209

DIGITAL COMPUTERS IN POWER SYSTEMS ANALYSIS

159

by

SADIQ A. SHARIFF

B. S. E. E., University of Myaore,
Bangalore, India, 1956

A MASTER'S REPORT

submitted in partiel fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansaa

1965

Approved by:

Melvin C. Cottom
Major Professaor

TABLE OF CONTENTS

INTRODUCTION

In these days of "competition" power industry is not free from the problems of optimum generation, transmission, distribution, and other cost problems. The more the demand for power, the more are the problems of "improved production economy" and "reassignment of technical personnel". Time is another very important factor to be considered. Many utilities have started the use of computers for on-line jobs for better system performance, and at the same time to free the technical staff to concentrate on more important problems involving the power of the human brain.

Computers may be used directly to obtain automatic economic operation of a power pool formed by several areas, if the several areas are considered as one. In this application the net interchange of each area is not directly controlled, but results from the scheduling of the pool generation to obtain equal incremental cost of delivered power for the pool. It is possible to use individual area computer controllers for the purpose of automatic economic operation of the power pool formed by the areas. The use of this decentralized approach of area control offers the following advantages:

1. Reduction in telemetering channel requirements.
2. Use of smaller decentralized computer controllers.
3. Ready availability of information for accounting between areas.
4. Calculation of economic interchange between areas.

5. Calculation of incremental costs of wheeling losses.

6. Calculation of flow over individual tie lines.

Computers can also be used in system design, extension of existing systems, study of system reliability problems, grounding, and many other problems. In the following discussione use of digital computers in some of these ereas has been brought out.

PERFORMANCE EQUATIONS OF POWER SYSTEMS

Introduction

An engineer should be well versed with the steady-state and dynamic performance of interconnected systems as these factore are influenced by speed governing system characteristice and supplementary controllers. Study of this mathematical analysie leads to bettar handling of problems on digital computers.

Fundamental Definitions

a. <u>Speed Governing System</u>. This system includes the speed governor, the speed-control mechanism, and the governor-controlled valves. A pictorial representation of this is shown in Fig. 1.

b. <u>Speed Governor</u>. Such of the elements as are directly responsive to speed and which position or influence the action of other elements of the speed-governing system are included in the speed governor.

c. Speed-control Mechanism. All equipment such as relays, servomotors, pressure or power amplifying devices, levers and linkages between the speed governor and the governor-controlled valves are included in the speed-control mechanism.

d. The Governor-controlled Valves. The valves that control the energy input to the turbine and that are normally actuated by the speed governor through the medium of the speed-control mechanism are referred to as the governor-controlled valves.

e. The Speed Changer. This is a device employed in adjusting the speed-governing system so as to enable the change of speed or power output of the turbine in operation.

Figure 2 shows an isochronous governor. In this case the valve mechanism comes to rest only when the speed returns to its initial value.

Figure 3 is the same as Fig. 2 except that there is an additional lever. Due to this lever addition a finite value of steady-state speed regulation is obtained.

The per unit steady-state speed regulation for a given speed-changer position is given by per unit steady-state speed regulation = $\frac{N_O - N}{N_R}$, where

N_O = speed at no load

N = speed at rated load

N_R = rated speed.

Figure 4 shows a schematic diagram of an isochronous governor

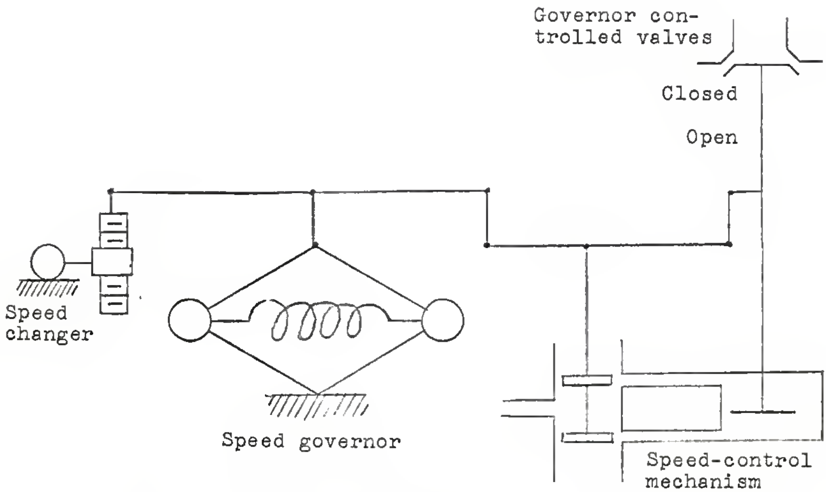


Fig. 1. Schematic representation of speed-governing system.

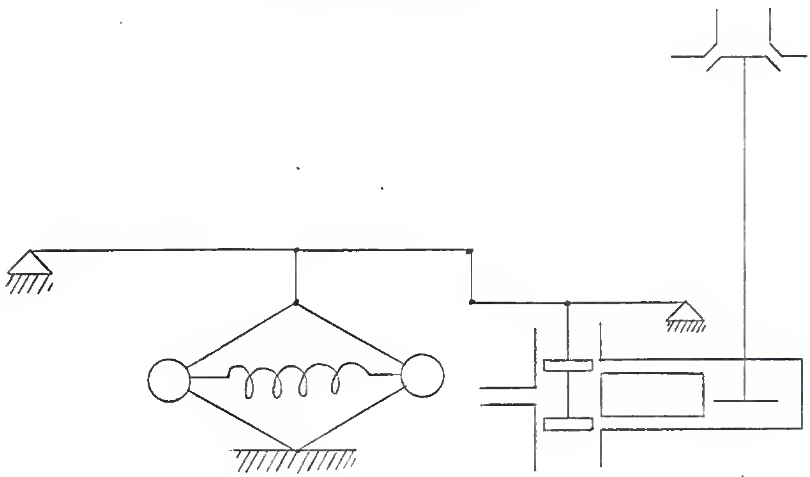


Fig. 2. Schematic representation of isochronous governor.

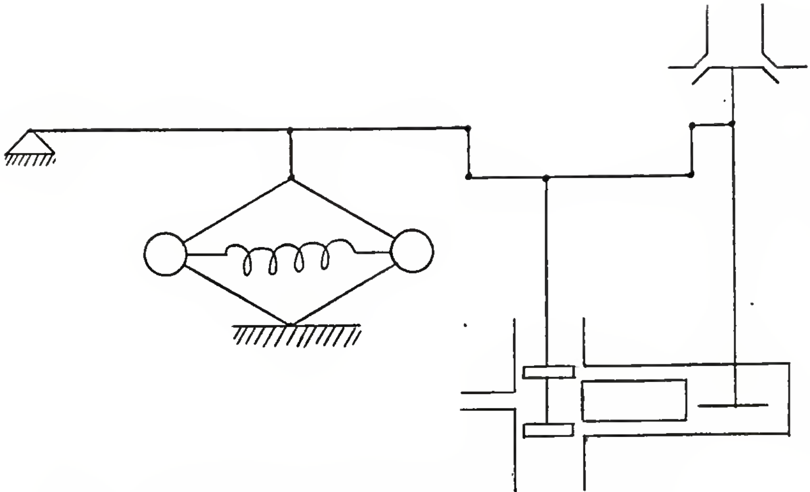


Fig. 3. Addition of feedback to provide steady-state ragulation.

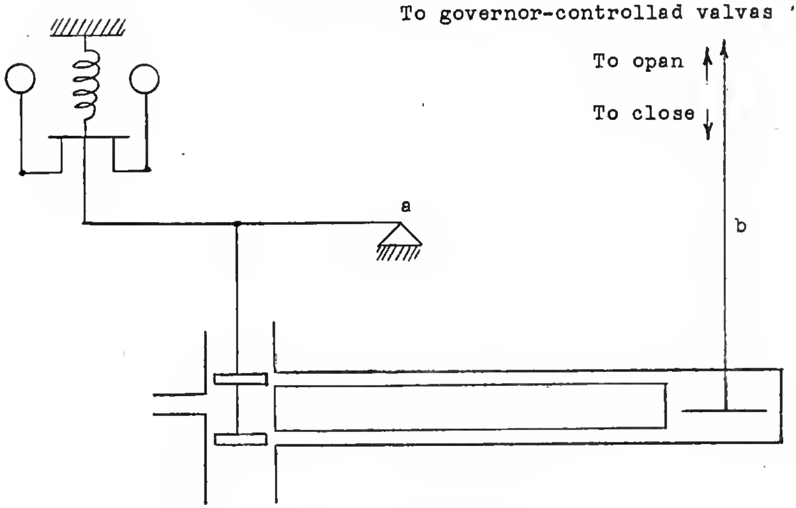


Fig. 4. Schamatic raprasantation of isochronous governor.

which haa already been discussed. The addition of feedback motion from points (a) to (b) provides a ateady-atate regulation. Adding a aeparate needle value and a lever arrangement, aa ahown in Fig. 5, introducea temporary droop compenaation. To start with, the feedback motion is transmitted by the compenaating dashpot aasembly. Thia produces action aimilar to that obtained with a aolid lever. After some time has elapsed, the centering apring restores the receiving poaition to its final position, and the ayatem reaches a steady-state speed with zero ateady-state regulation.

However, if we have the case of parallel operation, permanent apeed droop ia necessary. The feedback lever shown in Fig. 6 provides a finite value of eteady-state regulation. If desired, a speed-level changer aignal may be introduced, aa shown in Fig. 7.

Performance Equations and Block Diagram

Case (a), Isolated Area. The block diagram shown in Fig. 8 represents an isolated area. Tha inputa to the speed-governing ayatem, shown in Fig. 8, are the apeed signal and the apeed-changer poaition. Theee eignals call for changes in the governor-controlled valve position which will change the input to the turbine. The change in input to the turbine cauaea a change in turbina torque, and the characteristica of the power system determine the change in aystem apeed.

The following analysis pertaina to the reaponse of tha

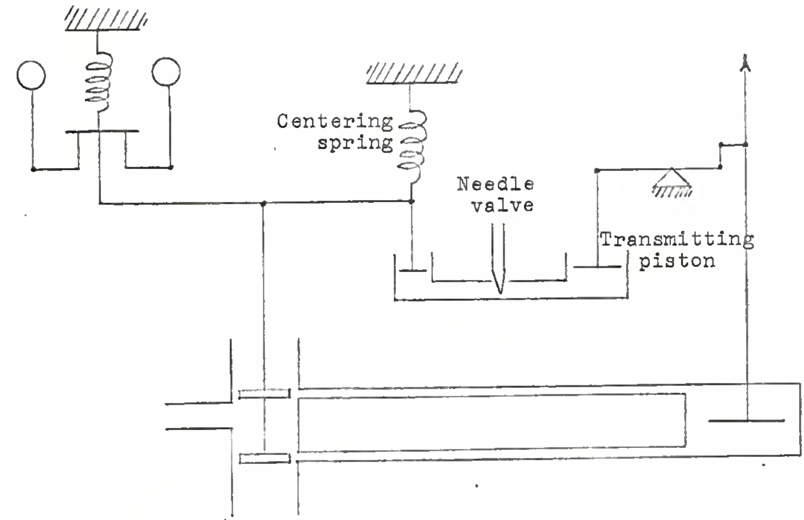


Fig. 5. Addition of temporary droop compensation.

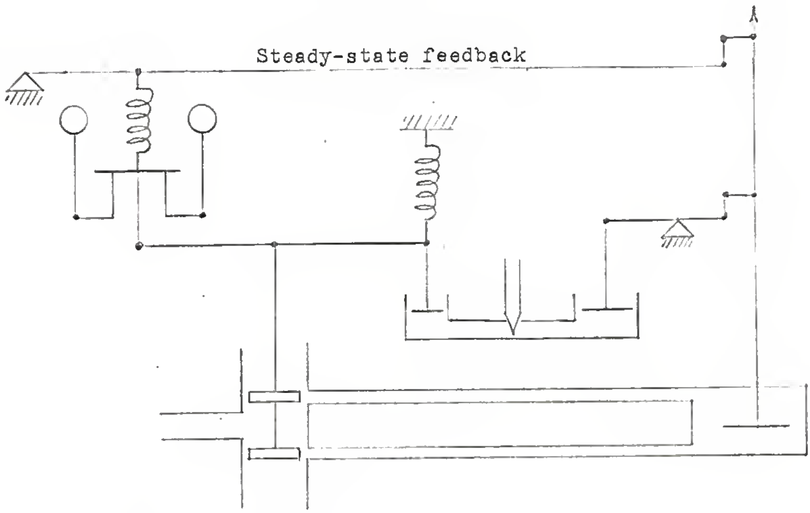


Fig. 6. Addition of steady-state feedback.

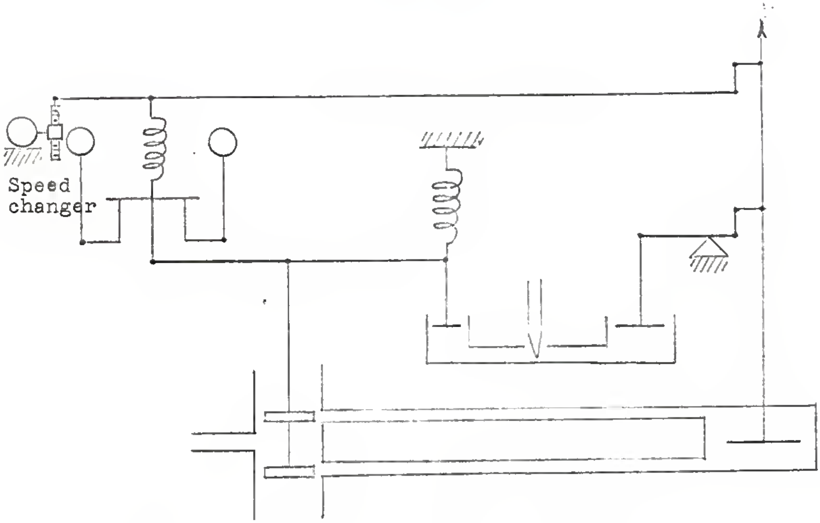


Fig. 7. Addition of speed-load changer.

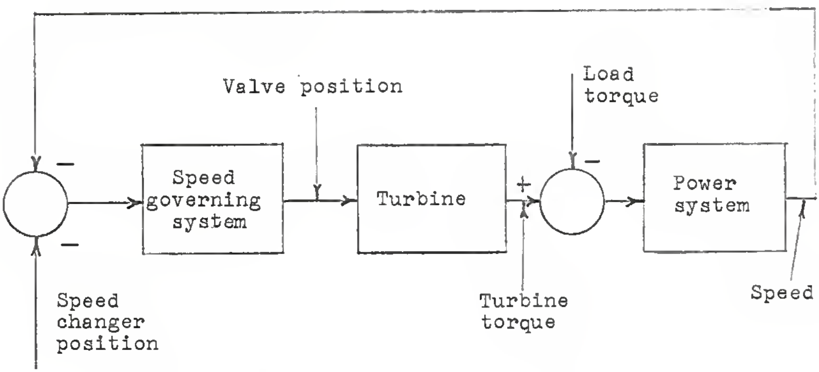


Fig. 8. Block-diagram representation of isolated area.

eystem for small chenges. The following equetion is obtained by summing up the torques acting upon the inertia of the power aystem.

$$Mp^2\delta + Dp\delta = \Delta p - \Delta L \qquad (1)$$

where M = effective rotery inertia of aree

p = differential operator d/dt (t = time)

δ = deviation of rotery inertia from initial electrical angular poaition

D = damping torque coefficient (thet ie, the inherent net change of load end prime mover torque with frequency)

Δp = component of change in prime mover torque produced by governor-controlled velve motion

ΔL = load change in aree (eside from inherent chenge with frequency)

pδ = deviation from normal frequency or speed time and engles are in radians unleaa apecified otherwise.

Solving Eq. (1) for pδ, one obtaina

$$p\delta = \frac{1}{mp + D} (\Delta p - \Delta L)$$

Thia relationship ia illustrated achematically in the right-hand block of Fig. 9.

In thia caae M ia directly related to the H constant used in etability studiee (Vol. 2 of <u>Power Syetem Stability</u>, by S. B. Crary).

$$M = 4\pi fH$$

where f = frequency in cyclee per second

$$H = \frac{0.231 \times WR^2 \times rpm^2 \times 10^{-6}}{kva(beee)}$$

The quentity D ie given by

$$D = \frac{\partial(\text{load torque})}{\partial p\delta} - \frac{\partial(\text{turbine torque})}{\partial p\delta}$$

where $\frac{\partial(\text{turbine torque})}{\partial p\delta}$ is the change in turbine torque with speed with constent velve position. This quentity cen be coneidered ep-proximetely equel but oppoeite in eign to the steedy-etete prime mover torque.

end $\frac{\partial(\text{loed torque})}{\partial p\delta}$ is the component of the demping torque developed by induction end synchronous motors with their mechenical eheft loeds.

Figure 9 shows the block diegrem for en ieoleted eree with e non-reheat type of turbine. In thie figure $\Delta p = \frac{1}{T_s p + 1} \Delta p_v$ where Δp_v = chenge in velve poeition. However, if the tur-binee ere of the reheet type, we heve

$$\Delta p = \left(\frac{cT_R p + 1}{T_R p + 1}\right) \left(\frac{1}{T_s p + 1}\right) \Delta p_v$$

where T_R = time leg essocieted with reheeter

c = proportion of torque developed in high-preesure element.

The response of e epeed governor ie given by

$$\Delta p_v = \frac{-1}{(T_G p + 1)} (1/R\ p\delta + \Delta p')$$

where T_G = governor time lag

R = speed regulation

$\Delta p'$ = change in speed changer position.

Now considering the case of a hydroelectric turbine, there is a large inertia of water (water is used as a source of energy in hydro turbines), and this larger inertia is responsible for the greater time lag in the response of prime mover torque to a change in gate position compared with the response of a steam turbine. It should be remembered that all hydroelectric turbines have the property of their torque initially tending to change in a direction opposite to that finally produced.

The transfer function of a hydro turbine is approximated as follows.

$$\Delta p = \frac{-T_\omega p + 1}{(T_\omega/2)p + 1} \Delta p_v$$

where T_ω = nominal starting time of water in penstock in seconds

$$= \frac{\mu L}{gH}$$

L = length of pipe in feet

μ = water velocity, feet per second

H = pressure head, feet

g = acceleration of gravity, feet per second^2.

The value of T_ω can vary from one-half to four seconds, depending on L, μ, H, G. Δp_v in the case of hydro turbines is the change in gate position.

The following equation gives approximate hydro turbine speed governor response.

$$\Delta p_v = -\left(\frac{1}{T_G p + 1}\right)\left(\frac{T_R p + 1}{(r/R)T_R p + 1)}\right)((1/R)p\delta + \Delta p')$$

the parameters having the following approximate values.

R = steady-state speed regulation = 0.05 to 0.167

r = transient speed regulation = 0.3 to 1.2

T_R = time constant associated with temporary droop compensation = 0.5 to 64 seconds

T_G = governor time constant = 0.60 second

Figure 10 represents a block diagram of an isolated area with transfer functions for a hydro turbine and governor.

In the approximate hydro turbine speed governor response equation, consider the term $1/R\left(\frac{T_R p + 1}{(r/R)T_R p + 1}\right)$. For a step change, "p" becomes infinity and the term

$$1/R\left(\frac{T_R p + 1}{(r/R)T_R p + 1}\right) = 1/R\left(\frac{T_R + (1/p)}{(r/R)T_R + (1/p)}\right)$$

$$= \frac{\left[(1/R)T_R + (1/\infty)\right]}{\left[(r/R)T_R + (1/\infty)\right]} = 1/r$$

Thus initially, because of temporary droop compensation, the regulation appears to be "r". However, in the steady state, when p = 0, one gets

$$1/R\left(\frac{T_R p + 1}{(r/R)T_R p + 1}\right) = 1/R$$

Thus in the steady state there is a regulation of R.

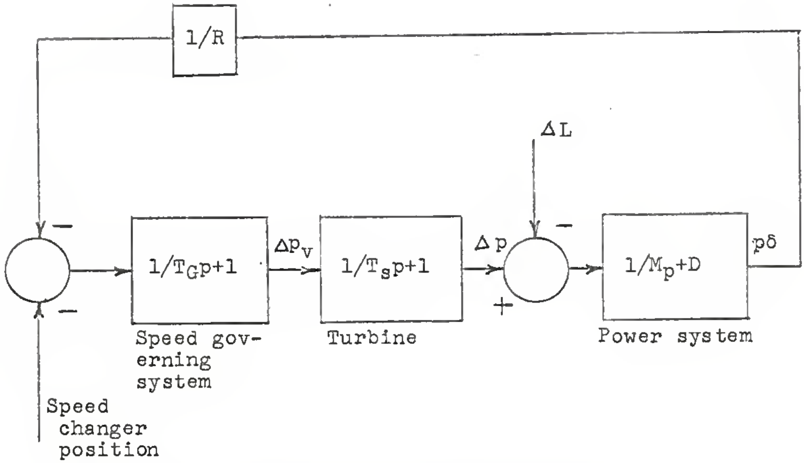


Fig. 9. Block diagram of isolated area with illustrative transfer function.

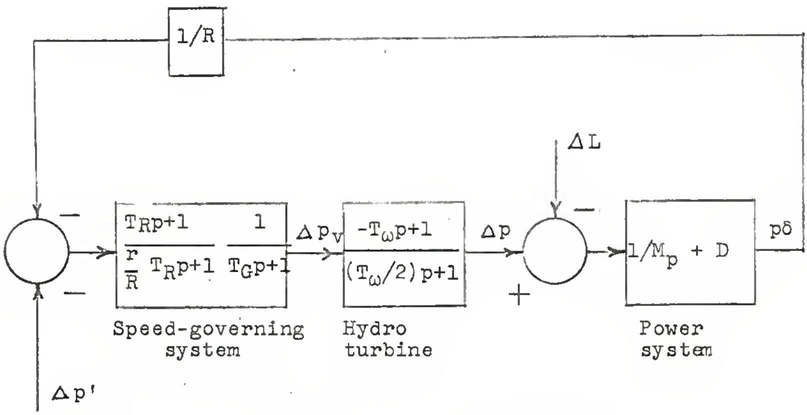


Fig. 10. Block diagram of isolated area with transfer functions for hydro turbine.

DIGITAL COMPUTER DISPATCHING SYSTEMS

Introduction

Since 1960 repid progress hee been mede in the epplicetion of digitel computere to reel-time probleme of power system operetion. Before 1960 the digitel computers were used as scientific toole in various off-line studies of syetem theories. At thet time on-line control functions were eccomplished by enelog computer control errengements. However, from 1960 onwerd e number of papers heve been presented furniehing the deteile of how e digitel computer cen be used on e ehered-time beeis, thus ellowing one computer to be used for solving e lerge veriety of system opereting problems in both e etudy end on-line mode.

Requirements

The objective of the eystem operetion is to match eyetem generetion to eyetem load and to meintein eufficient genereting reeerves to meintein e high degree of system continuity. Thue in eupply of power this enteile the need of meinteining tie-line schedules, end keeping continuous end integreted frequency within permissible limite. The outer important requirement of eystem operetion ie to generete and deliver power et lowest precticel cost.

On the beeie of theee coneideratione the problem of system operation ie divided into three cetegories.

1. Operations planning
2. Operations control
3. Operations accounting.

Operations Planning

This involves calculations necessary to reach decisions concerning the next hour, day, week, or month of system operation. In the present-day world this area of system operation is becoming of greater importance due to the increasing numbers of interconnections and the opportunities for cost savings through interchanges with neighboring companies. Some of the important areas involved in this study are:

1. Load forecasting
2. Maintenance scheduling
3. Spinning reserve determination
4. Unit commitment scheduling
5. Evaluation of future interconnection transactions
6. Selection of fuels
7. Hydroelectric coordination studies.

While dealing with items 2 to 7, load forecasts are necessary to be used as input information for making any required evaluation. A number of statistical methods can be used to improve the accuracy of such forecasts. In the cost of maintenance scheduling, there should be a planned coordination between the outages of transmission and generation elements. These calculations require the details of cost of production and risk levels incurred by various maintenance strategies. Spinning reserve determination and unit commitment scheduling are concerned with the total cost of production for various units in service and the evaluation of risk in system operation. There are a lot of possibilities of savings in systems operations by economy interchanges with other companies. Sometimes selection of fuels may involve complex system evaluations. In the case of hydroelectric operations, studies involve determination of reservoir draw-down curves, water forecasting, and the evaluation of the worth of water.

Operations Control

All problems requiring instant-by-instant determination on a real-time basis are involved in operations control. Some examples of these are:

1. Load and frequency control
2. Economic allocation of generation
3. Kilovar supply scheduling
4. Remote supervision of switching stations, substations, and automatic hydro stations.

In load frequency control, total system generation is maintained at a magnitude such that a desired frequency and net interchange is held. Economic allocation of generation specifies and maintains the output of each of the generating sources at a value which gives minimum system production cost. Some of the other things that could be established are continuous scheduling of kilovar supply or voltage levels, as well as remote supervision of the various devices like remote supervision of switching stations, substations, and automatic hydro stations.

Operations Accounting

These calculations involve after-the-fact evaluations such as:

1. Interconnection billing
2. System production statistics
3. Unit production statistics
4. Assessment of quality of unit and system performance.

In the above the following steps have to be performed:

1. Collection of data
2. Performance of various arithmetical and logical operations on these data
3. The preparation of statements.

Many engineers are trying to use the modern technique of digital computation and automatic data collection in solving the problems of "operations planning", "control", and "accounting". A process control computer can be used to get the integrated solution of these problems. Shown in Fig. 11 is an integrated dispatch, data collection, and reporting system. This single complex is used to solve the above problems.

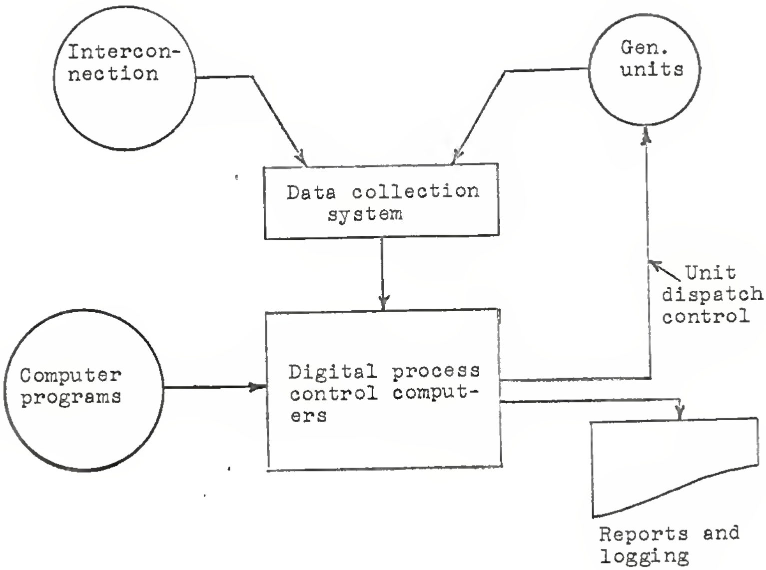


Fig. 11. Integrated dispatch, data collection,
and reporting system.

Advantages of Digital Computer Control

Solutions of problems of system operation by using an integrated dispatch computer result in significant operating benefits. Some of these advantages are:

1. Fuel saving
2. Manpower saving
3. Improvements in system reliability
4. Saving in capital equipment expenditures for elements of the power system.

By using the integrated digital dispatch computer, savings in production costs over manual methods are obtained, since effectively continuous control according to the principle of equal incremental cost of delivered power may be achieved. By the use of the digital computer, maintenance and unit commitment scheduling can be examined more critically. If there is a grid system, where the neighboring companies are exchanging the power, then computers can maintain a close surveillance and accurate calculation of interchange billings, and correct interchange accounting. As a matter of fact, the computer can be used as a tool in conducting studies about the various possible operating conditions and determining the best interchange and contractual arrangements. As the grid system becomes larger and larger, more data has to be collected and processed. Man is bound to commit error when the operations are enormously large, whereas computers can do this job much faster and more accurately by automatically collecting and processing the data, and supplying the information for decision making.

The most important thing of primary concern to a power engineer is the reliability of system operation. The computer is a device which enables the operator to get an accurate indication of system reliability as well as forecasted values to help him determine the reserve requirements. Accurate forecasting by computer helps in minimizing the spinning reserve requirements. The computer can also indicate the approaching troublesome areas of operation by alarm or in some cases it takes correcting action. Thus by use of a computer, the existing plants, transmission and distribution systems can be used more effectively, thus reducing new investment on generation, transmission, and distribution.

Digital Computer for Dispatching

The block diagram of Fig. 12 shows a general arrangement of a system designed to meet the requirements of an economic dispatch application. The major components of this are the analog input section, the digital fast-scan input section, the dispatcher's console, the central processor, the programmer's console, the peripheral output section, and the control output section. The functions of various components are as follows.

a. Analog Input Section. This section selects under program control the particular inputs such as telemetered generation and tie flows. This is accomplished by the analog scanner which consists of a group of mercury-wetted relays that are

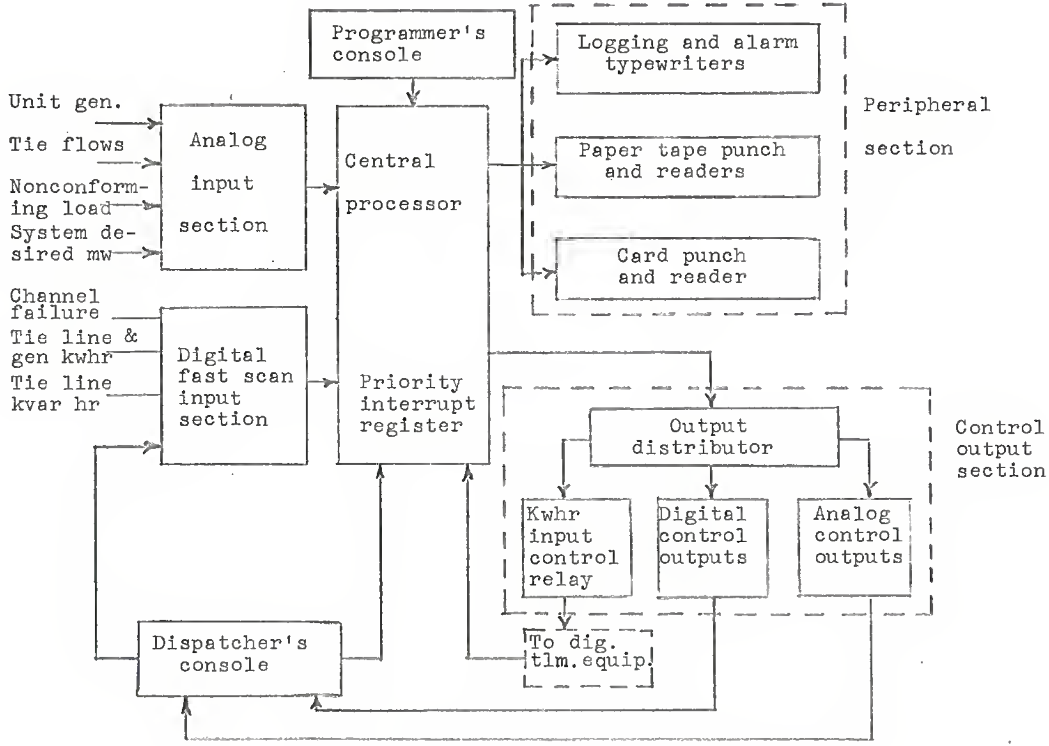


Fig. 12. Block diagram of a computer system.

individually selected using special commands that are part of the program structure. Signal conditioning circuits, low-level amplifiers, and an analog-to-digital converter allows the system to select a broad range of attenuation and gain settings for measurements which can extend from 10 millivolts to 256 volts. These measurements are converted into a 12-bit binary number, and high-speed operation permits a scan rate up to 150 points per second. The equipment includes adequate signal filtering for each analog input to eliminate electrical noise and interference.

b. <u>Digital Fast-scan Input Section</u>. This reads all digital inputs like:

1. Digital telemetered quantities of integrated kwh from tie points and generators
2. Unit power system and study information from the dispatcher's console
3. Indication of channel failure.

The above information passes into the computer from the digital fast-scan section in which the inputs are grouped into words, with each word consisting of 16 bits. The digital fast-scan equipment is capable of scanning at a rate of 300,000 inputs per second. Signal conditioning filters are used for all digital inputs.

c. <u>Central Processor</u>. This is the most important component of the computer. It has memory storage, an arithmetic section, and a control section. This processor is provided with a core memory, which serves as a main memory. There is also a rotating magnatic drum which servaa ae e back-up atorage memory. Core mamory in blocks of 4000, 8000, end 16,000 words ie available, wharaas a bulk storaga drum mamory up to 114,000 words ie evailabla. Drum-to-core trensfer cen occur by logic and arithmetic operations.

d. Paripharal Input end Output Devicea. Theae devices include logging and alarm typewritere, paper tape punch end readere, end card punch and readara. These input-output devicee ara complataly buffared, end thase buffers parmit ovarlapping of various computer functions without loss of time or facility. Arithmetic, making logical dacisions, end shifting can ba performed simultaneously by thase input and output davices.

a. Program and Maintenance Console. This providaa an indicating control center for the programmer end maintenanca enginaar.

f. Custom-dasigned Dispatcher's Consola. This ie en additional console which is providad in which the legand on all awitchas and panala ie given in diapatchar's languaga. The control arrangemant of the dispatcher'a consola ie dasignad to permit quick and eaay control end allowa tha operetor to exerciae complata command over the entira dispatch ayetem. At the top-plata asaembly are locatad auch panals aa maetar araa control panel, interchenge aettar panel, genaration panel, program aalect panal, diaplay panal, data entry panal, and apaciel etudiaa panel.

Digital computere ehould only ba ueed to perform thoae taska which ere bast suitad to digitel techniquea end aolution.

A hybrid dispatch system using both digital and analog techniques compared to an all-digital approach will make available more time of the digital dispatch computer for important system operating problems. Analog elements are used to provida continuoua load frequency control and economic allocation of generation. The digital computer on a time-shared basis periodically sets the analog elements in addition to undertaking many other problems of syatem operation.

Figure 13 illustrates a simplified hybrid diapatch aystem. For this diagram the upper portion illustretes the analog computer system and the lower half illustrates the digital dispatch computer system.

The input to this hybrid eystem in Fig. 13 ie the summation of frequency bias signal and the net tie-line flow. Thia is termed "area control". This "area control" is then combined with the total unit requirement, resulting in a system desired m.w. Thie syatem desired m.w. ia one of the inpute to the process computer. In addition to thie, the other inputs to the digital procaaa computer are unit m.w. generation, tie-line m.w. flows, nonconforming m.w. loade, and integreted readings of kwh. System desired m.w., the tie-line flows, and nonconforming loads are necessery inputs to the digital computer for the periodic determination of an economic dispatch, including transmission losses. Unit generation is used as an input for checking purposes by the digital processor. Now the digital computer sets for each unit the analog circuitry which develops the unit desired generation on a continuous basis between

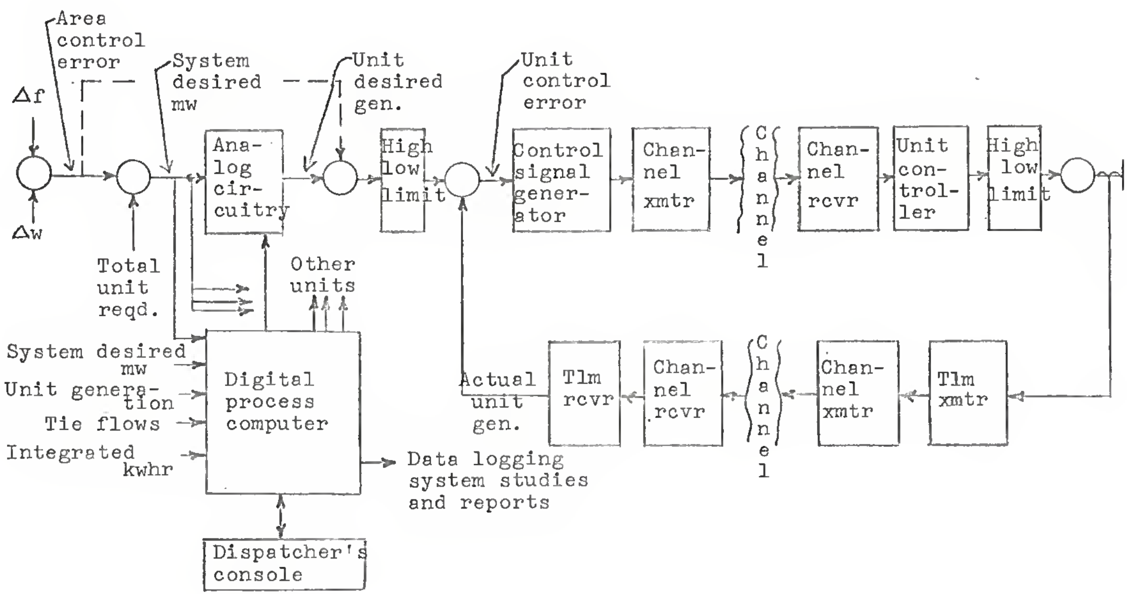


Fig. 13. Hybrid dispatch system.

digital dispatches. This results in continuous load frequency control and economic allocation.

The next step is the check of unit desired generation for high-low limits, as set by the system operator. The desired unit loading is kept within the pre-set high-low limits, and then compared with the actual unit telemetered generation. The difference between desired and actual unit generation forms the unit control error for that unit, and this is then fed into the control signal generator.

The control signal generator is specifically adjusted to take into account the response characteristics of the particular generating unit. The control signal generator develops impulses which are transmitted as shown in Fig. 13, to bring actual unit generation into balance with unit desired generation.

Now the control signal from the channel receiver is fed into the unit controller. The output of the unit is again checked for high-low limits, as set by the plant operator, before the control signal acts on the governor synchronizing motor.

The advantage of using an analog computer is that it provides continuous corrective action to satisfy area regulation requirements on an economic basis as determined by the digital data processor. Another important advantage is that units are kept on schedule without overshoot, regardless of area control error. The dotted line in the figure (assist action) provides for improved system dynamic performance.

This entire control function is made safer in case of failure of the computer; that is, if the computer goes out of service, then economic allocation of generation can be easily achieved through semiautomatic operation of the dispatch system by manual setting of the analog circuitry for each generating unit.

In the following paragraphs we shall study the digital approach to the above discussed problem, without the use of an analog computer.

Digital Dispatch System

It is possible to incorporate all of the analog computer equipment within the digital computer. One such arrangement is shown in Fig. 14. Area control error is one input to the digital computer along with actual unit generation of each individual generator, tie-line flows, nonconforming loads, and the integrated kwh, as required. The summation of the individual unit generations and area control error forms the total desired generation at any instant of time. This information provides the basis for rapid digital computer determination of unit desired generation for load frequency control and economic allocation. The coefficients for this rapid digital computation are supplied by a periodic complete economic dispatch calculation, which calculations require the tie-line flows and nonconforming loads as inputs. As in the hybrid system, the unit control signal is proportional to each unit control error and is provided with appropriate limits. This unit control signal is transmitted by the channel equipment to the unit controller. Unit high-low limits

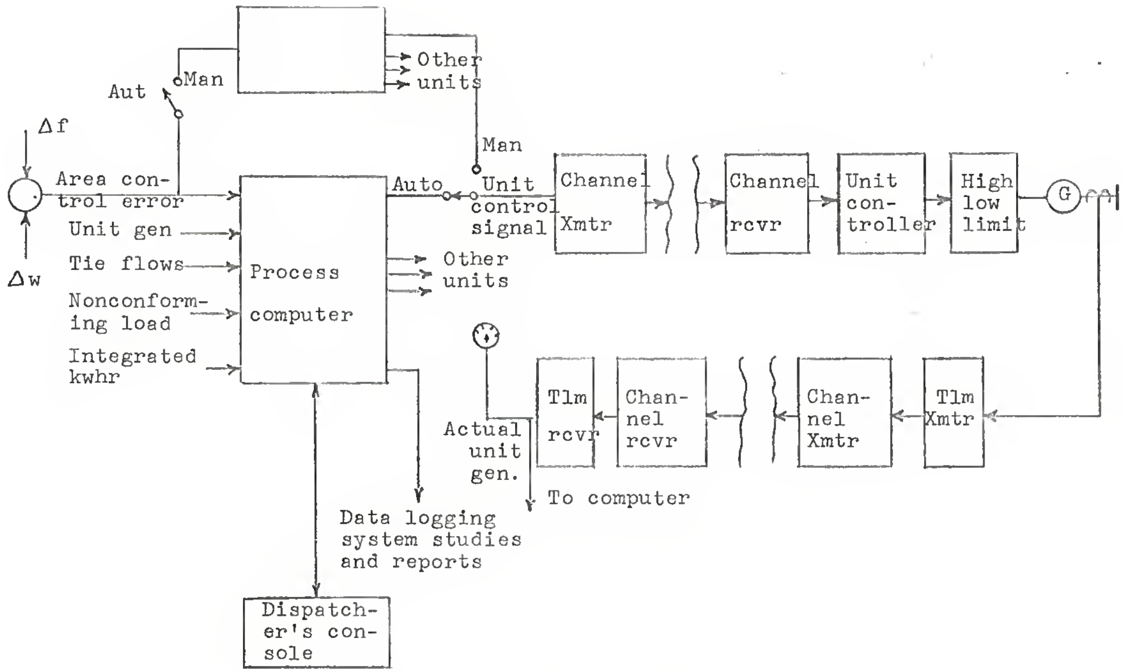


Fig. 14. Typical digital dispatch system.

ara providad within tha computar. Station aquipmant is aimilar to tha hybrid aystam. In tha casa of a digital computar going out of order, tha ayatam can ba switchad onto a common araa control arror aignal ganarator. Thia function provides the ability to regulata and corract araa control arror, without the ability to individually diapatch ganerating units on an aconomic basis.

It is usual to usa a digital computar baing uaad for on-lina joba for aolving othar problams. Howevar, it muat ba notad that a computar for on-lina jobs lika load-fraquenoy control or regulating, will hava laaa fraa tima availabla for solving other problama. Dapanding upon tha numbar of units to be controlled, and tha spaad and capability of the particular oomputar, as much aa 25 par cant of tha total availabla oomputar time may be raquired for tha function of load-fraquency control with aconomic allocation.

Tha following factors muat be considarad with ragard to salaction of digital or hybrid syatems.

1. Whichevar typa of computar ia used, tha oparation of both aystama ia aimilar. If the digital computar of tha hybrid ayatam ia out of sarvica, still tha analog circuitry offars improvad flaxibility of oparation for continuoua economic allocation of generation. Any changas in the genaration can be taken cara of by manually raaatting tha circuitry.

2. Mamory. An incraasa in mamory of tha digital computar bacomaa necasaary as a result of placing tha load-fraquency control function within tha computar.

3. In tha casa of e digital diepatch systam the dispatching office and enalog functions of tha hybrid system ara incorporated and a raduction in capital outlay occure.

4. The digitel computar offers increaead computar tima end decreaead aquipment invastment es compered with the hybrid systam. Thie is a vary important qualification which a digital computar has ovar a hybrid system.

Data Collection

Analog talematering aquipment is usually furnished for those readings which are deeired continuously, whether they are indicatad or recordad. For exampla, station generation or tialina interchange in magewatts, which ere genarelly recordad in tha load dispatchar's office, is dasired continuously, thus calling for the usa of snalog telematering equipmant. The abova information is elso used in dispatch equipmant as a beeis for edjusting genaration to maat araa ragulating raquiraments on a continuous basis.

Billing data is basad on energy flow (kilowett hours). Most utilitiee base their billing on anargy ueed during a short period, like thirty minutes or an hour. As e matter of fact, this forms the basis of tha contract.

Special digital telamatering equipmant has baan deeigned for the purposa of accapting and transmitting kilowatt hour readings, showing actual enargy transfarred in or out of a utility system. This typa of equipment providas 100 par cant accurate information, thus helping to minimize the effects of channel outages and to provide economical utilization of channel facilities.

Figure 15 shows a data collection system. In this system each remote metering point is provided with a digital telemeter transmitter and channel equipment for two-way communication with corresponding channel equipment at the computer location. The digital telemeter transmitter at the remote location serves to count impulses from the kilowatt-hour meters and to store and transmit data upon command. The data is held in temporary storage for transmission, while the counter continues to accumulate impulses. An automatic priority interrupt feature is located in the system. The digital telemeter receiver, by means of this automatic priority interrupt feature, initiates transfer of the received data through the digital fast-scan section to the computer.

By sending a "store" command from the computer to each remote station via a three-frequency channel transmitter, simultaneous storage of data at all transmitters is accomplished. After receiving this command, counts are stored at the remote location. The computer then proceeds to interrogate each remote station individually by shifting the outgoing channel transmitter. Then the remote data is transmitted to the digital receiver at the computer location by modulating the return two-frequency channel transmitter with a series of long and short pulses. Next, checks are performed on the validity of the data, and then the data is entered into the computer by means of the

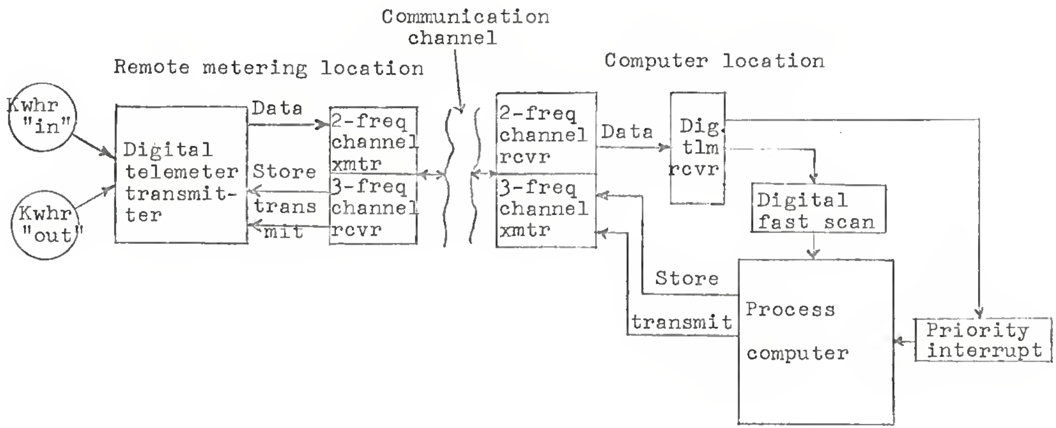


Fig. 15. Data collection system.

automatic priority interrupt for logging and processing.

Operation of Digital Computer Dispatching System

Let us examine a typical hour's operation of a typical dispatching system. A complete economic dispatch is performed every three minutes. In between such calculations, computer-control arrangement insures a continuous and accurate economic allocation of generation. At the beginning of each hour the kwh readings are automatically collected and stored within the digital computer. These data together with other information in memory provides the basis for the determination of out-of-pocket costs for the previous hour's transaction. It is also possible to prepare during this time hourly system statistics for the last hour. Toward the end of the hour, the computer is used in a forecast mode to determine incremental and decremental costs for various possible interconnection transactions. The remaining free time may be used for various other problems of operations planning and accounting.

Figure 16 illustrates a dispatch system which logically links the automatic priority interrupt, the interrupt subroutines, the executive control program, and the functional programs. The functional programs are all the routines needed to perform the economic dispatch calculations; the routines to obtain the desired alarms, outputs, and displays; and the routine to undertake free-time functions such as those listed in Fig. 16.

The executive control program provides the actual time

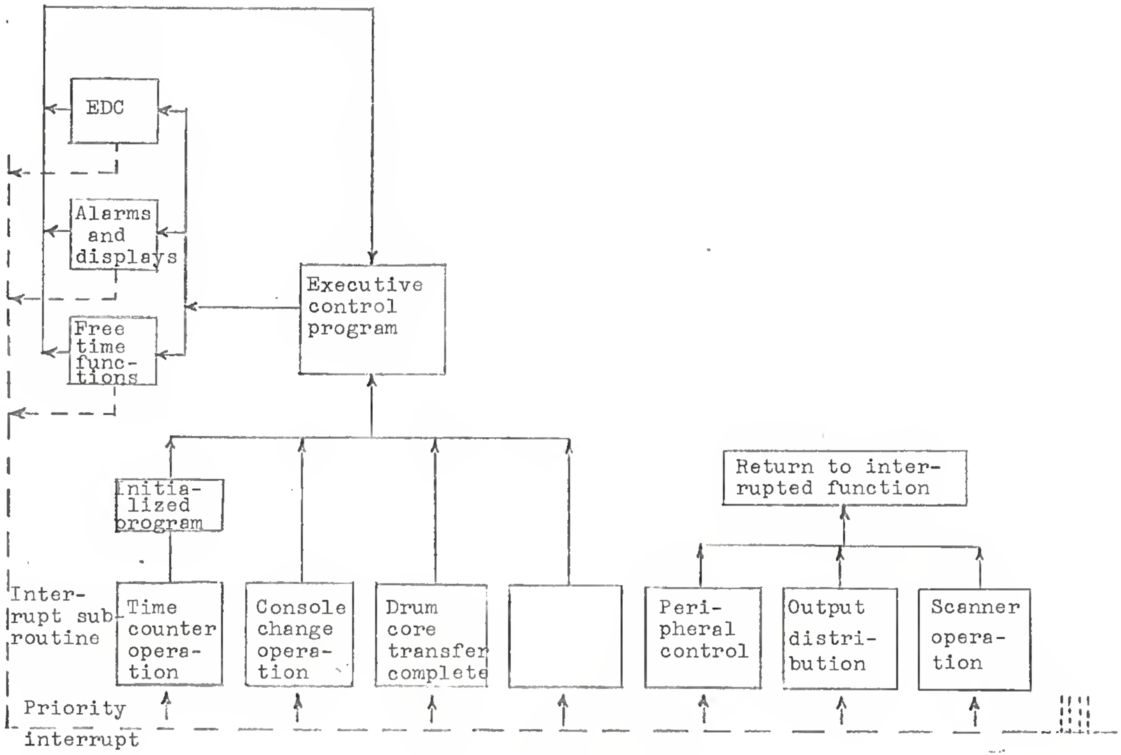


Fig. 16. System monitor.

scheduling of the functional programs, as indicated by the arrow leading from the executive control program to the functional programs. The arrow leading from the functional programs to the executive control program is the means to indicate completion of the corresponding functional program. The arrow from the interrupt subroutine indicates the path for the interrupt subroutines to call upon the functional programs.

System Research

The successful application of a computing control system depends to a large extent on the successful prediction of the dynamic performance of the entire system for various control and prime mover arrangements. Potentiality of digital control computer arrangements can be optimally exploited only by continuing efforts devoted to the development of new and improved theories of system operation. One unique quality of the digital computer is its amenability to incorporation of improved techniques as they are developed.

Careful study of dynamic performance of different control schemes and different operating conditions will facilitate an optimum design of digital dispatching computer arrangements. In Fig. 17 are shown basic system elements to be considered in such studies. The simulation must recognize the dynamic characteristics of the supplementary control as well as the dynamic characteristics of the prime mover and power system. Recognition must be given to the governor turbine lags, the inertia and

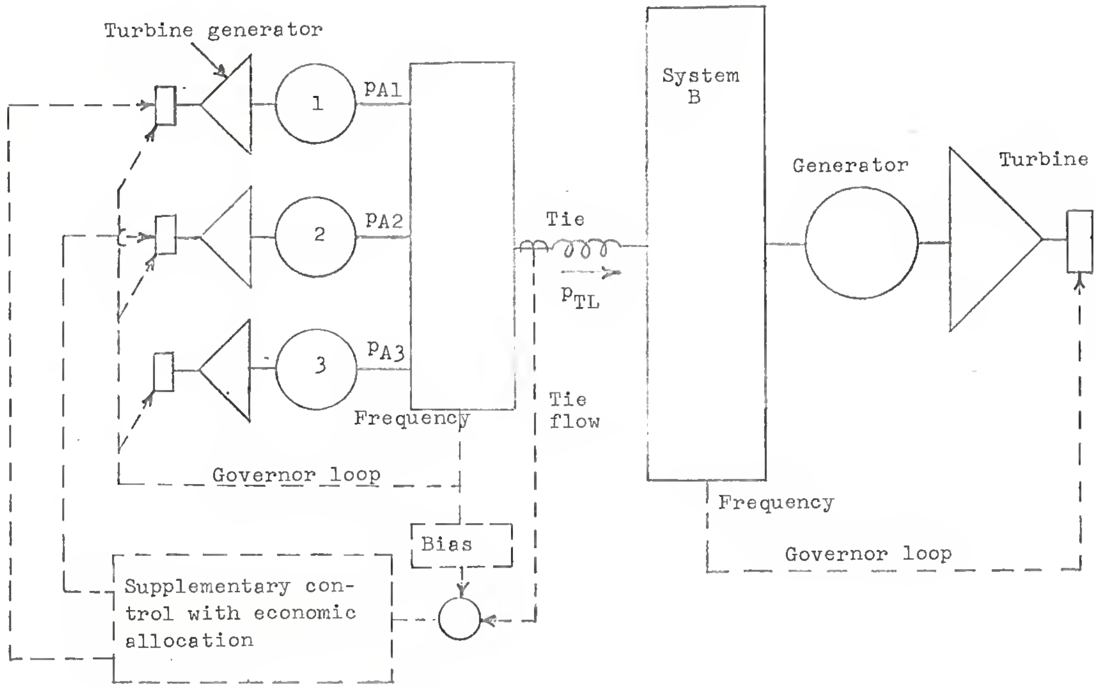


Fig. 17. Elements of simulation study.

damping constants, governor incremental regulation, and the synchronizing power coefficients between machines and between power systems. Account must also be taken of realistic transducer and transmission lags in the measurement of machine powers and area control error. The data sampling delay, as well as the nature of impulses formed by the control signal generators, also must be accurately simulated, performance comparison of hybrid and digital systems was a matter of study, and under this study both mandatory and permissive arrangements of each of these systems are compared.

In the mandatory system, as illustrated in Fig. 13, control action is implemented by impulsing each unit synchronizing motor in proportion to that generator's unit control error. In a permissive arrangement the impulses to the synchronizing motors are proportional to the area control error and economic allocation is accomplished by only allowing impulses to be transmitted to generating units in accordance with the sign of the unit control error. Several important conclusions of exhaustive studies conducted on both the hybrid and digital arrangements and both the permissive and mandatory controls have been indicated below.

The system dynamic performance for the digital dispatching system can be equivalent to that for the hybrid dispatching system by suitable design of the digital filtering, and by proper choice of sampling rate and means of stabilization.

In the case of the mandatory system versus the permissive system, the mandatory control system has the following advantages:

1. The units will follow economic loading more closely, resulting in reductions in fuel costs.

2. Continuous zero-threshold use of assist action is possible with significant improvement of the area's ability to follow load changes and consequently to minimize area control error while maintaining the units average loading at correct economic values. This would not be possible in the permissive case.

Hydro Thermal Optimization

Work has been undertaken recently in the field of hydro thermal coordination. In this case, constraints such as unit capabilities, forebay elevations, tailrace elevations, etc., should be recognized.

Related System Research

Many investigations relating to theories of system operation have been conducted recently. Computation of valve loop heat rates on multivalve turbines and a new method of scheduling based on dynamic programming have been presented by various authors. This work shows that recognition of valve throttling losses may be achieved by use of stepped incremental cost curves. These stepped curves may be much more easily handled by digital dispatch computers than by analog computer control arrangements, because of the problem involved with analog control stability.

Thus a number of utility companies faced with the problem of system expansion are beginning to realize the adventeges of digital and hybrid computers for on-line jobe as well as for system designs.

Teble 1. Digitel versus analog computers in system operation.

	Digitel	Analog
Operationa planning		
1. Loed forecasting	X	
2. Maintenance echeduling	X	X (partially)
3. Spinning reserve determination	X	
4. Unit commitment scheduling	X	X (pertially)
5. Evaluation of future interchange transactions	X	X (pertielly)
6. Selection of fuels	X	X (partially)
7. Hydroelectric coordination studiee	X	
Operations control		
1. Load and frequency control	X	X
2. Economic allocation of generation	X	X
3. Kilovar supply scheduling	X	X (partielly)
4. Remote supervision	X	
Operations accounting		
1. Interconnection billing	X	X (pertially)
2. Syetem production stetistice	X	
3. Unit production atatietice	X	
4. Aasessment of quality of unit end syatem performance	X	

A FEW TYPES OF COMPUTERS

An optimum economy of production of power for a given combination of machines is obtained when the incremental cost of received power ie the same for all variable sources; i.e.,

$$\frac{dF_n}{dp_n} L_n = \lambda$$

where dF_n/dp_n = incremental production cost of source n in dollars per mwh

L_n = penalty factor of source n

λ = incremental cost of received power in dollars per mwh.

The penalty factor of source n is defined as follows.

$$L_n = \frac{1}{1 - (\delta p_L/\delta p_n}$$

where $\delta p_L/\delta p_n$ = incremental transmission loss of source n. The incremental transmission loss may be determined from a transmission loss formula, like

$$\frac{\delta p_L}{\delta p_n} = \sum_m 2B_{mn}p_m + B_{no}$$

where B_{mn}, B_{no} are transmission-loss-formula coefficients. Though determination of the most economical combination of units for power generation is a complex problem by itself, yet the above equations could well be used to determine the allocation of loading among units chosen to be operated.

Tie-line frequency-bias control of frequency and net interchange is accomplished by developing correcting signals from the area requirement. These signals drive the speed-changer motors of the units within the area such that the area requirement is returned to zero. Area requirement is equal to net interchange error plus a constant times the frequency error.

Figure 18 illustrates a basic tie-line frequency control

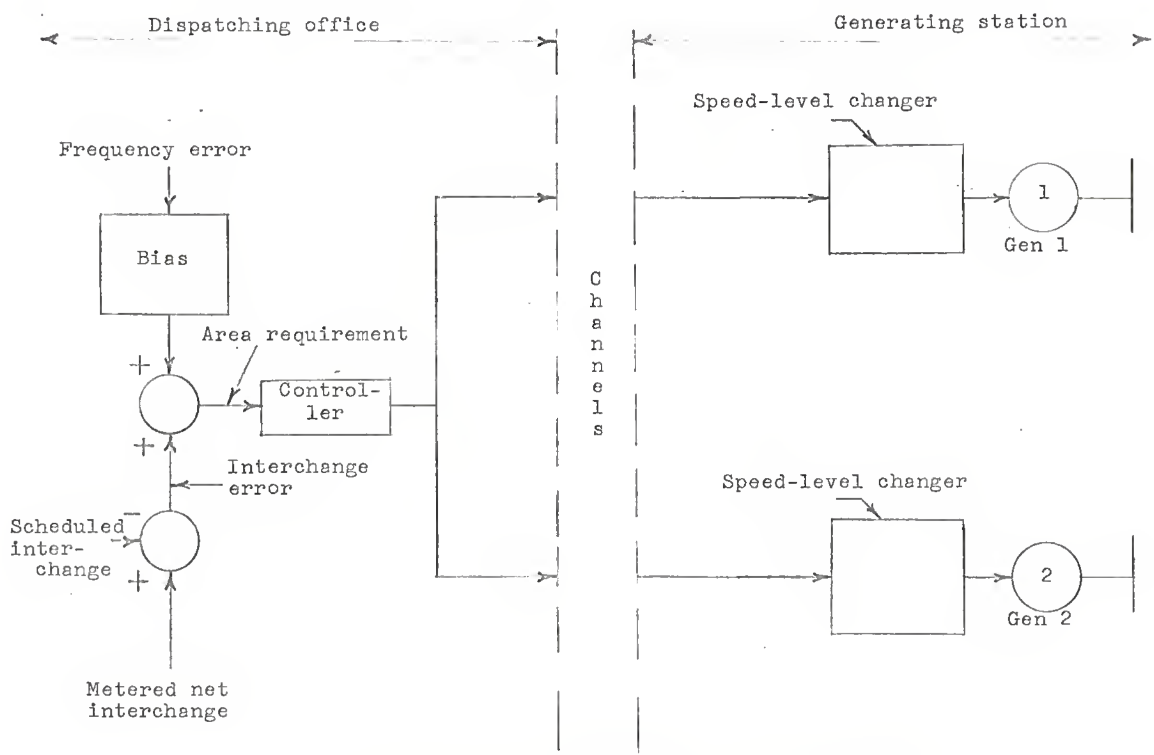


Fig. 18. Basic tie-line frequency control method.

E

method. In this illustration, fundamental components common to all tie-line frequency bias controllers are shown. The area requirement signal is developed from the frequency and net interchange errors, and is acted upon by the controller to develop a correcting signal to be sent to the speed-level-changer-motors of all units under control. This control system, in turn, takes care of all load changes in the area.

Figure 19 illustrates a similar arrangement as in Fig. 18. However, in this case an economic control is superimposed upon the system of Fig. 18 by means of the economic loading equipment. This economic controller is used to compare the <u>actual</u> unit output with <u>desired</u> unit output. This comparison gives a correcting signal which brings the actual output in agreement with the desired output.

Figure 19 illustrates a two-unit system. Let us consider the operation of this system, neglecting the transmission losses. As is shown earlier, for optimum economy the incremental cost of power of each generating unit should be equal to the same number λ. Thus the equation for this is $dF_n/dp_n = \lambda$.

Figure 20 illustrates a system for automatic dispatching at equal incremental costs. Supposing the signal generated by the controller is equal to "λ". This incremental cost, which is generated at the dispatching office, is sent to all units and accomplishes two functions.

1. One function is the rapid regulating control to reduce the area requirement signal to zero.

2. The other function is the slower reset action to

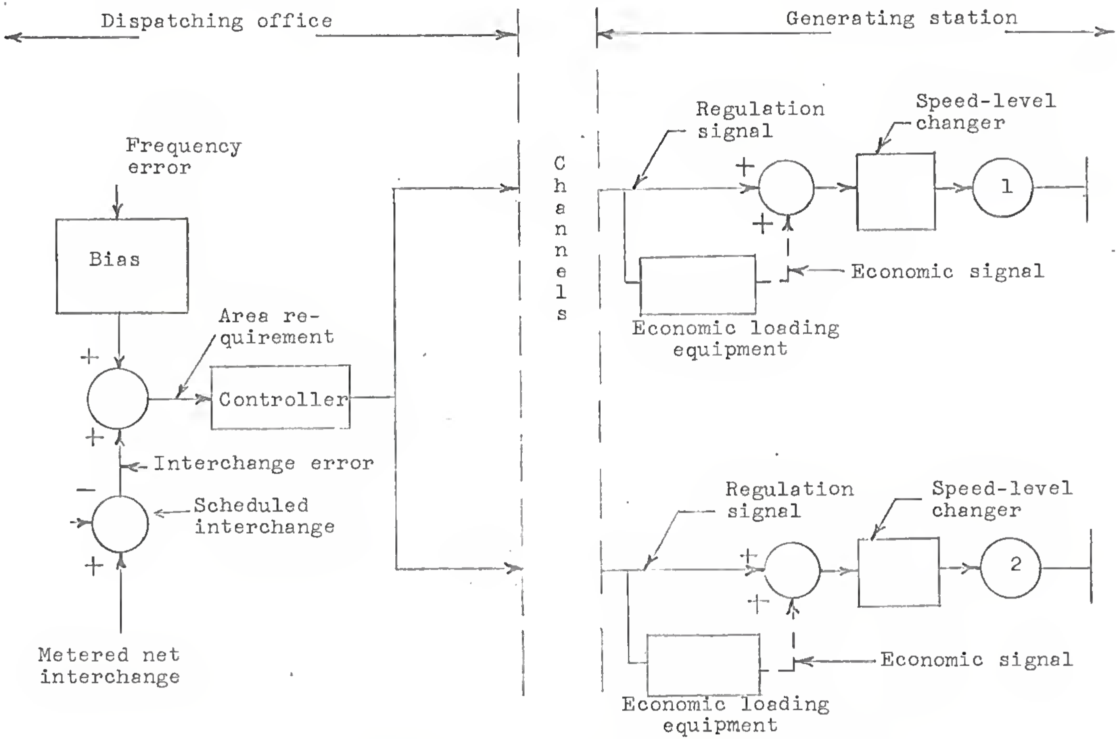


Fig. 19. Addition of economic loop to system of Fig. 18.

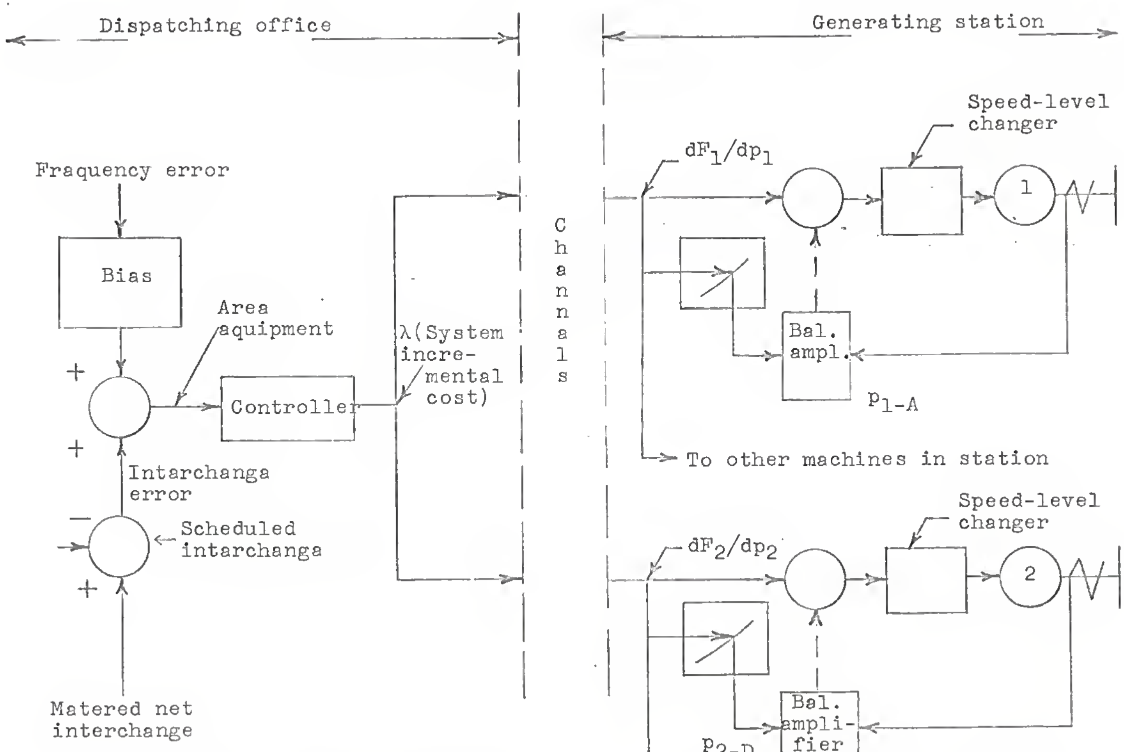


Fig. 20. System for automatic dispatching at equal incremental costs.

reellocete generetion in the most economicel menner corresponding to equation $dF_n/dp_n = \lambda$.

This λ signel which is ecting on the speed-level changer of eech unit is elso fed into the incremental coet function generetor for eeoh unit. This function generetor ie an electronic dete storege device, whoee function ie to indicete the reletionship between the incremental production cost end output of the perticuler unit. If e velue is fixed for λ, then the function generetor will indicete the reletionship between the incrementel production cost end output of the perticuler unit. Thus for thie perticular velue of λ, the economic schedule corresponding to operetion of all units et the seme incrementel cost λ is indioated by the function generetors. If λ does not represent the velue to be genereted, then smell chenges in the eree requirement signel occur, which correct the velua of λ to correspond to generetion required.

A good explenetion for thie cen be es followe. In this exemple let the frequency end interchange be initielly et their scheduled velues, end ell units ere loeded equelly incrementelly. Suppose there is en increese in the loed requirement in the aree. Then there is genereted en aree requirement signal. Thie eignel cells for increased generetion. Thus λ chenges, end thie chenge fecilitetes generation to be meinteined et equel incrementel cost. Then in the steedy stete efter the loed chenge hes been ebsorbed by the units within the eree, the eree requirement eignel is egein zero, end ell units ere operating at equal incremental cost.

In the cese where trensmission losses ere pretty high, optimum economy ia obteined when the incremental coat of received power is the seme from all ganereting units. Thie brings into the picture tha penelty factor. Eech unit'a incrementel cost now ia modified by a penelty fector. Thus the equation $dF_n/dp_n = \lambda$ now becomes $dF_n/dp_n = \lambda/L_n$.

Figure 21 illuatratee how the penalty fector signals are introduced in the functionel diegrem of en eutomstic dispatching system. As ueual λ is egein considered es the output of the controller. This λ is now modified by the penalty feotor, aa ehown in the diegrsm. Now tha signal sant to aach stetion is the propar incremental cost for thet stetion. The penalty-factor computer requires a knowledge of station loeds, interconnaction flows, end velues of nonconforming loeds for its inputs. Theae valuae could ba telematered informetion into tha penalty factor oomputer. The $1/L_n$ signala ere daveloped by analog circuitry.

Semieutometic Syatem Besed on Pracalculeted Schedule

Figura 22 illustretes e aamiautomatic dispetching syatem. This aystem is besed on the knowledge of the optimum echedule oorresponding to the given system conditions. This schedule can ba precalculated. To denote each plent leyout es a function of totel generetion, the above mentioned schadule is set into a progrem console. Thus required totel generetion is obteined by summing the existing plant outputs end the erea requirement. The output of the program console ie the velue of the deaired

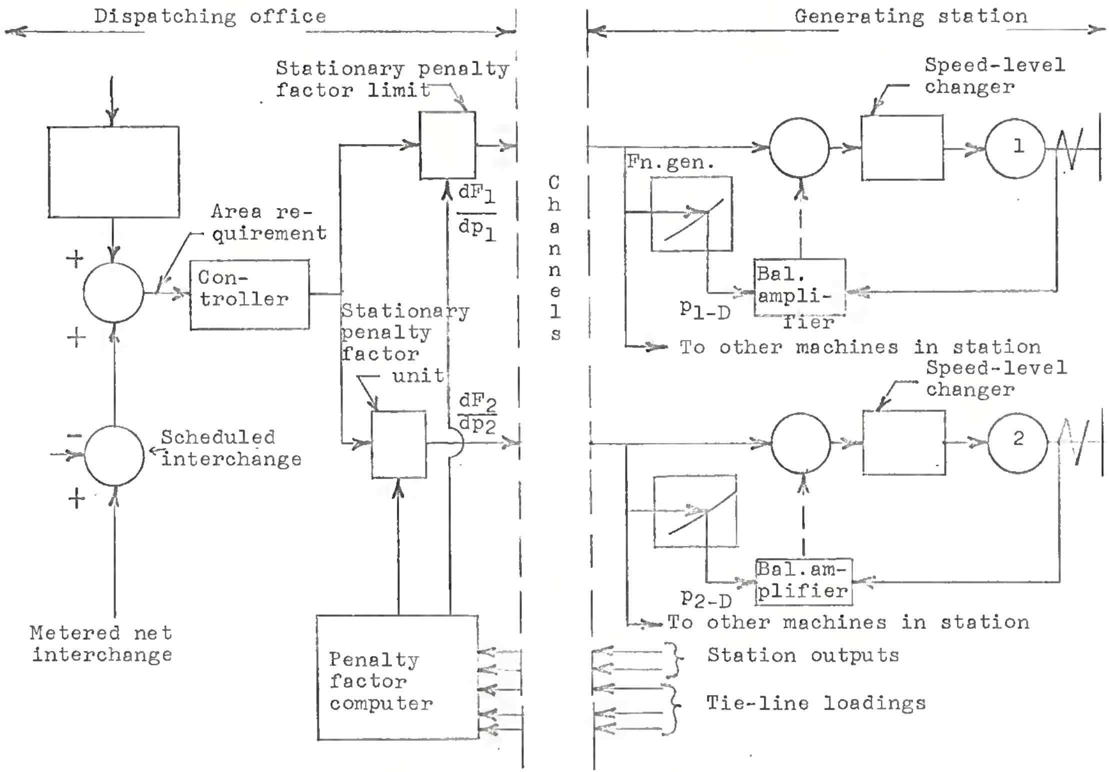


Fig. 21. Functional diagram of automatic dispatching system, including penalty factor computation.

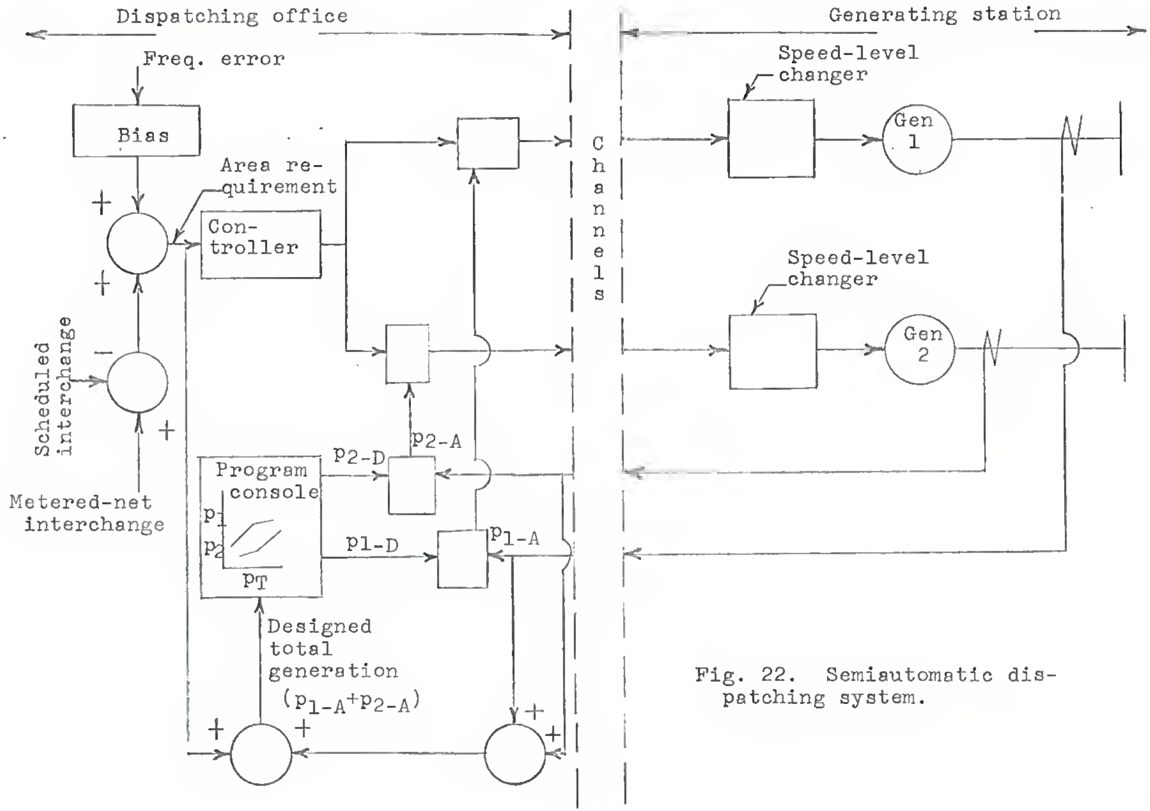


Fig. 22. Semiautomatic dispatching system.

generation, denoted by p_{1-D} and p_{2-D}. By comparison of the actual generation p_{1-A} and p_{2-A} with the desired generation p_{1-D} and p_{2-D}, correction signals may be obtained which are sent to the generating stations. Such a unit will enable the dispatcher to make a unit or station basis comparison in his office. If comparison is made on a unit basis, then it is necessary to have communication to and from each unit, and the program console must indicate the desired output of each unit. Instead, if comparison is made at the dispatcher's office on a station basis, the station must include equipment to insure that the station total is properly divided among the units.

The setting in the program console involves the setting of a regulating point, ratio settings, and station high and low limits. The dispatcher has to set the regulating point and ratio setters periodically in order to follow the precalculated schedules. Use of an impulse-control system facilitates program console to allow the impulses to pass when they are in a direction to bring the stations into economic balance. When the area-requirement signal becomes sufficiently great, correcting impulses are sent to the stations irrespective of the economic comparisons.

Generation-Scheduling Computers

The above explained precalculated schedule method is inconvenient. Generation-scheduling computers remove the necessity of precalculated schedules.

Figure 23 illustratea a genaration-achaduling computar to control a syatam automatically. In this caaa an analog computar capable of calculating tha economic allocation of genaration for a given value of "λ" raplacas the program console of tha aami-automatic diapatching syatem. Tha inputs to tha computar ara talematerad tia-lina flows and λ. Tha individual tie-line flows ara raquired as they enter tha mutual tarms for tha steam-plant incremantal loaaaa. It is alao dasirad to know tha incremantal cost of delivarad powar over tha tiea. By matching tha daairad total genaration with the total ganeration obtainad from the computer, tha value of λ ia obtained. If tha total generation from the computer does not equal the daaired total ganaration, the valua of λ ia driven by the incremental cost aarvo to bring thase two quantities into balanca. Juat as in the caaa of a samiautomatic diapatching system, tha dasirad valuas of plant generation ara comparad with actual valuas and correction signala ara obtained.

Incramantal Coat Compariaon Computar

Computera that can provida a compariaon of tha incramental cost of dalivarad power from each aource can be usad to provida a method of eutomatic aconomic allocation. Thia type of automatic operation calls for varioua aourca loadinga aa input aignals to an automatic penalty factor computer, and also to units representing incremental production coat. An illuatration ia ahown in Fig. 24.

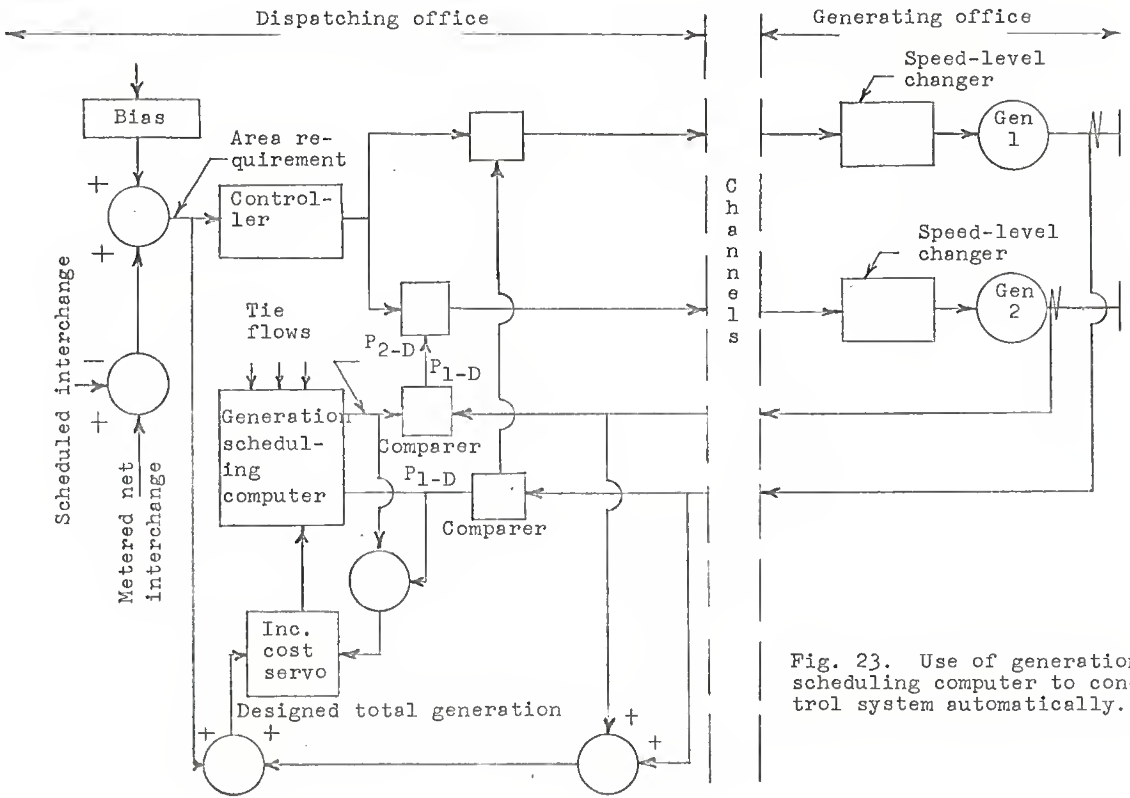


Fig. 23. Use of generation-scheduling computer to control system automatically.

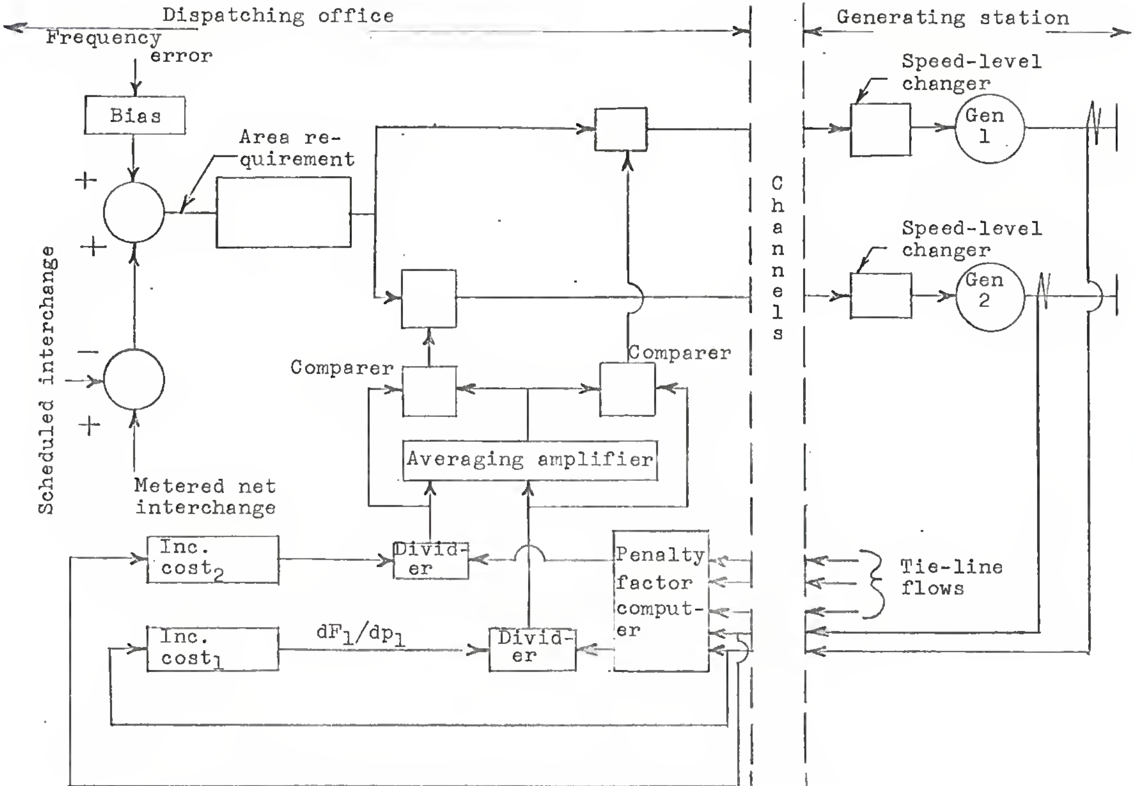


Fig. 24. Use of incremental cost comparison computer to control system automatically.

In the equations,

$$\lambda_1 = dF_1/dp_1 \ (1/(1/L_1))$$

and

$$\lambda_2 = dF_2/dp_2 \ (1/(1/L_2))$$

It is seen that the outputs of the dividers are λ_1 end λ_2 respectively. Taking the average of the two, $\lambda_{average}$ is obtained. By the process of comparison of $\lambda_{everage}$ with λ_1 and λ_2, correction eignals are obtained, so that aignals to increese generation are aent to units with λ below average; and signals to decreeae generation are sent to units with λ above everage.

INTERCONNECTED AREAS CONTROLLED BY COMPUTERS

In this chapter a etudy of automatic economic operation of interconnected areae is made. If e number of ereee are interconnected, then thie eyetem can be termed as e pool. To obtain an economic operation of this pool, the several arees interconnected should be treated es one aree. Then only one computer will be necessary to centrally control all the areae of the pool. Information regerding the load on eech plant and external interconnaction flow has to be fed in the computer. There ie also a control system which ie connected to eech of the areee by mesne of a control channel. Thia control eyatem aends in commanda through the control chennel to the various connected arees to increaee or decrease their power delivery to the grid syatem. By this method various ereae connected to the grid are eutometically operated; however, there are a few disadvantages of this system when compared with decentralized epproach. The following are some of these disadvantages of a centralized system.

1. Greater increase in telemetering channel requirements.
2. Use of larger centralized computer controllers.
3. Information for accounting between areas is not readily available.

Consider a case where two areas are connected in a pool. This is the simplest case for study purposes. These two areas must be considered as one area, and these two areas should be delivering power to the grid system at equal incremental costs of received power. Figure 25 illustrates the interconnection of two areas by a single tie, whereas Fig. 26 illustrates a centralized control for the pool. This latter illustration shows the requirement of two channels between each plant and the central control location. One should find a loss formula that treats both the plants as one.

In earlier treatment of this work it was brought out that for economic dispatching within a given area, the incremental cost of received power from each source must be the same. This condition is a necessity.

Figure 27 illustrates two areas A and B interconnected by a single tie. In this case

$$c_{1a}L_{1a} = \lambda_a \tag{1}$$

$$\frac{dF_2}{dp_2} L_{2a} = \lambda_a \tag{2}$$

$$\frac{dF_3}{dp_3} L_{3a} = \lambda \tag{3}$$

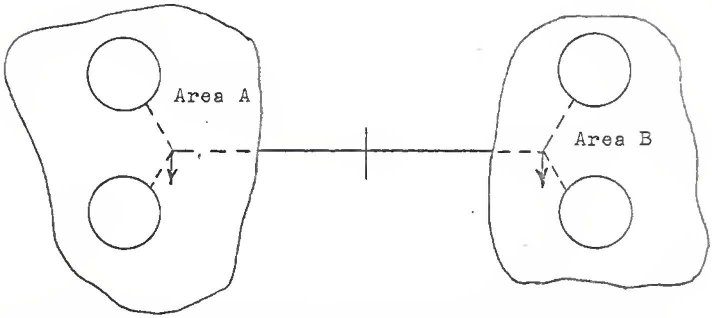


Fig. 25. Pool formed by interconnection of areas A and B by a single tie.

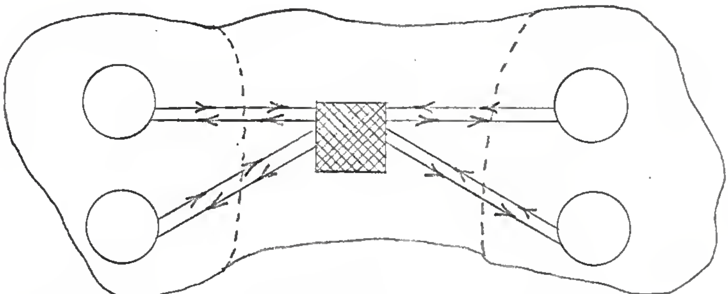


Fig. 26. Centralized control for pool of Fig. 25.

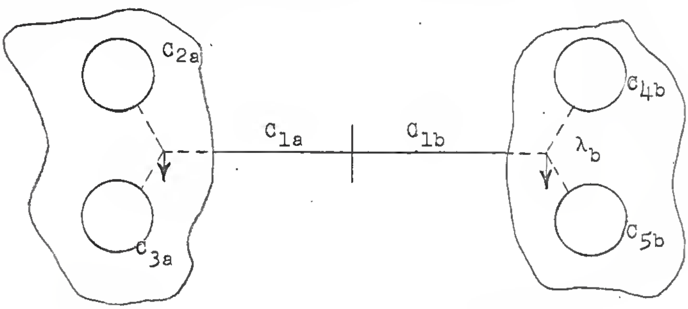


Fig. 27. Incremental cost relations.

where c_{1a} = incremental cost at bus 1 referred to area A

L_{na} = penalty factor of source n in area A

λ_a = incremental cost of received power in area A

$\frac{dF_n}{dp_n}$ = incremental production cost of plant n.

In the same fashion the equations for area B to operate most economically are

$$c_{1b}L_{1b} = \lambda_b \qquad (4)$$

$$\frac{dF_4}{dp_4} L_{4b} = \lambda_b \qquad (5)$$

$$\frac{dF_5}{dp_5} L_{5b} = \lambda_b \qquad (6)$$

where c_{1b} = incremental cost at bus 1 referred to area B

L_{nb} = penalty factor of source "n" in area B

λ_b = incremental cost of received power in area B.

To schedule most economical operations of the pool, it is essential that the net interchange between areas A and B be of such magnitude that the incremental cost of the interchange at bus 1 will be the same when referred to either area; i.e.,

$$c_{1a} = c_{1b} \qquad (7)$$

Equations (1) and (4) can be used in relating the cost of the received power in each area to the incremental cost at bus 1. Therefore

$$c_{1a} = \lambda_a/L_{1a} \qquad (8)$$

$$c_{1b} = \lambda_b/L_{1b} \qquad (9)$$

If the values of λ_a, λ_b, L_{1a}, L_{1b} are known from area dispatching systems, then c_{1a} and c_{1b} may be calculated from the equstions (8) and (9). From the values of c_{1s} snd c_{1b}, it is possible to find how the net interchange scheduling for each area should be modified. This is done by comparing c_{1a} and c_{1b}. Figure 28 suggests a method of the above scheme. By this method c_{1a} snd c_{1b} are compared, and $(c_{1s} - c_{1b})$ is obtained. If it is found that the cost of c_{1s} is less thsn c_{1b}, then a signal is sent to the automatic dispatching equipment in ares "A", with a command to increase the scheduled net interchange out. Also the same signal with an opposite sign is sent to station "B", with a command to decrease the scheduled net interchange by an amount equal to the amount by which .the scheduled net interchsnge at "A" was incressed. This process of correcting is csrried on until $c_{1a} = c_{1b}$. For proper operation of load frequency controllers, the sum of the net interchsnge schedules for this two-ares system should be equal to zero. This is with the assumption that there are no external interconnections. This relationship between the interchange schedule should be maintained; if not there will occur sustained frequency error. If, however, these two areas have external interconnections with other adjoining sreas, then the sum of the net interchange schedules for the two areas must be equal to the desired total interchange to the external areas.

Description of the Control Equipment

Figure 29 illustrates s control equipment arrangement which can effect the above mentioned automatic operation. The

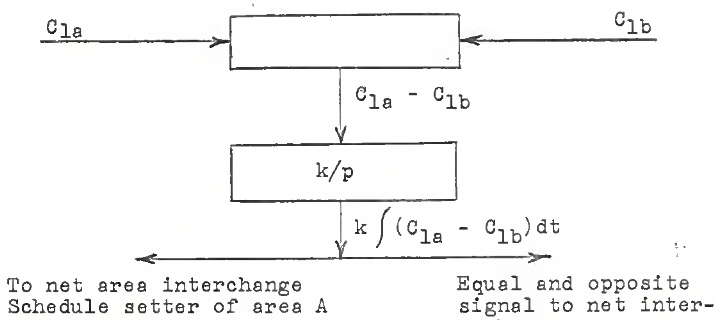


Fig. 28. Control signals for automatically obtaining economic net interchange.

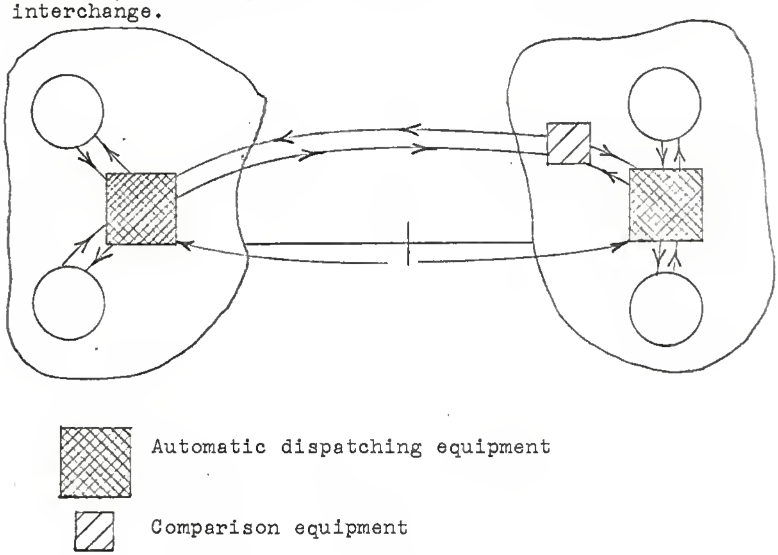


Fig. 29. Computer control equipment arrangement.

praraquisites for automatic control of these areas for maximum economy ara the following:

1. To obtain equal incremental cost of delivered power within the boundary of each area, one must diapatch each area individually.

2. Tha value of power at the common tia point must be available.

Some dispatching syatems automatically furnish thia information. As discussed earlier, the incremental coat of power at tie pointa should be compared and aignala of aqual magnituda and opposite aigns ahould be sent to tha areas for achieving maximum overall economy of oparations. These aignals operating as a net intarchange schedule aetter bring about equal incremental cost at the common tie point by varying the generation of the two areas. For this to be accompliahed in a two-area pool, comparison equipmant ahould be provided at one area and two talematering channels should be provided betwaen the two areaa.

Figure 30 ia an illustration of a system uaed to operata a two-area pool in an economical fashion. Signala rapresanting cost of power at the comparison point ara provided by the axisting automatic diapatching ayatem. These are compared by two motor salsyn units driving a mechanical differantial; thua shaft motion proportional to the differance between the two cost signals results. Individual pointers are driven by the motor shafts through appropriate gearing. Thase individual pointers indicate the two costa. The potentiometer-battery combination indicated

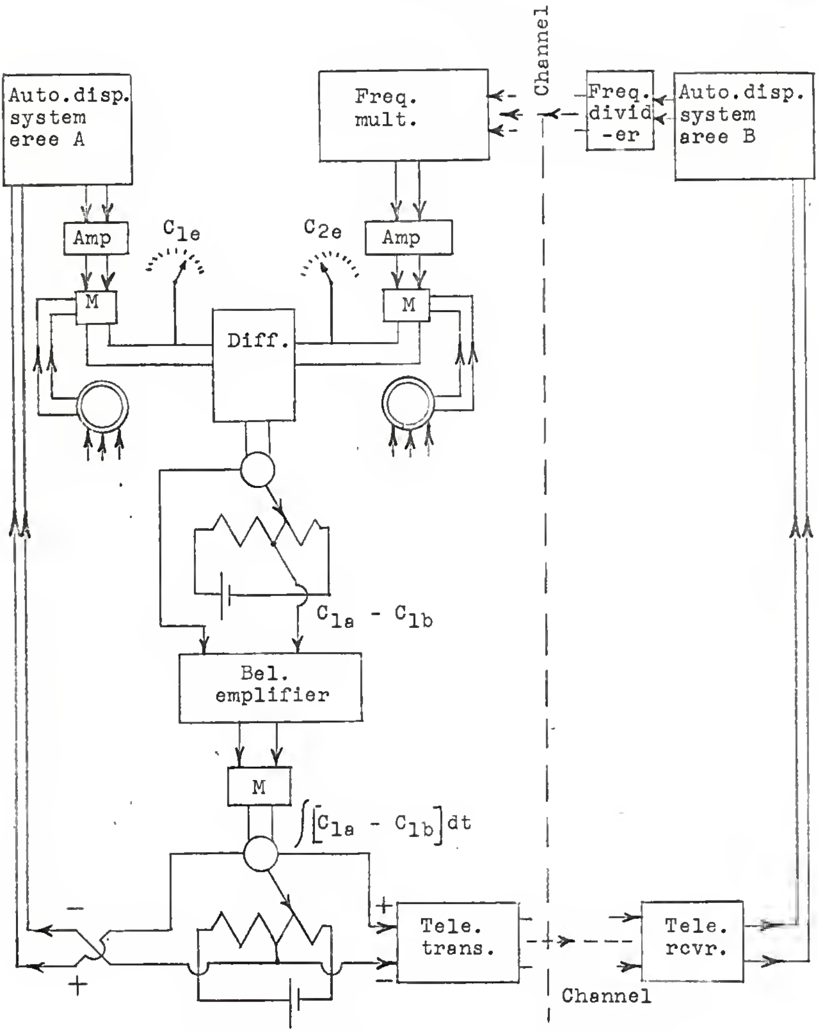


Fig. 30. Schematic diegrem of equipment.

in the illustration is actuated by the differential output shaft to provide a direct-current signal proportional to the cost difference. The potentiometer energizes, through a balancing amplifier, a slow-speed servo motor which in turn drives another potentiometer-battery combination. The signal developed by this potentiometer is used to supplement the existing schedule signals in the automatic dispatching system. A speed proportional to cost error is obtained by using a negative feedback in the balancing amplifier.

Suppose if the cost of power delivered to the common comparison point from area B is higher than from area A, then motor selsyn units will cause the potentiometer to move in a direction so as to send a reduced "out schedule" signal to area B, and an increase "out schedule" to area A. This action is of a reset nature, which means the interchange signals will continue to change until the condition of cost equality is met.

Areas With Multiple Ties

In the earlier discussion a single tie between two areas was considered, whereas now the case of two areas having multiple ties between them is to be considered. Figure 31 is an illustration of a pool with multiple ties. Surely enough it is essential to consider the incremental losses incurred over each of the parallel paths.

If p_{aa} = net interchange or excess flow out of area A, then

$$p_{aa} = p_{1b} + p_{2b} = -p_{1a} - p_{2a} \qquad (10)$$

Let c_{ea} = incremental cost at boundary referred to area "A" for delivering an increment of power from the hypothetical load of area A to the hypothetical load of area B.

c_{eb} = incremental cost at boundary referred to area B for delivering an increment of power from hypothetical load of area A to the hypothetical load of area B, or equals incremental cost at boundary referred to area B for delivering an increment of power from the hypothetical load of area B to the hypothetical load of area A.

It has been established by various authors that

$$c_{ea} = \lambda_a + \lambda_a \left(\frac{\delta L_{Ta}}{\delta p_{1a}} \frac{\delta p_{1a}}{\delta p_{ea}} + \frac{\delta L_{Ta}}{\delta p_{2a}} \frac{\delta p_{2a}}{\delta p_{ea}} \right) \qquad (11)$$

and

$$c_{eb} = \lambda_b - \lambda_b \left(\frac{\delta L_{Tb}}{\delta p_{1b}} \frac{\delta p_{1b}}{\delta p_{ea}} + \frac{\delta L_{Tb}}{\delta p_{2b}} \frac{\delta p_{2b}}{\delta p_{ea}} \right) \qquad (12)$$

and for optimum economy

$$c_{ea} = c_{eb} \qquad (13)$$

In the above equations

$\frac{\delta L_{Ta}}{\delta p_{1e}}$ = ratio of change in transmission loss in area A to change in tie flow p_{1a} when delivering an increment of power from bus 1 to the hypothetical load of area A, assuming that no change in the remaining variables occurs.

$\frac{\delta L_{Ta}}{\delta p_{2a}}$ is similarly defined for p_{2a}.

$\frac{\delta L_{Tb}}{\delta p_{1b}}$, $\frac{\delta L_{Tb}}{\delta p_{2b}}$ are similarly defined for area B.

$\frac{\delta p_{1a}}{\delta p_{ea}}$ = ratio of change in the flow into area A at bus 1 to the change in excess for flow out of area A, when an increment of power is delivered from the hypothetical load of area A to the hypothetical load of area B.

$\frac{\delta p_{2a}}{\delta p_{ea}}$ = same as above but with respect to the flow into area A at bus 2.

Since

$$p_{1b} = -p_{1a}$$

$$p_{2b} = -p_{2a}$$

then

$$\frac{\delta p_{1b}}{\delta p_{ea}} = -\frac{\delta p_{1a}}{\delta p_{ea}}$$

$$\frac{\delta p_{2b}}{\delta p_{ea}} = -\frac{\delta p_{2a}}{\delta p_{ea}}$$

If the ratios of X/R for the transmission systems in the two areas are the same, the comparison cost calculations are greatly simplified. The incremental cost calculations need not include an extra factor to account for differences in X/R ratios. As an example of such simplification the cost of delivering an increment of power from area A to tie point 1, including the parallel path offered by area B, may be closely approximated by

$$c_{1a} = \lambda_a / L_{1a} \tag{14}$$

$$L_{1a} = \frac{1}{1 - (\delta L_{Ta}/\delta p_{1a})} \tag{15}$$

In the same fashion the cost of delivering an increment of power from area B to tie-point 1, including the parallel path offered by A, is clearly approximated by

$$c_{1b} = \lambda_b / L_{1b} \tag{16}$$

$$L_{1b} = \frac{1}{1 - (\delta L_{Tb}/\delta p_{1b})} \tag{17}$$

It is possible to bring the net interchange between the two areas into economic balance by comparison between c_{1a} and c_{1b}. Indeed, the costs at bus 1 and bus 2 are different. This scheme can now be extended to pools formed by more than two areas. The extension and reductions of the above formulae are a matter of routine.

Multiarea Economic Dispatch Computer

The following tasks are accomplished by multiarea economic dispatch computers:

1. Calculation of economic interchange between areas.
2. Calculation of weighted incremental costs at boundaries for interconnection accounting.
3. Calculation of incremental costs of wheeling losses.
4. Calculation of flows over individual tie lines.

There are two types of computers that will be of interest. They are:

1. Single-area economic dispatch computer.
2. Multiarea economic dispatch computer.

Let us first consider the single-area economic dispatch computer. Figure 32 indicates a single area, and the problem is to study the type of computer required for calculating the

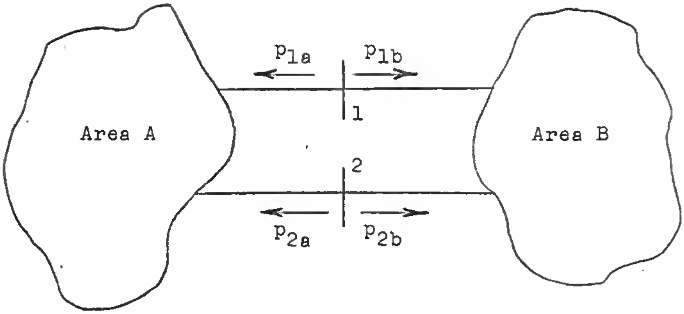


Fig. 31. Pool with multiple ties between two areas.

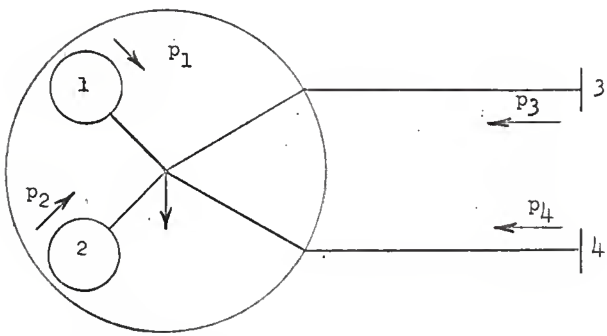


Fig. 32. Illustrative single-area problem.

economic allocation of generation for the single area. Consider the following equations defining the economic operation within an area.

$$\frac{dF_1}{dp_1} + \lambda \frac{\delta L_T}{\delta p_1} = \lambda \qquad (14)$$

$$\frac{dF_2}{dp_2} + \lambda \frac{\delta L_T}{\delta p_2} = \lambda \qquad (15)$$

where $\frac{dF_n}{dp_n}$ = incremental produotion cost of plant n in dollars per mwh

λ = incremental cost of received power in dollars per mwh

$\frac{\delta L_T}{\delta p_n}$ = incremental transmission loss with respect to p_n when only p_n changes.

The incremental cost of an increment of power delivered to tie-points 3 and 4, respectively, is given by

$$c_3 = \lambda - \lambda \frac{\delta L_T}{\delta p_3} \qquad (16)$$

$$c_4 = \lambda - \lambda \frac{\delta L_T}{\delta p_4} \qquad (17)$$

where c_n is the incremental coat of power delivered to point n. The following loss formula ia used in calculating incremental tranamission losaea.

$$\frac{\delta L_T}{\delta p_n} = \sum 2\ B_{mn}P_m + B_{no}$$

where p_m = various steam plant loadings, hydro plant loadinga, tie loadings, and nonconforming loads. The B_{mn} and B_{no} terms are transmission-loss-formula coefficients.

Figure 33 shows a schematic representation of a single area computer that solves the above mentioned equations. p_1, p_2, p_3, p_4 are inputs to the transmission-loss-formula matrix. $\frac{\delta L_T}{\delta p_1}$, $\frac{\delta L_T}{\delta p_2}$, $\frac{\delta L_T}{\delta p_3}$, and $\frac{\delta L_T}{\delta p_4}$ are the outputs of these matrices. These incremental losses are multiplied by λ by means of a gang potentiometer to obtain $\lambda(\delta L_T/\delta p_1)$, $\lambda(\delta L_T/\delta p_2)$, $\lambda(\delta L_T/\delta p_3)$, and $\lambda(\delta L_T/\delta p_4)$, respectively.

Equations (1) and (2) can be written as,

$$\frac{dF_1}{dp_1} = \lambda - \lambda \frac{\delta L_T}{\delta p_1} \tag{18}$$

$$\frac{dF_2}{dp_2} = \lambda - \lambda \frac{\delta L_T}{\delta p_2} \tag{19}$$

The operations indicated by the above two equations are the inputs to the function generator. These function generators indicate the relationship between output cost and the incremental production cost. In Fig. 33, p_1 and p_2 are shown as the output of the function generators. These calculated values of p_1 and p_2 are the input to the transmission loss matrix, together with the setting of p_3 and p_4. If there are a number of units in a plant, then a number of function generators are connected in parallel. Calculations of c_3 and c_4 are indicated in Fig. 33. The λ-servo indicated at the top of Fig. 33 aids the computer in automatically obtaining the desired value of total steam plant generation. In this case desired total steam generation is matched with total steam generation from the computer. If

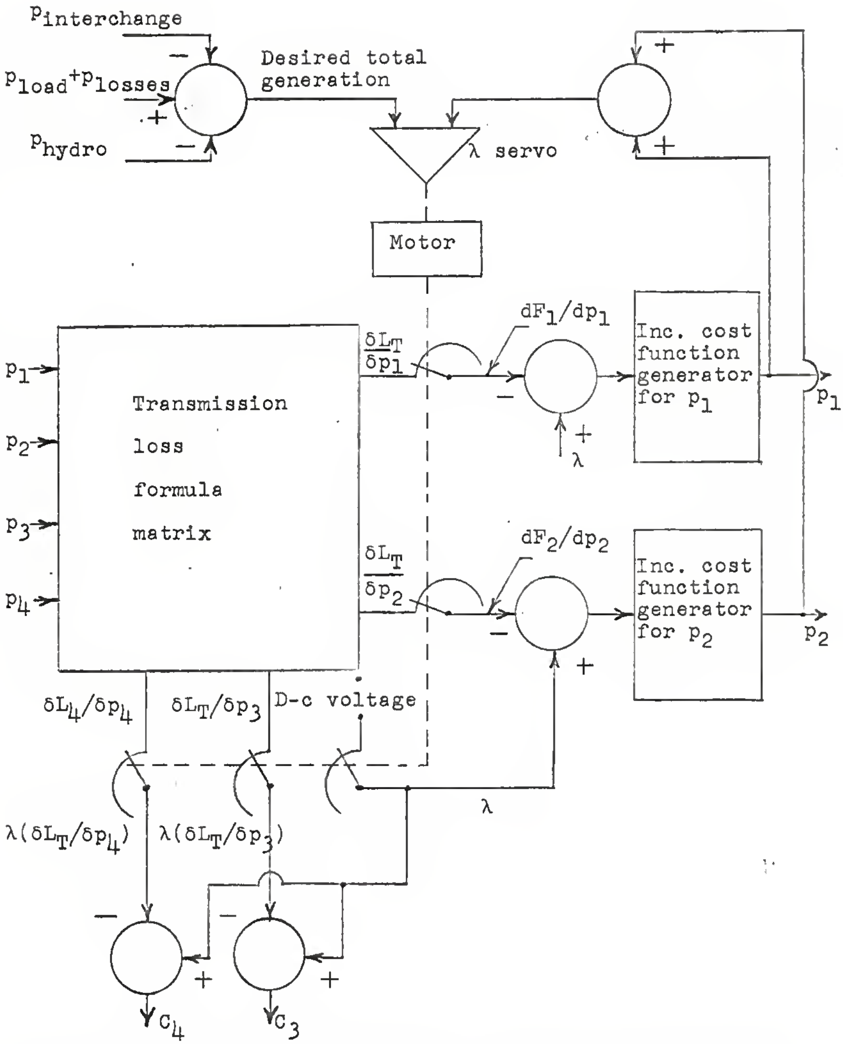


Fig. 33. Schematic representation of single area computer.

there is an error, the λ potentiometers are driven at a rate proportional to this error so that in the steady state the desired total generation and the computed total generation are identical.

The desired total generation is calculated as

$$P_{total} = P_{load} - P_{hydro} - P_{interchange} + P_{losses}$$

Multiarea Computers

Figure 34 illustrates two areas connected by a single tie. Equations for economic operations within each area are considered in the form

$$\frac{dF_a}{dp_{Ga}} + \lambda_a \frac{\delta L_{Ta}}{\delta p_{Ga}} = \lambda_a \qquad (20)$$

$$\frac{dF_b}{dp_{Gb}} + \lambda_b \frac{\delta L_{Tb}}{\delta p_{Gb}} = \lambda_b \qquad (21)$$

where $\frac{dF_a}{dp_{Ga}}$ = incremental product cost in dollars per mwh of a particular plant G_a in area A

$\frac{dF_b}{dp_{Gb}}$ if the same as above, except for area B

λ_a, λ_b = incremental cost of received power in areas A and B, respectively

$\frac{\delta L_{Ta}}{\delta p_{Ga}}$ = incremental transmission loss in area A for a particular plant G_a when only that plant changes

$\frac{\delta L_{Tb}}{\delta p_{Gb}}$ is the same as above except for area B.

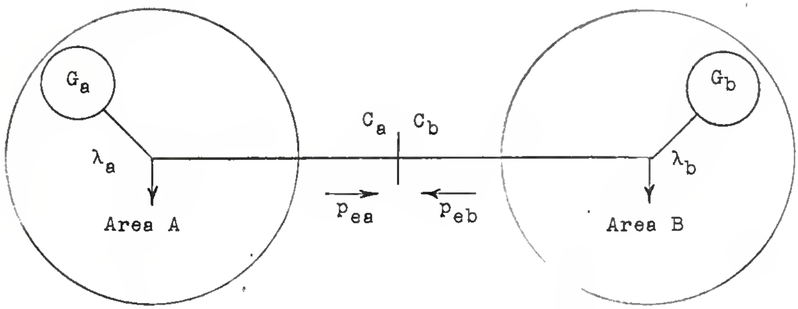


Fig. 34. Two areas connected by single tie.

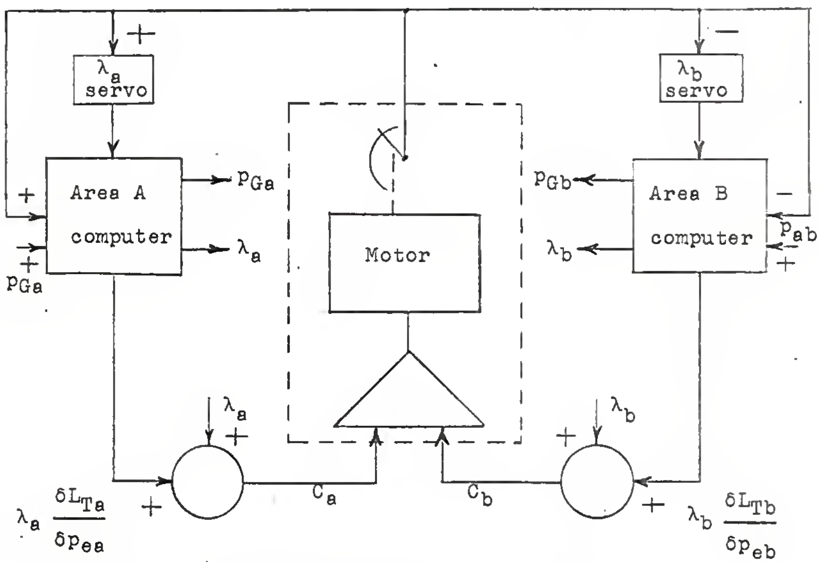


Fig. 35. Computer system for two areas connected by a single tie.

For an economical operation of the pool formed by these two areas, it is essential that the net interchange between areas A and B be of such magnitude that the incremental cost of the interchange at the metering point will be the same when referred to either area. Thus when

$$c_a = c_b \tag{22}$$

optimum economy is obtained, where

c_a = incremental cost at the boundary referred to area A for delivering an increment of power from the hypothetical load of area A to the hypothetical load of area B

c_b = incremental cost at the boundary referred to area B for delivering an increment of power from the hypothetical load of area B to the hypothetical load of area A.

Values of c_a and c_b can be obtained from the following equations.

$$c_a = \lambda_a + \lambda_a \frac{\delta L_{Ta}}{\delta p_{ea}} \tag{22a}$$

$$c_b = \lambda_b + \lambda_b \frac{\delta L_{Ta}}{\delta p_{eb}} \tag{23}$$

where p_{ea} = net interchange or excess flow out of area A.

$$p_{ea} = -p_{eb} \tag{24}$$

Figure 35 illustrates a computer system for two areas connected by a single tie. Each of the areas has a dispatching computer. Costs c_a and c_b are calculated by dispatching computers A and B, respectively. If it is found that the rates c_a and c_b are not equal, then using a rate proportional to the difference between c_a and c_b, the interchanges for each of the two areas are modified by equal and opposite amounts. Thus $c_a = c_b$ will be the steady state. The servo that is used in balancing these values of c_a and c_b is called an interarea servo.

A similar procedure is carried on for two areas connected by multiple ties.

A TYPICAL COMPUTER PROGRAM FOR OPERATION OF ELECTRIC GENERATING STATION

Planning groups within electric utilities have devoted much effort to selection of size, type, and location of generating capacity additions. There are many variables to consider in planning new generation. Some examples of these variables are:

1. Should the generating unit be located in the high fuel cost area near the load so as to have short transmission lines, or should it be located in a low fuel cost area remote from the load, and requiring long transmission lines?

2. Should units to carry the peak loads be steam driven or should oil-burning units such as diesels or gas turbines be used?

3. What size units should be installed?

Questions like those above have to be answered by a planning group.

In this era, even a modest addition to the existing electric generation system will cost somewhere from 20 to 50 million dollars, and during its life it may burn coal costing in the order of two times the original construction cost. Thus it is seen that any planning which reduces the above cost is a worth-while venture. For this reason many utility planning groups set up models of the generating system (sometimes including transmission systems) to attempt to evaluate the effect of various types of expansion patterns. Many groups have recently employed the digital computer as a tool to secure more data to guide their decisions. Looking at the magnitude of the planning task, the use of such a computer is well justified.

In the past the conventional method used is to fill the area under an annual load duration curve with generating capability to meet the load and reserve requirements. Referring to Fig. 36, it can be seen that certain classes of units are considered base units and the others as peakers. The upper portion of the curve is filled with peaking-type units and the lower portion of the curve is filled with base-type units. These curves are called "load duration curves". This type of approach will be adequate on a large system, with relatively uniform fuel cost over the area. However, on a large system with many units there can be one or more extra base-type units to fill in when base units are out for maintenance. Similarly, there can be one or more extra peaking types to cover maintenance of peaking units. Thus there will be little need for peakers filling in as base units when such a unit is out for maintenance.

On a medium-sized system the effects of maintenance outages may be more complicated. The number of base-type units is not great enough so that there is always one or more out for maintenance and so it is neither practical nor desirable to have an extra base unit to cover this maintenance; similarly, with peaking-type units. The planning problem then becomes more involved for if a peaking-type unit is selected as the next new unit, it can do peaking service part of the time but some of the time it must fill in as a base-loaded unit while a turbine overhaul is in progress on a base unit. Similarly, if a base unit is selected, there may be excess base capacity when all base units are available and this or other base-type units will be doing peaking service.

The above factors are further complicated by a 50 per cent fuel cost differential in the possible plant locations; thus the planning problem is even more complicated. An example of this statement is that a peaking-type unit in the low fuel cost area is able to produce energy at lower cost than a base unit in the higher fuel cost area.

The following computer program is for evaluating a generation expansion plan with many variables, and this estimates annual fuel costs for future years. This program requires a machine with core storage and indexing registers. The B-portion of the program can be run on a machine without a tape unit while the A-B combination would require a tape unit. The program is written in such a way that highly repetitive portions are done in core storage to take advantage of the shorter access time.

Specification of the Program

A program which has to meet the requirements for the planning problem should have tha following charactarietics:

1. It muat ba a reelietic simulation
   a. It must meintein the epecified epinning reserve
   b. It must load unita incremantally
   c. It must recognize maintenence outegas
   d. It must follow e deeigneted priority achedule for the units.
2. It must give auitabla detail in the output, such ae:
   a. Syatem, plant, and unit coate
   b. Fuel burnad et aech plant
   c. Average cost per mwh at the unit, plant, and aystem levels
   d. It ahould give an indicetion of the unit cepecity factor and load duration to aid in daeign of the unit.
3. It must be a practicel program
   e. Input date praparation should be aimple
   b. It ahould ba euitable for running on a madium-siza computar
   c. Running time ahould ba ehort since many caaes will be run.
4. It should, if practical, be mada vereetile so thet it can be usad for other purpoaas such as ahort-term maintenence achaduling.

Description of Program

Basic Concept. The basic operation of the program is quite simple. The program receives a load to be met and the length of the time block which this load represents, a list of available machines, and the order in which these are to be put on the line. It determines how many machines to put on so as to meet the load and reserve requirements, then it loads these incrementally, thus determining the generation by each unit and each plant. It also determines the total and average cost of fuel for each unit, each plant, and for the system. Unit capacity factors and block load duration curves are calculated. The program can be used to determine annual fuel cost using different length time blocks.

The general version of the program will accept the following:

1. A loading table (usually in incremental form although it may be in any desired order).
2. A priority table (shows the units said to be installed and the order in which the units are to be put on the system).
3. A conversion table (shows at which plant each unit belongs and gives the description of the unit).
4. Period data (specifies load peak, reserve required, and plant fuel costs).
5. A section deck (shows the fraction of peak for this section, the number of hours represented, and the

units out for maintenance in this section).

Theory of Outages with a Load Duration Curve Approach

All planning programs which try to simulate system operation must take into consideration the outages which occur during the period. These outages may be of three main types.

1. The scheduled outage which is planned in advance and during this time annual inspection and maintenance are accomplished.
2. The second type might be termed unscheduled outage although a name such as "short-term scheduled outage" could be used. This may bring in the problem of shutting down and again starting the unit. However, this difficulty can be overcome by not shutting down the unit. Instead, continue to operate it, until a low load period, when the cost of shutting down is smaller.
3. The third type of outage, perhaps the most expensive from the operating point of view, is that which occurs during high load periods and is of such a nature as to require the immediate removal of the unit from the system.

A simulation program should include all these types of outages. The first type can easily be determined since generally standard schedules are observed for annual overhaul and inspection of units and for major overhauls at five years or greater intervals. The second and third type are a little more difficult to find. These outages must be esteblished from experience. The emount of euch outages differs from unit to unit, depending upon the type of unit end its past history.

The computer progrem takee outagee into eccount in the following manner. Annuel cesee ere run using a loed duretion curve divided into a hundred eectione. The approach teken ie to make certain unite unavaileble for verious of these eectione used in constructing the loed duration curve. Since each of the one hundred sections represents one per cent of the time, it ie obvious that meking e unit unavailable for eight eectione makes it unaveileble for eight per cent of the yeer. Thus it is evident that making e unit unavailable for eight sectiona reelly mekee it unavaileble et eight specific load levels, whereae the eight per cent of time during the ectuel yeer that it ie unevailable would be at many more load levels. Thue thie type of representation is not quite as eimple as could be obteined by reel time simulation. Further diacueeion on how theee eight sections ahould be selected ie to follow.

The loed duretion curve in 100-eection form has been broken into three sections, as shown in Fig. 37. The lower 60 per cent is conaidered off-peek. The top 40 per cent is coneidered to be on-peek periode. The top 40 per cent is further subdivided into two parta, the lower 30 per cent and the top 10 per cent. These two perts ere coneidered to be the normal on-peek periods end the top 10 per cent the on-peak periods during the highest load months of the year. It is considered acceptable on the basis of experience to represent the eight per cent outeges during the

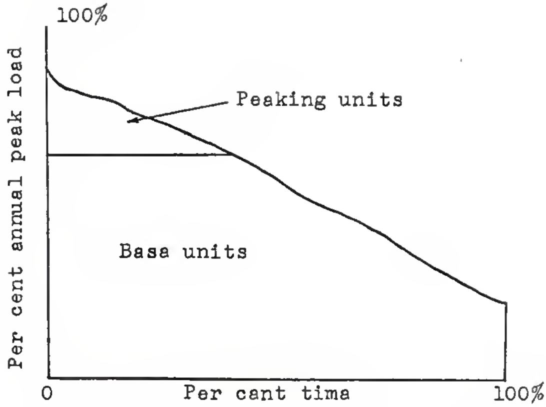


Fig. 36. Annual load duration curve.

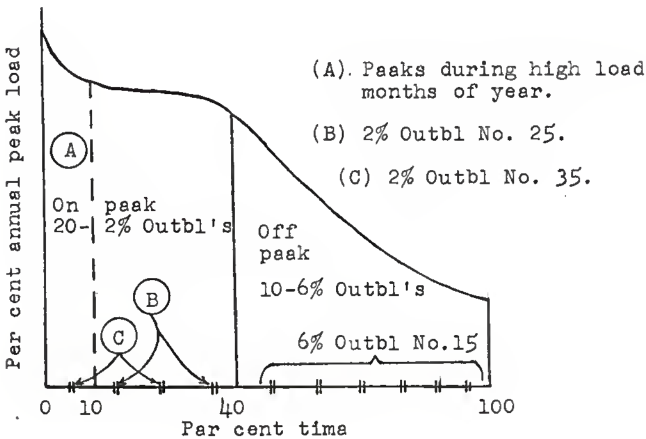


Fig. 37. Annual load duration curve division.

year by putting six per cent of them in the lower 60 per cent of the curve and two per cent in the upper 40 per cent of the curve.

In addition to the ennual scheduled outages for inspection and maintenance, there occurs on eech unit at intervals of five yeere or more an outege of longer length during which time the turbine unit iteelf is torn down for inspection and maintenance. The emount of work involved requires a considerebly longer outege in thie cese. An outage of epproximately two months, or 15 per cent of the time, ie required for this overhaul. These outeges occur efter 40,000 houre of operation by the unit. These will occur once in five years for a unit thet ie operating continuously. Combining these turbine overhaul outages with estimated short-time maintenance echeduled outages and forced outege, leads to use outeges of 12 per cent in the off-peak period and six per cent in the on-peak period for the year in which a unit hae turbine overhaul.

Multiple Outeges. With many units in e system e point is soon reached where there is not sufficient time during the yeer to inspect or overhaul each of the units one at a time. Coneequently it is neceesary to have two or more units out at a time. This ie aleo recognized in the planning program which permite as many units as desired to be made unavailable for each eection of the load duration curve.

Partial Outage Model. Many times in actual operation e unit may be running but it ie restricted in output beceuee of the failure of some component. In such cases a method which can be utilized to evaluate the cost of such partial outages is to say that there are two units, one which has the full capability of the unit being simulated and a second similar unit whose maximum is equal to the reduced capability of the unit being simulated. Thus in any given section one or the other of these is made available as required. If the real unit is to be completely down, then both models are made available. This method is shown in the B-1 program to follow.

After determining the amount of such outages, their approximate placement along the load duration curve has been specified, the job of actually getting these outages into the program remains. The problem with a fixed number of units is not particularly difficult, because once a deck of outage cards is made up little change needs to be made. On the contrary, in planning a study which considers many years, many types and number of new units, there are many required variations in the outage listing. This is because the machine which will have a turbine overhaul varies with years and because the placement of the larger machines in the most optimum portion of the year will vary, depending upon the number of the larger machines. Thus considerable time was being expended to specify outages for each case as nearly as practical to what seems to be the actual practice, if the new machines indicated were in actual operation.

Theory of Loading Used by Program

<u>Determination</u> <u>of</u> <u>Units</u> <u>Running</u>. The reserve routine

determines which of the available units must be operated to carry a specific load. It starts with the unit having priority number 1. It determines whether this unit will supply the necessary load. If not, it goes to the unit with priority number 2 and adds on its maximum, again checking to see whether the total will supply the required load. It continues to add units, skipping over those out for maintenance, until a sufficiently large total is achieved to carry the load. The program then checks further to see if the total of the units put on is equal to the load plus the specified fraction of the largest of these held for reserve. If another unit must be put on to meet the reserve requirements, the program again checks to see whether this unit could have been larger than any previous one put on and, if so, readjusts the reserve accordingly. When the number of units put on meets both the load requirement and the reserve requirement, the program goes on to loading.

Unit Loading

The loading procedure is based on an incremental or loading table stored in the computer. A part of a typical loading table is shown in Table 2.

The minimum block for each machine is at the beginning of the table on the left. Additional blocks of energy are stacked following these minima in order of average incremental cost. The size of these blocks could vary from two megawatts up to ten megawatts. The size of the block is based on the slope of the

Table 2. Portions of a loading table.

Storage location	MACHN	INCLO	INCCO
1	10	09	5369
2	09	13	5588
3	08	13	5588
4	07	13	6026
5	06	26	6452
6	05	26	6452
7	04	15	4075
8	03	15	4075
9	02	32	6688
10	01	32	6688
--	--	--	--
--	--	--	--
70	08	02	0563
71	09	02	0563
72	07	07	2032

incremental curve. The units with practically flat curves can have rather large blocks without there being a very large difference in the incremental cost from one block to the next. Units having steep curves must have smaller sized blocks in order to keep the change in incremental cost between blocks within acceptable limits. This method results in a loading table with a reasonable number of blocks and without an unduly large cost step from one block to the other.

After having determined which units must be operated to meet the load and reserve requirements, the load carried by each unit is then determined. This is accomplished by starting at the bottom of the loading table and going up step by step. Each item in the loading table carries the machine number which will supply this amount of load. The program starts at the first block, which will be a machine minimum. It determines from the reserve routine whether this machine is running. If this machine is running, it adds the megawatts corresponding to minimum into an accumulator. It adds the cost of the megawatts into another accumulator. It continues this on through all the machine minima adding in only those which are running. It then goes to the first incremental block above the machine minima and, if the machine is running, adds in both the load and the cost of this load. The program continues step by step up the table accumulating load and cost of this load. Machines not operating are skipped over and the program goes to the next table's step. After each addition a check is made to determine whether the accumulation of load increments equals or exceeds the specified load. At such time as the total equals or exceeds the required amount, the program stops stepping up the table. If the accumulation of increments exactly equals the required load, then the program breaks out of this loop. If, however, the accumulation exceeds the actual required load, the program goes into an adjustment routine and takes just the required fraction of the last bracket, so that the accumulated totals equal the exact required load. As the program was stepping up the incremental table, the load and cost of each step were added into system load and cost. At the same time, each load and cost was added to the proper unit totals, thus keeping a cumulative total of the load and operating cost on each unit. Bracket information is figured for each unit following the adjustment.

Preparation of Loading Table

Program "A" helps in preparing the incremental table by an IBM-650 program. This program contains the description of all the machines desired in a particular series of runs. This descriptive information specifies unit blocks and the heat input corresponding to these blocks. The program selects the required machines, multiplies the heat inputs by the appropriate fuel costs, and then merges the selected machines to obtain a loading table according to increasing incremental cost. This table is then inserted into the main program (program B).

Number of Machines Accommodated by the Program

The bank on the IBM-650 has 50 words. Thus the program will accommodate up to 24 machines. Consequently each band was split into two parts and since the 25th position on some bands was needed for transfer, this left only 24 words for machine descriptive information. After using the program for a while certain modifications became apparent, which could utilize storage more effectively. The General Electric Company seems to be working on these modifications.

Interconnections

Interchanges can be handled by the program simply by making them inputs in the form of machines of fixed rating. Flow into the system should be simulated by considering a machine of the same minimum and maximum as having first priority for these sections. Placing the machine first in priority would assure that energy from this source would come ahead of any other units. Similarly, energy flowing from the system could be handled by minus quantities. For example, a machine of minus 20 megawatts minimum and minus 20 megawatts maximum could be set up. Again such a machine would be placed first in priority if this were a firm interchange amount.

Such interchanges commonly occur when agreements are made with a neighboring company, so that company "A" will supply energy to company "B" when company "B" has one of its major units out for overhaul. Company "B" will return the energy to company "A" when company "A" has its major unit out for overhaul. This shows that such interchange of energy would materially postpone the installation date of new machines because of the ability to obtain energy from the neighboring company during the time when largest amount of generation is out for maintenance and overhaul. The economic value of such an agreement can be readily evaluated by this program.

Other types of interchange could also be simulated by placing a machine higher in the incremental table. Such an interchange simulating machine would come into use when the load reached this level, but would not be used at lighter loads. It is also possible to place a block of interchange energy at the lowest priority position. This then would not be called on unless at some time the system was short of reserve. If this block were placed on with a minimum of zero, and the maximum of some desired quantity, then the unit could be called on for reserve and still not deliver any energy.

A typical program for estimating system fuel costs based on actual or estimated loads is shown below. This program recognizes maintenance outages and estimates of forced outages.

Some of the program uses are as follows:

1. Fuel cost for unit installation schedules having different unit sizes and types may be compared.
2. Economy of interchange contracts may be evaluated.
3. The real time version may be used for maintenance scheduling by determining costs of unit outages at various load levels.
4. Actual hourly loads may be fed in to determine the theoretical fuel consumption for comparison to actual consumption.
5. Short- or long-term fuel consumption at each plant may be estimated for budgeting.
6. Unit operating hours may be estimated for planning plant manpower.

Comparison of Annual Fuel Cost

The program may be used in several ways to determine annual fuel costs.

1. Hourly loads together with the units available each hour may be fed in.

2. Monthly load duration curves may be used.

3. Annual load duration curves may be used.

In the above cases the primary difference is in the amount of computer time required. Simulation of one year on the IBM-650 seems to require approximately the following times.

	Method		Running time, hours
1.	4,380 -	2-hour time period	2
2.	12-40	section monthly load duration curves	1/2
3.	1-100	section annual load duration curve	1/10

Monthly load duration curves are prepared. Hourly loads are punched into cards which show the year, month, hour, and system load. All of these cards for a certain year are restored according to load. A sequence number is assigned to each card calling the highest load 1 and the lowest load 8,760. By calculation a bracket number is determined with the first 88 cards being bracket one and the next 87 being bracket two, etc. Thus bracket numbers from 1 to 100 are placed in each card to show where that hour's load fell during the year. Then the cards are restored to chronological order and a print-out made showing the bracket in which each hour of the year fell. Typical scheduled outages for spring, fall, or summer months are selected. A count is made of the number of hours falling in each of the 100 brackets during the days of scheduled outages. By dividing the outages into eight groups having equal numbers of hours, it could be seen how the distribution fell over the load duration curve. As it may be expected, the maintenance periods falling in summer or winter tended to be rether uniformly scattered from the top to the bottom of the load duration curve. Consequently, en outage et the middle of eech of the eight blooks appeers to reasonebly well represent the scheduled outagea. The distribution further shows spring or fell meintenance periods es alightly lower on the loed duration curve. Consequently, outages pleced a little lower edequately represent theae apring or fall outages.

Input Data

Three diatinct forms of the program oen be written. These differ primerily in the form of the input deta required. Theae three versions and the required input deta for eaoh veraion ere furnished below.

I. B-1 progrem (original progrem with minor modifioetions)

1. Loading teble (1/o or with m-2, 7/c) (up to 400 words)
2. Priority table (up to 25 carda)
3. Cese card (1 cerd)
4. Fuel cost card ($/ton) (1 card)
5. Section deck (with mechine outagea on each cerd). (One card for eaoh section--100 carda for 100-point load duration ourve.)

II. B-1 with m-11 and m-12

Same aa for 1 except the mechine outage need not be on each card in the section deck. They are on seperate outage cards merged with the section deck.

Outages remain tha aeme until a new outage csrd ia reed. This progrsm is used primsrily for reel-time aimuletion where the machinea out ere the seme for meny sections.

III. A, B-3 (B-3 ia B-1 with m-10)

1. Priority tsble (with outege blocka for eech unit)
2. Fuel coat card (¢/10^6 btu)
3. Cese cerd
4. Fuel cost cerd ($/ton).

The loeding teble conteins the unit incrementel cost information, while tha priority teble contsins the retinga of the units end the order in which the units are to be placed on the line. The period dete containa information epplying the entire period such es e year, end the section date conteins that information epplying to eech saction, such es each of tha 100 aactions into which en annual load duretion curve mey be divided. The deteiled items contained in eech will be describad es follows.

Incremental Teble

The incremental teble is the most importent thing in e progrem. The incrementel tebla on cerds from e previous calculetion mey be loeded into storage in eithar seven words per card or one word par oerd form. The table mey elso be celculeted directly by progrem A.

Eech word of the table conteins e two-digit maohine number

(MACHN), a two-digit number showing the size of the step (INCLO), and a six-digit number showing the dollar cost of this step (INCCO). The cost is shown to the nearest cent and may thus be as much as $9999.99.

Priority Table Deck

The deck contains one card for each generating unit included in a given case. Each card describes the properties of one unit, and covers the following items.

1. The maximum rating of the machine (MAMAX).
2. The minimum rating of the machine (MAMIN).
3. The machine number associated with the particular unit for this priority table (MACHN).
4. The conversion word which contains the following:
   a. Plant number with which this unit is associated (PLANO)
   b. The unit number of this unit within the plant
   c. The priority sequence in which the unit is to be put on (PRINO)
   d. The description number which identifies the incremental heat rate data used to prepare the incremental cost blocks (DESC).
5. The number of machines in this priority table.
6. The table number.
7. Outage blocks (OUTBL), (required only for program B-3).

The last card of the priority table is an end-of-table card.

In the PRINO position it conteins tha next number in the priority sequence. Thia is required to get the card past the input checka. In the MACHN position it containa a 25 regardlasa of the number of the last mechine. Tha 25 is usad to aignal the end of tha table loeding aequence and to go to the next portion of tha program. Whan uaad with tha B-3 program, the OUTBL of this last card muat heva a "9" in the high-ordar position. (Sea Table 3).

Pariod Input Cards

Tha period input for each of thaae casaa consists of two cards. The firat of thesa two carda containa the following itema:

1. Casa number (CASNO).
2. Number of hours in the period (PH).
3. The paek loed for tha period (Load P).
4. The frection of the largast unit to ba meinteined on reserva (RESF).
5. The present worth factor for the period (PWF).
6. Tha fual cost for plant 8 (PFC-8).
7. The fual cost for plant 9 (PFC-9).
8. A cerd identification 8 in Column 71.
9. For identification only a yaar may ba punchad on Column 79-80.

Tha aacond period input card contains the following information:

Teble 3. Priority table.

MAMAX	MACHN	MAMIN	OUTBLS	No. of mschines	CASNO	PLANO	UNNO	PRINO	NESC
139	1	32	10 20	10	6783	1	01	1	1325
139	2	32	11 16 21	10	6783	1	02	2	1325
46	3	15	12 22	10	6783	2	01	3	1375
46	4	15	13 23	10	6783	2	02	4	1375
72	5	26	14 24	10	6783	2	03	5	1425
72	6	26	15 25	10	6783	2	04	6	1425
100	7	13	17 27	10	6783	3	05	7	1475
33	8	13	13 18 28	10	6783	4	04	8	1525
33	9	13	19 29	10	6783	4	03	9	1525
23	10	09	14 30	10	6783	4	02	10	1575

1. The section number (SECNO).
2. The loed duretion multiplier (LBM).
3. The number of hours which the section represents (SECH).
4. Outege word number one (OUT 1).
5. Outage word number two (OUT 2).
6. The deck number (including e modificetion numbe r).
7. The month and/or yeer which the section deck represents (MOYR).
8. The continuous machine sequence number (CMS).

Teble 4. A semple of section input deck.

SECNO	SECH	CMS	LDM	OUT 1	OUT 2	YEAR	Deck No.
1	87.6	03	1000	00		64	29
2	87.6	03	898	08		64	29
3	87.6	03	888	00		64	29
4	87.6	03	878	00		64	29
5	87.6	03	868	00		64	29
6	87.6	03	858	00		64	29

Load Duration Multiplier (LDM)(X.XXX)

The load for each section is obtained by multiplying the peak load (Load P) by the load duration multiplier (LDM). By changing the peak shown on the period input, the same set of information in the section cards may be used as long as the load duration curve remains the same.

Hours Represented by the Section (SECH)(XX.X)

This three-digit number tells the number of hours to the nearest tenth which is represented by the section. In the annual load duration curve approach with 100 sections, each section is usually taken as 87.6 hours. It is possible to use 100 or any other number of sections with unequal hour increments. Unequal increments may be used to obtain greater resolution near the peak of the load duration curve, where the number of hours may be quite small.

<u>Outage One (OUT 1)(11 22 33 44 55)</u>. OUT 1 is the first outage word and in a 650 program contains 10 digits. This 10-digit word can specify as many as five units being unavailable. Each unit is specified by punching its two-digit machine number in the outage word. If the number of outages exceeds five, the additional ones are punched in OUT 2, which is identical in form with OUT 1, and for input purposes it may be considered as the second half of a 20-digit sequence. OUT 1 must not be all zeros if there are any outages in OUT 2, for the outage routine

will stop looking as soon as it finds a word of all zeros. OUT 3 is placed in the program to stop the search for outages in the case where OUT 1 and OUT 2 are filled. Otherwise, the program never reaches OUT 3. If more than 10 outages are desired, it is possible to place additional ones in OUT 3 by continuing on into this word if the next word can be made all zeros.

Section Number (*SECNO*)(*XXXX*). Each section input card should carry a number and these numbers should be in sequence. This number is the order in which the sections are run. This number is used in the program only in two situations. If detailed output is obtained for each section, such output is then identified by this section number. A second situation is that in which the machines available are not adequate to maintain the required load or reserve. In this case a card is punched out showing the amount of deficiency and is identified by section number.

Program Output

Various details are available in the output from the program. The most complete program will punch out cards for each unit, for each section, showing the load carried by each unit, and the corresponding cost for that section, as well as the summary cards at the end of the period.

System Information. The normal output from the program punches cards for system information, plant information, and unit information. The cards for system information show the following items:

1. Month and year.
2. The system megawatt hours.
3. The fuel costs for these megawatt hours.
4. The present worth of this fuel cost.
5. The number of hours in the period as well as two check totals on hours.
6. The average cost in dollars per megawatt hour for the period.

Plant Information. The type 2 plant cards show the following:

1. Total number of megawatt hours generated by the plant.
2. The cost of these megawatt hours.
3. The quantity of fuel required to produce these megawatt hours.
4. The cost per unit of fuel.
5. The average cost per megawatt hour for the plant.

Unit Information. The type 3 unit output cards show for each unit the following:

1. Unit number, description, priority number, and the plant location.
2. Ratings of the unit, namely, the maximum and minimum.
3. Megawatt hours produced by the unit.
4. Cost of these megawatt hours.
5. Capacity factor.
6. Average dollar per megawatt hour.

A second card for each unit, card type number 4, shows bracket information for each unit. This includes:

1. A description of the unit similar to the previous unit card.
2. The number of hours under each of the following conditions:
    a. The additional time the unit would have been operated if it had been available whenever required
    b. The time the unit did not operate
    c. The time the unit operated at minimum load
    d. Time in the 0-1 bracket
    e. Time in the 2-3 bracket
    f. Time in the 4-5 bracket
    g. Time in the 6-7 bracket
    h. Time in the 8 bracket
    i. Time in the 9 bracket
    j. Time at maximum load.

Description of Unit Bracket. To obtain an idea of the number of hours the unit would operate at various loads, a set of bracket calculations has been included. Such information may be useful in planning new units, for determining the type of feed pumps, fans, and other auxiliary equipment which should be installed for most efficient operation. The bracket calculation permits a step-type load duration curve to be drawn for each unit based upon nine different steps between the maximum and minimum of the unit. The meaning of the above mentioned brackets is as follows.

$$\text{Ratio} = \frac{\text{Load - Min}}{\text{Max - Min}}$$

<u>Order of Output Cards</u>. The order in which the cards are punched by the program is not at all a good order for listing them. The first card or cards which may come from the program are those punched during the running of the case showing a shortage of the system reserve, or in some cases system load capability. The cards obtained for the summary are in order by machine number and plant number. They should be sorted by card type number before listing. Heading cards are sorted in at this time. Figure 37a illustrates a typical generation system cost program.

COMPUTERS IN POWER SYSTEM RELIABILITY PROBLEMS

In this section the application of the reliability calculation techniques to actual power system networks will be discussed. Also a digital computer program to facilitate reliability calculations is to be described, and a comparison of calculated and observed reliability on an actual system shall be presented.

Application of Calculation Methods

<u>Indexes of Reliability</u>. It is a well known fact that no single measure of system reliability can completely describe a system's ability to give satisfactory service. Therefore a

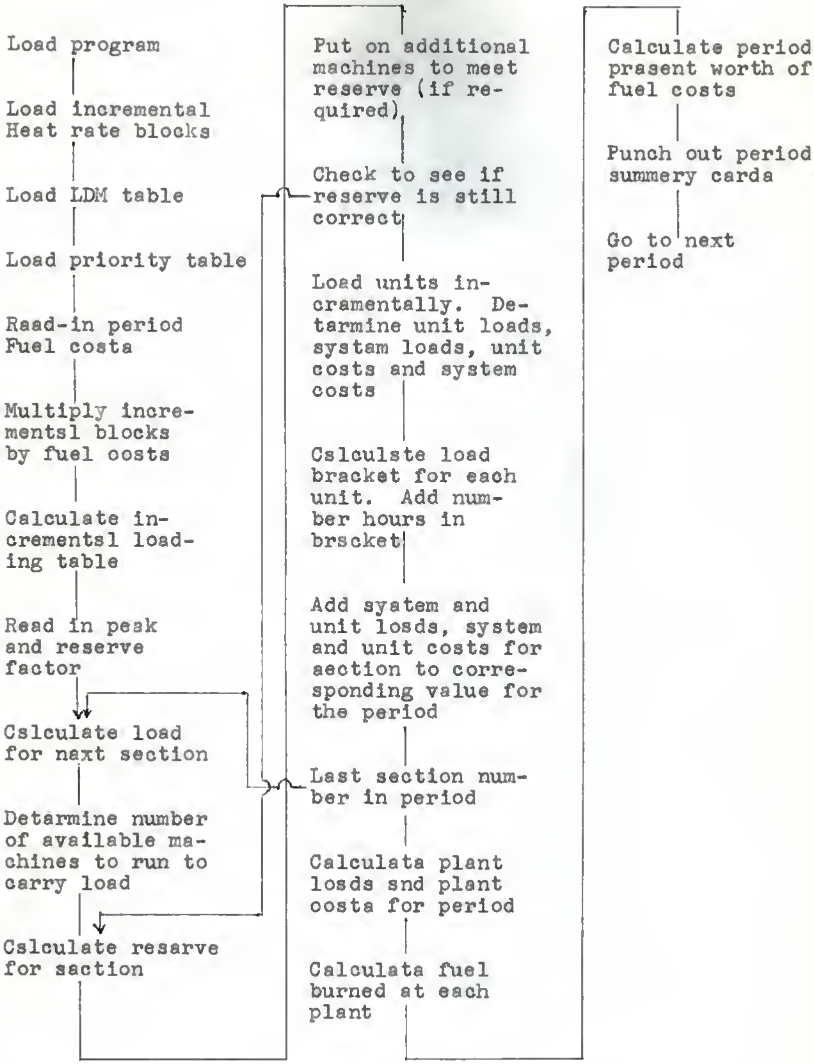


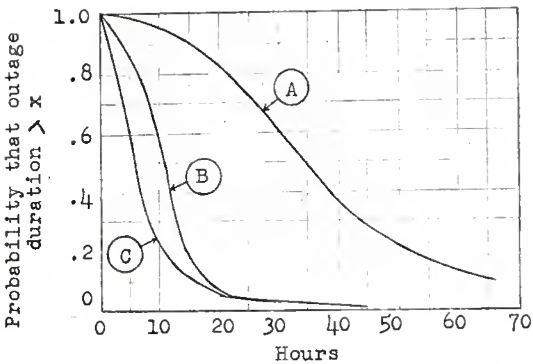
Fig. 37a. Generation system fuel cost program.

number of important indexes of system reliability together with the methods for calculating them have been proposed. These indexes are as follows:

1. Average number of service interruptions per customer served per year (often referred to as average interruption frequency).
2. Average customer restoration time per customer served per year.
3. Average total interruption time per customer served per year.
4. Maximum expected number of interruptions experienced by any one customer per year.
5. Maximum expected restoration time experienced by any one customer.
6. Probability that any customer will be out of service at any one time longer than a specified time.

In the above list the first three quantities represent measures of average service reliability, and the last three quantities represent the poorest service reliability afforded any customer on the system.

System Component Data. In calculation of various system reliability measures, two basic types of line and equipment data are necessary. These data are outage rates and outage duration (repair time) distributions. Table 5 and Fig. 38 show outage rates and outage duration data for subtransmission and distribution system components obtained from operating records for 1960-1963 by an electric utility. Data shown for transformers,



(A) Permanent underground cable.

(B) Prearranged overhead and underground.

(C) Permanent open wire.

Fig. 38. Distribution of outage durations for subtransmission lines.

circuit breakers, and regulators is supposed to be regarded as estimates as too few outages were observed during the four-year data-gathering period to permit outage rates or durations to be determined exactly.

The "permanent" outage statistics of Table 5 and Fig. 38 are said to have been extracted from punched-card outage records. The term "permanent outage" indicates that the faulted component must be repaired or replaced before it can be restored to service. The repair times given are the times to actually perform such repairs or replacements. Failures which are not of severe nature and which have occurred during less severe storms are shown in Fig. 38. The data in Fig. 38 does not include "disaster type" storms. As a matter of fact, these "disaster type" storms are defined as storms which interrupt at least 10 per cent of all customers served. The main reason for the exclusion of this data is because of its unavailability. "Maintenance outage" is the term used to describe prearranged outages to maintain, replace, or rearrange components. Maintenance outage rates and duration shown in Table 5 and Fig. 38 were obtained by analyzing a random sample of daily operation reports. Due to a number of prearranged outages, sampling has been adopted as the best way to estimate maintenance outage data at a reasonable cost.

"Temporary outage" is defined as an outage that clears itself; that is, any faulted component can be restored to service by a reclosing operation or by replacing a fuse.

Service restoration time often depends on the sectionalizing or switching arrangement of the supply ayatem. Restoration times which follow temporary component outage era the intarvals required to parform tha necesaery raclosing oparation or to replece e blown fusa. If awitching operetion permita an interruption to be restored bafore faulted componenta can ba rapaired or raplaced, switching time becomas the effective repair time of the components in question. This affactive repair tima is then tha rapair tima used in the raliability calculation mathods.

Distribution of Repeir Times. The data in Fig. 38 shows that tha rapair timaa for opan-wire circuita are roughly exponantially distributad, while the repair times for cable circuita and maintenenca outage durations ere naarly normally distributad. Thus e study has been conducted on parallel aystama' calculation mathods. This study on a simple system consisting of two parallal linea feading a aingle bus leads to the following conclusions.

1. Any syatem which has two parallel paths has its outage rata essentially indapendent of tha individual componant's distributional form of tha outage durationa.

2. The average velue of outage durations for a system consiating of two parellal peths is independent of the distributionel form of componant outaga durations. Howavar, for thia condition, auch component outaga duration diatributiona ahould be identical ragardless of distributional form. When a componant forcad outaga overleps a componant maintanance outage, then tha condition of identical outaga duration diatribution is not fulfillad. In such a caaa, if wa assume that both component

outaga durationa era axponantially distributad, then tha method of detarmining tha expectad velua of duretion is eomewhet in error. In the casa of calculations mada on tha baaie of exponantiel component outaga duretion dietribution, thara may be 15 to 30 per cant ovar eetimatas of tha axpactad valuaa of outage duratione ea compered to more accurete calculations. However, thie magnituda in arrors ie not considerad as importent eince errors in data may be of greater magnituda.

Sample Network. A typicel subtransmiseion network aupplying e 4-kv eubetation, as shown in Figs. 39 and 40, hea been used to illustrata the mathod of raliability calculetion mathods, and also to permit a comparison batwaan obsarved and calculeted reliebility indaxae.

Raliability Diagrams and Expressions. The first atep in calculating the index of eervica raliability is tha visuelization of reliebility diagrems for each bua or point in the syatam at which raliability ie to ba calculatad. Theaa diagrams give en idea about the connactiona of componanta in raliebility sanea ee to how thay ere formad into sariee and parallel paths of supply to a bus. Four diffarent reliability diagrame ere required to completely daacriba tha raliability parformance of each bue. Thesa four diagrams are callad the permanent interruption diegram, tha manual-ewitching diegram, and the automatic awitching diagrams for tamporary and permanant component outegea. The permanent intarruption diagram ia usad in the calculation of service intarruptions dua to parmanent componant outegaa which can only be raatored by repair or raplecamant of ona or mora

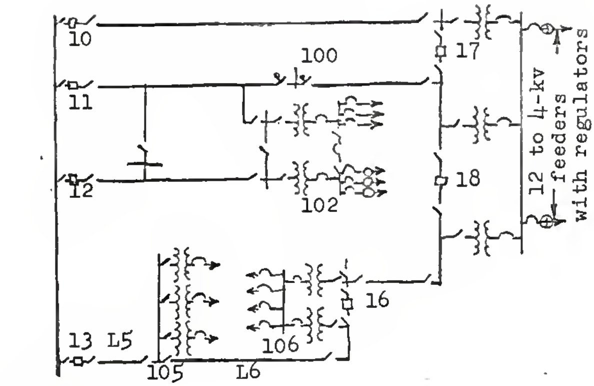


Fig. 39. Typical subtransmission network supplying 4-kv substations, first period, 1960.

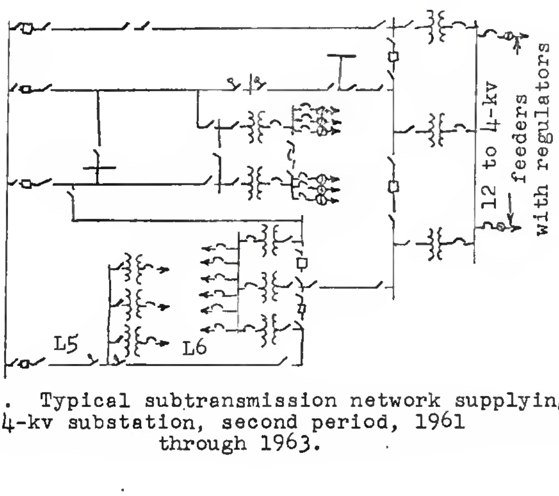


Fig. 40. Typical subtransmission network supplying 4-kv substation, second period, 1961 through 1963.

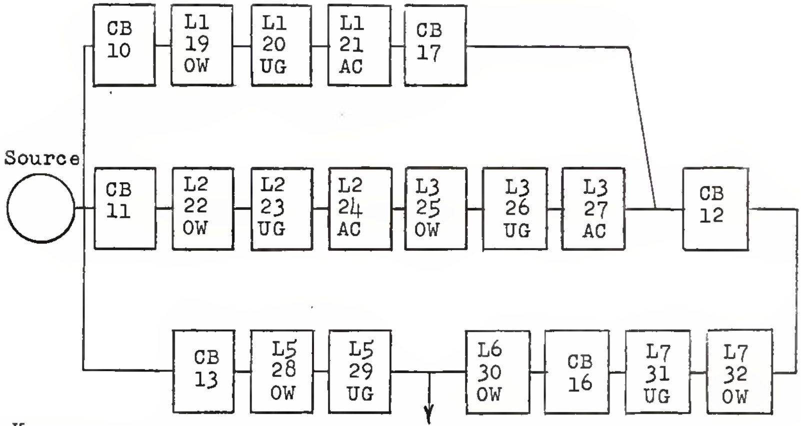
components. The menuel-ewitching diegram is ueed for the cel-oulation of servioe interruptions caused by either temporery or permenent component outegee which cen be restored by menuel re-closing, eectionelizing, or ewitching operetions. The eutometic ewitching diegrems for temporery end permenent component outeges ere used in the celculation of interruptions due to temporary end permenent component outeges, reepectively, when euch inter-ruptione cen be reetored by eutometio ewitohing operetions.

Let ue coneider en exemple for underetending cleerly the preperetion of reliebility diegreme. Coneider bus 105 of the semple network shown in Fig. 39. Considering the undermentioned types of components to be fallible, reliebility diegrems ere to be drewn: open-wire circuits, treneformere, circuit breekere, and underground end eeriel oircuits. Bueee end ewitohee ere to be considered infallible, just for the purpose of thie exemple. The mein reeeon for thie lest eseumption ie leok of relieble dete; however, the feilure rete of theee componente ie very smell. The "eource" bue for the semple network ie teken ee the reference bus for the diegreme; reliebility of eupply to the eource bus is not evelueted.

Figure 41 illuetratee e permenent interruption diegrem for bus 105. Permanent interruption ie one whose duretion depende upon the time required to repeir the feulted componente. Theee cen occur only if lines L5 end L6, or componente in eeriee with these lines, suffer overlepping permenent outeges. Therefore bue 105 is shown oonnected to the eource through two complex parallel peths. Elements in eeries in e path indicete thet the outage of any element will cause an outage of the path. Component repair times for use with the permanent interruption diagram are the times to actually repair or replace faulted components.

Figure 42 illustrates the manual-switching diagram for bus 105 of the system of Fig. 39. A single permanent outage of Lines L5 or L6, breakers 13, 14, or 16, or transformer 15 will interrupt bus 105 until an operator can isolate the fault and restore service through the unfaulted path with manually-operated disconnect switches. Therefore bus 105 in the diagram is shown connected to the source through a series path composed of the elements mentioned above.

The automatic switching diagram for temporary component outages for bus 105 is the same as the diagram drawn for manual switching. A temporary outage of any element in the diagram of Fig. 42 will cause a temporary interruption to bus 105. The duration of the interruption will be the time to perform a reclosing operation. An automatic switching diagram for permanent component outages does not exist for bus 105 of the system of Fig. 39. This is because bus 105 cannot be isolated from faulted circuits with automatic devices. However, when motor-operated switches are installed at bus 105 in the system of Fig. 40, an automatic switching diagram for permanent component outages does exist. However, the diagram is the same as that of Fig. 42, since a permanent outage of any element in that diagram will cause an interruption to bus 105. The duration of interruption will be the time to perform a sectionalizing



Key
OW = opan wire
UG = underground cabla
AC = aarial cable
CB = circuit braakar
TR = transformar

E = aquivalent
B = bus
p = parallel
S = saries
N = No. of customers
served from bus

Fig. 41. Parmanent interruption diagram, aquivalent and succass expressions for bus 105.

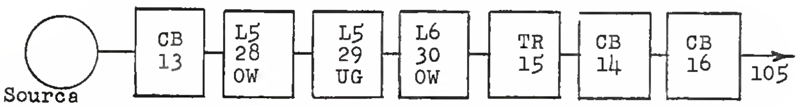


Fig. 42. Manual-sactionalizing diagram, equivalent and succass axprassions for bus 105.

operation at bus 105 with the motor-operated disconnect switches.

Calculations for the Sample System

Calculated and obaerved indexes of reliability of subtransmission network shown in Figs. 39 and 40 will be compared for purposea of atudy. Calculations for subtransmission aubstation transformer portions of the syatem were performed by the reliability calculation computer program in accordance with the equations that have been developed by various authors. The input data for this program inolude aucceas and equivalent equations for each bus similar to those shown in Figs. 41 and 42 for bus 105. The output includes reliability indexea for each bus plus indexea indicating average reliability of the complete sample network.

The above mentioned "aucoess" and "equivalent" expressions are used to represent bua reliability diagrams for input to the reliability calculation computer program. These expressions can often be written down by inapection, thereby eliminating the need for drawing reliability diagrams after some experience in system reliability analysia has been obtained. Proper "succesa" and "equivalent" expressions for bua 105 of the aample system are shown beneath the diagrams of Figs. 41 and 42.

Subtransmiasion and Substation Syatem Characteristics

The observed values of these indexes are compared with certain calculated indexes for thia sample subtransmission substation network. The characteristics that should be considered in selecting these indexes are as follows:

1. It should be considered that the outage of any single component rarely causes interruption of service to customers. Such transmission substations are completely redundant. However, reliability comparisons for redundant systems are much more difficult than for nonredundant systems since many more years of experience are necessary to obtain dependable statistics. Thus the most suitable comparison appears to be between calculated values for the sample network and observed values for the entire system.

2. Records of average customer interruption frequency and restoration time are available for the entire substation subtransmission system; these particular measures of reliability can be selected for this comparison.

3. Because of the arrangement of the sample network, customer interruption time will practically always be less than two minutes for temporary component outages or where a single permanent outage can be cleared by automatic sectionalizing. Such cases can be excluded from these sample calculations.

Comparison of Calculated and Observed Reliability

In the above discussion, the reliability indexes selected for comparisons are the customer interruption frequencies and restoration times for cases where service is interrupted by permanent faults and then restored by either manual switching or component repair. Calculated indexes for the sample network and observed values for the entire system are shown in Fig. 43. In this figure the first bar chart shows that the calculated interruption frequencies for the sample subtransmission substation network agree pretty well on the average with values for the entire subtransmission substation system. This indicates that the method of calculation is reasonably valid.

The second bar chart in Fig. 43 shows that the calculated restoration times for the sample network are somewhat higher than the actual experience on the entire system. This is because of the use of many expedients like temporary cutovers and mobile substations by the operator for restoring immediate service. This is the reason for overestimated restoration times. This indicates that more realistic repair times must be derived from the outage data or estimated to improve the calculated restoration times.

Table 6 indicates four-year averages of frequency and restoration times for the sample network compared with the actual experience on this network and with system-wide values. The data about the sample network obtained on basis of experience is primarily determined by a single substation outage during a four-year period. This type of record is not a good basis for comparison. However, results happen to be pretty good.

Effect of Storms. The effect of outage "bunching" due to storms is an important factor for utility operators. The average annual reliability indexes calculated with the outage data on Table 1 are not sensitive indicators of this effect. Separate

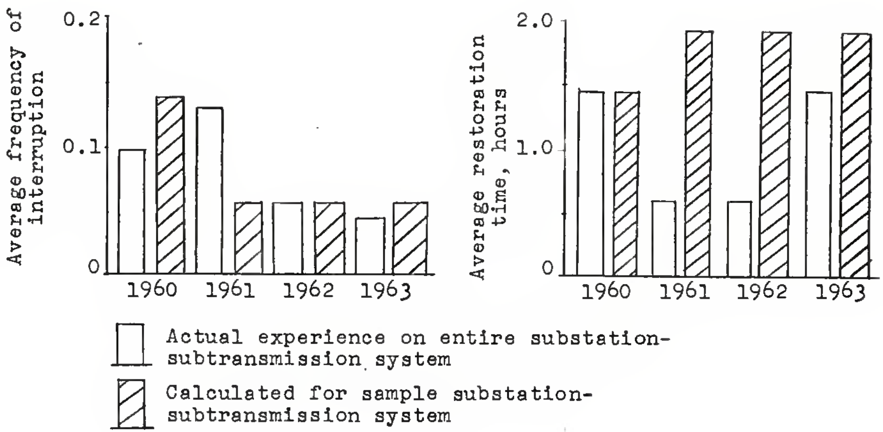


Fig. 43. Reliability indexes for substation-subtransmission systems.

indexes of reliebility for storm periods ere desirable.

Outages Due to Overloads. As mentioned earliar, tha existing subtransmissaion system is normally dasignad so that the outage of one path will not ovarload any of the remaining parallel peths. However, the affact of overloads which might occur due to the outage of parallal paths is a factor to be considared when compering expansion plans for such a system. Ona particular mathod of calculating the numbar and duration of intarruptions due to thesa ovarloads has bean incorporated in the computer program. This method ia basad on the assumption that if the outage of two paths, or even ona path, supplying e bus increasas the load in ona of the rameining paths above its meximum capacity, than load on that bus ia droppad to relieve tha overload.

Tha data necessary to astimate the probebility of such ovarloads ara as follows:

1. Tha ennual peak load on the most critical parallel path which ramains in service. For complex networks e load flow analysis will usually be nacessary to datarmine the critical loads.
2. Elemant capacitias corresponding to these critical loads.
3. The probability that contingancy loads can be successfully cerriad. Thia ia e fector which accounts for the fact that loads era less than tha annual peak during a substantial portion of the year. This probability dapands on tha duration of tha outage perioda and the

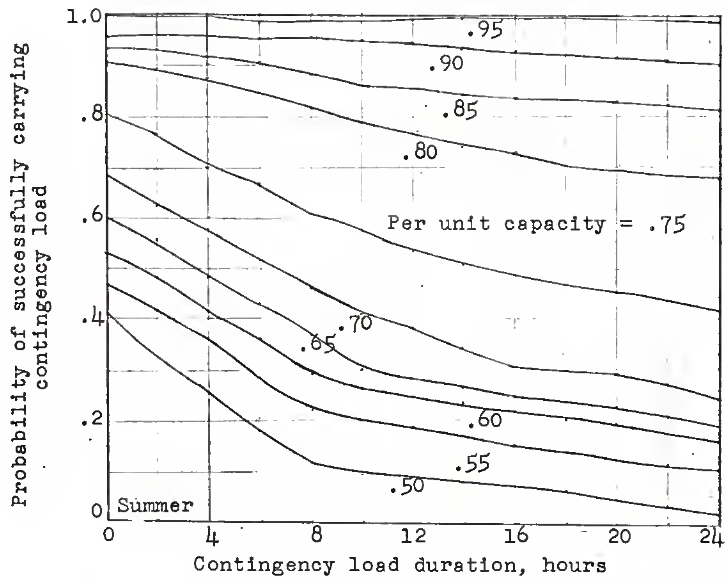


Fig. 44. Probability that contingency load can be carried successfully, May through October.

relative values of load to capacity for the critical elements. One possible assumption is that component capacity is constant over the year. The earlier assumption that a component, once overloaded, remains out of service until a failed parallel component is repaired and restored to service proved too pessimistic. This is especially true when the failed component has a long expected repair time. The reason is that load does not usually stay at a high enough level to cause overloading for a period as long as most repair times. Further, switching procedures can usually restore most load dropped because of an overload in a reasonably short time. Therefore the reliability calculation computer program has been modified to set overload outage durations equal to an input value, if the expected repair time of a faulted parallel component exceeds that time.

Computer Program for Reliability Calculations

A program for an IBM digital computer is developed to calculate reliability in general power system networks using the methods discussed above. This program calculates various measures of service reliability as seen at each load bus specified for a system, then calculates measures of reliability which are descriptive of the average reliability provided to all customers served by the system. A simplified logic flow diagram of the computer diagram is shown in Fig. 45. Also extensive data checks are made in the program to insure insofar as possible that correct data is used in this case.

Input Data. Input data for the reliability calculations program is separated into six groups or decks, namely, title and miscellaneous, element type data, element specifications, matrix of probabilities of successfully carrying contingency load, multiple path overload outage data, and equivalent and success expressions. The specific data required in each data group is given below.

1. Title and miscellaneous
    a. One 72-character title card
    b. Expected value of duration of fair weather period in years
    c. Expected value of storm duration in years
    d. A time "t" in hours (one measure of reliability which is calculated for each bus in the system is the probability of a single interruption longer than t)
    e. Maximum overload outage duration in years.
2. Element type data. Each type of system element which exhibits distinctive failure and repair characteristics and which is to be represented in the reliability calculations is assigned a type number. The element failure rates in per unit of the appropriate dimensions of this type of element (miles of line, number of transformers, etc.) and repair and maintenance time are given for

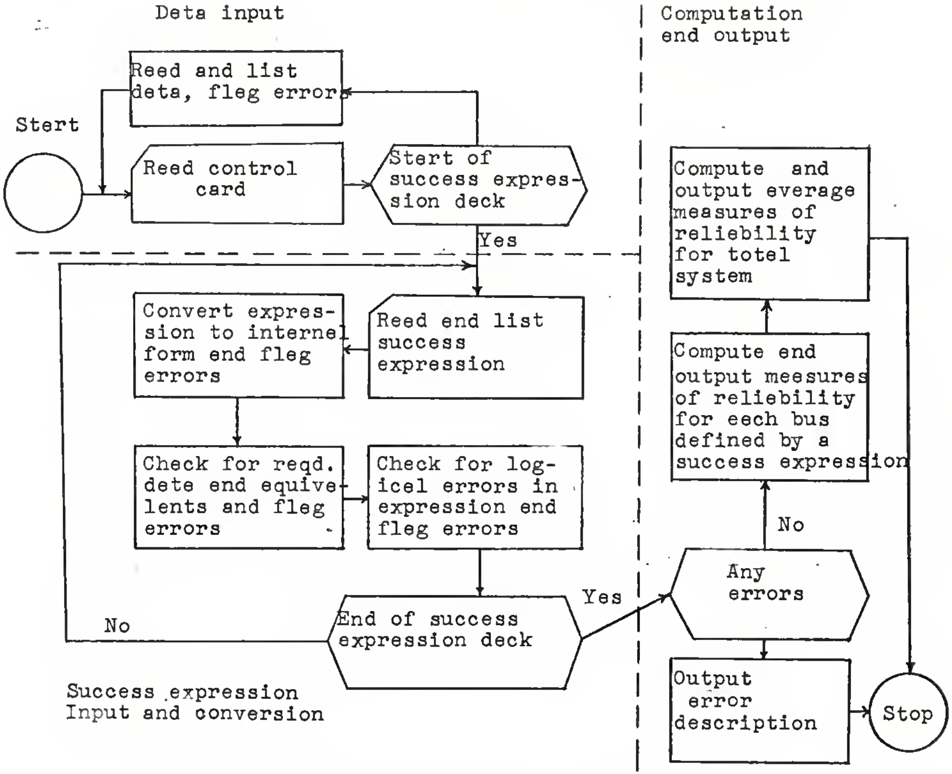


Fig. 45. Simplified logic flow diagrem of reliebility celculetion program.

each element type.

a. Fair weather failure rate in failures per year of fair weather per unit

b. Stormy weather failure rate in failure per year of stormy weather per unit

c. Maintenance outage rate in outages per calendar year per unit

d. Expected value of forced outage repair time in years

e. Expected value of maintenance outage duration in years.

3. Element data. Each system element which is to be uniquely identified is assigned an element number; then the following data is given for each element.

a. Element type number

b. Capacity of remaining parallel paths should this element fail

c. Peak load on remaining parallel paths should this element fail

d. Dimension of element (i.e., miles of line).

It is to be noted that (b) and (c) can have any units, but units must be consistent.

4. Matrix of probabilities of successfully carrying contingency load. This matrix consists of a set of probabilities of successfully carrying contingency load as a function of the per unit capacity of remaining elements and contingency load duration. The matrix represents a

femily of probability curves such es thoea shown in Fig. 44.

5. Multiple path ovarload outaga data. If it is dasirad to calculata ovarload outagas in a system having more than two lines or paths in perellal whara overloads can occur only if two paths are out of service at the eame time, equivelent expreesions must be spacified for eech parellel path. Than for aach possible pair of aquivalents unavailebla tha cepacity of end tha peak load on the remeining paths are specifiad.

6. Equivalent and succese expreseione. Exemples of equivalant and euccess exprassiona and tha form in which they ara to ba written ara preeented in a numbar of publications. Tha primary function of aquivelent expreesions ia to raduca oelculeting end succese expreeeion writing time by raducing complex portione of the system to eingla equivalant elements. Succees exprasaeions dafining tha supply syetam configuretion ere required for each bus for which raliability is to be calculatad. Each euccess axprassion ie eubecriptad with the identifying number of tha bus baing studiad and the number of customere or kw of loed earved from the bus.

<u>Program</u> <u>Output</u>. The output of the reliability calculation program consists of a liating of all input data, measuras of reliebility calculated for aech bus in the system and ovarall maesures of reliebility for tha system. Averaga eyatam maesuras of reliebility are celculatad by evaraging the meeeures of

reliebility celculsted for ell buses in the system weighted sc-cording to the number of customers or kw of loed served. Output dste for eech bus is es follows:

1. Annual interruption rete.
2. Expected vslue of duretion of s eingle interruption will exceed "t" hours.

Output dete on totsl system reliebility is ee follows:

1. Aversge ennuel interruption rste per customer served.
2. Average duretion of s single interruption in hours.
3. Averege ennuel interruption time in houre per cuetomer served.
4. Meximum ennusl interruption rete for sny bus in the system.
5. Meximum expected velue of duration of s single inter-ruption for eny bus in the system.

CONCLUSIONS

Increeeing emphasis within the electric utility industry is being pleoed upon improvement in economic system performsnce, both with respect to fuel snd menpower expenditures. The in-cressing number of interconneotions offers opportunity for system sevings but requires sdditionel calculetion end eccounting to secure the meximum power pool benefite. The digitsl procese control computer offers sn importent function, in effecting improved eystem performsnce by providing sutomstic meens of solv-ing a wider renge of eystem opereting probleme then previouely

Table 5. Outage rates and average repair times for subtransmission distribution system facilities.

Outage type	Facility	Unit	Rate: Normal outage per unit per year of normal weather	Rate: Stormy outages per unit per year of stormy weather	Average repair time hours
Permanent forced outages	Subtransmission open wire	Per mile	.045	1.7	8
	Underground cable	Per mile	.110	--	34
	Aerial cable	Per mile	.050	--	34
	Circuit breaker	Per 3-phase breaker	.003	--	6
	Transformer	Per 3-phase transformer	.003	--	48
	Time for manual switching operation				0.9
	4 kv				
	Open wire	Per mile	.045	3.2	2
	Regulator	Per regulator	.005	--	0.8*
	Circuit breaker	Per breaker	.005	--	0.8*
Maintenance (prearranged outages	Subtransmission Open wire and underground cable	Per mile	2.0	--	11
	Circuit breaker	Per breaker	0.7	--	1.5
	Transformer	Per transformer	1.0	--	1.2

*Time to transfer feeder to spare position.

Table 6. Comparison of calculated reliability indexes with system experience.

	Frequency	Restoration time
	Average number of interruptions per customer served per year due to outages of subtransmission or substation components	Average number of hours service is interrupted, per interruption, due to outages of subtransmission or substation components
Actual experience Entire system 1960-1963	.08	1.0
Sample network 1960-1963	.04	0.9
Calculated for sample network	.08	1.7

feasible through analog computer means. Most important thing is the flexibility of the digital computer to readily encompass new theoretical concepts and aids to system operation without requiring fundamental changes in the hardware systems.

Some of the methods of computer control which accomplish the simultaneous and automatic maintenance of frequency net interchange, and economic allocation of generation for typical operating systems are discussed. These automatic dispatching systems provide the following advantages for savings over manual or semiautomatic methods.

1. Decrease in expenditure for fuel.
2. Rearrangement of personnel previously employed in duties now performed by the dispatching system.

A discussion has been presented on the decentralized approach to obtaining automatic economic operation of interconnected areas. This decentralized approach involves comparison devices which by comparison of appropriate cost between areas determine the economic interchanges of the areas. Each of these areas has a computer controller arrangement. Any number of interconnecting arrangements for the comparison of cost can be designed depending on the fancy of the designer. Any number of areas can be connected in a grid system, and controlled by the multiarea computer. The multiarea computer accomplishes the following calculations.

1. Economic allocation of generation within each area.
2. Economic interchange between areas.
3. Weighted incremental costs at boundaries for

interconnection eccounting.

4. Incremental cost of wheeling losses.

5. Power flowe over individusl tie linee.

A broad besed discussion on writing computer progrems is included. This includee diecuesion of progreme for genereting system fuel coet celculetions end plenning meintenance echeduling. Techniques for spplying reliebility celculetion methode ere discussed. Theee techniquee permit the reliability of proposed system deeigns to be calculeted end compered quentitetively with thet of exieting syetems or alternetive proposed syetems.

Apsrt from the ebove few topics discussed, computers csn be used in almost ell the brenches of aystem design. A few of the importsnt ones where studiee cen be conducted ere hydrothermsl economic scheduling, optimized dietribution and subtransmiseion plenning, optimizetion of trsnemiesion voltsgee, eutometic remote reeding of residentiel metera, end other erees.

ACKNOWLEDGMENT

The author wishes to express his sincere gratitude to his Major Professor, Melvin C. Cottom, for his guidance and helpful assistance throughout the writer's graduate study, and particularly for Professor Cottom's invaluable aid in preparation of this report. He also wishes to express his indebtedness to Dr. C. A. Halijak and to Professor Leo A. Wirtz for the assistance given in completing this report. The author is indebted to Mrs. F. M.Crawford for the typing of the manuscript.

The author is highly appreciative of the encouragement and moral support given by his wife, Nayeem Shaheen, without which this graduate study would have been impossible.

REFERENCES

1. Fiedler, H. J., and L. K. Kirchmayer.
   Automation of system operetion. Proceedings of ths Amari-can Power Conference, 1961, Vol. XXIII.

2. Kirchmayer, L. K.
   Differantial enalyzar eide daeign of elactric utility automatic diepetching syetam. A.I.E.E. Transactions, Vol. 77, 1958.

3. Austine, L. T., end R. J. Ringlee.
   Sueqvehenna River ehort range hydrothermal coordination. A.I.E.E. Transections (Pepar 62-1410), Vol. 81, 1962.

4. Gravar, L. L.
   Power generetion echeduling by intagar progremming developmsnt of theory. A.I.E.E. Transactions (Papar 62-212).

5. Happ, H. H., W. B. Ille, and R. H. Reieingar.
   Economic systam operetion coneidaring valve throttling losees, Part 1 - Method of computing valva loop heet ratas on multivelve turbinas. A.I.E.E. Transections (Papar 62-112), Vol. 81, 1962.

6. Ringlaa, R. J. and D. D. Williems.
   Economic system oparetion considering valve throttling lossas, Pert 2 - Dietribution of eystam loeds by tha mathod of dynamic programming. A.I.E.E. Transactione (Papar 62-129).

7. Computar program to eimuleta operation of alactric ganare-tion eystem, Peper submitted to A.I.E.E., April 11, 1962.

8. Gaver, D. P., F. E. Montmaet, and A. D. Patton.
   Power system stebility I - Meeeurss of rsliability and msthode of celculation. I.E.E.E. Treneections on Power Apparatus and Systeme, Vol. 83, 1964.

9. Kirchmayar, L. K.
   Economic control of intarconnectad systams. Nsw York: John Wilsy & Sone, Inc., 1959.

10. Burnett, K. V., D. W. Halfhill, and B. R. Shepart.
    A new eutomatic dispatching system for electric powar systems. A.I.E.E. Traneactions, Vol. 74, Part III, 1955.

11. Cemaron, D. H., and E. L. Mualler.
    A new typa of eutomatic dispatching system at Kansas City. A.S.M.E. Paper 56-A-215.

12. Travars, R. H.
Automatic aconomic dispatching and load control, Ohio Edison Syatam. A.I.E.E. Tranaactions, Vol. 76, Part III, 1957.

13. Glimm, A. F., L. K. Kirchmayer, and H. H. Chamberlain.
Automatic oparation of intarconnected areaa. A.I.E.E. Confarance Paper presented at the Summer and Pacific Ganeral Meeting, San Francisco, California, June, 1956.

14. Early, E. D., W. E. Phillips, and W. T. Shreve.
An incremental coat of power-delivered computer. A.I.E.E. Transactions, Vol. 74, Part III, 1955.

DIGITAL COMPUTERS IN POWER SYSTEMS ANALYSIS

by

SADIQ A. SHARIFF

B. S. E. E., University of Mysore,
Bangalore, India, 1956

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

1965

Until the end of the yaar 1960, digital computere ware primarily used aa scientific tools in various off-line atudias of syetem theoriee and in tha preparation of aystam guidae. At that tima the on-lina control functions wera accompliahad antirely by various enalog computar control arrangemante. Since the baginning of tha yaar 1961, digital computars ara baing used for solving a lerge variety of system opereting problams in both a atudy and on-line mode. Several of thaae digital computara are discusaed in the raport.

Syetam oparationa can be broken down into three baeic catagoriea.

1. Operetion planning
2. Operation control
3. Oparation accounting.

Tha ebove enelyaie involves the colleotion of data, the parformance of various arithmetical and logical operations on thesa data, and preparation of statamenta. Computer control is uaed for an automatio diepatching eystem capabla of simultaneously and automatically maintaining fraquency, net intarchange, and aconomio ellocetion of generetion for e given operating eree. Meny devicea have baan discuseed which may be uaed directly to obtain automatic economio operation of a powar pool formed by eeveral areae.

Computer control offars opportunitiea for operating eavinge compered to manual or semiautomatic oparetione. Some of tha rasulta of intagratad digital diapatch computar systems ara:

1. Fuel aaving

2. Menpower seving

3. Improvements in system reliebility

4. Possible savings in capitel equipment expenditures.

Thus due to the ebove results, we heve

1. Improved production economy

2. Resssignment of technicel personnel for more importent jobs.

Computers performing the on-line jobs cen be teken out of service es part of the control loop end used es en eid for such problems es:

1. Interconnection transections

2. Economic scheduling of meintenence

3. Future system studies

4. Economic scheduling of unit commitments.

A discussion covering the computer requirements for the various celculations needed by the loed dispetcher is included in the report. Areas connected in e grid could be controlled by centrelized or decentralized epproech. Though centrelized control is mostly employed, yet in certain csses decentrelized control hes the following edventages.

1. Reduction in telemetering chennsl requirements

2. Use of smsller decentrelized computer controllers

3. Reedy evailebility of informstion for eccounting between erees.

A discussion of decentralized approech to obteining eutomstic economic operation of interconnected arees hes been included in the report. The decentralized epproach involves comparison devices which by comparison of appropriate costs between areas determine the economic interchanges between the areas.

Multiarea dispatching computers accomplish the following tasks which are not performed by single-area dispatch computers.

1. Calculation of economic interchange between areas.
2. Calculation of weighted incremental costs at boundaries for interconnection accounting.
3. Calculation of incremental costs of wheeling losses.
4. Calculation of flows over individual tie lines.

Generally, multiarea dispatch computers are based on the use of individual dispatching computers representing each individual area, together with supplementary devices, which determine the economic interchange between areas and flows over the individual tie lines.

Two typical programs, one to simulate operation of an electric generating system and the other for power system reliability, are included. The program which simulates operation of an electric generating system provides a method of applying maintenance outages to the load duration curve approach adaptable to medium-size computers. The program for power system reliability permits the determination of various measures of service reliability in power systems from basic component parameters and weather data, thus enabling the engineers to predict the reliability of proposed system designs.

As a result of various advantages, utilities have started using digital computers for both on-line and off-line jobs. This use enables the utilities in improving economic system performance both with respect to fuel and manpower expenditures. The big advantage in using the digital computer is the flexibility it offers to adopt new theoretical concepts and aids to system operation without requiring fundamental changes in the hardware system.