LOAD FLOW PROGRAM DEVELOPMENT

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PREFACE

The purpose of the project reported here was to develop a digital load flow computer program to be used by engineering students who wish to study the behavior of electric-energy systems.

I gratefully acknowledge the help and suggestions received from Professor Floyd W. Harris, my academic advisor. I would also like to thank the Kansas State University Computing Center in helping with the troubleshooting of my program when I could not find the error.

Alan G. Barta

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CHAPTER I

INTRODUCTION

The purpose of the project reported here was to develop a digital load flow computer program to be used by engineering students who wish to study the behavior of electric energy systems. Digital computer programs of this variety have existed in the industry for a number of years, however none have existed at Kansas State University. With the resurgence of interest in the study of electric energy systems on the part of students and faculty of the College of Engineering, it became apparent that there was a need for a package of digital computer programs that would allow one to study electric energy networks of realistic size. The program developed and reported here is the first such program.

The term load flow studies is used by engineers engaged in the planning, design, and operation of electric energy systems to describe technical studies requiring the solution of the static load flow equations of an electrical network for specified bus conditions.

In its most fundamental form the load flow problem can be stated as follows:

Given the following information about the network and its equipment

1. The injected real power at each bus except one (referred to as the swing or slack bus).
2. The desired voltage at all buses where there is an active source of reactive power (generator or synchronous condenser).
3. Capability limitations on the injected reactive power at the buses where there is an active source of reactive power.

4. The real and reactive demand (load) at every bus.
5. An appropriate model for each transmission line, each transformer (including static tap settings), and each static capacitor/reactor.
6. The bus interconnection scheme.

Determine

1. The injected real power at the slack bus.
2. The injected reactive power at all buses where there is an active source of reactive power.
3. The transmission line real and reactive power flows.
4. The real and reactive power flows through all transformers.
5. The magnitude and phase of all bus voltages.
6. The total system transmission losses.

The digital computer program developed by the author and presented in this report implements this classic form of the load flow problem.

The load flow problem differs from the classic network problem in that the primary objective of the load flow studies is to calculate power flows directly, whereas the primary objective in classic network studies is to calculate voltages and currents directly. This means that the load flow studies require that we solve a set of nonlinear algebraic equations rather than the linear set normally associated with the classic network problem. There is also a more subtle difference. The classic network problem is usually formulated in such a way that either the terminal voltage or terminal current of every energy source is specified, and one is required to calculate the voltages and currents associated with the passive (load) elements. The load flow problem is always formulated in such a way that the product of the current and voltage associated with the load elements is specified, and one is charged with finding the products of source terminal voltages and currents that are necessary to maintain network equilibrium. In the case of power networks, network equilibrium means maintain constant frequency.

Many numerical techniques [1, 2] have been used to solve the load flow equations. The more successful programs have used either the Gauss-Seidel or the Newton-Raphson procedure to solve the equations. Both procedures were studied and implemented in the program developed for this project.

The network equations have been formulated using either a loop frame of reference or the bus frame of reference. Each has some advantages and some disadvantages, depending upon one's ultimate objectives. The bus reference frame was selected for this project since it easily allows the modelling of shunt passive elements, i.e. passive elements with one terminal connected to a non-ground bus and one terminal connected to ground. Transmission line charging capacitances and static reactive power sources are examples of passive elements that are connected in this way. More detail about the actual formulation and solution of the network equations will be given later.

A brief history of the development of digital computer load flow programs is given in the last section of this chapter.

Chapter II gives the details concerning the equations to be solved and outlines the procedure used. A complete listing of the program is included in Appendix A, along with appropriate remarks identifying the program variable names.

Chapter III presents sample results from two electric energy systems that were used as test cases during the program development. One of these is a small system (14 buses and 20 transmission lines), and the other is a moderately large system (57 buses and 80 transmission lines). Both are test systems that have been used extensively in the industry to compare various numerical techniques. The data for these test systems was made available by the American Electric Power Service Corporation and represents a part of that system.

Chapter IV contains some suggestions for program improvement.

A User's Guide for the program is included as an Appendix B.

History of Load-Flow Studies

Many load flow studies of a power system are needed in order to operate that system satisfactorily. In the early days of power systems the only means of accomplishing these load flow studies was by hand calculations. The procedures, for even a simple system, were very tedious and time consuming. In 1929 the General Electric Company and the Massachusetts Institute of Technology built an A-C Network Analyzer [3]. This A-C network analyzer, also called an A-C calculating board or an A-C network calculator, was a single-phase miniature replica of an actual power system. It consisted of a number of A-C voltage sources, which could be adjusted in magnitude and phase. It included several resistors, inductances, and capacitances, all of which were adjustable. The voltage sources and circuit elements could be interconnected in many configurations to represent an actual network scaled down to a convenient size. The frequency used with the first board was 60 hertz, but other boards were built using frequencies of 440, 480 and 10,000 hertz [3]. The use of higher frequencies allowed the use of smaller components on the boards. The measurements made on the calculating board were easily converted by means of multiplying factors to values that would exist on the actual system or by meters with special scales where the system quantities could be read directly. The A-C calculating board was relied upon heavily because of its versatility and flexibility. Adding or deleting components which had been added or deleted to the actual system was a simple process. The calculating board was a tremendous time-saving device compared to the hand calculation method. In addition to its time-saving advantages, it could also be used for short circuit studies. In 1947 [4] , there were approximately fourteen calculating boards costing approximately two million dollars each. The importance of the calculating board is borne out by the fact that some 30 of the 50 calculating boards operated in North America in 1959 were installed after 1950, even though this same period saw the wide acceptance of the digital computers in solving electric energy system problems. Just before 1950 the idea of using a desk calculator to make the repetitious calculations necessary to solve the loop equations was developed. This idea was later expanded to the use of accounting machines. The use of these mechanical digital computers had the advantage of greater accuracy, less chance for error, fewer restrictions on the size of the network, and provided a means of determining the system losses. Another important feature the mechanical calculators had was that a nontechnical person could perform the computations [4] . The use of nontechnical persons was an important advantage because the costs incurred when using an A-C calculating board were substantial. A person had to have a great deal of experience in order to properly handle the calculating board and even then the process was time consuming and subject to errors. There were certain disadvantages associated with the mechanical calculators, such as the computed solution was more difficult to modify at the time it was being prepared and the mechanical calculators lacked the psychological advantage of the calculating boards where the measurements were taken on an actual electric circuit. The electronic digital computers of the future were destined to remove some of these disadvantages.

In the early 1950's the use of mechanical multipliers [1] was more commonplace and ideas such as using master card decks and computing two cases simultaneously made the calculations faster and just as accurate as the A-C calculating boards. About this same time electronic digital computers were being developed to the point where they were more readily available for these kinds of studies.

The task of obtaining a formal closed form solution for even a very simple network was often made more difficult because of differences in type of data generally available for the different buses in the system. The mechanical calculators used earlier often took hours to get the solution and some iterative process which converged on the solution was needed. The idea of using mesh equations and an impedance matrix [1] to solve the problem first appeared in the mid 1950's. In June 1956 a classical paper by J. B. Ward and H. W. Hale [2] was published suggesting the Gauss-Seidel iterative process and using node-pair voltage equations as a basis for formulating the solution. The nodal method using the bus admittance matrix was found to be more efficient since a matrix inversion technique was not needed as was the case with the mesh method. Ward and Hale made a number of significant contributions to the development of general purpose digital load flow programs. Among these are 1) establishment of a mathematical description of the network that included transformers with off-nominal turns ratios, 2) an iterative technique for determining bus voltages that satisfy prescribed bus conditions, 3) the computation of complete bus information such as the injected real and reactive powers, voltage magnitudes, and phase angles, and 4) the computation of the individual line flows. The use of the nodal method readily permitted rigorous representation of the off-nominal turns ratio that could be changed without extensive recomputation of the network parameters. Ward and Hale developed a general program which accepted any network up to 50 buses and 200 branches (lines).

The advent of the digital computer and the associated fast iterative processes permitted more effective planning of future cases to study. System planning could be made on a continuous basis rather than a periodic review and ideas of expanding the concept to include the economic-dispatch problem began to take form. Another advantage that the digital computer enjoyed when compared with the A-C calculating board was its accessability and relative cost of operation. When a power company did not own its own A-C calculating board, it was necessary to rent one. To rent one, one would reserve time on the board well in advance. The initial adjustments and all the contemplated conditions necessary for the study usually took a day. After a study was made much time was spent interpreting the results in order to make the necessary engineering decisions to determine what conditions should be studied next. As a result much time was consumed with the calculating board idle. On the other hand charges for using a digital computer are made for only the actual computation time and if one particular study appeared to be very important, data could be transmitted to a computing center, and the results could be obtained almost immediately. Data for the base case could be permanently stored on punched cards or tape. It was evident that from purely an economic standpoint, digital computers were quickly becoming the best means of performing load flow studies. Some of the other advantages of the digital computer include the handling of very large systems, whereas A-C calculating boards often times did not have enough sources, lines, and other components to solve an extensive problem. Also computer programs have the capability of including additional features such as automatic tap settings, automatic control of interchange, and the control of generator reactive power within prescribed limits.

Starting in the mid and late 1950's there was a push to optimize the Gauss-Seidel iterative process. The use of the so-called acceleration factor [5] to speed the convergence was being considered. Several studies were made to find an optimum acceleration factor. The bus voltages were multiplied by the acceleration factor to speed convergence. The optimum value of the acceleration factor was found to vary between 1.6 to 1.7. Since the bus voltages were complex quantities, the idea of using two acceleration factors [5], one for real part and one for the imaginary part of the voltages, became popular. Selecting the optimum acceleration factors was a guessing process, since the factors varied from system to system. Other ideas such as periodic "blasting" of the voltages towards the solution [6] by an extrapolation process were found to have little effect. The greatest single factor in determining the convergence speed was found to be the initial values selected for the bus voltages and angles. The best way to select these voltages [6] was to use the results from earlier studies as the initial values in future studies. Another important factor in determining speed of convergence was the acceptable tolerance of the results. Some of the earlier studies used tolerances [7] of 5×10^{-7} on voltage magnitudes. Later it was found practical to use voltage tolerances of 1×10^{-3}.

While optimization of the iterative process was going on, modifications to the input and output routines and additional auxiliary programs were being created. The input was being modified so as to allow a user to pick the kilovolt-ampere base to fit his needs. Bus numbers could be assigned [8] at the user's convenience with no restrictions regarding the sequence of numbers. The output modifications consisted of getting the results into a form that facilitates interpreting the results. Additional data such as bus power mismatches were incorporated to provide a measure of the precision of the results. Auxiliary programs performed such features as adding new lines or transformers or removing lines or transformers. Programs were developed to handle other outages such as temporary removal of facilities and for replacement of facilities that were previously taken out of service. There were also auxiliary programs for changing existing impedance values because of reconductoring, rerouting, double-circuiting or converting to a different voltage level.

In the late 1950's another method called the transfer-ratio or Hybrid method [7] came into the picture. It combined the driving-point transfer admittance method (nodal method) with the driving-point transfer impedance method (mesh method). It was the general approach, however problems arose in the time required for data preparations and in changing components for further studies. Once it was set up, the hybrid method converged much faster than the Gauss-Seidel method. The Gauss-Seidel method was still used, however, because of the ease of handling the input data and the ease with which system changes could be studied.

In the early 1960's a very sophisticated method came into use called the elimination method, or as it is now recognized, the Newton-Raphson [9] method. The approach of this method is to solve the non-linear equations dealing with the real and reactive powers at the buses.

One iteration in the Newton-Raphson method took approximately twice as long as one iteration [9] in the Gauss-Seidel method; however, if one were to compare the iteration count and the time per iteration, the Newton-Raphson method was much faster than the Gauss-Seidel method. Unlike the Gauss-Seidel method, the decrease in error with the Newton-Raphson method was independent of the size of the system. There were certain types of systems, especially those with negative reactances in some elements that would not converge with the Gauss-Seidel method [9]. The Newton-Raphson method handled these systems without any difficulty. The only disadvantage with the Newton-Raphson method was that it required more computer storage.

Throughout the 1960's improvements in the Newton-Raphson method have been in the matrix inversion process and in the development of various computer storage extension techniques. Improvements in the techniques used will be a continuous process. Areas such as computer methods for inverting matrices, and sophisticated acceleration factors will no doubt be the major areas of improvement.

CHAPTER II

LOAD FLOW ITERATIVE METHODS

Introduction

The load flow problem consists of the calculation of voltages and power flow of a network for specified bus conditions. Associated with each bus are six quantities: the real and reactive power generation, the real and reactive power load or power demand, the voltage magnitude, and the phase angle. Three types of buses are represented in load flow calculation and at a bus, four of the six quantities are specified. It is necessary to select one bus, called the swing bus, to provide the additional real and reactive generation to supply the transmission losses, since these are unknown until the final solution is obtained. At this bus the voltage magnitude, phase angle, real and reactive demands are specified. This is the reference bus. The remaining buses of the system are designated either as voltage controlled buses or load buses. The real power generation, voltage magnitude, and the real and reactive demands are specified at voltage controlled bus. The real and reactive generation and the real and reactive demand are specified at a load bus. The real and reactive generation are zero since load buses are characterized by their lack of generating equipment. See reference [10], Chapter 7, for additional information.

In the remainder of this chapter there will be some mathematical terminology used. At this point it seems appropriate to define this terminology.

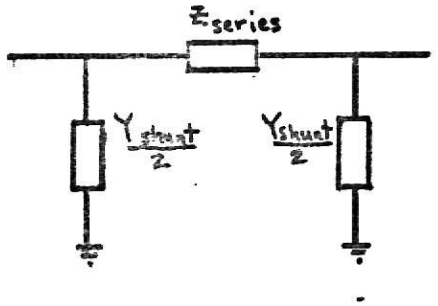
V	Magnitude
$\lvert V \rvert$	Absolute magnitude
$\dot{V}$	Complex quantity
$\underline{V}$	Vector quantity
$\underline{\dot{V}}$	Complex vector quantity
$\dot{V}^*$	Complex conjugate quantity

Also in this chapter formulation of suitable network models are discussed before an iterative method can be applied. The iterative methods discussed will be the Gauss-Seidel and the Newton-Raphson.

Network Representation

The network components must be modelled before an iteration process can be applied. The pi representation will be used for the transmission lines and transformers.

The transformer line [11] is represented by a per unit, series impedance and line shunt admittance. One-half of the line shunt admittance is put at each end of the model (see Figure 1a).



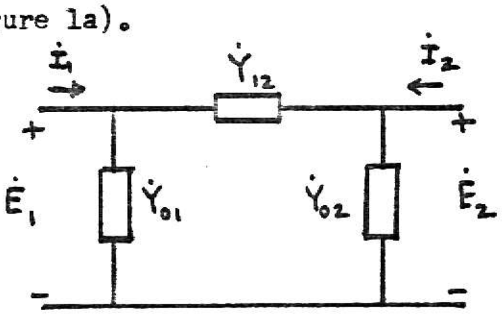


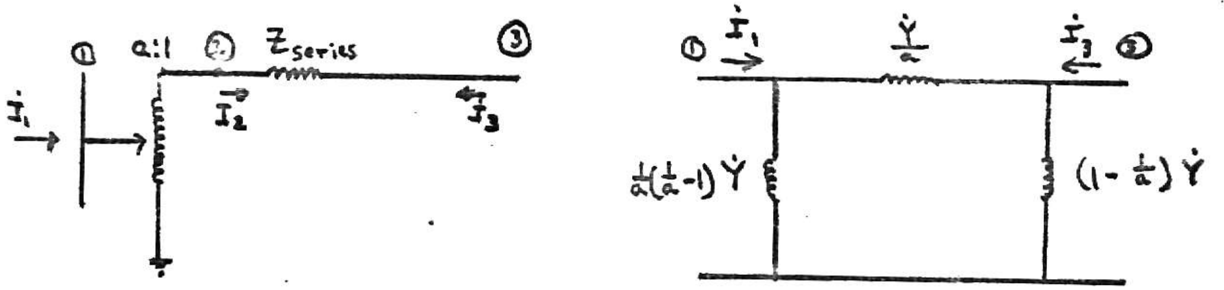
Figure 1. Transmission line representation (a) Equivalent pi circuit (b) Equivalent pi circuit with parameters expressed in admittance.

The nodal equation for the two port network in Figure 1b is

$$\begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \end{bmatrix} = \begin{bmatrix} \dot{y}_{11} & \dot{y}_{21} \\ \dot{y}_{12} & \dot{y}_{22} \end{bmatrix} \begin{bmatrix} \dot{E}_1 \\ \dot{E}_2 \end{bmatrix} \qquad (2\text{-}1)$$

where $\dot{y}_{11} = \dot{Y}_{12} + \dot{Y}_{01}$, $\dot{y}_{22} = \dot{Y}_{12} + \dot{Y}_{02}$, and $\dot{y}_{12} = \dot{y}_{21} = -\dot{Y}_{12}$.

The transformer with an off-nominal turns ratio can be represented by its per unit impedance connected in series with an ideal autotransformer as shown in Figure 2(a). An equivalent pi circuit [12] can be obtained as shown in Figure 2(b).



(a) (b)

Figure 2. Transformer representations (a) Equivalent circuit (b) Equivalent pi circuit with parameters expressed in terms of series admittance and off-nominal turns ratio.

The nodal equations for the two port network between nodes 2 and 3 (Figure 2(a)) can be written as

$$\begin{bmatrix} \dot{I}_2 \\ \dot{I}_3 \end{bmatrix} = \begin{bmatrix} \dot{Y} & -\dot{Y} \\ -\dot{Y} & \dot{Y} \end{bmatrix} \begin{bmatrix} \dot{E}_2 \\ \dot{E}_3 \end{bmatrix} \qquad (2\text{-}2)$$

where $\dot{Y} = 1/\dot{Z}$. The two port network between nodes 1 and 2 is an ideal autotransformer. Since $E_1 = aE_2$ and $I_2 = aI_1$ then E_1 , E_2 and I_1 , I_2 can be expressed in terms of E_1 , E_3 and I_1 , I_3 as

$$\begin{bmatrix} \dot{E}_2 \\ \dot{E}_3 \end{bmatrix} = \begin{bmatrix} 1/a & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{E}_1 \\ \dot{E}_3 \end{bmatrix} \qquad (2\text{-}3)$$

and

$$\begin{bmatrix} \dot{I}_1 \\ \dot{I}_3 \end{bmatrix} = \begin{bmatrix} 1/a & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_2 \\ \dot{I}_3 \end{bmatrix} \tag{2-4}$$

combining these equations yields

$$\begin{bmatrix} \dot{I}_1 \\ \dot{I}_3 \end{bmatrix} = \begin{bmatrix} 1/a & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{Y} & -\dot{Y} \\ -\dot{Y} & \dot{Y} \end{bmatrix} \begin{bmatrix} 1/a & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{E}_1 \\ \dot{E}_3 \end{bmatrix} \tag{2-5}$$

$$\begin{bmatrix} \dot{I}_1 \\ \dot{I}_3 \end{bmatrix} = \begin{bmatrix} \dot{Y}/a^2 & -\dot{Y}/a \\ -\dot{Y}/a & \dot{Y} \end{bmatrix} \begin{bmatrix} \dot{E}_1 \\ \dot{E}_3 \end{bmatrix} \tag{2-6}$$

Recalling the admittance matrix for the pi circuit of the transmission line that $\dot{y}_{11} = \dot{Y}_{01} + \dot{Y}_{12}$, $\dot{y}_{22} = \dot{Y}_{02} + \dot{Y}_{12}$, and $\dot{y}_{12} = \dot{y}_{21} = -\dot{Y}_{12}$, then $\dot{Y}_{12} = \frac{\dot{Y}}{a}$, $\dot{Y}_{01} = \frac{1}{a}\left(\frac{1}{a} - 1\right)\dot{Y}$, and $\dot{Y}_{02} = (1 - 1/a)\dot{Y}$. These relationships are used in forming the bus admittance matrix.

The static capacitors and/or reactors are handled as a per unit susceptance. The static capacitor or reactor is simply added to the diagonal of bus admittance matrix. The position along the diagonal is determined by the bus location.

Gauss-Seidel Method

The solution of the load flow problem [10, 12] is initiated by assuming voltages for all buses except the swing bus, where the voltage is specified and remains fixed. Then, the net injected complex power $\dot{S}_n$ at any bus n is

$$(\dot{S}_n)^* = P_n - jQ_n = \dot{I}_n\dot{V}_n^* \tag{2-7}$$

and the bus currents calculated for all buses except the swing bus are

$$\dot{I}_n = \frac{P_n - jQ_n}{\dot{V}_n^*} \qquad n = 2,3\cdots NB \tag{2-8}$$

where $\dot{I}_n$ is the net injected current and is positive when flowing into the bus and NB is the number of buses. The bus current can also be obtained from the equation

$$\dot{I}_n = \sum_{m=1}^{NB} \dot{Y}_{nm}\dot{V}_m \tag{2-9}$$

Equations (2-8) and (2-9) yield, upon solving for $\dot{V}_n$, a set of NB-1 equations. These equations are

$$\dot{V}_n = \frac{1}{\dot{Y}_{nn}}\left[\frac{P_n - jQ_n}{\dot{V}_n^*} - \sum_{\substack{k=1 \\ k\neq n}}^{NB} \dot{Y}_{nk}\dot{V}_k\right] \tag{2-10}$$

for $n = 2,3\cdots NB$.

To simplify equation (2-10) some constants [10] are defined.

$$\dot{A}_n = \frac{P_n - jQ_n}{\dot{Y}_{nn}} \qquad \text{for } n = 2,3\cdots NB$$

$$\dot{B}_{nk} = \frac{\dot{Y}_{nk}}{\dot{Y}_{nn}} \qquad \text{for } n = 2,3\cdots NB; \; k = 1,2\cdots NB \text{ (except } k = n) \tag{2-11}$$

Substituting (2-11) into (2-10) yields

$$\dot{V}_n^{u+1} = \frac{\dot{A}_n}{(\dot{V}_n^u)^*} - \sum_{\substack{k=1 \\ k\neq n}}^{NB} \dot{B}_{nk}\dot{V}_k^u \tag{2-12}$$

where the superscript u refers to the iteration count. The bus currents as calculated from equation (2-8), the swing bus voltage, and the estimated bus voltages are substituted into equation (2-12) to obtain a new set of bus voltages. These new voltages are used in equation (2-8) to recalculate the bus currents for subsequent solution of equation (2-12). The process is continued until changes in all bus voltages are within a specified tolerance. After the voltage solution has been obtained, the line flows and the power at the swing bus can be calculated. The sequence of steps for the load flow solution by the Gauss-Seidel iteration method is shown in Figure 3.

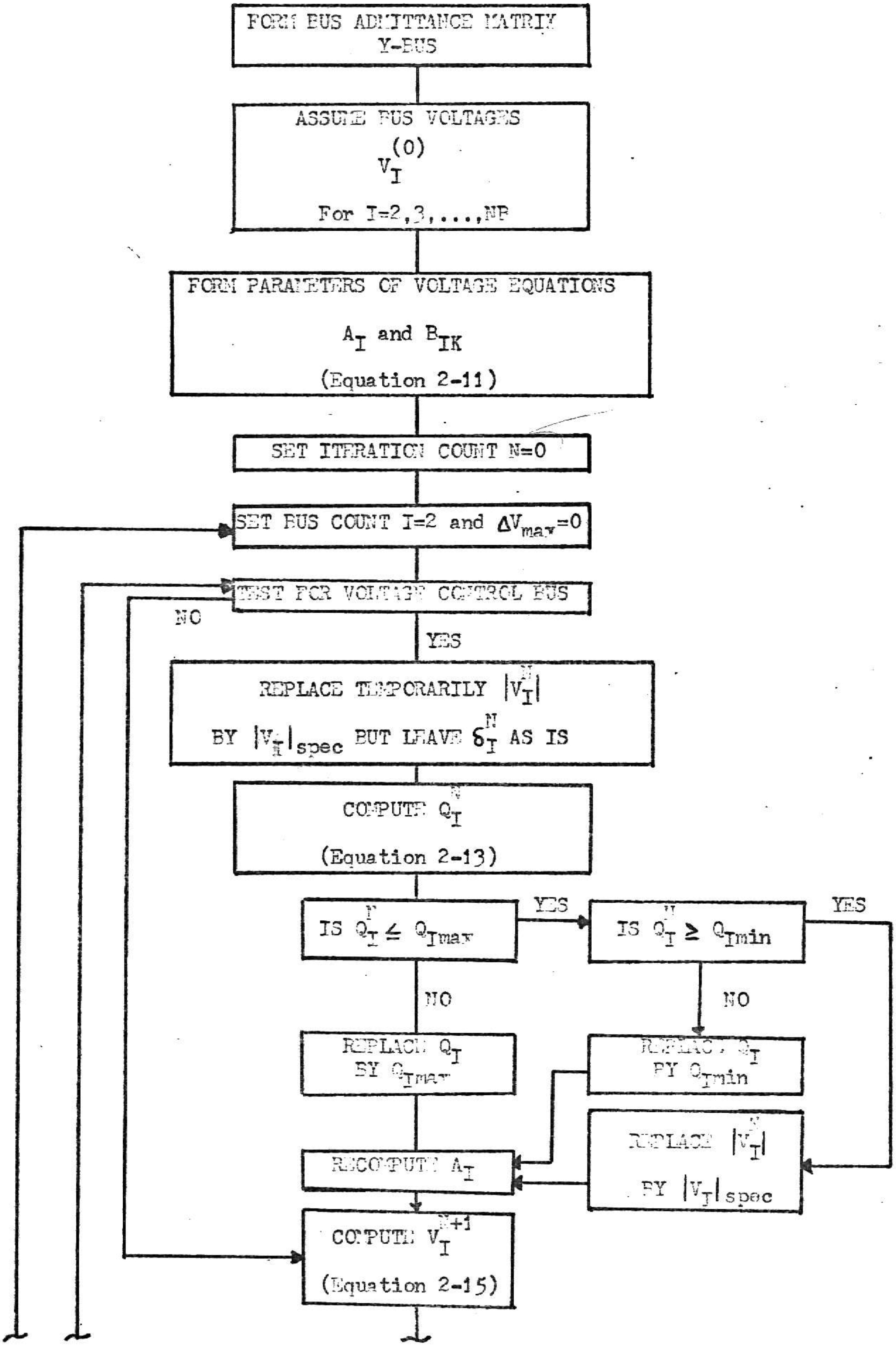
The injected reactive power at a voltage controlled bus must be calculated before proceeding with the calculation of the bus voltages. From equation (2-7) the reactive bus power is

$$Q_n = -\text{Imag}\left[\left(\sum_{m=1}^{NB} \dot{Y}_{nm}\dot{V}_m\right)(\dot{V}_n^*)\right] \qquad (2\text{-}13)$$

where $\dot{V}_n = e_n + jfn$ and $\dot{Y}_{nm} = G_{nm} - jB_{nm}$. The real and imaginary values of the bus voltage must satisfy the relationship

$$e_n^{\ 2} + f_n^{\ 2} = (\left|V_n\right| \text{ scheduled})^2 \qquad (2\text{-}14)$$

in order to calculate the reactive bus power required to provide the scheduled bus voltage. The phase angles [12] of the estimated bus voltages are $\delta_n^u = \arctan\,(f_n^u/e_n^u)$. Assuming the angles of the estimated and scheduled voltages are equal, then the new $e_n^u = \left\{\left|V\right| \text{scheduled}\right\} \cos\delta_n^u$ and the new $f_n^u = \left\{\left|V\right| \text{scheduled}\right\} \sin\delta_n^u$. These values are substituted back into equation (2-13) to obtain the reactive power which in turn is used in estimating the new bus voltage $\dot{V}_n^{u+1}$. The voltage control buses generally have maximum and minimum injected reactive power limits. If the calculated Q_n exceeds these limits, then the scheduled voltage can no longer be held and the reactive power is set equal to its limit. This procedure is also shown in Figure 3.


FORM BUS ADMITTANCE MATRIX Y-BUS
ASSUME BUS VOLTAGES $V_I^{(0)}$ For I=2,3,...,NB
FORM PARAMETERS OF VOLTAGE EQUATIONS A_I and B_{IK} (Equation 2-11)
SET ITERATION COUNT N=0
SET BUS COUNT I=2 and ΔV_{max}=0
TEST FOR VOLTAGE CONTROL BUS
NO
YES
REPLACE TEMPORARILY $|V_I^N|$ BY $|V_I|_{spec}$ BUT LEAVE δ_I^N AS IS
COMPUTE Q_I^N (Equation 2-13)
IS $Q_I^N \leq Q_{Imax}$
YES
IS $Q_I^N \geq Q_{Imin}$
YES
NO
NO
REPLACE Q_I BY Q_{Imax}
REPLACE Q_I BY Q_{Imin}
REPLACE $|V_I^N|$ BY $|V_I|_{spec}$
RECOMPUTE A_I
COMPUTE V_I^{N+1} (Equation 2-15)

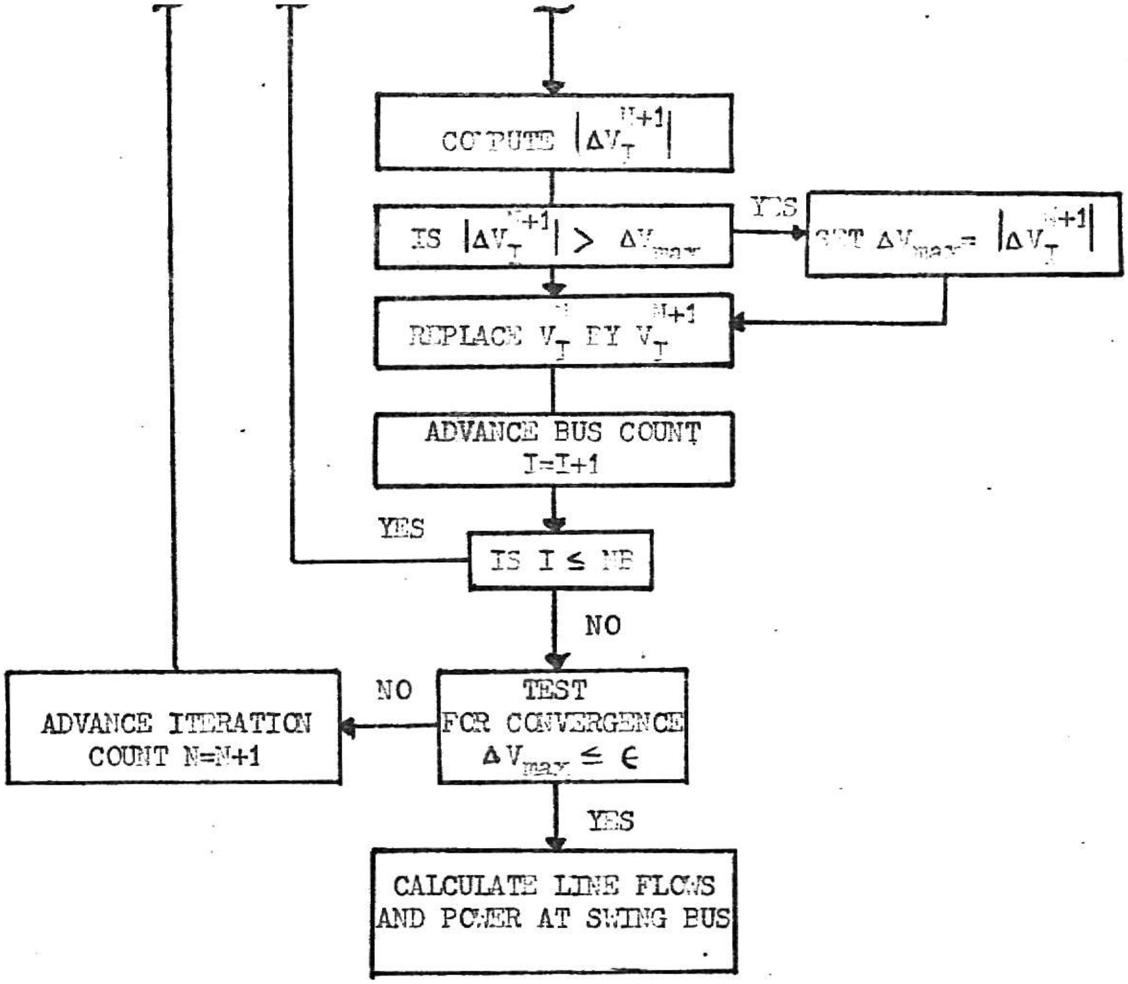


Figure 3 GAUSS-SEIDEL METHOD USING Y-BUS

Newton-Raphson Method

A set of nonlinear equations that express the scheduled injected bus powers in terms of bus voltages is used in the Newton-Raphson method [12]. The Newton-Raphson method is initiated by assuming voltages for all buses except the swing bus, where the voltage is specified and fixed. Then, a net real power and a net reactive power is calculated using the estimated bus voltages. These net real and reactive powers are then compared to the scheduled net bus powers. If the calculated powers are within a specified tolerance of the scheduled powers, then the line power flows and swing bus power is calculated. If the calculated powers are outside the tolerance then a new set of bus voltages are estimated. These new bus voltages are then used to calculate a new set of calculated net real and reactive bus powers to compare with the scheduled bus powers. The process is continued until changes in all calculated bus powers are within the specified tolerance. The key to the whole technique is the estimating of a new set of bus voltages. It can be shown that the net real and reactive powers form a set of nonlinear equations. By use of the Taylor's series it can also be shown that the change in the net real bus power (ΔP) relates to the changes in the real (Δe) and imaginary (Δf) parts of the bus voltages. The change in the net reactive bus power ΔQ has a similar relationship. A coefficient matrix called the Jacobian relating the Δe's and Δf's with the ΔP's and ΔQ's can be set up. The elements of the Jacobian are determined below. One then simply solves for the Δe's and Δf's which in turn are used in estimating a new set of bus voltages.

The remainder of this section will derive and demonstrate the equations used in the Newton-Raphson technique. The procedure used closely follows that given by Stagg and El-Abiad [12].

Upon substituting $\dot{V}_n = e_n + jf_n$ and $\dot{Y}_{nm} = G_{nm} - jB_{nm}$ into equation (2-9) and the results into equation (2-7) one obtains

$$P_n - jQ_n = (e_n - jf_n) \sum_{m=1}^{NB} (G_{nm} - jB_{nm})(e_m + jf_m) \qquad (2\text{-}15)$$

Separating this equation into its real and imaginary parts,

$$\begin{aligned} P_n &= \sum_{m=1}^{NB} \left\{ e_n(e_m G_{nm} + f_m B_{nm}) + f_n(f_m G_{nm} - e_m B_{nm}) \right\} \\ Q_n &= \sum_{m=1}^{NB} \left\{ f_n(e_m G_{nm} + f_m B_{nm}) - e_n(f_m G_{nm} - e_m B_{nm}) \right\} \end{aligned} \qquad (2\text{-}16)$$

The result is a set of nonlinear simultaneous equations with two equations for each bus. The net injected real and reactive bus powers are known and the bus voltage components are unknown for all buses except the swing bus, where the voltage remains a fixed value and the swing bus powers are unknown. Thus there are 2(NB-1) equations to be solved.

Using Taylor's Series a set of linear equations is formed expressing the relationship between the changes in net real (ΔP) and net reactive (ΔQ) powers with the bus voltage components. Using only the first term in the Taylor's series and neglecting the rest, a coefficient matrix called the Jacobian can be set up as follows

$$\begin{bmatrix} \Delta P_2 \\ \cdots \\ \Delta P_{NB} \\ \Delta Q_2 \\ \cdots \\ \Delta Q_{NB} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2}{\partial e_2} & \cdots & \frac{\partial P_2}{\partial e_{NB}} & \frac{\partial P_2}{\partial f_2} & \cdots & \frac{\partial P_2}{\partial f_{NB}} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{\partial P_{NB}}{\partial e_2} & \cdots & \frac{\partial P_{NB}}{\partial e_{NB}} & \frac{\partial P_{NB}}{\partial f_2} & \cdots & \frac{\partial P_{NB}}{\partial f_{NB}} \\ \frac{\partial Q_2}{\partial e_2} & \cdots & \frac{\partial Q_2}{\partial e_{NB}} & \frac{\partial Q_2}{\partial f_2} & \cdots & \frac{\partial Q_2}{\partial f_{NB}} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{\partial Q_{NB}}{\partial e_2} & \cdots & \frac{\partial Q_{NB}}{\partial e_{NB}} & \frac{\partial Q_{NB}}{\partial f_2} & \cdots & \frac{\partial Q_{NB}}{\partial f_{NB}} \end{bmatrix} \begin{bmatrix} \Delta e_2 \\ \cdots \\ \Delta e_{NB} \\ \Delta f_2 \\ \cdots \\ \Delta f_{NB} \end{bmatrix} \qquad (2\text{-}17)$$

In matrix form, equation (2-17) is

$$\begin{bmatrix} \Delta \underline{P} \\ \Delta \underline{Q} \end{bmatrix} = \begin{bmatrix} \underline{J}_1 & \underline{J}_2 \\ \underline{J}_3 & \underline{J}_4 \end{bmatrix} \begin{bmatrix} \Delta \underline{e} \\ \Delta \underline{f} \end{bmatrix}$$

One can derive the entries in the Jacobian matrix from the bus power equations (2-16) by finding the appropriate derivatives.

The off diagonal elements of $\underline{J}_1$ are

$$\frac{\partial P_n}{\partial e_m} = e_n G_{nm} - f_n B_{nm} \qquad n \neq m$$

and the diagonal elements of $\underline{J}_1$ are

$$\frac{\partial P_n}{\partial e_n} = 2e_n G_{nm} + \sum_{\substack{m=1 \\ m \neq n}}^{NB} (e_m G_{nm} + f_m B_{nm}). \tag{2-18}$$

The diagonal elements of $\underline{J}_1$ can be simplified somewhat by noting the bus current equation (2-9) can be separated into the real and imaginary parts. Thus, if $\dot{I}_n = c_n + jd_n$, then:

$$c_n = e_n G_{nn} + f_n B_{nn} + \sum_{\substack{m=1 \\ m \neq n}}^{NB} (e_m G_{nm} + f_m B_{nm})$$

$$d_n = f_n G_{nn} - e_n B_{nn} + \sum_{\substack{m=1 \\ m \neq n}}^{NB} (f_m G_{nm} - e_m B_{nm}) \tag{2-19}$$

where $(n = 1,2,3 \cdots NB)$.

Substituting the real part of the current into equation (2-18) the $\underline{J}_1$ diagonal becomes

$$\frac{\partial P_n}{\partial e_n} = e_n G_{nn} - f_n B_{nn} + c_n$$

The off-diagonal elements of $\underline{J}_2$ are

$$\frac{\partial P_n}{\partial f_m} = e_n B_{nm} + f_n G_{nm} \qquad n \neq m$$

and the diagonal elements of $\underline{J}_2$ after combining with equation (2-19) are

$$\frac{\partial P_n}{\partial f_n} = e_n B_{nn} + f_n G_{nn} + d_n.$$

The off-diagonal elements of $\underline{J}_3$ are

$$\frac{\partial Q_n}{\partial e_m} = e_n B_{nm} + f_n G_{nm} \qquad n \neq m$$

and the diagonal elements of $\underline{J}_3$ after combining with equation (2-19) are

$$\frac{\partial Q_n}{\partial e_n} = e_n B_{nn} + f_n G_{nn} - d_n.$$

The off-diagonal elements of $\underline{J}_4$ are

$$\frac{\partial Q_n}{\partial f_m} = -e_n G_{nm} + f_n B_{nm} \qquad n \neq m$$

and the diagonal elements of $\underline{J}_4$ after combining with equation (2-19) are

$$\frac{\partial Q_n}{\partial f_n} = -e_n G_{nn} + f_n B_{nn} + c_n.$$

Given an initial set of bus voltages, the real and reactive powers are calculated from equations (2-16). The ΔP's and ΔQ's are the differences between the scheduled and calculated powers. The Jacobian elements are evaluated from the calculated powers and estimated bus voltages. The new set of estimated bus voltages are then determined. This process is repeated until the ΔP's and ΔQ's are all within a specified tolerance. The flow diagram of the Newton-Raphson Method is shown in Figure 4.

In the case of voltage control buses the reactive bus power must be calculated at their buses before proceeding with the solution.

The equation for the voltage controlled bus is

$$\left|\dot{V}_n\right|^2 = e_n^2 + f_n^2 \qquad (2\text{-}20)$$

where equation (2-20) replaces the equation for the reactive bus power. The matrix equation for the new relationship is:

$$\begin{bmatrix} \Delta \underline{P} \\ \Delta \underline{Q} \\ \Delta |\underline{V}|^2 \end{bmatrix} = \begin{bmatrix} \underline{J}_1 & \underline{J}_2 \\ \underline{J}_3 & \underline{J}_4 \\ \underline{J}_5 & \underline{J}_6 \end{bmatrix} \begin{bmatrix} \Delta \underline{e} \\ \Delta \underline{f} \end{bmatrix}$$

The submatrices $\underline{J}_1$, $\underline{J}_2$, $\underline{J}_3$, and $\underline{J}_4$ are the same as before. The off-diagonal elements of $\underline{J}_5$, as oftained in equation (2-20) are

$$\frac{\partial \left|\dot{V}_n\right|^2}{\partial e_m} = 0 \qquad n \neq m$$

with the diagonal elements being

$$\frac{\partial \left|\dot{V}_n\right|^2}{\partial e_n} = 2e_n.$$

Similarly, the off-diagonal elements of $\underline{J}_6$ are

$$\frac{\partial \left|\dot{V}_n\right|^2}{\partial f_m} = 0 \qquad n \neq m$$

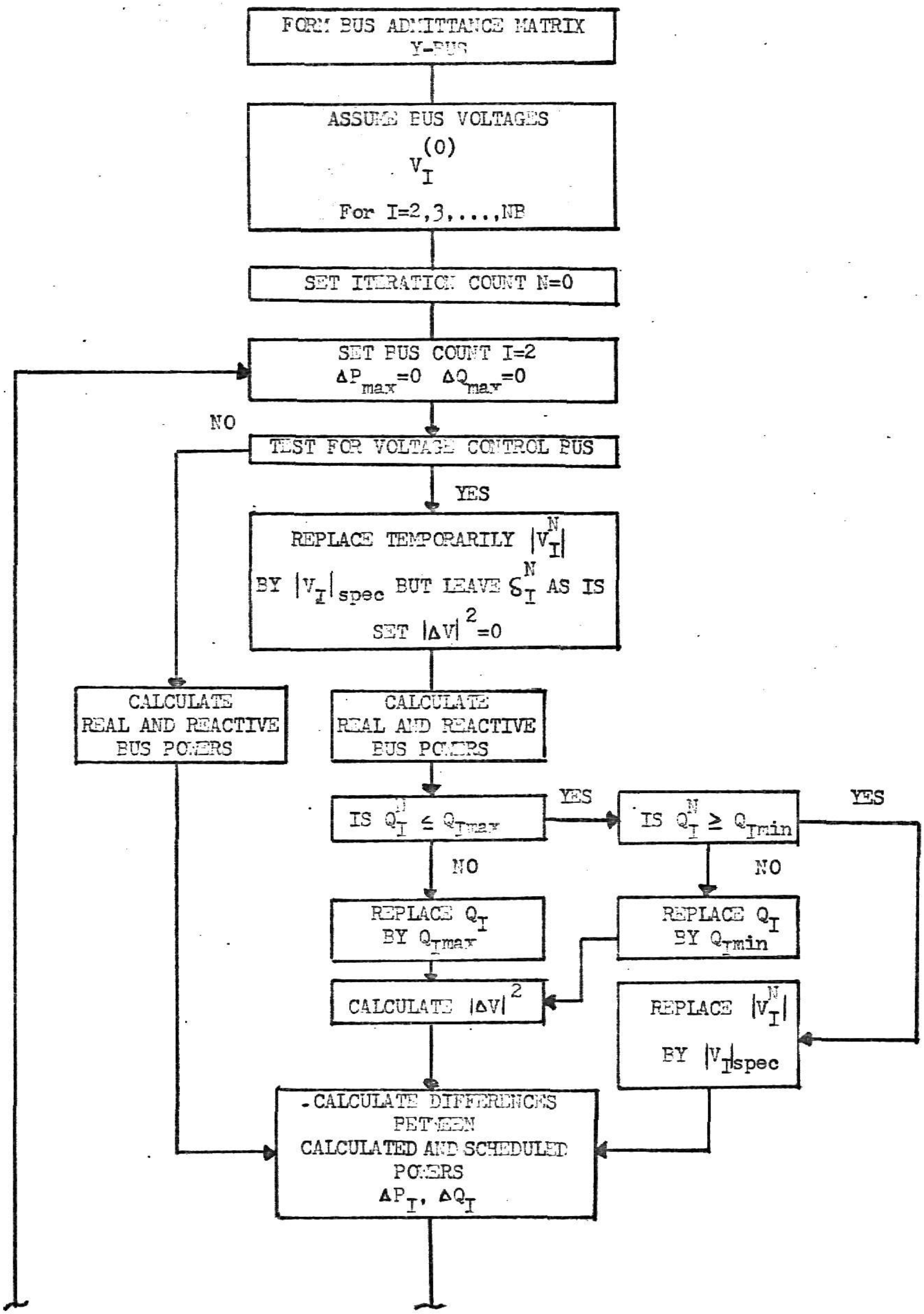
and the diagonal elements are

$$\frac{\partial \left|\dot{V}_n\right|^2}{\partial f_n} = 2f_n.$$

The change in the square of the voltage magnitude $\Delta\left|V_n\right|^2$ is zero unless a reactive power limit is encountered. In that case

$$\Delta\left|V_n^u\right|^2 = \left|V_n\right|^2_{\text{scheduled}} - \left|V_n^u\right|^2$$

where u is the iteration count.


FORM BUS ADMITTANCE MATRIX
Y-BUS
ASSUME BUS VOLTAGES
$V_I^{(0)}$
For I=2,3,...,NB
SET ITERATION COUNT N=0
SET BUS COUNT I=2
$\Delta P_{max}=0$ $\Delta Q_{max}=0$
NO
TEST FOR VOLTAGE CONTROL BUS
YES
REPLACE TEMPORARILY $|V_I^N|$
BY $|V_I|_{spec}$ BUT LEAVE δ_I^N AS IS
SET $|\Delta V|^2=0$
CALCULATE
REAL AND REACTIVE
BUS POWERS
CALCULATE
REAL AND REACTIVE
BUS POWERS
IS $Q_I^N \leq Q_{Imax}$
YES
IS $Q_I^N \geq Q_{Imin}$
YES
NO
NO
REPLACE Q_I
BY Q_{Imax}
REPLACE Q_I
BY Q_{Imin}
CALCULATE $|\Delta V|^2$
REPLACE $|V_I^N|$
BY $|V_I|_{spec}$
CALCULATE DIFFERENCES
BETWEEN
CALCULATED AND SCHEDULED
POWERS
ΔP_I, ΔQ_I

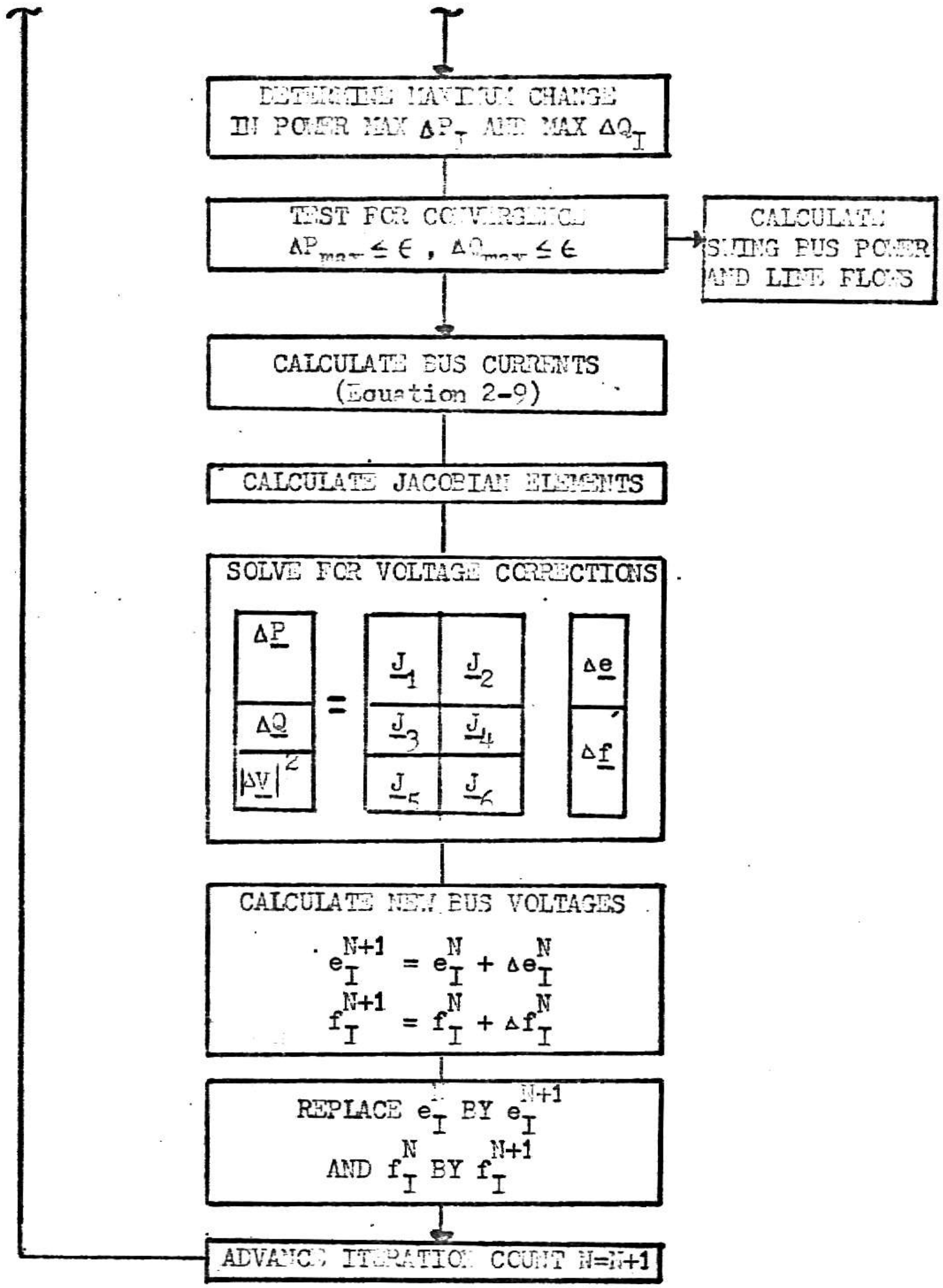


Figure 4 NEWTON-RAPHSON METHOD USING Y-BUS

Program Printout

This section contains the detailed computer program for the solution of the Static Load Flow Equations (SLFE).

The iterative computations of the SLFE follows the flow diagrams of Figures 3 and 4. The program implements only one iterative method at one time; the user has his choice.

The reader should note that the Newton-Raphson method is not as efficient as it should be. The Newton-Raphson routine was not optimized with respect to computation speed. Chapter IV presents some suggested improvements. Chapter III gives some sample results obtained for two test systems.

The starting point for Gauss-Seidel routine was taken from Appendix B of Elgerd's book [10], Electric Energy Systems Theory. The Newton-Raphson equations and routine were taken from Chapter 8 of Reference 12.

```
0001              COMPLEX*8 SERY(100),SERZ(100),SHTY(100),YSHT(100),ZSER(100),
                 1F(100),S(100),BI(060),VN(060),A(060),V(060),B(060,060),Y(060,060),
                 2CMPLX,CONJG,VIT,SUM,DX,VI,TS,TEO,TL
0002              REAL JB(119,119),LENGTH(100),TF(100),TS(100),QMIN(060),QMAX(060),
                 1VSPEC(060),P(060),Q(060),PG(060),PL(060),QG(060),QL(060),
                 2C(060),CMVAR(060),CP(060),CQ(060),DP(060),DQ(060),PV(060),DE(060),
                 3DF(060),OBASE,NBASE,ALPHA,DVMAX,DELTA,MAGV,DELV,CONV,TCR,CC,ST
0003              INTEGER SB(100),EB(100),ITER,NL,NB,NC,NR,MB,BN,K,L,M,BM
0004              COMMON/DATA/YSHT,ZSER,R,S,LENGTH,TS,PG,PL,QG,QL,VSPEC,QMIN,QMAX,
                 1C,CMVAR,P,Q,OBASE,NBASE,MAGV,DELTA,ALPHA,CC,ST,CONV,SB,EB,NB,NL,
                 3MB,NC,BN,BM,ITER
0005        100   FORMAT(4I5,4F5.0,F10.7,I5)
0006        102   FORMAT(I5,F10.5)
0007        104   FORMAT(F10.5,F6.2,F5.2)
0008        106   FORMAT(2I5,4F10.5,F5.3,F5.1)
0009        108   FORMAT(4F10.3)
0010        110   FORMAT('1'///T30,'FAILED TO CONVERGE IN',I4,'ITERATIONS')
0011        112   FORMAT('1',T20,'NEWTON-RAPHSON TECHIQUE CONVERGED IN',I4,1X,
                 1'ITERATIONS.  ALL VALUES ON',F6.0,1X,'MVA BASE'//)
0012        114   FORMAT('1',T20,'GAUSS-SEIDEL TECHNIQUE CONVERGED IN',I4,1X,
                 1'ITERATIONS.  ALL VALUES ON',F6.0,1X,'MVA BASE'//)
0013        116   FORMAT('0',T31,'VOLTAGE',T111,'INJECTED POWER'/T30,'MAGNITUDE',
                 AT42,'DELTA(DEGS)',T64,'GENERATION',T95,'LOAD',T114,'(STATIC)'/
                 AT33,'PU',T60,'MW',T74,'MVAR',T88,'MW',T102,'MVAR',T116,'MVAR')
0014        118   FORMAT('0',T20,'BUS',I5,2X,F7.3,5X,F9.4,5X,F9.3,5X,F9.3,5X,F9.3,
                 A5X,F9.3,5X,F9.3)
0015        120   FORMAT(' ',T30,I5,2X,F9.3,2X,F9.3,2X,'TAP',1X,F5.3)
0016        122   FORMAT(' ',T30,I5,2X,F9.3,2X,F9.3)
0017        124   FORMAT('1'//T48,'TOTALS',28X,'MW',11X,'MVAR'//T42,'GENERATION',24X,
                 AF11.3,2X,F11.3)
0018        126   FORMAT('0',T42,'STATIC CAP/REACTORS',28X,F11.3)
0019        128   FORMAT('0',T42,'LOAD',30X,F11.3,2X,F11.3)
0020        130   FORMAT('0',T42,'LINE LOSSES',23X,F11.3,2X,F11.3)
            C READ IN NUMBER OF OF LINES, NUMBER OF BUSES, NUMBER OF VOLTAGE CONTROL BUSES,
            C NUMBER OF STATIC CAPACITORS OR REACTORS, OLD BASE, NEW BASE, ITERATION METHOD
            C USED, TOTAL OR ONE-HALF SHUNT ADMITTANCE USED, MAXIMUM ITERATIONS ALLOWED,
            C AND TOLERANCE ALLOWED
0021              READ(5,100) NL,NB,BM,NC,OBASE,NBASE,GSNR,ST,CONV,ITER
0022              MB=BM+1
            C ASSUME STANDARD VALUES FOR OLD BASE AND NEW BASE IF NONE READ
0023              IF(OBASE.LE.0) OBASE=100.
0024              IF(NBASE.LE.0) NBASE=100.
0025              IF(GSNR.EQ.0) GO TO 1
            C STANDARD MAXIMUM ITERATIONS AND TOLERANCE ALLOWED FOR NEWTON RAPHSON METHOD
0026              IF(ITER.LE.0) ITER=15
0027              IF(CONV.LE.0) CONV=.001
0028              GO TO 2
            C STANDARD MAXIMUM ITERATIONS AND TOLERANCE ALLOWED FOR GAUSS SEIDEL METHOD
0029        1     IF(ITER.LE.0) ITER=75
0030              IF(CONV.LE.0) CONV=.0001
0031        2     CONTINUE
0032              DO 3 I=1,NB
0033              DO 3 J=1,NB
0034        3     Y(I,J)=CMPLX(0.0,0.0)
0035              DO 4 I=1,NB
0036        4     C(I)=0.0
0037              IF(NC.LE.0) GO TO 8
            C READ IN BUS NUMBER AND STATIC CAPACITOR/REACTOR VALUE IN PER UNIT
```

```
            DO 6 I=1,NC
            READ(5,102) BN,CC
            CC=CC*OBASE/NBASE
            Y(BN,BN)=CMPLX(0.0,CC)
      6     C(BN)=CC
      8     CONTINUE
      C READ IN SWING BUS VOLTAGE MAGNITUDE, ANGLE(IN DEGREES) AND THE
      C ACCELERATION FACTOR.
            READ(5,104) MAGV,DELTA,ALPHA
            DELTA=DELTA*ARSIN(1.0)/90.0
            V(1)=MAGV*CMPLX(COS(DELTA),SIN(DELTA))
      C ASSUME STANDARD ACCELERATION FACTOR IF NONE READ
            IF(ALPHA.EQ.0) ALPHA=1.65
      C READ IN STARTING BUS, ENDING BUS, SERIES IMPEDANCE, AND SHUNT ADMITTANCE IN
      C PER UNIT, ALSO TAP SETTING AND LENGTH -
            DO 10 I=1,NL
            READ(5,106) SB(I),EB(I),ZSER(I),YSHT(I),TR(I),LENGTH(I)
            ZSER(I)=ZSER(I)*NBASE/OBASE
            YSHT(I)=YSHT(I)*OBASE/NBASE
            TS(I)=TR(I)
            IF(TR(I).LE.0) TR(I)=1.0
            TR(I)=1/TR(I)
      C ASSUME STANDARD VALUE FOR LENGTH IF NONE READ
            IF(LENGTH(I).LE.0) LENGTH(I)=1.0
            SHTY(I)=YSHT(I)*LENGTH(I)
            IF(ST.NE.0) SHTY(I)=SHTY(I)/2
            SERZ(I)=ZSER(I)*LENGTH(I)
            SERY(I)=1.0/SERZ(I)
      C ASSEMBLE THE BUS ADMITTANCE MATRIX.
            L=SB(I)
            M=EB(I)
            Y(L,L)=Y(L,L)+(SERY(I)+SHTY(I))*TR(I)*TR(I)
            Y(M,M)=Y(M,M)+SERY(I)+SHTY(I)
            Y(L,M)=Y(L,M)-SERY(I)*TR(I)
      10    Y(M,L)=Y(L,M)
            K=MB+1
            IF(MB.LE.1) GO TO 13
      C READ IN VOLTAGE CONTROL BUS VOLTAGE MAGNITUDES AND REACTIVE POWER LIMITS.
            DO 12 I=2,MB
      12    READ(5,108) VSPEC(I),QMIN(I),QMAX(I)
      13    CONTINUE
      C READ IN SCHEDULED BUS POWERS IN MEGAWATTS AND MEGAVARS
            DO 14 I=1,NB
      14    READ(5,108) PG(I),QG(I),PL(I),QL(I)
      C WRITE OUT INPUTTED DATA
            CALL INPUT
      C CALCULATE NET REAL AND REACTIVE POWERS FOR ITERATION PROCESS
            DO 18 I=2,NB
      18    P(I)=PG(I)-PL(I)
            DO 20 I=K,NB
      20    Q(I)=QG(I)-QL(I)
            IF(MB.LE.1) GO TO 23
      C PUT POWERS IN PER UNIT AND ADJUST REACTIVE POWER LIMITS TO GENERATOR LIMITS
            DO 22 I=2,MB
            P(I)=P(I)/NBASE
            QMIN(I)=QMIN(I)-QL(I)
            QMAX(I)=QMAX(I)-QL(I)
            QMIN(I)=QMIN(I)/NBASE
```

```
0084     22    QMAX(I)=QMAX(I)/NBASE
0085     23    CONTINUE
0086           DO 24 I=K,NB
0087           P(I)=P(I)/NBASE
0088     24    Q(I)=Q(I)/NBASE
         C ASSUME INITIAL VALUES FOR BUS VOLTAGES
0089           DO 26 I=2,NB
0090     26    V(I)=CMPLX(1.0,0.0)
0091           N=0
0092           IF(GSNR.EQ.0) GO TO 600
         C BEGIN THE NEWTON RAPHSON ITERATION METHOD
0093           NR=2*(NB-1)
0094     206   DVMAX=0.0
0095           DO 224 I=2,NB
0096           VII=V(I)
         C FOR VOLTAGE CONTROL BUSES ADJUST VOLTAGE TO SPECIFIED MAGITUDE AND CALCULATE
         C REACTIVE POWER, IF Q LIMITS ARE EXCEEDED SET Q EQUAL TO LIMIT AND RETURN
         C VOLTAGE TO PREVIOUS VALUE
0097           IF(I-MB) 208,208,220
0098     208   V(I)=V(I)/CABS(V(I))*VSPEC(I)
0099           DV(I)=0.0
0100           SUM=CMPLX(0.0,0.0)
0101           DO 210 J=1,NB
0102     210   SUM=SUM+Y(I,J)*V(J)
0103           CP(I)=REAL(SUM*CONJG(V(I)))
0104           CQ(I)=-AIMAG(SUM*CONJG(V(I)))
0105           Q(I)=CQ(I)
0106           IF(CQ(I)-QMAX(I)) 212,220,214
0107     212   IF(CQ(I)-QMIN(I)) 216,220,220
0108     214   Q(I)=QMAX(I)
0109           CQ(I)=Q(I)
0110           GO TO 218
0111     216   Q(I)=QMIN(I)
0112           CQ(I)=Q(I)
0113     218   V(I)=VII
0114           DV(I)=VSPEC(I)**2-(CABS(VII))**2
0115           GO TO 223
0116     220   SUM=CMPLX(0.0,0.0)
0117           DO 222 J=1,NB
         C CALCULATE THE REAL AND REACTIVE POWERS
0118     222   SUM=SUM+Y(I,J)*V(J)
0119           CP(I)=REAL(SUM*CONJG(V(I)))
0120           CQ(I)=-AIMAG(SUM*CONJG(V(I)))
         C CALCULATE DIFFERENCES BETWEEN THE SCHEDULED AND CALCULATED POWERS
0121     223   DP(I)=P(I)-CP(I)
0122           DQ(I)=Q(I)-CQ(I)
         C DETERMINE MAXIMUM CHANGE IN POWERS.
0123           IF(ABS(DP(I)).GE.DVMAX) DVMAX=ABS(DP(I))
0124     224   IF(ABS(DQ(I)).GE.DVMAX) DVMAX=ABS(DQ(I))
         C TEST FOR CONVERGENCE
0125           IF(DVMAX.LE.CONV) GO TO 300
         C LIMIT ITERATIONS AS A PROTECTION AGAINST DIVERGENCE
0126           IF(N.LT.ITER) GO TO 226
0127           WRITE(6,110) N
0128           GO TO 1973
0129     226   N=N+1
         C CALCULATE BUS CURRENTS
0130           DO 228 I=2,NB
```

```
228   BI(I)=CMPLX(CP(I),-CQ(I))/CONJG(V(I))
C CALCULATE ELEMENTS OF THE JACOBIAN MATRIX
      DO 229 I=1,NB
      DO 229 J=1,NB
229   JJ(I,J)=0.0
C THE CALCULATION OF J-1 MATRIX
      DO 234 I=2,NB
      DO 232 J=2,NB
      IF(I.NE.J) GO TO 230
      JJ(I-1,J-1)=REAL(V(I))*REAL(Y(I,J))+AIMAG(V(I))*AIMAG(Y(I,J))+
     AREAL(BI(I))
      GO TO 232
230   JJ(I-1,J-1)=REAL(V(I))*REAL(Y(I,J))+AIMAG(V(I))*AIMAG(Y(I,J))
232   CONTINUE
234   CONTINUE
C THE CALCULATION OF J-2 MATRIX
      DO 240 I=2,NB
      DO 238 J=2,NB
      IF(I.NE.J) GO TO 236
      JJ(I-1,NB-2+J)=-REAL(V(I))*AIMAG(Y(I,I))+AIMAG(V(I))*
     AREAL(Y(I,I))+AIMAG(BI(I))
      GO TO 238
236   JJ(I-1,NB-2+J)=-REAL(V(I))*AIMAG(Y(I,J))+AIMAG(V(I))*
     AREAL(Y(I,J))
238   CONTINUE
240   CONTINUE
C THE CALCULATION OF J-3 MATRIX
      DO 246 I=K,NB
      DO 244 J=2,NB
      IF(I.NE.J) GO TO 242
      JJ(NB-K+I,J-1)=-REAL(V(I))*AIMAG(Y(I,I))+AIMAG(V(I))*REAL(Y(I,I))-
     AAIMAG(BI(I))
      GO TO 244
242   JJ(NB-K+I,J-1)=-REAL(V(I))*AIMAG(Y(I,J))+AIMAG(V(I))*REAL(Y(I,J))
244   CONTINUE
246   CONTINUE
C THE CALCULATION OF J-4 MATRIX
      DO 252 I=K,NB
      DO 250 J=2,NB
      IF(I.NE.J) GO TO 248
      JJ(NB-K+I,NB-2+J)=-REAL(V(I))*REAL(Y(I,I))-AIMAG(V(I))*
     AAIMAG(Y(I,I))+REAL(BI(I))
      GO TO 250
248   JJ(NB-K+I,NB-2+J)=-REAL(V(I))*REAL(Y(I,J))-AIMAG(V(I))*
     AAIMAG(Y(I,J))
250   CONTINUE
252   CONTINUE
      IF(MB.LE.1) GO TO 265
C THE CALCULATION OF J-5 MATRIX
      DO 258 I=2,MB
      DO 256 J=2,NB
      IF(I.NE.J) GO TO 256
      JJ(NR-MB+I,J-1)=2*REAL(V(I))
256   CONTINUE
258   CONTINUE
C THE CALCULATION OF J-6 MATRIX
      DO 264 I=2,MB
      DO 262 J=2,NB
```

```
                IF(I.NE.J) GO TO 262
                JJ(NR-MB+I,NB-2+J)=2*AIMAG(V(I))
          262   CONTINUE
          264   CONTINUE
          265   CONTINUE
        C INVERTING THE JACOBIAN MATRIX
                NRR=NR+1
                KK=0
                NN=0
                DO 288 K=1,NR
                DO 266 J=1,NR
          266   JJ(J,NRR)=0.0
                JJ(K,NRR)=1.0
                NN=KK+1
                LL=NN
                KK=KK+1
          268   IF(ABS(JJ(NN,KK))-1.E-4) 270,270,272
          270   NN=NN+1
                GO TO 268
          272   IF(LL-NN) 274,278,274
          274   DO 276 MM=1,NRR
                DTEMP=JJ(LL,MM)
                JJ(LL,MM)=JJ(NN,MM)
          276   JJ(NN,MM)=DTEMP
          278   DIV=JJ(K,K)
                DO 280 LJ=1,NRR
                J=NRR+1-LJ
          280   JJ(K,J)=JJ(K,J)/DIV
                DO 284 I=1,NR
                FAC=JJ(I,K)
                DO 284 LJ=1,NRR
                J=NRR+1-LJ
                IF(I-K) 282,284,282
          282   JJ(I,J)=JJ(I,J)-FAC*JJ(K,J)
          284   CONTINUE
                DO 286 J=1,NR
          286   JJ(J,K)=JJ(J,NRR)
          288   CONTINUE
                K=MB+1
        C DETERMINE THE REAL AND IMAGINARY VOLTAGE CHANGES
                DO 296 I=2,NB
                DE(I)=0.0
                DF(I)=0.0
                DO 290 J=2,NB
                DF(I)=DF(I)+JJ(NB-2+I,J-1)*DP(J)
          290   DE(I)=DE(I)+JJ(I-1,J-1)*DP(J)
                DO 292 J=K,NB
                DF(I)=DF(I)+JJ(NB-2+I,NB-K+J)*DQ(J)
          292   DE(I)=DE(I)+JJ(I-1,NB-K+J)*DQ(J)
                IF(MB.LE.1) GO TO 295
                DO 294 J=2,MB
                DF(I)=DF(I)+JJ(NB-2+I,NR-MB+J)*DV(J)
          294   DE(I)=DE(I)+JJ(I-1,NR-MB+J)*DV(J)
          295   CONTINUE
          296   CONTINUE
        C UPDATE BUS VOLTAGES
                DO 298 I=2,NB
          298   V(I)=V(I)+CMPLX(DE(I),DF(I))
```

```
0231            GO TO 206
          C THE START OF THE GAUSS-SEIDEL METHOD
0232      600   DO 605 I=2,NB
          C CALCULATING INITIAL CONSTANTS
0233            IF(I.LT.K) Q(I)=0.0
0234            IF(I.GT.MB) A(I)=(CMPLX(P(I),-Q(I)))/Y(I,I)
0235            DO 605 J=1,NB
0236      605   IF(I.NE.J) B(I,J)=Y(I,J)/Y(I,I)
0237      606   DVMAX=0.0
0238            I=2
0239      607   VII=V(I)
          C FOR VOLTAGE CONTROL BUSES ADJUST VOLTAGE TO SPECIFIED MAGITUDE AND CALCULATE
          C REACTIVE POWER, IF Q LIMITS ARE EXCEEDED SET Q EQUAL TO LIMIT AND RETURN
          C VOLTAGE TO PREVIOUS VALUE, CALCULATE A(I)
0240            IF (I-MB)608,608,615
0241      608   V(I)=(V(I)/CABS(V(I)))*VSPEC(I)
0242            SUM=CMPLX(0.0,0.0)
0243            DO 609 L=1,NB
0244      609   SUM=SUM+Y(I,L)*V(L)
0245            Q(I)=-AIMAG(SUM*CONJG(V(I)))
0246            IF(Q(I)-QMAX(I)) 610,614,611
0247      610   IF(Q(I)-QMIN(I)) 612,614,614
0248      611   Q(I)=QMAX(I)
0249            GO TO 613
0250      612   Q(I)=QMIN(I)
0251      613   V(I)=VII
0252      614   A(I)=(CMPLX(P(I),-Q(I)))/Y(I,I)
0253      615   SUM=CMPLX(0.0,0.0)
0254            VI=V(I)
0255            DO 616 L=1,NB
0256      616   IF(L.NE.I) SUM=SUM+B(I,L)*V(L)
0257            VN(I)=A(I)/CONJG(V(I))-SUM
0258            DX=VN(I)-VI
0259            VN(I)=VI+ALPHA*DX
          C DETERMINE THE MAXIMUM VOLTAGE DIFFERENCE BETWEEN ITERATIONS
0260            DELV=CABS(VN(I)-VII)
0261            IF(DELV.GE.DVMAX) DVMAX=DELV
          C UPDATE VOLTAGES AS AVAILABLE
0262            V(I)=VN(I)
0263            I=I+1
0264            IF(I.LE.NB) GO TO 607
          C UPDATE VOLTAGES BY ONE ITERATION
0265            N=N+1
          C COMPARE MAXIMUM VOLTAGE DIFFERENCE AGAINST CONVERGENCE CRITERIA
0266            IF(DVMAX.LE.CONV) GO TO 300
          C LIMIT ITERATIONS AS A PROTECTION AGAINST DIVERGENCE
0267            IF(N.LT.ITER) GO TO 618
0268            WRITE(6,110) N
0269            GO TO 1973
0270      618   GO TO 606
          C CONVERGENCE OBTAINED-FINAL CALCULATIONS
0271      300   SUM=CMPLX(0.0,0.0)
0272            DO 305 I=1,NB
0273      305   SUM=SUM+Y(1,I)*V(I)
          C CALCULATE SWING BUS POWER
0274            P(1)=REAL(SUM*CONJG(V(1)))
0275            Q(1)=-AIMAG(SUM*CONJG(V(1)))
0276            IF(GSNR.EQ.0) GO TO 307
```

```
0277            WRITE(6,112) N,NBASE
0278            GO TO 308
0279      307   WRITE(6,114) N,NBASE
0280      308   WRITE(6,116)
0281            DO 310 I=1,NB
0282            P(I)=P(I)*NBASE
0283      310   Q(I)=Q(I)*NBASE
0284            DO 311 I=1,MB
0285      311   QG(I)=Q(I)+QL(I)
0286            PG(1)=P(1)+PL(1)
0287            DO 340 I=1,NB
0288            DELTA=ATAN2(AIMAG(V(I)),REAL(V(I)))*90.0/ARSIN(1.0)
0289            MAGV=CABS(V(I))
0290            CMVAR(I)=(MAGV**2)*C(I)*NBASE
          C WRITE OUT CALCULATED BUS INFORMATION
0291            IF(CMVAR(I).EQ.0) GO TO 315
0292            WRITE(6,118) I,MAGV,DELTA,PG(I),QG(I),PL(I),QL(I),CMVAR(I)
0293            GO TO 320
0294      315   WRITE(6,118) I,MAGV,DELTA,PG(I),QG(I),PL(I),QL(I)
          C WRITE OUT LINE FLOWS
0295      320   DO 335 J=1,NL
0296            L=SB(J)
0297            M=EB(J)
0298            IF(L.EQ.I) GO TO 321
0299            IF(M.EQ.I) GO TO 323
0300            GO TO 335
0301      321   IF(TS(J).EQ.0) GO TO 322
0302            S(J)=V(L)*CONJG(V(L)*TR(J)*(TR(J)-1.)*SERY(J))*NBASE+
               AV(L))*CONJG((V(L)-V(M))*TR(J)*SERY(J))*NBASE                     S
0303            GO TO 325
0304      322   S(J)=(V(L)*CONJG((V(L)-V(M))*SERY(J)+V(L)*(SHTY(J))))*NBASE
0305            GO TO 325
0306      323   IF(TS(J).EQ.0) GO TO 324
0307            R(J)=V(M)*CONJG(V(M)*(1.-TR(J))*SERY(J))*NBASE+
               A(V(M))*CONJG((V(M)-V(L))*TR(J)*SERY(J))*NBASE                    R
0308            GO TO 325
0309      324   R(J)=(V(M)*CONJG((V(M)-V(L))*SERY(J)+V(M)*(SHTY(J))))*NBASE
0310      325   CONTINUE
0311            IF(M.EQ.I) GO TO 330
0312            IF(TS(J).EQ.0) GO TO 329
0313            WRITE(6,120) M,S(J),TS(J)
0314            GO TO 335
0315      329   WRITE(6,122) M,S(J)
0316            GO TO 335
0317      330   WRITE(6,122) L,R(J)
0318      335   CONTINUE
0319      340   CONTINUE
0320            TG=CMPLX(0.0,0.0)
0321            TCR=0.0
0322            TLD=CMPLX(0.0,0.0)
0323            TL=CMPLX(0.0,0.0)
          C CALCULATE THE TOTAL GENERATION, INJECTED POWER, LOAD AND LINE LOSSES
0324            DO 345 I=1,NB
0325            TG=TG+CMPLX(PG(I),QG(I))
0326            TCR=TCR+CMVAR(I)
0327            TLD=TLD+CMPLX(PL(I),QL(I))
0328      345   TL=TL+CMPLX(P(I),Q(I))+CMPLX(0.0,CMVAR(I))
0329            WRITE(6,124) TG
```

```
                  WRITE(6,126) TCR
                  WRITE(6,128) TLD
                  WRITE(6,130) TL
                  CALL MISMAT
          1973    CONTINUE
                  RETURN
                   END
```

```
0001              SUBROUTINE INPUT
            C THIS SUBROUTINE WRITES OUT THE INPUTTED DATA USED IN THE LOAD FLOW STUDY
0002              COMPLEX*8 ZSER(100),YSHT(100),R(100),S(100)
0003              REAL LENGTH(100),TS(100),PG(060),PL(060),QG(060),QL(060),
                 1VSPEC(060),QMIN(060),QMAX(060),C(060),CMVAR(060),P(060),Q(060),
                 2OBASE,NBASE,MAGV,DELTA,ALPHA,CC,CONV,ST
0004              INTEGER SB(100),EB(100),NL,NB,MB,NC,BN,ITER,M,BM
0005              COMMON/DATA/YSHT,ZSER,R,S,LENGTH,TS,PG,PL,QG,QL,VSPEC,QMIN,QMAX,
                 1C,CMVAR,P,Q,OBASE,NBASE,MAGV,DELTA,ALPHA,CC,ST,CONV,SB,EB,NB,NL,
                 3MB,NC,BN,BM,ITER
0006        100   FORMAT('1'//T57,'I N P U T  D A T A'/)
0007        102   FORMAT('0',T20,'NO. OF LINES(NL) =',I5,5X,'NO. OF BUSES(NB) =',
                 AI5,5X,'NO. OF CAPACITORS/REACTORS(NC) =',I5,//T20,
                 A'NO. OF VOLTAGE CONTROL BUSES (BM) =',I5//T20,
                 A'BASE FOR INPUTTED DATA(OLD BASE) =',1X,F6.0,1X,'MVA',5X,
                 A'BASE FOR OUTPUT(NEW BASE) =',1X,F6.0,1X,'MVA')
0008        104   FORMAT('0',T20,'TOLERANCE FOR CONVERGENCE =',F9.6,5X,
                 A'MAXIMUM NO. OF ITERATIONS ALLOWED =',I4)
0009        106   FORMAT('0',T20,'ACCELERATION FACTOR =',F6.2,1X,
                 A'(USED WITH GAUSS-SEIDEL METHOD ONLY)'//T20,
                 A'SWING BUS VOLTAGE MAGNITUDE =',F10.5,1X,'PU',5X,
                 A'SWING BUS PHASE =',F7.2,1X,'DEGREES'//)
0010        108   FORMAT('0',T20,'STATIC CAPACITORS/REACTORS (OLD BASE)'//T20,
                 A'BUS',5X,'SUSCEPTANCE'/)
0011        110   FORMAT(' ',T17,I5,5X,F10.5)
0012        112   FORMAT('0'//T20,'TRANSMISSION LINE DATA (OLD BASE)'/T20,
                 1'Y SHUNT IS TOTAL LINE CHARGING ADMITTANCE'/T20,'SB',5X,
                 2'EB',14X,'Z SERIES',19X,'Y SHUNT',11X,'LENGTH'/T40,'R',11X,'X',
                 314X,'G',11X,'B'/)
0013        113   FORMAT('0'//T20,'TRANSMISSION LINE DATA (OLD BASE)'/T20,
                 1'Y SHUNT IS ONE-HALF OF THE TOTAL LINE CHARGING ADMITTANCE'/T20,
                 2'SB',5X,'EB',14X,'Z SERIES',19X,'Y SHUNT',11X,'LENGTH'/T40,'R',
                 311X,'X',14X,'G',11X,'B'/)
0014        114   FORMAT(' ',T17,I5,2X,I5,5X,F10.5,2X,F10.5,5X,F10.5,2X,F10.5,5X,
                 AF5.1)
0015        116   FORMAT('0',T20,'TOTAL TRANSMISSION LINES =',1X,I5)
0016        118   FORMAT('0'//T20,'TRANSFORMER LINE DATA (OLD BASE)'/T20,
                 1'Y SHUNT IS TOTAL LINE CHARGING ADMITTANCE'/T20,'SB',5X,
                 2'EB',14X,'Z SERIES',19X,'Y SHUNT',12X,'TAP SETTING',11X,'LENGTH'/
                 3T40,'R',11X,'X',14X,'G',11X,'B'/)
0017        119   FORMAT('0'//T20,'TRANSFORMER LINE DATA (OLD BASE)'/T20,
                 1'Y SHUNT IS ONE-HALF OF THE TOTAL LINE CHARGING ADMITTANCE'/T20,
                 2'SB',5X,'EB',14X,'Z SERIES',19X,'Y SHUNT',12X,'TAP SETTING',11X,
                 3'LENGTH'/T40,'R',11X,'X',14X,'G',11X,'B'/)
0018        120   FORMAT(' ',T17,I5,2X,I5,5X,F10.5,2X,F10.5,5X,F10.5,2X,F10.5,9X,
                 AF5.3,14X,F5.1)
0019        122   FORMAT('0',T20,'TOTAL TRANSFORMER LINES =',1X,I5)
0020        124   FORMAT('0'//T20,'VOLTAGE CONTROL BUS DATA'//T20,'BUS',10X,'VSPEC',
                 A10X,'QMIN',10X,'QMAX'/T35,'PU',11X,'MVAR',10X,'MVAR'/)
0021        126   FORMAT(' ',T17,I5,6X,F10.3,5X,F10.3,4X,F10.3)
0022        128   FORMAT('0'//T20,'SCHEDULED BUS POWERS'//T20,'BUS',13X,
                 A'GENERATION',25X,'LOAD'/T33,'MW',12X,'MVAR',14X,'MW',12X,'MVAR'//)
0023        130   FORMAT(' ',T17,I5,5X,F10.3,5X,F10.3,7X,F10.3,5X,F10.3)
0024        132   FORMAT(' ',T17,I5,5X,F10.3,6X,'UNSPECIFIED',5X,F10.3,5X,F10.3)
0025        134   FORMAT(' ',T17,I5,6X,'UNSPECIFIED',4X,'UNSPECIFIED',5X,F10.3,
                 A5X,F10.3)
0026              WRITE(6,100)
0027              WRITE(6,102) NL,NB,NC,BM,OBASE,NBASE
```

```
              WRITE(6,104) CONV,ITER
              WRITE(6,106) ALPHA,MAGV,DELTA
              IF(NC.EQ.0) GO TO 15
              WRITE(6,108)
              DO 5 I=1,NB
              IF(C(I).EQ.0) GO TO 5
              C(I)=C(I)*NBASE/OBASE
              WRITE(6,110) I,C(I)
        5     CONTINUE
              DO 10 I=1,NB
        10    C(I)=C(I)*OBASE/NBASE
        15    CONTINUE
              IF(ST.EQ.0) GO TO 17
              WRITE(6,112)
              GO TO 18
        17    WRITE(6,113)
        18    M=0
              DO 20 I=1,NL
              YSHT(I)=YSHT(I)*NBASE/OBASE
              ZSER(I)=ZSER(I)*OBASE/NBASE
              IF(TS(I).NE.0) GO TO 20
              WRITE(6,114) SB(I),EB(I),ZSER(I),YSHT(I),LENGTH(I)
              M=M+1
        20    CONTINUE
              WRITE(6,116) M
              DO 25 I=1,NL
              IF(TS(I).NE.0) GO TO 30
        25    CONTINUE
              GO TO 40
        30    IF(ST.EQ.0) GO TO 32
              WRITE(6,118)
              GO TO 33
        32    WRITE(6,119)
        33    M=0
              DO 35 I=1,NL
              IF(TS(I).EQ.0) GO TO 35
              WRITE(6,120) SB(I),EB(I),ZSER(I),YSHT(I),TS(I),LENGTH(I)
              M=M+1
        35    CONTINUE
              WRITE(6,122) M
        40    CONTINUE
              IF(MB.LE.1) GO TO 50
              WRITE(6,124)
              DO 45 I=2,MB
        45    WRITE(6,126) I,VSPEC(I),QMIN(I),QMAX(I)
        50    CONTINUE
              WRITE(6,128)
              DO 65 I=1,NB
              IF(I.EQ.1) GO TO 60
              IF(I.LE.MB) GO TO 55
              WRITE(6,130) I,PG(I),QG(I),PL(I),QL(I)
              GO TO 65
        55    WRITE(6,132)I,QG(I),PL(I),QL(I)
              GO TO 65
        60    WRITE(6,134) I,PL(I),QL(I)
        65    CONTINUE
              RETURN
              END
```

```
0001              SUBROUTINE MISMAT
            C THIS SUBROUTINE CALCULATES THE MISMATCH AT EACH BUS EXCEPT AT THE SWING BUS
0002              COMPLEX*8 ZSER(100),YSHT(100),R(100),S(100),CMPLX,AMM,BMM,TMM
0003              REAL LENGTH(100),TS(100),PG(060),PL(060),QG(060),QL(060),
                 1VSPEC(060),QMIN(060),QMAX(060),C(060),CMVAR(060),P(060),Q(060),
                 2OBASE,NBASE,MAGV,DELTA,ALPHA,CC,CONV,ST
0004              INTEGER SB(100),EB(100),NL,NB,MB,NC,BN,ITER,BM
0005              COMMON/DATA/YSHT,ZSER,R,S,LENGTH,TS,PG,PL,QG,QL,VSPEC,QMIN,QMAX,
                 1C,CMVAR,P,Q,OBASE,NBASE,MAGV,DELTA,ALPHA,CC,ST,CONV,SB,EB,NB,NL,
                 3MB,NC,BN,BM,ITER
0006        100   FORMAT('1',T70,'MISMATCHES'//)
0007        102   FORMAT(' ',60X,F9.3,6X,F9.3)
0008        104   FORMAT('0',T42,'TOTAL MISMATCH',6X,F9.3,6X,F9.3)
0009        106   FORMAT('0',T42,'AVERAGE MISMATCH',4X,F9.3,6X,F9.3//)
0010              WRITE(6,100)
0011              TMM=CMPLX(0.0,0.0)
0012              DO 425 J=1,NB
0013              BMM=CMPLX(0.0,0.0)
0014              DO 415 I=1,NL
0015              L=SB(I)
0016              M=EB(I)
0017              IF(L.EQ.J) GO TO 405
0018              IF(M.EQ.J) GO TO 410
0019              GO TO 415
0020        405   BMM=BMM+S(I)
0021              GO TO 415
0022        410   BMM=BMM+R(I)
0023        415   CONTINUE
0024              IF(J.EQ.1) GO TO 420
            C CALCULATE THE BUS MISMATCH
0025              BMM=BMM-CMPLX(P(J),Q(J))-CMPLX(0.0,CMVAR(J))
0026        420   WRITE(6,102) BMM
0027              IF(J.EQ.1) GO TO 425
            C CALCULATE THE TOTAL MISMATCH
0028              TMM=TMM+BMM
0029        425   CONTINUE
0030              WRITE(6,104) TMM
            C CALCULATE THE AVERAGE MISMATCH
0031              AMM=TMM/(NB-1)
0032              WRITE(6,106) AMM
0033              RETURN
0034              END
```

CHAPTER III

SAMPLE SOLUTIONS

There are several factors one should consider in comparing methods. Among these factors include the number of iterations for convergence, time per iteration, tolerance allowed, type of computer used, size of system used, and finally the accuracy of the results.

A fourteen bus system was used to compare the Gauss-Seidel method with the Newton-Raphson method. The fourteen bus system contains seventeen transmission lines, three transformer lines, one static capacitor, and four voltage control buses. The input data is given on the next page.

The Gauss-Seidel method used .0001 tolerance for the bus voltages compared to .001 tolerance for the bus powers in the Newton-Raphson method. These tolerances used are approximately equivalent to each other.

Since the same computer and sample power system was used by both methods, one can rule out these factors in comparing methods.

Twenty-two iterations were required before convergence was obtained with the Gauss-Seidel as compared to six iterations with the Newton-Raphson method. However, in comparing time per iteration or total time, the Gauss-Seidel method was approximately 1¼ times faster than the Newton-Raphson method. Normally the Newton-Raphson method is faster, but no serious attempt was made to optimize the computer routine as given in this report. (See Chapter IV for suggested program improvements.)

The Newton-Raphson method has better accuracy in its results. This can be seen when comparing the mismatches. At all buses as well as the total and average mismatches the Newton-Raphson method was better. The results of these studies are given on the next pages.

A moderately large power system was also studied using the developed load-flow program. The results of that study are presented in the next several pages. The sample system contained 57 buses, 3 static capacitors, 6 voltage control buses, 63 transmission lines, and 17 transformer lines.

The program is dimensioned to handle as many as 60 buses, 100 lines (any combination of transmission and transformer lines), 100 static capacitors/reactors, and 59 voltage control buses.

Essentially, the program could handle any size power system. All that is needed is adequate computer core storage to handle the data.

I N P U T   D A T A

NO. OF LINES(NL) = 20   NO. OF BUSES(NB) = 14   NO. OF CAPACITORS/REACTORS(NC) = 1

NO. OF VOLTAGE CONTROL BUSES (BM) = 4

BASE FOR INPUTTED DATA(OLD BASE) = 100. MVA   BASE FOR OUTPUT(NEW BASE) = 100. MVA

TOLERANCE FOR CONVERGENCE = 0.000100   MAXIMUM NO. OF ITERATIONS ALLOWED = 75

ACCELERATION FACTOR = 1.65 (USED WITH GAUSS-SEIDEL METHOD ONLY)

SWING BUS VOLTAGE MAGNITUDE = 1.06000 PU   SWING BUS PHASE = 0.0 DEGREES

STATIC CAPACITORS/REACTORS (OLD BASE)

BUS	SUSCEPTANCE
9	0.19000

TRANSMISSION LINE DATA (OLD BASE)
Y SHUNT IS ONE-HALF OF THE TOTAL LINE CHARGING ADMITTANCE

SB	EB	Z SERIES R	Z SERIES X	Y SHUNT G	Y SHUNT B	LENGTH
1	2	0.01938	0.05917	0.0	0.02640	1.0
1	8	0.05403	0.22304	0.0	0.02460	1.0
2	3	0.04699	0.19797	0.0	0.02190	1.0
2	6	0.05811	0.17632	0.0	0.01870	1.0
2	8	0.05695	0.17388	0.0	0.01700	1.0
3	6	0.06701	0.17103	0.0	0.01730	1.0
6	8	0.01335	0.04211	0.0	0.00640	1.0
4	11	0.09498	0.19890	0.0	0.0	1.0
4	12	0.12291	0.25591	0.0	0.0	1.0
4	13	0.06615	0.13027	0.0	0.0	1.0
7	5	0.0	0.17615	0.0	0.0	1.0
7	9	0.0	0.11001	0.0	0.0	1.0
9	10	0.03181	0.08450	0.0	0.0	1.0
9	14	0.12711	0.27038	0.0	0.0	1.0
10	11	0.08205	0.19207	0.0	0.0	1.0
12	13	0.22092	0.19988	0.0	0.0	1.0
13	14	0.17093	0.34802	0.0	0.0	1.0

TOTAL TRANSMISSION LINES = 17

TRANSFORMER LINE DATA (OLD BASE)
Y SHUNT IS ONE-HALF OF THE TOTAL LINE CHARGING ADMITTANCE

SB	EB	Z SERIES R	Z SERIES X	Y SHUNT G	Y SHUNT B	TAP SETTING	LENGTH
6	7	0.0	0.20912	0.0	0.0	0.978	1.0

6	9	0.0	0.55618	0.0	0.0	0.969	1.0
8	4	0.0	0.25202	0.0	0.0	0.932	1.0

TOTAL TRANSFORMER LINES = 3

VOLTAGE CONTROL BUS DATA

BUS	VSPEC PU	QMIN MVAR	QMAX MVAR
2	1.045	-40.000	50.000
3	1.010	0.0	40.000
4	1.070	-6.000	24.000
5	1.090	-6.000	24.000

SCHEDULED BUS POWERS

BUS	GENERATION		LOAD	
	MW	MVAR	MW	MVAR
1	UNSPECIFIED	UNSPECIFIED	0.0	0.0
2	40.000	UNSPECIFIED	21.700	12.700
3	0.0	UNSPECIFIED	94.200	19.000
4	0.0	UNSPECIFIED	11.200	7.500
5	0.0	UNSPECIFIED	0.0	0.0
6	0.0	0.0	47.800	-3.900
7	0.0	0.0	0.0	0.0
8	0.0	0.0	7.600	1.600
9	0.0	0.0	29.500	16.600
10	0.0	0.0	9.000	5.800
11	0.0	0.0	3.500	1.800
12	0.0	0.0	6.100	1.600
13	0.0	0.0	13.500	5.800
14	0.0	0.0	14.900	5.000

GAUSS-SEIDEL TECHNIQUE CONVERGED IN 22 ITERATIONS. ALL VALUES ON 100. MVA BASE

		VOLTAGE MAGNITUDE PU	DELTA(DEGS)		GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	INJECTED POWER (STATIC) MVAR
BUS	1	1.060	0.0		232.349	-16.864	0.0	0.0	
		2	156.800	-20.369					
		8	75.549	3.506					
BUS	2	1.045	-4.9797		40.000	42.383	21.700	12.700	
		1	-152.507	27.627					
		3	73.184	3.567					
		6	56.136	-2.287					
		8	41.518	0.758					
BUS	3	1.010	-12.7164		0.0	23.399	94.200	19.000	
		2	-70.964	1.581					
		6	-23.330	2.806					
BUS	4	1.070	-14.2210		0.0	12.261	11.200	7.500	
		11	7.349	3.469					
		12	7.780	2.494					
		13	17.746	7.169					
		8	-44.054	-8.393					
BUS	5	1.090	-13.3651		0.0	17.371	0.0	0.0	
		7	0.027	17.359					
BUS	6	1.019	-10.3229		0.0	0.0	47.800	-3.900	
		2	-54.459	3.393					
		3	23.701	-5.419					
		8	-61.189	15.646					
		7	28.091	-9.423	TAP 0.978				
		9	16.095	-0.322	TAP 0.969				
BUS	7	1.062	-13.3674		0.0	0.0	0.0	0.0	
		5	-0.027	-16.912					
		9	29.104	5.794					
		6	-28.091	11.115					
BUS	8	1.020	-8.7821		0.0	0.0	7.600	1.600	
		1	-72.785	2.577					
		2	-40.616	-1.628					
		6	61.705	-15.349					
		4	44.054	12.821	TAP 0.932				
BUS	9	1.056	-14.9467		0.0	0.0	29.500	16.600	21.201
		7	-28.105	-4.990					
		10	5.247	4.298					
		14	9.436	3.664					
		6	-16.095	1.627					
BUS	10	1.051	-15.1049		0.0	0.0	9.000	5.800	
		9	-5.234	-4.263					
		11	-3.784	-1.524					
BUS	11	1.057	-14.7947		0.0	0.0	3.500	1.800	

		4	-7.295	-3.354					
		10	3.797	1.553					
BUS	12	1.055	-15.0755		0.0	0.0	6.100	1.600
		4	-7.708	-2.344				
		13	1.614	0.739				
BUS	13	1.050	-15.1578		0.0	0.0	13.500	5.800
		4	-17.535	-6.752				
		12	-1.607	-0.734				
		14	5.637	1.688				
BUS	14	1.036	-16.0389		0.0	0.0	14.900	5.000
		9	-9.319	-3.416				
		13	-5.583	-1.579				

TOTALS	MW	MVAR
GENERATION	272.349	78.550
STATIC CAP/REACTORS		21.201
LOAD	259.000	73.500
LINE LOSSES	13.349	26.251

MISMATCHES

	232.349	-16.863
	0.032	-0.018
	0.006	-0.011
	0.022	-0.023
	0.027	-0.012
	0.038	-0.024
	-0.013	-0.004
	-0.042	0.021
	-0.016	-0.003
	-0.018	0.013
	0.002	-0.001
	0.005	-0.005
	-0.005	0.002
	-0.003	0.005
TOTAL MISMATCH	0.035	-0.060
AVERAGE MISMATCH	0.003	-0.005

NEWTON-RAPHSON TECHIQUE CONVERGED IN 6 ITERATIONS. ALL VALUES ON 100. MVA BASE

		VOLTAGE MAGNITUDE PU	DELTA(DEGS)		GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	INJECTED POWER (STATIC) MVAR
BUS	1	1.060	0.0		232.386	-16.891	0.0	0.0	
		2	156.833	-20.390					
		8	75.553	3.499					
BUS	2	1.045	-4.9809		40.000	42.377	21.700	12.700	
		1	-152.538	27.654					
		3	73.188	3.565					
		6	56.138	-2.292					
		8	41.512	0.757					
BUS	3	1.010	-12.7180		0.0	23.391	94.200	19.000	
		2	-70.868	1.585					
		6	-23.333	2.806					
BUS	4	1.070	-14.2227		0.0	12.234	11.200	7.500	
		11	7.341	3.472					
		12	7.782	2.492					
		13	17.740	7.170					
		8	-44.063	-8.399					
BUS	5	1.090	-13.3682		0.0	17.362	0.0	0.0	
		7	-0.000	17.362					
BUS	6	1.019	-10.3242		0.0	0.0	47.800	-3.900	
		2	-54.461	3.398					
		3	23.705	-5.418					
		8	-61.220	15.661					
		7	28.087	-9.413	TAP 0.978				
		9	16.090	-0.320	TAP 0.969				
BUS	7	1.062	-13.3682		0.0	0.0	0.0	0.0	
		5	0.000	-16.915					
		9	28.087	5.786					
		6	-28.087	11.105					
BUS	8	1.020	-8.7827		0.0	0.0	7.600	1.600	
		1	-72.789	2.585					
		2	-40.610	-1.628					
		6	61.736	-15.362					
		4	44.063	12.828	TAP 0.932				
BUS	9	1.056	-14.9466		0.0	0.0	29.500	16.600	21.201
		7	-28.087	-4.984					
		10	5.239	4.306					
		14	9.438	3.665					
		6	-16.090	1.624					
BUS	10	1.051	-15.1043		0.0	0.0	9.000	5.800	
		9	-5.226	-4.271					
		11	-3.775	-1.530					
BUS	11	1.057	-14.7953		0.0	0.0	3.500	1.800	

		4	-7.286	-3.357				
		10	3.787	1.558				
BUS	12	1.055	-15.0775		0.0	0.0	6.100	1.600
		4	-7.710	-2.343				
		13	1.610	0.743				
BUS	13	1.050	-15.1590		0.0	0.0	13.500	5.800
		4	-17.528	-6.754				
		12	-1.604	-0.737				
		14	5.632	1.692				
BUS	14	1.036	-16.0389		0.0	0.0	14.900	5.000
		9	-9.321	-3.417				
		13	-5.579	-1.583				

TOTALS	MW	MVAR
GENERATION	272.386	78.473
STATIC CAP/REACTORS		21.201
LOAD	259.000	73.500
LINE LOSSES	13.386	26.174

MISMATCHES

	232.386	-16.891
	-0.000	0.006
	-0.001	-0.000
	-0.001	0.002
	-0.000	0.000
	0.001	0.007
	0.000	-0.024
	0.000	0.023
	0.001	0.010
	-0.001	-0.001
	0.001	0.001
	0.000	0.000
	-0.000	0.000
	0.000	0.000
TOTAL MISMATCH	0.000	0.024
AVERAGE MISMATCH	0.000	0.002

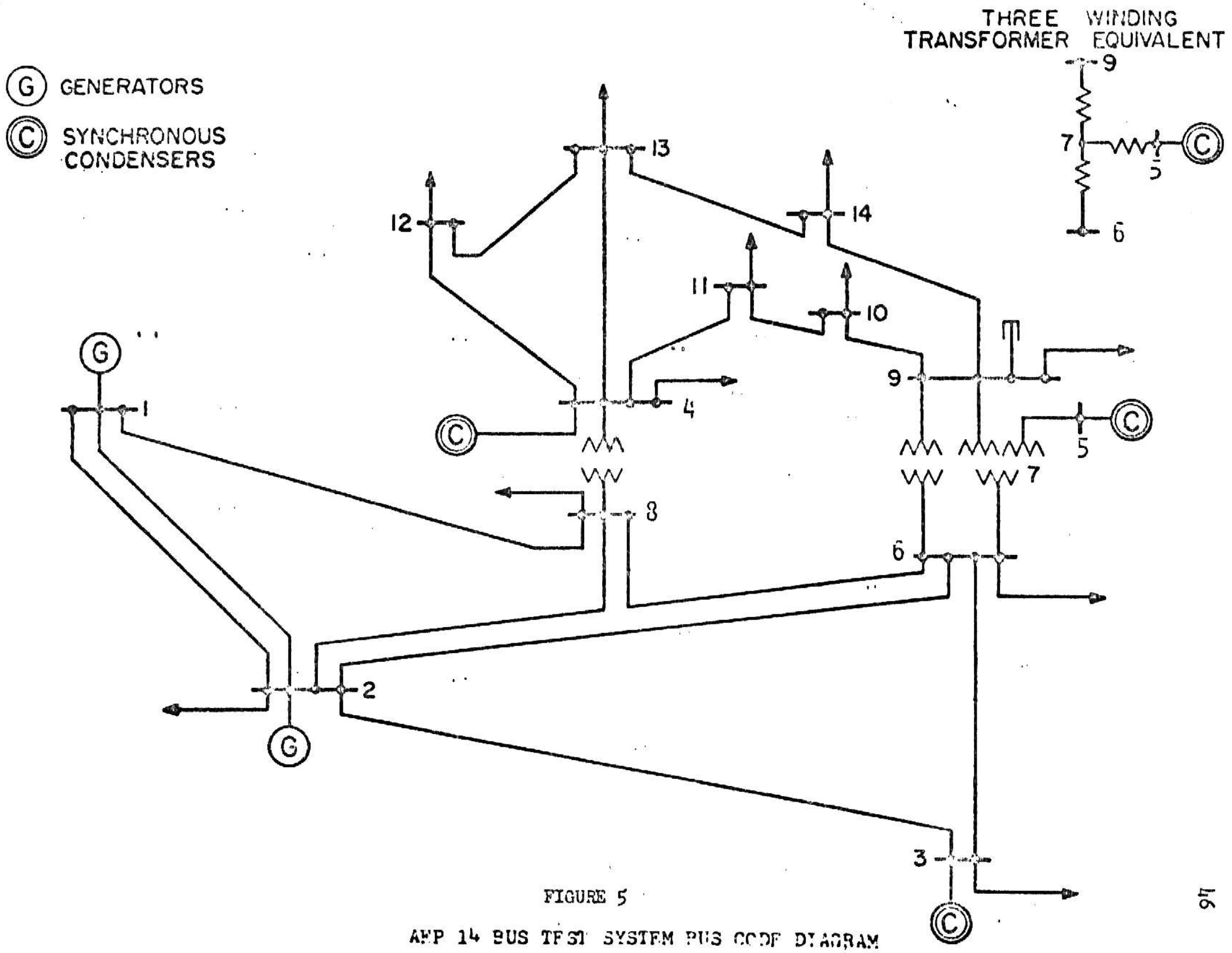


FIGURE 5

AEP 14 BUS TEST SYSTEM BUS CODE DIAGRAM

INPUT DATA

NO. OF LINES(NL) = 80 NO. OF BUSES(NB) = 57 NO. OF CAPACITORS/REACTORS(NC) = 3

NO. OF VOLTAGE CONTROL BUSES (BM) = 6

BASE FOR INPUTTED DATA(OLD BASE) = 100. MVA BASE FOR OUTPUT(NEW BASE) = 100. MVA

TOLERANCE FOR CONVERGENCE = 0.000100 MAXIMUM NO. OF ITERATIONS ALLOWED = 75

ACCELERATION FACTOR = 1.65 (USED WITH GAUSS-SEIDEL METHOD ONLY)

SWING BUS VOLTAGE MAGNITUDE = 1.04000 PU SWING BUS PHASE = 0.0 DEGREES

STATIC CAPACITORS/REACTORS (OLD BASE)

BUS	SUSCEPTANCE
18	0.10000
25	0.05900
53	0.06300

TRANSMISSION LINE DATA (OLD BASE)

Y SHUNT IS ONE-HALF OF THE TOTAL LINE CHARGING ADMITTANCE

SB	EB	Z SERIES		Y SHUNT		LENGTH
		R	X	G	B	
1	2	0.00830	0.02800	0.0	0.06450	1.0
2	3	0.02980	0.08500	0.0	0.04090	1.0
3	8	0.01120	0.03660	0.0	0.01900	1.0
8	9	0.06250	0.13200	0.0	0.01290	1.0
8	4	0.04300	0.14800	0.0	0.01740	1.0
4	10	0.02000	0.10200	0.0	0.01380	1.0
4	5	0.03390	0.17300	0.0	0.02350	1.0
5	6	0.00990	0.05050	0.0	0.02740	1.0
6	12	0.03690	0.16790	0.0	0.02200	1.0
6	11	0.02580	0.08480	0.0	0.01090	1.0
6	7	0.06480	0.29500	0.0	0.03860	1.0
6	13	0.04810	0.15800	0.0	0.02030	1.0
13	14	0.01320	0.04340	0.0	0.00550	1.0
13	15	0.02690	0.08690	0.0	0.01150	1.0
1	15	0.01780	0.09100	0.0	0.04940	1.0
1	16	0.04540	0.20600	0.0	0.02730	1.0
1	17	0.02380	0.10800	0.0	0.01430	1.0
3	15	0.01620	0.05300	0.0	0.02720	1.0
9	4	0.03020	0.06410	0.0	0.00620	1.0
10	5	0.01390	0.07120	0.0	0.00970	1.0
12	7	0.02770	0.12620	0.0	0.01640	1.0
11	13	0.02230	0.07320	0.0	0.00940	1.0
7	13	0.01780	0.05800	0.0	0.03020	1.0
7	16	0.01900	0.06130	0.0	0.01080	1.0
7	17	0.03970	0.17900	0.0	0.02390	1.0
14	15	0.01710	0.05470	0.0	0.00740	1.0

18	19	0.46100	0.68500	0.0	0.0	1.0
19	20	0.28300	0.43400	0.0	0.0	1.0
21	22	0.07360	0.11700	0.0	0.0	1.0
22	23	0.00990	0.01520	0.0	0.0	1.0
23	24	0.16600	0.25600	0.0	0.00420	1.0
26	27	0.16500	0.25400	0.0	0.0	1.0
27	28	0.06180	0.09540	0.0	0.0	1.0
28	29	0.04180	0.05870	0.0	0.0	1.0
25	30	0.13500	0.20200	0.0	0.0	1.0
30	31	0.32600	0.49700	0.0	0.0	1.0
31	32	0.50700	0.75500	0.0	0.0	1.0
32	33	0.03920	0.03600	0.0	0.0	1.0
34	35	0.05200	0.07800	0.0	0.00160	1.0
35	36	0.04300	0.05370	0.0	0.00080	1.0
36	37	0.02900	0.03660	0.0	0.0	1.0
37	38	0.06510	0.10090	0.0	0.01000	1.0
37	39	0.02390	0.03790	0.0	0.0	1.0
36	40	0.03000	0.04660	0.0	0.0	1.0
22	38	0.01920	0.02950	0.0	0.0	1.0
41	42	0.20700	0.35200	0.0	0.0	1.0
41	43	0.0	0.41200	0.0	0.0	1.0
38	44	0.02890	0.05850	0.0	0.00100	1.0
46	47	0.02300	0.06800	0.0	0.00160	1.0
47	48	0.01820	0.02330	0.0	0.0	1.0
48	49	0.08340	0.12900	0.0	0.00240	1.0
49	50	0.08010	0.12800	0.0	0.0	1.0
50	51	0.13860	0.22000	0.0	0.0	1.0
29	52	0.14420	0.18700	0.0	0.0.	1.0
52	53	0.07620	0.09840	0.0	0.0	1.0
53	54	0.18780	0.23200	0.0	0.0	1.0
54	55	0.17320	0.22650	0.0	0.0	1.0
44	45	0.06240	0.12420	0.0	0.00200	1.0
56	41	0.55300	0.54900	0.0	0.0	1.0
56	42	0.21250	0.35400	0.0	0.0	1.0
57	56	0.17400	0.26000	0.0	0.0	1.0
38	49	0.11500	0.17700	0.0	0.00300	1.0
38	48	0.03120	0.04820	0.0	0.0	1.0

TOTAL TRANSMISSION LINES = 63

TRANSFORMER LINE DATA (OLD BASE)

Y SHUNT IS ONE-HALF OF THE TOTAL LINE CHARGING ADMITTANCE

SB	EB	Z SERIES		Y SHUNT		TAP SETTING	LENGTH
		R	X	G	B		
8	18	0.0	0.55500	0.0	0.0	0.970	1.0
8	18	0.0	0.43000	0.0	0.0	0.978	1.0
21	20	0.0	0.77670	0.0	0.0	1.043	1.0
24	25	0.0	1.18200	0.0	0.0	1.000	1.0
24	25	0.0	1.23000	0.0	0.0	1.000	1.0
24	26	0.0	0.04730	0.0	0.0	1.043	1.0
10	29	0.0	0.06480	0.0	0.0	0.967	1.0
34	32	0.0	0.95300	0.0	0.0	0.975	1.0
11	41	0.0	0.74900	0.0	0.0	0.955	1.0
15	45	0.0	0.10420	0.0	0.0	0.955	1.0
14	46	0.0	0.07350	0.0	0.0	0.900	1.0
12	51	0.0	0.07120	0.0	0.0	0.930	1.0
13	49	0.0	0.19100	0.0	0.0	0.895	1.0

11	43	0.0	0.15300	0.0	0.0	0.958	1.0
40	56	0.0	1.19500	0.0	0.0	0.959	1.0
39	57	0.0	1.35500	0.0	0.0	0.980	1.0
6	55	0.0	0.12050	0.0	0.0	0.940	1.0

TOTAL TRANSFORMER LINES = 17

VOLTAGE CONTROL BUS DATA

BUS	VSPEC PU	QMIN MVAR	QMAX MVAR
2	1.010	-17.000	50.000
3	0.985	-10.000	60.000
4	0.980	-8.000	25.000
5	1.005	-140.000	200.000
6	0.980	-3.000	9.000
7	1.015	-50.000	155.000

SCHEDULED BUS POWERS

BUS	GENERATION		LOAD	
	MW	MVAR	MW	MVAR
1	UNSPECIFIED	UNSPECIFIED	55.000	17.000
2	0.0	UNSPECIFIED	3.000	88.000
3	40.000	UNSPECIFIED	41.000	21.000
4	0.0	UNSPECIFIED	75.000	2.000
5	450.000	UNSPECIFIED	150.000	22.000
6	0.0	UNSPECIFIED	121.000	26.000
7	310.000	UNSPECIFIED	377.000	24.000
8	0.0	0.0	0.0	0.0
9	0.0	0.0	13.000	4.000
10	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0
12	0.0	0.0	5.000	2.000
13	0.0	0.0	18.000	2.300
14	0.0	0.0	10.500	5.300
15	0.0	0.0	22.000	5.000
16	0.0	0.0	43.000	3.000
17	0.0	0.0	42.000	8.000
18	0.0	0.0	27.200	9.800
19	0.0	0.0	3.300	0.600
20	0.0	0.0	2.300	1.000
21	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0
23	0.0	0.0	6.300	2.100
24	0.0	0.0	0.0	0.0
25	0.0	0.0	6.300	3.200
26	0.0	0.0	0.0	0.0
27	0.0	0.0	9.300	0.500
28	0.0	0.0	4.600	2.300
29	0.0	0.0	17.000	2.600
30	0.0	0.0	3.600	1.800
31	0.0	0.0	5.800	2.900

32	0.0	0.0	1.600	0.800
33	0.0	0.0	3.800	1.900
34	0.0	0.0	0.0	0.0
35	0.0	0.0	6.000	3.000
36	0.0	0.0	0.0	0.0
37	0.0	0.0	0.0	0.0
38	0.0	0.0	14.000	7.000
39	0.0	0.0	0.0	0.0
40	0.0	0.0	0.0	0.0
41	0.0	0.0	6.300	3.000
42	0.0	0.0	7.100	4.400
43	0.0	0.0	2.000	1.000
44	0.0	0.0	12.000	1.800
45	0.0	0.0	0.0	0.0
46	0.0	0.0	0.0	0.0
47	0.0	0.0	29.700	11.600
48	0.0	0.0	0.0	0.0
49	0.0	0.0	18.000	8.500
50	0.0	0.0	21.000	10.500
51	0.0	0.0	18.000	5.300
52	0.0	0.0	4.900	2.200
53	0.0	0.0	20.000	10.000
54	0.0	0.0	4.100	1.400
55	0.0	0.0	6.600	3.400
56	0.0	0.0	7.600	2.200
57	0.0	0.0	6.700	2.000

GAUSS-SEIDEL TECHNIQUE CONVERGED IN 58 ITERATIONS. ALL VALUES ON 100. MVA BASE

		VOLTAGE MAGNITUDE PU	DELTA(DEGS)		GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	INJECTED POWER (STATIC) MVAR
BUS	1	1.040	0.0		478.358	128.613	55.000	17.000	
		2	101.979	75.037					
		15	148.911	33.506					
		16	79.186	-0.868					
		17	93.282	3.940					
BUS	2	1.010	-1.1863		0.0	-0.766	3.000	88.000	
		1	-100.665	-64.159					
		3	97.671	-4.611					
BUS	3	0.985	-5.9808		40.000	-1.428	41.000	21.000	
		2	-94.885	4.420					
		8	60.144	-8.206					
		15	33.773	-18.669					
BUS	4	0.980	-8.6613		0.0	0.780	75.000	2.000	
		8	-14.022	2.048					
		10	-17.806	-1.776					
		5	-42.513	-6.561					
		9	-0.624	5.042					
BUS	5	1.065	-4.4639		450.000	62.012	150.000	22.000	
		4	43.157	5.220					
		6	178.055	19.817					
		10	78.822	14.950					
BUS	6	0.950	-9.5715		0.0	1.786	121.000	26.000	
		5	-174.897	-9.110					
		12	17.161	-9.318					
		11	12.922	1.821					
		7	2.566	-15.857					
		13	2.341	-2.137					
		55	18.928	10.368	TAP 0.940				
BUS	7	1.015	-10.4610		310.000	128.016	377.000	24.000	
		6	-2.462	8.647					
		12	17.734	17.530					
		13	-0.506	59.877					
		16	-33.334	8.792					
		17	-49.402	9.143					
BUS	8	0.981	-7.3237		0.0	0.0	0.0	0.0	
		3	-59.722	5.915					
		9	13.777	-4.413					
		4	14.116	-5.069					
		18	13.956	2.413	TAP 0.970				
		18	17.866	1.160	TAP 0.978				
BUS	9	0.976	-8.5354		0.0	0.0	13.000	4.000	
		8	-13.647	2.216					
		4	0.634	-6.207					

BUS	10	0.984	-7.5878		0.0	0.0	0.0	0.0	
		4	17.972	-0.549					
		5	-77.932	-12.311					
		29	60.063	12.863	TAP 0.957				
BUS	11	0.974	-10.1947		0.0	0.0	0.0	0.0	
		6	-12.875	-3.748					
		13	-9.896	-4.486					
		41	9.187	3.463	TAP 0.955				
		43	13.600	4.763	TAP 0.958				
BUS	12	0.986	-11.4371		0.0	0.0	5.000	2.000	
		6	-17.027	5.671					
		7	-17.550	-19.978					
		51	29.585	12.309	TAP 0.930				
BUS	13	0.979	-9.7977		0.0	0.0	18.000	2.300	
		6	-2.339	-1.750					
		14	-10.366	22.057					
		15	-48.861	4.891					
		11	9.922	2.779					
		7	1.192	-63.650					
		49	32.468	33.361	TAP 0.895				
BUS	14	0.971	-9.3467		0.0	0.0	10.500	5.300	
		13	10.452	-22.822					
		15	-68.789	-9.376					
		46	47.859	26.889	TAP 0.900				
BUS	15	0.988	-7.1873		0.0	0.0	22.000	5.000	
		13	49.541	-4.920					
		1	-145.014	-23.748					
		3	-33.540	14.137					
		14	69.660	10.747					
		45	37.335	-1.207	TAP 0.955				
BUS	16	1.013	-8.8519		0.0	0.0	43.000	3.000	
		1	-76.552	7.062					
		7	33.545	-10.059					
BUS	17	1.017	-5.3922		0.0	0.0	42.000	8.000	
		1	-91.360	1.751					
		7	49.356	-9.755					
BUS	18	1.001	-11.7186		0.0	0.0	27.200	9.800	10.016
		9	-13.956	-1.324					
		8	-17.866	0.211					
		19	4.621	1.329					
BUS	19	0.971	-13.2242		0.0	0.0	3.300	0.600	
		18	-4.514	-1.170					
		20	1.216	0.567					
BUS	20	0.965	-13.4489		0.0	0.0	2.300	1.000	
		19	-1.211	-0.559					
		21	-1.087	-0.441					
BUS	21	1.010	-12.9308		0.0	0.0	0.0	0.0	
		20	1.087	0.453	TAP 1.043				
		22	-1.091	-0.471					

BUS	22	1.011	-12.8793		0.0	0.0	0.0	0.0	
		21	1.082	0.473					
		23	9.712	3.164					
		38	-10.710	-3.835					
BUS	23	1.010	-12.9446		0.0	0.0	6.300	2.100	
		22	-9.702	-3.149					
		24	3.367	1.137					
BUS	24	1.[illegible]	-13.2861		0.0	0.0	0.0	0.0	
		23	-3.344	-1.951					
		25	7.069	1.699	TAP 1.000				
		25	6.793	1.633	TAP 1.000				
		26	-10.467	-1.407	TAP 1.043				
BUS	25	0.984	-18.1563		0.0	0.0	6.300	3.200	5.711
		24	-7.069	-1.075					
		24	-6.793	-1.033					
		30	7.559	4.605					
BUS	26	0.960	-12.9779		0.0	0.0	0.0	0.0	
		24	10.467	1.464					
		27	-10.497	-1.449					
BUS	27	0.982	-11.5023		0.0	0.0	9.300	0.500	
		26	10.698	1.758					
		28	-19.992	-2.265					
BUS	28	0.997	-10.4680		0.0	0.0	4.600	2.300	
		27	20.251	2.665					
		29	-24.845	-4.971					
BUS	29	1.010	-9.7566		0.0	0.0	17.000	2.600	
		28	25.115	5.350					
		1[illegible]	-40.963	-10.503					
		52	17.[illegible]28	2.563					
BUS	30	0.964	-18.7032		0.0	0.0	3.600	1.800	
		25	-7.450	-4.441					
		31	3.849	2.643					
BUS	31	0.937	-19.3697		0.0	0.0	5.800	2.900	
		30	-3.773	-2.526					
		32	-2.028	-0.375					
BUS	32	0.952	-18.5087		0.0	0.0	1.600	0.800	
		31	2.052	0.412					
		33	3.791	1.844					
		34	-7.465	-3.149					
BUS	33	0.949	-18.5494		0.0	0.0	3.800	1.900	
		32	-3.784	-1.837					
BUS	34	0.961	-14.1595		0.0	0.0	0.0	0.0	
		32	7.465	3.840	TAP 0.975				
		35	-7.455	-3.880					
BUS	35	0.968	-13.9211		0.0	0.0	6.000	3.000	
		34	7.494	3.641					
		36	-13.491	-6.664					

BUS	36	0.978	-13.6542		0.0	0.0	0.0	0.0
		35	13.595	6.641				
		37	-17.039	-10.877				
		40	3.474	4.142				
BUS	37	0.987	-13.4713		0.0	0.0	0.0	0.0
		36	17.162	11.033				
		38	-21.016	-14.021				
		39	3.875	2.954				
BUS	38	1.014	-12.7440		0.0	0.0	14.000	7.000
		37	21.424	12.651				
		22	10.734	3.873				
		44	-24.328	5.681				
		49	-4.641	-10.424				
		48	-17.195	-18.784				
BUS	39	0.985	-13.5162		0.0	0.0	0.0	0.0
		37	-3.869	-2.945				
		57	3.854	2.991	TAP 0.980			
BUS	40	0.975	-13.5768		0.0	0.0	0.0	0.0
		36	-3.465	-4.128				
		56	3.453	4.170	TAP 0.958			
BUS	41	0.997	-14.0646		0.0	0.0	6.300	3.000
		11	-9.187	-2.769				
		42	8.886	3.197				
		43	-11.592	-2.868				
		56	5.599	-0.569				
BUS	42	0.968	-15.5297		0.0	0.0	7.100	4.400
		41	-8.700	-2.881				
		56	1.601	-1.521				
BUS	43	1.010	-11.3457		0.0	0.0	2.000	1.000
		41	11.592	3.459				
		11	-13.600	-4.456				
BUS	44	1.018	-11.8617		0.0	0.0	12.000	1.800
		38	24.504	-5.533				
		45	-36.512	3.748				
BUS	45	1.037	-9.2653		0.0	0.0	0.0	0.0
		15	-37.335	2.565				
		44	37.323	-2.555				
BUS	46	1.061	-11.1091		0.0	0.0	0.0	0.0
		14	-47.958	-24.985				
		47	47.862	24.962				
BUS	47	1.034	-12.5073		0.0	0.0	29.700	11.600
		46	-47.264	-23.546				
		48	17.567	11.883				
BUS	48	1.029	-12.6110		0.0	0.0	0.0	0.0
		47	-17.491	-11.785				
		49	0.092	-7.240				
		38	17.382	19.088				

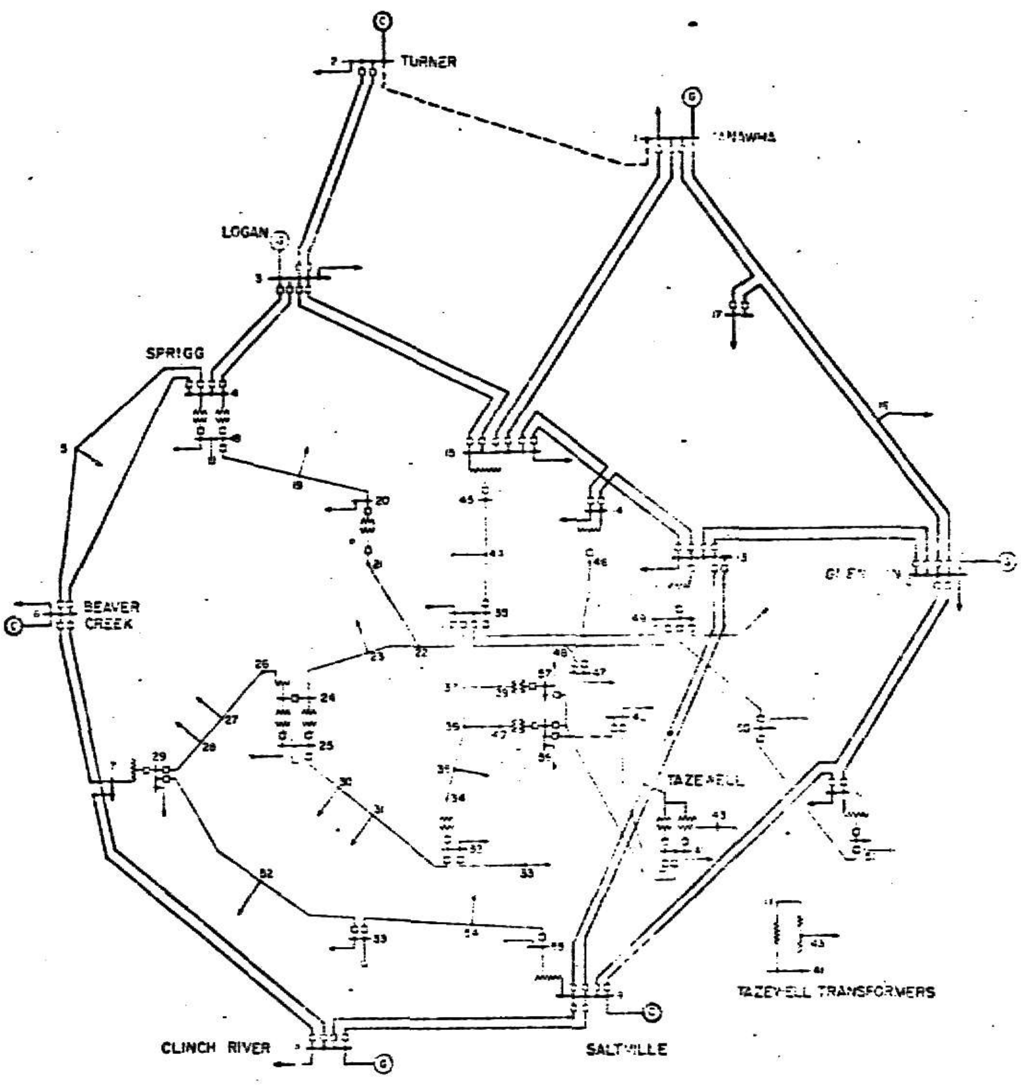
BUS	49	1.037	-12.9301		0.0	0.0	18.000	8.500	
		48	-0.653	6.787					
		50	9.733	4.617					
		13	-32.468	-24.903					
		38	4.779	10.006					
BUS	50	1.024	-13.4026		0.0	0.0	21.000	10.500	
		49	-9.647	-4.479					
		51	-11.353	-6.017					
BUS	51	1.053	-12.5183		0.0	0.0	18.000	5.300	
		50	11.571	6.363					
		12	-29.585	-11.660					
BUS	52	0.981	-11.4820		0.0	0.0	4.900	2.200	
		29	-17.465	-1.963					
		53	12.569	-0.242					
BUS	53	0.971	-12.2374		0.0	0.0	20.000	10.000	5.941
		52	-12.444	0.403					
		54	-7.558	-4.461					
BUS	54	0.996	-11.6952		0.0	0.0	4.100	1.400	
		53	7.711	4.650					
		55	-11.810	-6.051					
BUS	55	1.031	-10.7876		0.0	0.0	6.800	3.400	
		54	12.117	6.453					
		6	-18.928	-9.851					
BUS	56	0.970	-16.0734		0.0	0.0	7.600	2.200	
		40	-3.453	-3.832					
		41	-5.422	0.744					
		42	-1.590	1.540					
		57	2.965	-0.653					
BUS	57	0.966	-16.5984		0.0	0.0	6.700	2.000	
		39	-3.854	-2.672					
		56	-2.849	0.677					

MISMATCHES

423.357	111.615
0.007	-0.004
0.033	-0.027
0.035	-0.027
0.034	-0.024
0.020	-0.019
0.030	-0.027
-0.006	0.005
-0.013	0.009
0.003	0.003
0.016	-0.008
0.008	0.002
0.016	-0.012
0.022	-0.009
-0.017	0.009
-0.007	0.003
-0.004	-0.003
-0.002	-0.001
0.002	-0.003
0.002	0.000
0.007	-0.018
0.034	-0.198
-0.036	0.088
0.051	-0.025
-0.003	-0.014
-0.030	0.015
0.006	-0.007
0.006	-0.005
-0.020	0.010
-0.001	0.002
-0.000	-0.002
-0.022	-0.093
0.016	0.063
0.010	-0.040
0.003	-0.023
0.031	-0.094
0.022	-0.034
0.005	-0.003
-0.015	0.046
-0.012	0.043
0.005	-0.005
0.001	-0.002
-0.008	0.003
-0.007	0.016
-0.011	0.010
0.004	-0.023
0.003	-0.063
-0.018	0.063
-0.009	0.008
0.000	0.004
-0.014	0.003
0.005	-0.004
-0.002	0.002
0.001	-0.001
-0.010	0.002
-0.000	-0.001
-0.003	0.005

TOTALS	MW	MVAR
GENERATION	1278.358	319.012
STATIC CAP/REACTORS		21.668
LOAD	1250.797	336.399
LINE LOSSES	27.558	4.260

TOTAL MISMATCH	0.216	-0.412
AVERAGE MISMATCH	0.004	-0.007



AEP 57 BUS TEST SYSTEM BUS CODE DIAGRAM

FIGURE 6

CHAPTER IV

PROGRAM IMPROVEMENTS

General Improvements

There are several general improvements that could be made in the input and output routines of the program. These improvements should make the program more efficient and easier to use. Some of the possible improvements include development of a free format routine for the input data. Another improvement would be to eliminate the bus numbering system. A name could be associated with each bus and all pertinent bus data would be placed on one card. One then would name the swing bus and all voltage control buses. Upon doing this the computer would assign a numbering system and find the load flow solution. The output printout would give the bus name instead of a bus number.

Improvements in the output could involve rearrangement of the output printout for very large systems. One way would be to put all the individual bus information together and then printout a "From Bus." Below this output printout all line flows leaving the "From Bus" going to other buses. Use this output format for all buses. This would provide a more efficient method in finding specific information for very large systems. Other improvements could be to add additional information to the system totals such as tie line flows.

Some other possible general improvements could be making better use of computer storage such as taking advantage of the fact that the admittance matrix is symmetrical and sparse. Another idea could be to limit the number of voltage control buses and transformers. In this program one can have as many voltage control buses as there are total buses less one. This is a waste of storage since seldom is there NB/4 voltage control buses, where NB equals the total number of buses. The same can be said of transformers.

There are several other general improvements to this program and only time and experience with the program will make them realizable.

Gauss-Seidel Improvements

Improvements to the Gauss-Seidel iteration process could include use of acceleration factors for both the real and imaginary parts of the bus voltages. A scheme of changing the acceleration factors during the iteration process, to prevent divergence and to speed convergence, could be another possible improvement.

Newton-Raphson Improvements

There are several improvements that can be made to the Newton-Raphson method as implemented in the program reported here. The most important of these is the matrix inversion process used to invert the Jacobian matrix. The process, as now implemented, is very slow but reliable. One should be able to find a more efficient method of inverting the Jacobian matrix. The Jacobian matrix may have to be rearranged, since in forming it as described in this report results in the diagonal elements in the lower half of the matrix being zero. In rearranging one simply interchanges the J_3 matrix with the J_5 matrix, and the J_4 matrix with the J_6 matrix, making the Jacobian diagonal elements nonzero. Also one must not forget to rearrange the ΔQ's, $\Delta |V|^2$'s, Δe's, and Δf's accordingly. Implementation of the techniques [13] utilizing the advantages of sparse matrices are also possible avenues of approach.

Another idea in making the Newton-Raphson method more efficient and faster would be to introduce an acceleration factor or factors for the real and reactive calculated powers. This idea may take some effort to perfect since in the Gauss-Seidel process certain acceleration factors made particular systems diverge while others converged faster.

The author of the Newton-Raphson method implemented here makes no claims about its computational efficiency. The only claim is that it does work.

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APPENDIX A

NOMENCLATURE

Symbol	Quantity	Units
A	Gauss-Seidel constant	p.u. voltage^2
ALPHA	Acceleration factor	
B	Gauss-Seidel constant	
BI	Bus current	p.u. amperes
BM	Number of voltage control buses	
BN	Number of buses	
C,CC	Static capacitor/reactor	p.u. susceptance
CMVAR	Static injected power	MVAR
CONV	Convergence tolerance	p.u. V.A., p.u. voltage
CP	Calculated net real power	P.U. MW
CQ	Calculated net reactive power	p.u. MVAR
DE	Change in real part of bus voltage	p.u. voltage
DELTA	Bus voltage angle	degrees
DELV, DVMAX	Maximum voltage differences between iterations of Gauss-Seidel Method	p.u. voltage
DF	Change in imaginary part of bus voltage	p.u. voltage
DP	Change in net real power	p.u. MW
DQ	Change in net reactive power	p.u. MVAR
DV	Change in bus voltage	p.u. voltage
DX	Gauss-Seidel constant	p.u. voltage

Symbol	Quantity	Units
EB	Ending bus	
GSNR	Iterative method used	
ITER	Iterative limit	
JJ	Jacobian matrix	
L	Starting bus	
Length	Line length	Length
M	Ending bus	
MAGV	Bus voltage magnitude	p.u. voltage
MB	Number of voltage control buses plus one	
NB	Number of buses	
NBASE	New base	MVA
NC	Number of capacitor/reactors	
NL	Number of lines	
NR	Jacobian matrix size (2(NB-1))	
OBASE	Old bases	MVA
P	Net real power	p.u. MW
PG	Real power generation	MW
PL	Real power load	MW
Q	Net reactive power	p.u. MVAR
QG	Reactive power generation	MVAR
QL	Reactive power load	MVAR
QMAX	Voltage control bus maximum VAR limit	MVAR
QMIN	Voltage control bus minimum VAR limit	MVAR
R	Calculated line flow with ending bus as reference	MW,MVAR

Symbol	Quantity	Units
S	Calculated line flow with starting bus as reference	MW,MVAR
SB	Starting bus	
SERV	Series line admittance	p.u. Y
SERZ	Series line impedance	p.u. Z
SHTY	Line shunt admittance	p.u. Y
ST	Total line shunt admittance	
SUM	Gauss-Seidel constant	p.u. voltage
TCR	Total injected power	MVAR
TG	Total network generation	MW,MVAR
TL	Total line losses	MW,MVAR
TLD	Total network load	MW,MVAR
TR, TS	Off-nominal tap setting	
V,VI,VII,VN	Bus voltage	p.u. voltage
VSPEC	Voltage magnitude of voltage control bus	p.u. voltage
Y	Bus admittance matrix	p.u. Y
YSHT	Line shunt admittance	p.u. Y/length
ZSER	Series line impedance	p.u. Z/length

APPENDIX B

SLFE

User's Guide

I. PROGRAM DESCRIPTION

Static Load Flow Equations (SLFE) is a Fortran program which calculates, for a given power system, the "states" that will satisfy the given demands. Systems with up to 60 buses and 100 lines are possible.

Input to the program consists of:

1. System parameters
2. Static capacitors
3. Transmission line parameters
4. Transformer line parameters
5. Voltage control bus parameters
6. Generation and Load

All the impedances, line charging admittance, static capacitor/reactor susceptance, voltage magnitudes are in per unit on a known MVA base (old base). All powers are in megawatts and megavars.

Normal output consists of

1. Input data
2. Load Flow Solution
3. System Totals
4. Mismatch

SLFE uses either the Gauss-Seidel or Newton-Raphson technique.

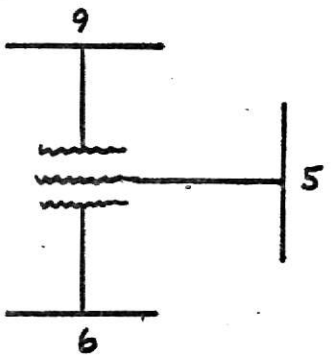
II. PROGRAM INPUT

SLFE uses a fix-format input. In addition, the program assumes nominal values for the old base (100. MVA), new base (100. MVA), Iteration Method Used (Gauss-Seidel), Total or one-half line shunt admittance used (one-half line shunt admittance), tolerance allowed (.0001 for Gauss-Seidel and .001 for Newton-Raphson), iteration limit (75 for Gauss-Seidel and 15 for Newton Raphson), and the acceleration factor (1.65), and only those differing from the assumed values need be inputted.

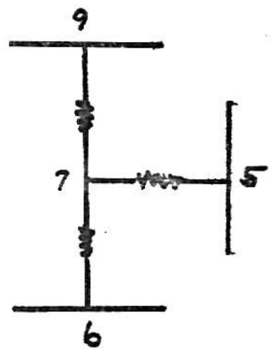
The following steps are used in preparing the system and data cards.

Step I. Identifying the system

Number the buses in a numerical order where bus 1 is the swing bus. Voltage control buses may have either a generator or a synchronous condenser. The swing bus must have a generator. Buses 2 to MB are voltage control buses, and buses (MB + 1) to NB (total no. of buses) are the load buses. It may be necessary to renumber the buses of a system in order to satisfy the above criteria. Also in counting buses the three winding transformer is considered to have a bus located at its midpoint. (See example below). Number the lines consecutively from 1 to NL (number of lines) where each transmission line counts as one line, and each three winding transformers counts as three lines (see below).



3 WINDING TRANSFORMER



EQUIVALENT CKT
3 lines, 4 buses

The remaining steps will describe the data, its order, and the data format. The data cards are placed in the following order.

1. System Parameter card
2. Static/Capacitor/Reactor cards (if any)
3. Swing bus voltage and phase angle card
4. Transmission line cards
5. Transformer line cards
6. Voltage control cards
7. Generation and Load cards

Step 2. System Parameter Card

This card consists of the number of lines (NL), number of buses (NB), number of voltage control buses (BM), number of static capacitor/reactors (NC), old MVA base (OBASE), new MVA base (NBASE), Iteration method used (GSNR), Total or one-half line shunt admittance used (ST), tolerance allowed for convergence (CONV), and maximum iterations allowed (ITER). The card is in the Format (4I5, 4F5.0, F10.7, I5).

Example: One has a 14 bus, 20 line system. Also the system contains 4 voltage buses, 1 static capacitor, line data is on 100 MVA base and line shunt admittance is given as one-half of the total line shunt admittance. Also the Newton-Raphson technique is the desired method for the load flow solution. The solution is desired to be on a 100. MVA base.

	NL	NB	BM	NC	OBASE	NBASE	GSNR	ST	CONV	ITER
	20	14	4	1			1			
	↑	↑	↑	↑			↑			
Col's	4,5	9,10	15	20			31-35			

(Note: If Gauss Seidel method was desired, columns 31-35 would have been left blank.)

Step 3. Static Capacitor/Reactor Card

This card or cards consist of the bus number (BN) at which the static capacitor/reactor is located, and the capacitive/reactive susceptance (CC). If there are no capacitors or reactors, then this section is omitted. The cards are in the Format (I5, F10.5).

Example: At bus 9 a capacitor of j.19

	BN	CC
	9	.19
	↑	↑
Col's	5	8-10

Step 4. Swing Bus Card

This card contains the swing bus voltage magnitude and phase angle (in degrees), and the acceleration factor. The acceleration factor is assumed to be 1.65 by the program. The entry for the acceleration factor is normally not made. The card is in the Format (F10.5, F6.2, F5.2).

Example: Swing bus voltage magnitude = 1.06
phase angle = 0 degrees

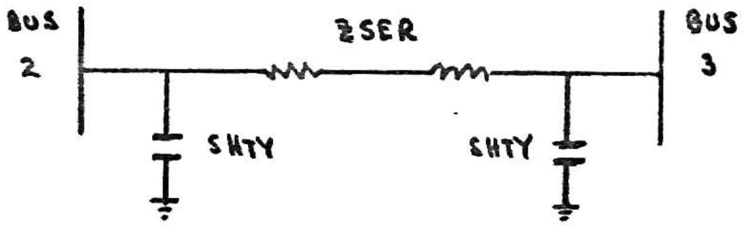
	MAGV	DELTA	ALPHA
	1.06		
	↑		
Col's	4 - 7		

A Blank is read as a zero.

Step 5. Line Cards (Transmission Lines)

These cards consist of the starting bus (SB), ending bus (EB), series impedance of the line (ZSER), one-half of the total line charging admittance (SHTY), and the line length.* The cards are in the Format (2I5, 4F10.5, 5X, **, F5.1).

Example: ZSER = .04699 + j.19797
SHTY = j.0219 SB = 2 EB = 3



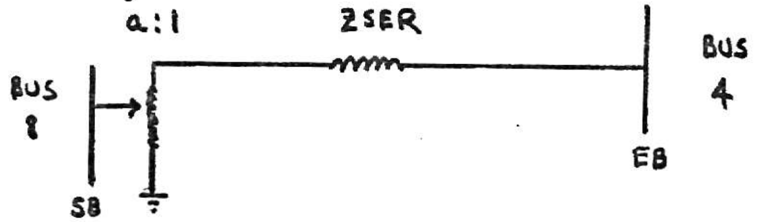
	SB	EB	ZSER		SHTY
	2	3	.04699	.19797	.0219
Col's	5	10	15-20	25-30	45-50

* Assumed to be unity if left blank.
** 5X means skip 5 columns.

Step 6. Line Cards (Two and three winding transformer lines)

The transformer line card is similar to transmission line card. The major difference is the designation of the starting bus (SB) and the ending bus (EB) in relation to the tap setting (TS). The starting bus is always the bus where the tap setting is not nominal. If the turns ratio is increased by changing the tap setting then $a < 1$ and conversely. The series impedance is usually pure reactance and the line charging admittance is usually considered zero. These cards are in the Format (2I5, 4F10.5, F5.3, F5.1).

Example: Tap setting = a = .932, SB = 8, EB = 4, ZSER = j.25202, SHTY = 0.0.



	SB	FB	ZSER	SHTY	TS
	8	4	.25202		.932
Col's	5	10	25 - 30		52 - 55

Step 7. Voltage Control Cards

If there are no voltage control buses other than the swing bus, then BM = 0 and this section is omitted. However, if there are, then this card contains the constant voltage magnitude and the range of reactive power, maximum and minimum values that can be supplied by the generator or synchronous condenser. There will be BM data cards. These cards are in the Format (3F10.3).

Example:

BUS	VOLT MAG PU	MIN Q MVAR	MAX Q MVAR
5	1.09	-6	24.0

	VOLT MAG	QMIN	QMAX	BN
	1.09	-6.0	24.0	5
Col's	6 - 9	15 - 18	25 - 28	73 - 80

These cards must be in a particular order. This order is the numerical bus number order. In this case there would be 3 voltage control cards before this one. Also note columns 73 - 80 are comment columns and the number 5 can be put in any columns from 73 - 80.

Step 8. Generation and Load Cards

The set of cards are the scheduled Generation and load powers for buses 1 to NB. The card contains the real and reactive generations and the real and reactive loads.

If the bus is the swing bus, the real and reactive generation is assumed zero. Also if the bus is a voltage control bus, then the reactive generation is assumed zero. The program will calculate these values. If values are inputted the program will ignore them.

These cards must be in a numerical bus order starting with bus 1 going to bus NB. Once again columns 73 - 80 can be used for keeping track of the order. These cards are in the Format (4F10.3).

Example:

BUS	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR
2	40	0	21.7	12.7

	PG	QG	PL	QL	BN
	40.0		21.7	12.7	2
Col's	5 - 8		25 - 28	35 - 38	73 - 80

Step 9. Combine the data cards in the order described in Step 1.

III. PROGRAM OUTPUT

The program output consists of input data, load flow solution, system totals, and mismatch.

The input data is the data the user inputted. This section of the output is used for troubleshooting in case of errors in the load flow solution or no load flow solution.

The load flow solution gives the technique, the number of iterations for convergence, and the base MVA value for the output. At each bus the PU voltage magnitude, phase angle (in degrees), real and reactive generation, real and reactive load, and the injected power (if any) by a static capacitor or reactor are given. Below each bus are the line flows. This information consists of the ending bus and the real and reactive line flow in megawatts and megavars. The positive values of real and/or reactive power indicate the power flow towards the ending bus, whereas negative values indicate flow away from the ending bus. If one desires to calculate the losses in a line one simply goes to two buses which the line is between and notes the line flow is given twice. Each bus is used as the reference bus in turn, therefore the line flows are negatives of each other. The sum of the line flows is the line loss.

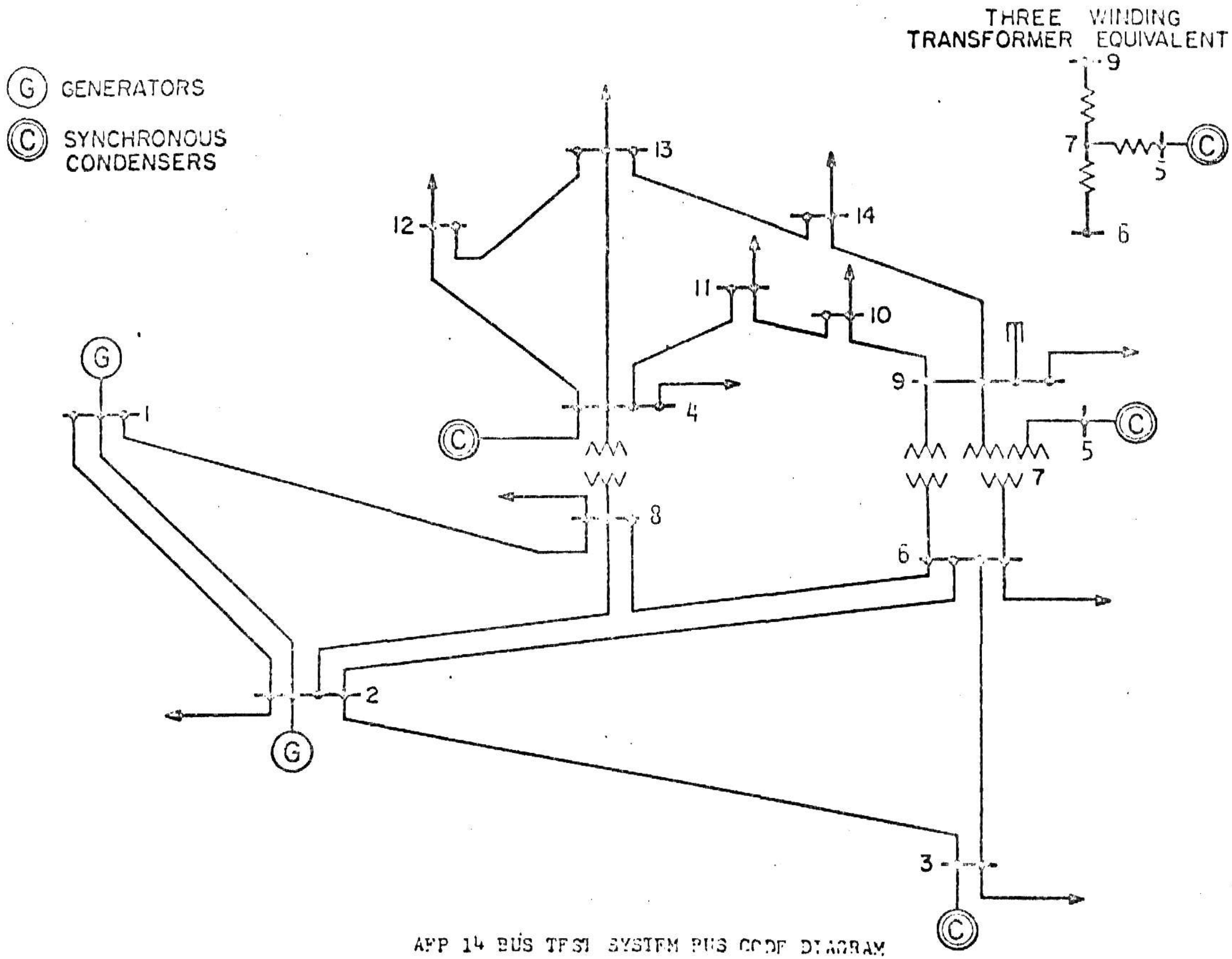
The system totals consist of total generation, load, injected power, and total losses. The total generation is simply calculated by adding the real and reactive generation at each bus. The static injected power and load are calculated similarly. The total losses are calculated by adding the total generation and the total static injected power and subtracting the total load.

The last part of the output is the mismatch. The mismatch tells how good the load flow solution is. The first value is the swing bus net power which is calculated by simply summing the line flows at bus 1. The remaining mismatch values are calculated by subtracting the total line flows from a bus from the net power at the bus. (Net power equals generation minus load.) Total mismatch is calculated by adding the individual mismatches. The average mismatch is the total mismatch divided by (NB-1).

IV. TROUBLESHOOTING

If problems arise in obtaining a load flow solution, then the input data listing is the best way to troubleshoot. If no input listing was printed then one either has the input cards in improper order or lacks the proper number of cards. Also values in the incorrect columns of the system parameter card may cause no listing.

Some of the more common mistakes are failure to correct the system bus indices if a power system already has a numbering system which does not correspond to the numbering system required by the program. Another common mistake is to enter data in an incorrect column. If a value is incorrect by a factor of 10, this often times makes the system diverge. The use of certain acceleration factors may also cause divergence. Another feature which is overlooked many times is that the system just converges slowly and more iterations are needed. This can be corrected by increasing the iteration limit.



AEP 14 BUS TEST SYSTEM BUS CODE DIAGRAM

AEP 14 BUS TEST SYSTEM
IMPEDANCE AND LINE CHARGING DATA

Line No.	Line Designation	Resistance Per Unit*	Reactance Per Unit*	Line Charging Per Unit*
1	1 - 2	.01938	.05917	.0264
2	1 - 8	.05403	.22304	.0246
3	2 - 3	.04699	.19797	.0219
4	2 - 6	.05811	.17632	.0187
5	2 - 8	.05695	.17388	.0170
6	3 - 6	.06701	.17103	.0173
7	6 - 8	.01335	.04211	.0064
8	6 - 7	0	.20912	0
9	6 - 9	0	.55618	0
10	8 - 4	0	.25202	0
11	4 - 11	.09498	.19890	0
12	4 - 12	.12291	.25581	0
13	4 - 13	.06615	.13027	0
14	7 - 5	0	.17615	0
15	7 - 9	0	.11001	0
16	9 - 10	.03181	.08450	0
17	9 - 14	.12711	.27038	0
18	10 - 11	.08205	.19207	0
19	12 - 13	.22092	.19988	0
20	13 - 14	.17093	.34802	0

* Impedance and line charging susceptance in per unit on a 100,000- kva base.
Line charging one-half of total charging of line.

AEP 14 BUS TEST SYSTEM
OPERATING CONDITIONS

Bus Number	Starting Bus Voltage		Generation		Load	
	Magnitude Per Unit	Phase Angle Degrees	MW	MVAR	MW	MVAR
1 *	1.06	0	0	0	0	0
2	1.0	0	40	0	21.7	12.7
3	1.0	0	0	0	94.2	19.0
4	1.0	0	0	0	11.2	7.5
5	1.0	0	0	0	0	0
6	1.0	0	0	0	47.8	-3.9
7	1.0	0	0	0	0	0
8	1.0	0	0	0	7.6	1.6
9	1.0	0	0	0	29.5	16.6
10	1.0	0	0	0	9.0	5.8
11	1.0	0	0	0	3.5	1.8
12	1.0	0	0	0	6.1	1.6
13	1.0	0	0	0	13.5	5.8
14	1.0	0	0	0	14.9	5.0

* Swing machine

AEP 14 BUS TEST SYSTEM
REGULATED BUS DATA

Bus Number	Voltage Magnitude Per Unit	Minimum MVAR Capability	Maximum MVAR Capability
2	1.045	-40	50
3	1.010	0	40
4	1.070	-6	24
5	1.090	-6	24

TRANSFORMER DATA

Transformer Designation	Tap Setting*
6-7	.978
6-9	.969
8-4	.932

* Off-nominal turns ratio, as determined by the actual transformer tap positions and the voltage bases. In the case of nominal turns ratio, this would equal 1.

STATIC CAPACITOR DATA

Bus Number	Susceptance** Per Unit
9	.19

** Susceptance in per unit on a 100,000-kva

I N P U T   D A T A

NO. OF LINES(NL) = 20   NO. OF BUSES(NB) = 14   NO. OF CAPACITORS/REACTORS(NC) = 1

NO. OF VOLTAGE CONTROL BUSES (BM) = 4

BASE FOR INPUTTED DATA(OLD BASE) = 100. MVA   BASE FOR OUTPUT(NEW BASE) = 100. MVA

TOLERANCE FOR CONVERGENCE = 0.000100   MAXIMUM NO. OF ITERATIONS ALLOWED = 75

ACCELERATION FACTOR = 1.65 (USED WITH GAUSS-SEIDEL METHOD ONLY)

SWING BUS VOLTAGE MAGNITUDE = 1.06000 PU   SWING BUS PHASE = 0.0 DEGREES

STATIC CAPACITORS/REACTORS (OLD BASE)

BUS	SUSCEPTANCE
9	0.19000

TRANSMISSION LINE DATA (OLD BASE)
Y SHUNT IS ONE-HALF OF THE TOTAL LINE CHARGING ADMITTANCE

SB	EB	Z SERIES R	Z SERIES X	Y SHUNT G	Y SHUNT B	LENGTH
1	2	0.01938	0.05917	0.0	0.02640	1.0
1	8	0.05403	0.22304	0.0	0.02460	1.0
2	3	0.04699	0.19797	0.0	0.02190	1.0
2	6	0.05811	0.17632	0.0	0.01870	1.0
2	8	0.05695	0.17388	0.0	0.01700	1.0
3	6	0.06701	0.17103	0.0	0.01730	1.0
6	8	0.01335	0.04211	0.0	0.00640	1.0
4	11	0.09498	0.19890	0.0	0.0	1.0
4	12	0.12291	0.25581	0.0	0.0	1.0
4	13	0.06615	0.13027	0.0	0.0	1.0
7	5	0.0	0.17615	0.0	0.0	1.0
7	9	0.0	0.11001	0.0	0.0	1.0
9	10	0.03181	0.08450	0.0	0.0	1.0
9	14	0.12711	0.27038	0.0	0.0	1.0
10	11	0.08205	0.19207	0.0	0.0	1.0
12	13	0.22092	0.19988	0.0	0.0	1.0
13	14	0.17093	0.34802	0.0	0.0	1.0

TOTAL TRANSMISSION LINES = 17

TRANSFORMER LINE DATA (OLD BASE)
Y SHUNT IS ONE-HALF OF THE TOTAL LINE CHARGING ADMITTANCE

SB	EB	Z SERIES R	Z SERIES X	Y SHUNT G	Y SHUNT B	TAP SETTING	LENGTH
6	7	0.0	0.20912	0.0	0.0	0.978	1.0

6	9	0.0	0.55618	0.0	0.0	0.969	1.0
8	4	0.0	0.25202	0.0	0.0	0.932	1.0

TOTAL TRANSFORMER LINES = 3

VOLTAGE CONTROL BUS DATA

BUS	VSPEC PU	QMIN MVAR	QMAX MVAR
2	1.045	-40.000	50.000
3	1.010	0.0	40.000
4	1.070	-6.000	24.000
5	1.090	-6.000	24.000

SCHEDULED BUS POWERS

BUS	GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR
1	UNSPECIFIED	UNSPECIFIED	0.0	0.0
2	40.000	UNSPECIFIED	21.700	12.700
3	0.0	UNSPECIFIED	94.200	19.000
4	0.0	UNSPECIFIED	11.200	7.500
5	0.0	UNSPECIFIED	0.0	0.0
6	0.0	0.0	47.800	-3.900
7	0.0	0.0	0.0	0.0
8	0.0	0.0	7.600	1.600
9	0.0	0.0	29.500	16.600
10	0.0	0.0	9.000	5.800
11	0.0	0.0	3.500	1.800
12	0.0	0.0	6.100	1.600
13	0.0	0.0	13.500	5.800
14	0.0	0.0	14.900	5.000

GAUSS-SEIDEL TECHNIQUE CONVERGED IN 22 ITERATIONS. ALL VALUES ON 100. MVA BASE

	VOLTAGE MAGNITUDE PU	DELTA(DEGS)		GENERATION MW	GENERATION MVAR	LOAD MW	LOAD MVAR	INJECTED POWER (STATIC) MVAR
BUS 1	1.060	0.0		232.349	-16.864	0.0	0.0	
	2	156.900	-20.369					
	8	75.549	3.506					
BUS 2	1.045	-4.9797		40.000	42.383	21.700	12.700	
	1	-152.507	27.627					
	3	73.194	3.567					
	6	56.136	-2.287					
	8	41.518	0.758					
BUS 3	1.010	-12.7164		0.0	23.399	94.200	19.000	
	2	-70.364	1.581					
	6	-23.330	2.806					
BUS 4	1.070	-14.2210		0.0	12.261	11.200	7.500	
	11	7.349	3.469					
	12	7.790	2.494					
	13	17.746	7.169					
	8	-44.054	-8.393					
BUS 5	1.090	-13.3651		0.0	17.371	0.0	0.0	
	7	0.027	17.359					
BUS 6	1.019	-10.3229		0.0	0.0	47.800	-3.900	
	2	-54.459	3.393					
	3	23.701	-5.419					
	8	-61.189	15.646					
	7	28.091	-9.423	TAP 0.978				
	9	16.095	-0.322	TAP 0.969				
BUS 7	1.062	-13.3674		0.0	0.0	0.0	0.0	
	5	-0.027	-16.912					
	9	28.104	5.794					
	6	-28.091	11.115					
BUS 8	1.020	-8.7821		0.0	0.0	7.600	1.600	
	1	-72.785	2.577					
	2	-40.616	-1.628					
	6	61.705	-15.349					
	4	44.054	12.821	TAP 0.932				
BUS 9	1.056	-14.9467		0.0	0.0	29.500	16.600	21.201
	7	-28.105	-4.990					
	10	5.247	4.298					
	14	9.436	3.664					
	6	-16.095	1.627					
BUS 10	1.051	-15.1049		0.0	0.0	9.000	5.800	
	9	-5.234	-4.263					
	11	-3.784	-1.524					
BUS 11	1.057	-14.7947		0.0	0.0	3.500	1.800	

		4	-7.295	-3.354				
		10	3.797	1.553				
BUS	12	1.055	-15.0755		0.0	0.0	6.100	1.600
		4	-7.708	-2.344				
		13	1.614	0.739				
BUS	13	1.050	-15.1578		0.0	0.0	13.500	5.800
		4	-17.535	-6.752				
		12	-1.607	-0.734				
		14	5.637	1.688				
BUS	14	1.036	-16.0389		0.0	0.0	14.900	5.000
		9	-9.319	-3.416				
		13	-5.583	-1.579				

TOTALS	MW	MVAR
GENERATION	272.349	78.550
STATIC CAP/REACTORS		21.201
LOAD	259.000	73.500
LINE LOSSES	13.349	26.251

MISMATCHES

	232.349	-16.863
	0.032	-0.018
	0.006	-0.011
	0.022	-0.023
	0.027	-0.012
	0.038	-0.024
	-0.013	-0.004
	-0.042	0.021
	-0.016	-0.003
	-0.018	0.013
	0.002	-0.001
	0.005	-0.005
	-0.005	0.002
	-0.003	0.005
TOTAL MISMATCH	0.035	-0.060
AVERAGE MISMATCH	0.003	-0.005

LOAD FLOW PROGRAM DEVELOPMENT

by

ALAN GLEN BARTA

B. S., Kansas State University, 1970

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1973

Name: Alan G. Barta Date of Degree: May 11, 1973

Institution: Kansas State University Location: Manhattan, Kansas

Title of Study: LOAD FLOW PROGRAM DEVELOPMENT

Major Field: Electrical Engineering

Scope and Method of Study: The purpose of the project reported here was to develop a digital load flow computer program to be used by engineering students who wish to study the behavior of electric-energy systems.

The digital computer program developed by the author and presented in this report implements the classic form of the load flow problem.

The Gauss-Seidel and Newton Raphson techniques were used to solve the power flow equations. Both procedures were studied and implemented for this project.

Findings and Conclusions: Two test cases were used during program development. The data for these test systems were made available by the American Electric Power Service Corporation and represents a part of that system. Both methods work, with the Newton-Raphson method giving more accurate results. However, due to lack of time the author was unable to optimize the Newton-Raphson technique to its fullest extent; as a result it is not as efficient with computer time as the Gauss-Seidel method implemented here. The author made several suggestions for possible improvements in both techniques for future users of the program.

MAJOR PROFESSOR'S APPROVAL Floyd W. Harris

VITA

Alan G. Barta

Candidate for the Degree of

Master of Science

Report: LOAD FLOW PROGRAM DEVELOPMENT

Major Field: Electrical Engineering

Biographical:

Personal Data: Born in Axtell, Kansas, March 24, 1947, the son of Glen and Grace M. Barta.

Education: Attended grade school in Wichita, Kansas; attended Junior High and High School in Manhattan, Kansas; graduated from Manhattan High School in May 1965; received the Bachelor of Science degree from Kansas State University, with a major in Electrical Engineering January 1970; completed requirements for the Master of Science degree in May, 1973.

Professional Experience: Entered the United States Army in April 1970 as a 2nd Lieutenant in the Signal Corp; Honorably Discharged December 1971; member of Institute of Electronic and Electrical Engineers; Engineer in Training, Kansas, 1970.