DISTRIBUTION NETWORK RECONFIGURATION FOR LOSS REDUCTION BY MULTI-BRANCH EXCHANGE METHOD

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ABSTRACT

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As structure and size of electric power distribution systems are getting more complex, distribution automation schemes become more attractive. One of the features that is desirable in an automated system is feeder reconfiguration for loss reduction. Loss reduction can make considerable savings for a utility and results in released system capacity. There is also improved voltage regulation in the system as a result of reduced feeder voltage drop.

In this thesis, multi branch exchange algorithm is introduced to solve the network reconfiguration for loss reduction problem. The proposed technique is based on heuristic techniques applied to constraint satisfaction optimization problems. A critical review of earlier methods related with feeder reconfiguration is presented. A computer program was developed using Matlab to simulate this algorithm and results of simulations demonstrate its advantages over single branch exchange method. Moreover, the results show that the final configuration is independent of the initial configuration and give assurance that any solution offered will have a radial configuration with all loads connected.

ÖZ

ÇOK DALLI DEĞİŞİM YÖNTEMİ İLE KAYIPLARI EN AZA İNDİRECEK FİDER DÜZENLEMESİ

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Teknolojik gelişmelere paralel olarak, büyük ve karmaşık yapısı nedeni ile elektrikdağıtım sistemlerindedeğişik otomasyon işlevlerinin kurulabilmesi ekonomik ve teknik açıdan giderek daha mümkün hale gelmektedir.Dağıtım sistemlerinin işletilmesi ve planlamasında hedeflenenkriterlerin biri de kayıpların azaltılmasıdır. Kayıpların azaltılması bir dağıtım şirketi için önemli tasarruf sağlayabilir ve sistem kapasitesinin daha etkin kullanılmasına yol açar. Fider düzenlemesi yolu ile kayıpların azaltılmasına ek olarak, gerilim düşümünün azaltılmasından dolayı sistemde daha iyi bir gerilim regülasyonu elde edilebilir.

Bu tez çalışmasında, dağıtım sistemlerinde orta gerilim fiderlerinde kayıpların azaltılması için fider düzenleme problemine çözüm olarak çok dallı değişim algoritması önerilmektedir Önerilen yöntem sınırlı optimizasyon problemlerine uygulanan sezgisel tekniklere dayanmaktadır. Bu algoritmanın simülasyonunu için Matlab'ta bilgisayar programı geliştirilmiştir.Yapılan simülasyonların sonuçları tek dal değişimi algoritmasına göre çok dallı değişim yönteminin daha iyi performansa sahip olduğunu göstermektedir.Ayrıca, simülasyon sonuçları, fider düzenlemesinde son çözümün başlangıç yapısından bağımsız olduğunu ve yöntemin sistemin radyal çalışmasını sağlamakta başarılı olduğunu göstermektedir.

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INTRODUCTION

Over the past few decades, electric power distribution systems received considerably less attention than transmission and generating systems [1]. This is due mainly to the fact that transmission and generating systems are usually very capital intensive, and inadequacies in either often lead to widespread catastrophic consequences. Consequently, more effort has gone into ensuring the adequacy of this part of the power system. Distribution systems are relatively cheap, and outages have a very localized effect. However, while relatively inexpensive, large sums of money are spent collectively on such systems.

A radial power distribution network is composed of a set of series components including transformers, busbars, disconnects, cables and lines between a utility and its customers. A customer connected to any load point in a distribution system requires all of the components between the point of connection and the supply point to be operating. Many power distribution networks are designed and constructed as groups of single radial feeders. Some networks are constructed as meshed systems, but operated as single radial feeder systems by using normally-open switches in the mesh. These normally open points ensure that, in case of any fault or during planned maintenance periods, the normally open point can be closed and another opened using switches to minimize the total load disconnected from the system. In order to make better use of system capacity, and to minimize I^2R losses in the distribution lines, these switches can also be used to transfer loads among feeders to meet new load requirements. For a given system, there will be a switching pattern that minimizes system losses. If there are N switches in a system, there are 2^N possible switching combinations. For modern distribution systems with thousands of load buses and hundreds or even thousands of switches, the challenge of finding the optimum switching pattern to minimize losses is formidable.

1.1 The Need for Distribution System Reconfiguration

Electric power distribution networks provide the link between a customer and utility. 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, feeders and laterals, as well as the cost of losses [3]. 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 1.

Table 1.The distribution of losses in a distribution network [5].

Segment	% of Revenue	% of Losses
Substation losses	0,66	17,1
Primary feeders	0,74	19
Distribution Transformers	2,14	55,1
Secondary feeder losses	0,13	3,4
Other losses	0,21	5,4

From Table 1, it can be seen that the biggest contributor to losses are the distribution transformers, accounting for 55.1% of all losses, 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 loss minimization, including [3]:

- Released transmission capacity;
- Released generation capacity;
- Released distribution substation capacity;
- Reduced energy losses;
- Reduced feeder voltage drop and consequently improved voltage regulation; and,
- Elimination of capital expenditures for system improvements.

1.1.1 Methods of Reducing Distribution System Losses

Several techniques can be employed to reduce distribution system losses. These techniques are as follows [3]:

a. Introduction of higher voltage levels;
b. Reconductoring;
c. Installation of capacitors;
d. System reconfiguration.

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. 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. Capacitors are also used for reduction of system losses but the fundamental purpose of capacitors is to regulate the voltage and reactive power flows at the point where they are installed [3]. The result is that many utilities operate at near unity power factor, and hence installation of capacitors is often not warranted.

Reference [6] provides benefit/cost ratios for various methods of loss reduction in distribution systems, and these are summarized in Table 2. 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 more economical options.

Table 2. Benefit/cost ratios for various methods of loss reduction [6].

Method of Loss reduction	Benefit/Cost ratio
Introduction of higher voltage levels	1,5-3
Reconductoring	0,6-7
Installation of capacitors	0,2-8
Feeder Reconfiguration	0-13

1.1.2 System Reconfiguration

Loss minimization through system reconfiguration can provide substantial savings to a utility. A radial power distribution network is composed of a set of series components including transformers, busbars, disconnects, cables and lines between a utility and its customers. Most electric power distribution systems are designed and constructed as single radial feeder systems. Some systems are loop designed and constructed, but radial operated by using normally open switches in the loop. These normally open switches reduce the amount of equipment exposed to a fault on any single feeder circuit and make sure that, in case of fault or during planned maintenance periods, the normally open switch can be closed and another opened in order to reduce the total load disconnected from the system.

A typical one line diagram of a distribution system is presented in Figure 1.Tie and sectionalizing switches are used to maintain the radial structure of the system. If one of the switches is closed, another is opened.

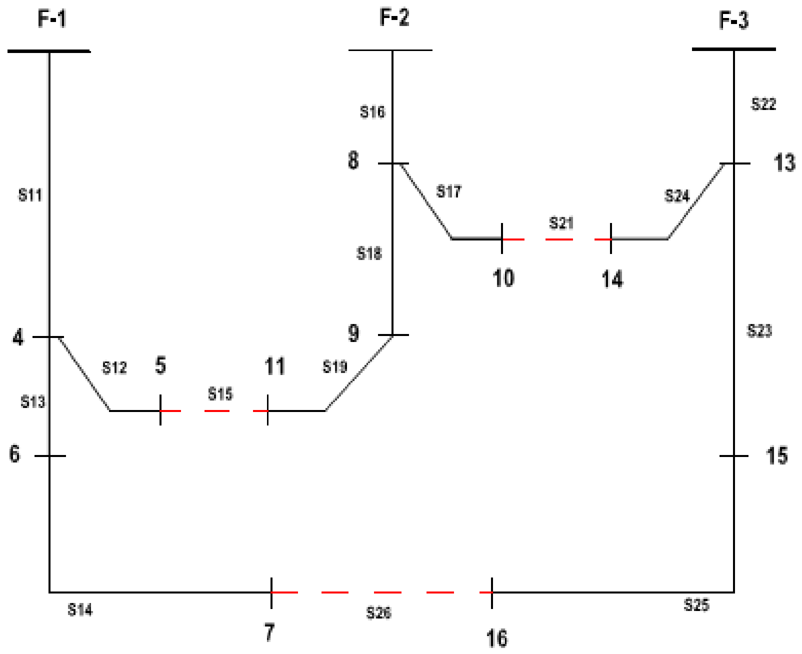

Figure 1. A distribution system with 3 feeders and 16 switches, 3 of which are open.

The greater the number of sectionalizing (or tie) switches, the greater the possibilities for reconfiguration. To have minimum losses, a network must be equipped with remotely-operated switches, preferably in every line section of the network to provide the maximum degree of flexibility. The most important advantage 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 [16]. The tradeoff is that these networks have lower overall reliability.

1.2 Feeder Reconfiguration As a Part of SCADA System

Recently 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 electric distribution system switches to improve system reliability through service restoration and fault isolation. These switches can also be used to make better use of system capacity and to transfer loads among feeders in a distribution system to meet new load requirements.

The distribution SCADA application is the core of many of the traditional distribution automation applications. While it typically has not included customer load control capabilities, it does act as the primary application to control substation and distribution network devices. It monitors the capacitor banks and reclosers and may also incorporate a variety of other sensor data.

Additionally, future applications will be designed to measure transformer performance and other pole-top uses. A traditional use of this distribution SCADA application has been fault location, isolation, and restoration. Typically, this involves the distribution SCADA system being used to communicate with circuit breakers and reclosers to monitor their status and respond to faults. One of the features of SCADA system is automatic feeder configuration. Feeder reconfiguration is an important sub problem of the overall power distribution system automation process. Feeder reconfiguration is one of the essential operations to be carried out in successful realization of the power distribution system automation. Electric distribution system automation is being carried out world over to improve the reliability of the distribution system and to reduce the losses that are occurring in the power distribution system. The feeders in the power distribution system are equipped with intelligent electronic devices (IED) which could be wireless automatic reclosers capable of forming a mesh system to autonomously communicate with each other without involvement of a central application. The mentioned IEDs can locally sense faults within sub system and communicate the status to the neighboring feeders. The feeders can react smartly to reconfigure the power distribution network topology to deenergize or to restore service to subsystems.

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.

1.3 Description of the Problem

The main objection to reconfiguration is that it is computationally expensive, i.e., as system size grows, so does the computation time. If there are N switches in a distribution network, there are 2^N possible configurations. For modern urban distribution systems, the number of distribution transformers may reach to several thousands, and each transformer may be supplied by several different feeders and substations [23]. Such systems are very complex, very difficult to monitor, and difficult to control optimally in real-time. Losses associated with each configuration must be calculated, and this requires a load flow analysis. The problem is compounded by the desire to maintain the radial configuration of the distribution system and by operational constraints, i.e., ensuring feeders and transformers are not overloaded and ensuring voltage drop limitations are not exceeded. As well, there is a need for efficient data structures and algorithms that will permit reconfiguration in real-time.

1.3.1 Dynamic Nature of Distribution Systems

Calculation of the losses for a configuration provides value for only one instant in time, based on current bus loads. However, distribution systems are very dynamic, and customers include industries, commercial centers and residential homes, all of which have changing load demands throughout the day, week and season of the year. A typical load profile over a twenty-four hour period for a residential load is shown in Figure 2. Thus, reconfiguration must be carried out on a regular basis (i.e., on-line and in real-time) as demand changes, further increasing the computational load. Each feeder in a distribution system has a different mixture of commercial, residential, and industrial type loads, and it is well known that the daily load variation of these load types are dissimilar. For example, a feeder which serves industrial loads could have peak loading during 8 AM to 5 PM, while a residential feeder could experience peak loading during 6 PM to 12 AM. Consequently, the peak loads on substation transformers, on individual feeders, or on feeder sections occur at different times. Seasonal, daily, and hourly time variations of load provide analysis points for the reconfiguration algorithm, where time varies over a daily cycle and/or a seasonal cycle.

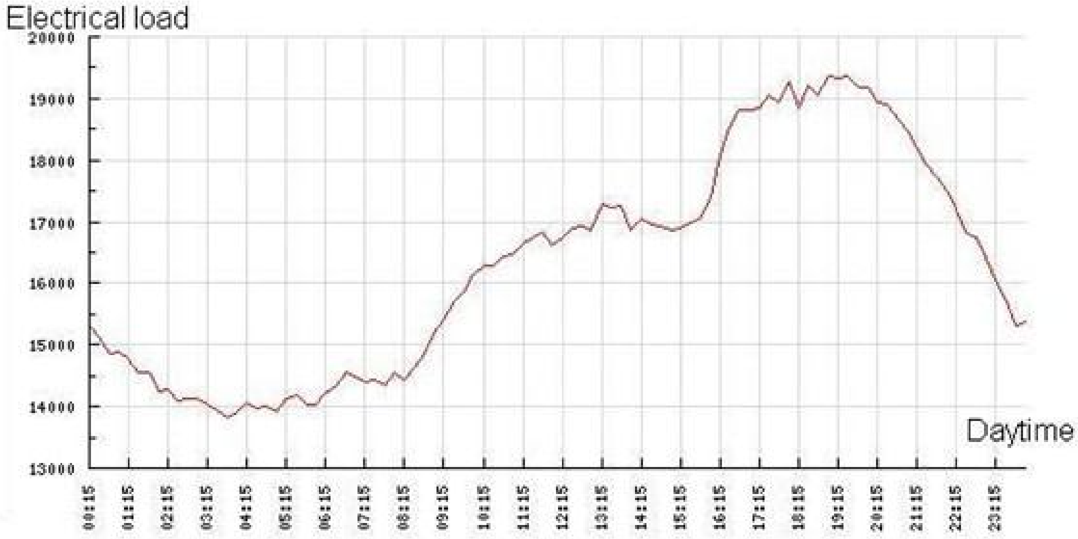

Figure 2. Load curve for a residential load for a winter week-day [27].

Benefits from seasonal loss reduction can be accomplished through manual switching, whereas benefits from the daily loss reduction require automatic switching. Feeder reconfiguration allows the transfer of loads from relatively heavy loaded feeders to relatively low loaded feeders. Such transfers are useful not only in terms of alternating the level of loads on the feeders being switched, but also in reducing the overall distribution system power losses and improving the voltage profile along the feeders. Moreover, this would improve the operating conditions of system, and enables the full utilization of system hardware capabilities. This could result in the deferral of capital expenditures and reduce operating expenses. In addition, the reconfiguration of an electrical distribution system to reduce losses has a natural tendency to balance loading among feeders. It places the system in a better position to respond to emergency load transfers. These switchings are, however, performed in such a way that the radiality and other operation constraints of the network are maintained. The number of such switching options is very large in a practical power distribution network. Therefore, the problem of determining the status of network, switches, when formulated as a nonlinear optimization problem, requires exhaustive solution times making the techniques inappropriate for on-line applications. Furthermore, while making a switch decision it is enough to know the relative changes in losses and knowing the exact values of changes in the line losses. This means that the switching operation should not be executed unless the resulting benefit is large enough to be justified. Hence, heuristic approaches, generally based on approximate load flow evaluation techniques, have been suggested to solve the reconfiguration problem.

1.3.2 Mathematical Representation of the Reconfiguration Problem

The reconfiguration problem can be expressed as follows:

Minimize: $$\sum_{i=1}^{n} I_i^2 R_i \, x_i \tag{1.1}$$

subject to $$\sum_{i=1}^{n} S_{ij} = D_j + Losses \tag{1.2}$$

$$S_{ij} \leq S_{ijmax} \tag{1.3}$$

$$\Delta V_{ij} \leq \Delta V_{ijmax} \tag{1.4}$$

$$\sum_{For\ all\ f_t} S_{ft} \leq S_{ftmax} \tag{1.5}$$

where the variables are defined as follows:

R_i the resistance of line section i

I_i the current in line section i

x_i the state value of switch i, where

$$x_i = 1, \text{ if the switch is closed} \tag{1.6}$$

$$x_i = 0, \text{ if the switch is open}$$

n Number of buses

S_{ij} Power flow along line section ij

R_i Demand at bus j

ΔV_{ij} Voltage drop across line section ij

ΔV_{ijmax} Maximum allowable voltage drop across line section ij

S_{ft} Power flow for feeder f_t

S_{ftmax} Maximum rated power flow for feeder f_t

f_t Subset of feeders supplied by transformer t

In the above formulation of the reconfiguration problem, Equation 1.1 represents the total losses of the distribution system. Equation 1.2 ensures that supply equals demand at every bus. Equation 1.3 ensures that a feeder is not overloaded (current, or thermal, limitation). Feeder voltage drop constraints are modeled by Equation 1.4. Equation 1.5 ensures that transformer buses are not overloaded. As noted earlier, the system must also remain in a radial configuration. Distribution losses are I^2Rlosses, and thus the problem is a nonlinear integer optimization problem, with a quadratic objective function, 0-1 type state variables, and linear constraint equations with state-dependent constraint formula. The value of the objective function is determined from the power flow solution given settings of the control variables. At each iteration, a new power flow is required to determine a new system operating point. The problem presents a heavy computational burden for even a moderately-sized distribution system.

1.4 Summary

Distribution system reconfiguration for loss minimization is a nonlinear optimization problem that presents an enormous computational burden for even systems of moderate size. Power flows must be carried out at each iteration to evaluate possible configurations, further adding to the computing time. Finally, the solution must be available in real-time if it is to be useful, due to the dynamic, time-varying nature of feeder toads.

In the next chapter, the work of previous researchers in solving the feeder reconfiguration problem is reviewed.

1.5 Thesis Organization

The material in this thesis is organized as follows:

Chapter II reviews the techniques proposed by earlier researchers, beginning with the algorithm of Merlin and Back [2] in 1975. Feeder reconfiguration techniques which employ heuristics, methods based on operations research techniques and algorithms that use "modern" techniques is reviewed in this chapter. Some works which is related with the algorithm implemented in this thesis is explained in detail;

Chapter III explains first, radial load flow algorithm, then the feeder reconfiguration algorithm based on maximum flow minimum cost problem, and examines the results obtained when the algorithm is applied to a test system;

Chapter IV presents the simulations and results obtained when the algorithm is applied to an electrical radial distribution system. First, the correctness of algorithms itself and their implementation in software are verified, and then the effectiveness of multi branch exchange algorithm is compared with single branch exchange algorithm in typical radial distribution system.

Chapter V summarizes the whole thesis and provides concluding remarks and recommendations for future work.

CHAPTER II

REVIEW OF RECENT RESEARCH IN RECONFIGURATION

In this chapter, recent research in reconfiguration is reviewed. Loss minimization in distribution systems by system reconfiguration continues to be a very active field of research. Beginning in 1975 with the work of Merlin and Back [2], a variety of techniques have since been proposed, including several algorithms that employ heuristics, methods based on classical operations research techniques, and algorithms that use "modern" techniques such as neural networks, expert systems and genetic algorithms. Feeder reconfiguration works reviewed in this chapter, are divided broadly into the categories of (1) heuristic techniques; (2) operations research techniques; and, (3) artificial intelligence techniques. The work of Civanlar, Grainger, Yin and Lee [28] is perhaps the most often cited reconfiguration algorithm, and will be examined in detail.

Optimization algorithms must select an alternative from among a very large set of possible solutions by using some form of numerical or nonnumeric computation to find a good (hopefully, the best) solution. To be successful, an algorithm must generate and examine all the alternative solutions, and not just a portion, i.e., it must be complete. Because of the large number of possible switching combinations in a distribution system, it is usually not feasible to examine each one.

2.1 Heuristic Techniques

To overcome the size limitation posed by modem distribution systems, or to reduce or eliminate the need to carry out power flows, many researchers turn to heuristics, or rules-of-thumb. The tradeoff becomes a question of solution quality versus computation time, i.e., finding the optimal solution in possibly an infinite amount of time, or finding a feasible suboptimal solution in a finite amount of time. There are several drawbacks to heuristic algorithms [29]:

1. The final network configuration often depends upon the initial configuration;
2. While losses may be reduced by employing heuristics, there is no guarantee that the final solution is optimal;
3. Even by employing heuristics, the computation time can still be quite large in a network of realistic size, which may contain thousands of branches and thousands of switches.

As well, most of the algorithms presented in this section ignore operational constraints, and thus they are of little interest to utilities. Most present-day distribution systems contain major components that operate close to their maximum load/capacity ratio, and thus it is crucial for algorithms to work around these limitations.

Even though heuristics are employed, at some point, a power flow must be done to ensure constraints have not been violated. Having identified invalid solutions due to constraint violations, most methods are not capable of incorporating this knowledge in finding an alternative solution.

2.1.1 The Work of Merlin and Back, and Related Works

The first work to observe the problem of reducing losses through distribution network reconfiguration was introduced by Merlin and Back in 1975 [2], who represented the distribution network as a spanning tree structure, with the buses represented by the nodes and line sections by the arcs of a graph. The final network configuration that reduced losses was determined from the values found for binary variables related with switch status. System constraints were neglected.

The behavior of the distribution system is approximated by performing a DC load flow as a meshed network, accounting only for the real component of the current in loss calculations, and assuming differences in bus voltage angles were negligible. The strength of the technique of Merlin and Back was that the obtained solution was independent of the initial status of switches. The method of Merlin and Back required an iterative process of removing the branch with the lowest load flow and then performing a minimal loss load flow until a radial distribution system was obtained.

This technique is similar to a technique examined by Willis et al. [39] for the distribution system planning problem, which includes determining network layout, equipment size and capacities, and a radial switching pattern. Although the primary goal in this problem is not to reduce system losses, but to minimize costs, their comparison results are useful.

The method of Shirmohammadi and Hong [29] differed from that proposed by Merlin and Back only in the inclusion of feeder current constraints, and in the use of a compensation-based power flow technique to ensure that the behavior of the weakly meshed distribution network is more accurately modeled. Both this method and that of Merlin and Back only minimize losses. However, they cannot guarantee that an optimum solution will be found.

In reference [30], Goswami and Basu introduced an algorithm similar to that of Merlin and Back [2], the primary difference being that the distribution network is never represented as a meshed system. Goswami and Basu argued that it is invalid to model distribution systems as meshed networks, as the optimum flow pattern for a meshed network will be different than that of a radial configuration. Thus, Goswami and Basu close only one switch at a time, carry out a power flow, and then open the switch carrying the smallest current to open the loop and return the system to its radial configuration. The algorithm terminates when the switch that is opened is the same switch that was initially closed. Three methods were presented to select which switch to close: (1) the switch having the greatest voltage across it; (2) the switch having the smallest voltage across it; and, (3) at random. Goswami and Basu note that, for the 37-bus system studied the method of switch selection did not affect the results.

Borozan et al. [3l] offered three algorithms to improve the method of Shirmohammadi and Hong. These algorithms were able to carry out the following operations faster than the original method: loop impedance matrix construction, partial re-ordering of network, and loop impedance matrix re-evaluation. Test results showed that the algorithms increased the speed of execution of Shirmohammadi and Hong's method, but the optimal solution was not always found, and voltage violations occurred.

Roytelman and Shahidehpour [23] used a method similar to that of Shirmohammadi and Hong. Their algorithm closes all open switches, carries out a load flow with branch reactance set to zero, and then opens the branch with the smallest current. The process is repeated until the network is restored to a radial configuration.

2.1.2 The Work of Civanlar, Grainger, Yin and Lee, and Related Works

The algorithm of Civanlar, Grainger, Yin and Lee [28] is perhaps the most often cited reconfiguration algorithm, and is often used as a bench mark to measure the performance of new algorithms. Civanlar, Grainger, Yin and Lee made use of heuristics to determine a configuration which would reduce losses. The following expression was developed to determine losses resulting from a load transfer between feeders:

$$\Delta P = Re\{(\textstyle\sum_{i \in D} I_i)(E_m - E_n)^*\} + R_{loop}|\textstyle\sum_{i \in D} I_i|^2 \quad (2.1)$$

where:

D the set of buses disconnected from feeder $(I)$and connected to another (II),

m tie bus of feeder I to which loads of feeder II are to be connected,

n tie bus of feeder II that will be connected to bus m via a tie switch,

I_i complex bus current at bus i,

R_{loop} series resistance of the path connecting two substations buses of feeder I and feeder II via closure of a specified tie switch,

E_m component of $E = R_{bus}I_{bus}$ corresponding to bus m,

R_{bus} bus resistance matrix of feeder I before the load transfer,

I_{bus} vector of bus currents for feeder I, and

E_n similar to E_m , but defined for bus n of feeder II.

The right-hand term in Equation (4.1) is always positive, and, hence, to have a drop in system losses (ΔP negative), it follows that a load transfer will only reduce system losses if there is a significant voltage difference across an open switch, and only if the load is being transferred from the higher voltage side to the lower voltage.

Civanlar et al. proposed the following two heuristic rules:

Rule-1. Reduction of losses can only be attained if there is a significant voltage difference across at open tie switch.
Rule-2. Reduction of losses will be achieved if loads on the higher voltage drop side of the tie switch are transferred to the other side

The high/low voltage rule is used to eliminate switching options for reconfiguration, and Equation (4.1) is then used to determine the change in system losses for the remaining switching possibilities. The option with the largest negative ΔP is selected and a power flow carried out. This process is repeated until there are no candidate switching options.

The advantages of the algorithm of Civanlar et al. are that it allows rapid determination of a switching configuration which reduces losses. The disadvantages are that the proposed network configuration depends on the initial switch status and system constraints are ignored.

Castro and Watanabe [32] extended the work of Civanlar et al. by making use of a more efficient search algorithm requiring less computational effort. Civanlar et al. considered branching on only the most promising switching option, which reduced solution time, but increased the likelihood of finding a local minimum. Castro and Watanabe proposed selecting the maximum number of feasible switching operations at each stage of the algorithm, which offered the advantage of finding a better solution in a shorter time. However, a global optimum was not assured, and they continued to use the high/low voltage rule. System constraints were not considered.

Baran and Wu [33] followed the approach taken by Civanlar et al. extending the work by introducing two different methods to approximate the load flow in a system after a load transfer between two substations, feeders or laterals, and making use of a set of power flow equations developed specifically for radial distribution feeders. Power flow was described by a set of recursive equations that used the real power, reactive power and voltage magnitude at the sending end of a branch to express the same quantities at the receiving end of the branch. Estimating these quantities at the first node in a network, the same quantities were determined for downstream nodes on a feeder using the equations developed in a forward update. A similar set of equations was developed for a backward update, where the update started from the last node of a feeder and proceeded towards the substation. By successively applying the forward and backward updates, a power flow solution was obtained. The two power flow solutions offered are (1) a simplified version; and, (2) a full version of the power flow just discussed.

For a two feeder system with 32 buses and 5 tie lines, the optimal solution was found using the simplified method. Interestingly enough, the global optimum was found "by accident," as it estimated a branch exchange as positive when it was, in fact, negative, allowing it to perform more iterations to find the global solution. Using the second proposed method, and a full power flow solution, the algorithm was unable to find the global optimum.

Sarfi et al. [22] partitioned the distribution system into groups of load buses, and then applied Civanlar’s technique [28] to minimize losses within each group of buses. When tested on the same system used by Civanlar et al. [28], Sarfi et al. achieved similar loss reduction results for one set of bus partitions, but, for a different set of partitions, no loss reduction was achieved. The results presented indicate that the solution quality was very dependent on the assignment of buses to groups, and how the network was partitioned.

Taleski and Rajicic [16] extended Civanlar's method to minimizing energy losses instead of power losses by incorporating data from daily load curves.

Fan et al. [34] used a single loop optimization technique whereby a normally-open switch is selected to be closed, and then the problem is to find a normally-closed switch to open in the loop such that line losses are minimized, similar to the method of Goswami and Basu [30]. The normally-open switch is selected by examining voltage differences across open switches to determine which switch experiences the largest voltage difference, similar to the method of Civanlar et al. In [35], Roytelman et al. sought to incorporate five objectives in a single objective function, including:

1. Minimization of feeder losses,
2. Minimization of the worst voltage drop,
3. Load balancing among supply transformers,
4. Minimization of service interruption frequency,
5. Balanced service to important customers (by ensuring all important customers are not served from the same transformer).

Objectives were weighted as deemed necessary. A two-stage approach was used. In the first stage, an initial solution was found using a technique similar to that of Merlin and Back [2] to determine a radial network configuration. Then, the solution was improved by closing a switch and opening an adjacent one to see the change in objective function. Civanlar's formula was used to determine changes in losses resulting from a branch exchange.

In [38], Peponis et al. combined reactive power control (through capacitor installation) and network reconfiguration. Peponis et al. compared the Civanlar and Shirmohammadi algorithms, and found that the Civanlar technique was approximately four times faster, but that the final solution was very dependent upon the initial configuration.

2.1.3 Other Heuristic Algorithms

Liu, Lee and Vu offered two approaches that they asserted would ensure a globally optimal solution [36]. One algorithm was based on a uniformly distributed load model (UDLM) and the other a concentrated load model (CLM). Liu, Lee and Vu demonstrated that by considering loads as current sinks, the current flowing through an arc could be represented by a sum of a basic current (y_k) and a constant (a_k).

The first algorithm identified which sectionalizing points had to be open for a minimal loss reconfiguration. When practical constraints such as line voltage drop were considered a global optimality could not be assured, and the authors noted that solutions could be found that violated the radial topology requirement In this method, if the system was assessed to be "non-optimal" (failure to meet set criteria), "non-optimal" feeder pairs would be selected and minimum loss positions determined until a tolerance was satisfied. Because the first algorithm relied on a piece-wise parabolic form of the loss function, sectionalizing points determined by the algorithm did not always correspond to actual switch positions, and hence the second algorithm was used to determine the actual switch positions for the optimal system configuration. This second method differed from the first in that all "non-optimal" pairs were assessed using loss estimation formulae and only the pair with the greatest loss reduction selected.

In [37], Aoki et al. noted that reconfiguration is used in Japan to balance loads among feeders and transformers for fear of fault occurrence, as well as to reduce system losses, but that the main emphasis is on load balancing. The authors assume all section loads are known, that all feeders are of equal capacity, and that the system is initially in a feasible (but not necessarily optimal) state. Loads are transferred between feeders by determining which feeder has the largest load, and which has the smallest, while ensuring the radial structure of the distribution system is maintained. This process is carried out until feeders and transformers are loaded as equally as possible. There is no guarantee that system losses are reduced.

2.2 Previous Works Based on Operations Research Methods

Numerical optimization techniques apply computed numerical formula and procedures to search (usually iteratively) for the best configuration. The advantages of these techniques include convergence to the mathematically optimal configuration, and that proven algorithms are widely available and understood. However, the disadvantages include mathematical complexity which may make programming and diagnosis difficult, and convergence that takes so long to be of no practical value.

Linear programming (LP) methods require all relations to be linear or approximated by linear functions and were popular in the early 1980s for solving such power system problems as the capacitor placement problem [46]. Only smaller systems were considered, as the computation times for larger systems made LP methods impractical. As well, solutions obtained were not always optimal, due to approximations introduced by the linearized models [47].

Few researchers have based solution to the reconfiguration problem solely on linear programming methods. Aoki et al. [40] divide distribution lines into segments according to the differences of the load distributions and line constants. The status of each switch in a system (open or closed) should be solved as a discrete optimization problem, but, since there are many switches, as well as line and voltage constraints to consider, finding a feasible solution would lead to large computation times. Aoki et al. approximate the variables identifying the locations of normally open switches as continuous variables, and, after solving the continuous problem, the location of the open switches is determined by rounding the solution to the nearest actual switch. The authors note that their solution is not necessarily optimal, but that on a 59-bus test system they were able to reduce losses by 5%.

In [41], Chen et al. develop equations to determine total feeder loss using regression analysts. The method develops an equation based on a specific feeder and the hourly load pattern at each bus. The method would not be suitable for the reconfiguration problem, as it would be necessary to recalculate the coefficients for the regression equation for each change of configuration, which would be difficult to accomplish in real-time.

Glamocanin formulated the reconfiguration problem as a transshipment problem with quadratic costs [42]. Using Giamocanin's method, it was first necessary to obtain a feasible solution as the starting basic solution. The quadratic simplex method was then used to improve the solution. System constraints were not included.

Huddleston, Broadwater and Chandrasekaren [43] offer a reconfiguration algorithm based on modeling the distribution system by a quadratic loss function as a function of switching currents and a set of feeder current constraints. Their algorithm assumes that the distribution system has a unity power factor (typical for many urban distribution systems), and thus the Loss function can be constructed as a DC model. The algorithm of Huddleston et al. looks for feeder sections having negligible currents to indicate open switches.

The work of Broadwater et al. [18] builds upon the previous work of Civanlar et al. [28], as well as that of Huddleston et al. [43]. The work of Broadwater et al. uses Civanlar's switching rule, a single switch pair operation per iteration and a direct search method incorporating Huddleston's loss function, including voltage and current constraints. The reconfiguration algorithm proposed calculates losses for each possible switch pair operation. A load flow is required at each iteration, after a new base case is developed as a result of a switching operation. There is no discussion of how long the algorithm takes to find a solution for a system. However, for a large distribution system, evaluating the losses for every possible switching combination would not be feasible. Niknam et al. proposed a hybrid algorithm based on Honey Bee Mating Optimization (HBMO) and a fuzzy set for the multi-objective distribution feeder reconfiguration [24].

2.3 Previous Work Based on Artificial Intelligence Methods

Artificial intelligence methods include techniques based on artificial neural networks, fuzzy systems, expert systems, simulated annealing and genetic algorithms.

2.3.1 Work Based on Artificial Neural Networks

Artificial neural networks (ANNs) have been proposed for many power system applications [58]. Their use appears well-suited to reconfiguration, as they can be used to map the relationship between the highly non-linear nature of a load pattern to a network topology which offers minimal line losses. Perhaps the most widely-used ANN is the back propagation network [19]. A typical back propagation network has an input layer, one or more hidden layers, and an output layer. Each layer is fully connected to the succeeding layer, and each layer consists of a number of Processing Elements (PEs). The output of the PE is determined by a transfer function, which can be the sigmoid function, hyperbolic tangent or sine functions.

If the network has some global error function associated with it, it is assumed that all processing elements and connections are to blame for an error (or for the actual output not being the same as the desired output), and responsibility for the error is attached by propagating the output error backward through the connections to the previous layer. This process is repeated until the input layer is reached. Hence, the name is back propagation. The input is forward propagated through the layers to the output layer, the error at the output determined, and then the error is back propagated through the network from the output to the input layer. During training, the global error function is minimized by adjusting the weights. ANNs prove themselves most useful in applications such as load forecasting where existing models do not have enough accuracy, and where vast amounts of historical data are available. Although the use of ANNs can offer reduced solution times for even large problems, three factors appear to limit their usefulness to a utility for the loss minimization problem [20]:

1. A considerable amount of time is required for collecting data and for training the neural network, as loads vary with the time of day and season of the year, as well as by customer type, resulting in enormous amounts of data;
2. Training must be carried out for each utility's distribution network and subsequent changes in the system must be accounted for;
3. Correct training data must be acquired to make sure that the Artificial Neural Networks offers meaningful results.

Kim, Ko and Jung proposed a two-stage algorithm based upon ANNs for distribution system reconfiguration for loss minimization [48], They proposed dividing the distribution network into load zones, with each load zone having a distinct set of two ANNs trained to classify the loading level and to reconfigure the zone based upon the assigned loads. The use of ANNs offered a fast solution, as no load flow operations were required within the solution algorithm. A multi-layered feed forward network topology was selected for the ANN in view of the adaptive learning capability of this topology. Training data was obtained by a solution of a quadratic programming problem, whose constraints included line voltage drop and current limits. Although good results were obtained by this algorithm, the training data used was simulated data for a small system. The massive amount of data needed to accurately model a system of realistic size, as well as the network training time, would most likely preclude this approach.

2.3.2 Work Based on Fuzzy Systems

Fuzzy set theory and fuzzy logic was introduced in the 1960s by Zadeh [21] as a formal tool for dealing with uncertainty, where vague descriptions for variables may be more or less precise (less or more fuzzy, respectively), depending upon the certainty with which a variable can be described. For example, it may be said that the load on a feeder is heavy. How heavy is "heavy?" Fuzzy set theory is employed to deal with this uncertainty. In the fuzzy domain, each variable is associated with a membership function that indicates the degree of satisfaction of the variable from zero to unity, and expressed by a set of ordered pairs, i.e.,

$$X = \{(x, \mu(x)) x \ is \ a \ possible \ value \ of \ varibale \ X\} \qquad (2.2)$$

where $\mu(x)$ is the membership function which denotes the possibility that variable X has the value x. A fuzzy set A of X is defined to be the set of ordered pairs, $\{(x, \mu_A(x))\}$, where $x \in X$ and $\mu_A(x) \in [0,1]$ is the degree of x in A. Consider a variable, L (representing the load) having the set of values {light, medium, heavy}. The values of the load are the labels of the fuzzy sets, $A_{low}(L)$,$A_{medium}(L)$, $A_{heavy}(L)$ on the domain of numeric loads, L. In this case, a load of $0.38\,p.u.$ is interpreted to be low with degree 0.21 and medium with degree 0.64. If-then rules are then used to relate these imprecise relationships.

Although the title of Reference [47] is "A Fuzzy-Based Optimal Reactive Power Control," this paper addresses, in fact, the reconfiguration problem, noting in its abstract that the authors present a mathematical formulation of the optimal reactive power control problem, where the objectives are "to minimize real power losses and improve the voltage profile of a given system."

In [47], Abdul-Rahman and Shahidehpour use a fuzzy-based linear programming approach. The method was tested on a 6-bus and 30-bus system, and voltage violations of 2% and 3%, respectively, were allowed, although not all buses were subject to the same violation. For the 6-bus case, it was found that the proposed method found a better solution than traditional LP methods with fewer iterations, but that the time per iteration was longer for the fuzzy method. For the 30-bus method, traditional LP methods found a better solution, but in a longer time. A large system of realistic size was not examined. The method cannot guarantee an optimum solution. As well, an operator roust specify the acceptable violation limits, and for which feeders and buses, and this may not be obvious.

2.3.3 Work Based on Expert Systems

An expert system is a computer program that represents and reasons with knowledge of some specialist subject with a view to solving problems or giving advice [55]. The system may act as an assistant to a human decision maker, or completely fulfill a function that normally requires human expertise. Unlike traditional sequential computer programs, expert systems simulate human reasoning about a problem, rather than simulating the problem itself. Heuristics are often employed.

Taylor and Lubkeman [49] proposed an expert system based upon extensions of the rules of Civanlar et al. [28]. They described the main objective of their work as being to avoid feeder thermal overloads, transformer overloads, and abnormal voltages. By satisfying these criteria, they asserted that they would simultaneously find a configuration for loss minimization. Taylor and Lubkeman used a best-first strategy to decrease the solution time. To drive the inference of the expert system developed five different rule sets were developed. Following each decision, a power flow calculation was necessary to update the network's working status. To reduce the search space considerably the use of the heuristic rules was demonstrated. However, the use of a best-first search strategy precludes the guarantee of finding a globally-optimal solution.

Chang, Zrida and Birdwell presented the requirements for a knowledge-based software package for control and analysis of power distribution systems [50]. The knowledge base would use tools specific to distribution analysis to make sure accurate, representative modeling. Feeder reconfiguration for loss minimization figures prominently in their proposed package and would be driven by an expert system.

Chang and Chung [51] describe the development of an expert system for on-line use of power system operators in a SCADA environment. The proposed system uses the method of Aoki et al. [40] to determine which loads to transfer, as well as several heuristic rules proposed by system operators. Chang and Chung note that the method of [40] was implemented in the computer language, Prolog, which, while being a useful language for expert systems, is not well-suited to the "number-crunching" required by the reconfiguration problem.

Recently, Sarfi [52] proposed an expert system combined with fuzzy logic. The method of Civanlar et al. [28] was used to obtain an initial, suboptimum configuration. Then, several rules were proposed to further optimize the network, taken into account network constraints. A large part of this work was based on conservation voltage reduction, which, as discussed earlier, may or may not be viable. As well, Sarfi only examined adjacent switches when considering which switch to close, leading to the possibility of suboptimum solutions

2.3.4 Work Based on Genetic Algorithms

Simulated evolution is intrinsically a robust search and optimization technique whose process can be applied to engineering problems where heuristic solutions are not available or provide unsatisfactory results [44]. The physical processes involved include reproduction, competition and selection. During reproduction, an individual's genetic program is transferred to its offspring. Competition is the result of expanding populations and finite resources, and selection is the result of competitive replication.

In the past two decades, interest has grown in solving problems using algorithms based on the principles of biological evolution [45]. These algorithms maintain a population of potential solutions, have some selection process based on the fitness of individuals within the population, and have some recombination operators. Perhaps the best-known of these methods is Holland's Genetic Algorithm [53]. Evolution programs are essentially probabilistic algorithms that maintain a population of n individuals, $P(t) = \{x_1^t, \ldots, x_n^t\}$ at iteration t. Each individual represents a possible solution for the problem at hand implemented as a data structure, S. Each solution x_n^t; is evaluated to determine its "fitness." The better individuals are selected to be parents for the next generation, and a new population, $P(t+1)$, for the next iteration is generated. Some of the offspring will undergo transformation as a result of application of genetic operators. Mutation is the operation whereby new individuals are created by making small changes to single individuals, typically on a single bit $(m_i: S \to S)$, while high order transformations c_j, create new individuals by combining parts from several individuals in an operation known as crossover $(c_j: Sx \ldots xS \to S)$. After several generations, the program converges, and the best individual hopefully represents the optimum solution [54].

Genetic algorithms manipulate a population of potential solutions to an optimization problem by operating on an encoded representation of the solutions equivalent to the genetic material of individuals in nature. Solutions are encoded as strings of binary bits. Each solution has associated with it a fitness value that allows the solution to be compared to all other solutions in the gene pool. The higher the fitness value, the higher the chances that an individual will survive and reproduce, and the larger its representation in the population. During reproduction, crossover is used to exchange portions of genetic material between strings. Mutation also occurs to cause sporadic and random alteration of bits. This plays the role of regenerating lost genetic material.

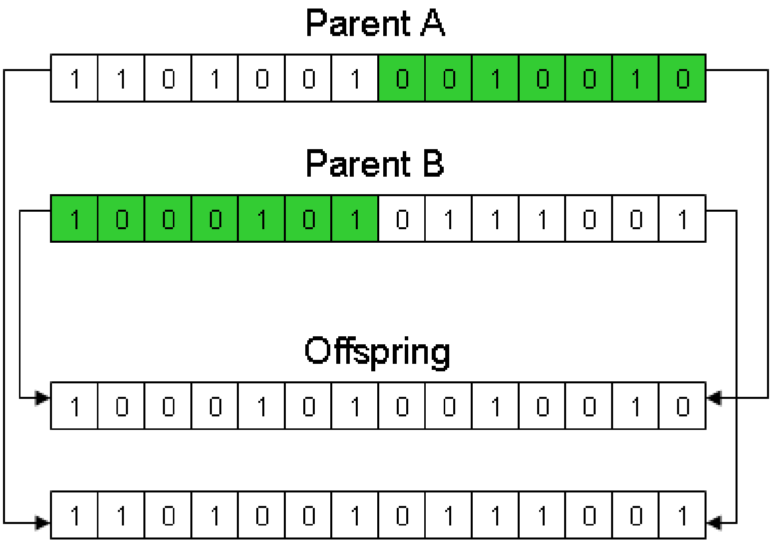

Figure 3. Crossover of two parents having crossover point of 7 [26].

Crossover is the crucial operation of genetic algorithms, and is illustrated in Figure 3. Pairs of strings are picked at random from the population for crossover. In single-point crossover, a crossover point is picked at random, and portions of the strings beyond that point are exchanged to form new strings. Crossover only proceeds if a randomly generated number in the range [0, 1] is greater than the crossover rate (specified at the start of the algorithm).

After crossover, strings are mutated by flipping a bit. The bit to be flipped is selected at random, and mutation proceeds only if a randomly generated number in the range [0, 1] is greater than the mutation rate specified at the start of the algorithm. Mutation allows strings to recover lost genetic material For example, if all of the bits in all of the strings in a population have converged to 1, crossover cannot generate a 0. However, mutation would allow this to occur.

Genetic algorithm can be applied to solve the feeder reconfiguration problems. Nara et al. [56] applied a genetic algorithm to minimize distribution system losses. Noting that the problem of distribution system reconfiguration for loss minimization is a problem of determining the position of open sectionalizing switches, they formulated the problem as a 0-1 integer programming problem with the following assumptions:

1. Section loads were uniformly distributed, balanced constant current loads
2. The power factor of section loads was 1.0
3. The current phase shift due to line impedance was negligible
4. The maximum voltage drop occurs at the end of a feeder, as capacitors are usually not installed in urban distribution systems.

Sections and switches were represented as binary numbers and subjected to mutation and crossover. A fitness function was developed to minimize losses, and included penalty terms for line and transformer capacity constraint violations, and excessive voltage drop. To avoid the need to carry out a power flow at each iteration, Nara et al. developed an expression similar to that of

Civanlar et al. [28] that allowed the estimation of the change in tosses as a result of a branch exchange (assuming an initial power flow was available).

However, even the computation time needed for GA is excessive, taking over an hour for the smaller system, and nearly 20 hours for the larger one. This can hardly be considered useful for real-time operation. Similar results were seen in [57], where Nara and Kitagawa repeated the work of [56], but added distribution transformer losses as part of the minimization process.

The excessive computation time is not surprising. As noted earlier, how constraints are handled strongly affects the performance of a GA. If the likelihood of producing illegal individuals is high, the GA wastes much of its time evaluating them. In both [56] and [57], Nara et al. assigned penalties to strings that violated voltage, line capacity and transformer capacity constraints, with the result that many solutions that violated one or more of the constraints were in all likelihood produced. Computation time was needed to evaluate these illegal solutions. As well, Nara et al. indicate that some solutions left the system in a loop configuration, or left some sections de-energized. These problems were not handled in the constraints, and thus part of the computation time was needed to check for those conditions.

In [56], it was noted that there were 1000 iterations of GA for each. However, figures presented showed that much of the improvement came in the first 200 iterations, but there was no way to know that the best solution had been found. No stopping mechanism was incorporated (save the 1000 iteration limit), nor was any mechanism proposed whereby the algorithm could "zoom in" on the best solution to try to find a better solution in a smaller search region.

2.4 Summary

Distribution system loss minimization through system reconfiguration is a difficult problem that has been investigated by many researchers. Most algorithms proposed to date suffer from one or more of the following shortcomings:

a. Losses are reduced, but not necessarily optimized, in that locally optimum solutions are found instead of global optimums;
b. Excessive computation time allows application to only small distribution systems of unrealistic size, or restricts their use to off-line applications;
c. The final solution depends upon the initial system configuration.

In the next chapter, modeling the reconfiguration problem as a constraint satisfaction optimization problem - which is the basis of this thesis is introduced.

CHAPTER III

FEEDER RECONFIGURATION ALGORITHM

As it is known, for a distribution system, the number of switching options is so great that conducting many load flow studies for all the possible options becomes not only extremely inefficient from computational stand point, but also unusable as a real-time feeder reconfiguration approach. For loss minimization, the sectionalizing and tie switches should be selected in order to achieve maximum reduction in losses. Theoretically, it is not a difficult task to measure whether the new system obtained through a feeder reconfiguration would incur lower losses. The change in losses can easily be computed from the result of two power flow studies simulating the system configurations after and before the feeder reconfiguration. It will be seen that the approach for estimating the change in losses requires additional information over the base case load flow solution. In addition, the algorithm performs a new load flow analysis for each switching option. For these reasons, a simple, flexible and very fast power flow method is implemented. In this chapter, first the radial load flow algorithm, then the feeder reconfiguration algorithm based on maximum flow minimum cost problem is presented.

3.1 Radial Power Flow Method

There are many load flow solution techniques and they can be classified into compensation based [9], Newton-Raphson based [7],[8], and forward/backward sweep based methods [10],[11]. Among these methods the forward/backward sweep-based method is more computationally efficient for solving load flow of radial networks and is simpler to implement. Since distribution network matrices in most cases are ill-conditioned and R/X ratio is very high, the Newton - Raphson based methods are not effective and efficient. The forward/backward sweep-based method can efficiently estimate active and reactive power values and bus voltage magnitudes. Any suitable power flow algorithm for on-line applications, such as feeder reconfiguration, should have the flexibility of accommodating any change in the network configuration or inclusion/exclusion of some components. Secondly, the algorithm should be fast enough for real time applications. The forward/backward sweep-based method used in this study is characterized by these properties. Solution speed of the algorithm is enhanced by using a suitable representation of network topology. The distribution network has a typical tree structure where the root of the tree being the source node. So a unique set of equations can be written for distribution network by applying Kirchhoff's current and voltage laws, and inserting the source bus in all equation. The method used in this study is based on the application of Kirchhoff's current and voltage laws during backward and forward trace procedures. The load flow algorithm uses the ordering procedure to speed up the power flow solution by ordering the nodes from the root (main source) to the end nodes during the forward and backward sweeps.

3.1.1 The Radial Network Topology Representation

Since the medium voltage distribution system is radial operated, it has been assumed that an intermediate node of the network has only one incoming and a few numbers of outgoing branches. Thus, any distribution network node should have this standard configuration, In other words, each sink node has only one parent node. So, each branch in a radial distribution system can be shown with a “parent-child” relationship. To clarify this scheme the one line diagram of a sample radial distribution system is presented in Figure 4

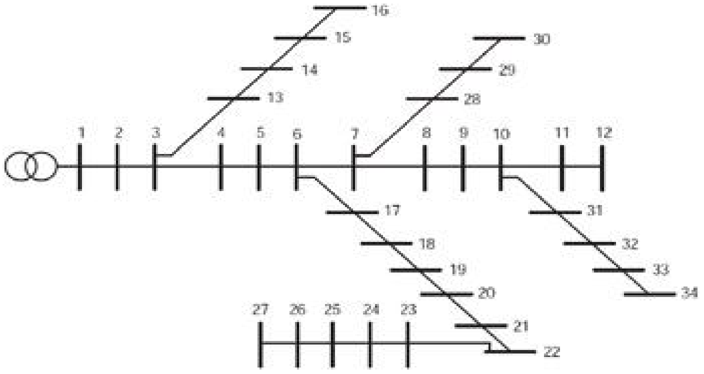

Figure 4. One line diagram of a sample radial distribution system.

With these features, each sink node n can be characterized as constant power sink, $S_n = P_n + jQ_n$, and the impedance of the line L which connects the sink node to its' source as$Z_L = R_L + jX_L$.

In order to obtain the load flow solution for a radial network efficiently, the network is first ordered by using the ordering subprogram which puts the nodes in sequential order. The subprogram starts from the root of each feeder and puts the tree in order. By using this procedure we can find the number and name of the nodes that a branch or transformer feeds.

3.1.2 Basic Aspects

The proposed solution for the load flow has the following aspects. The backward sweep serves to sum the currents in the branches from the end nodes to the source nodes. The forward sweep establishes the nodal voltages from the source to the end nodes based on the current obtained in backward sweep. To illustrate the mathematical operations involved for one node during the trace, a typical connection of nodes is given in Figure 5 where K is the sending node and R is the receiving node. J_r, in general, represents the current entering into node R from the source side

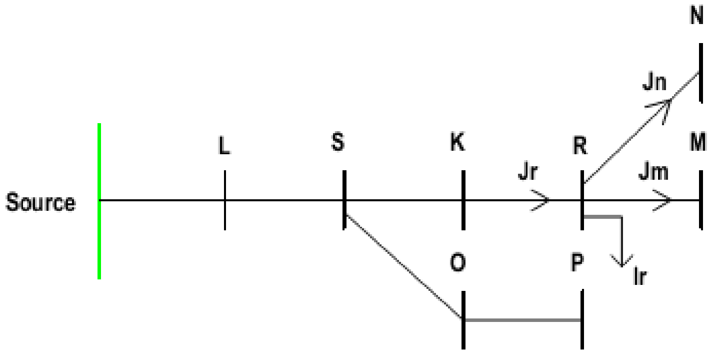

Figure 5. Typical connection of a radial distribution system.

1) Backward Update

In the backward sweep, for example at the node R**,** load current injection into $I_r^{(i)}$ is calculated as follows:

$$I_r^{(i)} = \left(\frac{S_r}{V_r^{(i-1)}}\right)^* \tag{3.1}$$

where

* - : complex conjugate operator

$S_r = P_r + jQ_r$: Complex load at node R, including shunt capacitors for reactive power compensation.

$V_r^{(i-1)}$: Complex voltage at node R during iteration $(i-1)$.

Starting from the end node and moving towards the source node, the current in each branch is updated as follows:

$$J_r = I_r + J_m + J_n \tag{3.2}$$

$I_r$is calculated by using Eq. (3.1)

2) Forward update

In the forward sweep, with the sending end voltage known, the receiving end voltage is calculated by employing a forward trace procedure based on the knowledge of the following data:

- Voltage at the source node is specified.
- Starting from the source node the voltage at each node is estimated as follows:

$$V_r^{(i)} = V_k^{(i)} - Z_r * J_r \tag{3.3}$$

Where:

Z_r- The series impedance of the line connecting node R to the previous node towards source.

J_r - The complex current flow through branch R.

V_r - The voltage at the source node of branch R.

The backward and forward sweeps are repeated successfully until convergence condition is achieved.

3.1.3 Implemented Solution Method

The method utilized in this thesis for load flow problem can be summarized as follows:

Step I. Read network and switching data including parameters, line data, voltage magnitude at source nodes, active and reactive load at each node, prespecified limit for convergence and maximum iteration number.

Step II. Initialize the voltage magnitude of each node as equal to that of the source nodes

Step III. Start iterations

Step IV. Compute the initial load current injections by using Equation (3.1).

Step V. Calculate the branch current J_i for each line using Equation (3.2)in reverse sequence of the ordering function (i.e., backward trace).

Step VI. Calculate the voltage for each node starting from the source node(s) using Equation (3.3) following the sequence defined by order function (i.e., forward trace).

Step VII. : With the new voltages, calculate the voltage mismatch in each node. If the maximum voltage mismatch is greater than a specified error go to step III).

Step VIII. Otherwise, present all the required results such as current in branches, voltages at buses, and power loss of the system.

The flow chart of the algorithm is presented in Figure 6.

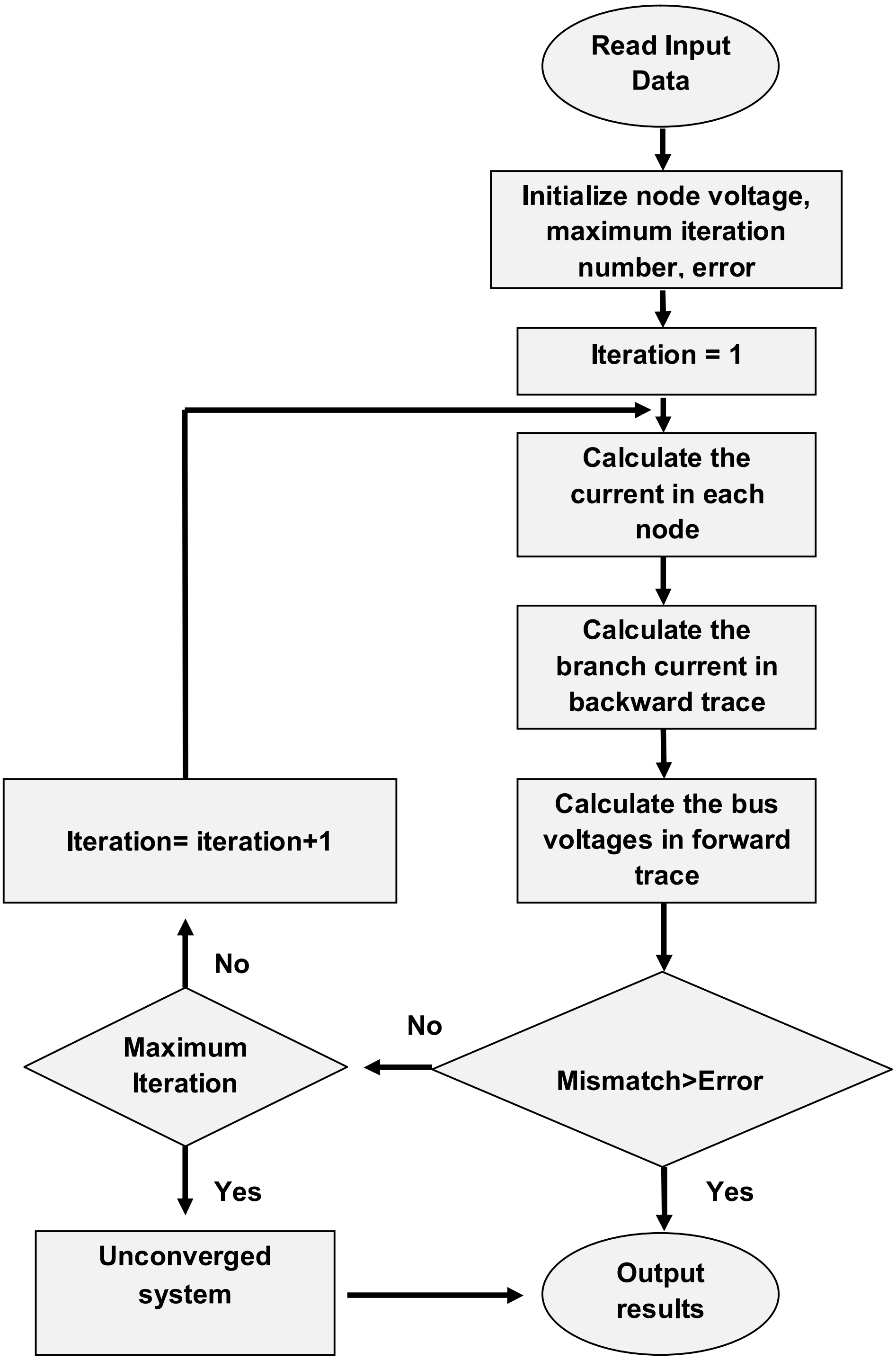

Figure 6. The flowchart of the load-flow algorithm

3.2The Network Reconfiguration Algorithm Based on MCMF Problem

The network reconfiguration algorithm that is going to be implemented in this thesis is an iterative heuristic algorithm which is described in Figure 7. There are two main steps in each iteration of the algorithm. In the first step, the power flow solution for the current configuration is computed using the forward/backward method which is explained in previous section. In the second step, incremental network changes that cause the largest loss reductions are searched. This approach's novelty is an enhanced branch exchange technique used for this search. Using a minimum cost maximum flow (MCMF) based modeling technique one can find sets of multiple branch exchanges that are implemented simultaneously during each iteration. For this purpose, first, the MCMF problem is constructed and solved and then the set of concurrent branch exchanges is identified from the minimum cost maximum flow solution. In the following section of the thesis, this method will be described in detail. This two- step process is repeated until no significant improvement between two consecutive iterations is achieved.

Minimum cost maximum flow formulation of the problem of searching concurrent branch exchanges is the merit of the implemented approach. During each iteration of the algorithm, the local optimality of the reconfiguration solution is improved by this technique and leads to larger loss reductions and reduced number of iterations. Consequently, it will significantly reduce the runtime.

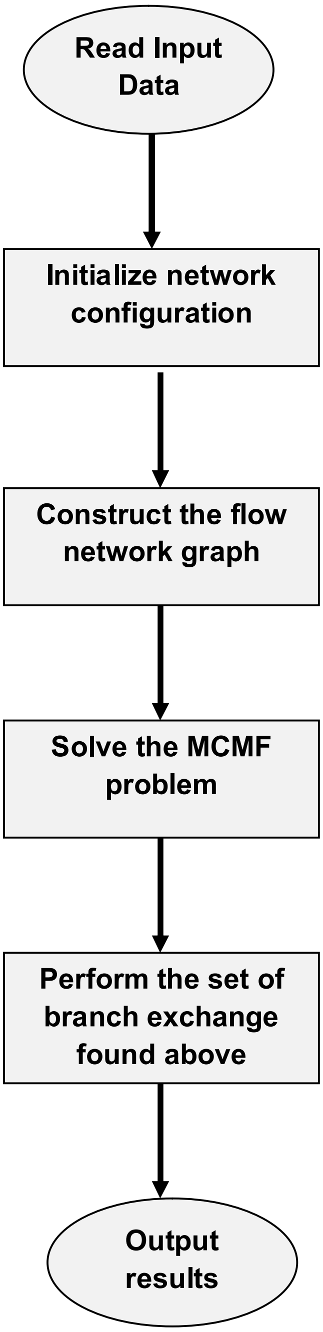

Figure 7. The flowchart of MCMF problem

3.2.1 Network Flow Based Multiple Concurrent Branch Exchanges

In this section the MCMF based modeling is presented. This modeling will be used to construct the MCMF problem whose solution will find the best set of concurrent branch exchanges. For this purpose, a simple radial power distribution system example is used which is presented in Figure 8. The implemented network reconfiguration algorithm is iterative and during each iteration a multiple first-order branch exchanges is searched, which cumulatively propose a larger reduction of losses compared to single branch exchange based techniques [12],[33].

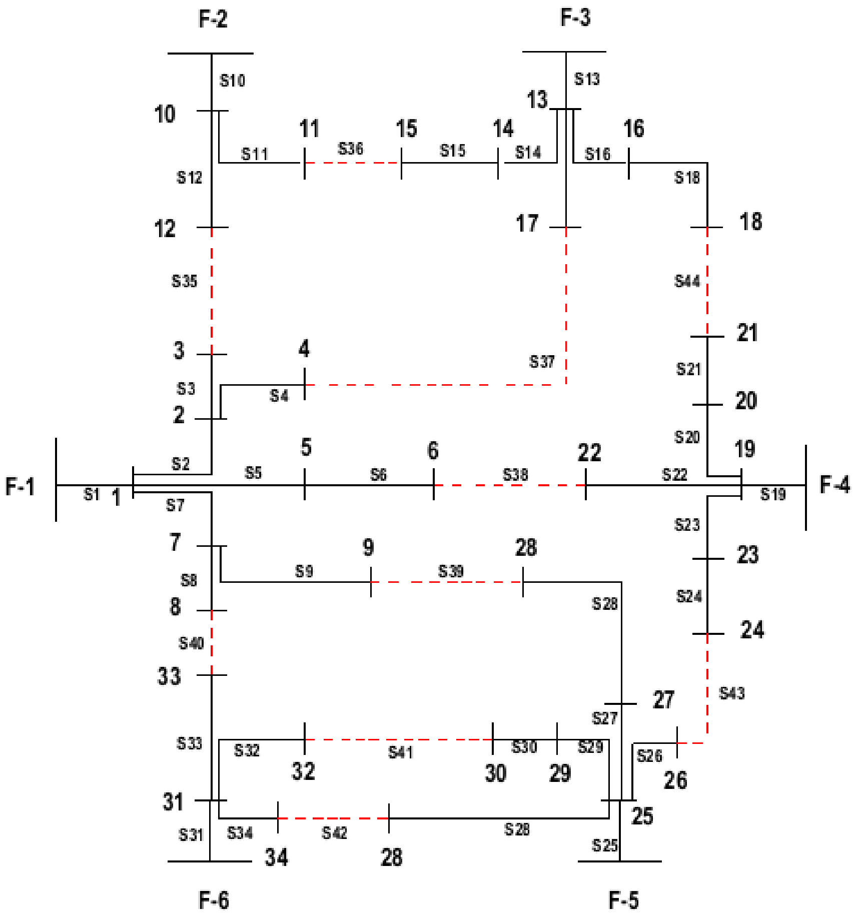

Figure 8. Example of a power distribution network with six feeders.

One can achieve a first-order branch exchange, first, by closing a tie switch then opening the closest sectionalizing switch. As an illustration, in Figure 8, there are the two first-order branch exchanges related with switch 35, these exchanges can be implemented first, by closing switch 35 then opening either switch 3 (load is transferred from feeder F1 to feeder F2) or switch 12 (load is transferred from F2 to F1).

In order to increase the amount of loss reduction during one iteration of the reconfiguration algorithm, one can select to close two or more tie switches simultaneously. However, in order for the loss reduction estimates to remain accurate, these multiple branch exchanges have to be independent. Two branch exchanges are independent if they are between different feeders. For example, in Figure 8, the branch exchange between feeders F1 and F2 is independent from the branch exchange between feeders F4 and F5.

The main idea lies in the way we identify the set of concurrent first-order branch exchanges. This problem is formulated as a minimum cost maximum flow problem. The solution of MCMF problem will find the best set of branch exchanges for loss reduction. The formulation above incurs the following steps, which will be described in detail in the next sections:

- Flow network graph will be constructed
- MCMF problem will be solved.
- The set of branch exchanges as found by the solution of the MCMF problem will be performed.

3.2.2 Construction of Flow Network Graph

It is important to construct the flow network graph for the correctness of the implemented approach. To describe it easier, the example system from Figure 8 is used to illustrate the construction of the minimum cost maximum flow network graph which is illustrated in Figure 9. The following graph construction rules are used to construct the flow network graph:

- The graph contains a sink T node and a source S node.
- There are two feeders in the graph: acceptor feeder and donor feeder. Depending on the number of feeders in the system (F), there can be up to $2 * F$ acceptor and donor feeder nodes, a donor feeder node is one of the nodes of the feeder tree, which will transfer or donate load to another feeder tree, associated with an acceptor node.
- In case a load transfer from feeder F_i to feeder F_j leads to a loss reduction, a pair of arcs from a donor feeder node $F_i$to acceptor feeder node F_j will be created. As we search for branch exchanges that cumulatively lead to largest loss reduction, we use loss reduction to select the best set of branch exchange,
- Between two feeders there can be only one arc. In the graph construction, we can use only one branch exchange that leads to the maximum reduction of losses in case there are more possible branch exchanges between two feedersF_i an$d$ F_j. In Figure 8, for example, we can see two possible branch exchanges between feeders F5 and F6 via switches S41 and S42, because of its larger reduction of losses only the branch exchange via switch S41 is taken into account during the graph construction which is shown in Figure 9.

3.2.3 The General MCMF Problem

Feeder reconfiguration algorithm will be solved using MCMF optimization technique. The MCMF method is developed for solution of different class of networks which occur in maximum flow and shortest path problems. Here, first the formulation of MCMF problem will be introduced, and then in the following sections, the adaptation of the feeder reconfiguration problem to a general MCMF problem will be presented.

After the construction of the flow network graph using the procedure explained in the previous section the MCMF problem can be defined, using the formulation from [13] as follows:

Minimize:

$$\sum_{(i,j)\in A} C_{ij}X_{ij}$$

Subject to:

$$\sum_{j:(i,j)\in A} X_{ij} - \sum_{j:(j,i)\in A} X_{ji} = b(i)$$

$$X_{ij} \in \{0,1\}$$

$$\forall_i \in V$$
$$\forall (i,j) \in A$$

Where:

X_{ij} is the flow through arc $(i,j) \in A$ and can be 1 or 0 due to all arcs have unit capacity,

C_{ij} is the cost associated with each arc,

$b(i)$ is the flow supply associated with node $I \in V$. Here, $b(i)$ is set only for the source and sink nodes. It is set to the minimum between the number of outgoing arcs from the source node and the number of incoming arcs into the sink node. For instance, in the flow network graph from Fig. 4 b(s)=2, and b(t)=-3 the smallest one between them is b(s)=2, so the sink side of graph will be also changed to b(t)=-2 which capture the fact that only two branch exchanges will be part of the solution.

3.2.4 Loss Reduction During Each Iteration

The application of MCMF algorithm to the solution of feeder reconfiguration problem has first been suggested by Abedei et al. [14]. The algorithm implemented in this thesis depends heavily on the approach presented in [14] but certain adaptations have been applied at certain stages of the implementation.

The best set of concurrent branch exchanges to be performed is indicated during each iteration of the implemented reconfiguration algorithm by the solution of the minimum cost maximum flow problem. The cumulated reduction of losses owing to these branch exchanges is guaranteed to be maximized by the MCMF solution. This characteristic is exclusive to the implemented reconfiguration approach and sets it except for previous work. In this section, a simple example is used to demonstrate that sorting-based reconfiguration algorithms would not be able to indicate the best solution, unless exhaustive solution enumeration is done, which would be very expensive. For instance, let us consider a distribution system that has ten tie switches and six feeders whose single line diagram is presented in Figure 8. By using loss reduction formula (2.2) and graph construction rules the list of possible branch exchanges is derived and shown in Table 3.

Table 3. The list of possible branch exchange between feeders.

Initial			Sorted		
Feeder i	**Feeder j**	**Loss Reduction**	**Donor Feeder**	**Acceptor feeder**	**Loss Reduction**
F1	F2	-6	F1	F2	-6
F1	F3	-8	F1	F3	-8
F1	F4	2			
F1	F5	-4	F1	F5	-4
F1	F6	2.6			
F2	F3	4			
F3	F4	-5	F4	F3	-5
F4	F5	-2	F4	F5	-2
F5	F6	3			
F5	F6	3.4			

As seen in Table 3, not every load transfer leads to a loss reduction and only the solutions with negative values have to be taken into account to construct a network graph. From the results obtained in Table 3, the flow network graph with two donor feeder nodes and three acceptor feeder nodes as illustrated in Figure 9 can be constructed. Each arc is tagged with a flow cost pair. The solution of the MCMF problem is highlighted using thicker arcs. A similar flow network is created during each iteration of the proposed MCMF based algorithm.

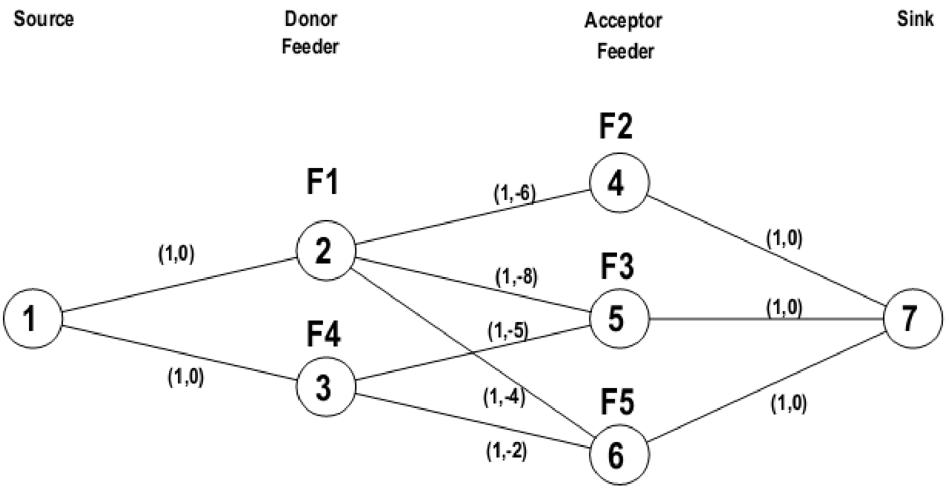

Figure 9. Illustration of the flow network graph construction.

From Figure 9, we can see four independent options and we need to select one that has the largest cumulated loss reduction. If we start to select multiple branch exchanges, first, by sorting all switches by their associated loss reductions, and then selecting greedily as many independent (independent means to be between different feeders) branch exchanges as possible, then the solution of the problem will be F1-F3 and F4-F5. Cumulative loss reduction of this solution is minus 10 which is not the best. The best solution is represented by F1-F2, and F4-F3 which have a cumulated loss reduction of minus 11.

Table 4. The independent branch exchanges

Group-1		**Group-2**		**Group-3**		**Group-4**	
Load Transfer	Loss Reduction	Load Transfer	Loss Reduction	Load Transfer	Loss Reduction	Load Transfer	Loss Reduction
F1 – F3	-8	F1 - F2	-6	F1 – F5	-4	F1 – F2	-6
F4 – F5	-2	F4 - F3	-5	F4 – F3	-5	F4 – F5	-2
	-10		**-11**		-9		-8

The MCMF problem is solved using linear programming since we optimize a linear function, and all constraints are linear. The solution of the minimum cost maximum flow problem practically dictates all the concurrent branch exchanges that are selected to be implemented during the current iteration. In other words, the load transfer between feeders represented by the flows which are occurred in the network flow graph found by the minimum cost maximum flow solution. As an illustration, in Figure 10, we can see the solution of the problem where lines highlighted by bold green color present concurrent load transfers between acceptor feeders F2, F3 and donor feeders F1, F4 which lead to maximum loss reduction.

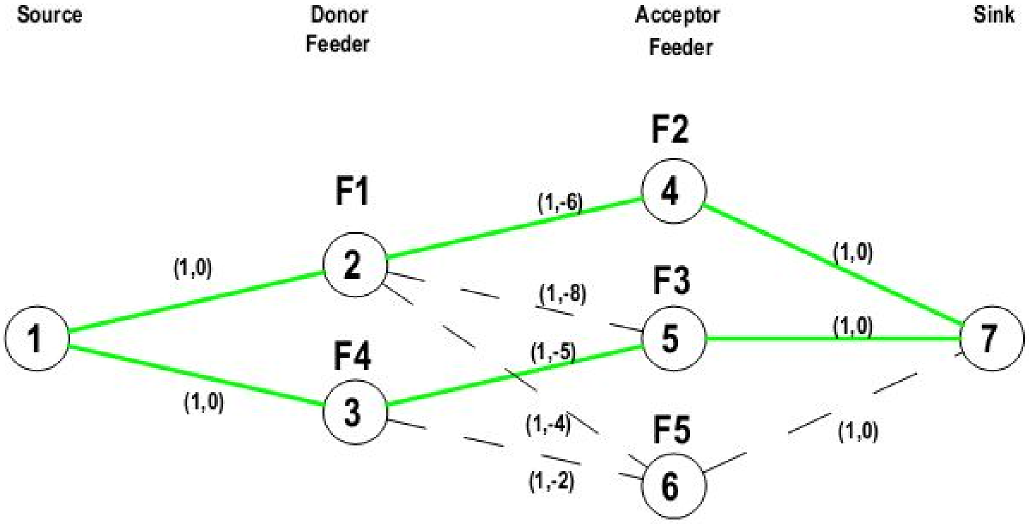

Figure 10. The result of MCMF problem.

The power system is reconfigured by closing switches S35 and S41 and opening switches S3 and S21 at the end of the current iteration. In Figure 11, this new configuration represents the initial configuration in the following iteration. It is important to point that the number of concurrent branch exchanges depends on the system size and the number of feeders can be any non negative integer.

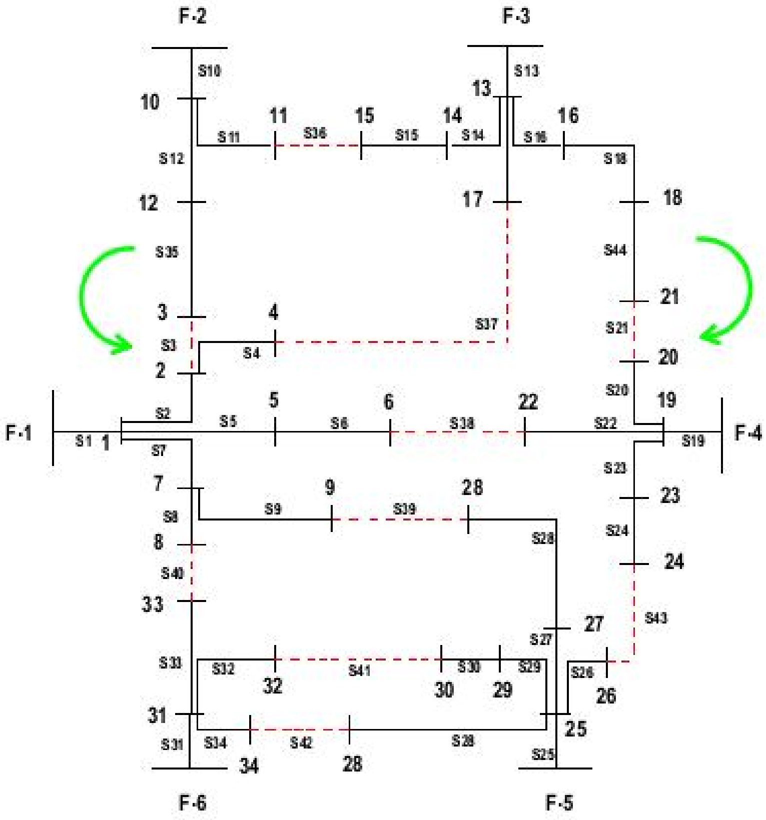

Figure 11. Power distribution network after the implementation of the multiple branch exchanges found by the solution of the MCMF problem.

CHAPTER IV

SIMULATIONS AND RESULTS

In this chapter, the previously defined minimum cost maximum flow algorithm is applied to distribution feeder reconfiguration on artificial radial distribution test systems. Here, the results and discussion of those results obtained from different test cases and simulations are presented. It also discusses the approach taken while performing the tests. The tests are performed on two distribution test cases 3 feeders 16 bus test system and 8 feeders 78 bus test system. In the first part of this chapter, in order to demonstrate the correctness of algorithms itself and their implementation in software the results of load flow and feeder reconfiguration algorithms are compared with the results of other researchers who implemented different methods. After, five different scenarios were created to show whether the feeder reconfiguration algorithm depends on the initial switching configuration. For this purposes the typical 3 feeder 16 bus radial distribution system is used. In the second part of this chapter, the effectiveness of multi branch exchange algorithm is compared with single branch exchange algorithm in typical 8 feeder 78 bus radial distribution system. The single line diagram of this system is shown in Figure 14.

In order to establish the effectiveness of the feeder reconfiguration algorithm, simulations were conducted using a tool developed in MATLAB environment. All simulations were implemented on the Intel(R) i5 2.27 GHz, 3.29 GB RAM compatible personal computer.

4.1 Verification of Implemented Algorithms

To demonstrate the effectiveness of the load flow and branch exchange algorithms in solving the network reconfiguration for loss minimization problem, the system shown in Figure 12 was used. This system was originally used by Civanlar et al. [28] to illustrate the performance of their algorithm and later many researchers have used this system to their works based on reconfiguration problem. In this system, 3 feeders supply 16 load buses. For the purposes of this simulation, it is assumed that there are 16 sections and each section has a sectionalizing switch, allowing a possibility of 2^{16}=65,536 configurations and three of these remain open to ensure the radial topology of the network. The data related with this system is given in Appendix A1.

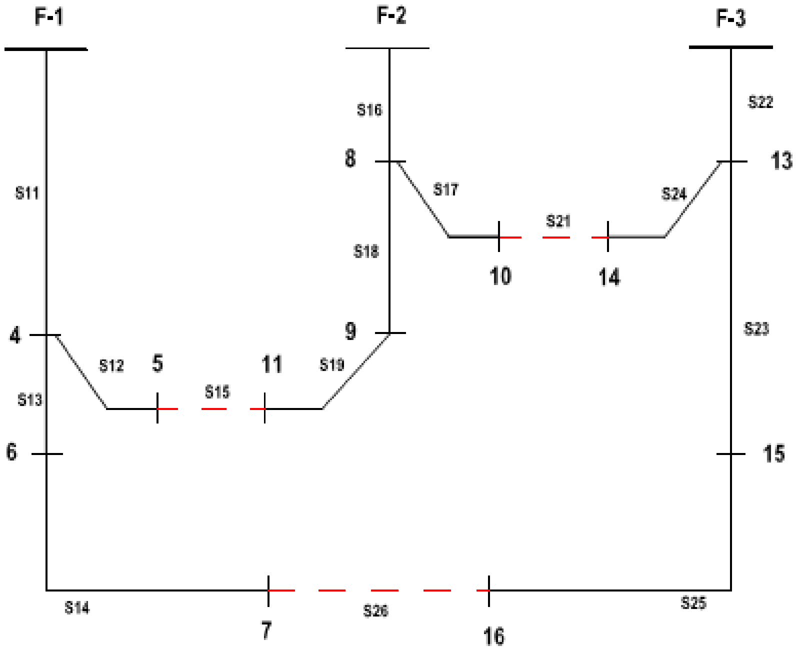

Figure 12. Test distribution system with 3 feeders and 16 sectionalizing switches.

To show the correctness of algorithms, the results obtained by single branch exchange algorithm was compared with the results of reconfiguration algorithm of Lin and Chin [15], then with the results of heuristic method developed by Singh et al. [17] and also with the results of system with optimal configuration[25]. The compared test results are shown in Table 5

Table 5. Summary of test results of 16 bus distribution system.

Methods	Power loss [p.u]		Open switches	
	Initial	Final	Initial	Final
Optimum[]			S15,S21,S26	S17,S19,S26
Singh at al. [17]	0,005114	0,004661	S15,S21,S26	S17,S19,S26
Lin at al. [15]	0,005115	0,004662	S15,S21,S26	S17,S19,S26
Single branch exchange	0,005114	0,004661	S15,S21,S26	S17,S19,S26

From the results given in Table 5, the initial and final power loss results of the different algorithms are same and it shows that the performance of load flow algorithm is correct.

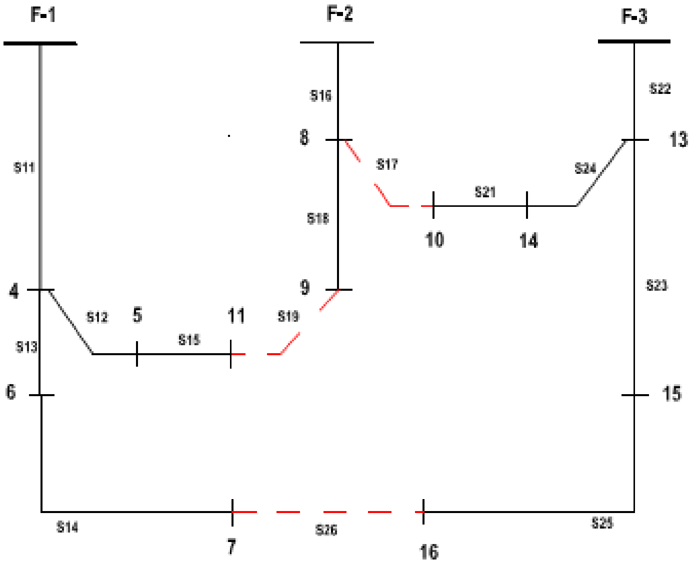

Figure 13. The distribution system after reconfiguration

From the Table 5 again, we can see that the switches to be opened are S17, S19, and S26 for the optimum operation (i.e. minimum loss), see Figure 13.

Thus final configuration of system is exactly the same with other works. For comparison purposes, all possible configurations have been run to find the global optimum. For the system in Figure 12, there are 2^{16}=65,536 possible switching combinations. However, of those, only 189 are feasible configurations, because the remainder configurations yield loads disconnected [25]. For example, if switch S11, S16 and S22 are open, none of the buses are supplied. A power flow was carried out for each of the feasible 189 configurations, and it was found that, for this system, the optimal configuration to minimize losses has switches S17, S19 and S26open. This final configuration is same with the one obtained by feeder reconfiguration algorithm used in this thesis, and validates the correctness of used algorithms, as well as the load flow algorithm. It is to be noted that the runtimes of used algorithms are not taken into account and only a quantitative comparison is done, because the runtimes reported in that works depend on the memory used, differences in processor speeds and algorithm implementation. We note that algorithm implementations of majority of previous works and their details on computational runtimes aren’t publicly available for comparison purposes.

In order to confirm that the implemented feeder reconfiguration method does not depend on the initial configuration, the initial switching configuration has been modified, and 5 different test cases were created, for example, in case 1, the configuration changed by closing the switches S15, S21 and S26 and opening the switches S12, S24 and S14. For this configuration the losses in per unit are 0.007192. Table 6 shows the results of five test cases.

Table 6. Test results of five different configurations

Case	Power loss [p.u.]		Iteration	Open switches	
	Initial	Final		Initial	Final
Case 1	0,007192	0,004661	4	S12,S24,S14	S17,S19,S26
Case 2	0,007242	0,004661	3	S13,S12,S17	S17,S19,S26
Case 3	0,008311	0,004661	4	S18,S23,S24	S17,S19,S26
Case 4	0,005485	0,004661	3	S19,S24,S25	S17,S19,S26
Case 5	0,004661	0,004661	1	S17,S19,S26	S17,S19,S26

It is to be noted that the single branch exchange method converges to the global optimum configuration. As shown in Table 6, although the initial configuration, power loss values and an iteration number of all cases are different the final configuration and power loss are same. It means that the implemented feeder reconfiguration algorithm does not depend on the initial configuration.

Generally, the results of test cases in Table 5 and Table 6show that the single branch exchange algorithm provides a general idea that this method can be used as feeder reconfiguration tool without any limit in practical networks and also can be used to solve the feeder reconfiguration problem.

4.2 Comparison of Multi Branch Exchange Method with Single Branch Exchange Method

In this chapter, the comparison between the multi branch exchange algorithm and the single branch exchange algorithm on power systems with 8 feeders 78 buses is presented (see Figure 14). The test results of comparison of two methods are summarized in Table 6. The power system test case is artificially created which line data is presented in Appendix A2.

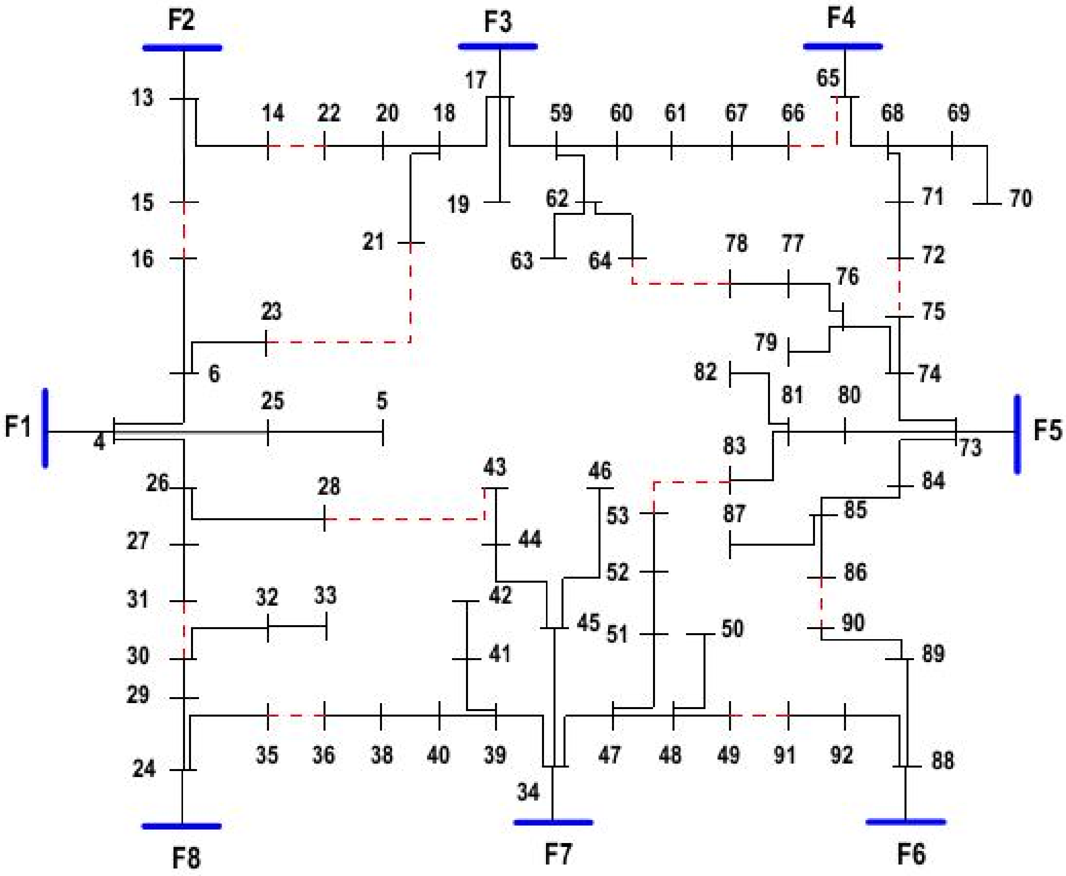

Figure 14. The radial distribution system with 8 feeders and 78 buses

Table 6. The results of comparison of two methods

Iteration	**SINGLE BRANCH EXCHANGE (Case1)**			**MULTI BRANCH EXCHANGE (Case 2)**		
	Power loss, KW	Opened switch	CPU run time, sec	Power loss, KW	Opened switch	CPU run time, sec
1	11,244	47-48	0,412	10,809	61-67, 48-47	0,354
2	10,040	43-44	0,283	9,526	43-44,89-90,22-20	0,303
3	8,846	53-52	0,358	8,282	27-26,53-52	0,345
4	8,411	61-67	0,265	**7,901**	4-6,39-40	0,275
5	8,047	40-39	0,373			
6	7,972	22-20	0,263			
7	7,920	26-27	0,269			
8	7,902	04-06	0,275			
9	**7,901**	89-90	0,281			
	Average execution time for iteration		0,309	Average execution time for iteration		0,319
	Total Execution Time		**3,170**	Total Execution Time		**1,665**

In order to better illustrate the behavior of the multi branch exchange approach, the loss reduction (kW) achieved during each iteration of the reconfiguration algorithms for the both algorithm is presented in Table 6. The number of iterations required by each reconfiguration algorithm in order to achieve the final loss reduction is reported in Table 6. For example, the multi branch exchange algorithm achieves the total loss reduction of 7.901 the during four iterations while the single branch exchange algorithm needs nine iterations to achieve the same amount of loss reduction for the test power distribution network in Figure 14. As shown in Figure 16 and Figure 17, the final configuration achieved using the multi branch exchange approach is similar to that achieved using the single branch exchange algorithm for test distribution system, but with significantly fewer iterations. Because, here, the single branch exchange algorithm performs one branch exchange in each iteration while the multi branch exchange algorithm performs two or three branch exchanges. For example, during the first iteration the multi branch exchange algorithm opened switches between 47-48 and 61-67 buses when the same operation is performed by single branch exchange algorithm during the iteration number 1 and 4. This is due to the network flow solution identifies multiple branch exchanges that yield larger loss reductions in each iteration, which in turn leads to faster convergence. As the test case size increases, the multi branch exchange reconfiguration approach improves the solution quality significantly. This can be explained by the fact that the minimum cost maximum flow solution is able to find the best set of concurrent branch exchanges during each iteration, especially when the number of possible branch exchanges increases.

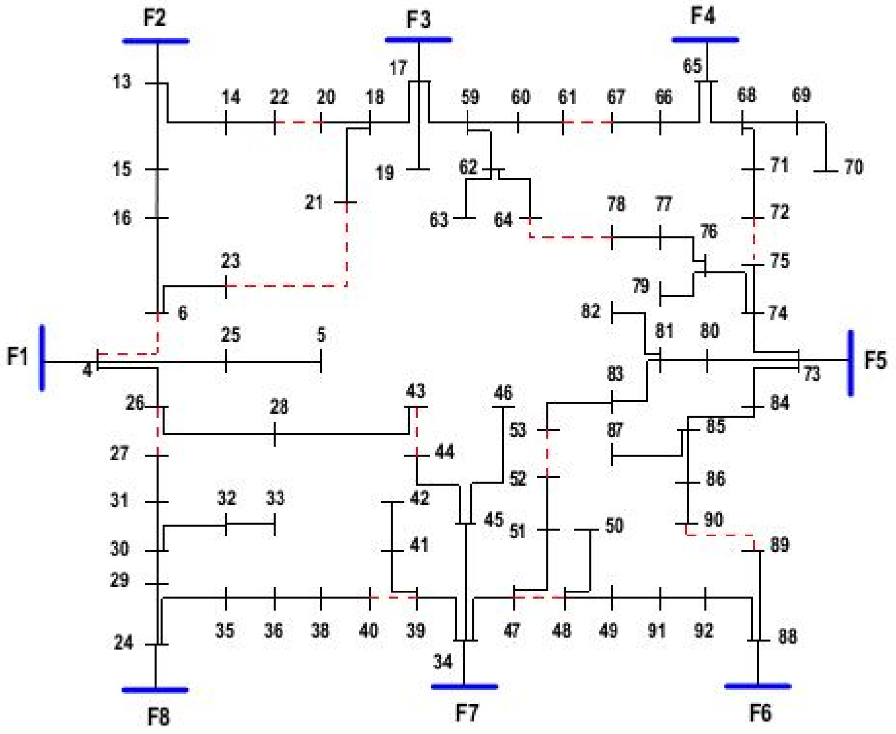

Figure 15. The distribution system after feeder reconfiguration

The runtime of both feeder reconfiguration approaches is governed by the number of times the reconfiguration algorithm is executed. Since the multi branch exchange algorithm terminates in much fewer iterations, the runtime savings become significant. If we compare the average execution time of two algorithms, we can see that the average time for multi branch exchange algorithm (0.319s) is more than that was achieved using the single branch exchange algorithm (0.309s) by only 3%. It is to be noted that this small difference means that the multi branch exchange algorithm additionally requires the runtime overhead responsible for constructing and solving the network flow problem. However, this runtime overhead is negligible. That is, the MCMF problem size (as number of vertices of the network-flow graph) is bound by $2F + S$, where S is the number of tie switches and F is the number of feeders in the system.

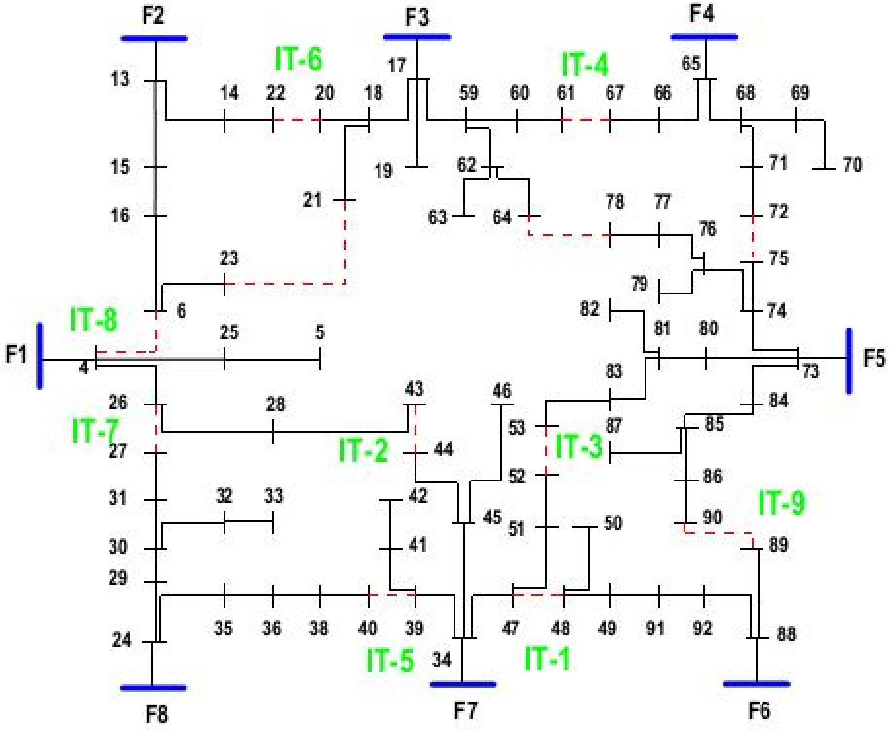

Figure 16. The iteration sequence of single branch exchange algorithm

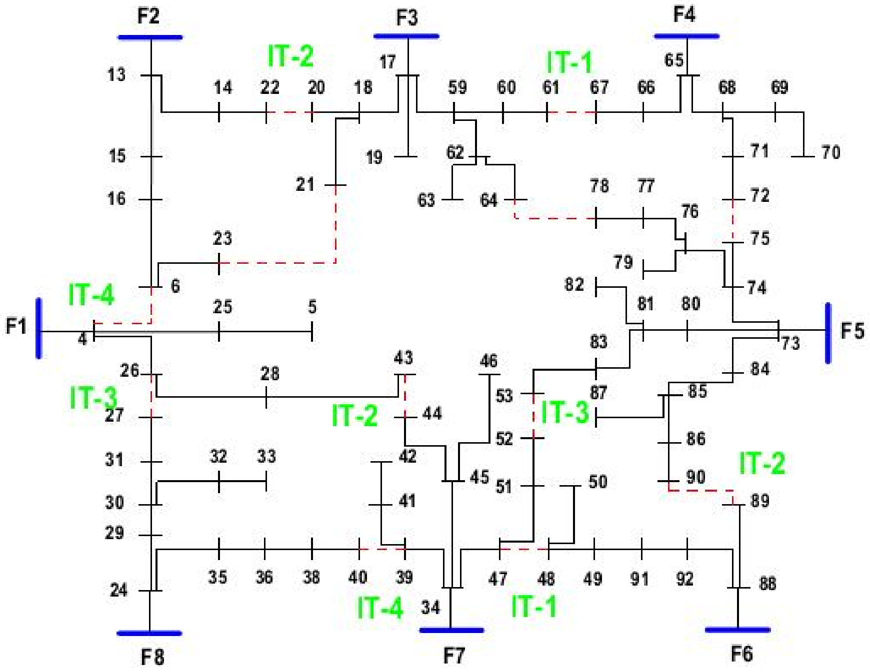

Figure 17. The iteration sequence of multi branch exchange algorithm

Finally, in order to compare the runtime of the multi branch exchange algorithm with single branch exchange algorithm, the total execution time of both reconfiguration algorithms are presented in Table 6.The computation time of algorithms is 3.17 and 1.665 seconds, respectively. The total execution time achieved using the multi branch exchange algorithm is much better than that achieved using the single branch exchange algorithm and with significantly fewer iterations. It can be seen that the multi branch exchange feeder reconfiguration algorithm achieved final loss reduction after four iterations while the same amount of loss reduction is achieved only after nine iterations using single branch exchange algorithm. It can be observed that the multi branch exchange algorithm is one of the fastest and therefore can be used as an efficient solution for online distribution feeder reconfiguration with application to distribution automation systems.

CHAPTER V

CONCLUSION

5.1 Conclusion

Loss minimization through system reconfiguration offers utilities the opportunity to reduce energy costs using existing equipment and at the same time, release system capacity. As outlined in the earlier chapters of this thesis, many algorithms have been proposed for loss minimization, but few have been adopted for use. Reasons for this most likely include inadequate consideration of system constraints, excessive computation time and difficulty in implementing the algorithms in software. It became clear in the early stages of this research that there was an important issue involved in the loss minimization problem. The issue was the optimization problem itself, and finding a method that provided optimal solutions in real time with very high runtime speed.

To guide the research, a radial load flow method based on forward and backward tracing has been implemented in this thesis and tested on typical distribution system. This load flow method is flexible and very fast.

Reconfiguration for loss reduction typically involves evaluating many combinations of switching options to determine which option offers the lowest losses. Obviously, in a large system, even with a very fast computer, the time needed to complete a load flow to evaluate every option would be prohibitive, and is the main reason for not carrying out an exhaustive search of all switching combinations. Computational complexity arising from the large dimensionally of the problem is identified and a criterion for reducing the number of candidate options is used. Also the formula for the loss estimation is a simple to use formula that removes the need to conduct numerous power flow studies, thereby significantly reduces the computational requirements. Accuracy analyzes and test results show that the estimation method is computationally very efficient and, in general, gives conservative results. In all calculations, both the real and reactive power flows are considered. Therefore, the approach can be used in searches to reconfigure those systems which are not well compensated.

Having developed the necessary data structures, and algorithms for manipulating them, the next step was to select an optimization technique to perform the loss minimization function. After a thorough review of earlier methods and their shortcomings, it became clear that the branch exchange method was the most promising, and Maximum Flow Minimum Cost technique was adopted for multi branch exchange method to speed up the algorithm.

The multi branch exchange algorithm captures the essential features of distribution systems. The algorithm can be run until a better solution will be found. The algorithm provides a significant contribution to distribution system operation. It identifies which switch should be opened for loss minimization through system configuration, and can be useful in determining which switches should be automated in a system, or which switches should be left open most of the time to reduce line losses. As mentioned earlier, the algorithm assures continuity of supply to all load buses while retaining a radial configuration. The final solution is independent of the original configuration, and the algorithm has a very high success rate in finding the global minimum.

The most important feature of implemented feeder reconfiguration method which makes it exclusively different from other reconfiguration methods is its runtime speed. As it is known feeder reconfiguration problem is an iterative nonlinear optimization problem, by reducing the number of iterations we can greedily reduce the overall computational runtime of program. Thus, as can be seen from chapter IV, for distribution system with 8 feeders the number of iteration of multi branch exchange method is approximately two times less than the number of iteration of single branch exchange method, but, when the size of the system increases the difference between the iteration number of two methods become more larger. Thus, this method shows it is advantage on huge electrical distribution systems comparing with other feeder reconfiguration algorithms. This advantage is one of the desirable features of smart grid systems and algorithm implemented in this thesis can be used as real time application.

5.2 Recommendations for Future Work

Distribution system planning and system restoration are two applications that are similar to the reconfiguration for loss minimization problem. In distribution system planning, planners attempt to determine network layouts, the position of switches and protective devices, and equipment capacities based on expected loads. In system restoration, operators attempt to restore power to as many customers as possible following system outages as a result of faults caused by weather, animals and accidents. In both cases, many configurations must be compared before deciding upon a final configuration. Thus, application of the MCMF algorithm to these problems should be examined.

A SCADA system interface should be developed for the multi-branch exchange algorithm. This would allow the algorithm to access online SCADA data, and allow MCMF to access historical system data, such as load curves for various customers. Instead of reacting to bus loads and determining a configuration to minimize losses based on information that is almost out of date as soon as it is recorded, it would be beneficial to have a method of predicting loads ahead of time. Access to SCADA data and a suitable forecasting technique would allow a system to be ready to respond to expected loads.

As faster computers become available, it can probably be said with some certainty that the execution speed of implemented algorithm in this thesis will be further reduced. However, for very large distribution systems, it would probably be beneficial to use more than one computer to determine the optimal configuration. Several computers could be slaves to a master computer that would direct them to determine system demands for a specific configuration. In this case, communication and coordination problems become issues. However, such a parallel implementation should be feasible, and could be examined.

Some fine tuning of the multi branch exchange algorithm may be possible. Since much of the processing time is spent carrying out load flows and updating the new system data, it makes sense to remember which switching combinations have already been examined, to ensure that they are not reexamined. However, an efficient method is needed to record those combinations that have already been examined.

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APPENDICES

APPENDIX A

A1. The Input data of Three Feeder Test System

Bus		Line Data		End bus Loading	
From	To	Resistance (p.u.)	Reactance (p.u.)	P (MW)	Q (MVAR)
0	4	0,075	0,1	2,00	1,60
4	5	0,08	0,11	3,00	0,40
4	6	0,09	0,18	2,00	-0,40
6	7	0,04	0,04	1,50	1,20
0	8	0,11	0,11	4,00	2,70
8	9	0,08	0,11	5,00	1,80
8	10	0,11	0,11	1,00	0,90
9	11	0,11	0,11	0,60	-0,50
9	12	0,08	0,11	4,50	-1,70
0	13	0,11	0,11	1,00	0,90
13	14	0,09	0,12	1,00	-1,10
13	15	0,08	0,11	1,00	0,90
15	16	0,04	0,04	2,10	-0,80
5	11	0,04	0,04		
10	14	0,04	0,04		
7	16	0,09	0,12		

A2. The Input data of Eight Feeder Test System

Bus		Line Data		End bus Loading	
From	To	Resistance (P.U.)	Reactance (P.U.)	P (MW)	Q (MVAR)
0	4	0,075	0,1	0,80	0,60
25	5	0,08	0,11	0,52	0,38
4	6	0,09	0,04	0,43	0,32
0	13	0,05	0,04	0,90	0,65
13	14	0,11	0,11	0,64	0,46
13	15	0,09	0,12	0,67	0,48
6	16	0,04	0,04	0,46	0,34
0	17	0,02	0,06	1,10	0,75
17	18	0,04	0,04	2,20	1,80
17	19	0,08	0,015	4,00	1,20
18	20	0,09	0,04	2,60	2,00
18	21	0,09	0,12	2,40	1,90
20	22	0,03	0,16	2,80	2,10
6	23	0,11	0,11	0,49	0,36
0	24	0,01	0,04	1,00	0,70
4	25	0,08	0,16	0,40	0,30
4	26	0,11	0,11	0,55	0,40
26	27	0,11	0,11	0,58	0,42
26	28	0,08	0,11	0,61	0,44
24	29	0,04	0,04	0,26	0,15
29	30	0,04	0,11	0,34	0,19
27	31	0,16	0,055	0,42	0,23
30	32	0,16	0,05	0,50	0,27
32	33	0,04	0,05	0,58	0,31
0	34	0,04	0,04	1,30	0,85
24	35	0,14	0,09	0,66	0,35
38	36	0,04	0,04	0,90	0,47
36	37	0,07	0,13	0,82	0,43
40	38	0,16	0,055	0,74	0,39
34	39	0,08	0,015	2,00	1,20
39	40	0,09	0,02	2,50	1,40
39	41	0,17	0,06	3,00	1,60
41	42	0,18	0,065	3,50	1,80
44	43	0,11	0,045	7,40	3,30

45	44	0,09	0,04	5,00	2,40
34	45	0,19	0,07	4,00	2,00
45	46	0,04	0,04	4,50	2,20
34	47	0,13	0,05	8,20	3,60
47	48	0,15	0,055	9,00	3,90
48	49	0,17	0,06	3,40	1,80
48	50	0,19	0,065	4,20	2,10
47	51	0,21	0,07	5,00	2,40
51	52	0,04	0,04	5,80	2,70
52	53	0,04	0,04	6,60	3,00
17	59	0,09	0,02	6,30	1,50
59	60	0,1	0,025	4,50	1,80
60	61	0,11	0,03	2,70	2,10
59	62	0,12	0,035	2,20	2,40
62	63	0,13	0,04	1,50	2,70
62	64	0,14	0,045	1,70	3,00
0	65	0,05	0,04	1,40	0,90
67	66	0,09	0,04	0,80	1,20
61	67	0,18	0,065	1,00	1,10
65	68	0,03	0,16	1,20	1,00
68	69	0,1	0,025	1,80	0,70
69	70	0,11	0,03	2,00	0,60
68	71	0,08	0,015	1,40	0,90
71	72	0,09	0,02	1,60	0,80
0	73	0,06	0,04	1,50	0,95
73	74	0,12	0,035	0,40	1,30
74	75	0,13	0,04	0,42	1,25
74	76	0,14	0,045	0,44	1,20
76	77	0,15	0,05	0,46	1,15
77	78	0,16	0,055	0,48	1,10
76	79	0,17	0,06	0,50	1,05
73	80	0,18	0,065	0,52	1,00
80	81	0,17	0,06	0,46	0,56
81	82	0,16	0,055	0,49	0,48
81	83	0,15	0,05	0,52	0,40
73	84	0,14	0,045	0,55	0,32
84	85	0,13	0,04	0,58	0,24
85	86	0,12	0,035	0,61	0,16
85	87	0,11	0,03	0,64	0,08

0	88	0,07	0,06	1,60	1,00
88	89	0,1	0,025	1,00	0,90
89	90	0,09	0,02	0,60	-0,50
92	91	0,07	0,01	1,00	0,90
88	92	0,08	0,015	0,60	0,70
14	22	0,15	0,05		
16	15	0,08	0,11		
21	23	0,17	0,06		
30	31	0,06	0,04		
28	43	0,15	0,05		
35	36	0,01	0,12		
65	66	0,09	0,12		
64	78	0,17	0,06		
72	75	0,16	0,055		
53	83	0,14	0,045		
49	91	0,13	0,04		
86	90	0,12	0,035		