APPLICATIONS OF LOAD FLOW BY HYBRID COMPUTER

by

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I. INTRODUCTION

1.1 STATEMENT OF PROBLEM

In order to operate an electric power system efficiently and reliably, it is necessary to have a knowledge of the system's voltages and power flows. It is vital to have continual access to this information because as the load on the system varies during the day the voltages and power flows will also vary, possibly causing generators to be allocated in an uneconomical manner. Also, it is often necessary to maintain voltage levels of certain buses within a tolerance and keep power flow on transmission lines from approaching their stability limit. Taking physical measurements of the system is slow and expensive and does not give much information for studying a system that has been altered. Therefore, it would be beneficial to be able to simulate the power system in some form.

A computer program designed to perform such a simulation can be called a load flow program. Usually, such information about the system as loads and generation is given to the program in order to calculate a result of the voltages at each bus and the power flows on each transmission line. In the earlier stages of the electric power industry power system simulation was attempted through network analyzers that employed alternating currents at a high frequency. The solutions obtained were reasonably fast and of sufficient accuracy to merit quick adoption of the network analyzers by the utilities. But before long the rapidly expanding utilities found that the analyzer became too bulky and cumbersome to simulate the larger systems.

By the end of the 1950's digital computers were more widely used by the power industry because of their accuracy, adaptability, ease of programming and lower cost. At first, the speed of the digital computer was very slow but with technological advances and more efficient programming techniques computer speeds increased.

Despite these advances, the digital computer has not been able to achieve the speed necessary for real-time interaction with the power system, except with the use of simplifying approximations which have limited applications.(1) Therefore, the major use of the digital computer has been to study power systems where time is not critical.

In the usual digital load flow solution there are two problems with accuracy. The information that is collected from the system and given to the program can have around ten percent deviation from the actual value. But the result from the problem can give at least seven significant figures. This can easily lure the user into a false sense of accuracy in the knowledge of the characteristics of the system.

Another related problem is reduced accuracy. In digital programs that solve large systems using a complex algorithm (i.e. Newton-Raphson) truncation error can become of consequence. Thus, the usual seven significant figures are not accurate enough. This error may necessitate resorting to a larger data word length and greatly increasing the memory storage requirement of an already immense program.

One of the most critical problems of the digital load flow is the time required to obtain a solution. For example, the time needed to obtain the solution to a smaller power system of 118 buses would range from one minute to over nine minutes depending on the solution technique used.(2) Therefore, it appears that a digital load flow solution has considerable limitation for continuous system monitoring.

At the 1971 Power Industry Computer Application Conference in Boston, Massachusetts, Mark Enns, T. C. Giras and Norman R. Carlson presented a paper that suggested a method of solving the load flow problem quickly.(3) Their method used a hybrid computer which is the union of the digital computer and the analog computer.

1.2 SCOPE OF INVESTIGATION

The analog computer operates with all of its components calculating the solution simultaneously or in a parallel manner. This characteristic of the analog computer allows it to determine the solution to certain problems at an extremely fast speed. Since the hybrid computer load flow method uses an analog computer, it also has the potential of being very fast. Although the analog computer does not have as much accuracy as the digital computer, it does tend to maintain uniform accuracy throughout the program, independent of the size of the program. By using quality equipment, this accuracy should be more than sufficient for power systems applications.

Therefore, the purpose of this study is to investigate the application of the hybrid load flow program. The intent is to construct the hybrid load flow program, expand the program to include other applications that require a load flow problem and take measurements in order to determine if the hybrid program has advantages over digital programs.

The first area to be studied is the construction and operation of the basic hybrid load flow. This is the building block for other applications programs and constitutes a major portion of the study. Given the net injected power at each bus and the transmission line parameters, the program will determine the voltages at all buses and the generation required at the slack bus. The program will also be extended to include voltage control buses.

The second area of study is the investigation of an algorithm that would determine the matrix Z_{BUS} referenced to the slack bus using the analog network required for the load flow program. This algorithm assembles the resistor network into a digital form for easy verification that it is set to the desired values. This program could be important for maintaining suitable accuracy in the load flow program.

A third area of study is the development of an economic dispatch program using the hybrid load flow program. The economic dispatch program would calculate the optimal load flow solution given the load flow data and generator cost curves.

Other areas mentioned in the study but not explored in any depth are power system stability, state estimation of a power system, and the inclusion of a DC transmission link in the power system network.

One severe limitation of this study is the size of the system to be simulated. Because the only equipment available is a general purpose analog computer, each computing component is much larger than components would be if they were designed specifically for the load flow program. Therefore, the analog program is very large and cumbersome for even a small simulation. It was determined that the largest system that could be simulated on existing equipment was six buses. That is, simulating a six-bus system should fully tax the facilities of the analog computer. The existing hybrid equipment is an EAI-580 analog computer interfaced with a GE-4020 process control digital computer. The hybrid interface was designed and constructed by the Computer Engineering Laboratory at Virginia Polytechnic Institute and State University. Using additional facilities to supplement the analog computer in an attempt to expand the simulation size was considered and rejected since the added complexity of operating two analog computers in parallel was not worth the benefit of a larger simulation. It was the researcher's opinion that the performance of a larger system could be adequately determined from the operation of the six-bus system.

II. THE HYBRID LOAD FLOW

2.1 CONCEPTS OF THE ELECTRIC POWER SYSTEM

The electric power system network can be separated into a passive portion and an active portion.[4] The passive portion includes transmission lines, synchronous condensors, reactors, transformers, capacitors and other similar devices. The active portion includes the generators and loads.

In developing a mathematical model for the network, the procedure used is called a nodal method. This means that a set of equations that will describe the network can be written as

$$\overline{\underline{I}}_{BUS} = [\, \overline{Y}_{BUS} \,]\, \overline{\underline{V}}_{BUS} \qquad (2.1.1)$$

where $\overline{\underline{I}}_{BUS}$ and $\overline{\underline{V}}_{BUS}$ are vectors of complex numbers representing the injected phasor current and the phasor voltage at each bus. The matrix $\overline{Y}_{BUS}$ is the bus admittance matrix whose elements are the short circuit admittances. Equation (2.1.1) can be rewritten

$$\overline{\underline{V}}_{BUS} = [\, \overline{Y}_{BUS} \,]^{-1}\, \overline{\underline{I}}_{BUS} = [\, \overline{Z}_{BUS} \,]\, \overline{\underline{I}}_{BUS} \qquad (2.1.2)$$

The matrix $\overline{Z}_{BUS}$ is the inverse of $\overline{Y}_{BUS}$ and is the bus impedance matrix whose elements are the open circuit impedances.

2.2 Representation of the Electric Power Network

The two major components of the power system network are the buses and the transmission lines. A model must be derived for each for simulation on the hybrid computer.

A network analyzer united with a digital computer is a type of hybrid computer. Some research has been done on this type of hybrid computer for solving power system problems[(5)]. In this case the power system's buses and transmission lines are modeled as simply miniature buses and transmission lines.

This study used an analog computer with D.C. operational amplifiers in its hybrid computer. In the paper presented by Mark Enns, T. C. Giras and Norman R. Carlson models were developed for both buses and transmission lines[(3)]. The following section explains the derivation of these models.

One accepted practice of modeling a transmission line is as an equivalent PI network as shown in Figure 2.1. This lumped parameter model is sufficient for steady state solutions. The PI-model has a series admittance and a shunt admittance to ground at each bus. Figure 2.2 is a block diagram of the series branch of the transmission line. This block diagram easily translates into an analog model that is used to simulate the transmission lines. It will be shown later that the shunt admittances will be added into the load at each of the buses.

Kirchhoff's current law states that the sum of the currents entering a junction is zero. Since a bus is a junction, it must satisfy this law. Therefore, a bus can be modeled as a device that forces the sum of the currents flowing into that bus equal to zero.

By defining an error current $\underline{\bar{I}}_e$ and using it in Equation (2.1.1), it can be written as

$$\underline{\bar{I}}_e = \underline{\bar{I}}_{BUS} - [\,\bar{Y}_{BUS}\,]\,\underline{\bar{V}}_{BUS} \qquad (2.2.1)$$

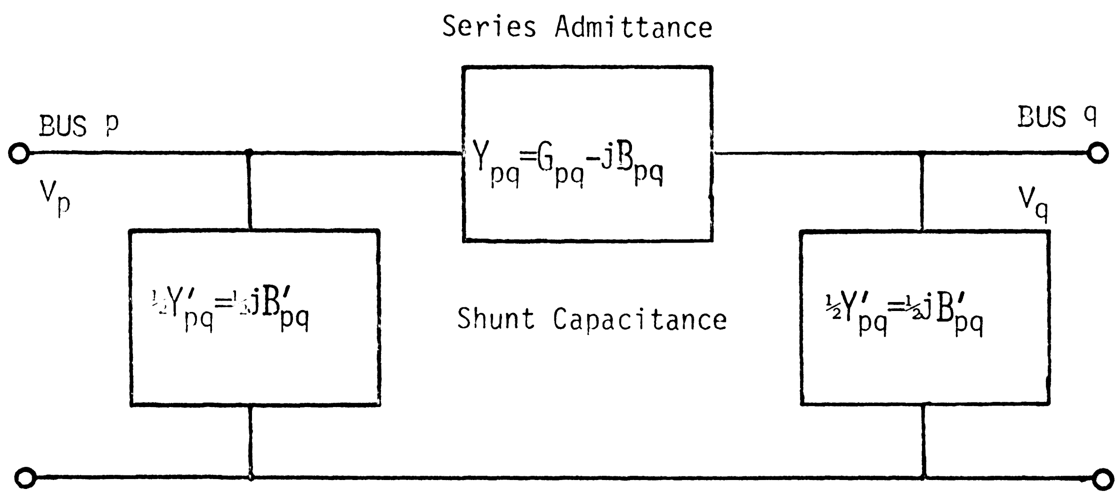


Figure 2.1 Equivalent Pi Network

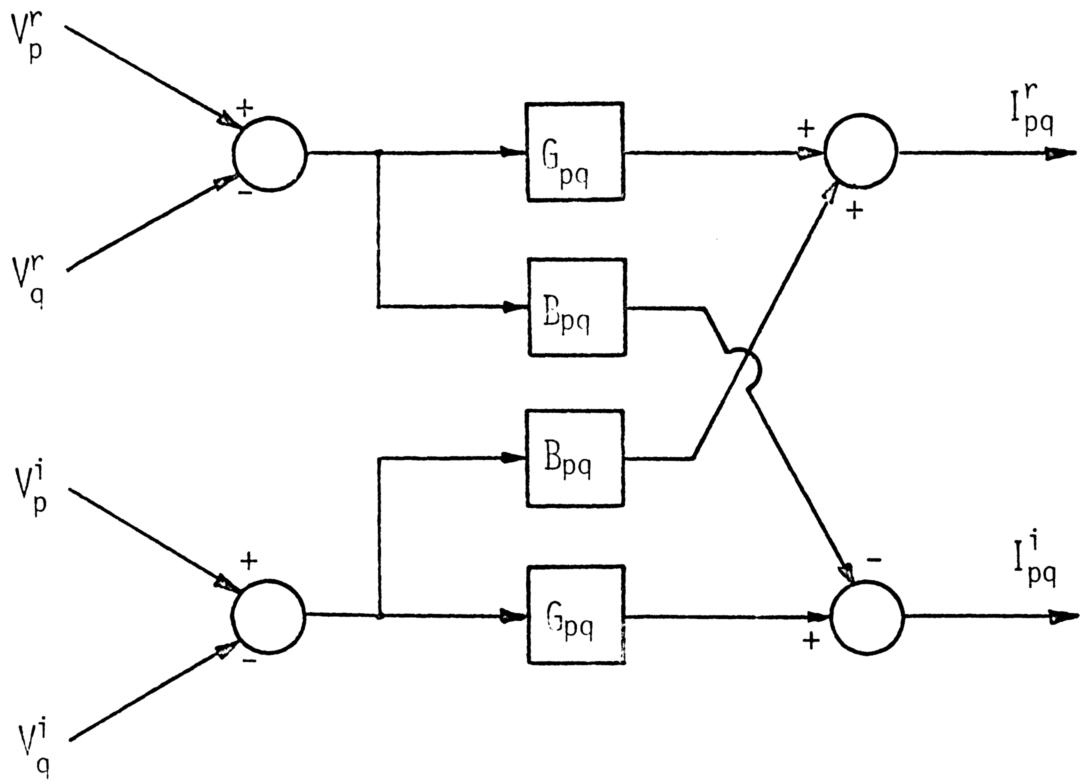


Figure 2.2 Block Diagram of Transmission Line

When steady state solution is reached, $\underline{\bar{I}}_e$ must equal zero. Since also at steady state, the bus voltages are constant or

$$\frac{d}{dt} \underline{\bar{V}}_{BUS} = \underline{\dot{\bar{V}}}_{BUS} = \underline{0} \qquad (2.2.2)$$

Then a dynamic equation, which will converge to the proper solution can be written as

$$\underline{\dot{\bar{V}}}_{BUS} = [\, \bar{K} \,]\, \underline{\bar{I}}_e \qquad (2.2.3)$$

The matrix K is a square diagonal weighting matrix whose entries are designed to allow faster convergence.

This equation is substituted into Equation (2.2.1) to give a final equation

$$\underline{\dot{\bar{V}}}_{BUS} = [\, \bar{K} \,]\, \underline{\bar{I}}_e = [\, \bar{K} \,](\, \underline{\bar{I}}_{BUS} - [\, \bar{Y}_{BUS} \,]\, \underline{\bar{V}}_{BUS}) \qquad (2.2.4)$$

This equation can be expressed in block diagram form as shown in Figure 2.3. The diagram shows the bus voltage ($\bar{V}_{BUS}$) being fed back through the remainder of the network ($\bar{Y}_{BUS}$) and subtracted from the injected current ($\bar{I}_{BUS}$).

This creates the error current ($\bar{I}_e$) which is integrated to affect the bus voltage ($\bar{V}_{BUS}$). Therefore, the bus voltage is going to continue to change until the error current goes to zero and thereby forcing the bus to solve Kirchhoff's current law. Figure 2.4 describes a detailed block diagram. This block diagram translates into an analog model that forms the bus module as shown in Figure 2.5.

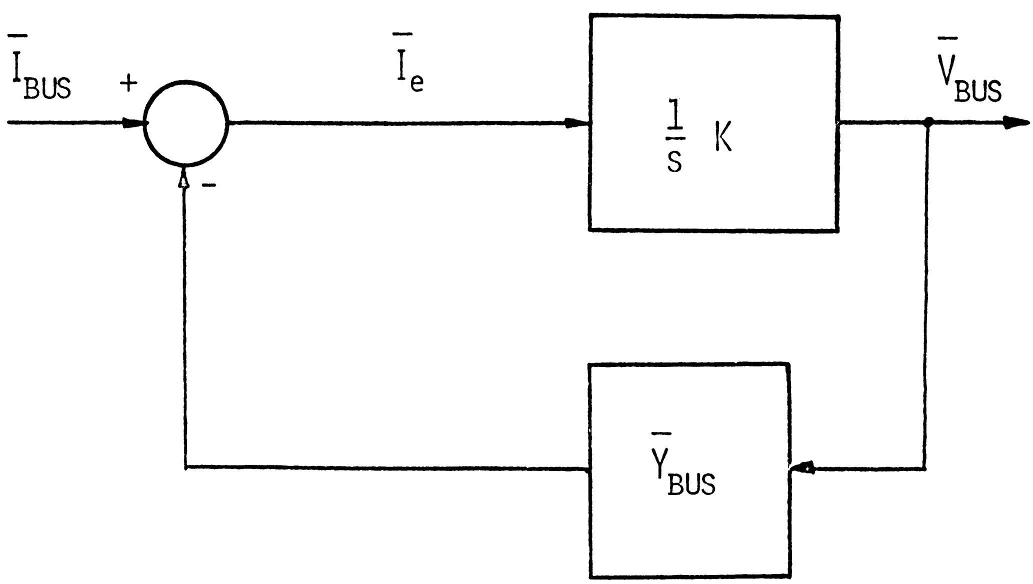


Figure 2.3 Block Diagram of Bus

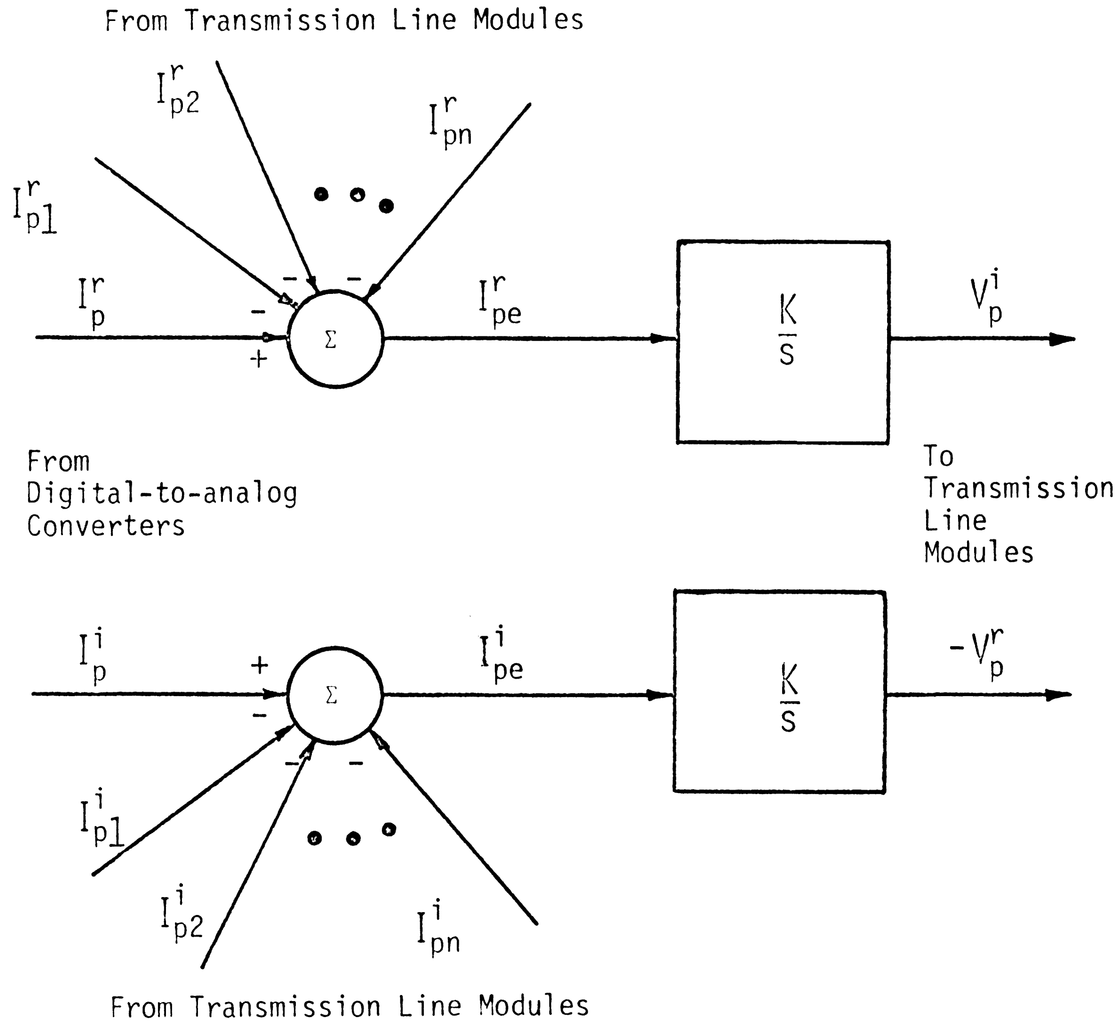


Figure 2.4 Detailed Block Diagram of Bus

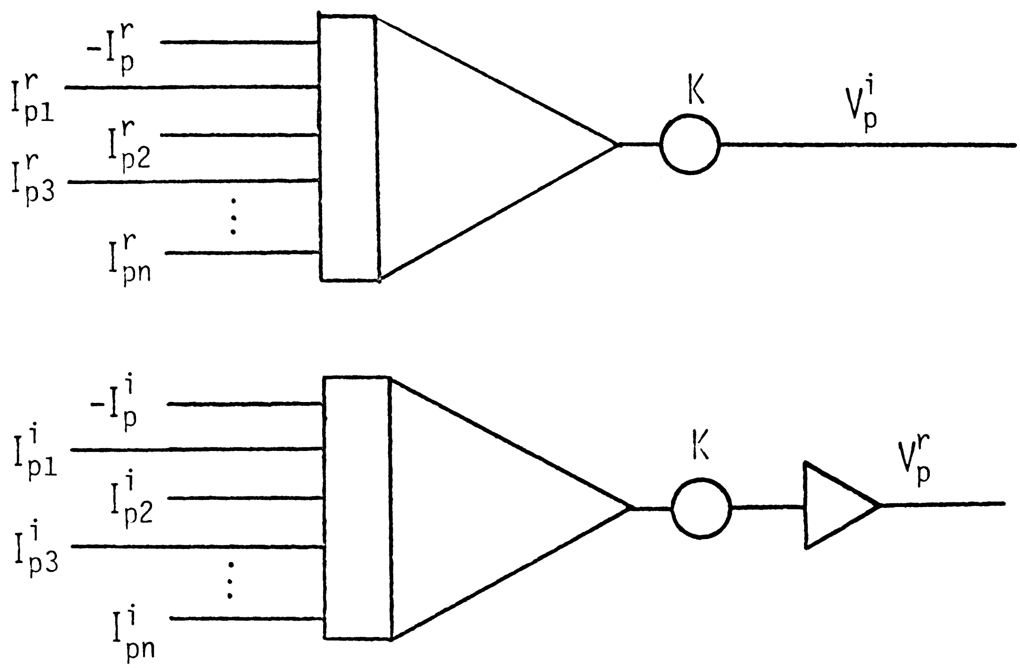


Figure 2.5 Analog Model of Bus

To summarize, the transmission line module takes the complex bus voltages at two buses and generates the line currents, and the bus module takes the line currents at that bus and generates the bus voltages.

Since the analog computer uses operational amplifiers rather than the alternating current devices which the network analyzer uses, both the complex bux voltages and complex line current are represented by D.C. voltages. Similarly, the line complex impedance is represented by resistors alone. These representations greatly simplify the simulation.

2.3 Representation of Generation and Loads

Power generation and load can be represented by two general methods. These are by digital representation or by analog representation. Analog representation has the advantage of operating in parallel with the remainder of the network and is therefore very fast. However, it requires many analog multipliers which are expensive and not very accurate.

In the initial programming of the simulation it was desirable to make the system as simple as possible. Therefore, a three-bus, three-line system was designed that used only analog representations of the loads. This was done in order to have an all-analog simulation that did not require digital calculation and control. A diagram of the analog program is shown in Figure 2.6.

This all-analog simulation was very helpful in detecting initial design error of the transmission line and bus modules.

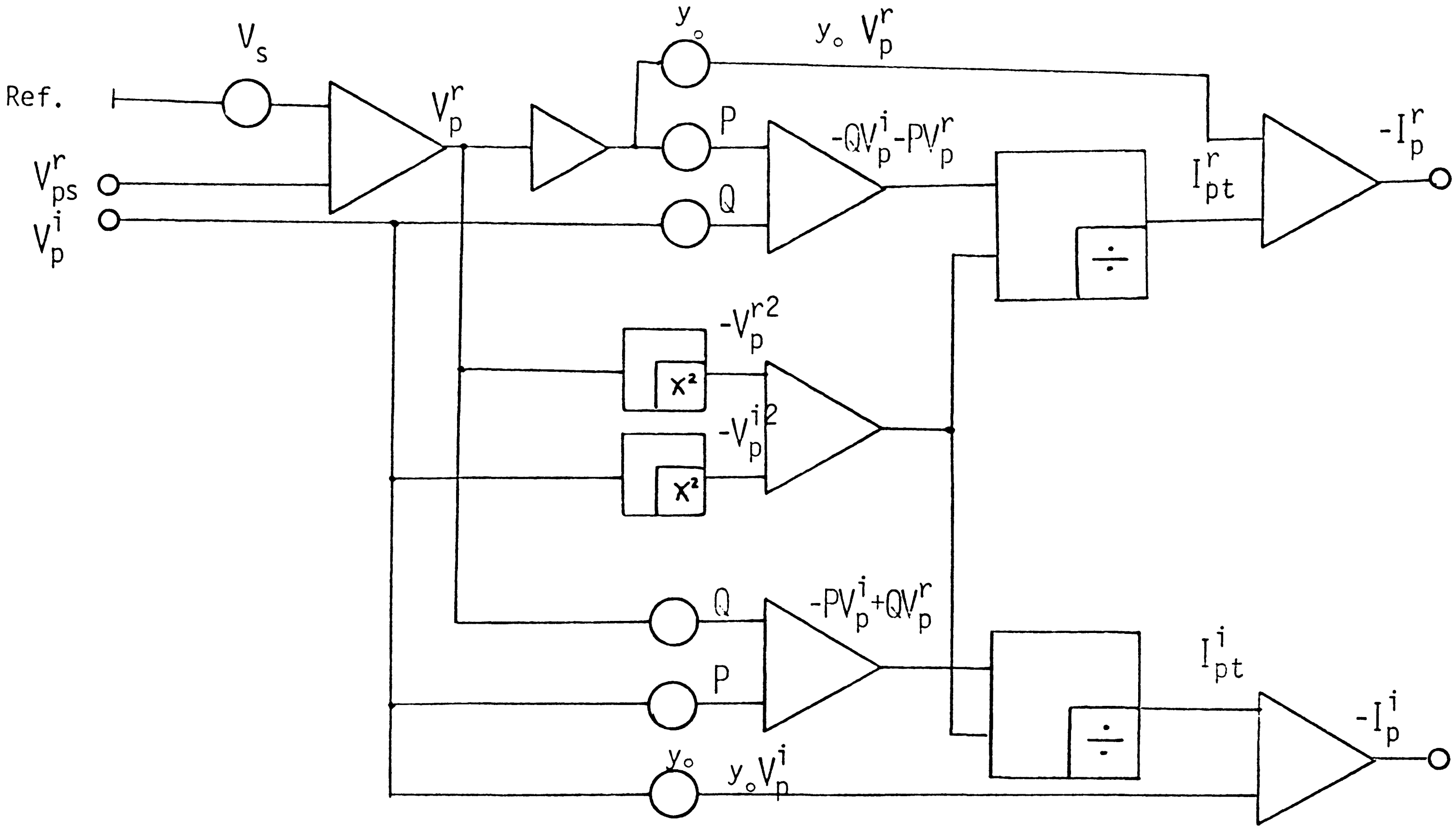


Figure 2.6 Analog Load Simulator

To digitally simulate the loads, the basic power equation required is

$$\overline{V}_p^* \overline{I}_p = \overline{S}_{pd}^* = P_{pd} - jQ_{pd} \qquad (2.3.1)$$

This can be rewritten as

$$\overline{I}_{pt}^{(K+1)} = \frac{P_{pd} - jQ_{pd}}{\overline{V}_p^{*\,(K)}} \qquad (2.3.2)$$

where I_{pt} is the total injected current at bus p. To calculate the net bus current, the amount that flows through the line-charging capacitance or other fixed impedances must be subtracted. Therefore, the equation finally becomes

$$\overline{I}_p^{(K+1)} = \frac{P_{pd} - jQ_{pd}}{\overline{V}_p^{*\,(K)}} - \overline{y}_{po} \overline{V}_p^{(K)} \qquad (2.3.3)$$

Therefore, this is the current that is calculated at each bus for its specific voltage. Note that P_{pd} and Q_{pd} can be positive to indicate a net generation or negative to indicate a net load.

When a bus is classified as voltage controlled, a slight modification of this algorithm must be made. Observing that the change in bus voltage magnitude is highly correlated to the reactive generation, a very simple algorithm can be developed. If a desired voltage magnitude at a bus ($|\overline{V}_{pd}|$) is specified, then the reactive generation can be modified to maintain the specified voltage by

$$Q_p^{(K+1)} = Q_p^{(K)} + \Delta Q_p^{(K)} = Q_p^{(K)} + \alpha(|\overline{V}_{pd}| - |\overline{V}_p^{(K)}|) \qquad (2.3.4)$$

where α is a weighting factor that gives best convergence. If the new

$Q_p^{(K+1)}$ goes beyond the limits of the reactive generation, then the generation is fixed at the limit, and the voltage is allowed to change as before.

2.4 Implementation of Hybrid Load Flow

Since the loads and generation are represented digitally, the hybrid load flow must iterate to a solution. The flow chart in Figure 2.7 shows six distinct sections of the load flow program.

The first section can be referred to as the initialization section. This part performs necessary tasks and initializations for the main program. The program then waits in this section for a command from the program operator.

The second section is the first part of the main program and can be called the calculation loop. In this section the bus voltage and injected power are used to calculate the injected bus current. This complex value of current is then sent through the digital-to-analog converter to the analog network. The operations of this block are performed for every bus except for the slack bus.

The third section is called the analog operation section. In this part the mode of the analog computer changes to OPERATE to allow the bus integrators to operate and determine the new steady state solution. The computer remains in OPERATE for a fixed period of time after which the mode is changed to HOLD to keep all the voltages of the network constant.

The fourth section is called the A/D loop. Here the values of the slack bus injected current and the bus voltages are brought into

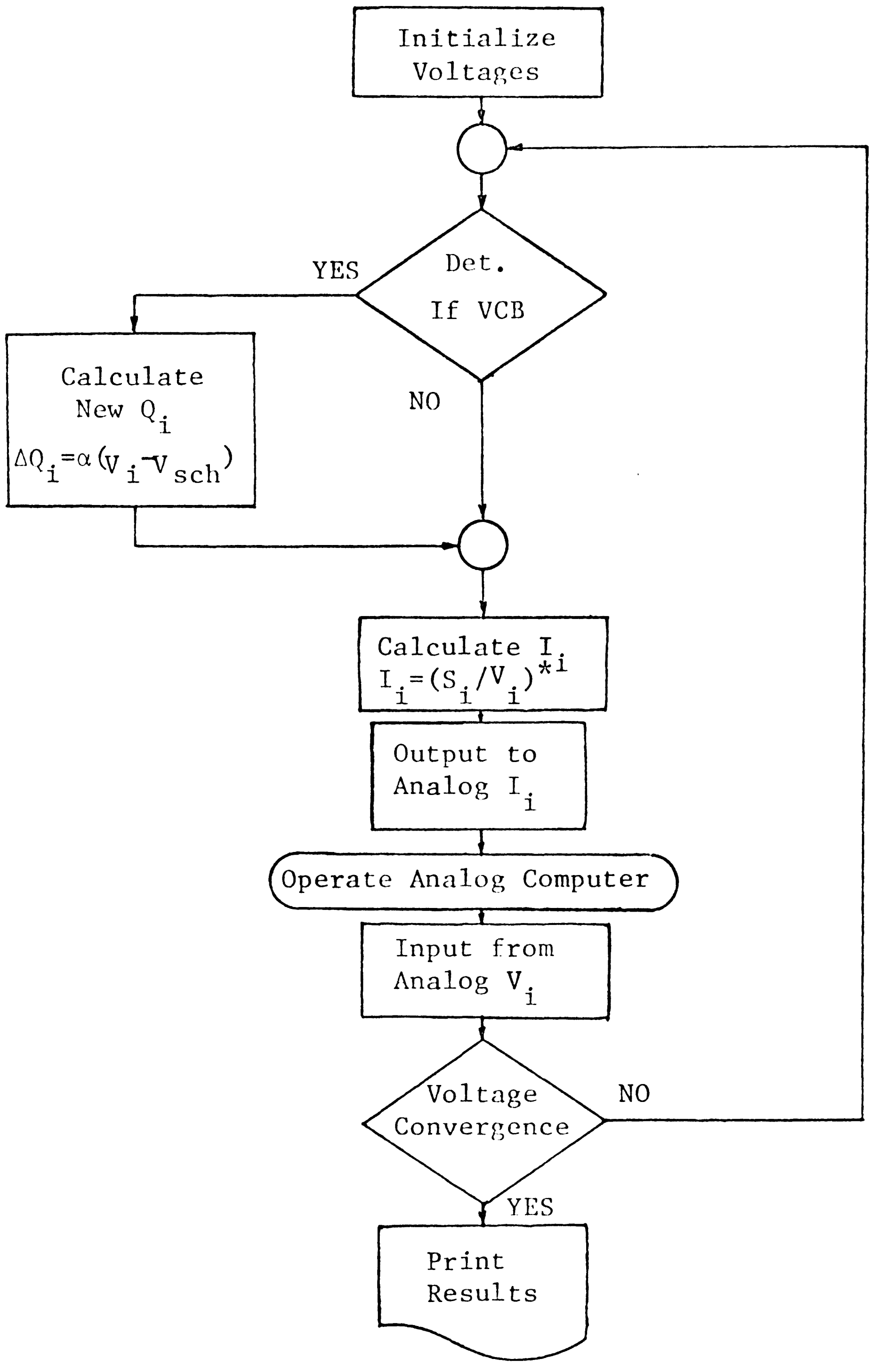


Figure 2.7 Flow Chart of Load Flow Program

the digital computer through an analog-to-digital computer. This process is repeated to obtain the complex bus voltage for all except the slack bus.

The next major section is called the convergence test loop. The change in bus voltage is determined in this section. This test is performed on each bus voltage until one of the tests fails. When there is a failure, the program goes back to the beginning of the calculation loop again for another iteration. If the test is passed, the program continues to the final section.

The final section is called the output section in which the data are converted and printed out in a neat format. After data for each bus are printed, the program goes to the very beginning to prepare for another run of the load flow.

Several different sizes and types of power systems were simulated in testing the hybrid load flow. Power systems consisting of three, four, five and six buses were studied. The simulation of the six bus system totally taxed the capabilities of the existing equipment such that if one analog component failed, a spare was not easily available. For this reason a five-bus system was chosen as the basic test system.

An example system given in computer methods in Power Systems Analysis by Stagg and El-Abiad was used because it had been fully evaluated by the authors.[6] A diagram of the system is shown in Figure 2.8 and the analog program of the system is shown in Figure 2.9.

The magnitude of each bus voltage obtained on the hybrid load flow was within one percent of the value obtained with a digital load

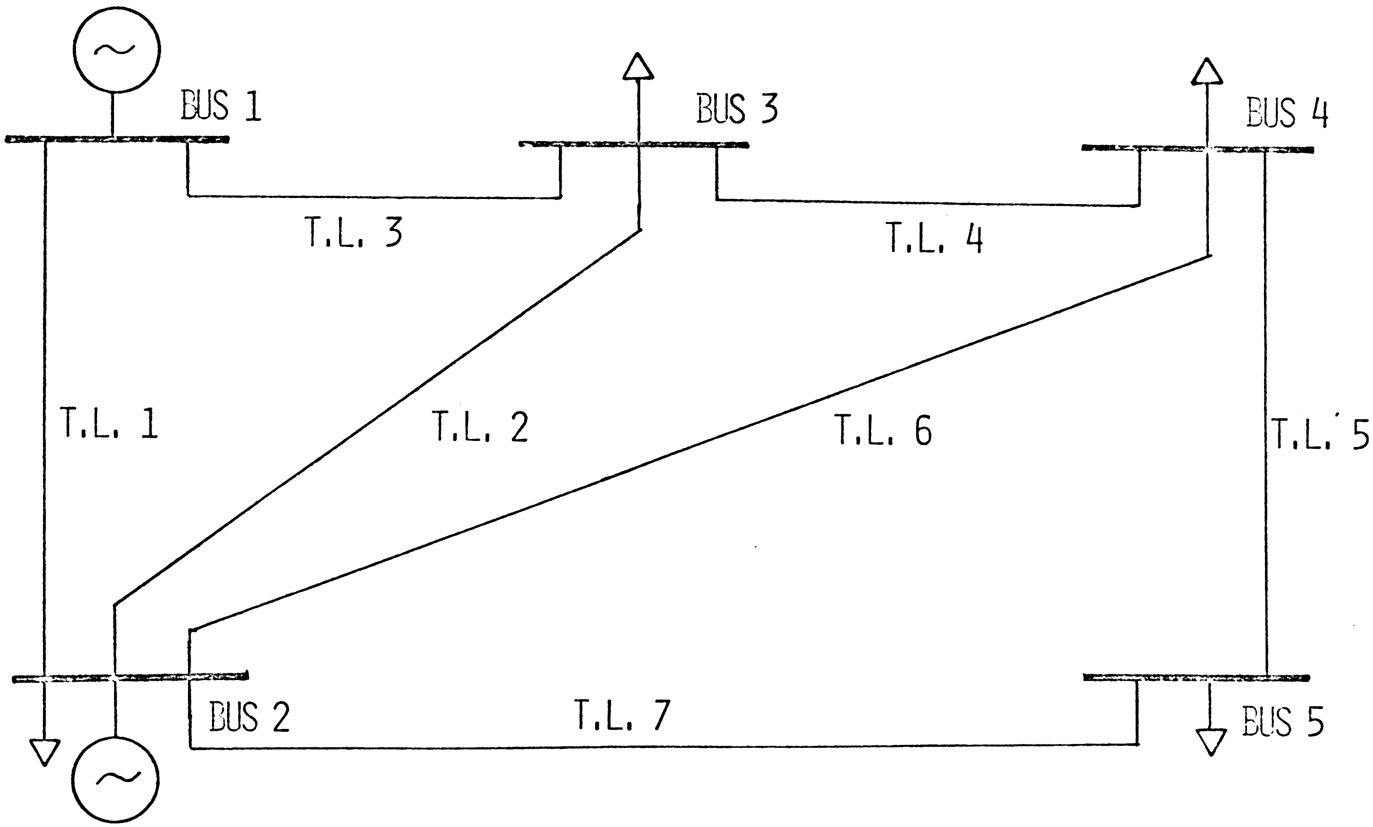


Figure 2.8 Diagram of Five-Bus System

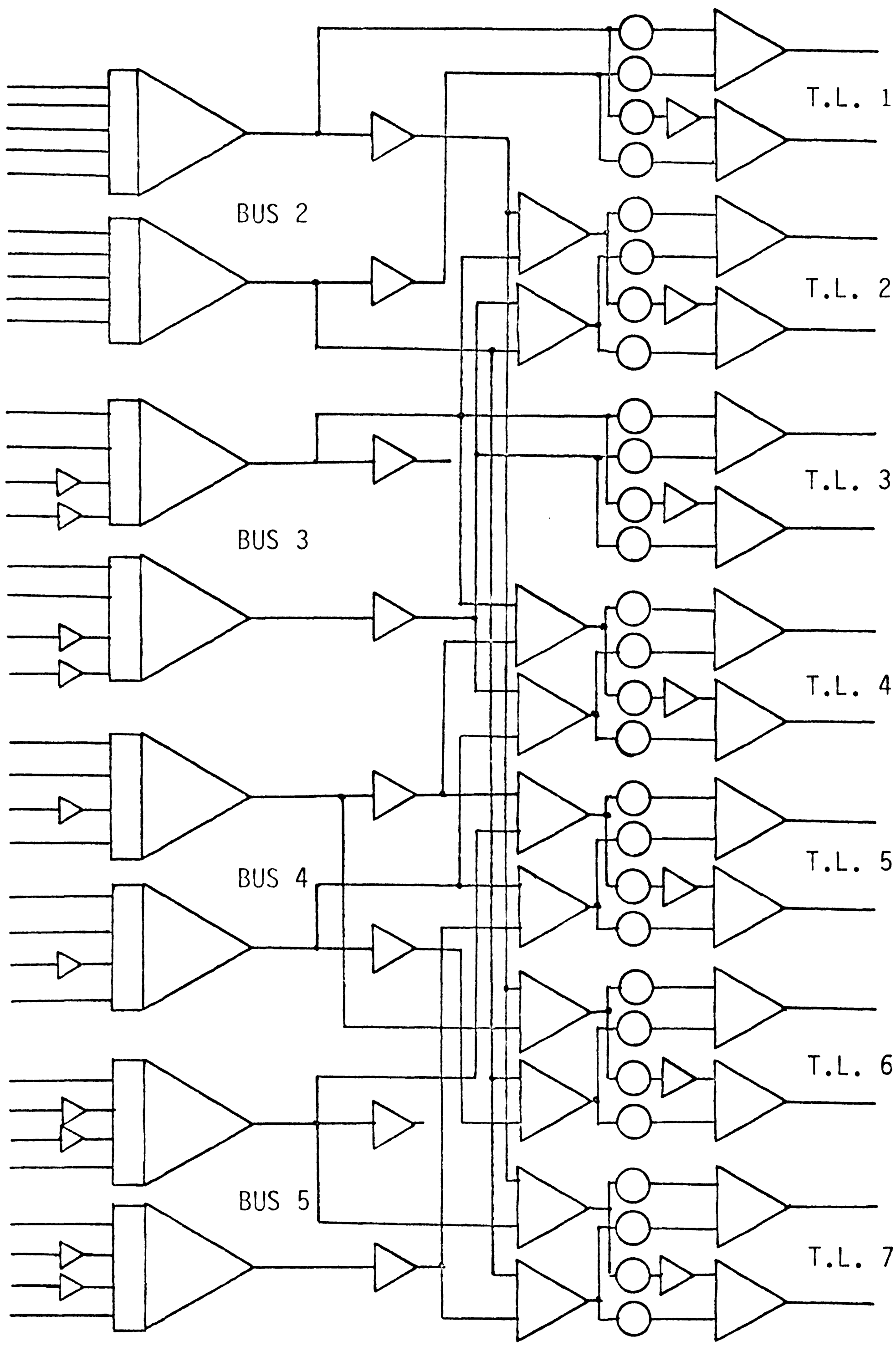


Figure 2.9 Analog Program of Five-Bus System

flow. Since the angle of the bus voltage tends to be small, its error was much larger. This is because there was usually random error generated by the A/D converters, the D/A converters and digital arithmetic which causes small signals to be severely distorted. Much effort was aimed at reducing this error by frequently calibrating the converters and scaling the analog program to make best use of the range of the converters. Table 2.1 shows the accurate results compared with hybrid load flow results.

Using the five-bus test system for the hybrid load flow, the solution was determined within five iterations. To obtain this result, the initial bus voltages were set equal to the slack bus and an error tolerance allowed on the real and reactive parts of the bus voltage equaling 0.00075.

The overall time required to arrive at the solution was, on the average, 115.3 milliseconds or about 23.1 milliseconds per iteration.

In order to be able to determine a solution time if equipment was available for a much larger system, portions of the hybrid program were measured to determine the time required to perform each function. Table 2.2 shows the time values obtained from measurements of each section of the program. Also given in the table is a function of the number of buses and voltage control buses which provide approximate values of the time required for each section.

All these functions can be linearly added together to produce the total time each iteration as a function of the number of kinds of buses. This researcher believes that the number of iterations required

Table 2.1 Comparison of Actual and Hybrid Load Flow Results

COMPLEX.BUS VOLTAGE

BUS NO.	HYBRID LOAD FLOW REAL	HYBRID LOAD FLOW IMAGINARY	EXACT SOLUTION REAL	EXACT SOLUTION IMAGINARY
1	1.0600	0.0000	1.0600	0.0000
2	1.0464	-0.0474	1.0462	-0.0513
3	1.0203	-0.0791	1.0204	-0.0892
4	1.0193	-0.0835	1.0192	-0.0950
5	1.0078	-0.1064	1.0121	-0.1090

COMPLEX BUS POWER

BUS NO.	HYBRID LOAD FLOW REAL	HYBRID LOAD FLOW IMAGINARY	EXACT SOLUTION REAL	EXACT SOLUTION IMAGINARY
1	1.2905	-0.2410	1.2950	-0.0750
2	-0.2000	-0.2000	-0.2000	-0.2000
3	0.4500	0.1500	0.4500	0.1500
4	0.4000	0.0500	0.4000	0.0500
5	0.6000	0.1000	0.6000	0.1000

Table 2.2 Time Values for Each Section of the Hybrid Load Flow

PORTION OF PROGRAM	FIXED TIME*	TIME PER BUS*	TIME PER VOLT. CONT. BUS*
CALCULATION LOOP	0.352	2.871	0.795
ANALOG OPERATION	5.968	-	-
A/D CONVERSION LOOP	-	1.083	-
DIVERGENCE TEST	0.016	-	-
CONVERGENCE TEST	0.025	0.015	-
TOTAL TIME	6.351	3.969	0.795

*Time in milliseconds.

for a system is a function of the error tolerance and not a strong function of the number of buses. This belief is based on experience with the small systems (3 and 4 buses) and observation that for the hybrid load flow all the buses converge to a solution at the same time, rather than serially, as with a digital computer.

Table 2.3 compares estimates of hybrid load flow solution times with the actual times required by four digital techniques for several standard IEEE test systems. Based on the assumption that the number of iterations required for convergence is relatively constant, the total solution time is also given. Note that these solution times do not include the time required to input new data to the program or the time required to print or display the results since these times are highly variable.

Table 2.3 Estimates of Solution Times for Standard IEEE Cases

Number of Buses	No. of Volt. Cont. Buses	Time Req. for Hybrid		Time Required for Digital Techniques			
		Per Iteration	Five Iterations	Gauss-Seidel	Newton-Raphson	Mod. Nodal Iterative	Fast Decoupled
14	4	0.0610	0.305	1.07	1.69	1.24	1.04
30	5	0.1251	0.625	3.11	10.71	5.16	2.79
57	6	0.2327	1.164	10.64	55.86	30.31	9.11
118	53	0.5114	2.557	107.37	560.80	310.34	35.57

NOTE: Time is in seconds.

III. APPLICATIONS OF HYBRID LOAD FLOW

The load flow program is the basic building block for solution algorithms of many power systems problems. The intent of this chapter is to study two applications programs which are based on the hybrid load flow. These are the determination of Z_{BUS} from the analog network and the solution of the optimal load flow problem.

3.1 Determination of Z_{BUS}

As stated earlier in this paper, the set of equations that describes a network such as an electric power system can be written in matrix form as

$$\underline{\overline{V}}_{BUS} = [\ \overline{Z}_{BUS}\ ]\ \underline{\overline{I}}_{BUS} \qquad (3.1.1)$$

For an electric power system the elements of $\underline{\overline{V}}_{BUS}$ are the complex voltages at each bus (node) and the elements of $\underline{\overline{I}}_{BUS}$ are the complex injected currents at each bus (node). Therefore, the elements of $\overline{Z}_{BUS}$ represent the relationship between the node voltage and the injected current.

Thus, the impedance matrix, $\overline{Z}_{BUS}$, provides an important mathematical representation of the power system network. Most research has dealt with methods of determining the impedance matrix since inverting the admittance matrix is such a complex process. One of the most popular methods of determining the impedance matrix may be described as "growing" the matrix. A brief explanation of this rather complicated method is given below. For a more complete description, the reader is referred to Analysis of Faulted Power Systems by P. M. Anderson[7].

According to Anderson, one of the fundamental difficulties in forming the impedance matrix is the ordering of the primitive matrix. This ordering process begins with an impedance which is connected directly to the reference node. The process continues to build the matrix step-by-step by connecting each successive impedance in a tree-type manner. With the introduction of each impedance, major modification of the impedance matrix is required.

Although the special nature of the impedance matrix has been used descriptively by Anderson and many others who have research the problem, it has not been used directly to determine the impedance matrix. After observing the natures of the impedance matrix and the hybrid load flow, this researcher theorized that the impedance matrix could be naturally determined from the analog network. The following section will further describe the nature of the $\bar{Z}_{BUS}$ impedance matrix. From this description the unique relationship between the analog network and the matrix $\bar{Z}_{BUS}$ will be revealed.

Equation (3.1.1) can be expanded and rewritten as

$$\begin{bmatrix} \bar{V}_1 \\ \bar{V}_2 \\ \vdots \\ \bar{V}_n \end{bmatrix} = \begin{bmatrix} \bar{Z}_{11} & \bar{Z}_{12} & \cdots & \bar{Z}_{1n} \\ \bar{Z}_{21} & \bar{Z}_{22} & \cdots & \bar{Z}_{2n} \\ \vdots & \vdots & & \vdots \\ \bar{Z}_{n1} & \bar{Z}_{n2} & \cdots & \bar{Z}_{nn} \end{bmatrix} \begin{bmatrix} \bar{I}_1 \\ \bar{I}_2 \\ \vdots \\ \bar{I}_n \end{bmatrix} \qquad (3.1.2)$$

If every current entering the node is equal zero except at the Kth node, Equation (3.1.2) would reduce to

$$\begin{bmatrix} \overline{V}_1 \\ \overline{V}_2 \\ \vdots \\ \overline{V}_n \end{bmatrix} = \begin{bmatrix} \overline{Z}_{1k} \\ \overline{Z}_{2k} \\ \vdots \\ \overline{Z}_{nk} \end{bmatrix} \overline{I}_k \quad ; \quad \overline{I}_j = 0,\ j \neq k \tag{3.1.3}$$

This equation, therefore, defines the characteristic of each element of Z_{BUS}. The diagonal elements of the impedance matrix are referred to as open circuit driving point impedances and the off-diagonal elements are called open circuit transfer impedances. The value of an arbitrary element of Z_{BUS} is

$$Z_{ik} = \left. \frac{\overline{V}_i}{\overline{I}_k} \right| \overline{I}_j = 0,\ j \neq k \quad ; \ i = 1, 2, \ldots, n \tag{3.1.4}$$

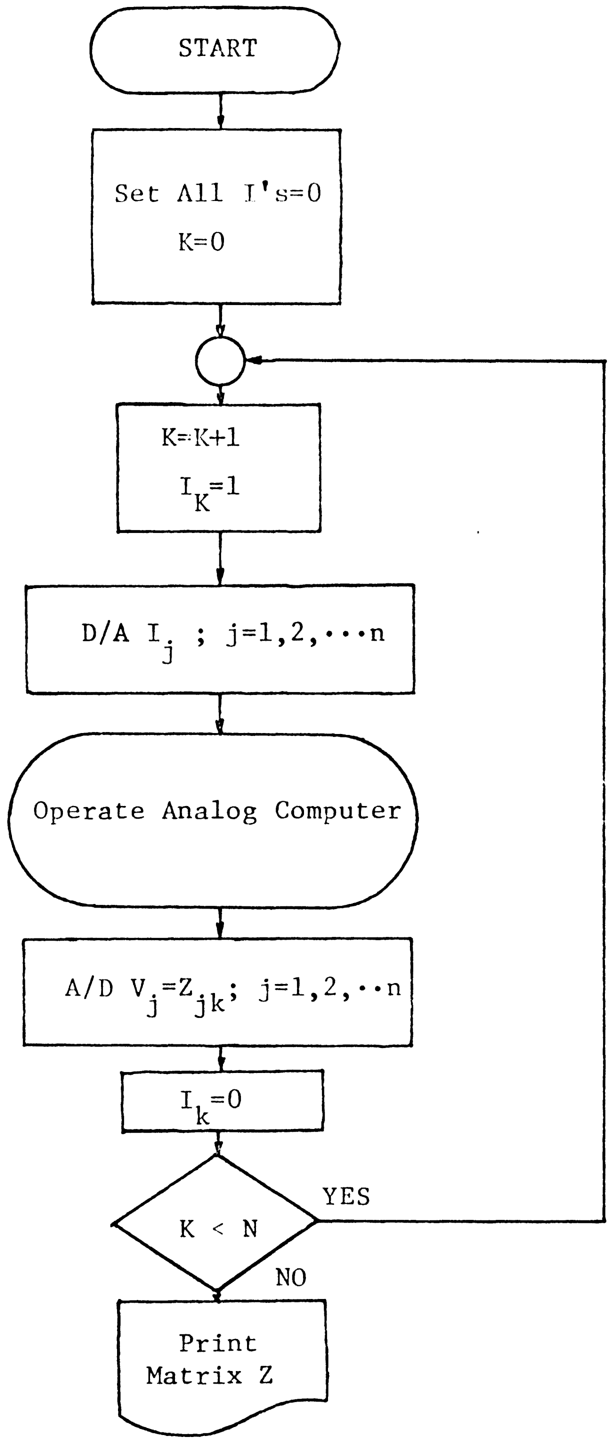
The measurement of the voltage $\overline{V}_i$ and the injected current $\overline{I}_k$ can be made with respect to any node in the network. This measurement is often made with respect to a ground or neutral node. It is also made with respect to another reference node. In a power system network this reference node is usually the slack bus.

The hybrid load flow network uses the slack bus as its reference bus. By doing this, the network is simplified because one less bus needs to be programmed, thus saving equipment. The hybrid load flow program specifies the injected current at each bus and reads all the bus voltages. Therefore, the hybrid load flow is naturally available to be operated by a program that can determine the impedance matrix of the network. A program to determine Z_{BUS} from the network would greatly simplify the checking of impedances in the analog network and thus improve the accuracy of the load flow program.

The algorithm used in the program to determine the Z_{BUS} impedance matrix is based on Equation (3.1.4). A simplified flow chart of this program is shown in Figure 3.1. The program delivers one unit of real current to one bus on the analog network while keeping all the other currents zero. After allowing the network to come to equilibrium, all the bus voltages are read by the digital computer through an analog to digital converter. This process is repeated until each bus of the network has been injected with one unit of real current. The bus voltages are stored in the digital computer in matrix form. This matrix of voltages is also the $\overline{Z}_{BUS}$ impedance matrix on a per-unit basis. This matrix can be printed out or statistically compared with the expected $\overline{Z}_{BUS}$ matrix to check if the network is correct.

This algorithm was programmed as described and implemented on the hybrid system. The program performed as designed, producing a $\overline{Z}_{BUS}$ matrix that was within five percent of the expected values. Little effort was made to reduce this error since it included a combination of many data errors. The program actually located a miswiring of the analog network. When the error was corrected, the load flow program produced more accurate results.

It is this researcher's opinion that the $\overline{Z}_{BUS}$ determination algorithm improves the reliability and accuracy of the hybrid load flow. It is also believed that it makes the hybrid load flow solution method much more competitive with digital solution methods.



3.1 Simplified Flow Chart of Z_{BUS}

3.2 OPTIMAL LOAD FLOW

An electric utility is most concerned about supplying all the power its customers demand at the least possible cost. Therefore, it is desirable to specify the parameters of the load flow in order to minimize production costs. One of the simplest methods is to make an "intelligent guess" based on much operating experience. However, the best-guess method is seldom the most efficient operating strategy. A better solution to the problem involves incorporating into the load flow program an algorithm that determines the optimum operating conditions based on certain criteria. A considerable amount of research effort has been and is continuing to be exerted in an effort to solve this optimal load flow problem[8-10].

The optimal criterion is often represented by a cost function. The components of the cost function are somewhat subjective but usually include the cost in dollars of operating each generator in relation to the amount of power it generates. For effective optimization, it is essential to minimize the cost function while also satisfying the constraints of the problem.

These constraints fall into two categories: equality constraints and inequality constraints. Equality constraints usually include the general load flow equations given as

$$\frac{\overline{S}_{Gk} - \overline{S}_{Dk}}{\overline{V}_k^*} = \Sigma_{i=1}^{n} \overline{y}_{ki} \overline{V}_i \; ; \; k = 1, 2, \ldots, n \quad (3.2.1)$$

The inequality constraints sometimes include keeping the bus voltages near their nominal values. Usually, however, these constraints require keeping the real power generation with an upper and lower limit. These limits are often based on equipment capabilities and regulatory requirements.

The optimal load flow problem can also be stated in more mathematical terms. The object is to minimize

$$C\ (\underline{\overline{V}}_{BUS},\ \underline{\overline{S}}_{G}) \tag{3.2.2}$$

subject to

$$\frac{\overline{S}_{Gk} - \overline{S}_{Dk}}{\overline{V}_k^*} = \Sigma_{i=1}^{n}\ \overline{y}_{ki}\ \overline{V}_i\ ;\ k = 1,\ 2,\ .\ .\ .,\ n \tag{3.2.3}$$

and

$$\underline{g}\ (\underline{\overline{V}}_{BUS},\ \underline{\overline{S}}_{G}) \leq \underline{0} \tag{3.2.4}$$

Here $C(\underline{\overline{V}}_{BUS}, \underline{\overline{S}}_{G})$ is a cost function which is a function of the bus voltages and the generated complex power, and $\underline{g}\ (\underline{\overline{V}}_{BUS}, \underline{\overline{S}}_{G})$ represents the set of inequality constraints which is also a function of the bus voltages and complex generated power.

The solution techniques for this type of power engineering problem have been extensively researched. A. M. Sasson and H. M. Merrill have written one of the better survey papers on the subject and list many excellent references(11). The more general problem of optimization is called mathematical programming. Since mathematical programming can be applied in so many fields, it is also highly researched.

Many of the optimization techniques require determination of the cost function gradient. Some of the most researched gradient methods include Newton's, Conjugate-Gradient and Steepest-Descent. Other methods that do not require a gradient such as Fibonacci search and conjugate directions, are simpler algorithms but approach the solution slowly. This paper does not intend to explain any of these optimization techniques but refers the interested reader to the book Introduction to Linear and Nonlinear Programming by D. G. Luenberger for further study[12].

The economic dispatch problem is a special case of the optimal load flow. The cost function for this case is the summation of the costs of generating real power at each generator. The set of equality constraints given in Equation (3.2.3) can be replaced by a single constraint

$$\Sigma \,\underline{\overline{S}}_G - \Sigma \,\underline{\overline{S}}_D - \Sigma \,\underline{\overline{S}}_L = 0 \qquad (3.2.5)$$

This means that the total generation must equal the total demand and the total losses. The inequality constraints consist of the power limits of each generator and possibly the limits of the magnitude of bus voltages.

Even with this simplified problem, a difficulty exists in determining the minimum cost. This problem has been investigated by O. I. Elgerd[13]. He has derived a set of equations similar to the gradient of the cost function. The equations are the approximate derivative of the total losses with respect to each real power generation and are given as

$$ITL_i = \frac{\partial P_L}{\partial P_{Gi}} \simeq 2 \Sigma_{k=1}^{n} (P_k \alpha_{ik} - Q_k \beta_{ik}); \; i=1, 2, \ldots, NG \qquad (3.2.6)$$

where
$$\alpha_{ik} = \frac{r_{ik}}{|\overline{V}_i||\overline{V}_k|} \cos (\delta_i - \delta_k)$$

and
$$\beta_{ik} = \frac{r_{ik}}{|\overline{V}_i||\overline{V}_k|} \sin (\delta_i - \delta_k)$$

The term ITL refers to incremental transmission losses. Note that the equations contain the term r_{ik} which is the real portion of the Z_{BUS} impedance matrix. Thus, using Equation (3.2.6) and the cost function along with the load flow solution, the economic dispatch problem can be solved.

This same algorithm can be implemented on the hybrid computer. The digital computer can calculate Equation (3.2.6) to determine how the generation should be changed to minimize the cost. Then the hybrid load flow runs as a subroutine to solve the power flow equations (the equality constraints). The inequality constraints can also be enforced by either the digital or analog computer.

Time did not allow complete implementation and testing of the economic dispatch program on the hybrid computer; therefore, no specific results can be concluded. Since the optimization algorithm has been successful on the hybrid computer, this researcher can foresee no physical reason why the hybrid economic dispatch program cannot be implemented. He believes that only time is necessary to make this program operational. Further discussion of the program will be given in Section (4.2), Conclusions and Suggestions for Further Research.

IV. CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

4.1 CONCLUSIONS OF THE HYBRID LOAD FLOW

The results shown in Tables 2.2 and 2.3 indicate that the hybrid load flow solution technique is a very fast solution algorithm. The assumption used to derive Table 2.3 is that all problems will converge in five iterations. If this assumption is erroneous and the number of iterations to solution increases with larger systems, the hybrid load flow should still be faster than existing digital methods. For example, if the 118-bus system actually required fifteen iterations rather than five, that total solution time would be 7.67 seconds. This solution time is still much faster than one 560.8 second solution time that has been reported, using a Newton-Raphson digital solution.[2]

It should be noted that the time measurements of the hybrid system are not optimal values. The speed of the hybrid system can be improved in a number of ways.

One change that could decrease the solution time would be to use a faster digital component in the hybrid computer. The GE-4020 computer presently used is a moderately fast digital computer, but recent technological advances in digital circuits have made it possible to purchase minicomputers significantly faster than the GE-4020. It should be reasonable to expect a 10 to 20 percent improvement in operating time with the selection of a more advanced digital computer as a component of the hybrid computer.

Another change in the hybrid system that could reduce solution time is the improvement of the digital-to-analog and analog-to-digital converters. The converters now employed by the hybrid interface are constructed with totally discrete components. This makes the converters slow and in need of frequent calibration in order to maintain acceptable accuracy.

Furthermore, the time required for the hybrid computer to perform a digital-to-analog conversion is 250 microseconds. However, there are devices on the market today which will perform this conversion in one microsecond, less time than it takes to perform any single instruction on the digital computer. Similarly, the time required to perform an analog-to-digital conversion on the hybrid computer is 500 microseconds, but there are devices available that can perform a conversion within fifteen microseconds.

The hybrid load flow program requires two analog-to-digital conversions and two digital-to-analog conversions for each bus per iteration. Therefore, it seems reasonable to expect that if modern converters are used in the hybrid computer one could expect a reduction of solution time by 1.465 milliseconds per bus per iteration. This change will result in approximately 25 percent reduction in solution time. Also, the modern converters would probably have better linearity and long-term stability than the ones used in this study.

In the process of programming the digital portion of the hybrid load, much effort was exerted in making the program efficient. However, the program is still far from optimal. Even though the program is written in assembler language, an experienced programmer could probably reduce the operating time considerably.

Another modification that could reduce the solution time would be to change the algorithm that controls the analog computer's operating time to a more sophisticated method. The method presently used sets a fixed time during which the analog computer is operated. This time is determined by the time required for the voltages on the analog computer to come to a steady state value during the first iteration. However, the time for the analog voltages to come to steady state on the last iteration is much less than the time required for the first iteration. Setting a fixed time to operate the analog computer is the simplest method of controlling the time but is not very efficient.

Since the digital computer is not performing any useful function while the analog computer is operating, it could be used to determine when the analog voltages are at steady state. The digital computer could periodically sample representative bus voltages through analog-to-digital converters to determine when the voltages stop changing with time.

Another approach to determine this would be to devise an analog program that could sense when the derivative of the bus voltages are constantly near zero. It appears that there are several algorithms which can be used to reduce the analog operation time which is presently about six milliseconds per iteration. Since the time saved by this change would not be a function of the number of buses, the time reduction for a large system simulation might be insignificant. An important by-product of this type of algorithm is that it guarantees that the analog computer will be at steady state during each iteration, even when the maximum time required is unknown. This could be very important when attempting contingency studies.

To summarize, the hybrid load flow program appears to be a fast solution technique with potential for even greater speed. By utilizing the methods discussed above to reduce solution time, it would not seem unreasonable to expect to obtain the solution to a 118-bus system in approximately one second.

Thus far, the limitations of the hybrid load flow have not been discussed. There are some severe limitations of the system which must be considered along with the advantages. Three areas of limitation are equipment, size and economics.

The equipment limitations are those characteristics of the devices employed which could restrict the hybrid load flow's usefulness. One restriction is the frequency response of the operational amplifiers in the analog computer. In this study the analog computer was operated at approximately the limit of its frequency response. It could have been operated much faster if the frequency response was higher. So the speed of the analog computer is limited by the frequency response of the operational amplifiers. The analog computer is also limited by the accuracy of the linear devices. This accuracy can be expected to be within 0.25 percent but could deviate considerably.

Unless a special analog computer is designed for the hybrid load flow, the size of the system that can be simulated is limited by the size of the assembled equipment. Since a six-bus system was the largest that could be represented on the large general analog computer in this study, a specially designed computer would be required to represent a system of a useful size. By using modern integrated circuits, such a computer could be designed easily and efficiently. Separate bus and transmission line modules could be designed to make interconnects simple and to tremendously reduce the size of the overall analog network.

The cost limitation will, no doubt, be the most difficult to avoid. Analog devices compared to digital devices are expensive. Their prices have been decreasing during the past several years but at a much slower rate than the prices of digital devices. Basically, because of the high demand, one could expect the price of the analog computer to increase relative to the digital computer. For contingency studies, extra devices must be added to the analog network to provide for cases where transmission lines are removed or buses are split. All of these extra devices increase the cost of the hybrid system.

Another important limitation of the proposed hybrid system is that it is a computing system that must be dedicated to the operation of the hybrid load flow. This means that it cannot be easily used for accounting, bookkeeping or any other purpose. The lack of adaptability also increases its cost.

The basic question that must be asked when determining if the hybrid load flow system is worthwhile is: Does the need to have a fast solution to the load flow justify the added expense of the system? Although the hybrid load flow does appear to be much faster than any digital program, its high cost may hinder its acceptance by the power industry.

4.2 SUGGESTIONS FOR FURTHER RESEARCH

The purpose of this section is to present recommendations which developed from the researcher's experience with the hybrid load flow.

First, it is recommended that the economic dispatch program using the hybrid load flow be completed. This researcher believes that the solution of this problem may be determined much faster than by using totally digital method. The algorithm for the solution to the economic dispatch problem is clearly defined and the programming should be straightforward. The unique situation that the load flow uses an analog network is not fully exploited in this algorithm of solving the economic dispatch problem. This researcher believes that other optimization techniques may be developed for this system that can more efficiently solve both the economic dispatch and the more general optimal load flow problems. For example, if the cost function was programmed on the analog computer, the computer could also determine the derivatives of the function and easily locate the minimum.

Another area of study that would naturally evolve from this work would be to increase the size of the simulated system by increasing the size of the hybrid computer. This extension could involve some expense but it would verify the equations derived to determine the operating time. This change could also show any scaling or stability problems which did not appear in smaller simulations.

With the addition of nonlinear analog devices, the analog computer could also simulate the transient response of the power system along with the steady state response. With the use of analog multipliers, the loads could be represented as constant impedances and/or constant power. Similarly, the generators could have a representation that is either simple or complex. By making these changes, there would be two benefits:

1) The hybrid load flow would produce the transient effects of many types of disruptions. With this type of simulation a systems operator could see the effect of a disruption before it is actually produced and, as an example, rapidly determine the best switching sequence of changes in the power system.

2) The hybrid load flow would no longer need to be iterative but would continuously determine the solution. This would greatly increase the solution speed.

All of these advantages do not come without added costs. The additional devices needed for a transient simulation are expensive. The reason for going to an iterative solution of the hybrid load flow is to avoid the extra cost of these devices. Nevertheless, creating the hybrid load flow to simulate transient effects would greatly increase the applicability of the system.

Finally, one further area of study for which the hybrid load flow would appear to be a natural candidate is state estimation. The system could be easily designed to accept on-line data from the power system.

Historically, there have been two major problems with an on-line state estimator. These include the problem of developing an algorithm fast enough to be useful and difficulty with noisy data. The hybrid load flow naturally tends to eliminate these problems because the solutions are fast and the integrators in the analog network act as a filter for the data.

From the recommendation for further study mentioned above, it becomes apparent that more areas of new research have been presented than solved. This study has shown that the hybrid load flow is indeed a powerful tool for the utility company. But it also appears that its full potential has not yet been realized.

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APPLICATIONS OF LOAD FLOW BY HYBRID COMPUTER

by

David Lee McMillan

(ABSTRACT)

The purpose of this study was to investigate the usefulness and practicality of the hybrid load flow program. After the load flow program was defined, the desirability for rapid solution times in certain applications was explained.

An analog model of an electric power system was developed. This model included representations of transmission lines, buses, loads and generations. When the hybrid load flow was implemented, the results indicated that the algorithm was very useful in terms of speed and accuracy.

An algorithm for determining the impedance matrix of the power system network was developed using the hybrid computer. When implemented, it proved helpful in improving the accuracy of the hybrid load flow. Application of the hybrid computer for use in an optimal load flow problem was also investigated. An algorithm for the economic dispatch problem was developed.

Finally, conclusions were made about the applicability of the hybrid load flow to the electric power industry and recommendations were presented for further research.