ANALYSIS OF TIME VARYING LOAD FOR MINIMUM LOSS DISTRIBUTION RECONFIGURATION

by

Asif H. Khan

Dissertation Submitted to the Faculty of the

Virginia Polytechnic Institute and State University in

partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

ELECTRICAL ENGINEERING

APPROVED:

Robert P Broadwater
Robert P. Broadwater, Chairman

SRahman
Saifur Rahman

Douglas K Lindner
Douglas K. Lindner

Lamine Mili
Lamine Mili

John A. Burns
John Burns

April, 1992

Blacksburg, Virginia

ANALYSIS OF TIME VARYING LOAD FOR MINIMUM LOSS DISTRIBUTION RECONFIGURATION

by

Asif H. Khan
Robert P. Broadwater, Chairman
ELECTRICAL ENGINEERING

(ABSTRACT)

A reconfiguration algorithm for electrical distribution system to reduce system losses is presented. The algorithm determines the switching patterns as a function of time. Either seasonal or daily time studies may be performed. Both manual and automatic switches are used to reconfigure the system for seasonal studies, whereas only automatic switches are considered for daily studies.

An algorithm for load estimation is developed. The load estimation algorithm provides load information for each time point to be analyzed. The load estimation algorithm can incorporate any or all of the following: spot loads, circuit measurements, and customer time-varying diversified load characteristics. Voltage dependency of loads is considered at the circuit level. It is shown that switching at the system peak can reduce losses but may cause a marginal increase in system peak. Voltage and current constraints are incorporated in the reconfiguration algorithm.

Data base tables and data structures used in the algorithm are described. Example problems are provided to illustrate results.

Acknowledgements

I would like to take this opportunity to express my deepest appreciation to Dr. Robert Broadwater for his help, unlimited support and guidance throughout the course of my study. His encouragement and advice have been a major factor in developing myself personally and professionally. It has been a real pleasure for me to work under his supervision and to gain from his knowledge and experience.

I am also grateful to Dr. Saifur Rahman for his guidance and help during the time this research was carried out . Also, I would like to thank Dr. Lindner, Dr. Mili, and Dr. Burns for their help and willingness to serve on my committee.

I would like to thanks all of my friends, and in particular Hesham Shaalan and Ossama Hazim who helped me during the final stages of my dissertation while I was working out of town. I would also like to thank Dr. Mckeon and Loretta Estes for their help and cooperation on various occasions during my stay at Virginia Tech.

My very special thanks to my parents and to my brother and sister for their encouragement, care, and great moral support during my entire life. Finally, I would also like to thank a very special friend and companion, my wife Amna, for her patience, understanding, and support during the last four months.

Table Of Contents

List Of Illustrations

List Of Tables

CHAPTER 1

Introduction

1.1 Background

Reconfiguration of electrical distribution systems has been approached from various perspectives. Algorithms have been evaluated for reconfiguration of the distribution system during fault conditions [1, 2]. These algorithms are concerned with restoring power to as many customers as possible. Also, distribution systems are routinely reconfigured during maintenance operation [3]. Another perspective that may be taken concerning reconfiguration of distribution systems is to reduce losses. The loss reduction perspective is considered in the present research. Only real losses are considered.

A distribution system comprised of a group of interconnected radial circuits whose configurations may be varied with switching operations is considered. Figure 1.1.1 shows a radial electrical distribution system comprised of five circuits. The radial nature of the system is maintained by open switches. These switches may be used to shift load from one circuit to another or to isolate failed components from the rest of the system during fault conditions. For example, load may either be transferred from Circuit 1 to Circuit 4 by opening switch sw12 and closing switch sw10 or from Circuit 4 to Circuit 1 by opening switch sw9 and closing switch sw10. Load may also be transferred

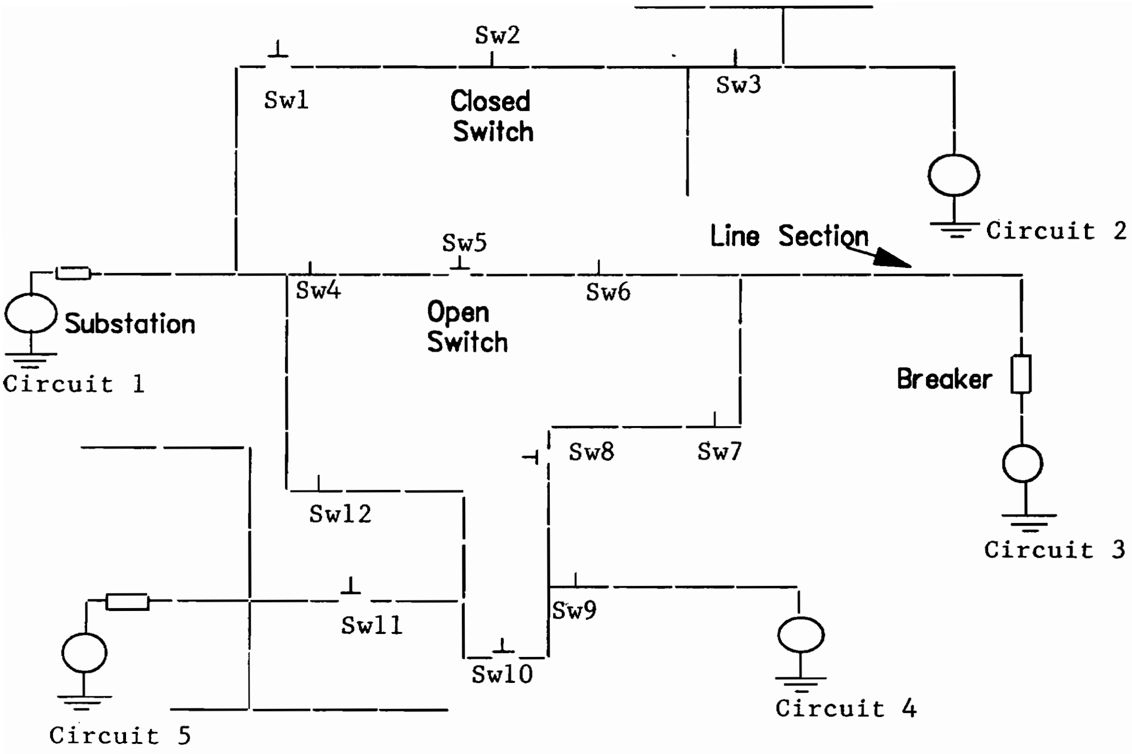

Figure 1.1.1 An Electrical Distribution System Comprised of Five Circuits.

either from Circuit 1 to Circuit 3 by opening switch sw4 and closing switch sw5 or from Circuit 3 to Circuit 1 by opening switch sw6 and closing switch sw5. Similarly, there are many other switch pair combinations exist. However, in future chapters it can be seen that many of the possible switch pair operations are eliminated in order to adhere to certain rules and constraints. Present research is focused on achieving a local minimum, rather than a global minimum to the minimum loss problem.

Presently, two types of switches exist in the market, manually operated and computer controlled automatic switches. Manually operated switches may require more than an hour to operate, whereas automatic switches take only a few seconds. Each circuit is also comprised of many line sections, as indicated in Figure 1.1.1. Numerous customers may be attached to these line sections. These customers draw power which varies as a function of time.

Ideally, during normal operating conditions, the configuration of the distribution system should be such that losses are minimal. Due to the time varying nature of customer loads, a single system configuration may not always result in the best loss profile. Thus, the distribution system should be reconfigured on a daily and seasonal basis to reduce losses. A distribution reconfiguration algorithm which aims to minimize the system's real losses as a function of circuit topology is developed here and implemented on an OS/2 based Personal Computer. The reconfiguration algorithm generates switching patterns corresponding to the reduced loss configuration of the distribution system. Only switches that exist in the three phase portion of the system are considered.

1.2 Time Varying Loads

Customer loads are subject to daily and/or seasonal variations. In general, loads on a distribution system change constantly and are strongly influenced by seasonal temperature variations. Utilities may use manual switching for seasonal variations. With the innovation of distribution automation, daily switching is also possible using computer controlled automatic switches. Thus, utilities may use automatic switching for daily load variations. The placement of switches to reduce losses is not an easy task because of the time varying nature of loads.

Estimation of feeder loads is important. If actual load data is not available, then an estimated load model may be used in modeling the distribution system. Present research incorporates a feeder load estimation algorithm which is based on a customer information system interface (viz: number and types of customers), feeder measurements, and diversified customer load curves obtained from load research experiments.

A typical daily load profile of an electrical distribution system may have peaks in the morning, around noon, and again in the evening [3]. This variation in the system load profile is due to fluctuations among circuit loading conditions. Fluctuations in circuit loading conditions are a result of diversified time varying loads served by the numerous system circuits. A circuit's load diversity is established by the daily electrical power demands of various customer types which are served by the circuit. Those customer types may be classified into three major catagories: residential, commercial, and industrial. Figures 1.2.1a and 1.2.1c show typical diversified load profile curves for residential type customers for Allegheny Power Systems for summer, winter, and fall season.

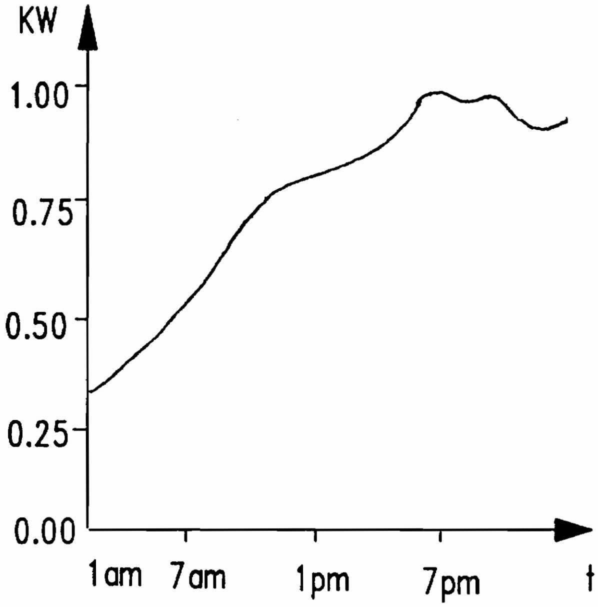

Figure 1.2.1a Typical Summer Normalized Diversified Load Profile.

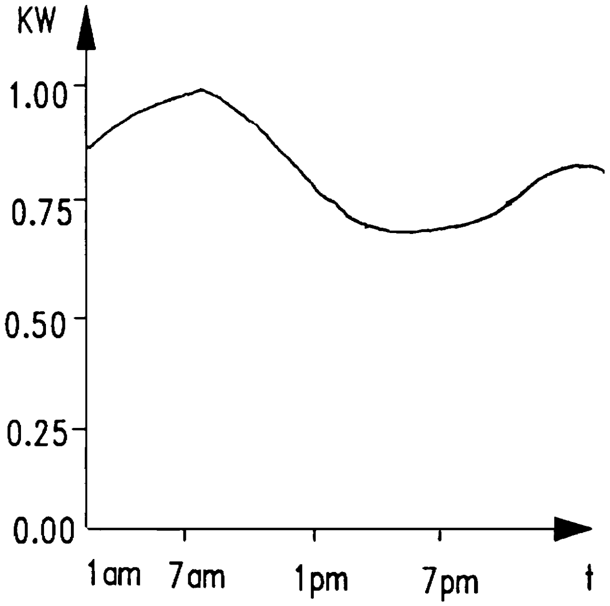

Figure 1.2.1b Typical Winter Normalized Diversified Load Profile.

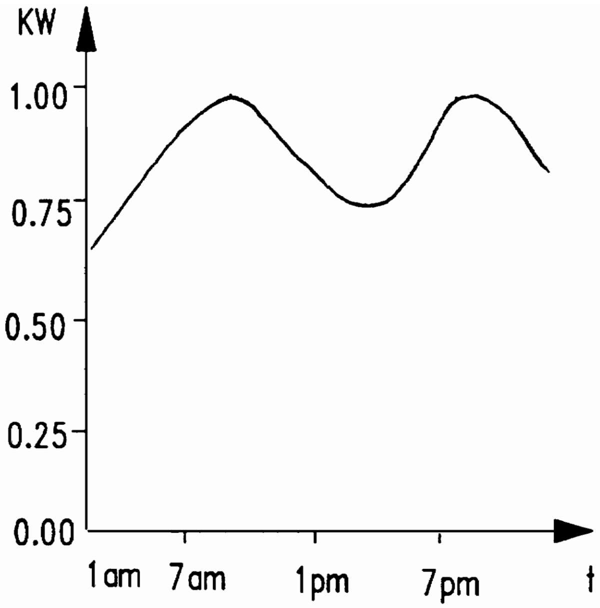

Figure 1.2.1c Typical Fall Normalized Diversified Load Profile.

The variation in time may be considered by time of day, type of day, and season. The time variation is considered across seasons given a time of day or across a day given a season. This leads to many data points to be analyzed by a reconfiguration algorithm. The reconfiguration algorithm presented here analyzes these data points automatically. The automatic analysis of time varying load patterns greatly reduces the manual work required. The outputs of the algorithm are switching patterns as a function of time, where time may vary over a daily cycle or a seasonal cycle. Benefits from seasonal loss reduction can be accomplished through manual switching, whereas benefits from daily loss reduction require automatic switching [4].

1.3 Need For A Distribution Reconfiguration Algorithm

The reconfiguration algorithm developed is an engineering tool which may be utilized to improve the operational efficiency of a distribution system. It can also be utilized as an on-line aid to distribution system operators since its execution time is in the order of seconds. The energy saved due to distribution reconfiguration may result in substantial amounts of money saved over a period of time. Thus, it can be used for distribution systems planning purposes as well.

The overall objectives of this dissertation can be stated as follows:

- Develop a distribution reconfiguration algorithm which may be utilized to analyze time varying loads in order to minimize a system's real losses as a function of circuit topology
- Investigate reconfiguration at peak loading conditions

- Investigate effects of distribution reconfiguration with voltage-dependent loads

1.4 Mathematical Problem Formulation

The problem to be solved may be mathematically expressed as follows :

For a given time T and year k ,

minimize $\{ f(\mathrm{Ploss}_{T,k}) \}$ over $\underline{sw}_{T,k}$

subject to

$$f(\underline{V}_{T,k}, \underline{S}_{T,k}(\underline{V}_{T,k}), \underline{sw}_{T,k}) = 0 \qquad [1.4.1]$$

$$\underline{I}(T,k) = f(\underline{V}_{T,k}, \underline{S}_{T,k}(\underline{V}_{T,k}), \underline{sw}_{T,k}) \qquad [1.4.2]$$

$$\underline{I}_{T,k} \leq \underline{I}\_\mathrm{rated} \qquad [1.4.3]$$

$$\mathrm{Vmin} \leq \underline{V}_{T,k} \leq \mathrm{Vmax} \qquad [1.4.4]$$

$$\mathrm{kw\_peak}_{T,k} \leq \mathrm{max\_kw\_peak} \qquad [1.4.5]$$

where,

$\mathrm{Ploss}_{T,k}$ = system's real losses at time T and year k,

$\underline{V}_{T,k}$ = vector of node voltages at time T and year k,

$\underline{S}_{T,k}(\underline{V}_{T,k})$ = vector of power as a function of time and voltage,

$\underline{sw}_{T,k}$ = vector of switch positions at time T and year k,

$\underline{I}_{T,k}$ = vector of current at time T and year k,

T = time of day, type of day, and season {t, d, Se },

k = k^{th} year,

$\underline{I}\_\mathrm{rated}$ = vector of rated equipment currents,

Vmin = lower bound for system voltage,

Vmax = upper bound for system voltage,

$kw\_peak_{T,k}$ = system peak in kw at time T and year k,

max_kw_peak = operator's predefined annual system peak in kw.

The objective is to minimize the real losses as a function of circuit topology for a given point in time. The circuit topology is a function of switch positions $\underline{sw}_{T,k}$. The objective function is subject to a set of nonlinear equations and linear inequality constraints. For a given time T and year k, the vector of complex powers $\underline{S}_{T,k}(\underline{V}_{T,k})$ is estimated at nominal voltage. The independent vector is $\underline{sw}_{T,k}$. The nonlinear function as described by Equation 1.4.1 is a representation of load flow equations.

An algorithm may be defined as a step-by-step programmable procedure for solving a problem. An algorithm which employs a search technique is described here. This algorithm runs on a distribution system with a given set of switch positions. It then searches over switch pair operations that result in a reduced loss configuration such that the inequality constraints [1.4.3] - [1.4.5] are not violated. If no such switch pair operations are found, then the algorithm has converged by definition and is assumed to be at a local minimum. The algorithm uses methods developed in previous works, and also attempts to make improvements over previous algorithms. Two major improvements are

1) Voltage-dependent load models, as represented by $\underline{S}_{T,k}(\underline{V}_{T,k})$,
2) and Constraint handling, as represented by inequalities [1.4.3] - [1.4.5].

The algorithm analyzes a discrete series of load conditions automatically, but it only analyzes a single loading condition at a time. Finally, the algorithm generates switching patterns versus time over a series of discrete load conditions,

$$\underline{S}_{T,k}(\underline{V}_{T,k}), \text{ where } \quad k = 1990, 1991, \ldots \qquad [1.4.6]$$

1.5 Contributions Of Work

The reconfiguration algorithm is build on aspects from earlier works. Algorithmic aspects of Civanlar's and Huddleston's methods are incorporated. That is, Civanlar's load switching rule [5] and Huddleston's quadratic loss function [3] are implemented in the reconfiguration algorithm. The next chapter covers these methods in detail. Contributions of the study partially lie in extending these previous works. The major and minor contributions of the present work are outlined here.

1.5.1 Major Contributions :

- Previous authors have developed algorithms which considered loading conditions at a single point in time, whereas the present algorithm analyzes various time varying loads. These loading conditions are based on time of day, type of day, and season. This leads to many data points to be analyzed by the reconfiguration algorithm and the present algorithm analyzes these data points automatically.

- Estimation of feeder loads is important. In the past, no significant effort has been performed in this regard. The present research incorporates a method of feeder load estimation which utilizes feeder measurement values at the substation, diversified customer load values, number of customers at a load point, and types of customers attached at a load point in a circuit.

- Loads are voltage dependent [6]. Previous reconfiguration studies have not reported the effect of voltage dependency of loads. This voltage dependency of loads is modeled and implemented in the present algorithm. The peak loading condition is analyzed in order to show that when a load is shifted from a lower to a higher voltage level circuit, the total system load may exceed the annual peak loading condition which is an undesirable result. The increased load is due to the load voltage dependency. In this situation voltage control may be used in conjunction with switching decisions. When switching voltage dependent loads at peak loading conditions, a coordinating voltage control system may be needed in order to reduce both system peak and losses. However, the voltage control cordination effect is not addressed in the present research.

1.5.2 Minor Contributions

- Placement of switches to reduce losses is an important but complicated task because of the time varying nature of loads. In the present research, the placement of both manual and automatic switches is evaluated in reference to their contribution to loss reduction. Placement of automatic switches as a function of daily loading and placement of both manual and automatic switches as a function of seasonal loading are considered in the present work. The automatic switches are to be placed before the manual switches in the circuits. Previous works have considered automatic switches or did not make distinctions.

- Previous works have not considered physical constraints such as circuit voltage limits and current overloading for realistic loading conditions. The present work incorporates a method of handling these physical constraints. This method reverses switching operations when constraints are violated and tags the offending switches so that they will not be considered in future iterations of the algorithm at the given point in time.

An overview of the remaining chapters of the dissertation is given here. A review of previous work is presented in the next chapter which includes a discussion about balanced loading due to reconfiguration, Civanlar's method, Huddleston's method, and Lee's two proposed algorithms. The database tables and data structures utilized by the algorithm are presented in Chapter 3. A feeder load estimation algorithm which involves the modeling of time varying loads is explained in Chapter 4. Modeling of segment and switching currents, the power flow algorithm, development of quadratic loss functions, loss function evaluation to determine switching operations, system constraints, and the reconfiguration algorithm steps are covered in Chapter 5. Chapter 6 outlines characteristics of the example problems and also presents the results. Finally, Chapter 7 gives conclusions and focuses attention on future work.

CHAPTER 2
Literature Review

Traditionally, utilities have been using manual switching for distribution reconfiguration. Their main concern was to restore power to as many customers as possible during fault conditions. There were not many computerized distribution reconfiguration algorithms available in the past. Today, algorithms are available which deal with the reconfiguration of distribution systems. The objectives of these algorithms vary from service restoration [1, 2] to maintenance operation [3]. Another objective concerning distribution reconfiguration is loss reduction. This chapter focuses attention on previous works in the context of minimum loss distribution reconfiguration.

2.1 Review of Previous Works from Loss Reduction Perspective

For equal substation voltages and line construction, reconfiguration for minimum losses should lead to balanced loading among substations [5]. Balanced loading places the system in a better posture to respond to emergency situations. For example, consider a system of three circuits. Circuit loading versus circuit number is plotted for the given system in Figure 2.1. Assume equal line construction for all three circuits and that each circuit has the same overload boundary, represented by the solid line. Figure 2.1(a)

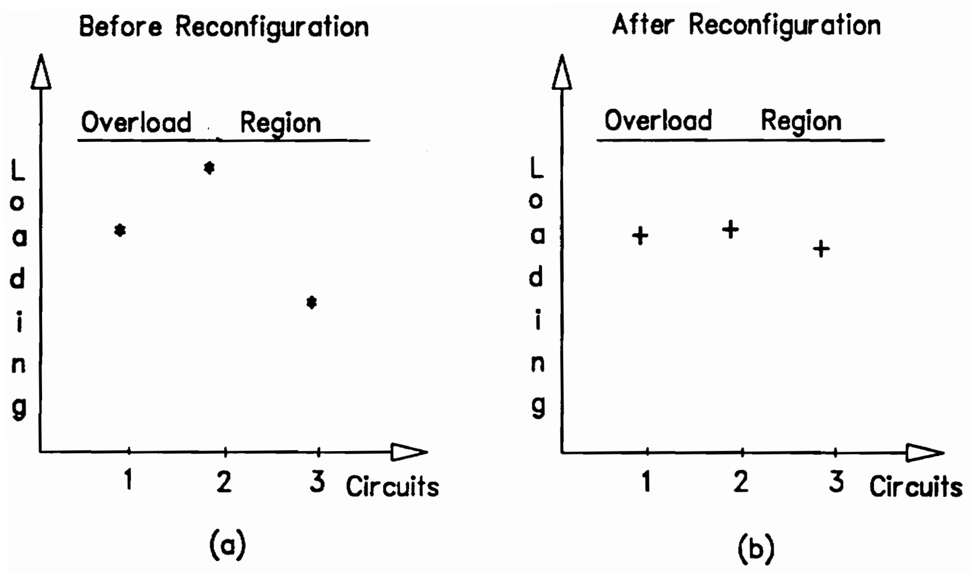

Figure 2.1 a) Circuit Loading Before Reconfiguration

b) Circuit Loading After Reconfiguration represents the system condition before reconfiguration to reduce losses and illustrates that Circuit 2 is operating very near to the overload boundary. If a fault occurs in a certain area of Circuit 3 and a few loads are switched from Circuit 3 to Circuit 2 in order to restore power, then Circuit 2 may well exceed the overload boundary. After reconfiguration of the system to reduce losses, a more balanced loading condition among the three circuits is achieved. That is, each of the three circuits is placed at approximately the same distance from the overload boundary, as shown in Figure 2.1(b). Therefore, reconfiguration to reduce losses may also provide the advantage of preparing all circuits to be ready to response to emergencies in neighboring circuits.

Five algorithms for distribution reconfiguration to reduce losses have been reported in the literature. The first algorithm, referred to as the Desultory algorithm, is not very efficient [7]. Even on a small distribution system it may take a substantial amount of computer run time to converge to a solution. The other four algorithms referred to as "Civanlar's Algorithm" [5], "Huddleston's Algorithm" [3], "Lee's Algorithm A1" [8], and "Lee's Algorithm A2 [8]" are much more concrete and efficient than Desultory algorithm. These four algorithms are breifly described here.

2.1.1 Civanlar's Approach

A major aspect of Civanlar's algorithm is that it does not allow load to be switched from a higher to a lower voltage level, thus reducing the total number of switching possibilities by approximately one-half. This method assumes circuits are operating at approximately the same voltage level, and switching is occuring from a circuit with more losses to a circuit with less losses. If loads are initially assumed to be voltage independent, then analysis may predict that losses will decrease when loads are switched from low to high voltage. However, most loads are voltage dependent, and switching a load to a higher voltage circuit generally results in more power being drawn for a short period of time. An example of such a load would be resistance heating which draws more power as a result of being switched to a higher voltage. Since more power is being drawn, the work may be performed in a shorter period of time. This additional power being drawn may cause losses to increase slightly over what was predicted by analysis (i.e., where analysis assumes constant power loads), but the major effect may be an increase in system load. Voltage dependency factors are not considered by Civanlar's method.

To illustrate some of the concepts which deal with the effect of load voltage dependency on system peak, an example is presented. The example is comprised of a system of two circuits,Circuit 1 and Circuit 2. The switching point voltages for these two circuits are denoted by

$v_1 =$ voltage level at switching point in Circuit 1, [2.1.1.1]

$v_2 =$ voltage level at switching point in Circuit 2, [2.1.1.1]

where,

$$v_2 > v_1. \quad [2.1.1.3]$$

Voltages before and after switching are assumed to remain constant.

The total system load, including losses, before and after reconfiguration are denoted by

Ps(idx) = total system power requirement including losses,   idx = 0 , 1

[2.1.1.4]

where,

index "idx = 0" represents quantities before reconfiguration

and index "idx = 1" represents quantities after reconfiguration.

The total losses in Circuits 1 and 2 before and after reconfiguration are

$L_1(idx)$ = Losses in Circuit 1, [2.1.1.5]

$L_2(idx)$ = Losses in Circuit 2, [2.1.1.6]

Assume that the losses are reduced in Circuit 1 and increased in Circuit 2 after the reconfiguration as given by

$L_1(1) < L_1(0)$, [2.1.1.7]

and $L_2(1) > L_2(0)$. [2.1.1.8]

The total system losses after reconfiguration are assumed to be less than the total system losses before reconfiguration,

$L_1(0) + L_2(0) > L_1(1) + L_2(1)$. [2.1.1.9]

The load is being switched from Circuit 1 to Circuit 2. Assume that the load being switched is voltage dependent. The following inequalitiy represents that the load switched to Circuit 2 after the reconfiguration is greater than the load being switched from Circuit 1 before reconfiguration,

$kw_2(1) > kw_1(0)$. [2.1.1.10]

where,

$kw_1(0)$ = load in Circuit 1 to be switched to Circuit 2, [2.1.1.11]

$kw_2(1)$ = load in Circuit 2 that resulted from switching $kw_1(0)$

from Circuit 1 to Circuit 2. [2.1.1.12]

Let $a = (L_1(0) + L_2(0)) - (L_1(1) + L_2(1))$, [2.1.1.13]

Let $b = kw_2(1) - kw_1(0)$, [2.1.1.14]

where,

a = decrease in losses, [2.1.1.15]

b = increase in load due to voltage dependency. [2.1.1.16]

If $b > a$, then the switching operation has resulted in increasing the total power needs of the system. At peak load, the peak of the system would be increased and hence

$Ps(1) > Ps(0)$. [2.1.1.17]

Neither Civanlar's method nor the Desultory method considered this type of system affect at peak conditions.

2.1.1.1 Civanlar's Algorithm

Civanlar's algorithm begins by executing power flow analysis calculations on a given distribution system in its current configuration. Then the algorithm randomly reconfigures itself by peforming switching operations (i.e., closing a tie line switch and opening a sectionalizing switch). This algorithm considers one switch pair operation at a time. Each new system configuration is compared with the old one using Equation 2.1.1.1.1 presented below, which is developed in Reference 5.

$$\Delta P = \mathrm{Re}\{2(\sum_{i \varepsilon D} I_i)(E_m - E_n)^*\} + R_{loop} |\sum_{i \varepsilon D} I_i|^2 \quad [2.1.1.1.1]$$

where,

D = set of buses which are disconnected from Feeder-II and connected to Feeder-I

m = tie bus of Feeder-I to which loads from Feeder-II will be connected

n = tie bus of Feeder-II that will be connected to bus m via a tie switch

I_i = complex injected bus current at bus i

R_{loop} = series resistance of the path connecting the two substation buses of Feeder-I and Feeder-II via closure of the specified tie switch

E_m = component of $E = R_{BUS}I_{BUS}$ corresponding to bus m. R_{BUS} is the bus "resistance" matrix of Feeder-I before the load transfer which is found using the substation bus as reference. I_{BUS} is the vector of bus currents for Feeder-I

E_n = similar to E_m but defined for bus n of Feeder-II

Re(.),

*, |.| = real part, complex conjugate, and magnitude operator, respectively.

Equation 2.1.1.1.1 is based on the well known relationship for real power losses $P = I^2R$. The system configurations are then compared and the one with the largest negative change in power losses ΔP is determined to be the best within a single switch pair operation from the original configuration. If the original configuration gives the largest negative change in losses, then the algorithm has converged by definition. Otherwise, the load flow calculations must be performed on the new configured system and the entire procedure is repeated.

2.1.2 Huddleston's Algorithm

Huddleston's method employs a quadratic loss function used to minimize system losses. The loss functions are developed for each circuit in the system. Huddleston formulated the optimization problem as follows:

$$\text{minimize } P_{loss} = \sum_{c=1}^{m} f_c(\underline{I}_{si}) \qquad [2.1.2.1]$$

subject to

$$A\underline{I}_{si} = b, \qquad [2.1.2.2]$$

$$\underline{I}_s = \underline{I} + \underline{BI}_{si}, \qquad [2.1.2.3]$$

and

$$\underline{I}_{si} \geq 0, \qquad [2.1.2.4]$$

where,

$f_c(\underline{I}_{si})$ = quadratic loss function for the c^{th} circuit,

$\underline{I}_{si}$ = vector of i switching currents,

$\underline{I}_s$ = vector of distribution system source currents,

b, I = constant vectors,

$\underline{A}, \underline{B}$ = constant matrices,

and m = number of circuits in the system being evaluated.

Equation 2.1.2.2 states that the loads at all switching points must be satisfied simultaneously taking into account the voltage dependency of loads. Equation 2.1.2.3 is a constraint on the source current which requires the source current to sum to the circuit load currents plus the switching currents that are attached to the circuit. Constraint 2.1.2.4 states that switching current must be equal to or greater than zero. Once the problem has been formulated, the IMSL subroutine QPROG [9] is employed to solve the quadratic optimization problem.

Huddleston's algorithm produces simultaneous multiple switching operations per iteration, whereas Civanlar's method involves a single switch pair operation per iteration. Huddleston's method takes fewer iterations than Civanlar's method to converge to a solution. However, a single iteration in Huddleston's method requires a longer computer run time than a single iteration in Civanlar's method.

Neither Huddleston's method nor Civanlar's method consider the physical constraints such as system voltage limits and current overloading. Huddleston's algorithm is based on an optimization model which does not address the circuit voltage and current overload constraints. These constraints may be checked using power flow analysis, but Huddleston's method involves simultaneous multiple switch pair operations, and it is difficult to determine which switch pair operation has violated the constraints.

Huddleston's algorithm did consider voltage dependency of loads in the system model but did not report on their effects.

2.1.3 Lee's Algorithms

Lee derived global optimality conditions for the loss minimization problem and proposed two algorithms referred to as A1 and A2: A1 is based on a uniformly distributed load model (UDLM) and A2 can be applied to both a uniformly distributed load model and to a concentrated load model (CLM). Brief descriptions of these two algorithms are presented next.

2.1.3.1 Algorithm A1:

Algorithm A1 may be run on a system with multiple feeder-pairs and it intends to find the optimum switch position vector $\underline{x}$ by focusing on one feeder-pair at a time. For every feeder-pair, the minimum loss switch position is obtained by minimizing a piece-wise quadratic function. The feeder-pairs are iterated until no loss reduction can be achieved in any feeder-pair. Consider the feeder-pair system shown in Figure 2.1.3.1.1. Note that the open switch can be located only on the direct path (DP) from Feeder F1 to Feeder F2 through switch S. A section of the feeder between two switches is referred to as a "zone". Let x represent the distance of the switch position in the feeder-pair with

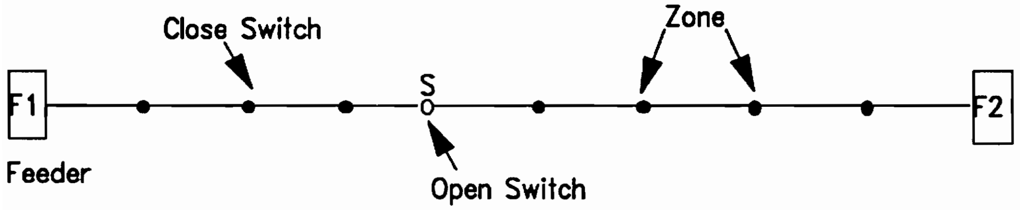

Figure 2.1.3.1.1. Configuration of a Feeder-Pair.

respect to the beginning of the feeder ($0<x<\Sigma l_{zk}$), where l_{zk} represents the length of zone k. Then, the loss function $h_T(x)$ of a feeder-pair is given by,

$$h_T(x) = h_i\left(x - \sum_{j=1}^{i-1} l_{zj} \right) \quad \text{for} \sum_{k=1}^{i-1} l_{zk} \leq x \leq \sum_{k=1}^{i} l_{zk} \qquad [2.1.3.1.1]$$

The loss function $h_i(t)$ where $0 \leq t \leq l_{zi}$ for each feeder-pair has a quadratic form [10], given by

$$h_i(t) = at^2 + bt + c_1 + c_2 \qquad [2.1.3.1.2]$$

where,

$$a = (s_i/l_{zi})^2 \sum_{k\varepsilon D} r_{zk} \qquad [2.1.3.1.3]$$

$$b = \left[\sum_{k\varepsilon D_1} r_{zk} (2J_k - s_k) - \sum_{k\varepsilon D_2} r_{zk} (2J_k - s_k)\right] (s_i/l_{zk}) \qquad [2.1.3.1.4]$$

$$c_1 = \sum_{k\varepsilon D} (J_k^2 - s_k J_k + s_k^2/3)\, r_{zk} \qquad [2.1.3.1.5]$$

c_2 = constant losses due to branches

D_1 = set of zones on DP from F1 to zone (i-1)

D_2 = set of zones on DP from F2 to zone i

D = set of zones on DP

J_k = total current flowing through zone k assuming t=0

s_k = load current of zone k

The objective is to minimize $h_i(t)$. The minimum of $h_i(t)$ will occur at

$$t_m = \begin{cases} -b/2a & \text{if } 0 < -b/2a < l_{zk} \\ 0 & \text{if } -b/2a < 0 \\ l_{zi} & \text{if } -b/2a > l_{zi} \end{cases} \qquad [2.1.3.1.6]$$

If the $t_m = -b/2a$, then the minimum of $h_T(x)$ is obtained. Otherwise, the neighboring section with decreasing losses will be chosen and the process will be repeated.

This algorithm guarantees global optimality, but does not consider constraints of circuit voltage limits and current overloading. Also, this algorithm may recommend switch positions which may not be located at actual switch positions. Furthermore, algorithm A1 can be applied only on UDLM.

2.1.3.2 Algorithm A2:

Again, refer to a simple feeder-pair system shown in Figure 2.1.3.1.1. Algorithm A2 can be applied to both UDLM and CLM. For concentrated loads, A2 attempts to find a set of switches to be opened by focusing on the actual switch locations during a process referred to as "move process". This process comprises the repeated use of the following "switch move". For a given feeder-pair, the current position of the open switch is moved to its neighboring switch position if a loss reduction may result without causing any operating constraint violation. The final solution is obtained when no loss reduction can be made in any feeder-pair. The move which results in the largest loss reduction is carried out first. To select the largest loss reduction switch move, two equations for the estimation of loss change are developed in Reference 8. One for UDLM (DL_u) and the other for CLM (DL_c). These equations are shown below,

$$\Delta L_u = \sum_{i \varepsilon S_1} R_i I_m (2I_i - s_i - I_m) - \sum_{i \varepsilon S_2} R_i I_m (2I_i - s_i + I_m) \qquad [2.1.3.2.1]$$

$$\Delta L_c = \sum_{i \varepsilon S_1} R_i I_m (2I_i - I_m) - \sum_{i \varepsilon S_2} R_i I_m (2I_i + I_m) \qquad [2.1.3.2.2]$$

where,

S_1 = set of zones from F1 to S

S_2 = set of zones from F2 to S

I_m = load current of the zone to be transferred

I_i = maximum current of zone i before the move

R_i = resistance of zone i (ohms).

For the UDLM case this algorithm does not guarantee the global optimality.

Both of the above mentioned algorithms assume a fictitious feeder loading. Reference 8 recommends feeder load estimation for future work. Also, load voltage dependency is not considered in this work. To derive global optimality conditions, practical constraints such as circuit voltage limits and equipment current overloading are ignored. However, to check for these constraints within the algorithms, a power flow referred to as an "approximate power flow" is employed for a feeder-pair.

2.1.4 Glavitsch Methods

Two methods are proposed by H. Glavitsch, one deals with network topology optimization with security constraints and the other deals with switching as means of control in the power system [11, 12]. In Reference 11, it is shown that with the aid of a method similar to linear programming, objective functions which incorporate line current, short circuit current, or losses can be formulated. By means of switching sequences consisting of elementary switching operations the desired objective function will be brought to its optimum value. Reference 12 shows an approach to modelling the switching opertaion which includes an explanation of the objective, constraints, and search techniques involved. Both of the above methods are based on network topology rather than radial topology.

CHAPTER 3

Database and Data Structures

A database may be defined as a large, organized collection of information that is accessed via software and is an integral part of a system function [13]. The reconfiguration algorithm is part of an integrated software package which is developed to model and simulate electric power distribution systems. The database is used to store and organize the data. Main aspects which are considered regarding database design are as follows:

1) define the information to be contained by the database,
2) types of queries to be submitted for processing,
and 3) the capacity of the database.

A data structure may be defined as a collection of one or more variables, possibly of different types, grouped together under a single name for convenient handling [14]. The data structures help to organize complicated data operations because they permit the treating of a number of variables as a unit instead of as separate entities. The reconfiguration algorithm utilizes data structures to simplify the implementation of computer code. The data from the database is brought into computer memory and stored into data structures.

3.1 Database Tables

The information in the database is stored in the form of tables. Furthermore, each table may be divided into one or more columns. The equipment utilized to build a distribution system are referred to here as electrical components or just components. Examples of such components are line sections, transformers, breakers, and protective devices. For the reconfiguration algorithm, the information pertinent to components and feeder loads in the electric power distribution system is stored in database tables. This section describes the database tables which are used in storing the data for the algorithm.

There are eleven database tables that are used by the reconfiguration algorithm. The names of these tables are listed in Table 3.1.1. Tables 1 and 2 are referred to as "ENGINEERING" tables because they store engineering data related to circuits and components. Tables 3 - 7 are referred to as "PARTS" tables because they store component specifications such as ratings, codes, types, etc. These PARTS tables comprise a library of tables called the "PARTS LIBRARY". Tables 8 and 9 are used to supply inputs needed by the reconfiguration algorithm. They store diversified customer loads and circuit measurements values, respectively. Tables 10 and 11 are referred to as "RECONFIGURATION OUTPUT" tables.

These eleven database tables are now described in detail. The variable names along with their definitions are also mentioned for each table.

3.1.1 Circuit Table

An electrical distribution system may be comprised of several circuits. The information related to these circuits is stored in the Circuit Table. Each row in the table contains information concerning a single circuit. The data

Table 3.1.1 List of Database Tables Used by the Reconfiguration Algorithm

Number	Table Name
1	Circuit Table
2	Component Table
3	Substation Table
4	Transformer Table
5	Capacitor Table
6	Controller Table
7	Line Imedance Table
8	Customer Load Table
9	Circuit Measurements Table
10	Switching Configuration Table
11	Operations Table

items in the Circuit Table pertinent to the reconfiguration algorithm are given in Table 3.1.1.1.

3.1.2 Components Table

Each circuit in the distribution system contains several electrical components. The Components Table contains information relevent to each component in the circuit. This table stores engineering, topological, and graphical data for each component in the system [15]. The information is stored when the circuit is built graphically. Table 3.1.2.1 shows data items in the Components Table relevent to the reconfiguration algorithm.

The following five tables are used by the power flow algorithm. Power flow is one of the major functions called by reconfiguration.

3.1.3 Substation Table

This table is a member of the PARTS LIBRARY and is used to store specifications regarding sources. The source specification includes Source Code, Source Order, Source Type, Primary side voltage, Customer side voltage, etc. Table 3.1.3.1 shows the data items in the Substation Table which are used by power flow algorithm.

3.1.4 Transformer Table

This table is one of the PARTS tables. The Transformer Table is used to store data such as winding impedances, KVA ratings, and voltage ratings. The Transformer Table includes data items described in Table 3.1.4.1.

3.1.5 Capacitor Table

The Capacitor Table is also a member of the PARTS LIBRARY. This table stores information pertinent to fixed or switched capacitors. Data items shown in Table 3.1.5.1 are stored in the Capacitor Table.

Table 3.1.1.1 Description of Data Items in Circuit Table

Data Item	Description
Circuit Name	user specified name for circuit
Circuit Number	user specified number associated with each circuit
Circuit Order	order in which the circuit is built graphically
Num_Of_Cmps	total number of components in a circuit
Q_Ckt_Analy	indicate whether circuit needs to be analyzed or not
cus[c][p]	number of customers based on customer type and phase in a circuit
Vol_Dep_Fac	circuit's voltage dependency factor defined as the fractional change in load amps per volt
Load_Scal[c]	customer type based load scaling factor
kw_Loss_Fac	loss factor to account for kilowatt losses in the circuit
kvr_Loss_Fac	loss factor to account for kilovar losses in the circuit

Table 3.1.2.1 Description of Data Items in Components Table

Data Item	Description
Tra_Ord	order in which component appears in the circuit
Component Code	user specified code for the component
Component Type	Character indicator associated with specific component type such as line sections, transformers, capacitors, etc.
Type Number	number associated with specific component type such as line section, transformer, capacitor, switch, etc.
Order	order in PARTS linked list for component
Forward Comp	first component encountered in forward trace
Back Comp	first component encountered in backward trace
FDP_Comp	feeder path component encountered during feeder path trace
Phase	phases that are present
Fdrlngth	distance of the component from the substation in miles
Cmplngth	component length in miles
Adj_Ckt	number of the circuit adjacent to that component

Table 3.1.2.1 Description of Data Items in Components Table Continued

Data Item	Description
kw_load[c][p]	component's kilowatt load based on customer type and phase
kvr_load[c][p]	component's kilovar load based on customer type and phase
spot_kw[p]	constant kilowatt load based on phase
spot kvr[p]	constant kilovar load based on phase
tap[p]	transformer tap based on phase
cus[c][p]	number of customers based on customer type and phase

Table 3.1.3.1 Description of Data Items in Substation Table

Data Item	Description
Source_Code	user specified code
Source_type	substation or cogenerator
Source_Ord	order in which source or cogenerator appears in linked list
Pri_Kv_Mag	primary side voltage magnitude in kilovolts
Cust_Vol	customer side voltage in volts
Phase_A_Ang	phase A voltage angle in degrees
Phase_B_Ang	phase B voltage angle in degrees
Phase_C_Ang	phase C voltage angle in degrees

Table 3.1.4.1 Description of Data Items in Transformer Table

Data Item	Description
Transformer_Code	user specified code for transformer
Transformer_Type	regulating transformer or fixed transformer
Transformer_Ord	order in which transformer appears in the linked list.
Tran_Pri_Vol	primary side voltage rating
Tran_Sec_Vol	secondary side voltage rating
Tran_KVA_Rating	KVA rating

Table 3.1.5.1 Description of Data Items in Capacitor Table

Data Item	Description
Capacitor_Code	user specified code
Capacitor_Type	switched capacitor or fixed capacitor
Capacitor_Ord	order in which capacitor appears in linked list.
Nominal Kvar	nominal kvar value

3.1.6 Controller Table

The information stored in this table is used to implement control actions in order to control voltage or power factor at a specific point in the circuit. Various columns in the Controller Table are described in Table 3.1.6.1.

3.1.7 Line Impedance Table

The Line Impedance Table stores impedances for line sections or cables existing in the PARTS LIBRARY. This Table stores self and mutual impedances. The data items stored in this table are described in Table 3.1.7.1.

If customer type load modeling is used, then the following two database tables are also utilized by the algorithm.

3.1.8 Customer Loads Table

The information in the Customer Loads Table is used in feeder load estimation. This table stores information associated with the diversified load curves based on customer type. The information on diversified load curves is obtained from load research. The data items stored in the Customer Loads Table are shown in Table 3.1.8.1.

3.1.9 Circuit Measurements Table

The Circuit Measurements Table stores of power factor and kilowatt measurements at the substation. This information is used in conjunction with the diversified load curves to estimate feeder loads. The data items in the Circuit Measurements Table are described in Table 3.1.9.1.

Table 3.1.6.1 Description of Data Items in Controllers Table

Data Item	Description
Controller_Code	user specified code for the controller
Controller_Type	switched capacitor, regulating transformer, or voltage regulator
Controller_Ord	order in which controller appears in linked list.
Cont_Variable	controlled variable
Tap Setting	transformer's tap or capacitor's kvar setting
Step Size	steps by which tap or kvar would increase or decrease
Minimum Setting	minimum setting of tap
Maximum Setting	maximum setting of tap

Table 3.1.7.1 Description of Data Items in Line Impedance Table

Data Item	Description
Line_Code	user specified line section or cable code
Line_Type	line type (i.e. line section or cable)
Line_Ord	order in which record appears in linked list.
ZR[3][3]	three by three reduced impedance matrix in which ground and neutral impedances have been eliminated
ZP[5][5]	five by five impedance matrix which includes the neutral and ground return paths

Table 3.1.8.1 Description of Data Items in Customer Loads Table

Data Item	Description
Customer_Type	indicates residential, commercial, or industrial customer type
Customer_Class	for each load point twelve customer classes are included, such as residential with water heater, small commercial, etc.
Season	summer, fall/spring, or winter
Type Of Day	weekday, weekend, or holiday
KW[hod]	array of twenty-four kilowatt values corresponding to each hour of the day hod = 1, 2, .., 24
Power Factor	power factor of circuit

Table 3.1.9.1 Description of Data Items in Circuit Measurements Table

Data Item	Description
Circuit_Name	user specified circuit name
Circuit_Number	user specified integer associated with the circuit
Circuit_Ord	order in linked list of circuits
Season	summer, fall/spring, or winter
Type Of Day	weekday, weekend, or holiday
KW[hod][p]	kilowatt value based on the phase for each hour of day, hod = 1, 2,.., 24, p = A, B, C
Pow_Fac[hod][p]	power factor value based on the phase for each hour of day hod = 1, 2, .., 24, p = A, B, C

The output of the algorithm is stored in the following two database tables referred to as "RECONFIGURATION OUTPUT" tables. The result stored in these tables are used to highlight switches for user selected time points.

3.1.10 Switching Configuration Table

The distribution system is reconfigured by operating switches. This table stores the switch status for all the switches in the system corresponding to each system configuration. A given set of switch statuses is only stored once and is given a unique configuration identification. Up to two-hundred and fifty switch statuses can be stored in the table. The Switching Configuration Table includes the data items described in Table 3.1.10.1.

3.1.11 Operations Table

This table is comprised of two-hundred and seventeen records which correspond to two-hundred and sixteen time points plus one. Each of these two-hundred and seventeen records represents a particular system configuration. Out of these two-hundred and seventeen records, two-hundred and sixteen correspond to the twenty-four hours of day, three types of day, and three seasons (fall and spring seasons are lumped together), whereas one corresponds to the base case system configuration (i.e. the configuration of the system prior to any switching operation). A non-unique configuration identification number is associated with each time point. After the reconfiguration analysis, the configuration identification numbers are set to correspond to switching patterns in the Switching Configuration Table. The Operations Table includes the data items shown in Table 3.1.11.1.

Table 3.1.10.1 Description of Data Items in the Switching Configuration Table

Data Item	Description
Configuration_ID	dentification number associated with each system configuration
Switch Status	indicates whether switch is open or closed

Table 3.1.11.1 Description of Data Items in Operations Table

Data Item	Description
Hour Of Day	hours of day from 12 midnight to 11 p.m.
Type Of Day	weekday, weekend, or a holiday
Season	summer, fall/spring, or winter
Configuration_ID	system configuration identification number
Kwh_loss	kilowatt hour loss for system

3.2 Data Structures

The reconfiguration algorithm does not have access to the database tables directly. The information in the database tables is brought into computer memory by database access algorithms. This information is stored in memory in the form of linked lists of data structures. These lists are a chain of data structures linked together using pointers and are available to the algorithm. Pointers are one of the most sophisticated features of the C programming language. A pointer provides an indirect means of accessing the value of a particular data item [16]. Figure 3.2.1 illustrates an example of a linked list of data structures. It is illustrated in Figure 3.2.1 that a linked list has a starting pointer and is terminated by NULL. Table 3.2.1 shows the correspondence between database tables and data structures used by the reconfiguration algorithm. It should be noted that data items in database tables and data structures do not have a one-to-one correspondence. In the following, the data structures used to implement the reconfiguration algorithm are described. It should be noted that the reader may not necessarily understand all data items, but they are described in detail in later chapters.

3.2.1. Circuit Data Structure

The Circuit Data Structure is defined for every circuit in the system. This data structure stores items pertinent to a specific circuit. Some prominent data items in the Circuit Data Structure are Circuit Order, Circuit Name, Circuit kilowatt Peak, and Circuit Voltage Dependency Factor. Table 3.2.1.1 illustrates the definition of data items in the Circuit Data Structure which are relevant to the reconfiguration algorithm. If there are several circuits in the system, then there is a linked list of Circuit Data Structures, where each data structure contains information about a single circuit in the system. This

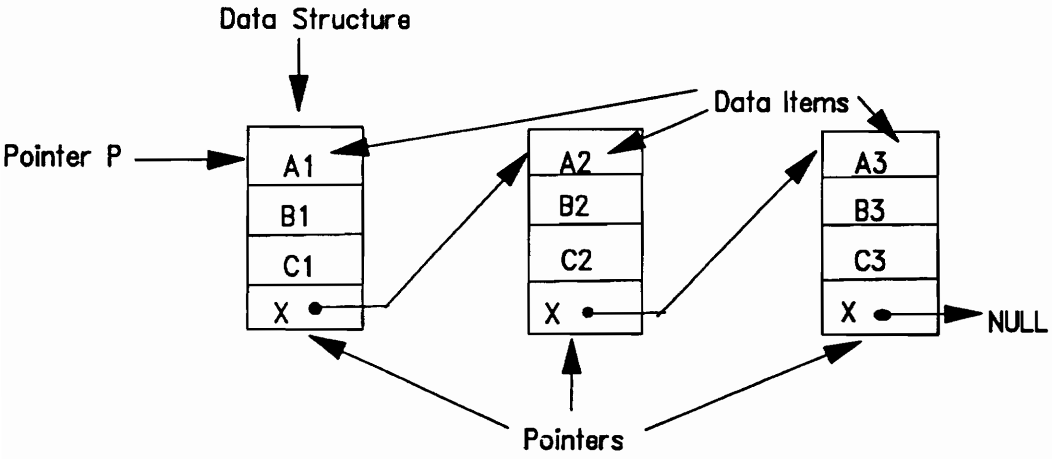

Figure 3.2.1 An Example of a Singly Linked List of Data Structures

Table 3.2.1 Correspondence Between Database Tables and Data Structures

Database Tables	Data Structures
Circuits	Circuit
Components	Component Trace
Substation	Source
Transformer	Transformer
Capacitor	Capacitor
Controller	Controller
Line Impedance	Line Impedance
Customer Load	Customer Diversified Load
Circuit Measurements	Circuit Measurements
Switching Configuration	Switch Configuration
Operations	Operations
-	No_Movement
-	System_Configuration
-	Systems

Table 3.2.1.1 Description of Data Items in Circuit Data Structure

Data Item	Description
ckt_nam	circuit name
ckt_num	circuit number
ckt_ord	order in which the circuit appears in the linked list
num_cmps	total number of components in the circuit
q_ckt_analy	variable used to indicate whether circuit needs to be analyzed or not
cus[j][p]	number of customers attached to a load point in the circuit based on customer type and phase
load_scal[j]	load scaling factor based on customer type
loss_factor[2]	loss factor to account for real and reactive losses in feeder measurements
cvol	circuit voltage dependency factor
year	year for estimated load
sea	season for estimated load (0 = summer, 1 = winter, and 2 = fall)
hod	hour of day for estimated loads (ranges from 0 to 23)
tyd	type of day for estimated loads (0 = weekday, 1 = weekend, and 2 = holiday)
kw_loss	kilowatt losses in circuit corresponding to year, season, type of day, and hour of day

Table 3.2.1.1 Description of Data Items in Circuit Data Structure Continued

Data Item	Description
swt_amps[6]	switching current in amps
sqr[6]	coefficients of square terms in loss function
mut[6][6]	coefficients of mutual terms in loss function
lin[6]	coefficients of linear terms in loss function
circuit_peak	circuit kilowatt peak
year_for_peak	year for circuit peak
season_for_peak	season for circuit peak
type_of_day_peak	type of day for circuit peak
hour_of_day_peak	hour of day for circuit peak
limit	variable used to indicate that voltage or current constraints have been violated
*sckt	pointer which is pointing to the first component present in the linked list of Component Trace Data Structures for a particular circuit
*eckt	pointer which is pointing to the last component present in the linked list of Component Trace Data Structures for a particular circuit
*ptr_ckts	pointer which is pointing to the next Circuit Data Structure in linked list

data structure also contains a pointer which is pointing to the first component present in the linked list of Component Trace Data Structures, which is decribed next, for that particular circuit.

3.2.2. Component Trace Data Structure

This data structure contains engineering, topological, and graphical data for each component. In addition to that it also stores the output of analysis programs such as power flow analysis, fault analysis, and reliability analysis. There are many components in a circuit and each component is represented by a Component Trace Data Structure. Thus, several such data structures are linked together to form a list of components in a circuit. This linked list of Component Trace Data Structures are formed using pointers. Figure 3.2.2.1 gives a pictorial view of the relationship between the Circuit and the Component Trace Data Structures.

The Component Trace Data Structure includes data items such as Component Order, Component Type, Component Code, Circuit Order, Feeder Type, Voltages, Currents, Power Flow, etc. The data items in this data structure relevent to the reconfiguration algorithm are defined in Table 3.2.2.1.

3.2.3 Source Data Structure

This data structure obtains the information from the Substation Table which is a member of the PARTS LIBRARY. If there is more than one source in the Substation Table, then there is a linked list of the Source Data Structures. Some of the prominent data items are Source Code, Source Type, Primary Kilovolts Magnitude, Customer Voltage, etc. Table 3.2.3.1 shows the data items in this data structure.

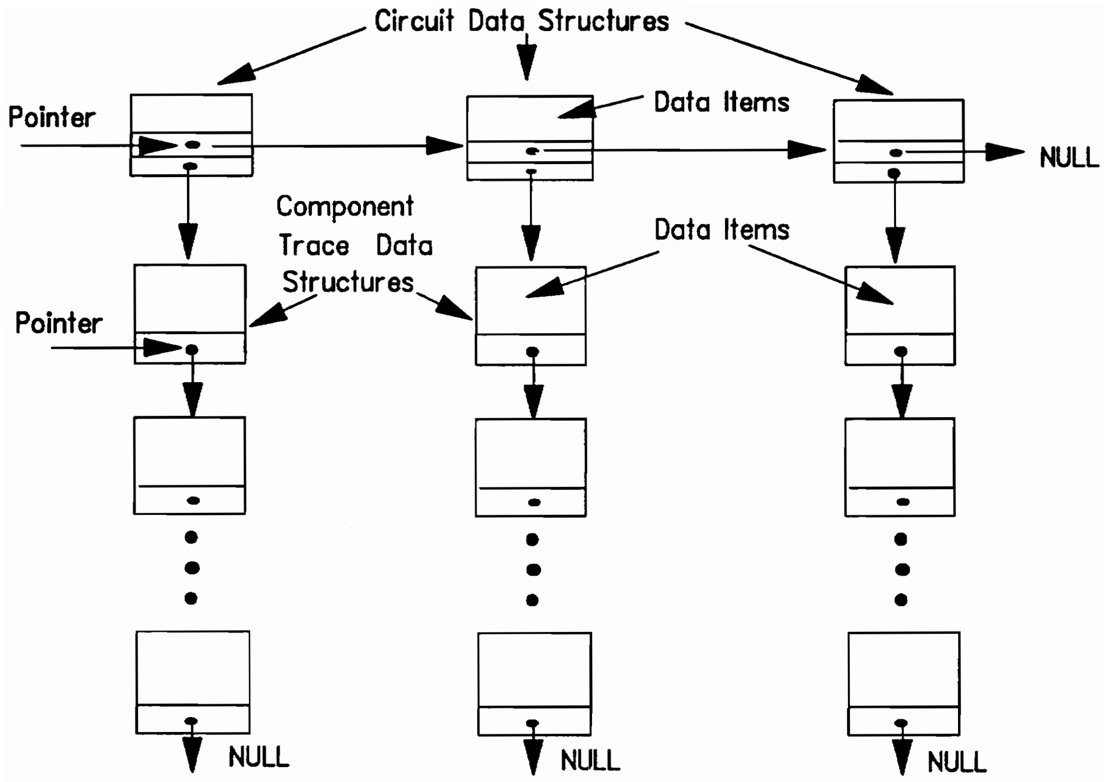

Figure 3.2.2.1 Pictorial View of Relationship Between Circuit and Component Trace Data Structures

Table 3.2.2.1 Description of Data Items in Component Trace Data Structure

Data Item	Description
tra_ord	order in which component appears in circuit
cmp_type	character description of component type (i.e. line section, transformer, breaker, etc)
type_num	code number associated with component type
ckt_ord	order of the circuit as it appears in linked list of Circuit Data Structures
enodedeg	variable used to indicate number of branches attached to a specific node
adj_ckt	circuit number for the circuit which is physically adjacent to the circuit under study. (The two circuits are separated by an open switch)
adj_cmp	number of the component in the adjacent circuit which is connected to the circuit under study via an open switch
f_cmp	forward component
b_cmp	backward component
fdp_cmp	feeder path component
*f_ptr	pointer which is pointing to the forward component
*b_ptr	pointer which is pointing to the backward component
*fdp_ptr	pointer which is pointing to the feeder path component
cmp_code	code assigned to each component

Table 3.2.2.1 Description of Data Items in Component Trace Data Structure Continued

Data Item	Description
ord	order in which component appears in linked list associated with the PARTS LIBRARY
phase	phase present (0 = A, 1 = B, and 2 = C)
fdrlngth	distance between component and the source (in miles)
cmplngth	component length (in miles)
tap_cmp	component that tap is associated with
tap[p]	transformer or capacitor tap for phase p
nom_kw[p]	kw value calculated at nominal voltage for each phase (includes both spot and customer loads)
nom_kvar[p]	kvar value calculated at nominal voltage for each phase (includes both spot and customer loads)
spot_kw[P]	constant kw load attached at a load point for each phase
spot_kvar[p]	constant kvar load attached at a load point for each phase
sp_pf	single phase power factor
tp_pf	three phase power factor
cus[j][p]	number of customers attched to a load point based on customer class and phase
cus_class[p]	customer classification based on phase

Table 3.2.2.1 Description of Data Items in Component Trace Data Structure Continued

Data Item	Description
limit	variable used to indicate whether constraints are violated at a component
message	set to 1 if message needs to be displayed
compath	common power flow path for two laterals
volts[p]	voltage at a load point for phase present
amps[p]	current through a component for each phase
pvolts[p]	voltage at a load point in polar form
pamps[p]	current through a component in polar form
nom_pvolts[p]	nominal current value in polar form
z[3][3]	3x3 impedance matrix
nom_load_amps[p]	nominal load amps for phase p
load_gen_amps[p]	either load or cogenerator amps
min_setpoint	minimum set point for controller
max_setpoint	maximum set point for controller
min_cont_setting	minimum controller setting
max_cont_setting	maximum controller setting
tap_step_size	step size used for tap increment or decrement
tap_sign[p]	used to indicate change in direction in controller motion

Table 3.2.2.1 Description of Data Items in Component Trace Data Structure Continued

Data Item	Description
controller_move	used to indicate controller movement
amps_index	index associated with segment currents
losses[p]	component losses for each phase
swt_amps_ckt1	switching current value in the circuit under study

Table 3.2.3.1 Description of Data Items in Source Data Structure

Data Item	Description
Source_Code	user specified code
Source_type	substation or cogenerator
Source_Ord	order in which source or cogenerator appears in the Substation Table
Pri_Kv_Mag	primary side voltage magnitude in kilovolts
Cust_Vol	customer side voltage in volts
Phase_Ang[p]	phases A, B, and C voltage angle in degrees
*ptr_sour	pointer which points to the next data structure of type Source in the linked list

3.2.4 Transformer Data Structure

This data structure acquires the information from the Transformer Table which is a member of the PARTS LIBRARY. There is a linked list of Transformer Data Structures if there is more than one transformer in the Transformer Table. Some important data items are Primary Voltage, Secondary Voltage, Kva Rating, and Winding Impedance. The data items in the Transformer Data Structure are shown in Table 3.2.4.1.

3.2.5 Capacitor Data Structure

The Capacitor Data Structure stores information regarding switched or fixed capacitors. The information in this data structure is derived from the Capacitor Table. If there is more than one capacitor in the Capacitor Table, then a linked list of Capacitor Data Structures is formed. Table 3.2.5.1 shows the definition of data items in the Capacitor Data Strcuture.

3.2.6 Controller Data Structure

This data structure stores information regarding controllers present in the PARTS LIBRARY. A linked list of Controller Data Structures is also defined which is comprised of various types of controllers. Some of the data items pertinent to the reconfiguration algorithm are controller code, controller type, controller order, etc. Table 3.2.6.1 shows the definition of data items in this data structure.

3.2.7 Line Impedance Data Structure

The Line Impedance Data Structure obtains the information regarding line sections and cables from the Line Impedance Table which is a member of the PARTS LIBRARY. If there are several types of lines present in Line Impedance Table, then there is a linked list of Line Data Structures. Some of the prominent data items are line code, line type, amps rating, and line impedance matrices. Table 3.2.7.1 illustrates

Table 3.2.4.1 Description of Data Items in Transformer Data Structure

Data Item	Description
Transformer_Code	user specified code for transformer
Transformer_Type	regulating transformer or fixed transformer
Transformer_Ord	order in which transformer appears in linked list
Pri_Vol	primary side voltage rating
Sec_Vol	secondary side voltage rating
KVA_Rating	KVA rating
Z	winding impedance
*ptr_xform	pointer which points to the next data structure of type Transformer in the linked list

Table 3.2.5.1 Description of Data Items in Capacitor Data Structure

Data Item	Description
Capacitor Code	user specified code
Capacitor Type	switched capacitor or fixed capacitor
Capacitor_Ord	order in which capacitor appears in the linked list
Nominal Kvar	nominal kvar value
Vol_Rating	voltage rating in volts
*ptr_caps	pointer which points to the next data structure of type Capacitor

Table 3.2.6.1 Description of Data Items in Controllers Data Structure

Data Item	Description
Controller_Code	user specified code for the controller
Controller_Ord	order in which controller appears in the linked list
Controller_Type	switched capacitor, regulating transformer, or voltage regulator
min_cont_set	minimum controller setting in terms of transformer tap or capacitor kvar injection
max_cont_set	maximum controller setting in terms of transformer tap or capacitor kvar injection
Step Size	steps by which tap or kvar may increase or decrease
Min_Setpoint	minimum setting in terms of voltage or power factor
Max Setpoint	maximum setting in terms of voltage or power factor
*ptr_cont	pointer to the next data structure of type Controller in the linked list

Table 3.2.7.1 Description of Data Items in Line Impedance Data Structure

Data Item	Description
Line_Code	user specified line section or cable code
Line_Type	line type (i.e. line section or cable)
Line_Ord	order in which record appears in the linked list
Amps Rating[2]	summer or winter amps rating
ZR[3][3]	three by three reduced impedance matrix in which ground and neutral impedances have been eliminated
*ptr_lines	pointer which points to the next data structure of type Line Impedance in the linked list

the definition of data items in the Line Impedance Data Structure.

3.2.8 Customer Diversified Load Data Structure

The Customer Diversified Load Data Structure stores the diversified load curve values based on customer class. These values are used in conjunction with circuit measurements in order to estimate the feeder loads. The definition of data items in the Customer Diversified Load Data Structure is shown in Table 3.2.8.1

3.2.9 Circuit Measurements Data Structure

The Circuit Measurements Data Structure contains information about the circuit's power factor and kilowatt measurements. Some of the major data items are Circuit Name, Circuit Order, Season, Type Of Day, Hour Of Day, Kilowatt, and Power Factor. Table 3.2.9.1 shows the definitions of the data items in the Circuit Measurements Data Structure.

3.2.10 Switch Configuration Data Structure

This is one of the output data structures used by the reconfiguration algorithm. The Switch Configuration Data Structure stores switch status (i.e. open or closed) for each switch in the system. It can store up to two-hundred and fifty switch statuses for each system configuration. An identification number is assigned to each system configuration. A given set of switch statuses is only stored once. The definition of the data items in the Switch Configuration Data Structure is shown in Table 3.2.10.1.

3.2.11 Operations Data Structure

The Operations Data Structure serves as one of the output data structures. This data structure stores season, type of day, hour of day, and configuration identification number. This structure also stores the kilowatt loss for that particular system configuration. Table 3.2.11.1 illustrates the definition of data items in the Operations Data Structure.

Table 3.2.8.1 Description of Data Items in Customer Diversified Load Data Structure

Data Item	Description
cus_type	0 = residential, 1 = commercial, 2 = industrial
cus_class	customer classification such as customers with water heaters or customers with air conditioners
ord	order in which record appears in the linked list of Customer Diversified Load Data Structures
sea	season (0 = summer, 1 = winter, and 2 = fall/spring)
tyd	type of day (0 = weekday, 1 = weekend, and 2 = holiday)
peak_kw[sea][tyd]	customer class based peak kw value, a function of season and type of day
nor_kw[sea][tyd][hod]	diversified kw customer load based on season, type of day, and hour of day
pow_fac[sea][tyd]	customer type based power factor, a function of season and type of day
des[51]	description of customer load
*ptr_load	pointer to the next data structure of type Customer Diversified Load in the linked list

Table 3.2.9.1 Description of Data Items in the Circuit Measurements Data Structure

Data Item	Definition
ckt_nam	circuit name
ckt_num	circuit number
ckt_ord	order in which circuit appears in the linked list of the Circuit Data Structures
sea	season (0 = summer, 1 = winter, and 2 = fall/spring)
tyd	type of day (0 = weekday, 1 = weekend, and 2 = holiday)
conf_id	configuration identification
kw[p][sea][tyd][24]	measured kilowatt value based on phase, season, type of day, and hour of day
pf[p][sea][tyd][hod]	measured power factor value based on phase, season, type of day, and hour of day
*ptr_ckt_mea	pointer to the next data structure of type Circuit Measurements in the linked list

Table 3.2.10.1 Description of Data Items in Switch Configuration Data Structure

Data Item	Description
conf_id	system configuration identification
swt_status[250]	switch status, open or closed
*ptr_swt_conf	pointer to the next data structure of type Switch Configuration in the linked list

Table 3.2.11.1 Description of Data Items in Operations Data Structure

Data Item	Description
sea	season (0 = summer, 1 = winter, and 2= fall/spring)
tyd	type of day (0 = weekday, 1 = weekend, and 2 = holiday)
hod	hour of day (ranges from 0 = 12 midnight, ..., 23 = 11 p.m.
conf_id	configuration identification
kw_loss	system kw loss for particular system configuration
*ptr_oper	pointer to the next data structure of type Operations in the linked list

3.2.12 No_Movement Data Structure

The No_Movement Data Structure contains two pointers. One pointer is pointing to an open switch which is tagged as not being available in future iterations because the operation of this open switch has caused system constraints to be violated. The other pointer is used to point to the next data structure of type No_Movement. Table 3.2.12.1 shows the definition of data items in the No_Movement Data Structure.

3.2.13 System Configuration Data Structure

The System Configuration Data Structure stores the system kilowatt loss referred to as the "loss model" for various configurations of the distribution system. It also contains three pointers with the first pointer pointing to a switch to be closed, the second pointer pointing to a switch to be opened, and the third pointer is used to make a linked list of System_Configuration Data Structures. All the data structures in the linked list are compared and the one with the maximum loss is selected and the corresponding switch pair operation is implemented. The definition of data items in this data structure is shown in Table 3.2.13.1.

3.2.14 System Data Structure

The System Data Structure stores information relevent to system peak loading. Some of the prominent data items in this data structure are System Peak, Year For Peak, Peak Hour Of Day, Peak Type Of Day, Peak Season. Table 3.2.14.1 shows the definition of data items in the System Data Structure.

Table 3.2.12.1 Description of Data Items in No_Movement Data Structure

Data Item	Description
*ptr_swt_clos	pointer to the open switch that is tagged as not being available for future iterations
*ptr_no_move	pointer to next data structure of type No_Movement in the linked list

Table 3.2.13.1 Description of Data Items in System Configuration Data Structure

Data Item	Description
loss_mod	kw loss corresponding to a single system configuration and referred to as loss model because of its use in the evaluation of loss functions
*ptr_swt_to_op	pointer to switch to be opened
*ptr_swt_to_cl	pointer to switch to be closed
*ptr_system_con	pointer used to make a linked list of System Configuration Data Structures

Table 3.2.14.1 Description of Data Items in System Data Structure

Data Item	Description
con_tot_kwhr_loss[s]	total kwhr loss summed over all time points after convergence for system type s
s_it_to_kwhr_loss[s]	total kwhr loss over all time points at the first iteration for system type s
con_sav_kwhr_loss[s]	kwhr loss for current time point at convergence for system type s
s_It_sav_kwhr_loss[s]	kwhr loss for current time point at first iteration for system type s
con_sys_peak[s]	kw peak of system over all time points at convergence for system type s
st_it_sys_peak[s]	kw peak of system over all time points at first iteration for system type s
con_cu_it_sys_peak[s]	system peak in kw for current time point at convergence for system type s
s_it_cur_sys_peak[s]	system peak in kw for current time point at first iteration for system type s
loss_at_peak[s]	kw losses of system at peak for system type s
year_for_peak	year for peak

Table 3.2.14.1 Description of Data Items in System Data Structure

Continue

Data Item	Description
season_for_peak	season for peak
type_of_day_peak	type of day for peak
hour_of_day_peak	hour of day for peak
num_tim_points	number of time points analyzed

CHAPTER 4

Feeder Load Estimates

Results from the reconfiguration algorithm are dependent upon good estimates of time varying loads. The reconfiguration algorithm determines switching patterns versus time over time varying loads. These time varying loads and estimation of loading conditions are discussed here. If available, the algorithm is designed to work with circuit measurements, a customer information system interface (i.e. number and type of customers), and diversified customer load curves. If this information is unavailable, then constant loads, referred to as spot loads, may be used for circuit loading. The diversified curves are developed from load research experiments, such as the Athen's automation experiments [6]. The information flow for estimation of the loading conditions is illustrated in Figure 4.1.

4.1 Time Varying Loads and Estimation of Loading Conditions

The variations in overall system loading are due to fluctuations in circuit loading. One circuit may be peaking while another circuit is at a relatively low load condition. Fluctuations in an individual circuit's load is a function of the various customer types served by the circuit. Three types of loads, or customers, modeled here are residential, commercial, and industrial. Diversified load characteristics of these three

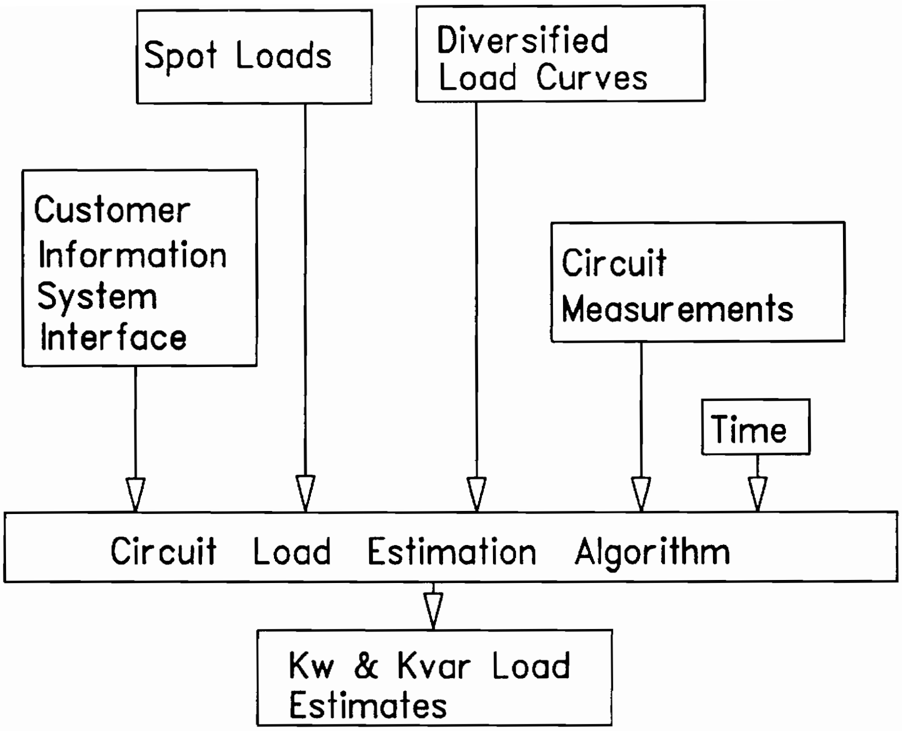

Figure 4.1. Information Flow Diagram for Circuit Load Estimation.

customer types are used in modeling time varying loading conditions. A load growth factor is also incorporated in the algorithm (i.e. loads are updated for future years by multiplying by a customer type dependent scaling factor). These updated loads are then utilized to study the affect of reconfiguration on future planning.

Load profile patterns fluctuate based on both daily and seasonal conditions. Here load variations are considered to be a function of hour of day, type of day, and season. Thus, circuit powers and power factors are a function of the time of day, type of day, and season. In this study twenty-four times of day, three types of days, and three seasons are considered. Typically, diversified customer load profiles for fall and spring seasons are alike; hence, out of these two seasons, only the diversified customer load curve for the fall season is considered in the present research. Figure 4.1.1 illustrates hour of day, type of days, and seasons considered for a total of two-hundred and sixteen time points. It is assumed that power factors of an individual customer type remain constant throughout the day for a given type of day. Therefore, they are considered to be a function of the type of day and season. The following quantities define the feeder KW measurements for a circuit as a five dimensional array, circuit power factor as a five dimensional array, and customer power factor as a four dimensional array, respectively,

$P\_mea_{t,d,Se,p,c}$ = KW measurement at the substation for circuit c, phase p based on hour of day, type of day, and season

$PF\_mea_{t,d,Se,p,c}$ = power factor for circuit c phase p at the substation based on hour of day, type of day, and season,

$PFcus\_mea_{d,Se,j,p}$ = power factor for the customer type j, phase p based on type of day and season.

Hour of Day	Types of Day	Seasons
12 midnight	Weekdays	Summer
1 a.m.	Weekends	Winter
2 a.m.	Holidays	Fall
3 a.m.		
4 a.m.		
5 a.m.		
.		
.		
.		
11 p.m.		

Figure 4.1.1 Hour of Day, Types of Days, and Seasons Utilized in Load Modeling.

The time varying reactive load at a given substation for a circuit can be determined using the real load at that substation in conjunction with the circuit power factor. The reactive load is also considered as a function of hour of day, type of day, and season. The substation KVAR flows for a given circuit may be derived as follows:

$$\text{theta} = \cos^{-1}(PF\_mea_{t,d,Se,p,c}), \qquad [4.1.1]$$

$$Q\_mea_{t,d,Se,p,c} = P\_mea_{t,d,Se,p,c} * \tan(\text{theta}) \text{ kvar}, \qquad [4.1.2]$$

where,

theta = angle by which voltage leads current,

$Q\_mea_{t,d,Se,p,c}$ = KVAR calculated for circuit c, phase p based on hour of day, type of day, and season.

The diversified KW curves for residential, commercial, and industrial customer types is used to allocate substation measurements at modeled load points throughout the circuit. The number of customers for each customer type is given at each load point in the circuit. The diversified kw curves will be parameterized according to hour of day, type of day, and seasons. These time varying load curves for each customer type may be obtained by considering a sufficiently large sample of days (e.g. number of days in each season) and a large sample of measured customer load values. The KW values are then averaged for each customer type. In this work an hourly average will be used. Figure 4.1.2 shows an example of diversified load curves for the summer season and for the three customer types, where diversified KW values are plotted against hour of day. The type of days are assumed to be weekdays.

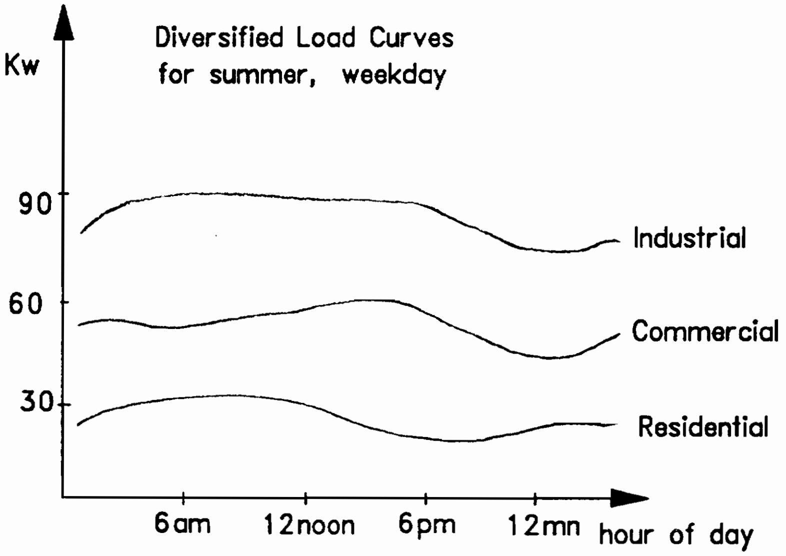

Figure 4.1.2. Diversified Load Curves for Residential, Commercial, and Industrial Type Customers for Summer Weekday.

The three customer types may be thought of as the three base components of the total system load. Thus, for a given hour of day the system's load is formed by summing the contributions of the three base components. It should be noted that the system peak may or may not occur simultaneously with any of the base component peaks.

The equations used to estimate line section loading from feeder measurements, the diversified load curves, the number of customers attached to the line section, real and reactive loss factors, and the load growth factors are now presented. The portion of the measured power allocated to customer type "j" is the ratio of total diversified load for customer type "j" to the total diversified load demand, which is independent of customer type, multiplied by the measured KW for circuit "c",

$$Pmcus_{j,p,c} = (Pdiv_{T,j,p} / Ptdiv_{T,p}) * P\_mea_{T,p,c}, \qquad [4.1.3]$$

where,

$Pmcus_{j,p,c}$ = portion of the measured KW at the substation allocated to customer type j for phase p and circuit c,

$Ptdiv_{T,p}$ = total diversified kw load based on hour of day, type of day, and season for phase p,

$Pdiv_{T,j,p}$ = diversified kw of customer class j based on hour of day, type of day, season and phase p,

The above equation is multiplied by the loss factor "Ploss" to account for KW losses that exists in the KW measured at the substation. Also, customer type based load growth factors are incorporated to update the loads for future years. Thus, Equation [4.1.3] can be written as

$$Pmloss_{j,p,k,c} = ls_{k,j} * Plos * Pmcus_{j,p,c} \qquad [4.1.4]$$

where,

$pmloss_{j,p,k,c}$ = portion of the measured KW allocated to customer type j for year k in circuit c,

$ls_{k,j}$ = load growth scaling factor for the kth year and for customer type j,

Plos = real loss factor, a function of circuit loading (to account for the real losses in the lines, assumed as less than 1)

Equation [4.1.4] is divided by the total number of customers of type j for phase p in circuit c to give the portion of the measured KW allocated to a single customer of type j. This is given by

$$Pms_{i,j,p,k,c} = (Pmloss_{j,p,k,c}) / tcus_{j,p,c} \qquad [4.1.5]$$

where,

$Pms_{i,j,p,k,c}$ = portion of the measured KW allocated to a single customer of type j at the ith load point for year k in phase p and circuit c,

$tcus_{j,p,c}$ = total number of customers of type j for phase p attached to circuit c,

Thus, the estimated KW load at the ith load point for each phase in circuit c and for customer type j based on hour of day, type of day, season, and year is obtained by multiplying Equation [4.1.5] by the number of customers for customer type j at the ith load point for each phase in circuit c based on time of day, type of day, and season. This is given by

$$P\_est_{i,j,p,T,k,c} = Pms_{i,j,p,k,c} * cus_{i,j,p,c} \quad [4.1.6]$$

where,

$P\_est_{i,j,p,T,k,c}$ = The KW estimate at the i^{th} load point for phase p for the j^{th} customer type based on hour of day, type of day, and season for the kth year and for circuit c,

$Pms_{i,j,p,k,c}$ = portion of the measured KW allocated to a single customer of type j at the i^{th} load point for year k in phase p and circuit c,

$cus_{i,j,p,c}$ = number of customers of type j for phase p at the i^{th} load point in circuit c.

Similarly, an expression for the reactive load estimate can be derived and written as

$$Q\_est_{i,j,p,T,k,c} = Qms_{i,j,p,k,c} * cus_{i,j,p,c} \quad [4.1.7]$$

where,

$Q\_est_{i,j,p,T,k,c}$ = KVAR estimate at the i^{th} load point for phase p for the j^{th} customer type based on hour of day, type of day, and season for the kth year and for circuit c,

$Qms_{i,j,p,\ k,c}$ = portion of the measured KVAR allocated to a single customer of type j at the i^{th} load point for year k in phase p and circuit c,

$cus_{i,j,p,c}$ = number of customers of type j for phase p at the i^{th} load point in circuit c.

Thus, for the given phase the generalized form of the real and reactive power estimates, utilizing the diversified kw values in conjunction with the circuit kw measurements at the i^{th} load point in a circuit for a particular hour of day, type of day, season, and year is obtained by summing over customers and adding in spot loads. This is given by

$$Ptest_{i,p,T,k,c} = \sum_{j=0}^{2} P\_est_{i,p,j,T,k,c} + Pspot_i \qquad [4.1.8]$$

$$Qtest_{i,p,T,k,c} = \sum_{j=0}^{2} Q\_est_{i,p,j,T,k,c} + Qspot_i \qquad [4.1.9]$$

Thus, for the given phase the complex power S at the i^{th} load point in the circuit for a particular hour of day, type of day, season and year is

$$S_{i,p,T,k,c} = Ptest_{i,p,T,k,c} + jQtest_{i,p,T,k,c} \qquad [4.1.10]$$

where,

$S_{i,p,T,k,c}$ = complex power at the i^{th} load point for phase p based on hour of day, type of day, season and year for circuit c,

$Ptest_{i,p,T,k,c}$ = real power estimate at the i^{th} load point for phase p based on hour of day, type of day, season and year for circuit c,

$Qtest_{i,p,T,k,c}$ = reactive power estimate at the i^{th} load point for phase p based on hour of day, type of day, season and year for circuit c,

$Pspot_i$ = constant kw at the i^{th} load point,

$Qspot_i$ = constant kvar at the i^{th} load point.

4.2 Example Problem

An example is presented to illustrate the estimation of loading conditions from the diversified load curves. For each customer type the actual KW per customer may be estimated using the measured circuit KW at the substation in conjunction with the diversified load curves. The measurement of the KW values in a circuit may be obtained by numerous ways. One way is by placing portable meters on the distribution feeders at the substation. The instantaneous measured KW values are then recorded. These measured KW values are distributed at the load points modeled throughout the circuit by using the diversified load values and number of customers by type at each load point. The loads are distributed such that they sum back to the measured KW values.

Sample diversified load profile patterns for residential, commercial, and industrial customer types based on fall, weekdays are given in Figures 4.2.1(a), 4.2.1(b), and 4.2.1(c), respectively. These load curves are based on field data obtained from Allegheny Power System [17].

At 8 a.m. the diversified KW per customer for each customer type are

$$Pdivpc_{8am,0,2,0} = 0.90 \text{ KW}, \quad [4.2.1]$$

$$Pdivpc_{8am,0,2,1} = 82.33 \text{ KW}, \quad [4.2.2]$$

$$Pdivpc_{8am,0,2,2} = 1453.00 \text{ KW}. \quad [4.2.3]$$

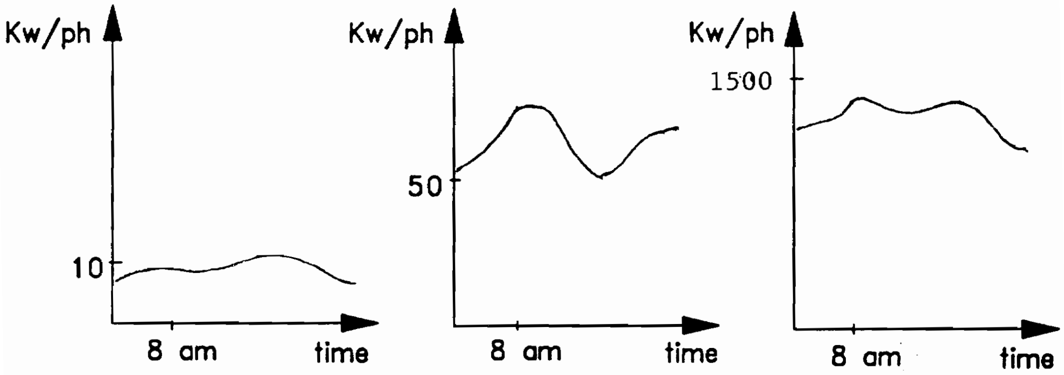

Figure 4.2.1. a) Diversified Load Curve for Residential

b) Diversified Load Curve for Commercial

c) Diversified Load Curve for Industrial

where,

$Pdivpc_{T,j}$ = diversified KW load per customer for customer of type j based on hour of day, type of day, and season.

The schematic of the circuit to be considered is shown in Figures 4.2.2(a) and 4.2.2(b). Assume that the given circuit is referred to as Circuit 0. It consists of three line sections and a source. Only phase A is considered in the estimation. Distribution of customers at each load point in the circuit for the three customer types are assumed. The number of customers attached to Load Point 0 are fifty-five with fifty residential and five industrial; the number of customers attached to Load Point 1 are eighty with thirty residential and fifty commercial; and the number of customers attached to Load Point 2 are twenty-five with twenty residential and five industrial. Hence, the total number of customers attached to the circuit is given by,

$$tcus_{j,p,c} = \sum_{i=0}^{2} cus_{i,j,p,c} \qquad [4.2.4]$$

$$\sum_{j=0}^{2} tcus_{j,p,c} = 160 \qquad [4.2.5]$$

where,

$tcus_{j,p,c}$ = for a given phase total number of customers of type j in circuit c, j = 0, 1, 2, and c = 0.

$cus_{i,j,p,c}$ = number of customers attached at the i^{th} load point for phase p and for customer of type j in circuit c,

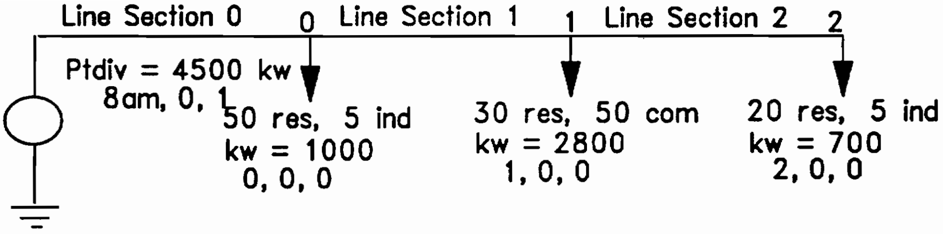

Figure 4.2.2. a) Load Estimation Example : Circuit Schemetic Showing Estimated KW for Phase A Using Diversified Load Curves for Each Line Section.

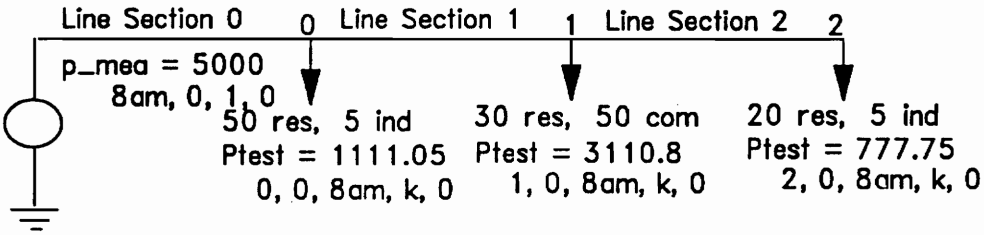

Figure 4.2.2. b) Load Estimation Example : Circuit Schemetic Showing Estimated KW for Phase A Using Measured KW in Conjunction With Diversified Load Curves for Each Line Section

Therefore,

$$tcus_{0,0,0} = \sum_{i=0}^{2} cus_{i,0,0,0} = 100 \qquad [4.2.6]$$

$$tcus_{1,0,0} = \sum_{i=0}^{2} cus_{i,1,0,0} = 50 \qquad [4.2.7]$$

$$tcus_{2,0,0} = \sum_{i=0}^{2} cus_{i,2,0,0} = 10 \qquad [4.2.8]$$

where,

$tcus_{0,0,0}$ = total number of residential customers for phase A in circuit 0,

$tcus_{1,0,0}$ = total number of commercial customers for phase A in circuit 0,

$tcus_{2,0,0}$ = total number of industrial customers for phase A in circuit 0.

The loads based on the diversified load curves at 8 a.m. which are attached to load points 0, 1, and 2, respectively, are given by

$$kw_{0,0,0} = cus_{0,0,0,0} * Pdivpc_{8am,0,2,0} + cus_{0,1,0,0} * divpc_{8am,0,2,1} + cus_{0,2,0,0} * Pdivpc_{8am,0,2,2} \qquad [4.2.9]$$

Therefore, utilizing Equations [4.2.1] - [4.2.3], we have

$kw_{0,0,0}$ = (50 x 0.90 + 5 x 1453.0) KW,

$kw_{0,0,0}$ = 7310.0 KW, [4.2.10]

Similarly,

$kw_{1,0,0}$ = 4143.5 KW, [4.2.11]

$kw_{2,0,0}$ = 7283.0 KW, [4.2.12]

where,

$kw_{i,p,c}$ = KW attached to i^{th} load point for phase p in circuit c based on diversified load curves.

By using the diversified KW values for each customer at 8 a.m. the total KW load from the diversified load curves is given by,

$$Ptdiv_{T,p} = Pdivpc_{T,0} * tcus_{0,0,0} + pdivpc_{T,1} * tcus_{1,0,0} + pdivcp_{T,2} * tcus_{2,0,0}, \quad [4.2.13]$$

where,

T represents t = 8am, d = 0 , Se = 2,

p = phase (p = 0, 1, 2, where 0 = phase A)

Hence, using Equations [4.2.1] - [4.2.3] and [4.2.6] - [4.2.8], we get

$$Ptdiv_{8am,0,2,0} = 0.90(100) + 82.33(50) + 1453.0(10)$$
$$= 18736.5 \text{ KW}. \quad [4.2.14]$$

where,

$Ptdiv_{T,p}$ = total estimated KW load using diversified KW curves based on hour of day, type of day and season (where T = t,d,Se) for phase p.

$Pdivpc_{T,j}$ = diversified KW per customer for customer of type j based on hour of day, type of day, and season (where T = t,d,Se),

$tcus_{p,j,c}$ = total number of customers for the j^{th} customer type for a given phase p in circuit c.

Assume the loss factor is equal to 1. Also, assume the instantaneous measured KW flow at the substation for the given circuit at 8 a.m. is

$$P\_mea_{8am,0,2,0,0} = 18900.0 \text{ KW}, \qquad [4.2.15]$$

where,

$P\_mea_{T,p,c}$ = total measured circuit KW at the substation for phase A based on hour of day, type of day, and season.

The total residential loading estimate using the diversified KW value from Equation [4.2.1] and total number of residential customers from Equation [4.2.5] is

$$Pdivpc_{8am,0,2,0} * tcus_{0,0,0} = 0.90 \times 100 = 90.00 \text{ KW}, \qquad [4.2.16]$$

therefore,

$$Pdiv_{8am,0,2,0,0} = 90.00 \text{ KW}, \qquad [4.2.17]$$

where,

$Pdiv_{T,p,j}$ = total residential loading using diversified KW values based on hour of day, type of day, season for phase A.

Residential measured KW, "kwm", is that part of the circuit measurement which is allocated to the residential customers. Thus, the total residential loading based on measured KW can be calculated as,

$$\frac{kwm_{0,0,0}}{p\_mea_{8am,0,2,0,0}} = \frac{Pdiv_{8am,0,2,0,0}}{Ptdiv_{8am,0,2,0}} \qquad [4.2.18]$$

$$kwm_{0,0,0} = \frac{90.0}{18736.5} \times 18900.0 = 90.78 \text{ KW}, \qquad [4.2.19]$$

Similarly, the total commercial and industrial loading based on measured KW values can also be calculated as

$$kwm_{1,0,0} = \frac{4116.5}{18736.5} \times 18900.0 = 4152.42 \text{ KW}, \qquad [4.2.20]$$

$$kwm_{2,0,0} = \frac{14530.0}{18736.5} \times 18900.0 = 14656.80 \text{ KW}, \qquad [4.2.21]$$

where,

$kwm_{j,p,c}$ = total KW loading for the j^{th} customer type for phase p in circuit c based on measured KW values.

The average residential, commercial, and industrial load estimate based on the measured circuit value at 8 a.m. is calculated as

$$kwav_{j,p,c} = \frac{kwm_{j,p,c}}{tcus_{j,p,c}} \qquad [4.2.22]$$

Therefore,

$$kwav_{0,0,0} = \frac{90.78}{100} = 0.91 \text{ KW}, \qquad [4.2.23]$$

$$kwav_{1,0,0} = \frac{4152.42}{50} = 83.05 \text{ KW}, \qquad [4.2.24]$$

$$kwav_{2,0,0} = \frac{14656.8}{10} = 1465.70 \text{ KW.} \qquad [4.2.25]$$

where,

$kwav_{j,p,c}$ = average load for a given phase for customer of type j in circuit c.

$j = 0, 1, 2.$

For phase A, the load estimates based on the actual system measurement ratioed with the results from the diversified load calculation for each load point can be obtained as,

$$Ptest_{i,p,T,k,c} = tcus_{j,p,c} \times kwav_{j,p,c}$$

$$Ptest_{0,0,8am,0,2,k,0} = (50 \times 0.91 + 5 \times 1465.7) \text{ KW}$$

$$Ptest_{0,0,8am,0,2,k,0} = 7373.95 \text{ KW} \qquad [4.2.26]$$

Similaraly,

$$Ptest_{1,0,8am,0,2,k,0} = 4179.80 \text{ kw,} \qquad [4.2.27]$$

$$Ptest_{2,0,8am,0,2,k,0} = 7346.70 \text{ kw,} \qquad [4.2.28]$$

where,

$Ptest_{i,p,T,k,c}$ = load estimate based on measured KW at the i^{th} load point for phase p based on hour of day, type of day, season and year for circuit c, Following the same procedure the KW load estimation may be obtained for phases B and C. Furthermore, KVAR feeder flow may be calculated using power factor and the KW feeder measurements, as given by Equations [4.1.1] and [4.1.2]. Also, KVAR diversified values are calculated using power factors and the diversified KW load values. These KVAR feeder flow and KVAR diversified values may then be used for the KVAR load estimation by following the same procedure.

CHAPTER 5

The Reconfiguration Algorithm

An algorithm may be defined as a step-by-step programmable procedure for solving a problem. A new algorithm for reconfiguration is presented here. The algorithm incorporates features from the algorithms discussed in Chapter 2. The algorithm does not allow load to be switched from a lower to a higher voltage, which is the rule observed by Civanlar [5]. The algorithm also utilizes the quadratic loss function of Huddleston for each circuit [3]. The modeling of switchable segments and switching currents is discussed. A brief description of the power flow algorithm is presented. The development and evaluation of the quadratic loss function is explained. The concepts related to system constraints are also described. Finally the major steps in the reconfiguration algorithm are presented.

5.1. Modeling of Switchable Segment and Switching Currents

The reconfiguration algorithm utilizes power flow results [18] in conjunction with circuit trace algorithms [3] in order to analyze the daily and seasonal time varying loads. Power flow results are used to build the quadratic loss function, whereas circuit trace algorithms, which involve a quadruply linked list of C language structures, are utilized to traverse the circuit either in reverse, forward or feeder path directions [3]. The terminology "reverse trace" implies traversing the circuit from a given component towards the source, whereas the terminology "forward trace" means traversing the circuit from the source towards the last component in the trace. This capability of traversing a circuit in reverse or forward directions is incorporated in both the reconfiguration and the power flow algorithms. This section describes the modeling of switchable segments and switching currents.

Reconfiguration analysis determines daily and seasonal switching patterns for various loading conditions. The switching patterns provide reduced loss configurations for the system. In evaluating switching patterns corresponding to a given time, the algorithm begins by executing an AC power flow over all circuits in the system, analyzing a circuit at a time.

In the analysis, the loads are to be modeled as voltage-dependent current loads. Current drawn by the loads is calculated in the power flow analysis. The total complex power for a given phase at the load point i, as given by Equation [4.1.10], divided by the complex voltage at that load point, results in the current drawn by the load at load point i. Thus, for the given phase p, the nominal load current at load point i is given by,

$$Il_{i,p,T,k,c} = \frac{S^{*}_{i,p,T,k,c}}{Vnom^{*}_{i,p,T,c}}, \qquad [5.1.1]$$

where,

$Il_{i,p,T,k,c}$ = nominal complex load current drawn by the load at load point i for phase p based on hour of day, type of day, season, and year in circuit c,

$S_{i,p,T,k,c}$ = nominal complex power at load point i for phase p based on hour of day, type of day, season, and year in circuit c,

$Vnom_{i,p,T,c}$ = nominal complex voltage at load point i for phase p based on hour of day, type of day, and season in circuit c.

The load currents are a function of the load voltages. This dependency is to be modeled using a voltage dependency factor associated with each circuit in the system. Such voltage-dependent load factors could be determined from experiments run on a circuit. Thus, the voltage-dependent load factor for a particular circuit can be defined as,

$$VDF_c = \frac{\text{fractional change in load amps}}{\text{volts}} \quad 1/\text{volts} \qquad [5.1.2]$$

where,

$$\text{fractional change in load amps} = \frac{I\_actual - I\_nominal}{I\_nominal},$$

VDF_c = voltage dependency factor for circuit c,

I_actual = actual current ,

I_nominal = nominal current.

The voltage dependency factor VDF_c may be specified as positive, negative, or zero. A positive voltage dependency factor may be used to simulate constant impedance type load behavior, whereas a negative voltage dependency factor may be used to simulate constant power type load behavior. The positive voltage dependency factor acts as if load current is directly proportional to the voltage variation (i.e. the load current value is increased with the increase in voltage and vice versa), and the negative voltage dependency factor acts as if the load current is inversely proportional to the voltage variation (i.e. the load current increases with a decrease in voltage value and vice versa).

If " $V_{i,p,T,c}$ " represents the complex voltage value at the i^{th} load point for a given phase based on hour of day, type of day, and season in circuit c which is deviated from its nominal value, then the voltage-dependent load current at the i^{th} load point in the circuit for a given phase p based on hour of day, type of day, season, and year is given by,

$$Ilvd_{i,p,T,k,c} = \{ 1 + VDF_c * (V_{i,p,T,c} - Vnom_{i,p,T,c}) \} * Il_{i,p,T,k,c}, \qquad [5.1.3]$$

where,

$Il_{i,p,T,k,c}$ = nominal complex load current drawn by the load at load point i for phase p based on hour of day, type of day, season, and year in circuit c,

$Ilvd_{i,p,T,k,c}$ = voltage-dependent load current drawn by the load at load point i for phase p based on hour of day, type of day, season, and year in circuit c,

$V_{i,p,T,c}$ = complex voltage value at load point i for phase p based on hour of day, type of day, and season in circuit c which is deviated from its nominal value.

$Vnom_{i,p,T,c}$ = nominal complex voltage at load point i for phase p based on hour of day, type of day, and season in circuit c.

VDF_c = voltage dependency factor for circuit c.

It can be seen that by setting the voltage-dependent load factor equal to zero, the voltage dependent load current at the i^{th} load point is equal to the nominal load current at the i^{th} load point.

Groups of components referred to as segments are used in analyzing circuits. A segment is composed of components that cannot be separated from each other. A segment consists of interior components and boundary components. The interior components may be line sections, voltage regulators, transformers, and capacitor banks. In a segment at least one boundary component must be a switch, fuse, reclosure, or breaker. A switchable segment is defined as a group of components that are electrically inseparable and may be switched from one circuit to another. The reverse circuit trace operation may be used to identify all switchable segments for a particular circuit. Figure 5.1.1 illustrates an example circuit which consists of a switchable and a non-switchable segments.

The results of power flow calculations are used in conjunction with a reverse trace performed on each circuit to calculate coefficients of quadratic loss functions. The coefficients of the loss function depend upon variables referred to as switching currents [3]. The switching currents are composed of load currents, located on the switchable segments, that can be switched among circuits using automatic or manual switches. The sum of all the load currents on a switchable segment contribute to form the segment current for that particular segment. Equation [5.1.4] represents the segment current for switchable segment s,

$$Iseg_{s,p,T,k,c} = \sum_{i=q}^{m} Ilvd_{i,p,T,k,c} , \qquad [5.1.4]$$

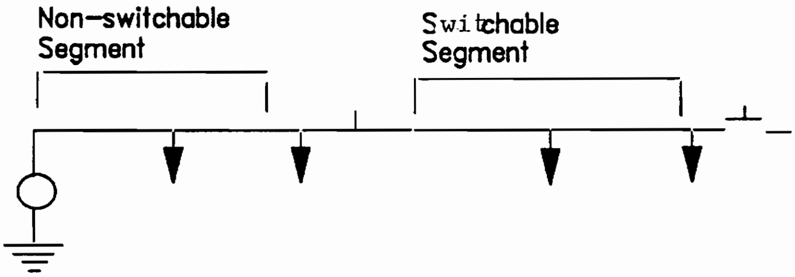

Figure 5.1.1. Circuit With Non-switchable and Switchable Segments

where,

$Iseg_{s,p,T,k,c}$ = switchable segment current in switchable segment s for phase p based on hour of day, type of day, season, and year for circuit c,

$Ilvd_{i,p,T,k,c}$ = voltage-dependent load current drawn by the load at load point i for phase p based on hour of day, type of day, season, and year in circuit c.

The quadratic loss functions may be used to estimate circuit losses as a function of switching currents. A switching current is a function of its voltage-dependent segment current. That is, when a load is switched to a higher voltage, the current drawn by the load will increase. Hence, the switching current may be represented by,

$$Isw_{s,p,T,k,c} = f(Iseg_{s,p,T,k,c}) \qquad [5.1.5]$$

where,

$Iseg_{s,p,T,k,c}$ = switchable segment current in switchable segment s for phase p based on hour of day, type of day, season, and year for circuit c,

$Isw_{s,p,T,k,c}$ = switching current in switchable segment s for phase p based on hour of day, type of day, season, and year for circuit c.

A system of two circuits is shown in Figure 5.1.2. The system is comprised of sources, line sections, and switches. Two of the switches are normally closed, whereas one is normally open. Quadratic loss functions are associated with each circuit. In the

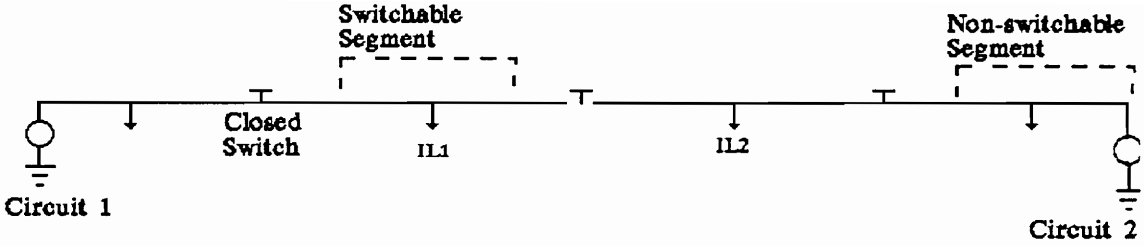

Figure 5.1.2 System of Two Circuits With Three Automatic Switches

quadratic loss function, each switching current is treated as a discrete variable which may take on up to three distinct values. The switching current associated with a segment is set to zero in the circuit loss function if the load is switched to the adjacent circuit. The switching current associated with the segment remains at its nominal value if no load is exchanged with the adjacent circuit. Finally, if load is switched to the circuit from the segment in the adjacent circuit, then the switching current is set equal to its nominal value plus the nominal value of the switching current being switched from the adjacent circuit modified by the voltage to which the current is being switched. Thus, the set of three distinct values that the switching current can take on is given by,

No switch movement :

$$Isw_{s,p,T,k,c} = Iseg_{s,p,T,k,c} \qquad [5.1.6a]$$

Load switched from adjacent circuit :

$$Isw_{s,p,T,k,c1} = Iseg_{s,p,T,k,c1} + Iseg_{s,p,T,k,c2} * \left[1 + \{VDF_{c1} * (V_{i,p,T,c1} - Vnom_{i,p,T,c1})\} \right] \qquad [5.1.6b]$$

Load switched away to adjacent circuit :

$$Isw_{s,p,T,k,c} = 0.0 \qquad [5.1.6c]$$

where,

$Iseg_{s,p,T,k,c}$ = switchable segment current in switchable segment s for phase p based on hour of day, type of day, season, and year for circuit c,

$Isw_{s,p,T,k,c}$ = switching current in switchable segment s for phase p based on hour of day, type of day, season, and year for circuit c,

$V_{i,p,T,c}$ = complex voltage value at load point i for phase p based on hour of day, type of day, and season in circuit c which is deviated from its nominal value,

$Vnom_{i,p,T,c}$ = nominal complex voltage at load point i for phase p based on hour of day, type of day, and season in circuit c.

VDF_c = voltage-dependency factor for circuit c.

5.2 Power Flow Algorithm

The power flow algorithm can be considered as one of the central parts of the distribution reconfiguration algorithm. The power flow algorithm developed may be used to obtain a single phase or a multiphase solution to the load flow problem for the radial electrical distribution system. The power flow algorithm utilizes circuit traces [3] in order to traverse a circuit in various directions (i.e. reverse trace, forward trace or feeder path trace).

The power flow algorithm is based on the voltage-dependent load current model. First, the nominal load currents are derived using the nominal complex power at each load point in the circuit and the nominal voltage, as given by Equation [5.1.1]. Then, using the circuit voltage dependency factor VDF_c, voltage-dependent load currents are developed using Equation [5.1.3]. The given parameters for the load flow problem are as follows:

1) Substation or swing bus voltage magnitude,

$|V_{i,p,T,c}|$

2) swing bus voltage angle, $\delta_{i,p,T,c}$ and

3) voltage-dependent load current at each bus,

$Ilvd_{i,p,T,k,c}$.

With the above three parameters in hand, power flow generates a comprehensive profile of the following quatities:

1) voltage values at each bus in the circuit, $V_{i,p,T,c}$

2) voltage-dependent load current flowing in each component in the circuit, $Ilvd_{i,p,T,k,c}$

3) KW flow in each component in the circuit,

4) power factor at each bus in the circuit.

The power flow algorithm is designed to model essentially all types of electrical distribution components such as substations, co-generators, tap changing transformers, fixed transformers, voltage regulators, switched capacitors, fixed capacitors, line sections, automatic and manual switches, and several types of protective devices such as, breakers, fuses, reclosures.

The power flow algorithm also incorporates a controller algorithm which is used to control voltages and power factors at a given bus. For example, when the power flow is run on a given circuit which contains a voltage regulator at a given bus, the voltage regulator tap may increase or decrease by a predefined tap step size depending upon the voltage value at the given bus. The tap takes continuous values till the required voltage is obtained at the given bus. Once the algorithm converges, the voltage regulator tap is set to the closest discrete value. This tap value is then stored in a database table. If power flow runs on the same circuit again, then the algorithm will converge more rapidly because the voltage regulator tap is already set to the value that results in convergence. The same controller procedure applies to tap changing transformers and switched capacitors present in any circuit.

The major steps of power flow algorithm are described below. Figure 5.2.1. shows a flow diagram of these steps.

0) Initialize Circuit Voltage Dependency Factor VDF_c to a user specified value or to a default value obtained from the Circuit Table in the database
1) Initialize voltage-dependent load amps to nominal load amps for all the components in the circuit (i.e. $Ilvd_{i,p,T,k,c} = Il_{i,p,T,k,c}$)
2) Initialize voltage magnitude and voltage angle tolerence values,$\Delta|V|$, $\Delta\delta$. These values will serve as convergence criteria for the power flow solution
3) Initialize all controller variables to zero
4) Initialize first iteration flag iter = 0
5) Obtain tap value for any transformer or voltage regulator present in the circuit from memory
6) Obtain nominal kvar injection value for any capacitor present in the circuit from computer memory (i.e. from the trace data structure to a local dummy variable)
7) Obtain tap step size in case of transformer or voltage regulator from computer memory
8) Obtain kvar step size in case of capacitor from computer memory
9) Initialize convergence flag conv = 0

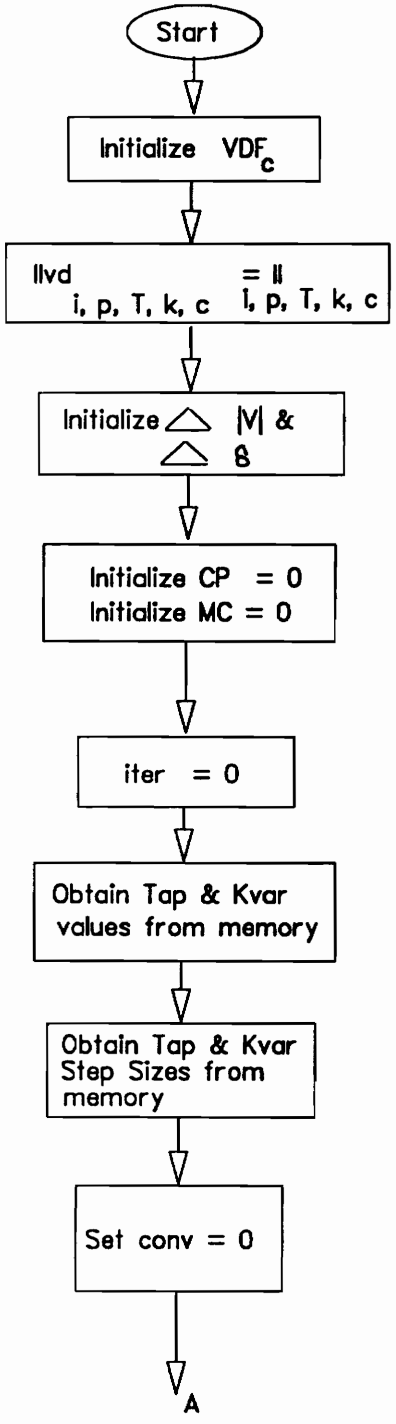

Figure 5.2.1 Flow Diagram for Power Flow Algorithm

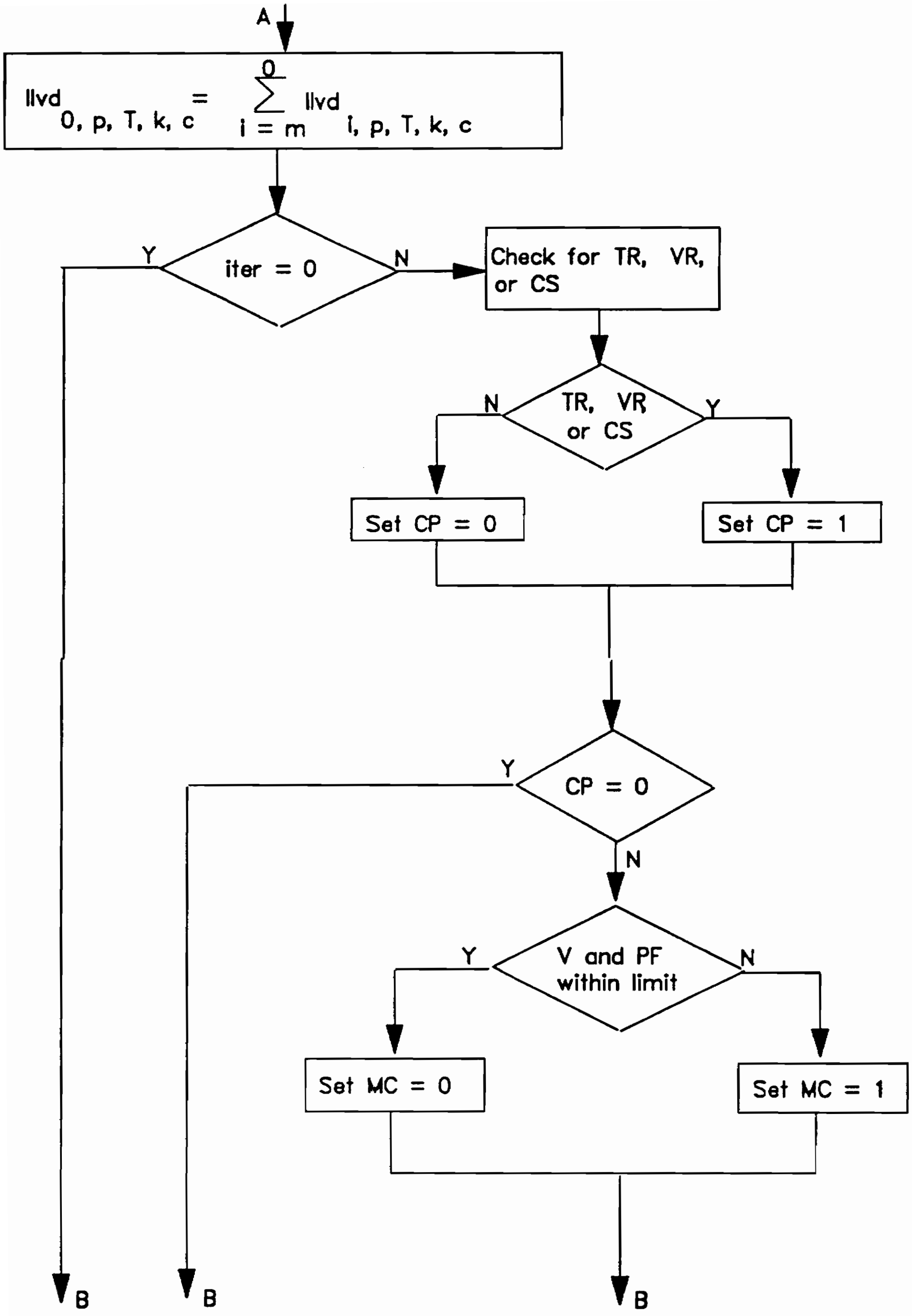

Figure 5.2.1 Flow Diagram for Power Flow Algorithm

Continued

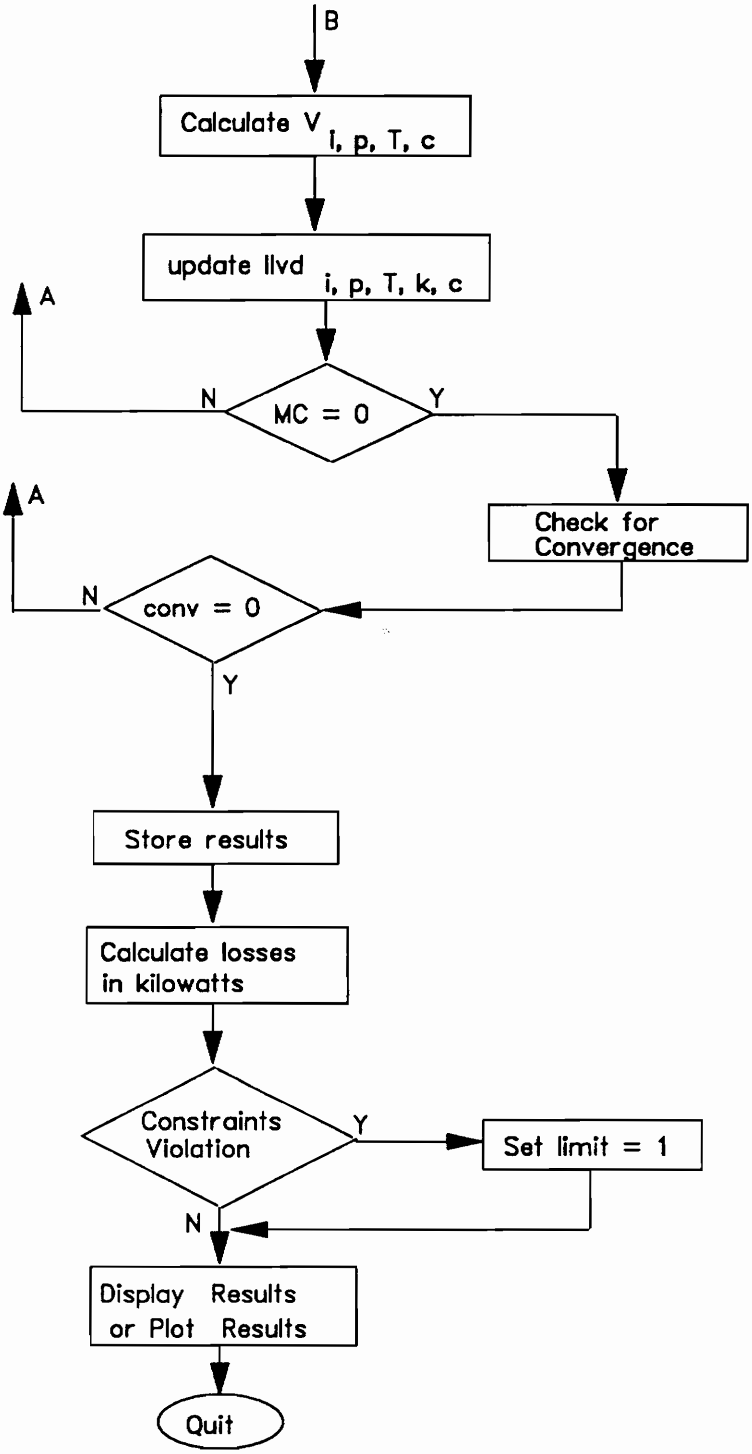

Figure 5.2.1 Flow Diagram for Power Flow Algorithm

Continued

10) Initialize circuit's constraint flag "limit = 0". This indicates that circuit voltages and currents are within limits

11) Perform reverse trace (i.e. traverse the circuit from the end component towards the source or substation) to sum the voltage-dependent load current at each node to the voltage-dependent load current downstream of the node. Eventually all load currents are summed at the substation.

   i) if iter = 0 then go to step (12)
      else if iter >=1, then check for flag controller_present "CP" (i.e. presence of a regulating transformer TR, a voltage regulator VR, or a switched capacitor CS)
      a) if a controller is present, then set flag "CP" = 1
      b) else set "CP" = 0, then go to step (12)

   ii) if controlled variable (i.e. voltage or power factor) is within the predefined upper and lower bounds, then set flag "MC" = 0
      else set "MC" = 1. This flag indicates that the controller is moved

12) Perform forward trace (i.e. traverse the circuit from the source towards the end component) on the

circuit to calculate end node voltages and update voltage-dependent load currents using voltage dependency factor VDF_c

13) a) if "MC" = 1, then do not check for convergence and go to step (11)
    b) if "MC" = 0, then check for convergence
14) Check for the convergence flag "conv"
    i) if conv = 0 , go to step (11)
15) Store results to the database tables
16) Calculate KW losses for all line sections and transformers present in the circuit
17) Check for voltage and current constraint violations
    i) if any constraint violations occur, then set circuit's constraint flag "limit = 1"
18) Display or Plot results

The power flow is an independent and separate module that may either be run as a stand alone analysis program or as an integral part of reconfiguration or other analysis programs. Currently, the power flow is setup to run in the following two modes,

i) over a single point in time, and
ii) over multiple points in time.

When run over multiple points in time, the algorithm executes on only one time point at a time generating a complete profile for voltages, currents, line power flows, and power factors.

5.3 Loss Function Model

The losses of the distribution system are modeled by a quadratic loss function which is developed a circuit at a time based on the real power losses, $P = I^2 \times R$. The model to develop the quadratic loss function is based on the concept of a "DC" power flow. The "DC" power flow implies that only the line resistances and the magnitude of the voltage-dependent load currents are considered. In the power flow all the loads are treated as voltage-dependent current loads, as indicated in Equation [5.1.3].

The quadratic loss functions that are calculated for the given system configuration are used to determine the switching operation that results in the greatest reduction in system losses. This switching operation is performed, and then a power flow is performed on the circuits that changed as a result of the switching operation. Loss functions for the circuits that changed are updated following the power flow execution. Once again, the switching operation is determined that results in the greatest reduction in system losses. If no such switching operation is found which reduces the system loss, then the algorithm has converged for the given loading condition.

The quadratic loss functions are functions of the switching currents. The coefficients of the quadratic loss functions are dependent on load currents, which cannot be switched, and the resistances of the lines which cannot be switched. These functions can be described as follows:

$$P\_loss_c = f(\underline{Isw}_{s,p,T,k,c}) \qquad [5.2.1]$$

If there are more than one switching current present in a circuit, then the loss function may be written in a general form as follows:

$$P\_loss_c = \underline{Isw}^T_{s,p,T,k,c} * \underline{C1} * \underline{Isw}_{s,p,T,k,c} + \underline{C2}^T * \underline{Isw}_{s,p,T,k,c} + C3 \qquad [5.2.2]$$

where,

P_loss_c = loss function for circuit c,

$\underline{Isw_{s,p,T,k,c}}$ = switching current in segment s for phase p based on hour of day, type of day, season, and year in circuit c (nx1 vector),

$\underline{C1}$ = nxn square matrix whose elements are a function of non_switchable line resistances and non-switchable load currents,

$\underline{C2}$ = nx1 vector whose elements are a function of non_switchable line resistances and non-switchable load currents,

C3 = constant terms which are a function of non_switchable line resistances and non_switchable load currents.

Thus,

$$\underline{Cs} = g(\, \underline{R}\, , \, |\, \underline{Ilvd}_{i,p,T,k,c} \,|\,) \qquad [5.2.3]$$

where,

$$\underline{Cs} = \begin{bmatrix} \underline{C1} \\ \underline{C2} \\ C3 \end{bmatrix} = \text{vector of coefficients}$$

$\underline{R}$ = line resistance vector nx1,

$|\underline{Ilvd}_{i,p,T,k,c}|$ = absolute value of the voltage-dependent load current (nx1 vector),

5.4 Development of Quadratic Loss Function

To build or update a quadratic loss function for a circuit, all the segments whose load can be switched from one circuit to another are determined. This is achieved by performing a reverse trace from an open switch to a closed switch. All the load currents on that segment collectively form the segment current. The switching current, a function of segment currents, is treated as a discrete variable in the loss function. After determining all the switching currents in a circuit, another reverse trace is performed to obtain the coefficients for the loss function. In the loss function each switching current has a squared term, a mutual term with each of the other switching currents in the circuit, and a linear term. The coefficients for these terms in the loss function are the load currents and resistances of the components in the interior segments of the circuit which were not included in switchable segments.

An example of the development of a loss function is now given [3]. The loss function is developed for the circuit shown in Figure 5.4.1. The circuit consists of six line sections. For illustration purposes only one subscript, load point or node number i, is used while the rest of the subscripts such as phase p, customer type j, etc. are dropped from the switching current and load current expressions. The switching segments are located at nodes 5 and 31 . The total current at node 5 is composed of the load current at node 5 and the switching current at node 5. Similarly, the total current at node 31 is the sum of load current and the switching current at node 31. The switching currents are represented by Isw_i while the load currents are represented by Il_i , where i represents the corresponding node number. The variables in the example circuit are switching currents Isw_5 and Isw_{31} . Hence, the variables appearing in the loss function are the two squared terms, a mutual term , and two linear terms. The component resistances are represented by R_{cp} with cp being the component number. The component forward trace for the example circuit is given by

22 - 20 - 9 - 29 - 5 - 18 - 6

The circuit is traversed in reverse order to produce the loss function in terms of the switching currents. The first component encountered in the reverse trace is component 6. The current flowing in component 6 is the sum of the total load current which in this case is Il_5 and the switching current Isw_5 . Therefore the coefficients for the Isw square and the linear term Isw_5 are added to the loss function for component 6. The loss coefficients for the squared term is R_6 and the loss coefficient for the linear term is $2*R_6*Il_5$. The loss coefficients for this component are added to the loss function in the appropriate places as indicated in Table 5.4.1.

The next component in the reverse trace is component 18. The current in this line section is the sum of the currents of component 6 and the load current of node 29, Il_{29}. These terms are added to the loss function as indicated in Table 5.4.1. The next component is component 5. This component also contains a load current and the switching current and its terms are added to the loss function in the same manner as for component 6, as shown in Table 5.4.1. The next component encountered is 29. This component contains only a load current, Il_{15} , which only contributes to the constant term of the loss function. Therefore this component adds nothing to the loss function as the component trace is traversed. The resulting loss function for the example circuit with the terms of each component summed together is as follows

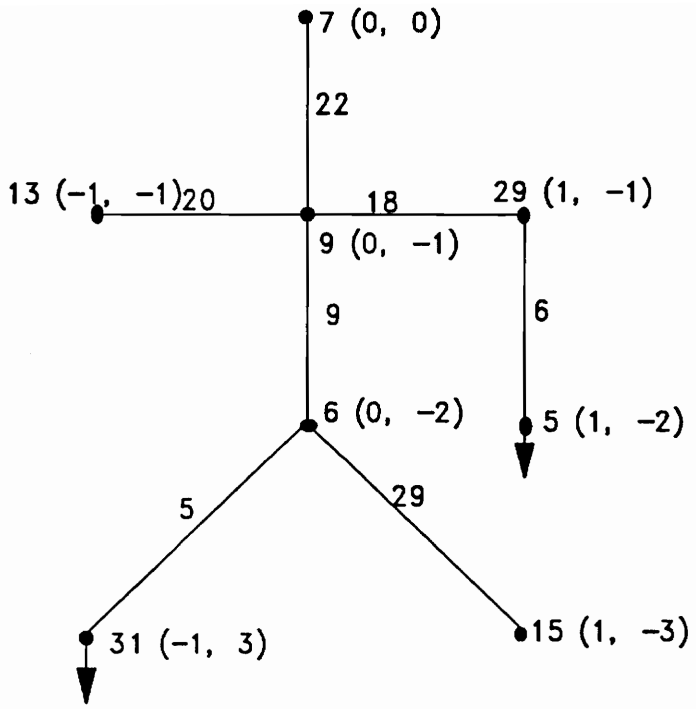

Figure 5.4.1 Example System Used to Illustrate the Development of Quadratic Loss Function

Table 5.4.1 Component Currents Separated into Load and Switching Currents and Coeffficients of Switching Current Terms in Loss Function

	Component Number	6	18	5	29	9	20	22
Component Currents	Load Current	Il_5	Il_5+Il_{29}	Il_{31}	Il_{15}	$Il_{31}+Il_{15}+Il_6$	--	$Il_5+Il_{29}+Il_{13}+Il_{15}+Il_6+Il_{31}+Il_9$
	Switching Current	Isw_5	Isw_5	Isw_{31}	--	Isw_{31}	--	Isw_5+Isw_{31}
	I^2sw_5	R_6	R_{18}	--	--	--	--	R_{22}
	I^2sw_{31}	--	--	R_5	--	R_9	--	R_{22}
	Isw_5Isw_{31}	--	--	--	--	--	--	$2R_{22}$
	Isw_5	$2R_6Il_5$	$2R_{18}(Il_5+Il_{29})$	--	--	--	--	$2R_{22}(Il_5+Il_{29}+Il_{31}+Il_{15}+ Il_6+Il_{13}+Il_9)$
	Isw_{31}	--	--	$2R_5Il_{31}$	--	$2R_9(Il_{31}+Il_{15}+Il_6)$	--	$2R_{22}(Il_5+Il_{29}+Il_{31}+Il_{15}+ Il_6+Il_{13}+Il_9)$

$$P\_loss_1 = K_5 x I^2 sw_5 + K_4 x I^2 sw_{31} + K_3 x Isw_{31} \; x Isw_5 + K_2 x Isw_5 + K_1 x Isw_{31} + K_0 \quad [5.4.1]$$

where,

$K_5 = R_6 + R_{18} + R_{22}$,

$K_4 = R_5 + R_9 + R_{22}$,

$K_3 = 2R_{22}$,

$K_2 = 2[R_6 Il_5 + R_{18}(Il_5 + Il_{29}) + R_{22}(Il_5 + Il_{29} + Il_{31} + Il_{15} + Il_6 + Il_{13} + Il_9)]$,

$K_1 = 2[R_5 Il_{31} + R_9(Il_{31} + Il_{15} + Il_6) + R_{22}(Il_5 + Il_{29} + Il_{31} + Il_{15} + Il_6 + Il_{13} + Il_9)]$,

K_0 = uncalculated constant term.

In general, the loss function is developed by traversing the circuit component trace in reverse order, and adding the terms of each component to the loss function as that component is reached in the trace. The terms that are added to the loss function depend on the current flowing through the particular component. The squared term for the switching current variable is added to the loss function only if the corresponding switching current flows through the component. The coefficient of the squared term is the resistance of that component. The mutual term of the switching current variable is added to the loss function only if both of the corresponding switching currents are flowing through the component. The mutual coefficient is the component resistance multiplied by two. Finally, the linear term of the switching current variable is added to the loss function only if both the corresponding switching current and a load current are flowing through the component. Its coefficient term is twice the sum of the load currents in the component multiplied by the resistance of the component. The constant term of the loss function is composed of the losses contributed by the load currents. The modeled load currents are not affected by changes in the configuration of the distribution system model; therefore, the constant term is not needed.

5.5 Loss Function Evaluation

The reconfiguration algorithm incorporates a direct search procedure [19] in order to determine the reduced loss configuration of the system. The procedure involves evaluating Huddleston's quadratic loss function for each circuit in the system, where each circuit in the system has a loss function associated with it. The loss functions are evaluated a switching operation at a time, over the number of possible switching operations for the circuit. A switching operation is defined as closing an open switch and opening a closed switch. A switching operation is also referred to as a switch pair operation. The manner in which the quadratic loss functions are used to determine switching configurations is considered in this section.

A switching current represents a voltage-dependent current load that may be shifted to an adjoining circuit. The switching currents are treated as variables in the loss functions. All possible values of switching current at each switchable segment in the circuit are used in evaluating the loss functions. These functions are evaluated in order to estimate the switch pair operation that results in greatest reduction in system losses. Once the switch pair operation is determined that results in the greatest reduction in system loss, the power flow will execute on the circuits that are changed due to the switching operation. If no switch pair operation is found for which the losses are reduced, then the algorithm has converged at the present configuration of the system.

The possible values a switching current may take on in the loss function will now be described. Assume an open automatic switch between two circuits referred to as

Circuit 0 and Circuit 1, as shown in Figure 5.5.1. This open automatic switch may be used in a switching operation to transfer load from Circuit 0 to Circuit 1 or vice versa. In order for this switching operation to be possible, a closed automatic switch must exist in both Circuit 0 and Circuit 1, upstream from the open automatic switch under consideration. Two switching currents, one for each of the two adjacent circuits, are associated with each open automatic switch. The set of possible values for each switching current is discrete and may consist of up to three values. These values represent switching load from Circuit 0 to Circuit 1, switching load from Circuit 1 to Circuit 0, and no movement of load at the given open switch (i.e. leave the open switch in the open position). The current in Segments 0 and 1, using Equation [5.1.4], may be represented by,

$$Iseg_{0,p,T,k,c} = \sum_{i=2}^{3} Ilvd_{i,p,T,k,c} \qquad [5.5.1]$$

$$Iseg_{1,p,T,k,c} = \sum_{i=2}^{3} Ilvd_{i,p,T,k,c} \qquad [5.5.2]$$

where,

$Iseg_{s,p,T,k,c}$ = switchable segment current in switchable segment s for phase p based on hour of day, type of day, season, and year for circuit c,

$Ilvd_{i,p,T,k,c}$ = voltage-dependent load current drawn by the load at load

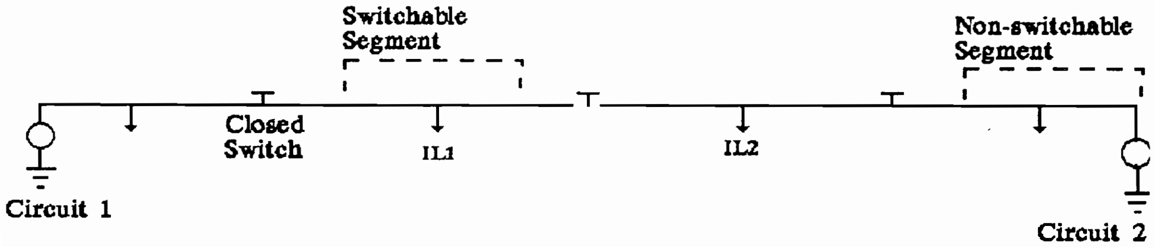

Figure 5.5.1 System of Two Circuits With Three Automatic Switches

point i for phase p based on hour of day, type of day, season, and year in circuit c.

Now the switching current in Circuit 0 may take on up to three discrete values, as indicated by Equations [5.1.6a] - [5.1.6c]. These three values comprise the current in Segment 0, the current in Segment 1 modified by the voltage-dependency factor plus the current in Segment 0, and zero. Hence,

No switch movement :

$$Isw_{0,p,T,k,0} = Iseg_{0,p,T,k,0} \qquad [5.5.3a]$$

Load switched from adjacent circuit :

$$Isw_{0,p,T,k,0} = Iseg_{0,p,T,k,0} + Iseg_{1,p,T,k,1} * [1 + \{ VDF_0 * (|V_{i,p,T,0} - Vnom_{i,p,T,0}|) \}] \qquad [5.5.3b]$$

Load switched away to adjacent circuit :

$$Isw_{0,p,T,k,0} = 0.0 \qquad [5.5.3c]$$

where,

$Iseg_{s,p,T,k,c}$ = switchable segment current in switchable segment s for phase p based on hour of day, type of day, season, and year for circuit c,

$Isw_{s,p,T,k,c}$ = switching current in switchable segment s for phase p based on hour of day, type of day, season, and year for circuit c,

$V_{i,p,T,c}$ = complex voltage value at load point i for phase p based on hour of day, type of day, and season in circuit c which is deviated from its nominal value,

$Vnom_{i,p,T,c}$ = nominal complex voltage at load point i for phase p based on hour of day, type of day, and season in circuit c.

VDF_c = voltage-dependency factor for circuit c.

Due to adhering to Civanlar's rule, switching load from a higher to a lower voltage level is not allowed. Hence, possible values a switching current may take on in the loss function are reduced by one-third, and thus, as to be seen, the number of loss function evaluations is also reduced by one-third.

Assume that there is no closed switch downstream from an open automatic switch in Circuit 0. In this case, the only load transfer consists of transferring load from Circuit 1 to Circuit 0. In this situation, the switching current may take on only two values. These values represent switching load from Circuit 1 to Circuit 0 and no movement of load at the given open switch. It should be noted that if the voltage level at the switching point in Circuit 1 is higher than the voltage level at the switching point in Circuit 0, then the load transfer is not allowed. In this case, no loss function evaluations are needed.

From the above discussion it is clear that the switching current is dependent upon the voltage level to which the load is being transferred. The value of the switching current may increase when load is switched from a lower voltage level to a higher voltage level. This important aspect is incorporated in the present work by considering a voltage-dependent load factor.

5.5.1 Demonstration of Civanlar's Rule:

A demonstration of Civanlar's rule, that is only allowing load to be transfered from a lower to a higher voltage level circuit to effect a loss reduction, is given here. Consider a system of two circuits (viz: Circuit 1 and Circuit 2), as shown in Figure 5.5.1.1. Assume both substations are at the same voltage level (i.e. $E = E_1 = E_2$).

Let $I_1^2R_1 + I_2^2R_2 = \text{Loss}_1$ [5.5.1.1]

Let $(I_1 + I_2)^2R_1 = \text{Loss}_2$ [5.5.1.2]

Let $(I_1 + I_2)^2R_2 = \text{Loss}_3$ [5.5.1.3]

Also,

$\text{Loss}_3 < \text{Loss}_1$ [5.5.1.4]

$\text{Loss}_3 < \text{Loss}_2$ [5.5.1.5]

$V_2 < V_1$ [5.5.1.6]

From Inequality [5.5.1.4], we have

$$(I_1 + I_2)^2R_2 < I_1^2R_1 + I_2^2R_2$$

or $(1 + 2I_2 / I_1) < (R_1 / R_2)$.

Since I_1, I_2, R_1, and $R_2 >= 0.0$,

therefore,

$(I_2 / I_1) < (R_1 / R_2)$ [5.5.1.7]

Inequality [5.5.1.5] gives,

$R_2 < R_1$ [5.5.1.8]

and Inequality [5.5.1.6] gives,

$V_2 < V_1$.

Consider Figure 5.5.1.1, voltages V_1 and V_2 are given by

$$V_1 = E - I_1R_1$$

$$V_2 = E - I_2R_2$$

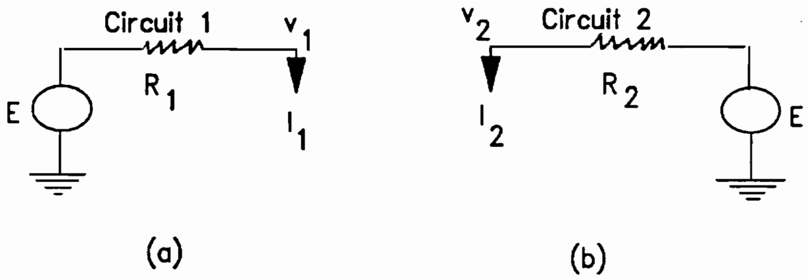

Figure 5.5.1.1 System of Two Circuits Used to Demonstrate Proof of Civanlar's Rule

or $-I_2R_2 + E < E - I_1R_1$

or $I_2 / I_1 > R_1 / R_2$. [5.5.1.9]

Where,

E = substation bus voltage,

v_i = voltage at load point i,

I_1 = current flow in Circuit 1,

I_2 = current flow in Circuit 2,

R_1 = line resistance in Circuit 1,

R_2 = line resistance in Circuit 2,

$Loss_1$ = losses with no load transfer,

$Loss_2$ = losses when load is switched from Circuit 2 to Circuit 1, and

$Loss_3$ = losses when load is switched from Circuit 1 to Circuit 2.

It can be seen that Inequalities [5.5.1.7] and [5.5.1.9] contradict each other. Hence, it is not possible to switch load from the higher voltage Circuit 1 to the lower voltage Circuit 2 (i.e. I_1 to I_2) and affect a loss reduction, or in other words to switch load from higher to lower voltage level circuit.

Q.E.D.

5.5.2 Loss Models :

Consider a distribution system with n open switches. Prior to any switching operation, the circuit loss functions are evaluated at the nominal switching current values. The loss functions associated with all the circuits are summed up and the base case loss model is obtained as given by

$$Ploss(0) = \sum_{c=0}^{N} P\_loss_c \qquad [5.5.2.1]$$

where,

N = maximum number of circuits,

P_loss_c = quadratic loss function for circuit c,

$Ploss(0)$= base case loss model.

The loss functions are then repeatedly evaluated for each possible switching operation, one switching operation at a time. Only load transfers from lower to higher voltage levels are considered. Here the voltage level is referred to the voltage at each end of an open switch which exists between two circuits. The switching current values are obtained using Equations [5.1.6a] - [5.1.6c]. The loss functions associated with all the circuits are then summed up for each possible switching operation. Thus, another loss model is developed for open switches in the system to be evaluated, as illustrated by,

$$Ploss_{sw}(1) = \sum_{c=0}^{N} P\_loss_c \Big|_{sw = 1, 2, .., n} \qquad [5.5.2.2]$$

where,

$Ploss_{sw}(1)$ = loss model based on load transfer for open switch sw,

sw = open switch.

It is to be noted that some open switches may be locked in place due to earlier constraint violations. Also, open manual switches will not be considered for the daily reconfiguration study.

The difference between the two loss models is obtained and the switching operation that produces the maximum decrease in system losses is selected, as indicated by

$$\Delta Ploss = \max_{sw} [\, Ploss(0) - Ploss_{sw}(1) \,] \qquad [5.5.2.3]$$

where,

$Ploss_{sw}(0)$ = base case loss model,

$Ploss_{sw}(1)$ = loss model based on load transfer associated with each open switch sw,

$\Delta Ploss$ = difference between the two models.

Note that if $\Delta Ploss <= 0.0$, then the algorithm has converged (i.e. no single switch pair operation produced a reduction in losses).

Next, voltage and current constraints are checked before the switching operation is implemented.

5.6 Voltage and Current Constraints

The reconfiguration algorithm incorporates constraints of circuit voltage limits and current overloading. These constraints are described in this section.

Current overloading implies that the current in a component has exceeded the rated current limit of that component. If an overload condition is created due to any switching operation, then the switching operation is reversed, and the resulting open switch is tagged as not being available for use in the reconfiguration evaluation. Then, in future iterations switching currents are not defined for those open switches that are tagged to remain open.

The circuit voltage constraints are considered in a similar fashion as current overloading. The voltage constraint simply means that the ending node voltage for each line section in the circuit must be kept within the predefined upper and lower bounds. The switching operation is reversed whenever a voltage constraint is violated. The resulting open switch is marked as not being available for reconfiguration evaluation anymore. On violation of any constraint, the set of loss functions are evaluated again to determine the next reduced loss configuration to be considered.

5.7. The Reconfiguration Algorithm Steps

The major steps in the reconfiguration algorithm are now presented. Figure 5.7.1 shows the flow diagram for the algorithm.

0) Initialize all flags, such as system constraint violation (SCE) and increased loss from power flow (PFE), to zero.

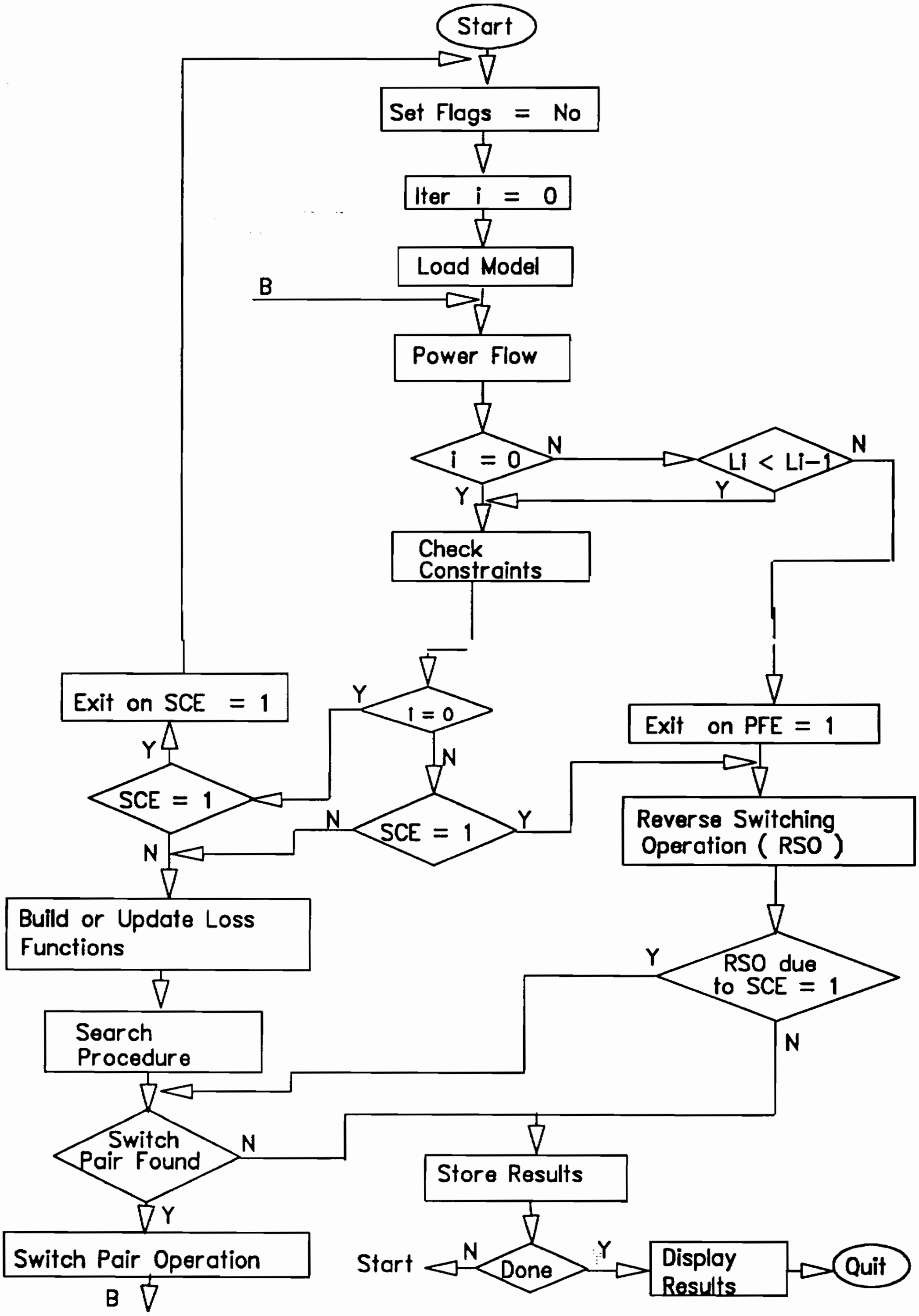

Figure 5.7.1. Reconfiguration Algorithm Flow Diagram.

1) Set first iteration flag = 0.

2) Select time point to be analyzed from the load model.

3) Perform power flow analysis on each circuit in the system whose loss function need to be developed.

4) If it is not the first iteration, then perform a check for reduction in system losses.

   i) If system losses do not decrease, then set " power flow flag" PFE = 1.

   ii) If PFE = 1, then go to step (8).

5) Check for system constraints.

   i) Check for voltage limits.

   ii) Check for equipment current overloads.

6) If any constraint is violated during the first iteration, then write a warning message to the user and go back to step (0).

7) If any of the system constraints are violated due to the switching operation after the first iteration, then set "system constraint flag" SCE = 1.

8) If SCE = 1 or PFE = 1, then reverse the switching operation. Mark the resulting open switch as not being available for further switching operations.

9) If reverse switching is due to the constraint violation (i.e. SCE = 1), then go to step (12).

10) If reverse switching is due to the flag PFE = 1, then go to step (14).

11) Update or build loss function for each circuit in the system.

12) Perform direct search.

13) If the reduced loss configuration is different from the existing configuration, then perform the switch pair operation as indicated in step (12).

Go to step (3).

14) Store results in data structures.

15) Go back to (0) and perform the process for the next loading condition to be analyzed.

16) Store results to database tables.

17) Highlight switches to be operated for user selected time points.

5.8. Summary

A new distribution reconfiguration algorithm, which utilizes Huddleston's quadratic loss functions to determine the reduced loss configuration of the system, is presented. The evaluation of these loss functions is discussed. Modeling of switchable and switching currents is shown. Concepts related to voltage dependency of loads are defined. A mathematical demonstration of Civanlar's rule is illustrated. Handling of voltage and current constraints are outlined.

CHAPTER 6

Example Problems and Results

This chapter presents example problems and their results. These examples are utilized to demonstrate the reconfiguration algorithm peformance. The example problems to be solved analyze time varying load patterns based on hour of day, type of day, and season. The analysis is performed for a number of loading conditions. These loading conditions are derived from one or more of the following quantities : spot loads, diversified customer loads, and KW feeder measurements.

In Example 1 the KW loading is based on spot loads only. The diversified customer load curves are used in conjunction with spot loads to derive the KW loading for Example 2. The diversified customer loads versus time patterns for each customer type, used in Example 2, are obtained from Allegheny Power System. In Example 3, the diversified customer loads versus time patterns for each customer type are assumed arbitrarily. These diversified loads are used in conjunction with feeder measurements to derive the loading condition for Example 3. The number of customers and customer types at each load point in a circuit are assumed to be known in all three example problems.

The actual KW loading per customer for each customer type may be estimated using measured circuit KW at the substation in conjunction with the cutomer type based diversified KW load curves, as described in Chapter 4. This estimated KW loading is distributed among customers at each load point in the circuit based upon the number of customers and type of customer. A similar estimation is performed for the KVAR loading. The next section describes the salient features and the results of the three example problems.

6.1. Example Problems

This section presents the results of the reconfiguration analysis on example circuits. Three example problems are considered which demonstrate use of the load models. The loading in the first example problem is based on spot loads only. Load modeling in the second example problem is based on residential and small commercial diversified load curves along with a spot load. The third example includes feeder measurements along with customer diversified load curves. The third example also illustrates the effect of voltage dependency of loads on system peak. Feeder voltage level is assumed to be 13.2 KV for all three examples. For ease of manual calculation to verify algorithm results, short line sections were assumed to be constructed with conductors and conductor configurations with an impedance of one ohm per mile. While loss reductions are shown to be small, they are demonstrated to exist and are small due to the choice of line impedance and length.

6.1.1 Example 1

This example illustrates the primary features of the reconfiguration algorithm. The problem is designed to test the performance of the algorithm, and therefore the solution is known in advance.

It is to be observed that the reconfiguration algorithm has a natural tendency to place the distribution system in a balanced loading condition [2,20]. As a result, the distribution system is in a better condition to respond to emergency situations.

The system is comprised of three circuits, as shown in Figure 6.1.1.1. Each circuit consists of one substation, eleven line sections, one breaker, and five switches. It can be seen from Figure 6.1.1.1 that there are five switches between any two substations.

System configurations may be classified as valid or invalid. For a system configuration to be valid, the power must always flow in one direction at any point in time for a given circuit in the system (i.e. there must be an open switch between two adjoining circuits in the system). Furthermore, there must not be a single load in the system without power supply (i.e. there must not be two open switches on the main feeder between two adjoining circuits).

For the system in Figure 6.1.1.1 to be valid, the number of open switches between any two substations at any point in time must equal to one. There are five possible switching configurations between any two substations. Since there are three substations with five switches between any two substations, the total number of possible switching configurations is five to the power three (i.e. one-hundred and twenty-five switching configurations).

For the purpose of simplicity, voltage dependency is assumed to be zero (i.e. constant current loads) in this problem. Table 6.1.1.1 shows the circuit loading in KW, KWh losses, and the voltage level for each circuit. The time point analyzed is a summer, weekday at 6 p.m. The algorithm took twelve seconds to converge. The results show that reconfiguration tends to balance loads, losses, and voltage levels among the three circuits. As a sanity check the load before and after reconfiguration remains the same at

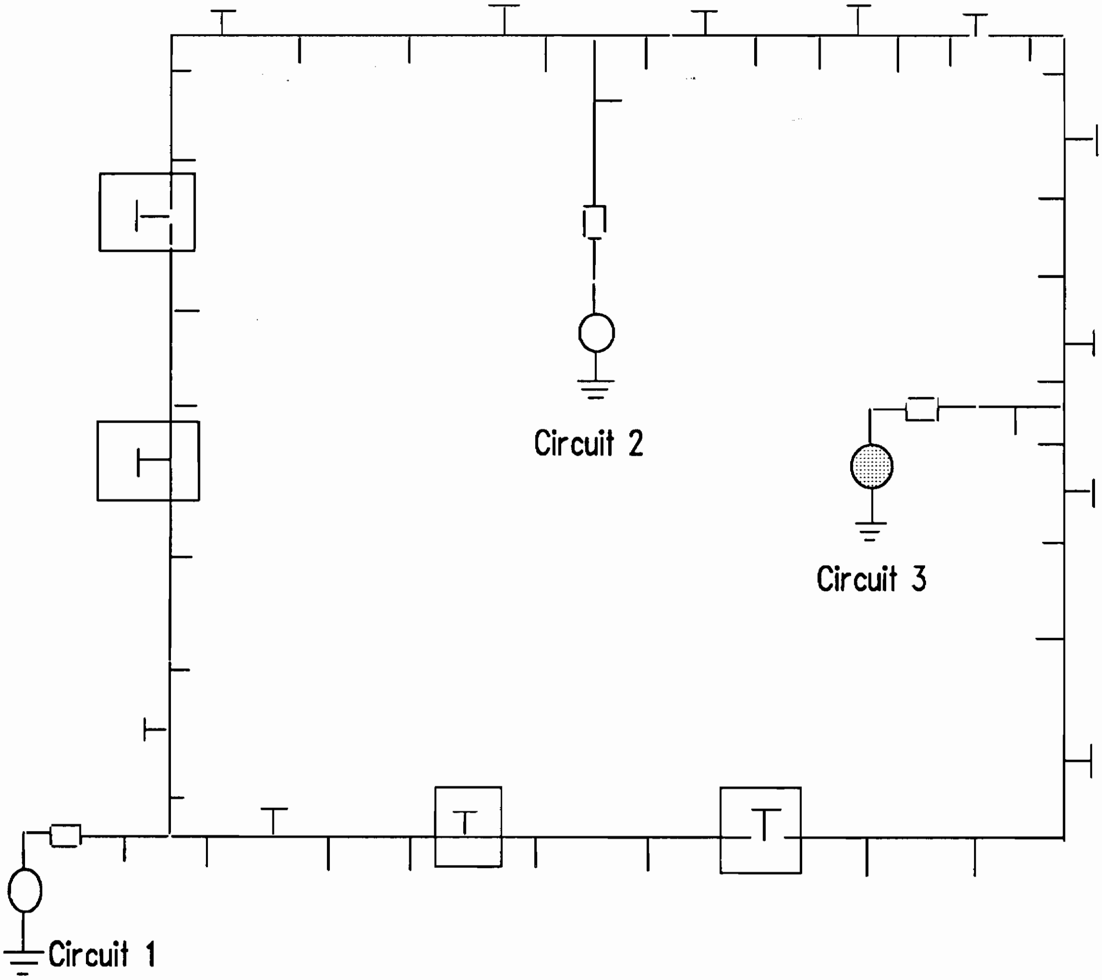

Figure 6.1.1.1 System of Three Circuits for Example 1 for Summer, Weekday, 6 p.m.

Table 6.1.1.1 Reconfiguration Results of Example 1

	Circuit 1	Circuit 2	Circuit 3
Before Reconfiguration :			
Total KW Load	7800	6000	6000
KWh Losses	698.3	413.2	413.2
Voltage Level	116	118	118
After Reconfiguration :			
Total KW Load	6600	6600	6600
KWh Losses	500	500	500
Voltage Level	117	117	117

19800 KW, while the losses are reduced by 25 KW. Operation of the four highlighted switches in Figure 6.1.1.1 produce the calculated results.

6.1.2 Example 2

The topology for the second example problem is shown in Figure 6.1.2.1. The system is comprised of two circuits with two substations, three line sections, two switches, and two breakers. Out of two switches in the system, one must be open and one must be closed at any given point in time.

This example illustrates how the reconfiguration algorithm performs switching operations based on customer loading conditions. These loading conditions are based on two seasons (summer and winter) and two types of day (weekday and weekend). The load estimation is based on diversified customer loads and spot loads. The voltage dependency of loads is assumed to be zero. The spot load of 300 KW is located at the midpoint of the system. This load is used to demonstrate the benefits available by taking advantage of load diversity between different customer classes. Two different customer classes, all electric residential and small commercial, are considered in this example problem.

Circuit 1 has 1000 all electric residential customers per phase while Circuit 2 has 341 small commercial customers per phase. These numbers are chosen such that the noncoincident circuit peak loading is equal for a summer weekday, but unequal for the weekend. Also, the noncoincident circuit peak loading is unequal for winter weekday and weekend. Figure 6.1.2.2 shows the diversified load curves for all

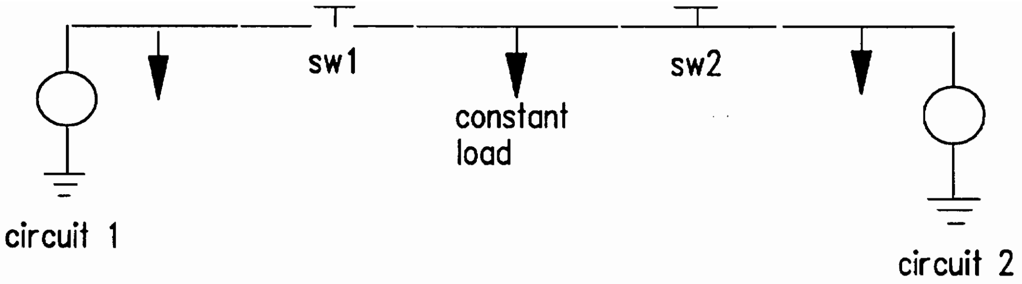

Figure 6.1.2.1 System of Two Circuits for Example 2.

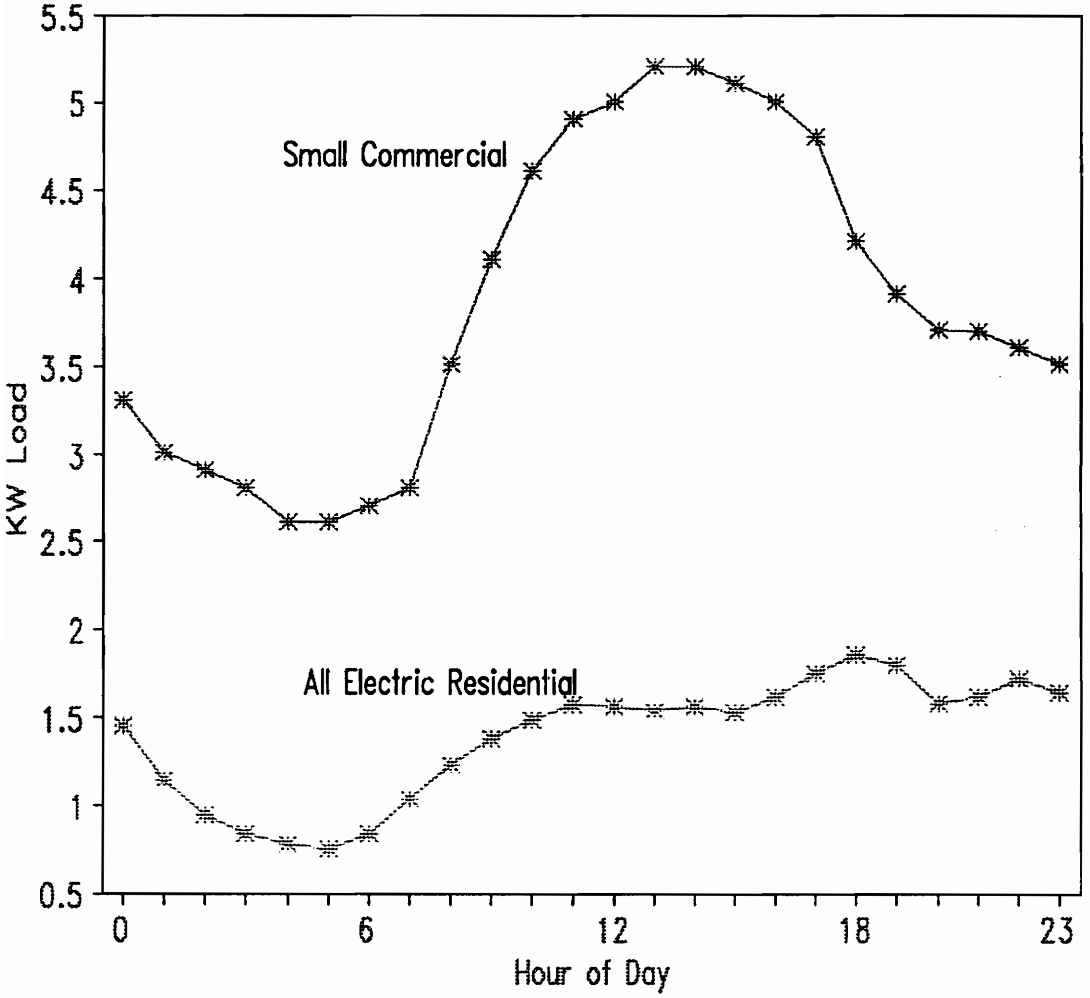

Figure 6.1.2.2 Load Curves for Example 2 for the Summer Weekday.

electric residential and small commercial customer classes for summer weekday. The diversified load curves are obtained from Allegheny Power System [17].

The two switches sw1 and sw2 can shift the constant spot load to either circuit depending on the circuit's loading conditions. Recommended switching changes shift the spot load to the circuit with the smaller load. Table 6.1.2.1 shows the switch positions. the recommended switching operation time points, and the circuit loading.

The constant spot load for the summer weekday is served 13 hours per day by Circuit 1, which has all electric residential customers, and 11 hours per day by Circuit 2, which has small commercial customers, whereas for the summer weekend Circuit 1 only supplies the spot load for 1 hour. In contrast to the summer results, results for winter weekdays and weekends reveal that the spot load is always served by Circuit 2 (i.e. switch sw1 always remains open while switch sw2 always closed). Table 6.1.2.1 shows switch status and the circuit KW loading for three time points for winter weekday and weekend.

6.1.3 Example 3

A system of three circuits which incorporates both manual and automatic switches is considered as shown in Figure 6.1.3.1. The system is composed of forty-one line sections, seven protective devices, three line-voltage regulators, and six switches. Among the six switches four are sectionalizing switches (viz. sw1, sw3, sw4, and sw5), whereas two are tie-line switches (viz. sw2 and sw6). All three substations are assumed to be at the same voltage level. Secondary side transformer voltages are assumed to be 13.2 KV for all three substations.

Table 6.1.2.1 Results of Example 2

Hour of Day	Switch 1 Status	Switch 2 Status	KW Loading Circuit 1	 Circuit 2
Summer Weekday:				
12 am	open	closed	4410	3840
2 am	closed	open	3150	3161
7 am	open	closed	3210	3297
9 am	closed	open	4200	3678
5 pm	open	closed	5280	5394
Summer Weekend:				
12 am	open	closed	4590	3614
5 am	closed	open	2850	2578
6 am	open	closed	2670	2786
Winter Weekday:				
12 am	open	closed	11220	3134
2 am	open	closed	10710	2827
5 pm	open	closed	12570	4504

Table 6.1.2.1 Results of Example 2 Continued

Hour of Day	Switch 1 Status	Switch 2 Status	KW Loading	
			Circuit 1	Circuit 2
Winter Weekend:				
12 am	open	closed	10890	3031
2 am	open	closed	10530	2919
5 pm	open	closed	12120	3451

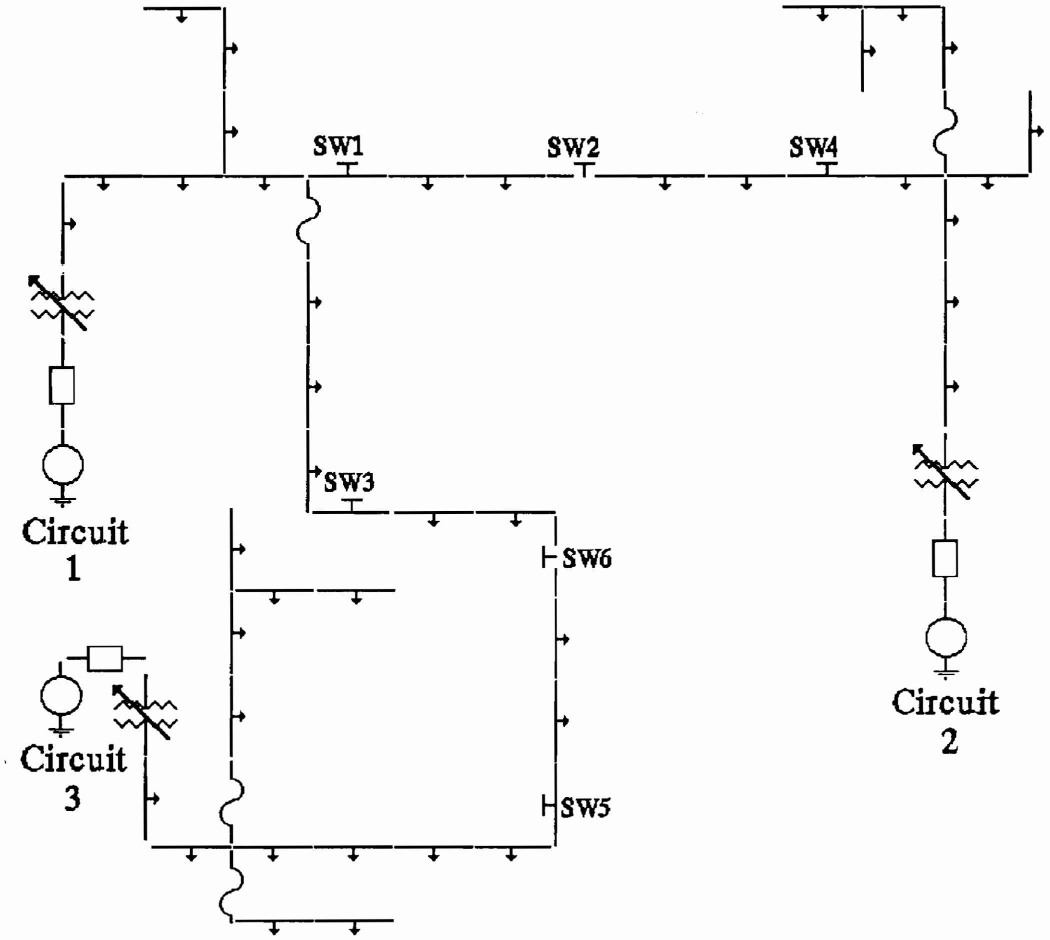

Figure 6.1.3.1. System of Three Circuits for Example 3.

Daily and seasonal switching patterns are analyzed as a function of both switch placement and switch statuses (switch status implies an open or a closed switch). The placement of manual and automatic switches into the system is performed interactively using a graphical interface. The reconfiguration algorithm is not designed to select switch placements automatically.

The reconfiguration algorithm is used to evaluate the effects of both manual and automatic switch placement in reference to their contribution to loss reduction. For instance, the system designer may select tentative manual/automatic switch positions.

The reconfiguration algorithm may then be used to evaluate the operation of the switches on system performance. If the reconfiguration algorithm is run over a seasonal load variation, then the operation of both the manual and automatic switches are considered by the algorithm. However, if the reconfiguration algorithm is run over a daily time pattern of load variations, then only the automatic switches are considered in the reconfiguration of the system.

All the switches in the system are initially assumed to be automatic. Thereafter, the reconfiguration analysis is performed on the system and the frequency of change in switch status is observed. If the status of any switch changes on a daily basis, then that particular switch is defined as an automatic switch, whereas if the status of any switch changes on a seasonal basis, then that particular switch is defined as a manual switch. If the status of any switch remains constant throughout year, then that particular switch is defined as manual. The justification for the existence of such a switch may be based on operational maintenance and reliabilty considerations. Otherwise, the switch could be eliminated.

The effect on system peak load when switching at the system peak with voltage-dependent loads is considered. All the loads may be modeled as voltage-dependent current loads, as indicated by Equation [5.1.2]. The switchable segment currents are composed of load currents, as expressed in Equation [5.1.4]. The switchable segment current value after the switching operation is based on the voltage-dependency factor and may be stated as,

$$I\_act_S = I\_nom_S * \{ 1 + VDF_C (V\_act_i - V\_nom_i)\}, \qquad [6.1.3.1]$$

where,

I_act_S = switchable segment current based on the voltage-dependency factor,
I_nom_S = voltage-independent value of the switchable segment current,
V_act_i = actual voltage value at the i^{th} load point,
V_nom_i = nominal voltage value at the i^{th} load point,
VDF_C = voltage-dependency factor for circuit c.

For the purpose of illustration, eight time points are selected for the summer season and eight for the winter. The type of day is assumed to be a weekday. The diversified KW and power factor values for each circuit in the system are also assumed. The spot loads are assumed to be zero. Figures 6.1.3.2a - 6.1.3.2c show assumed feeder KW measurement curves for circuits 1, 2, and 3 for a summer weekday. Figures 6.1.3.3a - 6.1.3.3c show assumed feeder KW measurement curves for circuits 1, 2, and 3 for a winter weekday. Figure 6.1.3.4 represents normalized residential, commercial, and industrial diversified load curves for a summer weekday. Figure 6.1.3.5 illustrates normalized residential, commercial, and industrial diversified load curves for a winter weekday.

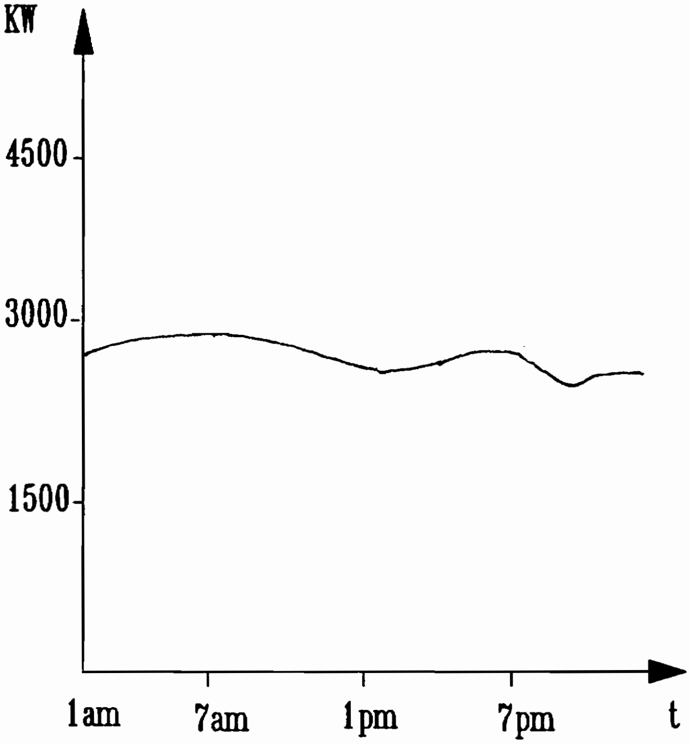

Figure 6.1.3.2a. Feeder Measurement for a Summer Weekday for Circuit 1 in Example 3.

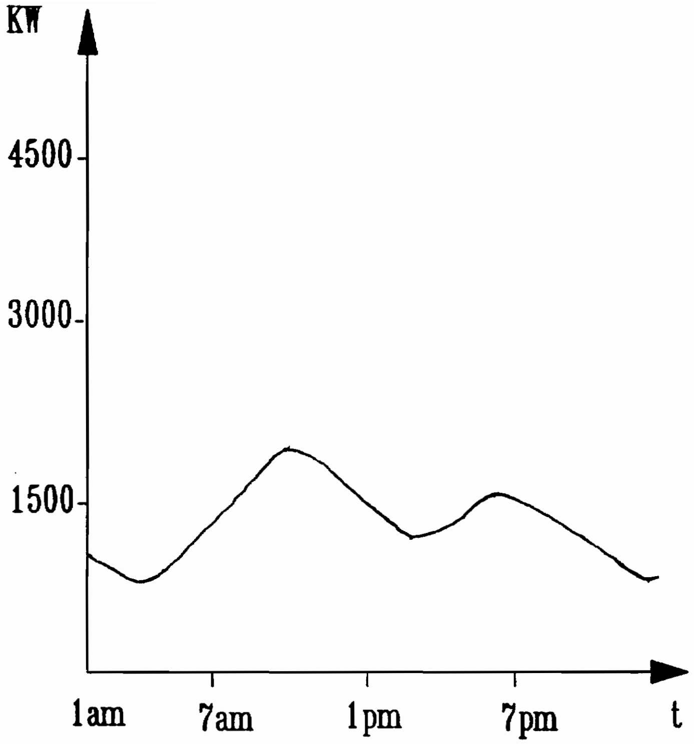

Figure 6.1.3.2b. Feeder Measurement for a Summer Weekday for Circuit 2 in Example 3.

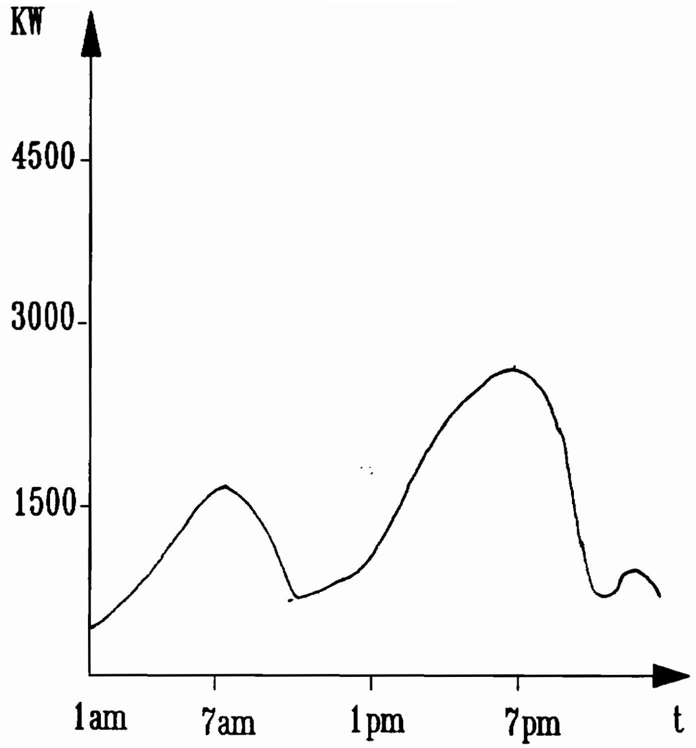

Figure 6.1.3.2c. Feeder Measurement for a Summer Weekday for Circuit 3 in Example 3.

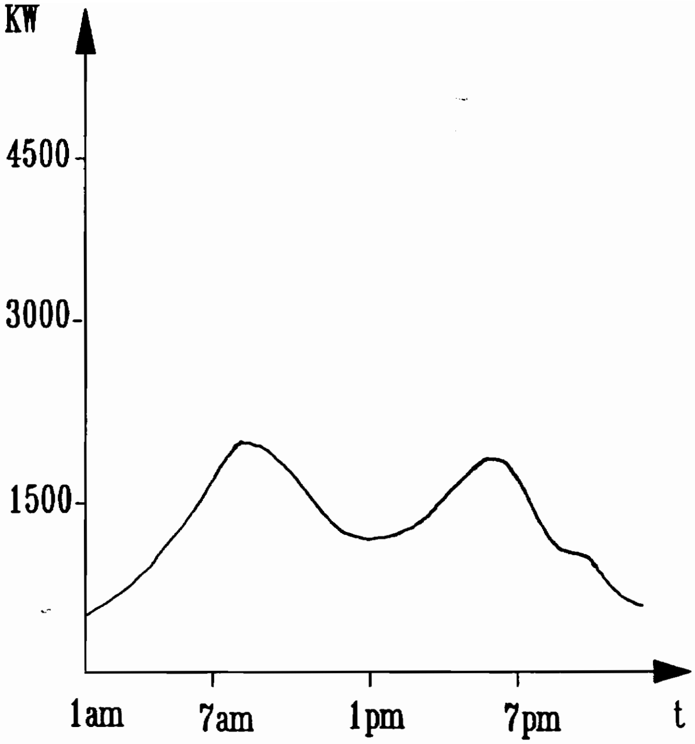

Figure 6.1.3.3a. Feeder Measurement for a Winter Weekday for Circuit 1 in Example 3.

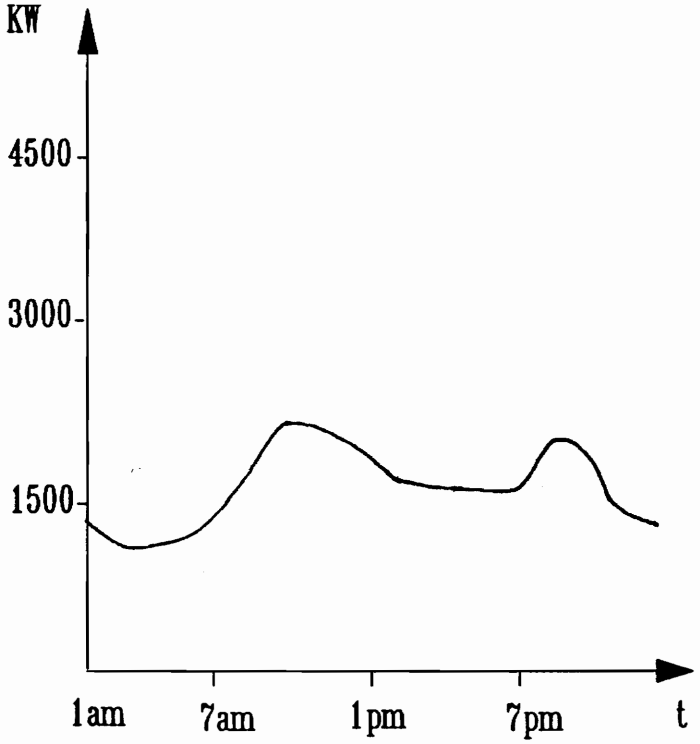

Figure 6.1.3.3b. Feeder Measurement for a Winter Weekday for Circuit 2 in Example 3.

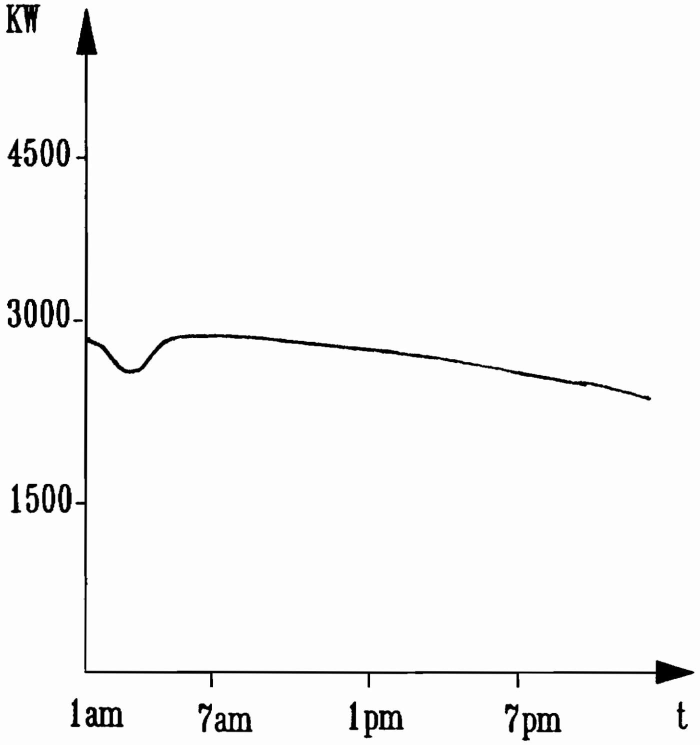

Figure 6.1.3.3c. Feeder Measurement for a Winter Weekday for Circuit 3 in Example 3.

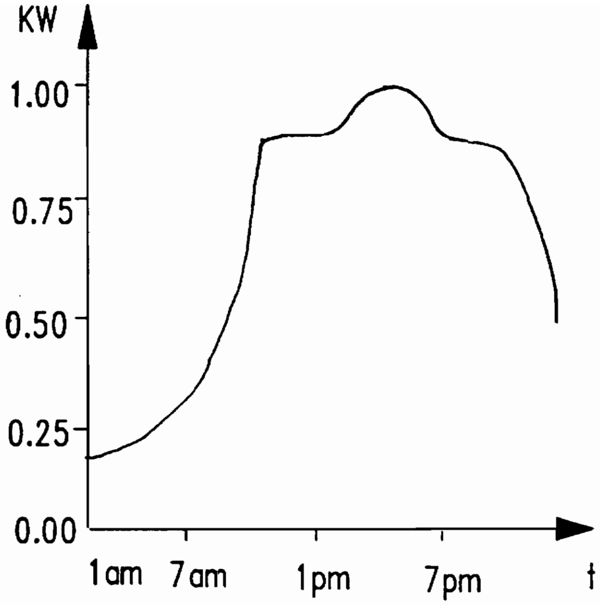

Figure 6.1.3.4 Normalized Diversified Load Curves for a Summer Weekday for Residential, Commercial, and Industrial Type Customers in Example 3.

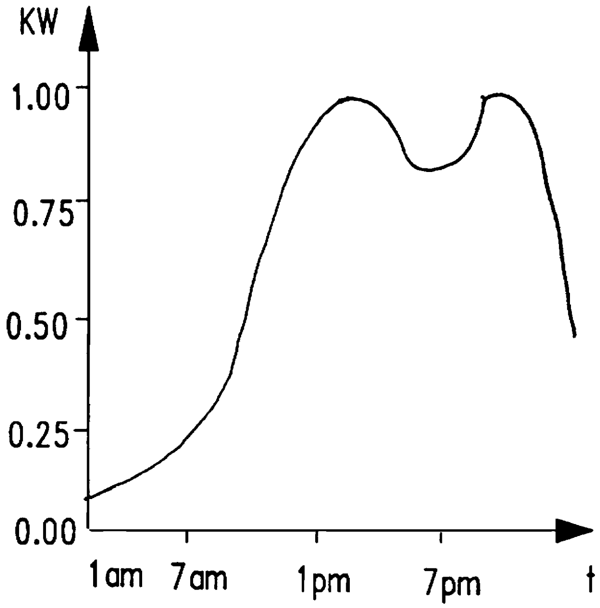

Figure 6.1.3.5. Normalized Diversified Load Curves for a Winter, Weekday for Residential, Commercial, and Industrial Type Customers in Example 3.

All switches are initially assumed to be automatic and then evaluated as to be automatic, manual, or no switch required. Table 6.1.3.1 indicates the switch statuses for each time point considered. From this table, it can be seen that switches sw1 and sw2 are a function of daily load variations and they change their status on a daily basis. Hence, it can be concluded that switches sw1 and sw2 may be of automatic type. The switches sw3 and sw5 change their status on seasonal basis. Therefore, switches sw3 and sw5 may be of manual type. Furthermore, it is seen that the sectionalizing switch sw4 and the tie line switch sw6 do not change their status for any of the time points analyzed. Thus sw4 and sw6 are not required from the loss reduction standpoint for the time points analyzed. However, for other time points they may change their status. In reality, they may be placed there for reliability or maintenance purposes.

Total loss reductions due to the reconfiguration over summer, winter, and fall seasons based on a single day were determined. The total loss reductions per day for summer, winter, and fall are shown in Table 6.1.3.2. Assuming 92 days for summer, 90 for winter, and 183 days for fall & spring, the total loss saving in KWHR over each season is shown in Table 6.1.3.3. From Table 6.1.3.3 it can be seen that the loss savings over a one year period is approximately 57067.0 KWHR.

It has been reported in the literature that most loads are voltage dependent [6], as given by Equation [5.1.3]. Total loading on the system changes when switching operations are performed with voltage dependency different from zero. This voltage dependency of loads is also modeled in the reconfiguration algorithm. Example 3 also demonstrates the effect of voltage dependency of loads on system peak and system losses.

Table 6.1.3.1 Switch Status for Sixteen Time Points Analyzed

(C = Closed, O = Open)

Season	Type Of Day	Hour	sw1	sw2	sw3	sw4	sw5	sw6
Summer	Weekday	1am	C	O	O	C	C	C
		2am	C	O	O	C	C	C
		4am	O	C	O	C	C	C
		8am	O	C	O	C	C	C
		9am	O	C	O	C	C	C
		3pm	O	C	O	C	C	C
		4pm	O	C	O	C	C	C
		8pm	O	C	O	C	C	C
Winter	Weekday	1am	O	C	C	C	O	C
		2am	O	C	C	C	O	C
		4am	O	C	C	C	O	C
		8am	O	C	C	C	O	C
		9am	O	C	C	C	O	C
		3pm	O	C	C	C	O	C
		4pm	O	C	C	C	O	C
		8pm	O	C	C	C	O	C

Table 6.1.3.2 Total Loss Reduction Per Day in KWHR for Each Season for Example 3

Season	Loss
Summer	252.2 KWHR
Winter	42.4 KWHR
Fall	164.2 KWHR

Table 6.1.3.3 Total Loss Saving for Each Season for Example 3

Season	Total Days	Loss
Summr	92	23202.4 KWHR
Winter	90	3816.0 KWHR
Fall/Spring	183	30048.6 KWHR

Table 6.1.3.4 and 6.1.3.5 show the effect of voltage dependency of loads on system peak and system losses, respectively. The losses saved must be greater than a specified threshold value. In this study 5 KW is used as the threshold value. The study is performed on a single time point with arbitrary selected voltage dependency factors of -0.03, -0.01, 0.00, 0.01, 0.03. The time point selected is summer, weekday, 2 a.m.

In order to simulate constant impedance type load behavior, positive voltage-dependent load factors are used, whereas constant power load behavior is simulated using negative voltage-dependent load factors. It can be seen from Table 6.1.3.4 that due to switching load from a lower to a higher voltage level, the negative voltage-dependent load factors contribute towards a decrease in system loading and the positive voltage-dependent load factors make the system loading go higher.

From Table 6.1.3.4, it is seen that at 0.01 and 0.03 voltage dependency factors, the increase in loading is 0.11% and 0.32%, respectively. As the voltage dependency factor is increased towards the positive side, the percent increase in system load also goes higher. At zero voltage dependency factor, the system load stays constant. As the voltage dependency factor is decreased (i.e. -0.01, -0.03), the system load goes lower. For example at -0.01 and -0.03 voltage dependency factors, the load is decreased by 0.11% and 0.34% respectively. From Table 6.1.3.5, it is seen that at -0.03, -0.01, 0.00, 0.01, and 0.03 voltage dependency factors, the percent decrease in KW loss due to reconfiguration is 16.34%, 15.68%, 15.36%, 15.0%, and 14.4% respectively. The pattern shows that as the voltage dependency is increased, the change in KW loss is decreased. Thus, it can be concluded from Table 6.1.3.5 that, if the system is not operating at annual peak, the loss savings may be worthwhile at any voltage dependency factor. Furthermore, if the system is operating at the annual peak, then switching operations are not recommended.

Table 6.1.3.4 Load in KW for Three Circuits as a Function of Voltage Dependency Factor for Summer, Weekday, 2 a.m. for Example 3

	Voltage-Dependent Factors				
	-0.03	-0.01	0.00	0.01	0.03
Base Case =	11161.8	11029.8	10965.8	10903.0	10781.0
After Switching =	11123.2	11017.4	10965.8	10914.9	10815.6
Change in Peak =	38.6	12.4	00.0	-11.9	-34.6

Table 6.1.3.5 Loss in KW for Three Circuits as a Function of Voltage Dependency Factor for Summer, Weekday, 2 a.m. for Example 3

		Voltage-Dependent Factors			
	-0.03	-0.01	0.00	0.01	0.03
Base Case =	317.5	307.4	302.6	297.9	288.9
After Switching =	265.6	259.2	256.1	253.1	247.3
Change in Peak =	51.9	48.2	46.5	44.8	41.6

CHAPTER 7

Conclusions And Recommendations

A new reconfiguration algorithm for electrical distribution systems, which analyzes time varying load patterns is presented. The present research deals with distribution reconfiguration from the loss reduction perspective. This chapter provides the conclusions and future recommendations on the research carried out regarding electrical distribution reconfiguration. The next section gives conclusions on major acheivements and contibutions of this research. Section 7.2 focus on enhancements to this algorithm which may be implemented in the future.

7.1 Conclusions

The following contributions have been made as a result of this work :

1) A new reconfiguration algorithm for electrical distribution systems, which analyzes diversified time varying load patterns to reduce system losses, is developed and implemented in the C language on an OS/2 operating system.

2) The reconfiguration algorithm incorporates a new load estimation algorithm which is used to estimate KW and KVAR values from the customer-type diversifed load curves and from feeder measurements.

3) The status of both manual and automatic switches is evaluated regarding their contribution to loss reduction.

4) It is demonstrated how the placement of both manual and automatic switches is evaluated regarding their contribution to loss reduction.

5) The algorithm operates on a series of loading conditions based on hour of day, type of day, and season and generate a reduced loss configuration for each given load condition.

6) Voltage dependency of loads is modeled. If the system is not operating at annual system peak, it is shown that loss savings are worthwhile at any voltage dependency factor.

7) It is shown that due to voltage dependency of loads, switching at annual system peak may cause the peak to increase.

8) System constraints such as circuit voltage limits and line current overloading are incorporated in the algorithm. Switching operations which violate system constraints are reversed and tagged as not being available for future iterations at the given time point.

7.2 Recommendations For Future Work

The following enhancements to this algorithm may be implemented in future.

1) The reconfiguration algorithm may be used as an online engineering tool in a distribution system control room by interfacing to feeder measurements and a Customer Information System database (CIS). The feeder measurements would be obtained from a

distribution automation system interface. Information from the Customer Information System database would need to be updated on a regular basis. This information includes customer types, number of customers on a given line, and location of customers.

2) An expert system, which validates the switching operations recommended by the reconfiguration algorithm, may be developed to be used in conjunction with the reconfiguration algorithm.

3) A Voltage and power factor coordinating control algorithm may be developed to be used with the reconfiguration algorithm.The control algorihtm should make it possible for switching operations to be performed at annual system peak without increasing system loading.

4) The present study searches for a local minimum. A global minimization technique, which incorporates system constraints, may be sought.

Bibliography

1. J. R. Redmon, C. H. Gentz, "Affect of Distribution Automation and Control on Future System Configuration", IEEE Transactions on Power Apparatus and Systems, pp.1923-1931, April 1981.

2. C. H. Castro, J. B. Bunch, T. M. Topka, "Generalized Algorithms for Distribution Feeder Deployment and Sectionalizing", IEEE Transactions on Power Apparatus and Systems, pp. 549-557, April 1980.

3. Charles T. Huddleston, "Reconfiguration Algorithm for Minimizing Losses in Radial Electric Distribution Systems", Tennessee Tecnological University, 1988.

4. R. E. Lee, C. L. Brooks, "A Methodand Its Application to Evaluate Automated Distribution Control", IEEE Transactions on Power Delivery, Vol.3, No. 1, pp. 1232-1240, July 1988.

5. S. Civanlar, J. J. Grainger, H. Yin, S. S. Lee, "Distribution Feeder Reconfiguration for Loss Reduction", IEEE Transactions on Power Delivery, Vol. 3, No. 3, pp. 1217-1223, July 1988.

6. P. A. Gnadt, J. S. Lawler, "Automating Electric Utility Distribution Systems: The Athens Automation and Control Experiment", Prentice-Hall, Inc., 1990.

7. L. V. McCall, B. J. Chambers, "Defining a Distrubution System for Computer Controlled Distribution Automation", IEEE Transactions on Power Apparatus and Systems, pp.2665-2669, August 1983.

8. Chen-Ching Liu, Seung J. Lee, Khoi Vu, "Loss Minimization of Distribution Feeders: Optimality and Algorithms" IEEE Transactions on Power Delivery, pp.1281-1289, April 1989.

9. IMSL User's Manual Math/Library, Vol. 3, Version 1, April 1987.

10. K. Aoki, T. Ichimori and M. Kanezashi, "Normal State Optimal Load Allocation in Distribution Systems", IEEE Transactions on Power Delivery, Vol. PWRD-2, No. 1, pp. 147-155, January 1987.

11. H. Glavitsch, R. Bacher, "Network Topology Optimization With Security Constraints", IEEE Transactions on Power Systems, Vol. PWRS-1, No. 4, pp. 103-111, November 1986.

12. H. Glavitsch, "Switching As Means Of Control In Power Systems", Electrical Power and Energy Systems, pp. 92-100, January 1985.
13. Roger S. Pressman, Software Engineering, McGraw Hill, New York, 1987.

14. Brian W. Kernighan, Dennis M. Ritchie, The C Programming Language, Prentice Hall, Englewood Cliffs, New Jersey, 1988.

15. Hamidreza Maghdan-D, "Computer-Aided Protection System Design for Electrical Distibution Systems With Automated Switches", Tennessee Technological University, 1989.

16. Stephen G. Kochan, Programming in ANSI C, Hayden Books, Indianapolis, Indiana, 1988.

17. Letter from W. F. Flemming, Providing Normalized Customer Load Table Data, January 15, 1991.

18. R. P. Broadwater, A. Chandrasekaran, C. T. Huddleston, and A. H. Khan, "Power Flow Analysis of Unbalanced Multiphase Radial Distribution Systems", Electric Power Research Journal, pp. 23-33, January, 1988.

19. M. J. Box, D. Davis, W. H. Swann, "Non-Linear Optimization Techniques, "Monograph No. 5, Oliver & Boyd, 1969.

20. R. E. Lee, R. H. Osborn, V. F. Wilreker, M. T. Bishop, "Analysis of Time Varying Distribution Circuit Current and Loss Characteristics", IEEE Transactions on Power Delivery, Vol. 2, No. 4, pp. 1249-1254, October 1987.

Vita

Asif Hayat Khan was born in Lahore, Pakistan on 14th December 1958. He finished his high school in 1977 and passed the Higher Secondary School Certificate Examination with distinction. In 1978 he started studing Electronics Engineering at Dawood Engineering College, Karachi, Pakistan. In 1983 he completed his undergraduate studies, obtaining a B.E. degree with high honors.

From March 1983 to September 1984, he worked as an Electronics Engineer in Azam Instruments Limited - a privately owned company. In Fall 1984 he started his M.S. in Electrical Engineering at Tennessee Technological University, Cookeville, Tennessee and recieved his M.S. degree in June, 1986. Subsequently he joined the Ph.D program in Electrical Engineering at Tennessee Technological University, Cookeville, Tennessee. From June 1986 to July 1989 he worked for Electric Power Center at Tennessee Technological University as a Graduate Research Instructor. In July 1989 he transferred to Virginia Polytechnic Institute and State University and there he continued his Ph.D program, specializing in the area of Power Distribution Systems Automation. His research interests include Application of Software Engineering in Power Systems and Database Systems. He has authored some papers in his fields of interests.

Asif Hayat.