Chapter 3

Problem Description And System Identification

3.1 Introduction

This chapter covers research problem formulation for optimal capacitor placement in distribution system. Various constraints, topologies and ways of reactive power reduction are discussed. Solution methods, which will be used for solving the problems, are addressed. System description of IEEE 30 bus system, its load flow analysis using ETAP software tool as well as particle swarm optimization are studied. Optimal locations and size of capacitor are determined using an objective function for the constraints like maintaining the voltage profile, power factor and total harmonic distortion. Other benefits of optimal capacitor configuration such as reduction in power loss, release of capacity and enhancement of reliability of the system. The solution methodology has two parts: (i) implementation of genetic algorithm for optimal capacitor placement using ETAP software and (ii) development and implementation of a novel algorithm OCP-PSO to estimate the optimal size of capacitors at the optimal buses. Section 3.2 discusses about genetic algorithm based problem description where, solution is carried out using ETAP software.
Reliability Analysis and OCP are two different modules in ETAP. Operating parameters of GA are discussed. Section 3.3 includes information of a novel tool development, based on dot net framework for OCP-PSO tool. Various parameters of PSO are discussed. Evaluation of loss reduction method, Failure rate reduction method, evaluation of customer cost damage function and development of OCP-PSO algorithm are discussed. Problem definition considering reliability cost and cost of losses are given.

Section 3.4 introduces a test system of IEEE 30 bus system. The proposed method has outperformed over all such methods in terms of the quality of solution and unique technology used to develop OCP-PSO based on reliability cost within the objective function which is evaluated using thermal loading depending on life expectancy based failure rate modification.

3.2 Problem Description Using Genetic Algorithm

3.2.1 Genetic algorithm & its parameters

GA is a search algorithm based on the mechanism of natural selection. Basically, a GA makes a population that evolves through time using reproduction and mutation process. Only individuals representing good solutions of the capacitor placement problem will survive longer, and their genetic information is to be presented in the next generation. At the end, after several generations, the interaction between these high quality individuals will produce a final population which represent the best solutions set of the problem.
Before the genetic algorithm procedure, the real parameters of the problem must be represented in genetic algorithm language. It means that location and size of the capacitors used are codified as a chromosome. The chromosome is divided in two parts. First part indicates location of the capacitors. The second part indicates the size of the capacitors used. In reproduction process, a pair of chromosomes is randomly selected, with the same structure. In the next step, chromosomes are treated separately; one for binary part and another for integer part. In binary part, for a given position, if two parents share value, the chromosome produced by reproduction will keep it. If values are different, the result for new chromosome is selected at random. In integer part, for a given position, result will be the average of values found in the parents. If result is not an integer value, it will be approximated until closer value at random is achieved.

**Mutation**: In mutation process, chromosome structure is modified. This change is performed at random, but there is a difference between binary and integer part. The GA is able to improve the quality of the randomly generated population very fast, and created good solutions in a very short time. The mutation operator aims to add diversity to the population of individuals. Similarly to the crossover, the mutation is divided into two parts. The first modifies the binary portion of the chromosome by choosing a position of the individual at random. The second part acts on the integer values by adding or subtracting a unity from its value. The choice of whether to add or subtract is also decided at random. Mutation is applied to 10% of the offspring. In general, higher mutation rates may slow down evaluation speed and hence should be avoided.

**Selection**: In the selection of individuals for recombination, selection of a leader uniformly at random is required. The next step is to choose which one
of the three supporters will take part in the recombination. This choice is also uniformly at random. Following this selection strategy, any pair of parents will belong to the same cluster. That makes the population act similarly to a multiple-population approach with a high migration rate.

**Crossover:** This causes pairs of individuals to exchange the genetic information with one another. The children are called crossover children. This is a procedure of choosing a random position in a string and swapping the characters. This random position is called the crossover point.

**Recombination:** After the selection of parents, input parameters in the recombination operator is utilized. The recombination returns a new individual called as offspring. Since the chromosome is composed of two distinct parts, they should be treated separately during the recombination process. There are, in fact, two recombination strategies: (i) chromosomes binary part and (ii) the integer part. In the binary part, we adopted the uniform crossover, where the offsprings allele is determined by randomly choosing the value present in one of the parents. If the parents share the same allele in a given position, the offspring will inherit this value. If the values are distinct, the offspring might inherit values zero or one with the same probability. In the integer part, average values found in parents is calculated. The values in the same position of the parents are added and divided by two. This will be the value inherited by the offspring. If the sum is odd, the division results in a non-integer value, which must be rounded up, or down, at random.

**Fitness function:** The fitness function quantifies the quality of the individual. Therefore, it will keep a close relation with the objective function of the problem. The first factor to be observed is the cost of the power losses, which takes into account the maximum voltage deviation observed in the distribution
network’s nodes for a given solution. Calculation of the power losses requires the execution of a load-flow algorithm. After recombination and mutation, GA submits all or some of the new individuals to a local search procedure for the purpose of improving their fitness function. This local search acts at the first part of the chromosome, i.e., trying to improve capacitor location. If a specific location already has a capacitor, the local search tests the possibility of dropping that capacitor (‘drop’). In case of deterioration of the solution, the position returns to the original value and the local search proceeds to the next one. This local search acts on the second part of the chromosome. It adjusts the sizes of the capacitors already present in the solution, trying to find the best size for each location. Only the sizes immediately above and below the present capacitor’s size are tested. For instance, if a 600 kVar capacitor is installed in a given position, the procedure tries the capacitors with sizes 400 and 800 kVar, looking for any improvement. Such tries are executed in a similar manner to the add/drop procedure, in one capacitor at a time; accepting any change that improves the fitness [84].

3.2.2 ETAP based genetic algorithm

ETAP currently utilizes the genetic algorithm (GA) for optimal capacitor placement problem. The genetic algorithm is an optimization technique based on the theory of natural selection. A genetic algorithm starts with a generation of solutions with wide diversity to represent characteristics of the whole search space. By mutation and crossover, good characteristics are selected and carried to the next generation. The optimal solution can be achieved through repeated generations. OCP uses the present worth method to perform alternative comparisons. It considers initial installation and operating costs, which include maintenance, depreciation, and loss reduction savings. The objective of optimal capacitor placement is to minimize the cost of the system. The detail study of objective function is included in section 3.2.4.
This cost is measured in four ways:

1. Fixed capacitor installation cost
2. Capacitor purchase cost
3. Capacitor bank operating cost (maintenance and depreciation)
4. Cost of real power losses

3.2.3 Reliability analysis using ETAP

Electric distribution system reliability analysis involves modeling different components of distribution systems, computing reliability indices at load points and for the overall AC system, and ranking the elements that contribute to the load point/bus/system indices EENS and ECOST. This section briefly discusses some fundamentals and underlying principles on the Distribution System Reliability Analysis program.

Distribution System Reliability Analysis Study

The Distribution System Reliability Analysis employs a new analytical algorithm to assess the reliability indices of mixed radial and meshed distribution systems. This algorithm basically uses the algorithm for radial distribution systems since the meshed network, if any, is first converted to a radial network. Therefore, the employed algorithm is quite efficient and suitable for large-scale distribution systems of general configurations.

Modeling Assumptions/Limitations in Reliability Analysis

The current distribution system reliability analysis makes the following assumptions:

- Only AC systems are considered.
- All switching devices operate successfully when required.
• Switching devices can be opened whenever possible to isolate a fault. Power supply can be restored to provide power to as many load points as possible using appropriate switching actions and available alternative supplies.

• All failures are statistically independent. Second-order faults can be considered.

**AC Component and System Modeling in Reliability Analysis**

A two-state up/down representation is used for the operation/repair cycle of an element (such as lines, cables, transformers, breaks, fuses, switches, loads and busbars). Normally open tie circuit connections can be taken into account. Currently, a normally open tie circuit connection is defined in the ETAP as the connection that satisfies:

(i) the two buses that it is connected are energized
(ii) it is composed of only the components of PDs
(iii) the connection is in service and
(iv) it contains at least one normally open PD.

As a default option of a sector interruption cost library, a Standard Industrial Classification (SIC) is used to divide customers into seven categories: large user, industrial, commercial, agriculture, residential, government & institutions and office & buildings. The sector interruption cost library gives the Sector Customer Damage Functions (SCDF), i.e., the interruption costs for several discrete outage durations. A log-log interpolation of the cost data is used where the interruption duration lies between two separate times. In the case of durations greater than the largest duration, a linear extrapolation with the same slope as that between the second largest and largest durations will be used to calculate the interruption cost. Any switching device, such as breaker, fuse, contactor, and switch, has the function of fault isolation. Only an over-current protective device (such as breaker and fuse) can interrupt fault currents. A fault in a radial sub-system is isolated by the nearest switching
device of any kind on its source side; a fault in a meshed sub-system is isolated
by its surrounding nearest switching devices. The associated set of isolated
load points is called the “isolated LP zone” of the faulted element. The af-
fected load points in the isolated LP zone of an element will be connected after
the repair of the faulty component, while the ones contained in its interrupted
LP zone but outside its isolated LP zone will have the supply restored after
a short switching or sectionalizing time. The switching time for a load is in-
ternally set to the switching time of the component that is the nearest to this
load. The component may be an equivalent cable, switching device or bus.
The EENS and ECOST for a bus are respectively defined as the Expected En-
ergy Not Supply and Expected Interruption Cost of the loads that are directly
connected to that bus due to the outage of that bus. The distribution sys-
tem reliability analysis study generates output reports showing system input
data, reliability indices results, element ranking information, and tabulation
of results. Some of these results can also be viewed directly from the one-line
diagram using the Distribution System Reliability Display Options Editor.

Reliability Assessment Analysis

Distribution system reliability assessment deals with the availability and
quality of power supply at each customers service entrance. Analysis of cus-
tomer failure statistics show that, compared to other portions of electrical
power systems, distribution system failures contribute as much as 90% towards
the unavailability of supply to a load. These statistics show how important the
reliability evaluation of distribution systems can be. The basic reliability in-
dices normally used to predict or assess the reliability of a distribution system
consist of three reliability indices:

1. Load point average failure rate
2. Average outage duration
3. Annual unavailability

In order to evaluate the severity or significance of a system outage, using the three basic indices mentioned above, two expanded sets of indices listed below must also be calculated. The two expanded sets of indices include the number and average load of customers connected at each load point in the system, and the customer interruption cost. The first set is the system reliability index, which consists of:

- System Average Interruption Frequency Index (SAIFI)
- System Average Interruption Duration Index (SAIDI)
- Customer Average Interruption Duration Index (CAIDI)
- Average Service Availability Index (ASAI)
- Average Service Unavailability Index (ASUI)

These additional indices can be used to assess the overall behavior of the distribution system. The second set includes the reliability cost/worth index:

- Expected Energy Not Supply (EENS)
- Expected Interruption Cost (ECOST)
- Interrupted Energy Assessment Rate (IEAR)

The indices EENS, ECOST, and IEAR can be those specifically for each load point or for the overall system. All of these indices can be used to evaluate the reliability of an existing distribution system and to provide useful planning information regarding improvements to existing systems and the design of new distribution systems. Moreover, in order to analyze the sensitivity of a reliability index EENS or ECOST with respect to failure rate of different elements, element contributions to that index and their rankings can be used. The rankings can be for a load point or the overall system. All of the indices
and rankings given above can be evaluated using the ETAP Reliability Analysis module. This module provides the tool to efficiently model various power system elements and devices to include their effects on the distribution system reliability, such as fault isolation and load restoration through the operation of switching devices. This module is suitable for reliability analysis of large-scale systems of general configurations. [Source: ETAP help guide]

3.2.4 Objective function of OCP using ETAP

Objective Function of OCP used in ETAP is given by Eqn. 3.1. The objective of optimal capacitor placement is to minimize the cost of the system. This cost is measured in four ways:

1. Fixed capacitor installation cost
2. Capacitor purchase cost
3. Capacitor bank operating cost (maintenance and depreciation)
4. Cost of real power losses

The majority of power systems operate at a lagging power factor due to inductive loads and delivery apparatus like lines and transformers. Power systems are inductive in nature, and require additional reactive power flow from the power grid. Excessive reactive power demand results in reduced system capacity, increased losses, and decreased voltage, as well as higher operating costs. Shunt capacitor banks are able to compensate for VAr requirements, but bank size, location, the capacitor control method, and cost considerations are important issues that need to be optimized during the design phase. An ideal solution would be a capacitor placement tool able to weigh all these factors and that considers load levels. This solution should also be able to place capacitors for voltage support and power factor correction, while minimizing the total cost of installation and operation. ETAP provides just such an application in
its Optimum Capacitor Placement (OCP) module. Cost can be represented mathematically as:

\[
min_f = \sum x_i C_{0i} + Q_{ci} C_{1i} + B_i C_{2i} T + C_2 \sum T_l P_{Ll} \quad (3.1)
\]

where,

- \(x_i\) - 0/1, 0 means no capacitor installed at bus i
- \(C_{0i}\) - Installation cost
- \(C_{1i}\) - Per kVAr cost of capacitor bank
- \(Q_{ci}\) - Capacitor bank size in KVAr
- \(B_i\) - Number of capacitor banks
- \(C_{2i}\) - Operating cost of per bank, per year
- \(T\) - Planning period(years)
- \(C_2\) - Cost of each kWh loss in Rs/kWh
- \(T_l\) - Time duration, in hours, of load level l
- \(P_{Ll}\) - Total system loss at load level l

The constraints for optimal capacitor placement are to meet the load flow limits. In addition to this, all voltage magnitudes of load (PQ) buses should be within the lower and upper bars. Load Power Factor (PF) should be greater than the minimum. It may be a maximum power factor bar. The constraints can be represented mathematically as:

\[
V_{min} < V < V_{max}
\]

\[
PF_{min} \leq PF
\]
3.3 Problem Description Using Particle Swarm Optimization

3.3.1 Particle swarm optimization & its parameters

Particle Swarm Optimization

Particle swarm optimization (PSO), in its historical version, is a collective and iterative method, with the emphasis on cooperation. Particle Swarm Optimization is an algorithm capable of optimizing a non-linear and multidimensional problem which usually reaches good solutions efficiently while requiring minimal parameterizations.

In PSO, All the particles share information, any particle knows what is the best position ever visited by any particle in the swarm. Each particle has velocity as formulated in Equ. 3.2 and position is mathematically represented in Equ. 3.3 as given below:

\[
V_{i(d+1)} = V_{i(d)} + C_1 \times r_0(p_{b,i,d} - x_{i,d}) + C_2 \times r_1(g_{b,i,d} - x_{i,d})
\] (3.2)

\[
x_{(i+1)d} = x_{id} + V_{id}
\] (3.3)

where,
- \(i\) - Particle index used as a particle identifier
- \(d\) - Dimension being considered  
  (Each particle has a position and velocity for each dimension)
- \(x_{id}\) - Position of particle \(i\) in dimension \(d\)
- \(V_{id}\) - Velocity of particle \(i\) in dimension \(d\)
- \(C_1\) - Acceleration constant for the cognitive component
- \(C_2\) - Acceleration constant for the social component
r - A random value between 0 and 1 
(stochastic component of the algorithm)

$pb_{id}$ - The location in dimension $d$ with the best fitness of all the visited locations in that dimension of particle $i$

$gb_{id}$ - The location in dimension $d$ with the best fitness of all the visited locations in that dimension of all the particles

If $V_{id} > \maxi_{i} \text{Velocity}$ Then $V_{id} = \maxi_{i} \text{Velocity}$

If $V_{id} < -\maxi_{i} \text{Velocity}$ Then $V_{id} = -\maxi_{i} \text{Velocity}$

Random variable $r$ is within 0 to 1. Considering maximum value of $r$ as 1, we can write $V_{id}$ in equation 3.2 as

$$V_{id} = (0.5 + \frac{r}{2})V_{id}$$

Also, $C_1$ and $C_2$ are the confidence coefficients also known as acceleration constant for cognitive and social components respectively. Factors depending on random variables $r_0$ and $r_1$ (0 to 1) is selected to each step improvement in evaluation up to the last iteration. Considering this, equation for position is represented by 3.3 and modified velocity is mathematically updated and reformulated by Eq. 3.4.

$$V_{(i+1)d} = (0.5 + \frac{r}{2})V_{id} + 2.0 \times r_0(p_{b, id} - x_{i,d}) + 2.0 \times r_1(g_{b, id} - x_{i,d}) \tag{3.4}$$

Particle swarm optimization (PSO) involves simulating social behavior among particles has been used for solving the capacitor placement problem in IEEE 30 bus system. The target problem is reformulated by a comprehensive objective function and set of inequality constraint with consideration of voltage profile, power factor and harmonic effect in addition to reliability cost which depend on factors like CCDF and failure rate, different loads levels, and practical aspect of fixed or switched capacitor banks. One motive for developing
the simulation was to model a capacitor placement and its sizing through PSO program for optimization of multi-dimensional cost function in IEEE 30 bus system based on human social behavior, which is of course not identical to fish schooling or bird flocking. One important difference is its abstractness. Birds and fish adjust their physical movement to avoid predators; optimal capacitor placement program avoids same bus for placement of capacitor and its sizing. This is a major distinction in terms of contriving a computer simulation, for at least one obvious reason: collision.

**Etiology Of Particle Swarm Optimization:** The particle swarm optimizer is probably best presented by explaining its conceptual development. As mentioned above, the algorithm began as a simulation of a simplified social milieu. Agents were thought of as collision-proof birds, and the original intent was to graphically simulate the graceful but unpredictable choreography of a bird flock.

**Nearest Neighbors Velocity Matching and Craziness:** A satisfying simulation was rather quickly written, which relied on two properties: nearest-neighbor “velocity matching” and “craziness”. A population of birds was randomly initialized with a position for each on a torus pixel grid and with X and Y positions. At each iteration, a loop in the program determined, for each agent (a more appropriate term than bird), which other agent was its nearest neighbor, then assigned that agent’s X and Y positions to the agent in focus. Essentially this simple decreased a synchrony of movement. Unfortunately, the flock quickly settled on a unanimous, unchanging direction. Therefore, a stochastic variable called craziness is introduced. At each iteration, some change are added to randomly chosen X and Y positions. Each agent “remembered” the best value and the XY position which had resulted in that value. The value is called $p_{best}$ and the positions $p_{bestx}$ and $p_{besty}$ (brackets indicate
that these are arrays, with number of elements = number of agents). If it is to the right of its \( p_{\text{best}_x} \), then its X velocity is adjusted negatively by a random amount weighted by a parameter of the system as formulated in Equ. 3.5.

\[
V_x[] = V_x[] - \text{rand()} \times \text{position} \tag{3.5}
\]

**Inertia weight ‘w’**: It is realized that there is no good way to guess whether \( p_{\text{best}} \) or \( g_{\text{best}} \) should be larger. Thus, these terms are used separately in this OCP-PSO algorithm. Further, it observed various ways of inertia ‘w’ consideration. An optimum value for the inertia \( w \) is considered by evaluating ‘w’ in particular situation which depends on iteration number. The value of ‘w’ is also depend on type of problem selected. Some of the researchers are considered the fixed value of inertia, which is not true as inertia is changing parameter, which depends on velocity and time. The value can be determined from some knowledge of a particular problem. The current simplified particle swarm optimizer adjusts weights by the following formula shown in Eqn. 3.6.

It is observed from previous literature that PSO give most success ratio for the range 0.4 to 0.9. In this work, we start PSO with higher value of 0.9 and decreased up to 0.4 as mathematically represented in Equ. 3.6.

\[
\text{InertiaW} = (w_i - 0.4) \frac{i_{\text{max}} - i}{i_{\text{max}}} + 0.4 \tag{3.6}
\]

Where,

\[
\begin{align*}
  w_i & = \text{inertia weight in ith iteration} \\
  i_{\text{max}} & = \text{maximum iteration} \\
  i & = \text{current iteration number}
\end{align*}
\]

### 3.3.2 Random values \( r_0 \) and \( r_1 \)

Today there are many methods to generate random number. In most of computing methods such as PSO, modeling of random numbers are necessary.
Since computers are based on a fixed hardware, and algorithms are deterministic, they cannot be used to create truly random numbers. When it is said to be random number generation by computers, we actually mean pseudorandom numbers, since they are not entirely random. These pseudorandom numbers are typically generated by a program which takes random bits as an input. However, if the seed (initial bit sequence entered) is the same, then the algorithm will usually return a similar sequence of numbers. Truly, random numbers are generated by random processes, e.g., a fair die roll, atmospheric noise. In this research work we used code based random number generator based on dot net programming code in microsoft visual studio.

3.3.3 Confidence coefficient $C_1$ and $C_2$

Particle swarm optimization is an effective evolution algorithm for optimizing. Based on analysis of particle movements during simulation, particle is up to control the value of $C_1$ and $C_2$, which effects convergence rate of PSO. Aiming at solving optimal capacitor placement problems, corresponding particle is adopted $C_1$ and $C_2$ to improve performance. $C_1$ and $C_2$ are also called as learning factors in addition to confidence coefficient. $C_1$ and $C_2$ usually equal to 2. However, other settings were also used in different case studies. But usually $C_1$ equals to $C_2$ and ranges from $[0, 4]$. We have selected $C_1=2.0$ and $C_2=2.0$ for this research due to its excellent performance.

3.3.4 OCP-PSO tool development

Introduction: OCP-PSO software is developed to remove the drawback of ETAP software. This software is developed in the dashboard format using dot net technology as shown in Fig. 3.1. ‘Capacitor configuration’ is a module which can be enable for providing capacitor information. Various parameters like capacitor voltage rating, KVAR rating, maximum number of capacitors, cost of capacitor, installation cost, operating cost, active power cost coeffi-
Figure 3.1: Dot net based dash board for OCP-PSO software using IEEE 30 bus system

cient, reactive power cost coefficient and customer type can be edited and set for evaluation purposes by pressing ‘Set Parameter’ tab (button). ‘Upload’ tab (button) is provided for uploading IEEE 30 bus information of bus and branch data required for evaluation. Similarly all load flow data is used to insert in the system by using this tab (button). Bus and branch data is memorized in the form of database table and can be used as and when required. Once bus and branch data is provided the reliability study is carried out by pressing ‘Before OCP Simulation’ tab (which is required for comparison with various case studies). These results can be stored in plot format as well as excel format. Customer composite damage function is selected from the equation corresponding to customer type. Simulation after capacitor placement is carried out using ‘OCP simulation with’ tab. Here, choice of constraints are provided. Voltage constraint, power factor constraint and all constraint is provided. All constraint is combination of voltage and power factor constraint. Results of
objective function is now available for selected constraint with all possible capacitors. These multiple objective functions are then passes through PSO tool by selecting proper PSO parameters (also called as parameter tuning). Result of PSO is the final simulation number, from which capacitor size and place is tabulated. Various algorithms are developed and used in OCP-PSO novel software as listed below.

- Algorithm for Simulation before capacitor placement
- Algorithm for uploading bus & branch data
- Algorithm for CCDF Evaluations
- Algorithm for Reliability Cost
- Constraints in OCP-PSO
- Algorithm to find Reliability indices during OCP
- Particle Swarm Optimization tool in OCP-PSO
- Algorithm for OCP-PSO System without PSOFEED table
- Algorithm to modify Failure rate
- Algorithm for combined OCP & PSO with PSOFEED table

3.3.5 Reliability cost and indices using OCP-PSO

Introduction to Reliability Cost

Considering the change of industrial process automation, integration of conventional approach resulted into need of highest supply Reliability. Even a short duration interruption causes high financial losses to various industrial customers. The performance and the cost of electricity supply of various distribution companies is going to be governed by quality and reliability of supply as electricity is considered as commodity. In today’s distribution network the
growth of non linear load is taking place at faster rate , while deciding the optimal capacitor configuration for enhancement of reliability in case of nonlinear load voltage distortion constraint in addition to voltage profile and power factor is essential. In problem formulation, objective function is developed considering reliability cost, which is evaluated as per following equation.

\[
ECOST = \lambda_i \times C_i \times L(a)_i
\]  

(3.7)

Where,

- ECOST - reliability Cost
- \( \lambda_i \) - failure rate at \( bus_i \)
- \( C_i \) - customer composite damage function at \( bus_i \)
- \( L(a)_i \) - average load

Eqn. 3.7 represents evaluation of reliability cost based on failure rate (denoted by \( \lambda_i \)). Number of interruptions or faults in given system network is mostly due to weak systems and results into poor power system operation and control. Failure rate can be decreased with strengthening power system by means of (i) proper reactive power management and control (ii) maintaining power factor towards unity and (iii) voltage profile. All these can be achieved by using proper capacitor placement and sizing.

**Failure rate modification (\( \lambda_{mod} \))**

Transformer winding temperature changes as per the loading of transformer. Even transmission line temperature also changes as par loading line. \( \Theta \) is temperature in the transformer winding or transmission line due to loading percentage. As loading increases or decreases, theta changes accordingly. Change in theta; also change the life of transformer unit as well as transmission lines between the buses. Failure rate of any equipment changes as per life of equipment. Using average load in MW, reactive power in MVAR and MVA rating,
Loading per unit is calculated by Eqn. 3.8.

\[ \text{Loading}_\text{pu} = \frac{\sqrt{(MW^2 + MV Ar^2)}}{MV A_{\text{rating}}} \]  

(3.8)

If \( \text{Loading}_\text{pu} < 0.0 \), Then \( \text{Loading}_\text{pu} = 0.0 \)

If \( \text{Loading}_\text{pu} > 1.8 \) Then \( \text{Loading}_\text{pu} = 1.8 \)

Now, Life expectancy table is prepared for the range 0.01 to 1.8 per unit loading of equipment using Eqn. 3.9. Loading per unit for a given bus is calculated and respective life per unit is collected from the life expectancy table. Life expectancy table is shown in chapter 4. Life calculated is without capacitor placement and hence this life is treated as per unit uncompensated life and represented by \( L_{uc} \). As per IEEE standard C57.100, 2011, life of transformer is mathematically represented by 3.9.

\[ \text{Life} = e^{-\left(\frac{n}{\Theta + 273} - A\right)} \]  

(3.9)

Where, A and B are constants and \( \Theta \) is temperature due to heat losses in transformers. We select \( A = 27.064 \) & \( B = 15000 \) due to same rating of transformer. Similarly in the simulation process, thermal stress of the equipment is increased or decreased by variation of number of capacitor placed at bus for OCP-PSO method, which changes the resultant current and hence the loading. New life expectancy from the table is collected and is treated as per unit compensated life and given by \( L_c \). Then modified Life \( L_m \) of transformer or transmission line is formulated in Eqn. 3.10.

\[ L_m = \frac{L_c - L_{uc}}{L_c} \]  

(3.10)

If actual Life of equipment is 1.0 per unit, then failed life or dead life \( L_f \) of
given equipment is calculated by,

\[ L_f = 1 - L_m \quad (3.11) \]

This failed life \( L_f \) is used as multiplying factor for the failure rate modification. Now modified failure rate is formulated as represented in Eqn. 3.12.

\[ \lambda_{\text{mod}} = \lambda_{\text{old}} \times L_f \quad (3.12) \]

Now using \( \lambda_{\text{mod}} \) from Eqn. 3.12, reliability cost can be evaluated using Eqn. 3.7.

**Customer composite damage function \( C_i \)**

\( C_i \) represented in Eqn. 3.7 is customer composite damage function (CCDF), which varies with customer type and duration of interruption. Cost due to interruption for a customer like industrial, commercial, agricultural, municipal or domestic is different. Hence this factor is dependent on customer type as well as interruption duration. Table 3.1 indicates about various customers cost Vs time duration. This information is from ETAP Manual used as default data for IEEE 30 bus system to evaluate \( C_i \).

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</table>
**Average load:** $L_{avg}$ is the average load connected at $bus_i$. Addition of a capacitor may affect the average load at $bus_i$. So it is required to evaluate $L_{avg}$ in simulation process continually.

**Reliability Indices**

All literature surveys showed that the most commonly used indices are SAIFI, SAIDI, CAIDI, and ASAI. These indices are sustained indices. Momentary indices are neglected as damage due to momentary indices are less as well as most of industries and other customers have backup facility for the same. In this work reliability indices are evaluated as formulated in Eqn. 3.13 to Eqn. 3.16 as given below.

1. **System average interruption frequency index** indicates, how often the average customer experiences a sustained interruption over a predefined period of time. Mathematically, this is given in Eqn. 3.13.

$$SAIFI = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers served}} \quad (3.13)$$

2. **System average duration index** indicates the total duration of interruption for the average customer during a predefined period of time. It is commonly measured in customer minutes or customer hours of interruption. Mathematically, this is given in Eqn. 3.14.

$$SAIDI = \frac{\sum \text{Customer interruption duration}}{\text{Total number of customers served}} \quad (3.14)$$

3. **Customer average interruption duration index** represents the average time required to restore service. Mathematically, CAIDI is given in
\[ CAIDI = \frac{\sum \text{Customer interruption duration}}{\text{Total number of customer interruptions}} \]  

(3.15)

4. **Average service availability index** represents the fraction of time (often in percentage) that a customer has received power during the defined reporting period. Mathematically, this is given in Equ. 3.16.

\[ ASAI = \frac{\text{Customer Hours Service Availability}}{\text{Customer Hours Service Demands}} \]  

(3.16)

3.3.6 **Objective function using OCP-PSO**

Objective function for optimal capacitor placement using OCP-PSO software is formulated by Equ. 3.17.

\[ \min f = ECOST + \sum_{i=1}^{Nbus} CC + \sum E_l \]  

(3.17)

Following constraints are applied during the simulation process,

\[
\begin{align*}
V_{\text{min}} &< V < V_{\text{max}} \\
PF_{\text{min}} &\leq PF \\
V_{THD} &\leq V_{THD}^{\text{max}}
\end{align*}
\]

Assumptions considered in the development of the objective function are,

1. Balanced network considered for simplicity

2. Capacitors are available in step size

Eqn. 3.17 is the objective function (also called as cost function) needs to evaluate using OCP-PSO to find optimal location of capacitor and its size for a given constraints in a given search space. All values of objective function are processed through the curve fitting using polynomial expression to form the
equation coefficient for each bus. These coefficients are provided as PSOFEED search space. PSO finds best capacitor size for given bus among all solutions. Fitness function is the solution to indicate simulation number from which capacitor size and best location can traced. Step by step evaluation process is discussed below.

**Step 1:** Reliability cost ECOST is evaluated as discussed in section 3.3.5.

**Step 2:** Evaluation of cost of capacitor

The capacitor cost CC is formulated as given in Eqn. 3.18.

\[
CC = x_i C_{0i} + Q_{ci} C_{1i} + B_i C_{2i} T
\]  

(3.18)

Where,

- \( x_i \) - 0/1, 0 means no capacitor installed at bus i
- \( C_{0i} \) - installation cost
- \( C_{1i} \) - per kVAr cost of capacitor bank
- \( Q_{ci} \) - capacitor bank size in KVAr
- \( B_i \) - number of capacitor banks
- \( C_{2i} \) - operating cost of per bank, per year
- \( T \) - planning period (years)

**Step 3:** Cost of energy loss is evaluated as under. Energy loss \( (E_l) \) is formulated by using power loss \( (P_{Li}) \) as discussed in Eqn. 3.19.

\[
E_l = T_i P_{Li}
\]  

(3.19)

Power loss in transmission line is combination of active and reactive power losses as mathematically expressed in Eqn. 3.20 and \( T_i \) is time duration (=8760Hrs).

\[
P_{Li} = \sum_{i=1}^{N_{bus}} P_{loss} + \sum_{i=1}^{N_{bus}} Q_{loss}
\]  

(3.20)

First component of Eqn. 3.20 is active power component where as second component is reactive power component treated separately for evaluation of
active and reactive power losses.

### 3.4 System Identification

**Introduction**: Optimal capacitor placement and sizing problem is formulated and explained in detail in section 3.3.6. Objective function is based on the requirements of benefits due to reliability cost, cost of capacitor, purchase cost, operating cost, maintenance cost and savings due to transmission and distribution loss reduction. This cost function is tested on IEEE 30 bus system. The one line diagram of an IEEE-30 bus system is shown in Fig.3.2. The System data is taken from IEEE PES Society and discussed in section A.2. IEEE 30 bus system includes following.

- Number of Branches = 41
- Number of 132 kV buses = 09
- Number of 33 kV buses = 19
- Number of 11 kV buses = 02
- Number of Load points = 23
- Number of generator buses = 06

#### 3.4.1 IEEE 30 bus system

IEEE 30 bus system is graphically shown in Fig.3.2. Various bus data is tabulated in Table 3.2. This bus information is utilized in various simulation process such as load flow analysis, reliability analysis and optimal capacitor placement program. Similarly branch data is tabulated in Table 3.3.
Table 3.2: Bus data of IEEE 30 Bus

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<tr>
<th>Bus No</th>
<th>Voltage Magnitude (p.u.)</th>
<th>Gen real Power (p.u.)</th>
<th>Gen Reac power (p.u.)</th>
<th>Load real Power (p.u.)</th>
<th>Load Reac power (p.u.)</th>
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Table 3.3: Line data of IEEE 30 Bus

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<td>28</td>
<td>0.0169</td>
<td>0.06</td>
<td>32</td>
<td>0.9536</td>
<td>0.0464</td>
</tr>
</tbody>
</table>
This chapter of thesis consists of problem description and system identification. This chapter focuses on objective function development using OCP-PSO for optimal capacitor location and sizing. Cost function is developed, which is multi objective function, consisting the reliability cost, capacitor cost and power loss cost. A case study is selected as IEEE 30 bus system is selected as test system for case studies.