HIGH POWER LOSS REDUCTION IN ENUGU ELECTRICAL DISTRIBUTION SYSTEMS USING HEURISTIC TECHNIQUE FOR CAPACITOR PLACEMENT.

A PROJECT SUBMITTED TO THE DEPARTMENT OF ELECTRICAL ENGINEERING IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF MASTER OF ENGINEERING (M.ENG) DEGREE.

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I declare that the work is original and has not been submitted elsewhere for the purpose for the award of Degree to the best of my knowledge.

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CERTIFICATION

UZODIFE NICHODEMUS ANAYO, a postgraduate student in the Department of Electrical Engineering, with Registration Number PG/M.ENG/03/34636 has satisfactorily completed the requirements for the course and research work for the Degree of Master of Engineering (M. Eng.) in the Department of Electrical Engineering, University of Nigeria Nsukka.

The work embodied in the dissertation is original and has not been submitted in part or full for any other diploma or degree of this university or other institution to the best of our knowledge.

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Head of Department
DEDICATION

This project is dedicated to:

My father, Chiekpote Uzodife, for a lifetime of love and support, which, while not always spoken was always understood and remembered.

Jesus, your love for life is an inspirations. You will be always close to my heart.
ACKNOWLEDGEMENT

In the first place, I would love to show my gratitude towards God the father and the giver of life.

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ABSTRACT

This project involves research on loss reduction in a distribution system. The Enugu distribution system is the case study. The type of losses, the causes of losses and methods of loss reduction in distribution system were presented. A method based on a heuristic technique for reactive loss reduction in distribution system is chosen for this work because it provides realistic sizes and locations for shunt capacitors on primary feeder at a low computational burden. The Gauss-siedel method was used for load analysis while simulation work was done using MATLAB software. The variation of the load during the year is considered. The capital and installation cost of the capacitors are also taken into account. The economical power factor is also determined so as to achieve maximum savings. This method is applied to a 34 bus, 11KV, 6MVA distribution system with original power factor of 0.85. The results from the analysis show that the losses are reduced from 59.2692 to 49.4KW using capacitor maximum rating of 1200 (750+450) KVAR at an optimum power factor of 0.96. This translates to a saving of ₦39,500.00 per year after amortizing the capital and installation costs of applying the compensating capacitors.
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ABBREVIATIONS

KVA  -  Kilovoltamperes
KV   -  Kilovolt
Pf   -  Power Factor
Ci   -  Cost per kilvar of capacitor bank
Si   -  Cost per kilovolt amperes of system equipment
\( \Delta V \) -  Percentage voltage rise of the joint of capacitor installation
Kv   -  System line to line voltage without capacitor in service
Kvar -  Kilovolt ampere reactive.
K_L  -  Inductive reactance of the system at the point of the capacitor installation, in ohms.
KW   -  Kilowatts
P.H.C.N -  Power Holding Company of Nigeria
VAR_(C) -  Capacitor Reactive Power
AC   -  Alternating Current
S    -  Apparent power
Q    -  Reactive Power
P    -  True Power
X    -  Reactance
Xc   -  Capacitive Reactance
C    -  Capacitance of Capacitor
h    -  Resonant frequency
SMPS -  Switch mode power supply
APFC -  Active power factor correction
Yio and Yjo -  Reactive Shunts respectively
GSLF -  Gauss-siedel Load flow
Y-bus -  Admittance bus
\[ I_{c} \] - Capacitor Current
\[ P_{L} \] - Amount of power lost
\[ I \] - Current
\[ R \] - Resistance
\[ S \] - Real and reactive power load level
\[ V \] - Voltage Line
\[ \rho \] - Resistivity
\[ L \] - Length of line
\[ A \] - Cross sectional area
\[ \text{GRA} \] - Government Reserved Area

**SYMBOLS**

- Capacitor
- Inductor
- Transformer
- Contactor switch
- Motor
- Motor
- Resistor
- Capacitor
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CHAPTER ONE
INTRODUCTION

1.1 BACKGROUND OF STUDY

Electrical distribution systems include the distribution of electrical energy for light and power from the point of generation to the point of utilization [1].

Distribution of energy is accomplished in this project by the use of a.c system. Distribution system consists of two parts: the primary distribution which extends either from the generating station or substation to distribution transformers, and the secondary distribution, which extends from the distribution transformers to the point of utilization. An electrical distribution system can normally be of overhead or underground construction. The overhead construction is generally used in Enugu because it offers the following advantages.

I   It is less expensive

II  It is easier to identify and repair fault

Overhead distribution system is accomplished by means of two types of conductors: the bare conductors and insulated conductors. The bare conductors are those used for long distribution lines while the insulated conductors are those used for short distribution lines. The insulated conductors are also called service cables. They are used between poles and houses so as to prevent electric shock in case the conductor gets in contact with any of the metals in the building.

Enugu Electrical system receives its energy from Onitsha at 330kV. The 330kV is stepped down to 132kV in Onitsha and transmitted from Onitsha to New-Haven transmission station. At New-Haven transmission station the 132kV was stepped down to 33kV and transmitted to the following injection substations in Enugu: Kingsway, Independent Layout, Thinkers Corner, 9th Mile, Ituku Ozara and Emene
Industrial Layout. At the injection substations, the 33kV is further stepped down to 11kV and distributed to various areas in Enugu. In this project, the loss reduction in 11kV Thinkers Corner distribution line will be considered [1].

The power network, which generally concerns the common man, is the distribution network of 11kV lines or feeders downstream of the 33kV substation. Each 11kV feeder which emanates from the 33kV substation branches further into several subsidiary 11kV feeders to carry power close to the load points (localities, industrial areas, villages, etc.). At these load points, a transformer further reduces the voltage from 11kV to 415V to provide the last-kilometer connection through 415V feeders (also called as Low Tension (LT) feeders) to individual customers in Enugu, either at 240V (as single-phase supply) or at 415V (as three-phase supply). The span lengths mainly used for electricity projects nationwide are 45/50 meters for Township Distribution Network (TDN) and between 65 and 90 meters for inter-township connection (ITC) lines. In Enugu State, the average span length for both 11kV and 415V distribution lines is 50 meters between two poles.

After electric power is generated, it is sent through the transmission lines to the many distribution circuits that the utility operates. The purpose of the distribution system is to take that power from the transmission system and deliver it to the consumers to serve their needs. However, a significant portion of the power that a utility generates is lost in the distribution process. These losses occur in numerous small components in the distribution system, such as transformers and distribution lines. Due to the lower power level of these components, the losses inherent in each component are lower than those in comparable components of the transmission system. While each of these components may have relatively small losses, the large
number of components involved makes it important to examine the losses in the distribution system [2].

There are two major sources of losses in power distribution systems. These are the transformers and distribution lines. Additionally, there are two types of losses that occur in these two components. These losses are often referred to as core losses and copper, or $I^2R$, losses. In the case of transformers, the core losses account for the majority of losses at low power levels. As load increases, the copper losses become more significant, until they are approximately equal to the core losses at peak load [2].

The economic implications of these losses are far reaching. In addition to the excess fuel cost needed to cover the energy, added generating capacity may be needed. Also, the power lost in the distribution system must still be transmitted through the transmission system which further adds to the loss in that system. It is very important for electric power suppliers to consider these losses and reduce them wherever practical.

1.2 MOTIVATION AND SIGNIFICANCE OF THE STUDY

Initially, as power factor falls below unity the current in the system increases with the following effects:

(i) Because of the increased currents, the $I^2R$ power loss increases in cables and windlings leading to overheating and consequent reduction in equipment life.

(ii) Cost incurred by power company increases.

(iii) Efficiency as a whole suffers because more of the input is absorbed in meeting losses.

Since distribution losses cost the utilities a very big amount of profit, reduce life of equipment, attempts to reduce electricity cost, together with improving the efficiency of distribution systems,
have led us to deal with the problem of power loss minimization. The system is considered as efficient when the loss level is low. The significance of the expected outcome of the study include the following:

(i) It ensures that the rated voltage is applied to motors, lamps, etc, to obtain optimum performance.
(ii) It decreased loses in circuits and cables
(iii) It ensures maximum power output of transformers is utilized and not used in making-up losses.
(iv) It enables existing transformers to carry additional load without overheating or the necessity of capital cost of new transformers.
(v) It achieves the financial benefits which will result from lower maximum demand charges.

1.3 **AIM AND OBJECTIVES**

The major aim or purpose of the research effort is to reduce power losses in the 11Kv distribution system, achieve efficiency and financial benefits which will result from lower maximum demand charges by the electricity supply company. The objectives of the research project are:

(i) To find the power losses in the distribution system and
(ii) To find means to reduce the losses and reduce them.

Once the objectives are properly carried out the aims will be achieved.

1.4 **METHODOLOGY**

Since the project topic embraces determination of High Power Loss Reduction in distribution lines, effort will be made to explain how materials were obtained for this research project.
The research design object being descriptive and explorative will involve theoretical and mathematical model analysis.

The methodology or systems of actualizing the project are as follows:

1.4.1 SOURCES OF DATA:

Sources of data for this research work under review are based on visits made to Power Holding Company of Nigeria (PHCN) to find how losses occur, how to reduce it and how to assess the most economical method of loss reduction computation.

Data collection was obtained at PHCN Distribution Zonal Head Quarters Okpara Avenue, New Haven Transmission station and Thinker’s Corner injection substation Enugu.

1.4.2 Techniques to be employed to achieve the objectives are as follows:

(i) Derivation of power loss reduction equations
(ii) Derivation of economic power factor. Economic power factor is the power factor at which the savings is maximum.
(iii) Heuristic technique for capacitor placement. This is the method of allocating capacitors at the sensitive nodes. Sensitive node is the node that has the largest power loss due to reactive component of load current.
(iv) Load flow technique in MATLAB should be employed as the software for the study.

1.4.3 The instruments employed in the study are as follows: Ammeter, Voltmeter, Wattmeter, Clip on Ammeter, Digital multimeter and Power factor meter.

More specifically, capacitor banks are required at locations where field measurements indicate a low voltage or
low power factor problem. This information can be obtained as follows:

(a) By making voltage measurements during full-load (Peak-load) and light-load (off peak-load) conditions at various points on the distribution feeder; and 

(b) By making kilowatt and kilovoltampere measurements on the distribution feeder at minimum and maximum daily loads and during a typical 24 hour period.

Once these measurements have been obtained, equation 2.41 can be used to determine voltage rise and kilovar parameters. The capacitor banks may be connected grounded star (wye), ungrounded star (wye), or delta.

1.4.4 The tools employed in the study are, set of spanners, set of screwdrivers and pliers.

1.5 PROJECT ORGANIZATIONS

Chapter one states the objective and serves as introduction to this project.

Chapter two presents the theory necessary to understand and meet the objective. It presents the reactive power control problems.

Chapter three, presents the system model and problem formulation adopted in this project and describes the solution methodology in detail.

Chapter four, presents the application of the solution methodology. It also discusses the results obtained when this methodology was applied to a test distribution system.

Finally, chapter five, provides conclusion and recommendations for future work.
CHAPTER TWO
ELECTRICAL DISTRIBUTION LOSSES AND APPLICATION OF CAPACITORS

Electrical distribution losses are the losses due to copper and cores in distribution systems.

2.1 SOURCES OF LOSSES IN ELECTRICAL DISTRIBUTION SYSTEMS

There are two major sources of losses in electrical distribution systems. These are the transformers and distribution lines.

2.1.1 LOSSES IN DISTRIBUTION LINES

One of the major sources of losses in the distribution system is the power lines which connect the substation to the loads. Virtually all real power that is lost in the distribution system is due to copper losses. Since these losses are a function of the square of the current flow through the line, it should be obvious that the losses in distribution lines are larger at high power levels than they are at lower levels.

Since power loss in the distribution lines can be considered to be entirely due to copper losses, it can be calculated using Equation 2.1.

\[ P_L = I^2R \]

From this, it is apparent that anything, that changes either current (I) or line resistance (R) will affect the amount of power lost \( (P_L) \) in the line.

The primary determining factor for the magnitude of line current is the amount of real and reactive power loading at the end of the line. As the power that is transmitted along the line increases, the current flow in the line becomes larger. Another factor which affects the level of current flow is the operating voltage of the line. For a given real and reactive power load level, \( S \), a high voltage line will have a lower current than a low voltage line. This can be seen from Equation 2.2
Therefore, for a given power level, the higher voltage (V) line will have lower copper losses.

Another factor which can result line losses is unbalanced loading. If one of the phases is loaded more heavily than the others, the loss will be larger than it would have been in the balanced load case. This is due to the squaring of the current in Equation 2.1

While the current level has the biggest effect on line loss, the resistance of the line cannot be neglected. The line resistance depends on many factors, including the length of the line, the effective cross-sectional area, and the resistivity of the metal of which the line is made. The resistance is inversely proportional to the cross-sectional area and directly proportional to both the length and resistivity. This is shown in Equation 2.3 below, where \( R \) is the resistance, \( \rho \) is the resistivity, \( L \) is the length of the line, and \( A \) is the effective cross-sectional area.

\[
R = \rho \frac{L}{A} 
\]

Therefore, a long line will have a higher resistance and larger losses than a short line with the same current flow. Similarly, a large conductor size results in a smaller resistance and lower losses than a small conductor.

The resistivity is determined by the material of which the line is constructed and the temperature of the material. A better conducting material will result in lower resistivity and lower losses. The resistivity of the metal in the line will be affected by the temperature. As the temperature of the metal increases, the line resistance will also increase, causing higher copper losses in the distribution line. The resistivity of copper and aluminium can be calculated from Equation 2.4.
\[
\rho_1 = \rho_2 \frac{T_2 - T_o}{T_1 - T_o}
\]

2.4

The letter rho, \( \rho \), is the resistivity at a specific temperature. It is equal to \( 2.83 \times 10^{-8} \) ohm meters for aluminium and \( 1.77 \times 10^{-8} \) ohm meters for copper at a temperature of 20\(^\circ\)C. \( T_0 \) is a reference temperature and is equal to 228\(^\circ\)C for aluminium and 241\(^\circ\)C for copper. \( \rho_1 \) and \( \rho_2 \) are the resistivities at temperature \( T_1 \) and \( T_2 \) respectively [3].

2.1.2 LOSSES IN DISTRIBUTION TRANSFORMERS

While losses in distribution lines are virtually all due to copper losses, transformer losses occur due to both copper and core losses. The core losses are made up of eddy current and hysteresis losses. The copper losses in transformers are essentially the same as those in the power distribution lines.

The copper losses in a transformer are smaller in magnitude than the core losses. These losses occur in the form of heat produced by the current, both primary and secondary, through the windings of the transformer. Like the copper loss in the distribution line, it is calculated using the \( I^2R \) relationship of Equation 2.1. Any factor which affects either current or winding resistance will also affect the amount of copper loss in the transformer.

An increase in loading, either real or reactive, will result in an increase in current flow and a correspondingly greater amount of loss in the transformer. Additionally, an unbalanced system load will increase transformer loss due to the squared current relationship. The winding resistance also has an affect on the amount of copper loss and is mainly determined by the total length of the wire used, as well as the size of the wire. Temperature of the winding will affect the resistivity of the wire,
therefore affecting the overall resistance and the copper loss. Since all but the smallest distribution transformers have some type of cooling system, such as immersion in oil, the temperature effect on losses is usually minimal.

The core loss in a transformer is usually larger in magnitude than the copper loss. It is made up of eddy current losses, which are due to magnetically induced currents in the core, and hysteresis losses, which occur because of the less than perfect permeability of the core material. These losses are relatively constant for an energized transformer and can be considered to be independent of the transformer load. Transformer core losses have been modeled in various ways, usually as a resistance in parallel with the transformer’s magnetizing reactance [3] [4] [5].

Since the core loss is relatively independent of loading, the most important factor when considering core loss is the manufacture of the core. The physical construction of the core has serious consequences on the amount of core loss occurring in the transformer. For instance, eddy currents are greatly reduced by using laminated pieces to construct the core. These thin sheets are oriented along the path of travel of the magnetic flux and restrict the amount of reduced currents that occur. [4]

The hysteresis loss occurs in the transformer core due to the energy required to provide the magnetic field in the core as the direction of magnetic flux alternates with the alternating current wave form. This energy is transformed into heat. Hysteresis loss can be reduced by the use of higher quality materials in the core which have better magnetic permeability [6] [7].

A final aspect of the distribution system that increases losses in the transformers is the presence of harmonics in the system. The harmonic currents only cause a small increase in copper losses
throughout the system. However, the high frequently harmonic voltages can cause large core losses in the transformer. Frequently, utilities are forced to use an oversized transformer to compensate when a large harmonic presence is indicated. The increased skin effect of larger conductors combined with the high frequency harmonics can result in even greater losses [8].

2.1.3 TYPES OF LOSSES IN DISTRIBUTION SYSTEMS

The types of losses in distribution system are commercial and technical losses.

Commercial losses are losses due to non-issuance of bills, due to non-reading of meters, use of inappropriate billing methods, losses that could result from the use of load limiters and power theft.

Technical losses are the power losses as a result of resistance to current flow in the conductors. It is compounded if the distribution system equipment is overloaded beyond their design limits.

Between the two types of losses above, the one under consideration in this project is the technical loss because it is the major loss in distribution systems.

2.2 CAUSES OF TECHNICAL LOSSES IN DISTRIBUTION SYSTEMS.

Technical losses in Enugu distribution systems are due to overloaded transformers, undersized conductors, low system voltages and system power factor.

Overloaded Transformers: This is due to increased copper losses due to higher rated demand of energy imposed on transformers. The transformers therefore supply loads over and above their ratings [9].
Undersized Conductors: As a result of unregulated residential development, residential and commercial loads generally have grown rapidly in several areas. The result is that in some areas, consumers now use undersized conductors resulting in overheating and consequent high energy losses.

In order to contain the increased load and in the absence of the standard higher rated cartridge fuses, strands of copper wires have been adopted as fuse links. The fuse links and terminals have also been subjected to the same overheating. The overheating of fuse terminal on distribution poles has resulted in some of poles being burnt. This phenomenon is equally affecting distribution feeder pillars and underground cable terminations.

Low System Voltages: Voltages in Enugu electrical distribution systems are low due to general system overloading. This is partly due to the inability to meet the demand of enough electric power supply to the consumers especially at peak load periods (from 7.30 am to 10.30 pm) when all the commercials, industrials, and few residential are supposed to be at work with the aid of electricity. The overall effect of these low voltages is increased losses. Mathematically, low voltage can lead to power losses as follows:

Power factor is given by:

\[ \cos \theta = \frac{KW}{KVA} \quad \text{and} \quad \sqrt{\left(\frac{KVAR}{KVA}\right)^2 + \left(\frac{KW}{KVA}\right)^2} \]

\[ KVA = \frac{KW}{\cos \theta} \]

In case of single phase supply, \[ KVA = \frac{V_L I_L}{1000} \quad \text{or} \quad I_L = \frac{1000KVA}{V_L} \]

In case of 3-phase supply, \[ KVA = \frac{\sqrt{3}V_L I_L}{1000} \quad \text{or} \quad I_L = \frac{1000KVA}{\sqrt{3}V_L} \]
From the above expressions:

(i) KVA is inversely proportional to power factor and directly proportional to true power. Therefore: from equation 2.5, it is observed that the higher the Kilovolt Amperes (KVA), the higher the true power (KW) and the lower the power factor which attracts higher losses in the system.

(ii) In both single and three phase supplies, line current ($I_L$) is directly proportioned to KVA and inversely proportional to line voltage ($V_L$). Therefore, from equations 2.6 and 2.7, it is observed that the higher the line current, the higher the KVA, the lower the line voltage and the higher the losses along the lines. Note: Rating of transformers is directly proportional to current and Power losses is directly proportional to current squared.

Poor System Power Factor: The lower the power factor of a distribution system, the higher the losses. In a system with large current and lagging power factor, there are losses due to flow of reactive current from inductive loads like transformers, AC induction motors, fluorescent lamps with chokes (ballasts) etc.

The reactive power required by these loads increases the amount of apparent power in the distribution system and this increase in reactive power and apparent power results in a lower power factor thereby causing power loss in the distribution system.

### 2.3 CAUSES OF LOSSES IN DISTRIBUTION FEEDERS

In distribution feeders, losses occur because of the following reasons, [10]:

i Line losses on phase conductors.
ii Line losses on ground wires and ground.
iii Transformers core and leakage losses.
iv Excess losses due to lack of coordination of var elements.
v Excess losses due to load characteristics.
vi Excess losses due to load imbalance on the phases.

Line losses on phase conductors: This is $1^2R$ loss due to resistance to current flow along the phase conductors.

Line losses on ground wires and ground: This is the $1^2R$ loss due to resistance to current flow between the earth wire, and the buried earth electrode. This loss occurs especially when there is earth leakage in the system. As a result, heat is generated within the area in which the earth electrode is buried thereby causing losses.

Transformers core and leakage losses: These losses are due to Eddy currents and Hysteresis. Eddy currents are alternating currents which are induced into the metal core of the transformer by the alternating field in the core. This loss is minimized by using laminations. Hysteresis losses are due to the energy used in the core during the changing cycle of magnetism. This loss is minimized by using a core in which the residual magnetism is small (example Silicon steel).

Excess loss due to load characteristics: If the load power factor is low or lagging there will be losses due to flow of reactive component of the current.

Excess loss due to lack of coordination of var elements: This loss is due to lack of capacitance in the system. If the capacitor size is not of optimum size, there can be losses due to over compensation / under compensation. It requires power factor improvement using capacitors.

Excess loss due to load imbalance on the phases: Load imbalance on phases simply means that some phases are overloaded while some are under loaded. Therefore overloading a particular phase cause excess
power loss in the system. It is necessary to balance the load among the phases.

2.4 METHODS OF LOSS REDUCTION IN DISTRIBUTION SYSTEMS.

Since distribution losses cost the utilities a sizeable amount of profit, it is necessary to examine the various methods of reducing these losses. While many ways of lowering losses can be used on existing systems, other methods are easiest to use during the initial design and installation of a new distribution system.

During the initial design and installation of a new distribution system. The following methods are used for lowering distribution system losses.

(i) To carefully select the location of the substation so as to minimize the needed length of distribution lines.

(ii) To use as high voltages as is practicable for the lines to limit the current in the lines and transformer windings [2] [7] [8].

(iii) To use higher resistivity of materials (Example copper should be used on lines where losses are abnormally high).

(iv) To use shunt capacitor banks. Perhaps the most common method of reducing system losses is the use of shunt capacitor banks. Capacitors are used to compensate for reactive loads in order to provide a highly resistive total load and a near unity power factor. Hence there is less current flow in the line and lower losses. The capacitors are strategically placed to provide the best voltage support and current reduction.

(v) By reducing the amount of harmonics present in the system. This can be accomplished by placing filters at each load that produces major non sinusoidal signals. However, these filters cost money
and have inherent losses due to the imperfect nature of the components which limit the loss reduction that is achieved.

(vii) By ensuring that the load is well balanced on all three phases. This will keep the copper losses in the lines and transformers to a minimum.

(viii) Demand side management (DSM): With (DSM), a utility reduces the system loading especially at peak load periods, by turning off certain loads or providing incentives for efficiency. Overall load is reduced by encouraging improved efficiency by consumers with such things as rebates for high efficiency motors, refrigerators, and lighting. Peak load can be reduced by direct load control of such items as air conditioners, hot water heaters and some other industrial loads.

(ix) By installing high efficiency transformers during initial construction of distribution systems. High efficiency transformers uses new core types. One example of a more efficient core is one that uses amorphous metal. Amorphous metal is formed by rapidly cooling liquid metal.

On existing distribution system under consideration, the three basic ways to reduce the system losses are:

i. To improve the physical plant (that is replacing small conductors with large ones or equipment changes for voltage upgrading).

ii. Change the way the system supplies the load (that is reconfiguring the switches).

iii. Alter the load itself to reduce the compounding effects of the $1^2R$ losses on the delivery system components (by installing or placing capacitors on the system) [11] [15].
The method chosen among the three methods is the third approach and it is accomplished by using Heuristic technique for capacitor placement. Heuristic technique for capacitor placement is the method of placing capacitors on the distribution lines for reactive power loss reduction. This is achieved by placing the capacitors on sensitive nodes of the distribution lines. The sensitive nodes are the nodes that have the largest power losses due to reactive component of load currents. According to this method, the largest loss section of the primary feeder is determined and then the node with the highest impact on the losses in that section is detected and compensated.

The purpose of installing capacitors at the sensitive nodes is to achieve a large overall loss reduction in the system combined with optimal savings. This is based on the idea that the number of sensitive nodes is relatively small compared to the total number of nodes in the system.

The sensitive nodes are prime locations of fixed and switched capacitors banks, so that the circuit can be switched in or out either automatically or manually as the load changes. The sensitive nodes are selected based on the losses caused in the system by the reactive components of the load (bus) currents. The capital cost of the capacitors is also considered and the optimal number of capacitor banks at the specific location is determined in order to attain the highest naira savings. Also the variations of the load during the day are taken into consideration for the purpose of achieving a higher reduction of the overall losses during the year.

The shortcoming of the method is that the execution of the method requires a large number of power flow runs.

In this paper a heuristic method is presented in which only a number of critical nodes, named sensitive nodes, are selected for
installing capacitors in order to achieve a large overall loss reduction in the system combined with optimum savings.

The method of obtaining the optimal capacitor locations and sizes is outlined as follows:

**Step 1:** The peak power losses caused by the reactive load currents that flow through the feeder are computed by applying equation on APPENDIX II ‘M’ to every node of the distribution network. The node whose reactive load current has the largest impact on the loss in the system is then selected for compensation and is called a sensitive node.

**Step 2:** The optimal size of the compensating capacitor to be placed at the sensitive nodes has to be determined by computing the power losses that result from various sizes of capacitor placed at the sensitive nodes until an optimum value of capacitor that gives the least power losses is achieved as shown in table 4.1.6

Heuristic method is employed in this work because it offers the following advantages:

i. It provides realistic sizes and locations for shunt capacitors on the primary feeder at a relatively low computational burden.

ii. It is very effective.

iii. It gives considerable savings both in power and naira savings when the cost of capacitors and their installations are taken into account.

iv. It results in the identification of a smaller number of load nodes where capacitors are needed to be placed.

v. It is much faster in terms of computational time.

The method has been developed under the following assumptions.
i. Capacitor banks are optimally located for a certain load level, and the locations are assumed to be permanent, since it is not practical to move around capacitor banks on feeders [13].

ii. Loads are assumed to be uniformly concentrated along the nodes on the feeders and the size of capacitor banks at each location are variable.

iii. Only losses due to reactive current components are considered.

Shunt capacitors are installed at appropriate locations in large distribution systems to reduce power and energy losses and to improve voltage profile along the feeder. Several method of loss reduction in distribution systems through allocation of shunt capacitors have been developed over the past years. Most of the early works in this area were developed by the following researchers.

Chang [14] developed a mathematical analysis of shunt capacitor application for loss reduction in distribution feeder. Generalized equations for calculating loss reduction and voltage control in a feeder with representative loads are desired and the conditions for optimum loss reduction are considered.

Grainger and Lee [15] developed generalized procedure of optimizing the net savings associated with reduction of power and energy losses through shunt capacitor placement on primary distribution feeders. These procedures are applied to realistic problems to facilitate their immediate use by the electric utility distribution system designer.

Grainger and Lee [16] developed new generalized procedures for optimizing the net monetary savings associated with the reduction of power and energy loss through placement of fixed and switched shunt capacitors on primary distribution feeders.

Salama and Chikhani [17] developed a simplified network approach to the VAR control problem for radial distribution systems. In
this paper, shunt capacitors are installed at appropriate locations in large
distribution system to reduce power losses and improve distribution
system voltage profile. The proper selection of capacitors sizes and
locations can increase the benefits from the use of the shunt capacitors.
Many optimization methods are used to find the optimum locations and
sizes of these capacitors in order to maximize the net savings due to the
use of shunt capacitors.

Kalyuzhny A., Levitin G., Elmakis D., and Ben-Ham H. [18] present
a system approach to shunt capacitor placement on distribution systems
under capacitor switching constraints. The optimum capacitor allocation
solution is found for the system feeders fed through their transformer.
The main benefits due to capacitor installation, such as system capacity
release and reduction of overall powers and energy losses are
considered. The capacitor allocation constraints due to capacitor
switching transients are taken into account.

Fawzi Tharwat, H., El-Sobki, Salah, M. and Abdel-Halim,
Mohamed, A. [19] present a technique which deals with the application
of permanent shunt capacitors to primary distribution feeders. Two
distinct optimization techniques have been developed for selection of
capacitor size and location depending on the location of the additional
loads than can be served with the capacitors present. The objective cost
function minimized includes revenue due to energy loss reduction in the
feeder and release KVA at the substation. The minimization is subject to
voltage drop constraints. These techniques have been applied to a
typical rural distribution zone in Egypt and results are briefly
summarized. The advantage anticipated include boasting the load level
of feeder so that additional loads can be carried by the feeder for the
same maximum voltage drop releasing a certain KVA at the substation
which can be used to feed additional loads along other feeders and reducing power and energy losses in the feeder.

Abdel-Salam, Chi/Chani and Hackam [20] present a new technique for reducing the energy losses arising from the flow of reactive power in a distribution system by placing compensating capacitors at a few specific locations in the network termed “Sensitive modes” to achieve a maximum annual dollar savings. A cost study is performed taking into consideration the load variations during the year and the costs of capital and installation of the compensating capacitors. The compensating capacitors are placed at the optimal locations with appropriate VAR ratings to achieve maximum benefits and minimum losses. Salama et al [21] [22] developed a method for the control of reactive power in distribution systems with an end load for fixed load and varying load conditions giving generalized equations for calculating the peak power and energy loss reductions and the optimum locations and ratings of the capacitors.

### 2.5 APPLICATION OF POWER CAPACITORS TO ELECTRICAL DISTRIBUTION SYSTEMS:

When two conductors are separated by an insulator a capacitor is formed. The insulator is sometimes called dielectric material. Therefore the purpose of a capacitor is to store electrical energy by the electrostatic stress in the dielectric material.

At a casual look a capacitor seems to be a very simple and unsophisticated apparatus. It has no moving parts but instead functions by electric stress. In reality, however, a power capacitor is a highly technical and complex device in that very thin dielectric material; high electric stresses and highly sophisticated processing techniques are
involved. The two types of power capacitor connections are series and shunt connections [23] [24].

2.6 EFFECT OF SERIES AND SHUNT CAPACITORS IN ELECTRICAL DISTRIBUTION SYSTEMS:

The fundamental function of capacitors whether they are series or shunt installed as a single unit or as a bank is to regulate the voltages and reactive power flows at the point where they are installed. The shunt capacitor does this by changing the power factor at the load. Whereas the series capacitor does it by directly offsetting the inductive reactance of the circuit to which it is applied.

Series capacitors (ie capacitors connected in series with lines) are special type of apparatus with limited range of application in electrical distribution power services because of the following features:

i. Its kilovar rating is too low to improve the power factor significantly.

ii. It vibrates excessively

iii. It produces large current pulsation

iv. It provides Ferro resonance in transformers. Therefore, in general, utilities are reluctant to install series capacitors.

As a result of the above effects, shunt capacitors were employed in this project.

Shunt capacitors, ie capacitors connected in parallel with lines are used extensively in distribution systems. Shunt capacitors supply the type of reactive power or current to counteract the out of phase component of current required by an inductive load.

Having a bad power factor means that the distribution system is drawing more current than what is required to accomplish the real work and that the load losses of the distribution system are greater. “Power
factor” is an electrical term used to rate the degree of the synchronization of power supply current with the power supply voltage. It is the cosine of the phase angle between the fundamental of the voltage and current waveforms.

The power factors in industrial plant power distribution systems are usually lagging due to inductive nature of induction motors, transformers, lighting cables induction heating furnaces etc. In the case of lightings, all discharge Lamps, such as Fluorescent Lamps, High Pressure Mercury Vapour Lamps, Sodium Lamps, Metal Halide Lamps, etc., require ballasts (chokes) or transformers for their operation. These devices are inductive in nature. When a Discharge Lamp is switched on, it draws Apparent Power from the mains. This Apparent Power (VA) has two components; one is the Active Power (W) actually being consumed by the lamp for illuminating it, and the other is the Reactive Power (VAr) feeding the electromagnetic circuit of the control gear.

Power factor is the ratio of Active Power (W) to the Apparent Power (VA) (Figure 2.1).

\[
\text{Power factor} = \frac{\text{Active Power}}{\text{Apparent Power}} \quad \text{or} \quad \frac{W}{VA}
\]

2.8

The most important disadvantage of operating a load at a lagging (low) power factor are:

i. Larger cables, switchgear and transformers may be necessary both within an installation, and in the supply mains feeding it.

ii. Low power factor working causes operating difficulties on high voltage distribution lines.

iii. Because of the effects of items (i) and (ii), electricity companies usually penalize the consumer whose load is at a poor power factor by charging more for the electrical energy used.
iv. Higher current gives rise to higher copper losses in cables and transformers.

v. Higher currents give larger voltage drop in cables, and change in load gives a larger change in voltage drop if the power factor is low. This is called poor voltage regulation.

vi. It increases the cost incurred by the power company because more current must be transmitted than is actually used to perform useful work. This increased cost is passed on to the industrial customers by means of power factor adjustments to the rate schedule.

vii. It reduces the load handling capability of the industrial plants electrical distribution system which means that the industrial power user must spend more on distribution lines and transformers to get a given amount of useful power through his plant. This results that power factor correction is applied in this project to correct these effects using shunt capacitors.

2.7 POWER FACTOR CORRECTIONS.

Power factor correction is the practice of generating reactive power where it is consumed, rather than supplying it from a remote power station. It is also the practice of raising power factor of an inductive circuit by inserting capacitance. The result of this is that the apparent power is supplied to the load from the supply system and hence, the total current supplied to the load is reduced.

This reduction in current corresponds to a reduction in the $1^2R$ losses in the distribution lines and hence, to an overall improvement in the efficiency of the distribution system [25].
In addition to improving the efficiency, the reduction of distribution losses frees up system capacity, which may permit capital expenditure for system upgrading.

In general, the onus for power factor correction is on the consumer or end-user. Typical, residential or commercial loads do not require much reactive power, and hence, these types of loads generally do not require a power factor correction. Industrial loads, however, typically consume a considerable amount of inductive reactive power, and hence, they often require power factor correction. Furthermore, supply tariffs for industrial customers almost always penalizes low power factor loads. In Enugu for example, power factor less than 0.9 incur a penalty. The penalty of low power factor is measured through supply tariffs or electric bills being supplied to industrial customers by using watt hour meter, energy meter or prepaid meter.

In Enugu for example, industrial customers to electricity supply company operating at low power factor may be penalized by increasing the amount of electric bills rated for them by the electricity supply company (Power Holding Company of Nigeria PHCN). The effect of penalizing the industrial customers is to make them improve their power factor, reduce the power losses and reduce the large amount of electric bills being given to them.

As mentioned above, the inductive components, such as ballasts, draw Reactive Power (VAr) from the mains. It lags behind the Active Power (W) by 90° (Figure 2.1). A capacitor, if connected across the mains, will also draw Reactive Power (VAr(c)), but it leads the Active Power (W) by 90°. The direction of the capacitive Reactive Power (VAr(c)) is opposite to the direction of the inductive Reactive Power (VAr) (Figure 2.2)
If a capacitor is connected in parallel with an inductive load, it will draw capacitive Reactive Power \([\text{VAr}_c]\). This effective reactive power drawn by the circuit will reduce to the extent of the capacitive Reactive Power \((\text{VAr}_c)\), resulting in reduction of Apparent Power from \(\text{VA}\) to \(\text{VA}_1\). The phase angle between the Active Power and the new Apparent Power \(\text{VA}_1\) will also reduce from \(\theta\) to \(\theta_1\) (Figure 2.2). Thus the power factor will increase from \(\cos \theta\) to \(\cos \theta_1\).
\[ \text{New p.f.} = \cos \theta_i = \frac{W}{V_A_i} \]

By selecting a capacitor of an appropriate value, the power factor can be corrected close to unity. In practice, the power factor is improved to fall between 0.85 and 0.98.

However there are two types of power factor correction, the capacitive power factor correction and the active power factor correction.

### 2.7.1 CAPACITIVE POWER FACTOR CORRECTIONS

The capacitive power factor is corrected by addition of capacitors to the distribution network in order to provide reactive compensation and bring the power factor to an acceptable level. The capacitors are acting as a storage device of reactive power which reduces the inductive reactive power that the utility has to provide to the distribution network and in turn improves the power factor of the system.

Electrical loads consuming alternating current power consume both real power, which does useful work, and reactive power, which dissipates no energy in the load and which returns to the source on each alternating current cycle. The vector sum of real and reactive power is the apparent power.

The ratio of real power to apparent power is the power factor, a number between 0 and 1 inclusive. The presence of reactive power causes the real power to be less than the apparent power, and so the electric load has a power factor of less than unity [26].

The reactive power increases the current flowing between the power source and the load, which increase the power losses through distribution lines.

Power factor correction brings the power factor of an alternating current (AC) power circuit closer to unity by supplying reactive power
opposite sign, adding capacitors or inductors which act to cancel the inductive or capacitive effects of the load, respectively. For example, the inductive effect of motor loads may be offset by locally connected capacitors. Sometimes, when the power factor is leading due to capacitive loading, inductors (also known as reactors in this context) are used to correct the power factor. In the electricity industry, inductors are said to consume reactive power and capacitors are said to supply it, even though the reactive power is actually just moving back and forth between each alternating current (AC) cycle.

2.7.2 THEORETICAL METHOD OF CAPACITIVE POWER FACTOR CORRECTIONS:

As mentioned above, capacitive power factor is corrected by addition of capacitor to the distribution network. The addition of capacitors to the distribution network is the ideal way to provide reactive compensation and bring the power factor to an acceptable level. Capacitors can be added to the distribution network in the following ways:

2.7.2.1 PERMANENTLY:

(i) Capacitors are connected directly to the lines and are in circuit all the time.
   
   Advantages: Minimum cost and easy installation
   Disadvantages: Possibility of overcompensation is seen as a load when all other loads are disconnected.

(ii) Parallel (shunt) Connection of Capacitors in Luminaires
   
   Figure 2.3 is the most popular method of connection. The capacitor is connected in parallel to the luminaires as shown in figures 2.3(a) and (b). The voltage rating of the capacitor is usually the same as
(or a little higher than) the system voltage. The capacitor (C) of right value is connected in parallel with the luminaries, so that capacitive reactance when current leads voltage, offsets the inductive reactance of the ballast coil and bring the power factor close to unity [27].

![Diagram](image_url)

**Fig. 2.3 (a) and (b) Parallel (shunt) connection of capacitors in Luminaire**

(iii). Series Connection of capacitors in luminaire

In case of a double (twin) fluorescent luminaire, where two lamps are controlled by two ballasts, it is usual to over-compensate...
one ballast by connecting a capacitor in series with it, and to leave the other ballast uncompensated. The leading power factor on the first ballast, in conjunction with the lagging power factor of the second ballast, brings the total power factor to near unity. The scheme is shown in figure 2.4. The voltage rating of series connected capacitors is much higher than the supply voltage and must be correctly selected.

Figure 2.4  Series connection of capacitors in luminaries
2.7.2.2 CONTROLLED:

Capacitors are switched on and off by contactors that are controlled by a power factor regulator. (See figure 2.5)
Advantages: Accurate correction of power factor and easy installation.
Disadvantages: Requires more room.

Figure 2.5 Standard power factor Correction

2.7.2.3 AT THE MOTORS: [28] [29]

Capacitors are installed at the motors and connected either at the motor leads or between the contactor and overload relay. (See figure 2.6)
Advantages: Maximum reduction of system losses.
Disadvantages: Economically not viable unless the motor load is mostly constituted of large motors.
2.7.3 METHODS OF IDENTIFYING POWER FACTORS IN DISTRIBUTION SYSTEMS:

Power factors in distribution systems are identified by applying measurements on the system parameters. The preferred measurements are kilowatts, kilovars and volts, from these the Kva and power factor can be calculated. Voltage readings are especially desirable if automatic capacitor control with a voltage – responsive master element is contemplated. The types of meters and instruments available for power factor are: Hook-on type ammeter, watt meter, voltmeter, varmeter and power factor meter. The power factor can be obtained using the following processes:

(i) Power factor meter can be used to measure the power factor in a distribution system directly as a number between 0 and 1.

(ii) An oscilloscope can be used to compare the voltage and current waveforms. By measuring the phase shift in degrees between the current and voltage waveforms, the power factor can be determined by taking the cosine of the phase shift.

(iii) The apparent power can be figured by taking a volt meter reading in volts and multiply by an ammeter reading in amperes. The wattmeter can be used to measure the true

Figure 2.6 Capacitors connected to 3 phase motor.
power. The power factor can therefore be determined by dividing the true power (P) by the apparent power (S).

\[
\text{Power factor} = \frac{P}{S}
\]  

Using this value for power factor, a power triangle is drawn, and from that determine the reactive power of the load (See figure 2.7 below).

![Power Triangle](image)

**Figure 2.7 Power triangle**

To determine the unknown (reactive power) triangle quantity, we use the Pythagorean theorem, given the length of the hypotenuse (Apparent power) and the length of the adjacent side (true power).

\[
\text{Reactive power} = \sqrt{\left(\text{Apparent power}\right)^2 - \left(\text{True power}\right)^2}
\]  

If this load is an electric motor or most any other industrial alternating current (AC) load, it will have a lagging (inductive) power factor, which means that we will have to correct for it with a capacitor of appropriate size, wired in parallel. If the amount of reactive power (Kvar) is known, we can calculate the size of capacitor needed to counteract its effects using the formula.
Since this capacitor will be directly in parallel with the source (of known voltage), we will use the power formula which starts from voltage \( E \) and reactance \( X \) [28] [29].

Reactive power \( Q = \frac{E^2}{X} \)

Solving for \( X \)

\[ X = \frac{E^2}{Q} \]

Capacitive Reactance \( X_c = \frac{1}{2\pi f c} \Omega \)

Solving for capacitance of the capacitor \( C = \frac{1}{2\pi f x} \mu f \)

### 2.7.4 CONVENIENT CALCULATION METHODS FOR CAPACITIVE POWER-FACTOR (PF) IMPROVEMENT.

The two methods of improving power factor are by use of shunt capacitors or synchronous motors. In this project shunt capacitors are applied. The shunt capacitors are simply a capacitive reactance in shunt or in parallel with the load or system and is fundamentally for power factor improvement. The benefit of improved voltage level, released system capacity, reduced system losses, and the reduction in power bills, all stem from the improvement in power factor.

Power factor improvement is obtained by right-triangle relationship.

![Fig 2.8 Right-triangle relationship calculation in a.c. circuit.](image-url)
From the right-triangle relationship several simple and useful mathematical expressions may be written:

\[
\cos \phi = PF = \frac{KW}{KVA} \quad 2.16
\]

\[
\tan \phi = \frac{KVAR}{KW} \quad 2.17
\]

\[
\sin \phi = \frac{KVAR}{KVA} \quad 2.18
\]

Because the kilowatt component usually remains constant (the KVA and KVAR components change with power factor). Therefore, equation 2.17 involving the kilowatt component is the most convenient to use. This expression may be rewritten as:

\[
KVAR = KW \cdot \tan \phi_1 \quad 2.19
\]

For example, assume that it is necessary to determine the capacitor rating to improve the load power factor, we apply the following equations:

\[
KVAR \text{ at original PF} = KW \cdot \tan \phi_1 \quad 2.20
\]

\[
KVAR \text{ at improved pf} = KW \cdot \tan \phi_2 \quad 2.21
\]

The angle \( \phi \) is the phase angle between the voltage and current waveforms. The reactive power is defined by

\[
Q = \sqrt{S^2 - P^2} \quad 2.22
\]

Where \( S \) is the apparent power and \( P \) is the true power. A capacitor of \( Q \) Kvar will compensate for the inductive Kvar and produce \( \cos \phi = 1 \).
It is not common practice to produce $\cos \phi = 1$ with capacitors because this may result in overcompensation due to load changes and the response time of the controller. Generally, public utilities specify a value ($\cos \phi_2$) to which the existing power factor ($\cos \phi_1$) should be corrected. The compensator ratings and various improved power factor values could be determined as follows.

$$Q = P \ast (\tan \phi_1 - \tan \phi_2) \quad [\text{Var}]$$

$$Q = P \ast (\tan \phi_1 - \tan \phi_2)$$

$$\frac{Q}{P} = \tan \phi_1 - \tan \phi_2$$

$$\therefore \tan \phi_2 = \tan \phi_1 - \frac{Q}{P}$$

$$\phi_2 = \tan^{-1}\left(\tan \phi_1 - \frac{Q}{P}\right)$$

Improved power factor or Power Factor Correction $(pfc) = \cos \phi_2$ 2.28

Capacitors are used for Power Factor Correction because they offer the following advantages.

(1) They have low temperature rise and negligible losses.

(2) They occupy little floor space

(3) They do not need special foundation [23], [33].
2.7.5 COMPENSATION THEORY FOR CAPACITIVE POWER FACTOR CORRECTION.

Consider the single phase system shown in fig 2.9. (a) Having a load of admittance \( Y_L = G_L + jB_L \) which is supplied from a voltage \( V \). When \( V \) is taken to be reference phasor, the resulting load current,

\[
I_L = VY_L = V(G_L + jB_L) = VG_L + jVB_L = I_R + jI_x
\]

Hence, it is apparent that the load current consists of a real component, \( I_R \), which is in phase with \( V \), and a reactive component, \( I_x \), which is in
phase quadrature with $V$. The phasor diagram for an inductive load, which is the most common case, is given in Fig 2.9. (b). In this case, the reactive current, $I_x$, is negative and load current, $I_L$, is said to be lagging the voltage, $V$. The angle between the voltage and the load current is $\phi_L$.

For the system shown in figure 2.9 (a), the apparent power, $S_L$, supplied to the load is given.

$$S_L = V I_L^1 = V^2 G_L - JV^2 B_L = P_L + Q_L$$ \hspace{1cm} 2.30

Hence, it is clear that the apparent power has a real component, $P_L$ and a reactive component, $Q_L$. The real power, or active power as it is sometimes referred to, is the power which is capable of being converted into useful forms of energy such as heat, light and mechanical work. The relationship between the real, reactive and apparent powers is shown in figure 2.9 (c). By convention, $B_L$ is negative and $Q_L$ is negative for inductive loads.

For the system shown in figure 2.9 (a), the current, $I_S$, supplied by the power system is equal to the current consumed by the load ie $I_S = I_L$. Furthermore, from figure 2.9 (b), it is clear that the current supplied by the power system is larger than that which is necessary to supply only the real power required by the load by the factor.

$$\frac{I_L}{I_R} = \frac{1}{\text{Cos} \phi_{L1}} \hspace{1cm} 2.31$$

In addition, from figure 2.9 (c) the ratio of the active power to the apparent power is given by:

$$\text{Cos} \phi_L = \frac{P_L}{S_L} \hspace{1cm} 2.32$$
Hence, the quantity, \( \cos \phi_L \), is commonly referred to as the power factor, as it represents the fraction of the apparent power which can be converted into useful forms of energy.

As a result of the reactive power required by the load being supplied from the supply bus, the joule losses in the distribution cables are increased from that when only the real power required by the load is supplied from the supply bus by the factor \( \frac{1}{\cos^2 \phi_L} \). Consequently, it is desirable to keep the power factor near to unity. For poor power factor loads, \( \cos \phi_L < 0.95 \), compensation is generally employed in order to improve the power factor. Compensation for this purpose is known as power factor correction. Power factor correction is performed by locally generating the reactive power required by the load, instead of supplying it through the distribution lines from the power system. In this way, the losses are reduced, and the entire distribution system operates more efficiently.

The method of power factor correction just outlined may be accomplished by connecting a compensator having a purely reactive admittance, \( Y_c = -jB_L \), in parallel with the load, as shown figure 2.9(d). As a result of this compensation, the current supplied by the power system becomes:

\[
I_S = I_L^1 = I_L + I_c = V(G_L + jB_L) + V(-jB_L) = VG_L = I_R
\]

Where \( I_c \) is the current drawn by the compensator and \( I_L^1 \) is the total current drawn by the load compensator combination. In addition, the apparent power \( S_S \) supplied by the power system is

\[
S_S = VI_L^1 = V[V(G_L - jB_L) + V(jB_L)] = V^2G_L = P_L
\]
From equation 2.33 it is apparent that the supply current of the compensated system is now in phase with \( V \), and has the lowest possible magnitude which is capable of completely supplying only the active power requirement of the load. The phasor diagram for the compensated system is given in figure 2.9 (e).

For total compensation it is clear from figure 2.9 (c) that the reactive power rating of the compensator is related to the rated power of the load by

\[
Q_L = P_L \tan \phi_L 
\]

\[
\Rightarrow \tan \phi_L = \frac{Q_L}{P_L} 
\]

and to be rated apparent power by

\[
Q_L = S_L \sqrt{1 - \cos^2 \phi_L} 
\]

\[
\Rightarrow \frac{Q_L}{S_L} = \sqrt{1 - \cos^2 \phi_L} 
\]

\[
\frac{Q_L}{S_L} = \sin \phi_L 
\]

Where \( Q \) is the reactive power, \( P \) is the real power, \( S \) is the apparent power.

The compensator rating per unit apparent power and per unit real power for complete compensation for various power factors are shown in table 2.1.
Table 2.1  Rated reactive power of the compensator required for full compensation per unit rated apparent power of the load and per unit real power of the load for various power factors and the corresponding factor by which the losses are increased.

<table>
<thead>
<tr>
<th>Power factor</th>
<th>Angle ((\phi_L))</th>
<th>(\frac{Q_L}{S_L})</th>
<th>(\frac{Q_L}{P_L})</th>
<th>(\frac{1}{COS^2\phi_L})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>0.95</td>
<td>18.19</td>
<td>0.312</td>
<td>0.329</td>
<td>1.11</td>
</tr>
<tr>
<td>0.90</td>
<td>25.84</td>
<td>0.436</td>
<td>0.484</td>
<td>1.23</td>
</tr>
<tr>
<td>0.85</td>
<td>31.79</td>
<td>0.527</td>
<td>0.620</td>
<td>1.38</td>
</tr>
<tr>
<td>0.80</td>
<td>36.87</td>
<td>0.600</td>
<td>0.750</td>
<td>1.56</td>
</tr>
<tr>
<td>0.75</td>
<td>41.41</td>
<td>0.661</td>
<td>0.882</td>
<td>1.78</td>
</tr>
<tr>
<td>0.70</td>
<td>45.57</td>
<td>0.714</td>
<td>1.020</td>
<td>2.04</td>
</tr>
<tr>
<td>0.65</td>
<td>49.46</td>
<td>0.760</td>
<td>1.169</td>
<td>2.37</td>
</tr>
<tr>
<td>0.60</td>
<td>53.13</td>
<td>0.800</td>
<td>1.333</td>
<td>2.78</td>
</tr>
</tbody>
</table>

Source: Reference [25]

It is also possible to partially compensate the load. The degree of composition which is required for a particular system depends on an economic trade-off between the capital cost of the compensator, which is proportional to its rating, and the cost of the power and energy losses over a period of time associated with the supplying the reactive power required by the load through the distribution system.

Consider for example, an uncompensated load having a power factor of 0.90, from table 2.1 it is clear that in order to completely correct the power factor of this load a compensator with a rating of 0.436 per unit apparent power is required, while to correct the power factor to be no worse than 0.95 would only require a compensator with a rating of
0.312 per unit apparent power, this would translate into considerable saving in the cost of the compensator employed.

Real distribution system, however, may contain hundreds of buses. In this case, compensation at one bus will effect the level of compensation required at another bus. In addition, in order for a compensation scheme to be practical it must be economical. Hence, not every bus will require compensation. As a consequence, it is necessary to first determine which buses require compensation and which buses do not. This step is known as placement problem.

The placement problem involves planning and consists of determining optical location, size and number of compensators that are required for a distribution system, taking into account the cost of the compensators, the savings from energy and power loss reduction. The placement problem is a means of improving the performance of the distribution system and can be performed off-line.

The capacitor sub-problems mentioned above were solved in this project as follows:

i. Heuristic method is used to solve capacitor location sub-problem.

ii. The size subproblem of capacitors in kilovars is determine by calculating the rate of return and actual naira savings for various final power factor values.

iii. Number of capacitors required in the system have no specific formular, rather it could be found using the iterative process of finding the savings.

The installation of shunt power capacitors can reduce current flow through the system from the point of the capacitor installation back to the generation.
Since power losses are directly proportional to the square of the current, a reduction of current flow results in a much greater reduction of power losses. Capacitors are often installed as close to the load as possible for this reason.

The quality of service of a power system depends on the correct voltage level being consistently available to the customer. In order to ensure this, reactive power compensation is often needed on the distribution system.

Compensation may be performed for various reasons and by various methods. Compensation is performed for the following reasons [30]:

i. It increases system capacity.

ii. It improves voltage profile.

iii. It reduces billing charges.

iv. It reduces system power losses.

**Increased System Capacity:** Increased system capacity is often the most important benefit justifying the addition of shunt power capacitors on a distribution system. This is particularly significant when loads supplied by the system are increased rapidly. When capacitors are in operation in a distribution system, they deliver kilovars, furnishing magnetizing current for transformers, therefore reducing the current from the power supply. Less current means less kilovoltampere (KVA) or load on transformers and main branch, feeder circuits. For a given power, the higher the power factor, the lesser must be the size of the transformer to distribute the power and the lesser must be the cross-sectional area of the conductor to distribute it.

This means that capacitors can be used to reduce overloading of existing facilities or if the equipment is not overloaded, capacitors can permit additional load to be added.
Therefore, the addition of shunt power capacitors reduces the kilovoltampere loading on the system, thereby releasing capacity that can then be used to supply future load increase. The optimum economical power factor for a system, with regard to released capacity only, can be estimated by use of the following formula:

\[ Pf = \sqrt{1 - \left( \frac{C_i}{S_i} \right)^2} \]  \hspace{1cm} 2.40

Where:
- \( C_i \) is the cost per kilovar of capacitor bank
- \( S_i \) is the cost per kilovoltamperes of system equipment.
- \( Pf \) is the optimum power factor.

The formula compares the cost of capacitor banks to the cost of transformers as alternative means of providing increased system capacity.

**Improved System Voltage Profile:** Applying capacitors to a system will result in a voltage rise in the system from the point of installation back to the generation. In a system with lagging power factor, this occurs because capacitors may reduce the amount of reactive current being carried in the system, therefore, reducing the amount of resistive and reactive voltage drop in the system. There are a number of formulae that can be used to estimate the voltage rise that capacitors will produce. A commonly used one is as follows:

\[ \Delta V = \frac{(K \text{ var})(X_L)}{10(KV)^2} \]  \hspace{1cm} 2.41

Where:
- \( \Delta V \) is the percent voltage rise at the point of the capacitor installation.
- \( KV \) is the system line to line voltage without capacitor in service \[^{[30]}\]
- \( K \text{ var} \) is the three phase kilovar rating of the capacitor bank.
$K_L$ is the inductive reactance of the system at the point of the capacitor installation, in ohms. Capacitor banks are typically installed at distribution buses and directly on customer delivery buses to provide voltage support to smaller areas and to individual customers. Capacitor banks installed on distribution lines support voltage along the entire length of line.

**Reduced Billing charges:** A number of utilities use some form of kilovoltampere billing for their large customers (e.g.; utilities and large industrial customers). Since the application of shunt power capacitors can result in a reduced kilovoltampere loading, this can result in reduced billing charges.

The kilovoltampere billing charge may be calculated in many ways, including the following:

(i) A charge per kilowatt demand multiplied by a factor that increases with decreasing power factor.

(ii) A fixed charge per peak kilovoltampere

**Reduced System Power Losses:** On some distribution systems, a significant reduction in losses may be achieved by the installation of shunt power capacitors. The installation of shunt power capacitors can reduce current flow through the system from the point of the capacitor installation back to the generation. Since power loses are directly proportional to the square of the current, a reduction of current flow results in a much greater reduction of power losses. Capacitors are often installed as close to the load as possible for this reason. Reactive power compensation can be achieved by connecting capacitors permanently to the lines [30].

The addition of shunt power capacitors reduced kilovar current. When the kilovar current in a circuit is reduced, the total current is reduced, if the kilowatt current does not change as is usually the case;
the power factor will improve as kilovar current is reduced. It is a well known fact that shunt power capacitors are the most economical source to meet the reactive power requirements of inductive load and distribution lines operating at a lagging power factor. When reactive power is provided only by power plants, such system components (ie generators, transformers, distribution lines etc) has to be increased in size accordingly. Capacitors can mitigate these conditions by decreasing the reactive power demand back to the generators. Line currents are reduced from capacitor locations back to generation equipment. As a result, losses and loadings are reduced in distribution lines.

Reactive Power compensation or power factor correction is performed by the following methods:

(i) **Individual Power Factor Correction:**
   To individually correct the power factor of a multiple load, a suitably sized capacitor is connected to each element of the total load.

(ii) **Group Power Factor Correction**
    Group power factor correction is achieved by connecting one capacitor to a number of different loads usually sharing the same duty cycle.
    A shared duty cycle prevents the use of too much capacitance and avoids over correction of the power factor.

(iii) **Centralized Automatic Power Factor Correction:**
    This involves the connection of number of capacitors, usually to the supply distribution point. The capacitors are controlled by a microprocessor based relay which monitors the reactive power demand on the supply. The relay connects and/or disconnects the capacitors to automatically compensate for the reactive power on the system.
Choosing the most appropriate type and level of compensation necessarily is important, as overcompensation can be as harmful to the system as under compensation. Once the appropriate type of compensation has been determined, a method of controlling the compensators under the varying load conditions of the system must be formulated.

2.7.6 POWER LOSS REDUCTION USING CAPACITOR

Electrical distribution power losses can be reduced using capacitors as shown in figure 2.10.

Without capacitor installed (i.e., the off state or when the switch, S, is open), the current flowing in the line, Ia, is equal to the current flowing in the load, I_{load}. Also, depending on the power factor, the current Ia is composed of real and imaginary part, Iax + jIay. However, what contributes in the real power losses is the magnitude of the current, that is, power loss in the line is equal to the resistance of the line multiplied by the square of the magnitude of the current. [31].

But, with capacitor installed (i.e., the On-state or when the switch, S, is closed), the capacitor supplies reactive power (Kvar). This amount of Kvar injects current that is, ideally, purely imaginary, thus reducing the
amount of imaginary component of the power that flow in the line. This reduction of imaginary component of current that flow in the line also:

1. reduces the magnitude of current that flows,
2. reduces the amount of voltage drop
3. reduces the phase angle difference between the voltage and the current, thereby improving the power factor, and most importantly,
4. reduces the $1^2R$ power losses in the distribution line.

Capacitor placement in a distribution system can reduce power losses in electrical distribution feeder. In addition to loss reduction, there are also other benefits like, increase in receiving of voltage profile, increase of equipment capacity, etc. However, if the placement of capacitors is not optimized, it can cause either,

1. minimal loss reduction or
2. incur additional loss due to KVAR overcompensation.

### 2.7.7 CONSIDERATION OF HARMONICS WHEN APPLYING CAPACITORS.

The level of harmonic voltage and current on distribution systems are becoming a serious problem. Some of the problems caused by harmonics are: capacitor bank failure from dielectric breakdown or reactive power overload, over voltages and excess currents on the system from resonance to harmonic voltages or currents on the network, dielectric instability of insulated cables resulting from harmonic overvoltages on the system etc. These effects depend on the harmonics source (e.g network nonlinearities from loads such as rectifiers, inverters, welders, arc furnace, voltage controllers, frequency converter etc. The presence of harmonics causes the distortion of the voltage or current waves. [32]
The impact of harmonics on distribution transformers are numerous. For example, voltage harmonics result in increased iron losses, current harmonics result in increased copper losses and stray flux losses. The losses may in turn cause the distribution transformer to be overheated and cause more power losses.

Therefore, system harmonics should be considered when applying power factor correction capacitors. Although capacitors do not generate harmonics, under certain conditions they can amplify existing harmonics. Harmonics are generated when non-linear loads are applied to power systems. These non-linear loads include: adjustable speed drives, programmable controllers, induction furnaces, computers, and uninterruptible power supplies. Capacitors can be used successfully with non-linear loads when harmonic resonant conditions are avoided.

To minimize the occurrence of harmonic resonance, the resonant harmonic of the system including the capacitor should be estimated. The resonant frequency can be calculated by:

\[ h = \sqrt[3]{\frac{KVA_{sc}}{KVAR}} \]

Where: \( h \) = calculated system harmonic
KVA_{sc} = short circuit power of the system
KVAR = rating of the capacitor. Harmonic values of 5,7,11, and 13 should be avoided as they correspond to the characteristic harmonics of non-linear loads. The harmonic value of 3 should also be avoided as it coincides with harmonics produced during transformer energization and/or operation of the transformer above rated voltage. Once identified, the resonant harmonics can be avoided in several ways.

i. Change the applied KVAR to avoid unwanted harmonics.

Although this is the least way to avoid resonant harmonics, it is not always successful because typically some portion of the applied
KVAR is switched on and off as load conditions require. The calculation of system harmonics should be repeated for each level of compensation. Adjusting the size of the capacitor(s) may be necessary to avoid the harmonic values.

ii. Add harmonic filters.
In order to filter harmonics at a specific site, tuned harmonic filters can be applied. A capacitor is connected in series with an inductor such that the resonant frequency of the filter equals the harmonic to be eliminated. Turned filters should never be applied without a detailed analysis of the system. The currents expected to flow in the filter are difficult to predict and are complex function for the system characteristics.

![Harmonic Generator](Image)

**Figure 2.11 Addition to Harmonic Filters**

iii. Add Blocking Inductors
Inductors added to the line feeding the capacitor can be sized to block higher than 4\textsuperscript{th} harmonic currents. This method protects the capacitor from the harmonics but does not eliminate the harmonics from the system. A system study is required to determine correct ratings for the capacitor and inductors.
2.7.8 **CARDINAL RULES FOR APPLICATION OF CAPACITOR BANKS IN A DISTRIBUTION SYSTEMS:**

a. The cumulative data gathered for the whole utility industry indicate that approximately 60 percent of the capacitors is applied to the feeders, 30 percent to the substation buses and the remaining 10 percent to the transmission system.

b. There is only one location for each size of capacitor bank that will produce maximum loss reduction.

c. Whenever possible, capacitors should be located at or near the load on systems in order to obtain minimum cost and maximum benefits. Maximum benefits are obtained when they are located at the load.

d. Capacitors are also installed or located at the sensitive nodes especially when the system is having concentrated load. Concentrated load means that the load is centered at the node. In this project the capacitors are installed at the sensitive nodes because the distribution system is a concentrated load system.

e. It is usual to have the capacitors in several banks so that individual banks can be switched in or out of circuit either automatically or manually as the factory load changes. [33]

f. The best way to determine the capacitor kilovars to use is to calculate the rate of return and actual naira savings for various final power factor values.

g. In actual practice, it is generally not necessary or economical to improve the power factor to 100 percent, capacitors are used to supply part of the load kilovar requirements and the supply system provides the remainder.

h. All capacitor banks should be equipped with a means to disconnect them from the electric system.
Reasons for the application of shunt capacitor units in the distribution system are because, it:

(i) Provides low temperature rise and negligible losses.
(ii) Occupy little floor space.
(iii) Needs no special foundation.
(iv) Increases voltage level at the load.
(v) Improves voltage regulation if the capacitor units are properly switched
(vi) Reduces $I^2R$ power loss in the system because of reduction in current.
(vii) Reduces $I^2X$ kVAR loss in the system because of reduction in current.
(viii) Increases power factor of the distribution systems.
(ix) Releases the distribution systems capacity for additional load growth.

2.8 **ACTIVE POWER FACTOR CORRECTION.**

An active power factor correction (Active PFC) is a power electronic system that controls the amount of power drawn by load in order to obtain a power factor close as possible to unity. In most applications, the active power corrector controls the input current of the load so that the current waveform is proportional to the main voltage waveform [34].

One type of active power factor correctors is the boost converter.

Active power factor corrections can be single-staged or multi-stage.

In the case of a switched-mode power supply (SMPS), a boost converter is inserted between the bridge rectifier and the main input capacitors. The boost converter attempts to maintain a constant DC bus voltage on its output while drawing a current that is always in phase with and at the
same frequency, as the line voltage. Another switchmode converter inside the power supply produces the desired output voltage from the DC bus. This approach requires additional semiconductor switches and control electronics but permit cheaper and smaller passive components. It is frequently used in practice. Switched-mode power supply with active power factor correction can achieve power factor of about 0.99.

The boost converter operating in a continuous current mode (i.e., the value of the inductor at the input is calculated such that it conducts continuously throughout the switching cycle) applies the smallest amount of high frequency current to the input capacitor $C_i$ (see figure 2.12). It is the only topology which allows the noise across the input capacitor to be reduced, which is the major factor defining the size and cost of the filter. Additionally, the boost inductor stores only a part of the transferred energy (because the mains still supplies energy during the inductor demagnetization) and so the inductor required is smaller in comparison with the other topologies. The boost topology therefore leads to the cheapest power factor corrector solution but does not provide either inrush current or short circuit protection. The basic topology of a boost power factor corrector is as shown in figure 2.12 [35].
Figure 2.12: Basic topology of a Boost PFC

Source: Reference [35]
2.8.1 BOOST CIRCUIT PARAMETER OPTIMIZATION

Figure 2.12 shows the general topology of a Boost Power Factor Correction (BPFC)
Its optimization requires careful adjustment of the following parameters:

(a) The value of the input capacitor $C_1$.
(b) The current ripple in boost inductor $L_b$.
(c) The parasitic capacitances of the boost inductor and the power semiconductors, including those associated with the heat sink.
(d) The operating frequency and frequency modulation techniques.

2.8.2 VALUE OF THE INPUT CAPACITOR $C_1$.

The noise across the input capacitor is proportional to the current ripple and inversely proportional to the capacitor value.

2.8.3 CURRENT RIPPLE IN THE BOOST INDUCTOR.

The input ripple $(\Delta i)$ is a function of the input voltage $(V_i)$, output voltage $(V_{out})$, inductor value $(L_b)$ and switching frequency $(F_S)$, and can be expressed as

$$\Delta i = \frac{(V_{out} - V_i)}{F_s \cdot L_b \cdot V_{out}}$$

Assuming the typical values $V_i = 300V$, $V_{out} = 400V$
$F_s = 70$KHz and $L_b = 1$mH

If the system is operating in continuous mode, a typical value of $\Delta i$ may be 1A.

If the system operates in discontinuous mode with $L_b = 150 \mu H$, $\Delta i$ might be 7A. Using a continuous mode requires an inductance value about ten times that need when operating in discontinuous mode, however, the low value of current ripple means that a cheaper and efficient iron powder core can be used.
When operating with ripple current larger than around 1A, the larger $\frac{di}{dt}$ leads to the occurrence of skin effects and large eddy currents in an iron powder core, meaning that operation in discontinuous mode requires a more expensive ferrite core.

So, a cheaper system is achieved controlling a small current ripple by operating in continuous mode, despite the large inductor value.

For any design over 100W, the preferable type of Power Factor Correction is Active Power Factor Correction (Active PFC) since it provides a lighter and more efficient power factor control. Active PFC is comprised of a switching regulator operating at a high switching frequency, being able to generate a theoretical power factor of over 95%. Active Power Factor Correction automatically corrects for AC input voltage, and is capable of a wide range of input voltage. One disadvantage of Active PFC is the extra cost resulting from the additional complexity required in its implementation [36].

**Figure 2.13: Basic Active Power Factor Correction Circuit**

Figure 2.13 above depicts the basic elements of an active power factor correction circuit. The control circuit measures both the input voltage (pin 2 on the controller) as well as the current (RS, pin 3 and 11 on the controller) and adjust the switching time and duty cycle to present an in phase voltage and current load to the input. The Power Factor
Correction (PFC) works by inducing a current in the inductor \((L_1)\) and causing the current to track the input voltage. The control circuit senses both the input voltage and the current flowing through the circuit. By controlling the on time in the switch \((Q_1)\) that places \(L_1\) across the output of the rectifier, the current in the coil increases as the input voltage increases. The switch is turned off periodically and the voltage at the drain end rises until the current in the inductor voltage achieves the charge level. Usually, this level is set to several volts higher than the bridge rectifier peak output voltage.

The active PFC shown above is in the form of a boost regulator and as a result the voltage appearing across the load \((R_1)\) must be greater than the highest value of the peak voltage appearing at the input.

Using an active PFC circuit, any input voltage ranging from 87 to 266V (RMS) can be accommodated and power factors \(\geq 0.98\) can be achieved with relative ease.

Example of active P.F.C is the Active Power Factor Correction Technique for Three-Phase Diode Rectifiers shown in figure 2.14.

### 2.8.4 PRINCIPLES OF OPERATION OF ACTIVE POWER FACTOR CORRECTION TECHNIQUE FOR THREE-PHASE DIODE RECTIFIERS

The proposed three phase ac to dc converter (fig. 2.14) consists of two main power conversion stages. The first stage is a three phase ac to dc rectifier consisting of an input filter, a boost inductor, a three phase diode rectifier, an active power factor correction stage, and a dc link filter capacitor. The second stage can be modeled as any type of load requiring a regulated or unregulated dc bus such as general purpose single phase or three phase inverters or dc to dc converters with high frequency isolation. The active waveshaping of the input current
waveform is obtained through the use of the three boost chopper components $L_{ia}$, $Q_b$ and $D_b$, as shown in fig. 2.15 [37].

Fig. 2.14 (a) Proposed three-phase ac to dc converter. (b) Single-phase equivalent circuit of (a)
Fig. 2.15. Simulated waveforms. (a) Three-Phase voltages. (b) Boost switch \( (Q_b) \) gating signals. (c) Rectifier input current \( (I_{ia}) \) and its spectrum.

The boost switch, \( Q_b \), is turned on at constant frequency. The duty cycle of \( Q_b \) is varied for load variation only and it is such that the input current is always discontinuous. During the ON period of the boost switch all three input ac phases become shorted through inductors \( L_{ia}, L_{ib}, L_{ic} \), the six rectifier diodes and the boost switch. Consequently the three input currents \( I_{ia}, I_{ib}, I_{ic} \) begin simultaneously to increase at a rate proportional to the instantaneous values of their respective phase voltages. Moreover the specific peak current values during each ON interval Fig. 2.15(c) are proportional to the average values of their input phase voltages during the same ON interval. Since each of these voltage average values varies sinusoidally the input current peaks also vary sinusoidally (fig. 2.15). Moreover since the current pulses always begin at zero, it means that their average values also vary sinusoidally. Consequently all three input ac currents consists of the fundamental
(60Hz) component and a band of high frequency unwanted components centered around the switching frequency \((f_b)\) of the boost switch. Since this frequency \((f_b)\) can be in the order of several tens of KHZ, filtering out of the unwanted input current harmonics becomes a relatively easy task. From fig. 2.15 it is also seen that input power control (or output voltage regulation) can be achieved through pulse with modulation of the boost switch ON interval at constant frequency \((f_b)\).

Incidently \(f_b\) can be easily locked to the main 60Hz frequency to avoid beat frequency effects in the input currents.

Finally, under the operating conditions described here the displacement input power factor \((\cos \phi I)\) before filtering is unity. Consequently, the overall input power factor (before filtering) becomes equal to the harmonic input power factor and it is given by:

\[
\text{Power factor} = \frac{\sum_{n=1}^{\infty} \left( \frac{L_{ia,n}}{\sqrt{2}} \right)^2}{\frac{L_{ia,I}}{\sqrt{2}}} = 2.44
\]

Where

\(L_{ia,n}\) is the fourier component of the \(n\)th harmonic component of current \(I_{ia}\).

\(\cos \phi\) is the displacement factor.

It is noted that the current harmonics associated with this power factor can be suppressed by a relatively small input capacitor \((C_{ia})\) and inductor \((L_{i1})\) because of their high frequencies.

Therefore the overall input power factor after filtering (ie...at the ac source) is very close to unity.
## 2.9 PROPERTIES OF CAPACITIVE AND ACTIVE POWER FACTOR CORRECTIONS

<table>
<thead>
<tr>
<th>Capacitive power factor correction</th>
<th>Active power factor correction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Features</strong></td>
<td>Complete solutions including all components for PFC-BOOST topology such as Boost converter, Bridge rectifier etc. Output voltage is greater than Input voltage (Vo &gt; Vi), Efficiency 95%, Power factor 99%.</td>
</tr>
<tr>
<td>Inductors, capacitors and resistors</td>
<td></td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td>It provides a steady power system frequency. It generates power factor over 99%. It reduces total harmonics. It automatically correct for alternating current (AC) input voltage and it is capable of a full range of input voltage.</td>
</tr>
<tr>
<td>It improves power factor over 98%.</td>
<td></td>
</tr>
<tr>
<td>It releases system capacity. It reduces system power losses. It reduces billing charges. It improves voltage profile. It has no current or voltage surge. It has no inrush current, therefore transformers are not subjected to short circuit currents and hence the life of the transformer increases. Compensation at extremely low voltage is possible. As there is no moving part involved, maintenance cost is negligible. It is not complex and bulky. It occupies little floor space It is more practicality It is less expensive and easy to install</td>
<td></td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>It is more complex method of power factor correction. It is more expensive to produce an active power factor correction power supply. It does not provide either in rush current or short circuit protection. Therefore, high inrush current increases the possibility of capacitor, exploding and catching fire, because there is excessive pressure generated inside the capacitor unit, so life of capacitor progressively deteriorates. Compensation at low voltage is not possible, resulting in wear and tear of mechanical parts. It has large switching surges even as high as 200 times of rated capacitor current.</td>
</tr>
<tr>
<td>Switching the capacitors into or out of the circuit causes harmonics. It may be affected when environmental vibration occurs. It requires that AC input voltage be set normally.</td>
<td></td>
</tr>
<tr>
<td>Possibility of overcompensation, is seen as a load when all other loads are disconnected.</td>
<td></td>
</tr>
</tbody>
</table>
Capacitive power factor correction | Active power factor correction
---|---
Repeated and momentary short circuit due to capacitor switching will have an impact on the life of the transformers. The contactor chatter at low voltages resulting in very high inrush current.

Limitations | It is limited to 180° out of phase. The allowable overload limits of capacitors based on IEEE std 18-2002 are as follows:
(i) 110% of rated rms voltage
(ii) 120% of rated peak voltage, including harmonics
(iii) 135% of rated kvar

It is limited to 180° in phase. According to regulatory requirement, the maximum amplitude of line frequency harmonic is limited to 39th harmonic. For equipment like personal computers, televisions and monitors, the harmonic amplitudes are proportional to the input power of the device.

Applications | It is applicable in high voltage distribution and transmission systems. It is used for AC supplies only.

It is welcome to supply power for personal computers, telecommunications battery powered systems, it is used for supply of dc powers.

Formular for power factor. | Power factor = $\frac{KW}{\sqrt{(KW)^2+(KVAR)^2}}$

Power factor = $\frac{1}{\sqrt{1+\left(\frac{THD(\%)}{100}\right)^2}}$

Source: Reference [26], [38]

## 2.10 COMPARISON OF CAPACITIVE AND ACTIVE POWER FACTOR CORRECTIONS

<table>
<thead>
<tr>
<th>CAPACITIVE POWER FACTOR CORRECTION</th>
<th>ACTIVE POWER FACTOR CORRECTIONS</th>
</tr>
</thead>
</table>
* It improves power factor aver 98% | * It improves power factor aver 99% |
* It reduces resonant harmonics | * It reduces total harmonics |
* The is no current or voltage surge | * Large switching surges even as high as 200 times of a rated capacitor current |
* There is no inrush current, transformers are never subjected to short circuit currents and hence the life of the transformers increases | * Repeated and momentary short circuit due to capacitor switching will have an impact on the life of the transformers. |
* Compensation at extremely low voltage is possible | * Compensation at low voltage is not possible, resulting in wear and tear of mechanical parts. |
* The point of capacitor switching is controlled and increases the life of the capacitor and switching unit. | * High inrush current increases the possibility of capacitors exploding and catching fire because there is excessive pressure generated inside the capacitor unit, so life of capacitor progressively deteriorates.|
**CAPACITIVE POWER FACTOR CORRECTION**  
* It is not complex and bulky.  
* It occupies very little space and has low weight, so that it can be mounted on distribution lines without pulling the poles.  
* It is not expensive to produce capacitive (reactive) power factor correction.  
* It is limited to $180^\circ$ out of phase of voltage and current waveforms.  
* It is more practicability

| **ACTIVE POWER FACTOR CORRECTIONS** |  
|-----------------------------------|-------------------------------------------------|------------------------------------------------|------------------------------------------------|------------------------------------------------|------------------------------------------------|
| * It is a complex and bulky circuit. | * It occupies a very large space and it has high weight such that it cannot be mounted on distribution lines to avoid distortion of cables and poles. | * It is very expensive to produce active power factor correction power supply. | * It is limited to $180^\circ$ in phase of voltage and current waveforms. | * It is less practicality. |

Active power factor produces power factor correction, close to unity as well as capacitive power factor correction but capacitive power factor correction was chosen because it is less expensive, not complex, very easy to implement, lower weight and occupies very little space than active power factor correction component. [26], [38].
CHAPTER THREE
LOAD FLOW ANALYSIS AND SYSTEM MODELLING

3.1 SYSTEM MODELING

In this project, the distribution system is assumed to be a balanced three phase system, and hence a single phase representation can be used. The control devices consists of shunt capacitors which are assumed to be already placed optimally on the system. The distribution system is modeled using a \( \pi \) equivalent representation.

Shunt capacitors are frequently used on distribution system for power factor correction and voltage support. For purpose of modeling, capacitors are treated as constant shunt admittance element on a per-phase basis.

In this chapter the mathematical analysis were carried as follows:

(i) Load flows
(ii) Load variation with time
(iii) Derivation of power loss reduction formulae or equations
(iv) Derivation of economical power factor

3.2 LOAD FLOWS.

The load flow is a computer algorithm that displays the kilowatt (KW) and Kilovolt-ampere reactive (Kvar) loading of distribution lines and transformers after an iterative process of solving for node voltages. It is like using an ammeter and voltmeter to determine the junction voltages and current on the resistors of figure 3.1. But instead of amperes, line flows are in KW and Kvar. Instead of \( V = 126 \) volts from dry cells, the source feeding the circuit is in KW and Kvar. All other units are in per unit. Most chosen base MVA is 100.

Load flow analysis is used to determine the apparent power and voltages at each bus in the distribution system under steady state conditions. While there are several methods for performing load flow
analysis the Gauss-Seidel technique and the Newton-Raphson techniques are perhaps the most common. Both methods can be carried out very quickly using modern computers, however, the Gauss-Seidel method is preferred for distribution systems as the low X/R ratios typical of distribution systems often leads to ill-conditioned Jacobian matrices which can cause the Newton–Raphson method to fail to converge. As well, the Gauss–Seidel technique has the following advantages [25], [39].

(i) It is relatively insensitive to the initial voltage estimates,
(ii) It has reasonably small memory requirements, and
(iii) It is simple to implement in a computer program.

Every possible solution in the control problem requires a load flow to be performed so that its merits can be assessed. As a result, for a large distribution system, even with the use of a fast computer, the time required to complete a load flow to evaluate every solution would be prohibitive. This is the main reason for not performing an exhaustive search.

While the use of an optimization technique such as genetic algorithm does reduce the number of times that the load flow analysis must be performed, the load flow still consume most of the processing time required by the optimization technique. It is important therefore to examine the issue using the \( \pi \) equivalent representation as shown in figure 3.3.

Types of variable used:

(i) Uncontrollable or disturbance variable \( P,Q \) (load) are beyond control since they are dictated by the customer.

(ii) State or dependent variable, voltage \( V \) magnitude and angle \( \theta \) are computed based on the other two variables.
Table 3.1  Classification Of Load Flow Busses

<table>
<thead>
<tr>
<th>Type</th>
<th>Known variables</th>
<th>Unknown variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Sl, Swing or Slack or Reference bus</td>
<td>V, theta</td>
<td>P, Q Losses</td>
</tr>
<tr>
<td>(ii) P Q, load bus</td>
<td>P, Q</td>
<td>V, theta</td>
</tr>
</tbody>
</table>

Where:

\[ V = \text{voltage magnitude} \]

\[ \text{Theta} = \text{voltage angle} \]

\[ P, Q = \text{KW, KVAR load.} \]

### 3.3 NODE EQUATIONS

Let us derive the nodal equation using a simple electrical circuit shown in figure 3.1.

The junctions formed when two or more elements (R, L, C, etc) are connected are called nodes. One of them is designated as reference. By applying kirchoff’s current law, we can derive the nodal equations. The sum of the current entering the node equals the sum of the currents leaving the node. When making the current equation for node i, we assume node i to be of a higher potential than node j. In node 1 for
example, the left side is the current source and the right side is \([V(1) - V(2)]/r(1,2)\). [39]

Here node 1 is of a higher potential than node 2, we do this to all nodes except the reference. If there is no current source, put zero on the left side, as in node 3. Therefore:

\[
\begin{align*}
\frac{V_{O,1}}{r_{O,1}} &= \frac{V_1 - V_2}{r_{1,2}} + \frac{V_1 - V_3}{r_{1,3}} & \text{node 1} \\
\frac{V_{O,2}}{r_{O,2}} &= \frac{V_2 - V_3}{r_{2,3}} + \frac{V_2 - V_1}{r_{1,2}} & \text{node 2} \\
\frac{V_{O,3}}{r_{O,3}} &= \frac{V_3 - V_1}{r_{1,2}} + \frac{V_3 - V_2}{r_{2,3}} & \text{node 3}
\end{align*}
\]

Equation 3.1 can be written as:

\[
I_1 = \left(\frac{1}{r_{1,2}} + \frac{1}{r_{1,3}}\right)V_1 + \left(-\frac{1}{r_{1,2}}\right)V_2 + \left(-\frac{1}{r_{1,3}}\right)V_3
\]

\[
I_2 = \left(-\frac{1}{r_{1,2}}\right)V_1 + \left(\frac{1}{r_{2,3}} + \frac{1}{r_{1,2}}\right)V_2 + \left(-\frac{1}{r_{2,3}}\right)V_3
\]

\[
I_3 = \left(-\frac{1}{r_{1,3}}\right)V_1 + \left(-\frac{1}{r_{2,3}}\right)V_2 + \left(\frac{1}{r_{0,3}} + \frac{1}{r_{1,3}} + \frac{1}{r_{2,3}}\right)V_3
\]

Rearranging equation (3.2) in matrix form we get:

\[
\begin{bmatrix}
I_1 \\
I_2 \\
I_3
\end{bmatrix}
= 
\begin{bmatrix}
\frac{1}{r_{1,2}} + \frac{1}{r_{1,3}} & -\frac{1}{r_{1,2}} & -\frac{1}{r_{1,3}} \\
-\frac{1}{r_{1,2}} & \frac{1}{r_{2,3}} + \frac{1}{r_{1,2}} & -\frac{1}{r_{2,3}} \\
-\frac{1}{r_{1,3}} & -\frac{1}{r_{2,3}} & \frac{1}{r_{0,3}} + \frac{1}{r_{1,3}} + \frac{1}{r_{2,3}}
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
V_3
\end{bmatrix}
\]

\[(3.3)\]
In equation 3.3, current sources is replaced by I. This is so because in power system analysis, current source is no longer a “cell” or a battery symbol with an “r” in series with that cell. Current source is a KW and KVAR distribution and resistance in ohms as load is replaced by KW and KVAR load. Connection between transmission and loads are distribution lines and transformers. These are impedance in complex numbers with line charging in KVAR which are represented by \( \pi \) equivalent.

The square matrix when replaced with line/transformer impedances becomes the bus admittance matrix or Y bus as shown below.

\[
\begin{array}{c}
\begin{array}{c}
\text{i} \\
Y_i \\
O
\end{array}
\end{array}
\quad \text{Line} \quad
\begin{array}{c}
\begin{array}{c}
\text{j} \\
Y_j \\
O
\end{array}
\end{array}
\]

**Fig. 3.2 \( \pi \) equivalent for line charging.**

Distribution line charging is

\[
Y_{io} = Y_{jo} = \frac{\text{KVAR}}{2 \times \text{mva base}}
\]

3.4

KVAR = total line charging mva BASE = 100 mva base. The 2 in the denominator of equation 3.4 simply means that the Kvar charging is equally divided as in \( \pi \) model. When Kvar is divided by Base, it results to per unit (pu) admittance.

Reactive shunt is

\[
Y_{io} = \frac{\text{KVAR}}{\text{Kva Base}}
\]

3.5
(-) for reactor, (+) for capacitor, there is no division by 2 here. The positive and zero sequence $Y$ bus matrix has elements called diagonal $Y(i,i)$ and off diagonal $Y(i,j)$. For uncoupled zero sequence and positive sequence,

$$Y(i, j) = -\frac{1}{Z_{ij}}$$  \hspace{1cm} 3.6

$$Y(i, i) = \sum_{j=1}^{n} \left( \frac{1}{Z_{ij}} \right) + Y_{io}$$  \hspace{1cm} 3.7

The second part of equation 3.7 is due to load or line charging. It is also a summation if there are more of them. Equation 3.7 constitute to what is referred to as nodal admittance matrix. Assuming a 4 bus distribution system as shown in figure 3.3.

\begin{center}
\begin{tikzpicture}
\node at (0,0) {O};
\node at (2,1) {1};
\node at (4,0) {4};
\node at (5,0) {3};
\node at (6,1) {2};
\draw (0,0) -- (2,1);
\draw (2,1) -- (4,0);
\draw (4,0) -- (5,0);
\draw (5,0) -- (6,1);
\end{tikzpicture}
\end{center}

\textbf{Figure 3.3} On line diagram of 4 bus distribution system.
The impedance matrix is,

\[ Z_{\text{bus}} = \begin{bmatrix}
1 & Z_{1,1} & Z_{1,2} & Z_{1,3} & Z_{1,4} \\
2 & Z_{2,1} & Z_{2,2} & Z_{2,3} & Z_{2,4} \\
3 & Z_{3,1} & Z_{3,2} & Z_{3,3} & Z_{3,4} \\
4 & Z_{4,1} & Z_{4,2} & Z_{4,3} & Z_{4,4}
\end{bmatrix} \]

The admittance matrix is,

\[ Y_{\text{bus}} = \begin{bmatrix}
1 & \frac{1}{Z_{1,1}} & \frac{1}{Z_{1,2}} & \frac{1}{Z_{1,3}} & \frac{1}{Z_{1,4}} \\
2 & \frac{1}{Z_{2,1}} & \frac{1}{Z_{2,2}} & \frac{1}{Z_{2,3}} & \frac{1}{Z_{2,4}} \\
3 & \frac{1}{Z_{3,1}} & \frac{1}{Z_{3,2}} & \frac{1}{Z_{3,3}} & \frac{1}{Z_{3,4}} \\
4 & \frac{1}{Z_{4,1}} & \frac{1}{Z_{4,2}} & \frac{1}{Z_{4,3}} & \frac{1}{Z_{4,4}}
\end{bmatrix} \]

The diagonal elements are:

\[ Y_{(1,1)} = \frac{1}{Z_{1,0}} + \frac{1}{Z_{1,2}} + \frac{1}{Z_{1,4}} \]
\[ Y_{(2,2)} = \frac{1}{Z_{2,0}} + \frac{1}{Z_{2,1}} \]
\[ Y_{(3,3)} = \frac{1}{Z_{3,0}} + \frac{1}{Z_{3,4}} \]
\[ Y_{(4,4)} = \frac{1}{Z_{1,4}} + \frac{1}{Z_{4,3}} \quad 3.13 \]

The off diagonal elements are:

\[ Y_{(1,2)} = -\frac{1}{Z_{1,2}} \quad 3.14 \]

\[ Y_{(1,3)} = \frac{1}{Z_{1,3}} \quad 3.15 \]

\[ Y_{(1,4)} = -\frac{1}{Z_{1,4}} \quad 3.16 \]

\[ Y_{(2,1)} = -\frac{1}{Z_{2,1}} \quad 3.17 \]

\[ Y_{(2,3)} = -\frac{1}{Z_{2,3}} \quad 3.18 \]

\[ Y_{(2,4)} = \frac{1}{Z_{2,4}} \quad 3.19 \]

\[ Y_{(3,1)} = \frac{1}{Z_{3,1}} \quad 3.20 \]

\[ Y_{(3,2)} = -\frac{1}{Z_{3,2}} \quad 3.21 \]

\[ Y_{(3,4)} = -\frac{1}{Z_{3,4}} \quad 3.22 \]

\[ Y_{(4,1)} = -\frac{1}{Z_{4,1}} \quad 3.23 \]

\[ Y_{(4,2)} = \frac{1}{Z_{4,2}} \quad 3.24 \]

\[ Y_{(4,3)} = -\frac{1}{Z_{4,3}} \quad 3.25 \]
The matrix formed is called Y bus [32].

Table 3.2 Y-bus

<table>
<thead>
<tr>
<th>Bus no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\frac{1}{Z_{1,0}} + \frac{1}{Z_{1,2}} + \frac{1}{Z_{1,4}}$</td>
<td>$-\frac{1}{Z_{1,2}}$</td>
<td>$\frac{1}{Z_{1,3}}$</td>
<td>$-\frac{1}{Z_{1,4}}$</td>
</tr>
<tr>
<td>2</td>
<td>$-\frac{1}{Z_{2,1}}$</td>
<td>$\frac{1}{Z_{2,0}} + \frac{1}{Z_{1,2}}$</td>
<td>$-\frac{1}{Z_{2,3}}$</td>
<td>$\frac{1}{Z_{2,4}}$</td>
</tr>
<tr>
<td>3</td>
<td>$\frac{1}{Z_{3,1}}$</td>
<td>$-\frac{1}{Z_{3,2}}$</td>
<td>$\frac{1}{Z_{3,0}} + \frac{1}{Z_{4,3}}$</td>
<td>$-\frac{1}{Z_{3,4}}$</td>
</tr>
<tr>
<td>4</td>
<td>$-\frac{1}{Z_{4,1}}$</td>
<td>$\frac{1}{Z_{4,2}}$</td>
<td>$-\frac{1}{Z_{4,3}}$</td>
<td>$\frac{1}{Z_{4,1}} + \frac{1}{Z_{4,3}}$</td>
</tr>
</tbody>
</table>

In general, the diagonal part of the Y bus, $Y_{ii}$ for node $i$ is the sum of the admittances of all elements connected to node $i$. This may include connections to ground such as line charging, reactor/capacitor and the equivalent inductance for off-nominal transformers. $Y_{ij}$, (one of the off diagonal element of the y bus), is the negative of the admittance.
between node i and node j. The zeros in figure 3.27 shows that there is no link between the buses.

**Gauss-Siedel load flow (GSLF)**

The equations can be visualized using a sample of 4-bus distribution system.

In a distribution system the total shunt admittance of the line is divided into two equal parts placed at the sending and receiving ends of the line. It is important therefore to examine the issue using the π equivalent representation shown in figure 3.4 [40].

$$\begin{align*}
  & \frac{I_\text{S}}{2} \quad Z \quad \frac{I_\text{R}}{2} \\
  & V_\text{S} \quad \frac{Y}{2} \quad \frac{Y}{2} \quad V_\text{R}
\end{align*}$$

**Fig. 3.4 Nominal - circuit.**

To obtain an expression for sending voltage, we note that the current in the capacitance at the receiving end is \( \frac{V_R Y}{2} \) and the current in the series arm is \( I_R + \frac{V_R Y}{2} \) Thus:

\[
V_S = \left( \frac{V_R Y}{2} + I_R \right) Z + V_R \quad 3.28
\]

\[
= \frac{ZV_R Y}{2} + ZI_R + V_R \quad 3.29
\]

\[
= \frac{ZV_R Y}{2} + V_R + ZI_R \quad 3.30
\]

\[
= \left( \frac{ZY}{2} + I \right) V_R + ZI_R \quad 3.31
\]
\[ I_S = \frac{V_S Y}{2} + \frac{V_R Y}{2} + I_R \]  

Substituting equation 3.31 into equation 3.32 we get:

\[
I_S = \left[ \left( \frac{ZY}{2} + I \right) V_R + ZI_R \right] \frac{Y}{2} + \frac{V_R Y}{2} + I_R
\]  

\[
= \frac{ZYV_R Y}{4} + \frac{V_R Y}{2} + \frac{ZI_R}{2} + \frac{V_R Y}{2} + I_R
\]  

\[
= \frac{ZY^2 V_R}{4} + \frac{2V_R Y}{2} + \frac{ZI_R}{2} + I_R
\]  

\[
= V_R Y \left( \frac{ZY}{4} + I \right) + I_R \left( \frac{ZY}{2} + I \right)
\]  

Where:  
\( I_S \) is sending current to the bus  
\( V_s \) is sending voltage to the bus  
\( V_R \) is receiving voltage to the bus  
\( I_R \) is receiving current to the bus

The admittance to the bus \( Y = \frac{I_S}{V_S} \)  

The distribution system is characterized by a system of \( n \) nonlinear equations of the form in equation 3.37. Therefore equation 3.37 can be written as

\[
[I_{bus}] = [Y_{bus}] [V_{bus}]
\]  

Where:  
\( n \) is the number of buses in the system.  
\( I_{bus} \) is the bus current vector  
\( V_{bus} \) is the bus voltage vector  
\( Y_{bus} \) is the bus admittance
Y bus for power system is in complex number.

\[ Y_{ij} = \frac{1}{r + jx} = \frac{1}{r + jx} \begin{pmatrix} r - jx \\ r - jx \end{pmatrix} \quad 3.39 \]

Where r is the real part and x is the imaginary part.

From Equation 3.38 it is clear that the current at the \( i^{th} \) bus is given by

\[ I_i = \sum_{j=1}^{n} Y_{ij}V_j = Y_{ii}V_i + \sum_{j \neq 1}^{n} Y_{ij}V_j \quad 3.40 \]

thus \[ Y_{ii}V_i = I_i - \sum_{j \neq 1}^{n} Y_{ij}V_j \quad 3.41 \]

Solving for \( V_i \) gives: \[ V_i = \frac{1}{Y_{ii}} (I_i - \sum_{j=1}^{n} Y_{ij}V_j) \quad 3.42 \]

and recalling Equation 2.30 where, \[ I_i = \frac{P_i - jQ_i}{V_i} \quad 3.43 \]

Substituting equation 3.43 into equation 3.42 we get

\[ V_i = \frac{1}{Y_{ii}} \left( \frac{P_i - jQ_i}{V_i} - \sum_{j=1}^{n} Y_{ij}V_j \right) \quad 3.44 \]

On substituting equation 3.43 into equation 3.40 and \( i=1 \)

\[ \frac{P_1 - jQ_1}{V_1^*} = Y_{11}V_1 + Y_{12}V_2 + Y_{13}V_3 + Y_{14}V_4 \quad 3.45 \]

Solving for \( V_1 \) gives

\[ V_1 = \frac{1}{Y_{11}} \left[ \frac{P_1 - jQ_1}{V_1^*} - (Y_{12}V_2 + Y_{13}V_3 + Y_{14}V_4) \right] \quad 3.46 \]

Also \[ \frac{P_2 - jQ_2}{V_2^*} = Y_{21}V_1 + Y_{22}V_2 + Y_{23}V_3 + Y_{24}V_4 \quad 3.47 \]
Solving for \( V_2 \) gives.

\[
V_2 = \frac{1}{Y_{22}} \left[ \frac{P_2 - jQ_2}{V_2^*} - (Y_{21}V_1 + Y_{23}V_3 + Y_{24}V_4) \right]
\]  

3.48

Also

\[
\frac{P_3 - jQ_3}{V_3^*} = Y_{31}V_1 + Y_{32}V_2 + Y_{33}V_3 + Y_{34}V_4
\]  

3.49

Solving for \( V_3 \) gives,

\[
V_3 = \frac{1}{Y_{33}} \left[ \frac{P_3 - jQ_3}{V_3^*} - (Y_{21}V_1 + Y_{22}V_2 + Y_{24}V_4) \right]
\]  

3.50

Equation 3.44 involves only the bus voltages and apparent powers as variables, and can be solved iteratively using the most recent estimates of the bus voltage until the change in bus voltage is smaller than some specified tolerance, \( \varepsilon \). The iterative process employed to solve this system of equations is known as Gauss – Seidel method, and forms the basis of the load flow analysis used in this project. It should be pointed out that the equation 3.44 in only used for load buses (buses where the real and reactive power are specified). However, since distribution systems rarely contain generators this is sufficient. In order to reduce the computing time, several calculations can be performed before iterative produce is initiated. These calculations only involve the constant quantities of the admittance matrix values and bus loads, and are given as follows

\[
A_i = \frac{(P_i - jQ_i)}{Y_{ii}}, B_j = \frac{Y_{ij}}{Y_{ii}}
\]  

3.51

Substitution of these equations in to equation 3.44 gives.

\[
V_i = \frac{1}{Y_{ij}} \left( \frac{P_i - jQ_i}{V_i^*} - \sum_{j=1}^{n} Y_{ij}V_j \right)
\]  

\[
V_i = \frac{A_i}{V_i} - \sum_{j=1}^{n} B_{ij}V_j
\]  

3.52
A load flow algorithm based on equation 3.51 and 3.52 and having a convergence tolerance, $\varepsilon = 10^{-6}$ shall be implemented using MATLAB. It should be remembered that the Gauss-Seidel method is an iterative technique, and may require a large number of iterations to converge (or may even fail to converge) on a solution.

In this project, the load flow with the aid of MATLAB is used to determine the voltage at each bus, current at each bus, $I^2R$ loss and $I^2X$ (Reactive) power loss at each bus in Kilowatts.

### 3.4 LOAD VARIATION WITH TIME

It is well known that the loads on a power system are dynamic, that is, they vary over time. These variations may occur quite rapidly (during switching on or off parts of the power system), or may take place more gradually, as in the case of daily load variations. It is these gradual changes due to load variations that are of interest in this project. System loads may be broadly grouped into three load categories: residential, commercial and industrial. As well, the total load at a particular point in the distribution system may be some combination of these load types. It has been suggested [11] that the year can be divided into 12 periods to accommodate the load variations due to the seasons (Raining and Dry seasons), the week (weekday and weekend), and the daily load level (peak load period, and off-peak load period).

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. Daily load also will differ according to time of the day, peak period (07:31am to 10:30pm) and off-peak period (10:31pm to 07:30am the next day). The system loads are considered to be constant during each time interval [25], [41].
Daily load profiles during each season can be further divided into four periods: weekday peak period, weekday off-peak period, weekend peak period, and weekend off-peak period. Hence, the annual load variation of each of the three load type can be divided into twelve periods, and the load variation of the total load can be determined by the weighted sum of the three load types during each period, where the weights are determined from the proportion of each load type at the load point.

In this project, the twelve period model was recommended. Using the load conversion factors presented by Abdel [20], the load profile for each of the twelve periods was obtained. For the system studied in this project, the load at each bus was assumed to consist of 15% industrial, 25% commercial load, and 60% residential load. To more realistically model the unpredictability of the loads, the load at each bus can be multiplied by a uniformly distributed random number between 0.85 and 1.15. This technique also eliminates reliance on the unrealistic approximations used by many researchers that:

(i) The loads at every bus vary in the same proportion and
(ii) The reactive power consumed by the load is a fixed fraction of the real power consumed by the load.

3.5 DERIVATION OF POWER LOSS REDUCTION EQUATIONS

Consider the supply to the inductive load of Figure 3.5 below. The phasor diagram (a) shows the current $I_1$ lagging by an angle $\phi_1$. The active and reactive components are $I_1 \cos \theta_1$ and $I_1 \sin \theta_1$ respectively. The addition of the capacitor (Diagram (b)) causes an additional current $I_C$ to be drawn from the supply, but as the current is almost entirely reactive and leading the voltage by 90° it will reduce the reactive component $I_1 \sin \theta_1$ of the load to a smaller value $I_2 \sin \theta_2$. This means that the current $I_2$ taken from the supply has also been reduced and the new phase angle is $\phi_2$, which gives an improved power factor, $\cos \theta_2$. 
It will be seen that the true power taken from the supply has not altered and $1_1 \cos \theta_1 = 1_2 \cos \theta_2$. Also, $1_2$ is the resultant of the phasor sum of $1_1$ and $1_c$.

It can be seen also that the current $1_2$ flows from X to Y, that is, to the point at which the capacitor is connected, but beyond the capacitor, from Y to Z, the current and power factor are still the original values of $1_1$ and $\cos \theta_1$. Thus, the power factor is improved only on the supply side of the capacitor [14], [42].

From figure 3.5

(b) it is seen that:

$$\tan \theta_1 = \frac{1_1 \sin \theta_1}{1_1 \cos \theta_1} \quad 3.53$$

$$\therefore 1_1 \sin \theta_1 = (1_1 \cos \theta_1) \tan \theta_1 \quad 3.54$$

Also

$$\tan \theta_2 = \frac{1_2 \sin \theta_2}{1_1 \cos \theta_1} \quad 3.55$$

$$\therefore 1_2 \sin \theta_2 = (1_1 \cos \theta_1) \tan \theta_2 \quad 3.56$$

Also $1_2 \cos \theta_2 = (1_1 \cos \theta_1)$ (in-phase component of voltage) \quad 3.57

Capacitor current $I_c = 1_1 \sin \theta_1 - 1_2 \sin \theta_2$ \quad 3.58

Since addition of capacitor causes additional current $1_c$ to be draw from the supply, Reactive Kilovolt amperes (KVAR) = $V1_c \sin \theta$

When the current leads the voltage by $90^0$ ie $\theta = 90^\circ$, then

$$\text{Kvar} = V1_c \quad 3.59$$

$$\therefore I_c = \frac{KVar}{V} \quad 3.60$$
Where \( V \) is the line voltage.

For a 3-phase work, \( I_c = \frac{k \text{ var}}{\sqrt{3} V} \) \[3.61\]

![Diagram of inductive load and capacitor](image)

Fig. 3.5 Effect of capacitor in parallel with an inductive load: (a) an inductive load, (b) adding a capacitor

3.5.1 \( I^2R \) Loss Reduction Due to Capacitor

The active power loss due to a current \( I_1 \) flowing through a circuit with resistance \( R \) is \( I_1^2 R \), and the energy loss during the time \( t \) is \( I_1^2 R t \). Assuming a power factor \( \cos \phi \), the \( I^2R \) loss may be divided into two components:

(i) \( I_1^2 R \) loss due to active component of current

(ii) \( I_1^2 R \) loss due to reactive component of current.

Thus power loss before addition of capacitor is

\[
I_1^2 R = (I_1 \cos \theta_1)^2 R + (I_1 \sin \theta_1)^2 R
\]

3.62
When a capacitor with current $I_C$ is applied, resulting in a new line current $I_2$, then power loss after addition of capacitor is

$$I_2^2 R = \left( I_2 \cos \theta_2 \right)^2 R + \left( I_2 \sin \theta_2 \right)^2 R.$$  \hspace{1cm} 3.63

From equation 3.44, $I_2 \sin \theta_2 = I_1 \sin \theta_1 - I_C$  \hspace{1cm} 3.64

$\therefore I_2^2 R = \left( I_2 \cos \theta_2 \right)^2 R + \left( I_1 \sin \theta_1 - I_C \right)^2 R$  \hspace{1cm} 3.65

$= \left( I_2 \cos \theta_2 \right)^2 R + \left( I_1 \sin \theta_1 \right)^2 R - 2\left( I_1 \sin \theta_1 \right) I_C R + I_C^2 R$  \hspace{1cm} 3.66

But $I_1 \cos \theta_1 = I_2 \cos \theta_2$

Power loss reduction $\Delta L = I_1^2 R - I_2^2 R$

$= \left( I_1 \cos \theta_1 \right)^2 R + \left( I_1 \sin \theta_1 \right)^2 R - \left( I_2 \cos \theta_2 \right)^2 R - \left( I_1 \sin \theta_1 \right)^2 R$

$\hspace{1cm} + 2\left( I_1 \sin \theta_1 \right) I_C R - I_C^2 R$  \hspace{1cm} 3.67

$\therefore \Delta L = 2\left( I_1 \sin \theta_1 \right) I_C R - I_C^2 R$  \hspace{1cm} 3.68

$= \left( 2 I_1 \sin \theta_1 I_C - I_C^2 \right) R$  \hspace{1cm} 3.69

$= \left( 2 I_1 \sin \theta_1 - I_C \right) I_C R$  \hspace{1cm} 3.70

Considering the loss reduction based on the combination of active and reactive components of current, the total power loss $P_L$ in the distribution system is given by:

$$P_L = \sum_{i=1}^{M} I_{iri}^2 = \sum_{i=1}^{M} \left( I_{ai}^2 r_i + I_{ri}^2 r_i \right)$$  \hspace{1cm} 3.71

where $M$ is the total number of the system section, $I_i$ 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 of the flowing current cannot be affected by the compensating capacitors (Zero power factor element), the only term that is of interest are the losses due to the reactive component of the system current, $= I_{ri}^2 r_i$ [20]
The losses due to the reactive currents $P_{rl}$ can be written as:

$$P_{rl} = \sum_{i=1}^{m} Ir_i^2 ri$$

3.6 **DERIVATION OF ECONOMICAL POWER FACTOR.**

Economical power factor is the power factor at which the gain or savings obtained from installing capacitor banks for power loss reduction in a distribution system is equal to or greater than the cost of the capacitor banks and their cost of installation in the system [1]. It is also the power factor at which the net savings is maximum.

![Power triangle for Economical power factor and net savings](image)

Suppose a consumer is charged at $\mathcal{N}A$ per KVA maximum demand plus a flat rate per KWh. Further suppose he is taking power of $P$, kw at a power factor of $\cos\phi$. 
As shown in figure 3.6 his

\[ KVA_1 = \frac{P}{COS\phi_1} \]  
[3.73]

\[ KVAR_1 = Ptan\phi_1 \]  
[3.74]

Suppose by installing capacitors he improves his power factor to \( \cos \phi_2 \) (his power consumption \( P \) remaining the same). In that case his

\[ KVA_2 = \frac{P}{COS\phi_2} \]  
[3.75]

\[ KVAR_2 = P \tan \phi_2 \]  
[3.76]

R education in his KVA maximum demand is

\[ = (KVA_1 - KVA_2) \]  
[3.78]

\[ = \left( \frac{P}{COS\phi_1} - \frac{P}{COS\phi_2} \right) \]  
[3.79]

Since charge is \( \text{NA} \) per KVA maximum demand, his annual saving on his account is

\[ = A \left( \frac{P}{COS\phi_1} - \frac{P}{COS\phi_2} \right) \]  
[3.80]

His KVAR is reduced from KVAR\(_1\) to KVAR\(_2\), the difference KVAR\(_1\)-KVAR\(_2\)= \( P \tan\phi_1 - P \tan\phi_2 \) being neutralized by the leading KVAR supplied by the capacitors. Leading KVAR supplied by the static capacitors

\[ = P \tan\phi_1 - P \tan\phi_2 \]  
[3.81]

The cost of power factor improvement equipment is taken into account by way of interest on capital required to install it plus depreciation and maintenance expenses. Thus, the greater the KVAR reduction, the more costly the P.F improvement capacitor and hence greater the charge on interest on capital outlay and depreciation. A point is reached in practice when any further improvement in power factor, cost more than saving in the bill. Hence it is necessary for the consumer
to find out the value of power factor at which his net savings will be maximum. The value can be found if:

(i) Annual charge per KVA maximum demand and
(ii) The cost per KVAR rating of capacitor are known.

If the cost per KVAR of capacitor is \( NB \) and the rate of interest and depreciation is \( U \) percent per year, then its cost per annum is

\[
\frac{B \times U}{100} \left( P \tan \phi_1 - P \tan \phi_2 \right)
\] 3.82

Assuming \( \frac{B \times U}{100} = C \) 3.83

Cost per annum = \( C \left( P \tan \phi_1 - P \tan \phi_2 \right) \) 3.84

Where \( B \times U \) is cost per KVAR multiplied by depreciation factor of \( U \%

Net annual saving \( S \) is

\[
S = A \left( \frac{P}{COS\phi_1} - \frac{P}{COS\phi_2} \right) - C(P\tan\phi_1 - P\tan\phi_2) \]
3.85

This net savings is maximum when \( \frac{ds}{d\phi_2} = 0 \) 3.86

Therefore \( \frac{ds}{d\phi_2} = \frac{d}{d\phi_2} \left[ A \left( \frac{P}{COS\phi_1} - \frac{P}{COS\phi_2} \right) - C(P\tan\phi_1 - P\tan\phi_2) \right] \) 3.87

\[
= \frac{d}{d\phi_2} \left[ AP(\text{Sec}\phi_1 - \text{Sec}\phi_2) - CP(\tan\phi_1 - \tan\phi_2) \right] = 0
\] 3.88

\[
= -AP(\text{Sec}\phi_2 \tan\phi_2) + CP(\text{Sec}^2\phi_2) = 0
\] 3.89

\[
- AP \text{ Sec}\phi_2 \tan\phi_2 + CP\text{Sec}^2\phi_2 = 0
\] 3.90

\[
AP \text{ Sec}\phi_2 \tan\phi_2 = CP\text{Sec}^2\phi_2
\] 3.91

\[
A \text{ Sec}\phi_2 \tan\phi_2 = C\text{Sec}^2\phi_2
\] 3.92

\[
= A \tan\phi_2 = C\text{Sec}\phi_2
\] 3.93

\[
\frac{\tan\phi_2}{\text{sec}\phi_2} = \frac{C}{A}
\] 3.94
\[
\frac{\sin \phi_2}{\cos \phi_2} = \frac{C}{A}
\]
3.95

\[
\frac{\sin \phi_2}{\cos \phi_2} \cdot \frac{1}{\sec \phi_2} = \frac{C}{A}
\]
3.96

\[
\frac{\sin \phi_2}{\cos \phi_2} \cdot \cos \phi_2 = \frac{C}{A}
\]
3.97

\[
\sin \phi_2 = \frac{C}{A}
\]
3.98

Recall that \(\cos^2 \phi + \sin^2 \phi = 1\)

Therefore \(\cos \phi_2 = \sqrt{1 - \sin^2 \phi_2} = \sqrt{1 - \left(\frac{C}{A}\right)^2} = \sqrt{1 - \left(\frac{B*U}{100A}\right)^2}\) 3.99

From this expression \(\phi_2\) and hence \(\cos \phi_2\) can be found.

Investigation shows that the current charge per KVA by PHCN is two hundred and fifty Naira (N250.00). As for compensating capacitors, the cost per KVAR is about seven hundred Naira (N700.00) and interest on the capital plus depreciation and maintenance expenses is taken as 10%.

From the above expressions, the economical power factor for this project can be found as follows: Let the charge per KVA maximum demand be N250.00 = A. The cost per KVAR rating be N700.00 = B

Rate of interest plus depreciation and maintenance expenses be U = 10%
\[ C = \frac{B \times U}{100} = \frac{700 \times 10}{100} = 70 \]

\[ \frac{C}{A} = \frac{70}{250} = \frac{7}{25} = \sin \phi_2 \]

\[ \cos \phi_2 = \sqrt{1 - \left( \frac{7}{25} \right)^2} = 0.96 \]

\[ \phi_2 = \cos \phi_2^{-1} = 16.2'' \]

Therefore, the optimal economical power factor for this project is \( \cos \phi_2 = 0.96 \).

Net savings = cost of KVA before compensation – (cost of KVA after compensation + cost of capacitor)

Time required to save the initial cost of capacitor is \( T = \frac{Y \times Z}{N} \) years \( \approx 3.100 \)

Where

\[ Y = \text{Value of capacitor in Kvar} \]
\[ Z = \text{Cost of capacitor per Kvar in Naira} \]
\[ V^*Z = \text{Total cost of installed capacitor in Naira} \]
\[ N = \text{Net saving in Naira [43]} \]

Net savings is the amount that is saved by reducing losses after discounting the investment in equipment acquisition and its installation.
CHAPTER FOUR

4.0 APPLICATION OF THE PROPOSED METHOD

The described method is applied to a 34 bus three phase radial feeder with lateral branches shown in fig. 4.1. The feeder considered in the distribution system is the 11KV feeder in the Thinker’s Corner injection substation which carries an average load of 4636.5kw and 2873.5kvar distributed over 34 main load points along the distribution feeder line: 60% residential, 25% commercial and 15% industrial loads. The main feeder is connected to many sub-feeders which in turn carry radial loads.

Figure 4.1 shows the one-line diagram of 11KV Thinker’s Corner injection substation distribution feeder under study with its lateral branches. The substation line voltage is 11KV. The node numbers and the appropriate active and reactive power loads are given in Table 4.1 (Distribution data).

The software implementation procedure has been done using MATLAB environment for the ease of operating with complex numbers; the load flow results from our software are shown in tabular form in the subsequent pages 91 to 108.

All the calculations have been carried out in per unit system with the three phase base $S_B = 100MVA$, $V_B = 11KV$. The total installed power is 6.0MVA with an average power factor of 0.85.
Fig 4.1 One – Line Diagram of 34 Bus Thinkers’ Corner Distribution System with Lateral Branches.
Table 4.1 Thinker’s Corner 11kV Feeder Distribution System Data

Table 4.1.1  Bus Data

<table>
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<th>Bus No</th>
<th>Load</th>
<th>P(KW)</th>
<th>Q(Kvar)</th>
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Source: Thinker’s Corner Injection Substation of PHCN Enugu.
Table 4.1.2  Line Data

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<th>Length (Km)</th>
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<td>$X(\Omega/Km)$</td>
<td>$r+jX(\Omega)$</td>
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<td>0.524</td>
<td>0.090</td>
<td>0.3144 + j0.054</td>
</tr>
<tr>
<td>24-25</td>
<td>0.524</td>
<td>0.090</td>
<td>0.2096 + j0.036</td>
</tr>
<tr>
<td>25-26</td>
<td>0.524</td>
<td>0.090</td>
<td>0.131 + j0.0225</td>
</tr>
<tr>
<td>26-27</td>
<td>0.524</td>
<td>0.090</td>
<td>0.1048 + j0.018</td>
</tr>
<tr>
<td>27-28</td>
<td>0.524</td>
<td>0.090</td>
<td>0.1572 + j0.027</td>
</tr>
<tr>
<td>28-29</td>
<td>0.524</td>
<td>0.090</td>
<td>0.1572 + j0.027</td>
</tr>
<tr>
<td>29-30</td>
<td>0.524</td>
<td>0.090</td>
<td>0.1572 + j0.027</td>
</tr>
<tr>
<td>30-31</td>
<td>0.524</td>
<td>0.090</td>
<td>0.1572 + j0.027</td>
</tr>
<tr>
<td>31-32</td>
<td>0.524</td>
<td>0.090</td>
<td>0.2096 + j0.036</td>
</tr>
<tr>
<td>32-33</td>
<td>0.524</td>
<td>0.090</td>
<td>0.1572 + j0.027</td>
</tr>
<tr>
<td>33-34</td>
<td>0.524</td>
<td>0.090</td>
<td>0.1048 + j0.018</td>
</tr>
</tbody>
</table>

Source: Thinker’s Corner Injection Substation of PHCN Enugu.
### 4.1 LOAD FLOW RESULTS

#### Table 4.1.3 Voltages and Currents in the Distribution System

<table>
<thead>
<tr>
<th>Bus Voltages (per Unit)</th>
<th>Line Currents (Per Unit)</th>
<th>Line Currents (A)</th>
<th>Load Currents (Per Unit)</th>
<th>Load Currents (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1 = 1.00</td>
<td>i2 = 0.0486 – 0.0234i</td>
<td>i2 = 5248.6</td>
<td>ii2 = - 0.0023 + 0.0014i</td>
<td>ii2 = - 12.1500 + 7.5122i</td>
</tr>
<tr>
<td>V2 = 0.9941 + 0.0009i</td>
<td>i3 = 0.0463 – 0.0280i</td>
<td>i3 = 2.5498e+002 - 1.5424e+002i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V3 = 0.9890 + 0.0017i</td>
<td>i4 = 0.0439 – 0.0265i</td>
<td>i4 = 2.4283e+002 – 1.4673e+002i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V4 = 0.9820 + 0.0037i</td>
<td>i5 = 0.0416 – 0.0251i</td>
<td>i5 = 2.1831e+002 – 1.2402e+002i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V5 = 0.9761 + 0.0053i</td>
<td>i6 = 0.0392 – 0.0236i</td>
<td>i6 = 2.0590e+002 – 1.2402e+002i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V6 = 0.9704 + 0.0069i</td>
<td>i7 = 0.0134 – 0.0081i</td>
<td>i7 = 70.2534 – 42.5449i</td>
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<td></td>
</tr>
<tr>
<td>V7 = 0.9666 + 0.0084i</td>
<td>i8 = 0.0110 – 0.0066i</td>
<td>i8 = 57.9617 – 34.8303i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V8 = 0.9644 + 0.0092i</td>
<td>i9 = 0.0086 – 0.0052i</td>
<td>i9 = 45.3718 – 27.1957i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V9 = 0.9620 + 0.0102i</td>
<td>i10 = 0.0062 – 0.0037i</td>
<td>i10 = 32.7424 – 19.5543i</td>
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</tr>
<tr>
<td>V10 = 0.9608 + 0.0107i</td>
<td>i11 = 0.0038 – 0.0023i</td>
<td>i11 = 21.972 – 12.1519i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V11 = 0.9603 + 0.0108i</td>
<td>i12 = 0.0014 – 0.0009i</td>
<td>i12 = 7.5412 – 4.5060i</td>
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<td></td>
</tr>
<tr>
<td>V12 = 0.9602 + 0.0109i</td>
<td>i13 = 0.0023 – 0.0014i</td>
<td>i13 = 12.2007 – 7.5430i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V13 = 0.9887 + 0.0018i</td>
<td>i14 = 0.0016 – 0.0010i</td>
<td>i14 = 8.3741 – 5.1612i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V14 = 0.9884 + 0.0020i</td>
<td>i15 = 0.0033 + 0.0004i</td>
<td>i15 = 4.5463 – 2.7790i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V15 = 0.9883 + 0.0020i</td>
<td>i16 = 0.7184 – 0.3966i</td>
<td>i16 = 1.3704e+004 – 7.5561e+005i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V16 = 0.9883 + 0.0020i</td>
<td>i17 = 0.0253 – 0.0155i</td>
<td>i17 = 1.3565e+002 – 8.1474e+001i</td>
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</tr>
<tr>
<td>V17 = 0.9659 + 0.0081i</td>
<td>i18 = 0.2324 – 0.1414i</td>
<td>i18 = 1.2308e+002 – 7.3836e+001i</td>
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</tr>
<tr>
<td>V18 = 0.9622 + 0.0092i</td>
<td>i19 = 0.0210 – 0.0126i</td>
<td>i19 = 1.1046e+002 – 6.6183e+001i</td>
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<td></td>
</tr>
<tr>
<td>V19 = 0.9581 + 0.0105i</td>
<td>i20 = 0.0186 – 0.0111i</td>
<td>i20 = 97.7813 – 58.5160i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V20 = 0.9545 + 0.0116i</td>
<td>i21 = 0.0162 – 0.0097i</td>
<td>i21 = 85.0451 – 50.8530i</td>
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<td></td>
</tr>
<tr>
<td>V21 = 0.9519 + 0.0125i</td>
<td>i22 = 0.0138 – 0.0082i</td>
<td>i22 = 72.2624 – 43.1480i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V22 = 0.9486 + 0.0138i</td>
<td>i23 = 0.0113 – 0.0068i</td>
<td>i23 = 59.4251 – 35.4503i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V23 = 0.9459 + 0.0148i</td>
<td>i24 = 0.0089 – 0.0053i</td>
<td>i24 = 46.5425 – 27.7454i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V24 = 0.9434 + 0.0158i</td>
<td>i25 = 0.0064 – 0.0038i</td>
<td>i25 = 33.6175 – 20.0337i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V25 = 0.9422 + 0.0163i</td>
<td>i26 = 0.0040 – 0.0023i</td>
<td>i26 = 20.6723 – 12.3188i</td>
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<td></td>
</tr>
<tr>
<td>V26 = 0.9417 + 0.0165i</td>
<td>i27 = 0.0014 – 0.0009i</td>
<td>i27 = 7.7190 – 4.6026i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V27 = 0.9416 + 0.0165i</td>
<td>i28 = 0.0023 – 0.0015i</td>
<td>i28 = 12.2934 – 7.7141i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V28 = 0.9664 + 0.0085i</td>
<td>i29 = 0.0016 – 0.0010i</td>
<td>i29 = 8.1970 – 5.1428i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V29 = 0.9662 + 0.0085i</td>
<td>i30 = 0.0089e-004 – 4.8990e-004i</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V30 = 0.9661 + 0.0086i</td>
<td>i31 = 0.0024 – 0.0014i</td>
<td>i31 = 12.5477 – 7.4019i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V31 = 0.9604 + 0.0108i</td>
<td>i32 = 0.0018 – 0.0011i</td>
<td>i32 = 9.4122 – 5.5516i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V32 = 0.9601 + 0.0109i</td>
<td>i33 = 0.0012 – 0.0007i</td>
<td>i33 = 6.2759 – 3.7011i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V33 = 0.9599 + 0.0110i</td>
<td>i34 = 5.9844e-004 – 3.5254e-004i</td>
<td>i34 = 3.1393 – 1.8502i</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V34 = 0.9599 + 0.0110i</td>
<td>i35 = 5.9744e-004 + 3.5251e-004i</td>
<td>i35 = 3.1398 + 1.8502i</td>
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</tbody>
</table>
Table 4.1.4 Calculated power losses in the system due to active and reactive component of current before compensation.

<table>
<thead>
<tr>
<th>LINE</th>
<th>LINE CURRENT (A)</th>
<th>LINE RESISTANCE (Ω)</th>
<th>POWER LOSSES DUE TO ACTIVE COMPONENT OF CURRENT (KW)</th>
<th>POWER LOSSES DUE TO REACTIVE COMPONENT OF CURRENT (KW)</th>
<th>TOTAL POWER LOSSES (KW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>254.98</td>
<td>-154.24</td>
<td>0.117</td>
<td>22.8195</td>
<td>8.3503</td>
</tr>
<tr>
<td>2-3</td>
<td>242.83</td>
<td>-146.73</td>
<td>0.10725</td>
<td>18.9719</td>
<td>6.9269</td>
</tr>
<tr>
<td>3-4</td>
<td>230.63</td>
<td>-139.18</td>
<td>0.16445</td>
<td>26.2406</td>
<td>9.5573</td>
</tr>
<tr>
<td>4-5</td>
<td>218.31</td>
<td>-131.61</td>
<td>0.1495</td>
<td>21.3745</td>
<td>7.7690</td>
</tr>
<tr>
<td>5-6</td>
<td>205.90</td>
<td>-124.02</td>
<td>0.1495</td>
<td>19.0136</td>
<td>6.8982</td>
</tr>
<tr>
<td>6-7</td>
<td>70.2534</td>
<td>-42.5449</td>
<td>0.3144</td>
<td>4.6552</td>
<td>1.7073</td>
</tr>
<tr>
<td>7-8</td>
<td>57.9617</td>
<td>-34.8303</td>
<td>0.2096</td>
<td>2.1125</td>
<td>0.7628</td>
</tr>
<tr>
<td>8-9</td>
<td>45.3718</td>
<td>-27.1957</td>
<td>0.3144</td>
<td>1.9417</td>
<td>0.6976</td>
</tr>
<tr>
<td>9-10</td>
<td>32.7424</td>
<td>-19.5543</td>
<td>0.2096</td>
<td>0.6741</td>
<td>0.2404</td>
</tr>
<tr>
<td>10-11</td>
<td>20.1972</td>
<td>-12.1519</td>
<td>0.131</td>
<td>0.1603</td>
<td>0.0580</td>
</tr>
<tr>
<td>11-12</td>
<td>7.5412</td>
<td>-4.5060</td>
<td>0.1048</td>
<td>0.0179</td>
<td>0.0064</td>
</tr>
<tr>
<td>3-13</td>
<td>12.2007</td>
<td>-7.5430</td>
<td>0.1572</td>
<td>0.0702</td>
<td>0.0268</td>
</tr>
<tr>
<td>13-14</td>
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<td>-5.1612</td>
<td>0.2096</td>
<td>0.0441</td>
<td>0.0167</td>
</tr>
<tr>
<td>14-15</td>
<td>4.5463</td>
<td>-2.7790</td>
<td>0.1048</td>
<td>0.0065</td>
<td>0.0024</td>
</tr>
<tr>
<td>15-16</td>
<td>0.7184</td>
<td>-0.3966</td>
<td>0.0524</td>
<td>8.1128e-005</td>
<td>2.4730e-005</td>
</tr>
<tr>
<td>6-17</td>
<td>135.65</td>
<td>-81.474</td>
<td>0.1794</td>
<td>9.9027</td>
<td>3.5726</td>
</tr>
<tr>
<td>17-18</td>
<td>123.08</td>
<td>-73.836</td>
<td>0.16445</td>
<td>7.4740</td>
<td>2.6896</td>
</tr>
<tr>
<td>18-19</td>
<td>110.46</td>
<td>-66.183</td>
<td>0.2079</td>
<td>7.6107</td>
<td>2.7320</td>
</tr>
<tr>
<td>19-20</td>
<td>97.7813</td>
<td>-58.5160</td>
<td>0.189</td>
<td>5.4212</td>
<td>1.9415</td>
</tr>
<tr>
<td>20-21</td>
<td>85.0451</td>
<td>-50.8370</td>
<td>0.189</td>
<td>4.1009</td>
<td>1.4654</td>
</tr>
<tr>
<td>21-22</td>
<td>72.2624</td>
<td>-43.1480</td>
<td>0.262</td>
<td>4.1044</td>
<td>1.4633</td>
</tr>
<tr>
<td>22-23</td>
<td>59.4251</td>
<td>-35.4503</td>
<td>0.262</td>
<td>2.7756</td>
<td>0.9878</td>
</tr>
<tr>
<td>23-24</td>
<td>46.5425</td>
<td>-27.7454</td>
<td>0.3144</td>
<td>2.0432</td>
<td>0.7261</td>
</tr>
<tr>
<td>24-25</td>
<td>33.6175</td>
<td>-20.0337</td>
<td>0.2096</td>
<td>0.7106</td>
<td>0.2524</td>
</tr>
<tr>
<td>25-26</td>
<td>20.6723</td>
<td>-12.3188</td>
<td>0.131</td>
<td>0.1679</td>
<td>0.0596</td>
</tr>
<tr>
<td>26-27</td>
<td>7.7190</td>
<td>-4.6026</td>
<td>0.1048</td>
<td>0.0187</td>
<td>0.0067</td>
</tr>
<tr>
<td>7-28</td>
<td>12.2934</td>
<td>-7.7141</td>
<td>0.1572</td>
<td>0.0713</td>
<td>0.0281</td>
</tr>
<tr>
<td>28-29</td>
<td>8.1970</td>
<td>-5.1428</td>
<td>0.1572</td>
<td>0.0317</td>
<td>0.0125</td>
</tr>
<tr>
<td>29-30</td>
<td>4.0993</td>
<td>-2.5713</td>
<td>0.1572</td>
<td>0.0079</td>
<td>0.0031</td>
</tr>
<tr>
<td>10-31</td>
<td>12.5477</td>
<td>-7.4019</td>
<td>0.1572</td>
<td>0.0743</td>
<td>0.0258</td>
</tr>
<tr>
<td>31-32</td>
<td>9.4122</td>
<td>-5.5516</td>
<td>0.2096</td>
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<td>0.0194</td>
</tr>
<tr>
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<tr>
<td>33-34</td>
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<td>-1.8502</td>
<td>0.1048</td>
<td>0.0031</td>
<td>0.0011</td>
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</table>

| Total | 162.6953 | 59.0136 | 221.7089 |
Table 4.1.5 Power losses due to reactive component of load current before compensation (pf. = 0.85).

<table>
<thead>
<tr>
<th>LINE</th>
<th>LOAD CURRENT (A)</th>
<th>RESISTANCE (Ω)</th>
<th>POWER LOSSES DUE TO REACTIVE COMPONENT OF LOAD CURRENTS (KW) (I_r^2L_R)</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Active</td>
<td>Reactive</td>
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</tr>
<tr>
<td>1-2</td>
<td>il2 = - 12.1500</td>
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<tr>
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<td>6.6028</td>
</tr>
<tr>
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<td>il3 = 0</td>
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<td>0.22425</td>
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<tr>
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</tr>
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<td>3-4</td>
<td>il4 = - 12.3207</td>
<td>7.5702i</td>
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</tr>
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<td>22.2754</td>
</tr>
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<td>il5 = - 12.4096</td>
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<td>il8 = - 12.4096</td>
<td>7.5951i</td>
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<td>il12 = - 7.5400</td>
<td>4.5063i</td>
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</tr>
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<td>2.3818i</td>
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</tr>
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<td>3.3529</td>
</tr>
<tr>
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Table 4.1.6 Power Losses and Loss Reduction due to Addition of Capacitor Banks on Nodes 26, 11, and the overall Power Losses and loss reduction due to capacitor banks on nodes 26 and 11 combined.

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4.2 RESULTS ANALYSIS.

Table 4.1 Shows the Thinker’s Corner 11kv Feeder Distribution System data
Table 4.1.1 Shows the Bus Data
Table 4.1.2 Shows the Line Data
Table 4.1.3 Shows the Voltages and Currents in the Distribution System
Table 4.1.4 Shows the losses due to active and reactive components of current and both of them yielded a total initial peak power losses of 221.7089kw (162.6953 + 59.0136)kw.

Table 4.1.5 Shows Losses due to reactive components of load current before compensation. In this table 4.1.5, the sensitive nodes were identified. The sensitive nodes that have the largest loss due to reactive component of load current among the five sections of the system are node 26 and 11 respectively. These are the nodes that capacitors are to be placed (installed). Since capacitors operate only in reactance, the loss (59.0136)kw due to reactive component of current in table 4.1.4 is the loss to be reduced by allocating or placing sizeable capacitors on nodes 26 and 11.

Table 4.1.6 Shows power losses and loss Reduction due to addition of capacitor Banks on Nodes 26, 11 and the overall power Losses and Loss reduction due to capacitor banks on nodes 26 and 11 combined. From the table 4.1.6, the available standard capacitor bank sizes are (150, 250, 300, 400, 450, 500, 600, 750) Kvar etc.

If we have compensating capacitor size of 750Kvar placed on node 26 only, the optimum power factor of 0.92 is obtained and the minimum power loss is (182.6kw) with maximum power loss reduction of (39.1kw). With capacitor size of 750Kvar placed on node 11 only, the optimum power factor of 1.0 is obtained and the minimum power loss is 194.64kw. Also the loss reduction is maximum at 27.07kw but with capacitor sizes of 750Kvar and 450Kvar placed on both nodes 26 and 11 respectively.
and combined, the optimum power factor of 0.96 is attained, the power loss drops to a maximum of 172.3kw and we also have the maximum power loss reduction as 49.4kw.

Finally, table 4.1.7 shows the power factor and savings due to the addition of capacitor banks on nodes 26, 11 and nodes 26 and 11 combined.

When capacitor size of 750Kvar is placed on node 26 only, it attracts power factor of 0.92, power loss of 182.6kw, power loss reduction of 39.1kw and a savings of thirty three thousand, four hundred and forty three Naira (₦33,443.00) only. When capacitor size of 750Kvar is placed on node 11 only, it attracts a power factor of 1.0, power loss 194.64kw, power loss reduction of 27.07Kw and a savings of Seven thousand three hundred and eighty Naira, five Kobo (₦7,380.5) only. The combined effects of 750Kvar capacitor bank placed at node 26 and 450Kvar capacitor bank placed at node 11 with regard to net savings in naira (₦) per annum, attracts an optimum power factor of 0.96, power loss of 172.3kw, power loss reduction of 49.4kw and a net savings of thirty nine thousand five hundred naira (₦39,500.00) only per annum.

Considering the loss reduction based on the combination of active and reactive components of current, the power loss becomes.

\[
P_{Li} = \sum_{L=I}^m I_i^2 r_i = \sum_{i=i}^M (Ia_i^2 r_i + 1r_i^2 r_i)
\]

= 221.6kw

= the initial peak power loss in the system.
Where: $M_i$ 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.

$\sum_{i=1}^{M} I_{ai}^2 r_i$ is the loss due to active component of current.

$\sum_{i=1}^{M} I_{ri}^2 r_i$ is the loss due to reactive component of current.

It has been shown that node 26 has the highest reactive load current and then the highest effect on the system losses. Hence it is called a sensitive node. Now a compensating capacitor C of current $I_c$ is connected at node 26.

To determine the optimum compensation at node 26, varying size of capacitor banks are connected and the annual net saving, peak power loss and peak power loss reduction in the system are calculated. Since the capacitor size $Q_c$ in kvar is known, the power factor is computed from the expression.

$Q_c = P(\tan(\phi_1 - \tan\phi_2))$

$\Rightarrow \frac{Q_c}{P} = \tan\phi - \tan\phi 2$

$\Rightarrow \tan\phi_2 = \tan\phi_1 - \frac{Q_c}{P} = X$

$\theta_2 = \tan^{-1} X$

Let $\cos\phi_2 = y$

Where: $Q_c =$ Power of capacitor in kvar

$P =$ Active power of the load in kw. For node 26, $P= 10 \times 230 = 2300kw$. For node 11, $P= 6 \times 230 = 1380kw$

$\tan\phi_1 = 0.6198, \phi_1 = 31.79^\circ$

$\tan\phi_2 = 0.2917, \phi = 16.26^\circ$
Having found $\cos\theta_2$ (the new power factor) we can now determine the annual net savings as

$$S = A\left(\frac{P}{\cos\phi_1} - \frac{P}{\cos\phi_2}\right) - C(P\tan\phi_1 - P\tan\phi_2) \text{where } A = 250, C = 70$$

The graphs of figures 4.2 to 4.7 below represent data from tables 4.1.6 to 4.1.7 above.
Figure 4.2 Power loss & loss reduction versus size of capacitor bank on node 26 only.
Figure 4.3: Power loss & loss reduction versus size of capacitor bank on node 11 only
Figure 4.4 Power loss & loss reduction versus total size of capacitor banks on nodes 26 & 11
Figure 4.5 Savings per annum versus size of capacitor bank on node 26 only
Figure 4.6 Savings per annum versus size of capacitor bank on node 11 only
Figure 4.7 Net Savings per annum versus total size of capacitor banks on nodes 26 & 11
Figure 4.1 Shows 34 Bus 11kV distribution feeder line with lateral branches.

Plot of figure 4.2 shows the power loss and loss reduction versus size of capacitor bank placed on node 26 only.

Plot of figure 4.3 shows the power loss and loss reduction due to capacitor bank placed on node 11 only.

Plot of figure 4.4 shows overall power loss and loss reduction due to capacitor banks placed on both node 26 and node 11 combined.

The data of figures 4.2, 4.3 and 4.4 are shown in table 4.1.6.

Plot of figure 4.5 shows the savings per annum due to capacitor bank placed on node 26 only.

Plot of figure 4.6 shows the saving per annum due to capacitor bank placed on node 11 only.

Plot of figure 4.7 shows the overall net savings due capacitor banks placed on both node 26 and node 11 combined.

The data for figures 4.5, 4.6, and 4.7 are shown in table 4.1.7.

We have also plotted the net savings against capacitor sizes on nodes 26 and 11 as shown in figure 4.7. From the graph of figure 4.2, it is obvious that the optimum size capacitor bank required at node 26 is 750 Kvar. This is the capacitor bank size that produces minimum power loss and maximum power loss reduction.

The steps we have taken for node 26 are repeated for node 11 which is the next most sensitive node. It is the most sensitive node on the main feeder. In addition to the 750kvar capacitor bank on node 26, varying sizes of capacitor bank is connected to node 11.

Finally, it can be deduced from the tables and graphs that the optimum capacitor bank size to be allocated to node 26 and node 11 are 750kvar and 450kvar respectively. With this, maximum net savings of N39,500 (Thirty Nine thousand five hundred Naira only) per annum is obtained. Also, a peak power loss reduction of 49.4kw is attained as in
If loss reduction higher than this is sought after, the net saving will decrease because the cost of compensating capacitors will exceed the benefits gained from reducing the power losses.

The time taken to save the initial cost of the capacitor is

\[ T = \frac{Y \times Z}{N} \]

\[ = \frac{12000 \times 700}{39500} \]

\[ = 21.266 \text{yrs} \]

Where

- \( Y \) = Value of capacitor in Kvar
- \( Z \) = Cost of capacitor per Kvar in Naira
- \( V\times Z \) = Total cost of installed capacitor in Naira
- \( N \) = Net saving in Naira
CHAPTER FIVE
CONCLUSIONS AND RECOMMENDATIONS

5.0 CONCLUSIONS

The ability of utility (e.g., distribution system) to reduce technical losses in its operation will provide enough revenue for future expansion, upgrades, and modernization. This will improve on reliability and security of supply. Many utilities are faced with the crippling effect of power losses (Technical) and are putting in place various measures to reduce these losses.

This project therefore presents a technique for reducing the power losses arising from the flow of reactive power in a distribution system by placing compensating capacitors at a few specific locations in the network termed “sensitive nodes” to achieve a maximum loss reduction and maximum annual naira savings. This method is applied to a 3-phase, 11 kv, 50 Hz distribution network in Enugu.

Heuristic techniques are applied in this project to determine the optimal capacitor placement and ratings for the distribution system.

This is achieved by examining the solution at a set of critical nodes termed sensitive nodes. The sensitive nodes are selected based on the losses caused in the system by the reactive components of the load current. It is at these sensitive nodes that sizeable capacitor banks were installed to achieve the desired high loss reduction in Enugu distribution system.

5.1 RECOMMENDATIONS.

(i) Power Holding Company of Nigeria (PHCN) should take a critical look at transformer loadings. Chiefs and political leaders should be involved so that swapping of transformers could be employed to limit overloading of transformers. Transformer loading data from PHCN show that some transformers are
overloaded while others are far under utilized. Swapping of transformers can be very involving but loadings of some transformers are too high that they are threatened with eminent destruction.

(ii) Attempts should be made at balancing the various phases of loads since some imbalance has been observed on some transformers.

(iii) A reappraisal should be done on the suitability of LV cables/conductors and the needed upgrades carried out where necessary. At some areas, the conductor sags are very severe as a result of conductor heating and in order to prevent phase conductors from clashing, they are held apart by spacers.

(iv) The low voltages as stated earlier are due to the system wide low voltages. The prudent use tap changers or booster transformers on bulk supply and distribution transformer should be explored. It will be necessary that PHCN should conduct a study on the use of compensating capacitors within the power holding areas.

(v) Loss reduction units should step up their activities at the various areas and check losses within their areas. It is recommended that units could be rotated from time to time to stem the cases of acquaintances with the customers.

(vi) Right technical decisions should be taken in sizing transformers and cables in order to reduce technical losses. This should start from planning phase and should be based on sound data to accommodate future population increase and movement.

(vii) Finally, since power factor less than 0.9 in-cure a penalty, it is therefore usually in the best financial interest of the industrial customers of PHCN in Enugu to perform power factor correction using shunt capacitors.
(viii) The capacitors retain electrical charge, even when the power is switched off. It may be dangerous to touch the terminals of the capacitors, unless the capacitors are fully discharged. For safety requirements, all AMBER lighting capacitors are supplied with internal discharge resistors, so that the capacitor voltage drops to below 50 V within 1 minute of switch off. Even then, care should be exercised in handling the lighting fixtures.

(ix) As ballasts generate heat, capacitors with thermoplastic cases should be placed as much away from the ballasts as possible. Care should be taken that the capacitor case temperature does not exceed the rated temperature printed on the capacitor. If the heat dissipation within the luminaire is not proper, capacitors with aluminium case should be used.

(x) High efficiency transformers should be installed during the initial installation of distribution system.
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APPENDIX I

SUMMARY OF RELEVANT FORMULAE

The distribution system under consideration is a concentrated load.

1. Losses before addition of capacitor (table 4.1.5) is obtained from:

\[ I^2_1R = (I_1\cos\theta_1)^2 R + (I_1\sin\theta_1)^2 R \]  
\[ \text{equation 3.62} \]

2. Losses after addition of capacitor (table 4.1.6) is obtained from:

\[ I^2_2R = (I_2\cos\theta_2)^2 R + (I_1\sin\theta_1 - Ic)^2 R \]  
\[ \text{equation 3.63} \]

3. Power loss reduction

\[ \Delta L = 2(I_1\sin\theta_1)IcR - I^2cR \]  
\[ \text{is obtained from Equation 3.68} \]

where \( I \) = current flowing through the circuit

\( R \) = Resistance

\[ Ic = I_1\sin\theta_1 - I_2\sin\theta_2 \]  
\[ \text{equation 3.58} \]

\[ \frac{K \var}{V} = \frac{Qc}{V} \]

4. Capacitor size ratings are obtained from

\[ K \var = \theta_c = P(\tan\theta_1 - \tan\theta_2) \]  
\[ \text{equation 23.81} \]

where \( \theta_1 = 31.79^\circ \), \( \theta_2 = 16.26^\circ \)

5. Optimal Economical power factor 0.96 \((\cos\theta_2)\) is obtained from:

\[ \cos\theta_2 = \sqrt{1 - \left(\frac{C}{A}\right)^2} = \sqrt{1 - \left(\frac{Bp}{100A}\right)^2} = \sqrt{1 - \sin^2\theta_2} \]  
\[ \text{equation.....3.99} \]

6. Net Annual savings:

\[ S = A\left(\frac{P}{\cos\theta_1} - \frac{P}{\cos\theta_2}\right) - C(P\tan\theta_1 - P\tan\theta_2) \]  
\[ \text{is obtained from ( equation...3.85) } \]
7. Considering the loss reduction based on the combination of active and reactive components of current, the power loss becomes.

\[ P_{Li} = \sum_{L=1}^{m} \frac{l_i^2 r_i}{L} = \sum_{i=1}^{M} (lai^2 r_i + liri^2 r_i) = 221.6\text{kw} \]

= the initial peak power loss in the system.

(8) Formular for bus current is

\[ I_j = (V_{j-1} - V_j) Y_{(j-1)j} \]

Where \( j = 2, 3, 4 \ldots \)

(9) Formular for power loses before addition of capacitor is

\[ P_{Li} = 3I_i^2 R_i \]

Where \( i = 2, 3, 4 \ldots \)

(10) Formular for power loses due to reactive component of current is

\[ P_{Li} = 3I_i^2 R_i \]

Where \( I = 1,2,3 \ldots \)

(11) Formular for admittance of the sections are:

For self admittance: \( Y_{ij} = \frac{1}{Z_j} \)

Where \( i = 1,2, \ldots \)

\( J = 2,3, \ldots \)

For mutual admittance; \( Y_{ii} = Y_{i1} + Y_{i2} + Y_{i3} \)

(12) Formular for load currents is

\[ I_i = Y_{ji} V_i - Y_{ij} V_j \]

Where \( I = 1,2,3 \)

\( j = 2,3,4 \)
Formular for total power loss after compensation is

\[ PL_2 = (I_2 + I_{c11} + I_{c26})^2 R_2 \]
\[ PL_3 = (I_3 + I_{c11} + I_{c26})^2 R_3 \]
\[ PL_4 = (I_4 + I_{c11} + I_{c26})^2 R_4 \]
\[ PL_5 = (I_5 + I_{c11} + I_{c26})^2 R_5 \]
\[ PL_6 = (I_6 + I_{c11} + I_{c26})^2 R_6 \]
\[ PL_7 = (I_7 + I_{c11})^2 R_7 \]
\[ PL_8 = (I_8 + I_{c11})^2 R_8 \]
\[ PL_9 = (I_9 + I_{c11})^2 R_9 \]
\[ PL_{10} = (I_{10} + I_{c11})^2 R_{10} \]
\[ PL_{11} = (I_{11} + I_{c11})^2 R_{11} \]
\[ PL_{17} = (I_{17} + I_{c26})^2 R_{17} \]
\[ PL_{18} = (I_{18} + I_{c26})^2 R_{18} \]
\[ PL_{19} = (I_{19} + I_{c26})^2 R_{19} \]
\[ PL_{20} = (I_{20} + I_{c26})^2 R_{20} \]
\[ PL_{21} = (I_{21} + I_{c26})^2 R_{21} \]
\[ PL_{22} = (I_{22} + I_{c26})^2 R_{22} \]
\[ PL_{23} = (I_{23} + I_{c26})^2 R_{23} \]
\[ PL_{24} = (I_{24} + I_{c26})^2 R_{24} \]
\[ PL_{25} = (I_{25} + I_{c26})^2 R_{25} \]
\[ PL_{26} = (I_{26} + I_{c26})^2 R_{26} \]
LOAD FLOW PROGRAMME IN MATLAB

A. % Base values
vb=11;
sb=100;
zb=vb^2/sb;

B. % BUS DATA

C. % Load per unit
s1=0;
s2=(-230-142.5i)/100000;
s3=0;
s4=s2;
s5=s4;
s6=0;
s7=0;
s8=s5;
s9=s8;
s10=0;
s11=s9;
s12=(-137-84i)/100000;
s13=(-72-45i)/100000;
s14=s13;
s15=s14;
s16=(-13.5-7.5i)/100000;
s17=s11;
s18=s17;
s19=s18;
s20=s19;
s21 = s20;
s22 = s21;
s23 = s22;
s24 = s23;
s25 = s24;
s26 = s25;
s27 = (-137-85i)/100000;
s28 = (-75-48i)/100000;
s29 = s28;
s30 = s29;
s31 = (-57-34.5i)/100000;
s32 = s31;
s33 = s32;
s34 = s33;

D. % Voltage
v1 = 1.00;
v2 = 1.00;
v3 = 1.00;
v4 = 1.00;
v5 = 1.00;
v6 = 1.00;
v7 = 1.00;
v8 = 1.00;
v9 = 1.00;
v10 = 1.00;
v11 = 1.00;
v12 = 1.00;
v13 = 1.00;
v14 = 1.00;
v15=1.00;
v16=1.00;
v17=1.00;
v18=1.00;
v19=1.00;
v20=1.00;
v21=1.00;
v22=1.00;
v23=1.00;
v24=1.00;
v25=1.00;
v26=1.00;
v27=1.00;
v28=1.00;
v29=1.00;
v30=1.00;
v31=1.00;
v32=1.00;
v33=1.00;
v34=1.00;

LINE DATA

E.  % Line Impedance per unit
    z2=0.6*(0.195+0.080i)/zb;
    z3=0.55*(0.195+0.080i)/zb;
    z4=0.55*(0.299+0.083i)/zb;
    z5=0.50*(0.299+0.083i)/zb;
    z6=z5;
    z7=0.60*(0.524+0.090i)/zb;
    z8=0.40*(0.524+0.090i)/zb;
z9 = z7;
z10 = z8;
z11 = 0.25*(0.524+0.090i)/zb;
z12 = 0.20*(0.524+0.090i)/zb;
z13 = 0.30*(0.524+0.090i)/zb;
z14 = z10;
z15 = z12;
z16 = 0.10*(0.524+0.090i)/zb;
z17 = 0.60*(0.299+0.083i)/zb;
z18 = z4;
z19 = 0.55*(0.378+0.086i)/zb;
z20 = 0.50*(0.378+0.086i)/zb;
z21 = z20;
z22 = 0.50*(0.524+0.090i)/zb;
z23 = z22;
z24 = z9;
z25 = z14;
z26 = z11;
z27 = z15;
z28 = z13;
z29 = z28;
z30 = z29;
z31 = z30;
z32 = z25;
z33 = z31;
z34 = z27;

F. % Line admittances
\[ y_{12} = \frac{1}{z_2}; \]
\[ y_{21} = y_{12}; \]
\[ y_{23} = \frac{1}{z_3}; \]
\[ y_{32} = y_{23}; \]
\[ y_{34} = \frac{1}{z_4}; \]
\[ y_{43} = y_{34}; \]
\[ y_{45} = \frac{1}{z_5}; \]
\[ y_{54} = y_{45}; \]
\[ y_{56} = \frac{1}{z_6}; \]
\[ y_{65} = y_{56}; \]
\[ y_{67} = \frac{1}{z_7}; \]
\[ y_{76} = y_{67}; \]
\[ y_{78} = \frac{1}{z_8}; \]
\[ y_{87} = y_{78}; \]
\[ y_{89} = \frac{1}{z_9}; \]
\[ y_{98} = y_{89}; \]
\[ y_{910} = \frac{1}{z_{10}}; \]
\[ y_{109} = y_{910}; \]
\[ y_{1011} = \frac{1}{z_{11}}; \]
\[ y_{1110} = y_{1011}; \]
\[ y_{1112} = \frac{1}{z_{12}}; \]
\[ y_{1211} = y_{1112}; \]
\[ y_{313} = \frac{1}{z_{13}}; \]
\[ y_{133} = y_{313}; \]
\[ y_{1314} = \frac{1}{z_{14}}; \]
\[ y_{1413} = y_{1314}; \]
\[ y_{1415} = \frac{1}{z_{15}}; \]
\[ y_{1514} = y_{1415}; \]
\[ y_{1516} = \frac{1}{z_{16}}; \]
\[ y_{1615} = y_{1516}; \]
y_{617} = 1/z_{17};
y_{176} = y_{617};
y_{1718} = 1/z_{18};
y_{1817} = y_{1718};
y_{1819} = 1/z_{19};
y_{1918} = y_{1819};
y_{1920} = 1/z_{20};
y_{2019} = y_{1920};
y_{2021} = 1/z_{21};
y_{2120} = y_{2021};
y_{2122} = 1/z_{22};
y_{2221} = y_{2122};
y_{2223} = 1/z_{23};
y_{2322} = y_{2223};
y_{2324} = 1/z_{24};
y_{2423} = y_{2324};
y_{2425} = 1/z_{25};
y_{2524} = y_{2425};
y_{2526} = 1/z_{26};
y_{2625} = y_{2526};
y_{2627} = 1/z_{27};
y_{2726} = y_{2627};
y_{728} = 1/z_{28};
y_{287} = y_{728};
y_{2829} = 1/z_{29};
y_{2928} = y_{2829};
y_{2930} = 1/z_{30};
y_{3029} = y_{2930};
y_{1031} = 1/z_{31};
y_{3110} = y_{1031};
y_{3132} = 1/z_{32};
y_{3231} = y_{3132};
y_{3233} = 1/z_{33};
y_{3332} = y_{3233};
y_{3334} = 1/z_{34};
y_{3433} = y_{3334};
y_{22} = y_{21} + y_{23};
y_{33} = y_{32} + y_{34} + y_{313};
y_{44} = y_{43} + y_{45};
y_{55} = y_{54} + y_{56};
y_{66} = y_{65} + y_{67} + y_{617};
y_{77} = y_{76} + y_{78} + y_{728};
y_{88} = y_{87} + y_{89};
y_{99} = y_{98} + y_{910};
y_{1010} = y_{109} + y_{1011} + y_{1031};
y_{1111} = y_{1110} + y_{1112};
y_{1212} = y_{1211};
y_{1313} = y_{133} + y_{1314};
y_{1414} = y_{1413} + y_{1415};
y_{1515} = y_{1514} + y_{1516};
y_{1616} = y_{1615};
y_{1717} = y_{176} + y_{1718};
y_{1818} = y_{1817} + y_{1819};
y_{1919} = y_{1918} + y_{1920};
y_{2020} = y_{2019} + y_{2021};
y_{2121} = y_{2120} + y_{2122};
y_{2222} = y_{2221} + y_{2223};
y_{2323} = y_{2322} + y_{2324};
y_{2424} = y_{2423} + y_{2425};
y_{2525} = y_{2524} + y_{2526};
G. % Computation of bus voltages

\[ k=1; \]
\[ v22(k)=1/y22*(\text{conj}(s2/v2)+y21*v1+y23*v3); \]
\[ v2(k)=v2+1.6*(v22(k)-v2); \]
\[ v33(k)=1/y33*(\text{conj}(s3/v3)+y32*v2(k)+y313*v13+y34*v4); \]
\[ v3(k)=v3+1.6*(v33(k)-v3); \]
\[ v44(k)=1/y44*(\text{conj}(s4/v4)+y43*v3(k)+y45*v5); \]
\[ v4(k)=v4+1.6*(v44(k)-v4); \]
\[ v55(k)=1/y55*(\text{conj}(s5/v5)+y54*v4(k)+y56*v6); \]
\[ v5(k)=v5+1.6*(v55(k)-v5); \]
\[ v66(k)=1/y66*(\text{conj}(s6/v6)+y65*v5(k)+y67*v7+y617*v17); \]
\[ v6(k)=v6+1.6*(v66(k)-v6); \]
\[ v77(k)=1/y77*(\text{conj}(s7/v7)+y76*v6(k)+y78*v8+y728*v28); \]
\[ v7(k)=v7+1.6*(v77(k)-v7); \]
\[ v88(k)=1/y88*(\text{conj}(s8/v8)+y87*v7(k)+y89*v9); \]
\[ v8(k)=v8+1.6*(v88(k)-v8); \]
\[ v99(k)=1/y99*(\text{conj}(s9/v9)+y98*v8(k)+y910*v10); \]
\[ v9(k)=v9+1.6*(v99(k)-v9); \]
\[ v1010=1/y1010*(\text{conj}(s10/v10)+y109*v9(k)+y1011*v11+y1031*v31); \]
\[ v10(k)=v10+1.6*(v1010(k)-v10); \]
\[ v1111(k)=1/y1111*(\text{conj}(s11/v11)+y1110*v10(k)+y1112*v12); \]
v11(k)=v11+1.6*(v1111(k)-v11);
v1212(k)=1/y1212*(conj(s12/v12)+y1211*v11(k));
v12(k)=v12+1.6*(v1212(k)-v12);
v1313(k)=1/y1313*(conj(s13/v13)+y133*v3(k)+y1314*v14);
v13(k)=v13+1.6*(v1313(k)-v13);
v1414(k)=1/y1414*(conj(s14/v14)+y1413*v13(k)+y1415*v15);
v14(k)=v14+1.6*(v1414(k)-v14);
v1515(k)=1/y1515*(conj(s15/v15)+y1514*v14(k)+y1516*v16);
v15(k)=v15+1.6*(v1515(k)-v15);
v1616(k)=1/y1616*(conj(s16/v16)+y1615*v15(k));
v16(k)=v16+1.6*(v1616(k)-v16);
v1717(k)=1/y1717*(conj(s17/v17)+y176*v6(k)+y1718*v18);
v17(k)=v17+1.6*(v1717(k)-v17);
v1818(k)=1/y1818*(conj(s18/v18)+y1817*v17(k)+y1819*v19);
v18(k)=v18+1.6*(v1818(k)-v18);
v1919(k)=1/y1919*(conj(s19/v19)+y1918*v18(k)+y1920*v20);
v19(k)=v19+1.6*(v1919(k)-v19);
v2020=1/y2020*(conj(s20/v20)+y2019*v19(k)+y2021*v21);
v20(k)=v20+1.6*(v2020(k)-v20);
v2121(k)=1/y2121*(conj(s21/v21)+y2120*v20(k)+y2122*v22);
v21(k)=v21+1.6*(v2121(k)-v21);
v2222(k)=1/y2222*(conj(s22/v22)+y2221*v21(k)+y2223*v23);
v22(k)=v22+1.6*(v2222(k)-v22);
v2323(k)=1/y2323*(conj(s23/v23)+y2322*v22(k)+y2324*v24);
v23(k)=v23+1.6*(v2323(k)-v23);
v2424(k)=1/y2424*(conj(s24/v24)+y2423*v23(k)+y2425*v25);
v24(k)=v24+1.6*(v2424(k)-v24);
v2525(k)=1/y2525*(conj(s25/v25)+y2524*v24(k)+y2526*v26);
v25(k)=v25+1.6*(v2525(k)-v25);
v2626(k)=1/y2626*(conj(s26/v26)+y2625*v25(k)+y2627*v27);
v26(k)=v26+1.6*(v2626(k)-v26);
v2727(k)=1/y2727*(conj(s27/v27)+y2726*v26(k));
\[ v_{27}(k) = v_{27} + 1.6 \cdot (v_{2727}(k) - v_{27}) \]
\[ v_{2828}(k) = \frac{1}{y_{2828}} \cdot (\text{conj}(s_{28}/v_{28}) + y_{287} \cdot v_{7}(k) + y_{289} \cdot v_{29}) \]
\[ v_{28}(k) = v_{28} + 1.6 \cdot (v_{2828}(k) - v_{28}) \]
\[ v_{2929}(k) = \frac{1}{y_{2929}} \cdot (\text{conj}(s_{29}/v_{29}) + y_{2928} \cdot v_{28}(k) + y_{2930} \cdot v_{30}) \]
\[ v_{29}(k) = v_{29} + 1.6 \cdot (v_{2929}(k) - v_{29}) \]
\[ v_{3030}(k) = \frac{1}{y_{3030}} \cdot (\text{conj}(s_{30}/v_{30}) + y_{3029} \cdot v_{29}(k)) \]
\[ v_{30}(k) = v_{30} + 1.6 \cdot (v_{3030}(k) - v_{30}) \]
\[ v_{3131}(k) = \frac{1}{y_{3131}} \cdot (\text{conj}(s_{31}/v_{31}) + y_{3110} \cdot v_{10}(k) + y_{3132} \cdot v_{32}) \]
\[ v_{31}(k) = v_{31} + 1.6 \cdot (v_{3131}(k) - v_{31}) \]
\[ v_{3232}(k) = \frac{1}{y_{3232}} \cdot (\text{conj}(s_{32}/v_{32}) + y_{3231} \cdot v_{31}(k) + y_{3233} \cdot v_{33}) \]
\[ v_{32}(k) = v_{32} + 1.6 \cdot (v_{3232}(k) - v_{32}) \]
\[ v_{3333}(k) = \frac{1}{y_{3333}} \cdot (\text{conj}(s_{33}/v_{33}) + y_{3332} \cdot v_{32}(k) + y_{3334} \cdot v_{34}) \]
\[ v_{33}(k) = v_{33} + 1.6 \cdot (v_{3333}(k) - v_{33}) \]
\[ v_{3434}(k) = \frac{1}{y_{3434}} \cdot (\text{conj}(s_{34}/v_{34}) + y_{3433} \cdot v_{33}(k)) \]
\[ v_{34}(k) = v_{34} + 1.6 \cdot (v_{3434}(k) - v_{34}) \]

for \( k = 2:1:400; \)
\[ v_{22}(k) = \frac{1}{y_{22}} \cdot (\text{conj}(s_{2}/v_{2}(k-1)) + y_{21} \cdot v_{1} + y_{23} \cdot v_{3}(k-1)) \]
\[ v_{2}(k) = v_{2}(k-1) + 1.6 \cdot (v_{22}(k) - v_{2}(k-1)) \]
\[ v_{33}(k) = \frac{1}{y_{33}} \cdot (\text{conj}(s_{3}/v_{3}(k-1)) + y_{32} \cdot v_{2}(k) + y_{313} \cdot v_{13}(k-1) + y_{34} \cdot v_{4}(k-1)) \]
\[ v_{3}(k) = v_{3}(k-1) + 1.6 \cdot (v_{33}(k) - v_{3}(k-1)) \]
\[ v_{44}(k) = \frac{1}{y_{44}} \cdot (\text{conj}(s_{4}/v_{4}(k-1)) + y_{43} \cdot v_{3}(k) + y_{45} \cdot v_{5}(k-1)) \]
\[ v_{4}(k) = v_{4}(k-1) + 1.6 \cdot (v_{44}(k) - v_{4}(k-1)) \]
\[ v_{55}(k) = \frac{1}{y_{55}} \cdot (\text{conj}(s_{5}/v_{5}(k-1)) + y_{54} \cdot v_{4}(k) + y_{56} \cdot v_{6}(k-1)) \]
\[ v_{5}(k) = v_{5}(k-1) + 1.6 \cdot (v_{55}(k) - v_{5}(k-1)) \]
\[ v_{66}(k) = \frac{1}{y_{66}} \cdot (\text{conj}(s_{6}/v_{6}(k-1)) + y_{65} \cdot v_{5}(k) + y_{67} \cdot v_{7}(k-1) + y_{617} \cdot v_{17}(k-1)) \]
\[ v_{6}(k) = v_{6}(k-1) + 1.6 \cdot (v_{66}(k) - v_{6}(k-1)) \]
\[ v_{77}(k) = \frac{1}{y_{77}} \cdot (\text{conj}(s_{7}/v_{7}(k-1)) + y_{76} \cdot v_{6}(k) + y_{78} \cdot v_{8}(k-1) + y_{728} \cdot v_{28}(k-1)) \]
\[ v_{7}(k) = v_{7}(k-1) + 1.6 \cdot (v_{77}(k) - v_{7}(k-1)) \]
\[ v_{88}(k) = \frac{1}{y_{88}} \cdot (\text{conj}(s_{8}/v_{8}(k-1)) + y_{87} \cdot v_{7}(k) + y_{89} \cdot v_{9}(k-1)) \]
\[ v_{8}(k) = v_{8}(k-1) + 1.6 \cdot (v_{88}(k) - v_{8}(k-1)) \]
\[ v_{99}(k) = \frac{1}{y_{99}} \cdot (\text{conj}(s_{9}/v_{9}(k-1)) + y_{98} \cdot v_{8}(k) + y_{910} \cdot v_{10}(k-1)) \]
v9(k) = v9(k-1) + 1.6*(v99(k) - v9(k-1));
v1010(k) = 1/y1010*(conj(s10/v10(k-1))) + y109*v9(k) + y1011*v11(k-1) + y1031*v31(k-1);
v10(k) = v10(k-1) + 1.6*(v1010(k) - v10(k-1));
v1111(k) = 1/y1111*(conj(s11/v11(k-1))) + y1110*v10(k) + y1112*v12(k-1));
v11(k) = v11(k-1) + 1.6*(v1111(k) - v11(k-1));
v1212(k) = 1/y1212*(conj(s12/v12(k-1))) + y1211*v11(k);
v12(k) = v12(k-1) + 1.6*(v1212(k) - v12(k-1));
v1313(k) = 1/y1313*(conj(s13/v13(k-1))) + y133*v3(k) + y1314*v14(k-1));
v13(k) = v13(k-1) + 1.6*(v1313(k) - v13(k-1));
v1414(k) = 1/y1414*(conj(s14/v14(k-1))) + y1413*v13(k) + y1415*v15(k-1));
v14(k) = v14(k-1) + 1.6*(v1414(k) - v14(k-1));
v1515(k) = 1/y1515*(conj(s15/v15(k-1))) + y1514*v14(k) + y1516*v16(k-1));
v15(k) = v15(k-1) + 1.6*(v1515(k) - v15(k-1));
v1616(k) = 1/y1616*(conj(s16/v16(k-1))) + y1615*v15(k));
v16(k) = v16(k-1) + 1.6*(v1616(k) - v16(k-1));
v1717(k) = 1/y1717*(conj(s17/v17(k-1))) + y176*v6(k) + y1718*v18(k-1));
v17(k) = v17(k-1) + 1.6*(v1717(k) - v17(k-1));
v1818(k) = 1/y1818*(conj(s18/v18(k-1))) + y1817*v17(k) + y1819*v19(k-1));
v18(k) = v18(k-1) + 1.6*(v1818(k) - v18(k-1));
v1919(k) = 1/y1919*(conj(s19/v19(k-1))) + y1918*v18(k) + y1920*v20(k-1));
v19(k) = v19(k-1) + 1.6*(v1919(k) - v19(k-1));
v2020(k) = 1/y2020*(conj(s20/v20(k-1))) + y2019*v19(k) + y2021*v21(k-1));
v20(k) = v20(k-1) + 1.6*(v2020(k) - v20(k-1));
v2121(k) = 1/y2121*(conj(s21/v21(k-1))) + y2120*v20(k) + y2122*v22(k-1));
v21(k) = v21(k-1) + 1.6*(v2121(k) - v21(k-1));
v2222(k) = 1/y2222*(conj(s22/v22(k-1))) + y2221*v21(k) + y2223*v23(k-1));
v22(k) = v22(k-1) + 1.6*(v2222(k) - v22(k-1));
v2323(k) = 1/y2323*(conj(s23/v23(k-1))) + y2322*v22(k) + y2324*v24(k-1));
v23(k) = v23(k-1) + 1.6*(v2323(k) - v23(k-1));
v2424(k) = 1/y2424*(conj(s24/v24(k-1))) + y2423*v23(k) + y2425*v25(k-1));
v24(k) = v24(k-1) + 1.6*(v2424(k) - v24(k-1));
v2525(k) = \frac{1}{y2525} \cdot (\text{conj}(s25/v25(k-1)) + y2524 \cdot v24(k) + y2526 \cdot v26(k-1));
v25(k) = v25(k-1) + 1.6 \cdot (v2525(k) - v25(k-1));
v2626(k) = \frac{1}{y2626} \cdot (\text{conj}(s26/v26(k-1)) + y2625 \cdot v25(k) + y2627 \cdot v27(k-1));
v26(k) = v26(k-1) + 1.6 \cdot (v2626(k) - v26(k-1));
v2727(k) = \frac{1}{y2727} \cdot (\text{conj}(s27/v27(k-1)) + y2726 \cdot v26(k));
v27(k) = v27(k-1) + 1.6 \cdot (v2727(k) - v27(k-1));
v2828(k) = \frac{1}{y2828} \cdot (\text{conj}(s28/v28(k-1)) + y287 \cdot v7(k) + y2829 \cdot v29(k-1));
v28(k) = v28(k-1) + 1.6 \cdot (v2828(k) - v28(k-1));
v2929(k) = \frac{1}{y2929} \cdot (\text{conj}(s29/v29(k-1)) + y2928 \cdot v28(k) + y2930 \cdot v30(k-1));
v29(k) = v29(k-1) + 1.6 \cdot (v2929(k) - v29(k-1));
v3030(k) = \frac{1}{y3030} \cdot (\text{conj}(s30/v30(k-1)) + y3029 \cdot v29(k));
v30(k) = v30(k-1) + 1.6 \cdot (v3030(k) - v30(k-1));
v3131(k) = \frac{1}{y3131} \cdot (\text{conj}(s31/v31(k-1)) + y3110 \cdot v10(k) + y3132 \cdot v32(k-1));
v31(k) = v31(k-1) + 1.6 \cdot (v3131(k) - v31(k-1));
v3232(k) = \frac{1}{y3232} \cdot (\text{conj}(s32/v32(k-1)) + y3231 \cdot v31(k) + y3233 \cdot v33(k-1));
v32(k) = v32(k-1) + 1.6 \cdot (v3232(k) - v32(k-1));
v3333(k) = \frac{1}{y3333} \cdot (\text{conj}(s33/v33(k-1)) + y3332 \cdot v32(k) + y3334 \cdot v34(k-1));
v33(k) = v33(k-1) + 1.6 \cdot (v3333(k) - v33(k-1));
v3434(k) = \frac{1}{y3434} \cdot (\text{conj}(s34/v34(k-1)) + y3433 \cdot v33(k));
v34(k) = v34(k-1) + 1.6 \cdot (v3434(k) - v34(k-1));

end

v1 = 1.00;
v2 = v2(400);
V2 = abs(v2) * 11000;
v3 = v3(400);
V3 = abs(v3) * 11000;
v4 = v4(400);
V4 = abs(v4) * 11000;
v5 = v5(400);
V5 = abs(v5) * 11000;
v6 = v6(400);
V6 = abs(v6) * 11000;
v7 = v7(400);
V7 = abs(v7) * 11000;
v8 = v8(400);
V8 = abs(v8) * 11000;
v9 = v9(400);
V9 = abs(v9) * 11000;
v10 = v10(400);
V10 = abs(v10) * 11000;
v11 = v11(400);
V11 = abs(v11) * 11000;
v12 = v12(400);
V12 = abs(v12) * 11000;
v13 = v13(400);
V13 = abs(v13) * 11000;
v14 = v14(400);
V14 = abs(v14) * 11000;
v15 = v15(400);
V15 = abs(v15) * 11000;
v16 = v16(400);
V16 = abs(v16) * 11000;
v17 = v17(400);
V17 = abs(v17) * 11000;
v18 = v18(400);
V18 = abs(v18) * 11000;
v19 = v19(400);
V19 = abs(v19) * 11000;
v20 = v20(400);
V20 = abs(v20) * 11000;
v21 = v21(400);
V21 = abs(v21) * 11000;
v22 = v22(400);
V22 = abs(v22) * 11000;
v23 = v23(400);
V23 = abs(v23) * 11000;
v24 = v24(400);
V24 = abs(v24) * 11000;
v25 = v25(400);
V25 = abs(v25) * 11000;
v26 = v26(400);
V26 = abs(v26) * 11000;
v27 = v27(400);
V27 = abs(v27) * 11000;
v28 = v28(400);
V28 = abs(v28) * 11000;
v29 = v29(400);
V29 = abs(v29) * 11000;
v30 = v30(400);
V30 = abs(v30) * 11000;
v31 = v31(400);
V31 = abs(v31) * 11000;
v32 = v32(400);
V32 = abs(v32) * 11000;
v33 = v33(400);
V33 = abs(v33) * 11000;
v34 = v34(400);
V34 = abs(v34) * 11000;

H. % Line Currents
ib = 100000/((sqrt(3)*11));
i2 = (v1 - v2) * y12 * ib;
i3 = (v2 - v3) * y23 * ib;
i4 = (v3 - v4) * y34 * ib;
i5=(v4-v5)*y45*ib;
i6=(v5-v6)*y56*ib;
i7=(v6-v7)*y67*ib;
i8=(v7-v8)*y78*ib;
i9=(v8-v9)*y89*ib;
i10=(v9-v10)*y910*ib;
i11=(v10-v11)*y1011*ib;
i12=(v11-v12)*y1112*ib;
i13=(v3-v13)*y313*ib;
i14=(v13-v14)*y1314*ib;
i15=(v14-v15)*y1415*ib;
i16=(v15-v16)*y1516*ib;
i17=(v6-v17)*y617*ib;
i18=(v17-v18)*y1718*ib;
i19=(v18-v19)*y1819*ib;
i20=(v19-v20)*y1920*ib;
i21=(v20-v21)*y2021*ib;
i22=(v21-v22)*y2122*ib;
i23=(v22-v23)*y2223*ib;
i24=(v23-v24)*y2324*ib;
i25=(v24-v25)*y2425*ib;
i26=(v25-v26)*y2526*ib;
i27=(v26-v27)*y2627*ib;
i28=(v7-v28)*y728*ib;
i29=(v28-v29)*y2829*ib;
i30=(v29-v30)*y2930*ib;
i31=(v10-v31)*y1031*ib;
i32=(v31-v32)*y3132*ib;
i33=(v32-v33)*y3233*ib;
i34=(v33-v34)*y3334*ib;
I. % Calculation of Losses
pl2=3*(i2)^2*real(z2)*zb;
pl3=3*(i3)^2*real(z3)*zb;
pl4=3*(i4)^2*real(z4)*zb;
prl=3*(i5)^2*real(z5)*zb;
pl6=3*(i6)^2*real(z6)*zb;
pl7=3*(i7)^2*real(z7)*zb;
pl8=3*(i8)^2*real(z8)*zb;
pl9=3*(i9)^2*real(z9)*zb;
pl10=3*(i10)^2*real(z10)*zb;
pl11=3*(i11)^2*real(z11)*zb;
pl12=3*(i12)^2*real(z12)*zb;
pl13=3*(i13)^2*real(z13)*zb;
pl14=3*(i14)^2*real(z14)*zb;
pl15=3*(i15)^2*real(z15)*zb;
pl16=3*(i16)^2*real(z16)*zb;
pl17=3*(i17)^2*real(z17)*zb;
pl18=3*(i18)^2*real(z18)*zb;
pl19=3*(i19)^2*real(z19)*zb;
pl20=3*(i20)^2*real(z20)*zb;
pl21=3*(i21)^2*real(z21)*zb;
pl22=3*(i22)^2*real(z22)*zb;
pl23=3*(i23)^2*real(z23)*zb;
pl24=3*(i24)^2*real(z24)*zb;
pl25=3*(i25)^2*real(z25)*zb;
pl26=3*(i26)^2*real(z26)*zb;
pl27=3*(i27)^2*real(z27)*zb;
pl28=3*(i28)^2*real(z28)*zb;
pl29=3*(i29)^2*real(z29)*zb;
pl30=3*(i30)^2*real(z30)*zb;
\[ pl_{31} = 3 \cdot (i_{31})^2 \cdot \text{real}(z_{31}) \cdot z_b; \]
\[ pl_{32} = 3 \cdot (i_{32})^2 \cdot \text{real}(z_{32}) \cdot z_b; \]
\[ pl_{33} = 3 \cdot (i_{33})^2 \cdot \text{real}(z_{33}) \cdot z_b; \]
\[ pl_{34} = 3 \cdot (i_{34})^2 \cdot \text{real}(z_{34}) \cdot z_b; \]

\[ plt = pl_2 + pl_3 + pl_4 + pl_5 + pl_6 + pl_7 + pl_8 + pl_9 + pl_{10} + pl_{11} + pl_{12} + pl_{13} + pl_{14} + pl_{15} + pl_{16} + pl_{17} + pl_{18} + pl_{20} + pl_{21} + pl_{22} + pl_{23} + pl_{24} + pl_{25} + pl_{26} + pl_{27} + pl_{28} + pl_{29} + pl_{30} + pl_{31} + pl_{32} + pl_{33} + pl_{34}; \]
\[ plt = 221.71 \]

J. % Losses due to active components of current
\[ pa_2 = 3 \cdot (\text{real}(i_2))^2 \cdot \text{real}(z_2) \cdot z_b/1000 \]
\[ pa_3 = 3 \cdot (\text{real}(i_3))^2 \cdot \text{real}(z_3) \cdot z_b/1000 \]
\[ pa_4 = 3 \cdot (\text{real}(i_4))^2 \cdot \text{real}(z_4) \cdot z_b/1000 \]
\[ pa_5 = 3 \cdot (\text{real}(i_5))^2 \cdot \text{real}(z_5) \cdot z_b/1000 \]
\[ pa_6 = 3 \cdot (\text{real}(i_6))^2 \cdot \text{real}(z_6) \cdot z_b/1000 \]
\[ pa_7 = 3 \cdot (\text{real}(i_7))^2 \cdot \text{real}(z_7) \cdot z_b/1000 \]
\[ pa_8 = 3 \cdot (\text{real}(i_8))^2 \cdot \text{real}(z_8) \cdot z_b/1000 \]
\[ pa_9 = 3 \cdot (\text{real}(i_9))^2 \cdot \text{real}(z_9) \cdot z_b/1000 \]
\[ pa_{10} = 3 \cdot (\text{real}(i_{10}))^2 \cdot \text{real}(z_{10}) \cdot z_b/1000 \]
\[ pa_{11} = 3 \cdot (\text{real}(i_{11}))^2 \cdot \text{real}(z_{11}) \cdot z_b/1000 \]
\[ pa_{12} = 3 \cdot (\text{real}(i_{12}))^2 \cdot \text{real}(z_{12}) \cdot z_b/1000 \]
\[ pa_{13} = 3 \cdot (\text{real}(i_{13}))^2 \cdot \text{real}(z_{13}) \cdot z_b/1000 \]
\[ pa_{14} = 3 \cdot (\text{real}(i_{14}))^2 \cdot \text{real}(z_{14}) \cdot z_b/1000 \]
\[ pa_{15} = 3 \cdot (\text{real}(i_{15}))^2 \cdot \text{real}(z_{15}) \cdot z_b/1000 \]
\[ pa_{16} = 3 \cdot (\text{real}(i_{16}))^2 \cdot \text{real}(z_{16}) \cdot z_b/1000 \]
\[ pa_{17} = 3 \cdot (\text{real}(i_{17}))^2 \cdot \text{real}(z_{17}) \cdot z_b/1000 \]
\[ pa_{18} = 3 \cdot (\text{real}(i_{18}))^2 \cdot \text{real}(z_{18}) \cdot z_b/1000 \]
\[ pa_{19} = 3 \cdot (\text{real}(i_{19}))^2 \cdot \text{real}(z_{19}) \cdot z_b/1000 \]
\[ pa_{20} = 3 \cdot (\text{real}(i_{20}))^2 \cdot \text{real}(z_{20}) \cdot z_b/1000 \]
\[ pa21=3*(\text{real}(i21))^2*\text{real}(z21)*zb/1000 \]
\[ pa22=3*(\text{real}(i22))^2*\text{real}(z22)*zb/1000 \]
\[ pa23=3*(\text{real}(i23))^2*\text{real}(z23)*zb/1000 \]
\[ pa24=3*(\text{real}(i24))^2*\text{real}(z24)*zb/1000 \]
\[ pa25=3*(\text{real}(i25))^2*\text{real}(z25)*zb/1000 \]
\[ pa26=3*(\text{real}(i26))^2*\text{real}(z26)*zb/1000 \]
\[ pa27=3*(\text{real}(i27))^2*\text{real}(z27)*zb/1000 \]
\[ pa28=3*(\text{real}(i28))^2*\text{real}(z28)*zb/1000 \]
\[ pa29=3*(\text{real}(i29))^2*\text{real}(z29)*zb/1000 \]
\[ pa30=3*(\text{real}(i30))^2*\text{real}(z30)*zb/1000 \]
\[ pa31=3*(\text{real}(i31))^2*\text{real}(z31)*zb/1000 \]
\[ pa32=3*(\text{real}(i32))^2*\text{real}(z32)*zb/1000 \]
\[ pa33=3*(\text{real}(i33))^2*\text{real}(z33)*zb/1000 \]
\[ pa34=3*(\text{real}(i34))^2*\text{real}(z34)*zb/1000 \]

\[ pr2=3*(\text{imag}(i2))^2*\text{real}(z2)*zb/1000 \]
\[ pr3=3*(\text{imag}(i3))^2*\text{real}(z3)*zb/1000 \]
\[ pr4=3*(\text{imag}(i4))^2*\text{real}(z4)*zb/1000 \]
\[ pr5=3*(\text{imag}(i5))^2*\text{real}(z5)*zb/1000 \]
\[ pr6=3*(\text{imag}(i6))^2*\text{real}(z6)*zb/1000 \]
\[ pr7=3*(\text{imag}(i7))^2*\text{real}(z7)*zb/1000 \]
\[ pr8=3*(\text{imag}(i8))^2*\text{real}(z8)*zb/1000 \]
\[ pr9=3*(\text{imag}(i9))^2*\text{real}(z9)*zb/1000 \]
\[ pr10=3*(\text{imag}(i10))^2*\text{real}(z10)*zb/1000 \]
\[ pr11=3*(\text{imag}(i11))^2*\text{real}(z11)*zb/1000 \]
\[ pr12=3*(\text{imag}(i12))^2*\text{real}(z12)*zb/1000 \]
\[ pr13=3*(\text{imag}(i13))^2*\text{real}(z13)*zb/1000 \]
\[ pr14=3*(\text{imag}(i14))^2*\text{real}(z14)*zb/1000 \]
\[ pr15=3*(\text{imag}(i15))^2*\text{real}(z15)*zb/1000 \]
\[ pr16 = 3*(\text{imag}(i16))^2*\text{real}(z16)*zb/1000 \]
\[ pr17 = 3*(\text{imag}(i17))^2*\text{real}(z17)*zb/1000 \]
\[ pr18 = 3*(\text{imag}(i18))^2*\text{real}(z18)*zb/1000 \]
\[ pr19 = 3*(\text{imag}(i19))^2*\text{real}(z19)*zb/1000 \]
\[ pr20 = 3*(\text{imag}(i20))^2*\text{real}(z20)*zb/1000 \]
\[ pr21 = 3*(\text{imag}(i21))^2*\text{real}(z21)*zb/1000 \]
\[ pr22 = 3*(\text{imag}(i22))^2*\text{real}(z22)*zb/1000 \]
\[ pr23 = 3*(\text{imag}(i23))^2*\text{real}(z23)*zb/1000 \]
\[ pr24 = 3*(\text{imag}(i24))^2*\text{real}(z24)*zb/1000 \]
\[ pr25 = 3*(\text{imag}(i25))^2*\text{real}(z25)*zb/1000 \]
\[ pr26 = 3*(\text{imag}(i26))^2*\text{real}(z26)*zb/1000 \]
\[ pr27 = 3*(\text{imag}(i27))^2*\text{real}(z27)*zb/1000 \]
\[ pr28 = 3*(\text{imag}(i28))^2*\text{real}(z28)*zb/1000 \]
\[ pr29 = 3*(\text{imag}(i29))^2*\text{real}(z29)*zb/1000 \]
\[ pr30 = 3*(\text{imag}(i30))^2*\text{real}(z30)*zb/1000 \]
\[ pr31 = 3*(\text{imag}(i31))^2*\text{real}(z31)*zb/1000 \]
\[ pr32 = 3*(\text{imag}(i32))^2*\text{real}(z32)*zb/1000 \]
\[ pr33 = 3*(\text{imag}(i33))^2*\text{real}(z33)*zb/1000 \]
\[ pr34 = 3*(\text{imag}(i34))^2*\text{real}(z34)*zb/1000 \]

\[ \text{prt} = pr2 + pr3 + pr4 + pr5 + pr6 + pr7 + pr8 + pr9 + pr10 + pr11 + pr12 + pr13 + pr14 + pr15 + pr16 + pr17 + pr18 + pr19 + pr20 + pr21 + pr22 + pr23 + pr24 + pr25 + pr26 + pr27 + pr28 + pr29 + pr30 + pr31 + pr32 + pr33 + pr34; \]

L. % Load Currents
\[
\begin{align*}
il2 & = \text{conj} \left( \frac{S_2}{V_2} \right) \\
il4 & = \text{conj} \left( \frac{S_4}{V_4} \right)
\end{align*}
\]
il5 = conj \left( \frac{S_5}{V_5} \right) \\

il8 = conj \left( \frac{S_8}{V_8} \right) \\

il9 = il8; \\

il11 = il9; \\

il12 = conj \left( \frac{S_{12}}{V_{12}} \right) \\

il13 = conj \left( \frac{S_{13}}{V_{13}} \right) \\

il14 = il13; \\

il15 = il14; \\

il16 = conj \left( \frac{S_{16}}{V_{16}} \right) \\

il17 = il11; \\

il18 = il17; \\

il19 = il18; \\

il20 = il19; \\

il21 = il20; \\

il22 = il21; \\

il23 = il22; \\

il24 = il23; \\

il25 = il24; \\

il26 = il25; \\

il27 = il12; \\

il28 = conj \left( \frac{S_{28}}{V_{28}} \right) \\

il29 = il28; \\

il30 = il29;
\[
il31 = \text{conj}\left(\frac{S_{31}}{V_{31}}\right)
\]

\[
il32 = \text{il31} ;
\]

\[
il33 = \text{il32} ;
\]

\[
il34 = \text{il33} ;
\]

**M.  \% Losses due to reactive component of load currents**

\[
l2 = (\text{imag}(\text{il2}))^2*0.117 ;
\]

\[
l4 = (\text{imag}(\text{il4}))^2*0.3887 ;
\]

\[
l5 = (\text{imag}(\text{il5}))^2*0.5382 ;
\]

\[
l8 = (\text{imag}(\text{il8}))^2*1.2117 ;
\]

\[
l9 = (\text{imag}(\text{il9}))^2*1.5261 ;
\]

\[
l11 = (\text{imag}(\text{il11}))^2*1.8667 ;
\]

\[
l12 = (\text{imag}(\text{il12}))^2*1.9715 ;
\]

\[
l13 = (\text{imag}(\text{il13}))^2*0.38145 ;
\]

\[
l14 = (\text{imag}(\text{il14}))^2*0.59105 ;
\]

\[
l15 = (\text{imag}(\text{il15}))^2*0.69585 ;
\]

\[
l16 = (\text{imag}(\text{il16}))^2*0.74825 ;
\]

\[
l17 = (\text{imag}(\text{il17}))^2*0.8671 ;
\]

\[
l18 = (\text{imag}(\text{il18}))^2*1.03155 ;
\]

\[
l19 = (\text{imag}(\text{il19}))^2*1.23945 ;
\]

\[
l20 = (\text{imag}(\text{il20}))^2*1.42845 ;
\]

\[
l21 = (\text{imag}(\text{il21}))^2*1.61745 ;
\]

\[
l22 = (\text{imag}(\text{il22}))^2*1.87945 ;
\]

\[
l23 = (\text{imag}(\text{il23}))^2*2.14145 ;
\]

\[
l24 = (\text{imag}(\text{il24}))^2*2.45585 ;
\]

\[
l25 = (\text{imag}(\text{il25}))^2*2.66545 ;
\]

\[
l26 = (\text{imag}(\text{il26}))^2*2.79645 ;
\]

\[
l27 = (\text{imag}(\text{il27}))^2*2.90125 ;
\]

\[
l28 = (\text{imag}(\text{il28}))^2*1.1593 ;
\]
\[
\begin{align*}
l29 &= (\text{imag}(l29))^2 \times 1.3165; \\
l30 &= (\text{imag}(l30))^2 \times 1.4737; \\
l31 &= (\text{imag}(l31))^2 \times 1.8929; \\
l32 &= (\text{imag}(l32))^2 \times 2.1025; \\
l33 &= (\text{imag}(l33))^2 \times 2.2597; \\
l34 &= (\text{imag}(l34))^2 \times 2.3645; \\
\end{align*}
\]

N. \% Losses and Loss reduction after placement of capacitor on node 26

for \( Qc26 = 0:150*1000:1500*1000; \)

\( ic26 = (Qc26/V26) \times i; \)

\( pl2 = 3 \times (\text{abs}(i2 + ic26))^2 \times \text{real}(z2) \times zb; \)

\( pl3 = 3 \times (\text{abs}(i3 + ic26))^2 \times \text{real}(z3) \times zb; \)

\( pl4 = 3 \times (\text{abs}(i4 + ic26))^2 \times \text{real}(z4) \times zb; \)

\( pl5 = 3 \times (\text{abs}(i5 + ic26))^2 \times \text{real}(z5) \times zb; \)

\( pl6 = 3 \times (\text{abs}(i6 + ic26))^2 \times \text{real}(z6) \times zb; \)

\( pl7 = 3 \times (\text{abs}(i7))^2 \times \text{real}(z7) \times zb; \)

\( pl8 = 3 \times (\text{abs}(i8))^2 \times \text{real}(z8) \times zb; \)

\( pl9 = 3 \times (\text{abs}(i9))^2 \times \text{real}(z9) \times zb; \)

\( pl10 = 3 \times (\text{abs}(i10))^2 \times \text{real}(z10) \times zb; \)

\( pl11 = 3 \times (\text{abs}(i11))^2 \times \text{real}(z11) \times zb; \)

\( pl12 = 3 \times (\text{abs}(i12))^2 \times \text{real}(z12) \times zb; \)

\( pl13 = 3 \times (\text{abs}(i13))^2 \times \text{real}(z13) \times zb; \)

\( pl14 = 3 \times (\text{abs}(i14))^2 \times \text{real}(z14) \times zb; \)

\( pl15 = 3 \times (\text{abs}(i15))^2 \times \text{real}(z15) \times zb; \)

\( pl16 = 3 \times (\text{abs}(i16))^2 \times \text{real}(z16) \times zb; \)

\( pl17 = 3 \times (\text{abs}(i17 + ic26))^2 \times \text{real}(z17) \times zb; \)

\( pl18 = 3 \times (\text{abs}(i18 + ic26))^2 \times \text{real}(z18) \times zb; \)

\( pl19 = 3 \times (\text{abs}(i19 + ic26))^2 \times \text{real}(z19) \times zb; \)

\( pl20 = 3 \times (\text{abs}(i20 + ic26))^2 \times \text{real}(z20) \times zb; \)

\( pl21 = 3 \times (\text{abs}(i21 + ic26))^2 \times \text{real}(z21) \times zb; \)

\( pl22 = 3 \times (\text{abs}(i22 + ic26))^2 \times \text{real}(z22) \times zb; \)
pl23=3*(abs(i23+ic26))^2*real(z23)*zb;
pl24=3*(abs(i24+ic26))^2*real(z24)*zb;
pl25=3*(abs(i25+ic26))^2*real(z25)*zb;
pl26=3*(abs(i26+ic26))^2*real(z26)*zb;
pl27=3*(abs(i27))^2*real(z27)*zb;
pl28=3*(abs(i28))^2*real(z28)*zb;
pl29=3*(abs(i29))^2*real(z29)*zb;
pl30=3*(abs(i30))^2*real(z30)*zb;
pl31=3*(abs(i31))^2*real(z31)*zb;
pl32=3*(abs(i32))^2*real(z32)*zb;
pl33=3*(abs(i33))^2*real(z33)*zb;
pl34=3*(abs(i34))^2*real(z34)*zb;

PL26=(pl2+pl3+pl4+pl5+pl6+pl7+pl8+pl9+pl10+pl11+pl12+pl13+pl
14+pl15+pl16+pl17+pl18+pl19+pl20+pl21+pl22+pl23+pl24+pl25+pl
26+pl27+pl28+pl29+pl30+pl31+pl32+pl33+pl34)/1000;
PLr26=221.71-PL26;
end

Qc26=0:150:1500;
PL26=[221.7 206.9 195.5 187.7 182.6 185.5 191.6 201.4
214.7 231.5];
PLr26=[0 14.9 26.2 34 38.3 39.1 36.4 30.1 20.4 7 -9.8];
figure(4.2)
plot(Qc26,PL26,'r')
grid on
hold on
plot(Qc26,PLr26,'b')
xlabel('Size of capacitor bank[Kvar]')
ylabel('Power Loss & Loss Reduction[KW]')
O. % Power factor & savings calculations for Capacitor on node 26
   \[ a_l = \arccos(0.85); \]
   \[ P = 3680; \]
   \[ A = 250; \]
   \[ C = 70; \]
   \[ Qc26 = 0:150:1500; \]
   \[ x = \tan(a_l) - \frac{Qc26}{P}; \]
   \[ a2 = \arctan(x); \]
   \[ y = \cos(a2); \]
   \[ S26 = A \times \left( \frac{P}{\cos(a1)} - \frac{P}{\cos(a2)} \right) - C \times (P \times \tan(a1) - P \times \tan(a2)); \]
   Figure (1)
   \[
   \text{plot (Qc26, S26, 'b')}
   \]
   \[
   \text{grid on}
   \]
   \[
   \text{xlabel ('Size of capacitor bank on node 26 [Kvar]')}
   \]
   \[
   \text{ylabel ('Savings [N']})
   \]

P. % Power Factor & Savings Calculations for Capacitor on node 11
   \[ a1=\arccos(0.85); \]
   \[ P=1380; \]
   \[ A=250; \]
   \[ C=70; \]
   \[ \text{for for Qc=0:150:1500;} \]
   \[ x=\tan(a1)-(Qc/P); \]
   \[ a2=\arctan(x); \]
   \[ y=\cos(a2); \]
   \[ S=A*((P/(\cos(a1)))-(P/(\cos(a2))))-C*(P*\tan(a1)-P*\tan(a2)); \]
   end

Q. % Losses and Loss Reduction after addition of capacitor on node 11
for Qc11-0:150*1000:1500*1000;
ic26=(Qc26/V26)*i;
ic11=(Qc11/V11)*i;
p12=3*(abs(i2+ic11))^2*real(z2)*zb;
p13=3*(abs(i3+ic11))^2*real(z3)*zb;
p14=3*(abs(i4+ic11))^2*real(z4)*zb;
p15=3*(abs(i5+ic11))^2*real(z5)*zb;
p16=3*(abs(i6+ic11))^2*real(z6)*zb;
p17=3*(abs(i7+ic11))^2*real(z7)*zb;
p18=3*(abs(i8+ic11))^2*real(z8)*zb;
p19=3*(abs(i9+ic11))^2*real(z9)*zb;
p10=3*(abs(i10+ic11))^2*real(z10)*zb;
p111=3*(abs(i11+ic11))^2*real(z11)*zb;
p112=3*(abs(i12))^2*real(z12)*zb;
p113=3*(abs(i13))^2*real(z13)*zb;
p114=3*(abs(i14))^2*real(z14)*zb;
p115=3*(abs(i15))^2*real(z15)*zb;
p116=3*(abs(i16))^2*real(z16)*zb;
p117=3*(abs(i17))^2*real(z17)*zb;
p118=3*(abs(i18))^2*real(z18)*zb;
p119=3*(abs(i19))^2*real(z19)*zb;
p120=3*(abs(i20))^2*real(z20)*zb;
p121=3*(abs(i21))^2*real(z21)*zb;
p122=3*(abs(i22))^2*real(z22)*zb;
p123=3*(abs(i23))^2*real(z23)*zb;
p124=3*(abs(i24))^2*real(z24)*zb;
p125=3*(abs(i25))^2*real(z25)*zb;
p126=3*(abs(i26))^2*real(z26)*zb;
p127=3*(abs(i27))^2*real(z27)*zb;
p128=3*(abs(i28))^2*real(z28)*zb;
\[ p129 = 3 \cdot (\text{abs}(i29))^2 \cdot \text{real}(z29) \cdot z_b; \]
\[ p130 = 3 \cdot (\text{abs}(i30))^2 \cdot \text{real}(z30) \cdot z_b; \]
\[ p131 = 3 \cdot (\text{abs}(i31))^2 \cdot \text{real}(z31) \cdot z_b; \]
\[ p132 = 3 \cdot (\text{abs}(i32))^2 \cdot \text{real}(z32) \cdot z_b; \]
\[ p133 = 3 \cdot (\text{abs}(i33))^2 \cdot \text{real}(z33) \cdot z_b; \]
\[ p134 = 3 \cdot (\text{abs}(i34))^2 \cdot \text{real}(z34) \cdot z_b; \]

\[ dI = 221.71 - p \]
end

R. % Power Factor and Savings calculations for Capacitor on node 11
\[ a1 = \text{acos} (0.85); \]
\[ P = 1380; \]
\[ A = 250; \]
\[ C = 70; \]
\[ Qcll = 0:150:1500; \]
\[ x = \tan (a1) - (Qc11/P); \]
\[ a2 = \text{atan} (x); \]
\[ y = \cos (a2); \]
\[ S11 = (A.*((P./(\text{cos}(a1))) - (P./(\text{cos}(a2)))) - C.*P.*\text{tan}(a1) - P.*\text{tan}(a2)) \]

Figure (1)
plot (Qc11, S11, ‘b’)
grid on
xlabel (‘Size of capacitor bank on node 11 [Kvar]’)
ylabel ('Savings [N]')

% Power loss and loss reduction after placement of capacitor on node 11 (capacitors on nodes 26 & 11)
for Qc11=750*1000:150*1000:2250*1000;
ic11=(Qc11/V11)*ib;
pl2=3*(abs(i2+ic26+ic11))^2*real(z2)*zb;
pl3=3*(abs(i3+ic26+ic11))^2*real(z3)*zb;
pl4=3*(abs(i4+ic26+ic11))^2*real(z4)*zb;
pl5=3*(abs(i5+ic26+ic11))^2*real(z5)*zb;
pl6=3*(abs(i6+ic26+ic11))^2*real(z6)*zb;
pl7=3*(abs(i7+ic11))^2*real(z7)*zb;
pl8=3*(abs(i8+ic11))^2*real(z8)*zb;
pl9=3*(abs(i9+ic11))^2*real(z9)*zb;
pl10=3*(abs(i10+ic11))^2*real(z10)*zb;
pl11=3*(abs(i11+ic11))^2*real(z11)*zb;
pl12=3*(abs(i12))^2*real(z12)*zb;
pl13=3*(abs(i13))^2*real(z13)*zb;
pl14=3*(abs(i14))^2*real(z14)*zb;
pl15=3*(abs(i15))^2*real(z15)*zb;
pl16=3*(abs(i16))^2*real(z16)*zb;
pl17=3*(abs(i17+ic26))^2*real(z17)*zb;
pl18=3*(abs(i18+ic26))^2*real(z18)*zb;
pl19=3*(abs(i19+ic26))^2*real(z19)*zb;
pl20=3*(abs(i20+ic26))^2*real(z20)*zb;
pl21=3*(abs(i21+ic26))^2*real(z21)*zb;
pl22=3*(abs(i22+ic26))^2*real(z22)*zb;
pl23=3*(abs(i23+ic26))^2*real(z23)*zb;
pl24=3*(abs(i24+ic26))^2*real(z24)*zb;
pl25=3*(abs(i25+ic26))^2*real(z25)*zb;
pl26=3*(abs(i26+ic26))^2*real(z26)*zb;
pl27=3*(abs(i27))^2*real(z27)*zb;
pl28=3*(abs(i28))^2*real(z28)*zb;
pl29=3*(abs(i29))^2*real(z29)*zb;
pl30=3*(abs(i30))^2*real(z30)*zb;
pl31=3*(abs(i31))^2*real(z31)*zb;
pl32=3*(abs(i32))^2*real(z32)*zb;
pl33=3*(abs(i33))^2*real(z33)*zb;
pl34=3*(abs(i34))^2*real(z34)*zb;
PL2611=(pl2+pl3+pl4+pl5+pl6+pl7+pl8+pl9+pl10+pl11+pl12+pl13+
pl14+pl15+pl16+pl17+pl18+pl19+pl20+pl21+pl22+pl23+pl24+pl25+
+pl26+pl27+pl28+pl29+pl30+pl31+pl32+pl33+pl34)/1000;
PLr2611=221.71-PL2611;
end

Qc2611=750:150:2250;
PL2611=[182.6 176.9 173.5 172.3 173.4 176.8 182.4 190.2 200.3 212.7
227.4];
PLr2611=[39.1 44.8 48.2 49.4 48.3 44.9 39.3 31.5 21.4 9 -5.7];

figure(4.3)
plot(Qc2611,PL2611,'r')
grid on
hold on
plot(Qc2611,PLr2611,'b')
xlabel('Size of capacitor bank[Kvar]')
ylabel('Power Loss & Loss Reduction[KW]')
T. % Power factor & Net Savings after Compensation

\[
a_1 = \cos^{-1}(0.85);
\]

\[
P = 3680;
\]

\[
A = 250;
\]

\[
C = 70;
\]

\[
\text{for } Q_{c2611} = 750:150:2250;
\]

\[
x = \tan(a_1) - \left(\frac{Q_c}{P}\right);
\]

\[
a_2 = \tan^{-1}(x);
\]

\[
y = \cos(a_2);
\]

\[
S_{2611} = A \times \left(\frac{P}{\cos(a_1)} - \frac{P}{\cos(a_2)}\right) - C \times (P \tan(a_1) - P \tan(a_2));
\]

\[
\text{end}
\]

\[
Q_{c2611} = 750:150:2250;
\]

\[
S_{2611} = [33.4 36.7 38.8 39.5 38.9 36.9 33.4 28.5 22.1 14.2 4.8];
\]

\[
\text{figure}(4.4)
\]

\[
\text{plot}(Q_{c2611},S_{2611},'r')
\]

\[
\text{grid on}
\]

\[
\text{xlabel('Size of capacitor bank[Kvar]')}
\]

\[
\text{ylabel('Net savings per annum[N]$ \times 10^3$')}
\]

\[
\text{End}
\]