Optimal Sectionalizer Placement in Radial Distribution System using Mutation Assisted Particle Swarm Optimization

Dissertation submitted in partial fulfillment of the requirements for the award of the degree of

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CERTIFICATE

I hereby certify that the work which is being presented in the dissertation entitled, **"Optimal Sectionalizer Placement in Radial Distribution System using Mutation Assisted Particle Swarm Optimization"** in partial fulfillment of the requirement for the award of the Degree of *Master of Engineering* in **Power Systems** and submitted in the ***Electrical & Instrumentation Engineering Department*** of the **THAPAR UNIVERSITY** is an authentic record of my own work carried out under the supervision of **Dr. Sanjay K. Jain**, Associate Professor, EIED.

The matter presented in this dissertation has not been submitted for the award of any other degree of this or any other University.

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

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Abstract

The placement of switches in distribution system is important and an inevitable pre-requisite in the electric power industry. As the distribution system are more prone to disturbances, the availability of supply to the customer is affected and so the cost of electricity and reliability. Therefore, achieving reliability levels by concurrently minimizing the total societal cost that includes utility investment cost and customer interruption cost are important issues.

In this dissertation, a value-based reliability planning approach is utilized to determine the number and location of sectionalizers. A solution methodology based on the heuristic Mutation Assisted Particle Swarm Optimization (MAPSO) is proposed to avoid premature convergence of PSO. The mutation operator is directed to come out from local minima to such discrete value problem. The location of circuit-breaker is predetermined in the feeder by default. The optimization is directed to utilize total cost which is the sum of system expected outage cost (ECOST) and switches cost, in association with system average interruption duration index (SAIDI) as two single objective functions. The proposed method is also implemented to solve total cost and SAIDI simultaneously using fuzzy decision making (FDM) approach. The performance of the proposed optimization method has been tested on 12-bus, 33-bus and 47-bus distribution system. The effect of section length on optimal placement of sectionalizer is also studied.

Contents

List of Figures

List of Tables

Chapter–1

INTRODUCTION

1.1 OVERVIEW

The primary function of the electric power system is to supply its customers an adequate supply as efficiently as possible with a reasonable degree of reliability. With growing demand and the pattern of the working habits of modern society, the utility have to continually provide uninterrupted power supply to its customers. However, it is not feasible to design a power system with 100% reliability. Power system engineers and managers therefore strive to obtain high level distribution reliability within socio-economic constraints.

In the power system context, the reliability can be defined as concern regarding the systems ability to provide an adequate supply of electrical energy [1]. Many utilities quantitatively measure the precedent performance of their systems and make use of the indices in a wide variety of managerial activities and assessments. Over the years, the distribution system has obtained considerably less consideration over reliability modelling compared to generating and transmission system. The reason behind this is the severe consequences of generating and transmission systems insufficiency for both environment and society. On the other hand, a distribution system is comparatively cheaper than the other two systems due to its localized effect. But, an analysis of the customer failure info shows that distribution system makes the maximum individual involvement to the unavailability of customers supply. The distribution systems account for upto 90% of all customer reliability problems, improving distribution reliability is the key to improving customer reliability [2].

1.1.1 *Hierarchial Levels of Power Systems*

Overall reliability evaluation of a power system involves a broad analysis of its three major functional zones of generation, transmission and distribution system. The fundamental techniques for adequacy assessment are commonly classified in terms of their function to each one of these zones. To obtain three distinct hierarchical levels of power system, the functional zones are combined as shown in Fig. 1.1. The adequacy assessment can be performed at each of these hierarchical levels with different requirements to be examined [3]. At HL-I, the generation system adequacy is to meet the load requirements and commonly referred as generating capacity reliability evaluation. HL-II adequacy assessment comprises of generation and the associated transmission system facilities. It is referred to as composite system adequacy evaluation. HL-III adequacy assessment takes into account the consideration of all three functional zones in order to calculate customer load point indices.

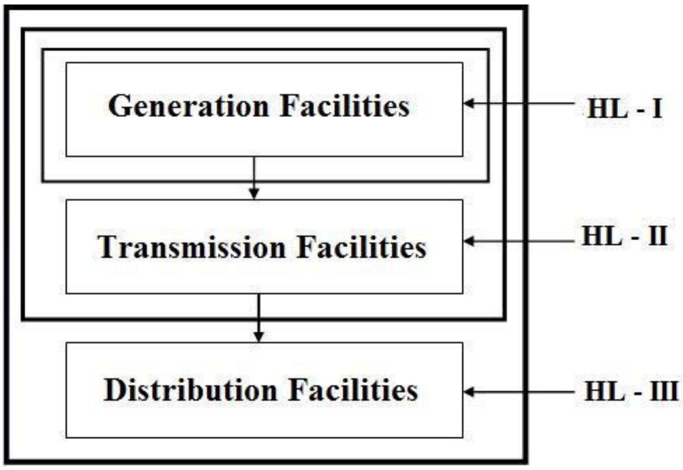

Fig. 1.1 Hierarchical levels in an electric power system

The traditional vertically integrated utility arrangement consisting of generation, transmission and distribution functional zones, as shown in Fig. 1.1, sometimes decomposed into distinct utilities in which each execute a particular function on the whole electrical energy delivery structure. Competitive pricing and deregulation also make it achievable for consumers to select their supplier based on price effectiveness. There is also a developing utilization of local generation set in the distribution functional zone. The individual section capacities may be quite little, but the total could be a considerable component of the total needed generation capacity. Over the last decade, power system structures have changed significantly and are still reforming with increasing demand of consumers. The fundamentals of reliability evaluation expanded over many decades remain equally applicable in the latest operating environment. However, the objectives of reliability evaluation have to be restructured and reformulated to meet the new paradigm.

1.1.2 *Need of Availability in Distribution System*

A distribution system is comparatively low-cost and service outages have a much localized effect than generating and transmitting systems. Therefore a lesser amount of attention has been given to quantitative assessment of distribution system for better designs and reinforcements. But, statistics of a particular distribution UK utility as shown in Table 1.1 reinforce the need of the reliability evaluation of distribution system due to their greatest contribution to interrupt supply to customers [1].

Table 1.1 Typical customer unavailability statistics

	Average unavailability per Customer per year	
CONTRIBUTOR	MINUTES	(%)
GENERATION&TRANSMISSION	0.5	0.5
132kV	2.3	2.4
66kV & 33kV	8.3	8.4
11kV & 6.6kV	58.8	60.7
LOW VOLTAGES	11.5	11.9
ARRANGED SHUTDOWNS	15.7	16.2
TOTAL	96.8	100

To evaluate the reliability indices in distribution system various aspects need to be considered. Firstly, even though a reinforcement plan may be relatively cheap, large sums of money are used collectively. Secondly, it is necessary to maintain a rational balance between reliability of various parts of a power system structure. Thirdly, a number of choices are accessible to the distribution engineer in order to attain allowable utility and customer reliability, including allocation of protection devices, alternative operating policies, alternative reinforcement scheme, improvements in maintenance policy, etc. These issues are now fully identified and an increasing number of utilities throughout the nation are introducing and regularly making use of quantitative reliability techniques [3].

1.2 LITERATURE REVIEW

The review of the literature is presented in brief to compliment the work done by authors in the area of switch placement and reliability computation in distribution system.

Billinton and Allan [1] gave the good compilation on quantitative reliability evaluation and significance of probability methods to problems concerning power system and its reliability. The reliability aspects in perspective described philosophical aspects and hierarchical framework of analysis.

Brown [2] consolidated pertinent topics on electric power distribution into one comprehensive volume balancing theory, practical knowledge, and real world applications. The service interruptions caused by various factors and strategies to develop reliability were discussed and incorporated into the component and system models.

Billinton and Allan [3] discussed philosophical characteristics concerning power-system reliability and illustrated the reliability features in perspective with hierarchical framework. To imitate the severity of a system outage, various reliability indices were evaluated.

Kennedy and Eberhart [4] introduced a concept for the nonlinear function optimization using particle swarm methodology and described the relationships between particle swarm optimization and both genetic algorithms and artificial life.

Esmin et al. [5] implemented PSO for developing an optimal power flow based on function of loss minimization. The tangent vector technique was used to identify the critical area of power system on the point of view of voltage stability.

Eberhart and Shi [6] focused on the computer science and engineering aspects of resources, applications and developments related to PSO, since its origin was reviewed. The tracking dynamic systems, inertia weights and constriction factors were briefly discussed for evaluating the performance of the optimization technique.

Moradi and Fotuhi-Firuzabad [7] developed and presented a three-state approach stimulated from the discrete version PSO, to determine the optimum number and locations of sectionalizers and breakers in radial distribution systems.

Rosendo and Pozo [8] described a hybrid PSO algorithm that utilizes path relinking and maintains the concept of the velocity update of the particles explored in PSO. A set of experiments was elaborated with the traveling salesman problem and the results were compared to other art metaheuristics.

Andrews [9] compared different mutation operators for PSO and empirically investigate them to enhance optimization performance. The PSO technique was integrated with a different mutation operator to avoid untimely converging on local optima.

Rugthaicharoencheep and Chalangsut [10] demonstrated reliability benefit with the objective for the optimal sizing and placement of distributed generators in an electric power distribution system to minimize the customer interruption cost using a tabu search algorithm and reliability worth analysis.

Chowdhury and Koval [11] presented the value-based assessment to an existing industrial distribution system arrangement to reduce interruptions cost. It suggests that development plans of an industrial distribution system can be optimized in terms of reliability and minimize the sum of economic of both the electric utilities and their customers.

Tippachon and Rerkpreedapong [12] presented an optimization technique for optimal switch and protective device placement in an electric power distribution system using multi-objective ant colony optimization. The formulation supported the minimization of the total cost of the system while simultaneously minimizing reliability indices.

Christopher Kigen and Odero [13] modeled a coordinated network controller as an optimization problem to maintain an optimal voltage profile in a radial distribution system along with distributed generation using PSO and the improvement in the voltage profile has been shown.

Jabbari et al. [14] proposed a multi-objective fuzzy adaptive particle swarm optimization algorithm to find the optimal location of automatic voltage regulators (AVRs) in the distribution system at the presence of distributed generators. The obtained results were compared with other evolutionary algorithms.

Chao [15] proposed a Dijkstra shortest path search algorithm through setting search space, pre-processing to eliminate redundant vertices and improving data structure. The results were analyzed before and after improvement through the simulation outcomes.

Madhav et al. [16] proposed a mixed-integer particle swarm optimization for determining optimal numbers and location of switches in a distribution system to achieve the required level of service availability. The reliability indices and profit on various automatic switches were calculated using a network equivalent technique.

Falaghi et al. [17] modeled Fault Indicators (FIs) to reduce fault localization and hence reduction in outage cost and outage duration. FIs allowed operators to identify the location of the fault in reliability assessment and compute reliability indices. Alekhya et al. [18] emphasized on feeder automation in distribution system using the theory of optimal switch placement in the quantitative reliability assessment. The means of automating a system using two- stage restoration for the reliable and economic-technical efficiency.

Panah et al. [19] introduced an approach to locate the place and number of remote control switches in distribution systems to have least consumers out of service using tabu search. Chen et al. [20] presented the immune algorithm (IA) to obtain the optimum location of switching devices by reducing the investment cost of switches and system cost of customer service outage.

The load flow is giving the steady state solution and has been reported widely in various literature. Teng [21] utilized the topological characteristics of radial distribution networks to make the direct load flow solution using two matrices namely, the bus-injection to branch-current matrix and the branch-current to bus voltage matrix and their simple matrix multiplication.

Billinton and Jonnavithula [22] introduced for a combinatorial constrained sectionalizer placement optimization problem using simulated annealing. A solution methodology determine the number of sectionalizing switches and the locations in the distribution system considering the reliability, maintenance and investment cost parameters.

Chowdhury and Koval [23] presented a framework of practical reliability problems in planning and operating electric power distribution system to confirm the results generated by commercial computer programs.

Elmakias [24] described the mathematical tool for reliability analysis and optimization techniques for reliability improvement in distribution systems and presented optimal insulation and sectionalizing methodologies.

1.3 OBJECTIVE OF THE WORK

The service continuity statistics in the different countries reflect the need of distribution automation to supply a more economical and reliable electric power to the consumers. Therefore, determination of optimum location and number of switches in distribution system automation is an important concern from a reliability point of view. In this dissertation, the work has been carried out with the objective to minimize the total cost and system average interruption duration index (SAIDI) to allocate the sectionalizers using mutation assisted particle swarm optimization technique. For true optimization, both the objectives should be accounted simultaneously and effectiveness be checked for different test systems.

1.4 ORGANISATION OF THE DISSERTATION

The worked carried out in this dissertation is organized in six chapters. The **Chapter 1** deals with brief overview, literature review, objective of the work and organization of the dissertation. The **Chapter 2** explains switch Placement using MAPSO and pseudo-code. The **Chapter 3** describes the formulation of distribution feeder problem. The **Chapter 4** highlights the value based reliability planning with illustrative example. The **Chapter 5** includes results and discussions pertaining to various cases. The **chapter 6** summarizes the conclusions and the scope of the future work.

Chapter–2

SWITCH PLACEMENT USING MAPSO

2.1 INTRODUCTION TO PSO

Particle swarm optimization technique (PSO) can be applied for the determination of the optimum number and location of sectionalizers in distribution system automation. PSO inspired by social behavior of bird flocking or fish schooling is a population-dependent stochastic optimization technique to solve nonlinear functions developed by Eberhart and Kennedy in 1995, [4]. The PSO technique is supposed to have lesser parameters than a Genetic Algorithm and does not stop at local maxima or minima in favor of global ones. This technique has several aspects of applications, developments and resources in engineering, computer science and medical science fields [5], [6]. Particle Swarm Optimization technique has been developed through simulation of various social models. The characteristics of the technique are as follows [7]:

- The optimization technique is based on studies about swarms such as a flock of birds and fish schooling.
- It is based on an easy concept. Therefore, requires few memories and short computational time.
- It was earlier developed for nonlinear optimization difficulties with continuous variables.

2.2 CONTINUOUS VERSION OF PSO

Particle swarm, a metaphor of social interactions of individuals find optimal points of complex multidimensional space by adjusting the paths of individual vectors, referred to as “particles”. They move stochastically toward the path decided by their own last performances and their neighbors best last performance. The algorithm initially treats problems with continuous variables which later on expanded to discrete variables. Some of the advantages and principles of PSO algorithm which makes it better than other heuristic algorithm are as follows [7]:

- PSO is based on the concept that the probability of discovering a better minimum near the as far as this found minimum is quite more than the other places in the search space. The particles (solutions) are therefore turning toward finding around the found minimum.
- It is a history-based optimization algorithm such that particles make use of their individual behavior linked with the previous iterations in each step.
- PSO has fewer parameters and easy to implement as compared to the other evolutionary optimization algorithms, such as Genetic Algorithm.

Consider the arrangement of a swarm population having each swarm dimension is $M \times N$ matrix where $M$and N are, respectively, the number of swarm size and swarm dimension. The greater the value of M, the more multidimensional search there over the searching space. There is, however, a trade-off between the computational time and convergence rate required for each iteration. Therefore, swarm size more than a particular value does not have any effect on the performance of the algorithm. N is decided based on the number of problem variables that is to be optimized.

In the initial step of the technique, the PSO is assigned to a group of particles which search for optimal location by updating generations. In each generation, each particles position is modified by the "pbest" and "gbest" values. The "pbest" is best solution obtained by each particle with respect to its performances in all previous generations and known as particle best solution, whereas "gbest" is the best value acquired by any of the agent in all previous iterations called global best solution. Considering these two values swarm updates its position and velocity as shown in Fig. 2.1.

$$V(t+1) = V(t) + C_1 \times rand_{1,t} \times (pbest(t) - X(t)) + C_2 \times rand_{2,t} \times (gbest(t) - X(t)) \tag{2.1}$$

$$X(t+1) = X(t) + V(t+1) \tag{2.2}$$

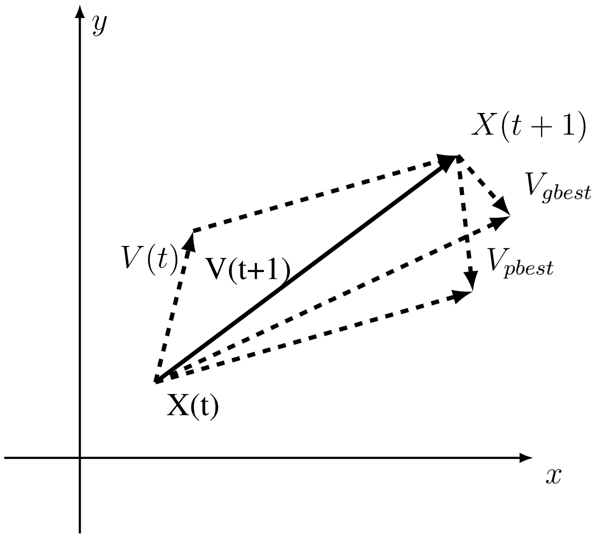

Fig. 2.1 Concept of modification of a searching point

where,

t = iteration number;

$V(t)$ = particle velocity at iteration number t;

$X(t)$ = particle position at iteration number t;

$pbest(t)$ = particle best solution at iteration number t;

$gbest(t)$ = global best solution at iteration number t;

$rand_{1,t}$ = random number one, between $(0, 1)$ at iteration number t;

$rand_{2,t}$ = random number two, between $(0, 1)$ at iteration number t;

C_1, C_2 = learning factors (Usually $C_1 = C_2 = 2$).

The learning factors C_1, C_2 have significant impacts on the convergence rate and must be valued experimentally. The first term of the RHS of eq. 2.1 signifies to diversify as the agent tries to discover new areas and the rest two terms of that are corresponding to intensify in the search procedure. Without intensification, the agent will continue “flying” in the one direction until and unless it hits the boundary. On the other hand, in the absence of the first term, the velocity of the “flying” agent is only decided by using its present position and its best positions in history.

2.3 DISCRETE VERSION OF PSO

Discrete binary version of PSO works on the same principle as continuous version and has been applied to various combinatorial problems [8]. The original continuous PSO further expanded to the discrete problem using discrete values such as grids for XY position and their velocity. In this binary version of PSO, PSO is modified as:

$$V_{i+1} = V_i + C_1 \times rand_{1,i} \times \triangle V_{i,1} + C_1 \times rand_{2,i} \times \triangle V_{i,2} \tag{2.3}$$

$$\triangle V_{i,1} = pbest_i - X_i \tag{2.4}$$

$$\triangle V_{i,2} = gbest_i - X_i \tag{2.5}$$

While parameters $pbest_i$ and $gbest_i$ and X_i can take any real value in eq. 2.1, these parameters are integers in $\{0, 1\}$ in eq. 2.3. V_i is limited to the interval $[0.0, 1.0]$ as it is a probability not velocity. To accomplish this last modification, a logical transformation $S(V_i)$ can be used and the resulting modify in the position can be defined as follows:

$$X_i = \begin{cases} 1, & rand_{(0,1)} < S(V_i) \\ 0, & otherwise \end{cases} \tag{2.6}$$

$$S(V_i) = \frac{1}{1 + e^{-V_i}} \tag{2.7}$$

where,

$S(V_i)$ = sigmoid limiting transformation;

$rand_{(0,1)}$ = random number uniformly distributed in the interval [0,1];

V_i = probability of X_i being 1 or 0.

During initialization, each swarm particle of a swarm is randomly assigned in state 0 or 1 and the value of the objective function is computed for this arrangement. “pbest” is found based on the performance of each particles agent in each iteration and “gbest” is computed based on all previous iterations. Then, in the subsequent iteration, two partial probability values $(\triangle V_i)$ are subtracted on or added from the previous probability of each particle. Therefore, the values of $\triangle V_{i,1} = pbest_i - X_i$ and $\triangle V_{i,2} = gbest_i - X_i$ in eq. 2.3 are minute changes of probability in every iteration that can be $-1, 0, or 1$. So sigmoid transformation only transforms V_i from the interval $[-\infty\ to + \infty]$ to$[0, 1]$. The flowchart for Particle Swarm Optimization algorithm is shown in Fig. 2.2. In the discrete binary version, trajectories are changes in the probability that a coordinate will take on a 0 or 1 value. Therefore, it is applicable to only one type of switch i.e., sectionalizer in this presented problem. In this case, for each location, there are two states:

(i) State 1: sectionalizer is present in the location.

(ii) State 0: sectionalizer is absent in the location.

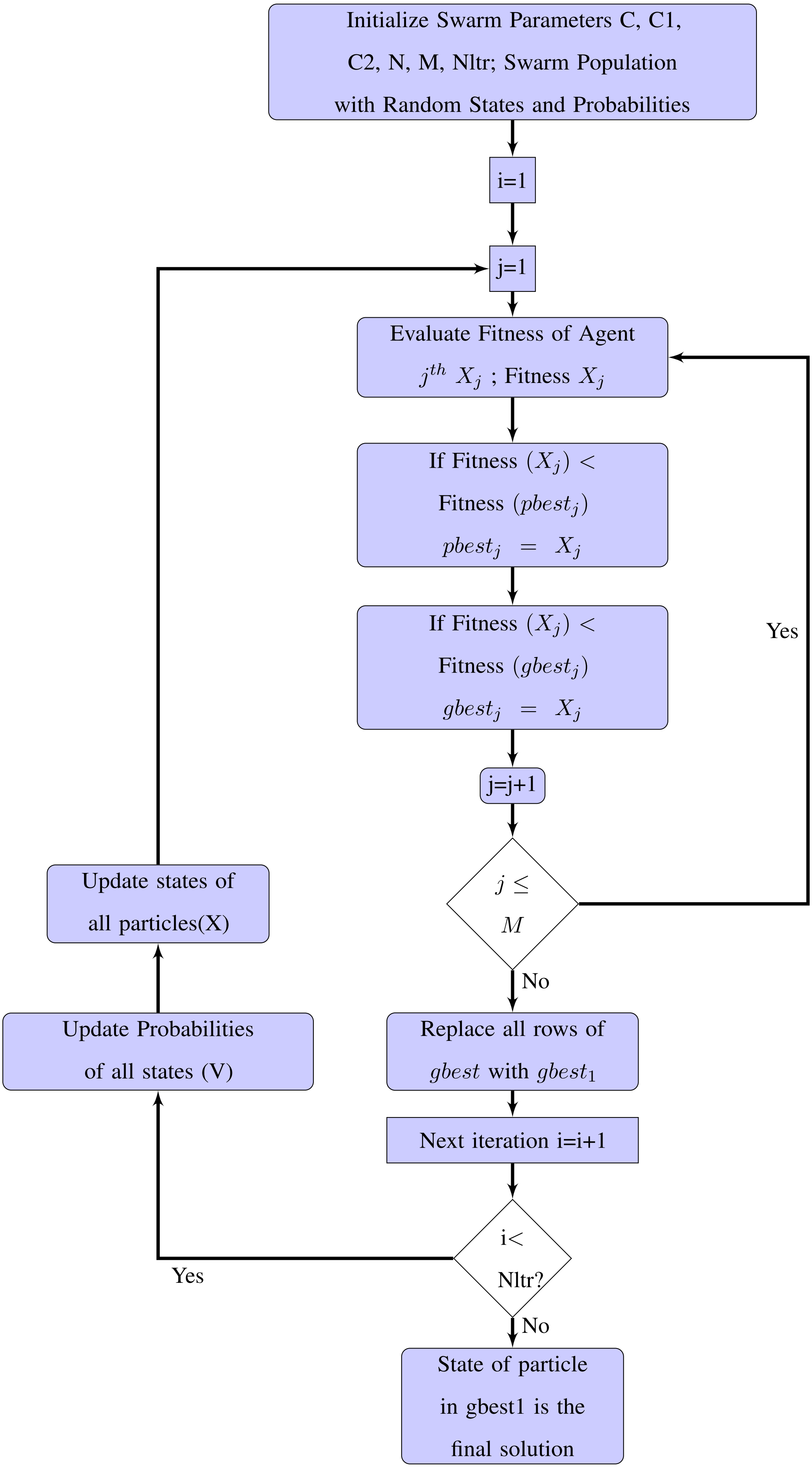

Fig. 2.2 Flowchart of the particle swarm optimization algorithm

2.4 MUTATION ASSISTED PARTICLE SWARM OPTIMIZATION

PSO get easily trapped in the local optima due to its knowledge sharing mechanism with the other particles. To avoid this premature convergence, mutation operator is used. Many research work shows mutation operator enhances the performance of PSO. Mutation points are randomly chosen from the $M \times N$ total number of bits in the population matrix. Increasing the mutation rate increases the algorithms flexibility to search outside the prevailing region of variable space. Mutation operator simply modifies the particle position with a uniformly generated arbitrary value in the dimensions permissible range. When implementing the mutation operator to the population, the particle dimensions are supposed to be a long string of values with each being mutated with a definite probability known as the mutation probability. Hence, the term mutation rate is given by following relation [9].

$$Mutation\ Probability = \frac{Mutation\ rate}{Swarm\ particles \times Swarm\ Dimensions} \tag{2.8}$$

2.4.1 *Pseudo-code for MAPSO*

```
//initializing swarm and velocities
for each $particle\ i\ in\ popsize$ do
    for each $dimension\ d\ in\ npar$ do
        $vel_{i,d} = velmin_d + rand \times (velmax_d - velmin_d)$
        $par_{i,d} = lower_d + rand \times (upper_d - lower_d)$
    end// for
    //initialize particles best position
    $pbest_i = x_i$
    //update the global best position
    if $pbest_i < f(gbest)$ then
        $gbest = pbest_i$
    end// if
end// for
//start iterations
for each $particle\ i\ in\ popsize$ do
    //update the particles best position
```

```
$if\ f(x_i) < f(pbest_i)\ then$
$pbest_i = x_i$
end//if
//update the global best position
$if\ f(pbest_i) < f(gbest)\ then$
$gbest = pbest_i$
end// if
end// for
//update particles velocity and position
for each $particle\ i\ in\ popsize$ do
for each $dimension\ d\ in\ npar$ do
$vel_{i,d} = vel_{i,d} + C_1 \times rand(0,1) \times (pbest_{i,d} - x_{i,d}) + C_2 \times rand(0,1) \times (gbest_d - x_{i,d})$
//update position
$x_{i,d} = x_{i,d} + vel_{i,d}$
end//for
end//for
//mutation operator
// total number of mutations
$nmut = ceil((popsize - 1) \times npar \times mutrate$
//row to mutate
$mrow = ceil(rand(1, nmut) \times (popsize - 1)) + 1$
//column to mutate
$mrow = ceil(rand(1, nmut) \times npar)$
//toggles bits
for$j = 1 : nmut$
$x(mrow_j, ncol_j) = abs(x(mrow_j, ncol_j) - 1)$
end// for
//advance iteration
$it = it + 1$
until $> MAX\ ITERATIONS$
```

DISTRIBUTION FEEDER PROBLEM FORMULATION

3.1 INTRODUCTION

The primary objective of the optimum switch number and placement problem is to minimize the investment costs for the feeders and interruption costs. According to load diversity of customers, number of customers connected to each load point, configuration of the node feeder distribution system, customer damage function (CDF), a number of reliability indices such as system average interruption frequency index (SAIFI), expected unsupplied energy due to power outages (EENS), system average interruption duration index (SAIDI) can be chosen as an objective function [10]. In this work, a reliability cost-worth approach is presented to solve the proposed problem of sectionalizer placement. Reliability of electric service depends on the two aspects, adequacy and economics, which can be evaluated by comparing the adequacy cost with adequacy worth. The reliability cost-worth curve shows that utility consumers will be given the least cost of the service when the combined customer interruption costs and utility costs are minimized. The fundamental concept of reliability cost-worth is comparatively simple and is summarized in Fig. 3.1 [11].

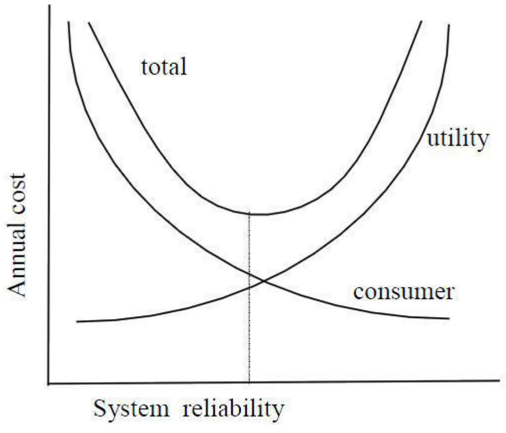

Fig. 3.1 Reliability cost-worth curve

3.2 OBJECTIVE FUNCTIONS

In reliability evaluation there are three basic reliability parameters. These are average failure rate, λ_s, average outage time, r_s, and average annual outage time, U_s. It is normally found in practise that system components have a failure rate which is approximately proportional to their length. Reliability parameters for series system with N components has given as below,

$$\lambda_s = \sum_{i}^{n} \lambda_i \tag{3.1}$$

$$U_s = \sum_{i}^{n} \lambda_i \, r_i \tag{3.2}$$

$$r_s = \frac{U_s}{\lambda_s} \tag{3.3}$$

In this thesis, system average interruption duration index (SAIDI) and total cost are used as objective functions that should be minimized using Mutated Assisted Particle Swarm Optimization (MAPSO) algorithm. They respond to the component failures, interruption duration, load connected, failure rates, repair rates of components and also make out various customer type data and their nonlinear customer damage functions. A recent EPRI (Electric Power Research Institute) research project has established that the most frequently used indices for assessing system performance were customer-related [25].

3.2.1 *System average interruption duration index (SAIDI)*

SAIDI is the average interruption duration for customers served during a year and commonly referred to as customer minutes of interruptions. It is determined by dividing the sum of all customer interruption durations during a year by the number of customers served during the year and to calculate the index following equation is used [12]:

$$SAIDI = \frac{sum\, of\, customer\, interruptions\, durations}{total\, number\, of\, customers} \tag{3.4}$$

$$= \frac{\sum_{i=1}^{n}(\sum_{s=1}^{n} \lambda_{is}\, r_{is})\, N_i}{\sum_{i=1}^{n} N_i} \tag{3.5}$$

where,

r_{is} = average outage time per interruption of load point i due to outages in section s;

λ_{is} = permanent failure rate;

N_i = number of customers of load point i.

For a fixed number of customers, SAIDI can be improved by reducing the duration or number of interruptions. Since both of these parameters reflect reliability improvements, a reduction in SAIDI indicates an improvement in reliability.

3.2.2 *System expected outage cost (ECOST)*

The system ECOST can be expressed as follows [7]:

$$System\ ECOST = \sum_{j=1}^{NC} \sum_{k=1}^{NIL} L_{kj}\, Cjk\,(r_j)\lambda_j(MW - \$/KW - yr) \tag{3.6}$$

where,

NIL = number of isolated load points due to a contingency j;

NC = number of contingencies;

L_{kj} = curtailed load at load point k due to contingency j;

r_j = average outage time of contingency j;

λ_j = average failure rate of contingency j;

$C_{jk(rj)}$ = outage cost ($/KW) of load point k due to outage j with an outage duration of r_j.

With the increase in number of switches, system reliability increases. However, factors, such as maintenance costs of switches, capital investment cost and installation costs must be considered in conjunction with the advantage derived by employing additional switches. The problem of optimization can be illustrated as:

$$Minimize[Total\ cost = ECOST(x_1, x_2, x_3 \ldots x_n, y_1, y_2, y_3 \ldots y_m) + n \times SEC + m \times BRC] \tag{3.7}$$

where,

ECOST = expected interruption cost;

x_i = i^{th} location where a sectionalizer is installed;

y_i = i^{th} location where a breaker is installed;

n = number of sectionalizers;

m = number of breakers;

SEC = cost associated with a sectionalizer;

BRC = cost associated with a breaker.

It is supposed that there are N possible locations for installing sectionalizers in the network. Therefore, the objective functions need to be optimized to locate sectionalizer in their best positions and switches cost includes capital cost, installation cost and maintenance cost [7]. The Dijkstra's algorithm and load flow analysis radial distribution are used to find load flow paths and sectionalizers in these paths and to calculate system total cost for each switch location sets [13].

3.2.3 *Combined SAIDI and Total Cost*

The multi-objective problem is formulated by taking into account SAIDI (OF_1) and total cost (OF_2) as objective functions. The decision regarding the best solution is obtained from fuzzy decision making approach. In this multi-objective optimization problem, a fuzzy membership function μ both 0 and 1 is substituted for each objective function [14]. Since our goal is to keep the both objective functions as low as possible, the membership function of each objective OF_i where, $i = 1$ and 2 is calculated as shown below:

$$\mu_{(OF)_i}(n) = \begin{cases} 1, & OF_i(n) \leq OF_i^{min} \\ \frac{OF_i^{max} - OF_i(n)}{OF_i^{max} - OF_i^{min}}, & OF_i^{min} < OF_i(n) < OF_i^{max} \\ 0, & OF_i(n) \geq OF_i^{max} \end{cases} \tag{3.8}$$

where,

OF_i^{max} and OF_i^{min} are maximum and minimum value of i^{th} objective function;

$OF_i(n)$ is objective function corresponding to the n^{th} solution in the population POP.

The fuzzy multi-objective problem, with membership function $\mu_{(OF)_i}(n)$ calculated for each of the objective function SAIDI (OF_1) and total cost (OF_2) can thus be defined:

$$Objective\, maximize\, \mu \;=\; max[min(\mu_{(OF)_1}(n), \mu_{(OF)_2}(n)] \tag{3.9}$$

The eq. 3.9 represents the degree of achievement of the overall objective.

3.3 APPLICATION OF DIJKSTRA'S ALGORITHM

Dijkstra algorithm is a graph search incremental path algorithm that solves the order of the shortest path problem for a graph with non-negative edge path generated one by one [15]. For a given source, the algorithm finds the shortest path between source vertex and the designated vertex by ending the procedure once the shortest path to the destination node has been determined. Therefore, this algorithm can be used to find the shortest path between the supply and the faulted section to minimize the number of load points to be isolated due to contingency.

Let the weight digraph $G = (V, E)$ with weight function given by $w : E \rightarrow R$ mapping edges to real-valued weights. If $e = (u, v)$,then we write $w(u, v)$ for $w(e)$.

- The path length $p = \{v_0, v_1, ..., v_k\}$ is the sum of the constituent edges weights:

$$length(p) = \sum_{i=1}^{k} w(v_{i-1}, v_i) \tag{3.10}$$

- The distance from u to v, is the distance of the minimum length path if there is a path from u to v, denoted $\delta(u, v)$,; and otherwise, it is ∞ .
- Maintain an $estimated[v]$ of the length $\delta(u, v)$ of the shortest path for each vertex v.
- $d[v] \geq \delta(s, v)$ and $d[v]$ is always equal the unknown path length ($d[v] = \infty$ in case no paths so far).
- Initially sets $d[s] = 0$ and all the other $d[v]$ values to ∞. The algorithm will then process the vertices one after another which new paths are processed and if necessary, $d[v]$ is updated for all $v \epsilon Adj[u]$. The processed vertexs estimate will be confirmed as being real shortest distance, i.e., $d[v] \geq \delta(s, v)$. The process is called *relaxation* by which an estimate is updated.
- When processing is done for all vertices, $d[v] \geq \delta(s, v)$ for all v.

We assume that w(e)≥0 for all $e \in E$. The algorithm preserves a priority queue $minQ$ that stores the unprocessed vertices with shortest-path estimates $d[v]$ as main values. It then again extracts the vertex u which consists of the minimum $d[u]$ from minQ and let goes all edges incident from u to any of the vertex in $minQ$. After one of the vertices is removed from minQ and all other relaxations are finished, the algorithm will take this vertex as processed and will not process it again. Dijkstras algorithm ends either when every vertex is inspected exactly once or when minQ becomes empty.

3.4 EVALUATION TECHNIQUE INVOLVED IN SECTIONALIZER PLACEMENT

In radial feeder system, the power flows from the substation to the consumer end along a single path. Whenever fault occurs in the system, the sectionalizer which is closest to the supply opens up to reduce customer service outage hours. The customers that are connected to the load points closest from the supply tend to experience the minimum number of outages and the greater availability. A typical radial feeder with a substation circuit breaker and four sectionalizers is shown in Fig. 3.2 [1]. During the existence of the fault anywhere in the system, the first sectionalizer which is located upstream the fault will operate and load to the downstream of sectionalizer will get isolated from the supply. If the fault is in section 3 then circuit breaker connected by default towards the supply side will trip and then sectionalizer located at section 3 will open to provide supply up to load point 3. Let sectionalizer are placed at each line section and assume one fault at a time for the reliability calculation, i.e., single outage. When a fault occurs in any of the section then C.B. will trip and all load points get deprived of supply. After a few hours, sectionalizer of faulted segment will open to remove the faulty section and close circuit breaker placed at the supply side. Once a fault that has occurred is cleared, sectionalizer

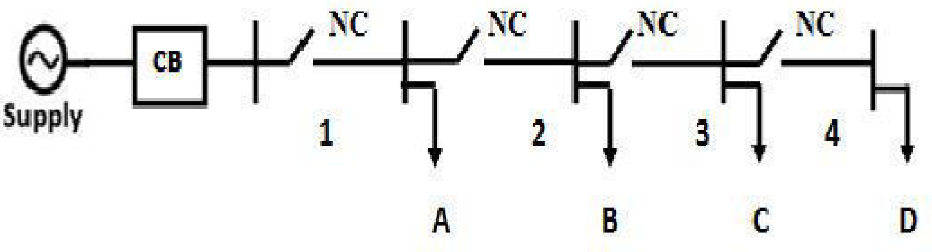

Fig. 3.2 A typical four load point radial feeder system

closes its contacts and restores the system with its all load points supplied by the station. Suppose the fault is in section 1, then circuit breaker will trip and disconnect all the load points till fault is repaired. Hence load points A, B, C and D have failure rate λ_1 and repair rate r_1. When a fault occurs in section 2 then C.B. will open first at the source side and load points have λ_2 failure rate. Now sectionalizer at section 2 will open and supply will be allowed till load point A within riso time, i.e., additional time required to detect the fault and open the sectionalizer of faulted part and reclose the CB to continue the supply [16]. The whole process is summarized as shown in the Table 3.1.

Table 3.1 Equivalent failure rate and repair rate of the system

Section/Load	Load point A			Load point B			Load point C			Load point D		
	λ	r	U	λ	r	U	λ	r	U	λ	r	U
1	λ_1	r_1	$\lambda_1 \times r_1$	λ_1	r_1	$\lambda_1 \times r_1$	λ_1	r_1	$\lambda_1 \times r_1$	λ_1	r_1	$\lambda_1 \times r_1$
2	λ_2	$riso$	$\lambda_2 \times riso$	λ_2	r_2	$\lambda_2 \times r_2$	λ_2	r_2	$\lambda_2 \times r_2$	λ_2	r_2	$\lambda_2 \times r_2$
3	λ_3	$riso$	$\lambda_3 \times riso$	λ_3	$riso$	$\lambda_3 \times riso$	λ_3	r_3	$\lambda_3 \times r_3$	λ_3	r_3	$\lambda_3 \times r_3$
4	λ_4	$riso$	$\lambda_4 \times riso$	λ_4	$riso$	$\lambda_4 \times riso$	λ_4	$riso$	$\lambda_4 \times riso$	λ_4	r_4	$\lambda_4 \times r_4$
	λ_{equ1}	r_{equ1}	U_{s1}	λ_{equ2}	r_{equ2}	U_{s2}	λ_{equ3}	r_{equ3}	U_{s3}	λ_{equ4}	r_{equ4}	U_{s4}

Therefore the effect of sectionalizer on the reliability can be summed using the following algorithm [17]:

(i) consider each one of the load point of the system;

(ii) consider failure mode of the each load point;

(iii) for each failure mode evaluate how service can be restored;

  (a) if supply can only be restored by repair, choose restoration time as the summation of fault location and repair time;

  (b) if supply can be restored by switching actions, choose restoration time as the summation of fault location and switching time;

(iv) calculate load point indices by evaluating all the events leading to failure of the load point and their associated restoration procedure;

(v) consider the overall indices of the system by suitably combining reliability indices of all the load points.

3.5 SOLUTION ALGORITHM

Any System is said to be reliable when supply is provided to the customers with reasonable cost profits. Hence, economic assessment of a system assists for a better utilisation of a system. Economic assessment or reliability worth can be approximated and studied with the concept of Customer Damage Functions (CDF) which helps in determining customer interruption costs and reliability worth which helps in measuring its cost worth and choose the optimal position of sectionalizer [18].

For a given contingency j, the following procedure is used to calculate objective function:

(i) consider a contingency j located in section S;

(ii) find the circuit breaker located by default in the path near the supply side;

(iii) disconnect the faulty zone from the rest of the system by this CB. A faulty zone is a zone associated with the primary protection zone of a failed component i.e., line section;

(iv) find the first sectionalizing switch in the path toward the feeder. If there is not any sectionalizing switch in the path before the breaker, go to the next step; otherwise, go to step (vi);

(v) find all load points which are de-energized by the CB trip and calculate objective function using (3.1) for the repair time required to restore energy (t_{rep}), then go to step (i);

(vi) find all load points which are de-energized by the CB trip and calculate objective function using (3.1) for the switching time of remote-controlled (RC) sectionalizers (t_{sec});

(vii) system total cost for contingency is the sum of the calculated ECOSTs, switches maintenance costs and installation costs then go to step (i);

To find the optimal number and positions of the sectionalizer succeeding steps should be executed [19]:

(i) examine all available positions to install sectionalizer;

(ii) place one single sectionalizer in all optimal positions and increase the number of sectionalizer one by one, then correspondingly calculate total cost and SAIDI for each mode;

(iii) compare all possible choices and obtain the best location for the sectionalizer;

(iv) consider the above algorithm, calculation of all possible positions for switch installation would be burdensome due to several choices in distribution systems. Hence, utilizing MAPSO could be a successful approach to optimize sectionalizer places and to minimize total cost of the system.

To minimize the customer service outage time for fault contingency in any of the sections of distribution systems, the following constraints are considered:

(i) The voltage drop of buses along the feeders has to be less than 5% after the proposed switching operation [20]. The distinctive load flow solution technique is used to exploits the power flow paths of radial distribution systems [21].

(ii) The radial distribution system is modeled by graph theory adjacency matrix and checking connections between nodes, determining disconnected load points is implemented by Dijkstras algorithm.

(iii) In this system, the investment cost of sectionalizer and a circuit breaker cost are $U.S.$ $\$4700$ and $U.S.$ $\$11800$, respectively. The annual maintenance cost is 2% of the annual investment cost. The life period of the switches is assumed to be 20 years with an interest rate of 8% [22].

(iv) It is assumed that sectionalizers are not fault-breaking switches. Sectionalizer switches are regarded as RC switch types. Once the fault is detected, the relevant sectionalizer will open and the circuit breaker gets reclosed. This process allows restoration of all load points between the supply point and the point of isolation before completing the repair process. Therefore, with the increase in the number of breaker type of switches, fewer load points are disconnected and, as such, the total system ECOST goes down [7].

Chapter–4

EXPLAINING VALUE BASED RELIABILITY PLANNING WITH AN EXAMPLE

4.1 INTRODUCTION

Reliability evaluation of electric power distribution system includes two approaches, namely, predictive assessment and historical assessment. Predictive assessment is concerned with the customer electric power supply adequacy whereas historical assessment involves analysis and collection of customer interruption data and service outage of the system. A value-based reliability assessment approach tries to locate the least cost solution where the entire cost comprises customer interruption cost plus the operating cost plus the utility investment cost. Predictive reliability evaluation combines mathematical models and historical outage data to approximate the performance of the system configuration [24]. The whole idea is to optimize the industrial expansion plans of distribution systems.

The steps involved in the value based reliability approach are given below [23]:

(i) Calculate the reliability of each load point considering system constraints and all interruption events.

(ii) Estimate the expected cost of interruptions for each year at each load point using appropriate customer damage functions (CDF).

(iii) Repeat step (i) and step (ii) for all load points and by summing each load point interruption cost, obtain the total system cost of interruptions.

(iv) Evaluate the cumulative present value (CPV) of the customer interruption costs for the radial distribution system over the economic period of the project plan.

(v) Evaluate the CPV of the cost of the utility reliability assessment development plan over the economic period of the project plan.

4.2 CONFIGURATION CHARACTERISTICS OF AN EXAMPLE SYSTEM

The value-based predictive reliability assessment example is taken from [23] to reveal the impact on the cost of interruptions and the duration and frequency of load point interruptions when certain constraints are imposed in a radial distribution system. The example illustrates the each load point reliability indexes and annual cost of outages when a fault occurs in various sections of the manually sectionalized radial distribution system. The distribution system's industrial service area load is supplied by a 25kV distribution feeder circuit as shown in Fig. 4.1. The lateral disconnects, step-down transformers, fuses, step-down transformers are supposed to be 100% available in the evaluation to make simpler the reliability value-based planning methodology [23].

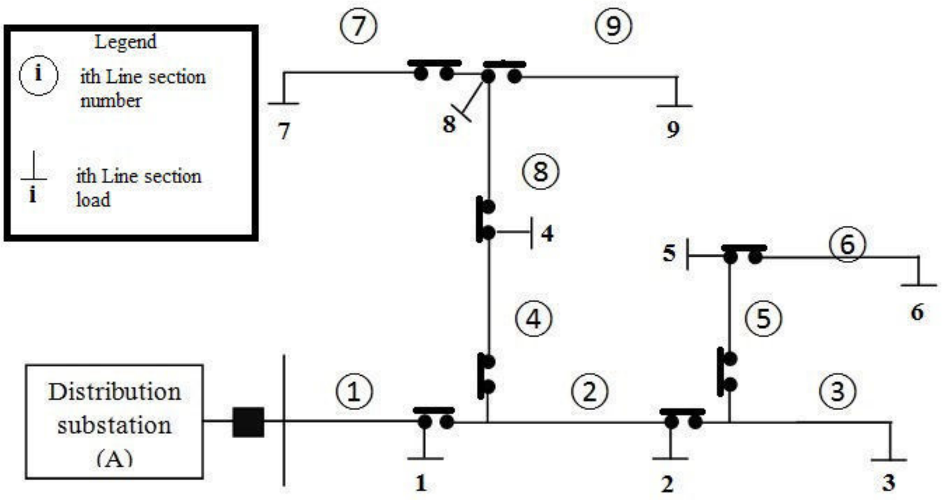

Fig. 4.1 Manually sectionalized example distribution feeder

The physical lengths of each section of line are shown in Table 4.1. The loading conditions at each load point are shown in Table 4.2. The multiple outages are neglected to simply make an emphasis on the basic concept behind the value-based methodology used for reliability planning. The interruption cost for a 1 hr interruption to a customer is $ 10.00 per average KW load interrupted and for a 4 hr interruption to a customer is $ 25.00 per average KW load interrupted [23].

Table 4.1 Distribution feeder line section lengths

Line Section number	1	2	3	4	5	6	7	8	9
physical length (km)	2	1	2	3	3	3	2	3	1

Table 4.2 Distribution feeder loads

Average load (KW)	800	400	800	1200	560	1040	400	800	1200
Peak Load(KW)	1000	500	1000	1500	700	1300	500	1000	1500

4.3 RELIABILITY CALCULATIONS FOR AN EXAMPLE SYSTEM

The customer interruption cost (CIC) associated with an outage in section j outage is given below:

$$CIC = \lambda_j \times L_p \times C(r_j, p) \tag{4.1}$$

where,

λ_j = failure rate of section j;

L_p = average load connected at load point p;

$C(r_j, p)$ = cost of interruption in $\$/kW$ for outage duration of r_j associated with section j.

The total interruption cost for each load point, say, p can be evaluated by summing up the cost of all section outages, i.e., $steps(i)$ and (ii) mentioned in above section and the total cost of customer interruptions can be evaluated using $step(iii)$. The calculation of the reliability indexes and cost of load point interruptions for load point-2, load point-4 and load point-6 are illustrated in Table 4.3, Table 4.4 and Table 4.5 respectively. The total annual cost of interruptions for the manually sectionalized distribution feeders is illustrated in Table 4.6 [23].

Table 4.3 Reliability indexes and annual cost of outage at load point- 2

Fault section	$\lambda(interruption/year)$	U(h/year)	r(h/interruptions)	Interruption Cost($ /year)
1	0.04	0.16	4	400
2	0.02	0.08	4	200
3	0.04	0.04	1	160
4	0.06	0.06	1	240
5	0.06	0.06	1	240
6	0.06	0.06	1	240
7	0.04	0.04	1	160
8	0.06	0.06	1	240
9	0.02	0.02	1	80
	0.40	0.58	$\frac{\sum U}{\sum \lambda} = 1.45$	$\$1,960.00$

Table 4.4 Reliability indexes and annual cost of outage at load point- 4

Fault section	$\lambda(interruption/year)$	U(h/year)	r(h/interruptions)	Interruption Cost($ /year)
1	0.04	0.16	4	1200
2	0.02	0.08	4	600
3	0.04	0.04	1	480
4	0.06	0.24	4	1800
5	0.06	0.06	1	720
6	0.06	0.06	1	720
7	0.04	0.04	1	480
8	0.06	0.06	1	720
9	0.02	0.02	1	240
	0.40	0.76	$\frac{\sum U}{\sum \lambda} = 1.90$	$\$6,920.00$

Table 4.5 Reliability indexes and annual cost of outage at load point- 6

Fault section	$\lambda(interruption/year)$	U(h/year)	r(h/interruptions)	Interruption Cost($ /year)
1	0.04	0.16	4	1040
2	0.02	0.08	4	520
3	0.04	0.16	4	1040
4	0.06	0.06	1	624
5	0.06	0.24	4	1560
6	0.06	0.24	4	1560
7	0.04	0.04	1	410
8	0.06	0.06	1	624
9	0.02	0.02	1	208
	0.40	1.06	$\frac{\sum U}{\sum \lambda} = 2.65$	$\$7,592.00$

Table 4.6 Total annual interruption cost for manually sectionalized system

Load point	$\lambda(interruption/year)$	U(h/year)	r(h/interruptions)	Interruption Cost
1	0.40	0.52	1.30	3680
2	0.40	0.58	1.45	1960
3	0.40	0.70	1.75	4400
4	0.40	0.76	1.90	6960
5	0.40	0.88	2.20	3584
6	0.40	1.06	2.65	7592
7	0.40	1.06	2.65	2920
8	0.40	0.94	2.35	5360
9	0.40	1.00	2.50	8400
			$Annual\ Cost\ of\ Interruptions$	$\$44,856.00$

Chapter–5

RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

In this dissertation work, the results have been obtained from the developed algorithm for optimal sectionalizer placement in the distribution system. The Mutation Assisted Particle Swarm Optimization (MAPSO) technique discussed in section $[2.4]$, is proposed to optimize switch places and minimize the objective functions namely, total cost and system average interruption duration index (SAIDI). The formulation of optimal sectionalizer placement optimization problem is described in chapter $[3]$. All the possible choices for placing sectionalizer have been analyzed and regarding total cost and SAIDI are calculated. Both the objectives are also accounted simultaneously using fuzzy decision making (FDM) approach. To describe the effectiveness of the proposed algorithm, the algorithm has been tested on three test systems, i.e. 12-bus, 33-bus and 47-bus distribution system. The effect of changing the section length of the distribution feeder system is also studied.

For economical analysis of the distribution systems, three cases are taken into account as given below:

Case 1: before installing any sectionalizer in the system.

Case 2: after installing only sectionalizers in all candidate positions.

Case 3: after installing sectionalizer by applying the proposed algorithm (MAPSO).

It is assumed that the feeder failure rate is 2 failures per 100 km per year and single customer is located at each load point. The parameter values assigned for MAPSO are $C_1 = 2$, $C_2 = 2$, $C = 1$ and $swarm\ size = 50$. The interruption cost for a 1 hr interruption to a customer is assumed to be $\$10.00$ per average KW load interrupted and for a 4 hr interruption to a customer is $\$25.00$ per average KW load interrupted [23].

5.2 12-BUS DISTRIBUTION SYSTEM

The following are the characteristics for 12-bus radial distribution system in Fig. 5.1.

Number of buses =12

Number of lines = 11

Slack Bus Number =1

Base Voltage= 12.66 kV

Base MVA = 100 MVA

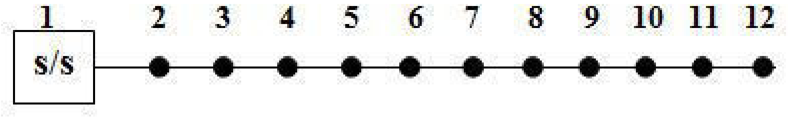

Fig. 5.1 Representation of 12-bus distribution system

5.2.1 *Optimize Total Cost*

For optimizing the total cost, the effect of section lengths on optimal location and numbers of the sectionalizers is calculated for 2 different conditions as given below:

(i) no change in length of any section.

(ii) increasing the length of all sections.

5.2.1.1 Results with original section lengths

For the economical point of view, the analysis of three Cases for 12-bus distribution system is shown in Table 5.1. The results shows the 24.63% reduction in total cost from 62,384.25 $U.S.\$/yr$ to 47,018.25 $U.S.\$/yr$, when compared with case 1 and 5% reduction in total cost from 50,015.5 $U.S.\$/yr$ to 47,018.25 $U.S.\$/yr$, when compared with case 2. The fixed cost resulted from the proposed methodology is increased by 2,424 $U.S.\$/yr$ in terms of cost of reliability. However, substantial decrease in customer interruption costs that ultimately lowers the total cost by 15,366 $U.S.\$/yr$ surpass the switches cost. The total cost convergence characteristics after 10 iterations of the proposed method is shown in Fig. 5.2.

Table 5.1 Economical analysis for* 12*-bus distribution system with original section lengths

	Case1	Case2	Case3
$ECOST(U.S.\$/yr)$	60356.25	39907.50	42566.25
$Switches\ Cost(U.S.\$/yr)$	2028	10108	4452
$Total\ Cost(U.S.\$/yr)$	62384.25	50015.5	47018.25

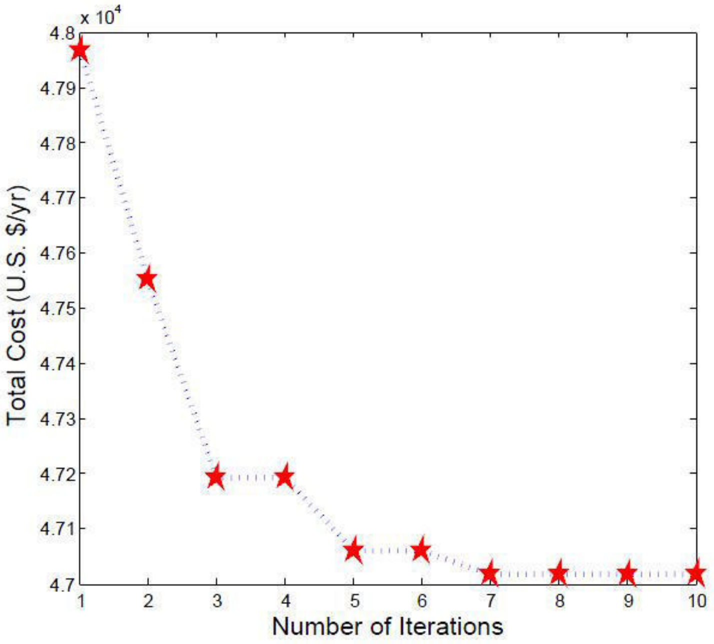

Fig. 5.2 Total cost convergence characteristics of the proposed MAPSO for 12-bus distribution system

The optimal solution obtained from the MAPSO for 12- bus system is shown in Table 5.2. It is concluded from the Fig. 5.3 that 3 sectionalizers reduces the total cost and hence, reduces the service outage to customers.

Table 5.2 Optimal location of switches for* 12*-bus system with original section lengths

Number of Sectionalizer	3
Sectionalizer Locations	4, 7, 9
Number of CircuitBreaker	1
Circuit Breaker Location	Supply side by default
Switches Cost(U.S.$/yr)	4452
ECOST(U.S.$/yr)	42566.25
SAIDI (hrs/customer − yr)	14.93
Total Optimum Cost	47018.25

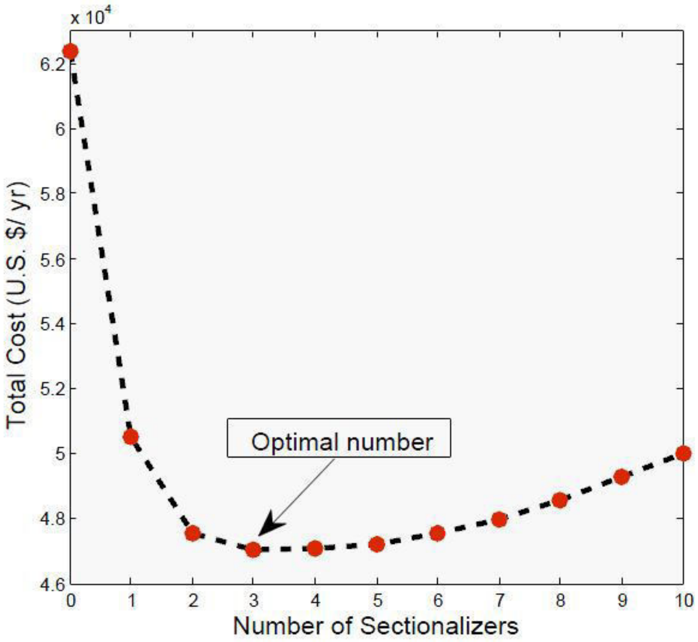

Fig. 5.3 Variation of total cost with number of sectionalizers for 12-bus distribution system with original section lengths

To analyze the value-based assessment of this distribution system, the number of sectionalizer is placed one by one at different location combinations formed by 11 sections of the system and the results are summarized in Table 5.3. The Fig. 5.4 infers that increasing the number of sectionalizers decreases the system ECOST but eventually increases sectionalizer's total installation and maintenance costs. The sum of interruption duration per customer per year also decreases with the increase in number of sectionalizers as shown in Fig. 5.5.

Table 5.3 Results for* 12*-bus distribution system with original section lengths

Number of Switches	System ECOST $(U.S.\$/yr)$	Switches Cost $(U.S.\$/yr)$	Total ECOST $(U.S.\$/yr)$	SAIDI $(hrs/customer - yr)$
0	60356.25	2028	62384.25	22.20
1	47681.25	2836	50517.25	16.88
2	43923.75	3644	47567.75	15.65
3	42566.25	4452	47018.25	14.93
4	41801.25	5260	47061.25	14.70
5	41126.25	6068	47194.25	14.42
6	40676.25	6876	47552.25	14.15
7	40282.50	7684	47966.50	13.96
8	40072.50	8492	48564.50	13.87
9	39967.50	9300	49267.50	13.81
10	39907.50	10108	50015.50	13.75

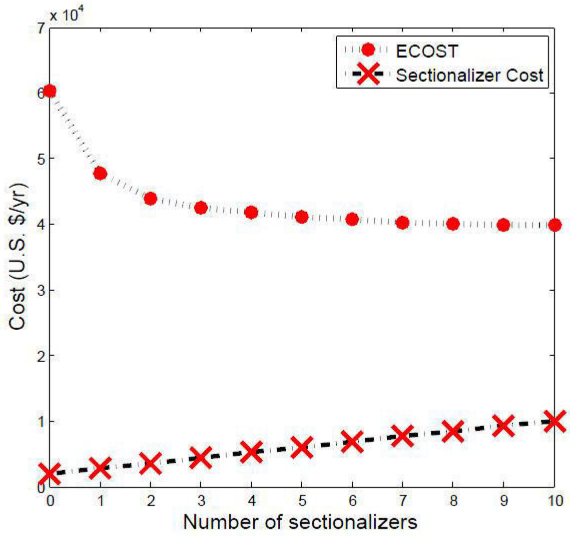

Fig. 5.4 Variation of ECOST and sectionalizer cost with number of sectionalizers for 12-bus distribution system with original section lengths

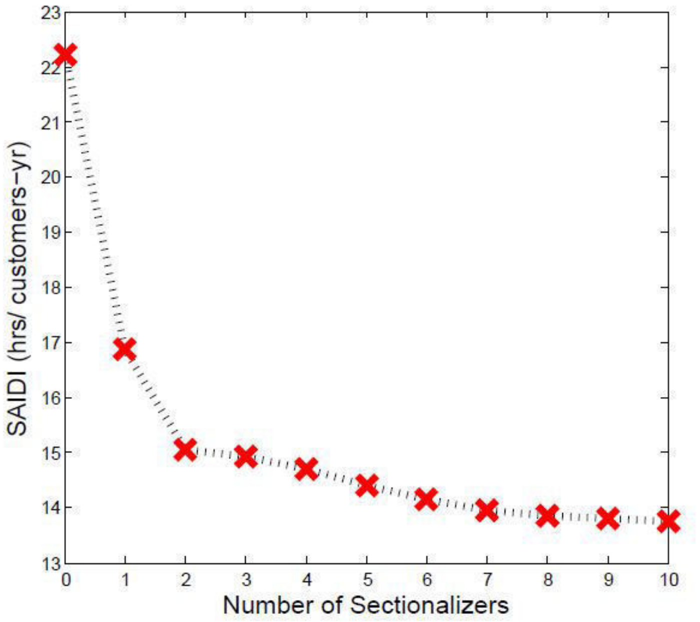

Fig. 5.5 Variation of SAIDI with number of sectionalizers for 12-bus distribution system with original section lengths

5.2.1.2 Results with Increased section lengths

The economical analysis of three Cases for 12-bus distribution system when length of each section is made twice of original length is shown in Table 5.4. According to the proposed methodology, allocating the optimum number of sectionalizers in the optimum locations results in the reduction in total cost from $12,2740.5$ $U.S.\$/yr$ (no sectionalizer present) to $88,228.5$ $U.S.\$/yr$ (sectionalizer at optimized locations) and from $89,923$ $U.S.\$/yr$ to $88,228.5$ $U.S.\$/yr$ when optimized solution is compared with the case of presence of sectionalizers at all sections of the system. The fixed cost resulted from the proposed methodology is increased by $4,848$ $U.S.\$/yr$ in terms of cost of reliability. However, it is out shadowed by a substantial decrease in customer interruption costs that ultimately lowers the total cost by $34,512$ $U.S.\$/yr$.

Table 5.4 Economical analysis for** 12**-bus distribution system with increased section lengths

	Case1	Case2	Case3
$ECOST(U.S.\$/yr)$	120712.5	79127	81352.5
$Switches\ Cost(U.S.\$/yr)$	2028	10108	6876
$Total\ Cost(U.S.\$/yr)$	122740.5	89923	88228.5

The optimal solution obtained from the MAPSO for 12-bus distribution system after changing the length to twice its original value is shown in Table 5.5. It can be observed that six sectionalizers placed at location $2, 4, 5, 7, 8$ and 9 reduces the total cost to $88, 228.5$ $U.S.\$/yr$. It is concluded from the Fig. 5.6 that 6 sectionalizers is an optimal number to reduce total cost.

Table 5.5 Optimal location of switches for* 12*-bus distribution system with increased section lengths

$Number\ of\ Sectionalizer$	6
$Sectionalizer\ Locations$	2, 4, 5, 7, 8, 9
$Number\ of\ CircuitBreaker$	1
$Circuit\ Breaker\ Location$	Supply side by default
$Switches\ Cost\ (U.S.\$/yr)$	6876
$ECOST\ (U.S.\$/yr)$	81352.5
$SAIDI\ (hrs/customer - yr)$	0.137
$Total\ Optimum\ Cost$	88228.5

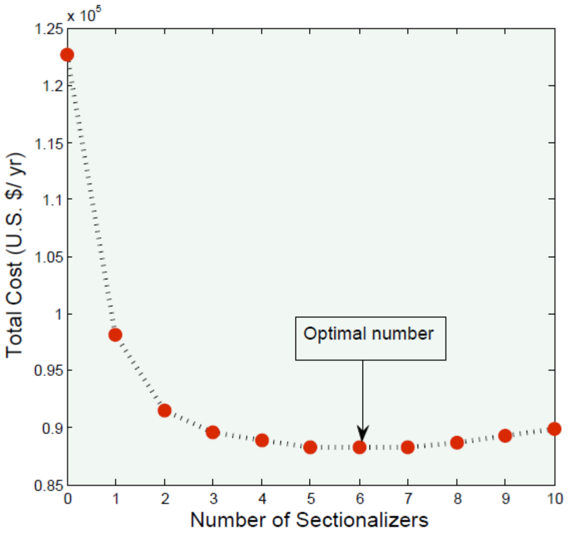

Fig. 5.6 Variation of total cost with number of sectionalizers for 12-bus distribution system increased section lengths

To analyze the optimal location of sectionalizers, the number of sectionalizer is increased one by one and the results are summarized in Table 5.6. Since the failure rate of a component is a function of length. The increment in the length of all sections by 100%, increases the optimal number of sectionalizer. Fig. 5.7 depicts that increase in number of sectionalizers, decreases the value of system ECOST but cost of sectionalizers increases with some proportion. This also results in decrease in the value of SAIDI as shown in Fig. 5.8.

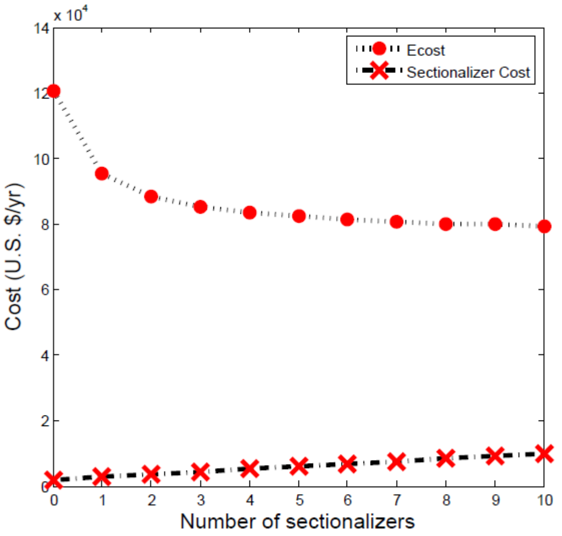

Fig. 5.7 Variation of total cost and sectionalizer cost with number of sectionalizers for 12-bus distribution system with increased section lengths

Table 5.6 Results for 12-bus distribution system with increased section lengths

Number of Switches	System ECOST ($/yr)	Switches Cost ($/yr)	Total cost ($/yr)	SAIDI ($hrs/customer - yr$)
0	120712.50	2028	122740.50	44.40
1	95362.50	2836	98198.50	33.76
2	88297.50	3644	91419.50	31.30
3	85142.50	4452	89584.50	29.86
4	83602.50	5260	88862.50	29.40
5	82252.50	6068	88320.50	28.85
6	81352.50	6876	88228.50	28.30
7	80565.00	7684	88249.00	27.92
8	80145.00	8492	88637.00	27.73
9	79935.00	9300	89235.00	27.62
10	79127.00	10108	89923.00	27.51

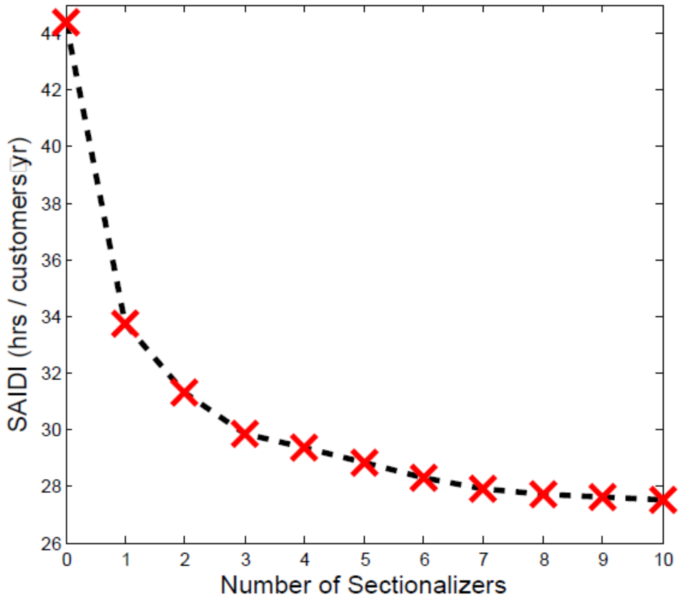

Fig. 5.8 Variation of SAIDI with number of sectionalizers for 12-bus distribution system with increased section lengths

5.2.2 Optimize Both Total Cost and SAIDI

The multi-objective solution from objectives total cost and SAIDI taking simultaneously for original section lengths using fuzzy decision making approach is shown in Table 5.7. The optimal locations are found at positions $2, 4, 5, 7, 8$ and 9 with SAIDI and total cost equal to 14.15 $hrs/customer - yr$ and 40676.25 $U.S.\$/yr$ respectively.

Table 5.7 Optimal location of switches for 12***-bus distribution system using FDM with original section lengths***

$Number\ of\ Sectionalizer$	6
$Sectionalizer\ Locations$	2, 4, 5, 7, 8, 9
$Number\ of\ CircuitBreaker$	1
$Circuit\ Breaker\ Location$	Supply side by default
$Switches\ Cost(U.S.\$/yr)$	6876
$ECOST(U.S.\$/yr)$	40676.25
$SAIDI\ (hrs/customer - yr)$	14.15
$Total\ Optimum\ Cost$	47552.25

The best solution using fuzzy decision making approach for increased length is shown in Table 5.8. The optimal number of sectionalizers are found be 7 located at positions $2, 3, 5, 7, 8, 9$ and 10 with SAIDI and total cost equal to 28.00 $hrs/customer - yr$ and $88,615.50$ $U.S.\$/yr$ respectively.

Table 5.8 Optimal location of switches for 12-bus distribution system using FDM with increased section lengths

$Number\ of\ Sectionalizer$	7
$Sectionalizer\ Locations$	2, 3, 5, 7, 8, 9, 10
$Number\ of\ CircuitBreaker$	1
$Circuit\ Breaker\ Location$	Supply side by default
$Switches\ Cost(U.S.\$/yr)$	7684
$ECOST(U.S.\$/yr)$	80932.5
$SAIDI\ (hrs/customer - yr)$	28.00
$Total\ Optimum\ Cost$	88616.50

5.3 33-BUS DISTRIBUTION SYSTEM

Following are the characteristics for 33-bus radial distribution system in Fig. 5.9. Number of buses =33
Number of lines = 32
Slack Bus Number =1
Base Voltage= 12.66 kV
Base MVA = 100 MVA

5.3.1 *Optimize Total Cost*

The economical analysis of three Cases for 33-bus distribution system is shown in Table 5.10. According to the proposed methodology, allocating an optimum number of sectionalizers in the optimum locations position results in a reduction in total cost from $39,828.125$ $U.S.\$/yr$ to $27,214.975$ $U.S.\$/yr$, i.e. by 31.66% when compared with case 1 and from $46,345.350$ $U.S.\$/yr$ to $27,214.975$ $U.S.\$/yr$, i.e. by 41.27% when compared with case 2. When the cost of reliability is considered, the fixed cost resulted from the proposed methodology is increased by $4,040$ $U.S.\$/yr$. However, it is out shadowed by a substantial decrease in customer interruption costs that ultimately lowers the total cost by $12,613.150$ $U.S.\$/yr$.

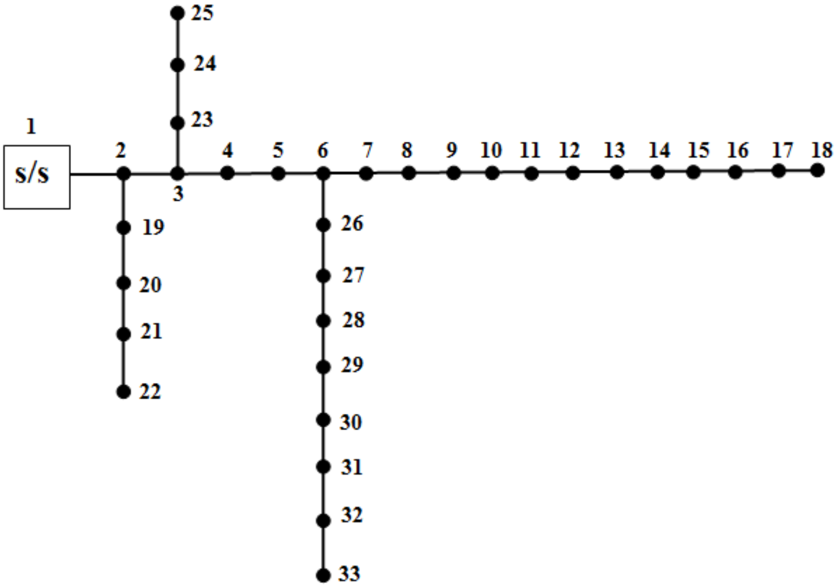

Fig. 5.9 Representation of 33-bus distribution system

Table 5.9 Economical analysis for 33*-bus distribution system*

	Case1	Case2	Case3
$ECOST(U.S.\$/yr)$	37800.125	19269.350	21146.975
$Switches\ Cost(U.S.\$/yr)$	2028	27076	6068
$Total\ Cost(U.S.\$/yr)$	39828.125	46345.350	27214.975

The best solution obtained from the MAPSO for 33-bus system is shown in Table 5.10. For the existing system, the SAIDI equals to 0.75 with the total cost of the system equal to $27,214.975$ $U.S.\$/yr$. The total cost convergence characteristic of the proposed method is shown in Fig. 5.10.

Table 5.10 Optimal location of switches for* 33*-bus distribution system

$Number\ of\ Sectionalizer$	5
$Sectionalizer\ Locations$	3, 8, 18, 22, 25
$Number\ of\ Circuit\ Breaker$	1
$Circuit\ Breaker\ Location$	Supply side by default
$Switches\ Cost(U.S.\$/yr)$	6068
$ECOST\ (U.S.\$/yr)$	21146.975
$SAIDI\ (hrs/customer - yr)$	0.75
$Total\ Optimum\ Cost$	27214.975

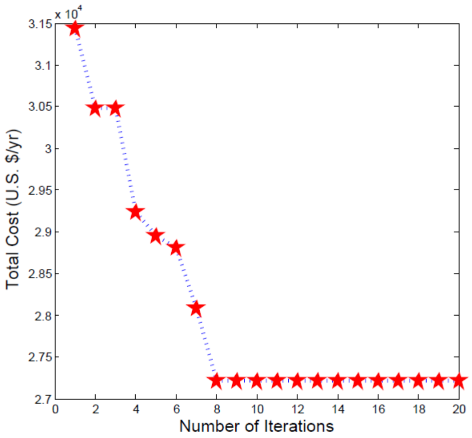

Fig. 5.10 Total cost convergence characteristic of the proposed MAPSO for 33-bus distribution system

To analyze all possible locations to allocate a specific number of sectionalizers,it is assumed that the fault occurs in the sections $5, 13, 17, 24,$ and 29 and results are summarized in Table 5.11. It can also be inferred from the Fig. 5.11 that after 9 sectionalizers the variation in SAIDI is negligible. So for 33-bus radial distribution system 9 sectionalizers can be placed to get utmost economical and reliable supply. However, the expense spent on installing sectionalizers resulted in $7,892.825\ U.S.\$/yr$ as optimized total cost and 2 sectionalizers ,at positions 5 and 24, as an optimal number to be placed in 33 node feeder distribution system for specified faulted sections as shown in Fig. 5.12. The Fig. 5.13 depicts that when the number of sectionalizers are increased, the system ECOST decreases with the increase in sectionalizer cost.

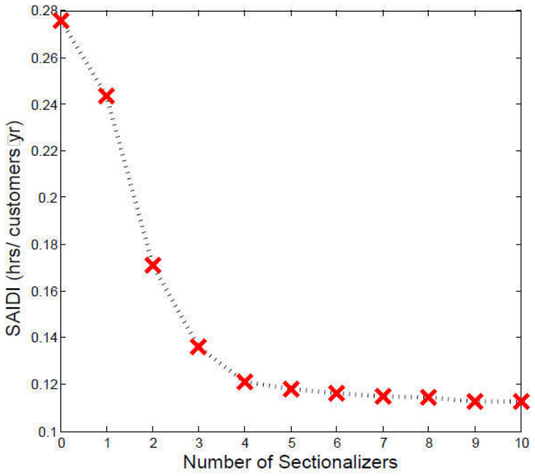

Fig. 5.11 Variation of SAIDI with number of sectionalizers for 33-bus distribution system

Table 5.11 Results for** 33**-bus distribution system with specified fault locations

Number of Switches	System ECOST $(U.S.\$/yr)$	Switches Cost $(U.S.\$/yr)$	Total Cost $(U.S.\$/yr)$	SAIDI $(hrs/customer-yr)$
0	6408.375	2028	8436.375	0.276
1	5932.275	2836	8768.275	0.243
2	4248.825	3644	7892.825	0.171
3	3647.850	4452	8099.850	0.136
4	3464.100	5260	8724.100	0.120
5	3423.825	6068	9491.825	0.118
6	3381.300	6876	10257.300	0.116
7	3374.100	7684	11058.100	0.114
8	3370.500	8492	11862.500	0.115
9	3346.200	9300	12646.200	0.112
10	3346.200	10108	13454.200	0.112
11	3346.200	10916	14262.200	0.112
31	3346.200	13454.20	31230.200	0.112

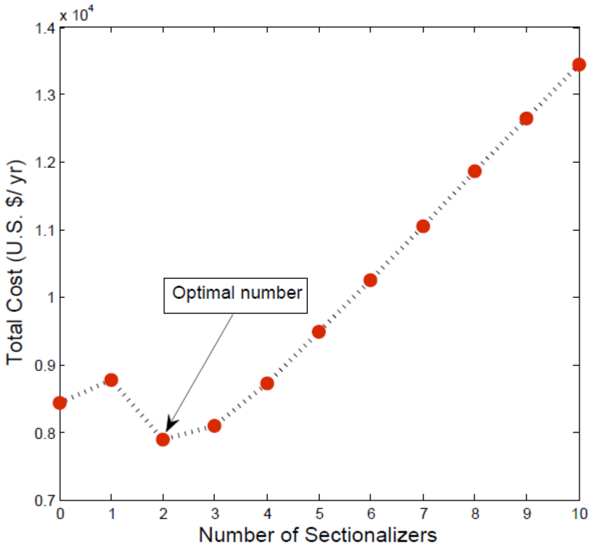

Fig. 5.12 Variation of total cost with number of sectionalizers for 33-bus distribution system

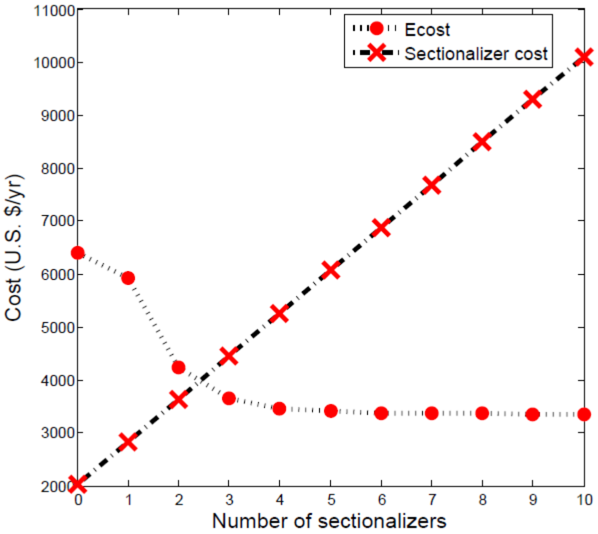

Fig. 5.13 Variation of system ECOST and sectionalizer cost with number of sectionalizers for 33-bus system

5.3.2 *Optimize Both Total Cost and SAIDI*

When the two objectives total cost and SAIDI are optimized simultaneously using FDM approach, the number of sectionalizers required are 12 as shown in Table 5.17 with SAIDI and total cost equal to 0.85 $hrs/customer - yr$ and 31782.724 $U.S.\$/yr$ respectively.

Table 5.12 Optimal location of switches for 33-bus distribution system using FDM

$Number\ of\ Sectionalizer$	12
$Sectionalizer\ Locations$	3, 4, 6, 8, 12, 16 17, 18, 22, 24, 27, 32
$Number\ of\ CircuitBreaker$	1
$Circuit\ Breaker\ Location$	Supply side by default
$Switches\ Cost(U.S.\$/yr)$	11724
$ECOST(U.S.\$/yr)$	20058.725
$SAIDI\ (hrs/customer-yr)$	0.70
$Total\ Optimum\ Cost$	31782.725

5.4 47-BUS DISTRIBUTION SYSTEM

Following are the characteristics for 47-bus radial distribution system in Fig. 5.14.

Number of buses =47

Number of lines = 46

Slack Bus Number =1

Base Voltage= 12.66 kV

Base MVA = 100 MVA

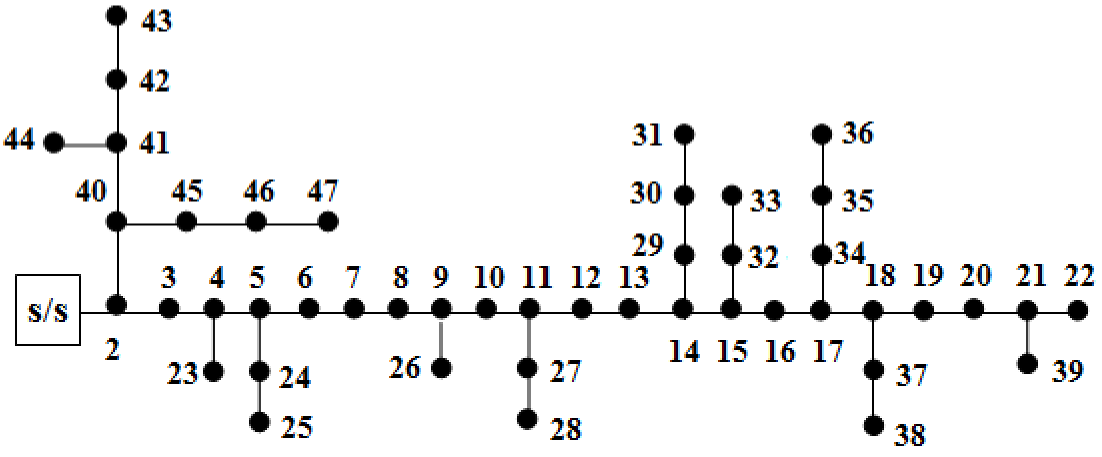

Fig. 5.14 Representation of 47-bus distribution system

5.4.1 *Optimize Total Cost*

The economical analysis of three Cases for 47-bus distribution system depicts that the total cost of the system gets reduced to $29,169.316$ $U.S.\$/yr$ as shown in Table 5.13. The fixed cost of switches i.e. $7,684$ $U.S.\$/yr$ is neglected by the considerable decrease in interruption hours of customers and optimal number of sectionalizers required to make the distribution system reliable as shown in Table 5.14. The total cost convergence characteristics after 10 iterations of the proposed method is shown in Fig. 5.15.

Table 5.13 Economical analysis for 47-bus distribution system

	Case1	Case2	Case3
$ECOST(U.S.\$/yr)$	31212.755	17438.115	21485.316
$Switches\ Cost(U.S.\$/yr)$	2028	38388	7684
$Total\ Cost(U.S.\$/yr)$	33240.750	55826.115	29169.316

Table 5.14 Optimal location of switches for 47-bus distribution system

$Number\ of\ Sectionalizer$	7
$Sectionalizer\ Locations$	5, 11, 15, 17, 18, 32, 39
$Number\ of\ Circuit\ Breaker$	1
$Circuit\ Breaker\ Location$	Supply side by default
$Switches\ Cost(U.S.\$/yr)$	7684
$ECOST\ (U.S.\$/yr)$	21485.316
$SAIDI\ (hrs/customer - yr)$	1.21
$Total\ Optimum\ Cost$	29169.316

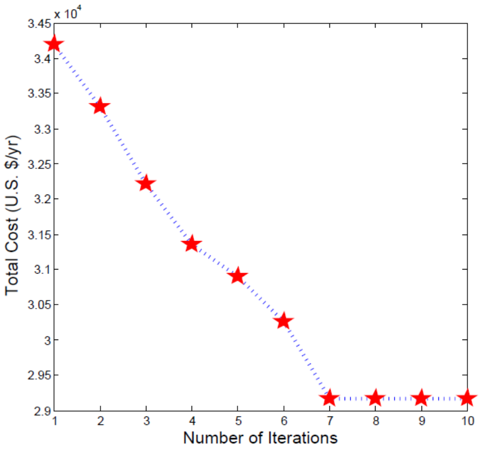

Fig. 5.15 Total cost convergence characteristics of the proposed MAPSO for 47-bus distribution system

Let the fault is restricted to sections $5, 14, 17, 23, 32$ and 45 to reduce the computational time required to find the optimized results. Then, on the basis of economical analysis of three Cases for 47-bus distribution system the total cost gets reduced to $6228.775\ U.S.\$/yr$ and corresponding SAIDI becomes $0.19\ hrs\ per\ customer - yr$ as given in Table 5.15. With the restriction on the number of sections that are prone to disturbances, optimal number of sectionalizers also gets reduced to 1 as given in Table 5.16.

Table 5.15 Economical analysis for 47***-bus distribution system with specified fault locations***

	Case1	Case2	Case3
$ECOST(U.S.\$/yr)$	4461.965	2273.456	3392.775
$Switches\ Cost(U.S.\$/yr)$	2028	38388	2836
$Total\ Cost(U.S.\$/yr)$	6489.965	40661.456	6228.775

Table 5.16 Optimal location of switches for 47***-bus distribution system with specified fault locations***

$Number\ of\ Sectionalizer$	1
$Sectionalizer\ Locations$	23
$Number\ of\ Circuit\ Breaker$	1
$Circuit\ Breaker\ Location$	Supply side by default
$Switches\ Cost(U.S.\$/yr)$	2836
$ECOST\ (U.S.\$/yr)$	3392.775
$SAIDI\ (hrs/customer - yr)$	0.194
$Total\ Optimum\ Cost$	6228.775

5.4.2 *Optimize Both Total Cost and SAIDI*

The proposed method MAPSO is implemented to solve two objectives total cost and SAIDI simultaneously using FDM approach, the number of sectionalizers required are 18 as shown in Table 5.17 with SAIDI and total cost equal to 0.99 $hrs/customer - yr$ and 35394.718 $U.S.\$/yr$ respectively.

Table 5.17 Optimal location of switches for 47***-bus distribution system using FDM***

$Number\ of\ Sectionalizer$	18
$Sectionalizer\ Locations$	5, 7, 11, 13, 14, 15, 18, 21, 22, 23, 27, 28, 29, 32, 33, 36, 37, 39
$Number\ of\ CircuitBreaker$	1
$Circuit\ Breaker\ Location$	Supply side by default
$Switches\ Cost(U.S.\$/yr)$	16572
$ECOST(U.S.\$/yr)$	18822.718
$SAIDI\ (hrs/customer - yr)$	0.99
$Total\ Optimum\ Cost$	35394.718

Chapter–6

CONCLUSION & FUTURE SCOPE

6.1 CONCLUSIONS

The MAPSO technique has been applied for optimal sectionalizer placement in the radial distribution system problem. The presented problem formulation determines the two objective functions namely total cost, which is the sum of system expected outage cost (ECOST) and switches cost, and the system average interruption duration index (SAIDI) by fuzzy decision making (FDM) approach. The effectiveness of the developed algorithm is tested to 12-bus, 33-bus and 47-bus distribution system. The following conclusions are drawn from the study:

- The MAPSO enhances the performance of the binary discrete optimization problem and converges in few iterations. Even, the mutation helps to come out from local minima.
- The specifying the fault locations improves the optimization as far as convergence is concerned.
- The formulation of fuzzy decision making approach is simple and effective in representing multi-objective problem as single objective optimization with respect to optimal sectionalizer placement solutions.
- The fuzzy decision making is providing best-compromised solution directly for various comparative parameters on different test systems.

6.2 FUTURE SCOPE

The scope of work after studying and analyzing the optimal sectionalizer placement problem using MAPSO is identified as:

- The optimization has been carried out for radial distribution systems. So, the investigation can be extended to meshed structures.

- The lateral distributions, disconnects, fuses, step-down transformers, and the alternative supply are assumed to be 100% available to simplify the methodology. Thereby the problem can be formulated taking into account the probability of load transfer of these components.

List of Publications

- Yashasvi Bansal and Sanjay K. Jain. Optimal sectionalizer placement in distribution system using mutation assisted particle swarm optimization. *International Journal of Electrical Power and Energy Systems.* (Communicated)

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Distribution Systems Data

(a) 12-bus Distribution system

The line and load data of 12- bus distribution system [26] is given in Table A.1 and Table A.2 respectively. The corresponding load flow solution is summarized in Table A.3.

Table A.1 Line data of 12-bus radial distribution system

$Branch\ No.$	$From\ Node$	$To\ Node$	$Branch\ Resistance(\Omega)$	$Branch\ Reactance(\Omega)$	$Distance\ Between\ Nodes(km)$
1	1	2	1.093	0.455	0.5
2	2	3	1.184	0.494	2.5
3	3	4	2.095	0.873	1.75
4	4	5	3.188	1.329	1.75
5	5	6	1.093	0.455	4
6	6	7	1.002	0.417	1
7	7	8	4.403	1.215	3.5
8	8	9	5.642	1.597	5
9	9	10	2.89	0.818	5
10	10	11	1.514	0.428	1
11	11	12	1.238	0.351	1.75

Table A.2 Load data of 12-bus radial distribution system

$Bus\ No.$	$P(kW)(avg.load)$	$Q(kVAR)$
1	0	0
2	60	60
3	40	30
4	55	55
5	30	30
6	20	15
7	55	55
8	45	45
9	40	40
10	35	30
11	40	30
12	15	15

Table A.3 Voltage magnitude and phase angle from 12-bus radial distribution system load flow solution

$Bus\ No.$	$Voltage\ Magnitude\ (pu)$	$Angle\ (Degree)$
1	1.000000	0.0000
2	0.995764	0.0877
3	0.991805	0.1683
4	0.985500	0.3024
5	0.977485	0.4713
6	0.975036	0.5228
7	0.972960	0.5677
8	0.966682	0.7546
9	0.960731	0.9260
10	0.958637	0.9815
11	0.957970	0.9989
12	0.957814	1.0041

(b) 33-bus Distribution system

The line and load data of 33- bus distribution system [27] is given in Table A.4 and A.5 respectively. The corresponding load flow solution is summarized in Table A.6.

Table A.4 Line data of 33-bus radial distribution system

$Branch\ No.$	$From\ Node$	$To\ Node$	$Branch\ Resistance(\Omega)$	$Branch\ Reactance(\Omega)$	$Distance\ Between\ Nodes(km)$
1	1	2	0.0922	0.0477	0.1
2	2	3	0.4930	0.2511	0.5
3	3	4	0.3660	0.1864	0.35
4	4	5	0.3811	0.1941	0.35
5	5	6	0.8190	0.7070	0.8
6	6	7	0.1872	0.6188	0.2
7	7	8	1.7114	1.2351	0.7
8	8	9	1.0300	0.7400	1
9	9	10	1.0440	0.7400	1
10	10	11	0.1966	0.0650	0.2
11	11	12	0.3744	0.1238	0.35
12	12	13	1.4680	1.1550	1.5
13	13	14	0.5416	0.7129	0.55
14	14	15	0.5910	0.5260	0.6
15	15	16	0.7463	0.5450	0.75
16	16	17	1.2890	1.7210	1.3
17	17	18	0.7320	0.5740	0.7
18	2	19	0.1640	0.1565	0.15
19	19	20	1.5042	1.355	1.5
20	20	21	0.4095	0.4784	0.4
21	21	22	0.7089	0.9373	0.7
22	3	23	0.4512	0.3083	0.45
23	23	24	0.8980	0.7091	0.9
24	24	25	0.8980	0.7011	0.9
25	6	26	0.2030	0.1034	0.2
26	26	27	0.2842	0.1447	0.3
27	27	28	1.0590	0.9337	1
28	28	29	0.8042	0.7006	0.8
29	29	30	0.5075	0.2585	0.5
30	30	31	0.9744	0.9630	0.95
31	31	32	0.3105	0.3619	0.3
32	32	33	0.3410	0.5302	0.35

Table A.5 Load data of 33*-bus radial distribution system*

$Bus\ No.$	$P(kW)(avg.load)$	$Q(kVAR)$
1	0	0
2	100	60
3	90	40
4	120	80
5	60	30
6	60	20
7	200	100
8	200	100
9	60	20
10	60	20
11	45	30
12	60	35
13	60	35
14	120	80
15	60	10
16	60	20
17	60	20
18	90	40
19	90	40
20	90	40
21	90	40
22	90	40
23	90	50
24	420	200
25	420	200
26	60	25
27	60	25
28	60	20
29	120	70
30	200	600
31	150	70
32	210	100
33	60	40

Table A.6 Voltage magnitude and phase angle from 33-bus radial distribution system load flow solution

$Bus\ No.$	$Voltage\ Magnitude\ (pu)$	$Angle\ (Degree)$
1	1.000000	0.0000
2	0.997015	0.0136
3	0.982883	0.0959
4	0.975373	0.1620
5	0.967948	0.2292
6	0.949470	0.1350
7	0.945946	-0.0966
8	0.932291	-0.2500
9	0.925960	-0.3245
10	0.920255	-0.3932
11	0.919386	-0.3858
12	0.917872	-0.3741
13	0.911697	-0.4672
14	0.909408	-0.5475
15	0.907981	-0.5859
16	0.906599	-0.6096
17	0.904552	-0.6885
18	0.903938	-0.6983
19	0.996486	0.0028
20	0.992909	-0.0642
21	0.992204	-0.0835
22	0.991567	-0.1039
23	0.979297	0.0649
24	0.972625	-0.0239
25	0.969300	-0.0676
26	0.947541	0.1745
27	0.944976	0.2307
28	0.933534	0.3137
29	0.925315	0.3916
30	0.921756	0.4969
31	0.917594	0.4125
32	0.916679	0.3894
33	0.916395	0.3817

(c) 47-bus Distribution system

The line and load data of 47- bus distribution system [28] is given in Table A.7 and A.8 respectively. The corresponding load flow solution is summarized in Table A.9.

Table A.7 Line data of 47-bus radial distribution system

Branch No.	From Node	To Node	Branch Resistance(Ω)	Branch Reactance(Ω)	Distance Between Nodes(km)
1	1	2	0.4565	0.2913	0.83
2	2	3	0.6875	0.4388	1.25
3	3	4	0.4400	0.2808	0.8
4	4	5	0.4785	0.3054	0.87
5	5	6	0.3080	0.1966	0.56
6	6	7	0.3685	0.2352	0.67
7	7	8	0.0825	0.0527	0.15
8	8	9	0.0770	0.0491	0.14
9	9	10	0.1980	0.1264	0.36
10	10	11	0.2805	0.1790	0.51
11	11	12	0.1650	0.1053	0.3
12	12	13	0.1980	0.1264	0.36
13	13	14	0.2090	0.1334	0.38
14	14	15	0.1540	0.0983	0.28
15	15	16	0.3630	0.2317	0.66
16	16	17	0.4345	0.2773	0.79
17	17	18	0.0385	0.0246	0.07
18	18	19	0.2255	0.1439	0.41
19	19	20	0.2915	0.1860	0.53
20	20	21	0.0770	0.0491	0.14
21	21	22	0.0715	0.0456	0.13
22	4	23	0.4345	0.2773	0.79
23	5	24	0.0770	0.0491	0.14
24	24	25	0.440	0.2808	0.8
25	9	26	0.3960	0.2527	0.72
26	11	27	0.0825	0.0527	0.15
27	27	28	0.2420	0.1544	0.44
28	14	29	0.6050	0.3861	1.1
29	29	30	0.2750	0.0.1755	0.5
30	30	31	0.6765	0.4317	1.23
31	15	32	0.3080	0.1966	0.56
32	32	33	0.4345	0.2773	0.79
33	17	34	0.3135	0.2001	0.57

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Table A.7 – *Continued from previous page*

Branch No.	From Node	To Node	Branch Resistance(Ω)	Branch Reactance(Ω)	Distance Between Nodes(km)
34	34	35	0.1595	0.1018	0.29
35	35	36	0.4455	0.2843	0.81
36	18	37	0.0385	0.0246	0.07
37	37	38	0.1595	0.1018	0.29
38	21	39	0.4950	0.3159	0.9
39	2	40	0.1925	0.1229	0.35
40	40	41	0.8250	0.5265	1.5
41	41	42	0.0770	0.0491	0.14
42	42	43	0.1210	0.0772	0.22
43	41	44	0.4015	2562	0.73
44	40	45	0.3245	0.2071	0.59
45	45	46	0.1925	0.1229	0.35
46	46	47	0.1540	0.0983	0.28

Table A.8 Load data of 47-bus radial distribution system

Bus No.	$P(kW)(avg.load)$	$Q(kVAR)$
1	0	0
2	0	0
3	44.76	39.47
4	111.90	114.16
5	0	0
6	88.77	85.57
7	38.42	25.82
8	78.70	73.68
9	67.51	47.12
10	7.46	3.82
11	47.74	35.81
12	50.36	35.15
13	51.10	39.66
14	0	0
15	58.19	40.62
16	54.83	38.27
17	0	0

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Table A.8 – *Continued from previous page*

$Bus\ No.$	$P(kW)(avg.load)$	$Q(kVAR)$
18	80.94	82.58
19	54.46	38.01
20	33.57	21.68
21	38.05	25.57
22	42.12	42.44
23	44.76	35.91
24	89.52	91.33
25	89.15	85.92
26	67.51	47.12
27	44.39	33.29
28	113.77	116.06
29	82.06	79.09
30	57.44	40.09
31	97.35	99.32
32	102.58	104.65
33	70.12	48.95
34	56.70	39.57
35	70.87	72.30
36	52.22	36.45
37	80.94	82.58
38	54.46	38.01
39	43.64	32.73
40	61.92	41.61
41	0	0
42	66.02	46.08
43	49.24	47.46
44	76.84	74.06
45	42.90	27.71
46	41.03	28.64
47	37.67	26.30

Table A.9 Voltage magnitude and phase angle from 47-bus radial distribution system load flow solution

$Bus\ No.$	$Voltage\ Magnitude\ (pu)$	$Angle\ (Degree)$
1	1.000000	0.0000
2	0.988082	0.0896
3	0.972581	0.2150
4	0.962860	0.2956
5	0.953072	0.3756
6	0.947361	0.4202
7	0.940878	0.4700
8	0.939456	0.4811
9	0.938194	0.4909
10	0.935204	0.5155
11	0.930988	0.5507
12	0.928868	0.5678
13	0.926419	0.5882
14	0.923942	0.6093
15	0.922510	0.6205
16	0.920005	0.6400
17	0.917240	0.6628
18	0.917067	0.6642
19	0.916584	0.6667
20	0.916117	0.6694
21	0.916018	0.6701
22	0.915984	0.6706
23	0.962669	0.2968
24	0.952925	0.3775
25	0.952510	0.3825
26	0.937937	0.4916
27	0.930848	0.5523
28	0.930543	0.5566
29	0.922401	0.6264
30	0.921947	0.6311
31	0.921211	0.6417
32	0.921945	0.6261
33	0.921647	0.6269

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Table A.9 – *Continued from previous page*

$Bus\ No.$	$Voltage\ Magnitude\ (pu)$	$Angle\ (Degree)$
34	0.916654	0.6672
35	0.916445	0.6693
36	0.916216	0.6699
37	0.917011	0.6648
38	0.916926	0.6650
39	0.915800	0.6711
40	0.987397	0.0933
41	0.985834	0.1069
42	0.985749	0.1074
43	0.985688	0.1082
44	0.985519	0.1106
45	0.987039	0.0939
46	0.986900	0.0942
47	0.986847	0.0943