CHAPTER 2
ELECTRIC POWER DISTRIBUTION SYSTEM CONFIGURATION

2.1 INTRODUCTION

The distribution system is considered not only as one of the important part of the electric power system but one of the most complicated systems created by the mankind. It constitutes the link between electricity utilities and consumers as shown in Figure 2.1. A typical distribution system will consist of one or more distribution substations consisting of one or more “feeders.” Components of the feeder may consist of the following:

- Three-phase primary “main” feeder
- Three-phase, two-phase (“V” phase), and single-phase laterals
- Step-type voltage regulators or load tap changing transformer (LTC)
- In-line transformers
- Shunt capacitor banks
- Three-phase, two-phase, and single-phase loads
- Distribution transformers (step-down to customer’s voltage)

Electric power distribution systems constitute the greatest risk to the interruption of power supply [1-3]. Traditionally, however, distribution systems have received less attention than generation and transmission, evidenced by the different in the number of publications [9]. However, the focus is moving towards distribution as the business focus change from consumers to consumers. Further, in present days of energy crises and with increasing concern for environmental pollution, energy conservation should be a priority.
Chapter 2: Electric Power Distribution System Configuration

1247 KV substation

Three-phase, four wire main feeder

Distribution Transformer

Two-wire, one phase laterals

Reclosing circuit

Feed point

Normally open switch for emergency

120/240

DT serving 4 to 20 homes

Three-phase load

Sectionalizing switches

Three-pole recloser

Switched capacitor bank

Sectionalizing switch normally-closed

Underground lateral

Normally-open tie to adjacent feeder

Residential area. Approximately 1000 homes per square mile. Feeder area. 1 to 4 mi² depending on load density. 15 to 30 single-phase laterals per feeder. 150 to 500 MVA short-circuit available at substation bus.

Figure 2.1. Electrical power distribution system
Very often, it is observed that electrical power utilities distribution system lacks in meeting the quality and reliability [10], firstly due to the technological factors and secondly due to the operating factors concerning deployment of electrical power distribution equipments and their loads. The major factors are:

1. Average power transmission loss of power utilities figures around 5-6% of total power demand where as 60-70% of the loss is estimated to be lost in distribution system.

2. Real time information communication and co-ordination of the protection scheme for the power distribution network configuration.

3. Electrical power distribution system suffers unbalanced feeder structure and unbalanced loading which affects system power quality and electricity prices.

4. Distribution feeder having mixture of commercial residential and industrial type loads with daily dissimilar load variations causes the peak loads at different times (non coincidence of peaks).

5. Requirement of efficient tools and techniques for multi-objective and nondifferential optimization problem of electrical distribution system.

Electrical power distribution system delivers power to the customers from a set of distribution substation feeders, usually placed in radial configuration so as to simplify over current protection, lower short circuit, simple switching and protecting equipment with lower reliability [17],[24]. In an automated distribution system, the configuration is changed from time to time so that the loads are supplied at the cost of minimize line losses. Distribution feeders have two type of switches-sectionalizing switches (normally closed) and tie switches (normally open). The network reconfiguration determines the status of these switches for a new topological structure in the normal state to enhance service reliability and reduce power losses. The network reconfiguration problem is a complex nonlinear combinatorial problem, since the status of switches is nondifferentiable and the normally open tie switches must be determined to satisfy system requirements [25].
As reported, about 30-40% of total investment is for distribution system in an electric power sector [31]. Therefore, loss reduction in distribution system can be efficient to reduce transmission loss in the whole power system. With this view, power utilities are especially concentrating on a loss minimization, power quality and reliability problem using network reconfiguration, as it does not require new equipment.

An effective feeder reconfiguration strategy takes advantage of the large degree of load diversity that exists on some distribution systems. That is, each distribution feeder has a different combination of commercial, industrial, and residential loads. These loads tend to vary in three time of day, week, and season that they require a peak power supply. Feeder reconfiguration would allow for the transfer of load from heavily loaded portion of the distribution system network to locations that are relatively lightly loaded. This would not only improve the operating conditions of the system, but it would also enable the full utilization of system hardware capabilities. This could result in the deferral of capital expenditures and reduced operating expenses.

The different load categories and classifications are obtained from the RBTS network data [44]. Bus 2 has four types of customer’s viz. residential, small user, government/institution and commercial. Bus 4 has three types of customer’s viz. residential, small user and commercial. All the load points of the two networks are classified as one of these customer types. The total peak load for Bus 2 is 20 MW, while the total peak for Bus 4 is 40 MW.

For the load modeling, hourly time-varying characteristics are incorporated. The weekly loads for 52 weeks are expressed as percentages of the annual peak load for the different customer types mentioned above. Figure 2.2 gives the load cycle for all the weeks in a year. An electric utility data [33] is used for the percent weekly, daily and hourly values. Figure 2.3 gives the daily loads for seven days as percentages of the weekly peak. Finally, the hourly load data as percentages of the daily peak as weekday or weekend for summer, winter and spring/fall weeks as shown in Figures 2.4, 2.5 and 2.6 respectively.
Chapter 2: Electric Power Distribution System Configuration

Figure 2.2. Weekly Load as Percent of Annual Peak

Figure 2.3. Daily Load as Percent of Weekly Peak
Chapter 2: Electric Power Distribution System Configuration

Figure 2.4. Hourly Load as Percent of Daily Peak in Summer Weeks

Figure 2.5. Hourly Load as Percent of Daily Peak in Spring/Fall Weeks
In the past, the power utility companies of this nation supplied electric energy to meet all customer demands when demands occurred. Recently, however, because of the financial constraints (i.e., high cost of labor, material, interest rates and space), environmental concerns, and the recent shortage (or high cost) of fuels, this basic philosophy has been re-examined and customer load management investigated as an alternative to capacity expansion.

The requirements of a successful distribution system program are specified by Scott [41] as follows:

1. It must be able to reduce demand during critical system load periods.
2. It must result in a reduction in new generation requirements, purchased power, and/or fuel costs.
3. It must have an acceptable cost/benefit ratio.
4. Its operation must be compatible with system design and operation.
5. It must operate at an acceptable reliability level.
6. It must have an acceptable level of customer convenience.
7. It must provide a benefit to the customer in the form of reduced rates or other incentives.
The operation and design standards for distribution networks have recently changed due to different factors. The most important of these are: the care about energy saving and, in general, about rational use of resources; cheap availability of the reliable measurement and control devices; higher demand for high quality of service from customers; electrical energy market deregulation; new systems for networks monitoring and control due to new relations between generation, distribution and users.

Distribution network expansion planning is one of the important activities in the distribution control centers. Several evaluation items such as new equipment installation cost, equipment utilization rate, reliability of the target distribution system, loss minimization should be evaluated considering increase of network loads and newly installed large customer loads when planning. Experienced persons have performed the planning conventionally [54]. However, only a few cases have been evaluated practically because of limited planning time. Therefore, it is difficult to evaluate optimality of generated plans from the above-mentioned points of view.
Recently, reduction of maintenance costs, retaining investment for equipment and energy saving are of primary concerns in power utilities [9],[58-59]. Therefore, more efficient distribution network is required to meet the today’s requirement without any expenditure on new equipment. Some of the important objectives of optimum distribution planning are:

i) Providing maximum possible reliability and reduced interruption costs.

ii) Minimizing the investment and maintenance costs.

iii) Minimizing power losses and achieving acceptable voltage levels.

More over, with increasing use of the Supervisory Control and Data Acquisition System (SCADA) and Distribution Automation Control (DAC) equipped with automated switches and remote monitoring facilities; thus distribution system reconfiguration becomes a more viable alternative for loss reduction, resulting the distribution feeder reconfiguration as a planning tool as well as a real time control tool [63],[68].
New technologies are spreading in distribution systems. These can be a key element to correctly meet the above cited factors. Indeed many systems are nowadays automated and they allow the centralized or distributed control of many elements such as tie-switches and shunt capacitor banks.

Generally, power distribution network reconfiguration provides services to as many customers as possible following fault coding and during planned outage for maintenance purposes with system loss minimization and load balancing of the network. It allows the transfer of loads from heavily loaded feeders or transformers to relatively less heavily loaded feeders or transformers. Such transfers are effective in terms of altering the level of loads on the feeders being switched as well as in improving the voltage profile along the feeders and have affecting reduction in the overall system power losses [69].

However, the network reconfiguration problem is a complex non-linear combinational problem due to non-differential status of switches and the normally open tie switches, determined to satisfy system requirement. From optimization point of view, the reconfiguration method have been used for loss reduction using different techniques (reported in the synopsis) on the other hand from service restoration point of view, the reconfiguration allows to relocate loads by using an appropriate sequence of switching operations with operating constraints taken into account.

Considerable researches have been carried out in power distribution network configuration since 1975 and are reported through research papers. However, their approaches are broadly classified under following three categories:

1) Classical methods combined with heuristic, where we find branch-and-bound and feeder-pair (loop) quadratic programming decomposition methods.

2) Heuristic based methods, where we find papers in branch-exchange; application of the compensation-based power flow technique to reduce Merlin and Back central idea and more recently, heuristic methods that account for other practical operational constraints like protection requirement and limited number of switching operations.

3) Modern artificial intelligence based methods, where we find papers in artificial neural network (ANN) expert systems, simulated annealing (SA), evolutionary programming, and genetic algorithm (GA).
Recently, it is found that modern heuristic methods such as GA, SA and Tabu Search (T-S) can be used for large combinational optimization problem. Tabu Search belongs to a family of methods, which also include SA, and GA. Tabu Search explores the whole solution space definitely based on the local search in which controlled up-hill move is admitted [98],[182]. So, a properly designed distribution system alone can render efficient and fault-free service to the consumers and at the same time reduce distribution losses to the minimum economically optimum level.

2.2 TYPES OF PRIMARY DISTRIBUTION

2.2.1. Radial Systems, including Duplicate and Throw-Over Systems
The radial-type system is the simplest and the one most commonly used. It comprises separate feeders or circuits “radiating” out of the substation or source, each feeder usually serving a given area. The feeder may be considered as consisting of a main or trunk portion from which there radiate spurs or laterals to which distribution transformers are connected, as illustrated in Figure 2.9.

Figure 2.9. Primary feeder schematic diagram showing truck or main feeds and laterals or spurs.
Chapter 2: Electric Power Distribution System Configuration

The spurs or laterals are usually connected to the primary main through fuses, so that a fault on the lateral will not cause an interruption to the entire feeder. Should the fuse fail to clear the line, or should a fault develop on the feeder main, the circuit breaker back at the substation or source will open and the entire feeder will be de-energized.

To hold down the extent and duration of interruptions, provisions are made to sectionalize the feeder so that unfaulted portions may be re-energized as quickly as practical. To maximize such re-energization, emergency ties to adjacent feeders are incorporated in the design and construction; thus each part of a feeder not in trouble can be tied to an adjacent feeder. Often spare capacity is provided for in the feeders to prevent overload when parts of an adjacent feeder in trouble are connected to them. In many cases, there may be enough diversity between loads on adjacent feeders to require no extra capacity to be installed for these emergencies.

Supply to hospitals, military establishments, and other sensitive consumers may not be capable of tolerating any long interruption. In such cases, a second feeder (or additional feeders) may be provided, sometimes located along a separate route, to provide another, separate alternative source of supply. Switching from the normal to the alternative feeder may be accomplished by a throwover switching arrangement (which may be a circuit breaker) that may be operated manually or automatically. In many cases,

Figure 2-10. Schematic diagram of alternate feed-throwover arrangement for critical consumers.
two separate circuit breakers, one on each feeder, with electrical interlocks (to prevent connecting a good feeder to the one in trouble), are employed with automatic throwover control by relays. See Figure 2-10.

2.2.2. Loop Systems, including both Open and Closed Loops

Another means of restricting the duration of interruption employs feeders designed as loops, which essentially provide a two-way primary feed for critical consumers. Here, should the supply from one direction fail, the entire load of the feeder may be carried from the other end, but sufficient spare capacity must be provided in the feeder. This type of system may be operated with the loop normally open or with the loop normally closed.

**a. Open Loop**

In the open-loop system, the several sections of the feeder are connected together through disconnecting devices, with the loads connected to the several sections, and both ends of the feeder connected to the supply. At a predetermined point in the feeder, the disconnecting device is intentionally left open. Essentially, this constitutes two feeders whose ends are separated by a disconnecting device, which may be a fuse, switch, or circuit breaker. See Figure 2-11.

![Figure 2-11. Open-loop circuit schematic diagram](image-url)
Chapter 2: Electric Power Distribution System Configuration

In the event of a fault, the section of the primary on which the fault occurs can be disconnected at both its ends and service re-established to the unfaulted portions by closing the loop at the point where it is normally left open, and reclosing the breaker at the substation (or supply source) on the other, unfaulted portion of the feeder.

Such loops are not normally closed, since a fault would cause the breakers (or fuses) at both ends to open, leaving the entire feeder de-energized and no knowledge of where the fault has occurred. The disconnecting devices between sections are manually operated and may be relatively inexpensive fuses, cutouts, or switches.

b. Closed Loop
Where a greater degree of reliability is desired, the feeder may be operated as a closed loop. Here, the disconnecting devices are usually the more expensive circuit breakers. The breakers are actuated by relays, which operate to open only the circuit breakers on each end of the faulted section, leaving the remaining portion of the entire feeder energized.

![Figure 2-12. Closed-loop circuit schematic diagram](image-url)
In many instances, proper relay operation can only be achieved by means of pilot wires which run from circuit breaker to circuit breaker and are costly to install and maintain; in some instances these pilot wires may be rented telephone circuits. See Figure 2-12.

To hold down costs, circuit breakers may be installed only between certain sections of the feeder loop, and ordinary, less expensive disconnecting devices installed between the intermediate sections. A fault will then de-energize several sections of the loop; when the fault is located, the disconnecting devices on both ends of the faulted section may be opened and the unfaulted sections reenergized by closing the proper circuit breakers.

2.3 ADVANTAGES OF RADIAL NETWORKS OVER MESHED NETWORKS

With the expansion in the use of electricity, the demands on the distribution systems became greater and more complex. They not only had to serve greater numbers of consumers, but had to supply their greater individual loads that now required closer supervision of voltage variations at the consumers’ terminals. Further, consumers demanded reliability in their service that could tolerate only fewer interruptions of shorter duration.

At this point, the design, construction, maintenance, and operation of distribution systems became a science involving technical and economic disciplines not only in the field of electrical engineering, but in mechanical, civil, chemical, and almost all other fields of engineering as well.

From the early, simple, “radial” circuit, i.e., a feeder supplied from one source, other more sophisticated designs evolved. Radial circuits were provided with sectionalizing points which enabled a faulted section of the circuit to be disconnected. This enabled the remainder of the circuit beyond the faulted section to be re-energized by connecting it to other sources, usually adjacent circuits. These “emergency” tie points, specifically provided for this purpose, also enabled loads to be transferred conveniently from one circuit to another.
Radial networks have some advantages over meshed networks as follows:

- lower short circuits current,
- simpler switching,
- protection equipment and
- providing lower overall reliability.

Therefore, to use the benefits of radial structure, and all at the same time to overcome the difficulties, distribution systems are planned and built as weakly meshed network but operated as radial network and reconfigured to provide a service to as many customers as possible during a fault condition, or during plant outage for maintenance purpose. Distribution system should be operated at minimum loss and cost subjected to a number of constraints as radial configuration, all loads are served, over current protective devices are co-ordinated, lines, transformer and other equipment are within current carrying capacity, and voltage magnitudes are within limits.

2.4. NEED FOR ELECTRIC POWER DISTRIBUTION SYSTEM RECONFIGURATION

Power distribution systems provide the final link between a utility and its customers. These systems face demands for ever-increasing power requirements, high reliability, more automation, and greater control complexity. At the same time, utilities face a scarcity of available land in urban areas, ecological considerations, the undesirability of rate increases, and the necessity to minimize investments and operating expenses. Planners must consider all of these factors, and, simultaneously, attempt to minimize the cost of substations, feeder and laterals, as well as the cost of losses [3].

Generally network reconfiguration is needed to

1. Provide service to as many customers as possible following a fault condition or during planned outage for maintenance purpose,

2. Reduce system losses and transfer of loads to avoid overload of network elements. Optimal operating condition can be considered to be obtained if reconfigured network presents (a) minimum losses, (b) minimum voltage deviation at the consumer feeding points and (c) maximum reliability.
As the demand for electrical power continues to grow, so, too, does the public's awareness of environmental issues and energy conservation. Utilities must maximize their use of existing equipment and optimize existing system capabilities as a means of generating more capacity without construction of new facilities. It has been estimated that 5% to 13% of total system generation is wasted in the form of distribution system losses [4], and therefore the reduction of these losses is important. In [5], Grainger and Kendrew examined the distribution of losses in a distribution network. Their results are summarized in Table 2.1.

Table 2.1. Summary of allocation of power losses in a distribution system.

<table>
<thead>
<tr>
<th>Segment</th>
<th>% of revenue</th>
<th>% of losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substation losses:</td>
<td>0.66</td>
<td>17.1</td>
</tr>
<tr>
<td>Primary feeders</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Φ</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>1Φ and 2Φ</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td><strong>Total feeder losses</strong></td>
<td>0.74</td>
<td>19.0</td>
</tr>
<tr>
<td>Distribution transformers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No-load loss</td>
<td>1.86</td>
<td></td>
</tr>
<tr>
<td>Loaded loss</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td><strong>Total transformer losses</strong></td>
<td>2.14</td>
<td>55.1</td>
</tr>
<tr>
<td>Secondary feeder losses</td>
<td>0.13</td>
<td>3.4</td>
</tr>
<tr>
<td>Other losses</td>
<td>0.12</td>
<td>5.4</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>3.88</td>
<td>100.0</td>
</tr>
</tbody>
</table>

From Table 2.1, it can be seen that the biggest contributor to losses are the distribution transformers, accounting for 55.1% of all losses (with no-load losses three times that of losses under load), and representing 2.14% of the utility's revenue. The next largest contributors are the primary feeders, which account for 19.0% of all losses, and which represent 0.74% of the utility's revenues. Thus, reduction of losses represents an effective means of cutting the cost of power to a utility.
As well, there are other economic benefits resulting from multi-objective solution, including [36]:

- Released generation capacity;
- Released transmission capacity;
- Released distribution substation capacity;
- Reduced energy (copper) losses;
- Reduced feeder voltage drop and consequently improved voltage regulation; and,
- Deferral / elimination of capital expenditures for system improvement /expansion.

A lot of work has been done concerning resistive line losses in distribution network through reconfiguration. Most of the recent research on distribution automation has been focused on minimum loss configuration problem, while an exhaustive search for all possible configurations would provide the most accurate and reliable solution, this is unrealistic as it takes a long time for real time application. There have been a number of works concerning resistive line losses reduction in network through reconfiguration [1-185]. Generally, there are two approaches to the reconfiguration problem:

i) First approach would be to determine the status of all switches in the network simultaneously. Due to the combinational nature of the problem very complicated mathematical technique should be used, and large computational time is needed. Usually, the solutions obtained by the methods using this approach represent a global optimum of the loss optimization problem.

ii) Second approach would be deal with the each possible loop (determined by the open tie switch) one at a time. Methods based on this approach are simpler and faster. The simplicity and speed are achieved by introducing heuristic techniques and approximation. Sometimes these method leads to local optimum that closely approximates the global optimum.

Traditional optimal configuration is obtained by minimizing power losses. For a given period a moment of time is chosen as a representative state of load condition in the networks (usually the system peak) and a power loss optimization method is used to
determine the configuration of network. The operational parameters mentioned above, i.e. losses, voltage quality and reliability, are directly related to network configuration and capacitor arrangement. The financial justification of the solution of each optimization subproblem is in this way affected by the solution of the other. Moreover, there is an optimum protection scheme that corresponds to each network configuration. This scheme must be updated at each step of reconfiguration processes [1, 2]. Thus, applicable optimization techniques for distribution network operation should be based on:

- The examination of the interaction between the solutions of optimization subproblems.
- The selection of the subproblem algorithms best suited to the solution of the overall optimization problem.

Most of the recent work on reconfiguration has either used branch exchange or segmental switch opening. Heuristic methods are applied in most cases to reduce the number of switches options considered.

2.5. METHODS OF REDUCING DISTRIBUTION SYSTEM LOSSES

Several techniques can be employed to reduce distribution system losses, and these will be examined in detail. These techniques are as follows [3]:

a. introduction of higher voltage levels;

b. reconductoring;

c. conservation voltage reduction;

d. installation of capacitors; and,

e. system reconfiguration.

Reference [6] provides benefit/ cost ratios for various methods of loss reduction in distribution systems, and these are summarized in Table 2.2.

Table 2.2. Benefit/cost ratios for Various Methods of loss reduction, [6].

<table>
<thead>
<tr>
<th>Method of Loss Reduction</th>
<th>Benefit / Cost ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction of higher voltage levels</td>
<td>1.5 to 3</td>
</tr>
<tr>
<td>Reconductoring</td>
<td>0.6 to 7</td>
</tr>
<tr>
<td>Installation of capacitors</td>
<td>2 to 8</td>
</tr>
<tr>
<td>Reconfiguration</td>
<td>0 to 13</td>
</tr>
</tbody>
</table>
It can be seen that the most expensive methods (in terms of benefit/cost ratio) are reconductoring and the introduction of higher voltage levels. System reconfiguration provides one of the most economical options.

### 2.5.1 Introduction of Higher Voltage Levels

The primary feeder voltage level is the most important factor affecting the system design, cost and operation. Operational and design aspects affected by the voltage level include feeder length and loading, the number and rating of distribution substations, system maintenance practices and type of pole-line design and construction [36]. In general, for a given percent voltage drop, the feeder length and loading are direct functions of the feeder voltage level, and may be expressed by a relationship known as the voltage-square rule. For example, if the feeder voltage is doubled, for the same voltage drop, the feeder can supply the same power four times the distance. The relationship is:

\[
\text{Voltage - square factor} = \left( \frac{V_{L-new}}{V_{L-old}} \right)^2
\]

Introduction of higher voltage levels involves extensive modification to existing networks, as well as to associated switchgear, transformers and substation equipment, and hence entails considerable cost to a utility that may or may not be economically feasible. For example, Toronto Hydro recently upgraded its distribution system to 13.8 kV, with projected savings of $620 million over 25 year [12]. On the other hand as a counter-example, with shrinking margins as a result of its regulatory agency's refusal to allow rate increases, Ottawa Hydro recently decided to suspend its upgrade of its 4.16 kV system to 13.8 kV as too costly [14].

### 2.5.2 Reconductoring

The resistance, \( R \), of a conductor of length, \( l \), resistivity, \( \rho \) and cross-sectional area, \( A \), is:

\[
R = \rho \frac{l}{A}
\]
It is apparent that line resistance can be decreased by using a conductor with a lower resistivity or by increasing the cross-sectional area of the conductor. The costs associated with reconductoring may be prohibitive, and probably are only justified in networks that are operating near their design capacity [15],[85].

2.5.3 Conservation Voltage Reduction

Conservation voltage reduction (CVR) is a method by which utilities lower substation transformer voltages by a few percent to reduce peak demand. Although there have been several studies of CVR, it is not clear that CVR is of benefit to all utilities, as there is an associated loss of revenue to a utility when the peak demand is reduced.

Several American studies provide conflicting conclusions regarding CVR. In [25], De Steese et al note that there is a potential of a 0.765% reduction in energy consumption for each 1% reduction in average voltage for residential customers. While Snohomish County PUD in the state of Washington found that energy swings were achieved from the implementation of CVR on distribution circuits, these swings were highly variable from circuit to circuit and were difficult to measure accurately [31]. However, reducing the distribution primary voltage did not result in lower real and reactive power demand on the distribution circuits tested. In a study by Detroit Edison, the opposite results were found, in that reducing the distribution primary voltage did result in lower real and reactive power demand [49]. However, this study concluded with the following comments:

"Although energy is saved when voltages are lowered, voltage reduction does not appear to be a practical, cost effective, and viable method of conserving energy. The cost of energy which customers would save would be offset by additional rate increases, additional operation and maintenance expenses, and it is likely that the quality of service for some customers would become a problem."

The performance and the operating life of equipment may be affected when the voltage at the terminals of the equipment deviates from its nameplate value. The effect may be minor or serious, depending on the deviation from the nameplate voltage rating and the characteristics of the equipment. In Canada, standards for voltage levels have been established [53], and utilities are bound by these standards. Practicing CVR may
lead to excessive voltage drop along long, heavily loaded feeders, and thus voltages have to be carefully monitored when CVR is used.

For induction motors, reference [25],[13] provides an indication of the general effects of voltage variations on induction motors. For a 10% voltage decrease, the starting and maximum running torque decrease 19%, while the slip increases 20-30%. There is a corresponding increase of 5-10% in the full-load current, corresponding to a temperature rise of 10-15%. Thus, in the case of predominantly induction motor loads, there will be an increase in line current, and hence an increase in line losses.

For resistance heating devices, the heat output varies approximately as the square of the impressed voltage. Thus, a 10% drop in voltage will cause a drop of approximately 19% in heat output. To produce the same amount of heating would then require the resistance heater to operate for longer periods, and thus energy conservation would not be achieved.

In summary, CVR is not beneficial when the loads are predominantly induction motors or resistance heating devices. As well, the reduction in voltage may lead to excessive voltage drops to some customers. The success of CVR is very system-dependent, and determined by such factors as predominant customer types, feeder lengths and loading.

2.5.4 Installation of Capacitors

The fundamental purpose of capacitors is to regulate the voltage and reactive power flows at the point where they are installed [56]. Shunt capacitors do not affect the current or power factor beyond their point of application and generation of reactive power at a power plant and its supply to a load located at a far distance is not economically feasible. In Ontario, customers whose power factor is less than 90% pay for the excessive reactive power demanded, and it is in their best interest to carry out power factor correction [14]. The result is that many municipal utilities operate at near unity power factor, and hence installation of capacitors is often not warranted.
2.5.5 System Reconfiguration

Loss minimization through system reconfiguration can provide substantial savings to a utility. By applying loss minimization techniques, a distribution automation project by the Pennsylvania Power and Light Company projected potential savings of over $100k by reducing losses by 14.6% in one year for a 230 MW distribution network [61].

A radial distribution system consists of a set of series components including lines, cables, disconnects, busbars and transformers between a utility and its customers. Most distribution systems are designed and constructed as single radial feeder systems. Some systems are constructed as meshed systems, but operated as single radial feeder systems by using normally-open switches in the mesh. These normally open points reduce the amount of equipment exposed to a fault on any single feeder circuit and ensure that, in the event of a fault or during scheduled maintenance periods, the normally open point can be closed and another opened in order to minimize the total load disconnected from the system.

A typical system one-line diagram is shown in Figure 2.13. Sectionalizing switches along a feeder and inter-feeder tie switches are used to maintain a radial structure. For every switch closed, another is opened. The greater the numbers of sectionalizing (or tie) switches, the greater are the possibilities for reconfiguration. To have minimum losses, a network must be equipped with remotely-operated switches, preferably in every line of the network to provide the maximum degree of flexibility. The primary benefit of a radial structure is that it simplifies fault detection, allowing a utility to quickly dispatch repair crews where needed, and to isolate faulted sections so that service to other sections can be restored. Radial networks have lower short circuit currents and simpler switching and protective equipment than meshed networks [54]. The tradeoff is that these networks have lower overall reliability.
Power utilities are turning increasingly to computers and telecommunications to monitor and control power systems. Considering the size and complexity of a modern utility, a human operator cannot hope to control a power system without automated assistance. SCADA (supervisory control and data acquisition) systems generate large amounts of data that cannot be rapidly assessed by a human operator, and thus there is a desire to automate human decision making tasks. SCADA systems allow the remote control of distribution system switches to improve system reliability through fault isolation and service restoration. These switches can also be used to transfer loads among feeders in a distribution system to meet new load requirements, and to make better use of system capacity.
Thus, loss minimization through system reconfiguration is an attractive option, as it uses existing equipment to reduce losses. Even those utilities that rely on manual switches can benefit from reconfiguration, although on a much-reduced basis, perhaps only carrying out reconfiguration once or twice per year.

Reference [77] describes the results of a distribution automation study conducted by Pacific Gas & Electric. Substation and feeder automation were identified as cost-effective areas benefiting from distribution automation. For feeders, automation included data acquisition from sectionalizes, line switches and fault indicator, as well as supervisory control of these devices for feeder reconfiguration and fault isolation. Economic benefits associated with feeder automation included reductions in capital expenditures due to deferment of additional feeders through more effective use of existing feeders, reductions in operations and maintenance costs, increased revenues as a result of loss reduction through feeder reconfiguration and faster service restoration following a fault.

The reconfiguration of an electric distribution system to reduce losses also has a natural tendency to balance loading among circuits, putting the system in a better position to respond to emergency load traders [80]. This is especially important when transformers and feeders are loaded close to their limits due to rapid load growth or delays in the construction of new substations and feeders [82].

Perhaps the most comprehensive study into system automation and reconfiguration has been that of the Athens Area Control Experiment (AACE), carried out by the Athens Utility Board (AUB), and thoroughly described in Reference [20]. The system automated during AACE was made up of 12 feeders, 35 load-break switches, 12 power reclosers, 5 voltage regulator banks, 29 capacitor banks and 21 fault detectors. A load-break switch was a three-phase, group operated switch with an electric motor operator costing approximately $11k, whose purpose was to isolate faulted lines and transfer loads while a circuit was energized. These switches were also used as tie switches between feeders. Power reclosers are similar to load-break switches, except their purpose is to clear temporary faults.

AUB saw an improvement in conventional system reliability indices through automation. It was also discovered that there were significant intangible benefits and
tangible cost benefits that were not measured through reliability indices. Automated fault
detection and remote control of switches and breakers lead to (1) significant reduction in
the time required to detect and locate faults; (2) faster isolation of faulted sections; and,
(3) faster load restoration above and below a faulted zone. Additionally, outages were
prevented, or the outage area was reduced (and hence the number of customers affected),
costs were saved by automating tasks that had previously been performed manually,
equipment problems were detected prior to catastrophic failure, and system safety was
improved. It was also possible to detect such things as abnormal load conditions and
insulation failure.

Reliability studies indicated that automation was fully justified. The time of
customer interruption of power was highly sensitive to the switching time required to
sectionalize a feeder and restore service after a fault, and thus remotely-operated switches
in place of manual switches increased reliability. The switches installed by AUB were
primarily to increase reliability rather than to optimize feeder loading. It was found that
hourly load transfers were sufficient.

Part of the AACE studies included determining if capacity utilization could be
improved as a result of automation. It was thought that remote load traders between
feeders would allow surplus equipment capacity at one location to make available to
other locations quickly and easily. However, the results obtained were less than
anticipated by AUB for a variety of reasons, including:

- Coincident peak loads on feeders;
- "Telescoped" feeder conductor diameters that decreased in discrete steps with
distance from the substation; and,
- Reconfiguration increased the impedance between source and load. This served to
increase losses, and at the same time increase the voltage drop along the feeder.

The drop in voltage resulted in a drop in customer loads.

As a result of AACE, AUB recommended more automated switches to allow
smaller load transfers. Most feeders had switches to sectionalize feeders into three or four
zones, which allowed only relatively large load transfers.

In [24],[26], Aoki et al review the principal functions of SCADA systems in
distribution systems, and note that algorithms for "automatic load transfer for secure or
economical operation require more research in order to put them into practical use as "no efficient algorithm for the sectionalizing-switch operation has been established, as it is a combinatorial optimization problem." At the same time, however, these algorithms are indispensable in distribution automation, and must be developed.

2.4 SUMMARY

With society, in all walks of life, becoming more dependent for its successful functioning on a good supply of electric energy, the link between the source and the consumer, the distribution system, assumes an ever more critical role. It is not only called upon to deliver ever greater quantities of electric energy, but the demand for ever higher standards of quality imposes on it requirements that become ever more stringent.

This chapter discusses some background material necessary for understanding the problem of distribution system. This chapter provides overview on the advantage of radial system, need of reconfiguration technique for loss minimization, examines several techniques for reducing distribution system losses, and introduces loss minimization through system reconfiguration; examines the difficulties in implementing loss minimization through reconfiguration;

The three objectives which are concluded:

- Individuate the most appropriate network model in order to optimize the reconfiguration policies.
- Select the optimization algorithm allowing an efficient exploration of the space of possible network configurations, in order to individuate those configurations capable of supporting service sustainability at the multi-objective purpose.
- Determine the trade-off between computing power and computational complexity in order to achieve faster-than-real-time solutions.