An Integrated Approach to the Reduction of Reactive Power Losses in Radial Distribution Network

by

Than Khong Hon

Dissertation submitted in partial fulfilment of
the requirements for the
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CERTIFICATION OF APPROVAL

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Approved by,

(Ir. Perumal Nallagownden)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

THAN KHONG HON

ABSTRACT

Distribution system forms an important part of the electrical power system connecting high voltage transmission lines to low voltage consumers through feeders, distributors and service mains. Losses will occur in the distribution line due to the resistance and reactance of the cables. Consequently, this will eventually lead into voltage instability of the system. Therefore, reduction of reactive power is required to compensate the losses.

The objective of this project is to compensate reactive power with appropriate methods. There are basically two commonly used methods: network reconfiguration and capacitor insertion. The scope of study would be on the capacitor insertion in radial distribution network. An existing algorithm will be studied and an integrated approach to the reduction of reactive power losses will be proposed.

This report will cover the progress and all findings in the two-semester final year project (FYP). This report consists of 6 main chapters where the first chapter serves as the introduction and background of the project. The next chapter is basically the literature review on all the relevant information. Methodology outlines the process flow as well as tools required for the project. The algorithm for single and multiple capacitor insertion will be introduced in Chapter 4. Chapter 5 will mainly cover on the results from the load flow simulation and results from single and multiple capacitors placement. Besides, comparison will be done between single and multiple capacitors as well as comparisons between the proposed method with the existing method. The conclusion of this report shall summarize the findings and recommendations for future project work.

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CHAPTER 1: INTRODUCTION

1.0 Introduction

This chapter illustrates the introduction part of the project. Introduction will consist of background of study, problems statement, objectives and scope of study.

1.1 Background of Study

Loss is a major issue in the distribution system as compared to transmission system. Since voltage in distribution system is lower; therefore higher current will produce higher power (I^2R) loss. This is cost ineffective and undesirable. The loss due to active component of current cannot be minimized because all active power must be supplied by the source. However, the loss due to reactive component of current can be reduced by supplying part of the reactive power demand locally.

This project involves of reviewing the existing methods as well as proposing a more efficient method for loss reduction. The cheapest and the simplest approach for loss reduction is by placing a capacitor as a source of reactive power at certain location of the network. The capacitor placement could be in series or parallel (shunt). The main part of the study will be on the location of bus and size of capacitor that should be placed. Algorithms are required to solve these problems. Load flow analysis on a distribution system requires a power system analysis software.

1.2 Problem Statements

Distribution system forms an important part of the electrical power system connecting high voltage transmission lines to low voltage consumers through feeders, distributors and service mains. Losses will occur in the transmission line due to the resistance and reactance of the cables. As in Table 1.1, in Malaysia the total transmission and distribution (T&D) losses contribute to approximately 10 percent. This is high as compared to most of the developed countries, i.e. Japan and (4.0%) and United States (7.0%). Basically there are two main types of losses, namely real power and reactive power losses. These losses will affect the overall efficiency of the system. Hence, investigation and identification of the losses are essential in the process of reducing these losses. By applying fundamental knowledge in power system, several techniques will be adopted and evaluated and the result will be validated using simulation software.

Table 1.1 Transmission and Distribution Losses

Country	T&D losses percent	Country	T&D losses percent
Japan	4.0	Switzerland	6.0
Denmark	4.0	Sweden	6.4
Germany	4.0	United States	7.0
Ghana	4.0	United Kingdom	7.0
Singapore	4.0	Taiwan	7.0
Guam	4.50[a]	Italy	7.4
Macau	4.81[a]	London	8.3
Korea	5.4	Malaysia	10.0
France	5.9	Thailand	10.3
Australia	6.0	Fiji	10.52[a]
Canada	6.0	Indonesia	12.0
China	6.0	Mexico	14.0
South Africa	6.0	Hong Kong	15.0

[a]Source is Electric Power in Asia and Pacific, United Nations, 1997

Source. World Development Report 1997, and London Electricity of UK

1.3 Objectives and Scope of Study

1.3.1 Objectives

The main objectives of this project are to conduct a study on the reduction of reactive power in radial distribution system. Therefore the fundamental objectives formulated are:

- To conduct a study on reactive power and losses
- To review the radial distribution system
- To review and to identify techniques and algorithms available for reactive power reduction
- To propose an algorithm for the loss reduction
- To evaluate the performance of techniques and algorithms proposed and to compare with other algorithms

At the end of the study, the best method in loss reduction will be adopted. The basic criteria taking into consideration will be the effectiveness, performance, reliability and simplicity of the method.

1.3.2 Scope of Study

The scope of the study will be narrowed down to only the distribution network rather than the entire transmission and distribution network. Mainly there are two types of distribution network, namely radial distribution network and ring main distribution network. Radial distribution network is chosen for practical reason. Most of the network available in Malaysia is radial distribution network because of the cheaper costs and the simplicity of the system. Moreover, this study is only limited to reactive power loss and compensation.

As a conclusion, this research will cover the reactive power losses in the radial distribution network and the techniques of reactive power reduction as shown in Figure 1.1.

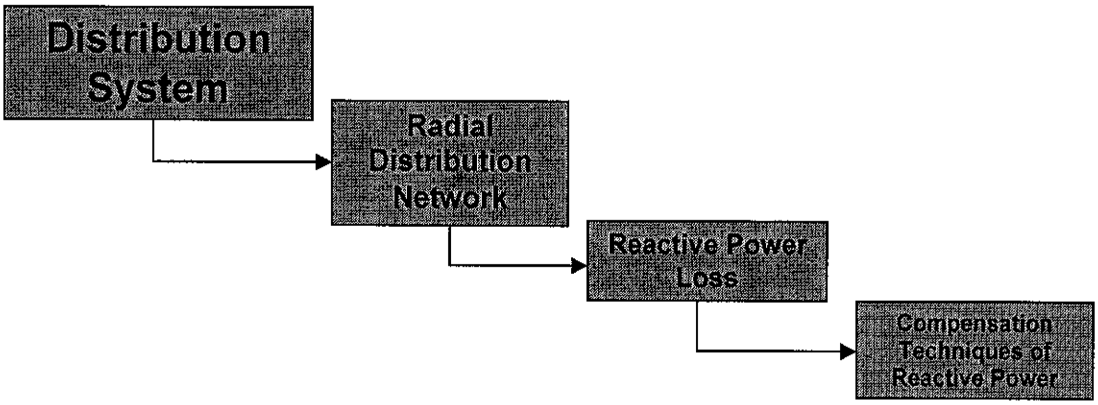


Figure 1.1 Scope of Study

CHAPTER 2: LITERATURE REVIEW

2.0 Literature Review

As for the literature review, the background study is as explained in Chapter 1. Basically the first part of the review involves of general description of distribution network and also types of network configuration. Then, concentration would be on the characteristics of reactive power as well as reactive power losses in distribution network particularly in radial distribution network. The effects of losses will be explained followed by methods for the reduction of line losses. Lastly, techniques of reduction such as network reconfiguration as well as series and shunt compensation using capacitor will be reviewed.

2.1 Overview of Distribution System

Basically a complete electric power system consists of generation, transmission and distribution (Figure 2.1). Generation in Malaysia is usually the responsibility of

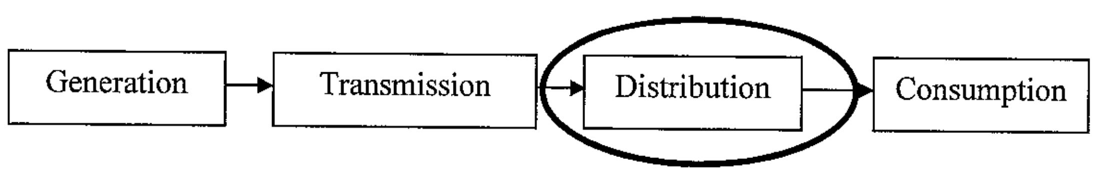


Figure 2.1 Electric Power System

independent power providers (IPPs). After the generation, Tenaga Nasional Berhad (TNB) will take care of the transmission as well as distribution of electricity to the consumers (in Peninsular). In the entire transportation process, there are various processes where the voltage needs to be step up for transmission and then step down for distribution at the substation.

Distribution system is part of the electric power system which connects the high voltage transmission network to the low voltage consumer service point. It comprises of distribution substations which convert the energy from primary system voltage for local distribution. Besides, it usually has feeders, distribution transformers and service lines which deliver the energy from the secondary circuits to the consumers.

Typically the transmission voltage from 132kV or higher. As for distribution system, the voltage is typically 240V and 415V. Basically there are two basics structures for distribution systems, radial distribution system and ring main distribution system.

2.1.1 Radial Distribution System

Radial distribution system is a distribution system that the distributor connects to the supply system on one end only. It is clearly that in such a case the end of the distributor nearest to the generating station would be heavily loaded. The advantage of this configuration is that the cost of implementation is cheaper than the ring main configuration. Disadvantage of this network is that when the nearest distributor has power interruption, it will affect the entire network. Most of the network configurations used in Malaysia is of this type.

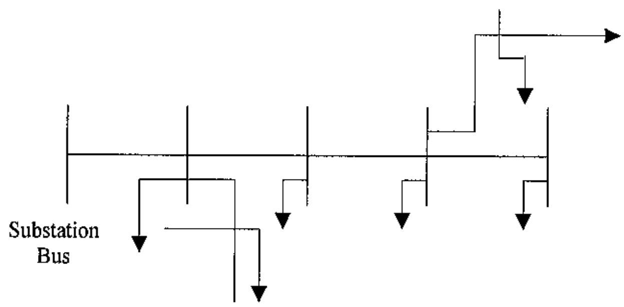


Figure 2.2 Radial Distribution Network

2.1.2 Ring Main Distribution System

Ring Main employs a feeder which covers the whole of supply finally returning to the generating station. From the figure below observed that each load will be fed by two supply lines. Hence this configuration is better as when if there is interruption on one side of the load, the supply can be taken from another direction of the supply. However, the implementation costs are higher as more cables are required.

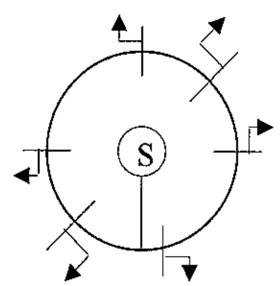


Figure 2.3 Ring Main Distribution Network

2.2 Review on Reactive Power and Losses

Reactive power is needed for inductive load, like a motor, compressor or ballast to generate and sustain a magnetic field in order to operate. It is also known as non-working power and the unit is KVAR or kilovolt-amperes-reactive.

In an alternating current system, when the voltage and current go up and down at the same time, only real power is transmitted and when there is a time shift at the same time, only real power is transmitted and where there is a time shift between voltage and current both active and reactive power are transmitted [1]. When the average in time is calculated, the average active power exists causing a net flow of energy from one point to another, whereas average reactive power is zero. This means that the amount of reactive power flowing in one direction is equal to the amount of energy flowing in the opposite direction. In other words, reactive power is neither produced nor consumed.

Reactive power is always associated with power factor. Power factor is defined as the ratio of real power (KW) to reactive power (KVAR). Mathematically is represented by KW/KVA. Therefore, amount of apparent power (KVA) increases as reactive power is required. In other words, reduction of reactive power has the same meaning with improvement of power factor and reduction of reactive power can reduce the total power (Figure 2.4).

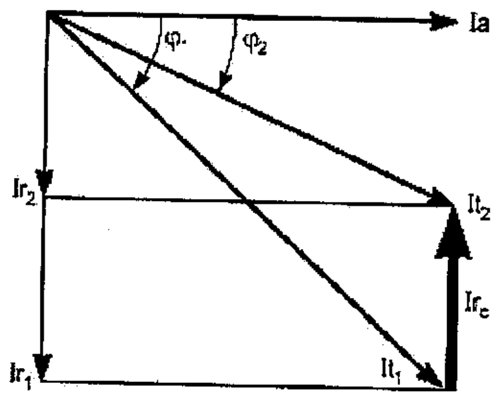


Figure 2.4 Reduction of Reactive Power can Reduce the Total Power

$$PowerFactor = \frac{RealPower}{ApparentPower} = \cos\theta = \frac{KW}{KVA} \quad (2.1)$$

2.2.1 Causes of Reactive Power Losses [2]

There are generally many factors contribute to losses in distribution system. The losses involve losses on the complete distribution system such as loss in feeder and loss in distribution transformer. It would be much easier to reduce the losses in the latter part by identifying the losses. Some of the main factors are:

i. **Feeder Length** – long distance distribution system results in high line resistance and reactance, low voltage and high current and leads to high I^2R and I^2X losses.

ii. **Inadequate Size of Conductor** – rural loads are usually scattered and generally fed by radial feeders and the feeders must be adequate.

iii. **Location of Distribution Transformers** – the farthest customers (from the distribution transformers) obtain an extremely low voltage even though a reasonably good voltage level is maintained at the transformer secondary.

iv. **Low Voltage** – when the voltage applied to an induction motor deviates from rated voltage, its performance is affected. This results higher current drawn for the same output, which leads to higher losses.

v. **Low Power Factor** – Low power factor contributes towards high distribution losses.

2.2.2 Effects of Losses in Reactive Power

As explained earlier, reactive power is associated with power factor. Higher loss of reactive power leads to low power factor. Low power factor is undesirable as it is expensive and inefficient. In addition, low power factor reduces electrical system's distribution capacity by increasing current flow and causing voltage drops. With the increase of power flow due to heavy loading, the system reactive power losses increase dramatically; this loss of reactive power may eventually lead to instability.

If reactive power cannot be supplied promptly enough in an area of decaying voltage, voltage may in effect collapse. Insufficient voltage support may in addition contribute to synchronous instability [3]. Thus, reactive power compensation is required to avoid voltage instability from occurred.

2.3 Review on Reduction of Reactive Power

There are various devices, techniques and methods adopted for the reduction of losses in distribution systems.

2.3.1 Reactive Power Compensation Devices

There are many types of reactive power compensation devices. The most commonly used device is by placing capacitors at the network branches.

Synchronous Condensers

Synchronous condensers are synchronous machines that are designed exclusively to provide reactive support. Synchronous condensers have all of the response speed and controllability advantages of generators without the need to construct the rest of the power plant. Synchronous condensers are more suitable to be used in transmission systems: at the receiving end of long transmissions.

Static VAR Compensators (SVC)

A static VAR compensator combines conventional capacitors and inductors with fast switching capability. It can be designed to span from absorbing to generating reactive power. Advantages include fast, precise regulation of voltage and unrestricted, largely transient-free, capacitor bank switching. Disadvantages of SVC they suffer from the same degradation in reactive capability as voltage drops and they do not have the short-term overload capability. Static VAR compensator could be made up from:

- Thyristor Controlled Reactor (TCR)
- Thyristor Switched Capacitor (TSC)
- Thyristor Switched Reactor (TSR)
- FC (fixed capacitor)
- Harmonic Filter

Static Synchronous Compensator (STATCOM)

The STATCOM is a solid-state shunt device that generates or absorb reactive power and is one member of a family of devices known as flexible AC transmission system (FACTS) devices. The advantages and disadvantages are similar to SVC.

Series Capacitors and Reactors

Series capacitors compensation is usually applied for long transmission. Series capacitors reduce the total reactance of the transmission line, which is often the main reason for their application. This improves power system stability, reduces reactive power losses and improves voltage regulation of the transmission line. Series capacitor reactive generation increases with the current squared, thus generating reactive power when it is most needed.

Shunt Capacitors Compensation

Shunt Capacitors compensation is the most popular devices used as compensation devices as it is efficient and cost effective. Capacitors supply amount of reactive power to the system at the point where they are connected. Suitable capacitor banks at grid or main substation are desirable to feed reactive power of lines, transformers and domestic consumers.

2.3.2 Construction of New Substation [2]

Before a new substation is to be constructed, various factors have to be considered. For example, consideration into the economical point of view is required when location of a new substation is determined. Other factors such as topography, land ownership, environment considerations, etc. would also influence the decision. The optimum site for a substation is defined as that location which will result in minimum cost for construction and minimum losses.

2.3.3 Reinforcement of the Feeder [2]

Studies on several distribution feeders have indicated that first few main sections of the feeder contribute to 60% to 80% of the feeder total losses. This is mainly due to the fact that the conductor size used at the time of erection of the feeder is not optimal with reference to the increased total load.

Addition of a new load on existing feeder is limited by its current carrying capacity. So if the existing feeder gets overloaded, the alternative for catering the extra load is only reinforcement of the feeder. Reinforcement of conductor is considered necessary as the smaller sized conductors results in higher losses due to interruptions will take place, which leads in loss of revenue.

2.3.4 Grading of Conductor [2]

Most of the case, the conductor used for radial distribution feeder is of uniform cross-section. However, the load magnitude at the substation is high and it reduces as proceed on the tail end of the feeder. This indicates that the use of a higher size conductor, which is capable of supplying load from the source point, is not necessary at tail end point. Similarly use of different conductor cross-section for intermediate sections will lead to a minimum both in respect of capital investment cost and line loss point of view.

2.3.5 Network Reconfiguration

Loss reduction in distribution network by network reconfiguration has been proposed by Verra, Perumal and Rajasekharareddy [4]. The solution algorithm for loss minimization has been developed based on a two-stage solution methodology. The first stage of this solution algorithm finds a loop, which gives the maximum loss reduction in the network. The second stage applies a proposed technique called distance-center technique. Therefore, the solution algorithm of the proposed method can identify the most effective branch exchange operations for loss reduction, with minimum computational efforts.

2.3.6 Shunt and Series Capacitor Insertion

Series and shunt capacitors in a power system generate reactive power to improve power factor and voltage, there by enhancing the system capacity and reducing the losses. In series capacitors the reactive power is proportional to the square of the load current, whereas in shunt capacitors it is proportional to the square of the voltage.

Shunt capacitors compensate reactive power by improving power factor (Figure 2.5) whereas the series capacitors compensate reactive power by directly countering the lagging component of the conductive load current at the point of installation.

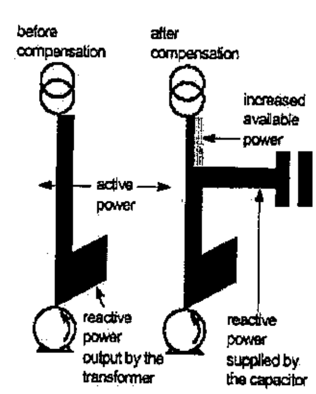


Figure 2.5 Shunt Capacitor Compensation

One of the disadvantages of series capacitors is that generally cost of installing a series capacitor is higher than that of a corresponding installation of a shunt capacitor. One of the reasons is that protective equipment for a series capacitor is often more complicated. Moreover, series capacitors may create certain disturbances such as Ferro-resonance in transformers, sub-synchronous resonance during motor starting, shunting of motors during normal operation and difficulty protection of the capacitors from system fault current.

A series capacitor can be considered as a voltage regulator that provides for a voltage boost that is proportional to the magnitude and power factor of the through current. A series capacitor betters the system power factor much less than a shunt capacitor and has little effect on the source current.

The magnitude of the source current can be reduced, the power factor can be improved and consequently the voltage drop between the sending send and the load is also reduced by application of shunt capacitor to a feeder.

Table 2.1 Factors Influencing the Choice between Shunt and Series Capacitors [5]

	Objectives	Preferences	
		Series Capacitor	Shunt Capacitor
1	To improve power factor	Second	First
2	To improve voltage level in an over head line	First	Second
3	To improve voltage level in an over head line system with a high power factor	Not used	First
4	To improve voltage in an underground system with a normal and low power factor	First	Not used
5	To improve voltage in an underground system with a high power factor	Not used	Not used
6	Reduce line losses	Second	First
7	Reduce voltage fluctuations	First	Second

CHAPTER 3: METHODOLOGY

3.0 Methodology

This chapter describes the methodology used in completing this project. It consists of the identification of procedure as well as tools required for the entire project. The project flow will be referred to these two sections.

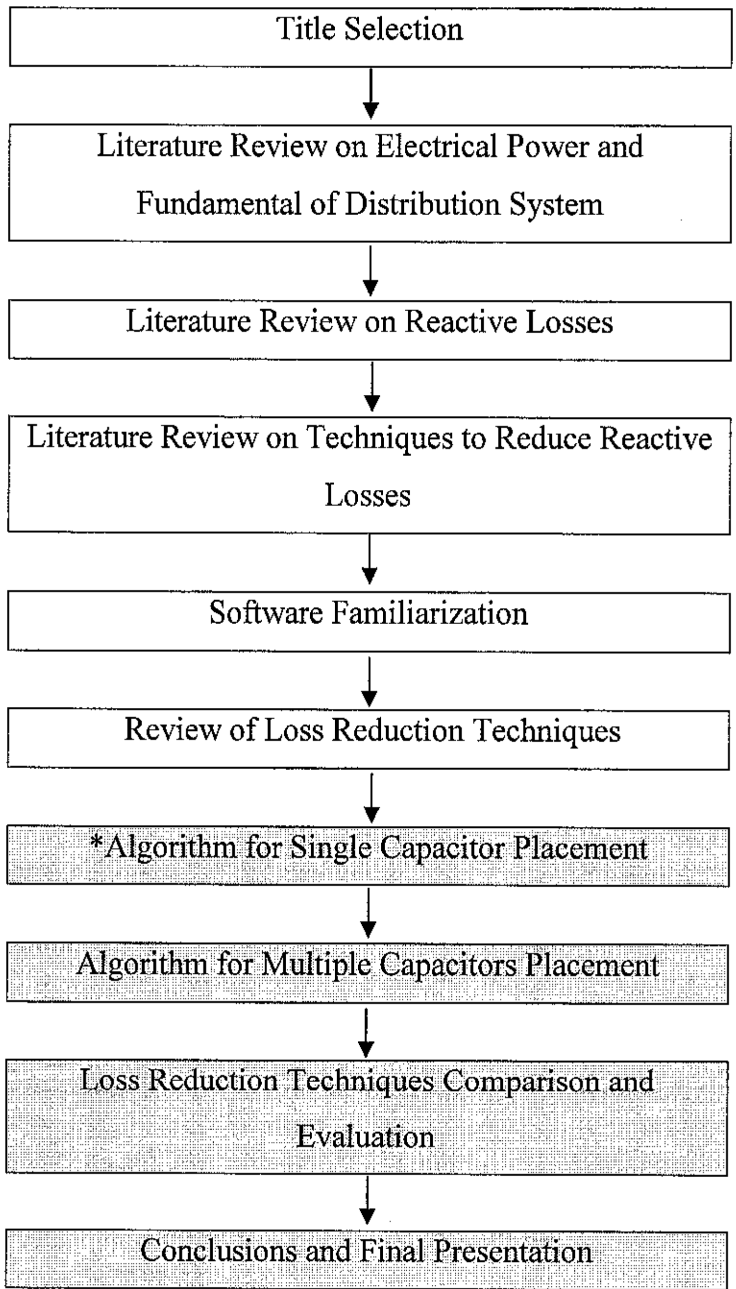
3.1 Procedure Identification

Gantt charts attached in Appendix I and Appendix II show milestones in completing this project for the two-semester final year project.

For the first semester, sufficient research and relevant background study were gathered. The research began with the literature review of electrical power and basic distribution system. The review continued with theories on losses specifically on reactive losses in radial distribution system. Then, techniques of reactive power were reviewed and evaluated. Next was identification of software. This involved using simulation software such as ERACS to do the load flow analysis. Thus, time were allocated in familiarizing with the software.

The second and final semester were applying those theories learnt and validating the proposed algorithm. This will involve of programming, simulations, calculations as well as results comparison.

For the second semester, basically it involved of all the project work. It began with load flow analysis using power system simulation software to obtain the respective voltages and currents at the nodes. Then algorithm was formulated as to calculate the location of capacitor placement together with the optimal values. Lastly was the comparison between the proposed method with the existing algorithm. Figure 3.1 summarizes the flow of the entire project.



* Continued from First Semester

Figure 3.1 Methodology Flow Chart

3.2 Tools Required

The tools and software required for the project would be power system simulation and analysis software. The software is used for simulating and calculating the voltage and current of respective busses by means of load flow analysis. By using the software, calculations will be much faster with the more accurate results. ERACS Power System Analysis software were used for this project as this software is more user-friendly and reliable.

As for the algorithm, MATLAB was used in place of Microsoft Visual C++ for this purpose as the calculations involve matrix computations. Furthermore, programming in MATLAB is more convenient as declarations are not required.

In addition, the distribution system used as the model of simulation was 34-bus IEEE standard test system.

3.2.1 ERACS Power System Analysis Software

ERACS is a powerful software used for power systems analysis and this software is useful in the latter stage of the project. This software has got all the main elements that available in a power system like bus bar, bus section, line, transformer, induction machine, synchronous machine grid infeed, shunt, etc.

The following modules are available:

- Graphical User Interface (GUI) – network construction, data storage, data and result display, etc.
- Load Flow – simulates a balanced load flow
- Fault – simulates short circuit faults
- IEC 909 – simulates fault conditions using IEC 909 techniques
- Harmonic Impedance – plot network impedance against harmonic number and identifies resonance conditions

- Protection Co-ordination – simulates the application of protection devices and their interaction under fault conditions.
- Transient Stability – for the dynamic study of the effect of disturbances on the network.

The network construction using ERACS to conduct the load flow analysis involves 5 steps:

Step 1: Open a new network and set the network information, data state information and, load flow parameters and libraries in the Network Properties Dialog

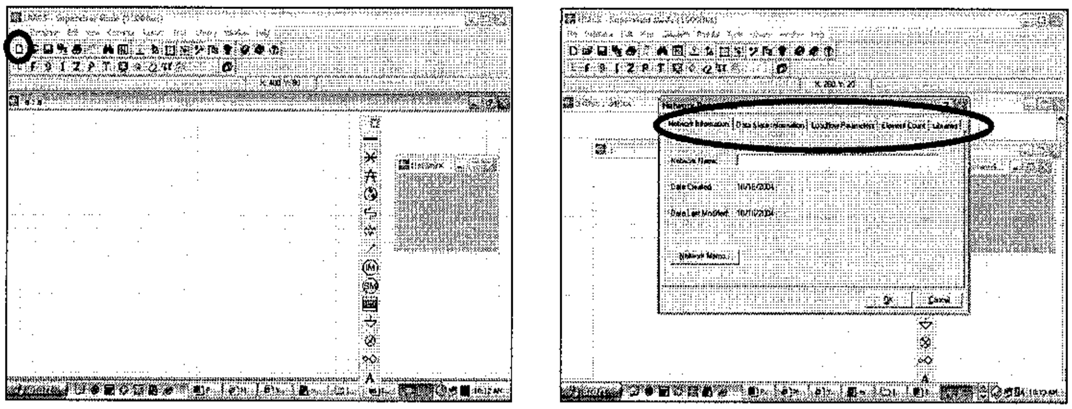


Figure 3.2 Open New Network and Set Network Properties

Step 2: Press the busbar  button in the Add Element toolbar and drag it onto the network diagram. Complete the busbar data entry dialog with the corresponding information. Repeat this step until the entire busbars of the network are added

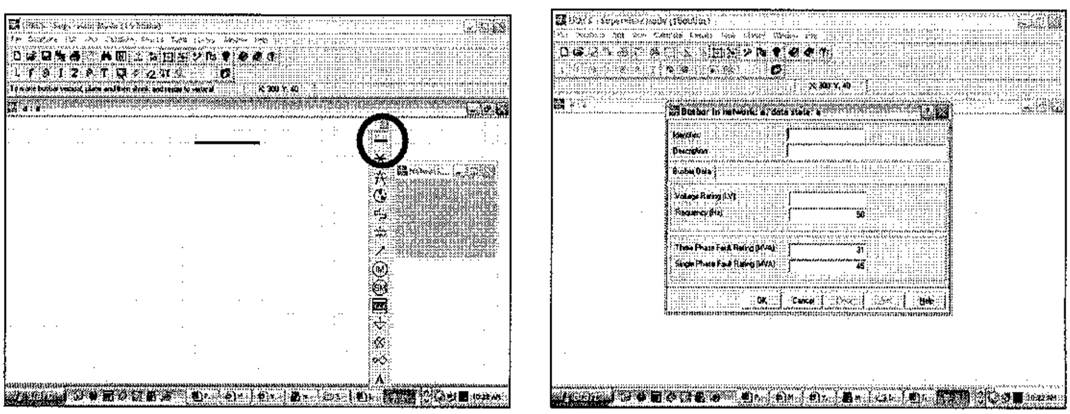


Figure 3.3 Busbar Entry

Step 3: With the same approach, the source grid , lines , and loads  are added to the network. For these elements, library has to be defined/referred or created with the corresponding parameters.

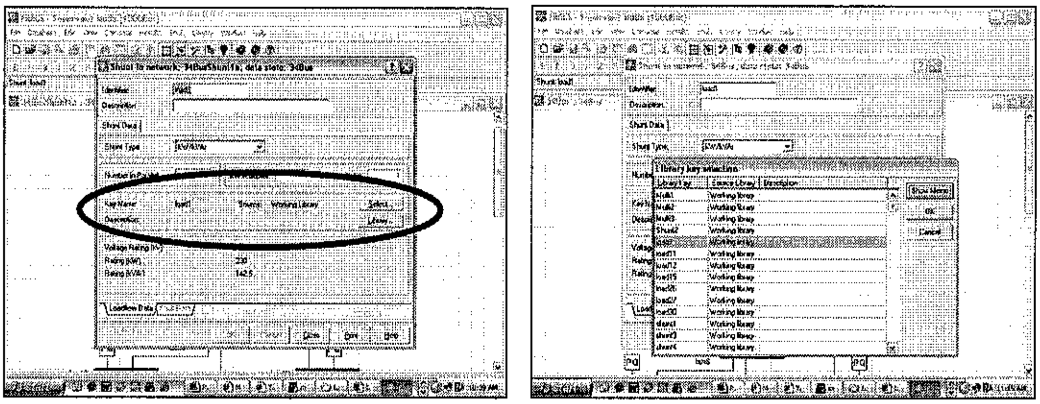


Figure 3.4 Library Entry

Step 4: Press "Select Data/Result"  to select and check the required parameters such as bus voltage, total real and reactive power loss, and line current that to be displayed.

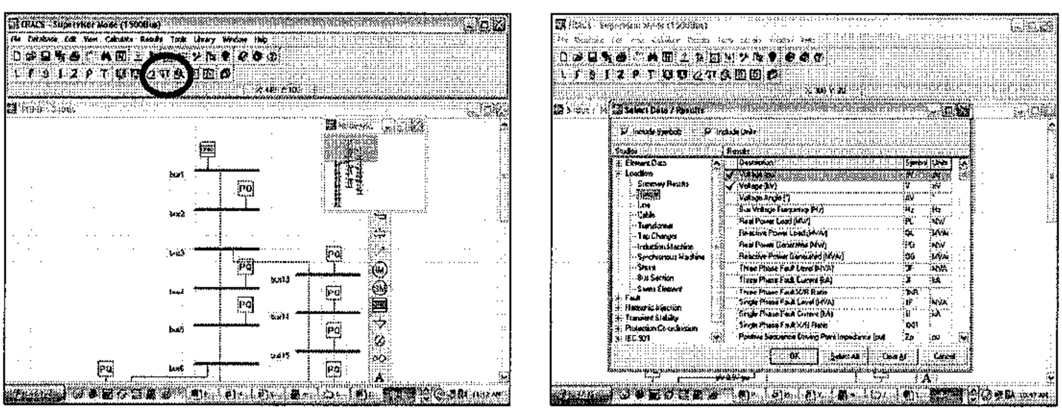
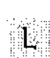


Figure 3.5 Results and Data Selection

Step 5: Press the "load flow"  button from the Calculate toolbar to run the load flow analysis. The results will be displayed and the data/results can be exported to an Excel file through "Results – Export Data / Results File".

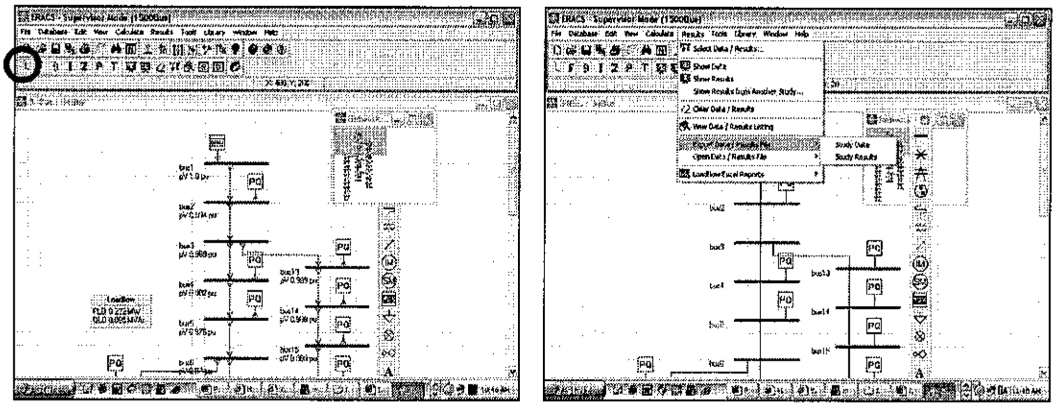


Figure 3.6 Load Flow Analysis and Results

3.2.2 IEEE 34-bus Standard Test System

A distribution system or test model is required for this project. The test model must be able to represent the real distribution system so that once the approach for loss reduction is successfully applied onto the test model; there will not be any problems to apply the approach onto a practical system. There are two main standard test systems commonly used in research, namely IEEE 33-bus and 34-bus standard test system. IEEE 34-bus standard test system will be used as the test model for this project. The network configuration, line and load data for IEEE 33-bus test system are included in Appendix III. As for IEEE 34-bus test system, the network configuration, line and load data is shown below:

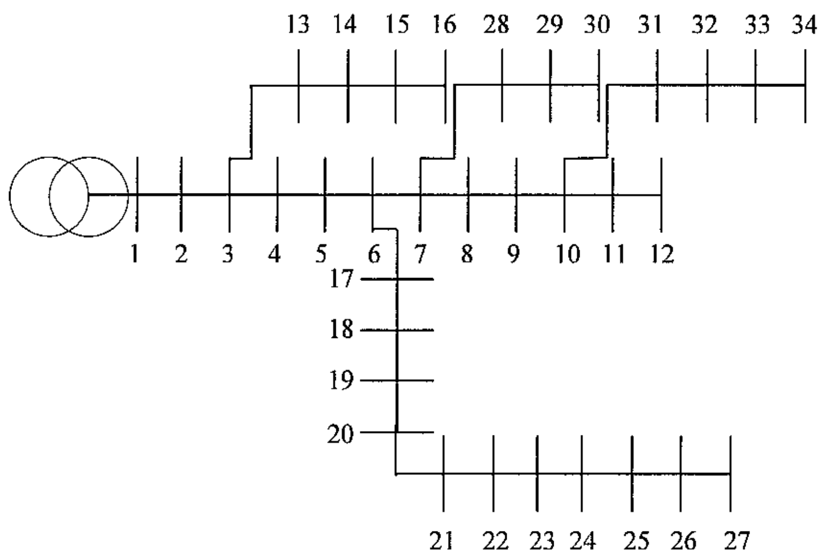


Figure 3.7 Single Line Equivalent of IEEE 34-bus Test System

Table 3.1 Line Data

No. of Nodes: 34
No. of Branches: 33

Base Voltage: 11kV
Base Load: 5MVA

Line	Sending End Node	Receiving End Node	Resistance (Ω)	Reactance (Ω)
1	1	2	0.11700	0.04800
2	2	3	0.10725	0.04400
3	3	4	0.16445	0.04565
4	4	5	0.14950	0.04150
5	5	6	0.14950	0.04150
6	6	7	0.31440	0.05400
7	7	8	0.20960	0.03600
8	8	9	0.31440	0.05400
9	9	10	0.20960	0.03600
10	10	11	0.13100	0.02250
11	11	12	0.10480	0.01800
12	3	13	0.15720	0.02700
13	13	14	0.20960	0.03600
14	14	15	0.10480	0.01800
15	15	16	0.05240	0.00900
16	6	17	0.17940	0.04980
17	17	18	0.16445	0.04565
18	18	19	0.20790	0.04730
19	19	20	0.18900	0.04300
20	20	21	0.18900	0.04300
21	21	22	0.26200	0.04500
22	22	23	0.26200	0.04500
23	23	24	0.31440	0.05400
24	24	25	0.20960	0.03600
25	25	26	0.13100	0.02250
26	26	27	0.10480	0.01800
27	7	28	0.15720	0.02700
28	28	29	0.15720	0.02700
29	29	30	0.15720	0.02700
30	10	31	0.15720	0.02700
31	31	32	0.20960	0.03600
32	32	33	0.15720	0.02700
33	33	34	0.10480	0.01800

Table 3.2 Load Data

Busbar	PL (kW)	QL (kVAR)
2	230	142.5
3	0	0
4	230	142.5
5	230	142.5
6	0	0
7	0	0
8	230	142.5
9	230	142.5
10	0	0
11	230	142.5
12	137	84
13	72	45
14	72	45
15	72	45
16	13.5	7.5
17	230	142.5
18	230	142.5
19	230	142.5
20	230	142.5
21	230	142.5
22	230	142.5
23	230	142.5
24	230	142.5
25	230	142.5
26	230	142.5
27	137	85
28	75	48
29	75	48
30	75	48
31	57	34.5
32	57	34.5
33	57	34.5
34	57	34.5

CHAPTER 4: ALGORITHMS FOR SHUNT CAPACITOR PLACEMENT

4.0 Introduction

Algorithm determines the size and location of capacitor that should be placed in the system where maximum loss saving occurs. There are equations involves in formulation of the algorithm. Two algorithms are presented: Single and multiple capacitors placement. Algorithm for single capacitor placing is by inserting a capacitor into the system one-by-one. A predefined number of capacitors are inserted to the system simultaneously for the algorithm for multiple capacitors placement.

4.1 Loss Reduction by Single Capacitor Placement [6]

Before the introduction of algorithm for single capacitor placement, there are essential formulas to be introduced and discussed.

The total I^2R loss (P_{Lt}) in a distribution system having *n* number of branches is given by:

$$P_{Lt} = \sum_{i=1}^{n} I_i^2 Ri \qquad (4.1)$$

And the loss associated with the active (I_a) and reactive (I_r) components of branch currents can be written as

$$P_{La} = \sum_{i=1}^{n} I_{ai}^2 Ri \qquad (4.2)$$

$$P_{Lr} = \sum_{i=1}^{n} I_{ri}^{2} Ri \qquad (4.3)$$

and the active and reactive components of branch currents can be computed by

$$I_{ai} = I \cos \theta \qquad (4.4)$$

$$I_{ri} = I \sin \theta \qquad (4.5)$$

where I and θ are magnitude and angle of the current respectively.

Assume that a single source radial distribution system with *n* branches and a capacitor is to be placed at bus *m* and α be a set of branches connected between the source and capacitor bus. In Figure 4.1, the bolded numbers are the bus numbers while the italic numbers are branches/lines numbers. Assume that a capacitor is placed at bus 23, the set of α consists of branches 1,2,3,4,5,16,17,18,19,20,21 and 22. The capacitor draws a reactive current I_c, and for a radial network it changes only the reactive component of current of branch set α. The current of other branches ($\notin$=α) are unaffected by the capacitor. Thus the new reactive current I_{ri}^{new} of the *i*th branch is given by

$$I_{ri}^{new} = I_{ri} + D_i I_c \qquad (4.6)$$

where D_i = 1; if branch i $\in$ α

= 0; otherwise

The complete sets of D_i are shown in Appendix IV.

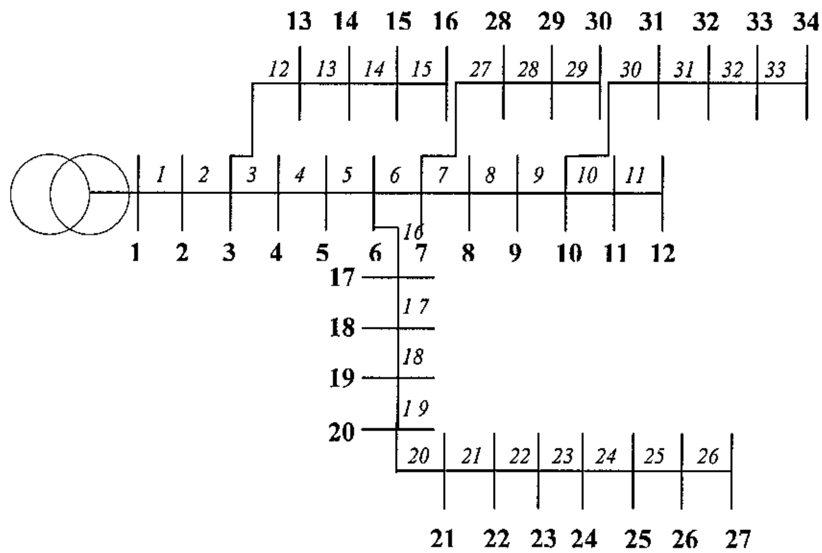


Figure 4.1 Single Line Diagram for 34-bus System

I_{ri} is the reactive current of the *i* th branch in the original system obtained from the load flow analysis. The loss P_{Lr}^{com} associated with the reactive component of branch currents in the compensated currents in the compensated system (when the capacitor is connected) can be written as

$$P_{Lr}^{com} = \sum_{i=1}^{n} (I_{ri} + D_i I_c)^2 Ri \qquad (4.7)$$

The loss saving S is the difference between equation 4.3 and 4.7 and is given by

$$\begin{aligned} S &= P_{Lr} - P_{Lr}^{com} \\ &= \sum_{i=1}^{n} I_{ri}^2 Ri - \sum_{i=1}^{n} (I_{ri} + D_i I_c)^2 Ri \\ &= \sum_{i=1}^{n} I_{ri}^2 Ri - \sum_{i=1}^{n} (I_{ri}{}^2 + 2 I_{ri} D_i I_c + D_i I_c{}^2) Ri \end{aligned}$$

$$= -\sum_{i=1}^{n} (2 D_i I_{ri} I_c + D_i I_c^2) Ri \qquad (4.8)$$

The capacitor current I_c that provides the maximum loss saving can be obtained from

$$\frac{\partial S}{\partial I_c} = -2 \sum_{i=1}^{n} (D_i I_{ri} + D_i I_c) Ri = 0 \qquad (4.9)$$

Thus the capacitor current for the maximum loss saving is

$$-2 \sum_{i=1}^{n} (D_i I_{ri} + D_i I_c) Ri = 0$$

$$\sum_{i=1}^{n} D_i I_c R_i = -\sum_{i=1}^{n} D_i I_{ri} R_i$$

$$I_c = -\frac{\sum_{i=1}^{n} D_i I_{ri} R_i}{\sum_{i=1}^{n} D_i R_i} = -\frac{\sum_{i \in \alpha} I_{ri} R_i}{\sum_{i \in \alpha} R_i} \qquad (4.10)$$

The corresponding capacitor size is $Q_c = V_m I_c$ (4.11)

V_m is the voltage magnitude of the capacitor bus *m*. The above process can be repeated for all busses to get the highest possible loss saving for a singly located capacitor. When the candidate bus is identified and compensated, the above technique can also be used to identify the next and subsequent bus to be compensated for loss reduction.

4.1.1 Algorithm for Single Capacitor Placement

Step 1: Conduct load flow analysis for the system using ERACS power system simulation software.

Step 2: Using equation 4.8 & 4.10, calculate the capacitor currents (I_c) and loss saving (S) from *i*=2 for all buses except source bus.

Step 3: Identify the maximum saving and the corresponding capacitor current and calculate capacitor size using equation 4.11.

Step 4: Check whether Q_c is positive or negative. Q_c positive means we need to inject reactive power at the bus. Q_c negative means we need to remove that much of reactive power.
If positive go to step 6.
Otherwise go to step 5.

Step 5: Check whether that node is already compensated or not. If not, abstain the next maximum saving, capacitor current and capacitor size and go to step 4. Otherwise go to step 6.

Step 6: Modify the reactive load on the network and conduct the load flow again.

Step 7: Check whether the saving obtain is more than 1kW. If the saving is significant, go to step 2. Otherwise, go to step 8.

Step 8: Stop the procedure.

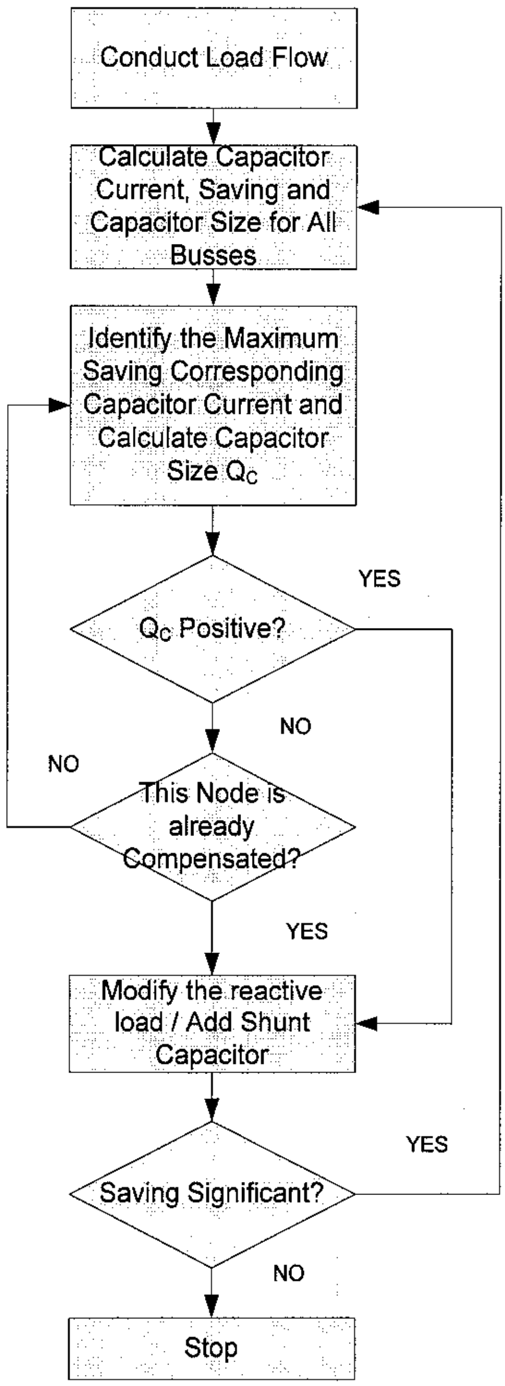


Figure 4.2 Algorithm for Single Capacitor Placement

4.2 Loss Reduction for Multiple Capacitors Placement [2]

The fundamental of multiple capacitors placement is basically an extended approach from single capacitor.

Let k be number of capacitor placed and α_j is a set of branches from the source bus to the jth capacitor bus. Assume that 3 capacitors are placed in the system as Figure 4.1 at busses 8, 21 and 25, the branch set α and the matrix D (n x k) can be written as:

α_1 (bus 8) = [1, 2, 3, 4, 5, 6, 7];

α_2 (bus 21) = [1, 2, 3, 4, 5, 16, 17, 18, 19, 20];

α_3 (bus 25) = [1, 2, 3, 4, 5, 16, 17, 18, 19, 20, 21, 22, 23, 24];

$$D = \begin{bmatrix} 111111100000000000000000000000000 \\ 111110000000000111110000000000000 \\ 111110000000000111111111000000000 \end{bmatrix}$$

where $D_i = 1$; if branch $i \in \alpha$

= 0; otherwise

Almost similar as single capacitor, the new reactive component branch current is:

$$[I_{ri}^{new}] = [I_{ri}] + [D][Ic] \qquad (4.12)$$

The loss P_{Lr}^{com} can be derived as:

$$P_{Lr}^{com} = \sum_{i=1}^{n} (I_{ri} + \sum_{j=1}^{k} D_{ij} I_{cj})^2 Ri \qquad (4.13)$$

The loss saving S can be obtained by difference between equation 4.3 and 4.13:

$$S = -\sum_{i=1}^{n} [2 I_{ri} \sum_{j=1}^{k} D_{ij} I_{cj} + (\sum_{j=1}^{k} D_{ij} I_{cj})^2] Ri \qquad (4.14)$$

Thus, for maximum loss saving:

$$\frac{\partial S}{\partial I_{c1}} = 0$$

$$\frac{\partial S}{\partial I_{c2}} = 0$$

.....

.....

$$\frac{\partial S}{\partial I_{ck}} = 0$$

After some algebraic manipulations:

$$[A][I_C]=-[B] \qquad (4.15)$$

where A is a k x k matrix and B is a k-dimensional vector:

$$A_{jj}=\sum_{i\in\alpha j} R_i \qquad (4.16)$$

$$A_{jm}=\sum_{i\in(\alpha_j \cap \alpha_m)} R_i \qquad (4.17)$$

$$B_j=\sum_{i\in\alpha j} I_{ri} R_i \qquad (4.18)$$

Finally, the capacitor current for maximum loss saving with the corresponding capacitors size can be computed by:

$$[I_C]=-[A]^{-1}[B] \qquad (4.19)$$

$$[Qc]=[Vc][Ic] \qquad (4.20)$$

4.2.1 Algorithm for Multiple Capacitors Placement

*Step 1:*Determine the bus locations and number of capacitors to be compensated based on the single capacitor.

Step 2: Form matrix D based on α_1, α_2 and α_3.

Step 3: Obtain matrix A (equation 4.16 and 4.17) and B (equation 4.18).

Step 4: Obtain inverse of matrix A.

Step 6: Calculate Capacitor Current (Ic) by equation (4.19).

Step 7: Calculate Capacitor Size (Qc) by equation (4.20).

Step 8: Modify the system and obtain the loss saving.

Step 9: Stop the procedure

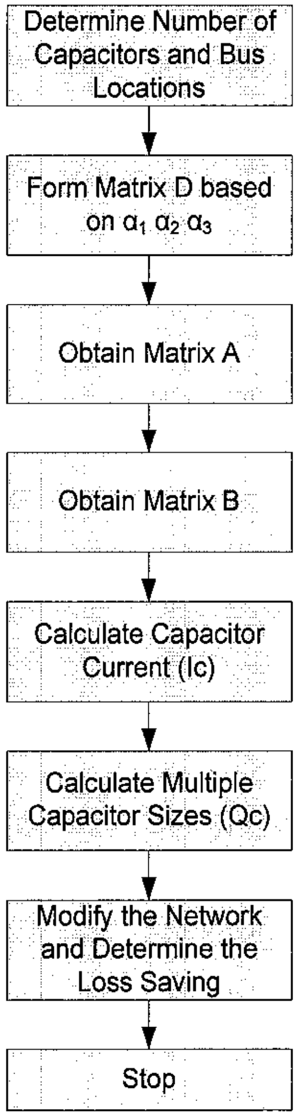


Figure 4.3 Algorithm for Multiple Capacitor Placement

CHAPTER 5: RESULTS AND DISCUSSIONS

5.0 Results and Discussions

Load flow analysis is the first step in determining the loss of the system. Then, algorithms for single or multiple capacitors can be applied to sort for the bus location and optimal capacitor size that has the maximum loss saving. The results for both single and multiple capacitors placement would be compared with an existing approach.

5.1 Load Flow Analysis

Load flow analysis is done by using ERACS to calculate the real and reactive power loss on the IEEE 34-bus system. The other main parameters interested are the bus voltage (in kV and p.u.) and line current (kA). The voltage profile is important so that it is within the accepted values. Line current is needed to calculate for the losses. The corresponding equations (4.2) and (4.3) are required to calculate the real and reactive power losses.

The simulation setup is as shown in Figure 5.1 and voltage profile is as shown in Table 5.1.

From Figure 5.1, the real and reactive loss for the 34-bus system is 0.222 MW and 0.065 MVar respectively. The real loss can be further decomposed into loss due to active and reactive component of branch current. In other words, the total loss due to the active and reactive branch current should be 0.222 MW.

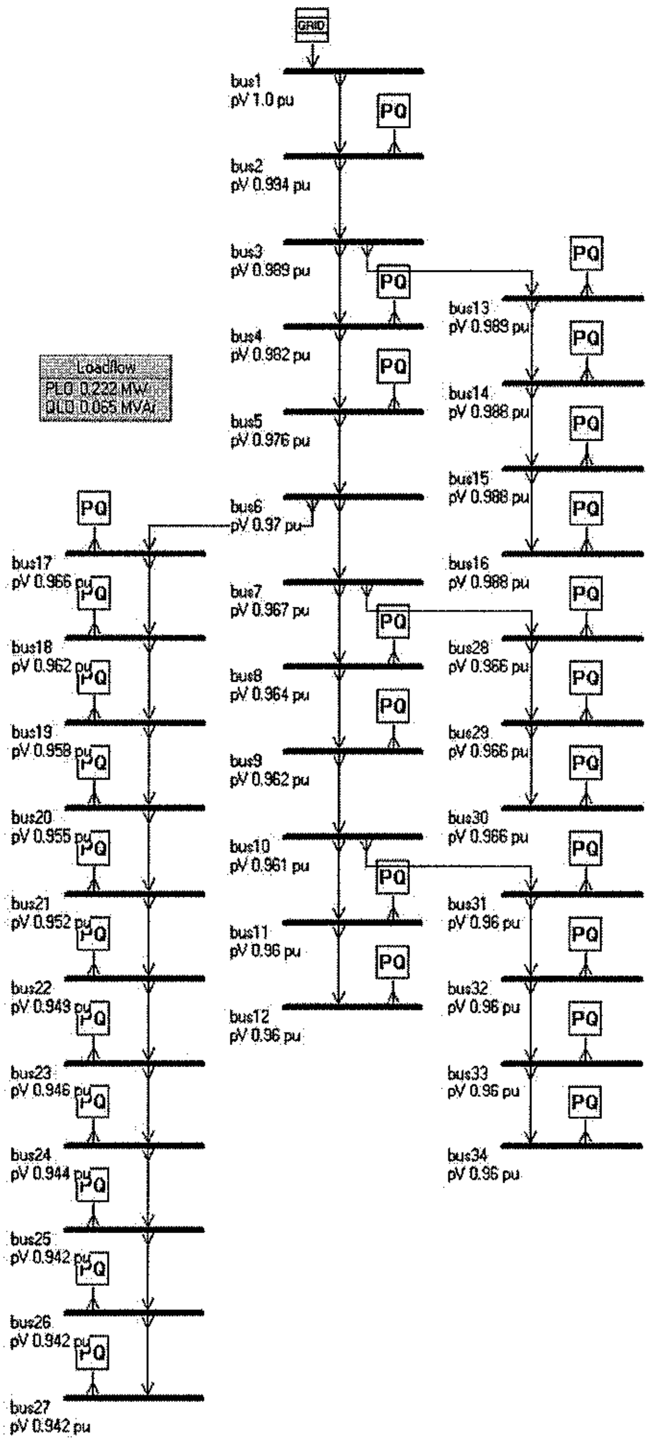


Figure 5.1 34-Bus Simulation Setup

Table 5.1 Voltage Profile

Busbar	Voltage (pu)	Voltage (kV)
1	1.00000	11.000
2	0.99414	10.936
3	0.98902	10.879
4	0.98205	10.803
5	0.97606	10.737
6	0.97041	10.675
7	0.96659	10.632
8	0.96448	10.609
9	0.96202	10.582
10	0.96083	10.569
11	0.96037	10.564
12	0.96024	10.563
13	0.98869	10.876
14	0.98838	10.872
15	0.98830	10.871
16	0.98829	10.871
17	0.96595	10.625
18	0.96225	10.585
19	0.95815	10.540
20	0.95486	10.503
21	0.95199	10.472
22	0.94872	10.436
23	0.94604	10.406
24	0.94351	10.379
25	0.94230	10.365
26	0.94183	10.360
27	0.94169	10.359
28	0.96625	10.629
29	0.96603	10.626
30	0.96591	10.625
31	0.96049	10.565
32	0.96015	10.562
33	0.95998	10.560
34	0.95992	10.559

5.1.1 Decomposition of Branch Current

The branch current has two components, which are active and reactive components. The associated equations are equation (4.2) and (4.3). Basically the loss associated with the active component of branch current cannot be minimized because all active power must be supplied by the source at the root bus. However, the loss associated with the reactive component of branch currents can be minimized by supplying part of the reactive power demand locally.

Table 5.2 showing the calculation of active and reactive branch current and followed by the calculation for the losses due to these current. From Table 5.2, the loss due to active branch current (I_{ai}) and reactive branch current (I_{ri}) are 0.162 MW and 0.059 MW respectively. Notice that the total real loss is same at 0.222MW as simulated earlier.

By having the decomposition of branch current, the effects of loss saving can be observed in the latter stage.

Table 5.2 Calculation of Losses

(i)	(ii)	(iii)	(iv)=(ii)sin(iii)	(v)=(ii)cos(iii)	(vi)	(vii)=$(v)^2$(vi)	(viii)=$(iv)^2$(vi)	(ix)=(vii)+(viii)
Line	Current (kA)	Angle (°C)	Current due to Reactive Component, I_{ri} (kA)	Current due to Real Component, I_{ai} (kA)	Resistance (Ω)	Real Loss Due to Real Component of Current (MW)	Real Loss Due to Reactive Component of Current (MW)	Total Real Loss (MW)
1	0.2980	-31.17	-0.15423	0.25498	0.11700	0.02282	0.00835	0.03117
2	0.2837	-31.14	-0.14671	0.24282	0.10725	0.01897	0.00693	0.02590
3	0.2694	-31.11	-0.13919	0.23066	0.16445	0.02625	0.00956	0.03581
4	0.2549	-31.08	-0.13160	0.21830	0.14950	0.02137	0.00777	0.02914
5	0.2404	-31.06	-0.12403	0.20593	0.14950	0.01902	0.00690	0.02592
6	0.0821	-31.20	-0.04252	0.07023	0.31440	0.00465	0.00171	0.00636
7	0.0676	-31.00	-0.03482	0.05794	0.20960	0.00211	0.00076	0.00287
8	0.0529	-30.94	-0.02719	0.04537	0.31440	0.00194	0.00070	0.00264
9	0.0381	-30.84	-0.01953	0.03271	0.20960	0.00067	0.00024	0.00091
10	0.0236	-31.03	-0.01217	0.02022	0.13100	0.00016	0.00006	0.00022
11	0.0088	-30.86	-0.00451	0.00755	0.10480	0.00002	0.00001	0.00002
12	0.0143	-31.72	-0.00752	0.01216	0.15720	0.00007	0.00003	0.00010
13	0.0098	-31.64	-0.00514	0.00834	0.20960	0.00004	0.00002	0.00006
14	0.0053	-31.44	-0.00276	0.00452	0.10480	0.00001	0.00000	0.00001
15	0.0008	-28.94	-0.00039	0.00070	0.05240	0.00000	0.00000	0.00000
16	0.1582	-30.99	-0.08145	0.13562	0.17940	0.00990	0.00357	0.01347
17	0.1435	-30.96	-0.07382	0.12306	0.16445	0.00747	0.00269	0.01016
18	0.1288	-30.93	-0.06619	0.11049	0.20790	0.00761	0.00273	0.01035
19	0.1140	-30.90	-0.05854	0.09782	0.18900	0.00543	0.00194	0.00737
20	0.0991	-30.87	-0.05085	0.08506	0.18900	0.00410	0.00147	0.00557
21	0.0842	-30.84	-0.04317	0.07229	0.26200	0.00411	0.00146	0.00557
22	0.0692	-30.82	-0.03545	0.05943	0.26200	0.00278	0.00099	0.00376
23	0.0542	-30.80	-0.02775	0.04656	0.31440	0.00204	0.00073	0.00277
24	0.0391	-30.79	-0.02002	0.03359	0.20960	0.00071	0.00025	0.00096
25	0.0241	-30.79	-0.01234	0.02070	0.13100	0.00017	0.00006	0.00023
26	0.0090	-30.81	-0.00461	0.00773	0.10480	0.00002	0.00001	0.00003
27	0.0145	-32.11	-0.00771	0.01228	0.15720	0.00007	0.00003	0.00010
28	0.0097	-32.11	-0.00516	0.00822	0.15720	0.00003	0.00001	0.00004
29	0.0048	-32.10	-0.00255	0.00407	0.15720	0.00001	0.00000	0.00001
30	0.0146	-30.53	-0.00742	0.01258	0.15720	0.00007	0.00003	0.00010
31	0.0109	-30.53	-0.00554	0.00939	0.20960	0.00006	0.00002	0.00007
32	0.0073	-30.53	-0.00371	0.00629	0.15720	0.00002	0.00001	0.00003
33	0.0036	-30.53	-0.00183	0.00310	0.10480	0.00000	0.00000	0.00000
					Total	**0.16271**	**0.05901**	**0.22172**

5.2 Single Capacitor Placement

After conducting the load flow analysis, branch current due to reactive component is computed. This information is required for the use in the algorithm. The algorithm for single capacitor placement as explained in section 4.1 is then applied.

A program is written in MATLAB to calculate the loss saving, capacitor current and capacitor size. At the same time, the program would be able to identify the branch with maximum loss saving with the corresponding capacitor size are as shown in Appendix V. The generated output of the program is attached in Appendix VI.

From Appendix VI, the maximum estimated loss saving is 45.18 kW when a capacitor with a size of 1010.48 kVAR is placed at bus 21.

Figure 5.2 and 5.3 summarizes the loss saving in kW for every bus when corresponding capacitor is placed at that particular bus.

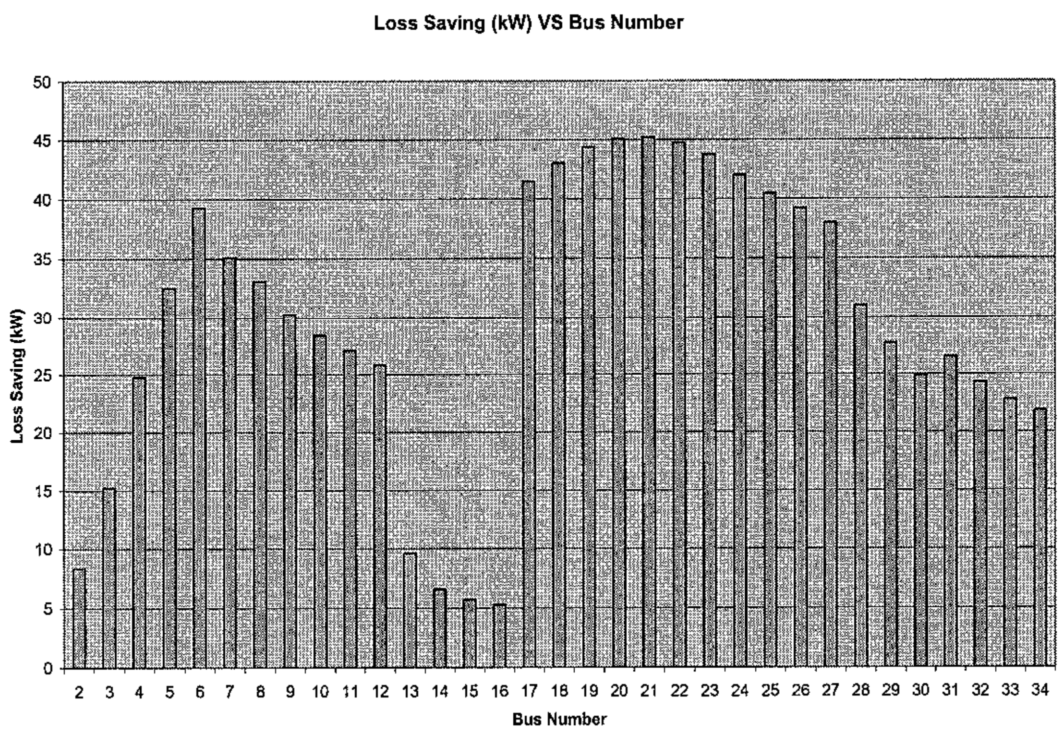


Figure 5.2 Loss Saving (kW) vs. Bus Number

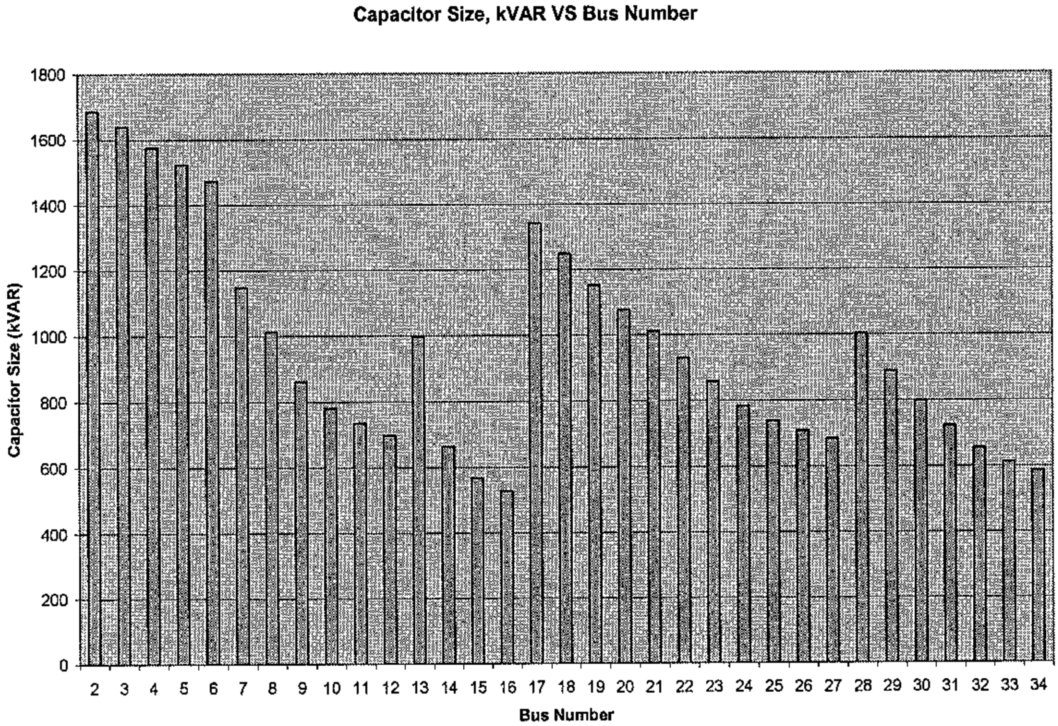


Figure 5.3 Capacitor Size (kVAR) vs. Bus Number

Thus, the 34-bus network in the ERACS is modified with a 1010.48 kVAR capacitor is inserted into bus 21 and run the load flow analysis again to obtain the new real and reactive losses. Table 5.3 showing losses before and after the capacitor compensation. The total real loss saved is 39.17 kW. Notice that the loss saved due to reactive branch current is 36.12 kW. There is not much saving for the loss due to active current, only 3.05 kW is saved, whereas the total reactive power loss saved about 11.81 kVAR.

Table 5.3 Losses of Before and After Compensation

Before Compensation			
Loss due to Active Branch Current (kW)	Loss due to Reactive Branch Current (kW)	Total Real Power Loss (kW)	Total Reactive Power Loss (kVAR)
162.71	59.01	221.72	65.11
After Compensation			
Loss due to Active Branch Current (kW)	Loss due to Reactive Branch Current (kW)	Total Real Power Loss (kW)	Total Reactive Power Loss (kVAR)
159.66	22.89	182.55	53.30

Another advantage of placing shunt capacitor is that the improvement of voltage profile in the network. This is because the current flowing in the line is decreased due to flow of less reactive component branch current, the voltage drop (IR) will decrease and hence improvement in voltage profile. Table 5.4 shows the voltage profile after capacitor compensation.

Table 5.4 Voltage Profile (After Compensation)

Busbar	Voltage (pu)	Voltage (kV)
1	1.00000	11.000
2	0.99458	10.940
3	0.98987	10.889
4	0.98333	10.817
5	0.97773	10.755
6	0.97247	10.697
7	0.96865	10.655
8	0.96655	10.632
9	0.96409	10.605
10	0.96291	10.592
11	0.96245	10.587
12	0.96232	10.585
13	0.98954	10.885
14	0.98923	10.882
15	0.98915	10.881
16	0.98914	10.881
17	0.96847	10.653
18	0.96518	10.617
19	0.96151	10.577
20	0.95861	10.545
21	0.95614	10.518
22	0.95288	10.482
23	0.95021	10.452
24	0.94769	10.425
25	0.94649	10.411
26	0.94602	10.406
27	0.94588	10.405
28	0.96832	10.651
29	0.96809	10.649
30	0.96798	10.648
31	0.96257	10.588
32	0.96223	10.585
33	0.96206	10.583
34	0.96200	10.582

The above methods are repeated until the power loss saving is less than 1.0 kW. The iterations are stopped after 5 iterations; when the power loss saving (kW) is 0.90 kW. Therefore, 4 capacitors are recommended to be inserted in order to take advantage of the cost benefits. Notice that the loss saving decreases as more capacitors are placed. Table 5.5 shows the total saving of 61.26 kW after 5 iterations.

Table 5.5 Results for 5 iterations of Capacitor Placement

No. of Capacitors	Real power loss due to real branch current (kW)	Real power loss due to reactive branch current (kW)	Total Real Power Loss (kW)	Reactive Power Loss (kVAR)	Power Loss Saving (kW)	Total Saving (kW)
1	159.66	22.89	182.55	53.30	39.17	39.17
2	158.77	10.56	169.33	49.36	13.22	52.39
3	158.31	5.02	163.33	47.80	6.00	58.39
4	158.18	3.18	161.36	47.24	1.97	60.36
5	158.05	2.41	160.46	46.93	0.90	61.26

Table 5.6 shows that the bus locations as well as the capacitors sizes for all five iterations. The first capacitor will be placed at bus 21, followed by bus 8, 25, 11 and bus 5 for subsequent compensation. The detail information for iteration 2, 3, 4 and 5 are attached in Appendix VII.

Table 5.6 Bus Locations and Capacitors Sizes

Iteration	Bus Location	Capacitor Size (kVAR)
1	21	1010.48
2	8	691.44
3	25	306.36
4	11	214.44
5	5	260.81

5.3 Multiple Capacitors Placement

The idea of placing multiple capacitors to reduce the losses is by placing few capacitors at one time (simultaneously). Three capacitors are placed simultaneously in this case. The bus locations that capacitors will be placed are based on the results obtained in single capacitor. Therefore, three capacitors will be placed at bus 21, 8 and 25.

A program is written in MATLAB to calculate the capacitor current (I_c) with the respective capacitor size. The program is attached in Appendix VIII. The generated output from the program is:

```
Ic =

0.0418
0.0535
0.0320


Qc =

437.2849
567.7093
331.5142
```

Thus three capacitors with sizes of 437.28 kVAR, 567.71 kVAR and 331.51 kVAR will be placed at bus 21, 8 and 25 respectively. The total real power loss saved is 48.96 kW while total reactive power loss saved is 14.31 kVAR as shown in Table 5.7.

Table 5.7 Calculation of Losses for Multiple Capacitors Placement

Before Compensation			
Loss due to Active Branch Current (kW)	Loss due to Reactive Branch Current (kW)	Total Real Power Loss (kW)	Total Reactive Power Loss (kVAR)
162.71	59.01	221.72	65.11
After Compensation			
Loss due to Active Branch Current (kW)	Loss due to Reactive Branch Current (kW)	Total Real Power Loss (kW)	Total Reactive Power Loss (kVAR)
158.95	13.81	172.76	50.80

5.4 Comparisons

Results obtained from single and multiple capacitors placement would be compared to observe the effectiveness and efficiency of the methods. At the same time, this method would also be compared with an existing method [7] (heuristic search strategies). Kilo-watt per Kilo-volt-amps-reactive ratio (kW/kVAR) would be introduced to see the efficiency of the method. The greater the ratio means that more saving (kW) can be obtained by the same amount of capacitor size (kVAR) or same amount of saving (kW) for less amount of capacitor size (kVAR). Greater ratio is desired as this shows that the method is more efficient.

5.4.1 Single and Multiple Capacitors Comparison

Table 5.8 and 5.9 show the results comparison for single and multiple capacitors. Although single capacitor approach can save more in terms of real power loss (kW), but multiple capacitor approach is more efficient. The kW/kVAR ratio for multiple capacitors approach is greater than single capacitor approach. The kW/kVAR ratio for multiple capacitor approach is 3.663 whereas single capacitor approach only has a ratio of 2.716. This indicates multiple capacitor approach can save more power loss with the same size of capacitor as compared to single capacitor approach.

Table 5.8 Results Comparison (Single Capacitor)

Iteration No.	Bus No.		Capacitor Size (kVAR)		Saving (kW)		100(kW / kVAR)	
	Proposed Method	Method (1)	Proposed Method	Method (1)	Proposed Method	Method (1)	Proposed Method	Method (1)
1	21	26	1010.48	1400	39.17	41.07		
2	8	11	691.44	750	13.22	10.64		
3	25	17	306.36	300	6	1.17		
4	11	4	214.44	250	1.97	0.81		
		TOTAL	2222.72	2700	60.36	53.69	2.716	1.9885

Table 5.9 Results Comparison (Multiple Capacitors)

Iteration No.	Bus No.		Capacitor Size (kVAR)		Saving (kW)		100(kW / kVAR)	
	Proposed Method	Method (1)	Proposed Method	Method (1)	Proposed Method	Method (1)	Proposed Method	Method (1)
1	21	26	437.28	1400				
2	8	11	567.71	750				
3	25	17	331.51	300				
		TOTAL	1336.51	2450	48.96	52.88	3.663	2.158

5.4.2 Comparison with Existing Method

The proposed method is compared with heuristic search strategies by M Chis, M.M.A Salama and S. Jayaram [7]. Table 5.8 and 5.9 show that the proposed method is more efficient than the existing method. The proposed method can save 60.36 kW with total 2222.72 kVAR of capacitors where the existing method only saves 52.88 kW with 2700 kVAR. Notice that the proposed method can save more loss (kW) with smaller size of capacitor (kVAR). Since usually the cost of capacitors is in costs/kVAR, thus it is cheaper by adopting the proposed method. Similarly, for multiple capacitors, the existing method has a higher kW/kVAR ratio of 3.663 as compared to 2.158 of the existing method. These show that the proposed method is more efficient for both single and multiple capacitors placement as compared to the existing method.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

As for the conclusion, the algorithms for single and multiple capacitors placement for loss reduction are successfully implemented using an integrated approach. ERACS power systems analysis software is used as simulation tool for load flow analysis. The program for calculating the capacitor size and identifying the bus location for maximum loss are written in MATLAB.

The proposed algorithm is tested on IEEE 34-bus test system. The results show that the algorithm for multiple capacitor placement is more efficient than the algorithm for single capacitor placement. The algorithms are also compared with the existing method developed by Chis, Salama and Jayaram [7]. Proposed method has the upper hand as it is more efficient as indicated by the kW / kVAR ratio.

This method can be applied to any radial distribution system with any number of busses. The assumption of this method is that the load distribution is uniform.

As recommendations for the future work, the algorithm can be implemented and applied into a real practical system instead of the IEEE test system. This can monitor the practical impact of the algorithm in the real network. At the same time, the cost-benefit of practical implementation can be analyzed.

Besides, the algorithm can also be improved to a user-interface program. Users can define any network by entering the required information such as number of busses, number of branches, etc other than doing modification inside the program. The program will be easier to maintain.

Another area that can be looked into is to extend the algorithm to solve for the ring main network and not limited to only radial distribution system.

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APPENDIX I: Milestone for the First Semester of 2 Semester Final Year Project

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	**Selection of Project Topic**														
2	**Preliminary Research Work**														
	-Introduction														
	-Objective														
	-List of references/literature														
	-Project planning														
3	**Submission of Preliminary Report**														
4	**Project Work**														
	- Review of Literature														
	➢ Review of Electrical Power														
	➢ Review of Reactive Losses														
	➢ Review of Causes of Reactive Power														
	➢ Review of Effects of Reactive losses														
5	**Submission of Progress Report**														
6	**Project work continues**														
	- Review of Literature (cont.)														
	➢ Review Types of Distribution System														
	➢ Review of Radial Distribution System														
	➢ Review of Techniques of Reactive Power Reduction														
	- Familiarize with Simulation Software														
7	**Summarize all Information and Prepare Interim Report**														
8	**Submission of Interim Report Final Draft**														
9	**Submission of Interim Report**														
10	**Oral Presentation**													**Week**	**15**

● Suggested milestone — Actual

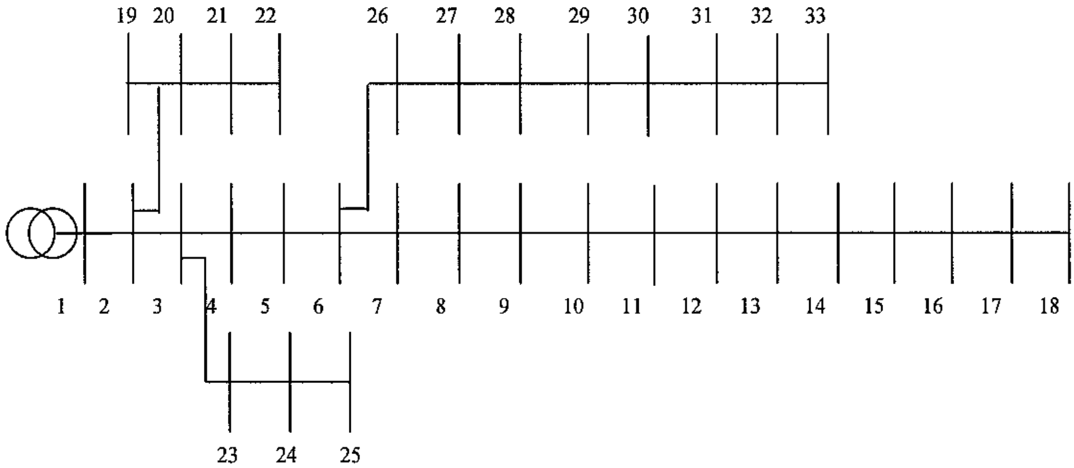
Process

APPENDIX II: Milestone for the Second Semester of 2 Semester Final Year Project

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Project Work Continue														
	-Load Flow Analysis Simulation														
	➢ IEEE 34-bus system														
2	Submission of Progress Report 1			●											
3	Project Work Continue														
	-Write Algorithm for Single Capacitor Placement														
4	Submission of Progress Report 2								●						
5	Project work continue														
	-Write Algorithm for Multiple Capacitor Placement														
	-Evaluate, Validate and Compare the Algorithm														
6	Submission of Dissertation Final Draft												●		
7	Submission of Project Dissertation													Week 20	
8	Oral Presentation													Week 20	

● Suggested milestone
Process
Actual

APPENDIX III: IEEE 33-BUS SYSTEM



Single Line Equivalent of 33-Bus System

Load Data

Branch no.	PL (kW)	QL (kVAR)
1	100.00	60.00
2	90.00	40.00
3	120.00	80.00
4	60.00	30.00
5	60.00	20.00
6	200.00	100.00
7	200.00	100.00
8	60.00	20.00
9	60.00	20.00
10	45.00	30.00
11	60.00	35.00
12	60.00	35.00
13	120.00	80.00
14	60.00	10.00
15	60.00	20.00
16	60.00	20.00
17	90.00	40.00
18	90.00	40.00
19	90.00	40.00
20	90.00	40.00
21	90.00	40.00
22	90.00	50.00
23	420.00	200.00
24	420.00	200.00
25	60.00	25.00
26	60.00	25.00
27	60.00	20.00
28	120.00	70.00
29	200.00	600.00
30	150.00	70.00
31	210.00	100.00
32	60.00	40.00

Line Data

No. of Nodes: 33 Base Voltage: 12.66kV
No. of Branches: 32 Base Load: 5.246mVA

Branch No.	Sending End Node	Receiving End Node	Resistance	Reactance
1	1	2	0.092200	0.047000
2	2	3	0.493000	0.251100
3	3	4	0.366000	0.186400
4	4	5	0.381100	0.194100
5	5	6	0.819000	0.707000
6	6	7	0.187200	0.618800
7	7	8	0.711400	0.235100
8	8	9	1.300000	0.740000
9	9	10	1.044000	0.740000
10	10	11	0.196600	0.065000
11	11	12	0.374400	0.123800
12	12	13	1.468000	1.155000
13	13	14	0.541600	0.712900
14	14	15	0.591000	0.526000
15	15	16	0.746300	0.545000
16	16	17	1.289000	1.721000
17	17	18	0.732000	0.574000
18	2	19	0.164000	0.156500
19	19	20	1.504200	1.355400
20	20	21	0.409500	0.478400
21	21	22	0.708900	0.937300
22	3	23	0.451200	0.308300
23	23	24	0.898000	0.709100
24	24	25	0.896000	0.701100
25	6	26	0.203000	0.103400
26	26	27	0.284000	0.144700
27	27	28	1.059000	0.933700
28	28	29	0.804200	0.700600
29	29	30	0.507500	0.258500
30	30	31	0.974400	0.963000
31	31	32	0.310500	0.361900
32	32	33	0.341000	0.530200

APPENDIX IV: TABLE FOR D_i

When a capacitor is place at:

	D_1, D_2, D_3, …………………………………………, D_{31}, D_{32}, D_{33}
Bus 2	1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 3	1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 4	1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 5	1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 6	1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 7	1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 8	1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 9	1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 10	1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 11	1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 12	1,1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 13	1,1,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 14	1,1,0,0,0,0,0,0,0,0,0,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 15	1,1,0,0,0,0,0,0,0,0,0,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 16	1,1,0,0,0,0,0,0,0,0,0,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 17	1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 18	1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 19	1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 20	1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 21	1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 22	1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0;
Bus 23	1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0;
Bus 24	1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0;
Bus 25	1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0;
Bus 26	1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0;
Bus 27	1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0;
Bus 28	1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0;
Bus 29	1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,0,0,0,0,0,0,0;
Bus 30	1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,0,0,0,0,0,0;
Bus 31	1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0;
Bus 32	1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,0,0;
Bus 33	1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,0;
Bus 34	1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,1;

APPENDIX V: PROGRAM FOR SINGLE CAPACITOR PLACEMENT

```
%PROGRAM TO CALCULATE CAPACITOR CURRENT (Ic), LOSS SAVINGS,
%SORT FOR THE MAXIMUM LOSS SAVING, IDENTIFY THE BRANCH NUMBER
%AND CALCULATE THE CAPACITOR SIZE (Qc)

%Define D, V, Ir and R

D=[     1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,0,0,0,0,0,0,0,0,0,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,0,0,0,0,0,0,0,0,0,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,0,0,0,0,0,0,0,0,0,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0;
        1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0;
        1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,1,1,1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0;
        1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0;
        1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,0,0,0,0,0;
        1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,0,0,0,0;
        1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0;
        1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,0,0;
        1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,0;
        1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,1];

V=[     10.936,10.879,10.803,10.737,10.675,10.632,...
        10.609,10.582,10.569,10.564,10.563,10.876,...
        10.872,10.871,10.871,10.625,10.585,10.540,...
        10.503,10.472,10.436,10.406,10.379,10.365,...
        10.360,10.359,10.629,10.626,10.625,10.565,...
        10.562,10.560,10.559];


Ir=[    -0.15423,-0.14671,-0.13919,-0.13160,-0.12403,...
        -0.04252,-0.03482,-0.02719,-0.01953,-0.01217,...
        -0.00451,-0.00752,-0.00514,-0.00276,-0.00039,...
        -0.08145,-0.07382,-0.06619,-0.05854,-0.05085,...
```

```
        -0.04317,-0.03545,-0.02775,-0.02002,-0.01234,...
        -0.00461,-0.00771,-0.00516,-0.00255,-0.00742,...
        -0.00554,-0.00371,-0.00183];

R=[     0.11700,0.10725,0.16445,0.14950,0.14950,...
        0.31440,0.20960,0.31440,0.20960,0.13100,...
        0.10480,0.15720,0.20960,0.10480,0.05240,...
        0.17940,0.16445,0.20790,0.18900,0.18900,...
        0.26200,0.26200,0.31440,0.20960,0.13100,...
        0.10480,0.15720,0.15720,0.15720,0.15720,...
        0.20960,0.15720,0.10480];


%Calculate and Display Ic

fprintf('Capacitor Current,Ic is:\n');

for m=1:33;          %outer loop
        num=0; denom=0;

   for n=1:33;       %inner loop
                num1=(D(m,n)*Ir(n)*R(n));        %numerator
                denom1=(D(m,n)*R(n));            %denominator
                num=num+num1;
                denom=denom+denom1;
   end       %end of inner loop

      Ic(m)=-num/denom;
                fprintf('Ic %2d = %9.5f \n',m,Ic(m));
end          %end of outer loop


%Calculate loss saving for each branch

fprintf('\nLoss Saving When Corresponding Optimal Capacitor is Placed at: \n\n');

for i=1:33;                 %outer loop
        total=0; S(i)=0;

   for j=1:33;      %inner loop
                total=-(2*D(i,j)*Ir(j)*Ic(i)+D(i,j)*Ic(i)*Ic(i))*R(j)*1000;
                S(i)=(S(i)+total);
   end    %end of inner loop
end       %end of outer loop


%Display loss saving, capacitor size for each branch

for k=1:33;
   fprintf('Bus %2d : \nLoss saving is %5.2f kW ',k+1,S(k));
   fprintf('with a capacitor size,Qc of %7.2f kVAR \n\n',V(k)*Ic(k)*1000);
end


%Sort for maximum loss saving, branch number and calculate Qc

max=0;
for p=1:33;
        if (max<S(p))
                max=S(p);
```

```
                no=p+1;
                Qc=V(p)*Ic(p)*1000;
  end
end

%Display maximum loss, capacitor size and branch number

fprintf('\nThe maximum loss saving is %5.2f kW ',max);
fprintf('when a shunt capacitor with a size of %8.2f',Qc);
fprintf('kVAR is placed at bus %2d \n\n',no);
```

APPENDIX VI: GENERATED OUTPUT OF PROGRAM

Capacitor Current,Ic is:
Ic 1 = 0.15423
Ic 2 = 0.15063
Ic 3 = 0.14579
Ic 4 = 0.14185
Ic 5 = 0.13798
Ic 6 = 0.10803
Ic 7 = 0.09536
Ic 8 = 0.08132
Ic 9 = 0.07386
Ic 10 = 0.06953
Ic 11 = 0.06607
Ic 12 = 0.09165
Ic 13 = 0.06097
Ic 14 = 0.05221
Ic 15 = 0.04858
Ic 16 = 0.12628
Ic 17 = 0.11792
Ic 18 = 0.10924
Ic 19 = 0.10253
Ic 20 = 0.09649
Ic 21 = 0.08906
Ic 22 = 0.08250
Ic 23 = 0.07549
Ic 24 = 0.07113
Ic 25 = 0.06838
Ic 26 = 0.06607
Ic 27 = 0.09442
Ic 28 = 0.08377
Ic 29 = 0.07510
Ic 30 = 0.06834
Ic 31 = 0.06208
Ic 32 = 0.05802
Ic 33 = 0.05553

Loss Saving When Corresponding Optimal Capacitor is Placed at:

Bus 2 :
Loss saving is 8.35 kW with a capacitor size,Qc of 1686.66 kVAR

Bus 3 :
Loss saving is 15.26 kW with a capacitor size,Qc of 1638.74 kVAR

Bus 4 :
Loss saving is 24.79 kW with a capacitor size,Qc of 1574.99 kVAR

Bus 5 :
Loss saving is 32.49 kW with a capacitor size,Qc of 1523.04 kVAR

Bus 6 :
Loss saving is 39.28 kW with a capacitor size,Qc of 1472.89 kVAR

Bus 7 :

Loss saving is 35.08 kW with a capacitor size,Qc of 1148.55 kVAR

Bus 8 :
Loss saving is 33.06 kW with a capacitor size,Qc of 1011.72 kVAR

Bus 9 :
Loss saving is 30.28 kW with a capacitor size,Qc of 860.52 kVAR

Bus 10 :
Loss saving is 28.40 kW with a capacitor size,Qc of 780.60 kVAR

Bus 11 :
Loss saving is 27.07 kW with a capacitor size,Qc of 734.50 kVAR

Bus 12 :
Loss saving is 25.82 kW with a capacitor size,Qc of 697.92 kVAR

Bus 13 :
Loss saving is 9.61 kW with a capacitor size,Qc of 996.84 kVAR

Bus 14 :
Loss saving is 6.59 kW with a capacitor size,Qc of 662.92 kVAR

Bus 15 :
Loss saving is 5.69 kW with a capacitor size,Qc of 567.54 kVAR

Bus 16 :
Loss saving is 5.30 kW with a capacitor size,Qc of 528.09 kVAR

Bus 17 :
Loss saving is 41.48 kW with a capacitor size,Qc of 1341.73 kVAR

Bus 18 :
Loss saving is 43.03 kW with a capacitor size,Qc of 1248.16 kVAR

Bus 19 :
Loss saving is 44.37 kW with a capacitor size,Qc of 1151.40 kVAR

Bus 20 :
Loss saving is 45.05 kW with a capacitor size,Qc of 1076.90 kVAR

Bus 21 :
Loss saving is 45.18 kW with a capacitor size,Qc of 1010.48 kVAR

Bus 22 :
Loss saving is 44.72 kW with a capacitor size,Qc of 929.43 kVAR

Bus 23 :
Loss saving is 43.73 kW with a capacitor size,Qc of 858.51 kVAR

Bus 24 :
Loss saving is 41.99 kW with a capacitor size,Qc of 783.53 kVAR

Bus 25 :
Loss saving is 40.46 kW with a capacitor size,Qc of 737.26 kVAR

Bus 26 :
Loss saving is 39.22 kW with a capacitor size,Qc of 708.37 kVAR

Bus 27 :

Loss saving is 38.00 kW with a capacitor size,Qc of 684.44 kVAR

Bus 28 :
Loss saving is 31.01 kW with a capacitor size,Qc of 1003.64 kVAR

Bus 29 :
Loss saving is 27.71 kW with a capacitor size,Qc of 890.09 kVAR

Bus 30 :
Loss saving is 24.94 kW with a capacitor size,Qc of 797.96 kVAR

Bus 31 :
Loss saving is 26.52 kW with a capacitor size,Qc of 722.01 kVAR

Bus 32 :
Loss saving is 24.31 kW with a capacitor size,Qc of 655.68 kVAR

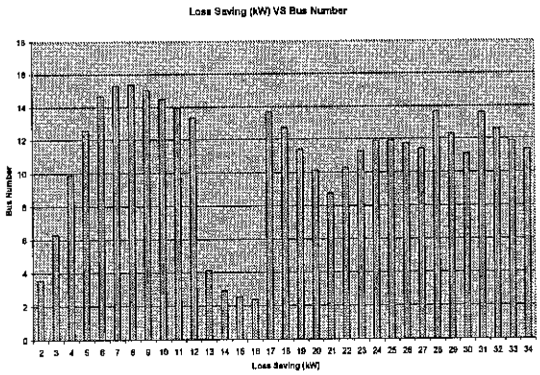
Bus 33 :
Loss saving is 22.82 kW with a capacitor size,Qc of 612.68 kVAR

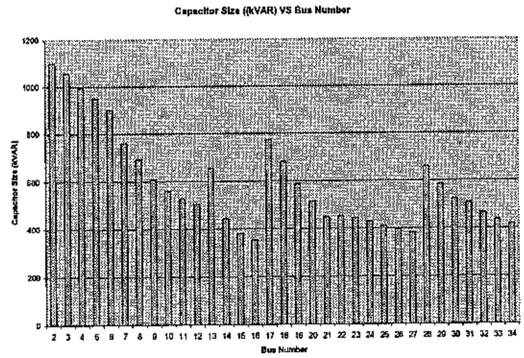
Bus 34 :
Loss saving is 21.87 kW with a capacitor size,Qc of 586.33 kVAR

The maximum loss saving is 45.18 kW when a shunt capacitor with a size of 1010.48kVAR is placed at bus 21

APPENDIX VII: RESULTS

Iteration: 2; Bus Location: 8; Capacitor Size: 691.44 kVAR





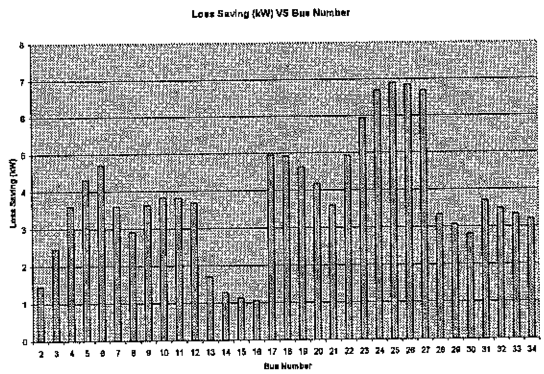
Voltage Profile

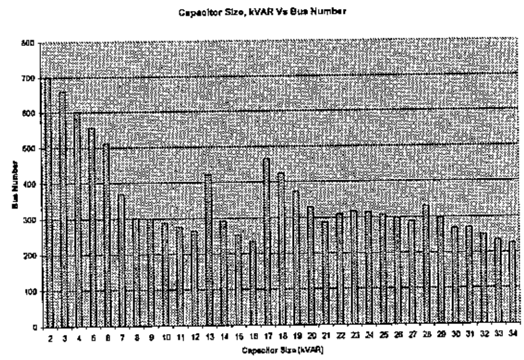
Busbar	Voltage (pu)	Voltage (kV)
1	1.00000	11.000
2	0.99458	10.940
3	0.98987	10.889
4	0.98333	10.817
5	0.97773	10.755
6	0.97247	10.697
7	0.96865	10.655
8	0.96655	10.632
9	0.96409	10.605
10	0.96291	10.592
11	0.96245	10.587
12	0.96232	10.585
13	0.98954	10.885
14	0.98923	10.882
15	0.98915	10.881
16	0.98914	10.881
17	0.96847	10.653
18	0.96518	10.617
19	0.96151	10.577
20	0.95861	10.545
21	0.95614	10.518
22	0.95288	10.482
23	0.95021	10.452
24	0.94769	10.425
25	0.94649	10.411
26	0.94602	10.406
27	0.94588	10.405
28	0.96832	10.651
29	0.96809	10.649
30	0.96798	10.648
31	0.96257	10.588
32	0.96223	10.585
33	0.96206	10.583
34	0.96200	10.582

Calculation of Losses

(i)	(ii)	(iii)	(iv)=(ii)sin(iii)	(v)=(ii)cos(iii)	(vi)	(vii)=(v)^2(vi)	(viii)=(iv)^2(vi)	(ix)=(vii)+(viii)
Line	Current (kA)	Angle (°C)	Current due to Reactive Component, I_{ri} (kA)	Current due to Real Component, I_{ai} (kA)	Resistance (Ω)	Real Loss Due to Real Component of Current (MW)	Real Loss Due to Reactive Component of Current (MW)	Total Real Loss (MW)
1	0.2603	-14.25	-0.06409	0.25229	0.11700	0.02234	0.00144	0.02378
2	0.2467	-13.25	-0.05656	0.24013	0.10725	0.01855	0.00103	0.01958
3	0.2332	-12.13	-0.04899	0.22800	0.16445	0.02565	0.00118	0.02683
4	0.2196	-10.86	-0.04136	0.21567	0.14950	0.02086	0.00077	0.02163
5	0.2062	-9.41	-0.03370	0.20343	0.14950	0.01856	0.00051	0.01907
6	0.0698	-4.77	-0.00580	0.06956	0.31440	0.00456	0.00003	0.00460
7	0.0574	2.03	0.00203	0.05736	0.20960	0.00207	0.00000	0.00207
8	0.0527	-31.69	-0.02768	0.04484	0.31440	0.00190	0.00072	0.00262
9	0.0380	-31.60	-0.01991	0.03237	0.20960	0.00066	0.00025	0.00091
10	0.0235	-31.79	-0.01238	0.01997	0.13100	0.00016	0.00006	0.00022
11	0.0087	-31.62	-0.00456	0.00741	0.10480	0.00002	0.00001	0.00002
12	0.0143	-31.91	-0.00756	0.01214	0.15720	0.00007	0.00003	0.00010
13	0.0098	-31.83	-0.00517	0.00833	0.20960	0.00004	0.00002	0.00006
14	0.0053	-31.62	-0.00278	0.00451	0.10480	0.00001	0.00000	0.00001
15	0.0008	-29.12	-0.00039	0.00070	0.05240	0.00000	0.00000	0.00000
16	0.1367	-11.77	-0.02789	0.13382	0.17940	0.00964	0.00042	0.01006
17	0.1231	-9.42	-0.02015	0.12144	0.16445	0.00728	0.00020	0.00748
18	0.1096	-6.47	-0.01236	0.10890	0.20790	0.00740	0.00010	0.00749
19	0.0965	-2.70	-0.00454	0.09639	0.18900	0.00527	0.00001	0.00528
20	0.0840	2.25	0.00330	0.08393	0.18900	0.00399	0.00001	0.00400
21	0.0837	-31.89	-0.04422	0.07106	0.26200	0.00397	0.00154	0.00551
22	0.0688	-31.87	-0.03633	0.05843	0.26200	0.00268	0.00104	0.00372
23	0.0539	-31.85	-0.02845	0.04578	0.31440	0.00198	0.00076	0.00274
24	0.0389	-31.85	-0.02053	0.03304	0.20960	0.00069	0.00026	0.00095
25	0.0239	-31.85	-0.01261	0.02030	0.13100	0.00016	0.00006	0.00022
26	0.0089	-31.87	-0.00470	0.00756	0.10480	0.00002	0.00001	0.00002
27	0.0145	-32.79	-0.00785	0.01219	0.15720	0.00007	0.00003	0.00010
28	0.0096	-32.79	-0.00520	0.00807	0.15720	0.00003	0.00001	0.00004
29	0.0048	-32.78	-0.00260	0.00404	0.15720	0.00001	0.00000	0.00001
30	0.0145	-31.29	-0.00753	0.01239	0.15720	0.00007	0.00003	0.00010
31	0.0109	-31.29	-0.00566	0.00932	0.20960	0.00005	0.00002	0.00007
32	0.0073	-31.28	-0.00379	0.00624	0.15720	0.00002	0.00001	0.00003
33	0.0036	-31.28	-0.00187	0.00308	0.10480	0.00000	0.00000	0.00000
					Total	**0.15877**	**0.01056**	**0.16932**

Iteration: 3; Bus Location: 25; Capacitor Size: 306.36 kVAR





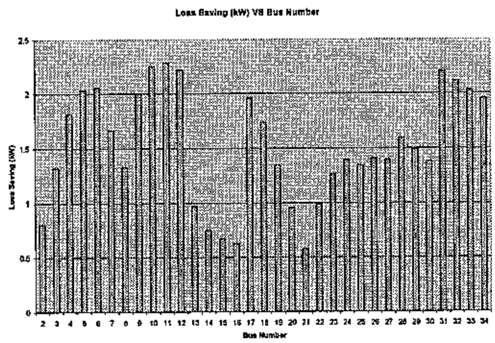
Voltage Profile

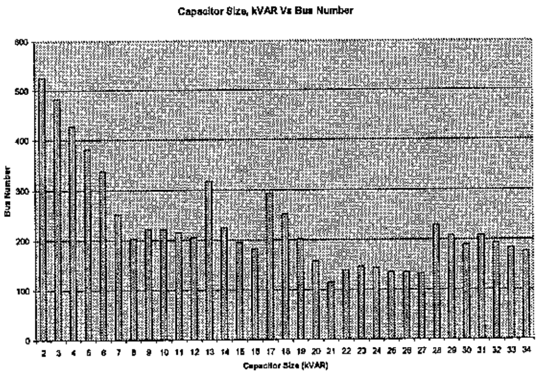
Busbar	Voltage (pu)	Voltage (kV)
1	1.00000	11.000
2	0.99500	10.945
3	0.99067	10.897
4	0.98454	10.830
5	0.97931	10.772
6	0.97442	10.719
7	0.97093	10.680
8	0.96905	10.660
9	0.96659	10.632
10	0.96541	10.620
11	0.96495	10.614
12	0.96482	10.613
13	0.99034	10.894
14	0.99003	10.890
15	0.98995	10.889
16	0.98994	10.889
17	0.97056	10.676
18	0.96739	10.641
19	0.96387	10.603
20	0.96109	10.572
21	0.95874	10.546
22	0.95562	10.512
23	0.95307	10.484
24	0.95071	10.458
25	0.94961	10.446
26	0.94914	10.441
27	0.94900	10.439
28	0.97059	10.677
29	0.97037	10.674
30	0.97026	10.673
31	0.96507	10.616
32	0.96473	10.612
33	0.96456	10.610
34	0.96451	10.610

Calculation of Losses

(i) Line	(ii) Current (kA)	(iii) Angle (°C)	(iv)=(ii)sin(iii) Current due to Reactive Component, I_{ri} (kA)	(v)=(ii)cos(iii) Current due to Real Component, I_{ai} (kA)	(vi) Resistance (Ω)	(vii)=$(v)^2$(vi) Real Loss Due to Real Component of Current (MW)	(viii)=$(iv)^2$(vi) Real Loss Due to Reactive Component of Current (MW)	(ix)=(vii)+(viii) Total Real Loss (MW)
1	0.2564	-10.77	-0.04791	0.25188	0.11700	0.02227	0.00081	0.02308
2	0.2432	-9.56	-0.04039	0.23982	0.10725	0.01851	0.00053	0.01903
3	0.2300	-8.20	-0.03282	0.22765	0.16445	0.02557	0.00053	0.02610
4	0.2169	-6.67	-0.02519	0.21543	0.14950	0.02082	0.00028	0.02110
5	0.2039	-4.92	-0.01750	0.20315	0.14950	0.01851	0.00014	0.01865
6	0.0698	-4.87	-0.00592	0.06955	0.31440	0.00456	0.00003	0.00460
7	0.0574	1.92	0.00193	0.05737	0.20960	0.00207	0.00000	0.00207
8	0.0527	-31.79	-0.02776	0.04479	0.31440	0.00189	0.00073	0.00262
9	0.0380	-31.70	-0.01997	0.03233	0.20960	0.00066	0.00025	0.00091
10	0.0235	-31.89	-0.01242	0.01995	0.13100	0.00016	0.00006	0.00022
11	0.0087	-31.72	-0.00457	0.00740	0.10480	0.00002	0.00001	0.00002
12	0.0143	-31.94	-0.00756	0.01214	0.15720	0.00007	0.00003	0.00010
13	0.0098	-31.86	-0.00517	0.00832	0.20960	0.00004	0.00002	0.00006
14	0.0053	-31.65	-0.00278	0.00451	0.10480	0.00001	0.00000	0.00001
15	0.0008	-29.15	-0.00039	0.00070	0.05240	0.00000	0.00000	0.00000
16	0.1341	-4.95	-0.01158	0.13360	0.17940	0.00961	0.00007	0.00968
17	0.1213	-1.80	-0.00381	0.12124	0.16445	0.00725	0.00001	0.00726
18	0.1089	2.11	0.00400	0.10883	0.20790	0.00739	0.00001	0.00740
19	0.0970	7.01	0.01184	0.09627	0.18900	0.00526	0.00008	0.00533
20	0.0861	13.25	0.01973	0.08381	0.18900	0.00398	0.00022	0.00420
21	0.0760	-21.35	-0.02766	0.07079	0.26200	0.00394	0.00060	0.00454
22	0.0615	-18.72	-0.01973	0.05825	0.26200	0.00267	0.00031	0.00297
23	0.0471	-14.47	-0.01177	0.04561	0.31440	0.00196	0.00013	0.00209
24	0.0332	-6.57	-0.00380	0.03298	0.20960	0.00068	0.00001	0.00069
25	0.0239	-32.26	-0.01276	0.02021	0.13100	0.00016	0.00006	0.00022
26	0.0089	-32.28	-0.00475	0.00752	0.10480	0.00002	0.00001	0.00002
27	0.0144	-32.89	-0.00782	0.01209	0.15720	0.00007	0.00003	0.00010
28	0.0096	-32.89	-0.00521	0.00806	0.15720	0.00003	0.00001	0.00004
29	0.0048	-32.89	-0.00261	0.00403	0.15720	0.00001	0.00000	0.00001
30	0.0145	-31.39	-0.00755	0.01238	0.15720	0.00007	0.00003	0.00010
31	0.0109	-31.39	-0.00568	0.00930	0.20960	0.00005	0.00002	0.00007
32	0.0073	-31.39	-0.00380	0.00623	0.15720	0.00002	0.00001	0.00003
33	0.0036	-31.39	-0.00187	0.00307	0.10480	0.00000	0.00000	0.00000
					Total	**0.15831**	**0.00502**	**0.16333**

Iteration: 4; Bus Location: 11; Capacitor Size: 214.44 kVAR





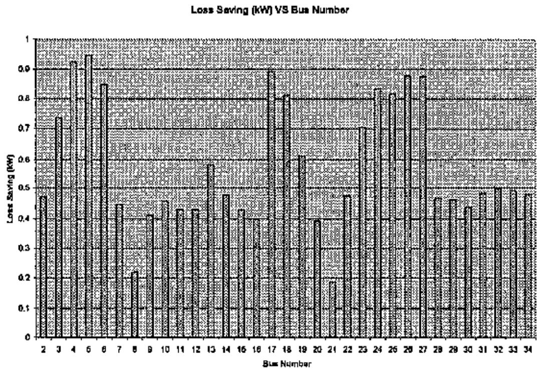
Voltage Profile

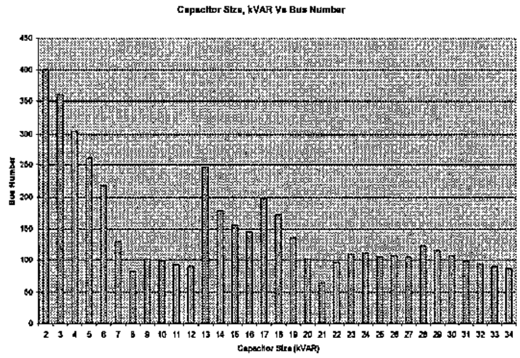
Busbar	Voltage (pu)	Voltage (kV)
1	1.00000	11.000
2	0.99509	10.946
3	0.99084	10.899
4	0.98479	10.833
5	0.97964	10.776
6	0.97483	10.723
7	0.97144	10.686
8	0.96963	10.666
9	0.96727	10.640
10	0.96616	10.628
11	0.96574	10.623
12	0.96561	10.622
13	0.99050	10.896
14	0.99020	10.892
15	0.99012	10.891
16	0.99011	10.891
17	0.97097	10.681
18	0.96781	10.646
19	0.96428	10.607
20	0.96151	10.577
21	0.95916	10.551
22	0.95604	10.516
23	0.95349	10.488
24	0.95113	10.462
25	0.95002	10.450
26	0.94956	10.445
27	0.94942	10.444
28	0.97110	10.682
29	0.97088	10.680
30	0.97077	10.678
31	0.96582	10.624
32	0.96548	10.620
33	0.96531	10.618
34	0.96525	10.618

Calculation of Losses

(i)	(ii)	(iii)	(iv)=(ii)sin(iii)	(v)=(ii)cos(iii)	(vi)	(vii)=(v)^2(vi)	(viii)=(iv)^2(vi)	(ix)=(vii)+(viii)
Line	Current (kA)	Angle (°C)	Current due to Reactive Component, I_{ri} (kA)	Current due to Real Component, I_{ai} (kA)	Resistance (Ω)	Real Loss Due to Real Component of Current (MW)	Real Loss Due to Reactive Component of Current (MW)	Total Real Loss (MW)
1	0.2545	-8.28	-0.03664	0.25185	0.11700	0.02226	0.00047	0.02273
2	0.2415	-6.92	-0.02911	0.23974	0.10725	0.01849	0.00027	0.01877
3	0.2286	-5.40	-0.02153	0.22758	0.16445	0.02555	0.00023	0.02578
4	0.2158	-3.69	-0.01389	0.21535	0.14950	0.02080	0.00009	0.02089
5	0.2031	-1.75	-0.00619	0.20301	0.14950	0.01848	0.00002	0.01850
6	0.0697	4.56	0.00555	0.06948	0.31440	0.00455	0.00003	0.00458
7	0.0589	13.16	0.01341	0.05735	0.20960	0.00207	0.00011	0.00218
8	0.0476	-19.92	-0.01622	0.04475	0.31440	0.00189	0.00025	0.00214
9	0.0334	-14.56	-0.00840	0.03233	0.20960	0.00066	0.00004	0.00070
10	0.0200	-2.29	-0.00080	0.01998	0.13100	0.00016	0.00000	0.00016
11	0.0087	-31.92	-0.00460	0.00738	0.10480	0.00002	0.00001	0.00002
12	0.0143	-31.96	-0.00757	0.01213	0.15720	0.00007	0.00003	0.00010
13	0.0098	-31.88	-0.00518	0.00832	0.20960	0.00004	0.00002	0.00006
14	0.0053	-31.67	-0.00278	0.00451	0.10480	0.00001	0.00000	0.00001
15	0.0008	-29.18	-0.00039	0.00070	0.05240	0.00000	0.00000	0.00000
16	0.1341	-5.03	-0.01175	0.13358	0.17940	0.00960	0.00007	0.00968
17	0.1212	-1.87	-0.00396	0.12114	0.16445	0.00724	0.00001	0.00725
18	0.1088	2.03	0.00386	0.10873	0.20790	0.00737	0.00001	0.00738
19	0.0970	6.94	0.01173	0.09629	0.18900	0.00526	0.00008	0.00533
20	0.0861	13.18	0.01963	0.08383	0.18900	0.00398	0.00022	0.00420
21	0.0760	-21.42	-0.02775	0.07075	0.26200	0.00393	0.00061	0.00454
22	0.0614	-18.79	-0.01977	0.05813	0.26200	0.00266	0.00031	0.00296
23	0.0471	-14.54	-0.01182	0.04559	0.31440	0.00196	0.00013	0.00209
24	0.0332	-6.64	-0.00384	0.03298	0.20960	0.00068	0.00001	0.00069
25	0.0239	-32.33	-0.01278	0.02019	0.13100	0.00016	0.00006	0.00022
26	0.0089	-32.35	-0.00476	0.00752	0.10480	0.00002	0.00001	0.00002
27	0.0144	-33.00	-0.00784	0.01208	0.15720	0.00007	0.00003	0.00010
28	0.0096	-32.99	-0.00523	0.00805	0.15720	0.00003	0.00001	0.00004
29	0.0048	-32.99	-0.00261	0.00403	0.15720	0.00001	0.00000	0.00001
30	0.0145	-31.58	-0.00759	0.01235	0.15720	0.00007	0.00003	0.00010
31	0.0109	-31.57	-0.00571	0.00929	0.20960	0.00005	0.00002	0.00007
32	0.0072	-31.57	-0.00377	0.00613	0.15720	0.00002	0.00001	0.00002
33	0.0036	-31.57	-0.00188	0.00307	0.10480	0.00000	0.00000	0.00000
					Total	**0.15818**	**0.00318**	**0.16136**

Iteration: 5; Bus Location: 5; Capacitor Size: 260.81 kVAR





Voltage Profile

Busbar	Voltage (pu)	Voltage (kV)
1	1.00000	11.000
2	0.99519	10.947
3	0.99104	10.901
4	0.98510	10.836
5	0.98003	10.780
6	0.97522	10.727
7	0.97184	10.690
8	0.97003	10.670
9	0.96767	10.644
10	0.96656	10.632
11	0.96615	10.628
12	0.96601	10.626
13	0.99071	10.898
14	0.99040	10.894
15	0.99032	10.893
16	0.99031	10.893
17	0.97137	10.685
18	0.96821	10.650
19	0.96468	10.612
20	0.96191	10.581
21	0.95956	10.555
22	0.95644	10.521
23	0.95390	10.493
24	0.95154	10.467
25	0.95043	10.455
26	0.94997	10.450
27	0.94983	10.448
28	0.97150	10.687
29	0.97128	10.684
30	0.97117	10.683
31	0.96622	10.628
32	0.96588	10.625
33	0.96571	10.623
34	0.96566	10.622

Calculation of Losses

(i)	(ii)	(iii)	(iv)=(ii)sin(iii)	(v)=(ii)cos(iii)	(vi)	(vii)=$(v)^2(vi)$	(viii)=$(iv)^2(vi)$	(ix)=(vii)+(viii)
Line	Current (kA)	Angle (°C)	Current due to Reactive Component, I_{ri} (kA)	Current due to Real Component, I_{ai} (kA)	Resistance (Ω)	Real Loss Due to Real Component of Current (MW)	Real Loss Due to Reactive Component of Current (MW)	Total Real Loss (MW)
1	0.2528	-5.20	-0.02293	0.25176	0.11700	0.02225	0.00018	0.02243
2	0.2402	-3.68	-0.01540	0.23971	0.10725	0.01849	0.00008	0.01856
3	0.2276	-1.97	-0.00781	0.22747	0.16445	0.02553	0.00003	0.02556
4	0.2153	-0.04	-0.00017	0.21530	0.14950	0.02079	0.00000	0.02079
5	0.203	-1.82	-0.00643	0.20290	0.14950	0.01846	0.00002	0.01848
6	0.0697	4.50	0.00546	0.06949	0.31440	0.00455	0.00003	0.00458
7	0.0589	13.09	0.01334	0.05737	0.20960	0.00207	0.00011	0.00218
8	0.0475	-19.99	-0.01624	0.04464	0.31440	0.00188	0.00025	0.00213
9	0.0333	-14.63	-0.00841	0.03222	0.20960	0.00065	0.00004	0.00070
10	0.0199	-2.36	-0.00082	0.01988	0.13100	0.00016	0.00000	0.00016
11	0.0087	-31.99	-0.00461	0.00738	0.10480	0.00002	0.00001	0.00002
12	0.0143	-31.99	-0.00758	0.01213	0.15720	0.00007	0.00003	0.00010
13	0.0098	-31.91	-0.00518	0.00832	0.20960	0.00004	0.00002	0.00006
14	0.0053	-31.70	-0.00279	0.00451	0.10480	0.00001	0.00000	0.00001
15	0.0008	-29.20	-0.00039	0.00070	0.05240	0.00000	0.00000	0.00000
16	0.134	-5.09	-0.01190	0.13347	0.17940	0.00959	0.00008	0.00966
17	0.1212	-1.94	-0.00410	0.12113	0.16445	0.00724	0.00001	0.00725
18	0.1088	1.97	0.00373	0.10874	0.20790	0.00737	0.00001	0.00738
19	0.097	6.88	0.01161	0.09630	0.18900	0.00526	0.00008	0.00533
20	0.086	13.11	0.01951	0.08376	0.18900	0.00398	0.00022	0.00419
21	0.0759	-21.49	-0.02780	0.07063	0.26200	0.00392	0.00061	0.00453
22	0.0614	-18.86	-0.01984	0.05811	0.26200	0.00265	0.00031	0.00296
23	0.0471	-14.61	-0.01188	0.04558	0.31440	0.00196	0.00013	0.00209
24	0.0332	-6.70	-0.00388	0.03297	0.20960	0.00068	0.00001	0.00069
25	0.0239	-32.40	-0.01281	0.02018	0.13100	0.00016	0.00006	0.00022
26	0.0089	-32.42	-0.00477	0.00751	0.10480	0.00002	0.00001	0.00002
27	0.0144	-33.06	-0.00786	0.01207	0.15720	0.00007	0.00003	0.00010
28	0.0096	-33.06	-0.00524	0.00805	0.15720	0.00003	0.00001	0.00004
29	0.0048	-33.06	-0.00262	0.00402	0.15720	0.00001	0.00000	0.00001
30	0.0145	-31.64	-0.00761	0.01234	0.15720	0.00007	0.00003	0.00010
31	0.0109	-31.64	-0.00572	0.00928	0.20960	0.00005	0.00002	0.00007
32	0.0072	-31.64	-0.00378	0.00613	0.15720	0.00002	0.00001	0.00002
33	0.0036	-31.64	-0.00189	0.00306	0.10480	0.00000	0.00000	0.00000
					Total	**0.15805**	**0.00241**	**0.16046**

APPENDIX VIII: PROGRAM FOR MULTIPLE CAPACITORS PLACEMENT

```
%Program to Calculate Capacitor Current Ic and Capacitor Size Qc

%Define Line Resistance (R), Current of Reactive Component (Ir) and Bus Voltage
R=[ 0.11700 0.10725 0.16445 0.14950 0.14950...
   0.31440 0.20960 0.31440 0.20960 0.13100...
   0.10480 0.15720 0.20960 0.10480 0.05240...
   0.17940 0.16445 0.20790 0.18900 0.18900...
   0.26200 0.26200 0.31440 0.20960 0.13100...
   0.10480 0.15720 0.15720 0.15720 0.15720 0.20960 0.15720 0.10480];

Ir=[-0.15423;-0.14671;-0.13919;-0.13160;-0.12403;...
   -0.04252;-0.03482;-0.02719;-0.01953;-0.01217;...
   -0.00451;-0.00752;-0.00514;-0.00276;-0.00039;...
   -0.08145;-0.07382;-0.06619;-0.05854;-0.05085;...
   -0.04317;-0.03545;-0.02775;-0.02002;-0.01234;...
   -0.00461;-0.00771;-0.00516;-0.00255;-0.00742 -0.00554;-0.00371;-0.00183];

V=[10.472;10.609;10.365];   %Voltage for bus 21,8 and 25

D =[     1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0;...
         1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;...
         1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0];

b=D';
x4=b(:,1).*b(:,2); %alpha 1 intersects alpha 2
x5=b(:,1).*b(:,3); %alpha 1 intersects alpha 3
x6=b(:,2).*b(:,3); %alpha 2 intersects alpha 3

%Define matric A
A(1,1)=R*b(:,1);
A(2,2)=R*b(:,2);
A(3,3)=R*b(:,3);
A(1,2)=R*x4;
A(1,3)=R*x5;
A(2,1)=R*x4;
A(2,3)=R*x6;
A(3,1)=R*x5;
A(3,2)=R*x6;

%Define matric B
b1=Ir.*b(:,1);
b2=Ir.*b(:,2);
b3=Ir.*b(:,3);
B(1,1)=R*b1;
B(2,1)=R*b2;
B(3,1)=R*b3;

%Calculate Capacitor Current (Ic)
Ic=-inv(A)*B

%Calculate Size of Capacitor (QC)
Qc=Ic.*V*1000
```