COMPUTER AIDED FAST DECOUPLED LOAD FLOW STUDY

BY
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CERTIFICATE

This is to certify that this work has been done by me and it has not been submitted elsewhere for the award of any degree or diploma or for publication.

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ALL PRAISES ARE FOR ALLAH, THE ALMIGHTY

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ABSTRACT

For a systematic solution of the problems of power systems, a necessary pre-requite would be a firm theoretical and conceptual basis for ideas in modern power system analysis. This work is an effort in this direction. In this context, Stott's fast decoupled load flow (FDLF) method which is distinctly superior to the existing traditional methods from the point of view of both speed and storage is presented. The solution is obtained in polar form through P - θ and Q-V decoupling and alternately iterating the active and reactive equations with simplified submatrices of the information matrix. An algorithm is developed for conducting the load flow study including all buses and lines of a power system network consisting of N-buses and corresponding interconnections. Provisions are kept for line charging, off-nominal turns ratio of transformers, fixed shunt capacitors and regulated voltage buses.

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LIST OF PRINCIPAL SYMBOLS

CHAPTER - II

N_1, N_2	= Turns Nos. of transformer.
N	= Turns ratio of transformer.
I_1, I_2	= Currents in the primary & secondary.
R_1, X_1	= Resistance and Inductance
Z, Z_1, Z_2, Z_3	= Impedances.
Z_{12}, Z_{23}, Z_{13}	= Leakage Impedances.
A	= Off-nominal turns ratio.
Y	= Admittance.
V	= Voltage.
I	= Current.
ψ	= Angular displacement.
Y_{pp}	= Self admittance of bus p.
Y_{pq}	= Mutual admittance bet^n bus p and q.
P	= Real power
Q	= Reactive power.
α	= Voltage angle
β	= Current angle.
θ	= $\alpha - \beta$ = phase angle bet^n voltage and current

CHAPTER - III

m	= No. of rows of a matrix
n	= No. of columns of a matrix.
i	= Name of a row (i_{th} row)
j	= Name of a column (j_{th} column)
a_{ij}	= Element of a matrix.
A	= Name of a matrix.
A^t	= Transpose of matrix A
A^*	= Conjugate of matrix A
A^+	= Adjoint of matrix A
A^{-1}	= Inverse of matrix A
U	= Unit matrix.
Y_{Bus}	= Bus admittance matrix.
Z_{Bus}	= Bus impedance matrix.
Y_{pp}	= Diagonal element for p bus.
Y_{pq}	= Off- diagonal element for p and q buses.

CHAPTER - IV

P_p & Q_p	= Real & Reactive power at the p_{th} bus.
$\|V_p\|$	= Voltage magnitude at the p_{th} bus.
θ_p	= Voltage angle of p_{th} bus.
S_p	= Total injected power at p_{th} bus.
I_p	= Current of p_{th} bus.
Y_{pp} & Y_{pq}	= Self and mutual admittances.
P_p^{sp}	= Specified real power at the p_{th} bus.
Q_p^{sp}	= Specified reactive power at the p_{th} bus.
ΔP	= Difference between specified and calculated real power.
ΔQ	= Difference between specified and calculated reactive power.
Y	= Per unit admittance.
G	= Per unit conductance.
B	= Per unit susceptance.
H,N,M,L	= Jacobians
B	= Name of a matrix.
B' & B''	= Submatrices of B matrix.
$Y'_{pq}/2$	= Half line charging admittance.

CHAPTER - V

N	=	No. of buses.
K	=	Iteration count.
P	=	Bus count.
K_q & K_v	=	Specified terminating set value .
$\Delta\theta$	=	Difference in angle
$\Delta\|V\|$	=	Difference in voltage magnitude.

ABBREVIATIONS

BPDB	=	Bangladesh Power Development Board.
FDLF	=	Fast Decoupled Load Flow.
G-S	=	Gauss- Seidal
IEEE	=	International Electrical & Electronic Engineering.
PAS	=	Power Apparatus and Systems.
N-R	=	Newton - Raphson.

CHAPTER - I

INTRODUCTION

1.1 GENERAL

Under normal conditions electrical power system operate in their steady-state mode and the basic calculation required to determine the characteristics of this state is termed load flow (or power flow). It is performed at the stage of planning, operation and control. For efficient management and control of power generation and distribution in a large power system, learning some parameters in advance such as the magnitude and phase angle of the voltage at each bus and the real and reactive power flowing in each line is of prime importance. This also helps the authority to plan, design and install facilities that must be provided to meet the growing needs of the consumers in future. Hence load flow study is a must in determining the best operation of existing systems as well as planning the future expansion of power systems.

With the advent of modern computers,power system engineers all over the world quickly took the advantage of computer solution of load flow problems and by today many methods of numerical solution have been proposed and practiced. Each method has its own merits and demerits. The fast decoupled load flow (FDLF) method recently developed by Stott[1] has been demonstrated to be computationally very efficient[2,3]. It is considered to be an attractive alternative to the classical Newton load flow method developed by Tinney and Hart[4].

We should however bear in mind that load flow studies are not only required in determining the static operating state of a system but also constitutes part of the programmes for studies such as system optimization and stability.

1.2 LITERATURE REVIEW

In the earliest days of electrical power system,they were operated as individual units and straight forward calculation was sufficient to predict the behaviour of the system under normal and abnormal conditions. With the continued growth of supply network and development of inter connections, this method became impractical. In the thirties network analyser had been developed to study system behavior, but the task of using network analyser was not only very difficult and tedious but also time consuming and called for a wastage of engineering tatents. The introduction of digital computer in the late forties opened a new horizon for faster and more efficient ways of analysis of power systems.

Numerous investigation and studies have been made and proposed in the field of load flow over the last two decades. Following are a few of the manyworks dealing with the development of Fast decoupled load flow (FDLF) method in power system analysis.

The founder of the modern FDLF method is Stott[1]. His idea originates from the paper by Tinney and Hart[4] published in 1967 which describes the solution of load flow problem by Newton's method. A book by stagg and others[5] published in 1968 on computer methods of power system analysis is a valuable addition in developing the computer aided load flow studies. As a review of Tinney's paper another paper by Stott[6] published in 1971 discusses the effective starting process of Newton's method and its merits and demerits. In a view to solve the P-θ and Q-V problems seperately in 1972 Stott[7] proposed a new load-flow method. With the further simplification, modification and assumptions of the Decoupled method Stott[1] in 1974 presents " Fast decoupled load flow" method. In the same year in a paper Stott[8] compares his proposed method with the other traditional methods.

Another two papers by Sasson[2] and Masiello[3] published in 1975 make some comments on Stott's review study. The paper by Horisberger and others[9] published in 1976 presents the static state-estimation procedure of the fast decoupled method. A paper by Felix[10] published in 1977 discusses the convergence criteria of the proposed method. The book by PAI[11] published in 1979 presents FDLF method with the others for academic study purposes. A paper by Rao and others[12] published in 1982 describes the method in another form. The same authors[13] discussed the empirical criteria for the convergence of the method in 1984. The suitability of the FDLF method for control purposes is described in a paper by Mescua[14] published in 1985.

1.3 SCOPE OF THE PRESENT WORK

The scope of this project work includes the theory and practical applications of the latest developed Fast decoupled method in load flow study using the high speed digital computer available in BUET computer center. Incidentally, so far we know, No such attempt has yet been made in Bangladesh for complete load flow studies with this method utilizing the locally available personnel and facilities. Fast decoupled method is, therefore, chosen as the basis of the investigations reported here. One must bear in mind while one intends to evaluate this work that this is not a professional job and instead of attacking industrial grade problems, it is aimed at to strengthen our commands over the different traditional methods of computer aided load flow study. However, it is expected that the results of this study will substantially contribute in the efforts of load flow study of BPDB and others. The generalized program is developed with the overall objective to take the advantage of computer use in the development of Bangladesh.

The following facilities are available in the generalized computer program developed for the proposed work:

(i) It is able to handle a set of non-linear algebric equations.

(ii) It is able to handle system having hundreds of buses, transformers, lines etc.

(iii) It is sufficiently accurate, speedy and not too time consuming.

(iv) It can form bus admittance matrix encountering all the effects of interconnections.

(v) Determination of Bus voltage magnitudes and angles.

(vi) Computation of MW and MVAR flow in the network.

(vii) Effect of rearranging circuits and effect of new circuits on loading.

(viii) Optimum system running conditions and load distribution.

(ix) Effect of termporary loss of generation and transmission on system loading.

(x) Optimum rating and tap range of transformers.

(xi) Improvement from change of conductor size and system voltage.

(xii) Line losses and power mismatches.

1.4 SUMMARY

Chapter - 1 presents general approach for load flow study, literature review and scope of the present work.

Chapter - 2 In this chapter there is a brief representation of power system pertinent to the present study.

Chapter - 3 This chapter is about matrices. Types of matrices and matrix operations required for load flow study are briefly described here.

Chapter - 4 Discusses the basic mathematical principles for the solution of load flow problems in Fast Decoupled Method, staring from the traditional methods.

Chapter- 5 Covers the development of an efficient computer program for the present study and the results of application of the developed program to a sample system.

Conclusions of the study are presented in chapter-6 which also includes a few suggestions for possible future extension of the work.

CHAPTER - II
POWER SYSTEM REPRESENTATION

2.1 INTRODUCTION

In this chapter the essential characteristics of some of the components of a power system related to the objective study is discussed in brief. What is meant by a single-line diagram and how it describes a system is the first attempt.

Importance is given towards the introduction of per-unit quantities, which are used in many calculations instead of actual units. Although the per-unit concept is quite simple, its application to three-phase circuits requires clarifications.

The main component for the transfer of power between different voltage levels is the transformer. The varities of transformer for various purposes is described.

Loads are considered as components of power system even though their exact composition and characteristics are not known with complete certainty. For the load flow study, the prediction of the loads to be expected is required.

2.2 SINGLE-LINE DIAGRAM

In dealing with power system of any complexity, one of the first essentials is a single line diagram, in which each polyphase circuit is represented by a single-line. Stripped of the complexity of several phase wires, the main power channels then stand out clearly, and the general plan of the system is evident.[19]

This diagram is a short- hand or symbolic representations of the principal connections,showing the equipment in its correct electrical relationship and usually having indicated on it, data essential for the determination of impedance diagram. With the recommended symbols for apparatus the single-line diagram of a very simple power system is shown in the following figure:

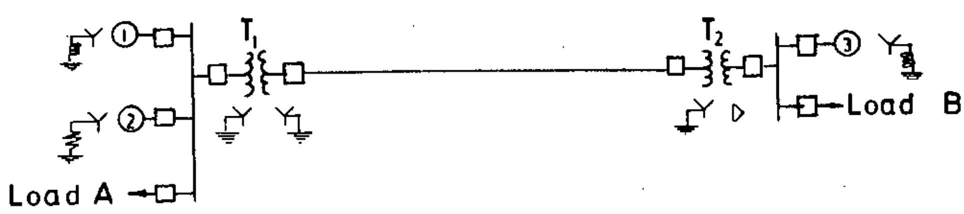


Fig. 2.1 One-line diagram of an electric system.

The purpose of the single-line diagram is to supply in concise form the significant information about the system. The importance of different features of a system varies with the problem under consideration and the amount of information included on the diagram depends on the purpose for which the diagram is intended. For instance, the location of circuit breakers and relays is unimportant in making a load-flow study. On the other hand, for the determination of the stability of a system under transient conditions resulting from a fault, the information about the location of circuit breakers and relays may be of extreme importance. Thus the information found on a single-line diagram must be expected to vary according to the problem at hand and according to the practice of the particular company preparing the diagram.

The impedance diagram is also a single-line diagram, on which are indicated on a common basis,the impedances of all lines and pieces of equipment related to the problem. The single- line impedance or reactance diagram drawn from Fig. 2.1 with proper reactance values on a system base voltage and base MVA is shown in Fig. 2.2.

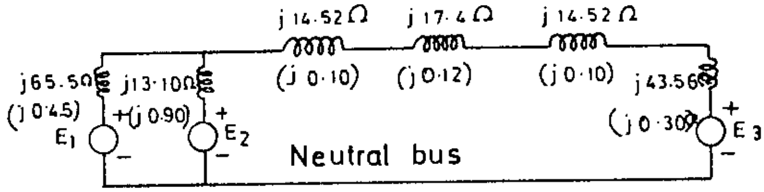


Fig. 2.2 Impedance or reactance diagram of Fig. 2.1

Because of the symmetry of phases it is usually sufficient to represent only one phase called the reference phase, or a phase. Under balanced condition of operation, the currents and voltages in other two phases are exactly equal to those in a phase and merely lag behind the a phase quantities by 120 and 240 electrical degrees. Hence, when the a phase quantities have been determined, the others follow directly.

2.3 THE PER UNIT SYSTEM

In the analysis of power system networks instead of using actual values of quantities it is preferable to express them as fractions of reference quantities, such as rated or full-load values. These fractions are called per unit (denoted by p.u.) and the p.u. value of any quantity is defined as:

$$\frac{\text{the actual value (in any unit)}}{\text{the base or reference value in the same unit}}$$

Some authorities express the p.u. value as a percentage. Although the use of p.u. values may at first sight seem a rather indirect method of expression there are in fact great advantages; they are as follows.

a) The apparatus considered may very widely in size; losses and voltage drops will also vary considerably. For apparatus of the same general type the p.u. voltage drops and losses are in the same order regardless of size.

b) It is seen that the use of $\sqrt{3}$'s with the use of p.u. quantities in three phase calculations is reduced.

c) By the choice of appropriate voltage bases the solution of networks containing several transformers is facilitated. The p.u. impedance of a transformer is independent of the winding considered.

d) p.u. values lend themselves more readily to automatic computation.

2.3.1 Base selection

For use in a power system study, all impedances and other quantities must be expressed on a common system base. The base is chosen depending on the size of the power system. The base voltage for each portion of the network is usually the nominal voltage of that portion and, if not stated, is thus understood. For portions of the network connected through transformers, however, the ratio of base voltage should equal the turns ratio of the transformer for the particular tap used, even if the turns ratio differs from the ratio of nominal voltages.

2.4 TRANSFORMERS

A transformer is a static piece of apparatus that-

i) Transfers electric power from one ckt. to another.

ii) It does so without a change of frequency.

iii) It accomplishes this by electro-magnetic induction.

iv) The working condition is that the two electric circuits must be in mutual inductive influence of each other.

According to construction and working purposes there may be different types of transformers.

2.4.1 Two-Winding Transformer:

The equivalent circuit of a two- winding transformer is shown in Fig. (2.3). Where all the quantities are refered to the side 1. In the T circuit the series arms represent the leakage impedances, and the shunt arm, the exciting impedance. In power transformers, the shunt branch current is negligible as compared to the load current and hence can be omitted from the

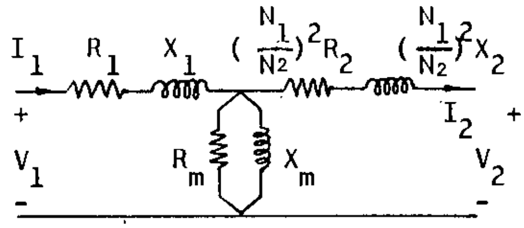


Fig. 2.3 Equivalent circuit of a transformer.

equivalent circuit. Under these circumstances the equivalent circuit reduces to a simple circuit as show in Fig. 2.4

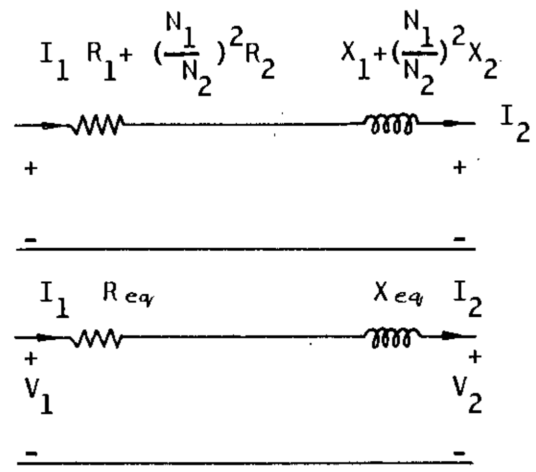


Fig. 2.4 Simplified equivalent circuit of a transformer.

2.4.2 Three-Winding Transformers

Three-winding transformers are represented, by Y circuits (Fig. 2.5) such that the impedance of each branch is the impedance of corresponding winding and the sum of the impedances of each pair of branches equals the short circuit impedance between the corresponding pair of windings with the remaining windings open. Magnetizing current is neglected.

The following relations are in use[21,22].

$$Z_1 = \tfrac{1}{2} (z_{12} + z_{13} - z_{23})$$

$$Z_2 = \tfrac{1}{2} (z_{12} + z_{23} - z_{13})$$

$$Z_3 = \tfrac{1}{2} (z_{13} + z_{23} - z_{12})$$

where,

$$Z = R + jx$$

Z_{12} = Leakage impedance of primary with secondary short circuited and tertiary open.

Z_{23} = Leakage impedance of secondary with tertiary short circuted and primary open.

Z_{13} = Leakage impedance of primary with tertiary short circuited and secondary open.

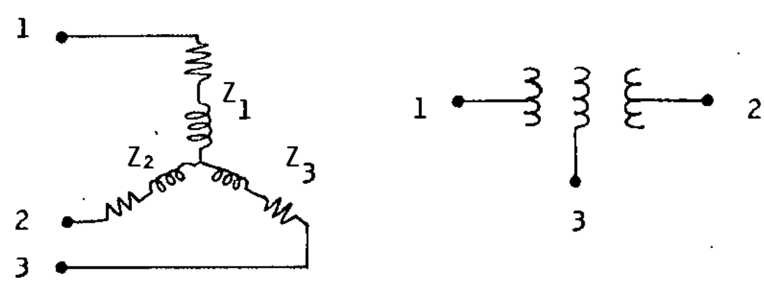


Fig. 2.5 (a) The equivalent circuit of a three-winding transformer. (b) Symbol for one-line diagram.

2.4.3 Autotransformers

An autotransformer consists of a common windings of turns N_1 and a series winding having N_2 turns. In Fig. 2.6 is shown a three-phase autotransformer. The per phase equivalent is shown in Fig. 2.7. Terminals a-n represent the low

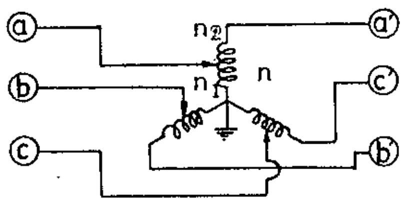


Fig. 2.6 Three winding autotransformer

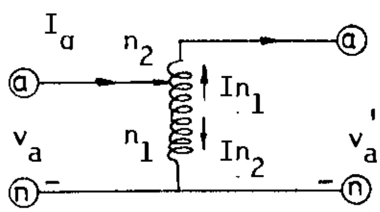


Fig. 2.7 Single-phase autotransformer.

voltage and terminals a'-n represent the high voltage side. The overall turns ratio is given by

$$\frac{V_a'}{V_a} = 1 + \frac{N_2}{N_1} = 1 + a = N$$

Autotransformers have the following disadvantages:
(1) the two sides are not electrically seperated, and
(2) the series impedance is lower than in two-winding transformers and may result in excessive short circuit current. On the other hand, its advantage is that for the same amount of copper and iron, we can get an auto-

transformer of a higher MVA rating than a two-winding transformer. This gain is much higher if the turns ratio is closer to unity. Thus, when the voltage levels are of the order of 2:1 or lower but high MVA is involved the autotransformer offers a distinct advantage.

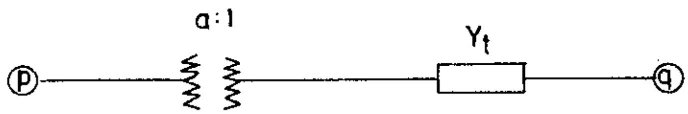
2.4.4 Representation of Transformers Having off- Nominal Turns Ratio (ONTR)

A transformer with off-nominal turns ratio can be represented by its impedance, or admittance, connected in series with an ideal autotransformer as shown in Fig.2.8. An equivalent π circuit can be obtained from this representation to be used in load flow studies. The elements of the equivalent π circuit, then, can be treated in the same manner as line elements.

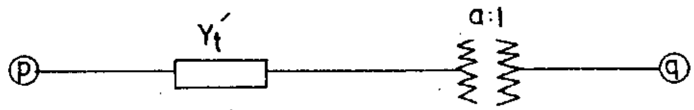
Two considerations arise when we consider the case that the off-nominal turns ratio is real.

(i) The P.u. value of series impedance of the transformer is put in series with an ideal transformer to allow for the difference in voltage. The off-nominal ratio represented by the symbol 'a' would assume a value around unity.

(ii) It is assumed that the series impedance of the transformer is unchanged when the tap position is varied.



(a)



(b)

Fig. 2.8 Two ways of representing off- nominal transformers.

There are two ways in which an off-nominal transformer can be represented as shown in the above figure. The series admittance in the two representations are related by

$$Y_t' = Y_t/a^2$$

With the ransformer ratio being normalized as a:1 the non-unity side is called the tap side. Thus in the first instance the series admittance of the transformer is connected to the unity side and in the second case it is connected to the tap side. The equivalent circuit is now derived from elementary considerations.

Let us consider Fig. 2.9 where the series impedance is connected to the unity side of the tap changer. To derive the equivalent

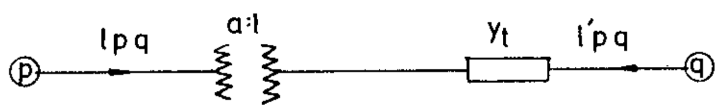


Fig. 2.9 Off-nominal transformer representation.

Circuit in terms of the two terminal elements the following procedure is followed. At node P

$$I_{pq} = (V_p - aV_q)\ \frac{Y_t}{a^2}$$

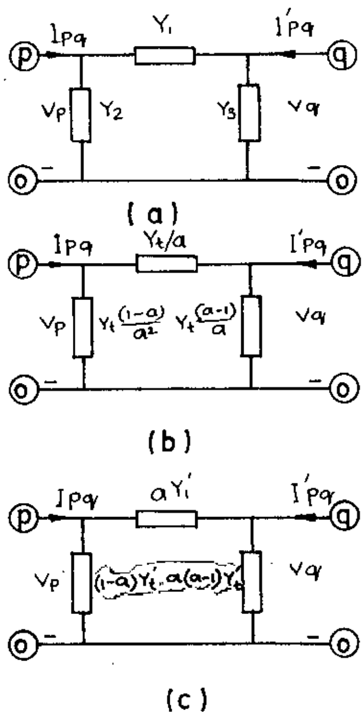
$$= \frac{V_p Y_t}{a^2} - \frac{V_q Y_t}{a} \qquad \ldots \qquad (2.1)$$

Similarly at node q

$$I'_{pq} = \left(V_q - \frac{V_p}{a} \right) Y_t$$

$$= V_q Y_t - \frac{V_p Y_t}{a} \qquad \ldots \qquad (2.2)$$

The above equations can be represented by means of an equivalent circuit as shown in Fig. 2.10 (a)



Writting node equations in Fig. 2.10(a) we get

$$I_{pq} = V_p Y_2 + (V_p - V_q) Y_1 \quad \ldots \qquad (2.3)$$

$$I'_{pq} = V_q Y_3 + (V_q - V_p) Y_1 \quad \ldots \qquad (2.4)$$

Comparing equations (2.3) and (2.4) with equations (2.1) and (2.2) we get

$$Y_1 + Y_2 = \frac{Y_t}{a^2}$$

$$Y_1 = \frac{Y_t}{a}, \text{ and } Y_1 + Y_3 = Y_t$$

Fig. 2.10 Equivalent circuits of off-nominal transformers.

Hence

$$Y_2 = \frac{Y_t}{a^2} - \frac{Y_t}{a}\ , \text{ and } Y_3 = Y_t - \frac{Y_t}{a}$$

The equivalent circuit is shown in Fig. 2.10(b). It is to be noted that all the admittances in the equivalent circuit are functions of the turn ratio a. Furthermore, the signs associated with Y_2 and Y_3 are always opposite. For example, if Y_1 represents an inductance, then for $a > 1$, Y_2 is an inductance and Y_3 is a capacitance. For $a < 1$, Y_2 is a capacitance and Y_3 is an inductance. The equivalent circuit in terms of Y_t' is shown in Fig. 2.10(c). As a approaches unity, the shunt branches in the π - equivalent both become infinite impedances and the series admittance approaches the value Y_t.

2.4.5 Phase shifting Transformers

A phase shifting transformer can be represented in load flow studies by its impedance, or admittance, connected in series with an ideal auto-transformer having a complex turns ratio, as shown in Fig. 2.12. Then the terminal voltages V_p and V_s are related by

$$\frac{V_p}{V_s} = a_s + jb_s = a(\cos\Psi + j\sin\Psi) \quad \ldots \quad (2.5)$$

where, a = Turns ratio

Ψ = Specified angular displacement

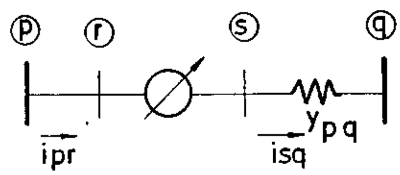


Fig. 2.12 Phase shifting transformer representation.

When a phase shifting transformer is connected between buses P and q, as shown above the self-admittance at bus P is:

$$Y_{pp} = y_{p1} + y_{p2} \quad \ldots \quad + \frac{y_{p2}}{a_s^2 + b_s^2} \quad \ldots + y_{pn} \quad ..(2.6)$$

The mutual admittance is

$$Y_{qp} = - \frac{y_{pq}}{a_s + jb_s} \quad \ldots \quad (2.7)$$

Similarly, self and mutual admittances at bus q are

$$Y_{qq} = y_{q1} + y_{q2} \quad \cdots \quad + y_{qp} \quad \cdots \quad + y_{qn} \quad \cdots (2.8)$$

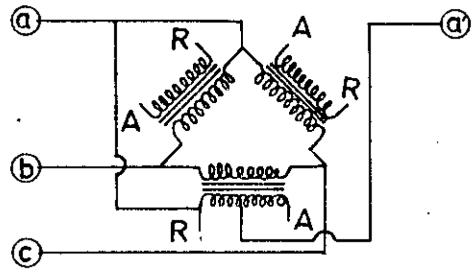
and

$$Y_{pq} = - \frac{y_{pq}}{a_s - jb_s} \quad \cdots \qquad (2.9)$$

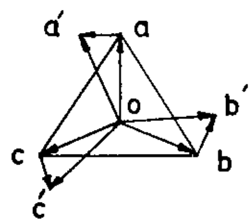
If the phase shift from bus p to bus s is positive, that is, if the sign of Ψ is plus, then the voltage at bus p leads the voltage at bus s.

A phase shifter regulates the flow of active power[24] by varying its phase angle Ψ.

In a phase shifting auto-transformer, the primary and secondary windings belong to different phases, thus resulting in both a change in tap ratio and a phase difference. This is illustrated in Fig. 2.13(a) which shows a simplified diagram for one phase of a 3-ϕ phase shifting transformer. In the figure it is seen that phase a secondary winding is excited by a voltage which is 90^o out of phase with phase a to neutral voltage. Fig. 2.13 (b) shows that, as the tap is varied



(a)



(b)

Fig. 2.13 Three-phase-shifting transformer

from R to A, the voltage across this winding changes from zero to aa'. Consequently, the secondary line to neutral voltage veries from oa to oa'. Thus, there is a phase shift as well as change in voltage ratio. Similarly, the phase b to neutral and phase c to neutral voltage on the secondary side will vary from ob to ob' and oc to oc' respectively.

As can be seen from the vector diagram the voltages in the series windings are advanced, a condition tending to cause more power to flow in the line in which the phase-shifting transformer is installed. By reversing the polarities in the series windings the voltage can be made to lag, with the result that the line would carry a reduced load.

2.5 TRANSMISSION LINES AND CABLES[22]

In power system analysis a section of a transmission line is often represented by a π network. The series arm of this circuit represents the normalized resistance and inductive reactance of the transmission line while each of the shunt arms represents the half of its total shunt capacitive susceptances. The circuit is shown in the following figure:

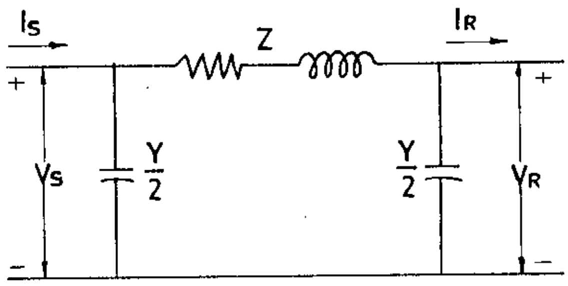


Fig. 2.14 Nominal-π circuit of a section of a transmission line.

2.6 MISCELLANEOUS EQUIPMENT

In the load flow analysis of a power system, equipment like[23] buses, current transformers, switches, circuit-breakers etc. are considered as having negligible impedance and shunt elements like potential transformers, lightning arresters and coupling capacitors are considered open-circuited.

2.7 LOADS

Generally, the term load refers to a device or a combination of devices that tap energy from the network. The magnitude of the load varies from a few-watt night lamp to a multimegawatt induction motor. The load varies second by second and with millions of consumers each using energy individually.[25] However loads are assumed to be lumped on the buses of major stations and substations. They should be expressed as vector power P + jQ, where P is the active power, and Q the reactive power.

2.7.1 Load Representation

In the representation of loads for load flow studies, it is important to know the variation of real and reactive power with variation of voltage. At a typical bus load may consist of

1. Induction motors 50 - 70%
2. Heating and lighting 20-30%
3. Synchronous motors 5-10%

For analytic purposes there are mainly three[11] ways of representing the load:

(i) CONSTANT POWER REPRESENTATION: Here both the specified MW and MVAR are assumed constant. This is the representation used in load flow studies.

(ii) CONSTANT CURRENT REPRESENTATION: In this scheme the load current I is computed as

$$I = \frac{P - jQ}{V^*} = |I| \angle (\theta - \phi)$$

Where $V = |V| < \theta$ and $\phi = \tan^{-1} \frac{Q}{P}$ is the

power factor angle.

The magnitude of I is held constant.

(iii) CONSTANT IMPEDANCE REPRESENTATION: This is the most frequently used representation of loads in stability studies. If the load MW and MVAR are assumed known and to remain constant the impedance is computed as

$$Z = \frac{V}{I} = \frac{|V|^2}{P-jQ}$$

or, the admittance is given as

$$Y = \frac{I}{V} = \frac{P-jQ}{|V|^2}$$

2.7.2 Concept of Complex Power[21]

If the phasor expressions for foltage and current are known, the calculation of real and reactive power is accomplished conveniently is complex form. If the voltage across and current into the certain load or part of a circuit are expressed by $V = |V| < \alpha$ and $I = |I| < \beta$, the product of voltage times the conjugate of the current is

$$VI^{*} = V\angle\alpha \times I\angle -\beta = |V|\ |I|\ \angle\alpha-\beta \qquad ...(2.10)$$

This quantity, called the complex power, is usually designated by S, In reactangular form

$$S = |V|\cdot|I|\ \text{Cos}\ (\alpha - \beta) + j|V|\ |I|\ \text{Sin}\ (\alpha - \beta)\ (2.11)$$

where $\alpha - \beta = \theta$ = The phase angle between voltage and circuit.

2.7.3 Sign Considerations

The complex power can be written as

$$S = P + jQ \qquad ... \qquad (2.12)$$

Reactive power Q will be positive when the phase angle $(\alpha - \beta)$ between voltage and current is positive that is, when $\alpha>\beta$, which means that current is lagging the voltage. Conversely Q will be negative for $\beta>\alpha$, which indicates current leading the voltage. This agrees with the selection of a positive sign for the reactive power of an inductive circuit and a negative sign for the reactive power of a capacitive circuit. To obtain the proper sign for Q, it is necessary to calculate S as VI^{*},rather than $V^{*}I$, which would reverse the sign for Q.

CHAPTER - III

MATRICES FOR LOAD FLOW STUDIES

3.1 INTRODUCTION

In recent years, the use of matrix algebra for the formulation and solution of complex engineering problems like load flow studies has become increasingly important with the advent of digital computers to perform the required calculations. The application of matrix notation provides a concise and simplified means of expressing complex networks. The use of matrix operations presents a logical and ordered process which is readily adaptable for a computer solution of a large system of simultaneous equations.

3.2 MATRIX AND TYPES OF MATRICES

A matrix is defined as a rectangular array of numbers, called elements, arranged in a systematic manner with m rows and n columns. These elements can be real or complex numbers. A double- subscript notation a_{ij} is used to designate a matrix element. The first subscript i designates the row in which the element lies, and the second subscript j designates the column. Some matrices with special characteristics are significant in matrix operations.

3.2.1 Square Matrix

When the number of rows equals the number of columns, that is, $m = n$, the matrix is called a square matrix and its order is equal to the number of rows (or columns). The elements in a square matrix a_{ij} for which $i=j$ are called diagonal elements. Those for which $i \neq j$ are called off-diagonal elements.

3.2.2 Sub- matrix

The matrix formed from a main-matrix with the rejection of some of its columns or rows is called a sub-matrix of the main. The order of the sub-matrix is always less than the main-matrix.

3.2.3 Column matrix

Matrices may have any number of rows and columns. A matrix of m rows and 1 column is called a column matrix and is designated as m x 1 matrix.

3.2.4 Transpose of a matrix ✓

If the rows and columns of an mxn matrix are interchanged, the result nxm matrix is the transpose and is designated by A^t if the original is A.

3.2.5 Conjugate of a matrix

If the elements of a matrix A are replaced by their complex conjugates (i.e. replacing an element a+jb by a-jb), then the resultant matrix is the conjugate of A and is denoted by A^*.

3.2.6 Adjoint

If each element of a square matrix A is replaced by its co-factor and then the matrix is transposed, the resulting matrix is an adjoint which is designated by A^+.

3.3 MATRIX OPERATIONS

Manipulation of matrices is governed by operations known as the rules of matrix algebra. These rules provide for an orderly method of solving equations. The definite rules and orderliness of matrix algebra are especially desirable in programming digital computers. The great importance of digital computers in power-system analysis makes an understanding of the basic matrix operations essential to power-system engineers, and matrix algebra is frequently the basis of load flow study.

3.3.1 Multiplication of matrices

The multiplication of two matrices indicated by C=AB is defined if and only if the number of columns of the first matrix A equals the number of rows of B. Thus if A is an mxq matrix and B is of dimension qxn, then the resulting matrix C is of dimension mxn. Any element C_{ij} of C is the sum of the products of the corresponding elements of the ith row of A and the jth column of B, that is,

$$c_{ij} = a_{i1} b_{1j} + a_{i2} b_{2j} + \dots + a_{iq} b_{qj}$$

$$c_{ij} = \sum_{k=1}^{q} a_{ik}\, b_{kj} \qquad i = 1,2, \ldots,m; j=1,2,\ldots ,n$$

The commutative law does not hold for matrix multiplication, i.e. $AB \neq BA$.

However, the following is true:

$$A\,(B+C) = AB + AC \qquad \text{(Distributive law)}$$

$$A\,(BC) = (AB)\,C = ABC \qquad \text{(Associative law)}$$

3.3.2 Inverse of a matrix

Division does not exist in matrix algebra except in the case of the division of a matrix by a scalar. But the objective of division in solving equations is accomplished by obtaining and manipulating the inverse matrix we must first define the unit matrix.

A unit matrix U is a square matrix all of whose elements on the principal diagonal are 1 and all of whose off-diagonal elements are o

Let us consider the set of equations:

$$\begin{array}{llll}
a_{11}x_1 + a_{12}x_2 + & \ldots & a_{1n}x_n = y_1 \\
a_{21}x_1 + a_{22}x_2 + & \ldots & a_{2n}x_n = y_2 \\
\ldots \quad \ldots & \ldots & \ldots \\
a_{n1}x_1 + a_{n2}x_2 + & \ldots & a_{nn}x_n = y_n
\end{array}$$

Which can be written in matrix form as

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & & \cdots & \\ a_{n1} & a_{n2} & & a_{nn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \cdots \\ x_n \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ \\ y_n \end{bmatrix}$$

AX=Y where A is now a nxn matrix, X is a nxl, and Y is a nxl matrix.

We define the inverse of a matrix A as that matrix which when post multiplied by A results in the unit matrix. The inverse of A is denoted by A^{-1}.

Thus

$$A^{-1} A = U$$

We make use of this fact in the matrix equation

$$AX = Y$$

We pre-multiply both sides by A^{-1}

$$A^{-1} AX = A^{-1}Y$$

$$UX = A^{-1}Y$$

But, $$UX = X$$

Hence, $$X = A^{-1}Y$$

Thus the concept of the inverse of a matrix is useful in the solution of matrix equations.

It may be shown that the inverse A^{-1} of A is obtained by applying the following rules:

1. Evaluate A the determinant of the matrix A
2. Replace each element of A by its respective co-factors, i.e. replace a_{ij} by $A_{ij} = (-1)^{i+j}$(minor of a_{ij})
3. Transpose the matrix of the co-factors, thus obtaining the adjoint A^{+} of A.
4. Divide each element of the adjoint matrix A^{+} by the determinant A . The resulting matrix is the inverse of A. Thus $A^{-1} = \frac{A^{+}}{A}$.

3.3.3 Singular and Nonsingular matrix

If the determinant of a matrix is zero then the inverse is not defined. Such a matrix is called a singular matrix. If the determinant is non-zero then it is called a non-singular matrix and a unique inverse exists.

3.4 BUS ADMITTANCE MATRIX

The network matrix obtained by the positive sequence admittances between the buses of a power system is called a bus admittance matrix[20]. The bus admittance matrix gives the mathematical representation of the layout of a power system. The bus admittance matrix is a two dimensional array of the self and mutual admittances of the buses. The number of rows and columns of this matrix is equal to the number of the buses in the system. All the diagonal elements of this system-matrix are the self-admittances of the buses and off-diagonal elements of this matrix are the mutual admittances. Depending on the system study the admittances of generators, transformers and loads very sometimes be omitted from the bus admittance matrix. However, for study of the overall system, these quantities will be considered along with other admittances in forming the total admittance matrix. The elements of the bus admittance matrix are often complex.

Let I_1, I_2, I_3, ... I_n be the currents supplied by the buses of an n bus system, their voltages being v_1, v_2, v_3 ... v_n. If the admittance between a pair of buses say 1-2, 2-3, etc. is y_{12},

y_{23}, etc.,

then

$$I_1 = y_{12}(v_1 - v_2) + y_{13}(v_1 - v_3) + \cdots + y_{1n}(v_1 - v_n)$$

$$= (y_{12} + y_{13} + \cdots + y_{1n})\, v_1 - y_{12}v_2 \cdots y_{1n}v_n$$

$$\pm Y_{21}v_1 + Y_{22}v_2 + \cdots + Y_{2n}v_n$$

$$\cdots \qquad \cdots \qquad \cdots$$

$$I_n = y_{n1}(v_n - v_1) + y_{n2}(v_n - v_2) + \cdots + y_{n,n-1}(v_n - v_{n-1})$$

$$= Y_{n1}v_1 + Y_{n2}v_2 + \cdots + Y_{nn}v_n$$

These equations can be written as a matrix equation in the form:

$$\begin{bmatrix} I_1 \\ I_2 \\ \cdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & & Y_{1n} \\ Y_{21} & Y_{22} & & Y_{2n} \\ & \cdots & & \\ Y_{n1} & Y_{n2} & & Y_{nn} \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ v_2 \\ \\ v_n \end{bmatrix}$$

or $I = YV$

The matrix Y is termed the "Bus admittance matrix". The diagonal elements of Y are termed the self admittances and the off-diogonal ones are the mutual admittances.

or, self admittances can be written as

$$Y_{11} = y_{12} + y_{13} + \quad \cdots \quad + y_{1n}$$

$$Y_{22} = y_{21} + y_{23} + \quad \cdots \quad + y_{2n}$$

$$\cdots \qquad \cdots \qquad \cdots$$

$$Y_{nn} = y_{n1} + y_{n2} + \quad \cdots \quad + y_{n,n-1}$$

and the mutual admittances

$$Y_{12} = -y_{12}$$

$$Y_{23} = -y_{23} \qquad \text{etc.}$$

3.5 FORMATION OF BUS ADMITTANCE MATRIX

To determine the elements of the bus admittance matrix Y_{BUS} from the transmission line and line charging admittances with ground as reference, the transmission line admittances are obtained by taking the reciprocal of the line impedances along with the total line charging admittance to ground at each bus[27].

Y_{BUS} matrix consists of diagonal Y_{pp} composed of sum of all admittances incident to node P and off-diagonal elements Y_{pq} equal to Y_{qp} which is composed of negative of admittance conneted between node P and q.

The admittance matrix for shunt elements is usually diagonal as there is normally no coupling between the components of each phase. This matrix is incorporated directly into the system admittance matrix, contributing only to the self-admittance of particular bus.

Let us consider the following sample system to illustrate the method of formation of the bus admittance matrix.

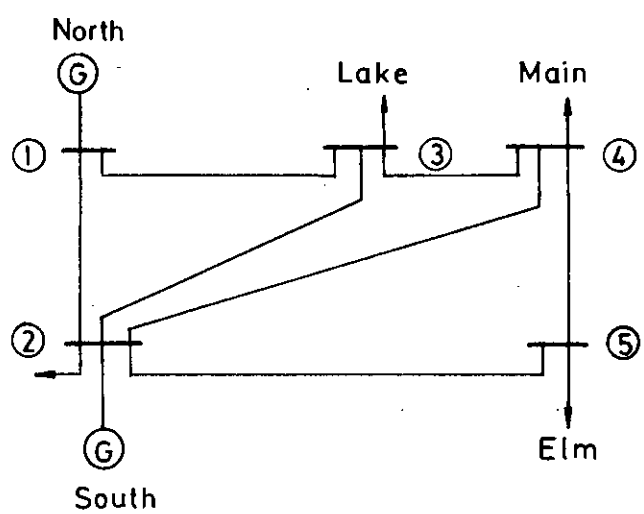


Fig. 3.1 Sample system for the formation of Y_{Bus}

Assuming no mutual coupling in the system many of the elements of the matrix will become zero. The diagonal element of the bus admittance matrix for bus 1 is

$$Y_{11} = y_{12} + y_{13} + y_1 \quad \text{where } y_1 = y'_{12}/2 + y'_{13}/2$$

The off- diagonal elements associated with different buses are just the sum of the corresponding branch admittances with negative sign.

Bus p \ Bus q	1	2	3	4	5
1	Y_{11}	Y_{12}	Y_{13}		
2	Y_{21}	Y_{22}	Y_{23}	Y_{24}	Y_{25}
3	Y_{31}	Y_{32}	Y_{33}	Y_{34}	
4		Y_{42}	Y_{43}	Y_{44}	Y_{45}
5		Y_{52}		Y_{54}	Y_{55}

Fig. 3.2 Bus admittance matrix

The general representation of the elements in accordance with network configuration may be written as :

$Y_{pq} = Y_{qp} = -\, y_{pq}$ $\quad p \neq q$ for off-diagonal element

and $Y_{pp} = \Sigma y_{pq} + y_p$ for diagonal elements

where $y_p = \Sigma y'_{pq}/2$

3.6 ADVANTAGES OF Y_{BUS} OVER Z_{BUS}

Z_{Bus} matrix is a full- matrix where as Y_{Bus} matrix is highly sparse[15] (A-2).It is relatively easy to construct and the methodology of solution being straightforward, programming becomes an easytask. The computer memory requirements for storing the Y_{Bus} admittance matrix is very low. It need store only a very few non-zero elements, it need not store the zeros of the matrix. Again the bus admittance being a symmetric matrix along the leading diagonal, the computer need store the upper triangular bus admittance matrix only and,in iterating only these entries are called for, through an efficient scheme of ordering and compact storage. The computations per iteration are small and are roughly proportional to the number of buses n. Inspite of all the above facilities of Y_{Bus}, sometimes Z_{Bus} is used in load-flow studies and is extremely valuable in fault calculations.

CHAPTER - IV

SYSTEM EQUATION AND SOLUTION TECHNIQUE

4.1 INTRODUCTION

Load flow studies form an important part of power system planning and operation. The load flow study of a power system is the determination of the magnitude and phase angle of the voltage at each bus and the real and reactive power flowing in each line under existing or contempleted conditions of normal operation. The two primary considerations in the development of an effective engineering computer program are : (1) the formulation of a mathematical description of the problem; and (2) the application of a numerical method for a solution. The analysis of the problem must also consider the inter-relation between these two factors.

The mathematical formulation of the load flow problem results in a system of algebraic nonlinear equations. The solution of the algebraic equations describing the power system are based on an iterative technique |Appendix - A| because of their nonlinearity. These are done in different ways. Even though many methods have been suggested over the past two decades, the Gauss-seidel G-S and Newton-Raphson N-R method are the most widely used. However, the Fast decoupled load flow (FDLF) method is gaining more popularity in recent years because of its simplicity, speed and low memory requirements. The latest method is developed starting from the Newton's.

4.2 ANALYTICAL DEFINITION AND BUS CLASSIFICATION

The complete definition of load flow requires knowledge of four variables at each bus k in the system.

P_k - real or active power

Q_k - reactive or quadrature power

V_k - voltage magnitude

θ_k - voltage phase angle

In a load flow solution two out of the four quantities are specified and the remaining two are required to be obtained through the solution of the equations. Depending upon which quantities have been specified, the buses are classified in the following categories:[11,29]

(i) Load bus or P-Q bus: A P-Q bus is where the total injected complex power is specified. It is desired to find out the voltage magnitude and phase angle through the load flow solution. At such a Kth bus we have

$$V_k I_k^* = S_k^{sp} = P_k^{sp} + JQ_k^{sp}$$

$$= (P_{Gk}^{sp} - P_{Lk}^{sp}) + j\,(Q_{Gk}^{sp} - Q_{Lk}^{sp}) \quad \ldots (4.1)$$

The subscripts G_k and L_k refer to generation and load respectively at the Kth bus. In the physical power system this corresponds to a load centre such as a city or an industry, where the consumer demands his power requirements.

(ii) Voltage controlled bus or P-V bus or Generator bus: A P-V bus is one where real power P is specified and voltage magnitude is maintained at a constant value by reactive power injection. It is required to find out the reactive power generation Q_G and the phase angle of the bus voltage. At such a bus we have

$$Re \mid V_k I_k^* \mid = P_k^{sp} = P_{Gk}^{sp} - = P_{Lk}^{sp} \quad \ldots \quad (4.2)$$

(iii) Slack, Swing or reference bus: It is a bus where voltage and phase angle are specified. The concept of a swing bus is necessary because, the I^2R losses are not known in advance, and hence it is not possible to fix injected real power at all the buses. It is customary to designate one of the voltage controlled buses, generally having the largest generation as the swing bus. At this bus real power P_s is not specified but is calculated at the end of the computation. Since we also need a reference phasor in the system, the phasor angle of the swing bus is also specified, generally as zero degrees. Thus the complex voltage V is specifed at the slack bus but P_s and Q_s are determined only after the load flow computation has converged. The following table summarises the above discussion:

Bus type	Quantities specified	Quantities to be obtained
Load bus	P,Q	$\|V\|$, θ
Generator bus	P, $\|V\|$	Q, θ
Slack bus	$\|V\|$, θ	P,Q

4.3 DATA FOR LOAD FLOW STUDIES

Either the self and mutual admittances which compose the bus admittance matrix Y_{Bus} or the driving point and transfer impedances which compose Z_{Bus} may be used in solving the load flow problem. However, we have confined our study to methods using admittances.

The information requred for a load flow solution is divided into three parts[5]. First is the base data which describes completely the network and operating conditions of the power system. This data includes line and transformer impedances, generation, loads, transformer taps, static capacitor and shunt reactor admittances, as well as information pertaining to the swing machine and the voltage regulating capability of the system. To facilitate data preparation all power system facilities are identified by actual power plant and substation names. Second are the study title, case number, and control statements which govern the sequence of operations for the calculation of a series of load flows. Finally, there is the data required to effect changes in the system representation and operating conditions for tbe calculation of subsequent cases. For interconnection studies network connections are described by using code numbers assigned to each bus, these numbers spacify the terminals of transmission lines and transformers. Code numbers are used also to identify the types of buses,[28] the location of static capacitors, shunt reactors, and those elements in which off-nominal turns ratios of transformers are to be represented.

4.4 FORMULATION OF LOAD FLOW EQUATIONS

The mathematical formulation of the load flow problem results in a system of algebraic non-linear equations.[26] As the number of unknowns are large and the nonlinearity in the equations make it impracticable to use any direct method, such as Gaussions elimination method[16] or cramer's rule[17] involving determinants. Iterative technique are the only alternative and are of special help because of large number of zero elements in the nodal equations of the power network. The solution must satisfy kirchnoff's laws, i.e. the algebraic sum of all flows at a bus must equal zero, and the algebraic sum of all voltages in a loop must equal zero one or the other of these laws in used as a test for convergence of the solution in the iterative computational method. The author has used the former. The bus current equations for a n bus system can be written as

$$I_p = \sum_{q=1}^{n} Y_{pq} V_q, \quad P = 1,2, \ldots ,n \quad \ldots \qquad (4.3)$$

Conjugating equation (4.3) and multiplying by V_p we get

$$V_p I_p^* = S_p = V_p \sum_{q=1}^{n} Y_{pq}^* \; V_q^* \quad \ldots \qquad (4.4)$$

Mathematically speaking, the complex load-flow equations are nonanalytic, and cannot be differentiated in complex form. So seperating into real and imoginar parts

$$P_p = \mathrm{Re} \left| V_p \sum_{q=1}^{n} Y_{pq}^* \; V_q^* \right| \quad P = 1,2, \ldots ,n \qquad (4.5)$$

$$Q_p = I_m \left[V_p \sum_{q=1}^{n} Y_{pq}^* V_q^* \right] \quad P = 1,2, \ldots, n \quad \ldots \quad (4.6)$$

In polar form

$$V_p = |V_p| \angle\theta_p, \ \theta_{pq} = \theta_p - \theta_q$$

and

$$Y_{pq} = G_{pq} + jB_{pq}$$

Equations (4.5) and (4.6) can be expressed in terms of the polar components as

$$P_p - |V_p| \sum_{q=1}^{n} ((G_{pq} \cos \theta_{pq} + B_{pq} \sin \theta_{pq}) |V_q|) = 0 \ .(4.7)$$

$$Q_p - |V_p| \sum_{q=1}^{n} ((G_{pq} \sin \theta_{pq} - B_{pq} \cos \theta_{pq}) |V_q|) = 0 \ .. \ (4.8)$$

$$P = 1,2, \ldots, n.$$

This formulation results in a set of nonlinear simultaneous equations, two for each bus of the system. The real and reactive powers P_p and Q_p are known and the magnitudes and the angles of voltages are unknown for all buses except the slack bus, where the voltage is specified and remains fixed. Thus there are 2(n-1) equations to be solved for a load flow solution.

4.5 NEWTON-RAPHSON METHOD USING Y_{BUS}.

The power flow problem involves the solution of a set of nonlinear simultaneous equation. Taking the first derivative of these equations a second set of variational equations are formed which are linear, and the iterative process is applied to the second set of equations. This process of solution is called the Newton-Raphson method[18]. Taylor's series expansion for a function of two or more variables is the basis of this method. Rational derivatives of order greater than I are neglected in the series expansion.

The set of linear equations for Newton-Raphson method expresses the relationship between the changes in real and reactive powers and the components of bus voltages. In polar form the change in real power corresponds the change in voltage angle while the change in reactive power correspo-nds the change in voltage magnitude.

The linear set of equations is solved to calculate P at every bus except the swing bus and Q at those buses where reactive power is specified. The differences between speci-fied and calculated values are used to determine the correc-tion of bus voltages. The process is repeated until the calculated values of P and Q at every bus differ from the specified values by less than the chosen precision index.

4.5.1 Derivation of the equations

Of the n total numbers of nodes, let the number of P-Q nodes be n_1, P-V nodes be n_2 and let there be one slack bus, so that $n = n_1 + n_2 + 1$. Our basic problem is to find the unknown voltage magnitudes $|V|$, (n_1 in number) at the P-Q and P-V buses. Let X be the vector of all, unknown $|V|$ and θ, and Y the vector of all specified variables. The dimension of X is $2n_1 + n_2$ and that of Y is $2n_1 + 2n_2 + 2$, thus

$$X = \begin{bmatrix} \left.\begin{matrix} |V| \\ \theta \end{matrix}\right\} & \begin{matrix}\text{on each} \\ \text{P-Q node}\end{matrix} \\ \left.\theta\right\} & \begin{matrix}\text{on each} \\ \text{P-V node}\end{matrix} \end{bmatrix} \qquad Y = \begin{bmatrix} \left.\begin{matrix} V_s \\ \theta_s \end{matrix}\right\} & \text{on slack node} \\ \left.\begin{matrix} P_p^{sp} \\ Q_p^{sp} \end{matrix}\right\} & \text{on each P-Q node} \\ \left.\begin{matrix} P_p^{sp} \\ |V|_p^{sp} \end{matrix}\right\} & \text{on each P-V node} \end{bmatrix}$$

From the set of equations (4.7) and (4.8) we select a number of equations equal to the number of unknowns in X to form the nonlinear load flow equations $F(X,Y) = 0$. Since Y is specified we may suppres it from the equations.

we form $F(X)$ as follows:

$$F(X) = \begin{cases} \text{Eq.(4.7) for each P-Q and P-V node with } P_p = P_p^{sp} \\ \text{Eq.(4.8) for each P-Q node with } Q_p = Q_p^{sp} \end{cases} = 0 \qquad (4.9)$$

Thus there will be $2n_1 + n_2$ equations, and this number is clearly equal to the number of unknowns in X.

These equations can be written in a different notation as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = 0 \qquad \ldots \qquad (4.10)$$

where

$$\Delta P_p = P_p^{sp} - |V_p| \Sigma ((G_{pq} \cos \theta_{pq} + B_{pq} \sin \theta_{pq}) |V_q|) \qquad (4.11)$$

$P = 1, 2, \ldots, n.$

$P \neq S$

$$\Delta Q_p = Q_p^{sp} - |V_p| \sum_{q=1}^{n} ((G_{pq} \sin \theta_{pq} - B_{pq} \cos \theta_{pq}) |V_q|) \qquad (4.12)$$

$P = 1, 2, \ldots, n$

$P \neq S$, $P \neq$ P-V node

Then the linear equation in Newton's method is given by

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}_{(k)} = \begin{bmatrix} H & N \\ M & L \end{bmatrix}_{(k)} \begin{bmatrix} \Delta \theta \\ \frac{\Delta V|}{|V|} \end{bmatrix}_{(k)} \quad \ldots \quad (4.13)$$

$\Delta\theta$ is the subvector of incremental angles at P-Q and P-V buses.

The variable corresponding to voltage magnitude increment $\Delta|V|$ at P-Q buses is divided by $|V|$. This brings about a symmetry in the elements of the co- efficient matrix. The submatrices H,N,M,L represent the negated partial derivatives of $|\Delta P|$ and $|\Delta Q|$ with respect to relevant θ's and V's . The square matrix of partial derivatives is called the Jacobian. The elements of the Jacobian are found by taking the partial derivatives of the expressions for P_p and Q_p and substituting therein the voltages assumed or calculated in the last previous iteration.

For $P \neq q$

$$H_{pq} = \frac{\partial P_p}{\partial \theta_q} = |V_p| \; |V_q| \; (G_{pq} \operatorname{Sin} \theta_{pq} - B_{pq} \operatorname{Cos} \theta_{pq}) \quad (4.14)$$

$$N_{pq} = V_q \frac{\partial P_p}{\partial V_q} = |V_p| \, |V_q| (G_{pq} \operatorname{Cos} \theta_{pq} + B_{pq} \operatorname{Sin} \theta_{pq}) \quad (4.15)$$

$$M_{pq} = \frac{\partial Q_p}{\partial \theta_q} = - \left| V_p \right| \left| V_q \right| (G_{pq} \text{Cos } \theta_{pq} + B_{pq} \text{Sin } \theta_{pq}) \qquad (4.16)$$

$$L_{pq} = |V_q| \frac{\partial Q_p}{\partial v_q} = \left| V_p \right| \left| V_q \right| (G_{pq} \text{Sin } \theta_{pq} - B_{pq} \text{Cos } \theta_{pq}) \qquad (4.17)$$

where

$$\theta_{pq} = \theta_p - \theta_q \text{ and } V_p = \left| V_p \right| (\text{Cos } \theta_p + j\text{Sin } \theta_p)$$

Hence, $H_{pq} = L_{pq}$

and $N_{pq} = - M_{pq}$

For $p = q$

$$H_{pp} = \frac{\partial P_p}{\partial \theta_p} = -Q_p - B_{pp} \left| V_p \right|^2 \quad \ldots \qquad (4.18)$$

$$L_{pp} = V_p \frac{\partial Q_p}{\partial v_p} = Q_p - B_{pp} \left| V_p \right|^2 \quad \ldots \qquad (4.19)$$

$$N_{pp} = V_p \frac{\partial P_p}{\partial v_p} = P_p + G_{pp} \left| V_p \right|^2 \quad \ldots \qquad (4.20)$$

$$M_{pp} = \frac{\partial Q_p}{\partial \theta_p} = P_p - G_{pp} \left| V_p \right|^2 \quad \ldots \qquad (4.21)$$

where

$$P_p = \left| V_p \right| \sum_{q=1}^{n} ((G_{pq} \text{Cos } \theta_{pq} + B_{pq} \text{Sin } \theta_{pq}) \left| V_q \right|) \qquad (4.22)$$

$$Q_p = \left| V_p \right| \sum_{q=1}^{n} ((G_{pq} \text{Sin } \theta_{pq} - B_{pq} \text{Cos } \theta_{pq}) \left| V_q \right|) \qquad (4.23)$$

All quantities in the linear equation (4.13) pertain to interation k, The linear equation when solved for $\Delta\theta$, $\frac{\Delta V}{|V|}$ gives the correction to be applied to $|V|$ and θ,i.e.

$$|V|^{(k+1)} = |V|^{(k)} + \Delta|V|^{(k)} \quad \ldots. \qquad (4.24)$$

and

$$\theta^{(k+1)} = \theta^{(k)} + \Delta\theta^{(k)} \quad \ldots \qquad (4.25)$$

Next we get a new set of linear equation evaluated at (k+1) th iteration and the process is repeated. Convergence is tested by the power mismatch criteria.

4.5.2 SYSTEM HAVING VOLTAGE CONTROL BUSES

We know that voltage controlled buses are those where voltage magnitude and real power are specified. The reactive power Q_p is initially unknown at these buses. A deviation from the normal computational procedures is hence, required to take into account this type of buses.

In the Newton-Raphson method, the reactive power at a voltage controlled bus is calculated at the end of an interation using (4.23) and $|V|$ is held at the specified value. If reactive power source (capacitor bank or synchronous condenser) of sufficient capacity cannot be provided then it is required to take into account the limits of reactive power source at the voltage control buses, when the calculated Q_p^k exceeds the max^m. Capability Q_p (max) of the source, the maximum value is taken as the reactive power at that bus. If the calculated value is less than minimum capability Q_p (min), the minimum value is used.

The sequence of steps required to include the effect of voltage controlled buses in the Fast decoupled iterative method is shown in the flow-chart in Fig. 4.1.

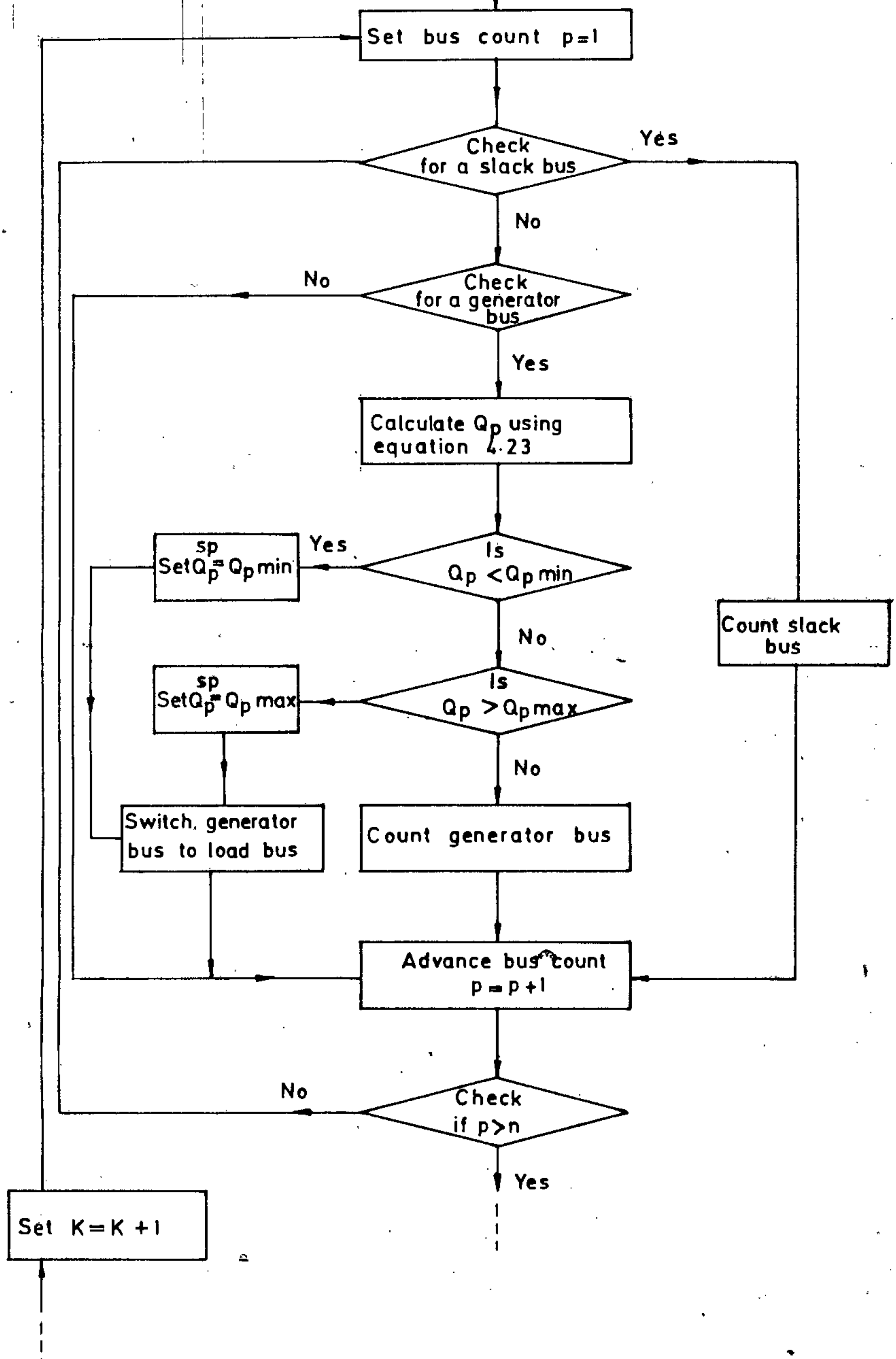


FIG. 4.1 CALCULATION OF REACTIVE POWER AT VOLTAGE CONTROLLED BUSES

4.5.3 Decoupled method

An inherent characteristic of any practical electric power transmission system operating in the steady-state condition is the strong interdependence between active powers and bus voltage angles and between reactive powers and bus voltage magnitudes correspondingly, the coupling between these 'P-θ' and 'Q-V' components of the problem are relatively weak. An emerging trend has therefore been to solve the P-θ and Q-V problem seperately.

The most successful decoupled load flow is that based on the Jacobian matrix equation for the formal Newton method. The first assumption under decoupled load flow method is that real power changes (ΔP) are less sensitive to changes in voltage magnitude and are mainly sensitive to angle. Similarly, the reactive power changes are less sensitive to change in angle but mainly sensitive to change in voltage magnitude. With these assumptions the submatrices N and M of equation (4.13) are neglected, since they represent the weak coupling between 'P-θ' and Q-V, the resulting linear equation becomes

$$[\Delta P] = [H] \quad [\Delta\theta] \qquad \ldots (4.26)$$

$$[\Delta Q] = [L] \quad \left[\frac{\Delta|V|}{|V|}\right] \qquad \ldots (4.27)$$

where for $p \neq q$

$$H_{pq}=L_{pq}= |V_p||V_q|(G_{pq}\text{Sin } \theta_{pq} - B_{pq}\text{Cos } \theta_{pq}) \ldots \quad (4.28)$$

and for p=q

$$H_{pp} = -B_{pp} |V_p|^2 - Q_p \quad \ldots \qquad (4.29)$$

$$L_{pp} = -B_{pp} |V_p|^2 + Q_p \quad \ldots \qquad (4.30)$$

There are two ways to solve equations (4.26) and (4.27)

(1) Solve for $\Delta\theta$ and $\frac{\Delta|V|}{|V|}$ simultaneously

(2) Solve for $\Delta\theta$ first from (4.26) and use this updated θ in (4.27) to solve for $\frac{\Delta|V|}{|V|}$ since L is a function of θ.

4.5.4 Fast decompled load flow

By further simplifications and assumptions, based on the physical properties of a practical system, the Jacobians of the decompled method can be made constant in value. This means they need be evaluated once only at the beginning of the study or for a particular network.

Fast decompled load flow method is derived from the polar decompled version (eqs. 4.26 & Eq. 4.27) with the following assumptions:

(i) V_p , V_q = 1.0 p.u. initially for all buses, except the P-V buses.

(ii) θ = 0.0 initially for all buses, except the slack bus.

(iii) $\cos \theta_{pq} = \cos(\theta_p - \theta_q) \simeq 1$

(iv) $G_{pq} \sin \theta_{pq} = G_{pq} \sin(\theta_p - \theta_q) << B_{pq}$

(v) $Q_p << B_{pp} |V_p|^2$

with the above assumptions the Jacobian elements now become

For $p \neq q$

$$H_{pq} = L_{pq} = -|V_p|\,|V_q|\;B_{pq} \qquad \ldots \qquad (4.31)$$

For p=q

$$H_{pp} = L_{pp} = -\,B_{pp}\;|V_p|^2 \qquad \ldots \qquad (4.32)$$

Matrices H and L are square matrices with dimension (n_1+n_2) and n_1 respectively.

with these equations (4.26) and (4.27) become

$$\left[\Delta P\right] = \left[|V_p|\;|V_q|\;B'_{pq}\right]\left[\Delta\theta\right] \qquad \ldots \qquad (4.33)$$

$$\left[\Delta Q\right] = \left[|V_p|\;|V_q|\;B''_{pq}\right]\left[\frac{\Delta|V|}{|V|}\right] \qquad \ldots \qquad (4.34)$$

where B'_{pq} and B''_{pq} are the elements of $\left[-B_{pq}\right]$ matrix. Further decompling and finalization of the fast decompled load flow algorithm is achieved by

a) Omitting from $[B']$ the representation of those network elements that predominently affect MVAR flows,i.e. shunt reactances and off-nominal in-phase transformer taps,

(b) Omitting from $[B'']$ the angle shifting effects of phase shifters,

(c) dividing each of the equations (4.33) and (4.34) by $|V_p|$ and setting $|V_q| = 1.0$ p.u. in the equations, and

(d) neglecting series resistance in calculating the elements of $|B'|$.

with these modifications the final fast decompled load flow equation becomes

$$\left[\frac{\Delta P}{|V|}\right] = \left[B'\right] \left[\Delta\theta\right] \quad \ldots \quad (4.35)$$

$$\left[\frac{\Delta Q}{|V|}\right] = \left[B''\right] \left[\Delta|V|\right] \quad \ldots \quad (4.36)$$

Both $[B']$ and $[B'']$ are real and sparse and have structures of $[H]$ and $[L]$ respectively. They are of order (n-1) and (n-m) respectively, where n is the number of busbars and m is the number of P-V busbars B'' is symmetric in value and so is B' if phase shifters are ignored; since the two matrices are constant and do not change during successive iterations for solution of the load flow problem they need be evaluated only once and inverted once during the first iteration and then used in all successive iterations. It is because of the nature of Jacobian matrices $[B']$ and $[B'']$ and the sparsity of these matrices that the method is fast.

4.6 COMPUTATION OF LINE FLOWS AND SLACK BUS POWER

After the computations of iterative solution have converged, line flows and slack bus power are calculated as follows:

Let the line connecting bus P to bus q (Fig. 4.2) have a series admittance of y_{pq} and a total line charging admittance of y'_{pq}. Then the current in the line is given by

$$i_{pq} = (V_p - V_q)\, y_{pq} + V_p\, y'_{pq}/2 \quad \ldots \quad (4.37)$$

The line flow from bus p to bus q is given by

$$P_{pq} + jQ_{pq} = V_p \left[(V_p - V_q)^* y^*_{pq} + V^*_p\, y'^*_{pq}/2 \right] \quad \ldots \quad (4.38)$$

Here P_{pq} is the real power flow from bus p to q and Q_{pq} is the reactive power flow from bus p to q.

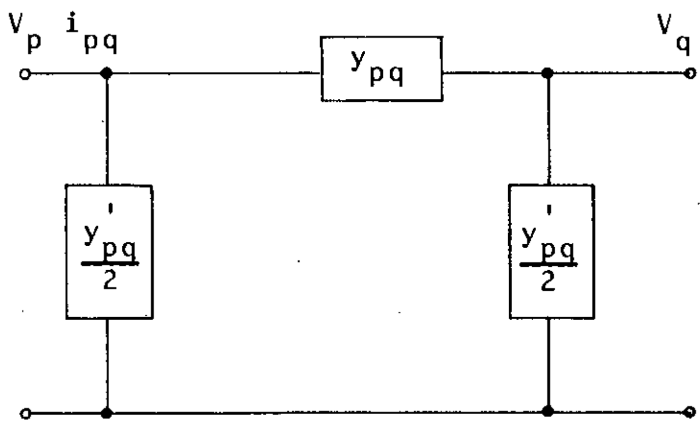


Fig.4.2 Equivalent circuit of a transmission link for evaluating line flows.

Similarly, the line flow from bus q to p is given by

$$P_{qp} + jQ_{qp} = V_q \left[(V_q - V_p)^* y_{pq}^* + V_q^* \, y_{pq}^{'*} /2 \right] \quad \ldots (4.39)$$

The line less (power loss) in the line p-q is given by the algebraic sum of

$$(P_{pq} + jQ_{pq}) \text{ and } (P_{qp} + jQ_{qp})$$

The slack bus power is calculated by summing the flows on the lines terminating on the slack bus.

Mismatch power is the power difference between the specified values and the estimated values.

CHAPTER - V

PROGRAM DEVELOPMENT AND TEST RESULTS

5.1 INTRODUCTION

In this chapter a computer program algorithm is presented incorporating the theory described in the previous chapters for the solution of load flow problems by Fast Decoupled Method. Following the algorithm a computer program in FORTRAN-IV language is developed to be run in IBM-4331 computer available at the computer center, BUET. The program which is capable of handling any power system is attached in Appendix-B. The subroutine "INVERS" for the inversion of any well- conditioned matrix is listed in Appendix-C. The developed program is tested with a very simple network shown in Fig. 5.3.

The results of the load flow study for a 6 bus and 7 line system has been given by Dhar[24] has been tabulated in Table 5.1 & Table 5.2. The data as given in Table 5.3 and Table 5.4 for the system were fed into the computer and the print out results are reproduced in Table 5.5 through Table 5.8. The two sets of the results were found to be almost identical. This check was undertaken in order to verify the program developed for this work.

5.2 BASIC ALGORITHM OF A LOAD FLOW PROGRAM

The basic algorithm which a load flow program use is depicted in Fig. 5.1. System data such as busbar power conditions, network connections and impedances, are read in and the admittance matrix formed. Initial voltages are specified to all buses; for base case load flows, P,Q buses are set to 1 + j0 while P,V busbars are set to V + j0.

The iteration cycle is terminated when the busbar voltages and angles satisfy the specified conditions. These conditions are accepted when power mismatches for all buses are less than a small specified tolerance. When a solution has been reached, complete terminal conditions for all buses are computed, line power flows and losses and system totals can then be calculated.

5.3 FEATURES OF THE COMPUTER PROGRAM

The program incorporates many automatic features to facilitate their use in power system planning, operating and interconnection studies. The principal objectives of these features are to make maximum use of computer's capability and to minimize the number of manual operations required by the engineer is specifying and

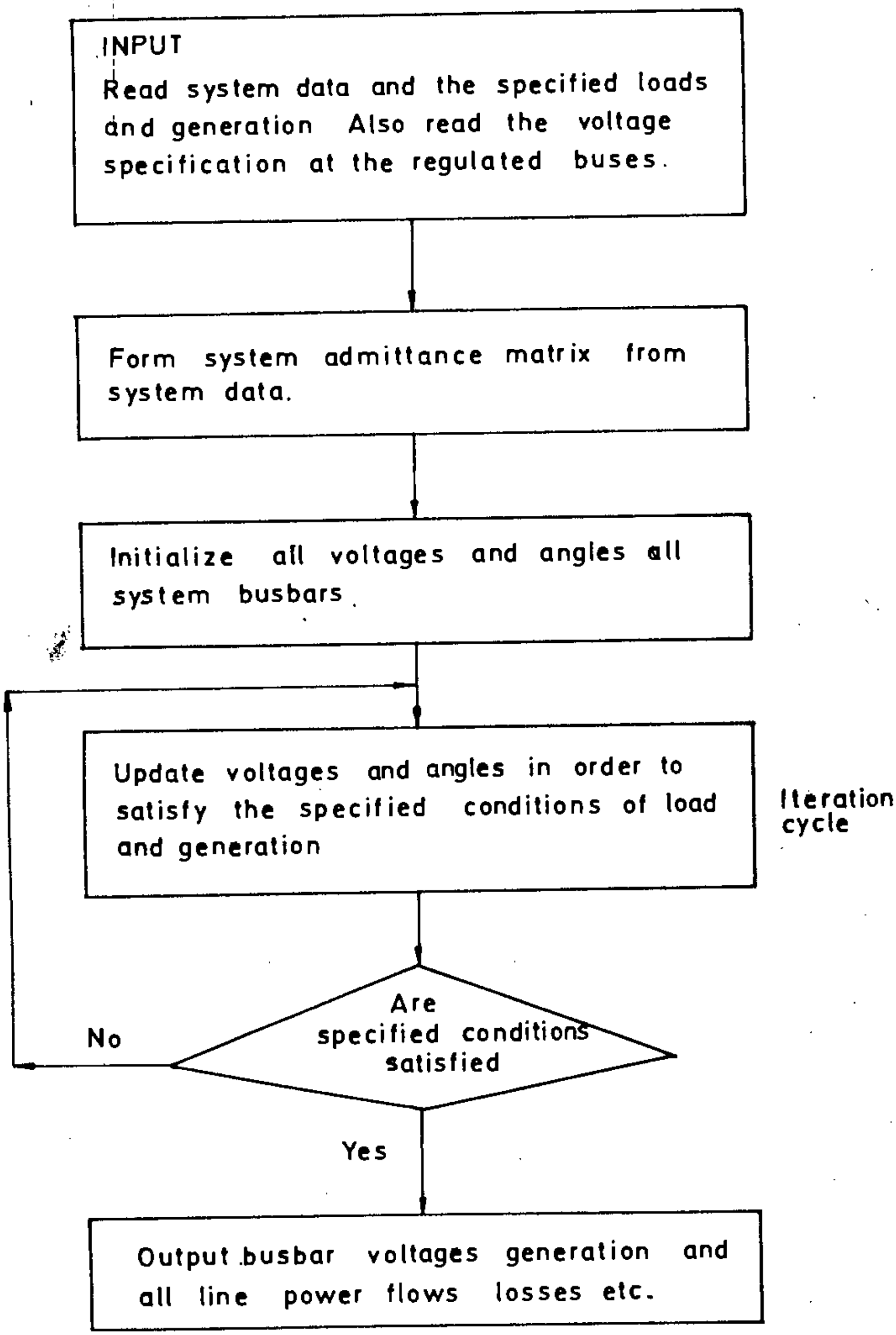


FIG. 5.1 FLOW DIAGRAM OF BASIC LOAD FLOW ALGORITHM

maintaining system data for the initial and subsequent load flow cases. The main components of the program are:

I. INPUT PROGRAM: The input program provides the computer with all known informations about the power system, viz. Number of buses and lines.

ii) Base values

iii) Bus name and number

iv) Specification of the Bus- i.e. wheather it is a swing bus or voltage controlled bus or load bus.

v) Bus voltage magnitude and phase angle with reference to the slack bus.

vi) Value of the tolerance limit to be reached and the maximum number of iterations to be allowed.

II. DATA ASSEMBLY PROGRAM:

This program prepares and checks data and performs all preliminary computational works to the iterative calculations.

III. PROGRAM FOR VOLTAGE CONTROLLED BUSES:

By this program at the begining of the iterative cycle the voltage controlled buses are checked according to their reactive power limits and recatagorized accordingly.

IV. PROGRAM FOR VOLTAGE AND POWER FLOW CALCULATION:

This is to instruct the computer to perform iterative calculations to obtain bus voltages & to use them for computing power flow in different lines and hence the line and transformer loadings.

V. OUTPUT PROGRAM:

This program includes the instructions to print out the system and station names together with assigned bus number to identify the load flow results. The bus voltages with their angles, the bus powers, line flows and power mismatches are printed.

VI. ADDITIONAL INPUT INFORMATIONS:

The additional input informations which may be included in the program are:

i) Existing capacitor banks.

ii) Phase shifting transformers.

iii) Upper and lower limit of MVA generation.

iv) Information about the tie line (Appendix- A)

v) Provision for system changes and data recording.

VII. ADDITIONAL OUTPUT INFORMATIONS:

The additional output information includes the use of the load -flow results for subsequent studies with some connecting comments.

The complete flow chart for this program is presented in Fig. 5.2. The sequence of steps for the solution of load flow problem using Fast Decoupled Method is explained as follows:

1. Set base values and system specifing values with convergence criterions..
2. Read line datas and bus datas.
3. Assume a suitable solution for all buses except the slack bus. Let $V_p = 1 + j0.0$ for $P = 1,2,...n$, $P \neq$ slack bus, $P \neq$ P-V bus.
4. Form bus admittance matrix Y_{Bus}.
5. Seperate real and imaginary parts of Y_{Bus} matrix and form G and B matrices.
6. Set iteration count $K = 0$ and other terminating conditions.
7. Set bus count $P = 1$
8. Check if P is a slack bus, If 'yes' , go on step-**11**.

9. Check if P is a voltage controlled bus. If 'No' go on step - 11.

10. The bus in question is a generator bus. Calculate reactive power (Q_p^k) using equation 4.23. Compare the Q_p^k with the given limits. If exceeds the limit, fix the reactive power to the corresponding nearer limit and treat the bus as a load bus for that iteration and go to the next step.

11. Advance the bus count by 1, i.e. P = P + 1 and check if all the buses have been accounted. If not go to step 8.

12. Form B' and B'' submatrices from B matrix and fix up B' submatrix.

13. Calculate ΔP_p^k using equation 4.11 for P= 1,2.... n, P $\neq$ slack bus.

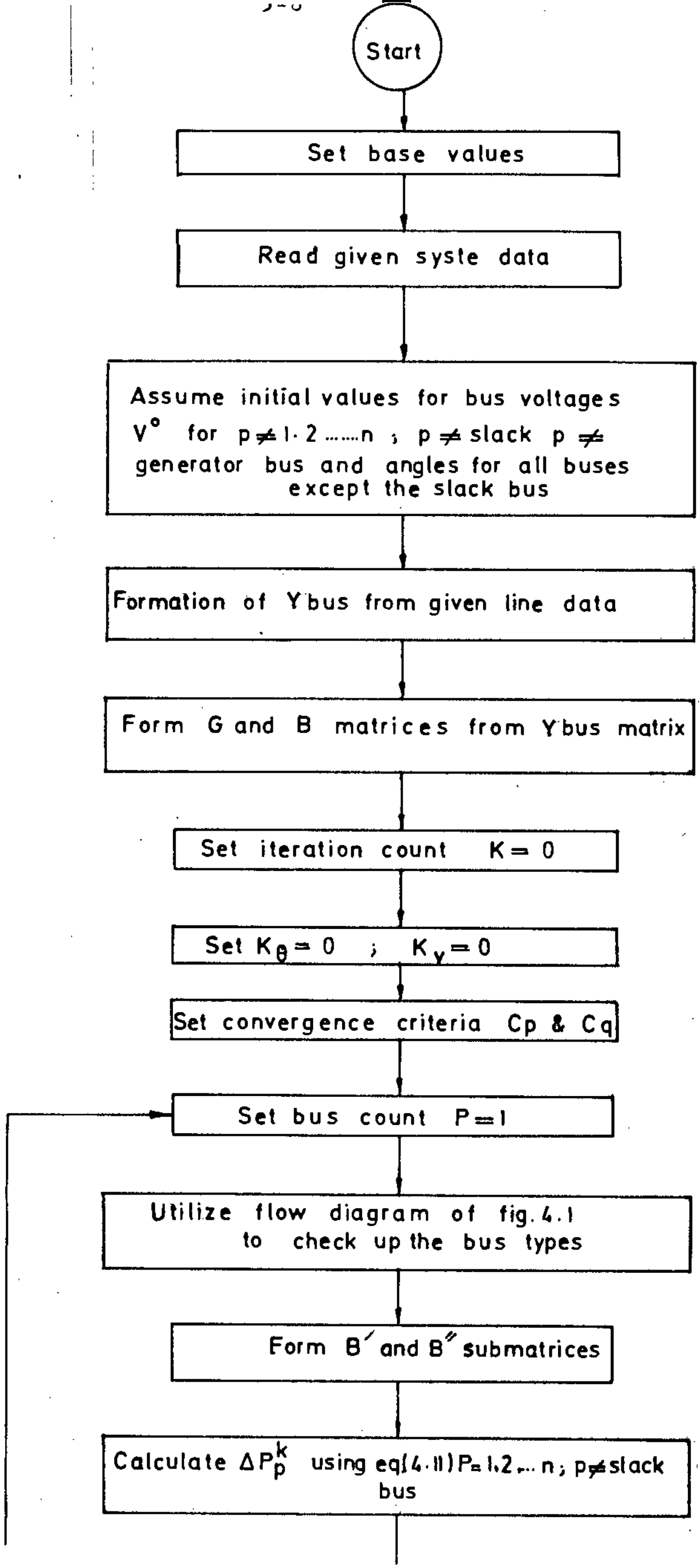
14. Determine the largest of the absolute value of the real power residue. If it is less than C_p, set K_θ = 1 and go to step 25.

15. Set KV = 0

16. Inverse B' matrix - and fix up.

17. Solve for $\Delta\theta^k$ using equation (4.35) for P=1,2....n; P $\neq$ slack bus.

18. Calculate θ_p^{k+1} by the equation (4.25) and replace θ_p^k by θ_p^{k+1} .


Start
Set base values
Read given syste data
Assume initial values for bus voltages V^{o} for $p \neq 1 \cdot 2 \ldots\ldots n$; $p \neq$ slack $p \neq$ generator bus and angles for all buses except the slack bus
Formation of Ybus from given line data
Form G and B matrices from Ybus matrix
Set iteration count K = 0
Set $K_{\theta} = 0$; $K_{V} = 0$
Set convergence criteria Cp & Cq
Set bus count P = 1
Utilize flow diagram of fig. 4.1 to check up the bus types
Form B' and B'' submatrices
Calculate ΔP_p^k using eq(4.11) P = 1,2,... n ; p ≠ slack bus

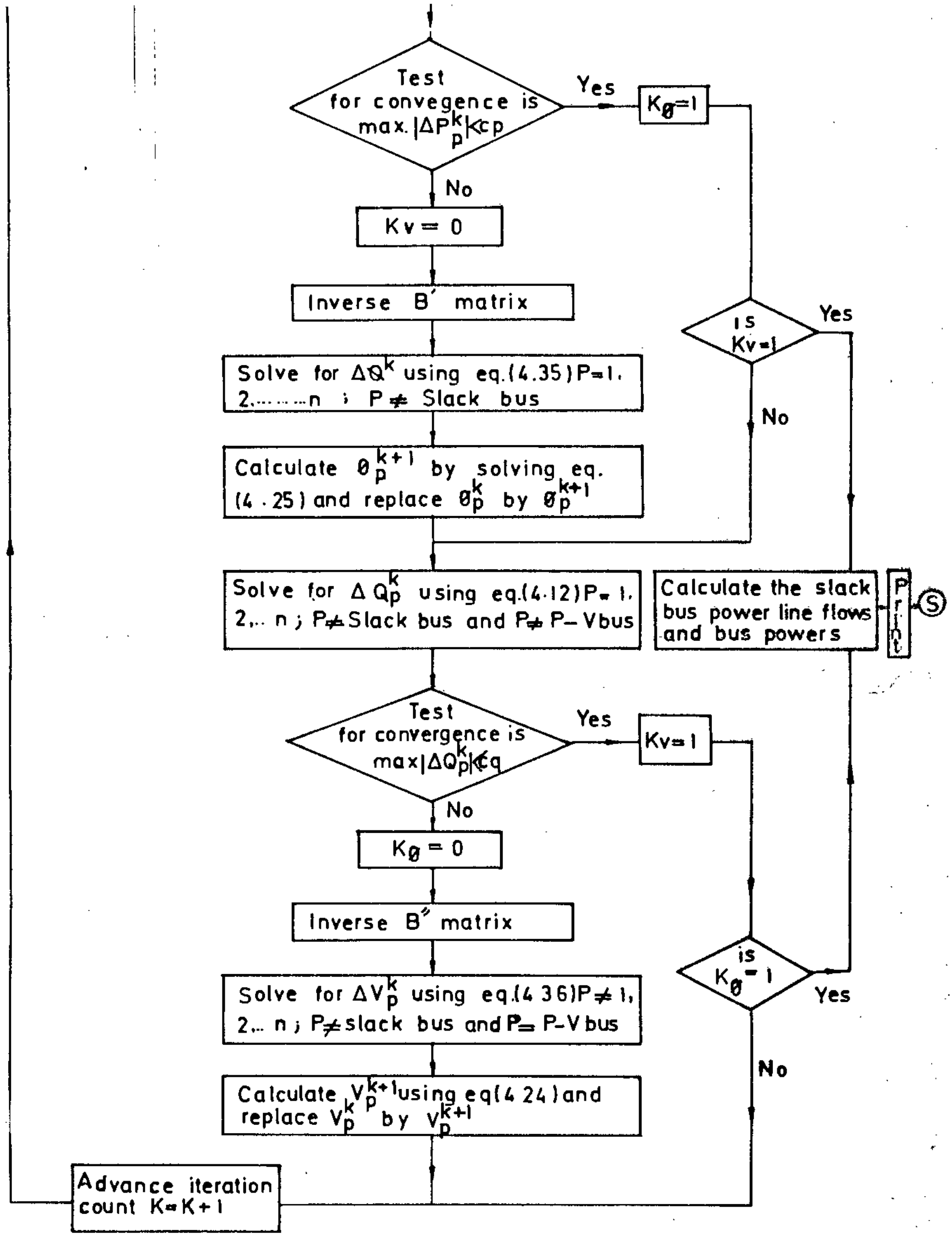


FIG. 5.2 FLOW CHART FOR LOAD FLOW STUDY USING FAST DECOUPLED TECHNIQUE.

19. Calculate ΔQ_p^k by the equation (4.12) for $P = 1,2,\ldots n$, $P \neq$ slack bus, $P \neq P - V$ bus, using the updated value of θ.

20. Determine the largest of the absolute value of the reactive power residue. If the absolute value is less than C_q, set $K_v = 1$ and go to step - 26.

21. Inverse B'' matrix.

22. Solve for ΔV_p^k using equation 4.36 for $P = 1,2,\ldots.n$; $P \neq$ slack bus, $P \neq P - V$ bus.

23. Calculate V_p^{k+1} by the equation (4.24) and replace V_p^k by V_p^{k+1}.

24. Advance interation court by 1 and go to step-7.

25. If $K_v = 1$, go to step 27, otherwise go to step 19.

26. If $K_\theta = 1$, go to step 27, otherwise go to step 24.

27. Evaluate bus and line powers and print the results.

5. 4 DESCRIPTION OF THE SAMPLE SYSTEM

The sample system as shown in Fig. 5.3 by a single -line diagram is taken under consideration for checking the developed program. The model consists of 6 buses and 7 lines. Line impedances, leakage reactances of transformers and line charging admittances have been shown in Table 5.3. The bus data is given Table 5.4. All these values are in per unit with an assumed base of 100 MVA.

In this study the bus number one has been referred as the slack bus and its voltage is held constant at $1.05 < 0^{o}$ P.u. The bus number two is designated as the voltage control bus with its reactive power limits. The remaining buses are identified as load buses. The fourth bus is a passive bus[18]. There are two off-nominal transformers T_1 and T_2 between the buses 3 and 4 & buses 5 and 6 respectively.

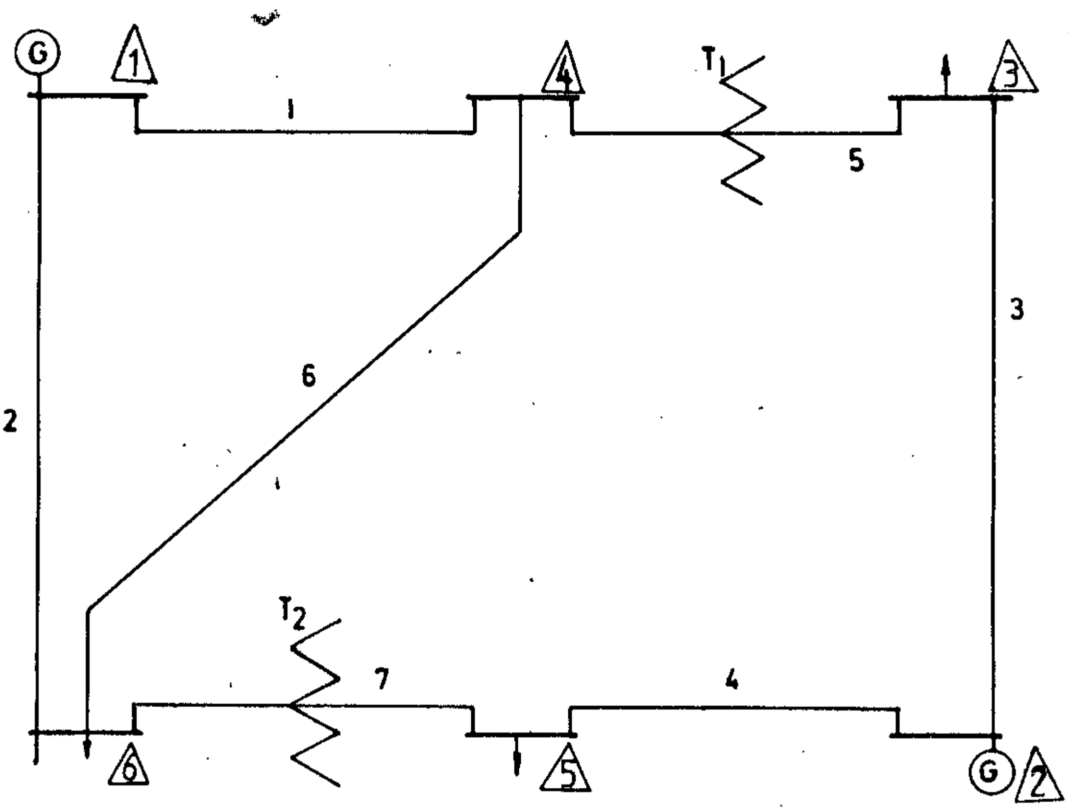


FIG. 5.3 SIX-BUS EXAMPLE SYSTEM

5.5 TEST RESULTS

The computer program developed for the proposed work has been used to solve the complete automatic load flow solution of a number of problems. But due to space limitation and for better comparison with the given results, the results on application to the sample problem described in the previous section are reproduced here.

The study required 5 iterations to converge with the precision index of 0.0001 p.u. for both real and reactive power mismatch. The changes of the real and reactive power differences and hence the corresponding differences of angles and voltage magnitudes are quite high for the first two iterations and oscillates around the correct values for the last two iterations. The real power residue reaches within limit during the 4th iteration and the reactive power residue within range during the 5th iteration. After the convergence the power flows (forward and backward) in different lines are calculated and are tabulated in table 5.5. The line losses of the different lines which are the differences between the forward and backward flows of the corresponding lines are given in table 5.7. The computed bus powers with their voltage magnitudes and angles are listed in table 5.6. The small mismatches between the given results and the computed results are mainly due to the round-off error. The difference between incoming line flows and outgoing line flows at any bus other than swing bus is called the power mismatch at the said bus, and is sometimes used as an indication of the accuracy of the over-all load flow solution. The mismatches at different buses are listed in table 5.8.

In developing the program the tendency for minimum computer memory requirement was always in consideration. Same DIMENSION has been used for multipurposes. The total memory requirement including one sub-routine is 510 kbytes. The number of cards in the program are 560. The total time required for the complete execution of the sample problem was 82 seconds.

TABLE 5.1

FINAL RESULT

BASE = 100 MVA

BUS NO.	VOLTAGE MAGNITUDE	PHASE ANGLE	ACTIVE POWER	REACTIVE POWER
1	1.05000	0.0	0.95206	0.43252
2	1.10000	- 3.34294	0.50016	0.18426
3	1.00080	-12.78397	-0.54999	-0.12987
4	0.92976	- 9.83605	-0.00002	-0.00001
5	0.91981	-12.33389	-0.30005	-0.17984
6	0.91920	-12.23905	-0.50002	-0.05008

TABLE 5.2

LINE FLOW VALUES

BASE = 100 MVA

LINE No.	BUS p	CODE q	POWER FLOW ACTIVE	POWER FLOW REACTIVE	BUS q	CODE p	POWER FLOW ACTIVE	POWER FLOW REACTIVE
1	1	4	0.50907	0.25339	4	1	-0.48497	-0.17147
2	1	6	0.44300	0.17913	6	4	-0.41654	-0.10860
3	2	3	0.17183	-0.00019	3	2	-0.15419	0.02582
4	2	5	0.32832	0.18446	5	2	-0.29527	-0.10945
5	3	4	-0.39580	-0.15569	4	3	0.39580	0.17971
6	4	6	0.08916	-0.00824	6	4	-0.08827	-0.01364
7	5	6	-0.00478	-0.07040	6	5	0.00478	0.07216

TABLE 5.3

IMPEDANCES AND CHARGING ADMITTANCES

BASE = 100 MVA & 132 KV

LINE NO.	BUS p	CODE q	IMPEDANCE Z_{pq}(p.u.)	HALF LWE CHARGING ADMITTANCE, $Y'_{pq}/2$(p.u)		OFF-NOMINAL-TURNS RATIO IN COMPLEX FORM	
1	1	4	0.080 + j0.370	0.0	+ j0.015	1.0	+ j0.0
2	1	6	0.123 + j0.518	0.0	+ j0.021	1.0	+ j0.0
3	2	3	0.723 + j1.050	0.0	+ j0.0	1.0	+ j0.0
4	2	5	0.282 + j0.640	0.0	+ j0.0	1.0	+ j0.0
5	3	4	0.000 + j0.133	0.0	+ j0.0	0.909	+ j0.0
6	4	6	0.097 + j0.407	0.0	+ j0.015	1.0	+ j0.0
7	5	6	0.000 + j0.3000	0.0	+ j0.0	0.975	+ j0.0

TABLE 5.4

SPECIFIED BUS LOADINGS AND VOLTAGES

BASE = 100 MVA

BUS NO.	CLASS	GENERATION		LOAD		VOLTAGE		REACTIVE POWER LIMIT		BUS TYPE
		P_G(p.u.)	Q_G(p.u.)	P_L(p.u.)	Q_L(p.u.)	MAGNITUDE	ANGLE	Q_{min}	Q_{max}	
1	SLACK BUS	-	-	-	-	1.05	0.0	-	-	2
2	P-V BUS	0.50	-	-	-	1.10	-	0.0	0.20	1
3	P-Q BUS	-	-	0.55	0.13	-	-	-	-	0
4	P-Q BUS	-	-	0.00	0.00	-	-	-	-	0
5	P-Q BUS	-	-	0.30	0.18	-	-	-	-	0
6	P-Q BUS	-	-	0.50	0.05	-	-	-	-	0

---TABLE 5.5 ---

-REPORT ON LINE FLOWS-

LINE	BUS CODE		POWER FLOW		BUS CODE		POWER FLOW	
NO.	P	Q	ACTIVE	REACTIVE	Q	P	ACTIVE	REACTIVE
1	1	4	0.509103	0.253451	4	1	-0.435006	-0.171517
2	1	6	0.443024	0.179160	6	1	-0.416561	-0.108609
3	2	3	0.171779	-0.000132	3	2	-0.154148	0.025738
4	2	5	0.326221	0.184536	5	2	-0.295178	-0.109543
5	3	4	-0.395841	-0.155736	4	3	0.395841	0.174330
6	4	6	0.089156	-0.008271	6	4	-0.088262	-0.013615
7	5	6	-0.004323	-0.070444	6	5	0.004823	0.068557

---TABLE 5.6 ---

---COMPLETE REPORT OF LOAD FLOW STUDY---

BUS	NAME	VOLTS	ANGLE	GENERATION M.W.(P.U.)	GENERATION M.VAR.(P.U.)	LOAD M.W.(P.U.)	LOAD M.VAR.(P.U.)
1	SLACK BUS	1.049997	0.0	0.952127	0.432621	0.0	0.0
2	P-V BUS	1.099997	-3.349048	0.500000	0.184404	0.0	0.0
3	P-Q BUS	1.000758	-12.784341	0.0	0.0	-0.549938	-0.130000
4	P-Q BUS	0.929735	-9.336103	0.0	0.0	-0.000009	-0.005458
5	P-Q BUS	0.919777	-12.334679	0.0	0.0	-0.300001	-0.179937
6	P-Q BUS	0.919186	-12.239073	0.0	0.0	-0.499999	-0.053667

---TABLE NO. 5.7---

-LINE LOSSES-

LINE NO.	REAL POWER	REACTIVE POWER
1	0.024097	0.031945
2	0.026463	0.070551
3	0.017632	0.025606
4	0.033044	0.074993
5	-0.000000	0.018592
6	0.000694	-0.021887
7	0.000000	-0.001887

CHAPTER - VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The main problem in the load flow solution is to find the unknown bus voltages (magnitudes and angles). Once the bus voltages are found out, line flows line losses and bus powers are easily computed. As a result efforts are made to find bus voltages as quickly as possible. A method of load flow solution is evaluated by its computing time, storage requirements in computer programming, no. of iterations, iterative solution time and the computing time required to modify network data and to effect system operating changes.

In comparison to the other methods, the rate of convergence of the FDLF method is faster than any other method, requiring a relatively lesser number of iterations. As for example for the solution of the cited problem in all 32 iterations are needed to get the final result in G- S method whereas only 5 iterations are required in FDLF method with the same precision index using Y_{Bus} matrix. Therefore one FDLF iteration is equivalent to about seven G- S iterations. Again the number of iterations for the G- S method increases directly as the number of buses of the network. But in FDLF method the number of iterations is virtually indpendent of the system size due to the quadratic characteristic of convergence.

The proper acceleration factor can reduce the no. of iterations in G-S method. For the quoted problem using the acceleration factor $\alpha = 1.5$, the final result has been obtained in 15 iterations. But the selection of optimum acceleration scheme for the reduction of number of iterations and faster convergence is a trial and error method and sometimes become very difficult to calculate. The advantage in this point with FDLF method is that no acceleration factor is required.

The traditional Newton- Raphson method is also faster than the conventional Gauss- Seidal method. But for large systems computer core requirements for Jacobian matrix is very large in figure and for the computation of the elements of the Jacobian for each iteration requires additional computer time. The time per iteration increases directly as the number of buses of the network. Hence prohibitive computer memory requirements limits its use in the presented form to only small to medium size network. On the contrary, the reduction in memory requirements with some assumptions and approximations of the FDLF method has been made it attractive.

The tolerances being specified for the net real and reactive power at each bus in FDLF method are meaningful to the evaluators who specifies the desired accuracy. In this method number of iterations can be reduced by using updated values instead of simultaneous solution for $|V|$ and θ. With the use of updated value tolerance is reached for the said example in 5 iterations against 7 iterations of simultaneous solution. The time per iteration for the method is less because the number of arithmetic operations is reduced. The total time is required is less than any other method.

Inspite of all the advantages mentioned above, the FDLF method suffers from the disadvantage of poor convergence characteristics for systems having lines with large R/X ratios. The reliability of the method cannot always be taken for granted not only for systems having lines with large R/X ratios but also for systems having lines with capacitive series reactances and depending on the ill- condition the solution may not converge at all. However, it is well established that the FDLF method is superior to all existing methods as long as it provides a solution.

The program has been developed largely as a user oriented program. The developed program can handle any size of power system network (just by changing the DIMENSION statements) depending on the size of the computer memory. With the given dimension the program is capable of handling a system consisting of maximum 99 transmission lines, corresponding buses and power stations. The program has been structured in a way to minimize the memory requirements and total execution time. The developed program is very efficient i.e. very fast with less human intervention, in generalized form and suitable for bulk power system network. With small variations for the desired system the results can be obtained by a single computer RUN.

6.2 SUGGESTIONS FOR FURTHER WORK

The method described so far for the proposed work is potentially an important one, and the encoureging results quoted will stimulate others to investigate the algorithm further. Some recommendations for the future extention of the work may include the following:

1. To reduce computer memory storage requirements more in storing the non-zero elements of the matrices only sparsity programming may be done. The method of dividing a large anetwork (if it is too large) in different sections and solving each of them individually also offers great promise from the point of view of the savings in the computer core storage. Any one of these or a combinations of both may lead to a program completely independent of network size.
2. Investigations may be carried out for improving the reliability of convergence with ill- conditioned systems.

3. The developed program may be modified for on-line digital computation for load flow analysis.

4. A load- flow solution is not only of interest in itself but forms the starting point for the fault and stability programs. A generalized computer program may be developed for the mentioned three purposes with some additions to the developed program as shown by the following program relationships.

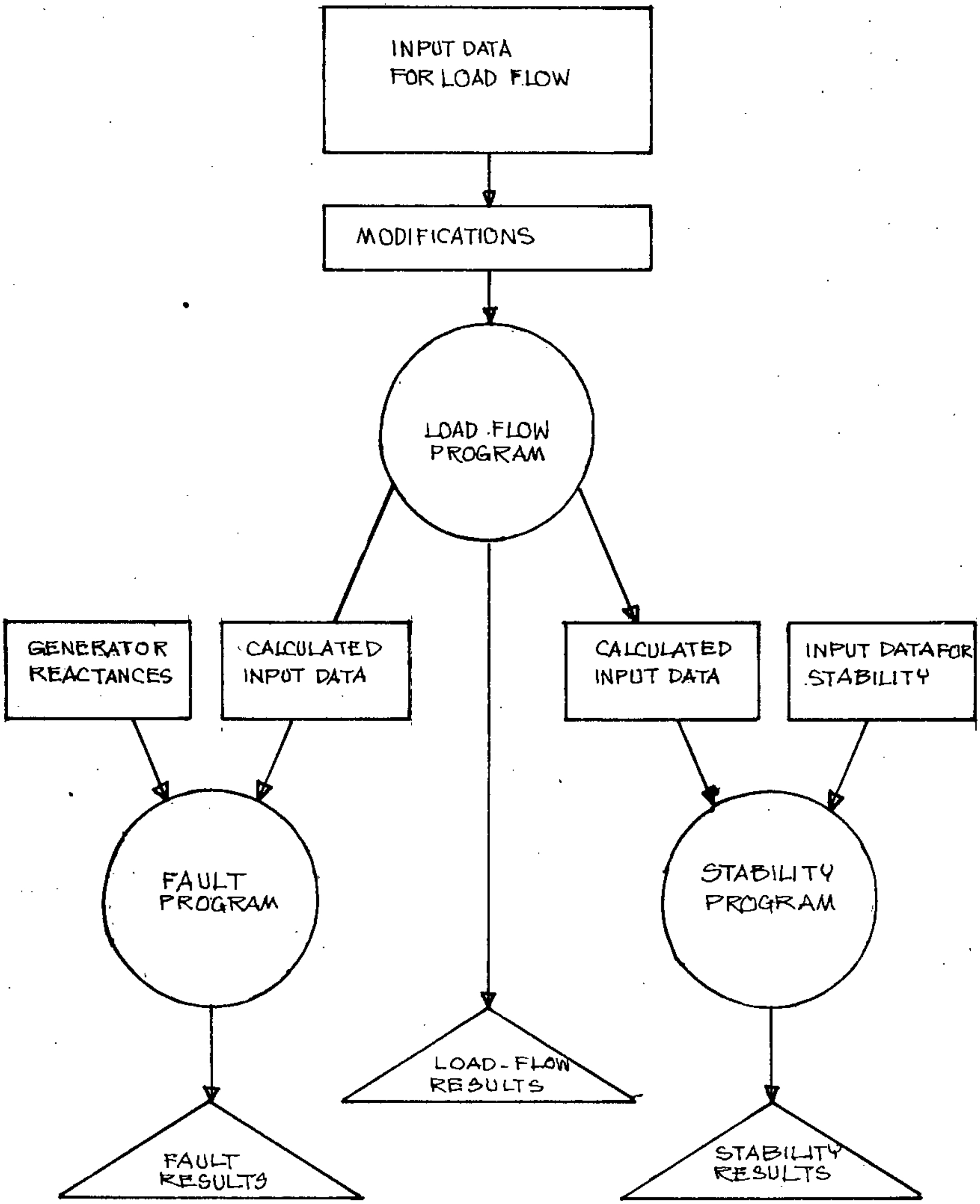


FIG. 6.1 PROGRAM RELATIONSHIPS.

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A- 1. ITERATIVE PROCESS

This is one of the techniques of solving non-linear equations. In this method, the unknown quantities are initially assumed and then set into the equation to be solved. The new value thus obtained replaces the initially assumed values and again set into the equation to obtain a new value. The same process is repeated until the values obtained for the unknowns converge to certain required limits. This is termed as iteration process. For digital solution of load flow problems iteration process has been employed by asigning estimated values to the unknown bus voltages and calculating a new value for each bus voltage from the estimated values at the other buses and the real and reactive power specified. A net set of values for voltage is thus obtained for each bus and used to calculate still another set of bus voltages. The iterative process is repeated until the changes at each bus are less than a specified minimum value.

A - 2. SPARSE MATRIX

In this type of matrix most of the elements are zero except a few non-zero elements. The degree of sparsity is determined by the number of zero elements. In a large power system the Y_{Bus} matrix is highly sparse. Since each bus is connected at best 3 to 4 other buses, in iterating for that bus only these entries are called for, through an efficient scheme of ordering and compact storage. By sparsity programming only the non-zero elements are stored. For the admittance matrix of order n the conventional storage requirements are n^2 words, but by sparsity programming 6b + 3n words are required, where b is the number of branches in the system. Typically b = 1.5n, and the total storage is 12n words. For a large system (say 500 buses) the ratio of storage requirements of conventional and sparse technique is about 40 : 1.

A - 3 TAP CHANGING UNDER LOAD TRANSFORMERS

Tap- changing- under- load transformer of magnitude and phase shifting type can control flow of both real and reactive power. Mainly it improves voltage conditions (both magnitude and phase) of the bus where voltage magnitude is less than the specified minimum. The standard change in tap-setting of the TCUL transformer is 5/8% per step.

The self admittances, Y_{pp} (for the bus p) and Y_{qq} (for the bus q) and the mutual admittance $Y_{pq} = Y_{qp}$, between the buses p and q must be recalculated for each and every change in tap-setting of the TCUL transformer.

5.4 TIE LINE CONTROL

In studies involving several interconnected power systems, the load flow solution must satisfy a specified net power interchange for each system. The first step in the procedure of solving the problem is to calculate a voltage solution for the entire system,with an assumed generation schedule for each system. Next,using this voltage solution,the individual tie line flows are calculated and algebrically summed by system to determine the actual net power interchanges,then,the actual and scheduled power interchanges for each system are compared to determine the adjustments that must be made in the assumed generation schedules.

APPENDICES

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      C  ****************************************************************
      C     PROJECT WORK-COMPUTER AIDED LOAD FLOW STUDY USING FAST DECOUPLED
      C     METHOD.
      C     SUPERVISOR-DR.JAMALUDDIN AHMED,ASSOCIATE PROFESSOR OF ELECTRICAL
      C     AND ELECTRONIC ENGINEERING DEPARTMENT,B.U.E.T,DHAKA,BANGLADESH.
      C     GENERALIZED PROGRAM DEVELOPED BY MD.SAIFUL HUDA,MASTER OF ENGINEERI
      C     NG STUDENT,FULL-TIME,ROLL NO.831327F,FACULTY OF ELECTRICAL & ELECT
      C     RONIC ENGINEERING,B.U.E.T,DHAKA,BANGLADESH.
      C     ****************************************************************
      C      ******************************************************************
      C******************************************************************************
      C      LOCATION----36026-48011,
      C      COMMON B1,B11,N
             DIMENSION ONTR(99),B1(44,44),B2(44,44),PG(99),QG(99),PL(99),QL(99)
            +,VM(99),VA(99),QMIN(99),QMAX(99), G(99,99),B(99,99),PK(99),QK(99),
            +DELP(99),DELPM(99,1),DANGM(99,1),B11(88,88),DELQ(99),DELQM(99,1),D
            +VOLTM(99,1),DANGL(99),DVOLT(99),NAME(99,3),VAD(99),BW(99,99),RLBUS
            +P(99),REBUSP(99)
             COMPLEX ZL(99),YH(99),YS(99,99),YL(99),YB(99,99),FLOW1(99),FLOW2(9
            +9),FLOWT(99),V(99),FSBP1,FSBP2,BUSP(99),LNC(99),FLOW3(99,99),FLOW4
            +(99,99),BIN(99),BOUT(99),BMISP(99),BGEN(99),BLOAD(99)
             INTEGER P(99),Q(99), LN(99), BN(99),IFLAG(99)
      C ZL=Z-LINE, YH=Y-HALF,   YS=Y-SHUNT,  YL=Y-LINE,   ONTR=OFF NOMINAL TURN RATIO
      C LNO=LINE NUMBER,  P,Q=BUS CODE,   NBUS=BUS NUMBER
      C      DANGM=ANGLE MATRIX, DVOLTM=VOLTAGE MATRIX
             BASE=1.0
             NBUS=6
             LNO=7
             CP=.00001
             CQ=.00001
             READ(1,2)  (LN(I),P(I),Q(I),ZL(I),YH(I),ONTR(I),I=1,LNO)
           2 FORMAT(3I5,5F10.4)
      C      *-----------------------------------------------------------*
      C      ***-----PRINTING OF SAMPLE PROBLEM LINE DATA AND BUS DATA.-----***
      C      *-----------------------------------------------------------*
             WRITE(3,2)  (LN(I),P(I),Q(I),ZL(I),YH(I),ONTR(I),I=1,LNO)
             READ(1,25)(BN(I),(NAME(I,J),J=1,3),PG(I),QG(I),PL(I),QL(I),VM(I),V
            +A(I),IFLAG(I),I=1,NBUS)
          25 FORMAT(I3,2X,3A4,F7.4,4F8.4,F5.3,I4)
             WRITE(3,28)(BN(I),(NAME(I,J),J=1,3),PG(I),QG(I),PL(I),QL(I),VM(I),
            +VA(I),IFLAG(I),I=1,NBUS)
          28 FORMAT(////,30X,'THE BUS DATA IS',/,30X,20('-'),///,(I3,2X,3A4,F7.
            +4,5F8.4,I4)/)
             QMIN(2)=0.0
             QMAX(2)=0.20
      C      *-----------------------------------------------------------*
      C      ***------------ FORMATION OF Y-BUS ADMITTANCE MATRIX.------------***
      C      *-----------------------------------------------------------*
             DO 4 I=1,LNO
             YL(I)=CMPLX(1.0,0.0)/ZL(I)
      C      IF(ONTR(I).NE.1.0) YL(I)=YL(I)/ONTR(I)
             WRITE(3,10)I,I,YL(I)
          10 FORMAT(/,5X,I5,5X,'YL(',I2,')=',F10.6,'+J',F10.6)
           4 CONTINUE
```

```
                NBUS=6
                DO 5 I=1,NBUS
                DO 5 J=1,NBUS
                YB(I,J)=CMPLX(0.0,0.0)
                YS(I,J)=CMPLX(0.0,0.0)
              5 CONTINUE
                DO 6 I=1,LNO
                A=ONTR(I)
C               IF(I.NE.11.OR.I.NE.12.OR.I.NE.15.OR.I.NE.36)GO TO 6
                YS(P(I),Q(I))=YL(I)*(1.0/A-1.0)
                YS(Q(I),P(I))=YL(I)*(A-1.0)
              6 CONTINUE
                WRITE(3,11)  ((I,J,YS(I,J),J=1,NBUS),I=1,NBUS)
C              +I,LNO)
             11 FORMAT  ('1',/,(5(1X,'YS(',I2,',',I2,')=',2F6.4)/))
C              +,')=',F10.4),/))
                N=NBUS
                DO 7 I=1,N
                DO 8 K=1,LNO
                II=P(K)
                JJ=Q(K)
                IF(II.NE.I.AND.JJ.NE.I) GO TO 8
                IF(II.EQ.I) J=JJ
                IF(JJ.EQ.I) J=II
                IF(J.EQ.0) GO TO 8
                IF(I.EQ.4.OR.I.EQ.6) GO TO 419
                YB(I,I)=YB(I,I)+YL(K)+YH(K)
                GO TO 420
            419 YB(I,I)=YB(I,I)+YL(K)/(ONTR(K)**2)+YH(K)
            420 YB(I,J)=YB(I,J)-YL(K)/ONTR(K)
                WRITE(3,12)I,I,YB(I,I),I,J,YB(I,J)
             12 FORMAT( /,10X,'YB(',I2,',',I2,')=',F10.4,'+J',F10.4,10X,'YB(',I2,
               +',',I2,')=',F10.4,'+J',F10.4)
              8 CONTINUE
C               IF(I.EQ.10)YB(I,I)=YB(I,I)+CMPLX(0.0,0.190)
C               IF(I.EQ.24)YB(I,I)=YB(I,I)+CMPLX(0.0,0.04)
              7 CONTINUE
                WRITE(3,9) ((I,J,YB(I,J),J=1,N),I=1,N)
              9 FORMAT('1',///,30X,'THE Y-BUS ADMITTANCE MATRIX OF THE SAMPLE SYST
               +EM IN P.U.',/,30X,60('-'),//,(4(2X,'YB(',I2,',',I2,')=',F8.4,'+J',
               +F8.4)/))
C               *------------------------------------------------------------*
C               ***----- FORMATION OF SUBMATRICES B1 AND B2 FROM Y-BUS--------***
C               *------------------------------------------------------------*
                N=NBUS-1
                DO 13 I=2,NBUS
                DO 14 J=2,NBUS
                L=I-1
                M=J-1
                B1(L,M)=-AIMAG(YB(I,J))
C               B1((I-1),(J-1))=-AIMAG(YB(I,J))
             14 CONTINUE
             13 CONTINUE
C               WRITE(3,17)(B1((I-1),J),J=1,N)
```

```
0064              WRITE(3,17)((L,M,B1(L,M),M=1,N),L=1,N)
0065           17 FORMAT('1',///,40X,'THE B1 MATRIX IS',/,40X,40('-'),/,(5(3X,'B1(',
                 +I2,',',I2,')=', F10.4),/))
0066              KIT=0
0067              KTH=0
0068              KV=0
            C     K=0
            C     DO 19 I=1,NBUS
            C     DO 19 J=1,NBUS
            C     G(I,J)=REAL(YB(I,J))
            C     B(I,J)=AIMAG(YB(I,J))
            C  19 CONTINUE
            C  80 DO 73 I=1,NBUS
            C     IF(I.EQ.2) IFLAG(I)=1
            C     IF(IFLAG(I).EQ.1) GO TO 74
            C     GO TO 73
            C  74 SUM2=0
            C     DO 75 J=1,NBUS
            C     SUM2=SUM2+(G(I,J)*SIN(VA(I)-VA(J))-B(I,J)*COS(VA(I)-VA(J)))*VM(J)
            C  75 CONTINUE
            C     QK(I)=VM(I)*SUM2
            C     WRITE(3,76) I,I,QK(I),I,VM(I)
            C  76 FORMAT('1',/,10X,'BUS NO=',I2,10X,'REACTIVE POWER=QK(',I2,')=',F10
            C    +.4,'BUS VOLTAGE=VM(',I2,')=',F10.4)
            C     IF(QK(I).LT.QMIN(I).OR.QK(I).GT.QMAX(I)) GO TO 77
            C     GO TO 73
            C  77 IFLAG(I)=0
            C     IF(QK(I).LT.QMIN(I)) QK(I)=QMIN(I)
            C     IF(QK(I).GT.QMAX(I)) QK(I)=QMAX(I)
            C     WRITE(3,78) I,QK(I)
            C  78 FORMAT('1',/,10X,'NEW VALUE OF QK(',I2,')=',F10.4)
            C  73 CONTINUE
0069           30 ICOUNT=0
0070              DO 79 I=1,NBUS
0071              IF(IFLAG(I).EQ.0)GO TO 79
0072              ICOUNT=ICOUNT+1
0073           79 CONTINUE
0074              I=1
0075              J=1
0076              N=NBUS-ICOUNT
0077              DO 15 L=1,N
0078              I=I+1
0079              IF(IFLAG(I).EQ.1) I=I+1
0080              J=1
            C     IF(I.EQ.3)I=I+1
0081              DO 16 M=1,N
0082              J=J+1
0083              IF(IFLAG(J).EQ.1) J=J+1
            C     L=I-2
            C     M=J-2
0084              B2(L,M)=-AIMAG(YB(I,J))
            C     B2((I-2),(J-2))=-AIMAG(YB(I,J))
            C     WRITE(3,250) L,M,B2(L,M),I,J,YB(I,J)
            C 250 FORMAT('1',///,10X,'B2(',I2,',',I2,')=',G10.4,10X,'YB(',I2,',',I2,
```

```
               C     +')=',F10.4,'+J',F10.4)
 0085                 16 CONTINUE
 0036                 15 CONTINUE
               C         WRITE(3,18)(B2((I-2),J);J=1,N)
 0087                    WRITE(3,18)((L,M,B2(L,M),M=1,N),L=1,N)
 0088                 18 FORMAT('1',///,40X,'THE B2 MATRIX IS',/,40X,40('-'),/,(5(3X,'B2(',
                        +I2,',',I2,')=', G10.4),/))
               C         N=NBUS-6
               C         DO 250 L=1,N
               C         DO 251 M=1,N
               C         BW(L,M)=22(I,J)
               C 251 CONTINUE
               C 250 CONTINUE
               C         WRITE(3,252)  ((L,M,BW(L,M),M=1,N),L=1,N)
               C 252 FORMAT('1',///,40X,'THE BW MATRIX IS',/,40X,40('-'),/,(5(3X,'BW(',
               C        +I2,',',I2,')=',F10.4),/))
               C  15 CONTINUE
               C         READ(1,25)(IBN(I),(NAME(I,J),J=1,3),PG(I),QG(I),PL(I),QL(I),VM(I),
               C        +VA(I),QMIN(I),QMAX(I),I=1,NBUS)
               C        +,NBUS)
               C  25 FORMAT(I3,2X,3A4,F7.4,7F8.4)
               C         WRITE(3,28)(IBN(I),(NAME(I,J),J=1,3),PG(I),QG(I),PL(I),QL(I),VM(I)
               C        +,VA(I),QMIN(I),QMAX(I),I=1,NBUS)
               C  28 FORMAT(////,30X,'THE BUS DATA IS',/,30X,20('-'),///,(I5,3X,3A4,8F8
               C        +.4)/)
               C         *-----------------------------------------------------------------*
               C         ***---SEPERATION OF REAL AND IMAGINARY PARTS OF Y-BUS MATRIX---***
               C         *-----------------------------------------------------------------*
 0089                    K=0
 0090                    DO 19 I=1,NBUS
 0091                    DO 19 J=1,NBUS
 0092                    G(I,J)=REAL(YB(I,J))
 0093                    B(I,J)=AIMAG(YB(I,J))
 0094                 19 CONTINUE
               C         WRITE(3,26) ((I,J,G(I,J),J=1,NBUS),I=1,NBUS)
               C  26 FORMAT(//,35X,'THE G-MATRIX IS',/,35X,24('-'),//,(5(1X,'G(',I2,','
               C        +,I2,')=', F10.4)/))
               C         WRITE(3,27) ((I,J,B(I,J),J=1,NBUS),I=1,NBUS)
               C  27 FORMAT(//,35X,'THE B-MATRIX IS',/,35X,24('-'),//,(5(1X,'B(',I2,','
               C        +,I2,')=', F10.4)/))
               C         DELP(I)=CHANGE OF REAL POWER,   DELQ(I)=CHANGE OF REACTIVE POWER
               C         KIT=0
               C         KTH=0
               C         KV=0
               C         *-----------------------------------------------------------------*
               C         ***---------------------ITERATION STARTS-------------------------***
               C         ***-----CALCULATION OF DELP AND FORMATION OF COLUMN MATRIX------***
               C         *-----------------------------------------------------------------*
               C  70 SUM1=0.0
 0_95                    SUM2=0.0
 0096                    KK=1
 0097                    KKK=1
 0098                    AMAX1=0.0
 0099                    AMAX2=0.0
```

```
0100              DO 20 I=1,NBUS
             C
0101              IF(I.EQ.1) GO TO 20
0102              SUM1=0.0
0103              DO 21 J=1,NBUS
0104              SUM1=SUM1+(G(I,J)*COS(VA(I)-VA(J))+B(I,J)*SIN(VA(I)-VA(J)))*VM(J)
0105           21 CONTINUE
0106              PK(I)=VM(I)*SUM1
0107              DELP(I)=(PG(I)-PL(I))/BASE-PK(I)
             C    AMAX1=ABS(DELP(2))
0108              IF(AMAX1-ABS(DELP(I)))39,40,40
0109           39 AMAX1=ABS(DELP(I))
0110           40 DELPM(KK,1)=DELP(I)/VM(I)
             C    KK=KK+1
             C    WRITE(3,23)I,PK(I),I,DELP(I),KK,DELPM(KK,1),AMAX1,SUM1
0111              KK=KK+1
             C 23 FORMAT(10X,'PK(',I2,')=',F10.4,5X,'DELP(',I2,')=',F10.4,5X,'DELPM(
             C   +',I2,',1)=',F10.4,5X,'AMAX1=',F10.4,5X,'SUM1=',F10.4,/)
             C    IF(I.EQ.1.OR.I.EQ.2.OR.I.EQ.5.OR.I.EQ.8.OR.I.EQ.11.OR.I.EQ.13) GO
             C   +TO 20
             C    SUM2=0.0
             C    DO 22 J=1,NBUS
             C    SUM2=SUM2+(G(I,J)*SIN(VA(I)-VA(J))-B(I,J)*COS(VA(I)-VA(J)))*VM(J)
             C    SUM2=SUM2+(G(I,J)*SIN(VA(I)-VA(J))-B(I,J)*COS(VA(I)-VA(J)))*VM(J)
             C 22 CONTINUE
             C    QK(I)=VM(I)*SUM2
             C    DELQ(I)=(QG(I)-QL(I))/BASE-QK(I)
             C    IF(AMAX2-ABS(DELQ(I)))41,42,42
             C 41 AMAX2=ABS(DELQ(I))
             C 42 DELQM(KKK,1)=DELQ(I)/VM(I)
             C    WRITE(3,24)I,QK(I),I,DELQ(I),KKK,DELQM(KKK,1),AMAX2,SUM2
             C    KKK=KKK+1
             C 24 FORMAT(10X,'QK(',I2,')=',F10.4,5X,'DELQ(',I2,')=',F10.4,5X,'DELQM(
             C   +',I2,',1)=',F10.4,5X,'AMAX2=',F10.4,5X,'SUM2=',F10.4,/)
0112           20 CONTINUE
             C HAS BEEN BROUGHT FROM THE NEXT PAGE
             C 20 CONTINUE
0113              IF(AMAX1-.0001)51,51,52
0114           52 KV=0
0115              GO TO 53
0116           51 KTH=1
0117              IF(KV-1.0)54,55,54
             C    *-----------------------------------------------------------*
             C    ***----INVERTION OF B1-MATRIX AND CALCULATION OF ANGLES--------****
             C    *-----------------------------------------------------------*
0118           53 N=NBUS-1
0119              CALL INVERS(B1,B11,N)
0120              WRITE(3,29)((I,J,B11(I,J),J=1,N),I=1,N)
0121           29 FORMAT('1',///,30X,'THE INVERSE OF B1 MATRIX IS',/,30X,30('-'),//,
                 +(6(1X,'B11(',I2,',',I2,')=',F6.4)/))
0122              DO 310 I=1,N
0123              DO 320 J=1,1
0124              DANGM(I,J)=0.0
0125              DO 31 K=1,N
```

```
0126            DANGM(I,J)=DANGM(I,J)+B11(I,K)*DELPM(K,J)
0127         31 CONTINUE
0128        320 CONTINUE
0129        310 CONTINUE
          C     WRITE(3,32)((DANGM(I,J),J=1,1),I=1,N)
          C  32 FORMAT(///,30X,'THE ANGLE MATRIX IS',/,30X,30('-'),//,(15X,5F10.4,
          C    +//))
0130            I=0
0131            DO 37 K=1,NBUS
          C     IF(K.EQ.1)GO TO 37
0132            IF(K.EQ.1)GO TO 37
0133            I=I+1
0134            DANGL(K)=DANGM(I,1)
0135            VA(K)=VA(K)+DANGL(K)
0136            VAD(K)=VA(K)*57.29578
          C     WRITE(3,35)K,DANGL(K),K,VA(K),K,VAD(K)
          C  35 FORMAT(///,10X,'DANGL(',I2,')=',F10.4,10X,'VA(',I2,')=',F10.4,10X,
          C    1'VAD(',I2,')=',F10.4,//)
0137         37 CONTINUE
0138            SUM2=0.0
0139            KKK=1
0140            AMAX2=0.0
          C     *------------------------------------------------------------------*
          C     ***-----CALCULATION OF DELQ AND FORMATION OF COLUMN MATRIX-----***
          C     *------------------------------------------------------------------*
0141            DO 50 I=1,NBUS
0142            IF(IFLAG(I).EQ.1.OR.IFLAG(I).EQ.2)                          GO
               +TO 50
0143            SUM2=0.0
0144            DO 22 J=1,NBUS
0145            SUM2=SUM2+(G(I,J)*SIN(VA(I)-VA(J))-B(I,J)*COS(VA(I)-VA(J)))*VM(J)
0146         22 CONTINUE
0147            QK(I)=VM(I)*SUM2
0148            DELQ(I)=(QG(I)-QL(I))/BASE-QK(I)
0149            IF(AMAX2-ABS(DELQ(I)))41,42,42
0150         41 AMAX2=ABS(DELQ(I))
0151         42 DELQM(KKK,1)=DELQ(I)/VM(I)
          C     WRITE(3,24)I,QK(I),I,DELQ(I),KKK,DELQM(KKK,1),AMAX2,SUM2
0152            KKK=KKK+1
          C  24 FORMAT(10X,'QK(',I2,')=',F10.4,5X,'DELQ(',I2,')=',F10.4,5X,'DELQM(
          C    +',I2,',1)=',F10.4,5X,'AMAX2=',F10.4,5X,'SUM2=',F10.4,/)
0153         50 CONTINUE
0154         54 IF(AMAX2-.0001)61,61,62
0155         62 KTH=0
0156            GO TO 63
0157         61 KV=1
0158            IF(KTH-1)64,55,64
          C     *------------------------------------------------------------------*
          C     ***---INVERTION OF B2 MATRIX AND CALCULATION OF BUS VOLTAGE----***
          C     *------------------------------------------------------------------*
0159         63 N=NBUS-ICOUNT
          C     DO 1001 I=1,N
          C     DO 1001 J=1,N
          C     B1(I,J)=B2(I,J)
```

```
          C1001 CONTINUE
0160            CALL INVERS(B2,B11,N)
          C
0161            WRITE(3,30)((I,J,B11(I,J),J=1,N),I=I,N)
0162         30 FORMAT(///,30X,'THE INVERSE OF B2 MATRIX IS',/,30X,30('-'),//,(6(3
               +X,'B22(',I2,',',I2,')=',F6.4),/))
0163            DO 330 I=1,N
0164            DO 340 J=1,1
0165            DVOLTM(I,J)=0.0
0166            DO 33 K=1,N
0167            DVOLTM(I,J)=DVOLTM(I,J)+B11(I,K)*DELQM(K,J)
0168         33 CONTINUE
0169        340 CONTINUE
0170        330 CONTINUE
0171            WRITE(3,34)((DVOLTM(I,J),J=1,1),I=1,N)
0172         34 FORMAT(///,30X,'THE VOLTAGE MATRIX IS',/,30X,30('-'),//,(5X,10F10.
               +4,//))
0173            I=0
0174            DO 38 K=1,NBUS
0175            IF(IFLAG(K).EQ.2.OR.IFLAG(K).EQ.1)                          GO
               +TO 38
0176            I=I+1
0177            DVOLT(K)=DVOLTM(I,1)
0178            VM(K)=VM(K)+DVOLT(K)
0179            IF(K.EQ.1.OR.K.EQ.2) VM(K)=VM(K)-DVOLT(K)
0180            WRITE(3,36)K,DVOLT(K),K,VM(K)
0181         36 FORMAT(///,10X,'DVOLT(',I2,')=',F10.4,10X,'VM(',I2,')=',F10.4,//)
0182         38 CONTINUE
0183            DO 73 I=1,NBUS
0184            IF(I.EQ.2) IFLAG(I)=1
0185            IF(IFLAG(I).EQ.1) GO TO 74
0186            GO TO 73
0187         74 SUM2=0
0188            DO 75 J=1,NBUS
0189            SUM2=SUM2+(G(I,J)*SIN(VA(I)-VA(J))-B(I,J)*COS(VA(I)-VA(J)))*VM(J)
0190         75 CONTINUE
0191            QK(I)=VM(I)*SUM2
0192            WRITE(3,76) I,I,QK(I),I,VM(I)
0193         76 FORMAT('1',/,10X,'BUS NO=',I2,10X,'REACTIVE POWER=QK(',I2,')=',F10
               +.4,'BUS VOLTAGE=VM(',I2,')=',F10.4)
0194            IF(QK(I).LT.QMIN(I).OR.QK(I).GT.QMAX(I)) GO TO 77
0195            GO TO 73
0196         77 IFLAG(I)=0
0197            IF(QK(I).LT.QMIN(I)) QK(I)=QMIN(I)
0198            IF(QK(I).GT.QMAX(I)) QK(I)=QMAX(I)
0199            WRITE(3,78) I,QK(I)
0200         78 FORMAT('1',/,10X,'NEW VALUE OF QK(',I2,')=',F10.4)
0201         73 CONTINUE
          C     *-------------------------------------------------------------*
          C     ****---------------------NEXT ITERATION STARTS----------------****
          C     *-------------------------------------------------------------*
0202         64 KIT=KIT+1
0203            WRITE(3,900)KIT
0204        900 FORMAT(/,10X,'NUMBER OF ITERATION=',I2)
```

```
0205          IF(KIT.EQ.50)GO TO 84
0206          GO TO 30
        C CALCULATION OF POWER STARTS
0207       55 DO 71 I=1,NBUS
0208          X=VM(I)*COS(VA(I))
0209          Y=VM(I)*SIN(VA(I))
0210          V(I)=CMPLX(X,Y)
0211          WRITE(3,98)I,V(I)
0212       98 FORMAT(/,10X,'V(',I2,')=',F10.4,'+J',F10.4)
0213       71 CONTINUE
        C     ***************************************************************
        C     *-----------COMPUTION OF LINE FLOWS AND LION-LOSSES-------------*
        C     ***************************************************************
0214          BASE=1.0
0215          DO 81 I=1,LNO
0216          YL(I)=CMPLX(1.0,0.0)/ZL(I)
0217          YL(I)=YL(I)/ONTR(I)
0218          FLOW1(I)=V(P(I))*(CONJG(V(P(I))-V(Q(I)))*CONJG(YL(I))
             +  +CONJG(V(P(I)))*(CONJG(YH(I))-CONJG(YS(P(I),Q(I)))))
0219          FLOW1(I)=FLOW1(I)*BASE
0220          FLOW2(I)=V(Q(I))*(CONJG(V(Q(I))-V(P(I)))*CONJG(YL(I))
             +  +CONJG(V(Q(I)))*(CONJG(YH(I))-CONJG(YS(Q(I),P(I)))))
0221          FLOW2(I)=FLOW2(I)*BASE
0222          IF(I.EQ.5) FLOW2(I)=FLOW2(I)+CMPLX(0.0,0.1189)
0223          FLOWT(I)=FLOW1(I)+FLOW2(I)
0224          WRITE(3,82)(P(I),Q(I),FLOW1(I),FLOW2(I),FLOWT(I))
0225       81 CONTINUE
0226          WRITE(3,106)
0227      106 FORMAT('1',////,55X,'---TABLE 5.5 ---',//,50X,'-REPORT ON LINE
             +FLOWS-',//,50X,24('-'),//,5X,115('-'),//,10X,'LINE',5X,'BUS CODE',
             +16X,'POWER FLOW',18X,'BUS CODE',16X,'POWER FLOW',//,10X,'NO.',6X,
             +'P',6X,'Q',10X,'ACTIVE',10X,'REACTIVE',10X,'Q',6X,'P',10X,'ACTIVE'
             +,10X,'REACTIVE',//,5X,115('-'))
0228          WRITE(3,82) (I,P(I),Q(I),FLOW1(I),Q(I),P(I),FLOW2(I),I=1,LNO)
0229       82 FORMAT((//,7X, I5,3X,I5,2X,I5,8X,F10.6,6X,F10.6,6X,I5,2X,I5,10X,F
             +10.6,4X,F10.6,//,5X,115('-'))/)
0230          FSBP1=FLOW1(1)+FLOW1(2)
        C     FSBP1=FSBP1*BASE
0231          FSBP2=FLOW2(1)+FLOW2(2)
        C     FSBP2=FSBP2*BASE
0232          WRITE(3,83)FSBP1,FSBP2
0233       83 FORMAT(////,5X,'THE SLACK BUS POWER IS=',/,5X,20('-'),//,'FSBP1=',
             +F10.4,'+J',F10.4,/,'FSBP2=',F10.4,'+J',F10.4)
0234          N=NBUS
0235          DO 99 I=1,N
0236          DO 99 J=1,N
0237          FLOW3(I,J)=CMPLX(0.0,0.0)
0238          FLOW4(I,J)=CMPLX(0.0,0.0)
0239       99 CONTINUE
0240          DO 93 I=1,LNO
0241          FLOW3(P(I),Q(I))=FLOW1(I)
0242          FLOW4(Q(I),P(I))=FLOW2(I)
        C     WRITE(3,94)(P(I),Q(I),FLOW3(P(I),Q(I)),Q(I),P(I),FLOW4(Q(I),P(I)))
        C  94 FORMAT('1',/,'FLOW3(',I2,',',I2,')=',F10.4,'+J',F10.4,10X,'FLOW4('
```

```
               C     +,I2,',',I2,')=',F10.4,'+J',F10.4,/)
 0243               93 CONTINUE
 0244                  DO 95 I=1,NBUS
 0245                  BUSP(I)=CMPLX(0.0,0.0)
 0246                  BIN(I)=CMPLX(0.0,0.0)
 0247                  BOUT(I)=CMPLX(0.0,0.0)
 0248                  DO 96 J=1,NBUS
 0249                  BUSP(I)=BUSP(I)+FLOW3(I,J)+FLOW4(I,J)
 0250                  BOUT(I)=BOUT(I)+FLOW3(I,J)
 0251                  BIN(I)=BIN(I)+FLOW4(I,J)
 0252               96 CONTINUE
 0253                  BMISP(I)=BIN(I)+BOUT(I)
 0254               95 CONTINUE
 0255                  WRITE(3,902)(I,BUSP(I),I=1,NBUS)
 0256              902 FORMAT(/,5X,'BUS NUMBER=',I5,5X,'BUS POWER=',F10.4,'+J',F10.4)
 0257                  DO 501 I=1,NBUS
 0258                  BGEN(I)=CMPLX(0.0,0.0)
 0259                  BLOAD(I)=CMPLX(0.0,0.0)
 0260              501 CONTINUE
 0261                  DO 556 I=1,NBUS
 0262                  IF(I.EQ.1.OR.I.EQ.2) GO TO 557
 0263                  GO TO 556
 0264              557 BGEN(I)=BUSP(I)
 0265              556 CONTINUE
 0266                  DO 558 I=1,NBUS
 0267                  IF(I.EQ.3.OR.I.EQ.4.OR.I.EQ.5.OR.I.EQ.6) GO TO 559
 0268                  GO TO 558
 0269              559 BLOAD(I)=BUSP(I)
 0270.             558 CONTINUE
 0271                  WRITE(3,107)
 0272              107 FORMAT('1',////,55X,'---TABLE 5.6 ---',//,40X,'---COMPLETE REPORT
                      +OF LOAD FLOW STUDY---',//,40X,40('-'),//,5X,115('-'),//,65X,'G E N
                      + E R A T I O N ',25X,'L O A D ',//,8X,'BUS',5X,'NAME',7X,'VOLTS',
                      +10X,'ANGLE',10X,'M.W.(P.U.)',9X,'M.VAR.(P.U.)',10X,'M.W.(P.U.)',
                      +9X,'M.VAR.(P.U.)',//,5X,115('-'))
 0273                  WRITE(3,903) (I,(NAME(I,J),J=1,3),VM(I),VAD(I),BGEN(I),BLOAD(I),I=
                      +1,NBUS)
 0274              903 FORMAT((/,9X,I1,3X,3A4,1X,F10.6,4X,F10.6,9X,F10.6,9X,F10.6,11X,F10
                      +.6,9X,F10.6,//,5X,120('-'))/)
 0275                  WRITE(3,108)(I,FLOWT(I),I=1,LNO)
 0276              108 FORMAT('1',////,55X,'---TABLE NO. 5.7---',//,55X,'-LINE LOSSES-',/
                      +/,55X,20('-'),//,16X,99('-'),//,20X,'LINE NO.',20X,'REAL POWER',20
                      +X,'REACTIVE POWER',//,(1(20X,I5,22X,F10.6,20X,F10.6),//,5X,99('-')
                      +/))
               C       WRITE(3,109)(I,BMISP(I),I=1,NBUS)
               C   109 FORMAT(/////////,55X,'---TABLE NO. 5.8---',//,55X,'---BUS MISMATCH
               C      + POWER---',//,55X,20('-'),//,20X,'BUS NO.',15X,'REAL POWER',20X,'
               C      + REACTIVE POWER',//,(1(19X,I5,17X,F10.6,20X,F10.6)/))
 0277               84 STOP
 0278                  END
```

// EXEC

1	1	4	0.0800	0.3700	0.0	0.0150	1.0000
2	1	6	0.1230	0.5180	0.0	0.0210	1.0000
3	2	3	0.7230	1.0500	0.0	0.0	1.0000
4	2	5	0.2820	0.6400	0.0	0.0	1.0000
5	3	4	0.0	0.1330	0.0	0.0	0.9090
6	4	6	0.0970	0.4070	0.0	0.0150	1.0000
7	5	6	0.0	0.3000	0.0	0.0	0.9750

THE BUS DATA IS

1	SLACK BUS	0.0	0.0	0.0	0.0	1.0500	0.0	2
2	P-V BUS	0.5000	0.0	0.0	0.0	1.1000	0.0	1
3	P-Q BUS	0.0	0.0	0.5500	0.1300	1.0000	0.0	0
4	P-Q BUS	0.0	0.0	0.0	0.0	1.0000	0.0	0
5	P-Q BUS	0.0	0.0	0.3000	0.1800	1.0000	0.0	0
6	P-Q BUS	0.0	0.0	0.5000	0.0500	1.0000	0.0	0

```
1     YL( 1)=  0.558269+J -2.581996
2     YL( 2)=  0.433934+J -1.827463
3     YL( 3)=  0.444861+J -0.646063
4     YL( 4)=  0.576541+J -1.308461
5     YL( 5)=  0.0     +J -7.518799
6     YL( 6)=  0.554102+J -2.324945
7     YL( 7)=  0.0     +J -3.333333
```

THE Y-BUS ADMITTANCE MATRIX OF THE SAMPLE SYSTEM IN P.U.

YB(1, 1)= 0.9922+J -4.3735	YB(1, 2)= 0.0 +J 0.0	YB(1, 3)= 0.0 +J 0.0	YB(1, 4)= -0.5583+J 2.5820
YB(1, 5)= 0.0 +J 0.0	YB(1, 6)= -0.4339+J 1.8275	YB(2, 1)= 0.0 +J 0.0	YB(2, 2)= 1.0214+J -1.9545
YB(2, 3)= -0.4449+J 0.6461	YB(2, 4)= 0.0 +J 0.0	YB(2, 5)= -0.5765+J 1.3085	YB(2, 6)= 0.0 +J 0.0
YB(3, 1)= 0.0 +J 0.0	YB(3, 2)= -0.4449+J 0.6461	YB(3, 3)= 0.4449+J -8.1649	YB(3, 4)= 0.0 +J 8.2715
YB(3, 5)= 0.0 +J 0.0	YB(3, 6)= 0.0 +J 0.0	YB(4, 1)= -0.5583+J 2.5820	YB(4, 2)= 0.0 +J 0.0
YB(4, 3)= 0.0 +J 8.2715	YB(4, 4)= 1.1124+J-13.9765	YB(4, 5)= 0.0 +J 0.0	YB(4, 6)= -0.5541+J 2.3249
YB(5, 1)= 0.0 +J 0.0	YB(5, 2)= -0.5765+J 1.3085	YB(5, 3)= 0.0 +J 0.0	YB(5, 4)= 0.0 +J 0.0
YB(5, 5)= 0.5765+J -4.6418	YB(5, 6)= 0.0 +J 3.4188	YB(6, 1)= -0.4339+J 1.8275	YB(6, 2)= 0.0 +J 0.0
YB(6, 3)= 0.0 +J 0.0	YB(6, 4)= -0.5541+J 2.3249	YB(6, 5)= 0.0 +J 3.4188	YB(6, 6)= 0.9880+J -7.6229

THE B1 MATRIX IS

B1(1, 1)= 1.9545	B1(1, 2)= -0.6461	B1(1, 3)= 0.0	B1(1, 4)= -1.3085	B1(1, 5)= 0.0
B1(2, 1)= -0.6461	B1(2, 2)= 8.1649	B1(2, 3)= -8.2715	B1(2, 4)= 0.0	B1(2, 5)= 0.0
B1(3, 1)= 0.0	B1(3, 2)= -8.2715	B1(3, 3)= 13.9765	B1(3, 4)= 0.0	B1(3, 5)= -2.3249
B1(4, 1)= -1.3085	B1(4, 2)= 0.0	B1(4, 3)= 0.0	B1(4, 4)= 4.6418	B1(4, 5)= -3.4188
B1(5, 1)= 0.0	B1(5, 2)= 0.0	B1(5, 3)= -2.3249	B1(5, 4)= -3.4188	B1(5, 5)= 7.6229

THE B2 MATRIX IS

B2(1, 1)= 8.165	B2(1, 2)=-8.272	B2(1, 3)=0.0	B2(1, 4)=0.0	B2(2, 1)=-8.272
B2(2, 2)= 13.98	B2(2, 3)=0.0	B2(2, 4)=-2.325	B2(3, 1)=0.0	B2(3, 2)=0.0
B2(3, 3)= 4.642	B2(3, 4)=-3.419	B2(4, 1)=0.0	B2(4, 2)=-2.325	B2(4, 3)=-3.419
B2(4, 4)= 7.623	B2(			

APPENDIX-C


```
C      ***************************************************************
C      *---- SUBROUTINE PROGRAM FOR THE INVERTION OF B1 & B2 MATRIX-----*
C      ***************************************************************
C      SUBROUTINE PROGRAM
       SUBROUTINE INVERS(X,Y,N)
C      COMMON X,Y,N
       DIMENSION X(44,44),Y(83,88)
       DO 200 I=1,N
       DO 200 J=1,N
       Y(I,J)=X(I,J)
   200 CONTINUE
       ITN=2*N
       I=1
   110 J=N+1
   100 IN=I+N
       IF(IN.EQ.J) GO TO 80
       Y(I,J)=0.0
       GO TO 90
    80 Y(I,J)=1.0
    90 J=J+1
       IF(J.LE.ITN) GO TO 100
       I=I+1
       IF(I.LE.N) GO TO 110
       K=1
   160 J=K
       S=Y(K,K)
   120 Y(K,J)=Y(K,J)/S
       J=J+1
       IF(J.LE.ITN) GO TO 120
       I=1
   150 IF(I.EQ.K) GO TO 140
       J=K
       S=Y(I,K)
   130 Y(I,J)=Y(I,J)-S*Y(K,J)
       J=J+1
       IF(J.LE.ITN) GO TO 130
   140 I=I+1
       IF(I.LE.N) GO TO 150
       K=K+1
       IF(K.LE.N) GO TO 160
       DO 190 I=1,N
       DO 190 J=1,N
       M=N+J
       Y(I,J)=Y(I,M)
   190 CONTINUE
       RETURN
       END
```

THE INVERSE OF B1 MATRIX IS

B11(1, 1)=0.9181 B11(1, 2)=0.2968 B11(1, 3)=0.2212 B11(1, 4)=0.4607 B11(1, 5)=0.2741 B11(2, 1)=0.2968
B11(2, 2)=0.4445 B11(2, 3)=0.2947 B11(2, 4)=0.2238 B11(2, 5)=0.1903 B11(3, 1)=0.2212 B11(3, 2)=0.2947
B11(3, 3)=0.2737 B11(3, 4)=0.1849 B11(3, 5)=0.1664 B11(4, 1)=0.4607 B11(4, 2)=0.2238 B11(4, 3)=0.1849
B11(4, 4)=0.5776 B11(4, 5)=0.3155 B11(5, 1)=0.2741 B11(5, 2)=0.1903 B11(5, 3)=0.1664 B11(5, 4)=0.3155
B11(5, 5)=0.3234 B11(

THE INVERSE OF B2 MATRIX IS

B22(1, 1)=0.3466 B22(1, 2)=0.2232 B22(1, 3)=0.0749 B22(1, 4)=0.1017 B22(2, 1)=0.2232 B22(2, 2)=0.2204
B22(2, 3)=0.0739 B22(2, 4)=0.1004 B22(3, 1)=0.0749 B22(3, 2)=0.0739 B22(3, 3)=0.3465 B22(3, 4)=0.1779
B22(4, 1)=0.1017 B22(4, 2)=0.1004 B22(4, 3)=0.1779 B22(4, 4)=0.2416 B22(

THE VOLTAGE MATRIX IS

-0.0152 -0.0827 -0.0849 -0.0375

DVOLT(3)=	-0.0152	VM(3)=	0.9848
DVOLT(4)=	-0.0827	VM(4)=	0.9173
DVOLT(5)=	-0.0849	VM(5)=	0.9151
DVOLT(6)=	-0.0375	VM(6)=	0.9125