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LOSS REDUCTION IN POWER DISTRIBUTION NETWORKS

by

TAREK SAAD SAYED ABDEL-SALAM

A Dissertation

Submitted to the Faculty of Graduate Studies
through the Department of Electrical Engineering
in partial fulfillment of the requirements for
the Degree of Doctor of Philosophy at the
University of Windsor

Windsor, Ontario

1994

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ABSTRACT

In this thesis, a new technique for power loss reduction in the distribution networks is presented. This technique depends mainly on applying compensating capacitors at certain nodes on the system (*sensitive* nodes) to compensate for the reactive current flow. These *sensitive* nodes are selected carefully, as they have the largest effect on the system loss reduction when they are injected with reactive power from compensating capacitors. The number of these *sensitive* nodes is very small compared to the number of the total system nodes. The *sensitive* node is selected by first identifying the branch which has the largest losses due to reactive power. Then, the node therein which has the largest reactive power is selected. The capacitor rating is determined by differentiating the system losses with respect to the load connected to that node. The compensating capacitors are placed at these optimal locations with appropriate VAR rating to achieve maximum benefits in dollar savings. This novel technique has been applied to the small size (200MVA) distribution network of the city of Kingston, Ontario, and to the medium size (560MVA) network of the city of Windsor, Ontario. The amortized capital and labour costs of the capacitor installation have been taken into account to calculate the net saving. Also, a method for implementing the load variations throughout the year is presented. The technique of applying compensating capacitors has been combined with a method of reconfiguration of the distribution system to reduce further the losses. The combination of the two methods has been applied to the distribution networks of the cities of Windsor and Kingston, Ontario, Canada. Significant savings have been obtained in both systems. This work provides a loss reduction algorithm that is superior to any other known technique.

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CHAPTER 1

INTRODUCTION

The rapidly escalating construction costs of electrical generating stations and the fuel used therein have focused attention on the need to reduce the power and energy losses in transmission and distribution lines. Accordingly, there is interest in methods that lead to energy savings and deferment of need for construction of new facilities.

In Canada and generally throughout the developed industrialized countries, the consumers of electrical energy are guaranteed a good quality of power, which means within certain tolerance of voltage (±5%), frequency (±0.5%), with minimum harmonics and with as short as possible interruption time. It is important to continue to make improvements in the distribution system to satisfy the load demand at a lower cost. The main objective of this thesis is to suggest improved techniques of cost effective reduction of the distribution system losses.

1.1.System Losses

The amount of power losses in the electric distribution system and where they largely occur in the system are of a great interest to the engineers in developing a rate structure for different classes of customers.

It is necessary to supply additional energy over that required to satisfy the load to compensate for the losses in the system. The locations of these losses may be found in the various components of the power system as follows:

1) Transmission system losses:

    a) High voltage transformer losses (the stepping-up transformer).

    b) Transmission line losses.

    c) Substation transformer losses (the stepping-down transformer).

2) Distribution system losses:

    a) Primary feeder and line equipment losses.

    b) Distribution transformer losses.

    c) Secondary and service losses.

    d) Meter losses.

Generally, loss reduction techniques on the transmission network are not as effective as those on the distribution network. Hence, this thesis focuses only on the reduction of power losses in distribution networks.

1.2.Distribution System Loss Reduction

In recent years, there has been a continuous need to accommodate higher loads and overcome delays in the construction of new generating facilities arising from environmental concerns and higher investment costs. Several methods of loss reduction in distribution systems have been reported over the years [1-40] and these will be critically reviewed in Chapter 2.

There are three basic methods to reduce system losses in the distribution system.

The first method is to reduce the equivalent resistance of the system conductors. The power loss in the conductor is given by I^2R, where I is the conductor current, and R is its equivalent resistance. Reducing the value of R results in a proportional reduction in the power losses. This can be achieved by replacing the small size conductors (overhead lines and underground cables) with a larger cross-sectional area, as the resistance is inversely proportional to the cross-sectional area, or by installing auxiliary conductors to work in parallel with the existing ones, so that the equivalent resistance is reduced. Although this method could give a large loss reduction, it is not cost effective, and it is not used unless there is a special need, as the cost of conductors and their installation are usually in excess of the cost of the energy saved.

The second method to reduce the power and energy losses on distribution systems is by system reconfiguration. Reconfiguration of the distribution system can be used as a planning tool as well as a real-time control tool. Most of the distribution systems are reconfigured radially [1], and modifying the radial structure of the distribution feeders from time to time, by changing the open/closed states of the switches to transfer loads from one feeder to another, may significantly improve the operating conditions of the overall system. Feeder reconfiguration allows the transfer of loads from heavily-loaded feeders to relatively lightly-loaded feeders and from higher-resistance routes to lower- resistance routes to obtain the least I^2R, where the resistance route is the total resistance from the source to the load point. Such transfers are effective not only in terms of altering the level of loads on the feeder being switched, and reducing the losses, but also in improving the voltage profile along the feeders and affecting reductions in the overall system power losses. Studies and experiments on feeder reconfiguration are ongoing in several utilities and the recent publications reflecting these efforts are critically reviewed in Chapter 2.

The third method of power loss reduction in distribution systems is the placement of compensating capacitors at specific load nodes. The reactive power flow in power system produces losses. These losses can be kept to a minimum by applying compensating capacitors in distribution points, to inject reactive power, and thus compensate for the inductive load power. Using this method, the reactive power flowing in the system conductors is reduced, and consequently the losses therefrom. As the compensating capacitors affect the losses due to the reactive power component, their effect is more pronounced when the power system has a low power factor. Additional advantages of the installation of capacitors include the boosting of voltage. This is to provide the feeder with the prescribed voltage range within the maximum and the minimum allowable values, respectively at light and heavy load conditions and improving the power factor. The optimum size and location of the capacitor can be determined on the basis of the maximum dollar savings in the energy loss and on the peak power loss reduction [20-40] on the condition that the voltage limits are not violated. The trend in recent years has been to install the capacitors in the primary distribution feeders rather than in the substations. This trend has been due to both the availability of pole-mounted equipment and because it is more economical to place the capacitor close to the reactive loads.

In this thesis only the last two methods for reducing the system losses are considered. It will be shown that these two methods are very cost effective especially when they work consecutively.

1.3.Main Goals of the Thesis

The main objective of this thesis is to study the power and energy losses in the distribution networks, to minimize the system losses using optimal feeder reconfiguration with compensating capacitor placement to achieve maximum annual dollar savings. The variations of the load during the day and for different seasons throughout the year are considered. Three different types of loads are considered namely, commercial, residential and industrial. A mathematical model is implemented and tested on several theoretical and real distribution systems, including the complete distribution system of the cities of Windsor and Kingston in Ontario. Large dollar savings per year are shown to result.

This thesis contains seven chapters. Chapter 1 introduces the thesis and clarifies the goals and direction of the research work. Chapter 2 is a survey and a critical review of the relevant previous work that has been published regarding the loss reduction in distribution systems. In Chapter 3, the variations of the loads with time during the day and throughout the year are considered, and typical chronological load curves are shown. Chapter 4 explains the mathematical models used for reconfiguring the feeders. Chapter 5 shows the new method presented in this thesis of capacitor application, the constraints that should not be violated and the financial requirement to gain the highest dollar savings resulting from power and energy loss reductions. Applications of this method are shown in Chapter 6, giving the results of the loss reduction and the dollar savings. Chapter 7 presents the conclusions derived from this study with the suggestions for future work.

CHAPTER 2

REVIEW OF LITERATURE

2.1.Introduction

This chapter reviews the published literature on the reduction of the losses in distribution feeders. It is divided into two sections: (1) the techniques of reconfiguration of the distribution network for attaining an optimal configuration with minimum system losses, and (2) the application of compensating shunt capacitors to reduce the feeder losses due to the reactive component of the current.

2.2.System Reconfiguration for Loss Reduction

Generally, electric distribution feeders are configured radially [1], for effective coordination of their protective systems.

Distribution feeders contain switches some of which are normally closed and others are normally open. In response to a fault, some of the normally closed switches are opened in order to isolate the faulted network branch. At the same time, some of the normally open switches are closed in order to transfer part or all of the isolated branches to other feeders. All switches are restored to their normal positions after the clearance of the fault [2].

Under normal operating conditions, distribution engineers periodically reconfigure the feeders by opening and closing switches (switching operation) in order to increase the network reliability and/or reduce line losses. The resulting feeders must remain radial and satisfy all load requirements and voltage constraints. Coordination of the protective scheme of the newly configured system is also necessary to ensure that the reliability is maintained at the required level.

Many previous techniques [3-18] for system reconfiguration have been reported to obtain loss reduction. The following section summarizes these different techniques.

2.2.1. Linear Programming

Linear programming methods have been used extensively for a number of years by power system planners to minimize the capital costs of constructing new or expanding existing power systems. The planner's attempts include the calculation and reduction of the system losses I^2R (where I is the current in and R the resistance of the feeder). It is important to review the linear programming method to determine its suitability for system reconfiguration. The linear programming method is a mathematical optimization technique initiated by Dantzig in 1947 [3]. The problem is formulated as

$$\begin{aligned} \text{minimize} \quad & Z = Cx \\ \text{subject to} \quad & Ax = b \\ & x > 0 \end{aligned} \tag{2.1}$$

where Z is the cost function (objective function) which needs to be minimized, x is a vector that represents the variables such as currents, voltages, switch status, etc., C is a transposed vector which represents the coefficients of the variables in the cost function. A is a coefficient matrix of the variables in the constraints equations and b is a vector representing the constraint limits. The linear programming method is only applied to the objective function with constraints all in the linear form. And when linear programming is applied to reconfigure the system, for the purpose of reducing the I^2R losses, the objective function is no longer linear and linear programming is not valid unless a linearization technique is used. Even when a linearization technique is used, the calculation of the system losses is not accurate, and in order to increase the accuracy, a piece-wise linear approximation of the cost factor has to be applied [3].

2.2.2. Heuristic Methods

Heuristic methods [4-7] are used mainly to reduce the large number of the switching options available to a manageable level. These methods do not result in an optimal solution, but they provide near-optimal results in a much shorter time. The computational time is an important factor especially for large systems. But there is a limitation for applying the heuristic methods to very large distribution systems where the number of nodes is of the order of thousands. The number of switching options is very large and using load flow calculations is not only inefficient from the point of view of computational time, but also not practical for real-time control. Shirmohammadi and Hong [2] have presented a formula that evaluates the results of closing a normally-open tie switch and opening a normally closed sectionalizing switch for the purpose of power system loss reduction. Using this formula, the losses can be calculated after each switching operation. The only data needed for this method are the section resistance, nodal voltages, and the currents changed by each switching operation. Using this approach, the available number of options is reduced to the number of normally open-tie switches plus the number of possible switches to be opened to maintain the system radiality. Using this heuristic method, the number of computations and thus feeders reconfiguration, even for a large system, becomes more manageable [3].

2.2.3. Merlin and Back's Method

The method proposed by Merlin and Back [4] depends mainly on opening the link having the lowest current flow in the network, and then applying the Branch and Bound procedure to reduce the system losses. They had constraints on the node voltages and line currents.

The method of system reconfiguration can be summarized as:

1) Close all possible switches to form a weakly meshed network.

2) Calculate the DC load flow. The DC load flow is a load flow calculation but with all sections represented by only their resistances and loads are represented by constant current loads.

3) Find the branch carrying the minimum current as determined by the DC load flow and switch it OFF to disturb the network with the least amount of disturbance, and then check the violation of voltage and currents. If the voltage or the current anywhere in the network exceeds the permissible limits, that switch is turned ON, and the next lowest current switch is opened.

d) This procedure is repeated until a radial configuration is reached.

2.2.4.Power Flow

For the last two decades, the Newton-Raphson method and the fast-decoupled power-flow solution techniques have solved the "well-behaved" power system efficiently [11]. The "well-behaved" power system means a reliable, low voltage drop and evenly loaded system. Many researchers implemented commercial packages based on the Newton-Raphson method and made some enhancement to solve the problem when the system is not "well-behaved", and the degree of the enhancement varies for different packages [11].

Other mathematical techniques are the Gauss and Gauss-Seidel methods. Although these methods are efficient and robust for the small power system, it is not recommended to use them for large power systems, as the convergence is very slow (large number of iterations), or the system does not converge at all [11].

Shirmohammadi et al. [11] published a method for solving the load flow equations. This method is based on breaking the interconnected grid at a number of points (break points) in order to convert the weakly meshed network into a radial network. The radial network is solved efficiently by the application of Kirchhoff's voltage and current laws (KVL and KCL). Then the current flows at the break points are taken into account by injecting currents at their two end nodes. The break point currents are calculated using the multi-port compensation method [12,13]. The multi-port compensation method is an iterative procedure based on calculating the Thevenin equivalent impedance (break point impedance) and then the equivalent

Thevenin voltage is obtained. Using the equivalent Thevenin circuit, the incremental break point current (change in break point current) and the break point current are calculated and updated. This procedure is repeated until a convergence is reached (convergence is reached when the break point voltage is within the prescribed limits).

The solution of the radial network with the additional current injections, completes the solution of the weakly meshed network. The numerical efficiency of the proposed compensation-based power flow method, however, diminishes as the number of the break points required to convert the meshed network to a radial configuration increases. This restricts the application of the method in practice to weakly meshed networks.

2.2.5. Distribution Feeder Deployment

For reconfiguring a distribution system, especially a large one, arranging the system data in a suitable format is a critical step for running the program with the least time and least storage memory. Carlos et al. [14] implemented a data base method to represent the configuration of the network, showing status of system switches and load locations. This method is very useful for computer programs that deal with power system behaviour and improvement such as system reconfiguration, system planning, load flow problem and compensating capacitor application. This method depends on numbering the system sections and load points and identifying every section by the two end load points, giving flags to the direction of the power flow at every section.

2.2.6.Other System Reconfiguration Methods and Research

Wagner et al. [3] compared the linear programming and the heuristic methods which are based on optimal or near-optimal load flow analysis, for the distribution system reconfiguration, in order to minimize the system losses. They concluded that the linear programming method in the form of a transportation algorithm is not suitable for real time application to feeder reconfiguration whilst heuristic approaches can provide substantial savings if properly formulated.

Glamocanin [15] formulated a simple algorithm to obtain an optimal network configuration based on solving the transshipment problem to reduce the distribution system power losses. His method depends mainly on linearizing the power loss function and considers the capacity limits for lines and substation transformers. Also, the node voltages violation limits are included in the algorithm. One of the advantages of Glamocanin's [15] algorithm is that the optimal configuration is independent of the original configuration.

Baran et al. [6] presented a general formulation and a solution method for the distribution system reconfiguration for the purpose of loss reduction and load balancing. They developed two approximate power flow methods with varying degrees of accuracy to give conservative estimates of loss reduction. Their solution employed a search over different radial configurations created by considering branch exchange type switches.

Nara et al. [16] optimally reduced the power system losses using a genetic algorithm (GA) for system reconfiguration. A genetic algorithm is a search algorithm based on the mechanics of natural selection and natural genetics. Nara et al. [16] applied the GA to the loss reduction reconfiguration problem, and they expected the GA would be a fast optimization technique when parallel computers are available.

A feeder reconfiguration method is presented by Hsu et al. [17] for the purpose of load balancing and power loss reduction under varying load conditions. The method is based mainly on heuristics, but they also considered the coordination of the protective devices.

Chen et al. [18] developed a systematic method to derive an optimal switching plan to achieve energy loss minimization for short term and long term operation of distribution systems.

Civanlar et al. [19] presented a computational formula for the purpose of loss minimization by system configuration. The method is based on selecting the best option to transfer a load from a feeder to another. A normally open-tie switch is closed and a normally closed sectionalizing switch is opened to attain system radiality. To decide which switch is to be opened to gain loss reduction the voltages at the two end nodes of the normally opened switch should be calculated, and transferring loads should not be from the lower voltage side to the higher voltage side. Using this method, the number of switching options is limited to a workable value, and optimal system configuration can be obtained very fast if the undesired options are expelled.

2.3.Capacitor Applications on Power Systems

With the growth in the size of power systems, research in the area of reactive power compensation is needed as an alternative to installation of new generating plants. Many researchers have tackled this problem [20-41] but due to the increased complexity of the power system, a cost effective and near optimum technique is needed.

2.3.1.Neagle and Samson

Neagle and Samson [20] have pioneered the application of compensating capacitors on the distribution feeders for the purpose of minimizing the losses due to the reactive power component. They concluded that the connection of a single capacitor rated 2/3 of the total reactive load at the 2/3 of the total length of a uniformly distributed load feeder, can reduce the losses due to the reactive power component by 89%. They also derived a formula giving the optimal rating and location of the compensating capacitors to obtain the maximum loss reduction for a fixed load level on the distribution feeders.

Neagle and Samson [20] also discussed the optimal loss reduction on feeders with uniformly distributed load, a uniformly decreasing load, and the loss reduction when more than one capacitor is used. They included in their work the voltage profile on the distribution feeder. They did not cover the operation of feeders with varying loads that are normally encountered in practice.

2.3.2.Compensating Capacitors with Varying Loads

Cook [21] commented that the traditional method of estimating the power loss in the distribution network, which used the loss factor concept, was not accurate. The loss factor, as defined by Cook [21], is the squared ratio of the root mean squared to the maximum currents.

$$Loss\ Factor = (\frac{I_{rms}}{I_{max}})^2 \qquad (2.2)$$

He gave a rigorous method for calculating the power and energy losses on the distribution feeder using a single capacitor. He gave an example for comparison, and proved the correctness of his method which used the load factor, the ratio of the average to the maximum currents, rather than the loss factor. Although Cook's paper considered the application of compensating capacitors, it did not deal with optimizing the loss reduction.

Duran [22] got the optimal number, locations and sizing of the shunt capacitors by implementing a cost function containing the number, locations and sizes of compensating capacitors. He deduced his formula for specific cases; i.e., when the capacitor cost is not considered, when the capacitor cost is proportional to the installed capacity and when the cost is proportional to installed capacity plus a fixed cost per installed bank were considered.

Chang [23] suggested a computer model to calculate the power loss for any number of radial distribution circuits. His model is used to calculate the losses in every line section, loss reduction due to compensating capacitors, the losses in other equipment such as transformers and voltage boosters, and the power losses at the peak load.

Chang [24] discussed the application of the shunt capacitors for voltage control and peak loss reduction. Although the power loss was reduced by this method, the control of the feeder voltage could not be adjusted to the desired value. This program contains two main parts: (1) it calculates the voltage profile of the feeder for both the light and full load conditions, and indicates if there is a voltage violation, and (2) it determines the optimal ratings and locations of the fixed and switched capacitors for improving the voltage profile, and for maximum power loss reduction.

In addition, Chang [25] analyzed mathematically the applications of the shunt capacitor for loss reduction in distribution feeders, and derived generalized equations for an optimum loss reduction. He presented the loss reduction results as a function of compensating capacitors values.

Bae [26] derived the best, though not the optimal, loss reduction in distribution feeders to suit the variations in the load levels, by obtaining the best location of a single capacitor and using the best capacitor rating. He got about 80% loss reduction at the peak load. He also minimized the yearly energy loss.

Bae based his idea on three consequent steps: first, he obtained the optimal location of the compensating capacitor and the corresponding loss reduction for the fixed load level condition, exactly as Neagle and Samson [20] did. The second step was to develop an equation for the best location of the compensating capacitor and the loss reduction for varying load level condition. To develop such an equation, Bae based his method on minimizing the difference between two optimal loss reduction values. The first one is the optimal loss reduction where the capacitor banks are optimally relocated at every new compensation range, and the second is the optimal loss reduction under fixed bank location condition.

Schmill [27] derived an equation for calculating the optimal locations, ratings of the fixed compensating capacitors, and timing of the switched capacitors for obtaining the optimal loss reduction condition on the distribution feeders. His study was for a uniformly loaded distribution feeder, but with eight cases of distribution operations. These eight cases included deriving loss equations on a uniform distribution feeder with a uniform resistivity without, and then with a different numbers of optimally located compensating capacitors. Also, he included in his cases the fixed and switching capacitor combination with considering the switching time to gain maximum loss reduction when the system was subjected to load variations. Finally, he provided a group of equations for loss reduction on a non-uniform distribution feeder with discrete loads using an optimally located compensating capacitor.

Fawzi et al. [28] implemented a dynamic programming technique to obtain the optimal number, locations and ratings of the compensating capacitors on a uniformly distributed load feeder, when there is an excess of the load at certain load points. They studied the application of the capacitors on a system already having a group of capacitors, and subjected to load increase.

Salama et al. [29,30] described the method of controlling the reactive power, necessary for reducing the total power loss on the distribution feeders. They considered the fixed, and then the variable load level conditions, but with end load, and obtained the equations of the loss reduction using a single capacitor. They calculated the energy loss in the feeder and the energy saving using the method suggested by Cook [21]. They studied the effect of the end load growth on the energy loss, and on the location and rating of the compensating capacitor.

Amer et al. [31] suggested a dynamic reactive power compensator, using a fixed capacitor, an inductor and two silicon controlled rectifiers (SCRs) to control the reactive power injected to the distribution feeder by changing the firing angle of the SCRs.

Following Amer et al. [31], Keene et al. [32], described a method to control the reactive power to obtain maximum loss reduction on the feeder using a microprocessor. Using the microprocessor, a certain value of firing pulses are injected to the SCR group to adjust the equivalent compensator susceptance in order to obtain the maximum loss reduction for any load level. Also, they studied the harmonics of the compensation power, and concluded that the fundamental component has a very large effect on the loss reduction compared to the upper harmonics. Keene et al.'s [32] work stopped at the design and analysis of the dynamic compensator, but they did not apply the method to a power system.

As a general application of Amer's [31] and Keene's [32] work, Kearley et al. [33] applied the dynamic compensation on a real-time closed loop system. A data acquisition system is logged to a power system model to read the reactive component of the load current. Then using the 2/3 rule given by Neagle and Samson [20], the optimal level of compensation is calculated, and is injected to the power system to perform the optimal loss reduction on the feeder at every change in the load level.

Grainger and Lee [34] solved the problem of minimizing the losses on the distribution feeders. They presented a generalized method to find the optimal size and locations of the compensating capacitors using the equal area criterion.

Grainger et al. [35], presented a new scheme for continuously controllable capacitive compensation for a primary distribution feeder. They studied the peak power loss, the energy loss and the cost of the compensating capacitors.

Grainger and Civanlar [36] reported on the maximization of the loss reduction in a distribution system having lateral branches (tree structure) using a group of switched and fixed capacitors. Also they suggested a direct approach to solve the problem.

Nayer and Kuppurajulu [37,38] applied a non-linear programming technique and a voltage correction method to minimize the use of the reactive power in distribution feeders. They minimized the use of capacitors by dividing the year into subdivisions, the day into intervals, assumed that the load is constant during each interval, and used the transformer tap setting for the voltage control [38].

Salama and Chikhani [39] presented a simplified method for reducing the power distribution system losses and for voltage regulation, using a group of optimally located compensating capacitors. They applied the method to a multi-lateral distribution system, with lumped loads. Their results included the voltage profile at the main feeder with capacitors, without capacitors and with a combination of capacitors and voltage regulators.

Bishop and Lee [40] applied a commercial package, CADPAD®, (Computer Aided Distribution Planning And Design) to a real network in Pennsylvania for the purpose of replacing the PCB-filled capacitors with non-PCB insulating fluid capacitors. They studied the loss reduction and voltage profile improvement. Their method was based on the 2/3 rule given by Neagle and Samson [20] to have an initial solution, and then they studied all possible combinations of capacitors to reach a minimum loss condition.

2.4. Loss Reduction by Reconfiguration and Capacitor Placement

A recent work has been published by Lee and Brooks [41] dealing with the continuous system reconfiguration of switches and capacitors with Automated Distribution Control. Lee and Brooks suggested a scheme for reconfiguration and capacitor application, and it can be summarized in six steps:

1. Determine the losses of the existing system.
2. Remove capacitors and optimally reconfigure the system.
3. Determine losses of the reconfigured system.
4. Apply capacitors to the reconfigured system.
5. Perform final load flow analysis to determine losses.
6. Tabulate and compare system load and loss results.

Also Lee and Brooks included the load variations during the year in the calculation by dividing the year into a finite number of periods assuming the load is constant during each of them. They used a program named Constrained Multi-Feeder (CMF) for the system reconfiguration, but they did not show the mathematical algorithm of the program or even a reference to it. Also they used a capacitor application technique based on installing a pre-estimated number of capacitors at each feeder in the network. Lee and Brooks's technique for capacitor application depends on changing the physical locations of the capacitors to have minimal losses whenever the load changes.

CHAPTER 3

LOAD VARIATIONS

3.1.Introduction

One of the most important factors that affect the energy loss calculation in power distribution systems is the load variation with time. Since the customer of electric power switches the power off when the appliance is not in use, the power system is subjected to changes in the load level. Changes in the load level result in fluctuations within the maximum and minimum values and during a defined interval of time (a day, a week, etc.).

Load variations depend mainly on two factors:

1-The usage by the customer of the power. Usually the customer's consumption of the power depends on the type of load (residential, commercial or industrial), and on the time when the power is used (day or night, weekday or weekend and winter or summer). For example, the customer uses an air conditioner in summer day time more than at night, while heating is used in winter nights more than at day time. All these factors affect the load level and the load profile, and must be considered in the load prediction.

2-The combination of the load. Generally, the maximum power capacity flowing in a cable feeding a group of customers is less than the summation of the individual maxima of the power used by the customers. This is because the probability of having individual maximum loads at the same moment is very small, and this probability is getting smaller when the number of individual customers is larger.

3.2.Load Data Implementation

Many classical [20, 21, 29, 30] and modern methods [3, 32, 33, 41] for load implementation and prediction of the load variations have been reported during the last three decades. This section is a critical review of these methods as to their suitability for loss reduction in distribution feeders.

3.2.1.Peak Load Consideration

Neagle and Samson [20] assumed the load without variations, and implemented their formulation using the peak value of the load. Although the method given by Neagle and Samson for loss reduction gives 89% loss reduction at the peak load, it may lead to an increase in the total losses when the load level goes down.

The formula given by Neagle and Samson [20] for loss reduction in a uniformly loaded distribution feeder using a single compensating capacitor located at the optimal location on the basis of the peak load value is

$$PER\ CENT\ LOSS\ REDUCTION = 3a\frac{ckVA}{kVAR}\left(2-a-\frac{ckVA}{kVAR}\right)100\% \quad (3.1)$$

where a is the normalized distance to the capacitor from the source, with an optimal value of 2/3 of the total length of the feeder when the load is at peak value. As it is not suitable to move the capacitor along the feeder when the load varies, the capacitor stays at that optimal position. The value *ckVA* is the rated reactive power supplied by the capacitor when the reactive power of the load is *kVAR*. At the optimal conditions the ratio *ckVA/kVAR* is 2/3. If the load drops to 50% while the fixed capacitor is at the same location, then the loss reduction is zero. If the load decreases to below 50% of the peak value, the loss will increase. This means that the representation of the load profile as a constant load is not suitable for loss reduction.

3.2.2. Using the Loss and Load Factors

Chang [23] calculated the system energy loss by estimating a loss factor, and the energy loss is calculated using the following equation:

$$EL = (L)\,(F_{LS})\,(8760) \qquad (3.2)$$

where EL is the annual energy loss during 8760 hours per year, F_{LS} is the estimated loss factor, and L is the power loss at the peak load.

Cook [21] defined the loss factor in terms of the current,

$$Loss\ Factor = \frac{1}{T}\int_0^T \left(\frac{i(t)}{I_{max}}\right)^2 dt \qquad (3.3)$$

where T is the time period during which the energy is used, and $i(t)$ is the current as a function of time. Cook [21] gave a numerical example to show that the use of the loss factor for calculating the loss reduction by a direct multiplication of the energy loss reduction times the loss factor is not an approximation, but it is an error and should not be used.

Then he presented a formula to calculate the energy loss reduction arising from using compensating capacitors on a uniformly distributed feeder as:

$$\Delta KWH = 8,760R(2I_{max}I_{c}LF-I_{c}^{2}) \tag{3.4}$$

where

ΔKWH = loss reduction afforded by a shunt capacitor.

I_{max} = maximum reactive load current without a capacitor.

I_c = Capacitor current.

LF = reactive load factor (ratio between average yearly reactive load current to maximum reactive load current).

R = line resistance.

Salama et al. [29] and Chang [25] treated the load variation problem by considering the peak load throughout the year, and the load factor F_{Ld}, as defined by Cook [21], and then they estimated the loss factor L_{LOSF} from the equation that was presented by Chang [25] as follows:

$$L_{LOSF} = 0.3F_{Ld}+0.7\,(F_{Ld})^{2} \tag{3.5}$$

The energy loss reduction was obtained by multiplying the peak power loss reduction times the loss factor.

This last method is more accurate than Neagle and Samson [20], but it did not give an accurate estimate of the energy loss reduction as the loss factor estimate depends on only two factors (peak load and load factor) so it can not represent the load variation accurately.

3.2.3.Time Period Method

A more accurate method for estimating the load variations depends mainly on dividing the year into a finite number of time intervals (periods), with an assumption that the load is constant within each of these intervals [3,41]. That constant load at each period can be obtained by one of two methods:

1- Load is measured every time sub-interval within the period (e.g. 15 minutes [41]), and an average value of the measured data is calculated to represent every time period by a constant load. But this method is very difficult as it is hard to measure all the variations of the loads at all the load nodes during the year at interval of 15 minutes especially for large systems, also it would be difficult to store these huge data.

2- The load at every time period is estimated, for many load types, by multiplying the maximum load throughout the year by a certain factor. These factors are implemented on the basis of (a) assumption regarding existing load curves, (b) experience of system planning engineers and (c) existing recent publications [3, 41].

These assumptions and recommendations can be summarized in the following points:

1- Load profiles for industrial loads are almost the same all over the year and are independent of the season, because air conditioning load in summer and heating load in winter represent a marginal portion of the total load. Thus the winter industrial load profile can be used for summer, spring and fall seasons.

2- The fluctuations of the industrial load during the day are within a range of 80-90%, in other words, the ratio of the minimum to the maximum of the industrial load during the year lies between 80-90%.

3- The ratio of the peak industrial load at weekend to that of the weekday is 65 to 70%.

4- Residential load profile is almost the same as the commercial load one, as they use the same type of loads of air conditioning, heating and lighting at the same time of the year, so they can be considered as one type of load.

5- The spring and fall seasons have the same profile for the residential and commercial load, so they can be considered as one season.

6- The residential and commercial load demand for spring/fall season is about 75% of the winter demand, with the same profile.

7- The maximum and minimum load of the winter for the residential and commercial load are approximately equal to those of the summer, with a difference that the summer air conditioning load is more significant during the day time, but the winter heating load is more prominent at night [3].

In the present work the load variation data is based on method 2 mentioned above. Factors thus obtained were considered to be reasonable by engineers of the Windsor Utilities Commission.

Figure (3.1) shows an example of a normalized load profile in the city of Kingston, Ontario [3] for a winter weekday industrial, weekday residential and a winter weekend residential loads. Figure (3.2) shows another example for a residential load throughout the year for a Pennsylvania Power and Light (PP&L) feeder [41].

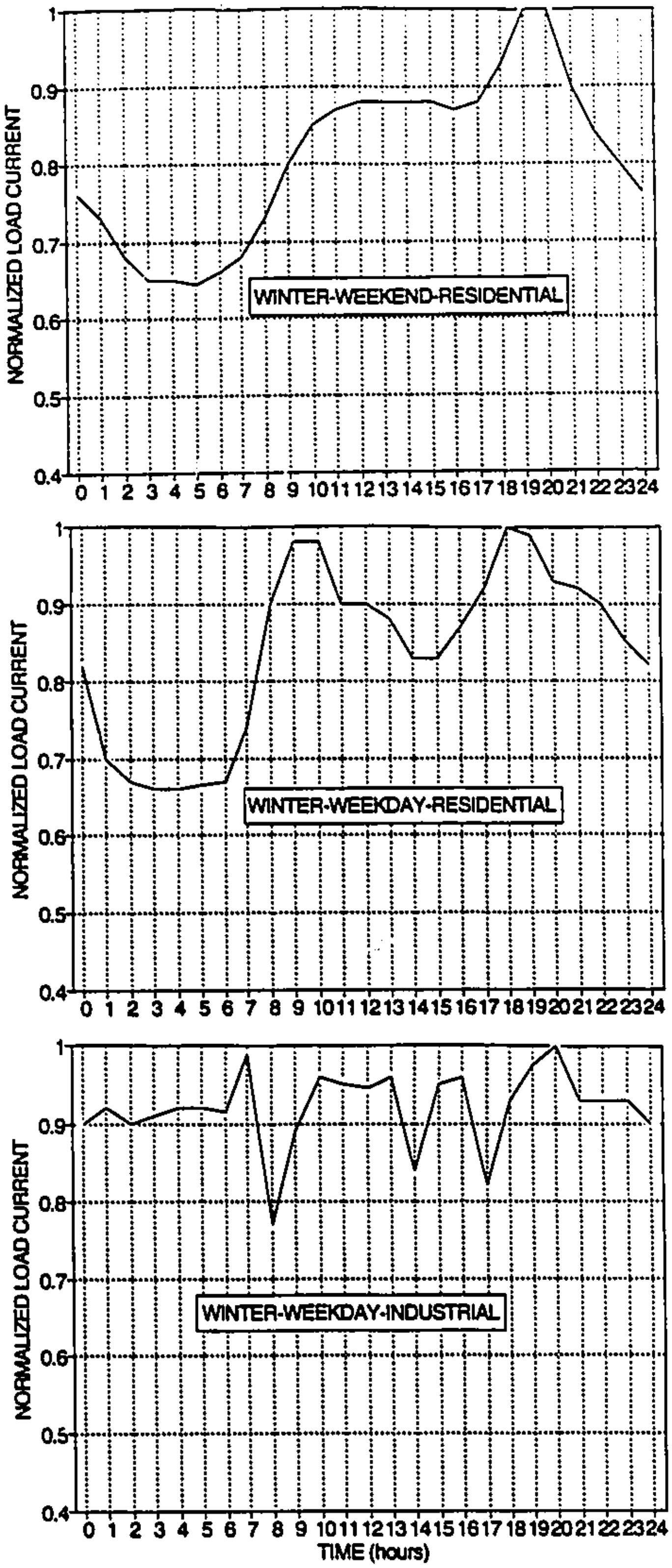

Fig.(3.1) Example of load variations for the City of Kingston.

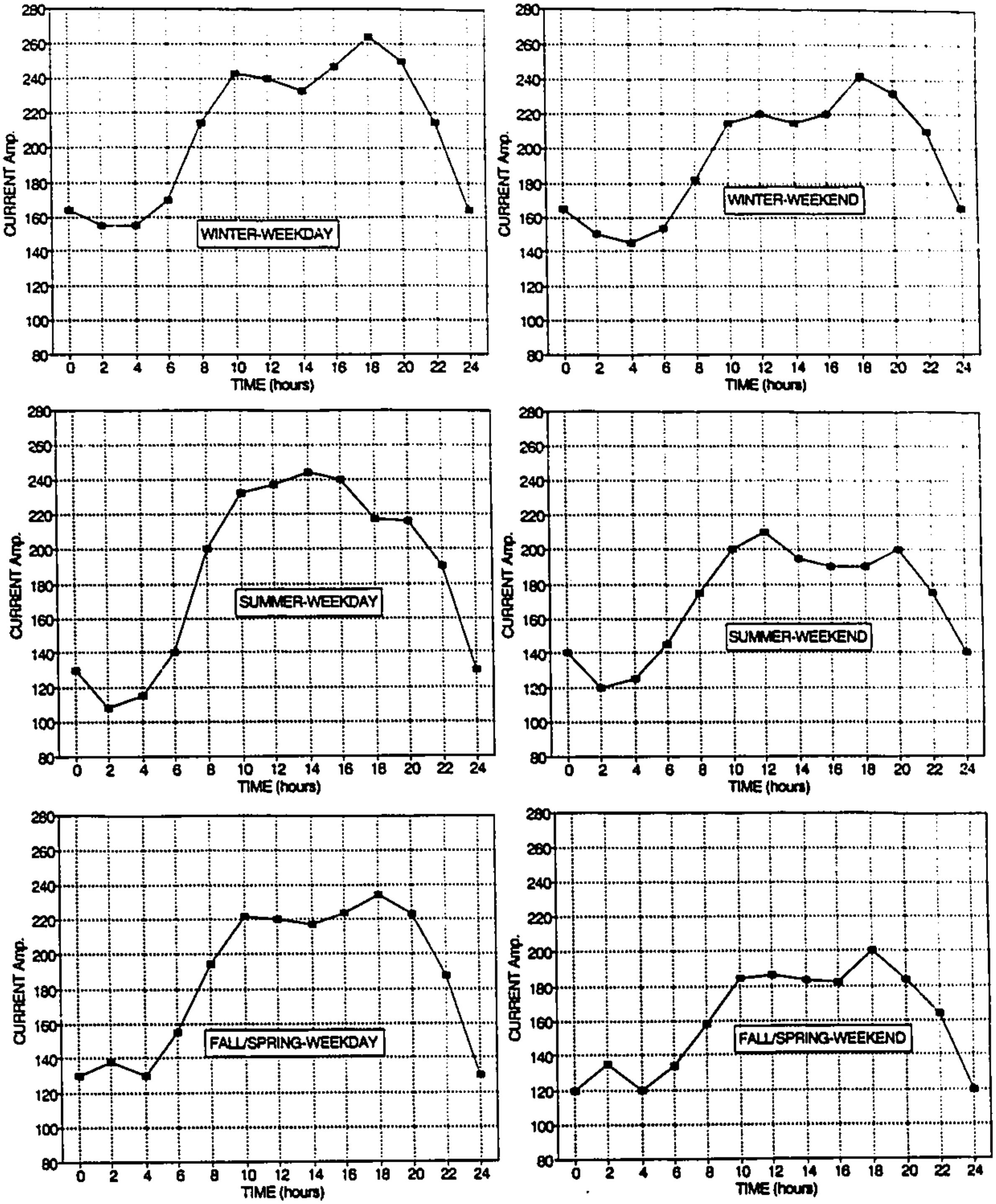

Fig.(3.2) Example of load curves for the PP&L, Pennsylvania

3.3. Model of Load Variations

Usually the load variations throughout the year are not known at every distribution feeder and at every load point (node) to the power utility. Measurements are taken of the power variation only in selected locations and often the distribution engineers are primarily interested in the maximum power levels which are measured in all feeders and in all load points. Hence, a model is required to predict the load levels throughout the year in all feeders and in all load points from the measured values of the maximum power in each node on the feeder.

A study conducted by the Pennsylvania Power and Light Co. monitored loads on eight distribution feeders for a period of one year [41]. By examining the recorded data, it has been determined that in order to model the load changes on a distribution system over a one year period, the year can be divided into three seasons: winter, summer and spring/fall. The months of the year are assigned to three seasons as follows:

Summer	:June, July and August.
Winter	:December, January and February.
Spring/Fall	:March, April, May, September, October and November.

In other parts of the United States and Canada some alteration in the season length is necessary to accommodate the variation of the load but the guiding principle remains the same.

Loads tend to follow the same patterns for each of these three season periods. Daily load profiles within each season will differ according to whether it is a weekday or a weekend/holiday. Daily load profiles will also vary depending on the type of the load: residential, commercial or industrial. The daily load will also vary according to the time of the day: peak period (07:31 to 22:30) and off-peak period (22:31 to 07:30 the next day). The system loads are considered to be constant during each time interval [3].

It has been suggested [41] that the year can be divided into 12 periods to accommodate the load variations due to the seasons (summer, winter and fall/spring), the week (weekday and weekend), and the daily load level (peak load period, and off-peak load period). The method used to render the highest financial return is as follows:

Denoting the time for each period as T_p so that:

$$\sum_{p=1}^{12} T_p = 8,760 \quad hours \tag{3.6}$$

where 8,760=24 h x 365 days is the total number of hours per year, and p the number of periods which varies from 1 to 12.

3.4.Implementation of the Load Variation System Data

It is necessary to know the load variation data during the year in order to obtain a cost effective compensation of the reactive power. Although the method proposed here to forecast the power load during the year gives an approximate estimate of the projected load, the data obtained are close to that used by the Windsor Utilities Commission (W.U.C.), and agree with existing recent publications [40, 41].

The proposed method essentially follows these steps:

1. As the maximum load at each node is known only at a specific period (measured by the power utility), the average load at each of these nodes can be calculated by assuming load factors $h_{s,p}$ where s takes the value 1 for the loads residential and commercial and 2 for industrial, and p takes the values 1 to 12 for the different periods. $h_{s,p}$ depends on the specific period and the type of load (residential, commercial and industrial) and is obtained from the available data of the maximum and the minimum of powers which permit calculation of the average power. $h_{s,p}$ is therefore the ratio of the average to the maximum powers in each period.

2. For the periods in which the data of the power levels are not available, these are calculated using factor ratios $f_{s,p}$ of the maximum load at each period (which we want to find), to the overall maximum power for those periods (in which the data are available). These factor ratios have been suggested by the local power utility and are based on their practical experience.

The factor ratio $g_{s,p}$ used in this study to obtain the average power in each period is calculated using the following relationship and is summarized below:

$$g_{s,p} = f_{s,p} \cdot h_{s,p} \tag{3.7}$$

To obtain the average power at any period the maximum power measured by the power utility is multiplied by $g_{s,p}$ to yield the average in that period. These factors are listed below.

Periods 1 to 12 are defined below for the different types of loads.

1.For residential and commercial loads

1- Winter, Weekday, High load for day. $g_{1,1}=92\%$

2- Winter, Weekday, Low load for day. $g_{1,2}=85\%$

3- Winter, Weekend, High load for day. $g_{1,3}=72\%$

4- Winter, Weekend, Low load for day. $g_{1,4}=67\%$

5- Fall/Spring, Weekday, High load for day. $g_{1,5}=69\%$

6- Fall/Spring, Weekday, Low load for day. $g_{1,6}=63\%$

7- Fall/Spring, Weekend, High load for day. $g_{1,7}=54\%$

8- Fall/Spring, Weekend, Low load for day. $g_{1,8}=50\%$

9- Summer, Weekday, High load for day. $g_{1,9}=85\%$

10-Summer, Weekday, Low load for day. $g_{1,10}=92\%$

11-Summer, Weekend, High load for day. $g_{1,11}=67\%$

12-Summer, Weekend, Low load for day. $g_{1,12}=72\%$

2.For industrial load

1- Winter, Weekday, High load for day. $g_{2,1}=92\%$

2- Winter, Weekday, Low load for day. $g_{2,2}=80\%$

3- Winter, Weekend, High load for day. $g_{2,3}=65\%$

4- Winter, Weekend, Low load for day. $g_{2,4}=60\%$

5- Fall/Spring, Weekday, High load for day. $g_{2,5}=92\%$

6- Fall/Spring, Weekday, Low load for day. $g_{2,6}=80\%$

7- Fall/Spring, Weekend, High load for day. $g_{2,7}=65\%$

8- Fall/Spring, Weekend, Low load for day. $g_{2,8}=60\%$

9- Summer, Weekday, High load for day. $g_{2,9}=92\%$

10-Summer, Weekday, Low load for day. $g_{2,10}=80\%$

11-Summer, Weekend, High load for day. $g_{2,11}=65\%$

12-Summer, Weekend, Low load for day. $g_{2,12}=60\%$

When a feeder has mixed loads of say residential and industrial, the proportions of each type is taken into account when calculating $g_{s,p}$.

Using this relatively simple method, large data files for the whole system are obtained.

If the actual data of the load profiles are available say to the engineers of relatively large power utilities then they can be employed directly. However, most of the smaller utilities are unable to obtain their profiles in all feeders and in all nodes and these factors are thought to be useful to them.

CHAPTER 4

DISTRIBUTION SYSTEM RECONFIGURATION

4.1.Introduction

Most of the distribution systems are reconfigured radially [1], because the radial system furnishes a better protective scheme than any other system of distribution, against faults. Usually the power distribution system has switches that are used for diverting some of the loads to other feeders in the events of a fault. Diverting of loads also occurs to make a balance between heavily loaded feeders and lightly loaded feeders. Also these switches are very important for sectionalizing the distribution feeder for a proper protective scheme. These switches can be used to improve the efficiency of the distribution system by optimizing the path with a minimum resistive route from the substation to the customer load point.

This chapter shows the methods used for reconfiguring the distribution systems with all the assumptions and the mathematical models for the purpose of minimizing the power losses on the distribution feeders. The main goal of the distribution system reconfiguration is to find the optimal distribution scheme that gives minimum losses and satisfies all system constraints such as node voltages and line currents.

4.2.Mathematical Techniques

Many mathematical methods have been employed for the purpose of optimal reconfiguration of the distribution systems in order to minimize the feeders losses [2-19]. The next section is a summary of these methods.

4.2.1.Linear Programming Method

The linear programming method has been used for more than forty years as an optimization technique for system planning, transmission and distribution costs, etc. The general formula of a linear programming problem is a cost function needs to be minimized or maximized within certain limits described by system constraints. This can be written in a mathematical form as

$$Z = C_1X_1+C_2X_2+...+C_nX_n = \sum_{i=1}^{n} C_iX_i \qquad (4.1)$$

where Z is the cost function to be minimized or maximized and the X^{s} are the variables affecting that function, C^{s} are constants coefficients to describe the proportionality of the cost function to the variables and n is the number of these variables. The limitations of the optimization technique are specified by the constraint equations, so that

$$\sum_{i=1}^{n} a_{ij}X_i \le b_j \quad , \qquad j=1,2,..,m \qquad (4.2)$$

where b_j is the limit for j^{th} constraint, and a_{ij} is the proportionality factor of the variable X_i in the equation of the j^{th} constraint, while m is the number of constraints limits.

Experience in linear programming shows that the solution of the problem is an intersection point (vertex) of the constraint equations.

As the loss equation is not linear and is proportional to the squared value of the current (I^2R), the linear programming technique is not suitable for loss minimization unless it is modified with some assumptions such as the linearization technique.

4.2.2.Linearization Technique

One of the linearization techniques used for linear programming approximation is the step-wise method. Here the non-linear cost function describing the system losses can be divided into ranges (Fig.(4.1)) [3]. For each range, an approximation is used to consider the cost function linear, and the proportional coefficient C_i is the slope of the straight line joining the two ends of the function. By increasing the number of ranges, the accuracy of calculation is enhanced, but the computational time also increases. Although this method gives a near optimal result, the calculation of the losses is not accurate [3].

4.3.Heuristic Method

Heuristic methods have been proposed [2-7]for finding the optimal or near optimal solution with fast computational time. Usually the heuristic technique requires a fewer number of iterations compared to any analytical method. One of the heuristic methods to reach an optimal configuration for minimizing system losses was proposed by Wagner et al. [3]. They considered all the possible switching options that may lead to a reduction in losses, calculated the losses and determined which option leads to

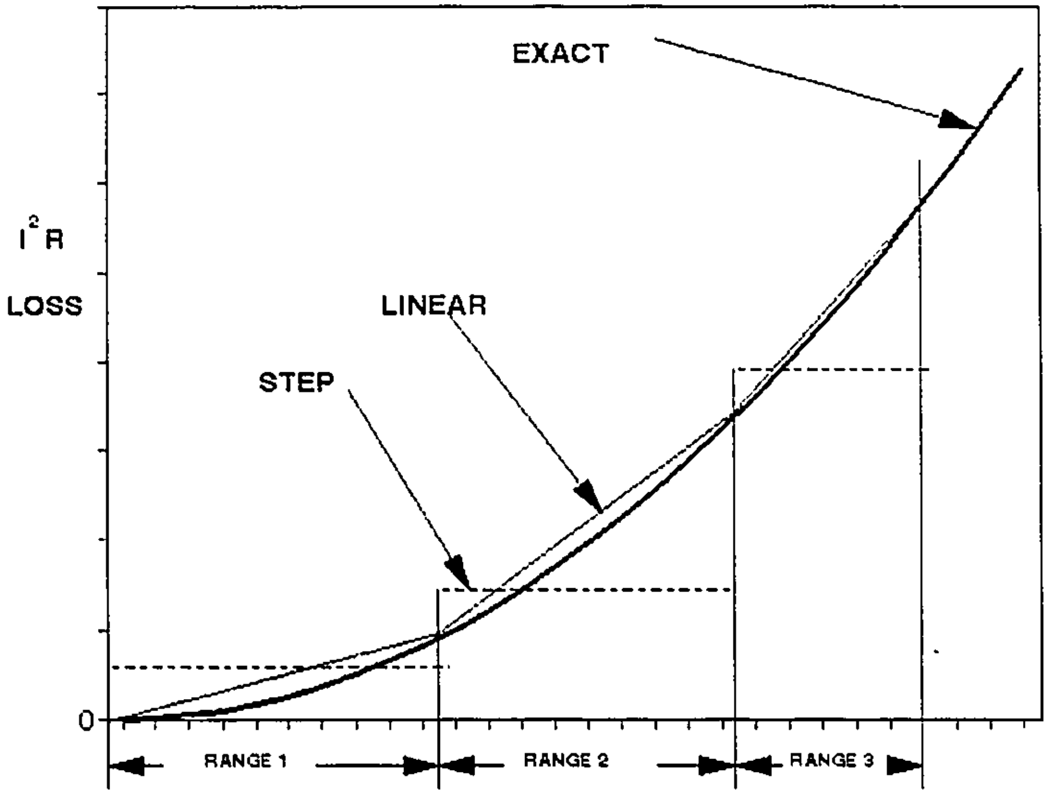

Fig.(4.1) Linearization Technique Used for Linearizing the Non-Linear Cost Function.

minimum losses. Switching option means closing a normally open tie switch and opening a normally closed sectionalizing switch to restore the radiality of the distribution system. Figure (4.2) illustrates a flow chart to demonstrate this method.

Wagner et al. [3] based their method on results given by Civanlar et al. [19]. These results show that the switching options that may lead to reduction in the system losses can be reduced to a workable number after disregarding those options that may lead to an excess in the system losses, lead to voltage limit violation, current excess or customer outages. Therefore the proper switching options can be predicted before calculating the losses. This can be performed by calculating the system voltages, and then the open switches with negligible voltage differences across are disregarded from switching options because closing these switches does not lead to a reduction in the losses [19]. Then, to obtain a reduction in the system losses the switches having large voltage difference are considered. Then, the transfer of the loads should be from the low voltage side of the switch to the higher voltage side. This means that the two voltage drops from the substation to the open switch ends are calculated and it is necessary to transfer loads from the higher voltage drop side to the lower voltage drop side. Using this technique the number of considered switching options is reduced. Although this method gives good results for system reconfiguration it is still difficult regarding the large number of switching options considered and the optimal solution is not guaranteed to be reached especially for a very large system where the number of nodes is of the order of thousands. Also a drawback of this method is that the final solution depends mainly on the original configuration. A better and faster method used for system reconfiguration is the optimal load flow method.

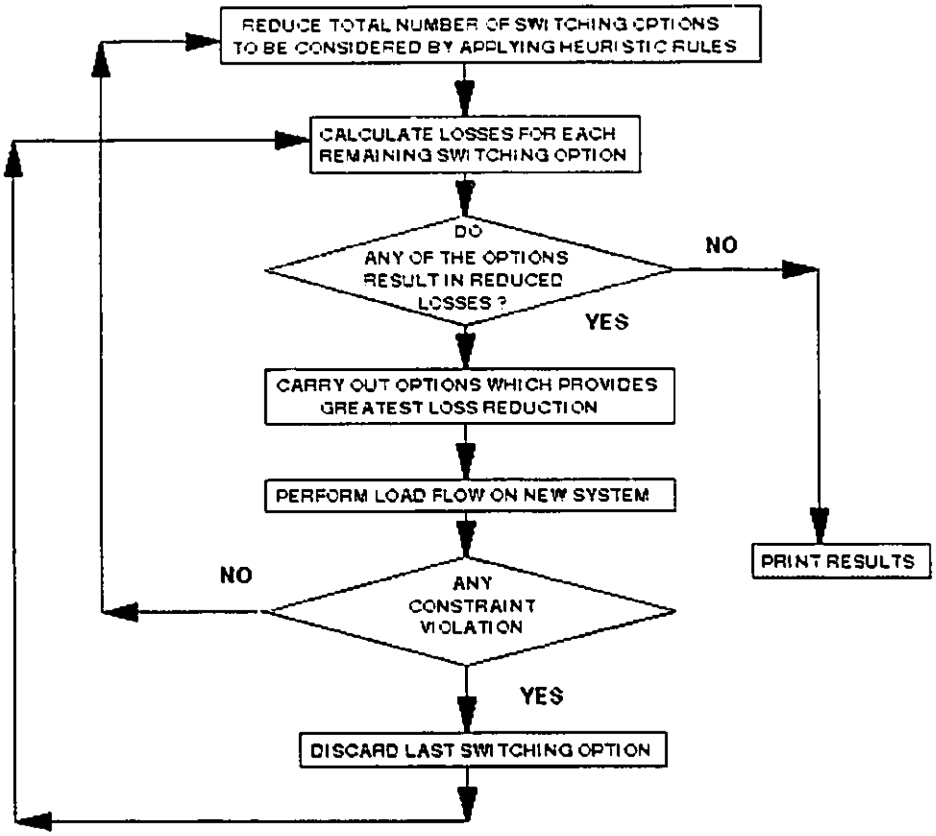

Fig. (4.2) Heuristic Method to Find the Optimal System Configuration.

4.4. Optimal Load Flow Method

The method used in this thesis for reconfiguration is proposed by Merlin and Back [4] and then modified by Shirmohammadi and Hong [2], with an additional subroutine by Wagner et al. [3] to ensure that no voltage or current violation exists during the switching operation. This method is based on a heuristic technique that can reach convergence in a few iterations which is very important in regard to the computational time [2-7].

Figure (4.3) shows a flow chart explaining the method proposed by Merlin and Back [4] for reconfiguration of distribution systems. The first step in this method is to read the system data. These data include static data such as number of sections, number of nodes, number of feeders, section resistances and reactances and dynamic data such as system configuration, switch table, node voltage and nodal load power components (active and reactive). The next step in this method is to close all the normally open switches to form a weakly meshed network and to perform an AC load flow. This step is important to represent the loads as constant power loads therefore the load currents vary with voltage variations, and this is needed for the convergence determination at the end of calculations. The next step is to apply the optimal load flow technique to the weakly meshed network. The optimal load flow technique is the same as the AC load flow except that the feeder section reactances are set to zeros. To reach a radial system, some of the switches should be opened, and this can be done in steps by opening the switch carrying the lowest current as determined by the optimal load flow technique. If the voltage or the current limits at any part of the

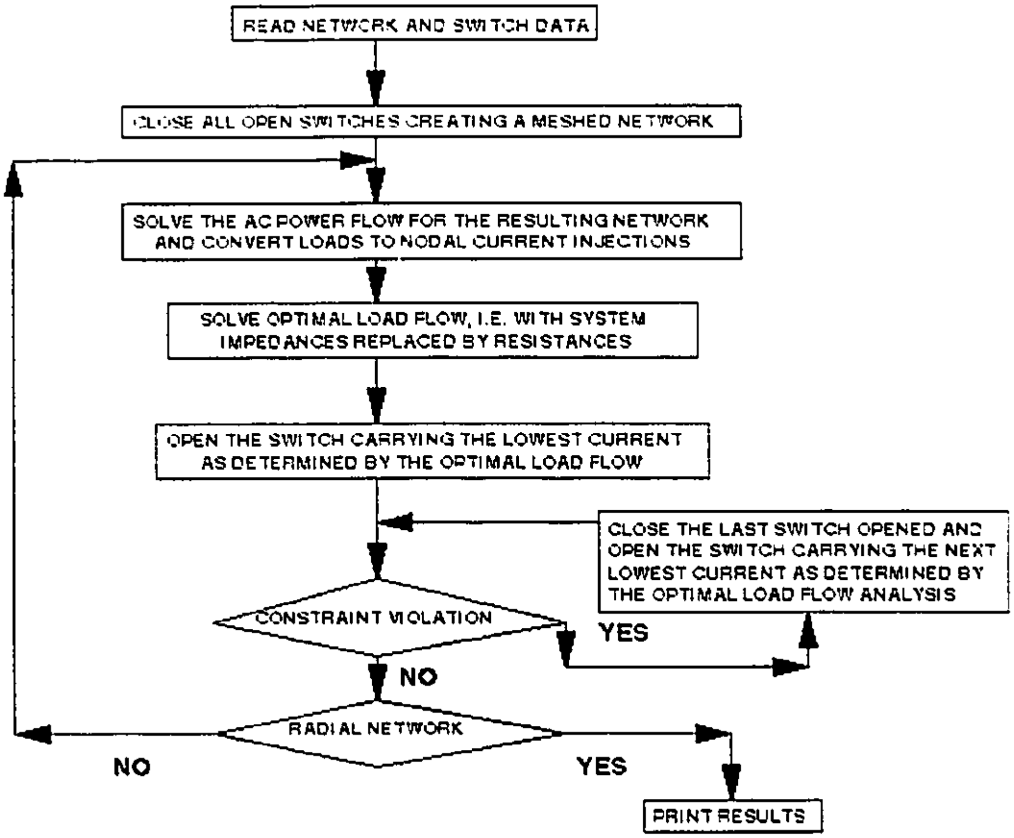

Fig. (4.3) Optimal Load Flow Method for System Reconfiguration.

network, is violated due to the opening that particular switch, then this particular switch is closed and the switch carrying the next lowest current is opened. This procedure is repeated until radial configuration is reached. This radial configuration is the optimal configuration regarding to the system losses for a certain load level and static system data.

4.4.1.Load Flow Analysis

For a large system, where the number of nodes is in the order of thousands, computation time is important and system reconfiguration techniques require an efficient load flow calculation algorithm. Shirmohammadi et al. [11] presented a fast and robust load flow algorithm for a radial system, and they suggested some modifications to use the same algorithm for a weakly meshed network. The weakly meshed network is a radial network containing only a few number of closed loops. The first step in this algorithm is to number the radial system branches and nodes. The numbering technique divides the network into layers (Fig.(4.4)), and gives a number to each section in a layer before the next layer is reached. Then each section L is identified by two end numbers $(L_1\ L_2)$, and the number of the end closer to the power source is smaller than the other end number. The next step in the load flow algorithm is to calculate the current at each node using the following equation [11]:

$$I_i^{(k)} = \left(\frac{S_i}{V_i^{(k-1)}}\right)^* - Y_i V_i^{(k-1)} \qquad i=1,2,\ldots,n \qquad (4.3)$$

where $V_i^{(k-1)}$ is the voltage at node i in the $(k-1)^{th}$ iteration and S_i is the apparent power at node i. Y_i is the summation of the total admittances at node i. Then the current at

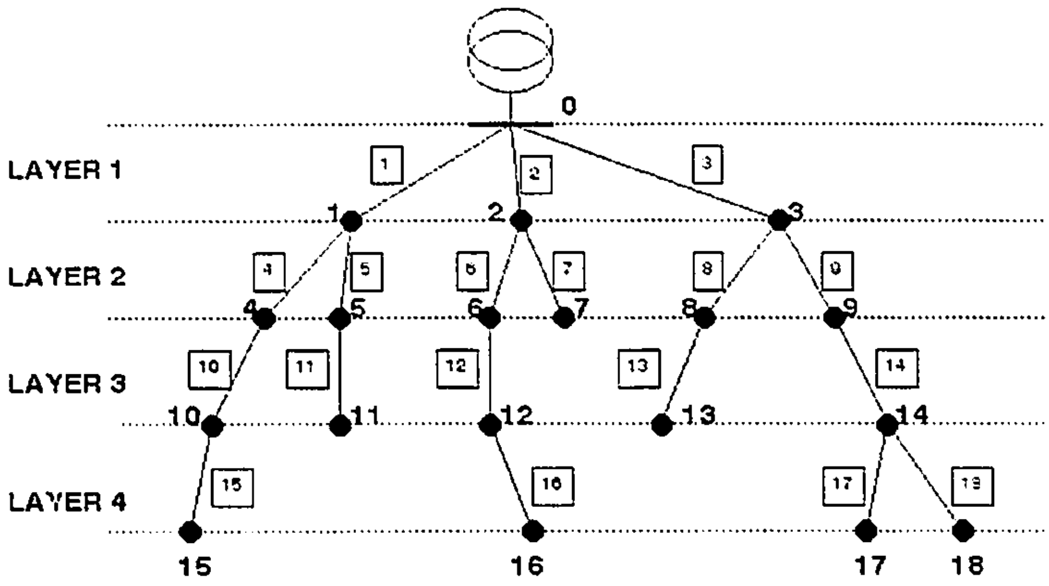

Fig. (4.4) Numbering Technique

every section is calculated using the backward sweep (Equation (4.4)). The backward sweep starts from the farthest section from the source and works back towards the source.

$$J_L^{(k)} = I_{L_2}^{(k)} + \Sigma(\mathit{all\ currents\ eminating\ from\ } L_2) \qquad (4.4)$$

where $J_L^{(k)}$ is the current flowing at section L at the k^{th} iteration. I_{L_2} is the load current at node L_2, where node L_2 is the downstream end of section L. Then the voltage at each node can be calculated by forward substitution in the equation:

$$V_{L_2}^{(k)} = V_{L_1}^{(k)} - Z_L J_L^{(k)} \qquad (4.5)$$

where Z_L is the series impedance of section L, while L_1 and L_2 are the two end nodes of the section L. This procedure is repeated until convergence is reached. Convergence can be determined by the power mismatch. The injected power at each iteration can be calculated from the following equation:

$$S_i^{(k)} = V_i^{(k)} (I_i^{(k)})^* - Y_i |V_i^{(k)}|^2 \qquad (4.6)$$

and the power component mismatch can be calculated as:

$$\begin{aligned} \Delta P_i^{(k)} &= Re[S_i^{(k)} - S_i] \\ \Delta Q_i^{(k)} &= Im[S_i^{(k)} - S_i] \\ i &= 1,2,\ldots,n \end{aligned} \qquad (4.7)$$

where P and Q are the real and imaginary power components. When the values of $\Delta P^{(k)}$ and $\Delta Q^{(k)}$ are less than a permissible tolerance, convergence is reached and calculations stop.

This method [11] can be applied to a weakly-meshed network by opening these loops at certain points (break points) to form a radial system. The procedure is continued as before with an addition that the break point can be considered as two ends of an open switch, with a current injection at each end, and if this current injection can be calculated the radial load flow analysis can be followed. To find the break point injected currents, the Thevenin's equivalent impedance is determined for each break point. This is done by injecting a unit current at each of the break points and the voltage across the two ends of the break point is calculated using the radial load flow analysis. The break point currents are set initially to zero, and the incremental changes in these currents are calculated from

$$\Delta J^{(k)} = [Z]^{-1} V^{(k)} \tag{4.8}$$

where $\Delta J^{k)}$ is the incremental change in the break point current at the k^{th} iteration, $V^{k)}$ is a vector representing the break point voltages at the k^{th} iteration, $[Z]$ is the equivalent impedance matrix at the break points and k is the iteration number. $[Z]^{-1}$ is the inverse of the matrix $[Z]$. When the incremental currents are obtained, the break point current J is updated by adding the incremental value to the previous value.

$$J^{(k+1)} = J^{(k)} + \Delta J^{(k)} \tag{4.9}$$

This procedure is repeated until convergence is reached. Convergence is determined when the break point voltages are zero, or less than a permissible tolerance.

Figure (4.5) shows a flow chart describing the method of load flow [11].

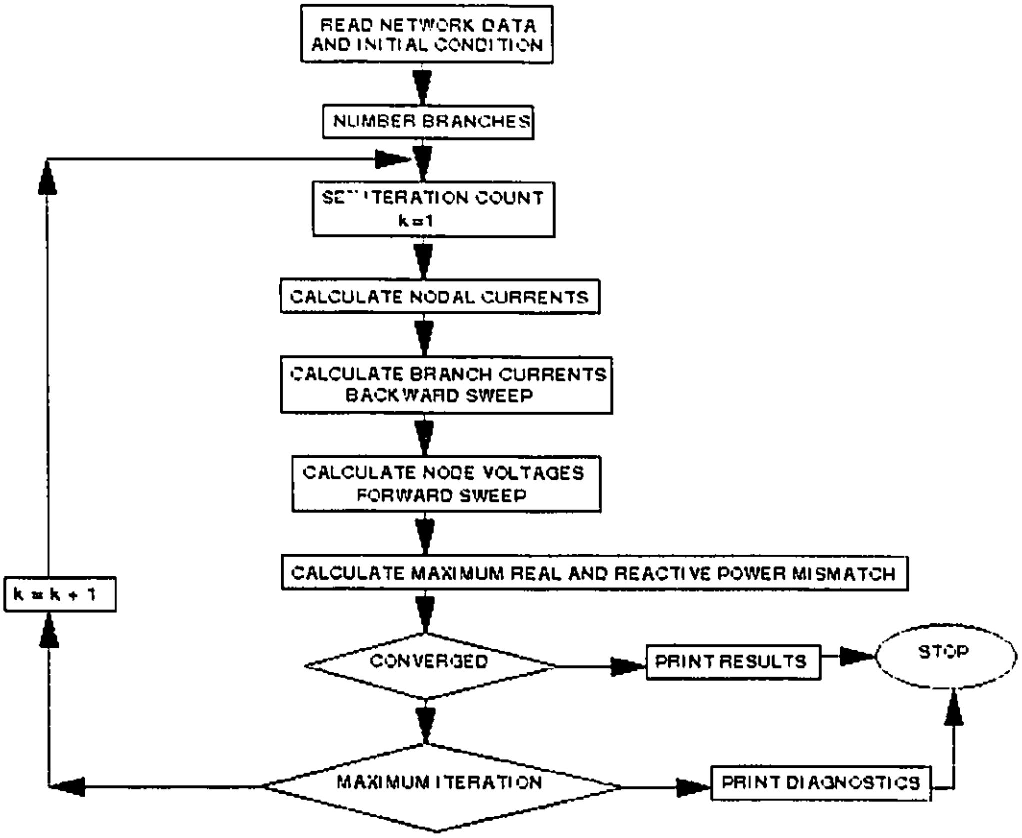

Fig.(4.5) Load Flow Analysis

4.5.Example of System Reconfiguration

As a model application of the Merlin and Back method, a three feeder system is shown in Fig.(4.6) The three feeder system has 13 load points, 3 normally open tie switches and 13 normally closed sectionalizing switches. Table (4.1) shows the data for the three feeder system [19]. This data with the switch table shown in Table (4.2) represent the static and dynamic data.

Table (4.2) shows 12 columns to represent the original configuration of the three feeder system, and this method of arranging the data was proposed by Castro [14].

* Column 1 is a serial number to identify every switch.

* Column 2 is 1 or 0 depending on whether the switch is connected directly to the substation or not respectively.

* Column 3 shows the original situation of the switch either open (0), or closed (1).

* Column 4 shows the updated switch status.

* Column 5 is a one end node of the switch.

* Columns 6, 7 and 8 are all switches connected to that node in Column 5.

* Column 9 is the other end node of the switch.

* Columns 10, 11 and 12 are all the switches connected to the other end node in Column 9.

Many switching options and many radial configuration can be obtained from the three feeder system shown in Fig. (4.6), but the configuration that leads to minimum losses is to close the normally open switches 5 and 11, and open switches

7 and 9, and this result is obtained either by regular trials, or by applying the proposed method.

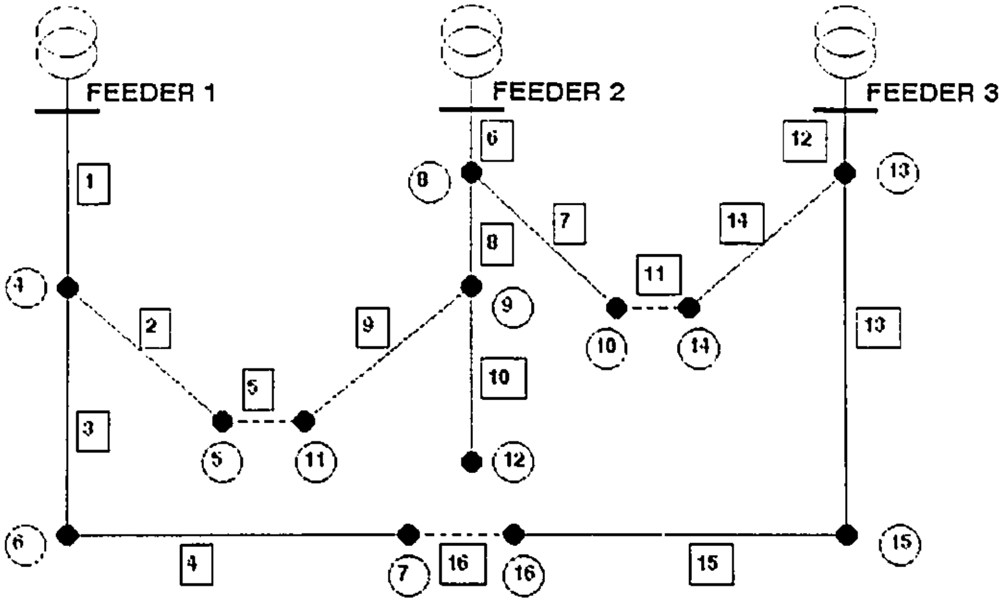

Fig.(4.6) Three Feeder System

Table (4.1) Data for the Three Feeder Distribution System.

Bus to Bus	Section Resistance (P.U)	Section Reactance (P.U)	End Bus Load (MW)	End Bus Load (MVAR)	End Bus Capacitor (MVAR)	End Bus Voltage (P.U)
1-4	0.075	0.1	2.0	1.6		$0.991\angle -0.370$
4-5	0.08	0.11	3.0	1.5	1.1	$0.988\angle -0.544$
4-6	0.09	0.18	2.0	0.8	1.2	$0.986\angle -0.697$
6-7	0.04	0.04	1.5	1.2		$0.985\angle -0.704$
2-8	0.11	0.11	4.0	2.7		$0.979\angle -0.763$
8-9	0.08	0.11	5.0	3.0	1.2	$0.971\angle -1.451$
8-10	0.11	0.11	1.0	0.9		$0.977\angle -0.770$
9-11	0.11	0.11	0.6	0.1	0.6	$0.971\angle -1.525$
9-12	0.08	0.11	4.5	2.0	3.7	$0.969\angle -1.836$
3-13	0.11	0.11	1.0	0.9		$0.994\angle -0.332$
13-14	0.09	0.12	1.0	0.7	1.8	$0.995\angle -0.459$
13-15	0.08	0.11	1.0	0.9		$0.992\angle -0.529$
15-16	0.04	0.04	2.1	1.0	1.8	$0.991\angle -0.596$
5-11	0.04	0.04				
10-14	0.04	0.04				
7-16	0.09	0.12				

Table (4.2) Switch Table of the Three Feeder Distribution System.

SWITCH NUMBER	SOURCE SWITCH	ORIGINAL POSITION	CURRENT POSITION	ZONES BOTH SIDES OF SWITCH AND SWITCH CONNECTED TO ZONES							
				Z1	S12	S11	S13	Z2	S21	S22	S23
1	1	1	1	4	2	3	0	0	0	0	0
2	0	1	1	4	1	3	0	5	5	0	0
3	0	1	1	4	1	2	0	6	4	0	0
4	0	1	1	6	3	0	0	7	16	0	0
5	0	0	0	5	2	0	0	11	9	0	0
6	1	1	1	8	7	8	0	0	0	0	0
7	0	1	1	8	6	8	0	10	11	0	0
8	0	1	1	8	6	7	0	9	9	10	0
9	0	1	1	9	8	10	0	11	5	0	0
10	0	1	1	9	8	9	0	12	0	0	0
11	0	0	0	10	7	0	0	14	14	0	0
12	1	1	1	13	13	14	0	0	0	0	0
13	0	1	1	13	12	14	0	15	15	0	0
14	0	1	1	13	12	13	0	14	11	0	0
15	0	1	1	15	13	0	0	16	16	0	0
16	0	0	0	7	4	0	0	16	15	0	0

CHAPTER 5

CAPACITOR APPLICATIONS

5.1.Introduction

Several methods of loss reduction in distribution systems using capacitors to compensate for the reactive power have been reported over the years [20-41]. But most of these methods have been applied to systems having very special features, such as uniformly distributed load feeders, uniformly sized feeders or simple feeders without any branches or laterals. In recent years there has been an urgency to increase the efficiency of power systems in order to accommodate higher loads and overcome delays in the construction of new generating facilities arising from environmental concerns and high investment costs.

5.1.1.The Uses of Capacitors

The use of compensating capacitors in the distribution systems has many well-known benefits for system performance improvement:

a. The capacitor improves the power factor of the distribution system as it can provide the network with more reactive power to compensate for the inductive reactive power drawn from the utility by the inductive loads. Improving the power factor is important for the generating plant stability, and there is less probability of magnetic field saturation in the generators.

b. The capacitor results in a reduction of the power system losses as the reactive current in the system feeders is reduced by the amount injected to the system via the compensating capacitors (the compensating capacitor can be considered as a pure leading power factor reactive load as the equivalent in phase load is negligible, and usually there is a discharging parallel resistor to reduce the capacitor voltage to 50 volts in one minute as it is recommended by National Electrical Safety Codes NESC). This leads to an increase in the current carrying capacity (Ampacity) of the distribution network, and more power can be sent without upgrading the protective equipment.

c. As a result of benefits (a) and (b), when the flowing current is reduced, the voltage profile on the distribution system is improved without changing the transformer taps. Improving the voltage with a compensating capacitor gives a better profile than with transformer tap changing. The latter raises the voltage everywhere by a certain percentage that may lead to an excess of the maximum allowable limit of the voltage at the customers close to the transformer. Improving the voltage using compensating capacitors can lead to flattening the profile to almost uniformly distributed voltage along the distribution feeder.

This thesis focuses on improvement of the power system loss reduction, with the voltage profile as a limiting constraint that should not be violated. The Canadian Standard Specifications state that the voltage on the distribution system should not exceed ±5% of the nominal value.

5.2. Capacitor Application

In this thesis, a novel technique for application of compensating capacitors is presented. The proposed method identifies the *sensitive* nodes which have a very large impact on reducing the losses in the distribution systems. The *sensitive* nodes are very small in number compared to the total number of the load nodes. The method is relatively fast, very effective and gives a considerable saving both in energy and in net dollars when the amortized costs of the capacitors with accessories and their installations are taken into account.

5.2.1. Numbering Technique

In this method, it is suggested that every section is given a number in the distribution network, so that the number increases with the section goes farther from the substation [2]. Also the nodes are numbered in the same way as the lower numbers are given to the nodes closer to the substation and the higher numbers to the nodes farther from the substation. This arrangement is necessary for implementing a data base file and to determine the direction of the load flow, when a load flow solution is carried out. To simplify the understanding of the number technique, the network is divided into layers starting from the substation. The numbering starts from the substation until the whole layer is completed; the numbering then continues with the next layer, until the entire network is completely numbered.

5.2.2. Capacitor Application Algorithm

The total power loss P_L in a distribution system can be obtained by adding the losses at all the system sections:

$$P_L = \sum_{i=1}^{M} I_i^2 r_i = \sum_{i=1}^{M} (I_{ai}^2 r_i + I_{ri}^2 r_i) \tag{5.1}$$

where M is the total number of the system sections, I_i is the current flowing in the i^{th} section having active and reactive components of I_{ai} and I_{ri} respectively, and r_i is the i^{th} section resistance.

As the losses due to the active component (in phase) of the flowing current can not be affected by the compensating capacitors (zero power factor elements), the only term that is of interest is the losses due to the reactive component of the system current $I_{ri}^2 r_i$. Then the losses due to the reactive current P_{rL} can be written as:

$$P_{rL} = \sum_{i=1}^{M} I_{ri}^2 r_i \tag{5.2}$$

For a radial tree distribution network, the current I_{ri} can be written as

$$I_{ri} = \sum_{j \in S_i} I_{dj} \tag{5.3}$$

where S_i represents the set of all the nodes that their load currents I_{dj} flow in the i^{th} section.

Equation (5.3) is a direct application of Kirchhoff's current law. And by substituting in equation (5.2), P_{rL} can be written as:

$$P_{rL} = \sum_{i=1}^{M} \{r_i \ (\sum_{j \in S_i} I_{dj})^2\} \tag{5.4}$$

To model the configuration of the system, a matrix [A] can be set up as follows:

$a_{ij} = 1$ if $j \in S_i$

$a_{ij} = 0$ if $j \notin S_i$

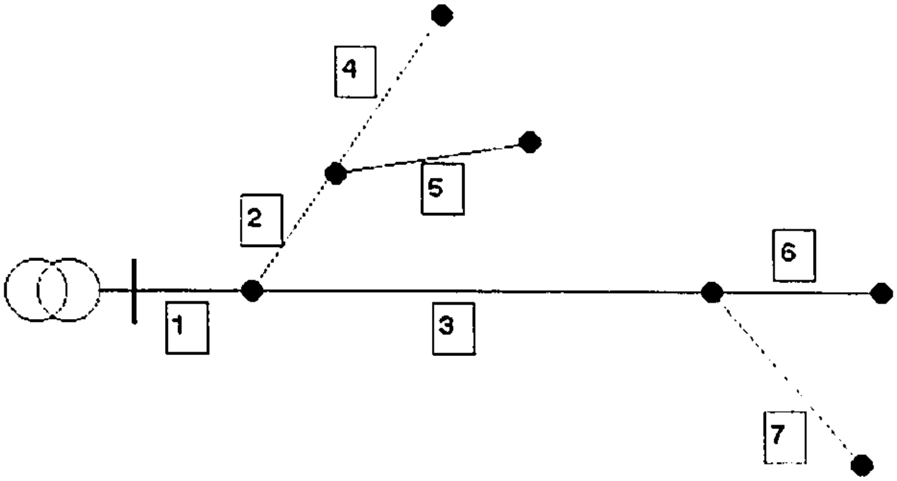

Fig. (5.1) Simple Radial System to Explain the A matrix.

If the simple distribution network shown in Fig.(5.1) is considered, the A matrix can be expressed as:

$$A = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \tag{5.5}$$

Equation (5.4) can be written as:

$$P_{rL} = [r]^T \left([A] \; [I_{dj}] \right)^2 \tag{5.6}$$

where $[r]$ is the system resistance vector and $[r]^T$ is the transposed matrix of $[r]$.

Equation (5.6) represents mathematically the main three factors affecting the losses in the distribution network: the resistances of the network sections that is given by the matrix $[r]$, the system configuration that is given by the matrix $[A]$, and the load currents represented by the matrix $[I_{dj}]$.

The first step of the proposed method is to find the largest lossy section in the system due to the reactive current component, and then to try to reduce these losses therein by as much as possible. Assuming section "h" has the largest loss among all the system sections, so that:

$$P_{rLh} = \underset{i=1}{\overset{M}{MAX}} \; \{P_{rLi}\} \tag{5.7}$$

and

where P_{rLh} is the power loss due to the reactive component in section h, r_h is the

$$P_{rL,h} = r_h \left(\sum_{j \in S_h} I_{dj} \right)^2 \tag{5.8}$$

resistance of section h and S_h represents the set of all nodes with their load currents I_{dj} in the h section.

If the node $K \in S_h$ has the highest reactive load I_{dK} then, it has the highest effect on the system losses, and it is called here a *sensitive* node. This relation can be expressed as:

$$I_{dK} = \underset{j \in S_h}{MAX} \{I_{dj}\} \tag{5.9}$$

Now, a compensating capacitor is connected at node K to change the reactive load current there from I_{dK} to I_{nK}, where I_{nK} is the new value of the reactive current component at the *sensitive* node K. To have maximum loss reduction, the value of I_{nK} can be determined by solving the equation:

$$\frac{\partial P_{rL}}{\partial I_{dK}} = 0 \tag{5.10}$$

To perform this differentiation, equation (5.4) can be expanded as follows:

$$\begin{aligned} P_{rL} = {} & r_1 [a_{11} I_{d1} + a_{12} I_{d2} + \ldots + a_{1k} I_{dk} + \ldots + a_{1N} I_{dN}]^2 \\ & + r_2 [a_{21} I_{d1} + a_{22} I_{d2} + \ldots + a_{2k} I_{dk} - \ldots - a_{2N} I_{dN}]^2 \\ & \qquad \vdots \\ & + r_M [a_{M1} I_{d1} + a_{M2} I_{d2} + \ldots + a_{Mk} I_{dK} - \ldots - a_{MN} I_{dN}]^2 \end{aligned} \tag{5.11}$$

and the result of the differentiation,

$$
\begin{aligned}
\frac{\partial P_L}{\partial I_{dk}} = {} & 2Xr_1[a_{11}I_{d1} + a_{12}I_{d2} + \ldots + a_{1k}I_{nk} + \ldots + a_{1N}I_{dN}]\,a_{1k} \\
& + 2Xr_2[a_{21}I_{d1} + a_{22}I_{d2} + \ldots + a_{2k}I_{nk} + \ldots + a_{2N}I_{dN}]\,a_{2k} \\
& \vdots \\
& + 2Xr_M[a_{M1}I_{d1} + a_{M2}I_{d2} + \ldots + a_{Mk}I_{nk} + \ldots + a_{MN}I_{dN}]\,a_{Mk} = 0
\end{aligned}
\tag{5.12}
$$

Solving equation (5.12) for the value of I_{nk}, the new value of the reactive load current at node K can be written as:

$$
I_{nK} = \frac{-[r_b]^T\ [A]\ \ [I_d]}{[r]\ \ [A_{i,K}]} \qquad , I_{dK}=0 \tag{5.13}
$$

where

I_{nK}=the new reactive load current at node K, after connecting a capacitor;

I_{dK}=the original reactive load current at node K, before connecting a capacitor;

$[A]$=the matrix of the system configuration;

$[A_{i,K}]$=the K^{th} vector of matrix $[A]$;

$[r]$=a vector representing the section resistances;

$[r_b]^T=[r]^T[B]$;

$[B]$=a diagonal matrix that has $b_{i,j}=a_{i,k}$ and zeros elsewhere; and

$[I_d]$=a vector representing the original reactive loads.

And the reactive current injection at node K is the difference between the new and the original load current there. The negative sign in equation (5.13) shows that the direction of the new reactive current at the *sensitive* node is in the opposite direction of the original inductive load. When the *sensitive* node (where the capacitor is installed) is determined, and the difference of the current injection at that node is specified (capacitor current), the nearest available standard MVAR rating or multiple units of the capacitor is chosen. After each step the node voltages are calculated to check for voltage violation, and if any exceeds the permissible limits, that capacitor is disconnected and the node having the next largest reactive load current on the highest lossy section is considered as the *sensitive* node.

This procedure is repeated until the system losses decrease to almost a steady value, and connecting more capacitors will have only a marginal reduction on the system losses. Figure (5.2) illustrates a flow chart describing the new method employed in this study.

Using the proposed method, it suffices to connect capacitors only to the *sensitive* nodes which are few in number to attain very large reduction in the losses arising from the reactive power component.

This method has been tested on many distribution networks (Fig.(4.6)) which are picked from recent publications [3,39]. Also, this method has been compared with another technique [39] and gives a larger loss reduction using a less compensation level.

5.3 Capacitor Ratings and Pricing

In order to calculate the annual saving gained from the capacitor application technique, the capacitor prices should be included in the calculations. Usually the capacitor bank is constructed from a group of small capacitors connected together in parallel to make a larger single phase bank, and then, for a three phase distribution system, three of these banks are connected to make a three phase capacitor bank. The

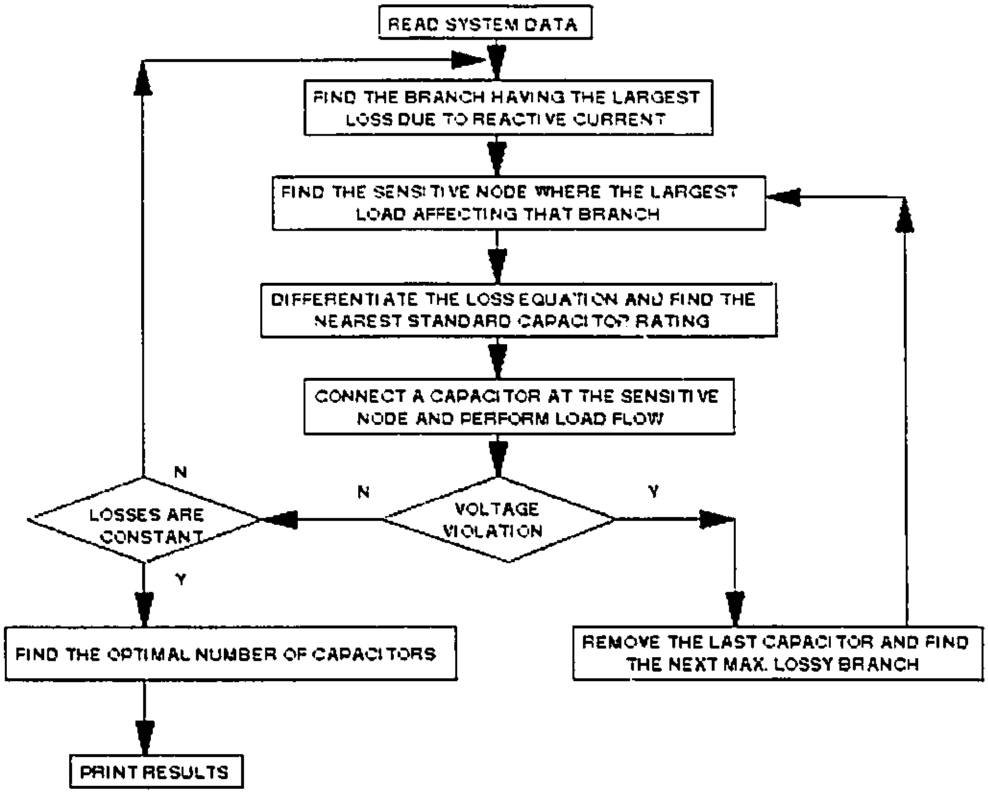

Fig.(5.2) Algorithm for identification of the *sensitive* nodes and determination of the optimal capacitor banks.

geometrical size, and accordingly the price, depends on the rated power.

The unit of the reactive power is the MVAR (Mega Volt Ampere Reactive), and it is the product of the voltage times the out of phase component of the current.

Table (5.1) shows typical values of compensating capacitor sizes commonly used in the 27.6 kV distribution network in the province of Ontario, Canada, and 1993 prices of capacitors and cost of their installation.

5.4. Load Variations and Optimal Capacitor Number

As the load varies during the year, some of the switches should be turned On and Off to have the optimal compensation level, in order to gain maximum power loss reduction throughout the year. Consider a year that has been divided into n periods each of T_p hours where p varies from 1 to n so that

$$\sum_{p=1}^{n} T_p = 8{,}760 \ hours \qquad (5.14)$$

and if the power loss reduction at period p using N_p capacitors is P_{p,N_p} then, the optimal number of capacitors to be used is that to satisfy equation (5.15).

$$\underset{N_p=1,2,\ldots, \quad p=1,2,\ldots,n}{MAX\ SAVING = MAX} \{C_e(\sum_{p=1}^{n} T_p P_{p,N_p}) - N_p C_v\} \qquad (5.15)$$

where C_e is the cost of 1 kWh (in 1993, cost of energy to the Windsor Utilities Commission, Windsor, Ontario, Canada is 2.15 ¢), and C_v is the amortized annual cost of each capacitor.

Table (5.1) Typical Values of Capacitor Sizes and Prices.

	SIZE (MVAR)	UNIT SIZE (MVAR)	PRICES (DOLLARS)		
			COST	INSTALLATION	TOTAL
1	0.9	3X0.3	7.252*	8,120	15.372
2	1.8	18X0.1	11,292**	12,180	23,472
3	5.4	18X0.3	14,489**	12,180	26,669
4	7.2	24X0.3	18,727**	12,180	30,907

* PRICES INCLUDE ACCESSORIES WITH SWITCHES

** PRICES INCLUDE ACCESSORIES WITHOUT SWITCHES. THEY ARE NOT NEEDED BECAUSE THESE CAPACITORS ARE NOT SUBJECTED TO SWITCHING.

The optimal number of the compensating capacitors at every period N_p may vary with the load levels, so that switching the capacitors On and Off is important to have varying compensation level in order to gain maximum dollar saving throughout the year. Therefore, a switching table is generated for that purpose.

If the load variations data throughout the year are available for all the load points, a set of load levels at every period of the year can be used to get the optimal number of compensating capacitors on a distribution network as discussed before. But in most cases these data are not available, and they should be implemented in order to include the load variations in the calculation. In this section, a simple but effective method is proposed to implement such data.

It has been suggested [41] that the year can be divided into 12 periods to accommodate the load variations due to the season (summer, winter and fall/spring), the week (weekend and weekday) and daily load level (peak load period and off-peak period).

Table (5.2) shows the different factors that can convert the global peak of the year to the average load at every period for both industrial and commercial and residential loads.

When a network has mixed loads of say the residential and industrial type, the proportions of each type is taken into account when calculating these conversion factors.

If the actual data of the load profiles are available, say to the engineers of relatively large power utilities, then they can be employed directly. However, most of the smaller utilities are unable to obtain their profiles in all feeders and in all nodes and these factors are thought to be useful to them also, when attempts are made to reduce the losses using reactive power compensation.

Table (5.2). Load Conversion Factors.

S.N.	Definitions	Industrial	Residential and commercial
1	Winter, Weekday, High Load for day	92%	92%
2	Winter, Weekday, Low load for day	80%	85%
3	Winter, Weekend, High load for day	65%	72%
4	Winter,Weekend, Low load for day	60%	67%
5	Fall/Spring, Weekday, High load for day	92%	69%
6	Fall/Spring, Weekday, Low load for day	80%	63%
7	Fall/Spring, Weekend, High load for day	65%	54%
8	Fall/Spring, Weekend, Low load for day	60%	50%
9	Summer, Weekday, High load for day	92%	85%
10	Summer, Weekday, Low load for day	80%	92%
11	Summer, Weekend, High load for day	65%	67%
12	Summer, Weekend, Low load for day	60%	72%

Now equation (5.15) can be written as:

$$MAX\ SAVING = MAX\ \{C_e(\sum_{p=1}^{12} T_p P_{p,N_p}) - N_p C_v\} \qquad (5.16)$$
$$N_p=1,2,\ldots, \quad p=1,2,\ldots,12$$

Using this method, the number of nodes to be injected with reactive power for the purpose of power loss reduction is very few compared to the total number of nodes in the system. Also, capacitors are connected only at the load points. Many other attempts at loss reduction using compensating capacitors recommend connecting capacitors at some percentage distance from the substation regardless if it is suitable to connect a capacitor there or not. In other words, the method employed in this thesis takes into account the solving of some technical problems that may appear at capacitor installation. Also, using only a few nodes for installing compensating capacitors is very cost effective, as the cost of two separate capacitors at two different nodes with installation is much higher than if these two capacitors are connected as one bank at one node as shown in Table (5.1).

This method of application of compensating capacitors has been applied to the distribution networks of the city of Windsor, Ontario and to the Kingston Public Utility Commission at Kingston, Ontario. The results are presented in Chapter 6.

5.4.1. Capacitor Switching

The compensator capacitors are usually connected to the distribution network via switches with a set of fuses for protection. Switching the capacitors On and Off is important to prevent under- and over-compensation with the variation of the load levels. Therefore, due to the variation of the load levels, some of the switches should be turned Off at specific periods during the year when they are not needed. A switching table for the compensating capacitors is developed. Switching the capacitors can be done either manually or using a processor with a clock that can control the switches according to a look up table (in this case the switching table).

To clarify the method, a sample result is shown in this section to show the effect of applying capacitors to the distribution network.

5.5. Sample Result

Consider the distribution feeder map shown in Fig.(5.3). The section number with resistances and reactances and the appropriate active and reactive power loads are given in Table (5.3). This feeder carries a maximum load of 19 MW, 8 MVAR distributed to 45 main load points, and carries 50% residential and the balance industrial loads. The latter ratio is taken into account when calculating the load conversion factors.

Figure (5.4) shows the A matrix representing the system configuration. The rows represent the section numbers, while the columns represent the node number.

Table (5.4) shows the losses (in kW) arising from the reactive current on the sample feeder, as a function of the number of the installed capacitors at different time periods. The times (in hours) for the different periods (from 1 to 12) are also shown in Table (5.4). It will be observed, for example, that for period number 8 applying 3 capacitors reduces the losses by about 86%, (from 16.9 to 2.4 kW) while for period number 2, 4 capacitors results in a reduction of the losses due to the reactive current by 71.6% (from 53.8 to 15.3 kW). As stated already, this feeder has 45 nodes while the number of the *sensitive* nodes determined in this study in which the capacitors are installed is only 3.

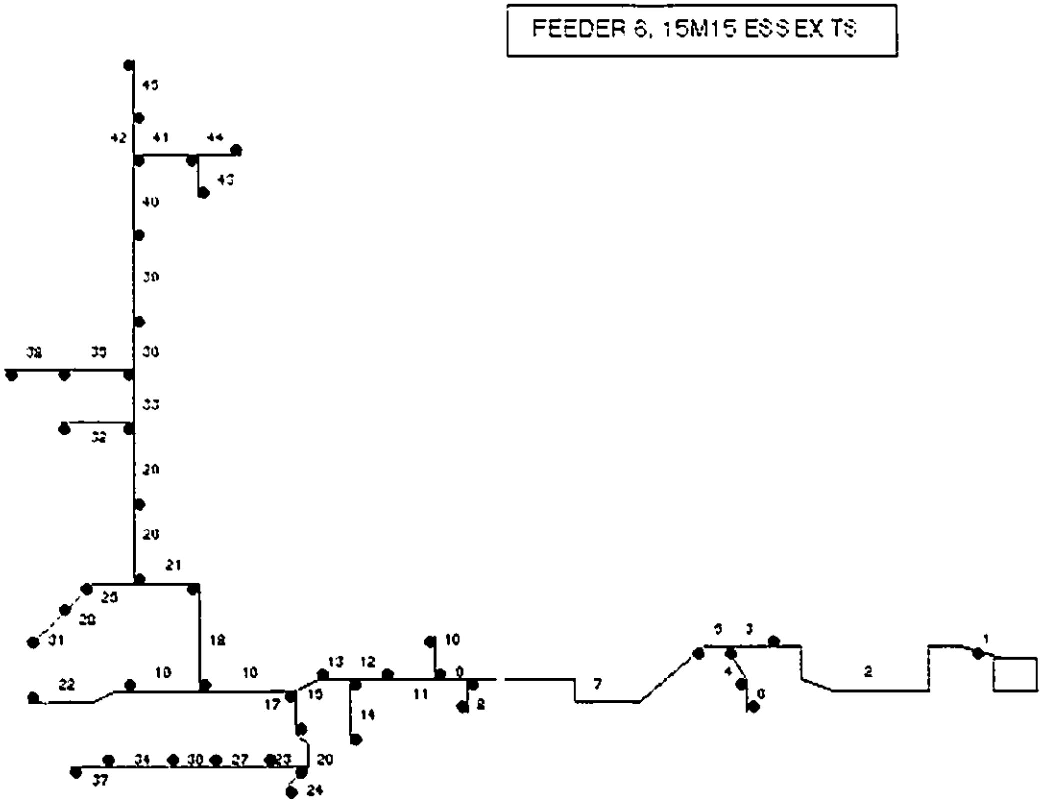

Fig.(5.3) Sample Feeder Map. Showing the Different Section Numbers.

Table (5.3) Electrical parameters giving the resistance (R), the inductive reactance (X) and the real (P) and reactive (Q) powers in sections 1 to 45 of the sample feeder.

Sec. No.	R Ω	X Ω	end of section (P) MW	end of section (Q) MVAR	Sec. No.	R Ω	X Ω	end of section (P) MW	end of section (Q) MVAR
1	0.0160	0.3700	0	0	24	0.0052	0.0137	0	0
2	0.1750	0.4100	0	0	25	0.0275	0.0390	0	0
3	0.0003	0.0008	0	0	26	0.0275	0.0390	0	0
4	0.0003	0.0008	0	0	27	0.0365	0.0266	0	0
5	0.0003	0.0008	0	0	28	0.0914	0.0675	0.2	0.11
6	0.0018	0.0013	0.48	0.232	29	0.0414	0.1096	0	0
7	0.1690	0.3990	0	0	30	0.0365	0.0266	0.02	0.012
8	0.0035	0.0083	0.12	0.056	31	0.0275	0.0395	0.164	0.08
9	0.0035	0.0083	0	0	32	0.0275	0.0550	0.95	0.42
10	0.0035	0.0083	0	0	33	0.0310	0.0822	0	0
11	0.0807	0.1918	0	0	34	0.3800	0.2820	0	0
12	0.0105	0.0243	0	0	35	0.0155	0.0410	0.33	0.096
13	0.0175	0.0416	0.1	0.05	36	0.0205	0.0552	3.752	1.816
14	0.0105	0.0250	0	0	37	0.0183	0.0013	4.412	2.136
15	0.0105	0.0250	0.12	0.065	38	0.0052	0.0137	1.432	0.595
16	0.0155	0.0410	0	0	39	0.0052	0.0137	0.597	0.26
17	0.0243	0.0583	0	0	40	0.0414	0.1103	4.73	1.429
18	0.0674	0.1790	0.12	0.033	41	0.0155	0.0413	0	0
19	0.0458	0.0655	0.282	0.134	42	0.0205	0.0550	0	0
20	0.0103	0.0275	0	0	43	0.0366	0.0269	0.312	0.152
21	0.0826	0.1186	0	0	44	0.0362	0.0965	0	0
22	0.1560	0.2239	0	0	45	0.0052	0.0137	0	0
23	0.0731	0.0540	0.828	0.4					

```
            111111111122222222223333333333444444
   123456789012345678901234567890123456789012345

1  111111111111111111111111111111111111111111111
2  011111111111111111111111111111111111111111111
3  001111111111111111111111111111111111111111111
4  000101000000000000000000000000000000000000000
5  000010111111111111111111111111111111111111111
6  000001000000000000000000000000000000000000000
7  000000111111111111111111111111111111111111111
8  000000010000000000000000000000000000000000000
9  000000001111111111111111111111111111111111111
10 000000000100000000000000000000000000000000000
11 000000000011111111111111111111111111111111111
12 000000000001111111111111111111111111111111111
13 000000000000101111111111111111111111111111111
14 000000000000010000000000000000000000000000000
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16 000000000000000101101100110110111011011111111
17 000000000000000010010011001001000100100000000
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37 000000000000000000000000000000000000100000000
38 000000000000000000000000000000000000010000000
39 000000000000000000000000000000000000001111111
40 000000000000000000000000000000000000000111111
41 000000000000000000000000000000000000000010110
42 000000000000000000000000000000000000000001001
43 000000000000000000000000000000000000000000100
44 000000000000000000000000000000000000000000010
45 000000000000000000000000000000000000000000001
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Fig.(5.4) The A Matrix Representing the Configuration of the Sample Feeder.

Table (5.5) shows the total losses (in kW) in the sample feeder, which arise from the combined active and reactive currents as a function of the number of the installed capacitors at different time periods. It is evident that the installation of capacitors only marginally affects the total losses, as the active current remains unchanged. For example, for period No.8, applying 3 capacitors reduces the total losses by 14.7% only (from 102 to 87 kW). Figure (5.5) shows the dollar value of the annual energy loss reduction, the amortized annual cost of multiple units of capacitors including the cost of capital and cost of installation and the effective annual dollar saving after incorporating the capacitors for a typical feeder. It will be seen that although the value of the annual energy saved increases with increasing number of capacitor units installed on the feeder (Fig. (5.5), curve a), it is not necessary that the higher energy saved is the most cost effective. The cost of the capacitors increases linearly with increasing number of the units installed (Fig.(5.5) curve b). Connecting 5 capacitors in the feeder (Fig.(5.5) curve c) will result in a maximum saving of about CAN $3,061 per year. Installing 6 or more will result in a decrease in the dollar saving because of the added costs of the additional capacitors compared to the cost of the energy saved.

As the load changes during the year, the installed capacitor VAR should vary to keep the power loss at the lowest value at every period. To achieve this objective, a switching table of the compensating capacitor units is developed. A typical switching sequence for the sample feeder is shown in Table (5.6).

It can be seen from Table (5.6) that switching of the capacitors depends on the particular period, i.e., the load level. This Table is important to prevent over-compensation which may lead to an increase in the feeder losses. Also Table (5.6) shows that at periods 7 and 8, only 3 unit capacitors out of 5 are required for these two periods to keep the losses at minimum value. Table (5.6) indicates that in this feeder there are only 3 *sensitive* nodes where capacitors are installed. These nodes are identified by the numbers 40, 37 and 36. Table (5.6) shows that for period No.7, capacitor No.3 (900) kVAR) at node 36, is switched off. Period No.7 is defined in Table (5.2). This capacitor is switched off during the high load, on the weekends (Saturdays and Sundays) over the Fall and the Spring months. Hence 2x26 weeks =52 switching operations (off) are carried out during the year.

5.5.Effect of Capacitor Placement on System Voltage

When a capacitor is installed somewhere in the power system, an increase in the system voltage is expected, and the largest increase occurs at the node where the capacitor is connected. The method presented in this thesis for capacitor application requires a healthy system from the voltage point of view, as the main goal of the thesis is to reduce the losses and not to improve the voltage profile, i.e., the voltage is within permissible limits before the capacitors are connected. It is understandable that connecting a compensating capacitor will not violate the lower limit of the voltage, but it may violate the upper limit as its effect is to increase the voltage. This problem has been taken into consideration when the *sensitive* nodes are identified.

Table (5.4) Losses (in kW) in the sample feeder, which arise from the reactive current as a function of the number of the installed capacitors at different time periods. Each capacitor unit is 0.9 MVAR.

		TOTAL NUMBER OF CAPACITORS								
period No.	T_r (hrs)	0	1	2	3	4	5	6	7	8
1	964	64.17	51.49	39.31	28.80	20.89	13.46	7.81	3.74	1.43
2	579	53.76	42.29	31.35	22.07	15.32	9.07	4.58	1.68	1.68
3	385	37.25	27.95	19.23	12.16	7.50	3.38	0.94	0.94	0.94
4	231	31.83	23.33	15.44	9.20	5.31	2.01	0.31	0.31	0.31
5	1960	33.94	25.17	16.90	10.33	6.14	2.49	0.52	0.52	0.52
6	1177	28.61	20.63	13.25	7.54	4.14	1.33	1.33	1.33	1.33
7	784	19.97	13.51	7.69	3.53	1.61	0.25	0.25	0.25	0.25
8	470	16.94	11.09	5.89	2.35	0.55	0.55	0.55	0.55	0.55
9	985	64.17	51.49	39.31	28.80	20.89	13.46	7.81	3.74	1.43
10	592	53.76	42.29	31.35	22.07	15.32	9.07	4.58	1.68	1.68
11	394	37.25	27.95	19.23	12.16	7.50	3.38	0.94	0.94	0.94
12	237	31.83	23.33	15.44	9.20	5.31	2.01	0.31	0.31	0.31

Table (5.5) Total losses (in kW) in the sample feeder, which arise from the combined active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor unit is 0.9 MVAR.

period No.	T_p (hrs)	TOTAL NUMBER OF CAPACITORS								
		0	1	2	3	4	5	6	7	8
1	964	359	346	334	323	315	307	301	297	295
2	579	305	293	283	272	265	259	254	251	251
3	385	216	207	198	191	186	182	179	179	179
4	231	186	178	170	163	159	156	154	154	154
5	1960	198	189	181	174	170	166	164	164	164
6	1177	169	160	153	147	144	141	141	141	141
7	784	120	113	107	103	101	100	100	100	100
8	470	102	96	91	87	86	86	86	86	86
9	985	359	346	334	323	315	307	301	297	295
10	592	305	293	283	272	265	259	254	251	251
11	394	216	207	198	191	186	182	179	179	179
12	237	186	178	170	163	159	156	154	154	154

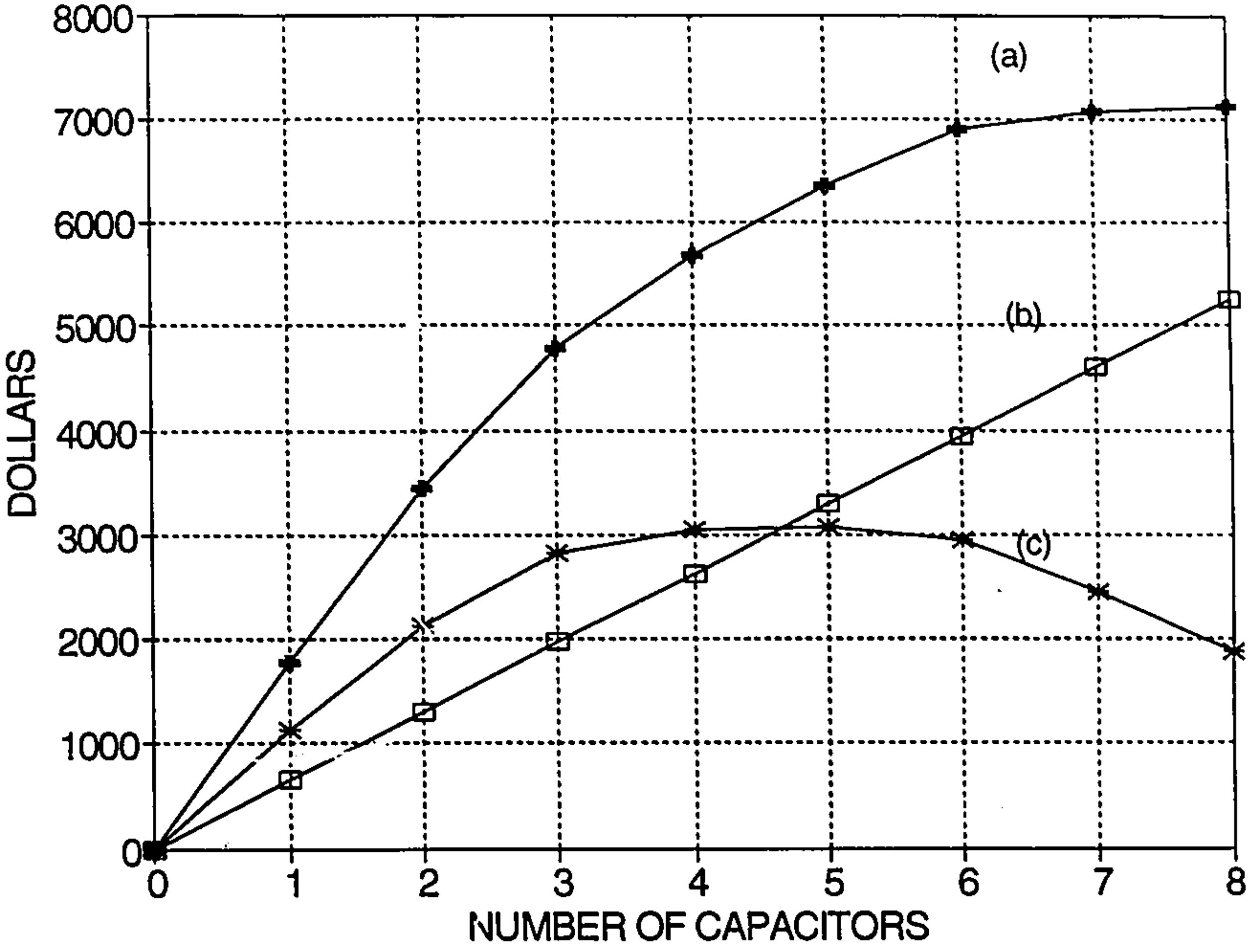

Fig. (5.5) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) of the sample feeder.

Table (5.6) Switching table for the sample feeder showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods. The capacitors are installed at only 3 nodes which have the numbers 38, 36 and 37. This feeder carries a maximum load of 19 MW and 8 MVAR distributed from 45 main load nodes.

no. of unit capacitors →	1	2	3	4	5
Sensitive node No. →	38	36	36	37	37
Period No.↓	Switch status				
1	1	1	1	1	1
2	1	1	1	1	1
3	1	1	1	1	1
4	1	1	1	1	1
5	1	1	1	1	1
6	1	1	0	1	1
7	1	1	0	1	1
8	1	1	0	1	0
9	1	1	1	1	1
10	1	1	1	1	1
11	1	1	1	1	1
12	1	1	1	1	1

If the voltage is violated when the capacitor is connected at the *sensitive* node (optimal location) this capacitor is moved to somewhere else, and thus the losses become higher than the minimum. This problem may be prevented by keeping the capacitor at the optimal location and reducing all the system voltage by a certain percentage by changing the tap of the substation transformer, with a condition that the lower permissible voltage anywhere is not violated. But sometimes this may lead to a voltage problem, as the tap changing on the transformer moves in discrete steps and therefore the voltage can only be changed in steps and not continuously. In the Windsor Utilities Commission, every distribution transformer has 16 steps for tap changing. Every step allows 355 V which amounts 1.286% on the base of 27.6 kV (the nominal voltage), with a total of 5.68 kV.

The method proposed in this thesis has an advantage over other methods, in that connecting capacitors at the *sensitive* nodes does not violate the maximum permissible voltage. This is because, using this method, the capacitors are applied to the highest loaded nodes where the voltage is very low and even with many capacitor units, the upper voltage limits are not violated.

CHAPTER 6

RESULTS AND DISCUSSION

6.1.Introduction

This chapter shows the results for applying the proposed method to two real distribution systems, for the power and energy loss reduction using compensating capacitors and with a combination of capacitors and system reconfiguration. The load variations throughout the year are considered, and the cost of compensating capacitors which include the amortized capital and labour are also taken into account. These costs are real costs, and not estimated, and are obtained from an industrial company selling and installing power capacitors.

Also the rate of the energy cost used in this study is the rate charged by Ontario Hydro, Canada, to the Windsor Utilities Commission. This is CAN$ 188,400 for 1 MW.Year in 1993. This rate is 2.15¢ per kWh.

6.2.Applications

The study in this thesis has been applied to two real systems; Windsor Utilities Commission (WUC) at the city of Windsor, Ontario, and the Public Utility

Commission (PUC) at the city of Kingston, Ontario.

6.2.1.WUC

WUC network in Windsor, Ontario serves a population of 200,000 through 38 distribution feeders supplied from 6 different substations (Fig.(6.1)). The maximum demand of WUC is 500 MW at an average power factor of 0.88. There are three types of load in Windsor; industrial (50%), residential (25%) and commercial load (25%). These proportions of the load have been taken into account when the load variations during the year are considered.

6.2.2.PUC

PUC network in the city of Kingston, Ontario, serves a mixture of residential and commercial loads with some light industry. The system contains 6 feeders to serve a population of 53,000 with a maximum demand of 150 MW at an average power factor of 0.92.

Note that the power factor in Kingston is higher than that in Windsor, as the main type of load in Kingston is residential and commercial where the major load is heating. In Windsor, where the industrial load is 50% of the total load, the power factor is lower due to the preponderance of industrial machinery.

6.3.Capacitor Applications

The technique for applying capacitors described in this thesis is applied to the 38 feeder distribution system in the city of Windsor, Ontario. Figures (6.2) to (6.39) show the individual feeders with the section numbers. The results show that the feeders can be divided into different categories regarding to the benefits gained from applying the capacitors.

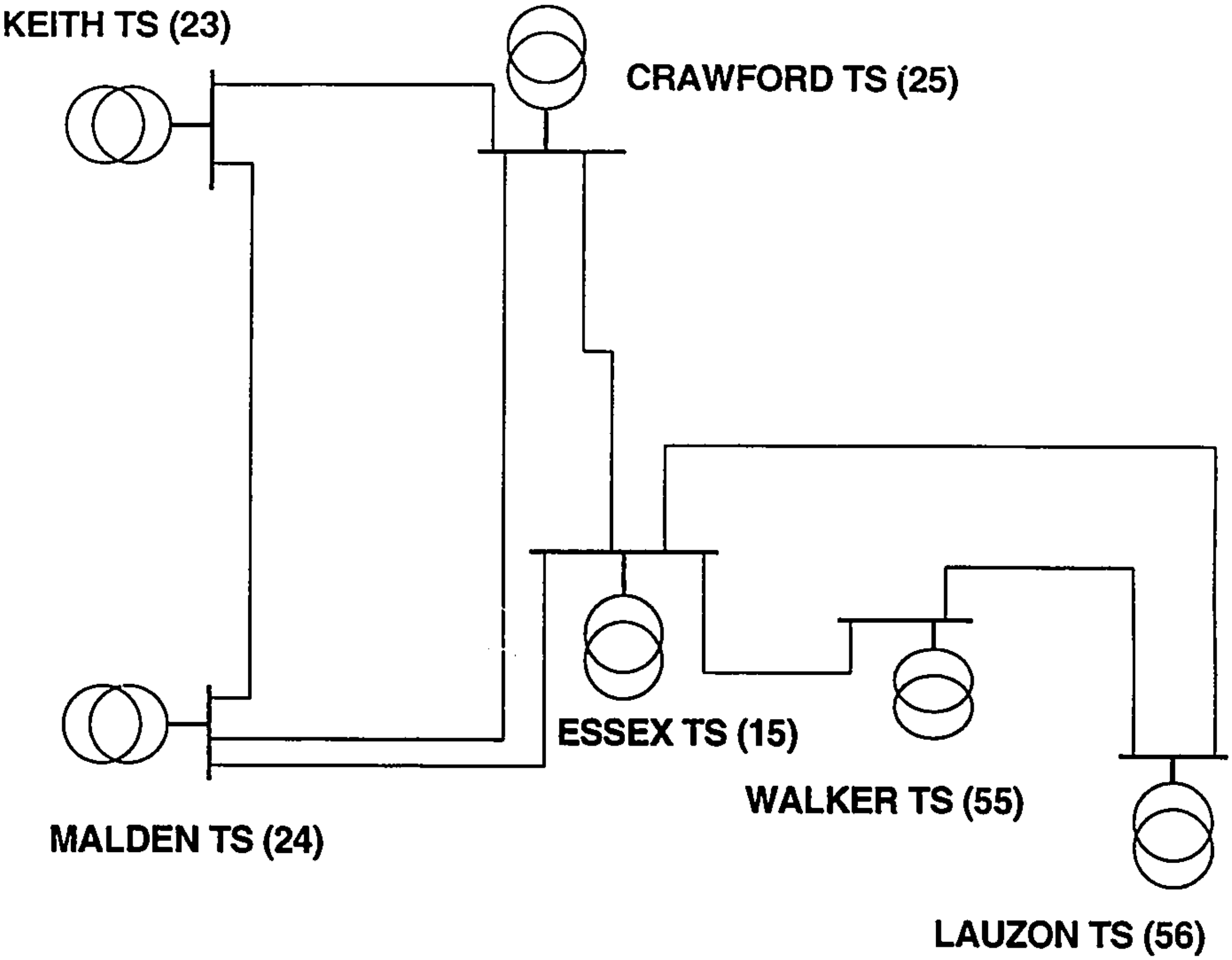

Fig.(6.1) Schematic diagram of WUC.

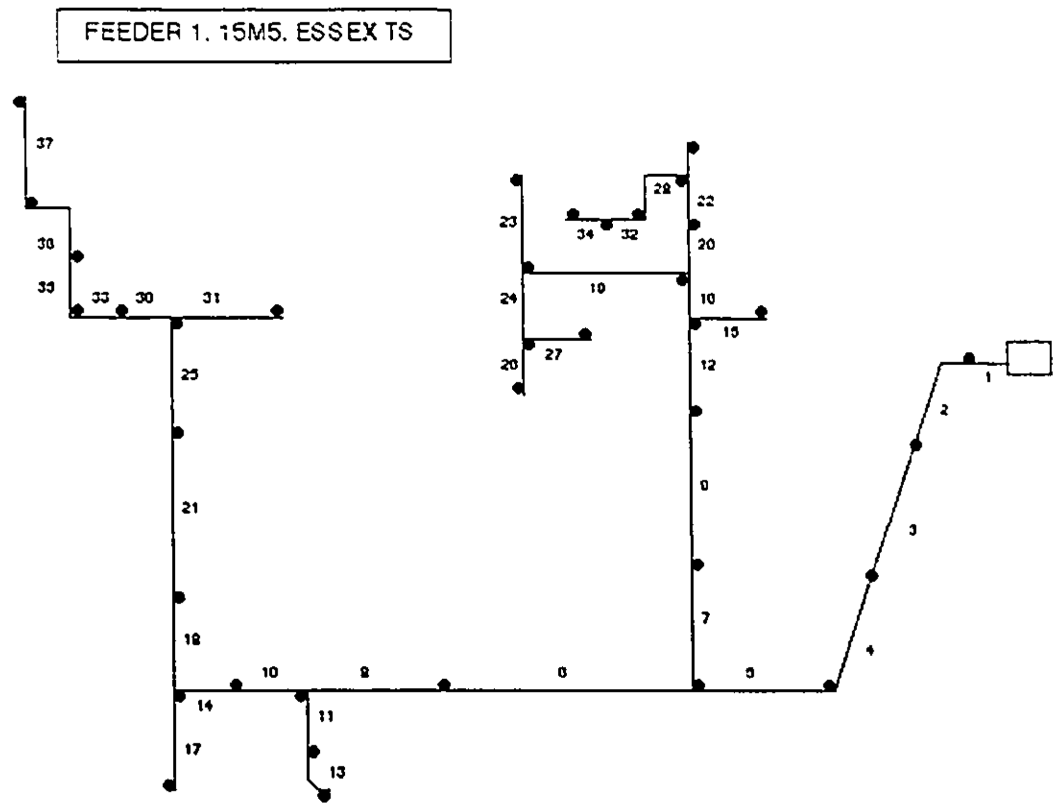

Fig.(6.2) Map of Feeder No. 1

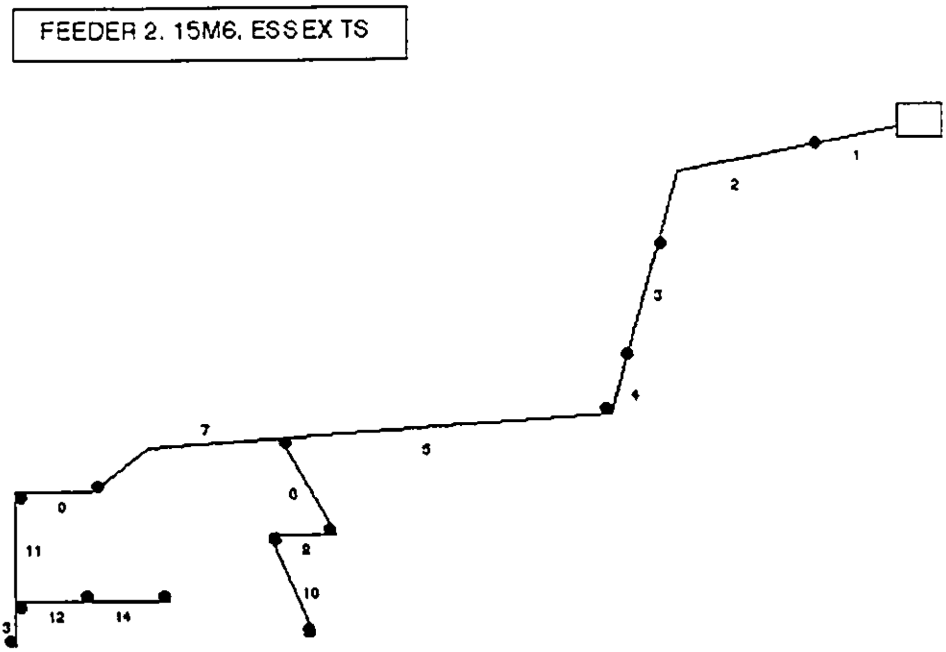

Fig.(6.3) Map of Feeder No. 2

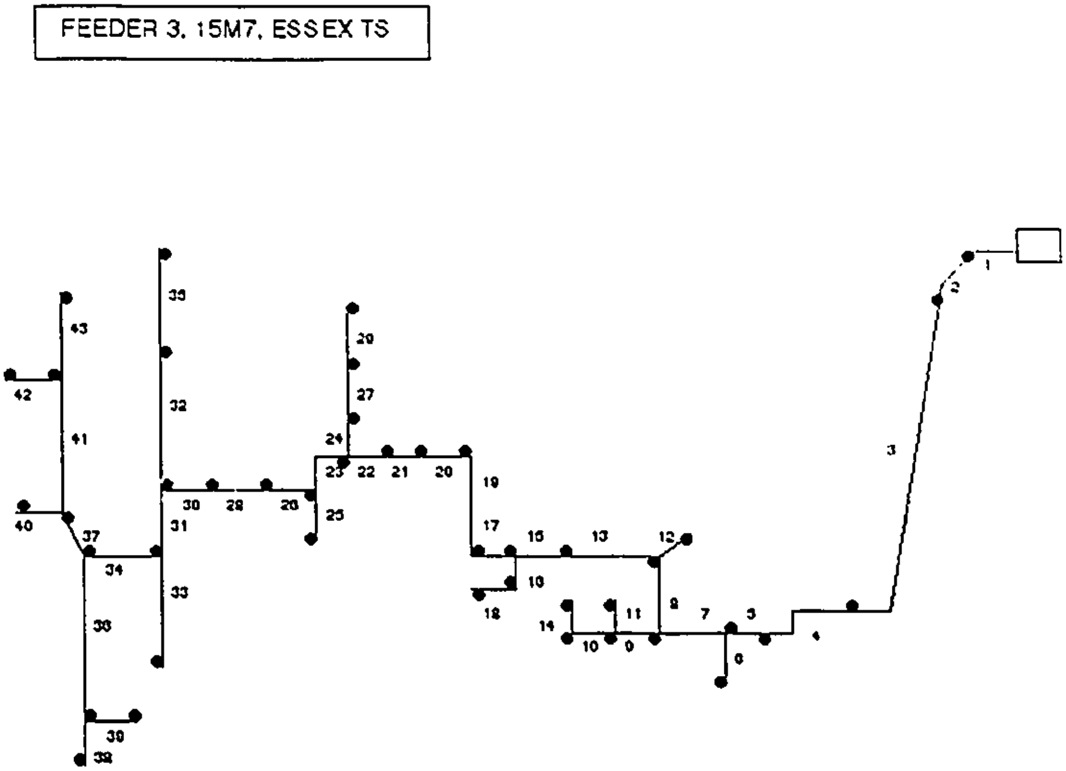

Fig.(6.4) Map of Feeder No. 3

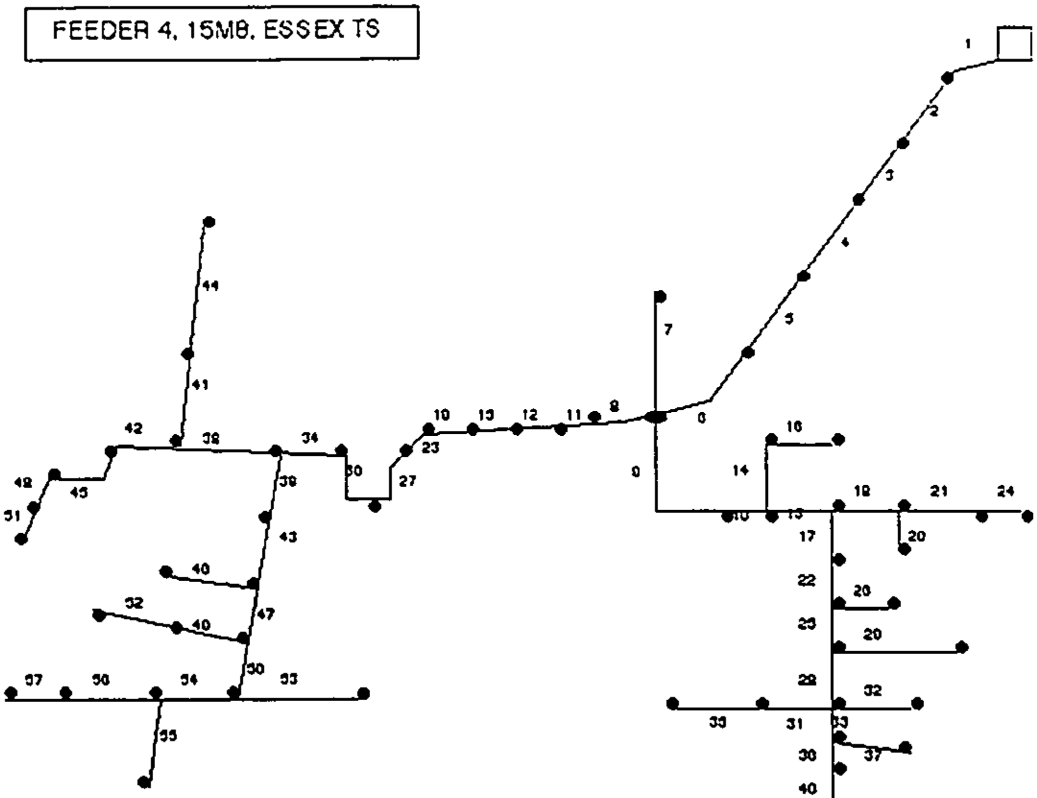

Fig.(6.5) Map of Feeder No. 4

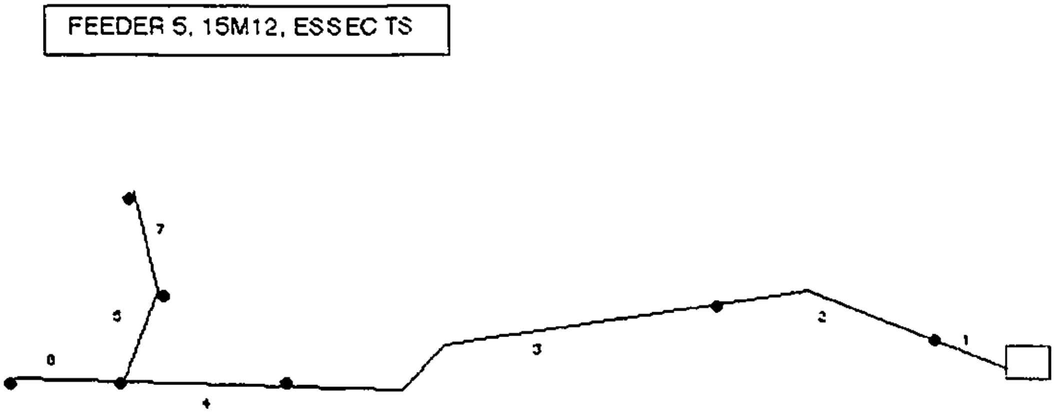

Fig.(6.6) Map of Feeder No. 5

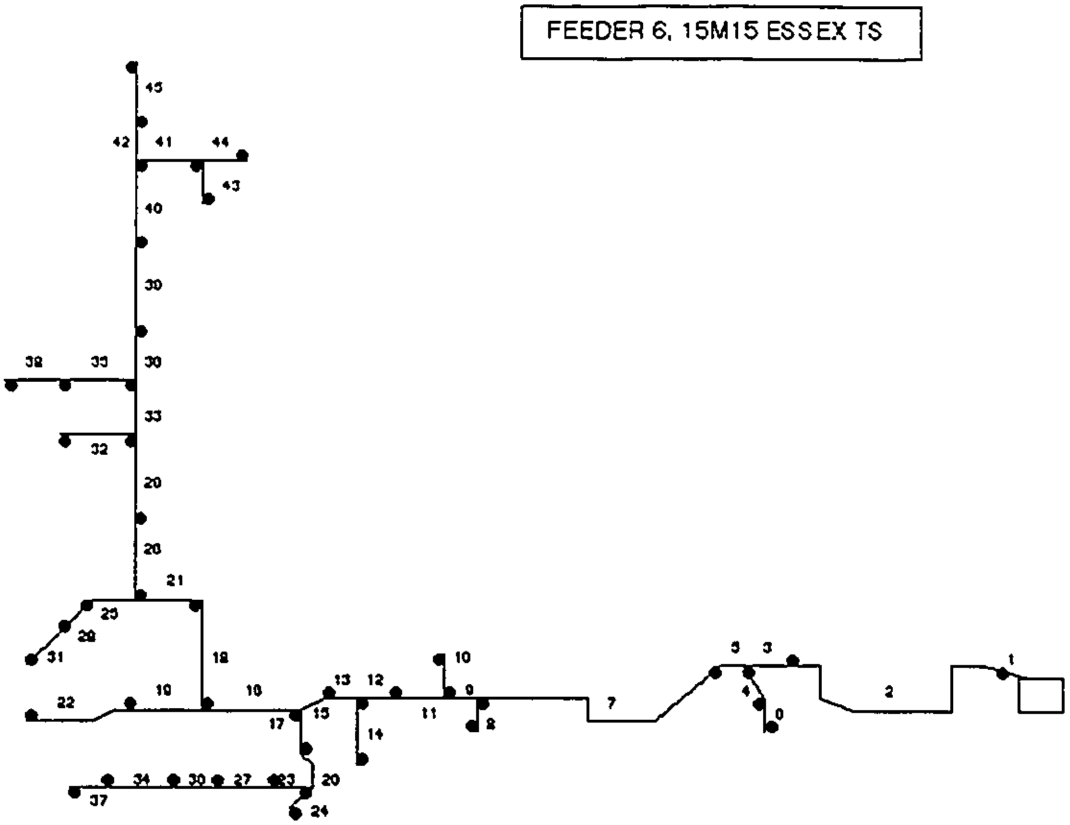

Fig.(6.7) Map of Feeder No. 6

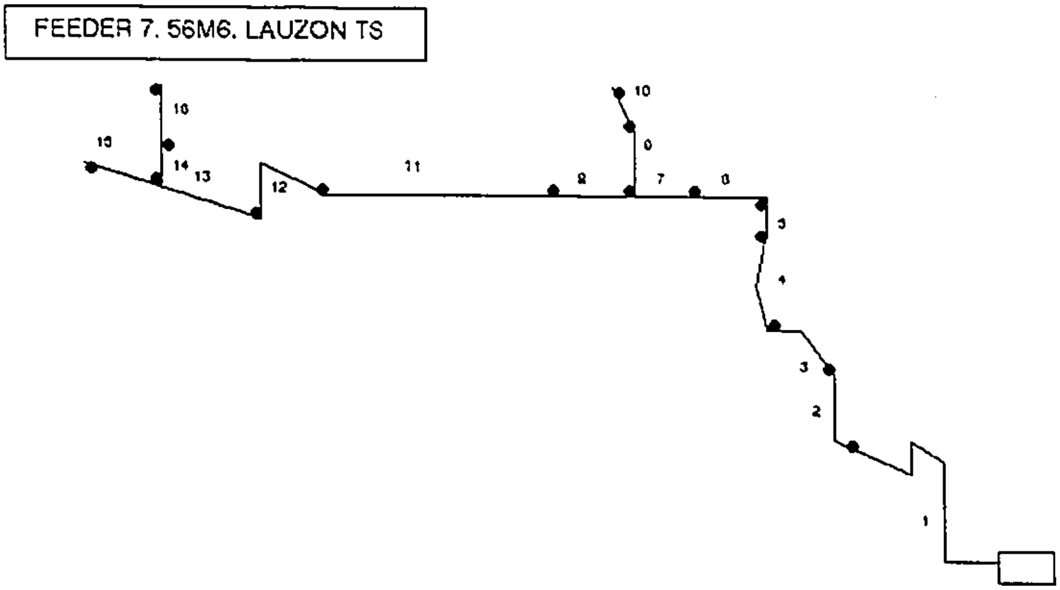

Fig.(6.8) Map of Feeder No. 7

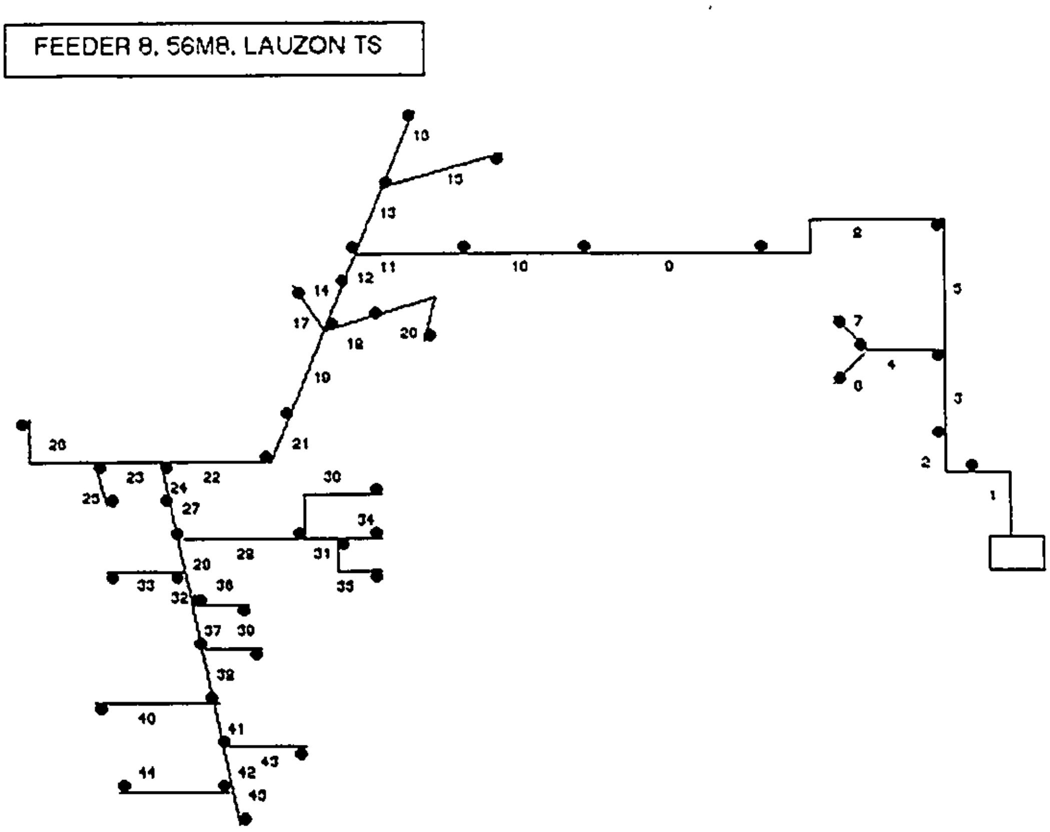

Fig.(6.9) Map of Feeder No. 8

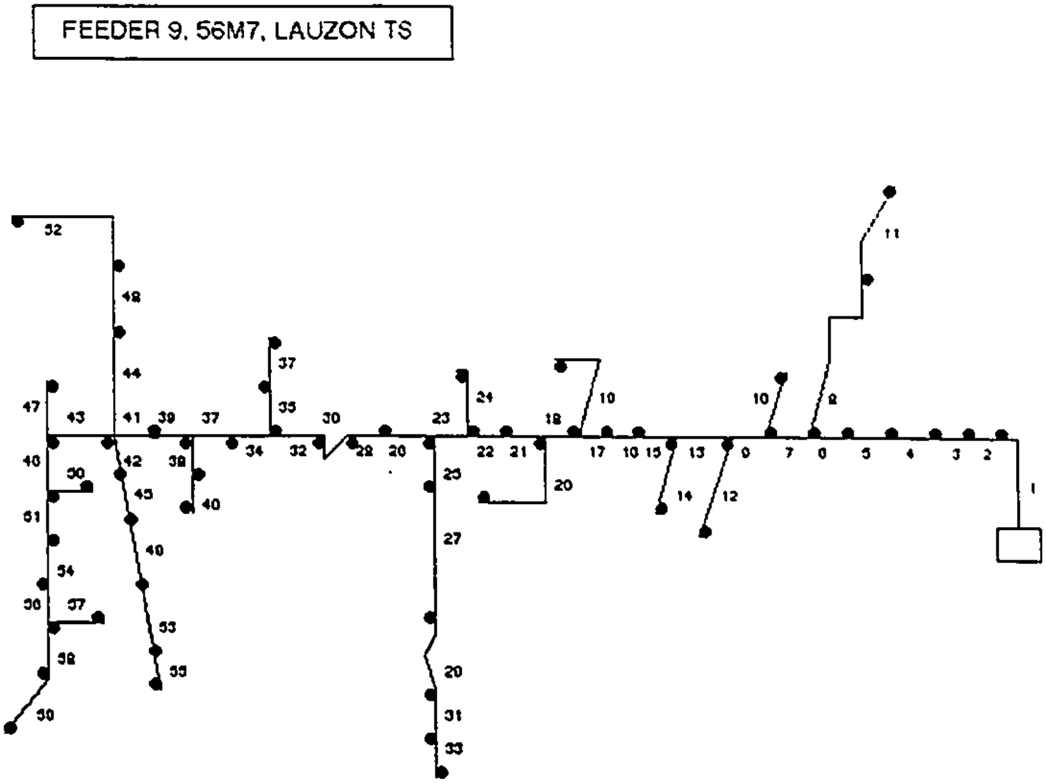

Fig.(6.10) Map of Feeder No. 9

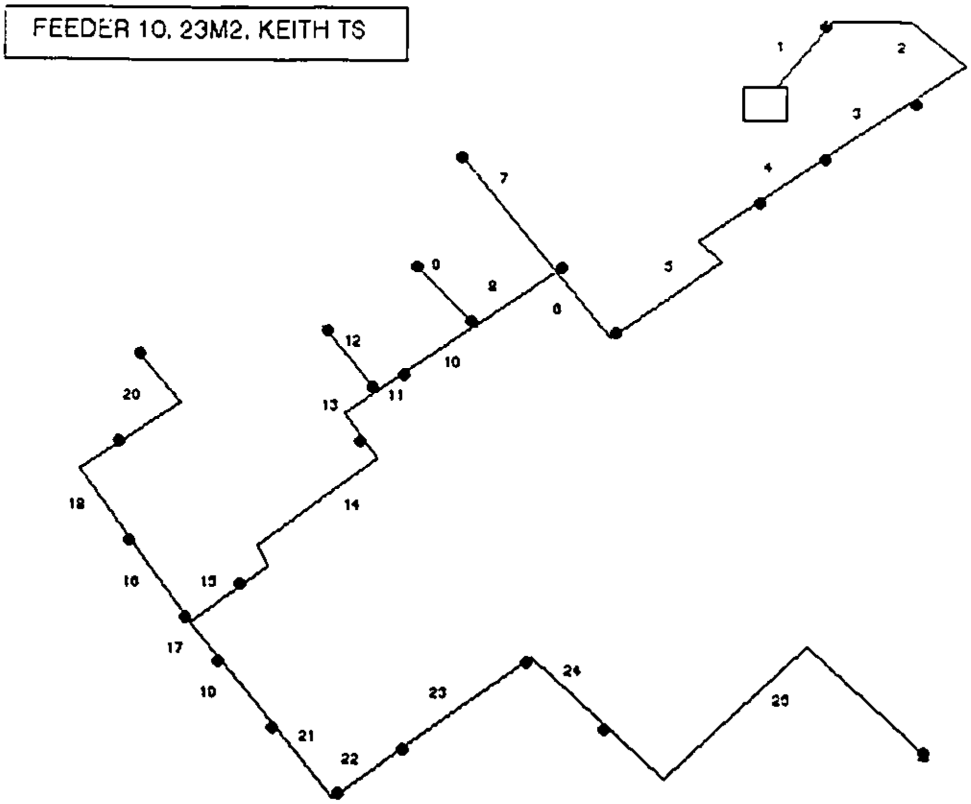

Fig.(6.11) Map of Feeder No. 10

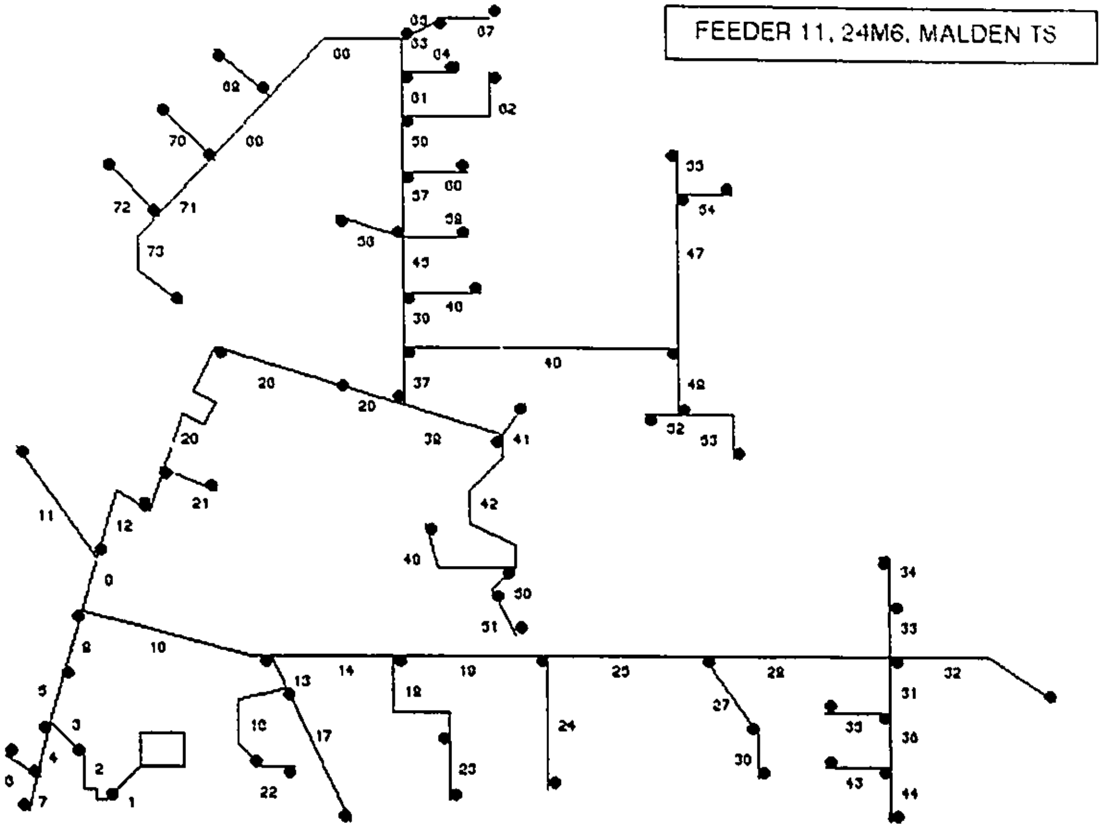

Fig.(6.12) Map of Feeder No. 11

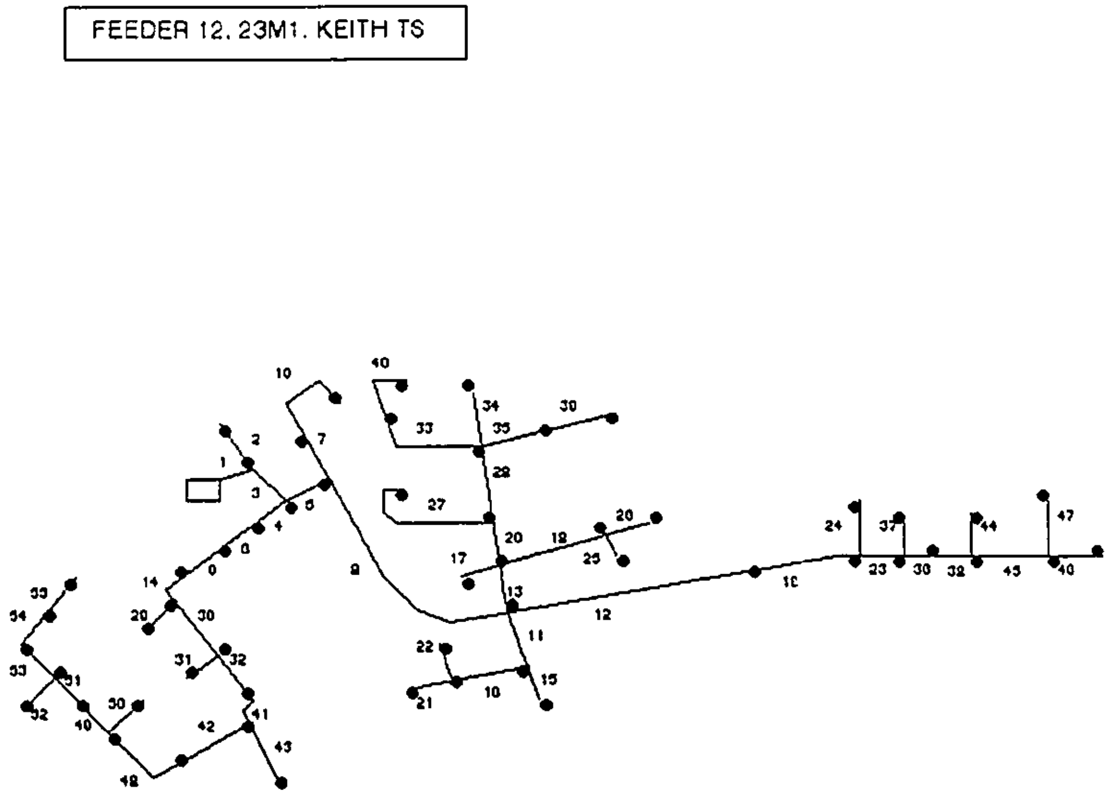

Fig.(6.13) Map of Feeder No. 12

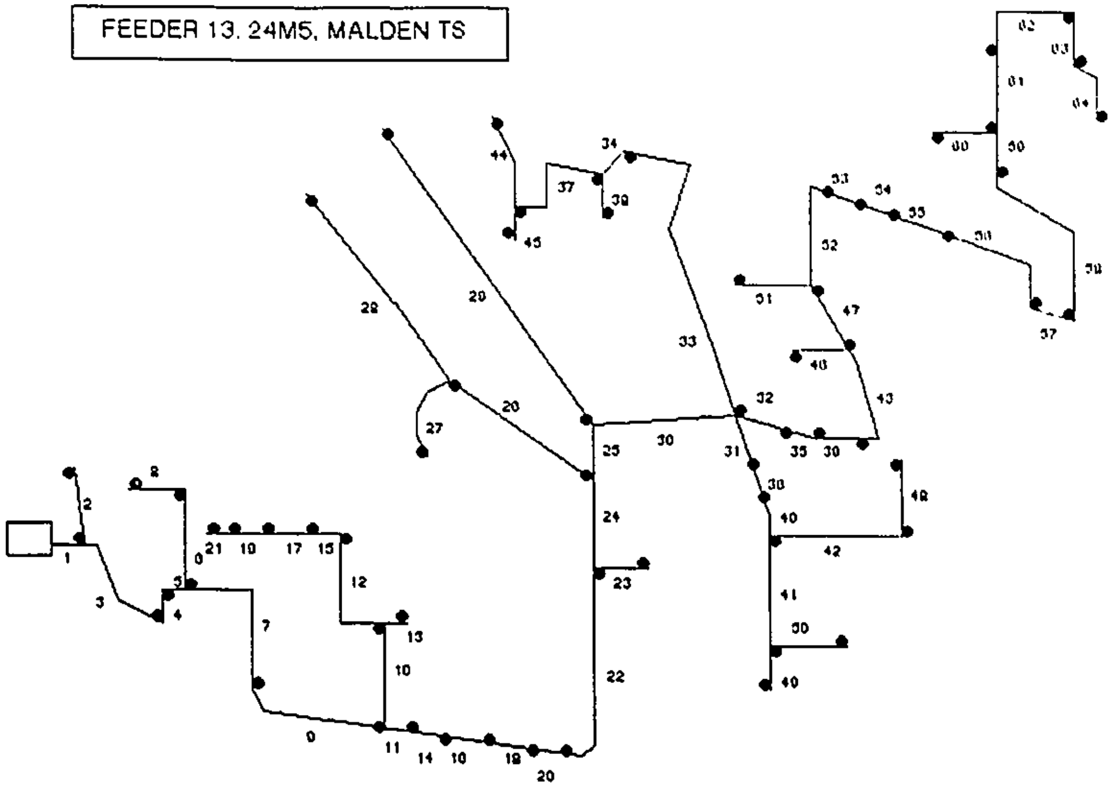

Fig.(6.14) Map of Feeder No. 13

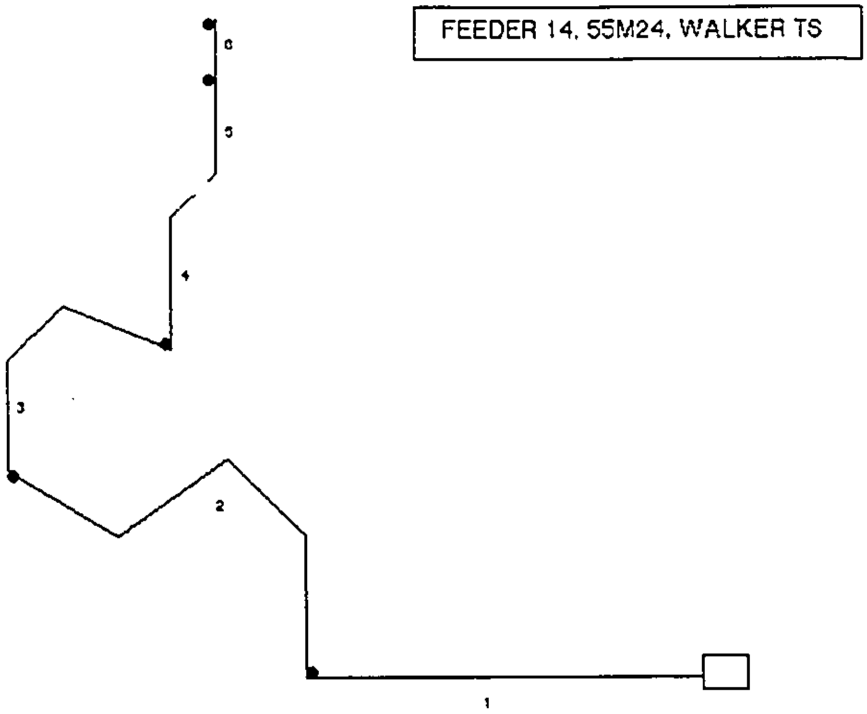

Fig.(6.15) Map of Feeder No. 14

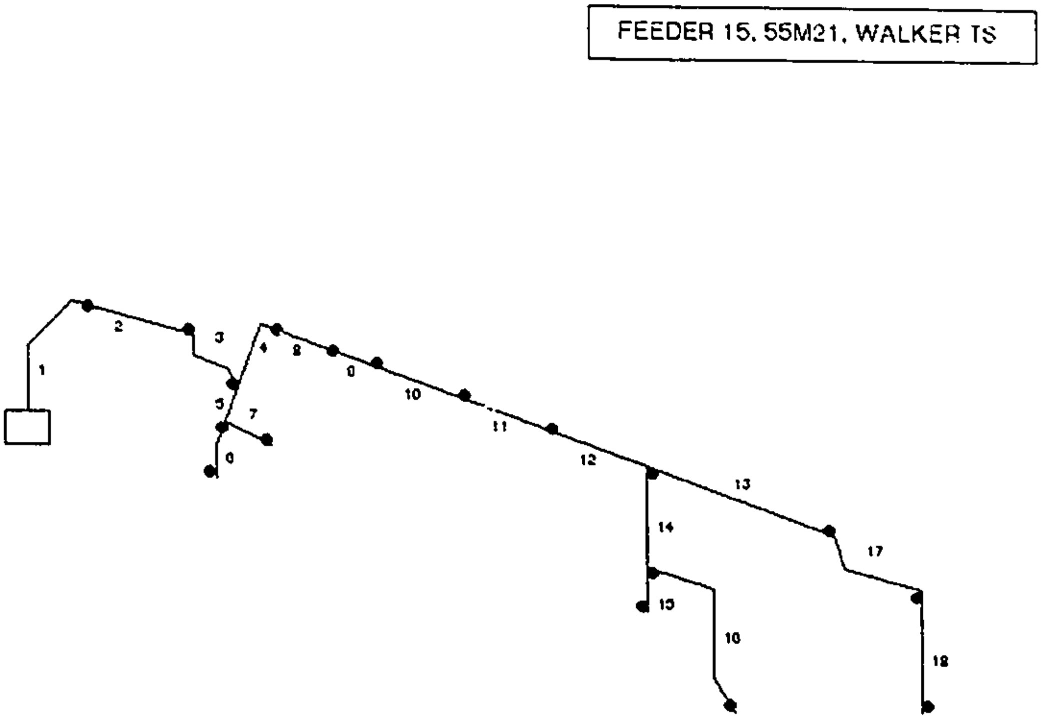

Fig.(6.16) Map of Feeder No. 15

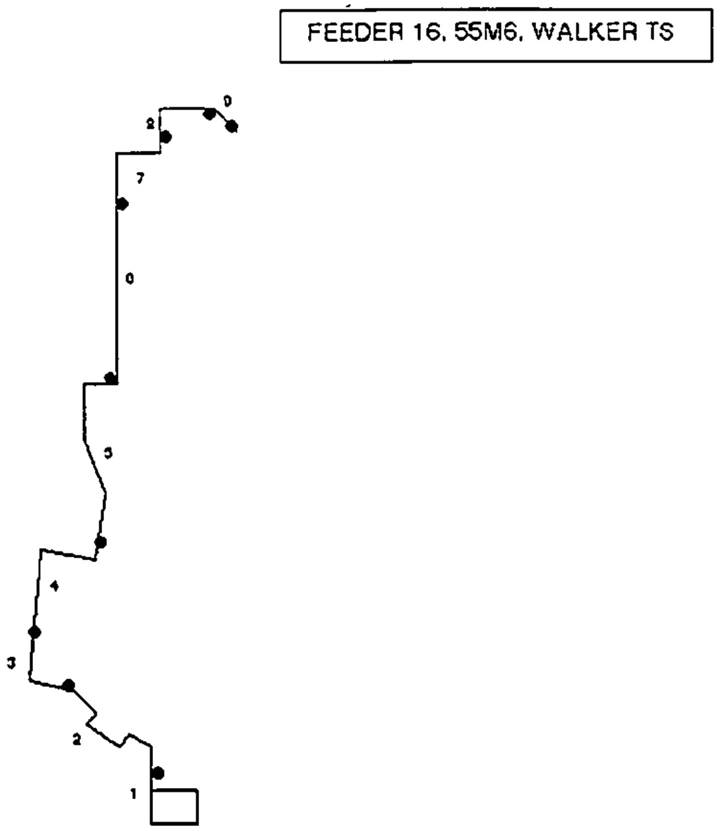

Fig.(6.17) Map of Feeder No. 16

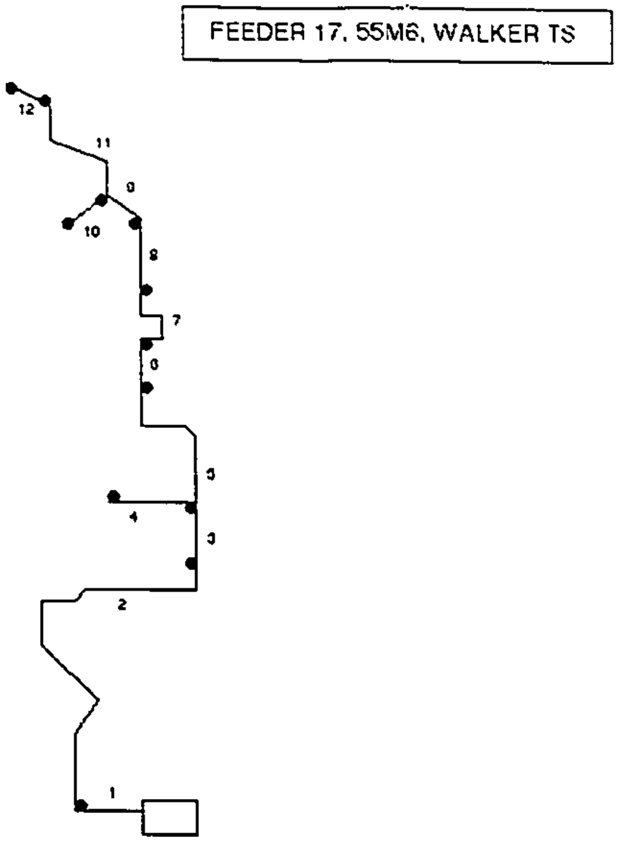

Fig.(6.18) Map of Feeder No. 17

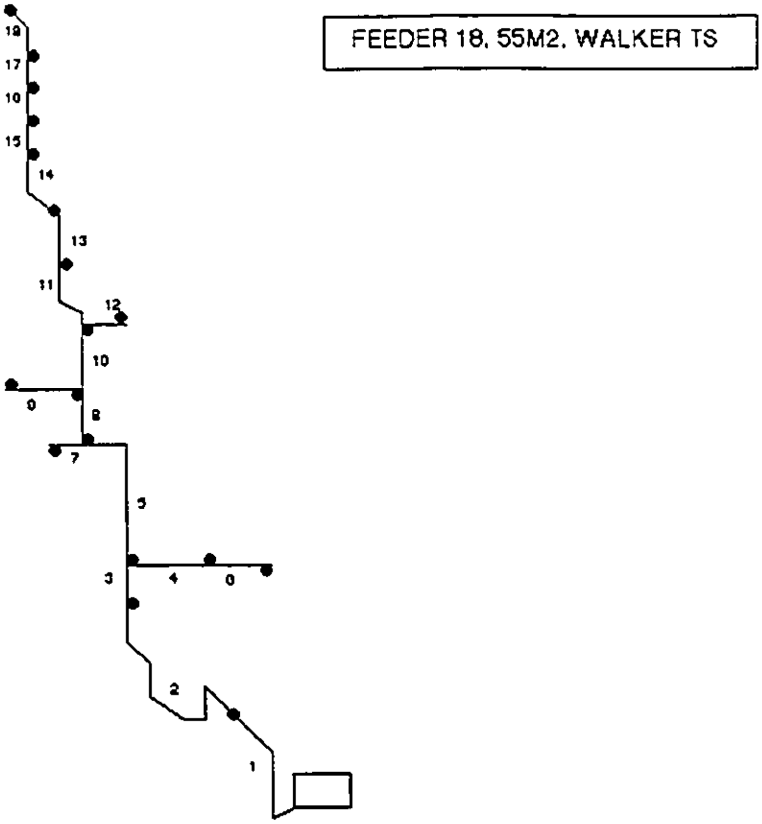

Fig.(6.19) Map of Feeder No. 18

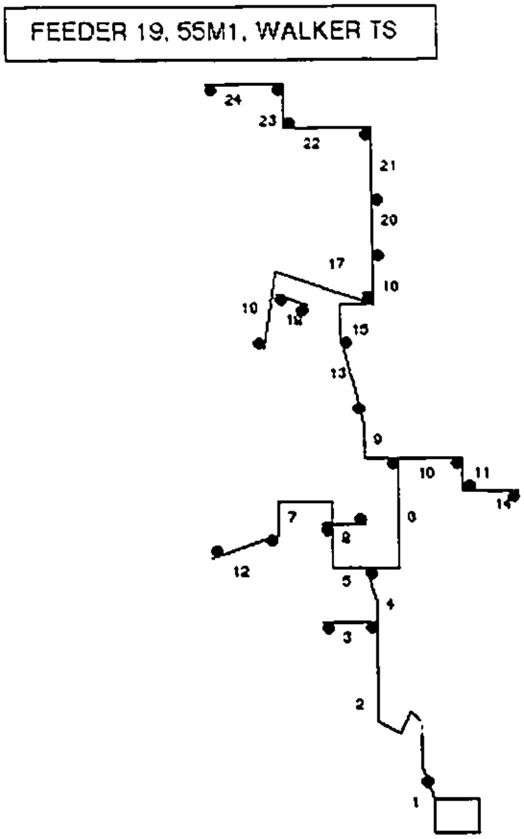

Fig.(6.20) Map of Feeder No. 19

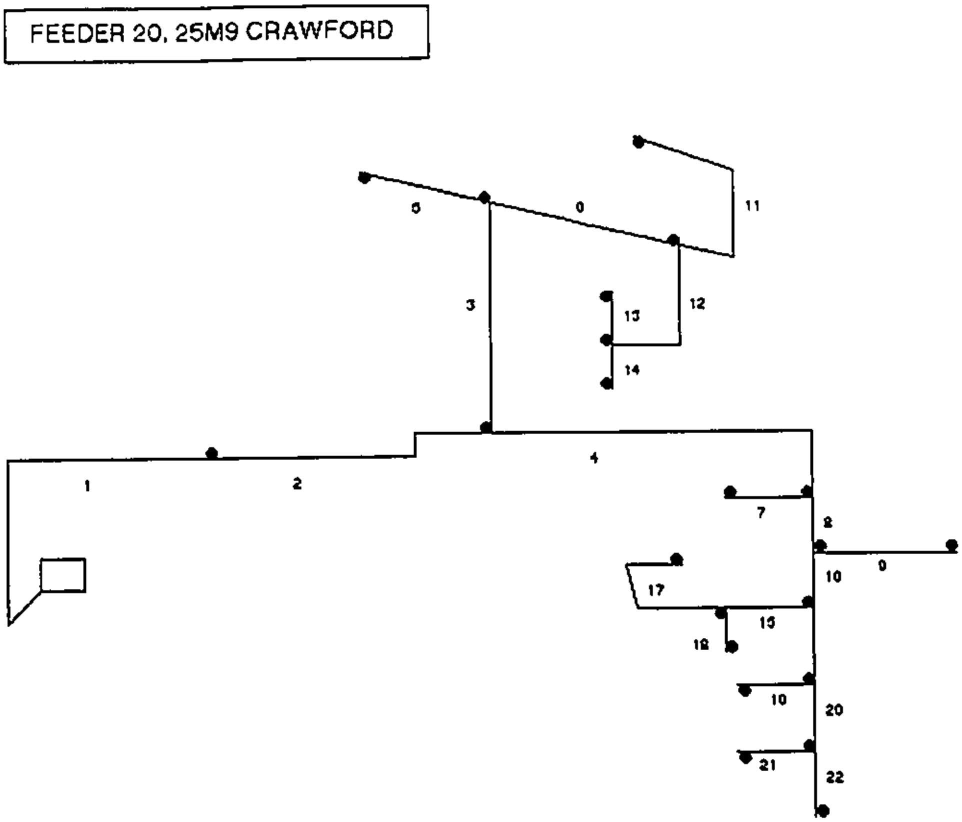

Fig.(6.21) Map of Feeder No. 20

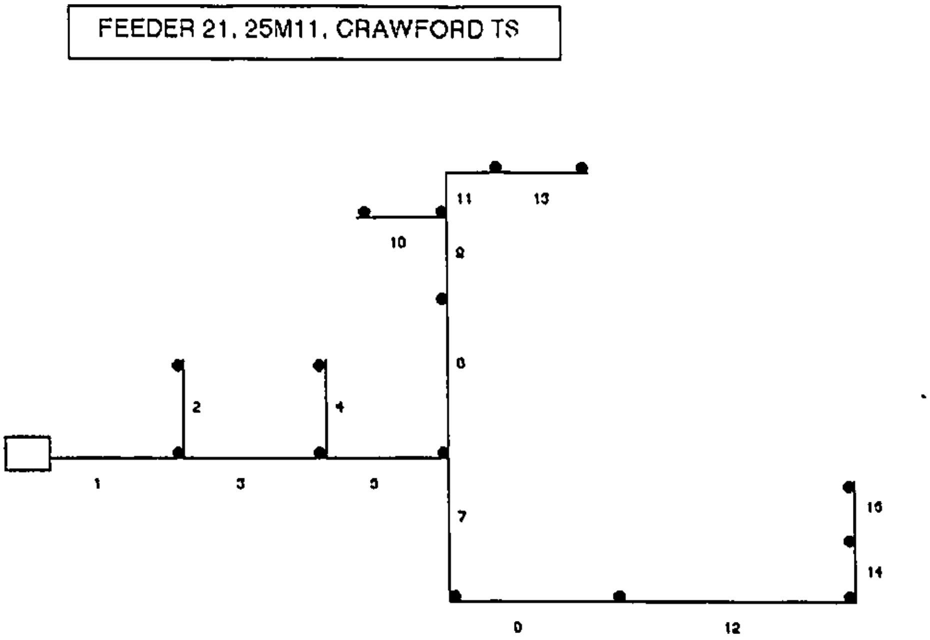

Fig.(6.22) Map of Feeder No. 21

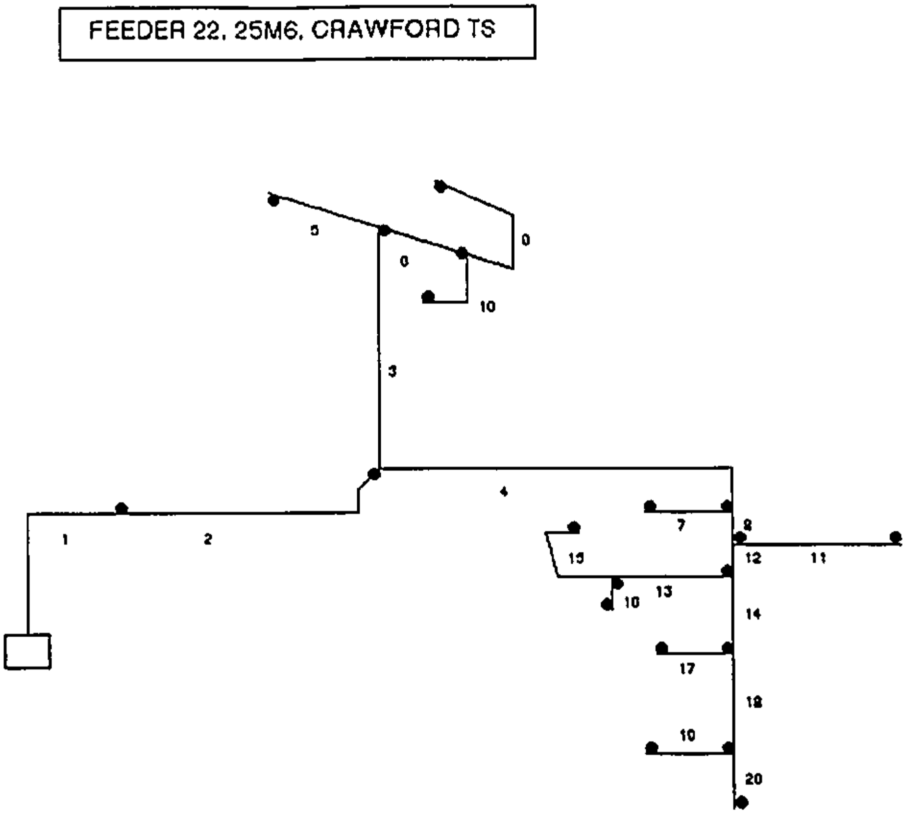

Fig.(6.23) Map of Feeder No. 22

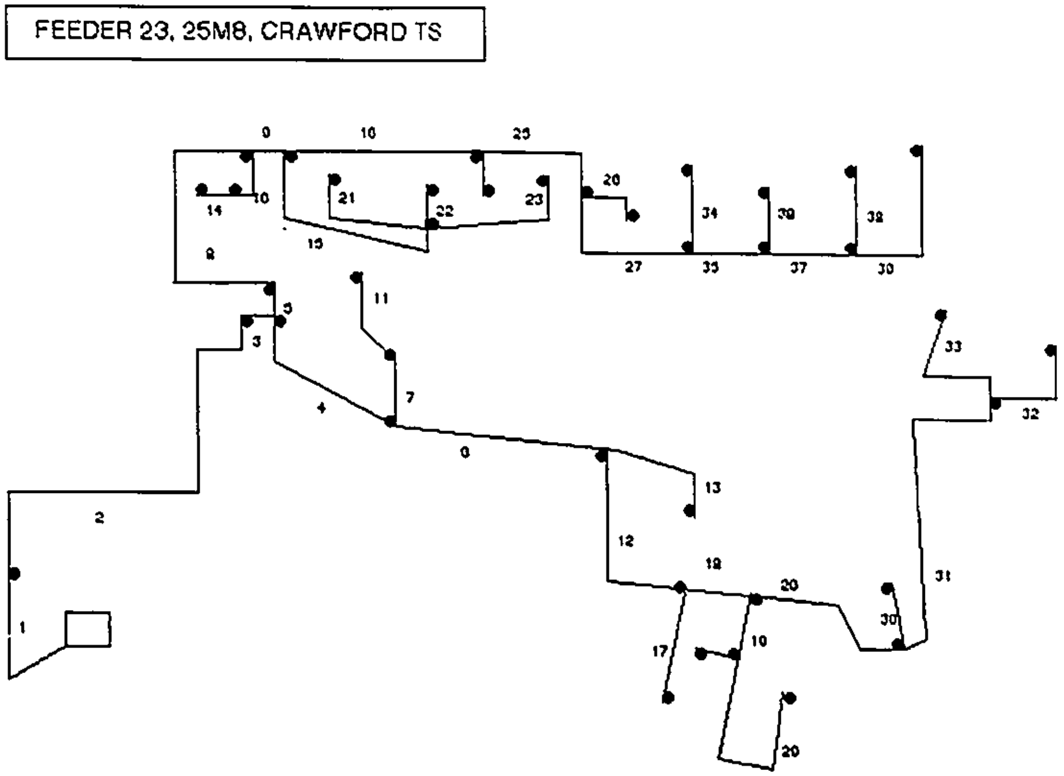

Fig.(6.24) Map of Feeder No. 23

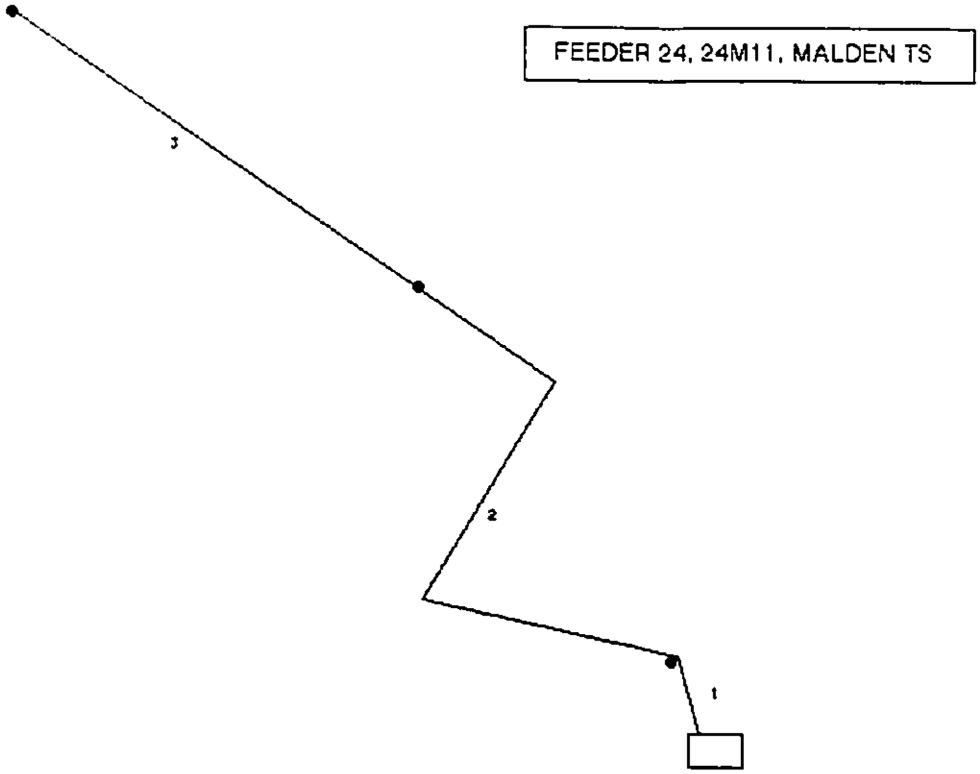

Fig.(6.25) Map of Feeder No. 24

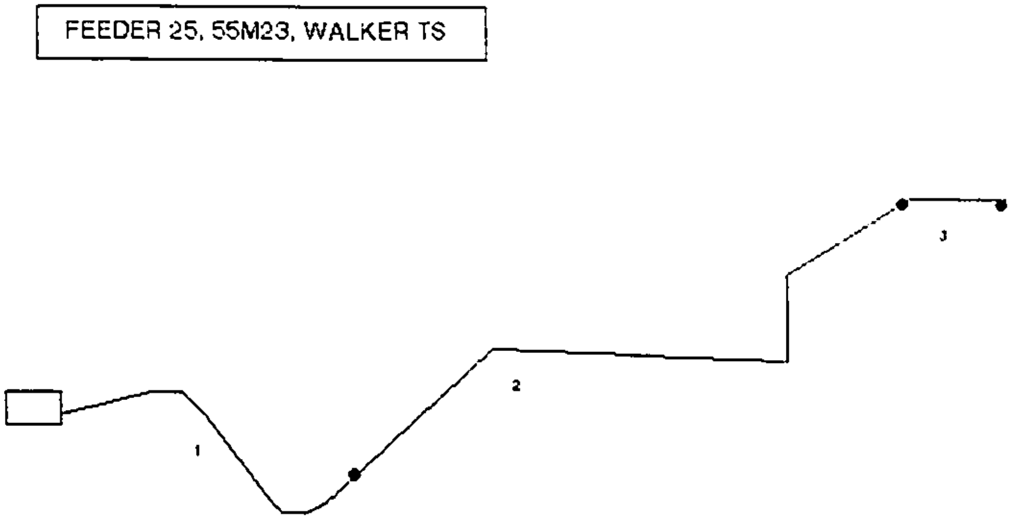

Fig.(6.26) Map of Feeder No. 25

FEEDER 26, 25M12, CRAWFORD TS

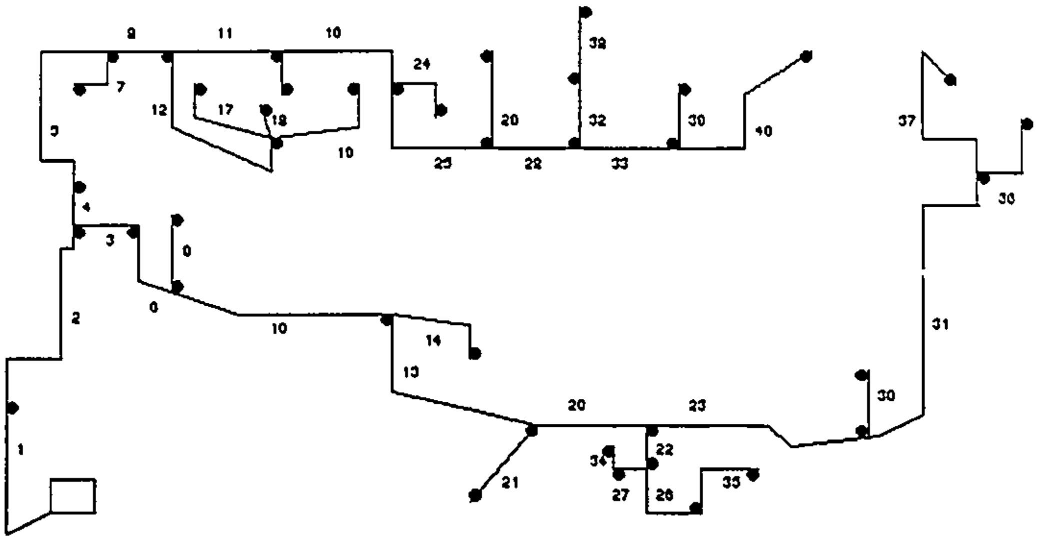

Fig.(6.27) Map of Feeder No. 26

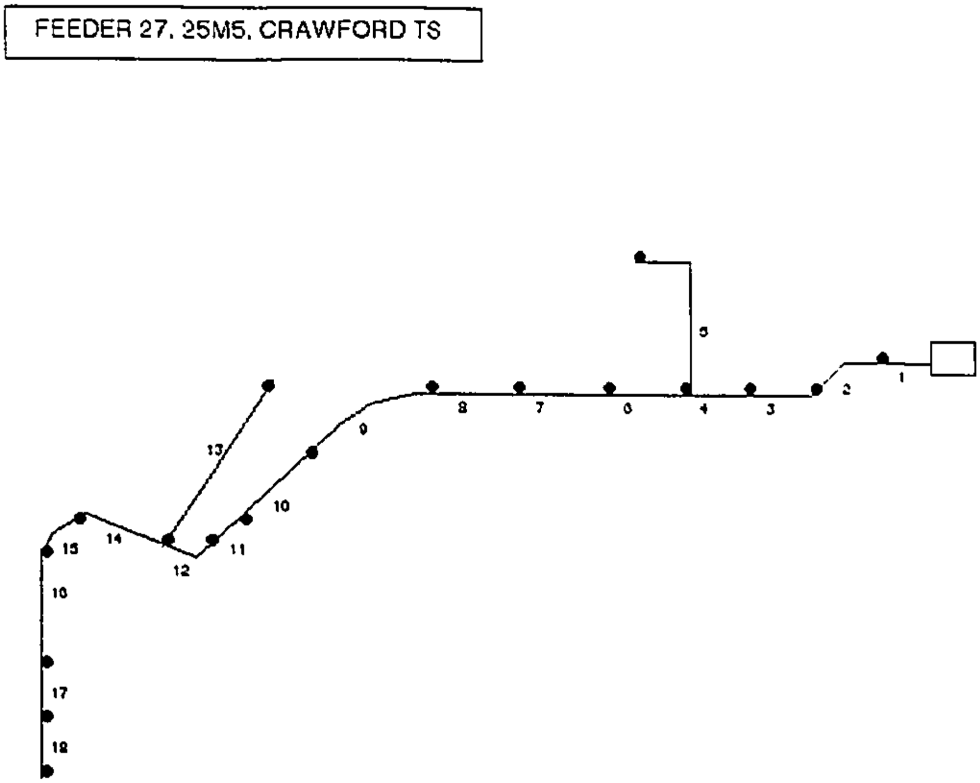

Fig.(6.28) Map of Feeder No. 27

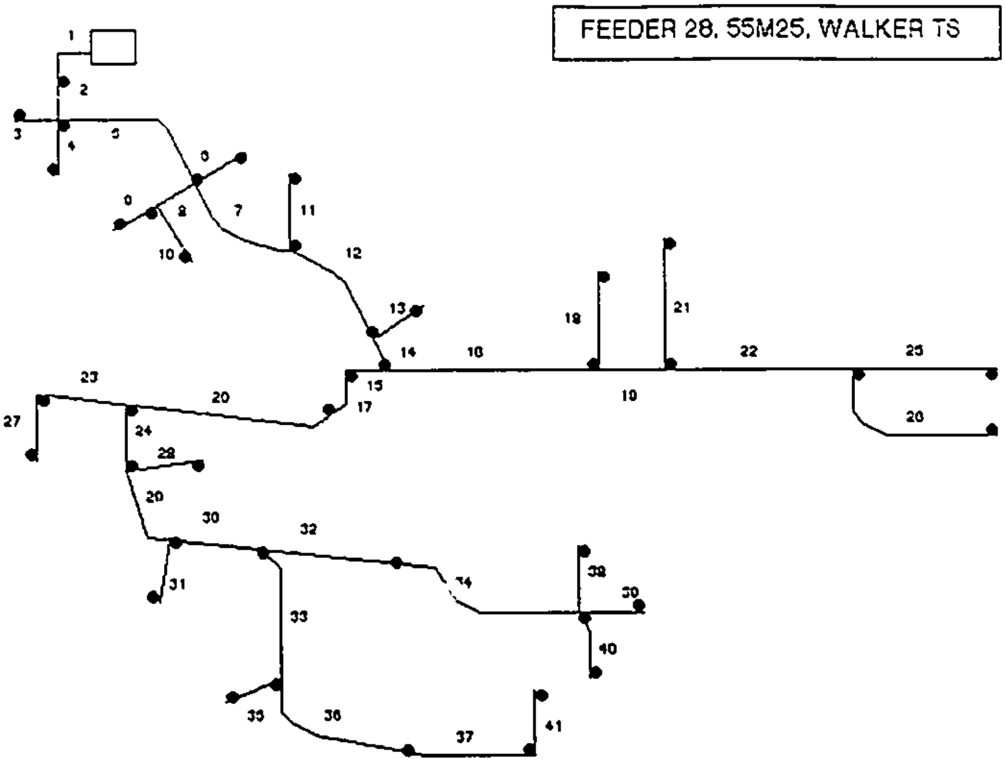

Fig.(6.29) Map of Feeder No. 28

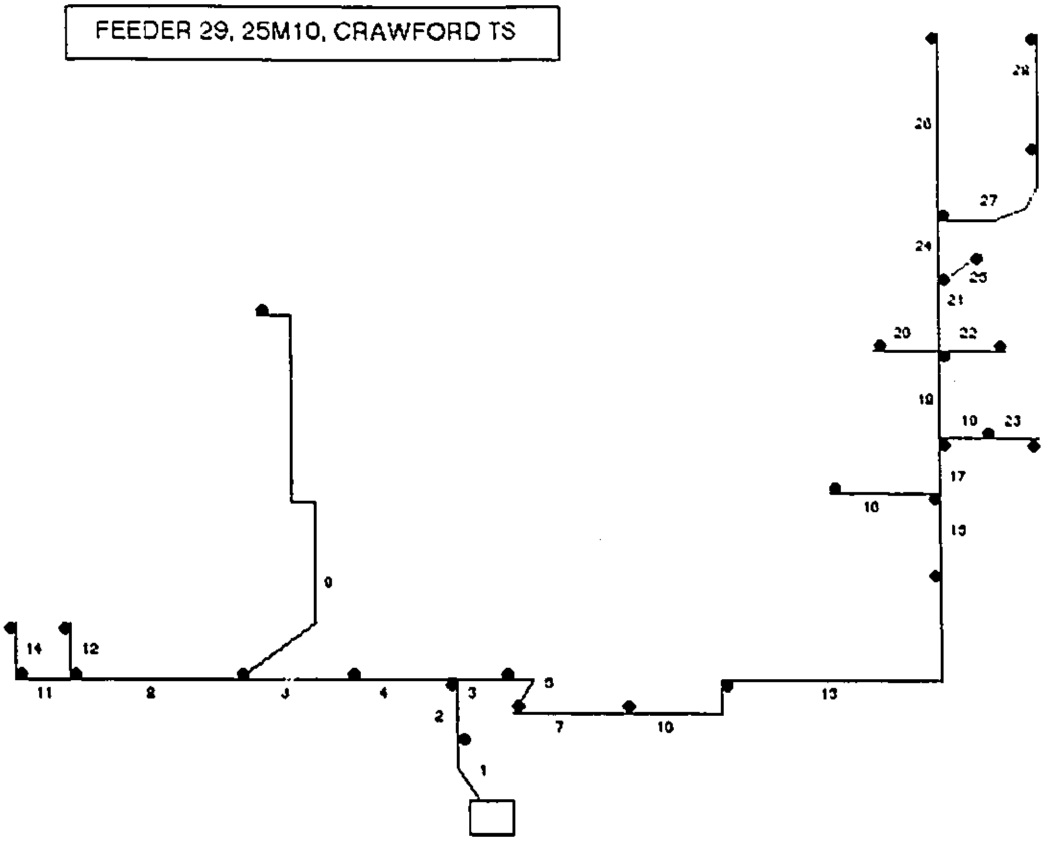

Fig.(6.30) Map of Feeder No. 29

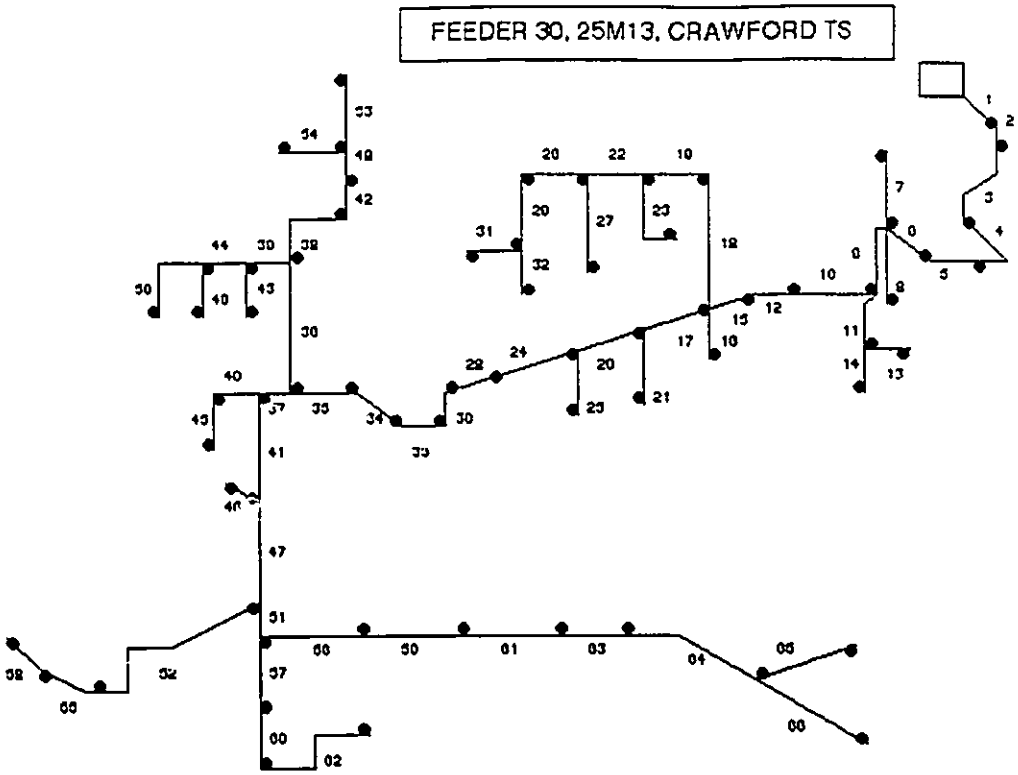

Fig.(6.31) Map of Feeder No. 30

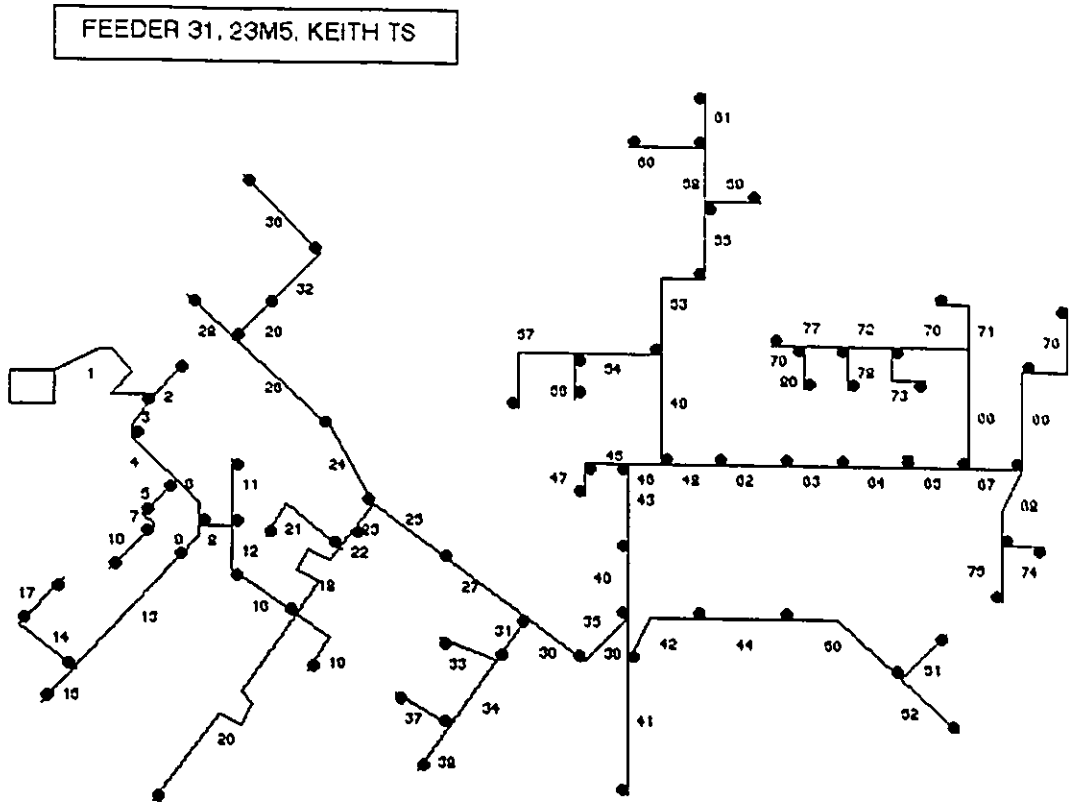

Fig.(6.32) Map of Feeder No. 31

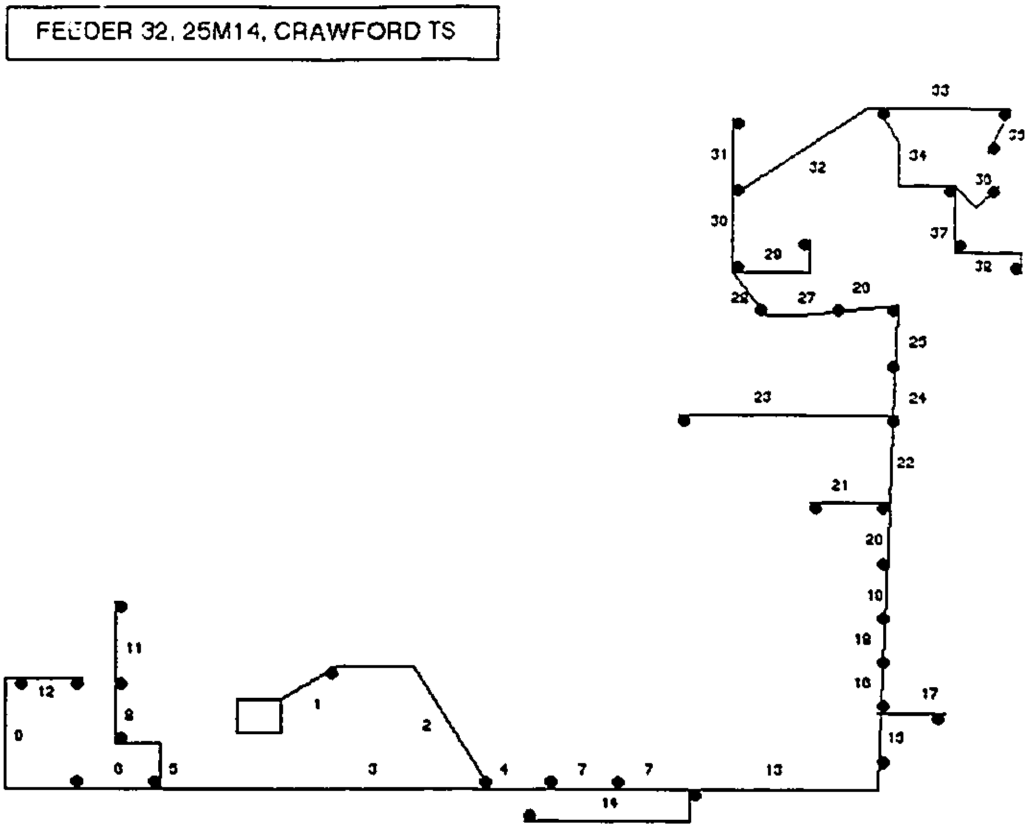

Fig.(6.33) Map of Feeder No. 32

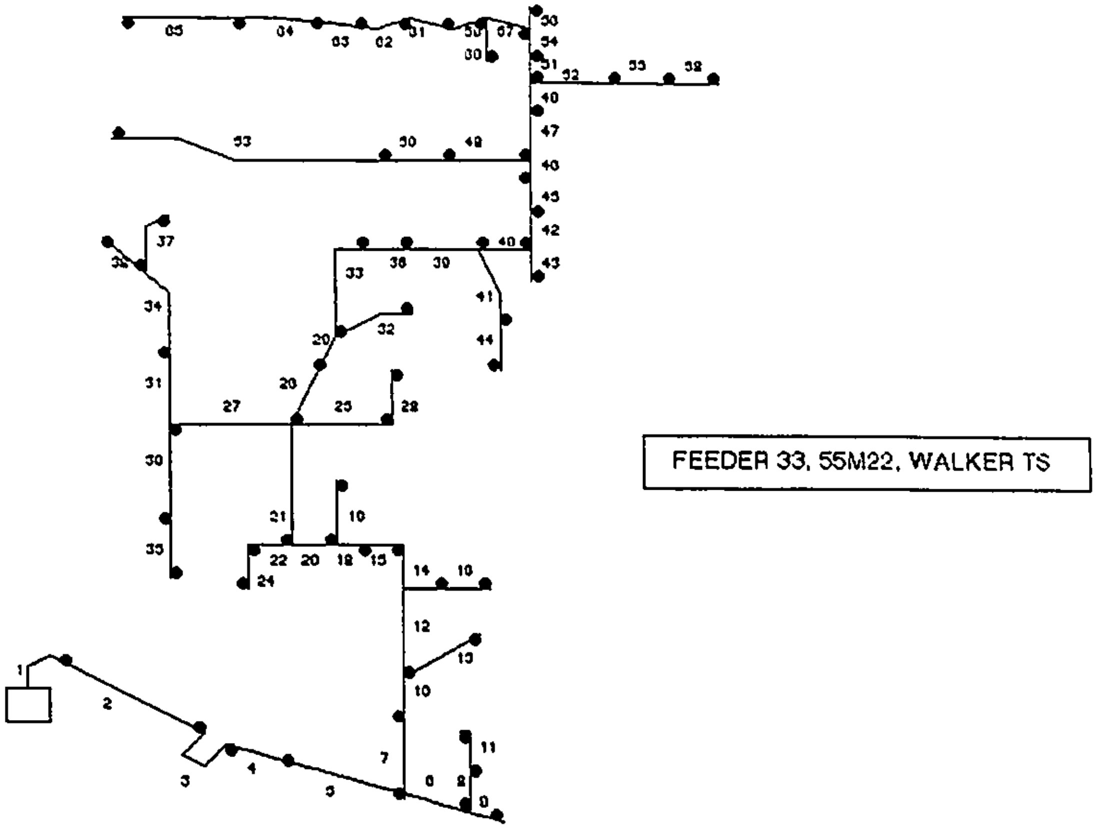

Fig.(6.34) Map of Feeder No. 33

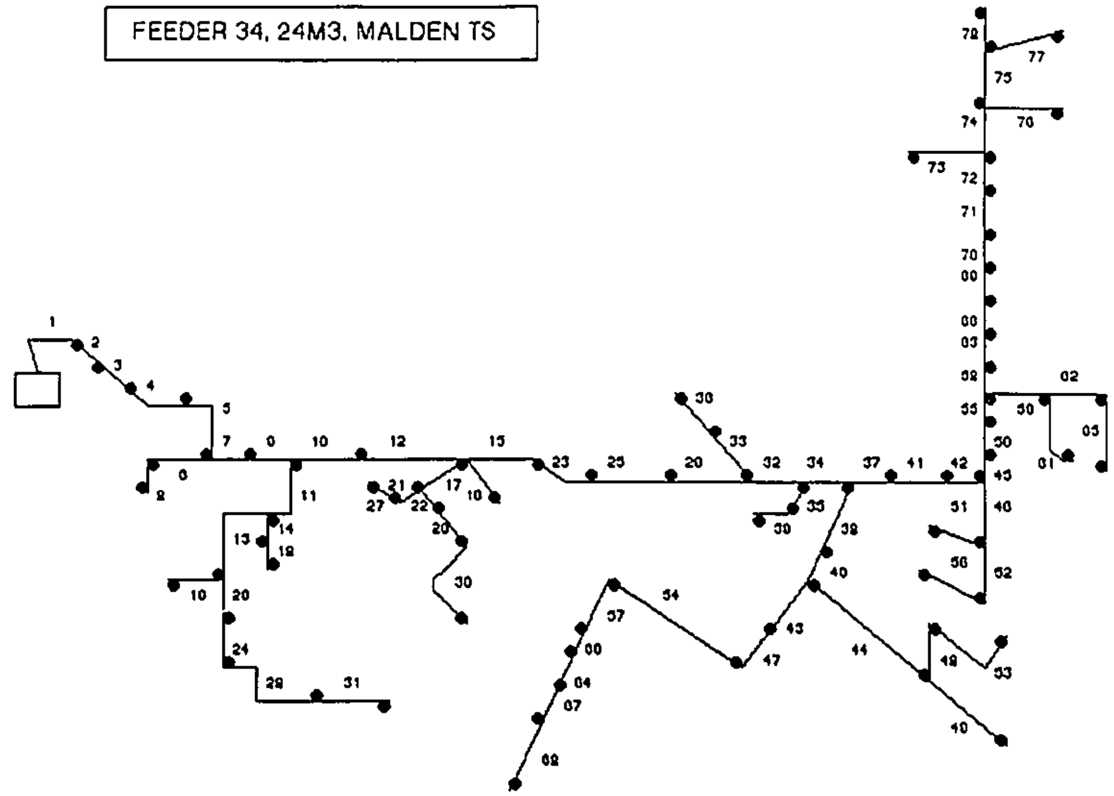

Fig.(6.35) Map of Feeder No. 34

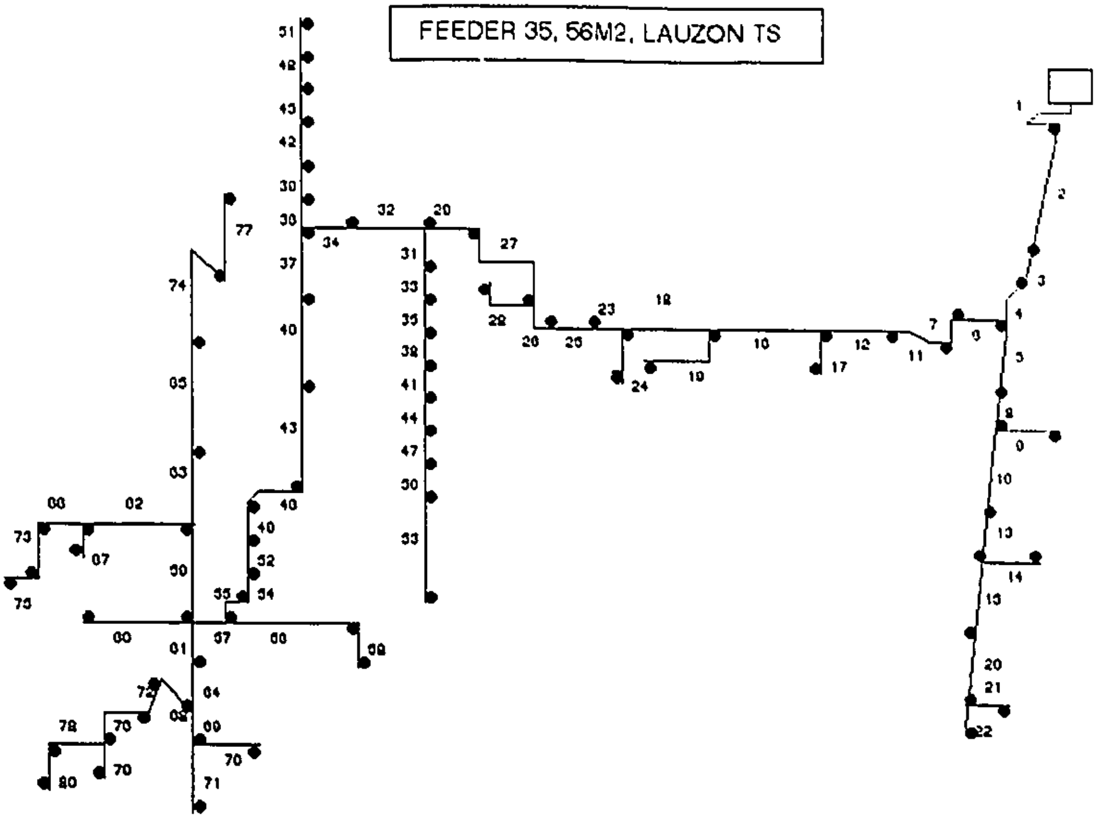

Fig.(6.36) Map of Feeder No. 35

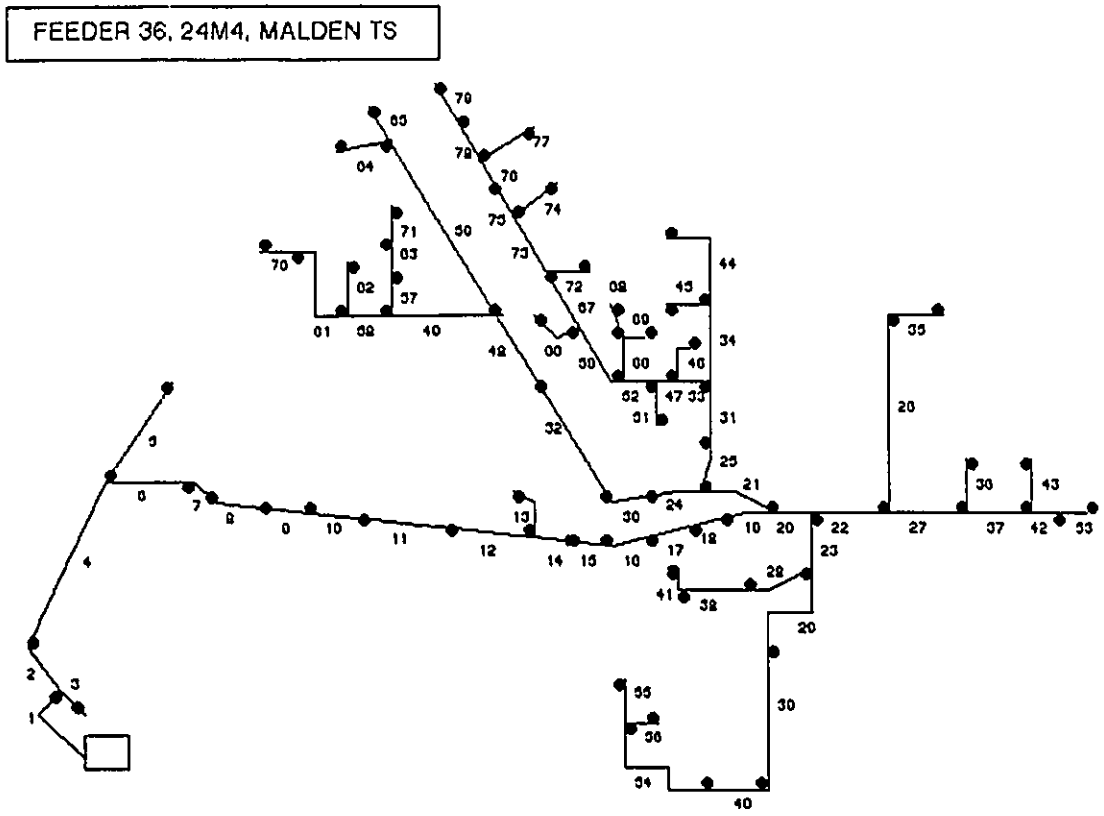

Fig.(6.37) Map of Feeder No. 36

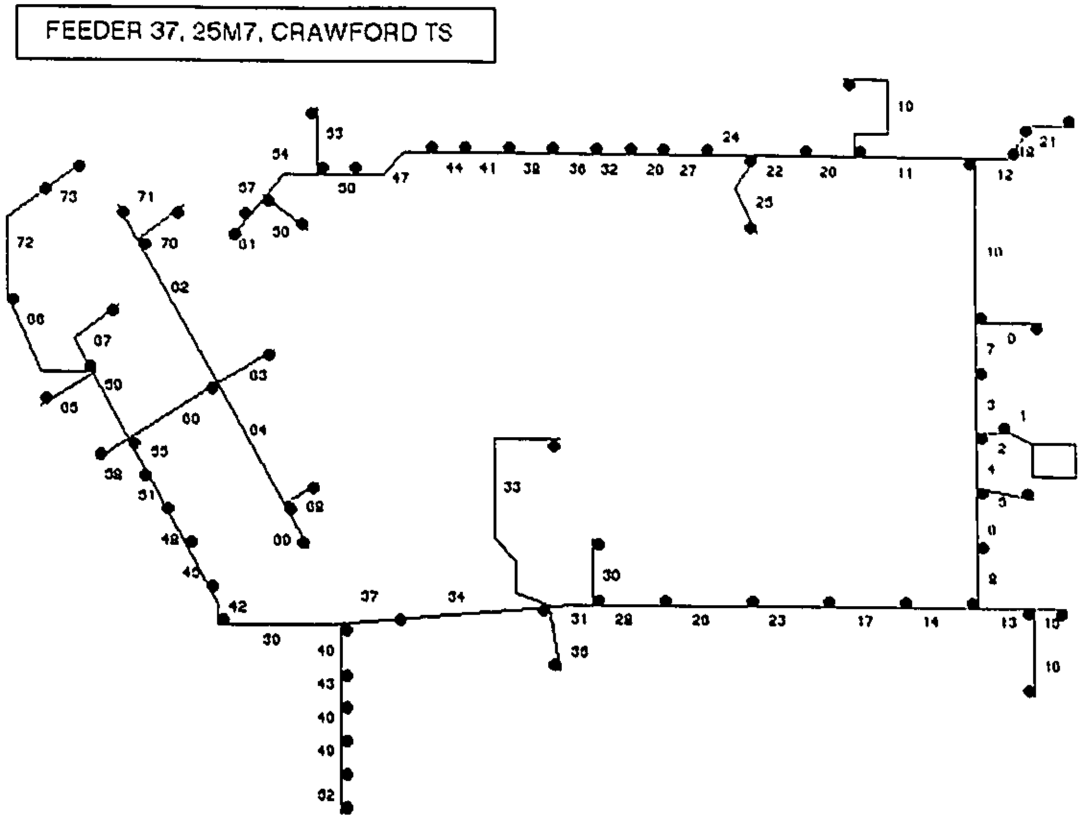

Fig.(6.38) Map of Feeder No. 37

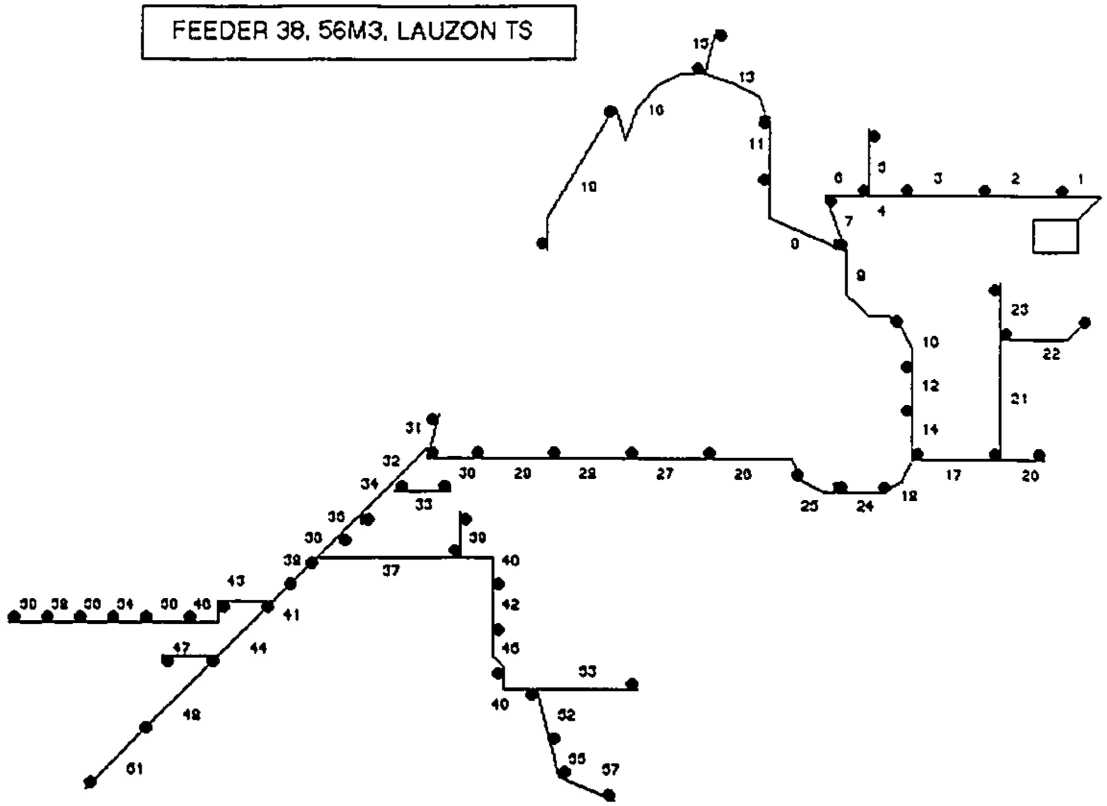

Fig.(6.39) Map of Feeder No. 38

The reason for these differences is attributed to the differences in the load levels and the feeder configuration. Also the cost of energy and the annual cost of the compensating capacitors affect these results.

6.3.1.Feeders Without Loads

In the WUC network there are three feeders, identified by the numbers 14, 16 and 24 with no load. These feeders may be used for future expansion of the network. These feeders are not included in the calculations, but they are mentioned here because they are a part of the WUC network.

6.3.2.Feeders Without Capacitors

A number of feeders in the WUC network, do not include capacitors as the optimal reactive power needed is less than the reactive power given by the capacitor unit (900 kVAR). These feeders are identified by the numbers 5, 15 and 20. The reason for this result is due to the low reactive load level in these feeders.

6.3.3.Feeders With Negative Net Dollar Savings

It should be emphasized, and as is well known, that although complete compensation of reactive power can be readily achieved with capacitors it is not always cost effective in terms of the difference between the energy saved and the cost of applying the capacitors. For example, a negative saving is obtained in feeder No. 18 (55M2, Walker TS) which carries a maximum load of 21 MW and 10.1 MVAR distributed via 19 main load points. Figure (6.40) shows that the annual dollar value of the reduction of energy at any number of capacitors is less than the annual cost of these capacitors. Accordingly, no capacitors are recommended to be installed on that feeder. This is provided that the only objective is to increase the net dollar profit of the power system.

Table (6.1) shows the losses on feeder no. 18 due to only the reactive power component as a function of the number of capacitor units at different time periods, while Table (6.2) shows the losses due to both active and reactive power. Other feeders identified by the numbers 2, 8, 21, 22, 23, 25, 26, 28 and 30 produce negative savings, therefore it is not recommended to connect any capacitors there.

6.3.4. Feeders With Positive Net Dollar Savings

In the WUC network, there are 22 feeders out of a total of 38, where positive dollar savings are obtained with compensating capacitors. Positive dollar saving is obtained by subtracting the annual cost of the compensating capacitors from the cost of the energy saved per year. An example of such feeders is number 34 (24M3, Malden TS), that carries a maximum of 23.8 MW and 14.7 MVAR, serving 79 main load points, and carries 50% residential and the balance is industrial loads. The latter ratio is taken into account when calculating the load conversion factors as shown in Chapter 3. The map of feeder no. 34, including the sectional numbering using the numbering technique explained in Chapter 5, is shown in Fig. (6.35).

Table (6.3) shows the losses in kW arising from only the reactive current in feeder No.34, as a function of the number of the installed capacitors at different periods (from 1 to 12).

It will be observed, for example, that for period number 8 applying 9 capacitors reduces the losses by about 96% (from 73 to 3 kW), while for period 2, 9 capacitors results in the losses due to the reactive current by about 74% (from 185 to 49 kW). As stated before, this feeder has 79 nodes while the number of the *sensitive* nodes determined in this study in which the capacitors are installed is only 8.

Table (6.4) shows the total losses (in kW) in feeder no. 34, which arise from the combined active and reactive currents as a function of the number of the installed capacitors at different time periods. It is evident that the installation of the capacitors has a lower effect on the total losses, compared to that of the losses due to only the reactive current, as the active current, which is in most cases larger in value than the reactive current, remains unchanged. For example, at period 8, applying 9 capacitors reduces the total losses by 31% (from 229 to 157 kW).

Figure (6.41) shows the dollar value of the annual energy loss reduction, the amortized annual cost of multiple units of capacitors including the cost of capital and cost of installation and the effective annual dollar saving after incorporating the capacitors for a typical feeder (no.34).

It will be seen that although the value of the annual energy saved increases with increasing the number of capacitor units installed on the feeder, it is not necessarily that the higher energy saved is the most cost effective. The cost of the capacitors increases linearly with increasing number of units installed. Connecting 14 capacitors in the feeder will result in a maximum saving of $21,589 per year (Fig. (6.41)). The number of capacitor banks which are to be installed on a given feeder is determined by adding the annual dollar saving of the 12 periods and thus the whole year. The number of capacitors which gives the maximum dollar saving is chosen.

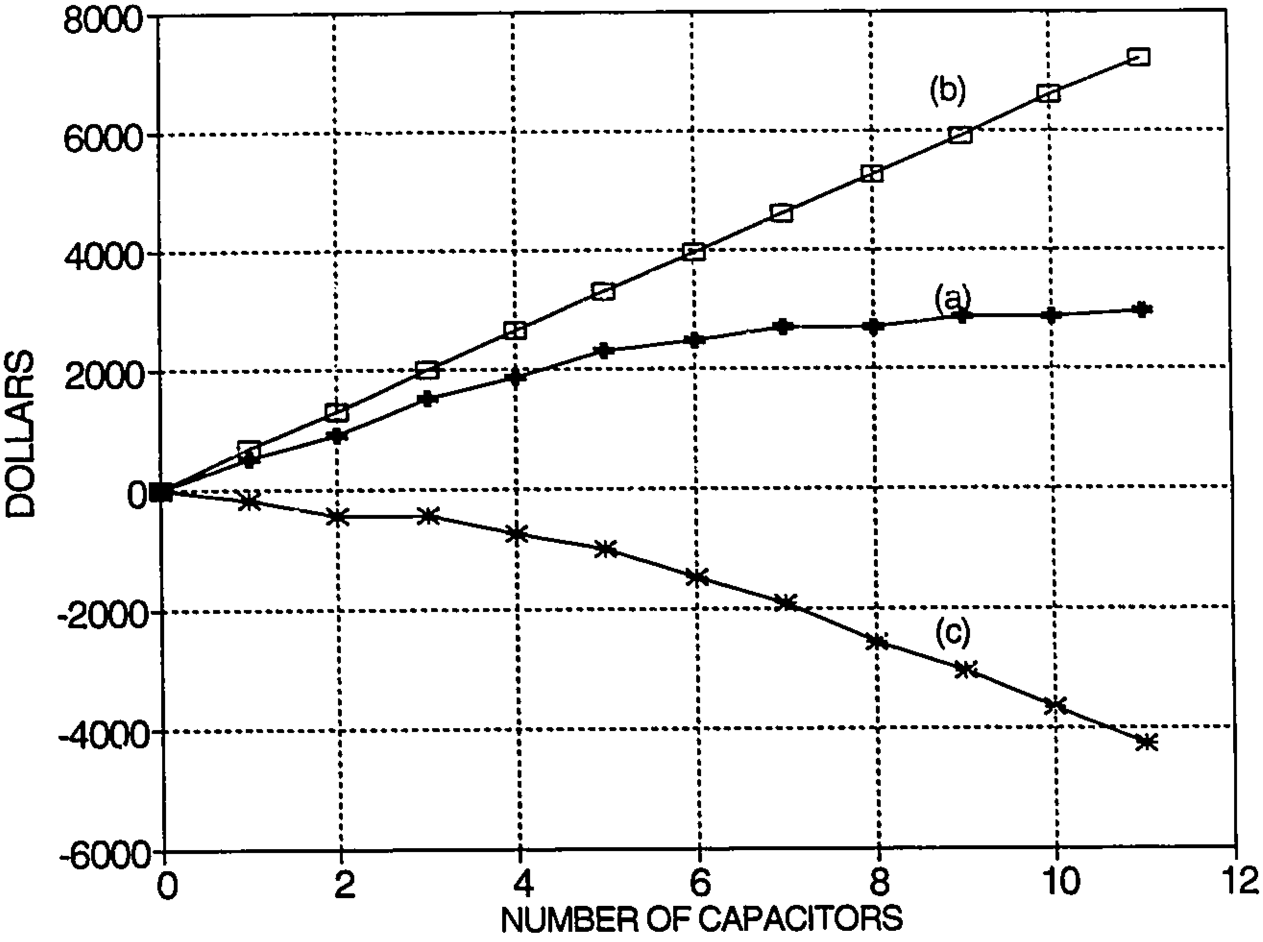

Fig.(6.40) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors including the cost of capital and cost of installation (b) and the net annual dollar saving (c) after subtracting the cost of the capacitors in feeder no.18.

Table (6.1) Losses (in kW) in feeder no. 18, arising from the reactive current, as a function of the number of the installed capacitors at different time periods. Each capacitor bank is 0.9 MVAR.

		Total Number of Capacitor Banks											
period No.	T_p (hrs)	0	1	2	3	4	5	6	7	8	9	10	11
1	964	22	19	16	12	10	6	5	3	1	1	0	0
2	579	18	15	12	9	7	4	3	1	0	0	0	0
3	385	12	10	8	5	3	1	1	0	0	0	0	0
4	231	10	8	6	4	2	1	0	0	0	0	0	0
5	1960	17	14	12	8	6	4	2	1	0	0	0	0
6	1177	13	11	9	6	4	2	1	0	0	0	0	0
7	784	9	7	4	3	1	1	0	0	0	0	0	0
8	470	8	6	3	2	1	0	0	0	0	0	0	0
9	985	18	15	12	8	6	4	3	1	0	0	0	0
10	592	14	11	9	6	4	2	1	0	0	0	0	0
11	394	16	13	11	7	6	3	2	1	0	0	0	0
12	237	14	11	9	6	4	2	1	0	0	0	0	0

Table (6.2) Total losses (in kW) in feeder no. 18, which arise from the combined active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor bank is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks											
		0	1	2	3	4	5	6	7	8	9	10	11
1	964	115	111	109	104	102	99	97	95	94	93	92	92
2	579	92	89	87	83	81	78	77	75	74	74	74	74
3	385	63	61	59	56	56	52	52	51	51	51	51	51
4	231	54	52	50	47	46	45	44	44	44	44	44	44
5	1960	88	85	82	79	77	74	73	72	71	70	70	70
6	1177	70	67	65	62	60	58	57	56	56	56	56	56
7	784	47	45	43	41	40	39	38	38	38	38	38	38
8	470	40	39	36	35	34	33	32	32	32	32	32	32
9	985	91	88	85	82	80	77	76	74	74	73	73	73
10	592	73	70	68	65	63	61	60	59	59	58	58	58
11	394	83	80	78	74	73	70	69	68	67	67	67	67
12	237	71	68	66	63	61	59	58	57	57	57	57	57

Table (6.3) Losses (in kW) in feeder no. 34, arising from the reactive current, as a function of the number of the installed capacitors at different time periods. Each capacitor bank is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks																
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	964	241	218	197	177	159	143	119	105	93	74	66	51	36	25	16	9	4
2	579	185	166	148	132	116	103	83	72	64	49	35	23	15	11	6	2	2
3	385	120	105	91	79	68	52	44	36	31	21	12	6	2	2	2	2	2
4	231	101	87	75	64	54	40	33	28	119	10	5	2	2	2	2	2	2
5	1960	175	156	139	123	108	88	77	66	59	44	31	20	13	7	2	2	2
6	1177	134	118	103	90	78	61	52	44	38	26	16	9	4	1	1	1	1
7	784	87	74	63	53	40	32	26	22	13	6	2	2	2	2	2	2	2
8	470	73	61	51	42	31	24	19	16	9	3	1	1	1	1	1	1	1
9	985	183	164	146	129	114	94	81	70	63	48	34	23	14	8	5	2	2
10	592	141	125	110	96	83	66	56	47	41	29	19	11	6	2	2	2	2
11	394	165	147	130	115	101	82	70	60	53	39	27	17	10	5	2	2	2
12	237	137	121	106	92	80	63	53	45	39	27	17	10	5	1	1	1	1

Table (6.4) Total losses (in kW) in feeder no. 34, arising from the combining the active and reactive current, as a function of the number of the installed capacitors at different time periods. Each capacitor bank is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks																
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	964	689	665	643	622	603	585	561	546	533	514	505	489	475	463	455	447	443
2	579	543	523	504	487	471	456	436	424	416	400	386	375	366	362	357	353	353
3	385	364	349	334	321	310	294	285	277	272	261	252	246	243	243	243	243	243
4	231	310	296	283	272	261	248	240	234	225	216	211	208	208	208	208	208	208
5	1960	515	495	477	461	445	425	412	401	393	378	365	354	347	341	337	337	337
6	1177	404	387	372	358	345	328	318	310	303	292	282	274	270	267	267	267	267
7	784	270	257	245	235	221	214	207	202	194	187	183	183	183	183	183	183	183
8	470	229	217	207	197	186	179	173	170	163	157	155	155	155	155	155	155	155
9	985	536	516	497	480	464	443	430	419	410	395	380	370	361	355	352	349	349
10	424	406	390	376	363	345	335	326	319	307	296	288	283	280	280	280	280	280
11	394	488	469	451	435	421	401	389	379	371	357	344	334	328	323	319	319	319
12	237	411	394	379	365	352	335	324	315	309	297	287	280	275	272	272	272	272

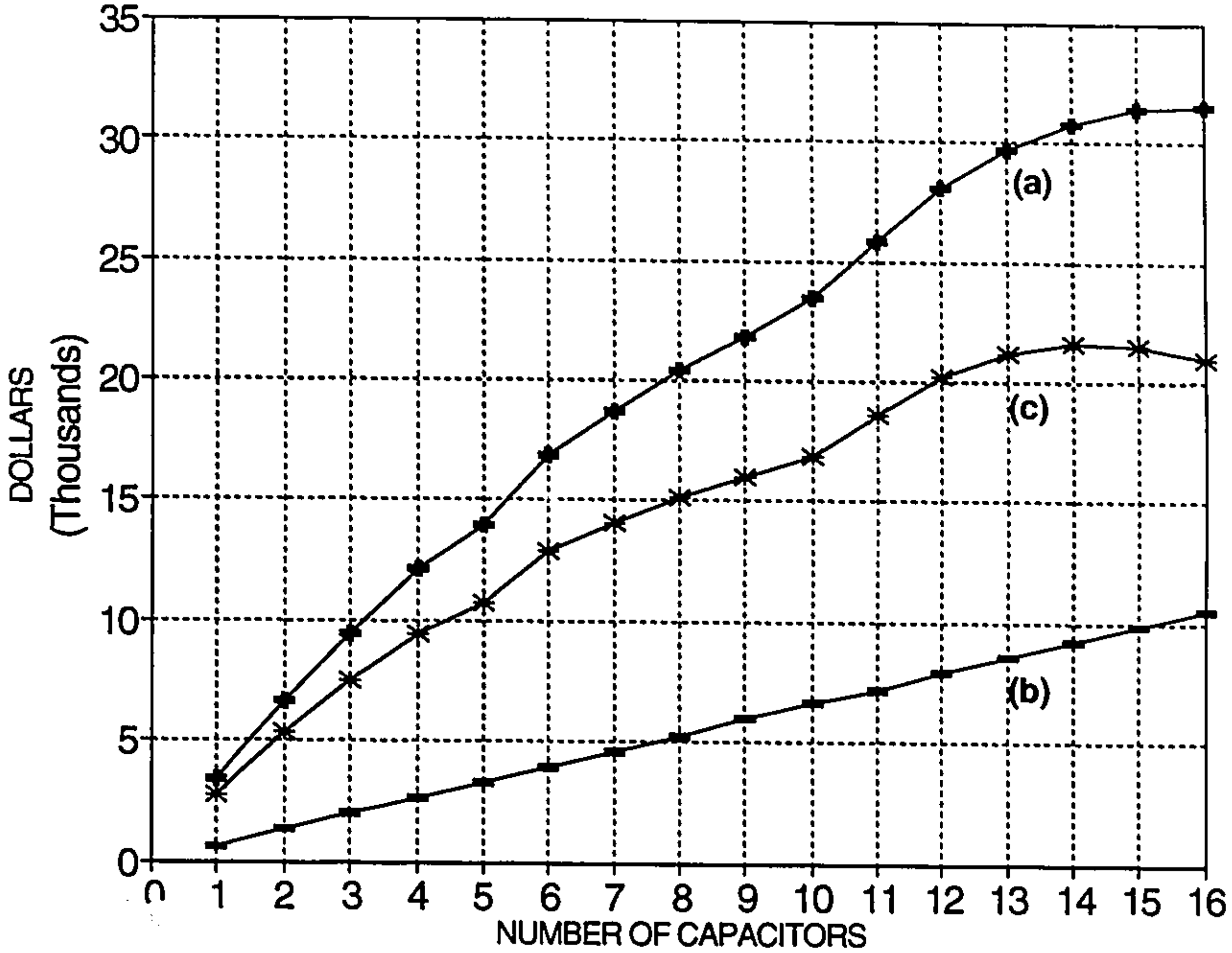

Fig.(6.41) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors including the cost of capital and cost of installation (b) and the net annual dollar saving (c) after subtracting the cost of the capacitors in feeder no.34.

For some periods the calculated losses in the feeder decrease to a steady value with a specified number of units of capacitors. This does not necessary give the maximum dollar saving for other periods, and it is required to continue the calculation with more capacitors to satisfy the requirement that in all periods the losses decrease to a steady state. Only then the dollar saving is summed up for the whole year for each of the capacitors used.

Figures (6.42) to (6.70) show the dollar value for the other feeders in the WUC network. Tables (6.5) to (6.34) show the total losses, while Tables (6.35) to (6.64) show the losses due to only the reactive component as a function of number of capacitors for different periods for the different feeders in the WUC network.

6.3.4.1.Switching Table

As the load changes during the year, the installed capacitor VAR should vary to keep the power loss at the lowest value at every period. To achieve this objective a switching table of the compensating capacitor units is developed. A typical switching sequence for feeder no. 34 is shown in Table (6.65).

It can be seen from Table (6.65) that the switching of the capacitors depends on the particular period, i.e. the load level. This table is important to prevent over-compensation which may lead to an increase in the system losses, that may arise from connecting unnecessary capacitors at a period with a relatively low load level. Also Table (6.65) shows that at periods 7 and 8, only 10 unit capacitors out of 14 are required for those two periods to keep the losses at the minimum value.

Table (6.65) indicates that in this particular feeder there are only 8 sensitive nodes where capacitors are installed. Those nodes are identified by the numbers 8, 18, 19, 39, 43, 54, 60 and 70.

Table (6.65) shows that for period no. 4, capacitor no. 6 (900 KVAR) at node 13 is switched off. Period 4 is defined in Chapter 3 of this thesis. This capacitor is switched off during the low load, in the weekend (Saturdays and Sundays) over the Winter months. Hence, 2x13 weeks =26 switching operations (off) are carried out during the Winter. Also this switch is kept off during periods 7 and 8, which are the Fall/Spring all the day in the weekends. Switching sequences for other feeders in the WUC networks are shown in Tables (6.66) to (6.68)

6.3.4.2. Feeders with Special Features

One of the most important feeders to be highlighted is feeder no. 3 (15 M7 ESSEX TS), that carries a maximum load of 21.87 MW and 9.81 MVAR distributed to 44 main load points. This feeder extends about 8.1 km (Fig. (6.71)). The special feature of this feeder is that there is no load connected for a distance of about 5.3 km (65.4% of the total length), and all the loads are concentrated in the remaining part of the feeder (2.9 km, 34.6% of the total length). Because of this feature, feeder No. 3 gives a very high dollar saving per year, as any capacitor installed will reduce the losses on a large portion of the feeder. Table (6.87) shows the losses due to reactive current on feeder No.3 as a function of the number of capacitors at different periods, while Table (6.88) shows the total losses as a function of number of capacitors at different periods. It can be calculated from Table (6.87) that using only one capacitor of 900 kVAR (costs $658 per year) the loss reduction on the year amounts 319.752

kWh with a saving of $6,875 per year based on 1993 costs of capacitors and energy. The net saving after subtracting the capacitor cost on feeder No.3 using only one capacitor is 6,875-658 = $6,217.

This big saving is attributed to the main structure of the feeder. As it can be seen from Table (6.88) that feeder No. 3 includes a total of 10 capacitor units to achieve maximum dollar saving throughout the year.

Figure (6.72) shows the dollar value of the annual energy loss reduction, the amortized annual cost of multiple units of capacitors including the cost of capital and cost of installation and the effective annual dollar saving after incorporating the capacitors in feeder No. 3.

6.3.4.3. Higher Capacitor Ratings for Higher Saving

As many of these capacitors are not subjected to any switching, combining two or more of 900 kVAR capacitors may lead to extra savings, as the cost of multiple units of low rated capacitors is higher than the cost of a single capacitor having the same rating. Therefore, at some locations on the feeders where the capacitors are installed (*sensitive* nodes), all the 900 kVAR compensating capacitors which are not subjected to any switching operations throughout the year, are combined in a single fixed capacitor having a rated value that equals the summation of those non-switchable capacitors. Table (6.89) shows the extra savings per year obtained from combining two or more of 900 kVAR capacitors.

6.4. Total Saving

When the WUC network in the city of Windsor is studied by separating the individual feeders, the results show a net of $167,845 that can be saved every year.

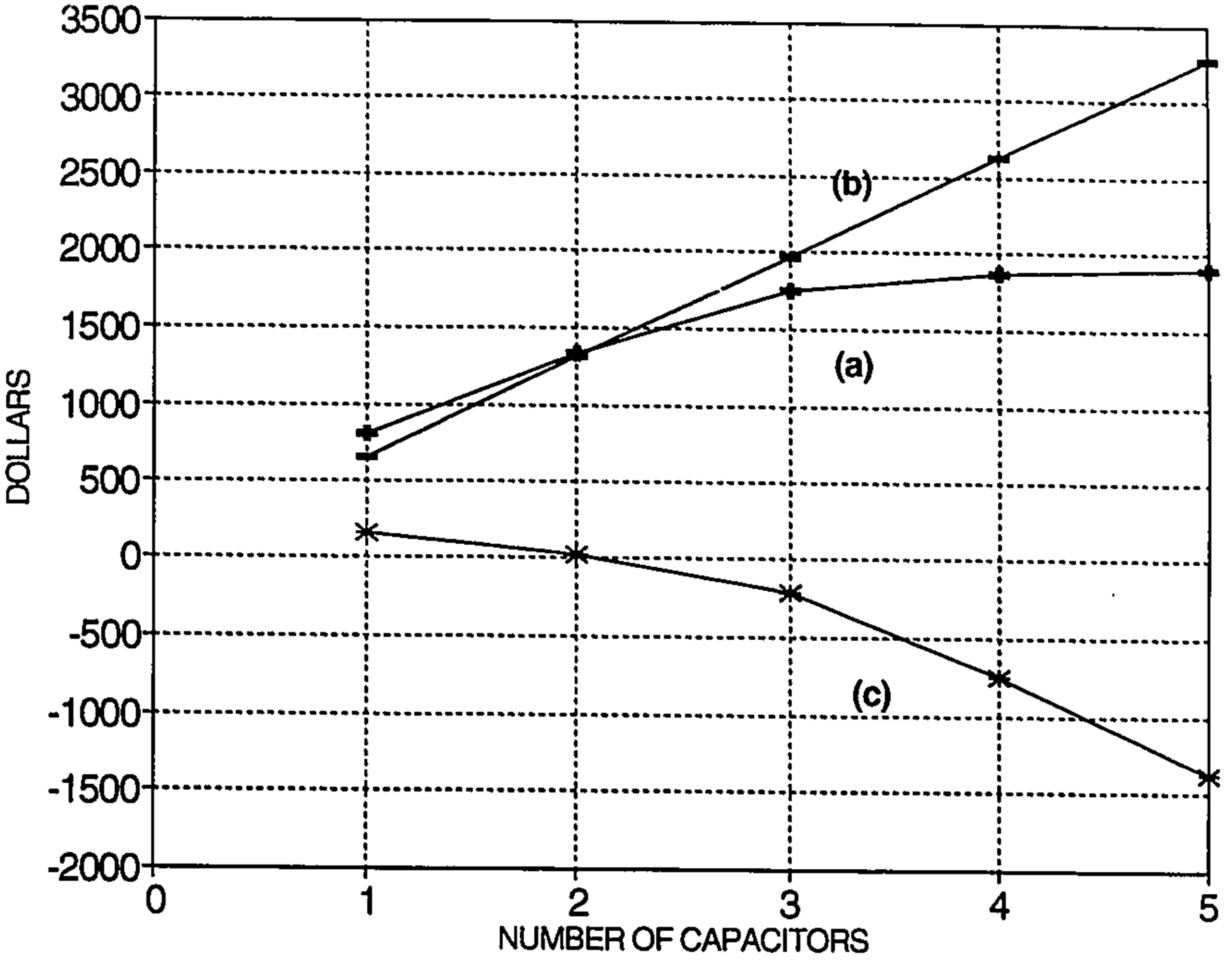

Fig.(6.42) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 1.

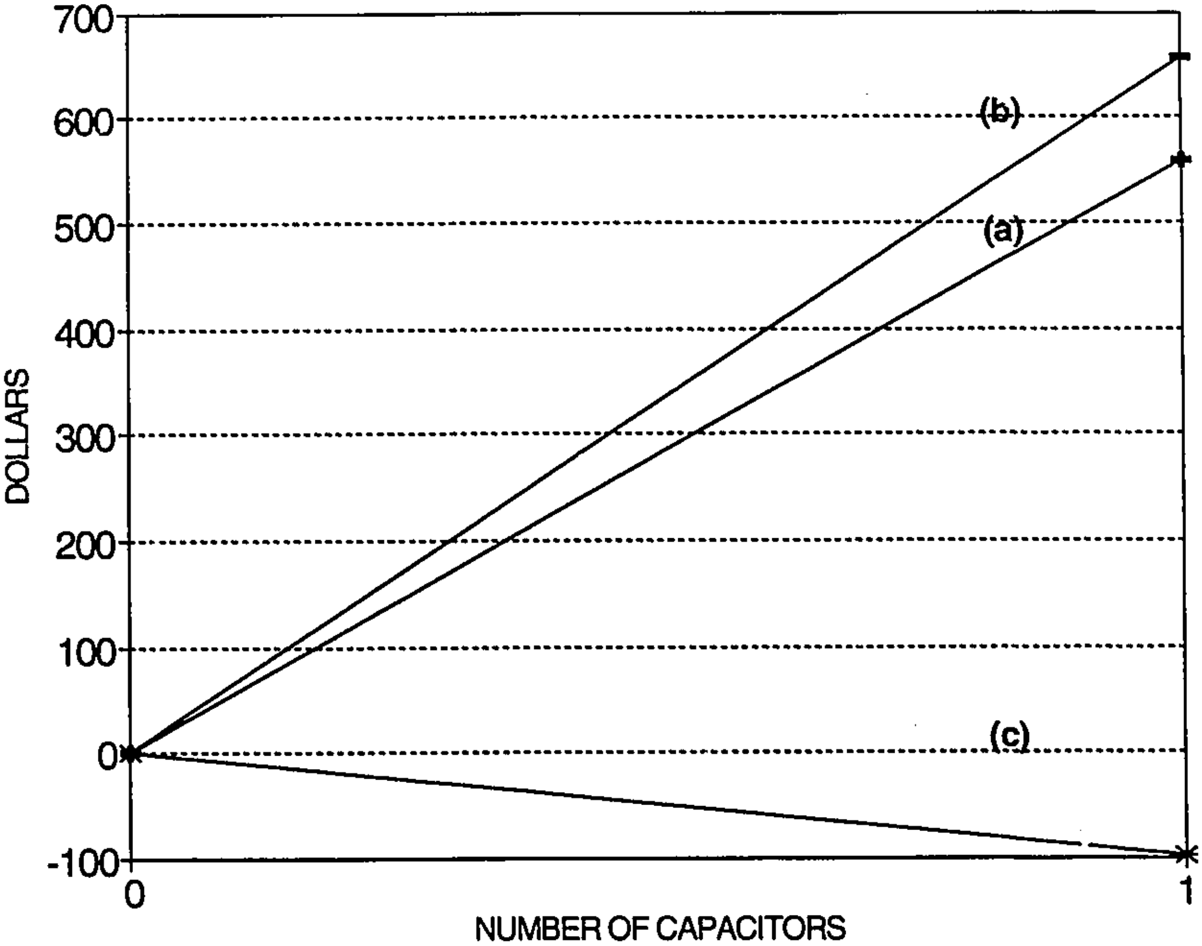

Fig.(6.43) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 2.

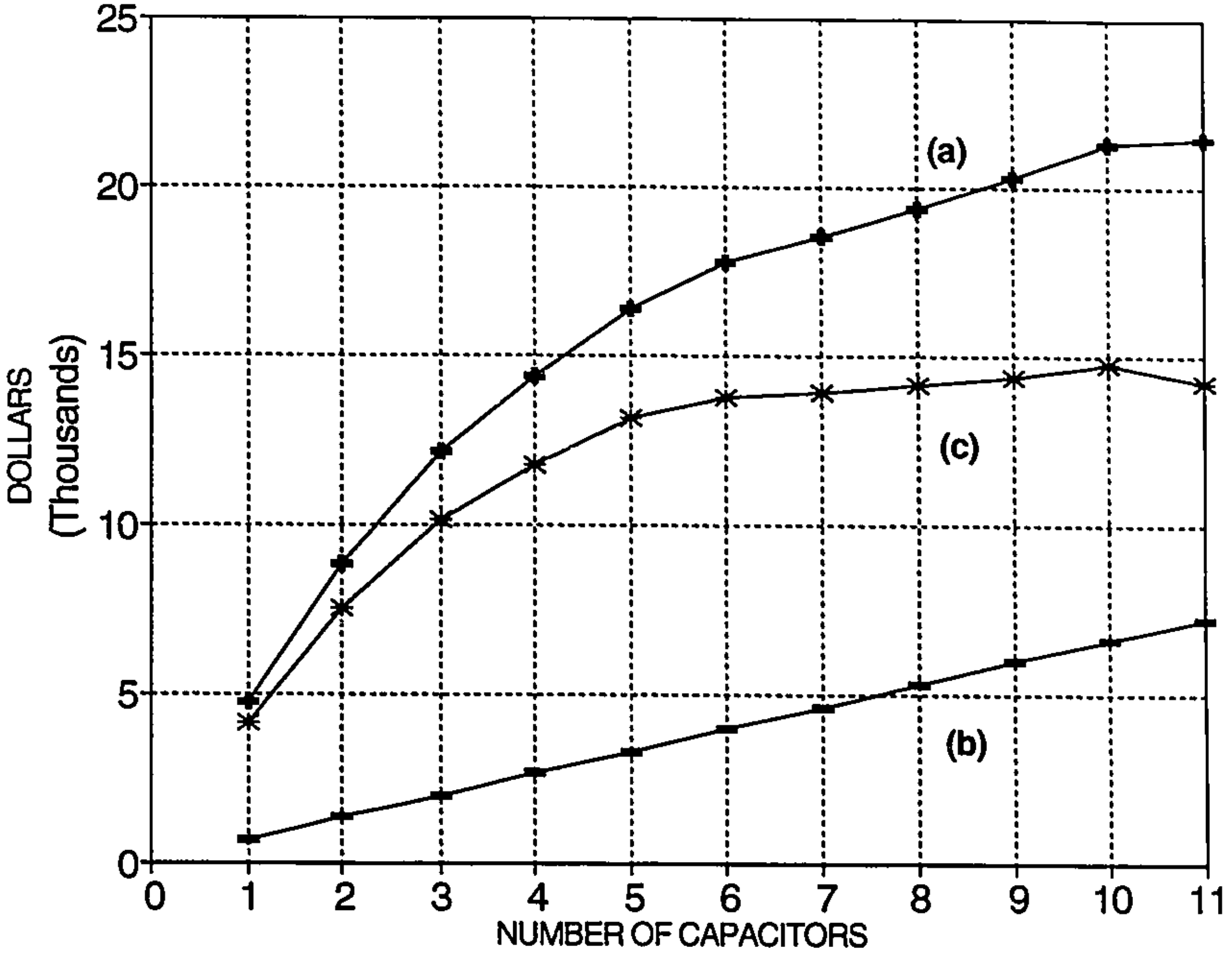

Fig.(6.44) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 4.

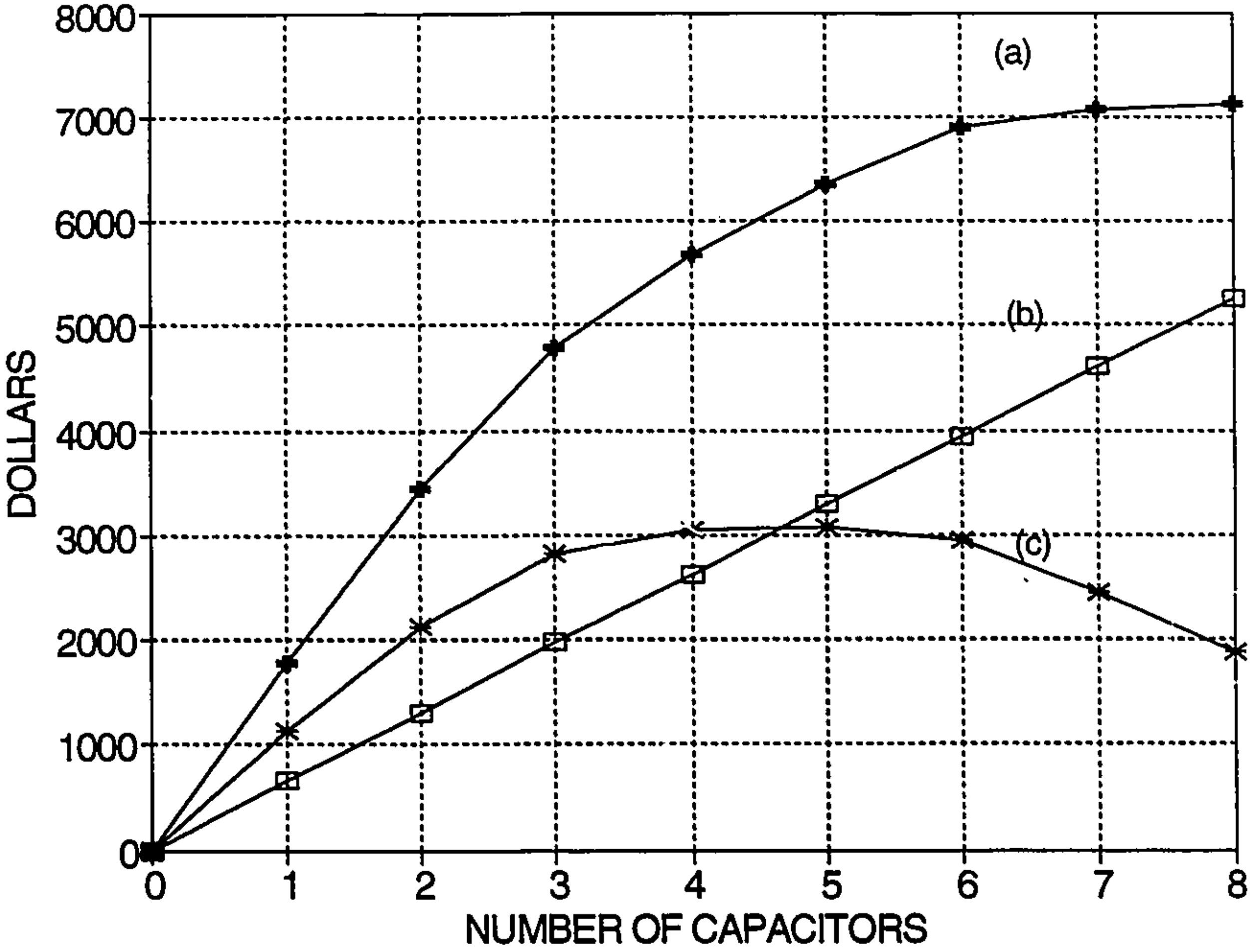

Fig.(6.45) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 6.

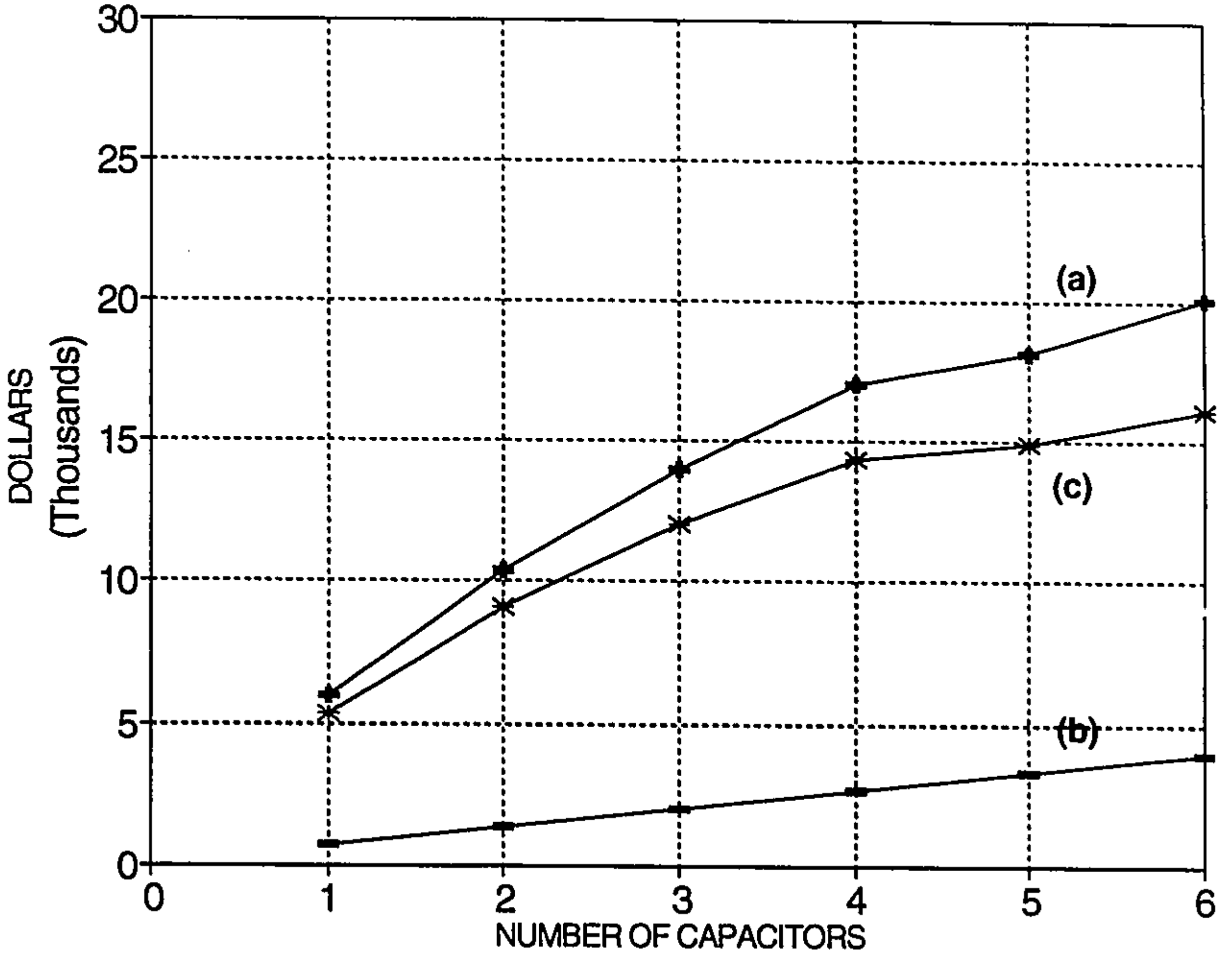

Fig.(6.46) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 7.

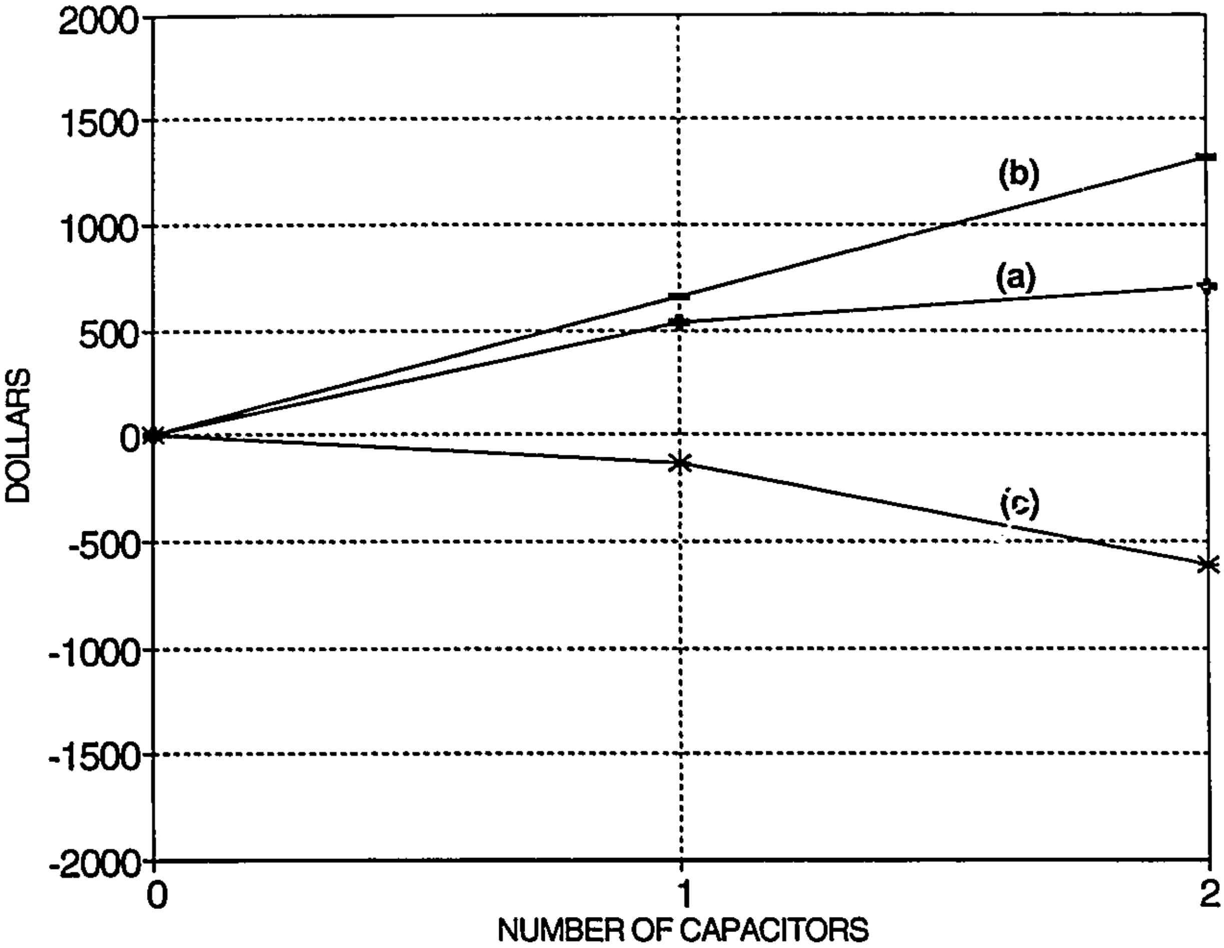

Fig.(6.47) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 8.

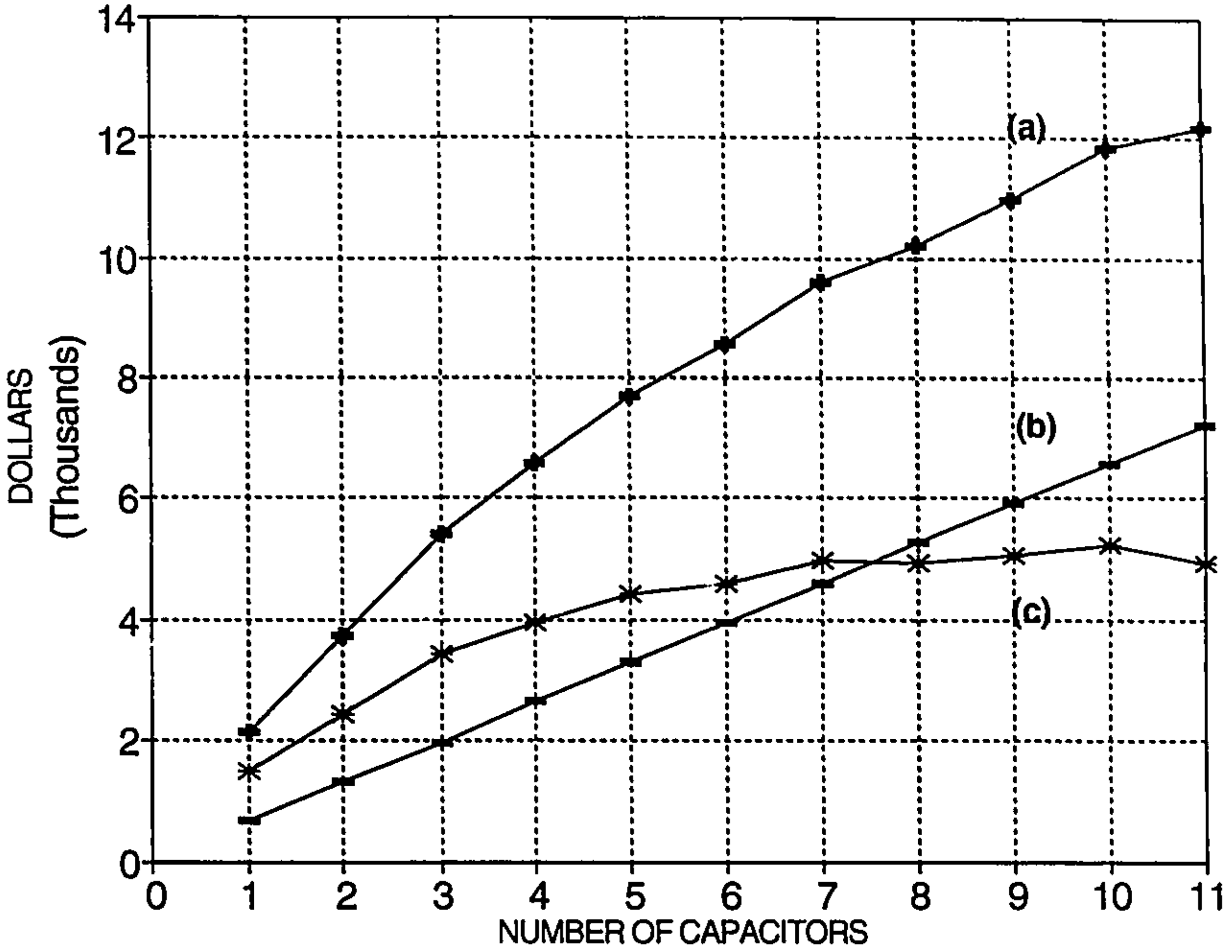

Fig.(6.48) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 9.

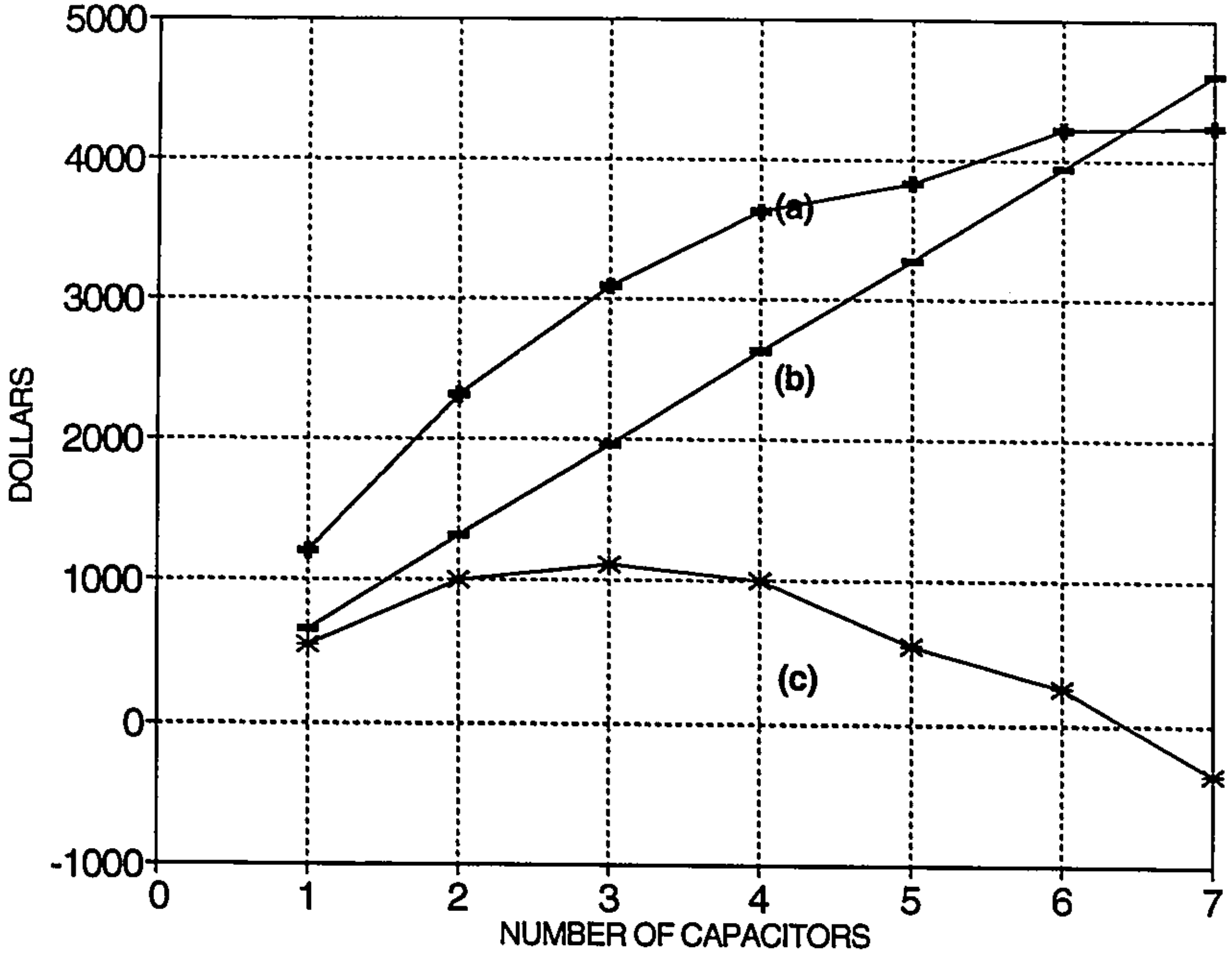

Fig.(6.49) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 10.

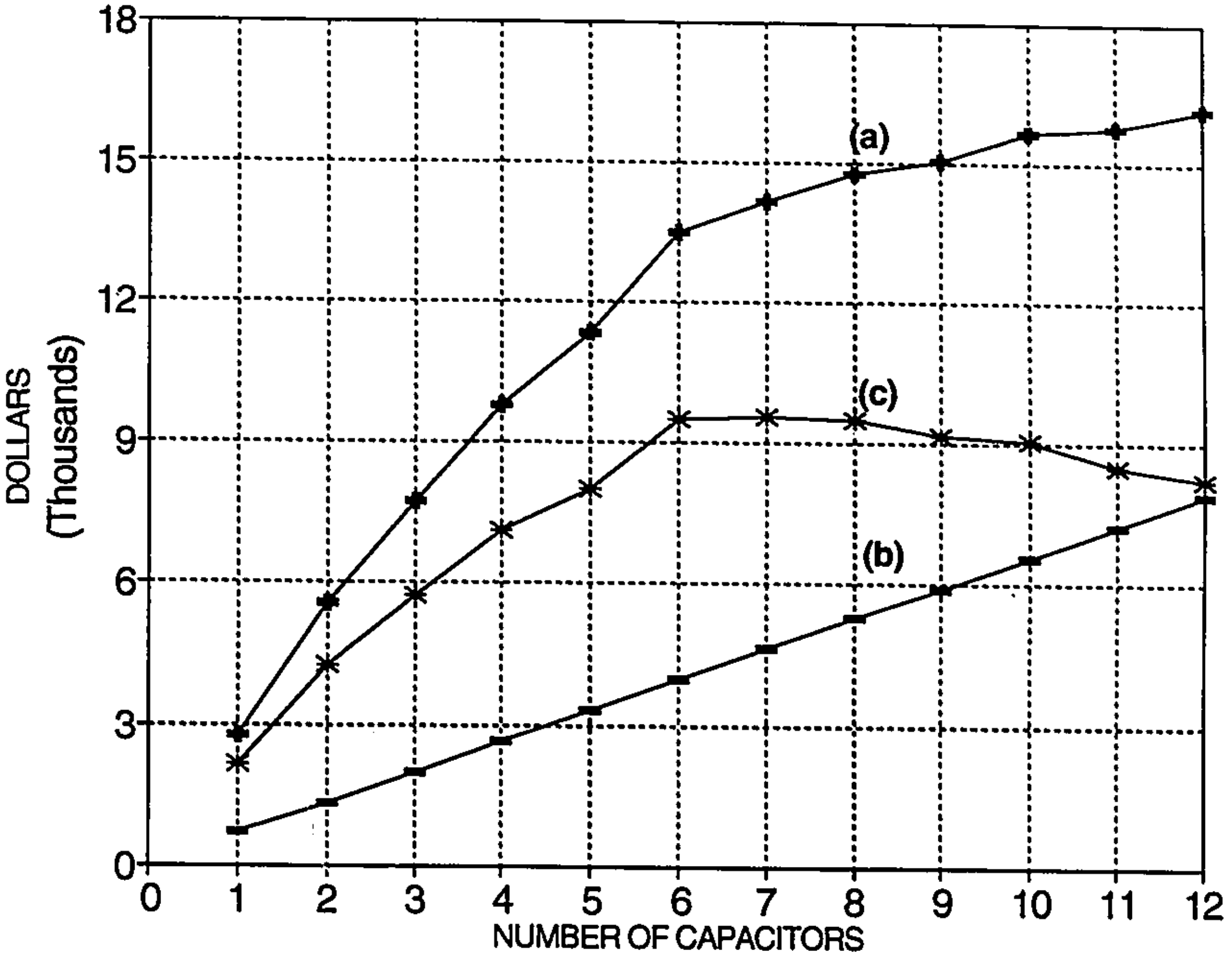

Fig.(6.50) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 11.

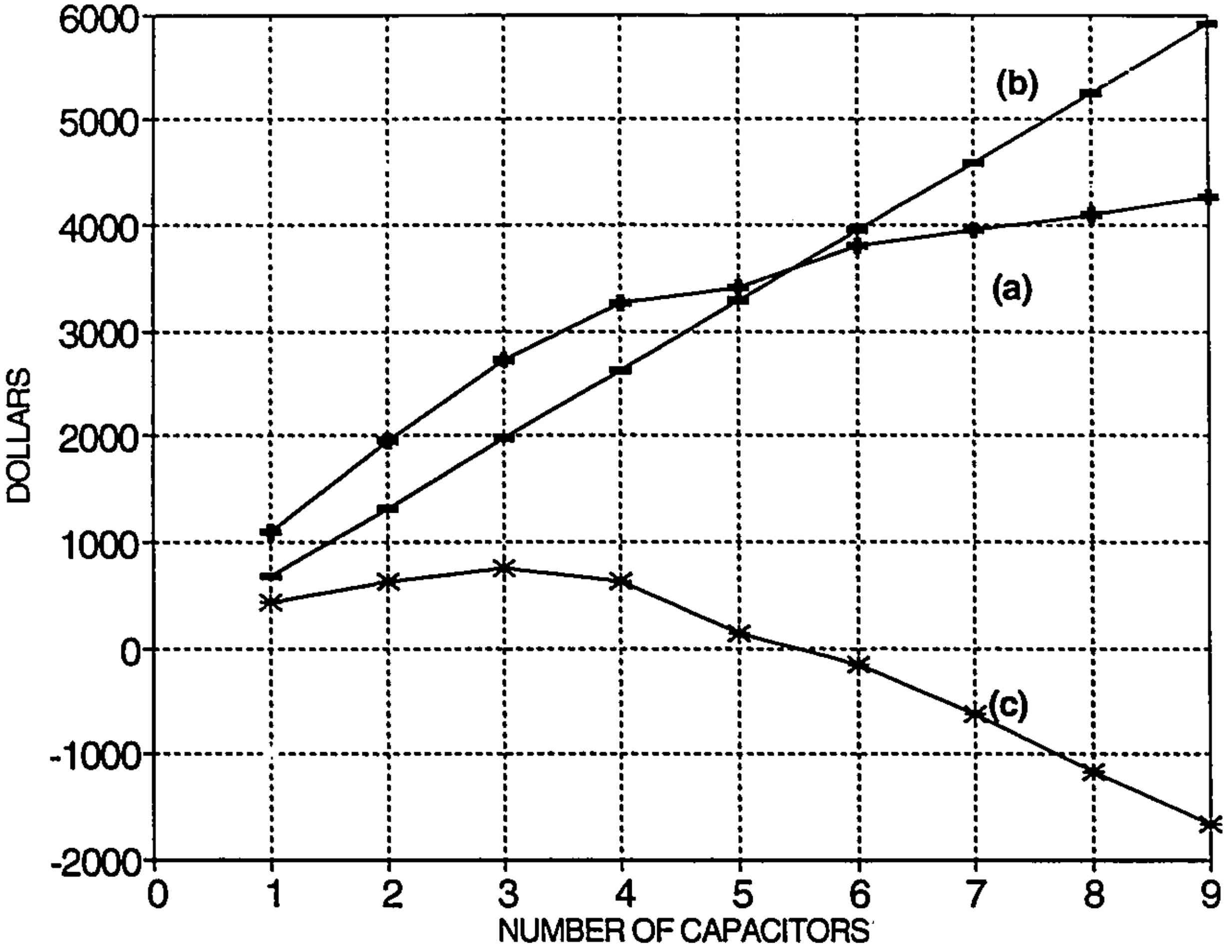

Fig.(6.51) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 12.

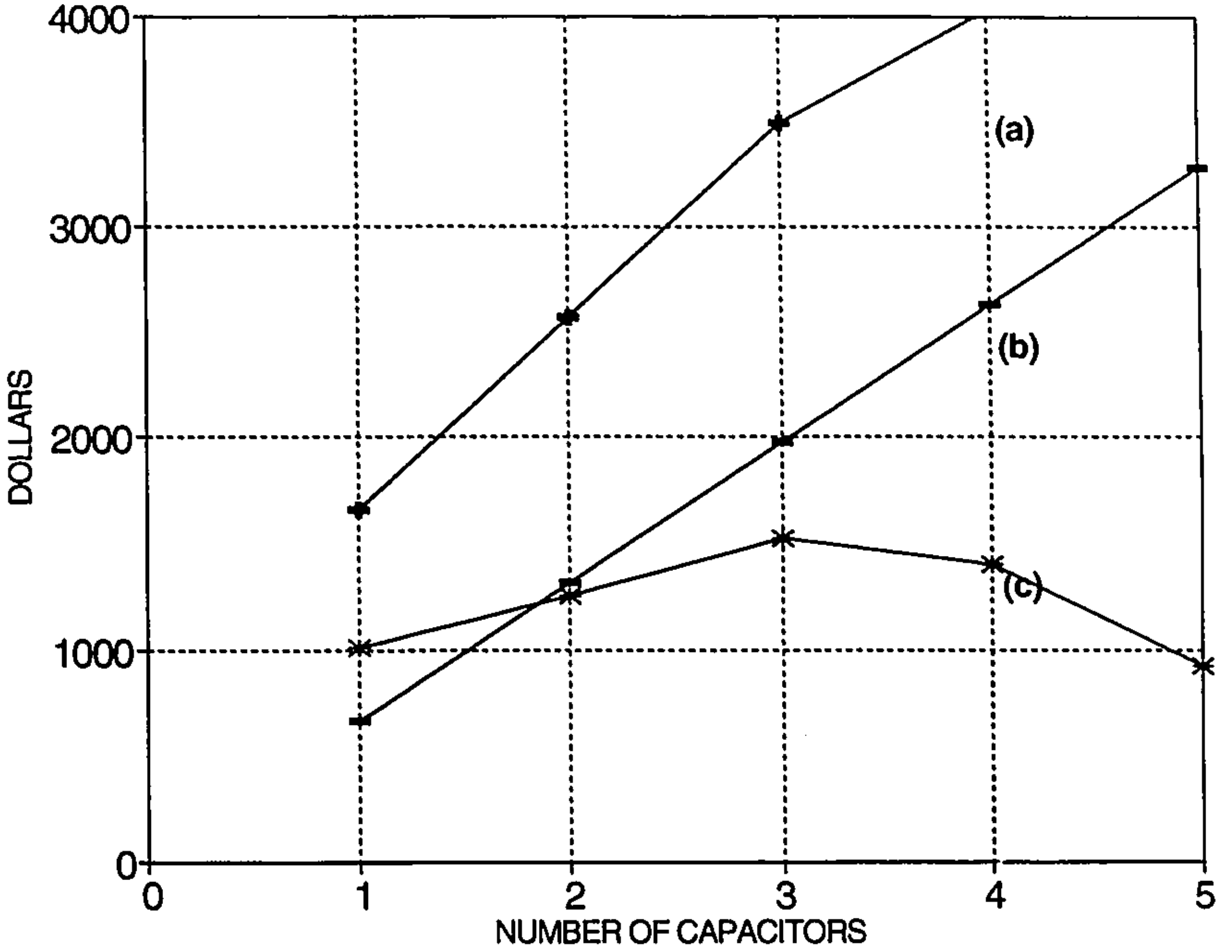

Fig.(6.52) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 13.

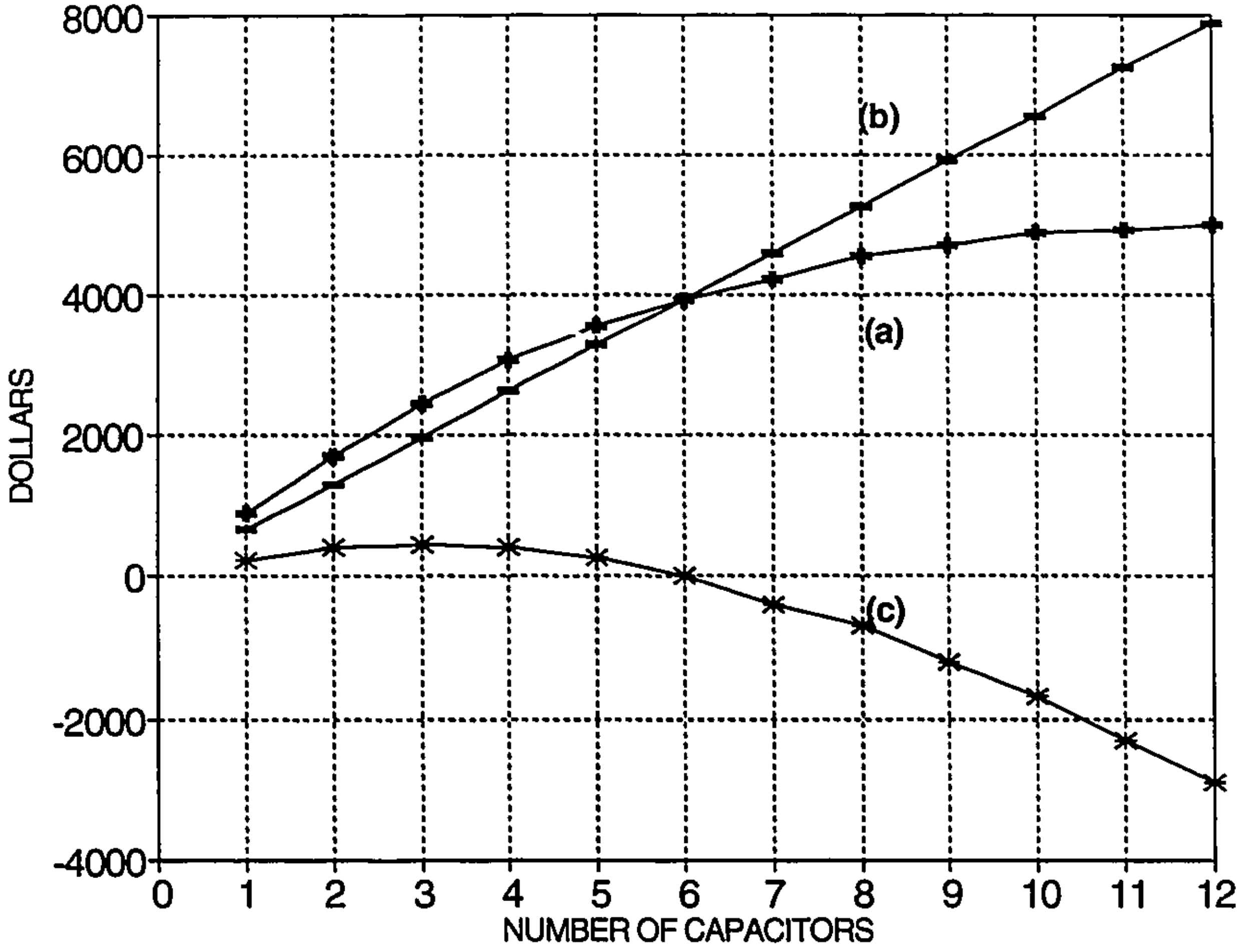

Fig.(6.53) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 17.

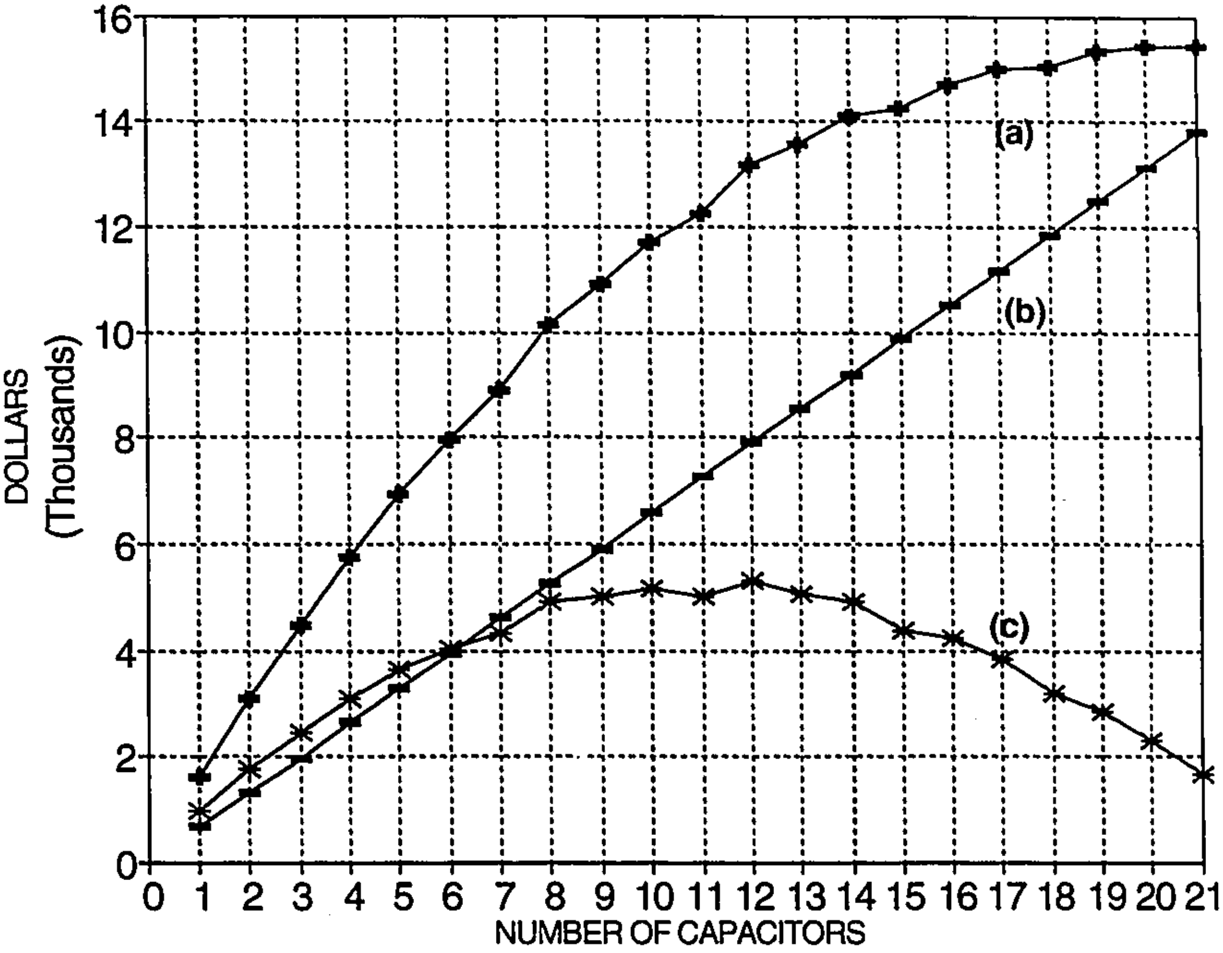

Fig.(6.54) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 19.

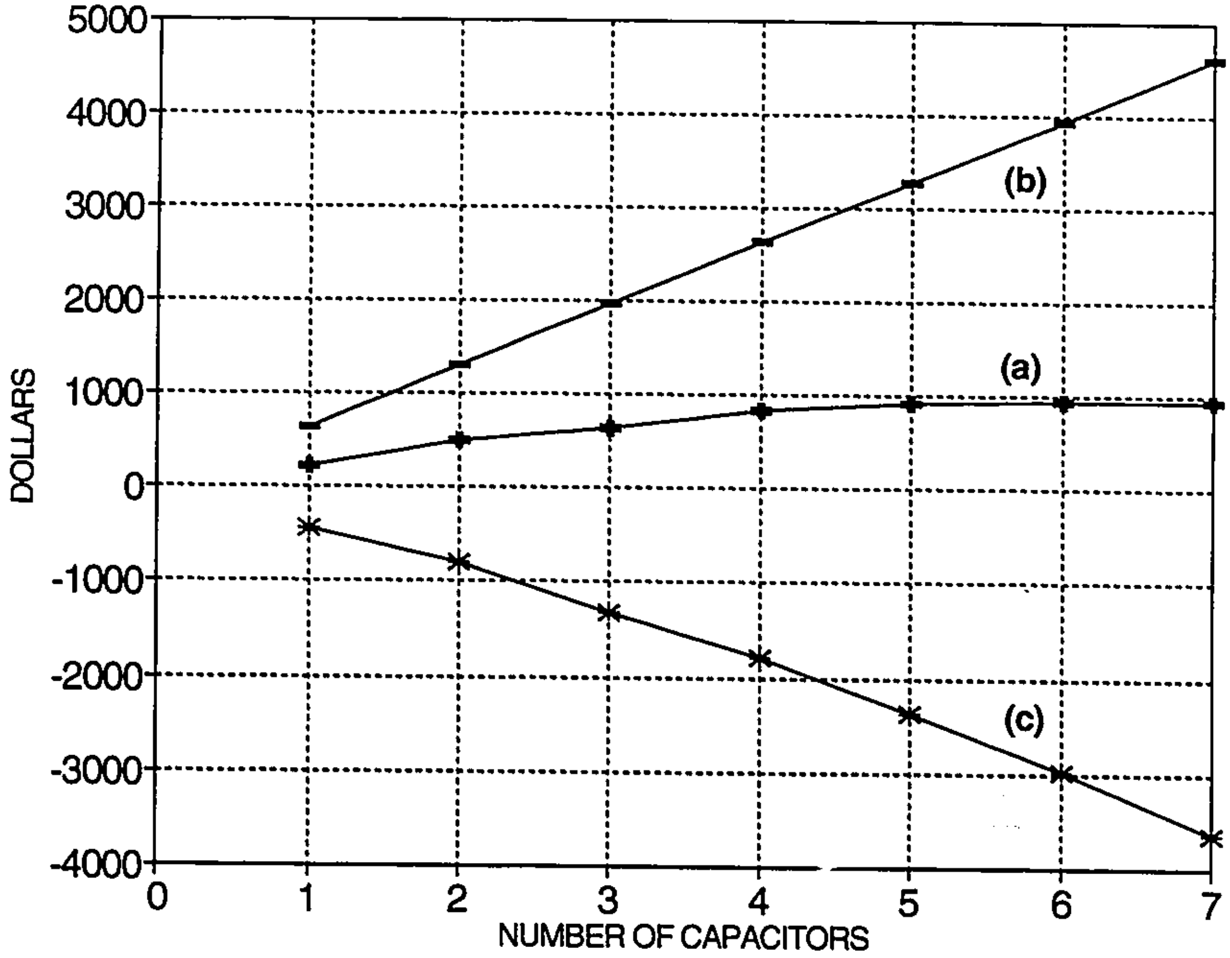

Fig.(6.55) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 21.

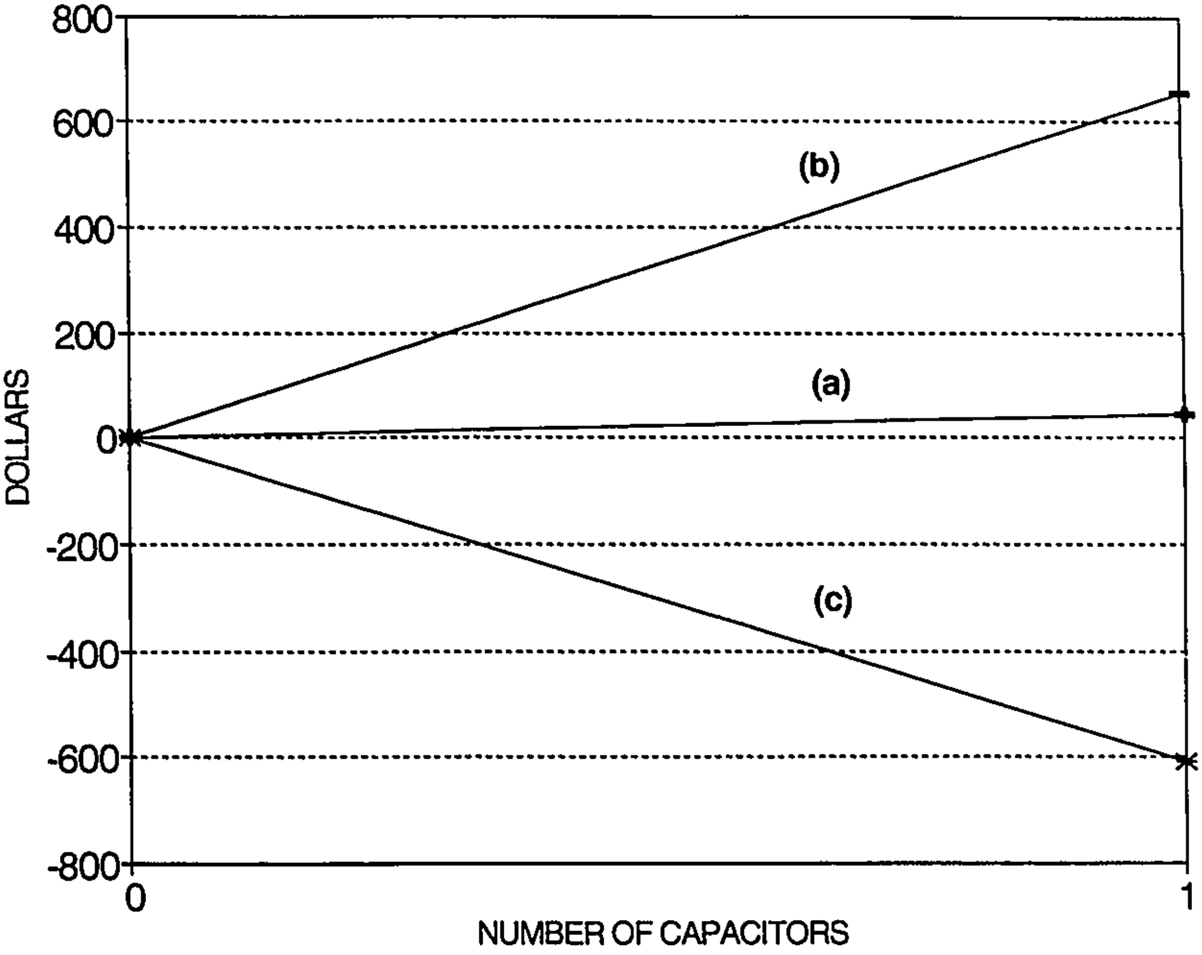

Fig.(6.56) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 22.

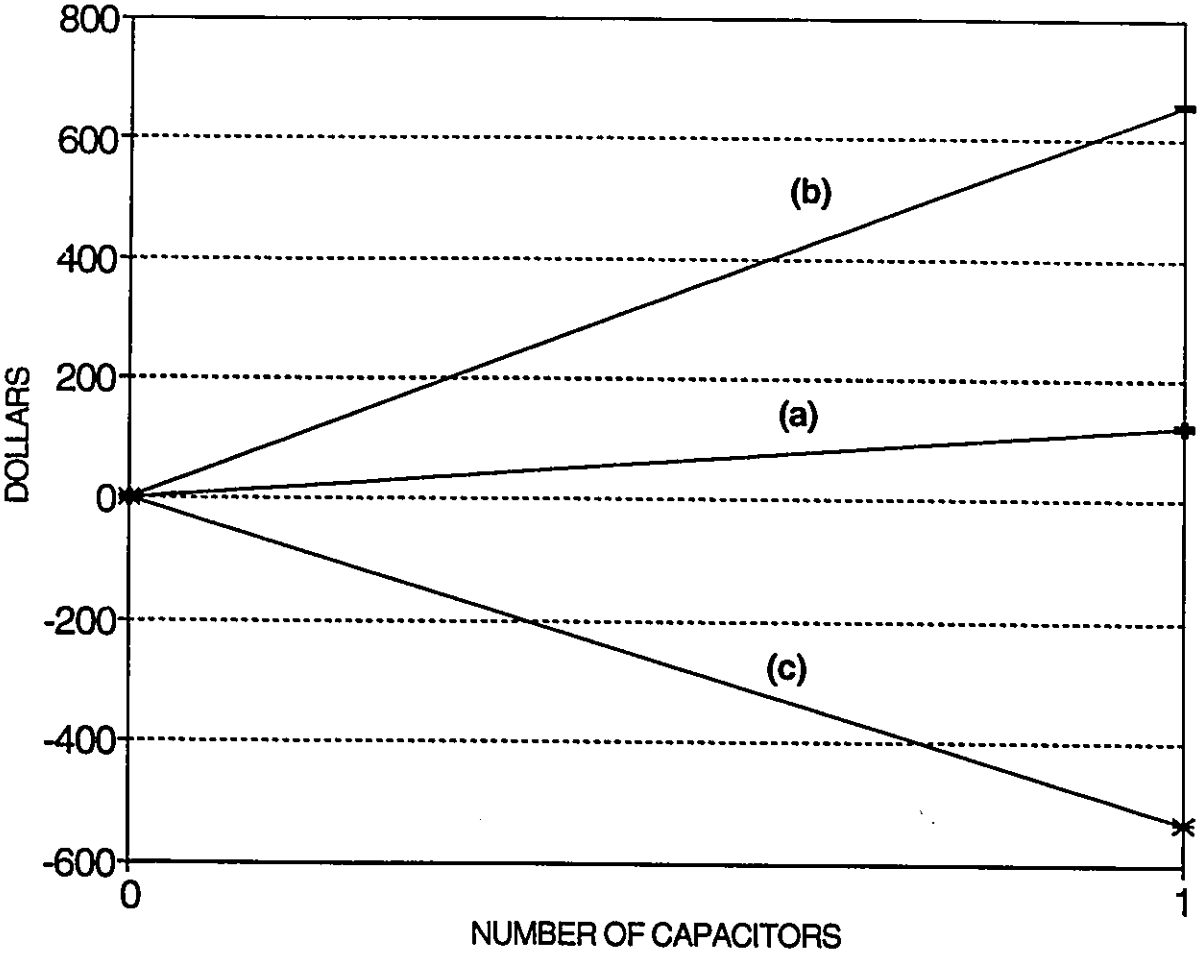

Fig.(6.57) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 23.

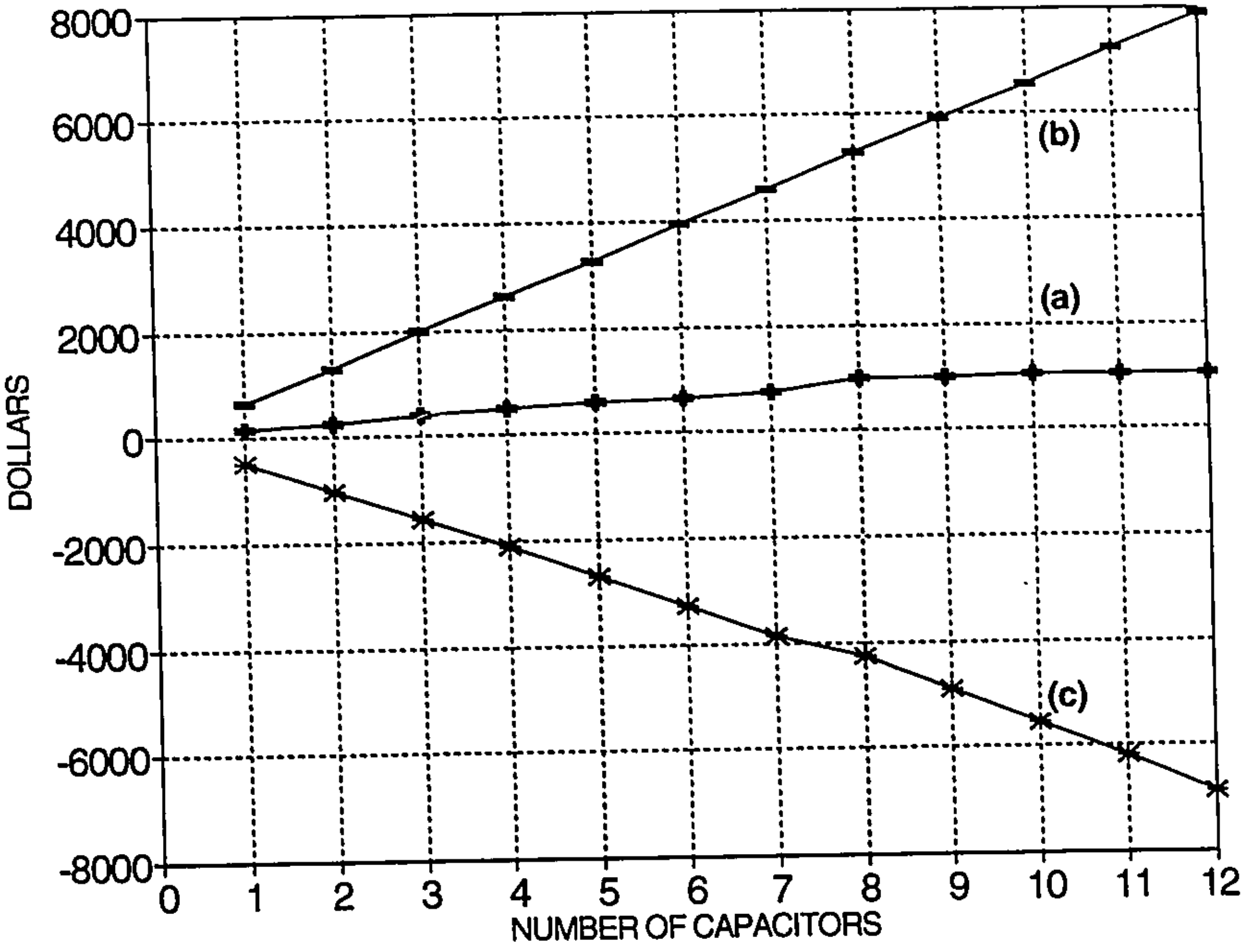

Fig.(6.58) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 25.

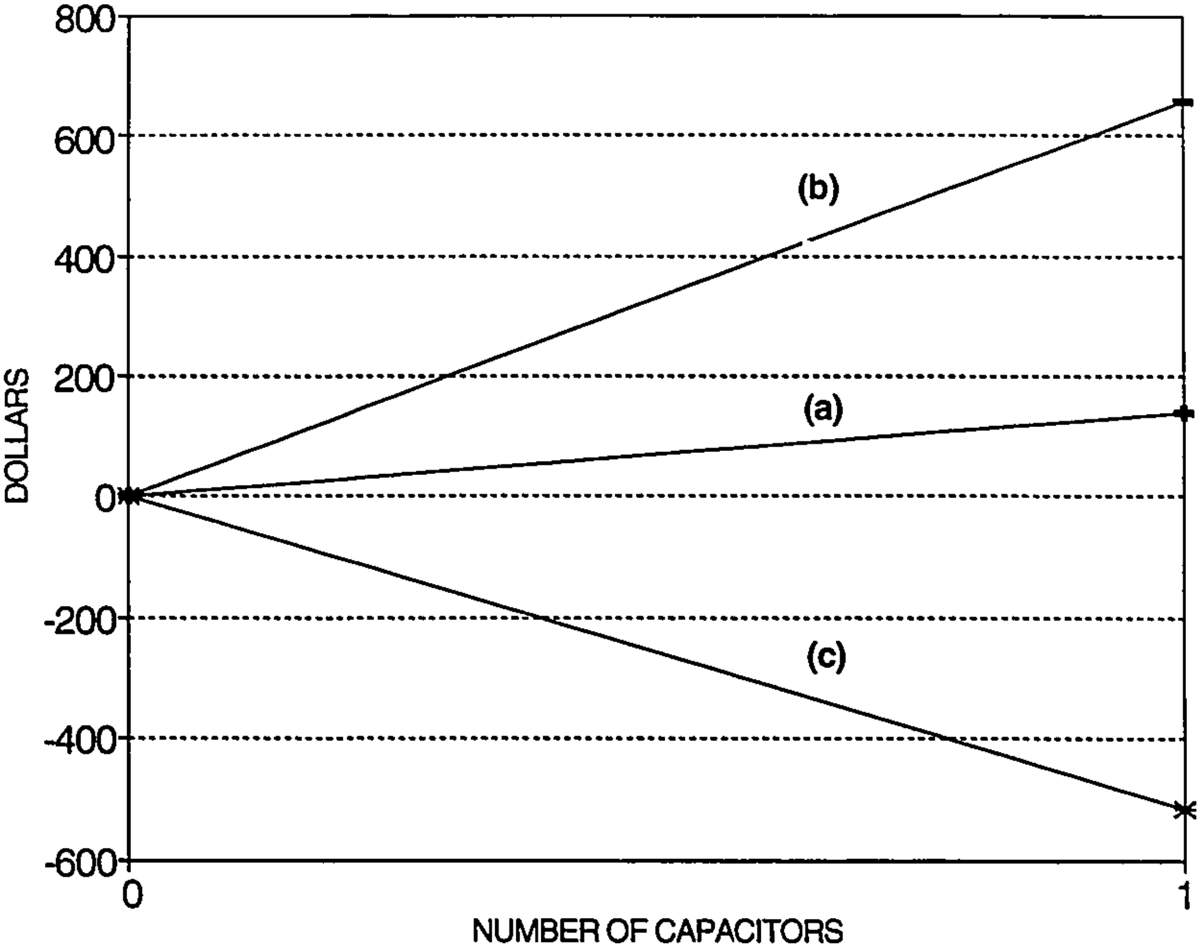

Fig.(6.59) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 26.

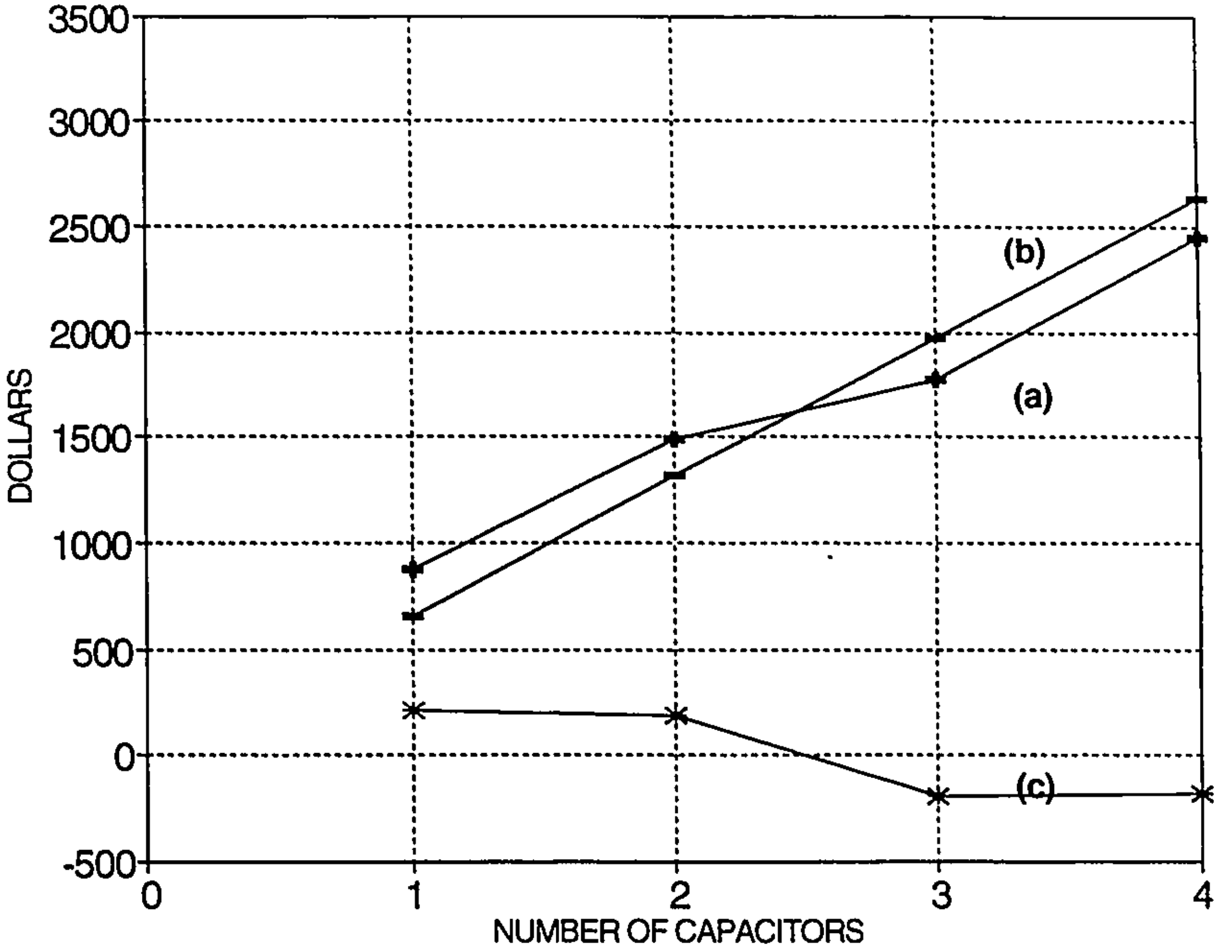

Fig.(6.60) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 27.

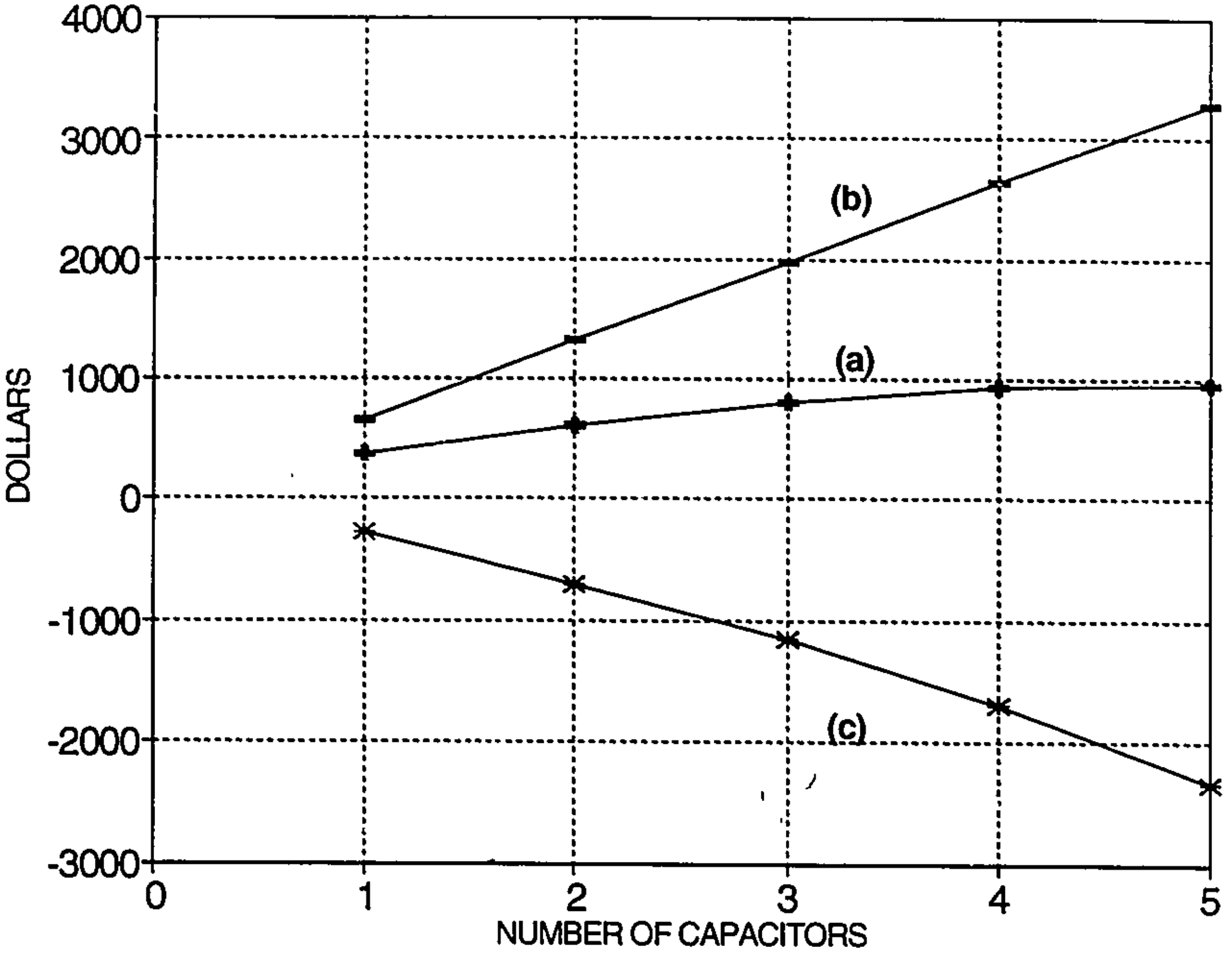

Fig.(6.61) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 28.

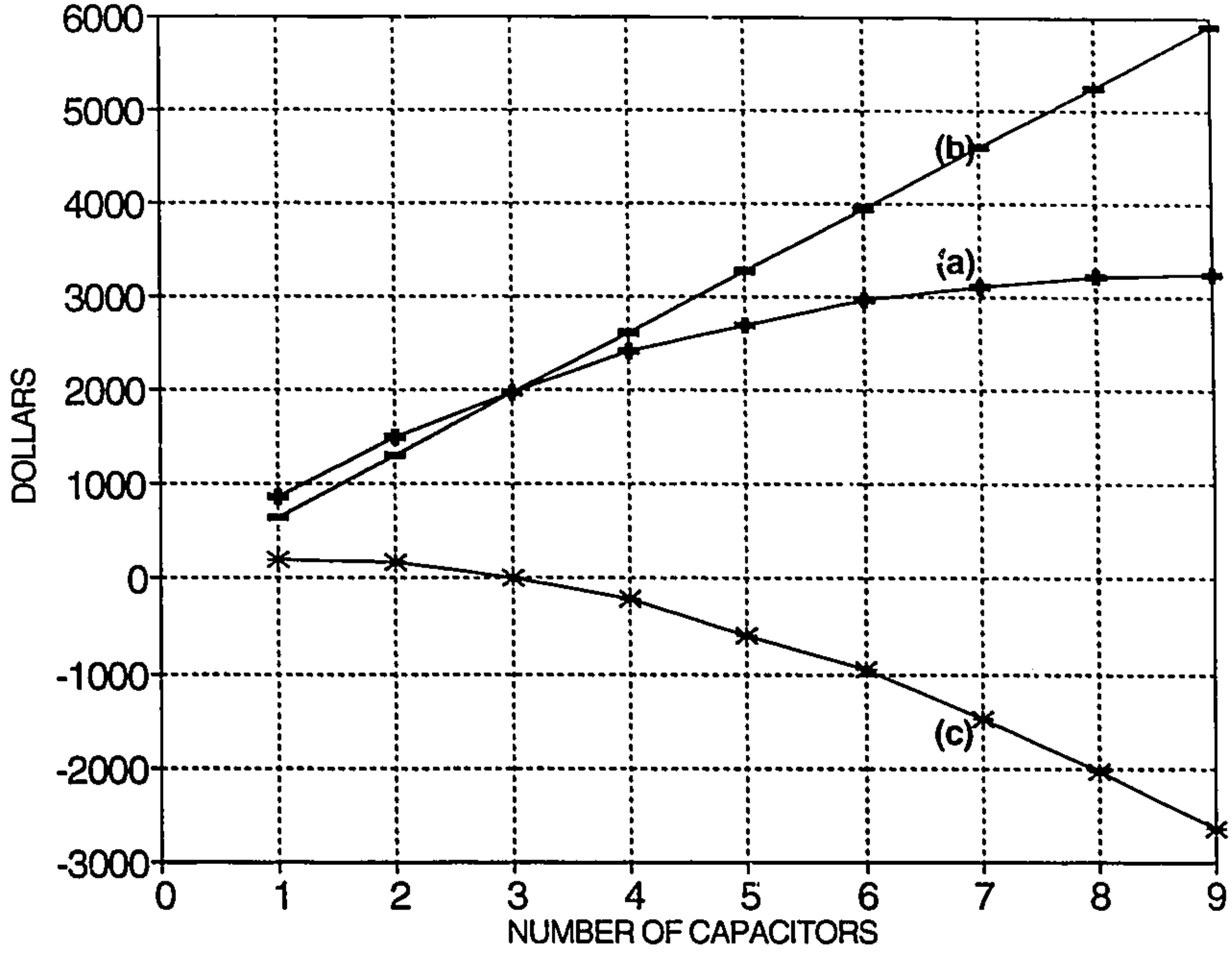

Fig.(6.62) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 29.

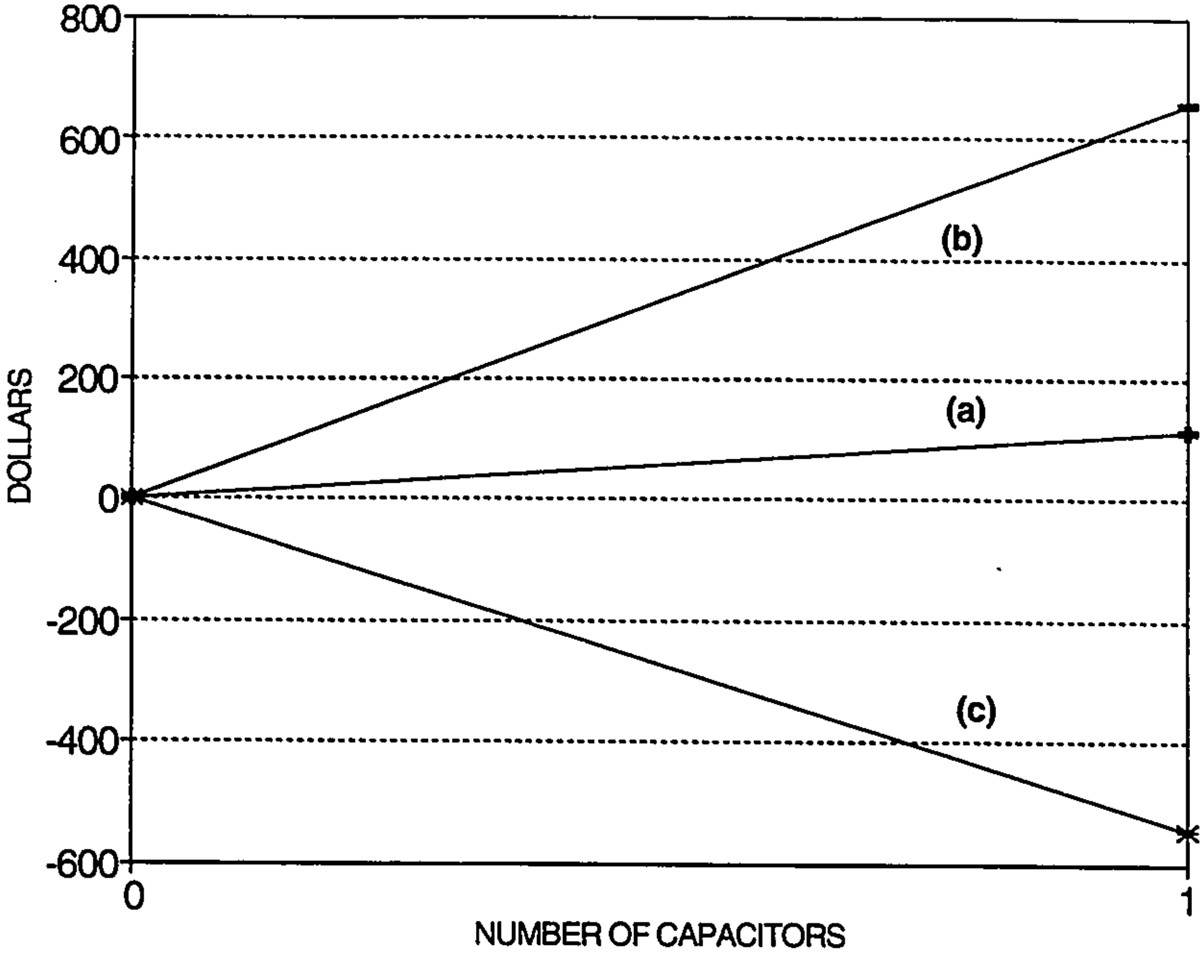

Fig.(6.63) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 30.

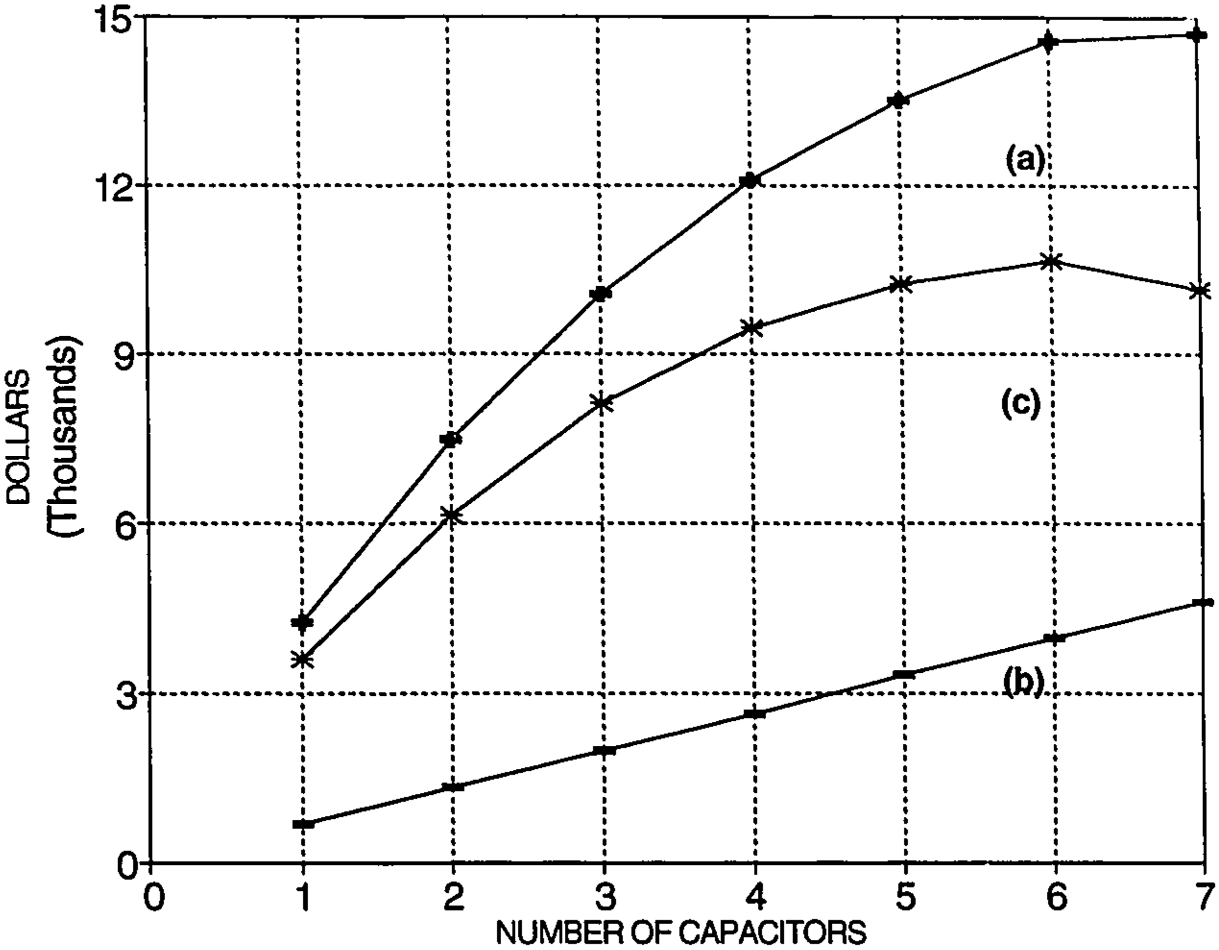

Fig.(6.64) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 31.

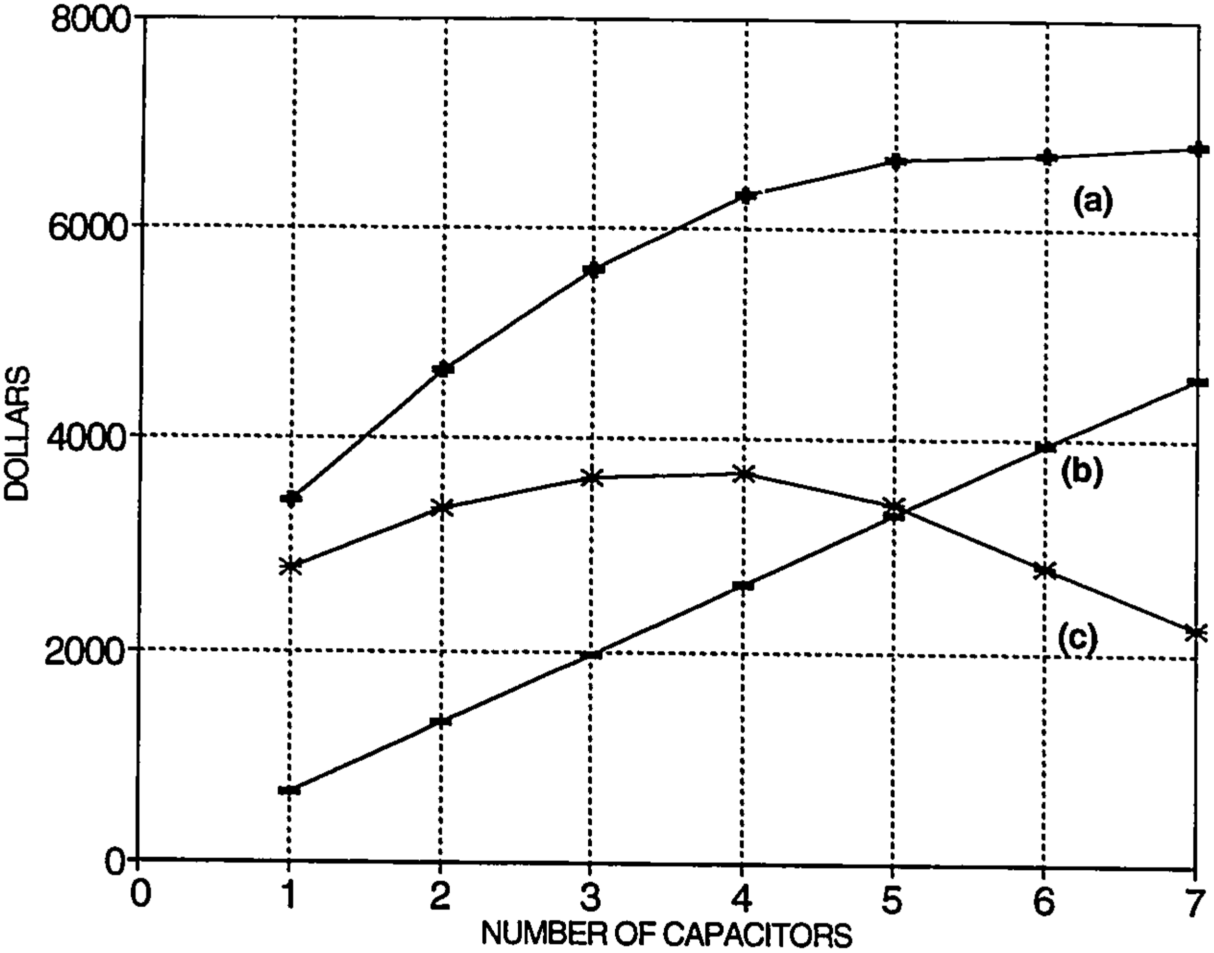

Fig.(6.65) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 32.

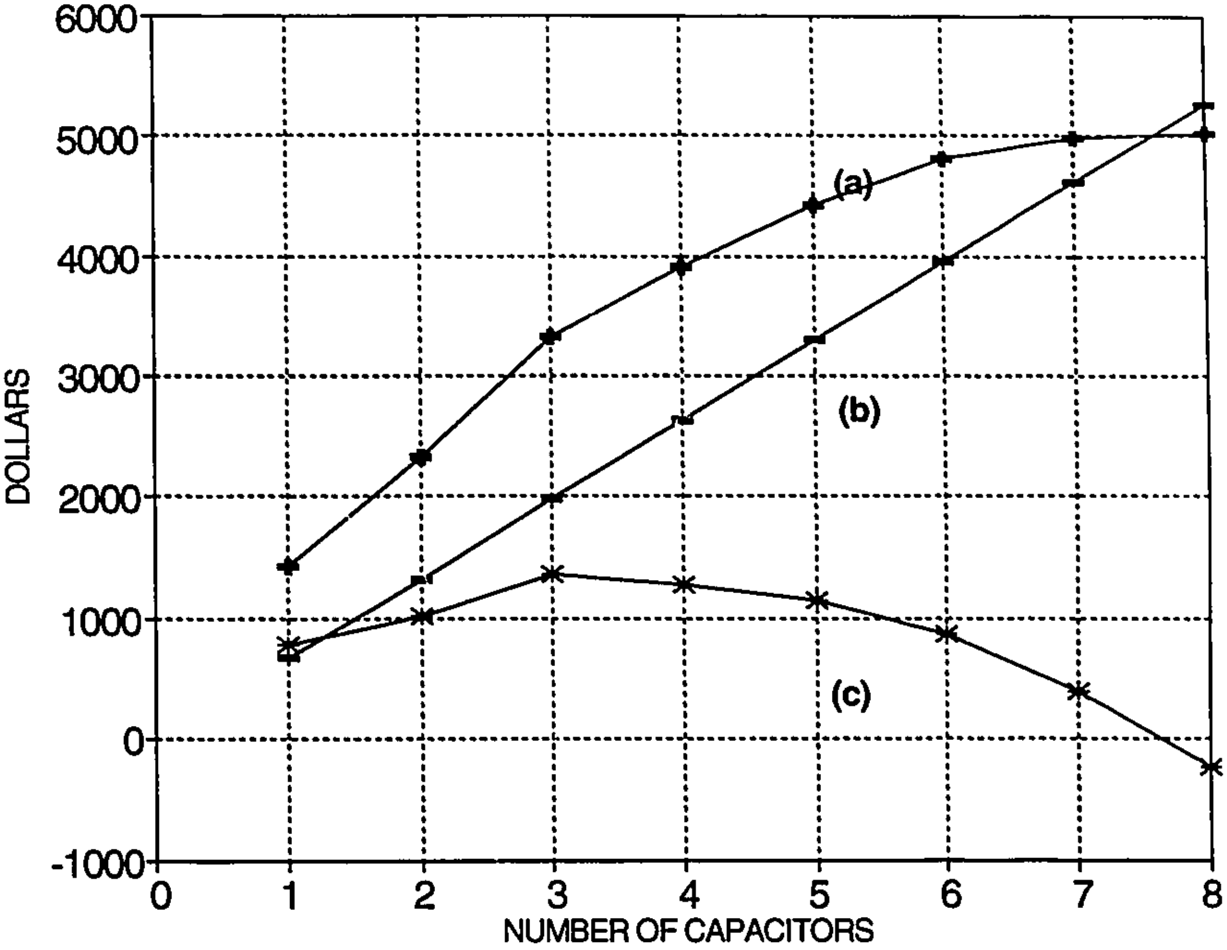

Fig.(6.66) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 33.

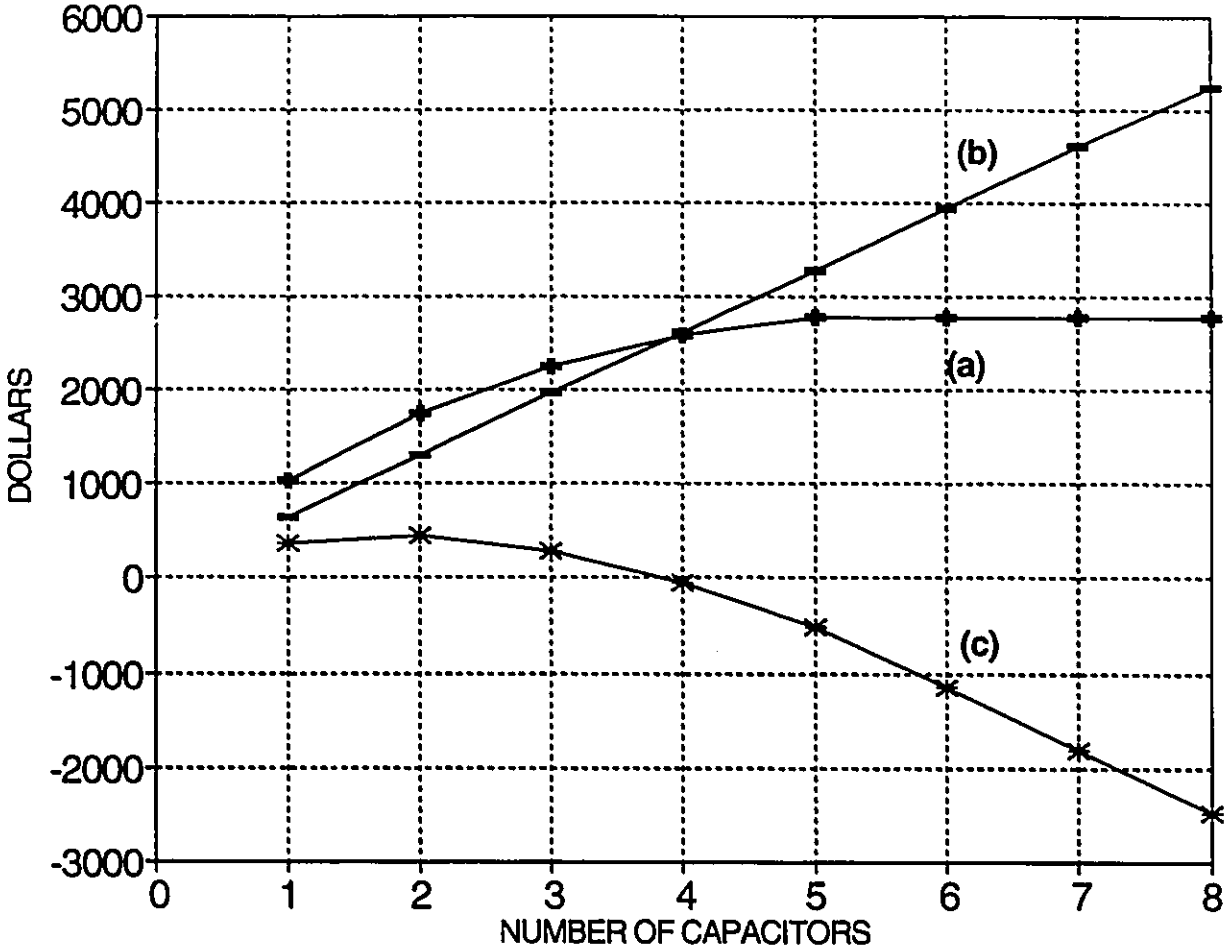

Fig.(6.67) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 35.

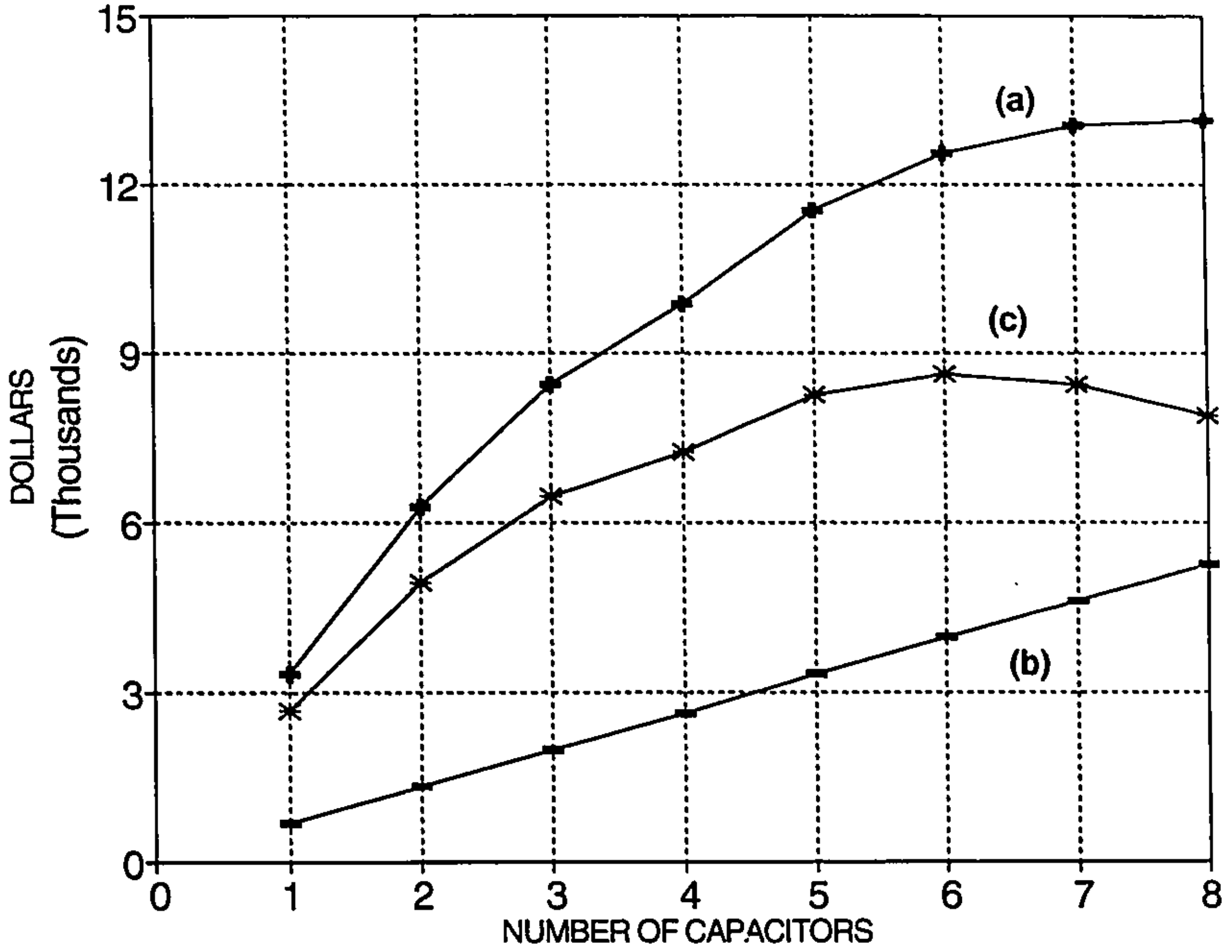

Fig.(6.68) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 36.

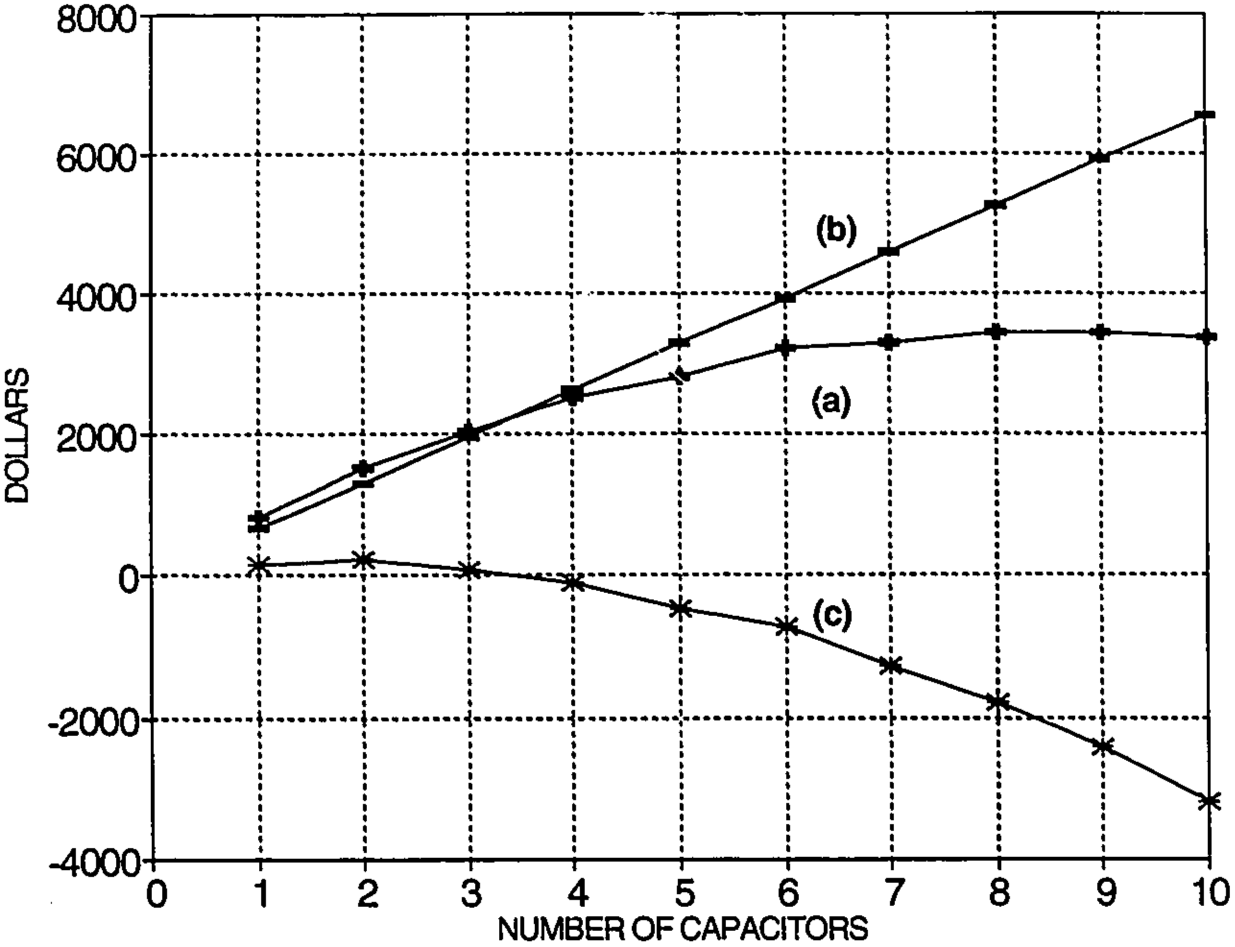

Fig.(6.69) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 37.

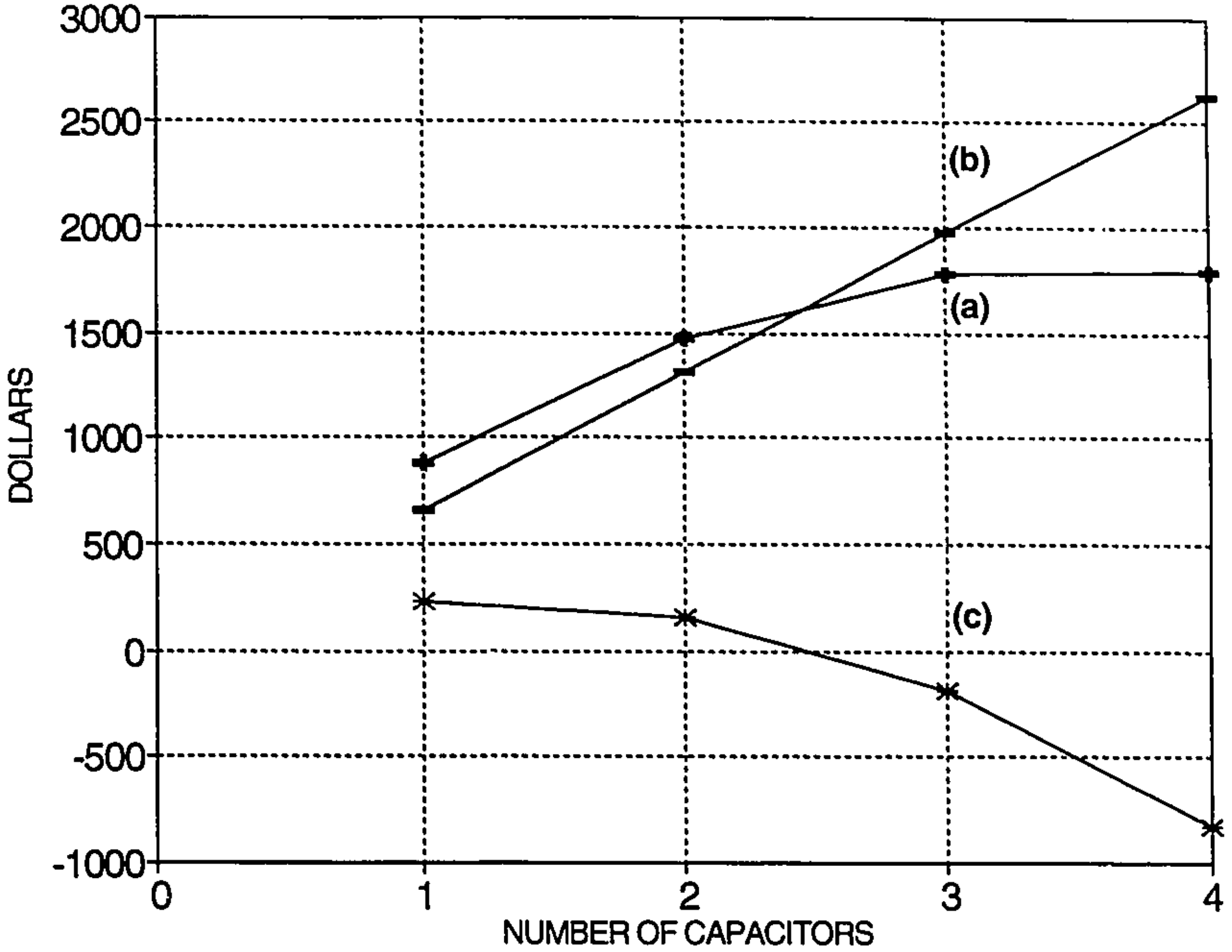

Fig.(6.70) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors (b) and the net annual saving (c) for feeder No. 38.

Table (6.5) Total losses (in kW) in feeder no.1, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks					
period No.	T_p (hrs)	0	1	2	3	4	5
1	964	73	66	62	57	54	53
2	579	61	56	51	48	46	46
3	385	43	38	35	33	33	33
4	231	37	33	30	28	28	28
5	1960	39	35	32	30	30	30
6	1177	18	16	15	14	14	14
7	784	23	20	19	18	18	18
8	470	20	17	16	16	16	16
9	985	43	38	35	33	33	33
10	592	37	33	30	28	28	28
11	394	73	66	62	57	54	53
12	237	61	56	51	48	46	46

Table (6.6) Total losses (in kW) in feeder no.2, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks	
period No.	T_p (hrs)	0	1
1	964	21	16
2	579	18	14
3	385	13	10
4	231	11	8
5	1960	12	9
6	1177	10	7
7	784	7	5
8	470	6	4
9	985	13	10
10	592	11	8
11	394	22	17
12	237	18	14

Table (6.7) Total losses (in kW) in feeder no.4. which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks												
period No.	T_p (hrs)	0	1	2	3	4	5	6	7	8	9	10	11	12
1	964	834	797	764	736	711	691	673	662	650	643	638	633	628
2	579	701	669	640	616	595	578	567	555	549	540	536	532	532
3	385	490	465	443	425	411	399	392	387	381	378	376	376	376
4	231	420	397	376	363	350	341	335	331	328	328	328	328	328
5	1960	447	423	403	387	374	363	357	353	350	346	346	346	346
6	1177	378	357	340	325	314	308	301	298	295	295	295	295	295
7	784	266	249	236	226	218	214	212	210	210	210	210	210	210
8	470	226	211	200	191	185	182	180	178	178	178	178	178	178
9	985	490	465	443	425	411	399	392	387	381	378	376	376	376
10	592	420	397	378	363	350	341	335	331	328	328	328	328	328
11	394	834	797	764	736	711	691	673	662	650	643	638	633	628
12	237	701	669	640	616	595	578	567	555	540	536	532	532	532

Table (6.8) Total losses (in kW) in feeder no.5, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks		
period No.	T_p (hrs)	0	1	2
1	964	2.8	2.0	1.7
2	579	2.3	1.7	1.4
3	385	1.7	1.1	1.1
4	231	1.4	1.0	1.0
5	1960	1.5	1.0	1.0
6	1177	1.3	0.9	0.9
7	784	0.9	0.6	0.6
8	470	0.8	0.5	0.5
9	985	1.7	1.1	1.1
10	592	1.4	1.0	1.0
11	394	2.8	2.0	1.7
12	237	2.3	1.7	1.4

Table (6.9) Total losses (in kW) in feeder no.6, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks								
		0	1	2	3	4	5	6	7	8
1	964	359	346	334	323	315	307	301	297	295
2	579	305	293	283	272	265	259	264	251	251
3	385	216	207	198	191	186	182	179	179	179
4	231	186	178	170	163	159	156	154	154	154
5	1960	198	189	181	174	170	166	164	164	164
6	1177	169	160	153	147	144	141	141	141	141
7	784	120	113	107	103	101	100	100	100	100
8	470	102	96	91	87	86	86	86	86	86
9	985	359	346	334	323	315	307	301	297	295
10	592	305	293	283	272	265	259	254	251	251
11	394	216	207	198	191	186	182	179	179	179
12	237	186	178	170	163	159	156	154	154	154

Table (6.10) Total losses (in kW) in feeder no.7, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks						
period No.	T_p (hrs)	0	1	2	3	4	5	6
1	964	690	609	552	507	473	444	421
2	579	514	467	430	400	376	356	340
3	385	317	292	273	256	243	233	233
4	231	263	243	227	214	204	196	196
5	1960	284	262	245	230	219	210	210
6	1177	233	215	201	190	181	181	181
7	784	156	144	135	128	123	123	123
8	470	131	121	113	108	108	108	108
9	985	317	292	273	256	243	233	233
10	592	263	243	227	214	204	196	196
11	394	690	609	552	507	473	444	421
12	237	514	467	430	400	376	356	340

Table (6.11) Total losses (in kW) in feeder no.8, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks		
period No.	T_p (hrs)	0	1	2
1	964	35	31	29
2	579	30	26	24
3	385	21	18	17
4	231	18	16	15
5	1960	19	17	16
6	1177	16	14	14
7	784	12	10	10
8	470	10	8	8
9	985	21	18	17
10	592	18	16	15
11	394	35	31	29
12	237	30	26	24

Table (6.12) Total losses (in kW) in feeder no.9. which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks											
		0	1	2	3	4	5	6	7	8	9	10	11
1	964	382	366	353	340	329	318	309	301	295	289	285	281
2	579	322	307	296	284	275	266	258	251	247	243	239	239
3	385	225	213	205	196	190	183	178	174	171	169	169	169
4	231	193	183	175	167	162	156	152	149	147	147	147	147
5	1960	205	195	187	178	173	167	162	158	156	156	156	156
6	1177	174	164	157	150	145	140	136	134	134	134	134	134
7	784	122	115	109	104	100	97	95	95	95	95	95	95
8	470	104	97	92	88	84	82	81	81	81	81	81	81
9	985	225	213	205	196	190	183	178	174	171	169	169	169
10	592	193	183	175	167	162	156	152	149	147	147	147	147
11	394	382	366	353	340	329	318	309	301	295	289	285	281
12	237	322	307	296	284	275	266	258	251	247	243	239	239

Table (6.13) Total losses (in kW) in feeder no.10, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks							
period No.	T_p (hrs)	0	1	2	3	4	5	6	7
1	964	143	135	127	121	116	112	110	109
2	579	114	107	100	95	91	89	87	87
3	385	77	72	67	63	61	60	60	60
4	231	66	61	56	54	52	52	52	52
5	1960	108	101	95	90	86	84	83	83
6	1177	85	79	74	70	68	66	66	66
7	784	58	53	49	46	45	45	45	45
8	470	49	45	41	39	38	38	38	38
9	985	112	105	99	94	90	88	86	86
10	592	89	83	78	74	71	69	69	69
11	394	102	96	90	85	82	80	79	79
12	237	87	81	75	72	69	67	67	67

Table (6.14) Total losses (in kW) in feeder no.11, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_r (hrs)	Total Number of Capacitor Banks												
		0	1	2	3	4	5	6	7	8	9	10	11	12
1	964	446	425	402	385	367	353	339	329	319	311	305	300	295
2	579	374	355	335	320	305	293	282	273	265	259	255	251	251
3	385	259	244	230	218	207	199	192	186	182	180	177	177	177
4	231	221	208	195	185	176	169	163	159	156	156	156	156	156
5	1960	236	222	208	198	188	181	174	169	166	166	166	166	166
6	1177	199	187	175	166	157	151	146	142	140	138	138	138	138
7	784	139	130	120	114	108	104	101	101	101	101	101	101	101
8	470	118	110	101	95	90	87	85	85	85	85	85	85	85
9	985	259	244	230	218	207	199	192	186	182	180	177	177	177
10	592	221	208	195	185	176	169	163	159	156	156	156	156	156
11	394	446	425	402	385	367	353	339	329	319	311	305	300	295
12	237	374	355	335	320	305	293	282	273	265	259	255	251	251

Table (6.15) Total losses (in kW) in feeder no.12, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks									
period No.	T_p (hrs)	0	1	2	3	4	5	6	7	8	9
1	964	182	175	168	162	157	153	150	148	147	145
2	579	155	148	142	137	133	129	127	126	124	123
3	385	110	104	100	96	93	91	90	89	88	88
4	231	95	90	86	82	80	78	77	76	76	76
5	1960	101	96	91	87	85	83	82	81	80	80
6	1177	86	81	77	74	72	70	70	69	69	59
7	784	61	57	54	52	50	50	50	50	50	50
8	470	52	49	46	44	43	42	42	42	42	42
9	985	110	104	100	96	93	91	90	89	88	88
10	592	95	90	86	82	80	78	77	76	76	76
11	394	182	175	168	162	157	153	150	148	147	145
12	237	155	148	142	137	133	129	127	126	124	123

Table (6.16) Total losses (in kW) in feeder no.13. which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks					
		0	1	2	3	4	5
1	964	140	129	122	115	110	107
2	579	112	102	96	91	87	85
3	385	76	68	64	60	59	59
4	231	65	58	55	51	50	50
5	1960	106	97	91	86	82	81
6	1177	84	76	72	67	65	65
7	784	57	51	47	45	45	45
8	470	49	43	40	38	38	38
9	985	110	101	95	89	86	84
10	592	88	80	75	70	68	68
11	394	101	92	87	81	78	77
12	237	86	77	73	68	66	66

Table (6.17) Total losses (in kW) in feeder no.17, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks												
		0	1	2	3	4	5	6	7	8	9	10	11	12
1	964	209	203	198	193	189	185	182	179	177	175	173	172	171
2	579	168	163	158	154	150	147	144	142	140	139	138	138	138
3	385	115	111	107	104	101	99	97	96	95	94	94	94	94
4	231	99	95	91	88	86	84	83	82	81	81	81	81	81
5	1960	160	155	150	146	142	139	137	135	133	132	131	131	131
6	1177	127	122	118	115	112	110	108	106	105	104	104	104	104
7	784	86	83	80	77	75	73	72	71	71	71	71	71	71
8	470	74	70	68	65	63	62	61	61	61	61	61	61	61
9	985	166	161	156	152	148	145	142	140	138	137	136	136	136
10	592	133	128	124	120	117	115	113	111	110	109	109	109	109
11	394	152	147	142	138	135	132	130	128	126	125	125	124	124
12	237	129	125	121	117	114	111	109	108	107	106	106	106	106

Table (6.18) Total losses (in kW) in feeder no.19, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_i (hrs)	Total Number of Capacitor Banks																					
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	964	552	541	531	522	513	505	497	490	481	475	468	463	457	452	447	444	440	437	435	433	432	431
2	579	441	432	423	415	407	400	394	388	381	375	370	365	361	357	354	351	349	347	345	345	345	345
3	385	302	294	287	281	275	269	265	259	255	250	247	245	242	240	238	237	237	237	237	237	237	237
4	231	258	251	245	239	234	229	224	220	216	213	210	208	206	204	203	203	203	203	203	203	203	203
5	1960	419	410	402	394	387	380	374	368	361	356	350	347	342	339	336	333	331	330	328	328	328	328
6	1177	333	325	318	311	304	299	293	287	283	278	275	271	268	266	264	262	261	261	261	261	261	261
7	784	226	220	214	209	204	199	195	191	188	185	182	181	179	178	178	178	178	178	178	178	178	178
8	470	193	187	182	177	172	169	164	162	156	154	153	152	152	152	152	152	152	152	152	152	152	152
9	985	436	426	418	410	402	395	389	383	376	371	365	361	356	353	349	346	344	343	341	340	340	340
10	592	348	340	332	325	319	313	308	301	297	292	288	284	281	279	276	275	273	273	273	273	273	273
11	394	398	390	381	374	367	360	354	347	342	336	332	327	324	321	318	316	314	313	312	312	312	312
12	237	339	331	323	316	310	304	299	292	288	283	280	276	273	271	268	267	266	266	266	266	266	266

Table (6.19) Total losses (in kW) in feeder no.21, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks							
period No.	T_r (hrs)	0	1	2	3	4	5	6	7
1	964	39	37	35	34	33	32	31	31
2	579	31	30	28	27	26	25	25	25
3	385	21	20	19	18	17	17	17	17
4	231	18	17	16	15	15	15	15	15
5	1960	29	28	26	26	24	24	24	24
6	1177	23	22	21	20	19	19	19	19
7	784	16	15	14	13	13	13	13	13
8	470	14	13	12	11	11	11	11	11
9	985	31	29	28	27	26	25	25	25
10	592	24	23	22	21	20	20	20	20
11	394	28	27	25	24	23	23	22	22
12	237	24	23	21	20	20	19	19	19

Table (6.20) Total losses (in kW) in feeder no.22, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks 0	1
1	964	2.2	1.8
2	579	1.7	1.4
3	385	1.2	1
4	231	1.0	0.8
5	1960	1.7	1.4
6	1177	1.3	1.1
7	784	0.9	0.9
8	470	0.7	0.7
9	985	1.7	1.4
10	592	1.4	1.1
11	394	1.6	1.3
12	237	1.3	1.1

Table (6.21) Total losses (in kW) in feeder no.23, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks	
period No.	T_p (hrs)	0	1
1	964	5	4
2	579	4	3
3	385	3	2
4	231	2	1
5	1960	4	3
6	1177	3	2
7	784	2	2
8	470	1	1
9	985	4	3
10	592	3	2
11	394	4	3
12	237	3	2

Table (6.22) Total losses (in kW) in feeder no.25, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks												
period No	T_i (hrs)	0	1	2	3	4	5	6	7	8	9	10	11	12
1	964	33	32	31	30	29	29	28	27	27	27	26	26	26
2	579	26	25	24	24	23	23	22	22	21	21	21	21	21
3	385	18	17	16	16	15	15	15	14	14	14	14	14	14
4	231	15	15	14	13	13	13	12	12	12	12	12	12	12
5	1960	25	24	23	23	22	21	21	21	20	20	20	20	20
6	1177	20	19	18	18	17	17	16	16	16	16	16	16	16
7	784	13	13	12	12	11	11	11	11	11	11	11	11	11
8	470	11	11	10	10	10	9	9	9	9	9	9	9	9
9	985	26	25	24	23	23	22	22	21	21	21	21	21	21
10	592	21	20	19	19	18	18	17	17	17	17	16	16	16
11	394	24	23	22	21	21	20	20	19	19	19	19	19	19
12	237	20	19	19	18	17	17	17	16	16	16	16	16	16

Table (6.23) Total losses (in kW) in feeder no.26, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks	
		0	1
1	964	6	4
2	579	4	3
3	385	3	2
4	231	3	2
5	1960	4	3
6	1177	3	2
7	784	2	1
8	470	2	2
9	985	4	3
10	592	3	3
11	394	4	3
12	237	3	2

Table (6.24) Total losses (in kW) in feeder no.27, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks				
period No.	T_p (hrs)	0	1	2	3	4
1	964	73	67	61	58	53
2	579	57	52	48	45	41
3	385	38	34	31	28	28
4	231	32	29	26	24	24
5	1960	54	49	45	43	39
6	1177	42	38	35	31	31
7	784	28	25	23	21	21
8	470	24	21	19	17	17
9	985	56	51	47	44	41
10	592	44	40	37	33	33
11	394	51	46	43	38	37
12	237	43	39	36	32	32

Table (6.25) Total losses (in kW) in feeder no.28, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks					
period No.	T_p (hrs)	0	1	2	3	4	5
1	964	50	47	46	44	43	42
2	579	40	38	36	35	34	34
3	385	27	25	24	23	23	23
4	231	23	22	21	20	20	20
5	1960	38	36	34	33	32	32
6	1177	30	28	27	26	26	26
7	784	20	19	18	17	17	17
8	470	17	16	15	15	15	15
9	985	40	37	36	34	34	34
10	592	32	30	28	27	27	27
11	394	36	34	33	31	31	31
12	237	31	29	27	26	26	26

Table (6.26) Total losses (in kW) in feeder no.29, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks									
period No.	T_p (hrs)	0	1	2	3	4	5	6	7	8	9
1	964	109	103	98	95	92	90	87	86	84	83
2	579	87	82	79	75	72	71	69	68	67	67
3	385	59	55	53	50	49	47	46	46	46	46
4	231	51	47	45	43	42	40	39	39	39	39
5	1960	83	78	75	71	68	67	65	64	63	63
6	1177	65	61	59	56	55	52	51	51	51	51
7	784	44	41	39	37	36	35	35	35	35	35
8	470	38	35	33	31	30	29	29	29	29	29
9	985	86	81	78	74	71	70	68	67	66	66
10	592	68	64	62	59	57	55	54	53	53	53
11	394	78	74	71	68	65	63	62	61	61	61
12	237	67	62	60	57	56	53	52	51	51	51

Table (6.27) Total losses (in kW) in feeder no.30, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks	
period No.	T_p (hrs)	0	1
1	964	9	8
2	579	8	7
3	385	5	4
4	231	4	4
5	1960	7	6
6	1177	6	5
7	784	4	4
8	470	3	3
9	985	7	6
10	592	6	5
11	394	7	6
12	237	6	5

Table (6.28) Total losses (in kW) in feeder no.31, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks							
period No.	T_p (hrs)	0	1	2	3	4	5	6	7
1	964	357	322	294	272	253	238	226	220
2	579	267	241	221	205	192	181	173	173
3	385	169	152	139	130	122	116	116	116
4	231	142	127	116	108	102	98	98	98
5	1960	251	227	208	193	180	170	163	163
6	1177	190	171	157	146	137	130	130	130
7	784	122	109	100	93	88	88	88	88
8	470	102	91	83	77	73	73	73	73
9	985	263	238	218	202	189	178	170	170
10	592	201	181	166	154	144	137	137	137
11	394	236	213	195	181	169	160	154	154
12	237	194	175	160	149	140	133	133	133

Table (6.29) Total losses (in kW) in feeder no.32, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks						
period No.	T_r (hrs)	0	1	2	3	4	5	6
1	964	141	129	119	111	104	100	96
2	579	110	100	92	86	81	78	78
3	385	72	65	60	56	53	53	53
4	231	61	55	50	47	45	45	45
5	1960	104	94	87	81	77	74	74
6	1177	80	73	67	62	59	59	59
7	784	53	47	43	41	39	39	39
8	470	45	40	36	34	34	34	34
9	985	108	98	91	84	80	77	77
10	592	85	77	70	66	62	60	60
11	394	98	89	82	76	72	70	70
12	237	82	74	68	63	60	58	58

Table (6.30) Total losses (in kW) in feeder no.33, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks								
period No.	T_p (hrs)	0	1	2	3	4	5	6	7	8
1	964	204	194	188	181	176	171	168	166	164
2	579	162	154	149	143	139	135	133	132	132
3	385	111	104	100	96	93	91	90	90	90
4	231	95	89	85	81	79	78	78	78	78
5	1960	154	146	141	135	132	128	126	125	125
6	1177	122	115	111	106	103	101	100	100	100
7	784	83	77	74	71	69	68	68	68	68
8	470	70	65	63	60	58	58	58	58	58
9	985	160	152	147	141	137	134	131	130	130
10	592	128	121	116	111	108	106	104	103	103
11	394	147	139	134	128	125	122	120	118	118
12	237	124	117	113	108	105	103	101	101	101

Table (6.31) Total losses (in kW) in feeder no.35, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks								
period No.	T_p (hrs)	0	1	2	3	4	5	6	7	8
1	964	141	134	129	125	122	120	119	119	119
2	579	113	107	102	99	97	95	95	95	95
3	385	77	72	69	67	65	65	65	65	65
4	231	66	62	59	57	56	56	56	56	56
5	1960	107	101	97	94	92	91	91	91	91
6	1177	85	80	77	74	73	72	72	72	72
7	784	58	54	51	50	49	49	49	49	49
8	470	49	46	43	42	42	42	42	42	42
9	985	111	105	101	98	96	94	94	94	94
10	592	89	84	80	78	76	75	75	75	75
11	394	102	96	92	89	87	86	86	86	86
12	237	87	82	78	75	74	73	73	73	73

Table (6.32) Total losses (in kW) in feeder no.36, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks								
		0	1	2	3	4	5	6	7	8
1	964	475	452	433	416	402	391	382	375	369
2	579	376	357	341	327	316	307	300	296	296
3	385	254	239	227	217	210	204	201	201	201
4	231	216	203	192	184	178	174	174	174	174
5	1960	357	338	323	310	299	291	285	281	281
6	1177	281	265	252	241	233	227	223	223	223
7	784	189	176	167	160	154	151	151	151	151
8	470	160	149	141	135	130	128	128	128	128
9	985	371	352	336	322	312	303	296	292	292
10	592	294	278	264	253	245	238	234	234	234
11	394	339	320	305	293	283	275	270	266	266
12	237	286	270	257	246	238	231	227	227	227

Table (6.33) Total losses (in kW) in feeder no.37, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks										
period No.	T_P (hrs)	0	1	2	3	4	5	6	7	8	9	10
1	964	141	136	131	128	124	121	118	117	116	115	115
2	579	113	109	105	101	98	96	94	93	92	92	92
3	385	78	74	71	68	66	64	64	63	63	63	63
4	231	66	63	60	58	56	55	54	54	54	54	54
5	1960	108	103	99	96	93	91	89	88	88	88	88
6	1177	86	82	78	76	73	71	70	70	70	70	70
7	784	58	55	52	51	49	48	47	47	47	47	47
8	470	50	47	44	43	41	41	40	40	40	40	40
9	985	112	107	103	100	97	95	93	92	91	91	91
10	592	90	86	82	79	77	75	74	73	73	73	73
11	394	102	98	94	91	88	87	85	84	83	83	83
12	237	87	195	83	80	77	75	73	72	71	71	71

Table (6.34) Total losses (in kW) in feeder no.38, which is arised from combining active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks				
period No.	T_p (hrs)	0	1	2	3	4
1	964	79	73	69	66	65
2	579	63	58	54	52	52
3	385	43	39	37	35	35
4	231	37	33	31	31	31
5	1960	60	55	52	50	50
6	1177	48	43	41	39	39
7	784	32	29	27	27	27
8	470	28	25	23	23	23
9	985	63	57	54	52	52
10	592	50	45	42	41	41
11	394	57	52	49	47	47
12	237	49	44	41	40	40

Table (6.35) Losses (in kW) in feeder no.1, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks					
		0	1	2	3	4	5
1	964	21	14	9	5	2	0
2	579	17	11	7	3	1	1
3	385	11	7	4	1	1	1
4	231	9	5	3	0	0	0
5	1960	10	6	3	1	1	1
6	1177	4	2	1	0	0	0
7	784	5	2	1	0	0	0
8	470	4	2	0	0	0	0
9	985	11	7	4	1	1	1
10	592	9	5	3	0	0	0
11	394	21	14	9	5	2	0
12	237	17	11	7	3	1	1

Table (6.36) Losses (in kW) in feeder no.2. arising from the reactive currents. as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks 0	Total Number of Capacitor Banks 1
1	964	5	1
2	579	5	1
3	385	3	0
4	231	3	0
5	1960	3	0
6	1177	2	0
7	784	1	0
8	470	1	0
9	985	3	0
10	592	3	0
11	394	6	1
12	237	5	1

Table (6.37) Losses (in kW) in feeder no.4, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks												
period No.	T_i (hrs)	0	1	2	3	4	5	6	7	8	9	10	11	12
1	964	205	170	139	111	88	68	51	40	28	23	18	14	9
2	579	168	137	109	86	65	49	39	26	21	13	9	6	6
3	385	111	87	66	48	34	23	16	12	6	3	2	2	2
4	231	93	71	53	37	25	16	11	7	5	5	5	5	5
5	1960	100	77	58	42	29	19	13	9	6	2	2	2	2
6	1177	83	62	45	31	20	14	8	5	3	3	3	3	3
7	784	56	40	27	16	9	5	3	1	1	1	1	1	1
8	470	47	32	21	12	6	3	1	0	0	0	0	0	0
9	985	111	87	66	48	34	23	16	12	6	3	2	2	2
10	592	93	71	53	37	25	16	11	7	5	5	5	5	5
11	394	205	170	139	111	88	68	51	40	28	23	18	14	9
12	237	168	137	109	86	65	49	39	26	21	13	9	6	6

Table (6.38) Losses (in kW) in feeder no.5, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks		
period No.	T_p (hrs)	0	1	2
1	964	1.0	0.3	0
2	579	0.9	0.2	0
3	385	0.6	0.1	0
4	231	0.5	0	0
5	1960	0.5	0.1	0.1
6	1177	0.5	0	0
7	784	0.3	0	0
8	470	0.3	0	0
9	985	0.6	0	0
10	592	0.5	0	0
11	394	1.0	0.3	0
12	237	0.9	0.2	0

Table (6.39) Losses (in kW) in feeder no.6, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks								
period No.	T_r (hrs)	0	1	2	3	4	5	6	7	8
1	964	64	52	39	29	21	14	8	4	1
2	579	54	42	31	22	15	9	5	2	2
3	385	37	28	19	12	8	3	1	1	1
4	231	32	23	15	9	5	2	0	0	0
5	1960	34	25	17	10	6	3	0	0	0
6	1177	29	21	13	8	4	1	1	1	1
7	784	20	14	8	4	2	0	0	0	0
8	470	17	11	6	2	1	1	1	1	1
9	985	64	52	39	29	21	14	8	4	1
10	592	54	42	31	22	15	9	5	2	2
11	394	37	28	19	12	8	3	1	1	1
12	237	32	23	15	9	5	2	0	0	0

Table (6.40) Losses (in kW) in feeder no.7. arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_r (hrs)	Total Number of Capacitor Banks						
		0	1	2	3	4	5	6
1	964	330	251	197	153	120	92	70
2	579	211	164	129	100	77	57	42
3	385	102	78	59	43	31	21	21
4	231	78	58	43	30	20	13	13
5	1960	87	65	49	35	24	15	15
6	1177	65	48	35	23	15	15	15
7	784	37	25	17	10	5	1	1
8	470	29	19	12	6	6	6	6
9	985	102	78	59	43	31	21	21
10	592	78	58	43	30	20	13	13
11	394	330	251	197	153	120	92	70
12	237	211	164	19	100	77	57	42

Table (6.41) Losses (in kW) in feeder no.8, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks		
period No.	T_p (hrs)	0	1	2
1	964	6	2	0
2	579	5	2	0
3	385	4	1	0
4	231	3	1	0
5	1960	3	1	0
6	1177	3	0	0
7	784	2	0	0
8	470	1	0	0
9	985	4	1	0
10	592	3	1	0
11	394	6	2	0
12	237	5	2	0

Table (6.42) Losses (in kW) in feeder no.9, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks											
period No.	T_p (hrs)	0	1	2	3	4	5	6	7	8	9	10	11
1	964	104	87	75	62	52	41	32	23	18	12	9	5
2	579	85	70	59	48	39	30	22	15	11	8	4	4
3	385	56	44	36	27	21	15	10	5	3	1	1	1
4	231	47	36	29	21	16	11	6	3	1	1	1	1
5	1960	50	39	32	24	18	12	8	4	2	2	2	2
6	1177	41	32	25	18	13	8	4	2	2	2	2	2
7	784	28	20	15	10	6	3	1	1	1	1	1	1
8	470	23	16	12	7	4	2	0	0	0	0	0	0
9	985	56	44	36	27	21	15	10	5	3	1	1	1
10	592	47	36	29	21	16	11	6	3	1	1	1	1
11	394	104	87	75	62	52	41	32	23	18	12	9	5
12	237	85	70	59	48	39	30	22	15	11	8	4	4

Table (6.43) Losses (in kW) in feeder no.10, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks							
		0	1	2	3	4	5	6	7
1	964	34	26	18	12	8	4	2	1
2	579	26	19	13	8	4	2	1	1
3	385	17	12	7	4	2	0	0	0
4	231	14	9	5	2	1	0	0	0
5	1960	25	18	12	7	4	2	0	0
6	1177	19	13	8	4	2	0	0	0
7	784	12	8	4	2	0	0	0	0
8	470	10	6	3	1	0	0	0	0
9	985	26	19	12	8	4	2	1	1
10	592	20	14	9	5	2	1	1	1
11	394	24	17	11	7	3	1	0	0
12	237	20	14	8	5	2	1	1	1

Table (6.44) Losses (in kW) in feeder no.11, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks												
period No.	T_p (hrs)	0	1	2	3	4	5	6	7	8	9	10	11	12
1	964	155	133	111	94	76	63	49	38	28	21	15	9	6
2	579	125	107	88	73	57	46	34	26	18	12	8	5	5
3	385	82	68	53	42	31	23	15	10	6	3	1	1	1
4	231	69	56	43	33	23	17	10	6	3	3	3	3	3
5	1960	74	60	47	36	26	19	12	8	4	4	4	4	4
6	1177	61	49	37	28	19	13	8	4	2	0	0	0	0
7	784	41	31	22	15	9	5	2	2	2	2	2	2	2
8	470	34	25	17	11	6	3	1	1	1	1	1	1	1
9	985	82	68	53	42	31	23	15	10	6	3	1	1	1
10	592	69	56	43	33	23	17	10	6	3	3	3	3	3
11	394	155	133	111	94	76	63	49	38	28	21	15	9	6
12	237	125	107	88	73	57	46	34	26	18	12	8	5	5

Table (6.45) Losses (in kW) in feeder no.12, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks									
period No.	T_p (hrs)	0	1	2	3	4	5	6	7	8	9
1	964	38	31	24	18	14	10	7	4	3	2
2	579	32	25	19	14	10	7	4	3	2	1
3	385	22	17	12	8	5	3	2	1	0	0
4	231	19	14	10	6	4	2	1	1	0	0
5	1960	21	15	11	7	4	2	2	1	0	0
6	1177	17	12	8	5	3	2	1	0	0	0
7	784	12	8	5	3	1	1	1	1	1	1
8	470	10	6	4	2	1	0	0	0	0	0
9	985	23	17	12	8	5	3	2	1	0	0
10	592	19	14	10	6	4	2	1	1	0	0
11	394	38	31	24	18	14	10	6	4	3	2
12	237	32	25	19	14	10	7	4	3	2	1

Table (6.46) Losses (in kW) in feeder no.13, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks					
period No.	T_p (hrs)	0	1	2	3	4	5
1	964	32	21	15	8	3	1
2	579	26	16	11	5	1	0
3	385	17	10	6	2	0	0
4	231	15	8	4	1	0	0
5	1960	24	15	10	4	1	0
6	1177	19	11	7	2	0	0
7	784	13	6	3	1	1	1
8	470	11	5	2	0	0	0
9	985	25	16	10	5	1	0
10	592	20	12	7	3	0	0
11	394	23	14	9	4	1	1
12	237	19	11	7	2	0	0

Table (6.47) Losses (in kW) in feeder no.17, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks												
period No.	T_p (hrs)	0	1	2	3	4	5	6	7	8	9	10	11	12
1	964	37	31	26	21	17	13	10	7	5	3	2	1	0
2	579	30	24	20	16	12	9	6	4	2	1	0	0	0
3	385	20	16	12	9	6	4	3	1	0	0	0	0	0
4	231	17	13	10	7	5	3	1	1	0	0	0	0	0
5	1960	28	23	19	15	11	8	5	4	2	1	0	0	0
6	1177	22	18	14	10	7	5	3	2	1	0	0	0	0
7	784	15	11	8	6	3	2	1	0	0	0	0	0	0
8	470	13	9	6	4	2	1	0	0	0	0	0	0	0
9	985	29	24	19	15	12	9	6	4	2	1	0	0	0
10	592	23	19	15	11	8	5	3	2	1	0	0	0	0
11	394	27	22	17	13	10	7	5	3	2	1	0	0	0
12	237	22	18	14	11	8	5	3	2	1	0	0	0	0

Table (6.48) Losses (in kW) in feeder no.19, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	I_r (hrs)	Total Number of Capacitor Banks																					
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	964	119	109	99	90	82	73	66	59	51	44	37	32	26	22	17	14	10	7	5	3	1	0
2	579	95	85	77	69	61	54	48	42	35	30	24	20	16	12	9	6	4	2	1	0	0	0
3	385	64	56	49	43	37	32	27	22	18	13	10	7	5	3	1	0	0	0	0	0	0	0
4	231	54	47	41	35	30	26	20	16	12	9	6	4	2	1	0	0	0	0	0	0	0	0
5	1900	90	81	73	65	58	51	45	39	32	28	22	18	14	11	8	5	3	1	0	0	0	0
6	1177	71	63	56	49	43	37	32	26	21	17	13	10	7	5	2	1	0	0	0	0	0	0
7	784	47	41	35	30	25	21	16	13	9	7	4	2	1	0	0	0	0	0	0	0	0	0
8	470	40	34	29	24	20	16	12	96	4	21	0	0	0	0	0	0	0	0	0	0	0	0
9	985	93	84	67	68	60	54	47	41	34	30	24	20	15	12	9	6	3	2	1	0	0	0
10	592	74	66	58	52	45	39	34	28	23	18	15	11	8	5	3	2	1	0	0	0	0	0
11	394	85	76	68	61	54	47	41	35	30	24	20	15	12	9	6	4	2	1	0	0	0	0
12	237	72	64	57	50	44	38	33	26	22	17	14	10	8	5	3	1	0	0	0	0	0	0

Table (6.49) Losses (in kW) in feeder no.21, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks							
period No.	T_p (hrs)	0	1	2	3	4	5	6	7
1	964	7	6	4	3	1	0	0	0
2	579	6	4	3	2	1	0	0	0
3	385	4	3	1	1	0	0	0	0
4	231	3	2	1	0	0	0	0	0
5	1960	5	4	2	2	1	0	0	0
6	1177	4	3	2	1	0	0	0	0
7	784	3	2	1	0	0	0	0	0
8	470	2	1	0	0	0	0	0	0
9	985	6	4	3	2	1	0	0	0
10	592	4	3	2	1	0	0	0	0
11	394	5	4	2	1	0	0	0	0
12	237	4	3	2	1	0	0	0	0

Table (6.50) Losses (in kW) in feeder no.22, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks	
period No.	T_p (hrs)	0	1
1	964	0.4	0
2	579	0.3	0
3	385	0.2	0
4	231	0.2	0
5	1960	0.3	0
6	1177	0.2	0
7	784	0.1	0.1
8	470	0.1	0.1
9	985	0.3	0
10	592	0.2	0
11	394	0.3	0
12	237	0.2	0

Table (6.51) Losses (in kW) in feeder no.23, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks	
		0	1
1	964	1.1	0.1
2	579	0.8	0
3	385	0.6	0
4	231	0.5	0
5	1960	0.8	0
6	1177	0.6	0
7	784	0.4	0.4
8	470	0.3	0.3
9	985	0.8	0
10	592	0.6	0
11	394	0.8	0
12	237	0.6	0

Table (6.52) Losses (in kW) in feeder no.25, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks												
period No	T_i (hrs)	0	1	2	3	4	5	6	7	8	9	10	11	12
1	964	6	5	4	3	3	2	1	1	1	0	0	0	0
2	579	5	4	3	2	2	1	1	1	0	0	0	0	0
3	385	3	2	2	1	1	1	0	0	0	0	0	0	0
4	231	3	2	1	1	1	0	0	0	0	0	0	0	0
5	1960	5	4	3	2	2	1	1	0	0	0	0	0	0
6	1177	4	3	2	2	1	1	0	0	0	0	0	0	0
7	784	2	2	1	1	0	0	0	0	0	0	0	0	0
8	470	2	1	1	0	0	0	0	0	0	0	0	0	0
9	985	5	4	3	2	2	1	1	0	0	0	0	0	0
10	592	4	3	2	2	1	1	0	0	0	0	0	0	0
11	394	4	3	3	2	2	1	1	0	0	0	0	0	0
12	237	4	3	2	2	1	1	0	0	0	0	0	0	0

Table (6.53) Losses (in kW) in feeder no.26, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks	
period No.	T_p (hrs)	0	1
1	964	1.2	0.2
2	579	1	0.1
3	385	0.6	0
4	231	0.5	0
5	1960	0.9	0.1
6	1177	0.7	0
7	784	0.5	0
8	470	0.4	0.4
9	985	1	0.1
10	592	0.7	0
11	394	0.9	0.1
12	237	0.7	0

Table (6.54) Losses (in kW) in feeder no.27, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks				
period No.	T_p (hrs)	0	1	2	3	4
1	964	22	16	12	8	3
2	579	17	11	8	5	1
3	385	10	6	4	1	1
4	231	8	5	3	0	0
5	1960	16	11	7	5	1
6	1177	11	7	5	1	1
7	784	7	4	2	0	0
8	470	6	3	2	0	0
9	985	16	11	8	5	1
10	592	12	8	5	1	1
11	394	14	10	7	2	1
12	237	12	8	5	1	1

Table (6.55) Losses (in kW) in feeder no.28, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks					
period No.	T_r (hrs)	0	1	2	3	4	5
1	964	8	5	3	2	1	0
2	579	6	3	2	1	0	0
3	385	4	2	1	0	0	0
4	231	3	2	1	0	0	0
5	1960	6	3	2	1	0	0
6	1177	4	2	1	0	0	0
7	784	3	1	0	0	0	0
8	470	2	1	0	0	0	0
9	985	6	3	2	1	0	0
10	592	5	3	1	0	0	0
11	394	5	3	2	0	0	0
12	237	4	2	1	0	0	0

Table (6.56) Losses (in kW) in feeder no.29, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks									
period No.	T_P (hrs)	0	1	2	3	4	5	6	7	8	9
1	964	26	20	15	12	8	7	4	3	1	0
2	579	20	15	12	8	5	4	2	1	0	0
3	385	13	9	7	4	3	1	0	0	0	0
4	231	11	7	6	3	2	1	0	0	0	0
5	1960	19	14	12	8	5	3	2	1	0	0
6	1177	15	10	8	5	4	2	0	0	0	0
7	784	10	6	5	2	1	0	0	0	0	0
8	470	8	5	4	2	1	0	0	0	0	0
9	985	20	15	12	8	5	4	2	1	0	0
10	592	15	11	9	6	4	2	1	0	0	0
11	394	18	13	11	7	4	3	1	1	1	1
12	237	15	11	9	5	4	2	1	0	0	0

Table (6.57) Losses (in kW) in feeder no.30, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks	
		0	1
1	964	1.2	0.3
2	579	0.9	0.2
3	385	0.6	0.1
4	231	0.5	0.1
5	1960	0.9	0.2
6	1177	0.7	0.1
7	784	0.5	0.5
8	470	0.4	0.4
9	985	0.9	0.2
10	592	0.7	0.1
11	394	0.8	0.1
12	237	0.7	0.1

Table (6.58) Losses (in kW) in feeder no.31, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks							
period No.	T_r (hrs)	0	1	2	3	4	5	6	7
1	964	151	116	89	70	50	36	24	20
2	579	103	77	58	43	29	19	11	11
3	385	57	40	28	19	11	5	5	5
4	231	46	31	20	13	7	2	2	2
5	1960	95	71	52	39	26	16	9	9
6	1177	66	47	33	23	14	8	8	8
7	784	38	25	16	10	4	4	4	4
8	470	30	19	11	6	2	2	2	2
9	985	101	76	56	42	28	18	10	10
10	592	71	51	36	26	16	9	9	9
11	394	88	65	47	35	23	14	7	7
12	237	68	49	35	24	15	8	8	8

Table (6.59) Losses (in kW) in feeder no.32, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_r (hrs)	Total Number of Capacitor Banks						
		0	1	2	3	4	5	6
1	964	47	35	25	17	11	6	3
2	579	35	25	17	11	6	3	3
3	385	21	14	8	4	2	2	2
4	231	17	11	6	3	1	1	1
5	1960	32	23	15	10	5	2	2
6	1177	24	16	10	6	3	3	3
7	784	14	9	5	2	0	0	0
8	470	12	7	3	1	1	1	1
9	985	34	24	17	10	6	3	3
10	592	25	17	11	6	3	1	1
11	394	30	21	14	9	5	2	2
12	237	24	16	10	6	3	1	1

Table (6.60) Losses (in kW) in feeder no.33, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks								
period No.	T_p (hrs)	0	1	2	3	4	5	6	7	8
1	964	40	30	25	17	13	8	5	3	1
2	579	31	23	18	12	8	4	2	1	1
3	385	20	14	10	6	3	1	0	0	0
4	231	17	11	8	4	2	1	1	1	1
5	1960	30	21	17	11	7	4	2	1	1
6	1177	23	16	12	7	4	2	0	0	0
7	784	15	9	6	3	1	0	0	0	0
8	470	12	7	5	2	1	0	0	0	0
9	985	31	22	18	11	8	4	2	1	1
10	592	24	17	13	8	5	2	1	0	0
11	394	28	20	15	10	7	3	1	0	0
12	237	23	16	12	7	4	2	0	0	0

Table (6.61) Losses (in kW) in feeder no.35, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks								
period No.	T_p (hrs)	0	1	2	3	4	5	6	7	8
1	964	25	18	13	9	6	4	3	3	3
2	579	19	14	9	6	4	3	2	2	2
3	385	13	8	5	3	2	1	1	1	1
4	231	11	7	4	2	1	1	1	1	1
5	1960	19	13	9	5	3	2	2	2	2
6	1177	15	10	6	4	2	2	2	2	2
7	784	10	6	3	2	1	1	1	1	1
8	470	8	5	2	1	1	1	1	1	1
9	985	19	13	9	6	4	3	2	2	2
10	592	15	10	7	4	2	2	2	2	2
11	394	18	12	8	5	3	2	2	2	2
12	237	15	10	6	4	2	2	2	2	2

Table (6.62) Losses (in kW) in feeder no.36, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks								
period No.	T_p (hrs)	0	1	2	3	4	5	6	7	8
1	964	107	85	66	50	36	25	16	10	5
2	579	82	63	47	34	23	14	8	3	3
3	385	52	38	26	16	10	4	1	1	1
4	231	44	31	20	13	6	2	2	2	2
5	1960	77	59	44	31	21	13	6	3	3
6	1177	59	43	31	20	12	6	2	2	2
7	784	38	26	16	10	4	1	1	1	1
8	470	32	20	12	6	2	0	0	0	0
9	985	81	62	46	33	22	14	8	3	3
10	592	62	46	33	22	14	7	3	3	3
11	394	73	55	40	28	19	11	5	2	2
12	237	60	44	31	21	13	7	2	2	2

Table (6.63) Losses (in kW) in feeder no.37, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

period No.	T_P (hrs)	Total Number of Capacitor Banks										
		0	1	2	3	4	5	6	7	8	9	10
1	964	27	21	17	13	10	7	4	2	1	1	0
2	579	21	17	12	9	6	4	2	1	0	0	0
3	385	14	11	7	5	3	1	1	0	0	0	0
4	231	12	9	6	4	2	1	0	0	0	0	0
5	1960	20	16	12	8	6	4	2	1	0	0	0
6	1177	16	12	8	6	4	1	1	0	0	0	0
7	784	11	7	5	3	1	0	0	0	0	0	0
8	470	9	6	4	2	1	0	0	0	0	0	0
9	985	21	16	12	9	6	4	2	1	0	0	0
10	592	17	13	9	6	4	2	1	0	0	0	0
11	394	19	15	11	8	5	3	1	1	0	0	0
12	237	16	12	9	6	4	2	1	0	0	0	0

Table (6.64) Losses (in kW) in feeder no.38, arising from the reactive currents, as a function of the number of the installed capacitors at different time periods. Each capacitor is 0.9 MVAR.

		Total Number of Capacitor Banks				
period No.	T_p (hrs)	0	1	2	3	4
1	964	14	8	4	1	1
2	579	11	6	3	0	0
3	385	8	3	1	0	0
4	231	6	3	0	0	0
5	1960	11	6	2	0	0
6	1177	8	4	1	0	0
7	784	6	2	0	0	0
8	470	5	2	0	0	0
9	985	11	6	2	0	0
10	592	9	4	1	0	0
11	394	10	5	2	0	0
12	237	9	4	1	0	0

Table (6.65) Switching table for feeder no. 34, showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods. The capacitors are installed at only 8 nodes which have the numbers 8, 18, 19, 39, 43, 54, 60 and 70. This feeder carries a maximum load of 23.8 MW and 14.7 MVAR distributed from 79 main load nodes.

cap. #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
node #	8	18	18	18	18	18	18	19	39	39	43	54	60	70
period ↓	switch status of the capacitor banks													
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	0	1	1	0	1	1	1	1
3	1	1	1	1	1	1	0	1	1	0	1	1	1	1
4	1	1	1	1	1	0	0	1	1	0	1	1	1	1
5	1	1	1	1	1	1	0	1	1	0	1	1	1	1
6	1	1	1	1	1	1	0	1	1	0	1	1	1	1
7	1	1	1	1	1	0	0	1	1	0	1	1	0	1
8	1	1	1	1	1	0	0	1	1	0	1	1	0	1
9	1	1	1	1	1	1	0	1	1	0	1	1	1	1
10	1	1	1	1	1	1	0	1	1	0	1	1	1	1
11	1	1	1	1	1	1	0	1	1	0	1	1	1	1
12	1	1	1	1	1	1	0	1	1	0	1	1	1	1

Table (6.66) Switching table for feeder no.1 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1
node #	32
period ↓	switch status of the capacitor banks
1	1
2	1
3	1
4	1
5	1
6	1
7	1
8	1
9	1
10	1
11	1
12	1

Table (6.67) Switching table for feeder no.3 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3	4	5	6	7	8	9
node #	29	29	29	29	27	18	18	18	16
period ↓	switch status of the capacitor banks								
1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	0	1
4	1	1	1	0	1	1	1	0	1
5	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	0	1
7	1	1	1	0	1	1	1	0	0
8	1	1	1	0	1	1	1	0	0
9	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	0	1
11	1	1	1	1	1	1	1	0	1
12	1	1	1	1	1	1	1	0	1

Table (6.68) Switching table for feeder no.4 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3	4	5	6	7	8	9	10
node #	20	22	38	48	48	51	51	51	51	51
period ↓	switch status of the capacitor banks									
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	0
4	1	1	1	1	1	1	1	1	1	0
5	1	1	1	1	1	1	1	1	1	0
6	1	1	1	1	0	1	1	1	1	0
7	1	1	1	1	0	1	1	1	0	0
8	1	1	1	1	0	1	1	1	0	0
9	1	1	1	1	1	1	1	1	1	0
10	1	1	1	1	0	1	1	1	1	0
11	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1

Table (6.69) Switching table for feeder no.6 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3	4	5
node #	37	37	38	36	36
period ↓	switch status of the capacitor banks				
1	1	1	1	1	1
2	1	1	1	1	1
3	1	1	1	1	1
4	1	1	1	1	1
5	1	1	1	1	1
6	1	1	1	1	0
7	1	1	1	1	0
8	1	0	1	1	0
9	1	1	1	1	1
10	1	1	1	1	1
11	1	1	1	1	1
12	1	1	1	1	1

Table (6.70) Switching table for feeder no.7 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3	4	5	6
node #	4	4	5	10	10	10
period ↓	switch status of the capacitor banks					
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	0
4	1	1	1	1	1	0
5	1	1	1	1	1	0
6	1	1	0	1	1	0
7	1	0	1	1	1	0
8	1	0	0	1	1	0
9	1	1	1	1	1	0
10	1	1	1	1	1	0
11	1	1	1	1	1	1
12	1	1	1	1	1	1

Table (6.71) Switching table for feeder no.9 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3	4	5	6	7	8	9	10
node #	12	19	19	19	27	37	37	37	37	52
period ↓	switch status of the capacitor banks									
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	0	1	1	1	1	0	1
4	1	1	1	0	1	1	1	1	0	1
5	1	1	1	0	1	1	1	1	0	1
6	0	1	1	0	1	1	1	1	0	1
7	0	1	1	0	1	1	1	0	0	1
8	0	1	1	0	1	1	1	0	0	1
9	1	1	1	0	1	1	1	1	0	1
10	1	1	1	0	1	1	1	1	0	1
11	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1

Table (6.72) Switching table for feeder no.10 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3
node #	14	14	20
period ↓	switch status of the capacitor banks		
1	1	1	1
2	1	1	1
3	1	1	1
4	1	1	1
5	1	1	1
6	1	1	1
7	1	1	1
8	1	1	1
9	1	1	1
10	1	1	1
11	1	1	1
12	1	1	1

Table (6.73) Switching table for feeder no.11 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3	4	5	6	7
node #	23	23	23	23	34	34	34
period ↓	switch status of the capacitor banks						
1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1
7	1	1	1	0	1	1	1
8	1	1	1	0	1	1	1
9	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1

Table (6.74) Switching table for feeder no.12 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3
node #	25	25	27
period ↓	switch status of the capacitor banks		
1	1	1	1
2	1	1	1
3	1	1	1
4	1	1	1
5	1	1	1
6	1	1	1
7	1	1	1
8	1	1	1
9	1	1	1
10	1	1	1
11	1	1	1
12	1	1	1

Table (6.75) Switching table for feeder no.13 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3
node #	20	30	50
period ↓	switch status of the capacitor banks		
1	1	1	1
2	1	1	1
3	1	1	1
4	1	1	1
5	1	1	1
6	1	1	1
7	1	1	1
8	1	1	1
9	1	1	1
10	1	1	1
11	1	1	1
12	1	1	1

Table (6.76) Switching table for feeder no.17 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3
node #	6	6	6
period ↓	switch status of the capacitor banks		
1	1	1	1
2	1	1	1
3	1	1	1
4	1	1	1
5	1	1	1
6	1	1	1
7	1	1	1
8	1	1	1
9	1	1	1
10	1	1	1
11	1	1	1
12	1	1	1

Table (6.77) Switching table for feeder no.19 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3	4	5	6	7	8	9	10	11	12
node #	12	12	12	12	12	12	12	12	12	21	21	21
period ↓	switch status of the capacitor banks											
1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	0	0	1	1	1
8	1	1	1	1	1	1	1	0	0	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1	1	1

Table (6.78) Switching table for feeder no.27 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1
node #	5
period ↓	switch status of the capacitor banks
1	1
2	1
3	1
4	1
5	1
6	1
7	1
8	1
9	1
10	1
11	1
12	1

Table (6.79) Switching table for feeder no.29 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1
node #	23
period ↓	switch status of the capacitor banks
1	1
2	1
3	1
4	1
5	1
6	1
7	1
8	1
9	1
10	1
11	1
12	1

Table (6.80) Switching table for feeder no.31 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3	4	5	6
node #	21	24	24	33	41	41
period ↓	switch status of the capacitor banks					
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	0	1	1	1
4	1	1	0	1	1	1
5	1	1	0	1	1	1
6	1	1	1	0	1	1
7	1	1	0	1	1	0
8	1	1	0	1	1	0
9	1	1	1	1	1	1
10	1	1	1	0	1	1
11	1	1	1	1	1	1
12	1	1	0	0	1	1

Table (6.81) Switching table for feeder no.32 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3	4
node #	11	11	11	11
period ↓	switch status of the capacitor banks			
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	1	1	1
5	1	1	1	1
6	1	1	1	1
7	1	1	1	1
8	1	1	1	0
9	1	1	1	1
10	1	1	1	1
11	1	1	1	1
12	1	1	1	1

Table (6.82) Switching table for feeder no.33 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3
node #	16	44	44
period ↓	switch status of the capacitor banks		
1	1	1	1
2	1	1	1
3	1	1	1
4	1	1	1
5	1	1	1
6	1	1	1
7	1	1	1
8	1	1	1
9	1	1	1
10	1	1	1
11	1	1	1
12	1	1	1

Table (6.83) Switching table for feeder no.35 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2
node #	44	70
period ↓	switch status of the capacitor banks	
1	1	1
2	1	1
3	1	1
4	1	1
5	1	1
6	1	1
7	1	1
8	1	1
9	1	1
10	1	1
11	1	1
12	1	1

Table (6.84) Switching table for feeder no.36 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3	4	5	6
node #	29	51	51	69	77	77
period ↓	switch status of the capacitor banks					
1	1	1	1	1	1	1
2	1	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	1	0	1	1
5	1	1	1	1	1	1
6	1	1	1	1	1	1
7	1	1	0	1	1	1
8	1	1	0	1	1	1
9	1	1	1	1	1	1
10	1	1	1	1	1	1
11	1	1	1	1	1	1
12	1	1	1	1	1	1

Table (6.85) Switching table for feeder no.37 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2
node #	30	31
period ↓	switch status of the capacitor banks	
1	1	1
2	1	1
3	1	1
4	1	1
5	1	1
6	1	1
7	1	1
8	1	1
9	1	1
10	1	1
11	1	1
12	1	1

Table (6.86) Switching table for feeder no.38 showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1
node #	33
period ↓	switch status of the capacitor banks
1	1
2	1
3	1
4	1
5	1
6	1
7	1
8	1
9	1
10	1
11	1
12	1

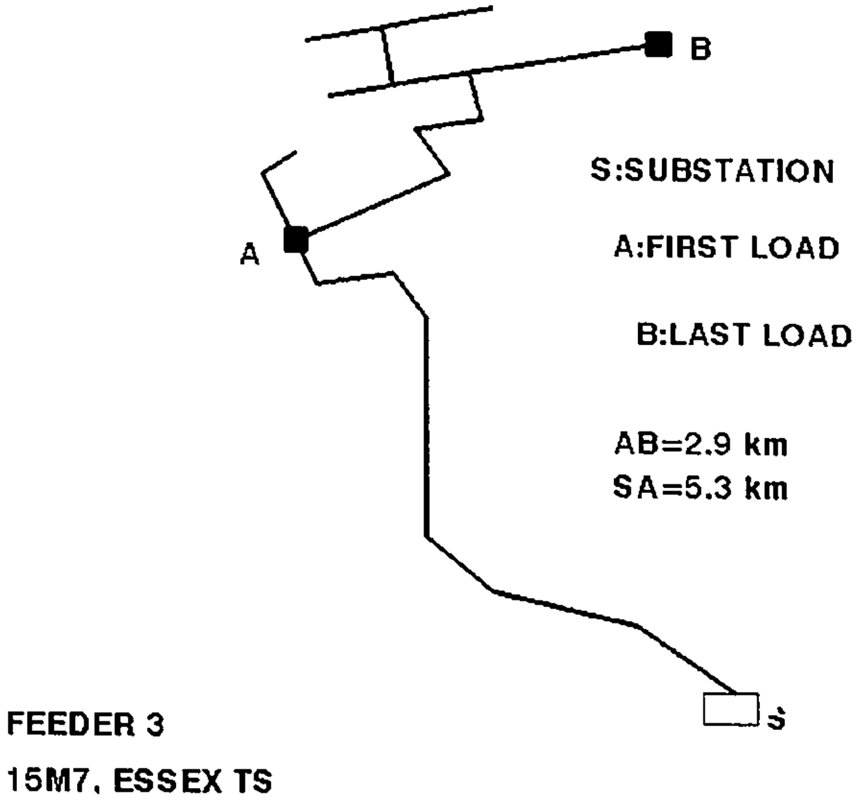

Fig.(6.71) Schematic diagram of feeder No.3.

Table (6.90) shows the number of nodes at each of the 38 feeders comprising the distribution system of the city of Windsor, the maximum active and reactive load, the number of the *sensitive* nodes and the recommended capacitor ratings to be installed at each feeder. It will be seen that the total installed capacitor rating is always less than the maximum inductive reactive power. This is in order to yield a maximum dollar saving. For example in feeder no.3 (Table (6.90)) the installed capacitor rating is about 83% of the reactive load, while in feeder no. 38 it is only 21.4%.

Table (6.91) represents the net dollar saving in every feeder after including the extra saving by combining the non-switchable capacitors. The net dollar saving to the power utility amounts to $167,845 per year with a total of 100.8 MVAR rating of installed compensating capacitors. This annual dollar saving is expected to increase in the future years as the cost of purchasing or generating the energy is projected to increase at a much higher rate than the amortized cost of the installed capacitors which remains at a steady value (7% rate was assumed). Also if the cost of the kWh is more than 2.15¢, which is the case in most Canadian and United States power utilities, higher savings will accrue. This is a considerable net dollar gain for a relatively small power utility. The energy saved is about 1.2 MW-Year worth about $225,500 per year. If this energy which has been saved using the reactive power compensation is sold to the consumer at a more realistic price of typically 8¢ per kWh, the retrieved dollar value of the saved energy is $841,088 per year. This will only apply if there is a power rationing by the generation utility (Ontario Hydro) due to unexpected excess demand over the supply available. The total maximum reactive power in the system can be obtained from Table (6.90) which amounts to 242.3 MVAR. Essentially only 41.6% of the reactive power is compensated. A compensation of the remainder is not cost effective in that it will not render a net dollar saving after taking into account the cost of acquiring and installing the capacitors.

6.5.Combining Reconfiguration With Capacitor Applications

The main features of the proposed method is illustrated in Fig.(6.73) and can be summarized in the following

1. Read all system data.
2. Apply the optimal reconfiguration technique.
3. Calculate the system losses.
4. Apply compensating capacitors. in the optimally reconfigured system. at sensitive nodes.
5. Calculate the system losses
6. Add the loss reductions after reconfiguration. (step 3). and those after capacitor application. (step 5).

This algorithm provides a loss reduction in a distribution system which is more cost effective than any other known algorithm.

The algorithm has been applied to PUC network in Kingston and to WUC in the city of Windsor. The number of the nodes in both systems were too large to be included in a single data file. and therefore it had to be aggregated.

Table (6.87) Losses (in kW) in feeder no. 3, arising from the reactive current, as a function of the number of the installed capacitors at different time periods. Each capacitor bank is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks										
		0	1	2	3	4	5	6	7	8	9	10
1	964	444	386	334	266	223	170	137	109	74	48	31
2	579	329	281	182	182	148	107	82	61	36	19	19
3	385	202	166	135	95	72	45	30	14	6	6	6
4	231	167	135	107	72	52	30	18	6	6	6	6
5	1960	308	262	221	167	135	96	72	53	30	15	15
6	1177	229	190	156	113	87	57	39	26	11	11	11
7	784	142	113	88	57	40	21	11	11	11	11	11
8	470	117	91	69	42	28	12	5	5	5	5	5
9	985	324	276	233	179	145	104	79	59	34	18	18
10	592	288	244	204	153	123	86	64	46	25	25	25
11	394	243	202	167	122	95	63	45	30	14	14	14
12	237	234	195	160	116	90	59	41	27	12	12	12

Table (6.88) Total losses (in kW) in feeder no. 3. which arise from the combined active and reactive currents as a function of the number of the installed capacitors at different time periods. Each capacitor bank is 0.9 MVAR.

period No.	T_p (hrs)	Total Number of Capacitor Banks										
		0	1	2	3	4	5	6	7	8	9	10
1	964	1710	1644	1584	1509	1461	1403	1365	1333	1295	1267	1248
2	579	1327	1273	1224	1164	1126	1081	1053	1029	1003	985	985
3	385	872	832	797	755	730	701	684	668	659	659	659
4	231	737	702	672	635	613	590	576	565	565	565	565
5	1960	1254	1202	1156	1099	1063	1021	994	972	948	932	932
6	1177	971	928	891	844	816	784	764	749	733	733	733
7	784	639	607	580	547	529	509	498	498	498	498	498
8	470	539	510	486	458	443	427	419	419	419	419	419
9	985	1309	1255	1207	1147	1110	1066	1038	1014	989	972	972
10	592	1021	976	937	889	859	825	804	788	771	771	771
11	394	1184	1135	1091	1036	1002	962	937	916	894	894	894
12	237	990	946	908	861	832	799	779	763	747	747	747

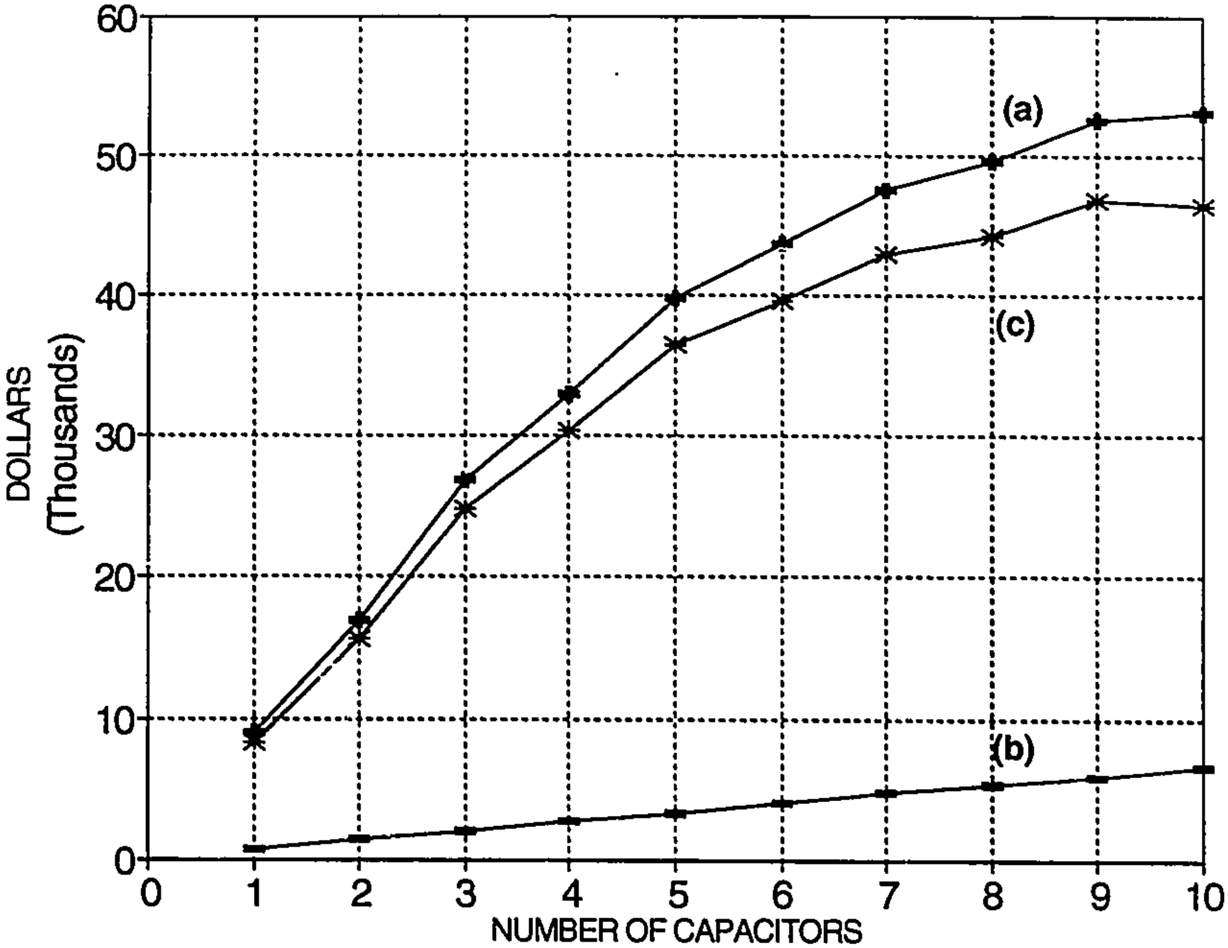

Fig.(6.72) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors including the cost of capital and cost of installation (b) and the net annual dollar saving (c) after subtracting the cost of the capacitors in feeder No.3.

Table (6.89) Extra saving arised from combining the 0.9 MVAR capacitor units in a bigger single capacitor.

Combination	Extra Saving Per Year (Dollars)
2X0.9 MVAR=1.8 MVAR	312
3X0.9 MVAR=2.7 MVAR	1,148
4X0.9 MVAR=3.6 MVAR	1,704
5X0.9 MVAR=4.5 MVAR	2,260
6X0.9 MVAR=5.4 MVAR	2,806
7X0.9 MVAR=6.3 MVAR	3,374
8X0.9 MVAR=7.2 MVAR	3,940

Table (6.90) 38 feeder distribution system of the city of Windsor, Ontario, showing the number of nodes supplying the loads in each feeder, the loads in MW and MVAR, number of *sensitive* nodes and the installed compensating capacitors in MVAR.

F.#	no.of nodes	LOAD MW	LOAD MVAR	sens. nodes	CAP. MVAR	F.#	no.of nodes	LOAD MW	LOAD MVAR	sens. nodes	CAP. MVAR
1	38	10	4.6	1	0.9	20	23	1.2	0.6	0	0
2	15	3.6	1.91	0	0	21	16	14.7	7	0	0
3	44	21.87	9.81	4	8.1	22	21	2.65	1.3	0	0
4	58	26.67	11.66	6	9.0	23	40	2.6	1.3	0	0
5	8	2.64	2.04	0	0	24	0	0	0	0	0
6	45	19	8	3	4.5	25	4	23.5	11.4	0	0
7	17	20.5	6.2	3	5.4	26	41	2.9	1.4	0	0
8	46	5.66	2.6	0	0	27	19	9.1	4.4	1	0.9
9	60	22.42	10.5	5	9.0	28	42	12.4	5.1	0	[illegible]
10	26	13.04	6.31	2	2.7	29	29	18.2	9.1	1	0.9
11	74	21.3	11.7	2	6.3	30	67	4.9	1.8	0	0
12	56	21.71	10.5	2	2.7	31	81	14.5	6.7	4	5.4
13	65	10	5.34	3	2.7	32	39	14.2	6.8	1	3.6
14	0	0	0	0	0	33	66	18	8	2	2.7
15	19	0.86	0.38	0	0	34	79	23.8	14.7	8	12.6
16	0	0	0	0	0	35	81	16.6	7.6	2	1.8
17	13	25.7	11.6	1	2.7	36	80	18.8	8.1	4	5.4
18	19	21	10.1	0	0	37	73	21.1	10	2	1.8
19	25	40	20	2	10.8	38	60	9.2	4.2	1	0.9

Table (6.91) Net dollar saving at every feeder and the total net annual saving after including the extra saving arised from fixed capacitor combination for WUC network.

Feeder No.	Saving $	Feeder No.	Saving $	Feeder No.	Saving $	Feeder No.	Saving $
1	153	11	11865	21	0	31	10658
2	0	12	1059	22	0	32	4827
3	48214	13	1520	23	0	33	1668
4	15867	14	0	24	0	34	23293
5	0	15	0	25	0	35	456
6	3373	16	0	26	0	36	8903
7	16427	17	1605	27	213	37	219
8	0	18	0	28	0	38	225
9	5862	19	9818	29	194		
10	1426	20	0	30	0	TOTAL	167,845

The system was aggregated by keeping the total switches unchanged but combining many load points at one location and taking into account some of the excess of the load current to compensate of the losses that may be ignored when aggregation takes place. The amount of this excess lies within 1 to 1.5% of the aggregated load power and these values were based on a previous experience gained from studying both systems. The PUC network in Kingston has mainly residential and commercial loads, which are expected to follow a similar load variation with time. Therefore only a single application of the reconfiguration technique was sufficient per year to determine the optimal configuration required to minimize the losses.

In order to reduce the number of nodes in the WUC network, each node was arranged to have almost an equal percentage combination of residential, commercial and industrial load types. It was expected that all the loads would also have similar load variation with time and one application of system reconfiguration would suffice. For other distribution systems this assumption may not be applicable. However, 12 optimal configurations can still be made for the 12 periods in the year.

6.5.1.The Distribution System of PUC of the City of Kingston

Figure (6.74) shows a single line diagram of the original (PUC) distribution network before reconfiguration. Figure (6.75) shows the optimally reconfigured network. An illustrative example of these results is highlighted in node No. 7 which is transferred from feeder I to feeder IV. This is because the route (IV-23), (23-21), (21-22), (22-9) and (9-7) has the lowest resistance for the power flowing via node No.7.

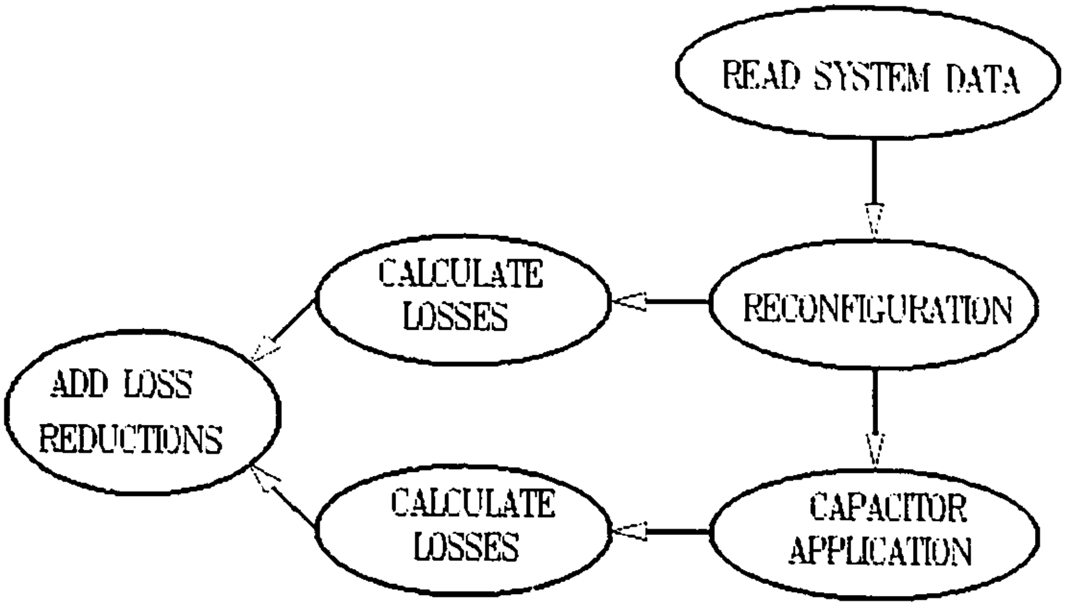

Fig.(6.73) Algorithm of reconfiguration with capacitor application combination.

The power in the new configuration route is less than that of the original route (1-1), (1-2), (2-4), (4-5), (5-6) and (6.7). In this configuration the load connected at node No. 7 contributes the lowest loss to the total system.

Table (6.92) shows the resultant power and energy losses before and after the reconfiguration of the PUC system in different periods throughout the year. It can be seen from Table (6.92) that the total energy loss decreases from 11,462.40 MWH to 9,108.99 MWH per year. This yield a reduction of 2,353.41 MWH per year. This reduction in the losses amounts to 20.5% of the original energy losses.

Compensating capacitors were then applied to the reconfigured system. Figure (6.76) shows the dollar value of the annual energy loss reduction (curve a), the amortized annual cost of multiple 0.9 MVAR units of capacitors including cost of capital and cost of installation (curve b) and the net annual dollar saving after subtracting the cost of the capacitors (curve c). It can be seen from Fig.(6.76) that although 29 capacitor units of 0.9 MVAR in the network give the largest loss reduction, connecting more than 16 such capacitors is not a cost effective proposition. This is because the gain from larger than 16 capacitor units is less than the cost of the extra units connected in the network. Typically, 16 capacitors of 0.9 MVAR each (14.4 MVAR) that are used to obtain maximum dollar savings represent only 18.2% of the total system reactive power. The remaining reactive power can not be compensated for in a cost effective manner.

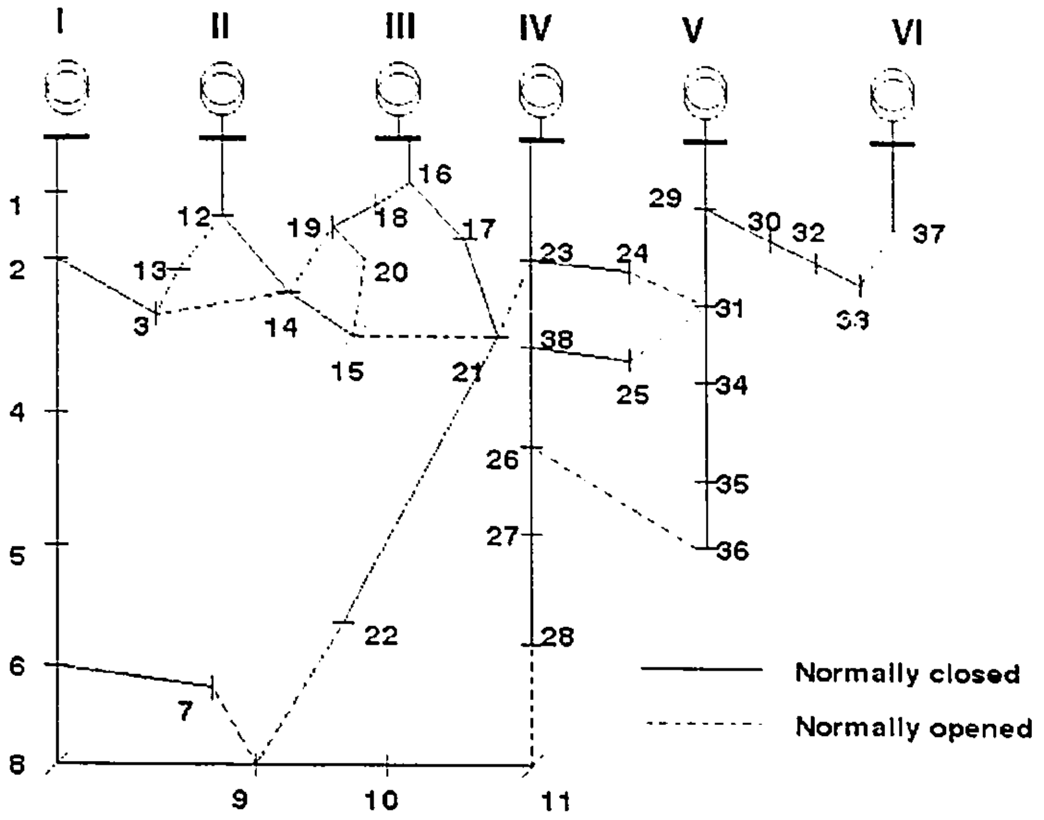

Fig.(6.74) Kingston PUC network before reconfiguration.

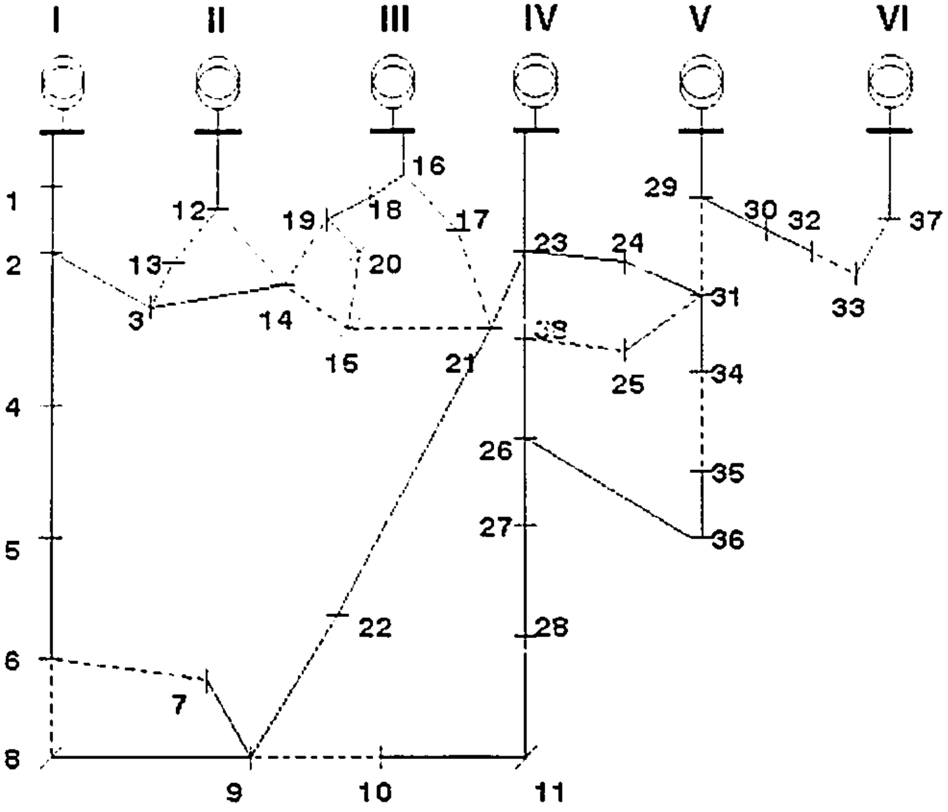

Fig.(6.75) Kingston PUC network after reconfiguration.

Table (6.92) Power and energy loss before and after system reconfiguration for the different periods for PUC Kingston distribution network.

period No.	T_p (hrs)	Losses (MW) Before Reconf.	Losses (MW) After Reconf.	Energy Loss (MWH) Before Reconf.	Energy Loss (MWH) After Reconf.
1	964	2.0358	1.6208	1,962.51	1,562.45
2	579	1.7370	1.3780	1,005.72	797.86
3	385	1.1164	0.9814	429.81	377.84
4	231	1.0785	0.8475	249.13	195.77
5	1960	1.1448	0.8998	2,243.38	1,763.61
6	1177	0.9536	0.7476	1,122.39	879.93
7	784	0.7015	0.5465	549.98	428.46
8	470	0.6015	0.4675	282.71	219.75
9	985	1.7370	1.3780	1,710.95	1,357.33
10	592	2.0348	1.6208	1,204.60	959.51
11	394	1.0785	0.8475	424.93	333.92
12	237	1.1640	0.9814	275.87	232.52
			TOTAL	11,462.40	9,108.99

Following compensation of the reactive power, the system maximum demand decreases from 200 to 195 MVA and the average power factor improves from 0.92 to 0.94. The losses at the peak load are reduced by 0.229 MW and the reduction in the total losses is 1331.2 MWH per year. This leads to an interesting finding in that because the change in the total load due to the reactive compensation by applying capacitors is relatively small, it is recommended first to reconfigure the system and then to apply compensating capacitors. This is because experience has shown that small changes in the load level, at few loads, does not affect the results of applying the reconfiguration technique. Also if the reconfiguration technique is applied first, and then capacitors were placed at the *sensitive* nodes, a further reconfiguration is not necessary as the same results would be obtained as those after the first reconfiguration.Table (6.12) shows the status of the capacitor switches which are installed at the *sensitive* nodes during the different periods in the year. For example capacitor No. 1 at node 8 is connected throughout the year, but capacitor No. 8 at node 10 should be turned OFF during periods 7 (Fall/Spring, Weekend, high load of the day) and 8 (Fall/Spring, Weekend, low load of the day) to attain minimum losses.

6.5.2.The Distribution System of WUC of the City of Windsor

Figure (6.1) shows a schematic diagram of the 6 substations of the distribution system of the city of Windsor with the possible links amongst them. Figures (6.77) and (6.78) show the reduced network in Windsor before and after attaining an optimal reconfiguration, respectively.

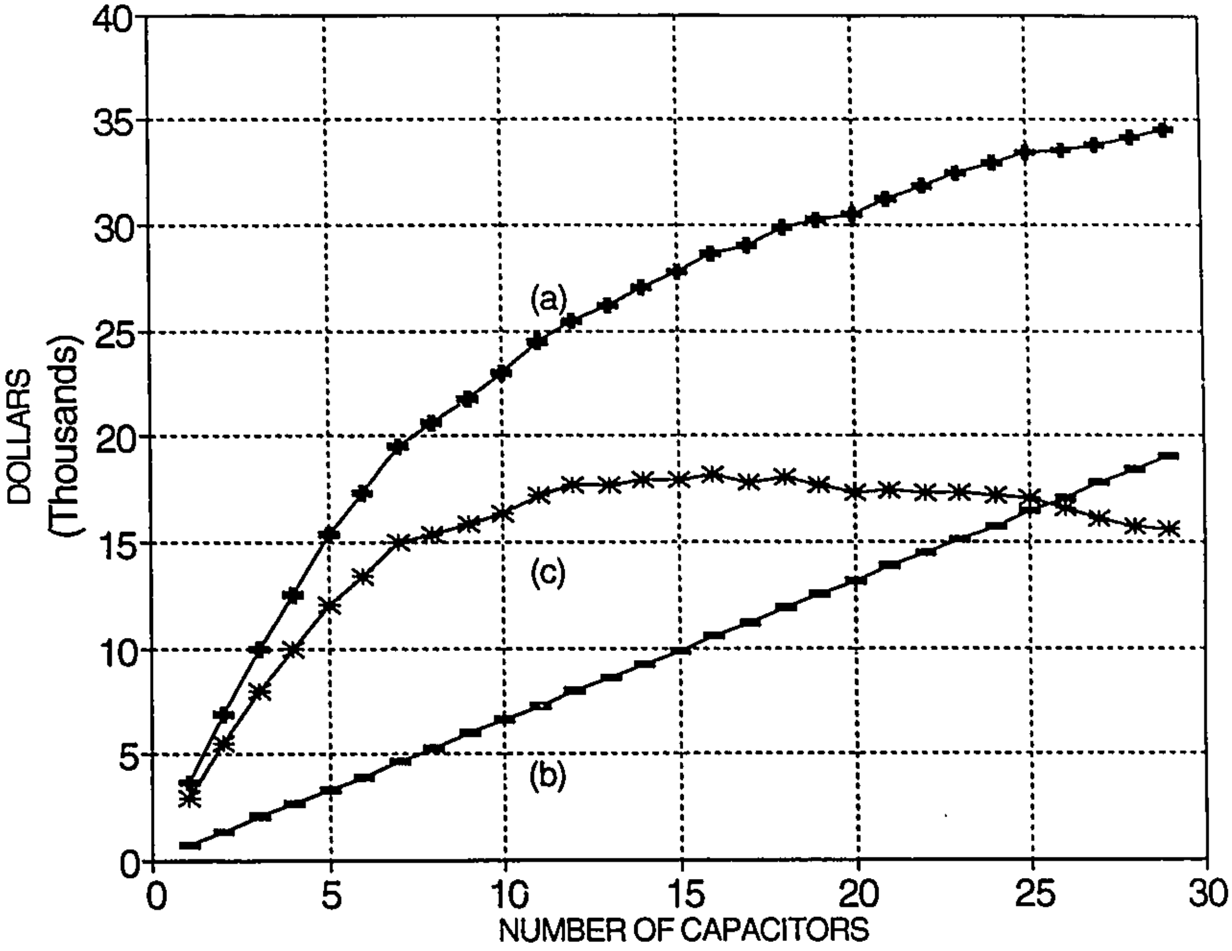

Fig.(6.76) Dollar value of the annual energy loss reduction (a), the amortized annual cost of multiple units of capacitors including the cost of capital and cost of installation (b) and the net annual dollar saving (c) after subtracting the cost of the capacitors for PUC network in Kingston.

For example, switch A which ties feeder 15M7 in substation Essex TS (15) to feeder 55M1 in Walker TS (55) is closed as load 'a' has a route with a lower resistance from 55M1 (0.670 Ω) than that of 15M7 (1.736 Ω). Another example is switch R that ties feeder 24M6 from Malden TS 24 to feeder 24M5 at the same substation should be closed as the resistive route for the load at node 'r' from 24M5 is less than that from 24M6. Table (6.94) shows the losses before and after system reconfiguration of the distribution system of the city of Windsor for different periods of the year. It can be seen from Table (6.94) that the energy losses decreased by 4,898.8 MWH per year which is a 8.1% reduction by reconfiguring the system. It should be noted that the percentage reduction in losses in the Windsor distribution system by reconfiguration is smaller than that of Kingston (24.1%), as the load in Windsor is more evenly distributed than that of Kingston. Figure (6.79) shows the net annual dollar saving in the Windsor network subsequent to applying compensating capacitors (curve c) to the reconfigured system, the amortized annual cost of applying the compensating capacitors including the cost of capital and cost of installation (curve b) and the cost of the annual energy loss reduction (curve a). It can be seen from Fig.(6.79) that the maximum dollar savings can be attained by applying 98 of 0.9 MVAR capacitor units. These give 88.2 MVAR to compensate for 33.2% of the system reactive power. The balance of the reactive power in the system is not cost effective to be compensated. The losses at the peak power have been reduced by 1.183 MW, while the energy saved is 8610 MWH per year.

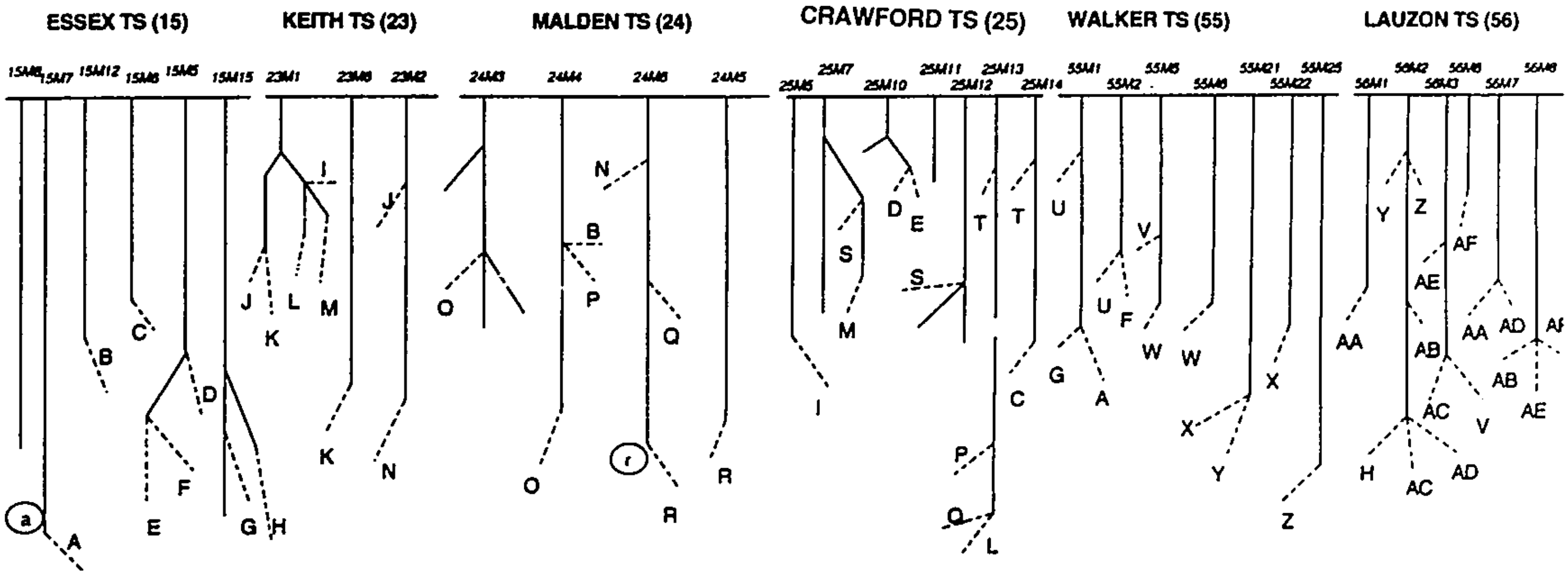

Fig.(6.77) Windsor WUC network before reconfiguration.

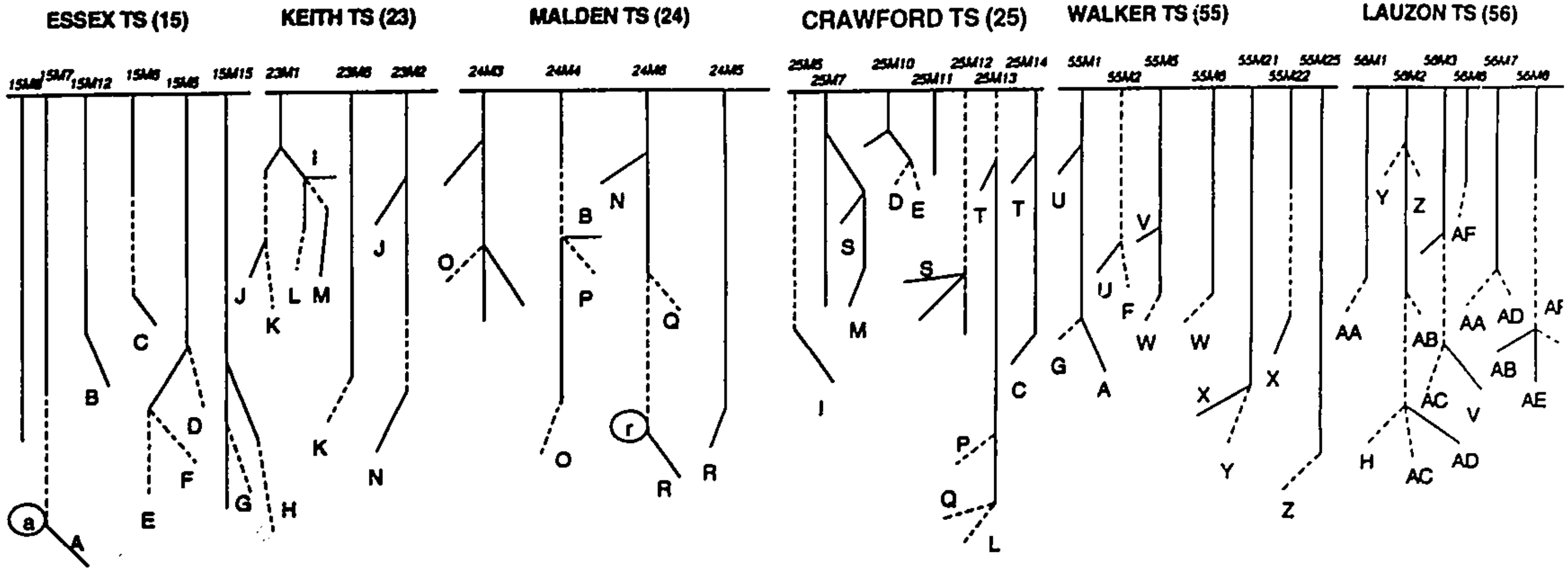

Fig.(6.78) Windsor WUC network after reconfiguration.

Table (6.93) Switching table for Kingston PUC network showing the status of the capacitor switches (1 for ON and 0 for OFF) at different time periods.

cap. #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
node #	8	8	8	10	10	10	10	10	10	10	11	11	11	11	27	27
period ↓	switch status of the capacitor banks															
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1
7	1	1	0	1	1	1	1	0	0	0	1	1	1	0	1	1
8	1	1	0	1	1	1	1	0	0	0	1	1	1	0	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1

Table (6.94) Power and energy loss before and after system reconfiguration for the different periods for WUC Windsor distribution network.

period No.	T_p (hrs)	Losses (MW) Before Reconf.	Losses (MW) After Reconf.	Energy Loss (MWH) Before Reconf.	Energy Loss (MWH) After Reconf.
1	964	9.7006	9.0570	9,351.38	8,730.94
2	579	7.8007	7.1902	4,516.61	4,163.13
3	385	5.3778	4.8681	2,070.46	1,874.23
4	231	4.6214	4.1573	1,067.54	960.34
5	1960	7.4271	6.8278	14,557.10	13,382.43
6	1177	5.8592	5.3241	6,896.28	6,266.45
7	784	4.0575	3.6321	3,181.08	2,847.58
8	470	3.4670	3.0866	1,629.48	1,450.69
9	985	[illegible] 9766	8.3410	8,841.95	8,215.89
10	592	8.4766	7.8498	5,018.15	4,647.08
11	394	4.9925	4.5051	1,967.03	1,775.01
12	237	4.9925	4.5051	1,183.21	1,067.71
			TOTAL	60,280.27	55,381.48

Table (6.95) gives a summary of the optimal results obtained after applying the algorithm of loss reduction on both Kingston and Windsor networks. Table (6.95) shows that the saving obtained for optimal reconfiguration on the Windsor network is $105,355 per year and after applying compensating capacitors using multiple units of 0.9 MVAR, an additional $114,843 can be saved per year. Many of the 900 kVAR capacitors at certain *sensitive* nodes are not subjected to any switching throughout the year. Therefore it is suggested to aggregate those capacitors in larger units, because the cost of the larger aggregate capacitors is lower than multiple capacitors for the same MVAR. If larger rated capacitors are used, as a combination of a group of fixed 0.9 MVAR capacitors, the saving from the compensating capacitor application can reach $136,250 per year in the reconfigured Windsor network.

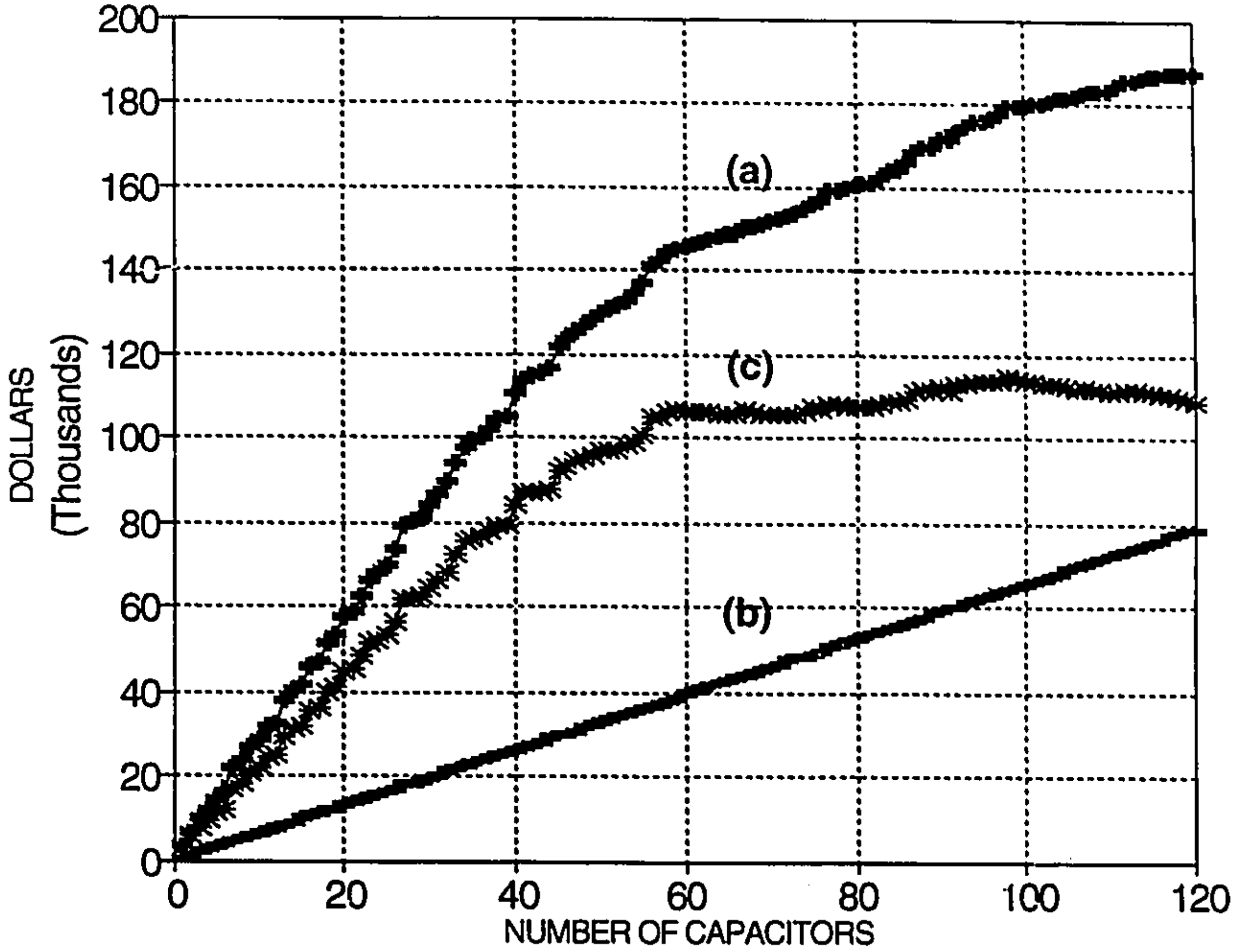

Fig.(6.79) Dollar value of the annual energy loss reduction (a), annual cost of capacitors (b) and the net annual dollar saving (c) for Windsor WUC network.

Table (6.95) Summary of annual savings using reconfiguration and reactive power compensation in both Kingston and Windsor distribution networks.

Kingston Distribution Network	$/year
Annual saving due to reconfiguration	50,349
Annual saving due to using capacitors of multiples of 0.9 MVAR	18,157
Annual saving due to using capacitors of 0.9, 1.8, 2.7, 3.6, 4.5, 5.4, 6.3 and 7.2 MVAR	21,632
Total annual saving with multiple of 0.9 MVAR banks (reconfiguration and capacitor application)	68,506
Total annual saving with aggregated capacitor banks (reconfiguration and capacitor application)	71,981
Windsor Distribution Network	
Annual saving due to reconfiguration	105,355
Annual saving due to using capacitors of multiple of 0.9 MVAR	114,843
Annual saving due to using capacitors of 0.9, 1.8, 2.7, 3.6, 4.5, 5.4, 6.3 and 7.2 MVAR	136,250
Total annual saving with multiple of 0.9 MVAR banks (reconfiguration and capacitor application)	220,198
Total annual saving with aggregated capacitor banks (reconfiguration and capacitor application)	241,605

CHAPTER 7

CONCLUSIONS AND FURTHER RESEARCH

7.1.Conclusions

1. Power system losses can be reduced by reconfiguration and compensation capacitor applications.

2. A heuristic method for system reconfiguration presented by Merlin and Back, and then modified by Shirmohammadi and Hong with additional subroutines by Wagner et al. is employed for system reconfiguration, and a new technique for capacitor application based on identifying the most *sensitive* nodes on the power system to the reactive power injection is presented.

3. Load variation during the year can be summarized using 12 different load levels covering seasonally, weekly and daily variations.

4. A list of conversion factors is implemented to estimate the load curve variations throughout the year using only the overall peak value of the load.

5. Optimal system reconfiguration followed by optimal capacitor application gives the least losses.

6. All the cost reduction due to reconfiguration can be saved as there are no expenses for system reconfiguration, because the existing switches are used.

7. The method presented in this work is applied to the Public Utility Commission at the city of Kingston, Ontario and to the city of Windsor (Windsor Utilities Commission). Only 33% of the reactive power in Kingston and 41% of that in Windsor is compensated. To compensate the balance is not cost effective.

8. Capacitor costs (capital and labour cost) are taken into account.

9. Three types of loads (commercial, residential and industrial) are considered.

10. Switching tables of capacitors (ON and OFF) for the Kingston and the Windsor networks are provided to prevent over and under-compensation when the load level changes. This is to keep the losses at a minimum level throughout the year.

7.2. Further Research

1. Capacitor application on distribution systems having unbalanced loads.

2. Capacitor application for voltage improvement.

3. Combination of capacitor application with voltage improvement.

4. More extensive combination of reconfiguration with capacitor application when many load types having different load profiles are involved.

5. Combining the loss reduction technique with voltage regulation taking into account the tap changing in the distribution transformers.

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