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A New Method for Calculating the Economic Benefits of Varying Degrees of Power Factor Correction for Industrial Plant Loads

Mohammed Ishaque
Portland State University

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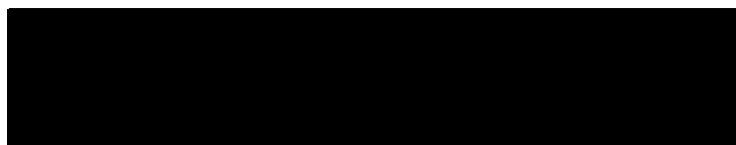
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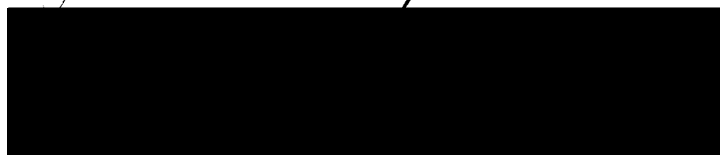
AN ABSTRACT OF THE THESIS OF Mohammed Ishaque for the Master of Science in
Electrical and Computer Engineering presented January 31, 1992.

Title: A New Method for Calculating the Economic Benefits of Varying
Degrees of Power Factor Correction for Industrial Plant Loads

APPROVED BY THE MEMBERS OF THE THESIS COMMITTEE:



Jack C. Riley, Chair



Richard D. Morris



Faryar Etesami

A comparative study of the economic benefits that can be obtained from different degrees of power factor correction for medium and small scale industrial installations is shown. A new approach for precise calculation of kws and $kvars$ required at different power factors is presented. These calculated values are used to find the return on investments for the capacitors needed for power factor correction. The developed method is easy to use, cost effective, accurate and will help electrical engineers with minimum knowledge of power systems to precisely determine the savings available by improving the power factor of an industrial load.

A NEW METHOD FOR CALCULATING THE ECONOMIC BENEFITS OF VARYING
DEGREES OF POWER FACTOR CORRECTION FOR INDUSTRIAL PLANT LOADS

by

MOHAMMED ISHAQUE

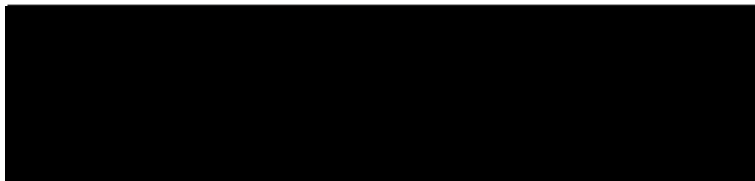
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requirements for the degree of

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in
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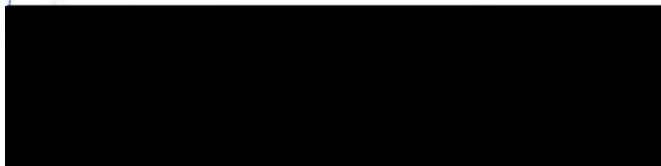
Portland State University
1992

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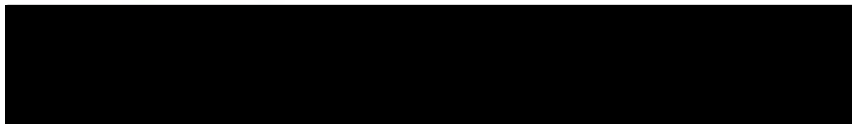


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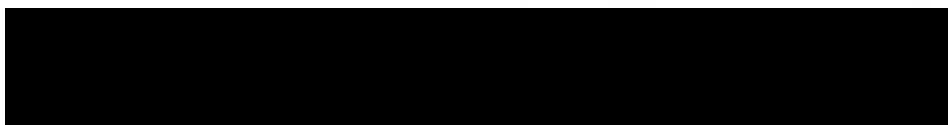


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Portland, Oregon

Mohammed Ishaque

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NOTATION AND GLOSSARY

θ	Phase angle in degrees
η	Efficiency in proportion parts
<i>hp</i>	Horse power in proportion parts
<i>pf</i> , PF	Power factor
APFCS	Automatic Power Factor Controllers
<i>kwhr</i>	Kilowatt hours
<i>kvarhr</i>	Reactive kilovolt ampere hours
kw	Kilo watts
kva	Kilo volt amperes
ACSR	Aluminium Conductor Steel Reinforced
Kws	Kilo watts
Kvar	Reactive kilo volt amperes
KV	Kilo volts
G_1	Generator_1 or Substation_1
G_2	Generator_2 or Substation_2
gen	Generator
V	Voltage in volts
G	conductance in siemens
B	susceptance in siemens
lag	Lagging power factor
lead	Leading power factor

W	Watt
R	Resistance in ohms
I	Current in amperes
X_c	Capacitive reactance in Farads
rpm	Revolution per minute
\propto	proportional to
X	Reactance in ohms
ε	error check
Y_{km}	Admittance between bus k and bus m in siemens
V_m	Voltage at bus m
P_k	Real power at bus k
Q_k	Reactive power at bus k
G_{km}	Conductance between bus k and m in siemens
B_{km}	Susceptance between bus k and m in siemens
$P_k(V, \theta)$	Real power at bus k as a function of voltage and phase
$Q_k(V, \theta)$	Reactive power at bus k as a function of voltage and phase
H,N,M,L	Partition of Jacobian matrix

CHAPTER I

INTRODUCTION

This thesis presents a new way of addressing the economic problems resulting from the expensive supply of unnecessary reactive power to industrial loads. A set of computer programs have been developed which address the financial merits of power factor correction plans. These programs can be used to test the anticipated savings of proposed power factor improvement strategies. To illustrate the use of these programs a reactive compensation scheme for a typical industrial load has been studied.

The cost of system losses due to the kilovar flow of reactive power is an important economic factor [2] which should not be overlooked. Modern industries are continually increasing their inductive loads thus requiring ever larger amounts of reactive power. Typical reactive loads are induction motors, (especially those operated at less than full load), transformers, arc welders, rectifiers, arc furnaces, fluorescent lamps and various types of electronic equipment [1]. Unless reactive power is dealt with locally a reactive burden results which is expensive for the utility system to supply. The most common devices used to improve poor power factors are capacitors, synchronous motors and synchronous capacitors. Improving the power factor leads to both important savings in power cost and improved plant efficiency.

The choice of the best power factor improvement plan depends on the cost of correcting the original combined power factor of the loads and the details of utility rate structures. Each of these factors should be individually studied before reaching any decision.

A suitable computer model for analyzing power factor economics has been developed. Programs have been written which calculate the influence of such items as plant power factors,

reactive power losses, demand charges, and power factor penalties. These programs can be used to find the effects of various degrees of power factor correction.

A model representing a medium size industrial load has been analyzed to demonstrate the application of the method. The cost saving strategies suggested by the example are discussed.

PROBLEM STATEMENT

Every year, millions of dollars are wasted in industrial plants because of the difficulty of determining the economic benefits of power factor improvement. An industrial plant operating at a low power factor will:

- (1) Reduce system capacity and performance by overloading cables and transformers.
- (2) Reduce line voltage levels, thus adversely affecting the efficiency of motor operation and decreasing incandescent lamp illumination.
- (3) Increase power cost when utility power factor clauses are enforced.
- (4) Introduce higher losses in generators, transformers and in the lines (copper loss) through which the reactive current flows.
- (5) Overload generators and lines unnecessarily with reactive current, thus requiring larger generators and transformers, and heavier lines.

The cost of increased losses due to increased kilovar flow will be borne by the user, whether it be a private industry or a public institution. Not only that, but if the kilovar flow exceeds a certain minimum level, the power factor of the plant will be low and the utility will impose a "power factor penalty". In 1978 the major electrical power supplier in the Northwest initiated a penalty clause in its wholesale power rates for customers with a power factor less than 95%. For each 0.5% decrement that the average monthly power factor is below 95%, 1% is added to the charge for peak power demand [32].

Millions of dollars are wasted in industrial plants because of the lack of understanding of the economic benefits of power factor improvement. On the one hand, because of the high cost of consulting services, medium and small size industries seldom seek technical assistance. On the other hand, no simple method exists for monitoring and analyzing the losses caused by reactive loads in industrial plants. Without this input it is difficult to determine the economic benefits of power factor improvement.

There has always been a need for a method of evaluating the economic benefits of power factor improvement for an existing system. Such a method should be fairly simple, reliable, and cost effective so that an electrical engineer with a minimum knowledge of power systems can determine the efficiency and cost situation of plant loads.

This dissertation presents a method and provides computer programs to implement it that can be used by a plant engineer to analyze and minimize the effects of electrical losses and power factor penalties.

PREVIOUS WORK

A search of the technical literature indicates that for medium and small scale industries very little attention has been paid to the economic benefits of accurate power factor correction analysis. No readily available methods for determining the cost savings for various amounts of power factor correction were found.

The literature did reveal two traditional methods for finding the combined power factor of a group of loads.

For the first method the combined power factor of the group is calculated using the name plate specifications of the individual loads. The calculations discussed in the literature are made by numerical, graphical or look-up table methods [33]. Name plate specifications can incorrectly predict the power factor at the generator or the substation since they typically have a

$\pm 10\%$ tolerance.

The second method uses portable kilowatt and power factor meters connected at load and motor control centers to determine the power factor at strategic locations [32]. Since there are no set rules to pinpoint where the worst power factors will be found, these locations are selected on a judgment basis depending on experience.

These traditional methods were still being used in a recent study of the economic benefits of power factor correction by Manolo E. Juguilon, R. Micheal Boger, and W. Dalos [32].

There are some methods available for dynamically adjusting power factor correcting devices. For example, Automatic Power Factor Controllers (APFCs) are used to switch power factor correcting capacitors in steps at load centers [31] to maintain a power factor within certain limits. APFCs operate in a window surrounding a power factor set point, and are usually used on systems under 600 volts [31]. Controlling all load centers in a complex industrial plants by a single APFC is not practical, especially when there are many load centers separated by considerable distances. Even if the controller is accurate, to $\pm 1\%$ at a power factor of 95%, the controller will work in a window from 94% - 96%. For power factor economics this difference can be significant.

Hopkin [3] suggested a completely different strategy from those of the traditional methods. He proposed that modified load flow calculations could be used to find the power factor at all load centers and generation sites. From these results the savings available from power factor correction could be determined. The only data required for his simulation are the ratings of the individual loads connected to the system. To the best of our knowledge his plan has not been used before.

SOLUTION APPROACH

The work discussed here concerns the computer implementation of Hopkin's suggestion. The information obtained from this modified load flow study is the magnitude and phase angle of the voltage at each bus and the real and reactive power flowing in each line [16]. This gives all the necessary information for calculating power factor economics.

A set of four programs have been written to analyze the economic benefits of power factor improvement proposals. These benefits can be found by using the programs to compare the charges for uncorrected loads with those for various levels of power factor correction. To use the programs, first the bus loads are determined by the program Pfactor.c using motor data. Next the voltage and phase information for individual buses are found by the program Loadflow.c using the output of Pfactor.c and assumed initial values. The output from Loadflow.c is used by Powerflow.c to find the transmission line losses. Lastly, the program CostCalc.c calculates compensated and uncompensated cost using the output of Pfactor.c, Loadflow.c, Powerflow.c and the total hours of plant operation per month.

The program, Pfactor.c, calculates the total real and reactive power magnitudes at individual buses of the proposed model. The inputs to this program are the efficiency, power factor and horse power ratings of the motors. The documentation of this program is presented in appendix A.

The program, Loadflow.c, finds the bus admittance matrix, Y_{bus} , and the existing voltage and power factor at the individual buses. The inputs to this program are the output of Pfactor.c, the initial voltage and angle at the buses, and the resistance and reactance of the transmission lines. The documentation of this program is presented in appendix B.

The program, Powerflow.c, calculates the magnitude and direction of real and reactive power flow in individual transmission lines and buses. The inputs to this program are the Y_{bus}

matrix, and the voltage and angle at the individual buses. The documentation of this program is presented in appendix C.

The last program, CostCala.c, calculates the monthly power bills for both phase compensated and uncompensated systems and gives the potential monthly cost savings. The inputs to this program are the utility rate schedule, plant power factor, real and reactive power at the buses, days per month, shifts per day and hours per shift. The documentation of this program is presented in appendix D.

The results of a typical comparative study of power factor economics are presented in chapter IV.

SIGNIFICANCE AND CONTRIBUTIONS

The operating characteristics of power generation and transmission systems are available from load flow data [16]. To find the most cost effective operating mode for a plant all of the load centers and generating stations need to be studied as an integrated system. Cost savings can result from strict control of the generation angle which can be accomplished using a load flow analysis.

Hopkin [3] suggested that a modified load flow study computer program could be employed to determine the kilowatts and kilovars for an entire system operating at various power factors. The best part of Hopkins's idea is that his method yields a comparative evaluation of the economic benefits for different degrees of power factor correction. Traditional methods would be error prone, time consuming and difficult, if not impossible, to use.

A method similar ours is used to calculate voltage, angle and other parameters at different grids of power distribution systems for power scheduling and dispatching purposes. However, the idea of implementing the method in industrial plants to calculate power factor economics is completely new.

The computer programs presented here have been written so that a plant engineer can make a practical analysis using readily available data.

ORGANIZATION OF THE THESIS

Chapter I is the introduction.

Chapter II provides the formal definitions of power factor and describes the effects of low power factor on electrical equipment, the causes of low power factor, the instruments required for power factor studies, the devices used for power factor improvement, the reasons for and benefits obtained from power factor correction.

Chapter III describes the algorithm used in the thesis for modified load flow study simulation.

Chapter IV presents the results of a computer analysis of a typical plant load, including the calculation of the economic benefits obtained from different degrees of power factor correction.

Chapter V presents conclusions and directions for future work.

CHAPTER II

POWER FACTOR

Active power in a single phase circuit can be expressed as:

$$P = |V_p| |I_p| \cos(\theta_v - \theta_i) \quad (2.1)$$

where

P = is the *active power* in watts

$|V_p|$ = is the phase voltage in rms volts

$|I_p|$ = is the phase current in rms amperes

θ_v = is the phasor angle of the phase voltage in radians

θ_i = is the phasor angle of the phase current in radians

$|V_p| |I_p|$ = is the *apparent power* in volt-amperes

$pf = \cos(\theta_v - \theta_i)$ = is the *power factor* in proportional parts

From the equation (2.1) the power factor can be expressed as:

$$\text{power factor} = \frac{\text{active power}}{\text{apparent power}} \quad (2.2)$$

In a similar manner for a single phase circuit reactive power can be defined as:

$$Q = |V_p| |I_p| \sin(\theta_v - \theta_i) \quad (2.3)$$

where

Q = is the *reactive power* in vars (reactive volt amperes)

$Qf = \sin(\theta_v - \theta_i)$ = is the *reactive factor* in proportional parts

from the equation (2.3) the reactive factor can be expressed as:

$$\text{reactive factor} = \frac{\text{reactive power}}{\text{apparent power}} \quad (2.4)$$

For polyphase circuits it can be shown that these definitions of power factor and reactive factor in terms of apparent, active and reactive power still hold.

Apparent power, S, (complex power) is made up of both active and reactive power.

Active Power, P, (or working power) is the power that is read on a power meter. Active power does useful work such as turning a lathe, heating the metal for making a weld, or heating and lighting a plant. Some loads, such as incandescent lights and resistive heaters require only active power.

Reactive power, Q, (nonworking power) is the power required to produce the magnetic flux necessary for the operation of induction devices. Reactive power energizes the magnetic circuits of transformers and motors, and the dielectrics of capacitors.

Active power and reactive power add in quadrature as shown in Figure 2(a).

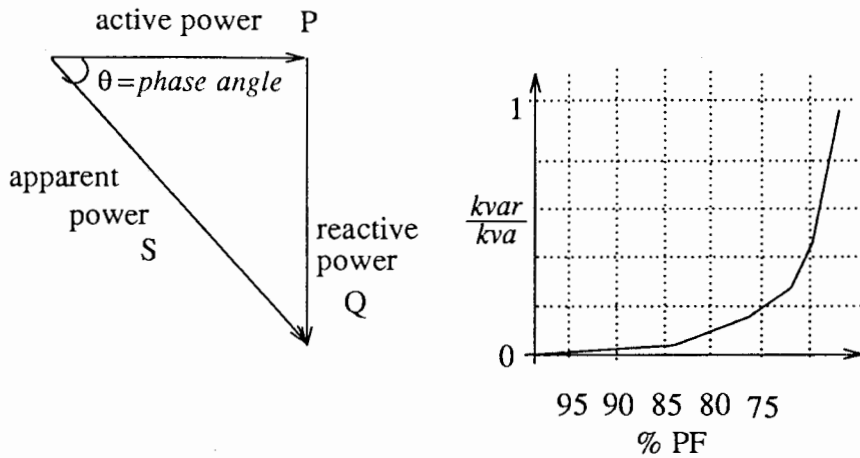
$$|S| = \sqrt{P^2 + Q^2} \quad (2.5)$$

Figure 2(b) shows the significant increase in loss at lower power factors.

LEADING AND LAGGING POWER FACTOR

The power factor may be either leading or lagging. The power factor is lagging if the load requires kilovars and leading if the load furnishes kilovars. Thus, an induction motor has a lagging power factor because its magnetizing requirements must be supplied by the power source. On the other hand, a capacitor or an over excited synchronous motor can supply kilovars and therefore has a leading power factor.

Table I shows the power factor for common operating conditions for both loads and generators, based on the direction of kilowatt and kilovar flow.



(a) power components in an a.c circuit (b) increase in loss with PF.

Figure 1. Right triangle relationship of current and power.

TABLE I
POWER FACTOR OF LOAD AND SOURCE

load type motor	load			generator		
	Kw	Kvar	pf^*	Kw	Kvar	pf^{**}
Induction	in	in	lag	out	out	lag
Sync. motor (over excited)	in	out	lead	out	in	lead
Sync. motor (under excited)	in	in	lag	out	out	lag

* Power factor measured at the load.

** Power factor measured at the generator.

THE EFFECTS OF LOW POWER FACTOR

At low power factors the total current flowing through conductors, lines and windings is greater than it needs to be. Since the power loss increases as the square of the current, a relatively small increase in current will cause a much larger increase in the loss.

Poor power factor reduces the output from an alternator, the performance of a transmission line, the regulation of transformers and the operating efficiency of the plant equipment. Figure 3 shows what happens at low power factor for typical loads.

For a typical alternator the amount of this reduction is shown in Figures 2(a) and 2(b). It is rather startling to observe that the kilowatt capacity of this alternator will drop from 1100 at unity power factor to 320 at 40% power factor. From the equation,

$$V_t = E_t - I_a (R_a + jX_s) \quad (2.6)$$

Where for the alternator,

V_t = terminal voltage in rms volts

E_t = No-load voltage in rms volts

I_a = armature current in rms amperes

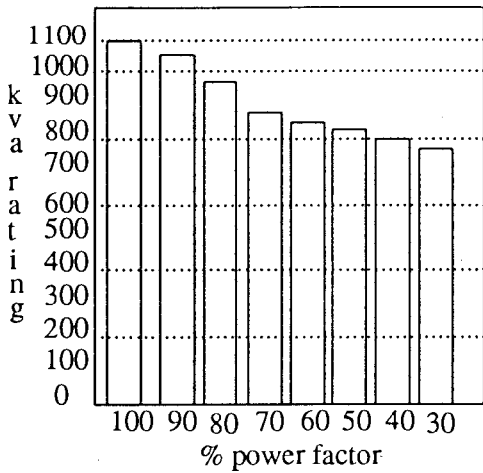
R_a = armature resistance in ohms

X_s = synchronous reactance in ohms

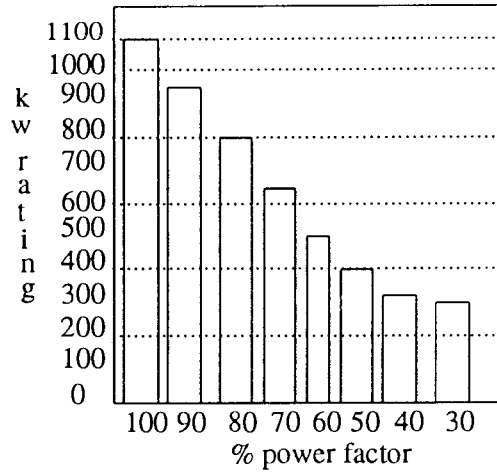
So if I_a increases (for low PF) there is a voltage drop due to R_a and X_s causing reduced terminal voltage V_t . This reduction of V_t will cause a reduced output capacity from the alternator.

For a typical transformer the performance reduction is shown in Figures 2(c) and 2(d). Not only does the power handling capacity of the transformer fall off badly, but the regulation gets much poorer.

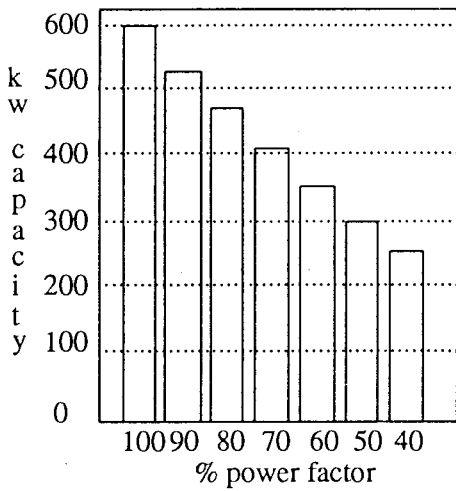
$$\text{regulation} = \frac{\text{no load voltage} - \text{full load voltage}}{\text{full load voltage}}$$



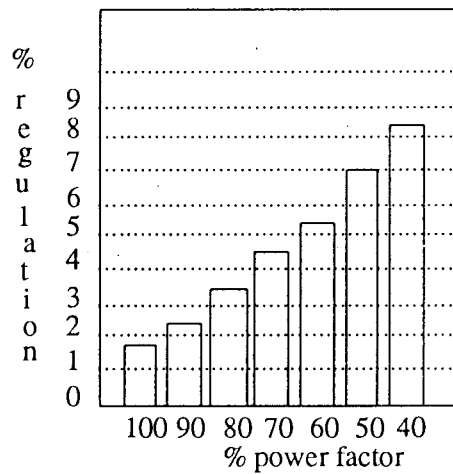
(a) small reduction of kva capacity of an alternator at lower pf



(b) drastic reduction of kw rating of an alternator at lower pf



(c) reduction of kw capacity of a transformer at lower pf



(d) drastic increase of regulation of a transformer at lower pf

Figure 2. Effects of low power factor on alternators and transformers.

CAUSES OF LOW POWER FACTOR

Many types of electrical equipment can reduce the power factor [5]. Chief among these, and by far the most widely used, is the induction motor. Also electric welding equipment, electric induction furnaces, transformers, neon signs, and other types of inductive equipment installed in a plant tend to lower the power factor.

METHODS OF POWER FACTOR MEASUREMENT

Power factor may be measured directly or computed from other measurements [7]. There are two convenient methods of finding the power factor of a plant by knowing the individual load ratings including their power factors.

The power factors of individual loads are usually specified. These power factors can be used to calculate the power factor for the combined load by summing the *kws* and *kvars* separately. The two results are then combined vectorially to find the total kva. The power factor is then given as the ratio of kw to kva.

The second method uses a tedious graphical approach which will not be discussed here.

PRACTICAL METHODS OF POWER FACTOR IMPROVEMENT

Reactive power is necessary for the operation of many types of electrical equipment and it must be supplied from some source. Since the transmission of reactive current through lines and transformers results in unnecessary expensive losses, it is desirable to generate reactive power near where it is required.

Static capacitors and switched capacitors offer a practical method of producing reactive power for medium size motors and other equipment [8]. Such capacitors are usually connected in shunt across the line. For example, a 30 kw load with an 80% power factor can be corrected

to 90% power factor by adding an 8 kvar capacitor ($3 \text{ kw} \times 0.266$) as shown in table II.

Synchronous motors and synchronous capacitors may also be used to control the power factor. They can be adjusted to supply either lagging or leading power or to operate at unity power factor.

REASONS FOR IMPROVING POWER FACTOR

- (1) Reduce Total Power Loss in the Plant
- (2) Improve Voltage performance
- (3) Improve the Power Capacity of the Plant
- (4) Improve the Transmission and Distribution Systems capacity
- (5) Reduce power cost and avoid penalties

CHAPTER III

LOAD FLOW

Under normal conditions electrical transmission systems operate in a steady state mode. The characteristics of this state can be found by a load flow (or power flow) calculation.

The objective of load flow calculations is to determine the steady state operating characteristics of the power generation and transmission system for a given set of bus loads. Active power generation is normally specified according to the least expensive dispatching practice and the generator voltage magnitude is normally maintained at a specified level by the automatic voltage regulator acting on the machine excitation. Loads are normally specified by their constant active and reactive power requirement and are assumed to be unaffected by the small variations of voltage and frequency expected during normal steady state operation.

The load flow solution is expected to provide the bus voltage magnitudes and angles, the active and reactive power flow in the individual transmission units, the losses and the reactive power generated or absorbed at voltage controlled buses.

The load flow problem is formulated in its basic analytical form in this chapter with the network represented by linear, bilateral and balanced lumped parameters. However, the power and voltage constraints make the problem non linear and an iterative numerical solution is required. For the iterative process an arbitrary set of initial values of the inputs are selected. After first iteration the results are tested and if they match the initial values within the specified tolerance, a solution has been obtained. If the calculated values differ from the initial ones, a new selection must be tried. The calculated values obtained in the first trial become a new set of initial values. The process then repeats. Finally, when calculated values agree with the initial

values within the specified tolerance, a solution has been found.

The first practical digital solution methods for load flow were the Y -matrix iterative methods [14]. These were suitable because of the low storage requirements, but had the disadvantage of converging slowly or not at all. Z -matrix methods were developed which overcame the reliability problem but at a sacrifice of storage and speed for large systems. The Newton-Raphson method was developed at this time and was found to have very strong convergence and reasonable computing requirements.

GLOSSARY OF LOAD FLOW TERMS

The complete power flow solution requires the determination of four variables at each bus k in the system.

P_k = real power

Q_k = reactive power

V_k = voltage magnitude

θ_k = voltage phase angle

When two of these variables are given at each bus the aim of the load flow analysis is to solve for the remaining two.

We define three different bus conditions based on the steady state assumptions of constant system frequency and constant voltages.

Voltage controlled bus (PV bus) The total injected active power P_k is specified, and the voltage magnitude V_k is maintained at a specified value by reactive power injection. This type of bus generally corresponds to a generator where P_k is fixed by a turbine governor setting and V_k is fixed by automatic voltage regulators acting on the machine excitation.

Nonvoltage controlled bus (Load bus) The total injected power, $P_k + jQ_k$, is specified at this bus. In the physical power system this corresponds to a load center such as a city or an

industry, where the consumer receives his power requirements. Both P_k and Q_k are assumed to be unaffected by small variations in bus voltage.

Slack (swing) bus This bus is required because the system losses are not known precisely in advance of the load flow calculation. Therefore, the total injected power cannot be specified at all of the buses. The slack bus voltage is usually assigned as the system phase reference, and its complex voltage $V_s = f(V, \theta)$ is therefore specified. The analogy in a practical power system is the generating station which has the responsibility of system frequency control.

NEWTON-RAPHSON METHOD

A load flow calculation solves a set of simultaneous nonlinear algebraic power equations for the unknown variables at each node in a system [15]. For this study the Newton-Raphson method was chosen for analysing the load flow.

The generalized Newton-Raphson method is an iterative algorithm for solving a set of simultaneous analytic nonlinear equations in an equal number of unknowns. At each iteration of the Newton-Raphson method, the nonlinear problem is approximated by a linear matrix equation. Given a set of non-linear equations,

$$\begin{aligned}
 f_1(x_1, x_2, \dots, x_n) &= y_1 \\
 f_2(x_1, x_2, \dots, x_n) &= y_2 \\
 f_3(x_1, x_2, \dots, x_n) &= y_3 \\
 &\dots\dots\dots \\
 f_n(x_1, x_2, \dots, x_n) &= y_n
 \end{aligned}
 \tag{3.1}$$

and the initial estimate for the solution vector

$$x_1^0, x_2^0, \dots, x_n^0$$

Assume $\Delta x_1, \Delta x_2, \dots, \Delta x_n$ are the total corrections for $x_1^0, x_2^0, \dots, x_n^0$ respectively, so that the equations (3.1) are solved, i.e.,

$$\begin{aligned}
 f_1(x_1^0 + \Delta x_1, x_2^0 + \Delta x_2, x_n^0 + \Delta x_n) &= y_1 \\
 f_2(x_1^0 + \Delta x_1, x_2^0 + \Delta x_2, x_n^0 + \Delta x_n) &= y_2 \\
 f_3(x_1^0 + \Delta x_1, x_2^0 + \Delta x_2, x_n^0 + \Delta x_n) &= y_3 \\
 \dots\dots\dots \\
 f_n(x_1^0 + \Delta x_1, x_2^0 + \Delta x_2, x_n^0 + \Delta x_n) &= y_n
 \end{aligned}
 \tag{3.2}$$

Each equation of the set (3.2) can be expanded by Taylor's theorem for a function of two or more variables. For example, the following is obtained for the first equation:

$$\begin{aligned}
 f_1(x_1^0 + \Delta x_1, x_2^0 + \Delta x_2, \dots, x_n^0 + \Delta x_n) &= f_1(x_1^0, x_2^0, \dots, x_n^0) + \Delta x_1 \left. \frac{\partial f_1}{\partial x_1} \right|_0 + \\
 &\quad \Delta x_2 \left. \frac{\partial f_1}{\partial x_2} \right|_0 + \dots + \Delta x_n \left. \frac{\partial f_1}{\partial x_n} \right|_0 + \phi_1
 \end{aligned}
 \tag{3.3}$$

where ϕ_1 is a function of $\Delta x_1, \Delta x_2, \dots, \Delta x_n$ and second, third, etc., derivatives of the function f_1 . If the initial estimate for the x_i s is near the solution value, the Δx_i s will be relatively small and all terms of higher powers can be neglected. The linear set of equations resulting is as follows:

$$\begin{aligned}
 f_1(x_1^0, x_2^0, \dots, x_n^0) + \Delta x_1 \left. \frac{\partial f_1}{\partial x_1} \right|_0 + \Delta x_2 \left. \frac{\partial f_1}{\partial x_2} \right|_0 + \dots + \Delta x_n \left. \frac{\partial f_1}{\partial x_n} \right|_0 &= y_1 \\
 f_2(x_1^0, x_2^0, \dots, x_n^0) + \Delta x_1 \left. \frac{\partial f_2}{\partial x_1} \right|_0 + \Delta x_2 \left. \frac{\partial f_2}{\partial x_2} \right|_0 + \dots + \Delta x_n \left. \frac{\partial f_2}{\partial x_n} \right|_0 &= y_2 \\
 \dots\dots\dots \\
 f_n(x_1^0, x_2^0, \dots, x_n^0) + \Delta x_1 \left. \frac{\partial f_n}{\partial x_1} \right|_0 + \Delta x_2 \left. \frac{\partial f_n}{\partial x_2} \right|_0 + \dots + \Delta x_n \left. \frac{\partial f_n}{\partial x_n} \right|_0 &= y_n
 \end{aligned}
 \tag{3.4}$$

In matrix form, equations (3.4) are

$$\begin{bmatrix} y_1 - f_1(x_1^0, x_2^0, \dots, x_n^0) \\ y_2 - f_2(x_1^0, x_2^0, \dots, x_n^0) \\ \dots\dots\dots \\ y_n - f_n(x_1^0, x_2^0, \dots, x_n^0) \end{bmatrix} = \begin{bmatrix} \left. \frac{\partial f_1}{\partial x_1} \right|_0 & \left. \frac{\partial f_1}{\partial x_2} \right|_0 & \dots & \left. \frac{\partial f_1}{\partial x_n} \right|_0 \\ \left. \frac{\partial f_2}{\partial x_1} \right|_0 & \left. \frac{\partial f_2}{\partial x_2} \right|_0 & \dots & \left. \frac{\partial f_2}{\partial x_n} \right|_0 \\ \dots\dots\dots \\ \left. \frac{\partial f_n}{\partial x_1} \right|_0 & \left. \frac{\partial f_n}{\partial x_2} \right|_0 & \dots & \left. \frac{\partial f_n}{\partial x_n} \right|_0 \end{bmatrix} \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \dots \\ \Delta x_n \end{bmatrix}
 \tag{3.5}$$

or

$$D = J C \quad (3.6)$$

Where J is the jacobian for the functions f_i and C is the change vector Δx_i . The elements of the matrices D and J are evaluated by substituting the current values of the X_i s. Hence a solution for the Δx_i can be obtained by the application of any method for the solution of a system of linear equations. The new values for X_i 's are calculated from

$$x_i^1 = x_i^0 + \Delta x_i \quad (3.7)$$

The process is repeated until two successive values for each x_i differ only by a specified tolerance. In this process the elements of J can be reevaluated each iteration, or only every K th iteration provided the Δx_i are changing slowly.

The Newton-Raphson algorithm will converge quadratically if the functions have continuous first derivatives in the neighborhood of the solution, the Jacobian matrix is nonsingular, and the initial approximations of x are close to the actual solutions. However the method is sensitive to the behavior of the functions $f_n(x_1, x_2, \dots, x_n)$ and hence to their formulation. The more linear they are, the more rapidly and reliably Newton's method converges.

Equations Relating to Newton-Raphson Load Flow Analysis

The load flow problem can be solved by the Newton-Raphson method using a set of Non-linear equations to express the specified real and reactive power in terms of bus voltages. The derivation of the fundamental equations starts with the formulation of the nodal network equations, choosing the buses as the nodes,

$$I_k = \sum_{m=1}^n Y_{km} V_m, \quad k = 1 \rightarrow n, \text{ and } m = 1 \rightarrow n \quad (3.8)$$

Where,

I_k = the current flowing into bus k in amperes.

V_m = the voltage at bus m in volts

Y_{km} = the admittance between bus k and bus m in siemens

The power at the k^{th} bus is then given by

$$S_k = P_k + j Q_k = V_k I_k^* \quad (3.9)$$

by equation (3.8) and (3.9) we get,

$$P_k + j Q_k = V_k \sum_{m=1}^n Y_{km}^* V_m^* \quad (3.10)$$

Mathematically speaking, the complex load flow equations are nonanalytic, and cannot be differentiated in complex form. In order to apply Newton's method, equation (3.10) is separated into its real and imaginary components with $V_k = |V_k| \angle \theta_k$, $V_m = |V_m| \angle \theta_m$, and $Y_{km} = |Y_{km}| \angle \theta_{km}$. Using polar coordinates we calculate $P_k(V, \theta)$ and $Q_k(V, \theta)$ as,

$$P_k = \sum_{m=1}^n V_k V_m (G_{km} \cos \theta_{km} + B_{km} \sin \theta_{km}) \quad (3.11)$$

$$Q_k = \sum_{m=1}^n V_k V_m (G_{km} \sin \theta_{km} - B_{km} \cos \theta_{km}) \quad (3.12)$$

where, $\theta_{km} = \theta_k - \theta_m$

For the PQ buses i.e., the load buses, the equations used are (3.11) and (3.12)

For the PV buses only equation (3.11) is used, since Q_k is not specified.

For the slack buses no equations are used because both voltage and angle are specified at this bus.

After specifying P and Q for all buses except the slack bus, ΔP_k and ΔQ_k are calculated as follows,

$$\Delta P_k = P_{k,speci} - P_{k,calcu} \quad (3.13)$$

$$\Delta Q_k = Q_{k,speci} - Q_{k,calcu} \quad (3.14)$$

After finding ΔP and ΔQ the jacobian, consisting of the partial derivatives of P_k and Q_k with respect to the variables (V, θ) , is calculated, the jacobian matrix looks like,

$$\begin{bmatrix} H & N \\ M & L \end{bmatrix}$$

where the elements are

for $m \neq k$

$$H_{km} = \frac{\partial P_k}{\partial \theta_m} = V_k V_m (G_{km} \sin \theta_{km} - B_{km} \cos \theta_{km}) \quad (3.15a)$$

$$N_{km} = V_m \frac{\partial P_k}{\partial V_m} = V_k V_m (G_{km} \cos \theta_{km} + B_{km} \sin \theta_{km}) \quad (3.15b)$$

$$M_{km} = \frac{\partial Q_k}{\partial \theta_m} = -V_k V_m (G_{km} \cos \theta_{km} + B_{km} \sin \theta_{km}) \quad (3.15c)$$

$$L_{km} = V_m \frac{\partial Q_k}{\partial V_m} = V_k V_m (G_{km} \sin \theta_{km} - B_{km} \cos \theta_{km}) \quad (3.15d)$$

for $m = k$

$$H_{kk} = \frac{\partial P_k}{\partial \theta_k} = Q_k - B_{kk} V_k^2 \quad (3.15e)$$

$$N_{kk} = V_k \frac{\partial P_k}{\partial V_k} = P_k + G_{kk} V_k^2 \quad (3.15f)$$

$$M_{kk} = \frac{\partial Q_k}{\partial \theta_k} = P_k - G_{kk} V_k^2 \quad (3.15g)$$

$$L_{kk} = V_k \frac{\partial Q_k}{\partial V_k} = Q_k - B_{kk} V_k^2 \quad (3.15h)$$

As an example for ΔP_2 , ΔP_3 , ΔQ_2 and ΔQ_3 , the matrix is:

$$\begin{bmatrix} \Delta P_2 \\ \Delta P_3 \\ \Delta Q_2 \\ \Delta Q_3 \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2}{\partial \theta_2} & \frac{\partial P_2}{\partial \theta_3} & \frac{\partial P_2}{\partial V_2} & \frac{\partial P_2}{\partial V_3} \\ \frac{\partial P_3}{\partial \theta_2} & \frac{\partial P_3}{\partial \theta_3} & \frac{\partial P_3}{\partial V_2} & \frac{\partial P_3}{\partial V_3} \\ \frac{\partial Q_2}{\partial \theta_2} & \frac{\partial Q_2}{\partial \theta_3} & \frac{\partial Q_2}{\partial V_2} & \frac{\partial Q_2}{\partial V_3} \\ \frac{\partial Q_3}{\partial \theta_2} & \frac{\partial Q_3}{\partial \theta_3} & \frac{\partial Q_3}{\partial V_2} & \frac{\partial Q_3}{\partial V_3} \end{bmatrix} \begin{bmatrix} \Delta \theta_2 \\ \Delta \theta_3 \\ \Delta V_2 \\ \Delta V_3 \end{bmatrix} \quad (3.16)$$

after inverting the jacobian equation (3.16) becomes,

$$\begin{bmatrix} \Delta \theta_2 \\ \Delta \theta_3 \\ \Delta V_2 \\ \Delta V_3 \end{bmatrix} = [J^{-1}] \begin{bmatrix} \Delta P_2 \\ \Delta P_3 \\ \Delta Q_2 \\ \Delta Q_3 \end{bmatrix} \quad (3.17)$$

Solving equation (3.17) we get,

$$\begin{bmatrix} \Delta \theta_2^1 \\ \Delta \theta_3^1 \\ \Delta V_2^1 \\ \Delta V_3^1 \end{bmatrix} = \begin{bmatrix} \text{incremental} \\ \text{values of} \\ \Delta \theta \\ \Delta V \end{bmatrix} \quad (3.18)$$

The values found for $\Delta \theta_k$ and ΔV_k are added to the previous values of voltage magnitude and angle to obtain new values for V_k and θ_k for starting the next iteration, which is,

$$\begin{aligned} V_{i+1} &= V_i + \Delta V^1 \\ \theta_{i+1} &= \theta_i + \Delta \theta^1 \end{aligned} \quad (3.19)$$

This process is repeated until the precision index applied to the quantities in either column matrix is satisfied.

RELATED PROGRAMS

Apart from the Newton-Raphson load flow simulation program Loadflow.c, the procedure utilizes three other programs namely, Pfactor.c, Powerflow.c and CostCalc.c.

- (1) Pfactor.c calculates the real and reactive power magnitude at individual buses of the proposed model for input to Loadflow.c. A flow chart is shown in Figure 4 and the program is given in appendix A.

- (4) With the information obtained from the previous program the program "Powerflow.c" (appendix C) is run to calculate the individual line losses resulting from the real and reactive power flow through the transmission lines.
- (5) Knowing the line losses at different power factors (step 4), the partial reactive compensation required for drift in voltage and angle, and the real and reactive power required at the individual buses (step 3), we can find the cost of power at the individual buses. The program "CostCalc.c" is used to calculate the power bill and monthly savings.

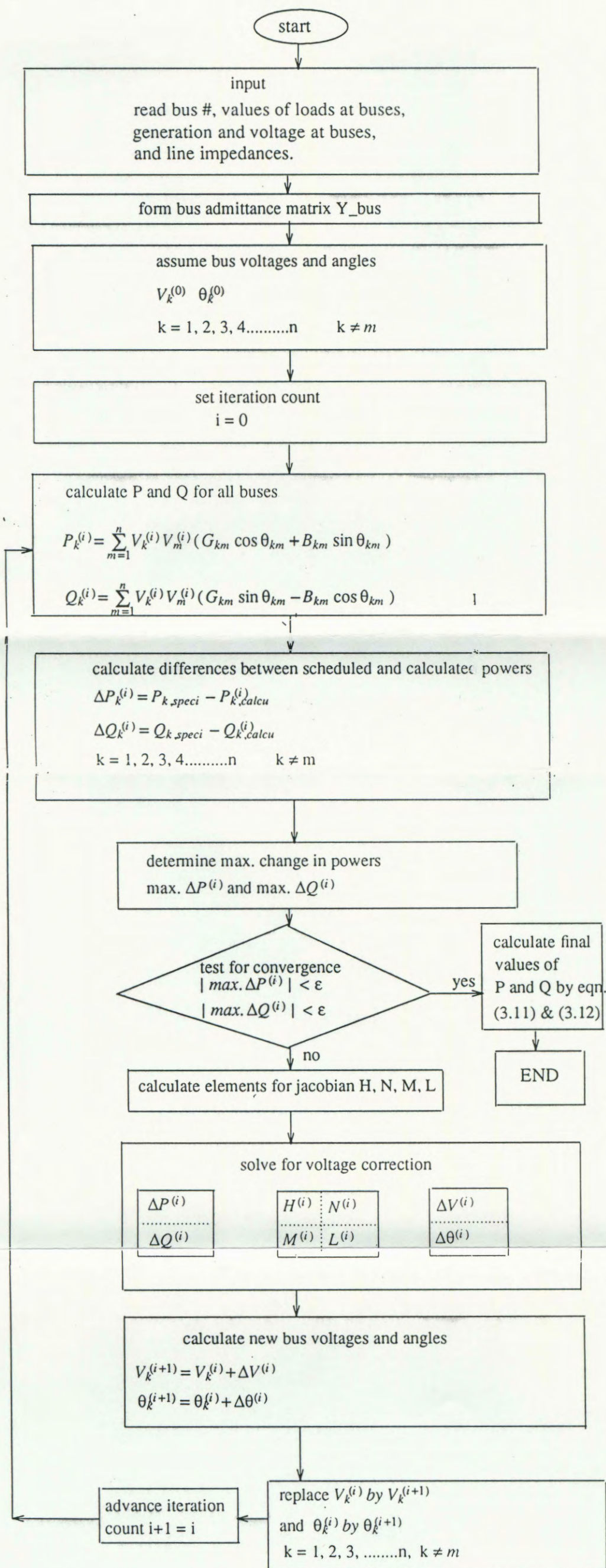


Figure 3. Flow chart of Newton-Raphson algorithm.

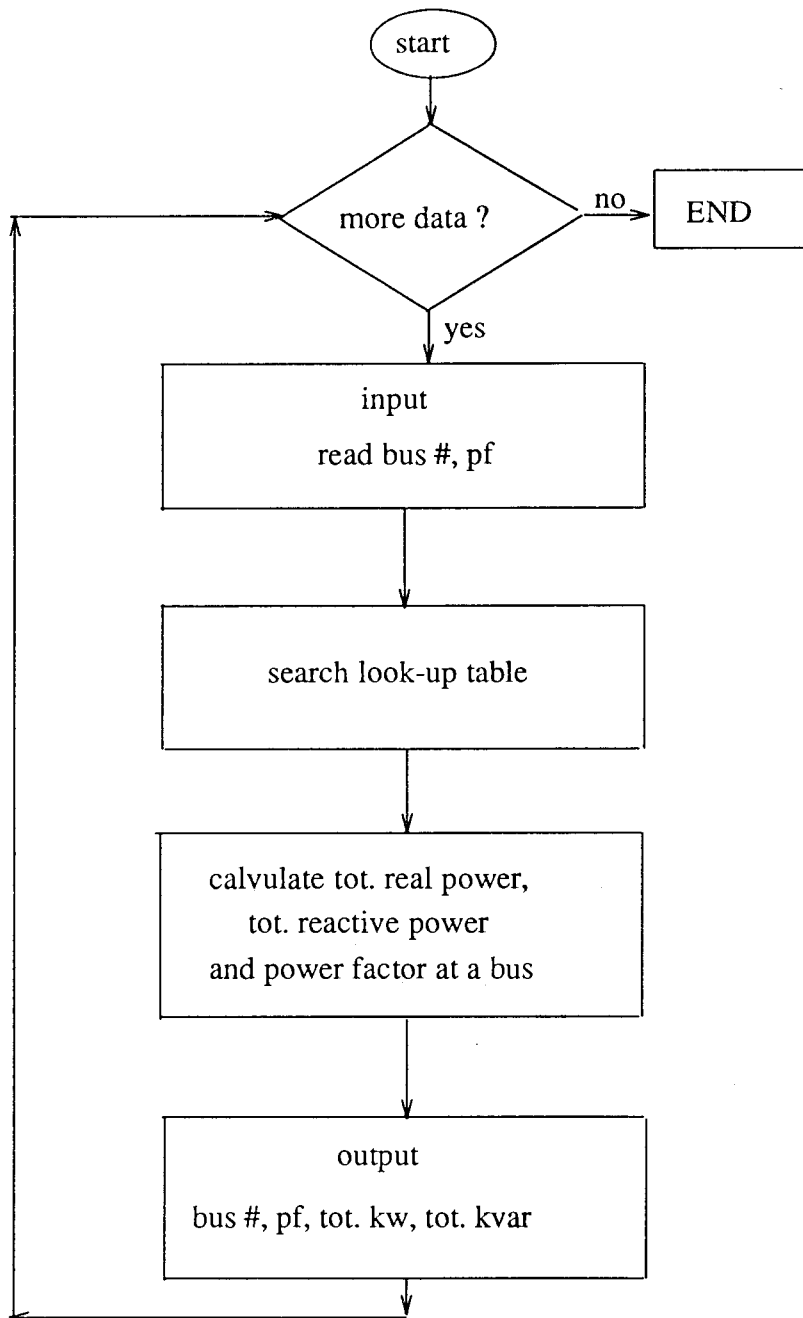


Figure 4. Flow chart of Pfactor.c.

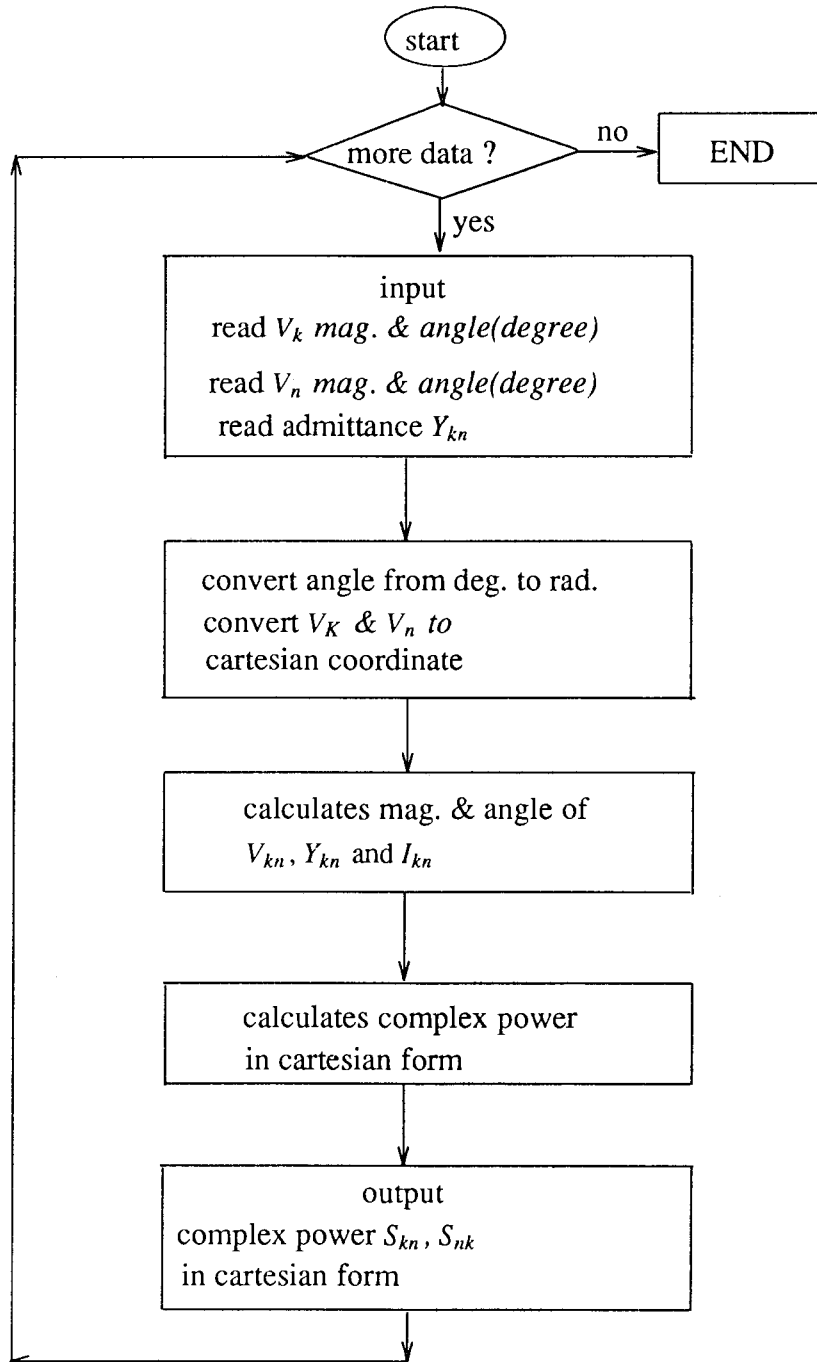


Figure 5. Flow chart of Lineflow.c.

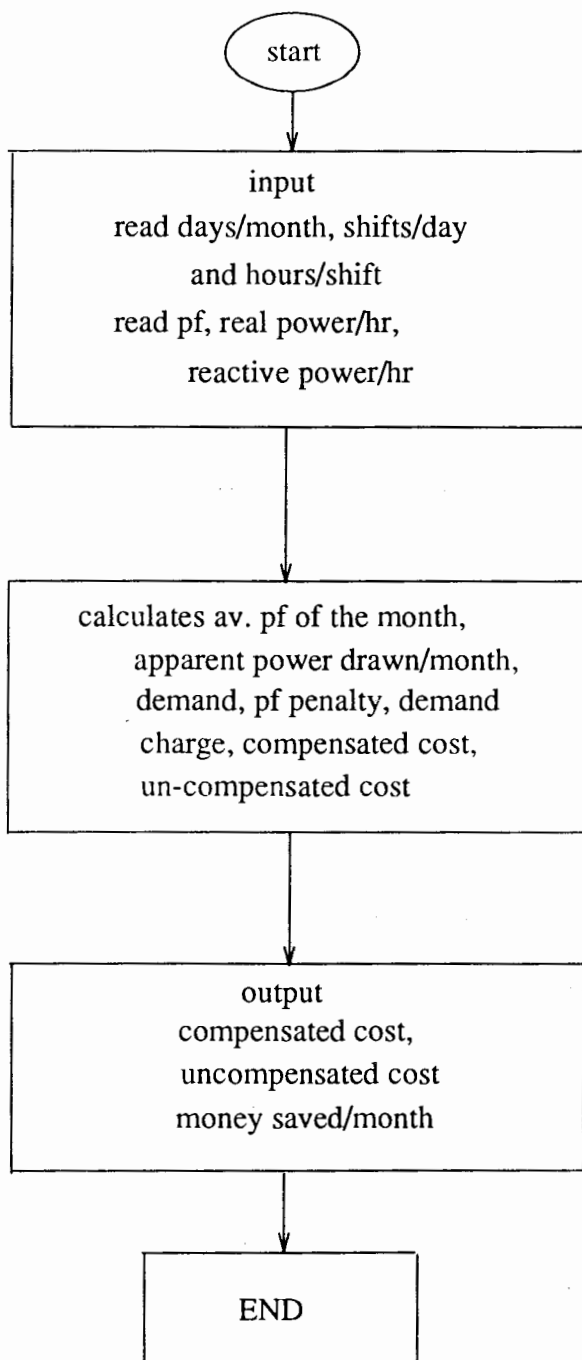


Figure 6. Flow chart of CostCalc.c.

CHAPTER IV

RESULTS

A POWER DISTRIBUTION MODEL

The model, shown in Figure 7 representing a typical medium size industrial load was chosen to demonstrate the application of the method. Loads considered at individual load centers are shown in the model.

The Assumptions of the Model are:

- (1) All lines are chosen to be one mile long. ACSR PENGUIN WSP H27 BUNDLE CONDUCTORS having $R = 0.456$ ohms/mile and $X = 0.859$ ohms/mile are used.
- (2) A Single line diagram representing a balanced 3ϕ system is used to describe the model.
- (3) The system may be considered to be connected to two substations or generators or to one substation and a generator for a constant power supply of greater reliability.
- (4) Bus_4 of the system has small inductive loads and bus_6 has moderately high inductive loads. At times the power factor at bus_4 could automatically improve if fewer motors were in operation, in that case bus_6 could be directly benefited by linking bus_6 to bus_4.
- (5) Individual load centers are fed through separate transformers to isolate them from the main 13.8 kv supply lines. This isolation has the advantage of confining faults to individual load centers so that they do not affect the others.
- (6) Present day power transformers are highly efficient, thus loss incurred in the transformers are neglected.

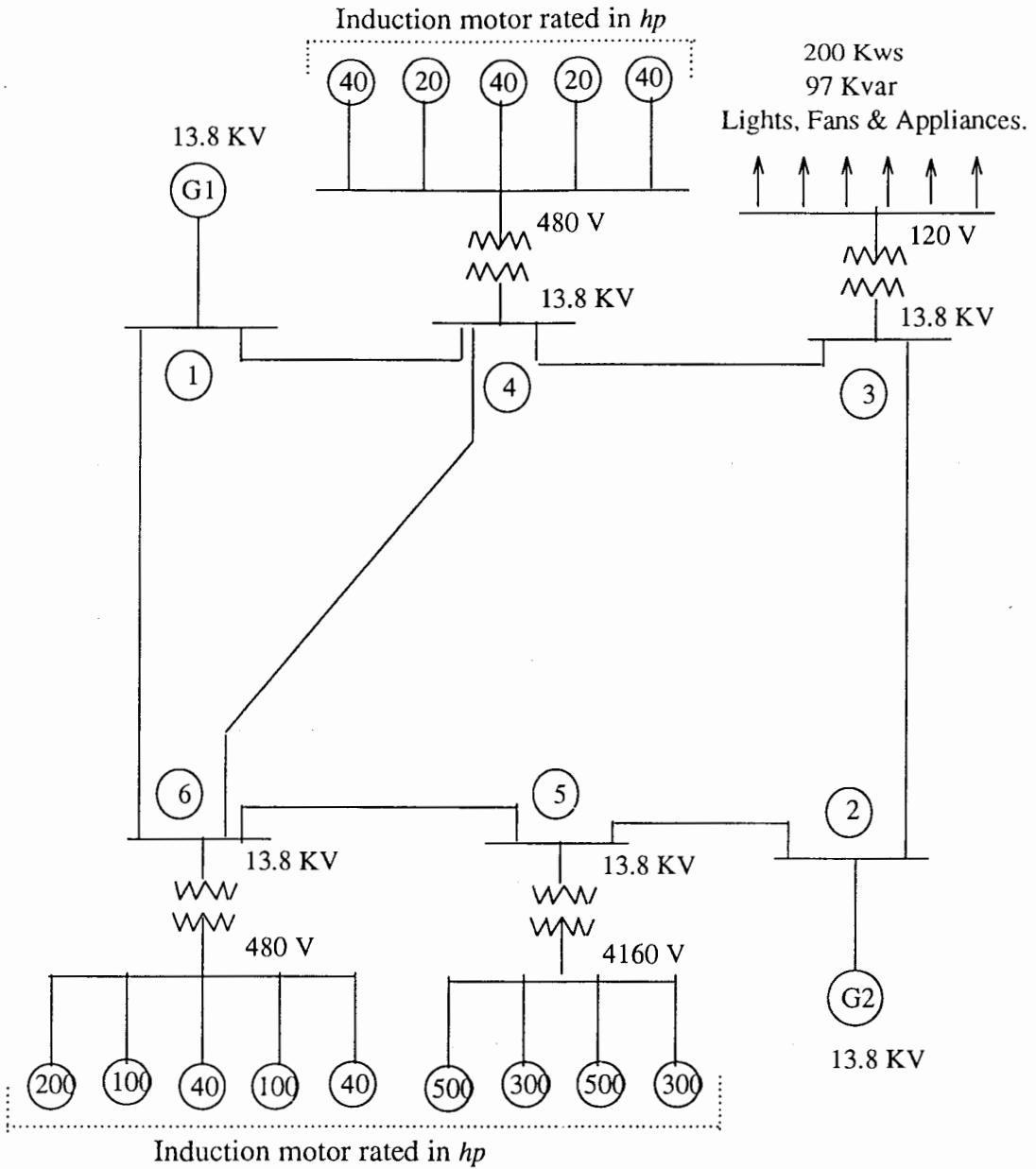


Figure 7. A power distribution model.

- (7) There are no constraints on the generators G_1 and G_2 to supply real or reactive power to the load buses when the load bus power factor falls below 95%.

THE SYSTEM Y_BUS

The system Y_bus data obtained from Loadflow.c is shown in the Table III below. The Y_bus data is used in the calculation of line flow at different power factors.

TABLE III
SYSTEM Y_BUS

	1	2	3	4	5	6
1	4.390 -j8.331	0	0	-2.432 +j4.595	0	-1.957 +j3.737
2	0	3.915 -j7.473	-1.957 +j3.737	0	-1.957 +j3.737	0
3	0	-1.957 +j3.737	3.915 -j7.473	-1.957 +j3.737	0	0
4	-2.432 +j4.595	0	-1.957 +j3.737	6.347 -j12.063	0	-1.957 +j3.737
5	0	-1.957 +j3.737	0	0	3.915 -j7.473	-1.957 +j3.737
6	-1.957 +j3.737	0	0	-1.957 +j3.737	-1.957 +j3.737	5.872 -j11.210

SIMULATION RESULTS AT 95% POWER FACTOR

Real and Reactive Loads at Load Buses

Given the η , pf and the hp of a motor the real and reactive power input of the motor can be calculated as shown below:

$$\text{Real power input (kw input)} = \frac{hp \times 0.746}{\eta}$$

$$\text{Reactive power input (rkva input)} = kw \text{ input} \times \tan [\cos^{-1}(pf)]$$

BUS_6. At bus_6 we have 1 × 200 hp, 2 × 100 hp and 2 × 40 hp of $\eta = 92\%$.

therefore,

$$kw \text{ input} = 480 \times \frac{0.746}{0.92} = 389.2174 \text{ kw}$$

here, $\theta = \tan[\cos^{-1}(0.95)] = 0.3286$

and, $rkva\ input = 389.2174 \times 0.3286 = 127.9295\ kvar$

BUS_5. At bus_5 we have $2 \times 500\ hp$, and $2 \times 300\ hp$ of $\eta = 92\%$.

Calculating the same way as shown above we get,

$kw\ input = 1297.3913\ kw$ and,

$rkva\ input = 426.3189\ kvar$

BUS_4. At bus_4 we have $3 \times 40\ hp$, and $2 \times 20\ hp$ of $\eta = 92\%$.

Calculating the same way as shown above we get,

$kw\ input = 129.7391\ kw$ and,

$rkva\ input = 42.6432\ kvar$

BUS_3. At bus_3 we have lights, fans, computers and other domestic and office usable appliances comprising a load of

$kw\ input = 200\ kws$

$rkva\ input = 97\ kvars$

Partial Compensation at the Load Buses

Results of the load flow simulation at 95% power factor and the partial compensation required at individual bus levels are shown in the Table IV and Table V respectively.

It is seen from the Table IV that the

Total reactive power at the load end = 693.57139 kvars

Total real power at the load end = 2016.41747 kws

Total reactive power generated = 1016.76296 kvars

Total real power generated = 2189.1258 kws

Using Table II capacitor sizes for partial compensation at the load buses are,

TABLE IV
LOAD FLOW OUTPUT AT PF = 95%

bus #	volts	angle	generation		load	
	p.u	degree	P(kw)	Q(kvar)	P(kw)	Q(kvar)
1	1.00000	-18.099	933.22684	420.14783	0.00000	0.00000
2	1.00000	-18.066	1255.9017	596.61513	0.00000	0.00000
3	0.96241	-19.778	0.00000	0.00000	199.97647	96.98819
4	0.95719	-20.154	0.00000	0.00000	129.72434	42.63184
5	0.85486	-25.784	0.00000	0.00000	1297.5334	426.07247
6	0.91739	-22.225	0.00000	0.00000	389.18320	127.87889

TABLE V
PARTIAL COMPENSATION AT THE LOAD BUSES AT PF = 95%

BUS #	KVA	PRE. PF%	FIN. PF%	CORREC. FAC	CAPA. SIZE(kvar)
6	409.6542	92.57	95	0.07933	32.4978
5	1365.6979	90.04	95	0.155	211.6832
4	136.5499	93.87	95	0.039	5.3254
3	222.255	94.10	95	0.0315	7.001

Line Flow From Bus_1 to Bus_6

$$I_{16} = (V_1 - V_6) \times Y_{16}$$

$$I_{16} = (1.0 e^{-18.099} - 0.91739 e^{-22.22})(-1.957 + j3.737)$$

$$I_{16} = -0.3336 + j 0.3074.$$

therefore,

$$S_{16} = (V_1) \times I_{16}^*$$

$$S_{16} = (1.0 e^{-18.099})(-0.3336 - j0.3074)$$

$$S_{16} = -0.4127 - j0.1886$$

again,

$$I_{61} = (V_6 - V_1) \times Y_{61}$$

$$I_{61} = (0.91739 e^{-22.22} - 1.0 e^{-18.099})(-1.957 + j 3.737)$$

$$I_{61} = 0.3336 - j 0.3074$$

therefore,

$$S_{61} = (V_6) \times I_{61}^*$$

$$S_{61} = (0.91739 e^{-22.22})(0.3336 + j 0.3074)$$

$$S_{61} = 0.3900 + j 0.1453$$

Line loss between bus_1 and bus_6:

$$S_{16} + S_{61} = -0.023 - j 0.043$$

Line Flow From Bus_1 to Bus_4

$$I_{14} = (V_1 - V_4) \times Y_{14}$$

$$I_{14} = (1.0 e^{-18.099} - 0.9572 e^{-20.15})(-2.432 + j 4.595)$$

$$I_{14} = (-0.2143 + j 0.1921)$$

therefore,

$$S_{14} = (V_1) \times I_{14}^*$$

$$S_{14} = (1.0 e^{-18.099})(-0.2143 - j 0.1921)$$

$$S_{14} = -0.2634 - j 0.116$$

again,

$$I_{41} = (V_4 - V_1) \times Y_{41}$$

$$I_{41} = (0.9572 e^{-20.15} - 1.0 e^{-18.099})(-2.432 + j 4.595)$$

$$I_{41} = 0.2143 - j 0.1921$$

therefore,

$$S_{41} = (V_4) \times I_{41}^*$$

$$S_{41} = (0.9572 e^{-20.15})(0.2143 + j 0.1921)$$

$$S_{41} = 0.2559 + j 0.1019$$

Line loss between bus_1 and bus_4:

$$S_{14} + S_{41} = -0.008 - j 0.014$$

Line Flow From Bus_3 to Bus_4

$$I_{34} = (V_3 - V_4) \times Y_{34}$$

$$I_{34} = (0.9624 e^{-19.78} - 0.95719 e^{-20.15})(-1.957 + j 3.737)$$

$$I_{34} = -0.0293 + j 0.01827.$$

therefore,

$$S_{34} = (V_3) \times I_{34}^*$$

$$S_{34} = (0.9624 e^{-19.78})(-0.0293 - j 0.01827)$$

$$S_{34} = -0.0325 - j 0.007$$

again,

$$I_{43} = (V_4 - V_3) \times Y_{43}$$

$$I_{43} = (0.95719 e^{-20.15} - 0.9624 e^{-19.78})(-1.957 + j 3.737)$$

$$I_{43} = 0.0293 - j 0.01827$$

therefore,

$$S_{43} = (V_4) \times I_{43}^*$$

$$S_{43} = (0.95719 e^{-20.15})(0.0293 + j 0.01827)$$

$$S_{43} = 0.03236 + j 0.00675$$

Line loss between bus_3 and bus_4:

$$S_{34} + S_{43} = -0.00014 - j 0.00025$$

Line Flow From Bus_4 to Bus_6

$$I_{46} = (V_4 - V_6) \times Y_{46}$$

$$I_{46} = (0.95719 e^{-20.15} - 0.91739 e^{-22.22})(-1.957 + j 3.737)$$

$$I_{46} = (-0.1608 + j 0.1507)$$

therefore,

$$S_{46} = (V_4) \times I_{46}^*$$

$$S_{46} = (0.95719 e^{-20.15})(-0.1608 - j 0.1507)$$

$$S_{46} = -0.1942 - j 0.0824$$

again,

$$I_{64} = (V_6 - V_4) \times Y_{64}$$

$$I_{64} = (0.91739 e^{-22.22} - 0.95719 e^{-20.15})(-1.957 + j 3.737)$$

$$I_{64} = -(-0.1608 + j 0.1507)$$

therefore,

$$S_{64} = (V_6) \times I_{64}^*$$

$$S_{64} = (0.91739 e^{-22.22})(0.1608 + j 0.1507)$$

$$S_{64} = 0.1888 + j 0.07223$$

Line loss between bus_4 and bus_6:

$$S_{46} + S_{64} = -0.005 - j 0.010$$

Line Flow From Bus_2 to Bus_3

$$I_{23} = (V_2 - V_3) \times Y_{23}$$

$$I_{23} = (1.0 e^{-18.07} - 0.9624 e^{-19.78})(-1.957 + j 3.737)$$

$$I_{23} = (-0.1463 + j 0.1379)$$

therefore,

$$S_{23} = (V_2) \times I_{23}^*$$

$$S_{23} = (1.0 e^{-18.07})(-0.1463 - j 0.1379)$$

$$S_{23} = -0.1818 - j 0.0858$$

again,

$$I_{32} = (V_3 - V_2) \times Y_{32}$$

$$I_{32} = -(1.0 e^{-18.07} - 0.9624 e^{-19.78})(-1.957 + j 3.737)$$

$$I_{32} = -(-0.1463 + j 0.1379)$$

therefore,

$$S_{32} = (V_3) \times I_{32}^*$$

$$S_{32} = (0.96241 e^{-19.78})(0.1463 + j 0.1379)$$

$$S_{32} = 0.1774 + j 0.07731$$

Line loss between bus_2 and bus_3:

$$S_{23} + S_{32} = -0.004 - j 0.008$$

Line Flow From Bus_2 to Bus_5

$$I_{25} = (V_2 - V_5) \times Y_{25}$$

$$I_{25} = (1.0 e^{-18.07} - 0.85486 e^{-25.78})(-1.957 + j 3.737)$$

$$I_{25} = (-0.5848 + j 0.5554)$$

therefore,

$$S_{25} = (V_2) \times I_{25}^*$$

$$S_{25} = (0.85486 e^{-25.78})(-0.5848 - j 0.5554)$$

$$S_{25} = -0.7282 - j 0.3466$$

again,

$$I_{52} = (V_5 - V_2) \times Y_{52}$$

$$I_{52} = -(1.0 e^{-18.07} - 0.85486 e^{-25.78})(-1.957 + j 3.737)$$

$$I_{52} = -(-0.5848 + j 0.5554)$$

therefore,

$$S_{52} = (V_5) \times I_{52}^*$$

$$S_{52} = (0.85486 e^{-25.78})(0.5848 + j 0.5554)$$

$$S_{52} = 0.6566 + j 0.2100$$

Line loss between bus_2 and bus_5:

$$S_{25} + S_{52} = -0.072 - j 0.137$$

Line Flow From Bus_5 to Bus_6

$$I_{56} = (V_5 - V_6) \times Y_{56}$$

$$I_{56} = (0.85486 e^{-25.78} - 0.91739 e^{-22.22})(-1.957 - j 3.737)$$

$$I_{56} = (0.2484 - j 0.2484)$$

therefore,

$$S_{56} = (V_5) \times I_{56}^*$$

$$S_{56} = (0.85486 e^{-25.78})(0.2484 + j 0.2484)$$

$$S_{56} = 0.2835 + j 0.0988$$

again,

$$I_{65} = (V_6 - V_5) \times Y_{65}$$

$$I_{65} = -(0.85486 e^{-25.78} - 0.91739 e^{-22.22})(-1.957 - j 3.737)$$

$$I_{65} = -(0.2484 - j 0.2484)$$

therefore,

$$S_{65} = (V_6) \times I_{65}^*$$

$$S_{65} = (0.91739 e^{-22.22})(0.2484 + j 0.2484)$$

$$S_{65} = -0.2971 - j 0.1247$$

Line loss between bus_5 and bus_6:

$$S_{56} + S_{65} = -0.014 - j 0.026$$

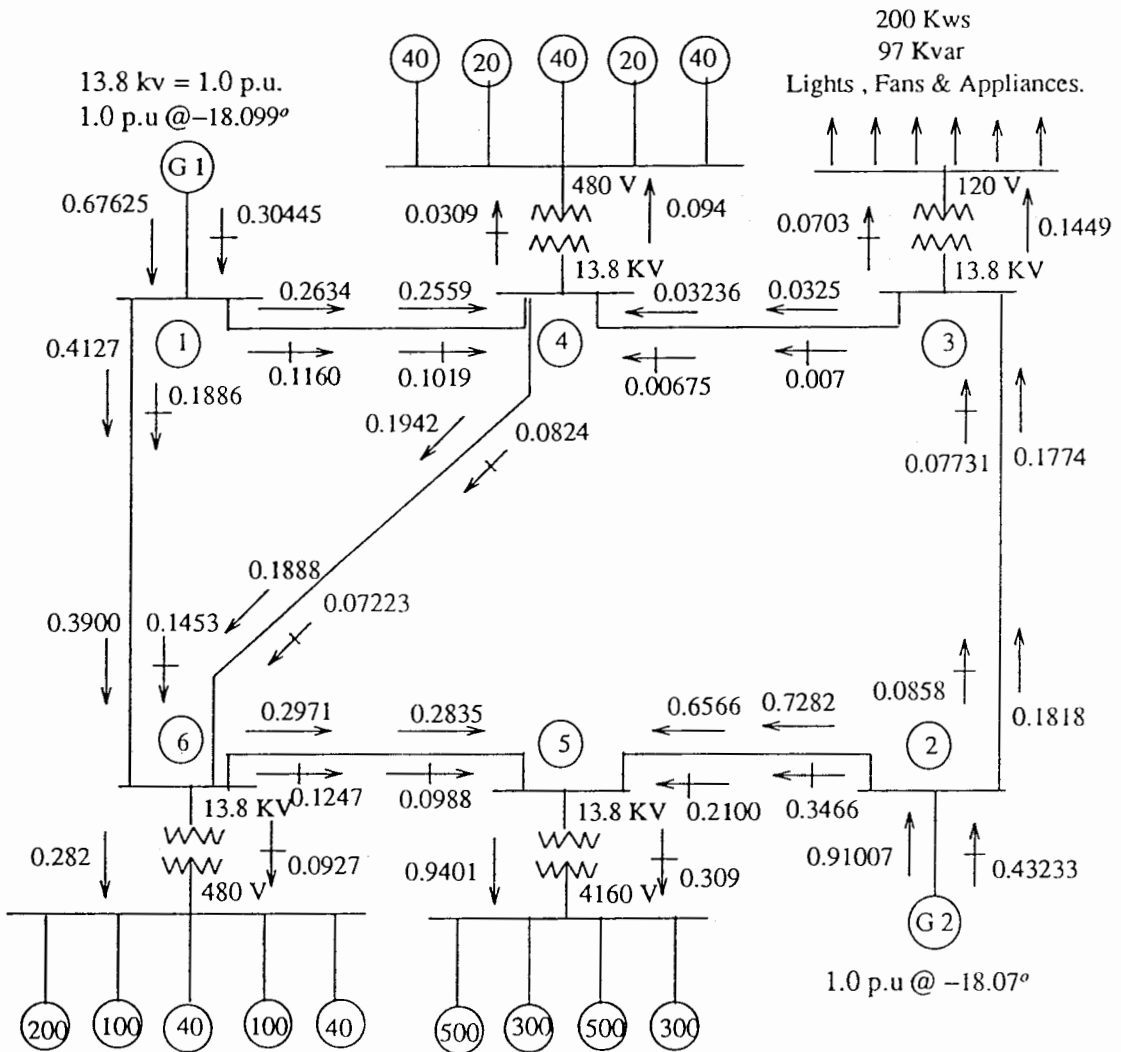


Figure 8. Line flow for pf=95%.

Reactive Power Loss in the Individual Lines Per Mile

$$\text{Bus}_1 \text{ to Bus}_6 = (0.1886 - 0.1453) \times 1380 + 337 = 0.18 \text{ kvar}$$

$$\text{Bus}_1 \text{ to Bus}_4 = (0.116 - 0.1019) \times 1380 + 273 = 0.07 \text{ kvar}$$

$$\text{Bus}_3 \text{ to Bus}_4 = (0.007 - 0.00675) \times 1380 + 337 = 0.001 \text{ kvar}$$

$$\text{Bus}_2 \text{ to Bus}_3 = (0.0858 - 0.07731) \times 1380 + 337 = 0.035 \text{ kvar}$$

$$\text{Bus}_6 \text{ to Bus}_5 = (0.1247 - 0.09788) \times 1380 + 337 = 0.11 \text{ kvar}$$

$$\text{Bus}_2 \text{ to Bus}_5 = (0.3466 - 0.21) \times 1380 + 337 = 0.56 \text{ kvar}$$

$$\text{Bus}_4 \text{ to Bus}_6 = (0.0824 - 0.07223) \times 1380 + 337 = 0.042 \text{ kvar}$$

Therefore total reactive power losses in the lines = 0.998 kvar

Real Power Loss in the Individual Lines Per Mile

$$\text{Bus}_1 \text{ to Bus}_6 = (0.4127 - 0.39) \times 1380 + 337 = 0.093 \text{ kw}$$

$$\text{Bus}_1 \text{ to Bus}_4 = (0.2634 - 0.2559) \times 1380 + 273 = 0.038 \text{ kw}$$

$$\text{Bus}_3 \text{ to Bus}_4 = (0.0325 - 0.03236) \times 1380 + 337 = 0.00057 \text{ kw}$$

$$\text{Bus}_2 \text{ to Bus}_3 = (0.1818 - 0.1774) \times 1380 + 337 = 0.018 \text{ kw}$$

$$\text{Bus}_6 \text{ to Bus}_5 = (0.2971 - 0.2835) \times 1380 + 337 = 0.055 \text{ kw}$$

$$\text{Bus}_2 \text{ to Bus}_5 = (0.7282 - 0.6566) \times 1380 + 337 = 0.29 \text{ kw}$$

$$\text{Bus}_4 \text{ to Bus}_6 = (0.1942 - 0.1888) \times 1380 + 337 = 0.022 \text{ kw}$$

Therefore total real power losses in the lines = 0.516 kw

Total Capacitive Compensation at the Buses

From line flow data of pf = 95% and from the reactive line losses we calculate the compensation required at the individual buses:

$$\text{At Bus}_5 = 0.309 \times 1380 + 0.56 + 0.11 = 427.09 \text{ kvar}$$

$$\text{At Bus}_6 = 0.0927 \times 1380 + 0.18 + 0.042 = 128.15 \text{ kvar}$$

$$\text{At Bus}_4 = 0.0309 \times 1380 + 0.001 + 0.07 = 42.71 \text{ kvar}$$

$$\text{At Bus}_3 = 0.0703 \times 1380 + 0.035 = 97.05 \text{ kvar}$$

Therefore total bus compensation = 695.00 kvar

TABLE VI
COMPENSATION AT BUSES AT PF=95%

bus #	generator	capa. size (kvar)
6	-	128.15
5	-	427.09
4	-	42.71
3	-	97.05

Cost of Energy

From the simulation result we see that,

$$\text{Tot. kvar required per hour} = 694.56 \text{ kvar/hr}$$

$$\text{Tot. kws required per hour} = 2016.933 \text{ kws/hr}$$

Considering a typical situation where the plant runs for two shifts, 8 hours per shift and 5 days in a week, we find,

$$\text{Required generation of kvar/month} = 694.56 \times 2 \times 8 \times 20 = 222259.20 \text{ kvar}$$

$$\text{Required generation of kws/month} = 2016.933 \times 2 \times 8 \times 20 = 645418.56 \text{ kw}$$

Using the formula,

$$\begin{aligned} \text{Average pf} &= \frac{\text{Tot kw}}{\sqrt{(\text{Tot kw}^2 + \text{Tot kvar}^2)}} \\ \text{pf} &= \frac{2016.933}{\sqrt{(2016.933^2 + 694.56^2)}} \\ \text{pf} &= 94.55\% \end{aligned}$$

Uncompensated Energy Bill

$$\text{kva drawn in one month} = \sqrt{(222259.20^2 + 645418.56^2)} = 682615.75544 \text{ kva}$$

$$\text{Demand} = \sqrt{(694.56^2 + 2016.933^2)} = 2133.17424 \text{ kva}$$

$$\text{pf penalty of} = (95 - 94.55) \times 2 = 1\%$$

Energy = 682615.75544 kws

demand = 2133.17424 kws

pf penalty = $2133.17424 \times 0.01 = 21.33$ kws

The total bill is = $682615.75544 \times 0.02 + 2133.17424 \times 4.14 + 21.33 \times 4.14 = 22571.97$ dollars.

where, energy charge = 0.02 dollar/kwhr

demand charge = 4.14 dollar/kwhr, and

pf penalty charge = 4.14 dollar/kwhr

Compensated Energy Bill

By compensating the kvar keeping a pf = 95% to avoid the power factor penalty, the reactive power that can be drawn safely from the utility without paying a pf penalty can be calculated as,

$$0.95 = \frac{Tot\ kw}{\sqrt{(Tot\ kw^2 + Tot\ kvar^2)}}$$

$$0.95 = \frac{645418.56}{\sqrt{(645418.56^2 + Tot\ kvar^2)}}$$

The total kvar that could be safely drawn from the utility = 212138.82186 kvar

Therefore, the amount of kvar that needs to be compensated is = generated kvar - safe drawn kvar

The kvar to be compensated = $222259.20 - 212138.82186 = 10120.378$ kvar $\div 320 = 31.63$ kvar/hr

After compensation kva drawn/month = $\sqrt{(645418.56^2 + 212138.82186^2)} = 679387.95789$ kva

The new demand is = $\sqrt{(2016.933^2 + (694.56 - 31.63)^2)}$

Demand = 2123.087 kva

Energy = 679387.95789 kws

Demand = 2123.087 kws

The total bill is = $679387.95789 \times 0.02 + 2123.087 \times 4.14 = 22377.34$ dollars.

where, the energy charge = 0.02 dollar/kwhr, and

the demand charge = 4.14 dollar/kwhr

Money saved/month = Uncompensated bill - compensated bill = $22571.97 - 22377.34 = 194.63$ dollars.

Cost of Capacitor Compensation

Two separate costs are involved in capacitive compensation, namely,

- Installed costs (include site preparation, fence, relays,.. etc.), costs 6.00 dollars/kvar
- Cost of small banks of capacitors, costs 10.00 dollars/kvar

From the Table XII total kvar to be compensated is 694.56 kvar.

The total compensation cost = the total kvar (to be compensated) \times (the installed cost + the cost of capacitor banks)

The total compensation cost = $694.56 \times (6.00 + 10.00) = 11112.96$ dollars.

Therefore, dividing compensation cost by monthly excess bill we get,

$$11112.96 \div 194.63 = 57 \text{ months}$$

i.e., the total investment for capacitor compensation is equivalent to 57 months excess bill.

SIMULATION RESULTS AT 90% POWER FACTOR

Real and Reactive Loads at Load Buses

Given the η , pf and the hp of a motor the real and reactive power input of the motor can be calculated as shown below:

$$\text{Real power input (kw input)} = \frac{hp \times 0.746}{\eta}$$

$$\text{Reactive power input (rkva input)} = kw \text{ input} \times \tan [\cos^{-1} (pf)]$$

BUS_6. At bus_6 we have $1 \times 200 \text{ hp}$, $2 \times 100 \text{ hp}$ and $2 \times 40 \text{ hp}$ of $\eta = 92\%$.

therefore,

$$kw \text{ input} = 480 \times \frac{0.746}{0.92} = 389.2174 \text{ kw}$$

$$\text{here, } \theta = \tan[\cos^{-1}(0.90)] = 0.4832$$

$$\text{Now, } rkva \text{ input} = 389.2174 \times 0.4832 = 188.5066 \text{ kvar}$$

BUS_5. At bus_5 we have $2 \times 500 \text{ hp}$, and $2 \times 300 \text{ hp}$ of $\eta = 92\%$.

Calculating the same way as shown above we get,

$$kw \text{ input} = 1297.3913 \text{ kw and,}$$

$$rkva \text{ input} = 628.3553 \text{ kvar}$$

BUS_4. At bus_4 we have $3 \times 40 \text{ hp}$, and $2 \times 20 \text{ hp}$ of $\eta = 92\%$.

Calculating the same way as shown above we get,

$$kw \text{ input} = 129.7391 \text{ kw and,}$$

$$rkva \text{ input} = 62.8355 \text{ kvar}$$

BUS_3. At bus_3 we have lights, fans, computers and other domestic and office usable appliances comprising a load of

$$kw \text{ input} = 200 \text{ kws}$$

$$rkva \text{ input} = 97 \text{ kvars}$$

Partial Compensation at the Load Buses

Results of the load flow simulation at 90% power factor and the partial compensation required at individual bus levels are shown in the Table VII and Table VIII respectively. It is seen from the above Table VII that the,

$$\text{Total reactive power at the load end} = 975.85136 \text{ kvars}$$

$$\text{Total reactive power at the load end} = 975.85136 \text{ kvars}$$

TABLE VII
LOAD FLOW OUTPUT AT PF= 90%

bus #	volts	angle	generation		load	
	p.u	degree	P(kw)	Q(kvar)	P(kw)	Q(kvar)
1	1.00000	-18.099	937.09308	570.60622	0.00000	0.00000
2	1.00000	-17.918	1283.6459	788.42852	0.00000	0.00000
3	0.95897	-19.605	0.00000	0.00000	199.98655	96.77199
4	0.95040	-19.952	0.00000	0.00000	129.72921	62.77199
5	0.82576	-25.173	0.00000	0.00000	1297.7161	627.68737
6	0.90197	-21.849	0.00000	0.00000	389.20468	188.42460

Total real power at the load end = 2016.6366 kws

Total real power generated = 2220.73902 kws

Total reactive power generated = 1359.03474 kvars

Now, by Table II capacitor size for partial compensation at the load buses are,

TABLE VIII
PARTIAL COMPENSATION AT THE LOAD BUSES AT PF = 90%

BUS #	PRE. PF%	FIN. PF%	CORREC. FAC	CAPA. SIZE(kvar)
6	92.82	95	0.07158	30.95
5	90.50	95	0.141	203.2582
4	93.99	95	0.035	5.044
3	94.20	95	0.028	6.216

Line Flow From Bus_1 to Bus_6

$$I_{16} = (V_1 - V_6) \times Y_{16}$$

$$I_{16} = (1.0 e^{-18.099} - 0.90197 e^{-21.85})(-1.957 + j 3.737)$$

$$I_{16} = (-0.3153 + j 0.37459)$$

therefore,

$$S_{16} = (V_1) \times I_{16}^*$$

$$S_{16} = (1.0 e^{-18.099})(-0.3153 - j 0.37459)$$

$$S_{16} = -0.41607 - j 0.2581$$

again,

$$I_{61} = (V_6 - V_1) \times Y_{61}$$

$$I_{61} = -(1.0 e^{-18.099} - 0.90197 e^{-21.85})(-1.957 + j 3.737)$$

$$I_{61} = -(-0.3153 + j 0.37459)$$

therefore,

$$S_{61} = (V_6) \times I_{61}^*$$

$$S_{61} = -(0.90197 e^{-21.84973})(-0.3153 - j 0.37459)$$

$$S_{61} = 0.3897 + j 0.2077$$

Line loss between bus_1 and bus_6:

$$S_{16} + S_{61} = -0.026 - j 0.05$$

Line Flow From Bus_1 to Bus_4

$$I_{14} = (V_1 - V_4) \times Y_{14}$$

$$I_{14} = (1.0 e^{-18.099} - 0.9504 e^{-19.95})(-2.432 + j 4.595)$$

$$I_{14} = (-0.2016 + j 0.2295)$$

therefore,

$$S_{14} = (V_1) \times I_{14}^*$$

$$S_{14} = (1.0 e^{-18.099})(-0.2016 - j 0.2295)$$

$$S_{14} = -0.26289 - j 0.15553$$

again,

$$I_{41} = (V_4 - V_1) \times Y_{41}$$

$$I_{41} = -(1.0 e^{-18.099} - 0.9504 e^{-19.95})(-2.432 + j 4.595)$$

$$I_{41} = -(-0.2016 + j 0.2295)$$

therefore,

$$S_{41} = (V_4) \times I_{41}^*$$

$$S_{41} = -(0.9504 e^{-19.95})(-0.2016 - j 0.2295)$$

$$S_{41} = 0.25449 + j 0.13967$$

Line loss between bus_1 and bus_4:

$$S_{14} + S_{41} = -0.008 - j 0.016$$

Line Flow From Bus_3 to Bus_4

$$I_{34} = (V_3 - V_4) \times Y_{34}$$

$$I_{34} = (0.95897 e^{-19.61} - 0.9504 e^{-19.95})(-1.957 + j 3.737)$$

$$I_{34} = (-0.02917 + j 0.03246)$$

therefore,

$$S_{34} = (V_3) \times I_{34}^*$$

$$S_{34} = (0.95897 e^{-19.61})(-0.02917 - j 0.03246)$$

$$S_{34} = -0.0368 - j 0.01994$$

again,

$$I_{43} = (V_4 - V_3) \times Y_{43}$$

$$I_{43} = -(0.95897 e^{-19.61} - 0.9504 e^{-19.95})(-1.957 + j 3.737)$$

$$I_{43} = -(-0.02917 + j 0.03246)$$

therefore,

$$S_{43} = (V_4) \times I_{43}^*$$

$$S_{43} = -(0.9504 e^{-19.95})(-0.02917 - j 0.03246)$$

$$S_{43} = 0.036593 + j 0.01954$$

Line loss between bus_3 and bus_4:

$$S_{34} + S_{43} = -0.000207 - j 0.0004$$

Line Flow From Bus_4 to Bus_6

$$I_{46} = (V_4 - V_6) \times Y_{46}$$

$$I_{46} = (0.9504 e^{-19.95} - 0.90197 e^{-21.86})(-1.957 + j 3.737)$$

$$I_{46} = (-0.1525 + j 0.1876)$$

therefore,

$$S_{46} = (V_4) \times I_{46}^*$$

$$S_{46} = (0.9504 e^{-19.95})(-0.1525 - j 0.1876)$$

$$S_{46} = -0.197096 - j 0.1182$$

again,

$$I_{64} = (V_6 - V_4) \times Y_{64}$$

$$I_{64} = -(0.9504 e^{-19.95} - 0.90197 e^{-21.86})(-1.957 + j 3.737)$$

$$I_{64} = -(-0.1525 + j 0.1876)$$

therefore,

$$S_{64} = (V_6) \times I_{64}^*$$

$$S_{64} = -(0.90197 e^{-21.84973})(-0.1525 - j 0.1876)$$

$$S_{64} = 0.19066 + j 0.10592$$

Line loss between bus_4 and bus_6:

$$S_{46} + S_{64} = -0.0006 - j 0.012$$

Line Flow From Bus_2 to Bus_3

$$I_{23} = (V_2 - V_3) \times Y_{23}$$

$$I_{23} = (1.0 e^{-17.92} - 0.95897 e^{-19.61})(-1.957 + j 3.737)$$

$$I_{23} = (-0.1467 + j 0.1523)$$

therefore,

$$S_{23} = (V_2) \times I_{23}^*$$

$$S_{23} = (1.0 e^{-17.92})(-0.1467 - j 0.1523)$$

$$S_{23} = -0.1864419 - j 0.09972$$

again,

$$I_{32} = (V_3 - V_2) \times Y_{32}$$

$$I_{32} = -(1.0 e^{-17.92} - 0.95897 e^{-19.61})(-1.957 + j 3.737)$$

$$I_{32} = -(-0.1467 + j 0.1523)$$

therefore,

$$S_{32} = (V_3) \times I_{32}^*$$

$$S_{32} = -(0.95897 e^{-19.61})(-0.1467 - j 0.1523)$$

$$S_{32} = 0.1815 + j 0.09339$$

Line loss between bus_2 and bus_3:

$$S_{23} + S_{32} = -0.005 - j 0.006$$

Line Flow From Bus_2 to Bus_5

$$I_{25} = (V_2 - V_5) \times Y_{25}$$

$$I_{25} = (1.0 e^{-17.92} - 0.82576 e^{-25.17})(-1.957 + j 3.737)$$

$$I_{25} = (-0.5623 + j 0.6776)$$

therefore,

$$S_{25} = (V_2) \times I_{25}^*$$

$$S_{25} = (1.0 e^{-17.92})(-0.5623 - j 0.6776)$$

$$S_{25} = -0.7435 - j 0.4718$$

again,

$$I_{52} = (V_5 - V_2) \times Y_{52}$$

$$I_{52} = -(1.0 e^{-17.92} - 0.82576 e^{-25.17})(-1.957 + j 3.737)$$

$$I_{52} = -(-0.5623 + j 0.6776)$$

therefore,

$$S_{52} = (V_5) \times I_{52}^*$$

$$S_{52} = -(0.82576 e^{-25.17})(-0.5623 - j 0.6776)$$

$$S_{52} = 0.65823 + j 0.30896$$

Line loss between bus_2 and bus_5:

$$S_{25} + S_{52} = -0.085 - j 0.163$$

Line Flow From Bus_5 to Bus_6

$$I_{56} = (V_5 - V_6) \times Y_{56}$$

$$I_{56} = (0.82576 e^{-25.17} - 0.90197 e^{-21.85})(-1.957 + j 3.737)$$

$$I_{56} = (0.2339 - j 0.3053)$$

therefore,

$$S_{56} = (V_5) \times I_{56}^*$$

$$S_{56} = (0.82576 e^{-25.17})(0.2339 + j 0.3053)$$

$$S_{56} = 0.28205 + j 0.14599$$

again,

$$I_{65} = (V_6 - V_5) \times Y_{65}$$

$$I_{65} = -(0.82576 e^{-25.17} - 0.90197 e^{-21.85})(-1.957 + j 3.737)$$

$$I_{65} = -(0.2339 - j 0.3053)$$

therefore,

$$S_{65} = (V_6) \times I_{65}^*$$

$$S_{65} = -(0.90197 e^{-21.84973})(0.2339 + j 0.3053)$$

$$S_{65} = -0.298322 - j 0.17706$$

Line loss between bus_5 and bus_6:

$$S_{56} + S_{65} = -0.016 - j 0.031$$

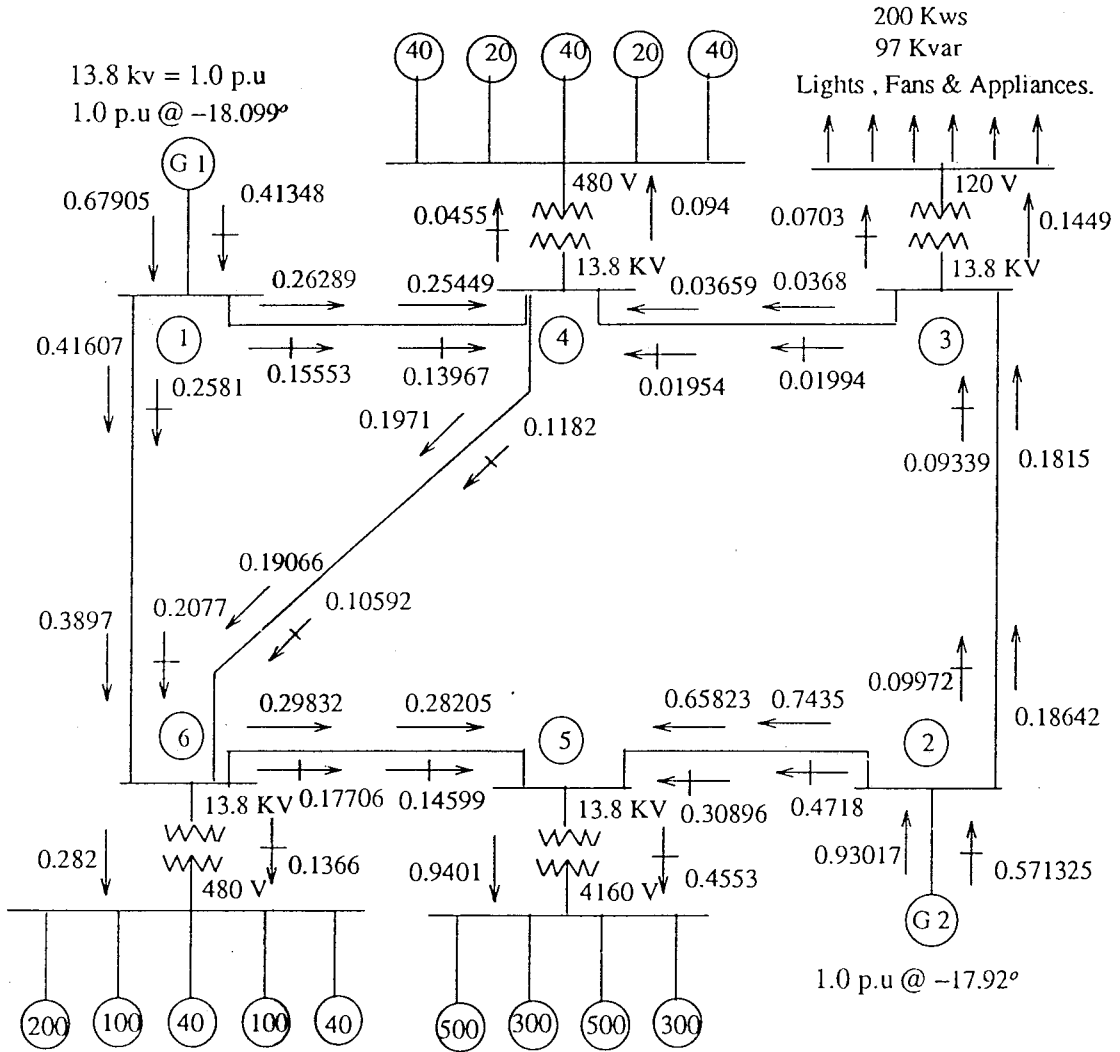


Figure 9. Line flow for pf=90%.

Reactive Power Loss in the Individual Lines Per Mile

$$\text{Bus}_1 \text{ to Bus}_6 = (0.2581 - 0.2077) \times 1380 + 337 = 0.206 \text{ kvar}$$

$$\text{Bus}_1 \text{ to Bus}_4 = (0.15553 - 0.13967) \times 1380 + 273 = 0.08 \text{ kvar}$$

$$\text{Bus}_3 \text{ to Bus}_4 = (0.01994 - 0.01954) \times 1380 + 337 = 0.0016 \text{ kvar}$$

$$\text{Bus}_2 \text{ to Bus}_3 = (0.09972 - 0.09339) \times 1380 + 337 = 0.026 \text{ kvar}$$

$$\text{Bus}_6 \text{ to Bus}_5 = (0.17706 - 0.14599) \times 1380 + 337 = 0.13 \text{ kvar}$$

$$\text{Bus}_2 \text{ to Bus}_5 = (0.4718 - 0.30896) \times 1380 + 337 = 0.667 \text{ kvar}$$

$$\text{Bus}_4 \text{ to Bus}_6 = (0.1182 - 0.10592) \times 1380 + 337 = 0.05 \text{ kvar}$$

Therefore total reactive power losses in the lines = 1.16 kvar

Real Power Loss in the Individual Lines Per Mile

$$\text{Bus}_1 \text{ to Bus}_6 = (0.41607 - 0.3892) \times 1380 + 337 = 0.11 \text{ kw}$$

$$\text{Bus}_1 \text{ to Bus}_4 = (0.26289 - 0.25449) \times 1380 + 273 = 0.04 \text{ kw}$$

$$\text{Bus}_3 \text{ to Bus}_4 = (0.0368 - 0.03659) \times 1380 + 337 = 0.0008 \text{ kw}$$

$$\text{Bus}_2 \text{ to Bus}_3 = (0.18642 - 0.1815) \times 1380 + 337 = 0.02 \text{ kw}$$

$$\text{Bus}_6 \text{ to Bus}_5 = (0.29832 - 0.28205) \times 1380 + 337 = 0.067 \text{ kw}$$

$$\text{Bus}_2 \text{ to Bus}_5 = (0.7435 - 0.65823) \times 1380 + 337 = 0.35 \text{ kw}$$

$$\text{Bus}_4 \text{ to Bus}_6 = (0.1971 - 0.19066) \times 1380 + 337 = 0.026 \text{ kw}$$

Therefore total real power losses in the lines = 0.614 kw

Total Capacitive Compensation at the Buses

From line flow data of pf = 90% and from the reactive line losses we calculate the compensation required at the individual buses:

$$\text{At Bus}_5 = 0.4553 \times 1380 + 0.667 + 0.13 = 629.11 \text{ kvar}$$

$$\text{At Bus}_6 = 0.1366 \times 1380 + 0.206 + 0.05 = 188.764 \text{ kvar}$$

$$\text{At Bus}_4 = 0.0455 \times 1380 + 0.08 + 0.0016 = 62.872 \text{ kvar}$$

$$\text{At Bus}_3 = 0.0703 \times 1380 + 0.026 = 97.04 \text{ kvar}$$

Therefore total bus compensation = 977.786 kvar

TABLE IX
COMPENSATION AT BUSES AT PF=90%

bus #	generator	capa. size (kvar)
6	-	188.764
5	-	629.11
4	-	62.872
3	-	97.04

Cost of energy

From the simulation result we see that,

$$\text{Tot. kvar required per hour} = 977.0113 \text{ kvar/hr}$$

$$\text{Tot. kws required per hour} = 2017.25 \text{ kws/hr}$$

Considering a typical situation where the plant runs for two shifts, 8 hours per shift and 5 days in a week, we find,

$$\text{Required generation of kvar/month} = 977.0113 \times 2 \times 8 \times 20 = 312643.616 \text{ kvar}$$

$$\text{Required generation of kws/month} = 2017.25 \times 2 \times 8 \times 20 = 645520.00 \text{ kws}$$

Using the formula,

$$\begin{aligned} \text{Average pf} &= \frac{\text{Tot kw}}{\sqrt{(\text{Tot kw}^2 + \text{Tot kvar}^2)}} \\ \text{pf} &= \frac{645520.00}{\sqrt{(645520.00^2 + 312643.616^2)}} \\ \text{pf} &= 90\% \end{aligned}$$

Uncompensated Energy Bill

$$\text{kva drawn in one month} = \sqrt{(312643.616^2 + 645520.00^2)} = 717246.19276 \text{ kva}$$

$$\text{Demand} = \sqrt{(977.0113^2 + 2017.25^2)} = 2241.39435 \text{ kva}$$

$$\text{pf penalty of} = (95 - 90) \times 2 = 10\%$$

Energy = 717246.19276 kws

Demand = 2241.39435 kws

pf penalty = $2241.39435 \times 0.1 = 224.1349$ kws

The total bill is = $717246.19276 \times 0.02 + 2241.39435 \times 4.14 + 224.1349 \times 4.14 = 24645.03$ dollars

where, the energy charge = 0.02 dollar/kwhr

the demand charge = 4.14 dollar/kwhr, and

pf penalty charge = 4.14 dollar/kwhr

Compensated Energy Bill

By compensating the kvar keeping a pf = 95% to avoid the power factor penalty, the reactive power that can be drawn safely from the utility without paying a pf penalty can be calculated as,

$$0.95 = \frac{Tot\ kw}{\sqrt{(Tot\ kw^2 + Tot\ kvar^2)}}$$

$$0.95 = \frac{645520.00}{\sqrt{(645520.00^2 + Tot\ kvar^2)}}$$

Tot. kvar (could be drawn safely from the utility) = 212172.16358 kvar

Therefore, the amount of kvar needs to be compensated is = generated kvar - safe drawn kvar.

kvar to be compensated = $312643.616 - 212172.16358 = 100471.4525$ kvar $\div 320 = 313.9733$ kvar/hr

After compensation kva drawn/month = $\sqrt{(645520.00^2 + 212172.16358^2)} = 679494.73684$ kva

New demand is = $\sqrt{(2017.25^2 + (977.0113 - 313.9733)^2)}$

Demand = 2123.42105 kva

Energy = 679494.73684 kws

Demand = 2123.42105 kws

The total bill is = $679494.73684 \times 0.02 + 2123.42105 \times 4.14 = 22380.86$ dollars.

where, the energy charge = 0.02 dollar/kwhr, and

the demand charge = 4.14 dollar/kwhr

Money saved/month = Uncompensated bill - compensated bill = $24645.03 - 22380.86 = 2264.17$ dollars.

Cost of Capacitor Compensation

From the Table XIII total kvar to be compensated is 977.0113 kvar.

The total compensation cost = $977.0113 \times (6.00 + 10.00) = 15632.18$ dollars.

Dividing compensation cost by monthly excess bill we get,

$15632.0113 \div 2264.17 = 7$ months.

i.e., the total investment for capacitor compensation is equivalent to 7 months excess bill.

SIMULATION RESULTS AT 85% POWER FACTOR

Real and Reactive Loads at Load Buses

Given the η , pf and the hp of a motor the real and reactive power input of the motor can be calculated as shown below:

$$\text{Real power input (kw input)} = \frac{hp \times 0.746}{\eta}$$

$$\text{Reactive power input (rkva input)} = kw \text{ input} \times \tan [\cos^{-1}(pf)]$$

BUS_6. At bus_6 we have $1 \times 200 \text{ hp}$, $2 \times 100 \text{ hp}$ and $2 \times 40 \text{ hp}$ of $\eta = 92\%$.

therefore,

$$kw \text{ input} = 480 \times \frac{0.746}{0.92} = 389.2174 \text{ kw}$$

$$\text{here, } \theta = \tan [\cos^{-1}(0.85)] = 0.61974$$

$$\text{and, } rkva \text{ input} = 389.2174 \times 0.61974 = 241.2153 \text{ kvar}$$

BUS_5. At bus_5 we have 2×500 hp, and 2×300 hp of $\eta = 92\%$.

Calculating the same way as shown above we get,

kw input = 1297.3913 kw and,

$rkva$ input = 804.0509 kvar

BUS_4. At bus_4 we have 3×40 hp, and 2×20 hp of $\eta = 92\%$.

Calculating the same way as shown above we get,

kw input = 129.7391 kw and,

$rkva$ input = 80.4051 kvar

BUS_3. At bus_3 we have lights, fans, computers and other domestic and office usable appliances comprising a load of

kw input = 200 kws

$rkva$ input = 97 kvars

Partial Compensation at the Load Buses

Results of the load flow simulation at 85% power factor and the partial compensation required at individual bus levels are shown in the Table X and Table XI respectively.

TABLE X

LOAD FLOW OUTPUT AT PF = 85%

bus #	volts p.u	angle degree	generation		load	
			P(kw)	Q(kvar)	P(kw)	Q(kvar)
1	1.00000	-18.099	947.22452	708.97856	0.00000	0.00000
2	1.00000	-17.837	1310.9405	970.32831	0.0000	0.00000
3	0.95576	-19.484	0.00000	0.00000	199.95266	97.025689
4	0.94407	-19.786	0.00000	0.00000	129.71328	80.459462
5	0.79812	-24.651	0.00000	0.00000	1296.97813	804.21262
6	0.88749	-21.528	0.00000	0.00000	389.11633	241.25388

It is seen from the Table X that the

Total real power at the load end = 2015.7604 kws

Total reactive power at the load end = 1222.95163 kvars

Total reactive power generated = 1679.30687 kvars

Total real power generated = 2258.16508 kws

Now, by Table II capacitor size for partial compensation at the load buses are,

TABLE XI

PARTIAL COMPENSATION AT THE LOAD BUSES AT PF = 85%

BUS #	PRE. PF%	FIN. PF%	CORREC. FAC	CAPA. SIZE(kvar)
6	93.02	95	0.066	30.2173
5	90.88	95	0.1304	198.9393
4	94.09	95	0.0318	4.8616
3	94.27	95	0.02555	5.6785

Line Flow From Bus_1 to Bus_6

$$I_{16} = (V_1 - V_6) \times Y_{16}$$

$$I_{16} = (1.0 e^{-18.099} - 0.88749 e^{-21.58})(-1.917 + j 3.737)$$

$$I_{16} = (-0.3006 + j 0.4375)$$

therefore,

$$S_{16} = (V_1) \times I_{16}^*$$

$$S_{16} = (1.0 e^{-18.099})(-0.3006 - j 0.4375)$$

$$S_{16} = -0.42165 - j 0.3225$$

again,

$$I_{61} = (V_6 - V_1) \times Y_{61}$$

$$I_{61} = -(1.0 e^{-18.099} - 0.88749 e^{-21.58})(-1.917 + j 3.737)$$

$$I_{61} = -(-0.3006 + j 0.4375)$$

therefore,

$$S_{61} = (V_6) \times I_{61}^*$$

$$S_{61} = -(0.88749 e^{-21.53})(-0.3006 - j 0.4375)$$

$$S_{61} = 0.39066 + j 0.2633$$

Line loss between bus_1 and bus_6:

$$S_{16} + S_{61} = -0.031 - j 0.059$$

Line Flow From Bus_1 to Bus_4

$$I_{14} = (V_1 - V_4) \times Y_{14}$$

$$I_{14} = (1.0 e^{-18.099} - 0.94407 e^{-19.78})(-2.432 + j 4.595)$$

$$I_{14} = (-0.1922 + j 0.2641)$$

therefore,

$$S_{14} = (V_1) \times I_{14}^*$$

$$S_{14} = (1.0 e^{-18.099})(-0.1922 - j 0.2641)$$

$$S_{14} = -0.2647 - j 0.19128$$

again,

$$I_{41} = (V_4 - V_1) \times Y_{41}$$

$$I_{41} = -(1.0 e^{-18.099} - 0.94407 e^{-19.78})(-2.432 + j 4.595)$$

$$I_{41} = -(0.94407 e^{-19.78} - 1.0 e^{-18.099})(-2.432 + j 4.595)$$

$$I_{41} = -(-0.1922 + j 0.2641)$$

therefore,

$$S_{41} = (V_4) \times I_{41}^*$$

$$S_{41} = -(0.94407 e^{-19.78})(-0.1922 - j 0.2641)$$

$$S_{41} = 0.255 + j 0.17315$$

Line loss between bus_1 and bus_4:

$$S_{14} + S_{41} = -0.01 - j 0.018$$

Line Flow From Bus_3 to Bus_4

$$I_{34} = (V_3 - V_4) \times Y_{34}$$

$$I_{34} = (0.95576 e^{-19.48} - 0.94407 e^{-19.78})(-1.937 + j 3.737)$$

$$I_{34} = (-0.02778 + j 0.04589)$$

therefore,

$$S_{34} = (V_3) \times I_{34}^*$$

$$S_{34} = (0.95576 e^{-19.48})(-0.02778 - j 0.04589)$$

$$S_{34} = -0.03966 - j 0.03249$$

again,

$$I_{43} = (V_4 - V_3) \times Y_{43}$$

$$I_{43} = -(0.95576 e^{-19.48} - 0.94407 e^{-19.78})(-1.937 + j 3.737)$$

$$I_{43} = -(-0.02778 + j 0.04589)$$

therefore,

$$S_{43} = (V_4) \times I_{43}^*$$

$$S_{43} = -(0.94407 e^{-19.78})(-0.02778 - j 0.04589)$$

$$S_{43} = 0.03934 + j 0.03188$$

Line loss between bus_3 and bus_4:

$$S_{34} + S_{43} = -0.00032 - j 0.001$$

Line Flow From Bus_4 to Bus_6

$$I_{46} = (V_4 - V_6) \times Y_{46}$$

$$I_{46} = (0.94407 e^{-19.78} - 0.88749 e^{-21.53})(-1.947 + j 3.737)$$

$$I_{46} = (-0.1456 + j 0.2226)$$

therefore,

$$S_{46} = (V_4) \times I_{46}^*$$

$$S_{46} = (0.94407 e^{-19.78})(-0.1456 - j 0.2226)$$

$$S_{46} = -0.20047 - j 0.15121$$

again,

$$I_{64} = (V_6 - V_4) \times Y_{64}$$

$$I_{64} = -(0.94407 e^{-19.78} - 0.88749 e^{-21.53})(-1.947 + j 3.737)$$

$$I_{64} = -(-0.1456 + j 0.2226)$$

therefore,

$$S_{64} = (V_6) \times I_{64}^*$$

$$S_{64} = -(0.88749 e^{-21.53})(-0.1456 - j 0.2226)$$

$$S_{64} = 0.19269 + j 0.136358$$

Line loss between bus_4 and bus_6:

$$S_{46} + S_{64} = -0.008 - j 0.015$$

Line Flow From Bus_2 to Bus_3

$$I_{23} = (V_2 - V_3) \times Y_{23}$$

$$I_{23} = (1.0 e^{-17.84} - 0.95576 e^{-19.48})(-1.927 + j 3.737)$$

$$I_{23} = -0.1462 + j 0.1658$$

therefore,

$$S_{23} = (V_2) \times I_{23}^*$$

$$S_{23} = (1.0 e^{-17.84})(-0.1462 - j 0.1650)$$

$$S_{23} = -0.190005 - j 0.11304$$

again,

$$I_{32} = (V_3 - V_2) \times Y_{32}$$

$$I_{32} = -(1.0 e^{-17.84} - 0.95576 e^{-19.48})(-1.927 + j 3.737)$$

$$I_{32} = - -0.1462 + j 0.1658$$

therefore,

$$S_{32} = (V_3) \times I_{32}^*$$

$$S_{32} = -(0.95576 e^{-19.48})(-0.1462 - j 0.1658)$$

$$S_{32} = 0.18463 + j 0.10277$$

Line loss between bus_2 and bus_3:

$$S_{23} + S_{32} = -0.005 - j 0.01$$

Line Flow From Bus_2 to Bus_5

$$I_{25} = (V_2 - V_5) \times Y_{25}$$

$$I_{25} = (1.0 e^{-17.84} - 0.79812 e^{-24.65})(-1.927 + j 3.737)$$

$$I_{25} = (-0.5426 + j 0.7946)$$

therefore,

$$S_{25} = (V_2) \times I_{25}^*$$

$$S_{25} = (1.0 e^{-17.84})(-0.5426 - j 0.7946)$$

$$S_{25} = -0.7599 - j 0.5902$$

again,

$$I_{52} = (V_5 - V_2) \times Y_{52}$$

$$I_{52} = -(1.0 e^{-17.84} - 0.79812 e^{-24.65})(-1.927 + j 3.737)$$

$$I_{52} = -(-0.5426 + j 0.7946)$$

therefore,

$$S_{52} = (V_5) \times I_{52}^*$$

$$S_{52} = -(0.79812 e^{-24.65})(-0.5426 - j 0.7946)$$

$$S_{52} = 0.6581 + j 0.39577$$

Line loss between bus_2 and bus_5:

$$S_{25} + S_{52} = -0.102 - j 0.194$$

Line Flow From Bus_5 to Bus_6

$$I_{56} = (V_5 - V_6) \times Y_{56}$$

$$I_{56} = (0.79812 e^{-24.65} - 0.88749 e^{-21.53})(-1.957 + j 3.737)$$

$$I_{56} = (0.2229 - j 0.3603)$$

therefore,

$$S_{56} = (V_5) \times I_{56}^*$$

$$S_{56} = (0.79812 e^{-24.65})(0.2229 + j 0.3603)$$

$$S_{56} = 0.28169 + j 0.18713$$

again,

$$I_{65} = (V_6 - V_5) \times Y_{65}$$

$$I_{65} = -(0.79812 e^{-24.65} - 0.88749 e^{-21.53})(-1.957 + j 3.737)$$

$$I_{65} = -(0.2229 - j 0.3603)$$

therefore,

$$S_{65} = (V_6) \times I_{65}^*$$

$$S_{65} = -(0.88749 e^{-21.53})(0.2229 + j 0.3603)$$

$$S_{65} = -0.30143 - j 0.2248$$

Line loss between bus_5 and bus_6:

$$S_{56} + S_{65} = -0.02 - j 0.038$$

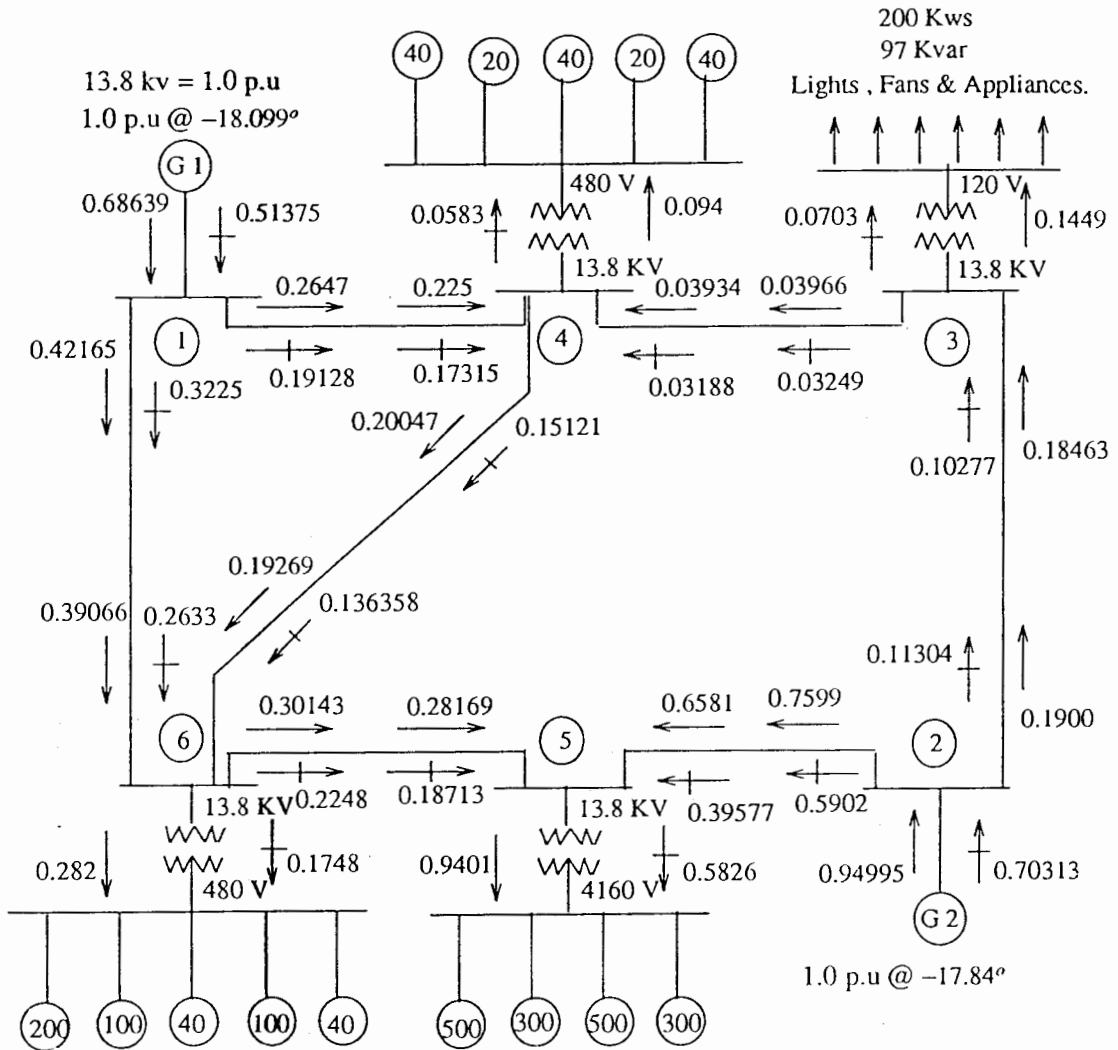


Figure 10. Line flow for pf=85%.

Reactive Power Loss in the Individual Lines Per Mile

$$\text{Bus}_1 \text{ to Bus}_6 = (0.3225 - 0.2633) \times 1380 \div 337 = 0.24 \text{ kvar}$$

$$\text{Bus}_1 \text{ to Bus}_4 = (0.19128 - 0.17315) \times 1380 \div 273 = 0.09 \text{ kvar}$$

$$\text{Bus}_3 \text{ to Bus}_4 = (0.03249 - 0.03188) \times 1380 \div 337 = 0.0025 \text{ kvar}$$

$$\text{Bus}_2 \text{ to Bus}_3 = (0.11304 - 0.10277) \times 1380 \div 337 = 0.04 \text{ kvar}$$

$$\text{Bus}_6 \text{ to Bus}_5 = (0.2248 - 0.18713) \times 1380 \div 337 = 0.15 \text{ kvar}$$

$$\text{Bus}_2 \text{ to Bus}_5 = (0.5902 - 0.39577) \times 1380 \div 337 = 0.796 \text{ kvar}$$

$$\text{Bus}_4 \text{ to Bus}_6 = (0.15121 - 0.136358) \times 1380 \div 337 = 0.06 \text{ kvar}$$

Therefore total reactive power losses in the lines = 1.38 kvar

Real power Loss in the Individual Lines Per Mile

$$\text{Bus}_1 \text{ to Bus}_6 = (0.42165 - 0.39066) \times 1380 \div 337 = 0.127 \text{ kw}$$

$$\text{Bus}_1 \text{ to Bus}_4 = (0.2647 - 0.225) \times 1380 \div 273 = 0.2 \text{ kw}$$

$$\text{Bus}_3 \text{ to Bus}_4 = (0.03966 - 0.03934) \times 1380 \div 337 = 0.0013 \text{ kw}$$

$$\text{Bus}_2 \text{ to Bus}_3 = (0.19 - 0.18463) \times 1380 \div 337 = 0.04 \text{ kw}$$

$$\text{Bus}_6 \text{ to Bus}_5 = (0.30143 - 0.28169) \times 1380 \div 337 = 0.081 \text{ kw}$$

$$\text{Bus}_2 \text{ to Bus}_5 = (0.7599 - 0.6581) \times 1380 \div 337 = 0.417 \text{ kw}$$

$$\text{Bus}_4 \text{ to Bus}_6 = (0.20047 - 0.19269) \times 1380 \div 337 = 0.0318 \text{ kw}$$

Therefore total real power losses in the lines = 0.8978 kw

Total Capacitive Compensation at the Buses

From line flow data of $\text{pf} = 85\%$ and from the reactive line losses we calculate the compensation required at the individual buses:

$$\text{At Bus}_5 = 0.5826 \times 1380 + 0.796 + 0.15 = 804.934 \text{ kvar}$$

$$\text{At Bus}_6 = 0.1748 \times 1380 + 0.24 + 0.06 = 241.524 \text{ kvar}$$

$$\text{At Bus}_4 = 0.0583 \times 1380 + 0.0025 + 0.09 = 80.546 \text{ kvar}$$

$$\text{At Bus}_3 = 0.0703 \times 1380 + 0.04 = 94.054 \text{ kvar}$$

Therefore total bus compensation = 1224.0593 kvar

TABLE XII
COMPENSATION AT BUSES AT PF=85%

bus #	generator	capa. size (kvar)
6	-	241.524
5	-	804.934
4	-	80.546
3	-	94.05

Cost of Energy

From the simulation result we see that,

Tot. kvar required per hour = 1224.3316 kvar/hr

Tot. kws required per hour = 2016.6582 kws/hr

Considering a typical situation where the plant runs for two shifts, 8 hours per shift and 5 days in a week, we find,

Required generation of kvar/month = $1224.3316 \times 2 \times 8 \times 20 = 391786.112$ kvar

Required generation of kws/month = $2016.6582 \times 2 \times 8 \times 20 = 645330.624$ kws

Using the formula,

$$\begin{aligned} \text{Average pf} &= \frac{\text{Tot kw}}{\sqrt{(\text{Tot kw}^2 + \text{Tot kvar}^2)}} \\ \text{pf} &= \frac{645330.624}{\sqrt{(645330.624^2 + 391786.112^2)}} \\ \text{pf} &= 85.48\% \end{aligned}$$

Uncompensated Energy Bill

kva drawn in one month = $\sqrt{(391786.112^2 + 645330.624^2)} = 754948.98624$ kva

Demand = $\sqrt{(1224.3316^2 + 2016.6582^2)} = 2359.215582$ kva

pf penalty of = $(95 - 85.48) \times 2 = 20\%$

Energy = 754948.98624 kws

demand = 2359.215582 kws

$$\text{pf penalty} = 2359.1574 \times 0.2 = 471.843116 \text{ kws}$$

The total bill is = $754948.98624 \times 0.02 + 2359.215582 \times 4.14 + 471.843116 \times 4.14 = 26819.56$ dollars

where, the energy charge = 0.02 dollar/kwhr

the demand charge = 4.14 dollar/kwhr, and

pf penalty charge = 4.14 dollar/kwhr

Compensated Energy Bill

By compensating the kvar keeping a pf = 95% to avoid the power factor penalty, the reactive power that can be drawn safely from the utility without paying a pf penalty can be calculated as,

$$0.95 = \frac{\text{Tot kw}}{\sqrt{(\text{Tot kw}^2 + \text{Tot kvar}^2)}}$$

$$0.95 = \frac{645330.624}{\sqrt{(645330.624^2 + \text{Tot kvar}^2)}}$$

The total kvar that could be drawn safely from the utility = 212109.91869 kvar

Therefore, the amount of kvar that needs to be compensated is = generated kvar - safe drawn kvar.

The kvar to be compensated = $391786.112 - 212109.91869 = 179676.1934$ kvar + 320 = 561.4881 kvar/hr

After compensation kva drawn/month = $\sqrt{(645330.624^2 + 212109.91869^2)} = 679295.39368$ kva

New demand is = $\sqrt{(2016.6582^2 + (1224.3316 - 561.4881)^2)}$

Demand = 2122.79811 kva

Energy = 679295.39368 kws

demand = 2122.79811 kws

The total bill is = $679295.39368 \times 0.02 + 2122.79811 \times 4.14 = 22374.29$ dollars.

where, the energy charge = 0.02 dollar/kwhr, and

the demand charge = 4.14 dollar/kwhr

Money saved/month = Uncompensated bill - compensated bill = 26819.56 - 22374.29 = 4445.27 dollars.

Cost of Capacitor Compensation

From the Table XIV total kvar to be compensated is 1224.3316 kvar.

The total compensation cost = $1224.3316 \times (6.00 + 10.00) = 19589.31$ dollars.

Dividing compensation cost by monthly excess bill we get,

$19589.31 + 4445.27 = 4.4$ months

i.e., the total investment for capacitor compensation is equivalent to 4.4 months excess bill.

SIMULATION RESULTS AT 80% POWER FACTOR

Real and Reactive Loads at Load Buses

Given the η , pf and the hp of a motor the real and reactive power input of the motor can be calculated as shown below:

$$\text{Real power input (kw input)} = \frac{hp \times 0.746}{\eta}$$

$$\text{Reactive power input (rkva input)} = kw \text{ input} \times \tan [\cos^{-1} (pf)]$$

BUS_6.

At bus_6 we have $1 \times 200 \text{ hp}$, $2 \times 100 \text{ hp}$ and $2 \times 40 \text{ hp}$ of $\eta = 92\%$.

therefore,

$$kw \text{ input} = 480 \times \frac{0.746}{0.92} = 389.2174 \text{ kw}$$

here, $\theta = \tan [\cos^{-1} (0.80)] = 0.7500$

and, $rkva \text{ input} = 389.2174 \times 0.7500 = 291.9130 \text{ kvar}$

BUS_5. At bus_5 we have 2×500 hp, and 2×300 hp of $\eta = 92\%$.

Calculating the same way as shown above we get,

kw input = 1297.3913 kw and,

$rkva$ input = 973.0435 kvar

. At bus_4 we have 3×40 hp, and 2×20 hp of $\eta = 92\%$.

Calculating the same way as shown above we get,

kw input = 129.7391 kw and,

$rkva$ input = 97.3045 kvar

BUS_3. At bus_3 we have lights, fans, computers and other domestic and office usable appliances comprising a load of

kw input = 200 kws

$rkva$ input = 97 kvars

Partial Compensation at the Load Buses

Results of the load flow simulation at 80% power factor and the partial compensation required at individual bus levels are shown in the Table XIII and Table XIV respectively.

It is seen from the Table XIII that the:

Total real power at the load end = 2016.55969 kws

Total reactive power at the load end = 1458.73493 kvars

Total reactive power generated = 2009.23358 kvars

Total real power generated = 2308.25645 kws

Now, by Table II capacitor size for partial compensation at the load buses are, as shown in the Table XIV.

TABLE XIII
LOAD FLOW OUTPUT AT PF = 80%

bus #	volts	angle	generation		load	
	p.u	degree	P(kw)	Q(kvar)	P(kw)	Q(kvar)
1	1.00000	-18.099	969.44779	847.21379	0.00000	0.00000
2	1.00000	-17.886	1338.8086	1162.01979	0.0000	0.00000
3	0.95246	-19.452	0.00000	0.00000	199.97583	96.987159
4	0.93753	-19.665	0.00000	0.00000	129.72784	97.279559
5	0.76907	-24.237	0.00000	0.00000	1297.6586	972.64805
6	0.87241	-21.259	0.00000	0.00000	389.19742	291.82018

TABLE XIV
PARTIAL COMPENSATION AT THE LOAD BUSES AT PF = 80%

BUS #	PRE. PF%	FIN. PF%	CORREC. FAC	CAPA. SIZE(kvar)
6	93.19	95	0.0601	29.24
5	91.19	95	0.1213	196.714
4	94.17	95	0.0291	4.71
3	94.29	95	0.02485	5.523

Line Flow From Bus_1 to Bus_6

$$I_{16} = (V_1 - V_6) \times Y_{16}$$

$$I_{16} = (1.0 e^{-18.099} - 0.87241 e^{-21.26})(-1.917 + j 3.737)$$

$$I_{16} = (-0.2902 + j 0.5027)$$

therefore,

$$S_{16} = (V_1) \times I_{16}^*$$

$$S_{16} = (1.0 e^{-18.099})(-0.2902 - j 0.5027)$$

$$S_{16} = -0.432 - j 0.3876$$

again,

$$I_{61} = (V_6 - V_1) \times Y_{61}$$

$$I_{61} = -(1.0 e^{-18.099} - 0.87241 e^{-21.26})(-1.917 + j 3.737)$$

$$I_{61} = -(-0.2902 + j 0.5027)$$

therefore,

$$S_{61} = (V_6) \times I_{61}^*$$

$$S_{61} = -(0.87241 e^{-21.26})(-0.2902 - j 0.5027)$$

$$S_{61} = 0.39495 + j 0.31689$$

Line loss between bus_1 and bus_6:

$$S_{16} + S_{61} = -0.037 - j 0.071$$

Line Flow From Bus_1 to Bus_4

$$I_{14} = (V_1 - V_4) \times Y_{14}$$

$$I_{14} = (1.0 e^{-18.099} - 0.93753 e^{-19.67})(-2.432 + j 4.595)$$

$$I_{14} = (-0.1868 + j 0.29918)$$

therefore,

$$S_{14} = (V_1) \times I_{14}^*$$

$$S_{14} = (1.0 e^{-18.099})(-0.1866 - j 0.29918)$$

$$S_{14} = -0.2705 - j 0.22634$$

again,

$$I_{41} = (V_4 - V_1) \times Y_{41}$$

$$I_{41} = -(1.0 e^{-18.099} - 0.93753 e^{-19.67})(-2.432 + j 4.595)$$

$$I_{41} = -(-0.1868 + j 0.29918)$$

therefore,

$$S_{41} = (V_4) \times I_{41}^*$$

$$S_{41} = -(0.93753 e^{-19.66})(-0.1866 - j 0.29918)$$

$$S_{41} = 0.2594 + j 0.20519$$

Line loss between bus_1 and bus_4:

$$S_{14} + S_{41} = -0.011 - j 0.021$$

Line Flow From Bus_3 to Bus_4

$$I_{34} = (V_3 - V_4) \times Y_{34}$$

$$I_{34} = (0.95246 e^{-19.45} - 0.93753 e^{-19.66})(-1.937 + j 3.737)$$

$$I_{34} = (-0.0235 + j 0.06027)$$

therefore,

$$S_{34} = (V_3) \times I_{34}^*$$

$$S_{34} = (0.95246 e^{-19.45})(-0.0235 - j 0.06027)$$

$$S_{34} = -0.040246 - j 0.04666$$

again,

$$I_{43} = (V_4 - V_3) \times Y_{43}$$

$$I_{43} = -(0.95246 e^{-19.45} - 0.93753 e^{-19.66})(-1.937 + j 3.737)$$

$$I_{43} = -(-0.0235 + j 0.06027)$$

therefore,

$$S_{43} = (V_4) \times I_{43}^*$$

$$S_{43} = -(0.93753 e^{-19.66})(-0.0235 - j 0.06027)$$

$$S_{43} = 0.03978 + j 0.04578$$

Line loss between bus_3 and bus_4:

$$S_{34} + S_{43} = -0.000466 - j 0.001$$

Line Flow From Bus_4 to Bus_6

$$I_{46} = (V_4 - V_6) \times Y_{46}$$

$$I_{46} = (0.93753 e^{-19.66} - 0.87241 e^{-21.26})(-1.947 + j 3.737)$$

$$I_{46} = (-0.1396 + j 0.2588)$$

therefore,

$$S_{46} = (V_4) \times I_{46}^*$$

$$S_{46} = (0.93753 e^{-19.66})(-0.1396 - j 0.2588)$$

$$S_{46} = -0.2049 - j 0.1844$$

again,

$$I_{64} = (V_6 - V_4) \times Y_{64}$$

$$I_{64} = -(0.93753 e^{-19.66} - 0.87241 e^{-21.26})(-1.947 + j 3.737)$$

$$I_{64} = -(-0.1396 + j 0.2588)$$

therefore,

$$S_{64} = (V_6) \times I_{64}^*$$

$$S_{64} = -(0.87241 e^{-21.26})(-0.1396 - j 0.2588)$$

$$S_{64} = 0.1954 + j 0.16627$$

Line loss between bus_4 and bus_6:

$$S_{46} + S_{64} = -0.01 - j 0.018$$

Line Flow From Bus_2 to Bus_3

$$I_{23} = (V_2 - V_3) \times Y_{23}$$

$$I_{23} = (1.0 e^{-17.88} - 0.95246 e^{-19.45})(-1.927 + j 3.737)$$

$$I_{23} = (-0.1424 + j 0.1805)$$

therefore,

$$S_{23} = (V_2) \times I_{23}^*$$

$$S_{23} = (1.0 e^{-17.88})(-0.1424 - j 0.1805)$$

$$S_{23} = -0.191 - j 0.128$$

again,

$$I_{32} = (V_3 - V_2) \times Y_{32}$$

$$I_{32} = -(1.0 e^{-17.88} - 0.95246 e^{-19.45})(-1.927 + j 3.737)$$

$$I_{32} = -(-0.1424 + j 0.1805)$$

therefore,

$$S_{32} = (V_3) \times I_{32}^*$$

$$S_{32} = -(0.95246 e^{-19.45})(-0.1424 - j 0.1805)$$

$$S_{32} = 0.1851 + j 0.1169$$

Line loss between bus_2 and bus_3:

$$S_{23} + S_{32} = -0.006 - j 0.011$$

Line Flow From Bus_2 to Bus_5

$$I_{25} = (V_2 - V_5) \times Y_{25}$$

$$I_{25} = (1.0 e^{-17.88} - 0.76907 e^{-24.24})(-1.927 + j 3.737)$$

$$I_{25} = (-0.522 + j 0.9189)$$

therefore,

$$S_{25} = (V_2) \times I_{25}^*$$

$$S_{25} = (1.0 e^{-17.88})(-0.522 - j 0.9189)$$

$$S_{25} = -0.7791 - j 0.71414$$

again,

$$I_{52} = (V_5 - V_2) \times Y_{52}$$

$$I_{52} = -(1.0 e^{-17.88} - 0.76907 e^{-24.24})(-1.927 + j 3.737)$$

$$I_{52} = -(-0.522 + j 0.9189)$$

therefore,

$$S_{52} = (V_5) \times I_{52}^*$$

$$S_{52} = -(0.76907 e^{-24.24})(-0.522 - j 0.9189)$$

$$S_{52} = 0.656249 + j 0.4795568$$

Line loss between bus_2 and bus_5:

$$S_{25} + S_{52} = -0.123 - j 0.235$$

Line Flow From Bus_5 to Bus_6

$$I_{56} = (V_5 - V_6) \times Y_{56}$$

$$I_{56} = (0.76907 e^{-24.24} - 0.87241 e^{-21.26})(-1.957 + j 3.737)$$

$$I_{56} = (0.2164 - j 0.4188)$$

therefore,

$$S_{56} = (V_5) \times I_{56}^*$$

$$S_{56} = (0.76907 e^{-24.24})(0.2164 + j 0.4188)$$

$$S_{56} = 0.2840 + j 0.2254$$

again,

$$I_{65} = (V_6 - V_5) \times Y_{65}$$

$$I_{65} = -(0.76907 e^{-24.24} - 0.87241 e^{-21.26})(-1.957 + j 3.737)$$

$$I_{65} = -(0.2164 - j 0.4188)$$

therefore,

$$S_{65} = (V_6) \times I_{65}^*$$

$$S_{65} = -(0.87241 e^{-21.26})(0.2164 + j 0.4188)$$

$$S_{65} = -0.30846 - j 0.27208$$

Line loss between bus_5 and bus_6:

$$S_{56} + S_{65} = -0.024 - j 0.047$$

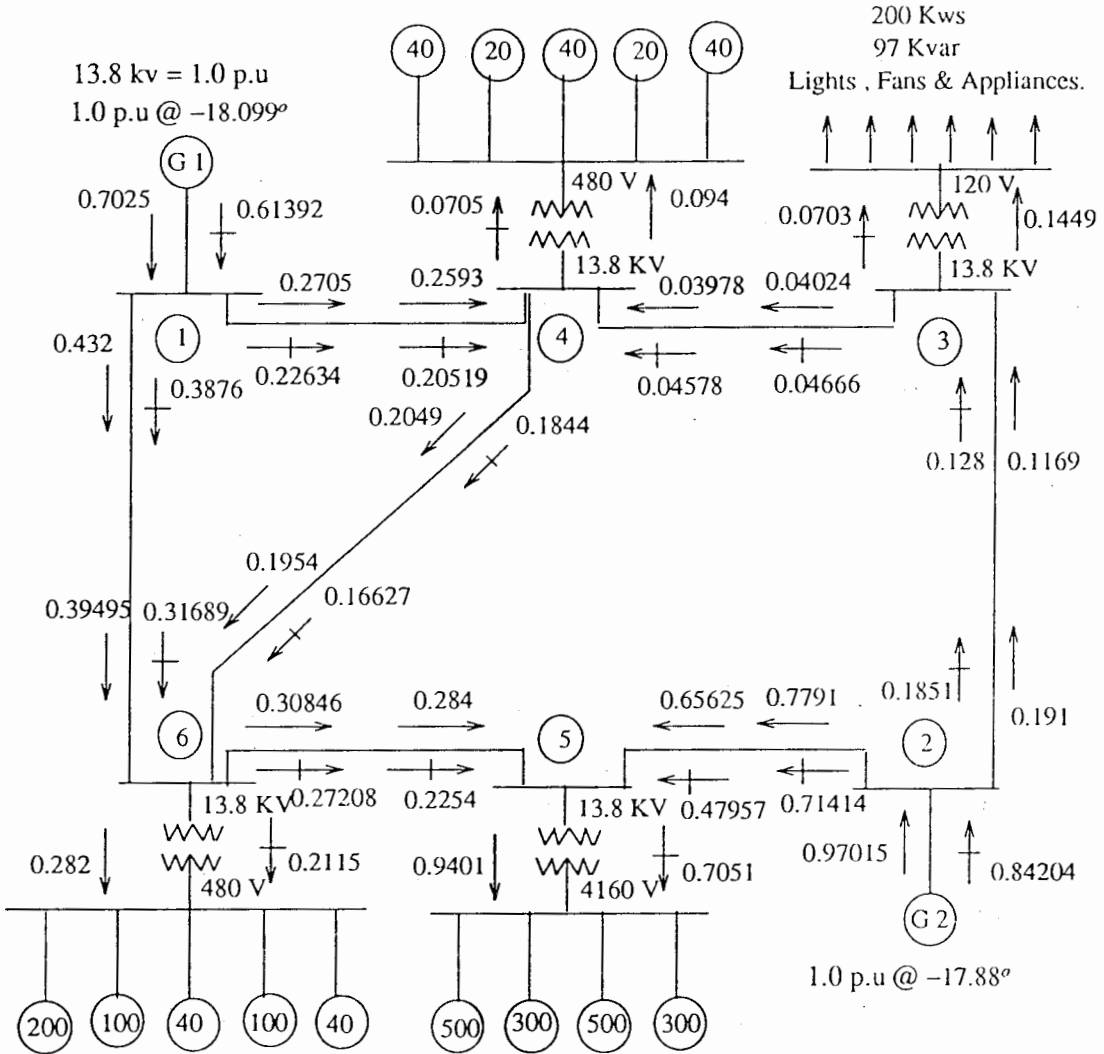


Figure 11. Line flow for pf=80%.

Reactive Power Loss in the Individual Lines Per Mile

$$\text{Bus}_1 \text{ to Bus}_6 = (0.3876 - 0.31689) \times 1380 + 337 = 0.29 \text{ kvar}$$

$$\text{Bus}_1 \text{ to Bus}_4 = (0.22634 - 0.20519) \times 1380 + 273 = 0.107 \text{ kvar}$$

$$\text{Bus}_3 \text{ to Bus}_4 = (0.04666 - 0.04578) \times 1380 + 337 = 0.004 \text{ kvar}$$

$$\text{Bus}_2 \text{ to Bus}_3 = (0.1851 - 0.128) \times 1380 + 337 = 0.23 \text{ kvar}$$

$$\text{Bus}_6 \text{ to Bus}_5 = (0.27208 - 0.2254) \times 1380 + 337 = 0.19 \text{ kvar}$$

$$\text{Bus}_2 \text{ to Bus}_5 = (0.71414 - 0.47957) \times 1380 + 337 = 0.96 \text{ kvar}$$

$$\text{Bus}_4 \text{ to Bus}_6 = (0.1844 - 0.16627) \times 1380 + 337 = 0.074 \text{ kvar}$$

Therefore total reactive power losses in the lines = 1.854 kvar

Real Power Loss in the Individual Lines Per Mile

$$\text{Bus}_1 \text{ to Bus}_6 = (0.432 - 0.39495) \times 1380 + 337 = 0.152 \text{ kw}$$

$$\text{Bus}_1 \text{ to Bus}_4 = (0.2705 - 0.2593) \times 1380 + 273 = 0.0566 \text{ kw}$$

$$\text{Bus}_3 \text{ to Bus}_4 = (0.04024 - 0.03978) \times 1380 + 337 = 0.002 \text{ kw}$$

$$\text{Bus}_2 \text{ to Bus}_3 = (0.191 - 0.1169) \times 1380 + 337 = 0.303 \text{ kw}$$

$$\text{Bus}_6 \text{ to Bus}_5 = (0.30846 - 0.284) \times 1380 + 337 = 0.1 \text{ kw}$$

$$\text{Bus}_2 \text{ to Bus}_5 = (0.7791 - 0.65625) \times 1380 + 337 = 0.5 \text{ kw}$$

$$\text{Bus}_4 \text{ to Bus}_6 = (0.2049 - 0.1954) \times 1380 + 337 = 0.039 \text{ kw}$$

Therefore total real power losses in the lines = 1.152 kw

Total Capacitive Compensation at the Buses

From line flow data of $\text{pf} = 80\%$ and from the reactive line losses we calculate the compensation required at the individual buses:

$$\text{At Bus}_5 = 0.7051 \times 1380 + 0.96 + 0.19 = 974.188 \text{ kvar}$$

$$\text{At Bus}_6 = 0.2115 \times 1380 + 0.29 + 0.074 = 292.234 \text{ kvar}$$

$$\text{At Bus}_4 = 0.0705 \times 1380 + 0.004 + 0.107 = 97.40 \text{ kvar}$$

At Bus_3= $0.0703 \times 1380 + 0.23 = 97.244$ kvar

Therefore total bus compensation = 1461.06 kvar

TABLE XV
COMPENSATION AT BUSES AT PF=80%

bus #	generator	capa. size (kvar)
6	-	292.234
5	-	974.188
4	-	97.4
3	-	97.244

Cost of Energy

From the simulation result we see that,

Tot. kvar required per hour = 1460.5889 kvar/hr

Tot. kws required per hour = 2017.7117 kws/hr

Considering a typical situation where the plant runs for two shifts, 8 hours per shift and 5 days in a week, we find,

Required generation of kvar/month = $1460.5889 \times 2 \times 8 \times 20 = 467388.448$ kvar

Required generation of kws/month = $2017.7117 \times 2 \times 8 \times 20 = 645667.744$ kws

Using the formula,

$$\text{Average pf} = \frac{\text{Tot kw}}{\sqrt{(\text{Tot kw}^2 + \text{Tot kvar}^2)}}$$

$$\text{pf} = \frac{645667.744}{\sqrt{(645667.744^2 + 467388.448^2)}}$$

$$\text{pf} = 81\%$$

Uncompensated Energy Bill

kva drawn in one month = $\sqrt{(645667.744^2 + 467388.448^2)} = 797081.4243$ kva

Demand = $\sqrt{(1460.5889^2 + 2017.7117^2)} = 2490.87945$ kva

pf penalty of = $(95 - 81) \times 2 = 28\%$

Energy = 797081.4243 kws

demand = 2490.87945 kws

pf penalty = $2490.87945 \times 0.28 = 697.44625$ kws

The total bill is = $797081.4243 \times 0.02 + 2490.87945 \times 4.14 + 697.44625 \times 4.14 = 29141.30$ dollars

where, the energy charge = 0.02 dollar/kwhr

the demand charge = 4.14 dollar/kwhr, and

pf penalty charge = 4.14 dollar/kwhr

Compensated Energy Bill

By compensating kvar keeping a pf = 95% to avoid the power factor penalty, the reactive power that can be drawn safely from the utility without paying a pf penalty can be calculated as,

$$0.95 = \frac{Tot\ kw}{\sqrt{(Tot\ kw^2 + Tot\ kvar^2)}}$$

$$0.95 = \frac{645667.774}{\sqrt{(645667.774^2 + Tot\ kvar^2)}}$$

The total kvar that could be drawn safely from the utility = 212220.72468 kvar

Therefore, the amount of kvar needs to be compensated is = generated kvar - safe drawn kvar.

The kvar to be compensated = $467388.448 - 212220.72468$

$$= 255167.7234\ kvar \div 320 = 797.39914\ kvar/hr$$

After compensation kva drawn/month = $\sqrt{(645667.744^2 + 212220.72468^2)} = 679650.25684$ kva

Now the new demand is = $\sqrt{(2017.7117^2 + (1460.5889 - 797.39914)^2)}$

Demand = 2123.90705 kva

Energy = 679650.25684 kws

Demand = 2123.90705 kws

The total bill is = $679650.25684 \times 0.02 + 2123.90705 \times 4.14 = 22385.98$ dollars.

where, the energy charge = 0.02 dollar/kwhr, and

the demand charge = 4.14 dollar/kwhr

Money saved/month = Uncompensated bill - compensated bill = 29141.30 - 22385.98 = 6755.32 dollars.

Cost of Capacitor Compensation

From the Table XV total kvar to be compensated is 1460.5889 kvar.

The total compensation cost =

Dividing compensation cost by monthly excess bill we get,

$23369.42 \div 6755.32 = 3.5$ months

i.e., the total investment for capacitor compensation is equivalent to 3.5 months excess bill.

SUMMARY OF COST OF ENERGY AND TIME OF RECOVERY

TABLE XVI

SUMMARY OF COST OF ENERGY

pf %	uncompensated bill(monthly)	compensated bill(monthly)	dollar saved	
			per month	per year
95	22571.97	22377.34	194.63	2335.56
90	24645.03	22380.86	2264.17	27170.04
85	26819.56	22374.29	4445.27	53343.24
80	29141.30	22385.98	6755.32	81063.84

From the Table XVII it is evident that the proposed capacitive compensation is highly cost effective and takes short period to recover the capital investment providing long term savings in electrical energy use.

TABLE XVII

COST EFFECTIVE AND TIME OF RECOVERY

pf %	excess bill per month(dollars)	tot. cost of capacitor compensation(dollars)	recovery time (months)
95	194.63	11112.96	57
90	2264.17	15632.18	7
85	4445.27	19589.31	4.4
80	6755.32	23369.42	3.5

CHAPTER V

CONCLUSIONS AND FUTURE WORK

A set of computer programs for analyzing the power cost savings obtainable by improving the power factor of an industrial load have been developed and demonstrated.

The costs, related to the power factor resulting from inductive loads, can be reduced by applying shunt capacitors. The capacitors represent a one time expense that can be paid from the resulting utility bill savings. As the power factor is improved, a point is reached beyond which further correction becomes much less cost effective. The advantage of the method shown here is that the savings can be calculated for different amounts of power factor correction and the results can be compared before actually trying one.

For this new method a modified load flow solution was used to provide data for power factor economics studies. This new approach has not been tried before in industrial plants.

The proposed power system model has the advantage of confining faults to individual load centers so that they do not affect the performance of other load centers.

Recent developments in computer technology, such as convenient hardware, compact random access memory, fast central processing units and math coprocessors, have made computing services available in virtually all office and business environments at affordable prices. The programs developed here can be practically executed on a personal computer with 640K base memory and a math coprocessor.

Future work for increasing the usefulness of this method could proceed in the direction of combining the programs into a single interactive package with various alternatives. Some possible user options might be:

- (1) To find the total line loss
- (2) To find the loss for each individual transmission line
- (3) To determine the compensation for a particular bus at a specific power factor
- (4) To calculate the money saved per month or per year for a particular power factor correction
- (5) To find the power factor penalty for a particular load situation
- (6) To find the demand charge as a function of the power factor
- (7) To find the energy charge as a function of the power factor.
- (8) To calculate the time to recover the equipment and installation costs for reaching a particular power factor

The usefulness of the programs for larger installations could be improved by expanding the programs to deal with more than 10 buses.

The actual implementation of the programs will doubtless suggest still other possibilities.

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APPENDIX A

THE PROGRAM SOURCE CODE FOR THE CALCULATION OF
REAL AND REACTIVE POWER AT THE BUSES

```

/*****
* Pfactor.c
* This program calculates the power factor and total real power and
* total reactive power at a particular bus. It reads power factor
* and bus# and outputs the bus#, power factor, total real power and
* total reactive power.
* Input:
* power factor, bus#
* output:
* bus#
* power factor
* total kw
* total rkva
*****/
#include <stdio.h>
#include <math.h>
#define MULFAC 0.81086956 /* multiplication factor (0.746/efficiency)*/
#define BASE 1380.0 /* base value */

/* look-up tables for possible bus numbers */
int kwLUT[4][4] = { 3, 0, 0, 0,
                   4, 40, 20, 0,
                   5, 500, 300, 0,
                   6, 200, 100, 40 };
int facLUT[4][4] = { 3, 0, 0, 0,
                    4, 3, 2, 0,
                    5, 2, 2, 0,
                    6, 1, 2, 2 };

main()
{
    double pf, tantheta, theta;
    double kw[3], rkV[3]; /* kilowatt, reactive kilovolt */
    double kwa, rkva; /* totals */
    int busno; /* number of buses */
    int i, j;

    /* input pf and busno values */
    printf("\nEnter PF (decimal form) ==>");
    scanf("%lf", &pf);
    printf("Enter busno (3->6) ==>");
    scanf("%d", &busno);
    /* search for the busno in the look-up table */
    i = 0;
    while (i < 4)
        if (busno == facLUT[i][0])
            break;
        else
            i++;
}

```

```

if (i == 4)
{ printf("busno is not in look-up tables\n");
  exit(0);
}
/* determine total kw and rkv */
tantheta = sqrt(1 - pf*pf)/pf;
theta = atan(tantheta);
if (busno == 3)
{ kwa = 200;
  rkva = 97;
}
else
{ /* compute kw and rkv values for busno from kWLUT */
  for (j=1; j<4; j++)
  { kw[j-1] = kWLUT[i][j] * MULFAC;
    rkv[j-1] = kw[j-1] * tantheta;
  }
  /* get total kw and rkv using the factors in facLUT */
  kwa = rkva = 0;
  for (j=1; j<4; j++)
  { kwa += kw[j-1] * facLUT[i][j];
    rkva += rkv[j-1] * facLUT[i][j];
  }
}
printf("\nBus_no = %ld,    PF = %4.2lf\n", busno, pf);
printf("Tot_kw = %7.5lf,  Tot_rkv = %7.5lf\n",
      kwa/BASE, rkva/BASE);
}
/***** end pfactor.c *****/

```

APPENDIX B

THE PROGRAM SOURCE CODE FOR LOAD FLOW
CALCULATION USING THE NEWTON-RAPHSON METHOD

```

/*****
* Loadflow.c
* This program uses the Newton-Raphson method to solve modified
* load flow problems for systems upto 10 buses. Line and bus
* specifications are entered, then the program calculates the
* admittance matrix and a mismatch vector. The mismatch vector
* compared to the maximum allowable error (epsilon). If any of
* the mismatch components of the vector is greater than epsilon,
* then the program calculates the new voltage and angles. These
* new voltage and angles are then used to recalculate the mismatch
* vector. The iterations continue until the mismatch is less
* than epsilon for all components.
* Input:
* Initial bus real power, initial bus reactive power, initial bus
* voltage, initial bus angle for each buses and the given generated
* and load values of real power and reactive power.
* Output:
* Bus #, bus voltage, bus angle, generated real and reactive power,
* real and reactive power at the load.
*****/

/*****
* "EPS" is the error check factor against which all elements
* of the  $\Delta P$  and  $\Delta Q$  values are checked for proper
* convergence of the linear equations.
* "BASEV" is a multiplier which is 1380 volts.
* "bus" is the number of buses used in this problem.
* "unknown" is the number of unknown quantities or parameters
* of this problem, whose values are to be found out.
* "p[bus]" is the real power at the [bus].
* "Q[bus]" is the reactive power at [bus].
* "G[bus][bus]" is the conductance value bus_bus.
* "B[bus][bus]" is the susceptance value bus_bus.
* "theta[bus]" is the voltage angle at a particular bus.
* "V[bus]" is the voltage at a particular bus.
* "GPQ[unknown]" are the specified (given) values of the P & Q
*****/

#include <stdio.h>
#include <math.h>
#define PI      3.14159
#define EPS     0.001 /* Error check factor */
#define BASEV   1380 /* Multiplier*/
#define bus     6 /* Number of buses*/
#define unknown 9 /* Number of unknown parameters */

double P[bus], Q[bus], G[bus][bus], B[bus][bus], theta[bus];
double V[bus], GPQ[unknown], temp[unknown], delta[unknown], Y[unknown];
double X[unknown], jacob[unknown][unknown], H[bus][bus];

```

```
double N[bus][bus], M[bus][bus], L[bus][bus], angle[bus];
double P_of_Gen[bus], Q_of_Gen[bus], P_of_Load[bus], Q_of_Load[bus];
int num = 1, check;
```

```
/* MAIN FUNCTION */
```

```
main()
{
int l,m,n,o,p,q;

GBGEN(); /* Generates G + jB matrix */

printf("\n Input initial real power for each buses:\n");
for ( m = 1; m <= bus; ++m )
{
scanf("%lf", &P[m] );
printf("%9.3f",P[m]);
}
printf("\n");

printf("\n Input initial reactive power for each buses:\n" );
for ( n = 1; n <= bus; ++n )
{
scanf("%lf", &Q[n] );
printf("%9.3f",Q[n]);
}
printf("\n");

printf("\n Input initial voltage for each buses:\n" );
for ( o = 1; o <= bus; ++o )
{
scanf("%lf", &V[o] );
printf("%9.3f",V[o]);
}
printf("\n");

printf("\n Input initial angle for each buses:\n" );
for ( p = 1; p <= bus; ++p )
{
scanf("%lf", &theta[p] );
printf("%9.3f",theta[p]);
}
printf("\n");

printf("\n Input the given values for p[] and Q[]:\n" );
for ( q = 1; q <= unknown; ++q )
{
scanf("%lf", &GPQ[q] );
printf("%9.3f",GPQ[q]);
```

```

    }
        printf("\n");

check = 0;
while(check == 0)
{
    BDELTPQ(); /* Generate  $\Delta P$  &  $\Delta Q$  and check for EPS */
    JACOBIAN(); /* Generates Jacobian matrix */
    VXY(); /* L_U decomposition of jacobian matrix & */
        /* generates new  $\theta$  & new  $V$ . */
}
PQ(); /* Calculates final values of P & Q */
final(); /* Prints final values of unknowns */
printf("\n\n\n\n");
}

/* GENERATION OF G[][] AND B[][] MATRIX */

/*****
* This procedure reads bus #, impedance values, half line
* charge admittance, and off_nominal turns ratio values
* from the data file and generates Y_bus matrix,
* Y_bus = G + jB. It then prints out the Y_bus matrix
* in the form Y_bus = G + jB.
*****/

GBGEN()
{
    double zlr, zli, den;
    double ylr, yli;
    double hych, aline;
    double alph;
    double cond,sus;
    int I,J,K;

        for (I= 1; I<= bus; ++I)
            for (J=1; J<= bus; ++J)
                {
                    G[I][J]= 0;
                    B[I][J]= 0;
                }

    for (K=1; K<=7 ; ++K)
    {
        scanf("%d%d%lf%lf%lf%lf",&I,&J,&zlr,&zli,&hych,&aline);
        den = sqrt(zlr*zlr + zli*zli);
        alph = -atan(zli/zlr);
        ylr = (1/den)*cos(alph);
    }
}

```



```

yli = (1/den)*sin(alph);
cond = ylr;
sus = yli;

if (aline !=1)
{
    G[I][J]= G[I][J] - cond/aline;
    G[J][I]= G[J][I] - cond/aline;
    B[I][J]= B[I][J] - sus/aline;
    B[J][I]= B[J][I] - sus/aline;
    B[I][I]= B[I][I] + sus/aline + sus*(1/(aline*aline) - 1/aline);
    B[J][J]= B[J][J] + sus/aline + sus*(1 - 1/aline);
}
else
{
    G[I][J]= G[I][J] - cond;
    G[J][I]= G[J][I] - cond;
    G[I][I]= G[I][I] + cond;
    G[J][J]= G[J][J] + cond;
    B[I][J]= B[I][J] - sus;
    B[J][I]= B[J][I] - sus;
    B[I][I]= B[I][I] + sus + hych;
    B[J][J]= B[J][J] + sus + hych;
}
}

/* prints Y_BUS Matrix */

printf("\n Y_bus Matrix :\n");
printf("\n");
for(I=1; I<=bus; ++I)
{
    for(J=1; J<=bus; ++J)
        if (B[J][I] > 0)
            printf("%6.3f+j%5.3f ", G[I][J], fabs(B[I][J]));
    else
        printf("%6.3f-j%5.3f ", G[I][J], fabs(B[I][J]));
    printf("\n");
}
}

```

```
/* GENERATION OF THE  $\Delta P$  &  $\Delta Q$  */
```

```

/*****
* First part of this procedure calculates  $P_2, P_3,$ 
*  $P_4, P_5, P_6$  and  $Q_3, Q_4, Q_5, Q_6$ 
* from the equations (3.11) and (3.12) and stores them in the array
* temp[i] : where i = 1 .....9.
* Last part of the procedure subtracts calculated values of P's and Q's
* from the specified values of P's and Q's to get  $\Delta P_2$  to  $\Delta P_6$ 
* and  $\Delta Q_3$  to  $\Delta Q_6$ .
* The  $\Delta P$  and  $\Delta Q$  values are then compared with EPS
* (error check).
*****/

```

```
BDELTPQ()
```

```

{
  double temp[unknown], delta_P_max, delta_Q_max;
  int i, k, j;

  k = unknown - bus;
  for ( i = 1; i <= (bus - 1); ++i )
  {
    temp[i] = 0;
    for ( j = 1; j <= bus; ++j )
    {
      temp[i] += V[j]*(G[i+1][j]*cos(theta[i+1] - theta[j])
      + B[i+1][j]*sin(theta[i+1] - theta[j]));
    }
    temp[i] *= V[i+1];
  }
  for ( i = bus; i <= unknown; ++i )
  {
    temp[i] = 0;
    for ( j = 1; j <= bus; ++j )
    {
      temp[i] += V[j]*(G[i-k][j]*sin(theta[i-k] - theta[j])
      - B[i-k][j]*cos(theta[i-k] - theta[j]));
    }
    temp[i] *= V[i-k];
  }

  for ( i = 1; i <= unknown; ++i )
  {
    delta[i] = GPQ[i] - temp[i];
    if ( fabs(delta[i]) > EPS )
      check = 0;
  }
  delta_P_max = fabs(delta[1]);
  for ( i = 2; i <= (bus - 1); ++i )

```

```

{
    if ( delta_P_max < fabs(delta[i]))
        delta_P_max = fabs(delta[i]);
}

delta_Q_max = fabs(delta[bus]);
for ( i = (bus + 1); i <= unknown; ++i)
{
    if (delta_Q_max < fabs(delta[i]))
        delta_Q_max = fabs(delta[i]);
}

    /* CHECKING IF DELTA P AND DELTA Q < EPS */

    printf("\n\n=====");
    printf("\n\n ITERATION # %d" , num);
    printf("\n-----");
    printf("\n");
    printf("\n MAX_ERROR_OF P = %8.5f", delta_P_max);
    printf("\n MAX_ERROR_OF Q = %8.5f", delta_Q_max);
    printf("\n\n BUS #   ANGLE(rad)  VOLTAGE ");
    printf("\n");

if ((delta_P_max < EPS) && (delta_Q_max < EPS ))
    check = 1;

num +=1;
}

    /* GENERATE H,N,M & L PARTITIONS OF THE MATRIX */

/*****
* This procedure creates the H,N,M,L matrices by equations (3.15)
* which are partitions of the partial derivative matrices. The jacobian
* matrix is from the H,N,M,L matrices, with the rows and columns,
* & neglecting slack bus values. The procedure then does the forward Gauss
* elimination on the jacobian matrix for L_U decomposition.
*****/

JACOBIAN()
{
    int i,j,k;

    k = unknown - bus;
    for ( i = 1; i <= bus; ++i )
    {
        for ( j = 1; j <= bus; ++j )
        {
            if ( j == i )

```

```

    {
      H[i][j] = -Q[i] - B[i][j]*V[i]*V[i];
      N[i][j] = P[i] + G[i][j]*V[i]*V[i];
      M[i][j] = P[i] - G[i][j]*V[i]*V[i];
      L[i][j] = Q[i] - B[i][j]*V[i]*V[i];
    }
    else
    {
      H[i][j] = V[i]*V[j]*(G[i][j]*sin(theta[i]
        - theta[j]) - B[i][j]*cos(theta[i]
        - theta[j]));
      N[i][j] = V[i]*V[j]*(G[i][j]*cos(theta[i]
        - theta[j]) + B[i][j]*sin(theta[i]
        - theta[j]));
      M[i][j] = - N[i][j];
      L[i][j] = H[i][j];
    }
  }
}

/* GENERATES JACOBIAN MATRIX */

for ( i = 1; i <= (bus - 1); ++i )
{
  for ( j = 1; j <= (bus - 1); ++j )
    jacob[i][j] = H[i + 1][j + 1];
  for ( j = bus; j <= unknown; ++j )
    jacob[i][j] = N[i+1][j-k];
}
for ( i = bus; i <= unknown; ++i )
{
  for ( j = 1; j <= (bus - 1); ++j )
    jacob[i][j] = M[i-k][j+1];
  for ( j = bus; j <= unknown; ++j )
    jacob[i][j] = L[i-k][j-k];
}

/* L AND U OF THE JACOBIAN MATRIX */

for ( i = 2; i <= unknown; ++i )
{
  for ( j = i; j <= unknown; ++j )
  {
    jacob[j][i-1] /= jacob[i-1][i-1];
    for ( k = i; k <= unknown; ++k )
      jacob[j][k] -= jacob[i-1][k]*jacob[j][i-1];
  }
}
}

```

```
/* CALCULATE V,X,AND Y MATRICES */
```

```

/*****
* Calculates the Y matrices by back substitution using the
* lower triangular matrix of the modified jacobian matrix & the
*  $\Delta P$  &  $\Delta Q$  are generated in this procedure.The
* matrix is determine by back substitution using the
* triangular matrix of the modified jacobian matrix and the Y
* matrix so generated. The X matrix then corresponds to
*  $\Delta \theta^s$  and  $\Delta V^s$  which when added to the
*  $\theta^s$  and  $V^s$  to give the new set of values for the
* variables. VXY() prints out the values of  $\theta^s$  and
* the values of the  $V^s$  at the each iteration.
*****/

```

```
VXY()
```

```

{
    int i,j,k;

    /* CALCULATE Y MATRIX */

    Y[1] = delta[1];
    for (i = 2; i <= unknown; ++i)
    {
        Y[i] = delta[i];
        for (j = 1; j <= (i - 1); ++j)
            Y[i] -= jacob[i][j] * Y[j];
    }
    for (i = 1; i <= unknown; ++i)

        /* CALCULATE X MATRIX */

        X[unknown] = Y[unknown]/jacob[unknown][unknown];
        i = unknown - 1;
        while (i > 0.0)
        {
            X[i] = Y[i];
            j = unknown;
            while (j > i)
            {
                X[i] -= jacob[i][j] * X[j];
                j -= 1;
            }

            X[i] /= jacob[i][i];
            i -= 1;
        }
}

```

```

    /* CALCULATE VOLTAGE AND ANGLE */
    k = unknown - bus;
    for ( i = 2; i <= bus; ++i)
        theta[i] += X[i - 1] ;
    for ( i = 3; i <= bus; ++i )
        V[i] += X[i+k] * V[i] ;

        /* printf VOLTAGES AND ANGLES */

    for ( i = 1; i <= bus; ++i )
        printf("\n%4d%14.5f%14.5f", i, theta[i], V[i]);
}

    /* CALCULATE P AND Q OF THE SYSTEM */

/*****
* After final iteration i.e, when all the elements of the
*  $\Delta P$  and  $\Delta Q$  are found less than EPS values, this
* procedure calculates the final values of P and Q by equations (3.11) and (3.12).
*****/

PQ()
{
    int i,j;

    for ( i = 1; i <= bus; ++i )
    {
        P[i] = 0.0;
        Q[i] = 0.0;
        for ( j = 1; j <= bus; ++j )
        {
            P[i] += V[j]*(G[i][j]*cos(theta[i] - theta[j])
                + B[i][j]*sin(theta[i] - theta[j]));
            Q[i] += V[j]*(G[i][j]*sin(theta[i] - theta[j])
                - B[i][j]*cos(theta[i] - theta[j]));
        }
        P[i] *= V[i];
        Q[i] *= V[i];
    }

    for ( i = 1; i <= bus; ++i)
    {
        if (P[i] < 0.0)
        {
            P_of_Load[i] = fabs(P[i]);
            P_of_Gen[i] = 0.0;
        }
    }
}

```

```

else
    {
        P_of_Gen[i] = P[i];
        P_of_Load[i] = 0.0;
    }
    if (Q[i] < 0.0)
    {
        Q_of_Load[i] = fabs(Q[i]);
        Q_of_Gen[i] = 0.0;
    }
    else
    {
        Q_of_Gen[i] = Q[i];
        Q_of_Load[i] = 0.0;
    }
}
}

/* SOLUTION OF THE PROBLEM */

/*****
* This procedure converts the per_unit values of  $P_{gen}$ ,
*  $Q_{gen}$ ,  $P_{load}$ ,  $Q_{load}$  to their actual values by
* multiplying with the multiplier. It also converts the phase
* angle values from radian to degrees and prints the values
* of the final results.
*****/

final()
{
    int i;

    printf("\n\n\nSOLUTION TO THE PROBLEM : ");
    printf("\n\n=====");
    printf("\nBUS   VOLTS   ANGLE   GENERATION   LOAD");
    printf("\n #       (degr)  p(MW)  Q(MVAR)   p(MW)  Q(MVAR)");
    printf("\n===== \n");
    for (i = 1; i <= bus; ++i)
    {
        P_of_Gen[i] *= BASEV;
        Q_of_Gen[i] *= BASEV;
        P_of_Load[i] *= BASEV;
        Q_of_Load[i] *= BASEV;
        angle[i] = (theta[i] * 180.0)/PI;
        printf("\n %d%9.5f%11.5f%11.5f%11.5f%10.5f", i, V[i], angle[i],
            P_of_Gen[i], Q_of_Gen[i], P_of_Load[i], Q_of_Load[i]);
    }
    printf("\n_____ \n");
}

/**** END OF THE LOAD_FLOW PROGRAM. *****/

```

APPENDIX C

THE PROGRAM SOURCE CODE
FOR LINE FLOW CALCULATIONS


```

/*****
* Lineflow.c
* This program calculates the real and reactive power flowing through
* a transmission line in both directions. It reads the voltages and
* angles of two buses and the complex admittances of the line joining
* buses, and outputs the complex power flow in both directions.
* Input:
* V1 magnitude in volts, v1 angle in degrees,
* v2 magnitude in volts, v2 angle in degrees,
* Y real in ohms,    Y imaginary in ohms.
* Output:
* S12_real
* S12_reactive
* S21_real
* S21_reactive
*****/
#include <stdio.h>
#include <math.h>
#define PI 3.14159

struct element {
    double mag; /* magnitude */
    double ang; /* angle */
};
struct ecomplex {
    double re; /* real part */
    double im; /* imaginary part */
};

struct element v[3]; /* v1, v2 of buses 1, 2 respectively */
struct element vL[3], iL[3], yL[3]; /* ?L[1] :1->2, ?L[2] :2->1 */
struct ecomplex y, sC[3]; /* complex admittance, powers of line */

main ()
{ double temp1, temp2;
  int j;

  /* input magnitudes and angles of v1, v2 */
  printf("\nEnter magnitudes and angles(degrees) of:\n");
  for (j=1; j<3; j++)
  { printf(" v%1d ==>", j);
    scanf("%lf%lf", &temp1, &temp2);
    v[j].mag = temp1;
    v[j].ang = temp2 * PI/180; /* radians */
  }
  /*****
  printf("\n");
  for (j=1; j<3; j++)
    printf("v[%1d].elem: (%8.3lf,%8.3lf)\n"

```

```

        j, v[j].mag, v[j].ang * 180/PI);
****/
/* input real and imaginary parts of the complex admittance y */
printf("Enter real and imaginary parts of y ==>");
scanf("%lf%lf", &temp1, &temp2);
y.re = temp1; y.im = temp2;
/* Get the magnitudes and angles of y12=yL[1], y21=yL[2] */
GetMagni(y.re, y.im, &temp1);
yL[1].mag = yL[2].mag = temp1;
GetAngle(y.re, y.im, &temp2);
yL[1].ang = yL[2].ang = temp2; /* degrees */
****/
printf("\ny.comp:    (%8.3lf,%8.3lf)\n", y.re, y.im);
for (j=1; j<3; j++)
    printf("y121[%1d].elem: (%8.3lf,%8.3lf)\n"
           j, yL[j].mag, yL[j].ang);
****/
/* Get magnitudes and angles of v12=vL[1], v21=vL[2] */
GetvL();
****/
for (j=1; j<3; j++)
    printf("v121[%1d].elem: (%8.3lf,%8.3lf)\n",
           j, vL[j].mag, vL[j].ang);
****/
/* Get magnitudes and angles of i12=iL[1], i21=iL[2] */
iL[1].mag = iL[2].mag = vL[1].mag * yL[1].mag;
iL[1].ang = (vL[1].ang + yL[1].ang) * PI/180; /* radians */
iL[2].ang = (vL[2].ang + yL[2].ang) * PI/180;
****/
for (j=1; j<3; j++)
    printf("i121[%1d].elem: (%8.3lf,%8.3lf)\n",
           j, iL[j].mag, iL[j].ang * 180/PI);
****/
/* Get the complex powers s12=sC[1], s21=sC[2] */
GetsC();
/* Print the components of the complex powers */
printf("    real    reactive \n");
printf("s12:  %10.5lf %10.5lf\n", sC[1].re, sC[1].im);
printf("s21:  %10.5lf %10.5lf\n", sC[2].re, sC[2].im);
} /* end main */

/*+++++
*GetMagni() : returns the magnitude given the complex components/
*+++++*/
GetMagni (x,y,z)
double x, y, *z;
{
    *z = sqrt(x*x + y*y);
} /* end GetMagni */

```

```

/*+++++
 * GetAngle() : determines the angle and its sign according to its
 * quadrant, given the complex components. Returns the value of
 * the angle in degrees.
 *++++*/
GetAngle (x, y, z)
double x, y, *z;
{
    if (x==0) *z = 90;
    else
    { *z = atan(fabs(y) / fabs(x)) * 180/PI; /* angle in degrees */
      if ((x>0) && (y<0)) *z = -1 * *z;
      else if ((x<0) && (y>0)) *z = 180 - *z;
      else if ((x<0) && (y<0)) *z = *z - 180;
      /* else if ((x>0) && (y>0)) z = z */
    }
} /* end GetAngle */

/*+++++
 * GetvL() : determines the magnitudes,angles of v12,v21 given v1,v2
 *++++*/
GetvL()
{ struct ecomplex vC[3]; /* complex components of v1,v2,v12,v21 */
  double temp;
  int j;
  int l;

  /* Get the complex components of v1=vC[1], v2=vC[2] */
  for (l=1; l<3; l++)
      GetComplex (v[l].mag, v[l].ang, &vC[l]);
  /****
  for (j=1; j<3; j++)
      printf("v[%1d].comp: (%8.3lf,%8.3lf)\n",
             j,vC[j].re, vC[j].im);
  *****/
  /* use vC[1], vC[2] for the complex components of v12 and v21 */
  vC[1].re = vC[1].re - vC[2].re; /* v12re = v1re - v2re */
  vC[1].im = vC[1].im - vC[2].im; /* v12im = v1im - v2im*/
  vC[2].re = -1 * vC[1].re; /* v21re = -v12re */
  vC[2].im = -1 * vC[1].im; /* v21im = -v12im */
  /****
  for (j=1; j<3; j++)
      printf("v121[%1d].comp: (%8.3lf,%8.3lf)\n",
             j, vC[j].re, vC[j].im);
  *****/
  /* find magnitudes,angles of v12,v21 from complex components */
  GetMagni(vC[1].re, vC[1].im, &temp);
  vL[1].mag = vL[2].mag = temp;
  GetAngle(vC[1].re, vC[1].im, &vL[1].ang); /* degrees */

```

```

    GetAngle(vC[2].re, vC[2].im, &vL[2].ang);
} /* end GetvL */

/*+++++
* GetComplex() : determines the complex components z.re, z.im given
* the magnitude and angl(radians)
*++++*/
GetComplex(magni, angle, z)
double magni, angle;
struct ecomplex *z;
{
    z->re = magni * cos(angle);
    z->im = magni * sin(angle);
} /* end GetComplex */

/*+++++
* GetsL() : determines the complex components of the power that
* flows in the line in both directions
*++++*/
GetsC()
{ struct ecomplex iC; /* complex components of i12,i21,i12c,i21c*/
  struct element iCL, sL; /* mag, angles of i12C,i21C, s12,s21 */
  int j;

  for (j=1; j<3; j++)
  { GetComplex(iL[j].mag, iL[j].ang, &iC);
    /*****/
    printf("i121[%1d].comp: (%8.3lf,%8.3lf)\n", j, iC.re,iC.im);
    /*****/
    /* use iC to hold the complex components of i12c, i21c*/
    /* iC=i12c.re (j=1), iC=i21.re (j=2) */
    iC.im = -1 * iC.im; /* i12c.im = -i12.im, i21c.im=-i21.im */
    /*****/
    printf("i121c[%1d].comp:(%8.3lf,%8.3lf)\n", j, iC.re,iC.im);
    /*****/
    GetMagni(iC.re, iC.im, &iCL.mag);
    GetAngle(iC.re, iC.im, &iCL.ang); /* degrees */
    /*****/
    printf("i121c[%1d].elem:(%8.3lf,%8.3lf)\n",
           j, iCL.mag, iCL.ang);
    /*****/
    sL.mag = v[j].mag * iCL.mag;
    sL.ang = v[j].ang + (iCL.ang * PI/180); /* radians */
    /*****/
    printf("s121[%1d].elem: (%8.3lf,%8.3lf)\n",
           j, sL.mag, sL.ang *180/PI);
    /*****/
    /* get complex components of powers s12=sC[1], s21=sC[2] */
    GetComplex(sL.mag, sL.ang, &sC[j]);
  }
}

```

```
}
```

```
 } /* end GetsC */
```

```
 /***** end lineflow.c *****/
```

APPENDIX D

THE PROGRAM SOURCE CODE
FOR COST CALCULATION

```

/*****
* CostCalc.c
* This program calculates monthly energy bill for compensated
* reactive power and uncompensated reactive power in a plant.
* Input:
* days/month, shifts/day, hours/shift
* pf, rkva drawn/hr, kw drawn/hr
* output:
* -No_compensation power cost-
* pf penalty =
* energy/month, energy charge =
* demand, demand charge =
* pf penalty, penalty charge =
* total cost =
* -Compensation power cost-
* pf penalty =
* energy/month, energy charge =
* demand, demand charge =
* pf penalty, penalty charge =
* total cost =
* safely drawn rkva =
* monthly savings =
*****/
#include <stdio.h>
#include <math.h>
#define DCOST 4.14 /* unit cost for demand charges */
#define ECOST 0.02 /* unit cost for energy charges */

main()
{ double pf, avepf; /* power factor and average in a month */
  double hrkva, hkww; /* power drawn per hour */
  double days, shifts, hours; /* days/mo, shifts/day, hrs/shift */
  double mhrr, mrkva, mkkw, mkva; /* hrs,kw,rkva,kva. for a month */
  int pfpenalty; /* % penalty in terms of % of pf */
  double demandch; /* power subjected to demand charge */
  double bill; /* total power cost for no-compensation */
  double saferkva, comrkva; /* rkva with compensated power */
  double tempd; /* temporary variable for doubles */

  /* input data for power consumption determination */
  printf("\nenter days/mo, shifts/day, hours/shift ==> ");
  scanf("%lf%lf%lf", &days, &shifts, &hours);
  printf("\nenter pf, and rkva, kw drawn per hour ==>");
  scanf("%lf%lf%lf", &pf, &hrkva, &hkww);

  mhrr = days * shifts * hours; /* total hours in one month */
  /***/
  printf("\ndays/month = %5.2lf, ", days);
  printf("shifts/day = %3.2lf, ", shifts);

```

```

printf("hours/shift = %5.2lf\n", hours);
printf("total hours/month = %5.2lf\n", mhrs);
printf("\n pf = %4.2lf, rkva/hr = %10.5lf, kw/hr = %10.5lf\n",
      pf, hrkva, hkwh);
/****/
/* determine power drawn in one month */
mrkva = hrkva * mhrs;
mkwh = hkwh * mhrs;
mkva = sqrt(mkwh*mkwh + mrkva*mrkva);
/* determine average pf in a month */
avepf = mkwh/mkva * 100;
printf("\naverage plant power factor = %6.2lf\n", avepf);

/**** No-compensation power cost determination *****/
printf("\n****No-compensation power cost****\n");
/* determine %pf penalty */
tempd = (0.95*100 - avepf)*2;
if (tempd > (double)(int)tempd)
    pfpenalty = (int)tempd + 1;
else
    pfpenalty = (int)tempd;
printf("power factor penalty = %6.2lf\n", (double)pfpenalty);
/* power charges in kwhrs: energych=mkva, demandch, penaltych*/
demandch = sqrt(hkwh*hkwh + hrkva*hrkva);
TabulateCharges(mkva, demandch, demandch*pfpenalty/100, &bill);
/**** Compensated power cost determination *****/
printf("\n****Compensated power cost ****\n");
/* rkva that may be drawn safely from the utility */
tempd = mkwh/0.95;
saferkva = sqrt(tempd*tempd - mkwh*mkwh);
printf("rkva that may be drawn safely = %10.5lf\n", saferkva);
/* rkva to be compensated to avoid pf penalty in rkva/hr */
comrkva = (mrkva - saferkva) / mhrs;
/* kva drawn per month after compensation */
mkva = sqrt(mkwh*mkwh + saferkva*saferkva);
/* power charges in kwhrs: energych=mkva, demandch, penaltych=0*/
tempd = hrkva - comrkva;
demandch = sqrt(hkwh*hkwh + tempd*tempd);
TabulateCharges(mkva, demandch, 0.0, &tempd);
/* monthly savings with compensation */
printf("\nMonthly savings = %8.2lf\n", bill - tempd);
} /* end main */

/*****
* TabulateCharges() : tabulates the kwh charges incurred, the
* corresponding costs and the total power cost (bill)
*****/
TabulateCharges(energy, demand, penalty, totalcost)
double energy, demand, penalty, *totalcost;

```



```
{
  printf("\n          kw-hr      dollars\n");
  printf("energy charge : %13.5lf : %10.2lf\n",
        energy, energy*ECOST);
  printf("demand charge : %13.5lf : %10.2lf\n",
        demand, demand*DCOST);
  printf("penalty charge: %13.5lf : %10.2lf\n",
        penalty, penalty*DCOST);
  *totalcost = energy*ECOST + (demand + penalty)*DCOST;
  printf("TOTAL COST          : %10.2lf\n", *totalcost);
} /* end TabulateCharges */
/***** end CostCalc *****/
```