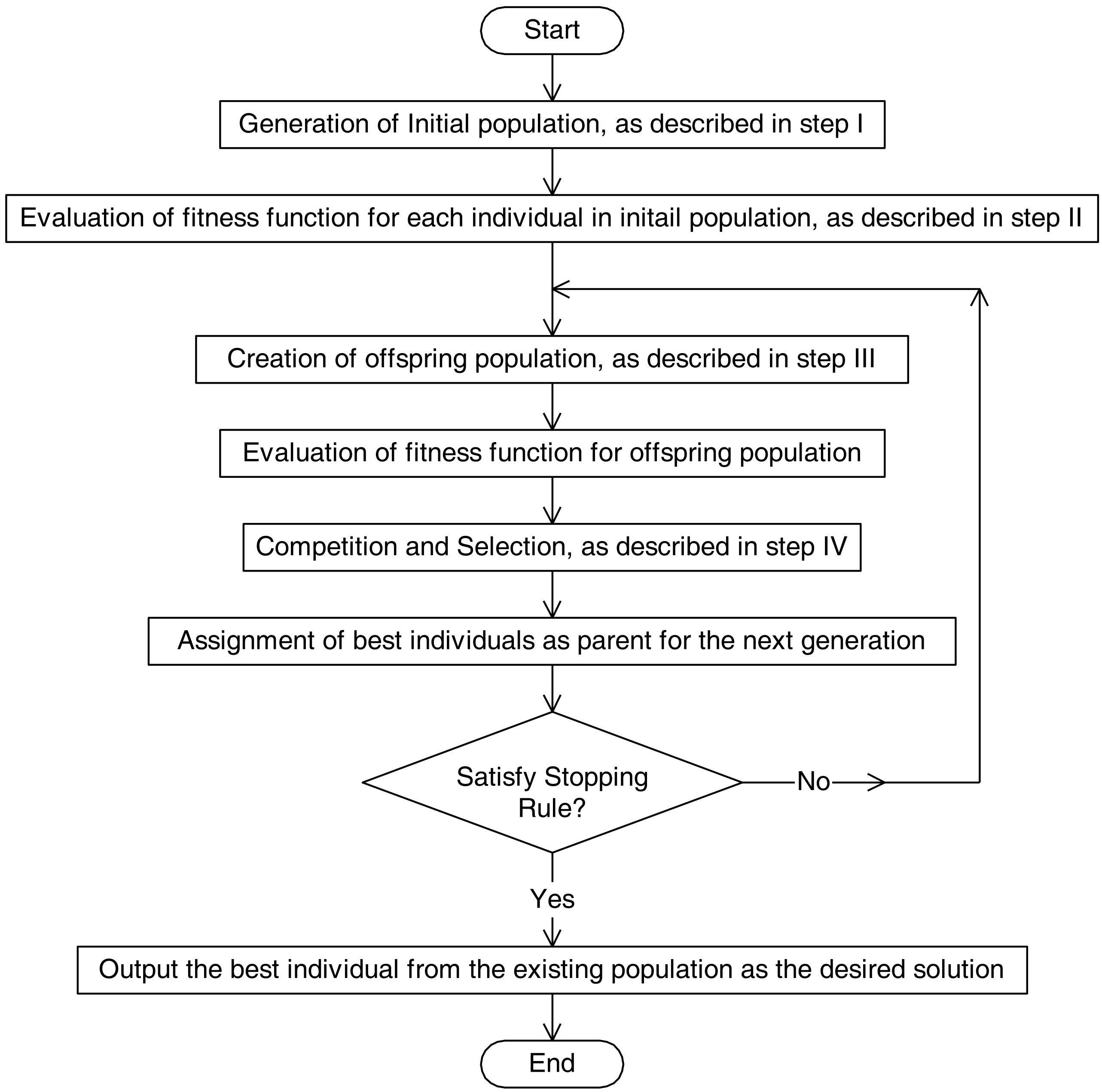

Figure A.1: Flow chart for Evolutionary Programming

A.2 Genetic Algorithm (GA)

Genetic algorithm (GA) is the heuristic optimization technique that mimics the process of natural evolution. Thus, GA implements the optimization strategies by simulating evolution of species through natural selection. GA is a global optimization technique that can be used for constrained as well as unconstrained optimization problems [74–77]. The three main rules employed by GA are selection, crossover and mutation [58]. The steps for implementing GA are as follows:

Step 1 Initialize the population (set of solutions).

Step 2 Calculate fitness value (quality of a solution) for each individual (solution to a problem) in the population. A fitness function value quantifies the optimality of a solution. The value is used to rank a particular solution against all the other solutions. A fitness value is assigned to each solution depending on how close it is actually to the optimal solution of the problem.

Step 3 Reproduce selected individuals to form a new population. Reproduction consists of forming a new population with the same total number of individuals by selecting from members of the current population with a stochastic process that is weighted by each of their fitness values.

Step 4 Perform Crossover and Mutation on the population.

Crossover is the process of exchanging portions of the strings of two parent individuals. An overall probability is assigned to the crossover process, which is the probability that, given two parents, the crossover process will occur. This crossover rate is often in the range of 0.65 to 0.80.

Mutation is the occasional introduction of new features in to the solution strings of the population pool to maintain diversity in the population. Mutation consists of flipping bits at random, generally with a constant probability for each bit in the population. The probability of mutation can vary widely according to the application and the preference of the user. Values of between 0.001 and 0.01 are usual for the mutation probability. This means that the bit at each site on the bit string is flipped, on average, between 0.1 and 1.0 percent of the time. One fixed value is used for each generation and often is maintained for an entire run.

Step 5 Move to step 2 until the stopping condition (convergence criterion) is met.

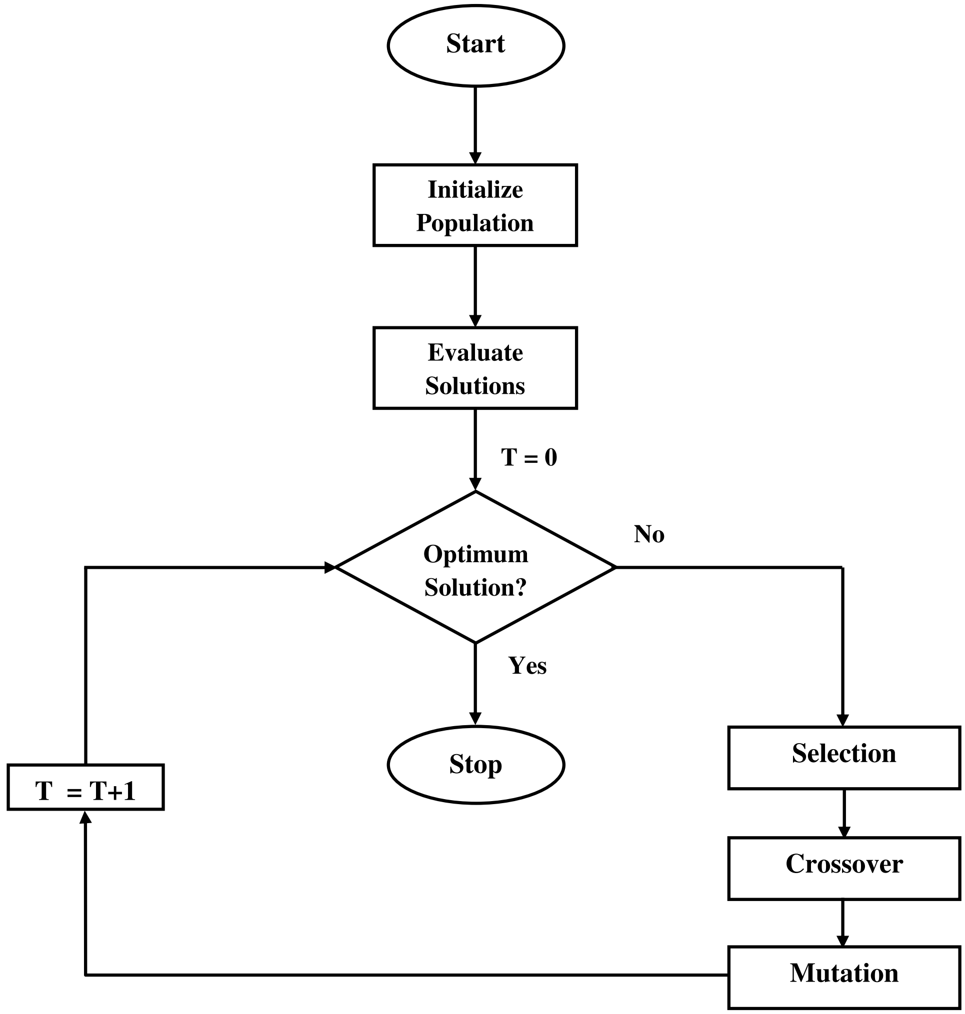

Figure A.2: Flow chart for Genetic Algorithm

A single encoding of part of the solution space is called *Gene* and a ”string of genes” is known as *Chromosome*. The number of chromosomes available to test form a *Population*. The main stages of a GA based approach are illustrated in Fig. A.2 with the help of a flow chart.

A.3 Differential Evolution (DE)

In this section, the various steps of differential evolution (DE) algorithm is briefly discussed whose detailed explanation can be found in [59]. DE algorithm was first proposed by Price and Storn in 1995 [78]. It is a simple, robust and effective optimization algorithm having only few control parameters [79]. However, like other conventional evolutionary algorithms, DE also has the defect of quick performance deterioration for large dimension of search space [80]. The steps of DE algorithm are as follows:

Step I. Population initialization : The initial population is randomly chosen which is a set of N_p, D-dimensional vectors,

$$x_{i,1}, \quad i = 1, 2, ..., N_p, \tag{A.6}$$

covering the entire parameter space. Here, N_p is the number of populations and D is the number of decision variables.

Step II. Mutation : Corresponding to each vector, $x_{i,Gen}, \quad i = 1, 2, ..., N_p,$ $Gen = 1, 2, ..., G_{max}$ known as target vector, a new modified vector known as mutant vector is generated as follows:

$$v_{i,Gen+1} = x_{k_1,Gen} + F(x_{k_2,Gen} - x_{k_3,Gen}) \tag{A.7}$$

Where, G_{max} is the maximum number of generations. k_1, k_2 and k_3 are mutually exclusive integers other than i and between 1 and N_p. F is a constant known as mutation factor having a value between 0 and 2 [59]. The process of generation of $v_{i,Gen+1}$ for 2-dimensional parameter vectors are depicted in Fig. A.3 [59].

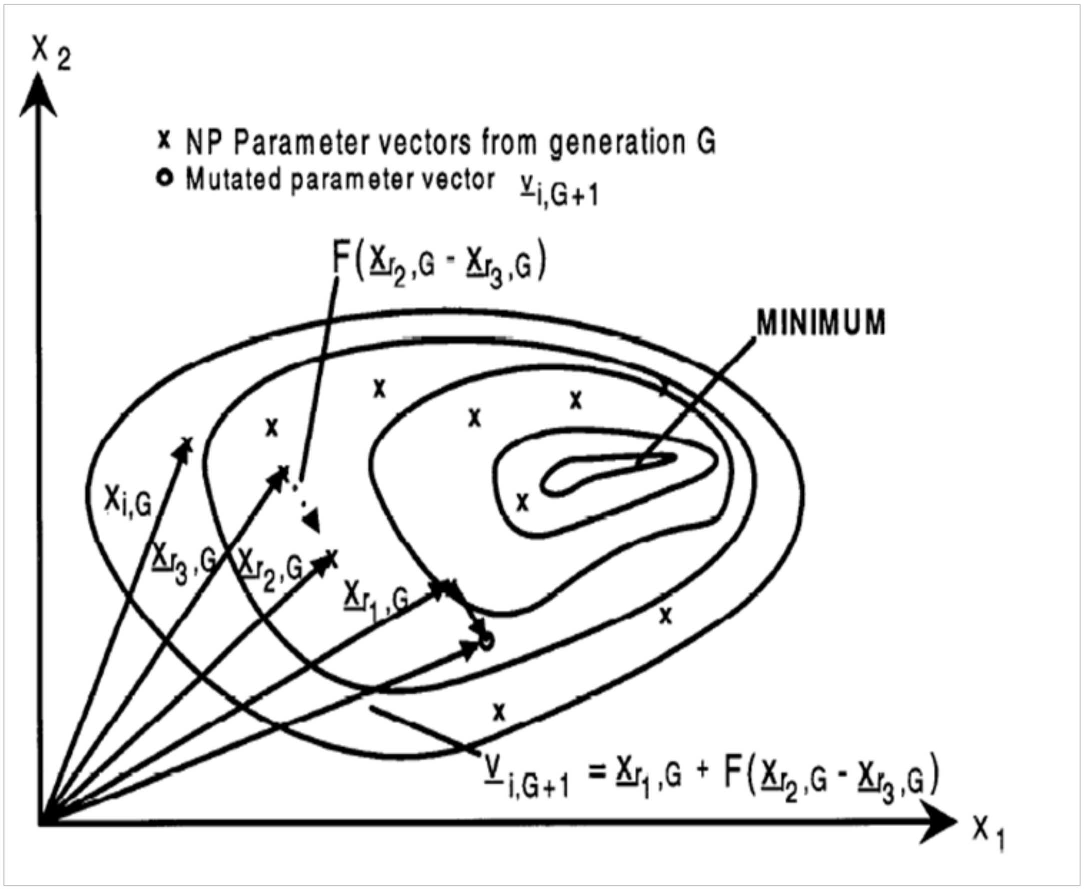

Figure A.3: Contour lines of a 2-dimensional cost function

Step III. Crossover : To increase the diversity of the parameter vectors, a new vector known as trial vector is generated as follows:

$$u_{i,Gen+1} = (u_{1i,Gen+1}, u_{2i,Gen+1}, ..., u_{Di,Gen+1}) \tag{A.8}$$

Where,

$u_{ji,Gen+1} = v_{ji,Gen+1}$, if $rand(j) \leq CR$ or $j = ranbk(i)$

otherwise, $u_{ji,Gen+1} = x_{ji,Gen+1}$, $\forall j = 1, 2, ..., D$.

$rand()$ is a uniform random number between 0 and 1, $ranbk()$ is randomly chosen index between 1 and D and CR is a constant known as crossover rate. Generally, the values of F and CR are taken as 0.5 and 0.4, respectively [62]. Fig. A.4 shows the crossover process for 7-dimensional parameter vectors [59].

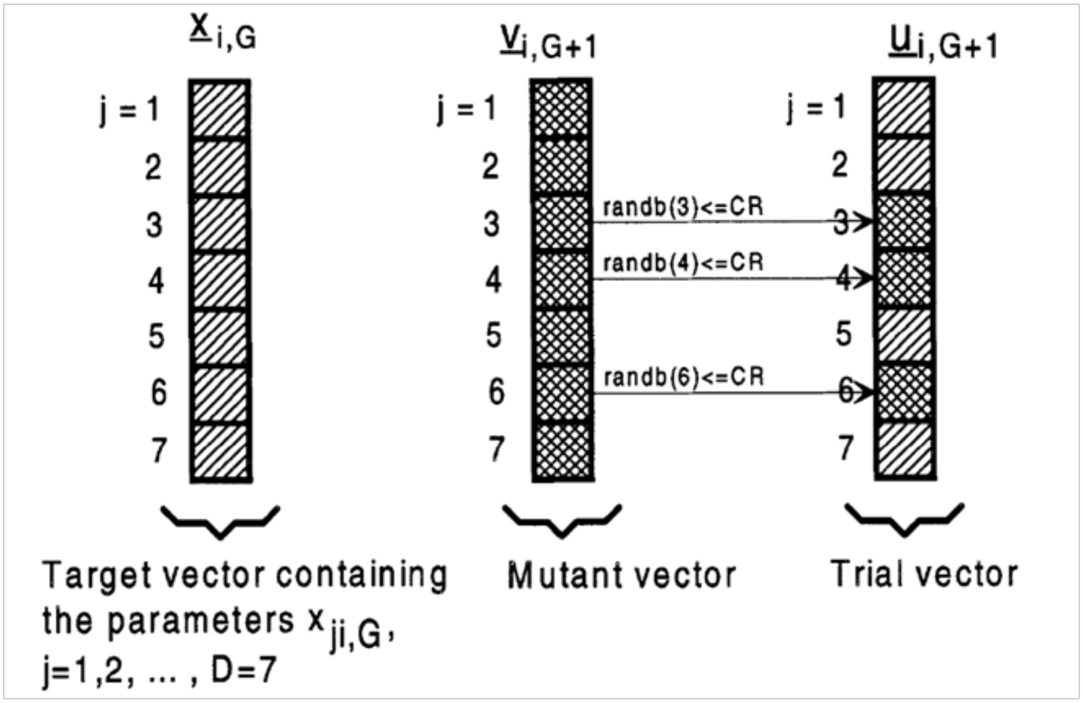

Figure A.4: Crossover process in DE

Step IV. **<u>Selection</u>** : The fitness values of 'target vector' and 'trial vector' are compared. If the fitness value of 'trial vector' is better than the 'target vector', then the 'target vector' is replaced by 'trial vector', otherwise fitness of the 'target vector' is retained, thereby generating an updated population.

Step V. **<u>Stopping criteria</u>** : Move to step II until the stopping condition (convergence criterion) is met.

A.4 Mixed-Integer Nonlinear Programming (MINLP)

In this section, mixed-integer nonlinear programming (MINLP) algorithm is briefly discussed whose details can be found in [81–84]. MINLP problems combine the mixed-integer linear programming (MILP) and nonlinear programming (NLP) as subproblems. It has continuous and discrete variables in the objective function and/or the constraints. The general form of a MINLP is given by,

$$\begin{aligned} \textit{minimize} \quad & f(x,y) \\ \textit{subject to} \quad & g(x,y) \leq 0 \\ & x \in X \quad Continuous \\ & y \in Y \quad Integer \end{aligned} \tag{A.9}$$

The functions f and g are nonlinear objective function and nonlinear constraint function, respectively. The two decision variables x and y are having bounding-box type restrictions. x is a continuous variable, whereas y is required to have integer values. The algorithm build for solving MINLP include the combination of Integer Programming (IP), Linear Programming (LP) and NLP, e.g., outer approximation, branch and bound, global optimization. The commercially available solvers used for MINLP are as follows [83]:

1. fminconset
2. alphaBB
3. AlphaECP
4. ANTIGONE
5. AOA
6. BARON
7. bnb
8. BONMIN
9. Couenne
10. CPLEX

11. DICOPT
12. FICO Xpress-Optimizer
13. FICO Xpress-SLP
14. FilMINT
15. Gurobi
16. Knitro
17. LaGO
18. LindoAPI
19. MIDACO
20. MILANO
21. MINLP BB
22. MINOTAUR
23. MISQP
24. MOSEK
25. OQNLP
26. SBB
27. SCIP

fminconset solver was developed by I. Solberg, and is available as MATLAB source. For convex MINLP, this solver guarantees for global optimal solution. It utilizes a branch-and-bound algorithm and for the bounding step, it makes use of nonlinear relaxations. The NLP subproblems of MINLP are solved by **fmincon** function available in the MATLAB optimization toolbox [85].

Appendix B

Data for 69-bus and 118-bus test systems

Table B.1: Line data for 69-bus test system

Feeder section	From bus	To bus	r (Ω)	x (Ω)	Feeder section	From bus	To bus	r (Ω)	x (Ω)
F1	1	2	0.0005	0.0012	F35	3	36	0.0044	0.0108
F2	2	3	0.0005	0.0012	F36	36	37	0.064	0.1565
F3	3	4	0.0015	0.0036	F37	37	38	0.1053	0.123
F4	4	5	0.0251	0.0294	F38	38	39	0.0304	0.0355
F5	5	6	0.366	0.1864	F39	39	40	0.0018	0.0021
F6	6	7	0.3811	0.1941	F40	40	41	0.7283	0.8509
F7	7	8	0.0922	0.047	F41	41	42	0.31	0.3623
F8	8	9	0.0493	0.0251	F42	42	43	0.041	0.0478
F9	9	10	0.819	0.2707	F43	43	44	0.0092	0.0116
F10	10	11	0.1872	0.0619	F44	44	45	0.1089	0.1373
F11	11	12	0.7114	0.2351	F45	45	46	0.0009	0.0012
F12	12	13	1.03	0.34	F46	4	47	0.0034	0.0084
F13	13	14	1.044	0.345	F47	47	48	0.0851	0.2083
F14	14	15	1.058	0.3496	F48	48	49	0.2898	0.7091
F15	15	16	0.1966	0.065	F49	49	50	0.0822	0.2011
F16	16	17	0.3744	0.1238	F50	8	51	0.0928	0.0473
F17	17	18	0.0047	0.0016	F51	51	52	0.3319	1.1114
F18	18	19	0.3276	0.1083	F52	9	53	0.174	0.0886
F19	19	20	0.2106	0.0696	F53	53	54	0.203	0.1034
F20	20	21	0.3416	0.1129	F54	54	55	0.2842	0.1447
F21	21	22	0.014	0.0046	F55	55	56	0.2813	0.1433
F22	22	23	0.1591	0.0526	F56	56	57	1.59	0.5337
F23	23	24	0.3463	0.1145	F57	57	58	0.7837	0.263
F24	24	25	0.7488	0.2475	F58	58	59	0.3042	0.1006
F25	25	26	0.3089	0.1021	F59	59	60	0.3861	0.1172
F26	26	27	0.1732	0.0572	F60	60	61	0.5075	0.2585
F27	3	28	0.0044	0.0108	F61	61	62	0.0974	0.0496
F28	28	29	0.064	0.1565	F62	62	63	0.145	0.0738
F29	29	30	0.3978	0.1315	F63	63	64	0.7105	0.3619
F30	30	31	0.0702	0.0232	F64	64	65	1.041	0.5302
F31	31	32	0.351	0.116	F65	11	66	0.2012	0.0611
F32	32	33	0.839	0.2816	F66	66	67	0.0047	0.0014
F33	33	34	1.708	0.5646	F67	12	68	0.7394	0.2444
F34	34	35	1.474	0.4873	F68	68	69	0.0047	0.0016

Table B.2: Bus data for 69-bus test system

Bus No.	P_{load} (kW)	Customer type	Bus No.	P_{load} (kW)	Customer type	Bus No.	P_{load} (kW)	Customer type	Bus No.	P_{load} (kW)	Customer type
2	0	1	19	0	1	36	26	2	53	4.35	2
3	0	1	20	1	3	37	26	2	54	26.4	3
4	0	1	21	114	3	38	0	1	55	24	2
5	0	1	22	5.3	1	39	24	2	56	0	1
6	2.6	1	23	0	1	40	24	1	57	0	2
7	40.4	1	24	28	2	41	1.2	2	58	0	3
8	75	2	25	0	1	42	0	2	59	100	1
9	30	1	26	14	2	43	6	1	60	0	2
10	28	1	27	14	1	44	0	1	61	1244	1
11	145	2	28	26	1	45	39.22	3	62	32	2
12	145	2	29	26	1	46	39.22	2	63	0	3
13	8	1	30	0	2	47	0	3	64	227	2
14	8	1	31	0	3	48	79	1	65	59	3
15	0	2	32	0	1	49	384.7	2	66	18	2
16	45.5	1	33	14	2	50	384.7	1	67	18	1
17	60	3	34	19.5	1	51	40.5	2	68	28	2
18	60	2	35	6	1	52	3.6	3	69	28	3

Table B.3: System failure data for 69-bus test system

Feeder section	λ (f/yr)	r (hrs)	Feeder section	λ (f/yr)	r (hrs)	Feeder section	λ (f/yr)	r (hrs)	Feeder section	λ (f/yr)	r (hrs)
F1	0.1	4	F18	0.1	2	F35	0.15	2	F52	0.1	4
F2	0.15	5	F19	0.1	4	F36	0.1	2	F53	0.15	5
F3	0.2	6	F20	0.15	5	F37	0.1	4	F54	0.2	6
F4	0.25	3	F21	0.2	6	F38	0.15	5	F55	0.25	3
F5	0.15	2	F22	0.25	3	F39	0.2	6	F56	0.15	2
F6	0.1	2	F23	0.15	2	F40	0.25	3	F57	0.1	2
F7	0.1	4	F24	0.1	2	F41	0.15	2	F58	0.15	2
F8	0.15	5	F25	0.1	4	F42	0.1	2	F59	0.1	2
F9	0.2	6	F26	0.15	5	F43	0.1	4	F60	0.25	3
F10	0.25	3	F27	0.2	6	F44	0.15	5	F61	0.15	2
F11	0.15	2	F28	0.25	3	F45	0.2	6	F62	0.1	2
F12	0.1	2	F29	0.15	2	F46	0.25	3	F63	0.1	4
F13	0.1	4	F30	0.1	2	F47	0.15	2	F64	0.15	5
F14	0.15	5	F31	0.1	4	F48	0.1	2	F65	0.2	6
F15	0.2	6	F32	0.15	5	F49	0.25	3	F66	0.25	3
F16	0.25	3	F33	0.2	6	F50	0.15	2	F67	0.15	2
F17	0.15	2	F34	0.25	3	F51	0.1	2	F68	0.1	2

Table B.4: Line data for 118-bus test system

Feeder section	From bus	To bus	r (Ω)	x (Ω)	Feeder section	From bus	To bus	r (Ω)	x (Ω)	Feeder section	From bus	To bus	r (Ω)	x (Ω)
F1	1	2	0	0	F40	40	41	0.12	0.0789	F79	79	80	0.266	0.1227
F2	2	3	0.036	0.01296	F41	41	42	0.405	0.1458	F80	80	81	0.266	0.1227
F3	3	4	0.045	0.0162	F42	42	43	0.405	0.1458	F81	81	82	0.266	0.1227
F4	4	5	0.015	0.054	F43	29	44	0.33	0.194	F82	82	83	0.233	0.115
F5	5	6	0.015	0.054	F44	44	45	0.31	0.194	F83	83	84	0.496	0.138
F6	6	7	0.015	0.0125	F45	45	46	0.13	0.194	F84	80	85	0.196	0.18
F7	7	8	0.018	0.014	F46	46	47	0.28	0.15	F85	85	86	0.196	0.18
F8	8	9	0.021	0.063	F47	47	48	1.18	0.85	F86	86	87	0.1866	0.122
F9	3	10	0.166	0.1344	F48	48	49	0.42	0.2436	F87	87	88	0.0746	0.318
F10	10	11	0.112	0.0789	F49	49	50	0.27	0.0972	F88	64	89	0.559	0.3687
F11	11	12	0.187	0.313	F50	50	51	0.339	0.1221	F89	89	90	0.186	0.1227
F12	12	13	0.142	0.1512	F51	51	52	0.27	0.1779	F90	90	91	0.186	0.1227
F13	13	14	0.18	0.118	F52	29	53	0.391	0.141	F91	91	92	0.26	0.139
F14	14	15	0.15	0.045	F53	53	54	0.406	0.1461	F92	92	93	0.154	0.148
F15	15	16	0.16	0.18	F54	54	55	0.406	0.1461	F93	93	94	0.23	0.128
F16	16	17	0.157	0.171	F55	55	56	0.706	0.5461	F94	94	95	0.252	0.106
F17	11	18	0.218	0.285	F56	56	57	0.338	0.1218	F95	95	96	0.18	0.148
F18	18	19	0.118	0.185	F57	57	58	0.338	0.1218	F96	90	97	0.16	0.182
F19	19	20	0.16	0.196	F58	58	59	0.207	0.0747	F97	97	98	0.2	0.23
F20	20	21	0.12	0.189	F59	59	60	0.247	0.8922	F98	98	99	0.16	0.393
F21	21	22	0.12	0.0789	F60	30	61	0.187	0.261	F99	2	100	0.0625	0.0265
F22	22	23	1.41	0.723	F61	61	62	0.133	0.099	F100	100	101	0.1501	0.234
F23	23	24	0.293	0.1348	F62	2	63	0.028	0.0418	F101	101	102	0.1347	0.0888
F24	24	25	0.133	0.104	F63	63	64	0.117	0.2016	F102	102	103	0.2307	0.1203
F25	25	26	0.178	0.134	F64	64	65	0.255	0.0918	F103	103	104	0.447	0.1608
F26	26	27	0.178	0.134	F65	65	66	0.21	0.0759	F104	104	105	0.1632	0.0588
F27	4	28	0.015	0.0296	F66	66	67	0.383	0.138	F105	105	106	0.33	0.099
F28	28	29	0.012	0.0276	F67	67	68	0.504	0.3303	F106	106	107	0.156	0.0561
F29	29	30	0.12	0.2766	F68	68	69	0.406	0.1461	F107	107	108	0.3819	0.1374
F30	30	31	0.21	0.243	F69	69	70	0.962	0.761	F108	108	109	0.1626	0.0585
F31	31	32	0.12	0.054	F70	70	71	0.165	0.06	F109	109	110	0.3819	0.1374
F32	32	33	0.178	0.234	F71	71	72	0.303	0.1092	F110	110	111	0.2088	0.0753
F33	33	34	0.178	0.234	F72	72	73	0.303	0.1092	F111	111	112	0.2301	0.0828
F34	34	35	0.154	0.162	F73	73	74	0.206	0.144	F112	100	113	0.6102	0.2196
F35	35	36	0.21	0.1383	F74	74	75	0.233	0.084	F113	113	114	0.1866	0.127
F36	36	37	0.12	0.0789	F75	75	76	0.591	0.1773	F114	114	115	0.3732	0.246
F37	37	38	0.15	0.0987	F76	76	77	0.126	0.0453	F115	115	116	0.405	0.367
F38	38	39	0.15	0.0987	F77	65	78	0.669	0.2412	F116	116	117	0.489	0.438
F39	39	40	0.24	0.1581	F78	78	79	0.266	0.1227	F117	110	118	0.2445	0.0879

Table B.5: Bus data for 118-bus test system

Bus No.	P_{load} (kW)	Customer type	Bus No.	P_{load} (kW)	Customer type	Bus No.	P_{load} (kW)	Customer type	Bus No.	P_{load} (kW)	Customer type
2	0	1	32	475.25	2	62	440.52	3	92	243.53	1
3	150.054	1	33	151.43	1	63	478.8	2	93	243.53	1
4	34.315	1	34	205.38	1	64	120.94	3	94	134.25	1
5	73.016	1	35	131.6	2	65	139.11	2	95	22.71	1
6	144.2	1	36	66.195	2	66	391.78	1	96	49.513	1
7	104.47	2	37	73.904	1	67	27.741	2	97	383.78	1
8	28.547	1	38	114.77	2	68	52.814	3	98	49.64	1
9	87.56	1	39	918.37	1	69	66.89	1	99	22.473	1
10	198.2	2	40	210.3	2	70	467.5	1	100	100.66	1
11	146.8	2	41	66.68	2	71	594.85	1	101	456.48	1
12	26.04	1	42	42.207	1	72	132.5	1	102	522.56	1
13	52.1	1	43	433.74	1	73	52.699	1	103	408.43	1
14	141.9	2	44	112.54	3	74	869.79	1	104	141.48	1
15	21.87	1	45	53.963	2	75	31.349	1	105	104.43	1
16	33.37	3	46	393.05	3	76	192.39	1	106	96.793	1
17	32.43	2	47	326.74	1	77	65.75	1	107	493.92	1
18	20.234	1	48	536.26	2	78	62.93	1	108	225.38	1
19	156.94	3	49	76.247	1	79	30.67	1	109	509.21	1
20	546.29	3	50	53.52	2	80	62.53	1	110	188.5	1
21	180.31	1	51	40.328	3	81	114.57	1	111	305.08	1
22	93.167	1	52	39.653	2	82	81.292	1	112	54.38	1
23	85.18	2	53	62.1	3	83	31.733	1	113	211.14	1
24	168.1	1	54	92.46	2	84	33.32	1	114	67.009	1
25	125.11	2	55	85.188	1	85	531.28	1	115	162.07	1
26	16.03	1	56	345.3	2	86	507.03	1	116	48.785	1
27	26.03	1	57	22.5	3	87	26.39	1	117	33.9	1
28	594.56	1	58	80.551	1	88	45.99	1	118	918.03	1
29	120.62	2	59	95.86	2	89	238.15	1			
30	102.38	3	60	62.92	1	90	294.55	1			
31	513.4	1	61	448.4	2	91	485.57	1			

Table B.6: System failure data for 118-bus test system

Feeder section	λ (f/yr)	r (hrs)	Feeder section	λ (f/yr)	r (hrs)	Feeder section	λ (f/yr)	r (hrs)	Feeder section	λ (f/yr)	r (hrs)
F1	0.1	4	F31	0.15	5	F61	0.15	2	F91	0.15	2
F2	0.15	5	F32	0.2	6	F62	0.1	2	F92	0.1	2
F3	0.25	3	F33	0.25	3	F63	0.1	4	F93	0.1	4
F4	0.15	2	F34	0.15	2	F64	0.15	5	F94	0.15	5
F5	0.1	2	F35	0.1	2	F65	0.2	6	F95	0.2	6
F6	0.1	4	F36	0.1	4	F66	0.25	3	F96	0.25	3
F7	0.15	5	F37	0.15	5	F67	0.15	2	F97	0.15	2
F8	0.2	6	F38	0.2	6	F68	0.1	2	F98	0.1	2
F9	0.25	3	F39	0.25	3	F69	0.1	4	F99	0.1	4
F10	0.15	2	F40	0.15	2	F70	0.15	5	F100	0.15	5
F11	0.1	2	F41	0.1	2	F71	0.2	6	F101	0.2	6
F12	0.1	4	F42	0.1	4	F72	0.25	3	F102	0.25	3
F13	0.15	5	F43	0.15	5	F73	0.15	2	F103	0.15	2
F14	0.2	6	F44	0.2	6	F74	0.1	2	F104	0.1	2
F15	0.25	3	F45	0.25	3	F75	0.1	4	F105	0.25	3
F16	0.15	2	F46	0.15	2	F76	0.15	5	F106	0.15	2
F17	0.1	2	F47	0.1	2	F77	0.2	6	F107	0.1	2
F18	0.1	4	F48	0.25	3	F78	0.25	3	F108	0.1	4
F19	0.15	5	F49	0.15	2	F79	0.15	2	F109	0.15	5
F20	0.2	6	F50	0.1	2	F80	0.1	2	F110	0.2	6
F21	0.25	3	F51	0.1	4	F81	0.1	4	F111	0.25	3
F22	0.15	2	F52	0.15	5	F82	0.15	5	F112	0.15	2
F23	0.1	2	F53	0.2	6	F83	0.2	6	F113	0.1	2
F24	0.1	4	F54	0.25	3	F84	0.25	3	F114	0.1	4
F25	0.15	5	F55	0.15	2	F85	0.15	2	F115	0.15	5
F26	0.2	6	F56	0.1	2	F86	0.1	2	F116	0.2	6
F27	0.25	3	F57	0.1	4	F87	0.1	4	F117	0.25	3
F28	0.15	2	F58	0.15	5	F88	0.15	5			
F29	0.1	2	F59	0.2	6	F89	0.2	6			
F30	0.1	4	F60	0.25	3	F90	0.25	3			