

A SURVEY OF THE APPLICATION OF
ANALOG AND DIGITAL COMPUTER
METHODS TO POWER SYSTEM CONTROL

A THESIS

Presented to
the Faculty of the Graduate Division
by
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In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Electrical Engineering

Georgia Institute of Technology

May 1960

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AND DIGITAL COMPUTER METHODS TO POWER
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Approved:

Date of Approval: May 27-1960

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FOREWORD

Grateful acknowledgment is extended to Dr. W. J. McKune for his suggestion of the topic with which this thesis is concerned and for his early guidance in the organizational development of the subject. It is regretted that unforeseen circumstances made it impossible for him to continue in his original capacity as Thesis Advisor.

In replacing Dr. McKune as Thesis Advisor, Dr. F. O. Nottingham has very graciously accepted a heavy responsibility at a difficult time, and his continued help and encouragement are greatly appreciated. Further acknowledgment is accorded Dr. B. J. Dasher and Messrs. H. P. Peters and E. R. Weston for their willing cooperation and support.

Finally, the assistance of Messrs. H. L. Lowe and W. Wallace in reviewing parts of the manuscript, the permission given by Mr. W. A. Summers to draw on some of his earlier works, and the understanding and support of many friends in many respects is gratefully acknowledged.

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ABSTRACT

The primary purpose of this study has been to investigate the extent to which -- and the manner in which -- automatic economic dispatching and other basic functions of power system control and operation may be performed by electronic analog and/or digital computer methods, and to review the feasibility of the conceptual techniques currently available or presently envisioned for such applications. In fulfilling this purpose, this study presents -- in effect -- a comprehensive survey of what has been done in the general field of computerized power system control, of why this was done, of what is currently being done, and of what is believed will ultimately be done.

For the purposes of this study, power system control has been taken to embrace the operation and control of both the power systems themselves and the generating stations within these systems. However, as a matter of choice, attention has been focused principally on operation and control in a system-wide sense, while central station control and operation has been touched upon only briefly.

In recent years, the effects of the continuing growth of the electric power industry have centered great interest on the benefits to be derived from the computerization of many power system control functions. Concurrently, the important advances made in the new field of computer technology have permitted ever more sophisticated and more effective computer systems to be applied to the practical realization of

these expected benefits. This study serves to map some of the areas in which the potentials of analog and digital computers may be applied to the demands of a dynamic electric power industry.

The importance to economic system operation of proper power transmission loss evaluation is first considered, and it is seen that digital computers play a significant role in the preparation of the transmission loss formulas used to accurately describe these losses. In turn, the theory of economic coordination of incremental transmission losses and incremental production costs is explored, and it is seen that either analog or digital methods are suitable for the basic problem of solving the resulting coordination equations. The use of off-line computers to aid in the preparation of generating schedules based on predicted conditions is seen to offer some rewards but is found to be only a partial solution for many electric utility systems.

For those power systems which can justify greater efforts at optimum economic operation, the benefits available through the use of on-line computers in automatic economic dispatching systems are then reviewed. The requirements of modern automatic dispatching systems are thoroughly investigated in terms of the computer capabilities necessary to a successful, practical installation of this type. On the basis of this analysis of requirements, and in the light of the special characteristics and peculiar attributes of both the analog and the digital computer, the current predominance of analog computers in such systems is justified.

However, various possible functions are suggested for a comprehensive computer system which would be concerned with more than just economic dispatching of generation, and it is seen that the realization of systems of the type proposed will tend to stimulate a transition to the wider use of digital computers in automatic dispatching. In fact, it is noted that the anticipated justifiability of such comprehensive computer systems may even now be giving rise to the first evidences of such a transition.

Finally, by way of supporting the above conclusion regarding a trend toward the use of digital computers in comprehensive computer systems for power system application, and in an effort to lend perspective to the present study, the recent developments in power plant automation are briefly considered. The need for digital computers in such plant automation schemes is indicated, and it is suggested that this requirement will tend to accelerate the wider acceptance of digital computers in power system control as progress is made toward the ultimate goal of an integrated computer system for the fully coordinated operation and control of both the power system and its component generating stations.

PART I

THE COMPUTING REVOLUTION AND ITS RELATION TO AN EXPANDING ELECTRIC POWER INDUSTRY

Any consideration of the application of new concepts and revolutionary techniques to a particular technological field must first be justified in terms of that field's present status and of the future demands which are expected to be placed upon it.

The electric power industry in the United States is even now a highly developed field of basic importance to the nation's economy and industrial might. Its previous growth has been rapid, as is immediately illustrated by the fact that all over the United States most power systems have doubled in physical size about every ten years for the past several decades. Indeed, there are many statistics (1) available that will attest to the tremendous expansion and sustained growth which have characterized the power industry for many years, and particularly since about 1940.

More important, however, is the fact that, in an era in which electric energy is supplying an ever-increasing portion of man's needs and wants, the electric power industry's growth is expected to continue at an even greater rate than that evidenced in past years. (2)

These bright prospects for continuing growth are actually the fundamental reason for today's efforts to apply electronic analog and digital computer methods to the general field of power system control. The complexities of power system and central station operation and

control, and the many economic aspects associated with the continued growth of an already highly developed field, have created and will -- to an ever-increasing degree -- continue to create certain demands which it is believed can only be met through the application of computer methods.

Thus, not only is this industry showing such strong signs of good health as to permit the development and incorporation of new concepts and techniques, but also this very same healthy condition is creating many demands which will only be met through the adoption of such concepts and techniques.

Further investigation of these growth trends will afford a fuller understanding of some of the problems faced by electric utilities in the various phases of power system control. ("Power system control" is here taken to include both system and station operation and control, and the following development will consider these two areas in a separate though parallel manner.)

Studies recently undertaken by the author's company* have surveyed the power industry's expected growth during the period from 1955 through 1975. (3) At the end of 1955, the total installed thermal generating capacity in the United States was about 90 million kw; the predicted 325 million kw for the end of 1975 represents a 261 per cent increase in twenty years. These figures are an indication of the degree of industry growth expected; needless to say, sustained growth of this type will have far-reaching consequences. For one thing, the

*Ebasco Services Incorporated, New York, N. Y.

"average" turbine-generator unit size is expected to increase from 78 mw in 1955 to 325 mw in 1975 (and the largest unit in service from about 300 mw in 1955 to 1000 mw in 1975). Of course, there will be a corresponding increase in the plant dollar investment for a unit of "average" size during these years.

A complete review of the many facets of the power industry growth predictions would be beyond the scope of this study -- further reports on expected growth rates and the demands which they will create is available in the literature of the field. Nevertheless, some general conclusions are possible on the basis of the limited data given above.

The indicated rise in installed thermal capacity implies an associated increase in overall power system equipment. It follows that the greater the size and amount of equipment to be operated and controlled, the greater are the demands placed on the men and devices that must perform these functions. (This is particularly true in view of the fact that sharp increases in the complexity of such equipment will frequently accompany increases in size and amount.) There is little question as to the ability of properly designed devices to meet the demands made of them (provided the demands are compatible with those for which the devices were designed), but as will be seen in greater detail later, the demands made of the men responsible for power system operation and control have already approached an upper limit on many electric utility systems. In short, as a result of heavy load growth, power systems have expanded to the point where -- in some instances -- the many and varied aspects of system operation have become too large a burden for

any man or group of men to support without serious loss of efficiency and dependability. Consequently, a pressing need exists for some means of relieving system operators of many of those tasks which are not entirely dependent on human abilities. Moreover, with the continued growth of power systems, this need will become more urgent and more widespread.

Some additional conclusions may be derived from the previously cited increases expected in the plant dollar investment per "average" unit and in the size of "average" units. It should be clear that where a greater monetary value is placed on a unit, there exists a proportionately greater unit potential damage figure (in dollars) corresponding to either a limited or a major accident. Where outage time and the repair of damages due to a limited accident might cost \$ 50,000 in 1956, they would cost \$ 180,000 in 1975 (not considering increased labor costs or decreased purchasing power); for a major accident, the figures are \$ 750,000 and \$ 2.5 million, respectively. (3) This rise in "risk dollars" represents the increasing penalty for what may be no more than a single error in judgment or procedure, and as this penalty becomes financially prohibitive, the requirement for a means of greatly reducing the opportunities for such errors in power plant operation and control becomes vastly more urgent.

One ever-present source of errors is human operation, and thus the above requirement may be interpreted in part as a need for also curtailing the extent of human participation in central station operation and control. Of course, it is in addition necessary to make the non-human controls as dependable as possible, but the difference is that

electrical and mechanical and other types of control are generally predictable in their behavior, whereas human control is often entirely unpredictable.

Finally, in connection with "risk dollars" and accidents which may damage expensive plant equipment, it may be mentioned that human safety is also extremely important -- in fact, it is difficult to assign a "risk dollars" value to accidents involving human injury or loss of life. In a few words, the power plant of tomorrow dare not be any less safe for humans than the power plant of today.

Increased equipment and human safety in the power plants of tomorrow will be achieved not only through a reduction in the extent of human participation in central station operation but also through the development and introduction of more refined and sophisticated controls and protective systems. To be sure, advances in station design and in other areas will also contribute toward increased safety, but the viewpoint adopted in this work is the one which concerns itself primarily with the contributions to be derived from reduced human participation in station or system operation and from other advances in the field of control engineering. And while it is felt that the question of human safety is not as meaningful when overall system operation is considered, the matter of equipment safety is -- on the other hand -- still relatively applicable, and essentially the same argument may be developed to justify increased system-wide equipment safety through reduced human participation in system operation and through the application of advanced control engineering techniques on a system level.

One result of the increasing size of "average" units is the increased significance attached to a given per cent error in unit performance. Since a 1/4 per cent fuel saving in the operation of the "average" sized unit of 1975 will be worth much more than it was for the "average" sized unit of 1955 (3), greater efforts will be directed in the years ahead toward reducing measurement and control errors affecting unit performance and toward the more effective utilization of the design capabilities of plant equipment. Similarly, the increasing size of power systems and the correspondingly increased significance of power transmission losses lead to operating economy considerations which dictate the concentration of greater efforts toward the improvement of system performance and toward the more effective utilization of system design capabilities. (The more effective utilization of design capabilities will also reduce relative investment costs.)

With respect to central station operation, it is doubtful that the reliability or precision of operation by humans can be increased enough (if at all) to make any appreciable contribution toward fuel savings. And with regard to overall system operation, as will be seen in greater detail later, the same human limitations (which are fundamentally limitations of time, space, and the volume of information to be processed, plus the human limitations on sensing and reaction) effectively preclude operation at the optimum generating efficiency (in terms of the total system fuel cost to meet the existing load demand). In both cases there again appears the requirement for reducing the extent of human participation in order to achieve greater economies, and in both cases it also appears that control engineering advances bringing

more refined and sophisticated measurement, control and operating techniques will further contribute toward improved operating economies. Finally, it is noted that additional improvements in operating economy should be possible through the more effective utilization of the design capabilities of both the generating stations and the power systems.

A review of the present and anticipated effects of the continuing growth of power systems indicates that, with respect to overall system operation, the increasing complexities of such operation (with the attendant burden on system operators), the increasing importance of equipment safety (with the human susceptibility to errors of judgment and procedure), and the increasing economic importance of optimum efficiency of operation (with the inherent human limitations on precision and dependability) have resulted in a pressing requirement for replacing a large measure of the human participation presently found in system operation. Similarly, with respect to station operation, this same growth pattern -- in terms of certain economic aspects (such as the "measure of accident risk") and in terms of the human limitations on reliability and precision of control -- has again led to the requirement for reducing the extent of human participation. Furthermore, with respect to both system and station operation, it is seen that advances in the field of control engineering are also expected to play a significant role in helping to meet some of the anticipated demands of the power industry, and finally, it is seen that efforts toward the more effective utilization of design capabilities are expected to reap additional benefits.

These are certainly not the only means with which to satisfy the demands of an expanding power industry. Improvements in many other areas are anticipated. For example, it is expected (3) that increased steam temperatures and pressures will reduce thermo-electric unit net heat rates from an average of 11,700 Btu/kwhr for units entering service in 1955 to approximately 9000 Btu/kwhr for those entering service in 1975, and of course, such advances will materially contribute toward improved plant operating economies. Likewise, studies bearing on the economic selection of generating capacity additions and other phases of system planning will go a long way toward meeting many of the anticipated demands in a system-wide sense. In short, all promising prospects for reduced operating and investment costs and for improved methods for meeting some of the other demands of a growing power industry will be eagerly sought after in the years ahead.

The novel concept, however, is the one which suggests that much may be accomplished by replacing many forms of human participation in system and station operation and control with electronic computers, and this is for many an area of greater interest. Indeed, it is the area with which this study is primarily concerned.

In addition to fulfilling the requirement for reducing the extent of human participation in system and station operation, the application of electronic computers to these functions will of itself represent one of the more important of the control engineering advances which have already been looked upon as another means of helping to meet the demands of a growing power industry. In many instances, more refined

and sophisticated controls, protective or supervisory systems, and measurement or instrumentation techniques will be possible largely because computerization has been accomplished. And finally, the very fact that a computer is being used in the system or station operation and control procedures will generally permit a major advance in the direction of more effective utilization of system or station design capabilities, since the computer's unique abilities will often prove ideally suited to such efforts.

Another question which should be considered in attempting to justify the computerization of power system control is one which is concerned with the best application of human resources. The more obvious aspect of this problem involves an anticipated shortage of plant operating personnel as more and more units come into service. (3) Unless the electric power industry is able to increase its share of the country's available manpower pool, plant automation (or the use of computer methods in plant operation) will become essential to the industry's continued growth, simply because of the severe labor shortage which would otherwise be faced.

A more subtle aspect of the question of human resources concerns the relative suitability of humans and machines for different tasks. Whereas man may be characterized as slow, inconsistent, ingenious, easily bored by repetitious tasks, affected by human environment, and capable of deductive reasoning, it is known that computers and related automatic equipment are fast, consistent, stupid, incapable of boredom, unaffected by human environment, and capable only of making preplanned decisions. It is therefore apparent that there are certain functions for

which automatic equipment is vastly more qualified than humans, and of course, the reverse is also true. Many of the functions of system and station operation and control which are presently performed by humans are better suited to the use of computer methods. On the other hand, human abilities are necessary in such areas as the analysis of unusual situations, system planning, maintenance and trouble-shooting, and many others. Sensible utilization of both men and machines requires that each group be assigned those duties and functions for which it is best suited. In fact, this consideration is one of the most compelling reasons for the present trends toward computerization in so many industries and fields of human activity.

Many of the factors which have been cited as stimulants to the further application of computers in the electric power industry have been effectively reduced to a requirement for curtailing the extent of human participation in system and station operation and control. This is a convenient means of tying the various factors together for easy reference, but it must be emphasized that this is not the sole aim of computerization. The intent is not simply to replace humans with machines on a grand scale. Rather, the aims are to meet some of the anticipated demands of a growing power industry, i.e., to reduce operating and investment costs wherever possible, to relieve system or station operators of many burdensome duties and meanwhile prepare for the expected labor shortage, and in general to permit safer, more reliable, and more efficient operation in all respects. The matter of replacing humans with machines simply happens to be the common denominator of these various factors.

The matter of replacing humans with machines, however, is itself a subject worthy of note. Within the past decade the strides made in the new field of computer technology have been fantastic (4-16), and as a result, electronic computers are finding an ever-increasing variety of applications in many fields of endeavor. Many of these efforts have centered on anticipated economic benefits, but a great many others have been aimed mainly at substituting machine methods for human methods in situations where human talents were unable to realize even a significant portion of their full potential or simply wherever the machine capabilities were clearly far in excess of human abilities. Applications of the latter types have often been largely the result of a desire to match both human and machine characteristics to the tasks for which they are best suited, but it should be noted that the philosophies of modern times will also generally require some form of economical or financial justification for such applications. Less tangible benefits derived from replacing humans with machines will certainly be well received, but the real criterion for accepting or rejecting any proposed computer application will generally be found in the profit and loss sheets.

Similarly, it is well to speak of various rewards (sometimes intangible) expected from the use of computers in power system control, but the economic merits of such applications will always have to be kept in mind, and the ensuing discussions will occasionally rely on an acceptance of this modern-day fact of life.

Considering the computing revolution further, it may be noted that numerous power industry computer applications have already been

realized. (17-34) Indeed, it would be well within the limits of reason to suggest that the fortuitous confluence of the two trends toward growth and evolution presently seen in the fields of computers and electric power will prove mutually stimulating and mutually rewarding. From the power industry viewpoint, at least, the amazing growth of computer technology has occurred at a most convenient time, for just when some of the problems and needs of an expanding power industry have begun to be seriously felt, the means with which to solve many of these problems and meet many of these demands has become available. Similarly, it would appear that the whole new host of computer applications now coming to light in the power industry will prove a catalyst, to some extent at least, in the evolution of a computer technology still in its infancy. In any case, this study will proceed with the viewpoint that both fields stand to gain a great deal from continued efforts to link the two growth cycles. In fact, part of the function of this study will be to pursue an investigation of the potential which exists for continued computer applications in the power industry, and though no specific mention of the effect of such applications on the field of computers will be made, the implication should be clear.

Before proceeding to consider what may be accomplished by coupling advances in the two fields of computers and electric power, some mention of the background history and of the scope intended for this investigation should be made. Also, a basic distinction between computerization or automation in overall system operation and in central station operation has appeared earlier in this section, and this viewpoint will merit further definition.

Briefly reviewing the historical background which paved the way for the later automation of various power system operating functions, it may be noted that the gradual but continued trend toward the centralization of system control and system operating functions evidenced in the last several decades has been one of the more important developments which conveniently prepared both the mental attitudes associated with power system operation and the power systems themselves (physically) for the advent of computerization. Had the trends toward centralization not progressed as far as they did, or had they developed more slowly, the later application of computer control would have been less easily realized and might well have been considerably delayed. In fact, computerization of power system operating functions is effectively only a culmination of this trend toward centralization.

Another trend observed in power system growth over the years has been the now widely recognized movement toward the integration of power systems to form extensive interconnected areas operating as cooperative power pools. (35) There are many benefits available to the individual members of an integrated system, and this fact is the cohesive force which stimulates cooperative participation by each member of the interconnection. Among the benefits are such operating advantages as improved service continuity, increased capability because of load diversity, improved voltage and frequency regulation, plus the economic advantages of lower overall production costs, deferment of capital expenditures, and associated savings. And insofar as power system computerization is concerned, the integration of systems permits a single computer system to serve a larger area. As a matter of

fact, the extensive interconnections are the systems which have the greatest need for computer control methods.

The functions referred to in mentioning power system operation and control may now be considered. In so doing, the previously mentioned distinction between power system operation and central station operation will also be considered.

First, it may again be noted that the general field of power system control is here taken to include both overall system operation and individual power plant operation (and, as a matter of course, "operation and control" is often taken as equivalent to "operation"). Then, for the purposes of this study, it will be convenient to define power system operation to include such functions as the allocation of generation for optimum operating economy, the maintenance of an essentially constant system frequency, and the observance of scheduled net interchanges over the tie-lines with neighboring systems. To these basic functions of system operation may be added the functions of protective relaying, fault isolation, automatic load-shedding, and other miscellaneous operating requirements. In fact, there are many functions and assorted requirements which pertain to system operation, but the area to which computer methods are most readily adaptable is primarily concerned with economic generation allocation and load-frequency control.

The economic allocation of generation has become increasingly important as the growth of interconnected systems has heightened the influence of transmission losses on allocational patterns. Both in the preparation of a formula describing transmission losses and in the solution of equations which define the optimum allocation, computer

methods have found wide application. When the computerized solution of transmission loss formulas and economic loading equations is coupled with the use of modern load-frequency control equipment, it is possible to develop fully automatic, closed-loop control systems concerned with the three primary system operating functions of achieving optimum economy of operation, maintaining an essentially constant system frequency, and meeting the desired net interchange schedules. This is the type of control system which will receive major attention as the application of analog and digital computer methods to power system control is investigated in this study. The potential value of computer applications in other system operation areas will receive slight attention, but it may be noted at this point that as the trend toward computerized power system operation gains momentum, many subsidiary operating functions will probably also be found adaptable to computer methods.

The computerization of central station operation has found growing acceptance in more recent times. Following consideration of the application of computers to transmission loss formula calculations, economic generation scheduling, and closed-loop automatic dispatching systems (in which economic loading and load-frequency control are coupled), it will be convenient to briefly consider the role of computers in central station operation and control. The latter area of application includes many functions involved in the production of electric energy at the generating stations in particular, whereas system operation is concerned with system-wide applications of a broader nature. Nevertheless, central station control is now approaching the point where it will be possible to start-up, run, and shut-down electric generating

stations in a fully automatic, computer-controlled manner. The potential value of computers in central station operating procedures is believed to be enormous, and hence this topic merits inclusion in a survey of computer applications to the broad field of power system control. More important, on the basis of analyses of the requirements of automated procedures in the two fields of system operation and station operation, it should be possible to derive some conclusions regarding the compatibility of these two automation trends.

PART II

THE MAJOR PROBLEM AREAS IN THE COMPUTERIZED OPERATION OF POWER SYSTEMS

Chapter I

POWER TRANSMISSION LOSSES

The significance of the transmission losses incurred in delivering power from the generating stations to the load centers within power systems, and in transferring power over the interconnections between neighboring systems, cannot be overemphasized.

Indeed, this study is in large measure predicated on the fact that such losses exist and that they must, in many cases, be carefully evaluated and considered in the selection of system operating procedures.

On a great many systems, optimum efficiency of generation and load supply can only be achieved if these losses are completely defined over the entire range of system operating conditions. The availability of a transmission loss formula is consequently a prime necessity in these times in which, because of the continuing growth of power systems, even the smaller gains in operating efficiency will reap substantial economic savings.

However, transmission loss formulas are also valuable for other purposes. The facility with which a loss formula may be evaluated to yield both incremental and total losses for a large number of operating conditions was one of its first recognized advantages, for this permitted hour-by-hour loss tabulations to be included in the dispatching logs.

Transmission loss formulas also found early applications in generation forecasting and system planning. Since then the development of loss formulas for interconnected systems has introduced other applications.

In connection with system planning, for instance, a knowledge of the losses in a system as a function of the interchange power will often be a contributing factor in determining where an intertie between two systems should be located.

An extremely important use of loss formulas is in the evaluation of transmission losses (both incremental and total) under different interconnection transactions for purposes of billing. For example, a company selling power to another will need to know the transmission losses on its own system which are associated with this sale so that the cost of these losses may then be added to the production costs in order to determine the total cost or value of the power at the interconnection. Loss formulas now available permit proper interconnection billing procedures to be instituted regardless of the complexity of the overall systems. Such billing procedures are concerned with the allocation of transmission loss costs among the various divisions of an integrated system or among outside companies that merely transfer power across portions of the system.

With regard to the latter, a system operating in parallel with a neighboring system may not be directly involved in the sale or purchase of energy during a particular interconnection transaction, but rather only provide an additional path for the flow of power; in such a case, however, this system should certainly be compensated for the increased

transmission losses incurred on its facilities during the period of the transfer. The state of loss formula theory has been advanced to the point where it is now possible to assess these losses.

In other cases, several companies combine to jointly supply a large load, and workable means for sharing the cost of transmission losses are of great importance. The incremental loss formula is valuable in determining the change in losses attributable to many intercompany transactions of the nature of those mentioned above, and at a later point the feasibility of attempting such evaluations as part of the normal operation of an advanced dispatching system will be touched upon briefly.

With respect to this study, however, transmission loss formulas are of interest mainly because of their application to the coordination of incremental production costs and incremental transmission losses for optimum economic system operation. In this connection, loss formulas are used in the preparation of precalculated economic dispatch schedules and in automatic economic dispatching. In order to permit fuller appreciation of the details of their application to such functions, it will be convenient to first review the essentials of loss formula theory.

The "breakthrough" in the matter of analytically representing the total transmission losses of a power system in terms of its source loadings came as a result of the pioneer work of Mr. E. E. George in 1942. (36) This work was the first step toward the development of a transmission loss formula which would adequately express the total system losses over a wide range of system load and operating conditions. Prior to that time, it had been necessary to determine losses by

detailed calculation of each individual line on an a-c network analyzer.

The method described by Mr. George is based on the principle of superimposing the load distribution from each source, determining the current in each line as an algebraic sum of the individual load flows, squaring this expression for current, and setting up an equation for losses in terms of power generation at the various plants and of directional power flows at each interchange point (an outward flow of power at an interchange point is considered as negative generation). The form of the loss formula is then given by the following:

$$\begin{aligned}
 P_L = \text{total transmission losses} &= G_A^2 K_{AA} + G_B^2 K_{BB} \\
 &+ G_C^2 K_{CC} + \dots \\
 &+ G_A G_B K_{AB} + G_A G_C K_{AC} + G_B G_C K_{BC} + \dots
 \end{aligned} \tag{1}$$

where G_A , G_B , etc., are the various plant and interconnection loadings, and where the K constants may be interpreted as representing the network impedance characteristics, the generator bus voltages, phase angles, and power factors, and the load pattern of the power system to which the formula applies.

In general, the formula contains a power-squared term for each generating station or interconnection and a power-product term for each pair of stations or tie-lines. It is seen that the procedure consists chiefly in deriving a special loss formula for a given power system; stipulation of the prevailing conditions of generation, load and interchange then permits rapid evaluation of the corresponding total system losses, since the formula involves only multiplication and addition.

In many cases, the number of sources included in the formula may be reduced to only the more influential ones without greatly affecting the accuracy of the loss calculations. Generators within a station can usually be combined, and small plants may sometimes be eliminated by combining with local loads--it may even be feasible to combine separate plants which are electrically close together. Another simplification results from the fact that power systems generally have a planned order of loading plants, except during infrequent emergency situations. Even if this order changes seasonally or with hydro or fuel conditions, calling for, say, three different loading schedules during the year, it is preferable to use three corresponding loss formulas with variables for only the regulated plants rather than one formula with a variable for each plant.

The simplicity of the loss formula is the key to its value, for once the K constants have been calculated for a given power system, it provides a readily accessible indication of the total losses for any one of a wide range of loading conditions--only the introduction of a major change in system configuration will require modification of the formula's coefficients.

Mr. George's original development of the transmission loss formulas was significant in that it demonstrated the potential of this new tool and paved the way for further advances. However, much work remained to be done on the perfection of better techniques for calculating the formula's constant coefficients.

In 1945 and 1946, Mr. George's method for deriving the constants was greatly simplified by the development of a procedure for using the

network analyzer to replace the tedious trial-and-error determinations of power flows from each generating plant and interconnection which were previously needed in setting up the loss coefficients (see Appendix II of reference 37). In 1948 and 1949, the superposition method of deriving loss formulas was extended and generalized (38); also, improved techniques for evaluating the constants by use of the network calculator were presented. Even at this point, however, the synthesis of loss formula coefficients from the network calculator data still required a large amount of calculation after all the measurements had been made.

Before proceeding to further advances in the development of transmission loss formulas, it would be wise to consider the assumptions made in the derivation of these formulas. Two basic approximations are involved:

1. For a given total load, each individual substation load is represented as a certain equivalent load current (defined as the sum of line-charging, synchronous condenser, and load current at that bus) which has a constant magnitude and fixed relative angular position with respect to other load currents, regardless of the manner in which the total generation is apportioned among the sources.
2. As the total system load varies through its normal cycles, the magnitude of each individual load current varies proportionately and maintains its fixed relative angular position with respect to other load currents.

Concerning the second approximation, suitable values of load currents may be obtained from a selected, typical, intermediate power-flow condition which is taken as the normal or reference condition. Also, if a major load does not conform with the pattern of variation

followed by the rest of the system, this load may be treated as a negative source and introduced as an additional variable in the formula (such industrial loads as aluminum, steel, and paper mills generally require this treatment). If many loads vary in a non-uniform manner, it may be necessary to develop two or three sets of constants in order to adequately represent the entire daily load cycle -- each set will then be used during a certain part of the day. For many systems, however, the loads can be considered homogeneous, i.e., varying together as the system changes from a light to a heavy total load.

On the basis of these assumptions, a derivation of a general loss formula is presented in Appendix II of reference 38. It is also shown there that if the source bus voltage angles remain fixed at the value attained in some typical, intermediate operating condition, and if the magnitudes of the source bus voltages remain essentially constant, and finally if each source operates at a constant power factor, then a simplified loss formula may be written as

$$\begin{aligned}
 P_L = & P_1^2 B_{11} + P_2^2 B_{22} + \dots + P_s^2 B_{ss} \\
 & + 2P_1 P_2 B_{12} + 2P_1 P_3 B_{13} + 2P_1 P_4 B_{14} + \dots \\
 & + 2P_2 P_3 B_{23} + 2P_2 P_4 B_{24} + \dots \\
 & + 2P_3 P_4 B_{34} + \dots + 2P_{s-1} P_s B_{(s-1)s}
 \end{aligned} \tag{2}$$

where P_L = total power transmission losses

s = total number of variable power sources

P_m, P_n = source loadings, in kw

B_{mn} = transmission loss coefficients (B-constants)

An equivalent form in shorthand notation is

$$P_L = \sum_{m=1}^s \sum_{n=1}^s P_m P_n B_{mn} \quad \text{kw} \quad (3)$$

The form of these equations is the same as that used in Mr. George's original work. Also, it must be emphasized that these formulas very definitely depend on some rather restrictive assumptions.

The development of transmission loss formulas was further advanced in application and enhanced in methods of derivation through the introduction of tensorial analysis methods. (39) In 1951, an improved method of obtaining a transmission loss formula involving considerably less network analyzer data and a fraction of the arithmetic calculations of the methods previously used was presented. (40) This new method essentially only required impedance measurements on the open-circuited transmission network and a normal load flow study. Manipulation of this data to produce the loss formula was accomplished using the concepts of tensor analysis. (41, 42)

An important characteristic of the tensorial analysis approach is that at any stage of the development the assumptions concerning the system operating conditions for which the loss formula will be valid may be arbitrarily extended or restricted at will to suit immediate needs, without jeopardizing the validity of any other portion of the analysis. Thus, when new transmission lines, generators, loads, and tie-lines are added in any combination and are inserted between any desired points of an existing system, it is possible to make corrections in the original loss formula and arrive at a new loss formula for the enlarged

system without having to start from scratch again and make new impedance and normal load flow measurements on the network calculator. In an era of rapidly expanding systems, this is a valuable characteristic of the tensorial approach.

Furthermore, the use of tensor analysis causes the necessary numerical computations to be arranged in a systematic form involving matrices which is readily adaptable to automatic digital computing techniques.

Further contributions to the evolution of transmission loss formulas came in 1952. (43, 44) Using tensor analysis concepts, procedures for evaluating the transmission losses for any desired radial interconnection of individual companies by operating on the loss formulas of the individual divisions were presented. The method requires only a knowledge of the total interchange between companies and does not require that the flows over the individual tie-lines be known. Also important is the fact that the individual company loads are allowed to vary independently of each other, thus eliminating one of the basic assumptions of the earlier methods. Finally, the calculations and network analyzer measurements required in determining a total loss formula for a group of interconnected companies was reduced by application of this method.

Again in 1953, further advances in the development of loss formulas were made. (45, 46) The procedures mentioned above were extended to include the case of parallel or looped operation of several interconnected companies. This made it possible to study an interconnected system whose complete representation would require more

capacity than that available on a given analyzer by setting up and studying the individual companies one at a time. Of greater consequence was the fact that this work involved the development of methods suitable to digital computers which could greatly reduce the labor and time required for the preparation of transmission loss formulas.

Meanwhile, in 1952, procedures devoid of tensor analysis concepts for working with the loss formulas of interconnected systems and of the individual companies comprising the integrated system were presented. (47) In particular, a method for obtaining incremental loss equations whereby the change in transmission losses in a part of a larger interconnected system is expressed as a function of changes in loading at both internal and foreign sources was developed. From the coefficients of the incremental loss equation it became possible to derive the coefficients of a total loss equation for the individual company. Though the derivations included the earlier assumption that all loads in the interconnected system vary together (except in the incremental loss equation, for which the loads are not permitted to vary at all), the work did introduce a more accurate representation of source characteristics in that it provided for the ratio of reactive to real power generation at any source to vary in a prescribed and suitably chosen manner as the source loading changed, whereas previously the power factor had been assumed constant.

In 1953, further simplifications and improvements in the calculation of transmission loss formulas applicable to individual systems satisfying certain restrictions on the generator angles and the load voltages and power factors were also presented. (48) Though as early

as 1952 the engineers on the Bonneville Power Administration system had reported that computer programs for the calculation of loss coefficients were being prepared, Dr. L. K. Kirchmayer, et al., in the work just mentioned applied a model II card programmed calculator (CPC) and associated equipment secured from the International Business Machines Corporation to the calculation of a loss formula for a system involving 21 variable sources. At that time, it was stated that the overall calculating time required was greatly reduced and that the application of automatic digital computing machines had proved to be more economical than manual calculation.

Not long thereafter an IBM type 650 data-processing machine (a high-speed, internally programmed, magnetic drum digital computer) was also applied to the calculation of transmission loss formulas. Compared to the CPC, the 650 computer reduced the digital calculating time by approximately one-fourth and the calculating cost by approximately one-half. It was at about this time (1953) in the development of transmission loss formula theory that serious interest in the application of large digital computers to such problems began to spread throughout the industry. Significant advances in this area were to follow in the ensuing years.

Another major contribution to the development of loss formulas was made in 1954. (49, 50) Derivations were presented for three distinct types of loss formulas using only simple circuit theory and without resorting to complex mathematical techniques (e.g., matrix algebra, tensorial analysis, etc.). This work served to emphasize the fact that there is more than one approach to transmission loss formulas. The

three methods were designated the in-phase, current-form, and power-form methods. The first, because it considers only the in-phase components of load currents, is restricted to simplified power systems of a predominantly radial character. The other two methods, however, are more widely applicable.

The current-form loss formula determines total line losses as a function of generator and tie-line currents. The loss coefficients for this formula are easier to calculate than for the power-form loss formula, and the total computation time on a digital computer is shorter. This method does not require the assumption of fixed source power factors, and it has made possible the study of the effect of reactive power flow over the interconnections on a system's transmission losses.

The power-form loss formula is identical to that originally developed by Mr. George and improved by succeeding contributors -- see equation (3). It is the most useful form for economic dispatch studies since it expresses the system transmission losses as a function of the single variable \underline{P} (net power generation or supply) at each generating station and tie-line. Incremental production costs at each generating station are also expressed in terms of net station output power, and hence the procedure of minimizing total production costs for economic dispatch is simplified.

The power-form loss formula is derived using a base case, well-centered in the range of system operation for which its use is contemplated. It is exact for the base case and a close approximation for considerable deviations therefrom. The assumptions employed in the

complete derivation (50) are the same as those cited earlier, and independent load variation is again prohibited. Also, a minor assumption which has not been mentioned previously (although it has been used in other developments) is that the transformation ratios are unity around each closed loop of the network.

As yet very little has been said about incremental transmission losses, but actually these are of prime concern in the economic dispatch equations, as will be seen later. Understanding of how differential and incremental transmission losses should be treated has grown with the development of total transmission loss formulas, and many of the previously cited references (particularly references 38 and 47) have also considered incremental losses in some detail.

The incremental loss associated with source \underline{n} may be defined as the increment in total transmission losses that results from an increment in total system load which is supplied by source \underline{n} . For the purposes of this study, it will not be necessary to consider the more sophisticated and complete approach to the derivation of an incremental loss formula. Suffice it to say that for a differential increase in the total system load supplied by source \underline{n} , the change in total loss is found by differentiation of equation (2) or (3) *:

$$\frac{\partial P_L}{\partial P_n} = 2P_1 B_{1n} + 2P_2 B_{2n} + \dots \quad (4)$$

$$+ 2P_n B_{nn} + \dots + 2P_s B_{sn}$$

* The B_{mn} matrix is a symmetric matrix and hence $B_{mn} = B_{nm}$.

$$\frac{\partial P_L}{\partial P_n} = 2 \sum_{m=1}^s P_m B_{mn} = 2 \sum_{m=1}^s P_m B_{nm} \quad (5)$$

where $\frac{\partial P_L}{\partial P_n}$ = incremental transmission losses associated with source n.

These equations are exact (provided, of course, that the original assumptions for the validity of the total loss formula are fully satisfied) for differential increments, but in the case of finite increments they are only approximate, and an additive correction should be applied. The economic dispatch, or coordination, equations to be presented later are differential equations which include the term $\frac{\partial P_L}{\partial P_n}$, and hence for the solution of these equations it is certainly adequate to represent incremental transmission losses by equation (5). It also should be clear at this point why the power-form loss formula is more directly applicable to economic dispatch studies. Finally, it may be noted that the implied significance of the partial derivative is that an increase in total load is shared by all loads in a prescribed (linear) manner, and that the resulting increment in loss is assigned to the one generating station which picks up the increase.

Where it is desired to calculate directly the incremental losses associated with a finite increment in system load, it should be remembered that equation (5) is only approximate for finite increments. A more complete discussion of incremental losses would consider the change in losses caused by shifting a small block of generation from one source to another while holding all loads and other sources constant (38, 47), but this problem is of little concern in the present work.

The final refinement in loss formula theory to be specifically considered here was introduced in 1955. (51, 52) In order to cope with those systems for which the assumption that all loads vary together as constant complex fractions of the total system load introduces serious discrepancies and errors in loss representation, a so-called "general loss formula" which permits substation loads to vary at independent rates was presented. This formula eliminates some of the assumptions previously employed and relaxes others; concerning the latter, it will only be mentioned here that each individual load current is assumed to be a linear complex function of the total load current. The form of the general loss formula is

$$P_L = \sum_{m=1}^s \sum_{n=1}^s P_m B_{mn} P_n + \sum_{n=1}^s B_{n0} P_n + K_{L0} \quad (6)$$

where B_{n0} and K_{L0} are constants defined in terms of an entirely conceptual condition known as that of "zero system power supply."

From the above, the general form of the incremental loss formula is

$$\frac{\partial P_L}{\partial P_n} = 2 \sum_{m=1}^s P_m B_{mn} + B_{n0} \quad (7)$$

On some power systems it will be found that a reasonably accurate representation of total and incremental losses requires use of the general loss formulas, whereas for other systems the additional accuracy gained is not sufficient to warrant the use of these more complicated formulas. Of course, it is desirable to represent the losses as

accurately as possible within practical limits, but the magnitude of the increased accuracy of loss representation and economic dispatch solutions resulting from use of the general loss formulas should be carefully weighed against the additional computation and man-hours required for preparation of the more complete formulas.

For a further investigation of the more recent advances in the art of accurately and completely describing power transmission losses, the technical literature of the field should be consulted. (53-59) Widespread attention and activity continues to be focused on loss formula theory and application, and this interest will from time to time presumably lead to further refinements and improvements. With respect to the present state of the art, however, adequate description of transmission losses for inclusion in the coordination equations is possible in the great majority of the economic dispatching applications.

One further method for the representation of a system's incremental transmission losses is really not of great concern in connection with this study, since it does not express the losses as a function of the source powers. This radically different method will be mentioned, however, for to ignore it entirely would seem to imply that it is not a valuable method, whereas actually the contrary is true. Furthermore, the desire to use this new method of expressing incremental transmission losses in the coordination equations has recently led to attempts to derive new coordination equations (60) which would be better suited to the new method of describing losses, and it is conceivable that this new approach might eventually supplant the now traditional use of power-form loss expressions and the conventional coordination equations which

are to be given in the next chapter. This new type of incremental loss formula is useful as a means of rigorously expressing the incremental losses and changes in total losses in terms of functions of voltage phase angles, driving point and transfer impedances, and voltage magnitudes. (58, 59) In certain limiting cases, the formula may be reduced to an expression involving only reactance-to-resistance ratios (i.e., X/R ratios) and differences in voltage phase angles. References 58 and 59 may be consulted for more complete treatments of the voltage phase angle method of describing transmission losses.

It has been seen that the processing of raw data (obtained from network calculator measurements and load flow studies) required for the calculation of loss formula coefficients may be accomplished more expediently with the aid of digital computers. Indeed, once the essential raw data is available, the problem of developing a transmission loss formula for a given power system may definitely be considered digital in nature, since the data conversion or translation process is fundamentally only a series of matrix operations. Even now, the use of digital computers in the preparation of loss formulas is widespread; as digital computers become more widely available, the number of such applications will certainly increase.

In viewing the application of analog and digital computer methods to power system control, and in considering the availability of transmission loss formulas as a prerequisite to optimum system control, the outstanding conclusion at this point of the analysis is that the problem of preparing transmission loss formulas is basically digital in nature.

PART II

Chapter 2

THE COORDINATION OF INCREMENTAL TRANSMISSION LOSSES AND INCREMENTAL PRODUCTION COSTS FOR THE ECONOMIC ALLOCATION OF GENERATION

The optimum economic loading of generating units has been cited as an essential function of power system operation, but the basic implications of economic dispatching and the evolution of the need for it have not been sufficiently exposed. These topics will now be considered, and the application of computers to the coordination of transmission losses and production costs will then be investigated.

As long as the available generating capacity of a power system exceeds the total system load, some question exists as to how this load should best be apportioned among the various generating units available for service and as to how much power should be bought or sold over tie-lines with neighboring systems. The allocation of plant generation to effect optimum operating economy has always been a primary consideration in the electric utility industry, and of course, a major factor in determining the most desirable allocation of generation among plants is the total* power production cost -- though other factors exist. (61)

Within the last decade it has been more widely recognized that the proper criterion in achieving economic allocation is that total power production cost which describes the cost of producing and delivering

*"Total" costs are so designated to distinguish them from the "incremental" costs to be considered later.

power to the customer at the load point, but in earlier years consideration had generally only been given to the total power production cost as measured or evaluated at the generating station. The difference in these two viewpoints, of course, is a consequence of the fact that transmission losses are incurred in delivering power from the generating sites to the load centers.

As a means of approach to the general problem of economic allocation of generation, it will be convenient to consider first the analysis on the basis of the total power production cost as evaluated at the generating plant.

The total production cost of power at a generating station is a composite of the total fuel cost plus a complex assortment of various other total costs associated with the generation of electric energy at that particular plant, among which are the costs of labor, supplies, maintenance, water, and similar items. The predominating item, however, is generally the total cost of fuel.

Rather than deal with the total costs mentioned above, it has long been known that incremental costs should be used in determining the economic allocation of generation among the units of a plant or among the plants of a system, and the theory of incremental rates (62) is now universally accepted.

A graph of the fuel input (ordinate) to a generating unit as a function of the unit's power output (abscissa) is known as an "input-output curve." Mathematically, the "incremental fuel rate" of a unit is defined to be the first derivative of the unit's fuel input with respect to the power output. In other words, the incremental fuel rate at any given

output is numerically equal to the slope of the input-output curve at that point on the curve which corresponds to the specified output.

Where the fuel input is expressed in BTU/hour and the unit's output is measured in kilowatts, the incremental fuel rate is then given in BTU/kw-hr.

Where the cost of fuel in cents/BTU is known, the unit's input may be expressed in dollars/hour, and the incremental fuel rate is then given in dollars/kw-hr. The term "incremental heat rate" is commonly used interchangeably with incremental fuel rate, but strictly speaking, the former should be measured in BTU/kw-hr and the latter in dollars/kw-hr. In any case, a graph of the incremental fuel rate (ordinate) as a function of the unit's output (abscissa) is known as a "heat rate curve," and such a curve shows the rate of change of the input with respect to the output as a function of the output. As will be seen later, heat rate curves play a fundamental role in the economic allocation of generation.

To show that incremental rates are of greater concern than absolute efficiencies in the economic allocation of generation, consider that a plant is called upon to furnish a specified additional or incremental output above and beyond the output level at which it has been operating. The increment of output will be furnished at a cheaper cost if this increment is assigned to the generating unit having the lowest incremental fuel rate at that level of total power output, rather than to the unit having the highest absolute efficiency. The criterion is not the relative absolute efficiencies of the units but the relative efficiencies of generating the additional or incremental output, and therein lies the explanation for the now widespread use of incremental rate theory.

The incremental fuel cost of a generating plant is a composite of the incremental fuel costs of its individual units, and a curve may be plotted for this composite quantity as a function of the total plant power output. To the plant's incremental fuel cost may then be added the subsidiary incremental production costs corresponding to labor, maintenance, and supplies for that plant. The resulting graph of plant incremental production costs as a function of plant power output is used in allocating generation among the plants of a power system.

On the other hand, where it is desired to determine the optimum generation allocation among the individual units of a power system, the unit incremental production costs must be known. The incremental production cost for each unit in a plant is arrived at by combining each unit's incremental fuel cost with a suitably chosen fraction of the plant's overall subsidiary production costs, i.e., appropriate proportions of the subsidiary production costs for the entire plant are assigned to each of the individual units in that plant.

A problem related to the use of incremental production costs is that no known method exists for expressing the previously listed subsidiary costs (particularly the maintenance cost) as a function of the instantaneous total power output with any reasonably good degree of accuracy. This problem is frequently overcome, however, by assuming these subsidiary incremental costs to be a fixed percentage of the incremental fuel cost at each plant (or at each unit). Of course, the matter of accurately representing all the various costs which have been mentioned is an art in itself (63-67); however, here it is only necessary that the proper meaning be given to each of the costs mentioned.

For several decades the analysis of generation allocation problems was carried out only on the basis of the incremental production costs, and these efforts were directed at minimizing the total power production cost as evaluated at the generating sites rather than at the load points. To understand the criterion which formed the basis of this approach to generation scheduling, consider that all the plants of a power system are not operating at the same incremental production cost. Accordingly, some plants will then be operating at higher incremental production costs than others, and it should be possible to decrease the dollars per hour input to the system by increasing the generation at the lower incremental cost plants and decreasing the generation at the higher incremental cost plants. In the limiting case, it can be shown that all sources should be operated at the same incremental production cost. This concept of equal incremental production costs at all plants of the system was the basis of all attempts at the economic allocation of generation during many years.

A simple and ingenious tool known as the incremental fuel cost slide-rule served as an aid in applying this criterion in the preparation of generation schedules. (62,68) This slide-rule consists essentially of a number of movable elements which may be displaced and properly adjusted to compensate for the differences in incremental fuel costs (or incremental production costs) at the various plants. Reading the slide-rule then provides a direct indication of the power output which each plant should assume in order to satisfy the criterion of equal incremental costs for the prevailing total system load.

Where the tie-line transmission losses are negligible, it is seen

that the economic division of load among two or more interconnected generating stations is simply a problem of operating the stations at loads which correspond to the same incremental production cost.

To be sure, it was not long before it was generally recognized that transmission losses should also be considered in the scheduling of plant loadings, for operation at equal incremental production costs would certainly result in the transmission of power from low-production-cost areas to high-production-cost areas, and this would clearly lead to transmission losses whose presence, it would seem, might be significant enough to have some bearing on the economic distribution of generation assignments. Particularly in the case of widespread systems where it is necessary to transmit power over long distances from the generating stations to the load centers, and where significant variations in fuel cost across the system are more likely to occur, it was quite apparent that some error resulted from not including the associated line losses in the economic loading analysis.

It should be mentioned at this point that the criterion of equal incremental production costs is correctly applicable to the determination of the economic division of load among generators located at the same bus, and that this criterion may also be fairly accurately applied to a closely knit metropolitan system in which the generators are located practically at the load centers. But for widespread systems on which the losses are appreciable, and on which fuel costs are less likely to be approximately the same all across the system, the allocation of generation on the basis of the total power production cost as evaluated at the generating stations is not very sensible.

In those situations where it was quite obvious that severe losses in operating economy resulted from ignoring the transmission losses, the system load dispatcher generally attempted to account for the presence of these losses in an approximate manner. These attempts, however, were usually restricted to a few of the simpler cases (such as scheduling the tie-line loading between two plants), and where more complex configurations were encountered, trial-and-error calculations became so involved and so time-consuming that satisfactory analysis was difficult, if not impossible.

Clearly, such procedures could not be considered entirely acceptable, but further progress in the art of economic loading was made to await the introduction of a systematic and analytically justifiable method for the inclusion of the effect of transmission losses in the scheduling of generation. The continuing expansion of integrated power systems and the interconnection of operating companies for the purposes of economy interchange were instrumental in arousing further interest in the need for properly considering transmission losses, since these developments caused the losses to become increasingly influential factors in securing optimum operating economy.

The first major step in the development of a method for the coordination of incremental production costs and incremental transmission losses was presented in 1949. (37) This method involved the use of the network calculator to solve a set of simultaneous, linear, algebraic equations relating the variables of incremental production cost and incremental transmission loss for the preparation of predicted plant loading schedules for a large power system. The approach was aimed at

minimizing the total power production cost as measured at the load point, rather than at the generating plant; i.e., the conditions which would result in the minimum cost of delivered power were examined. These conditions were defined in terms of equations that dictated the necessary relationships among the incremental production costs, the incremental transmission losses, and the incremental delivered power costs which must exist for the economic allocation of generation including the effect of transmission losses.

Solutions for the optimum generating schedules under a variety of station and system loading conditions were provided through the use of an electrical analog of the equations mentioned above. The procedure consisted of designing an electrical circuit whose equations of performance were identical to the given equations, and then representing this circuit on a network analyzer. Once the choice of suitable scale factors and the adjustment of the analyzer set-up had been realized so that a given combination of machines, transmission lines, production costs, and total system generation were properly represented, the measurement of the currents in the circuit provided data which could be appropriately interpreted to yield the optimum generator loading schedule.

This first method for coordinating incremental production costs and incremental transmission losses was significant in that it finally made available a systematic and analytically justifiable means for including the effect of transmission losses in the determination of plant loading schedules. But as is the case with many revolutionary discoveries, the first use of this new method was hindered by difficulties with

still unrefined techniques and by troublesome operating details. The method worked, but not with the degree of simplicity and directness which might be considered desirable.

Further developments in coordination methods then led to the introduction of a set of simultaneous, nonlinear, partial differential equations which is now the basis for nearly all attempts at the economic allocation of generation. These equations are known as the "coordination equations," and they are of the following general form:

$$\frac{dF_n}{dP_n} + \lambda \frac{\partial P_L}{\partial P_n} = \lambda \quad (8)$$

where F_n = total input (fuel and subsidiary production costs) to power source \underline{n} , in cents/hour

P_n = loading of power source \underline{n} , in kw

$\frac{dF_n}{dP_n}$ = incremental production cost of power source \underline{n} , in cents/kw-hr

P_L = total system transmission losses, in kw

$\frac{\partial P_L}{\partial P_n}$ = incremental transmission losses associated with power source \underline{n} (non-dimensional)

λ = incremental cost of delivered power, in cents/kw-hr

It should be noted that the \underline{n} variable power sources include both generating stations (or units) and interconnections with neighboring systems. The interconnections are considered as sources of positive or negative power (according to the direction of power flow), and the

corresponding inputs F_n for these sources may be interpreted in terms of the prevailing levels of power flow over the various tie-lines and the associated sale or purchase prices attached to the energy exchanged.

It is important to note that the derivation of the coordination equations is predicated upon the assumption that every variable power source is characterized by an incremental heat rate curve having no sections with negative slope, i.e., the curves must everywhere exhibit either positive or zero slopes. This restriction on the validity of the coordination equations, however, rarely presents any difficulty in practice because the heat rate curves normally are continuously increasing (monotonic) functions of an increasing source output.

The meaning of the coordination equations requires some elaboration. First, the derivation of the equations employs the method of Lagrangian multipliers (69) which is frequently of use in calculus problems involving maxima and minima with subsidiary conditions. In this case, it is desired to minimize the total input $F_t = \sum_{n=1}^s F_n$ from the \underline{s} power sources to the system, for a given total received system load P_R , and subject to the following equation of constraint:

$$\sum_{n=1}^s P_n - P_L - P_R = 0 \quad (9)$$

This equation of constraint represents a subsidiary condition which requires that the total received load be equal to the sum of all source generations less the total transmission losses.

Since only one subsidiary condition exists, it is only necessary to use one Lagrangian multiplier, λ . The Lagrangian multiplier is simply

an undetermined constant, and the result of the application of Lagrange's method is that a system of $s + 1$ simultaneous equations is made available. This system includes the s equations given in equations (8) plus the single equation (9). It is then possible to solve these $s + 1$ equations for the s variables P_n plus the additional variable λ . When the variables P_n and λ assume those values dictated by a solution of these equations, the power system will be in economic balance and operating at the minimum input in dollars/hour for the existing total system load. These $s + 1$ equations are also known as the coordination equations, although the abbreviated form given in equations (8) is more common.

A solution of equations (8) and (9) for the variables P_n and λ , however, will yield the optimum generation allocation only for the single total system load P_R which was used in equation (9). As the values of P_R used are changed to permit solutions for the optimum generation allocation over the entire range of expected total system loads, the value of the undetermined constant λ will also change, and it will be found that for each value of total received load P_R , there will be a single corresponding value of λ . Thorough investigation of the physical significance of λ will uncover the fact that it is simply the incremental cost of delivered power, i.e., the incremental cost of power as measured at the load centers (rather than at the generating stations). (70)

And of course, it is entirely reasonable that a single value of the incremental cost of delivered power should correspond to each value of total system load. The result is that once the value of λ corresponding to the total load P_R at which it is desired to find the optimum economic allocation of generation is known, this constant value may be substituted

in equations (8), and it is then only necessary to solve the s equations (8) for the s variables P_n . In practice, of course, the constraint represented by equation (9) will automatically be imposed by the power system itself.

The above discussion explains why it is often possible to use only the abbreviated form of the coordination equations which is given in equations (8). However, where the incremental cost of delivered power λ corresponding to a particular total system load P_R is not known, the complete coordination equations given by equations (8) and (9) must be used.

In order to solve equations (8), or equations (8) and (9), for the desired values of P_n and λ , all the other variables must be eliminated. In equation (8), P_L may be expressed in terms of P_n using equations (3) or (6) of the preceding chapter, or $\frac{\partial P_L}{\partial P_n}$ may be directly replaced with equations (5) or (7). Similarly, P_L in equation (9) may be replaced with equations (3) or (6), and of course, P_R in equation (9) is a constant. Finally, $\frac{dF_n}{dP_n}$ in equation (8) may be replaced with an analytical expression describing the incremental production cost as a function of P_n and this illustrates the need for accurate incremental production cost curves expressed in terms of the variable power source loadings.

The above considerations also illustrate the value of a loss formula which expresses a power system's incremental transmission losses in terms of the loadings of the system's generating stations and interconnections. Indeed, it may be noted that the development of the coordination equations was in part dependent upon the prior discovery of a suitable means for representing the incremental transmission

losses. Prior to 1942, economic dispatching of generation had always been based on incremental station costs, either ignoring transmission losses altogether or considering them in an approximate manner, simply because transmission loss formulas were not available in a handy form which would permit their use on an hour-to-hour basis for generation scheduling.

At this point it is also of interest to point out that, whereas the economic allocation of generation without consideration of transmission losses requires that the generating stations (or units) be operated at equal incremental production costs, the economic allocation of generation with proper consideration of transmission losses requires that the sources of generation be operated so as to result in equal incremental costs of delivered power at all load centers. This is evident upon considering that equations (8) require that all of the n variable power sources adjust their generations P_n in such a manner that a single value (λ) of the incremental cost of delivered power shall prevail on a system-wide basis. Verbally, equations (8) state that the total production cost to supply a given total system load is a minimum when the incremental cost of delivered power is the same from every variable power source. Though the incremental production costs may vary from station to station, all such deviations will be exactly offset by the prevailing distribution of incremental transmission losses between the various sources and the various load centers, with the result that an increment of delivered power can be supplied by any source at the same net cost.

Equations (8) may be manipulated and rewritten in another form:

$$\lambda = \frac{1}{1 - \frac{\partial P_L}{\partial P_n}} \times \frac{dF_n}{dP_n} \quad (10)$$

This form of the coordination equations shows that a "penalty factor" K_n , where

$$K_n = \frac{1}{1 - \frac{\partial P_L}{\partial P_n}}, \quad (11)$$

may be used to indicate the extent to which the presence of transmission losses causes the incremental cost of delivered power to differ from the incremental production cost of each source n . The penalty factor concept has been found useful in applying the coordination theory to the actual assignment of generation in practice.

It may be noted that the total system input F_t in terms of production costs is consumed partly in useful load, partly in transmission losses, partly in plant thermal losses and auxiliary equipment requirements, and partly in meeting subsidiary operating expenses (e.g., labor, maintenance, etc.). The power delivered to the load centers as useful power is fixed under a given condition of total system load demand, but the plant losses and the transmission losses are variables which depend on the allocation of generation. The thermal efficiency (or net heat rate) at a given plant depends on the output of that plant alone, but on the other hand, the transmission losses in a complex network are dependent simultaneously on the output of all of the system's plants. The optimum generation schedule for supplying a given set of loads at maximum overall efficiency will not in general yield either maximum

total station efficiency or maximum transmission efficiency. Generally, some compromise between the opposing effects of station losses and transmission losses will result, and only in rare instances will a given generating schedule by extreme coincidence yield simultaneously the minimum transmission losses and the minimum total station production cost.

It must be emphasized that the ideal pattern of generation allocation given by a solution of equations (8) and (9) cannot always be obtained in actual practice due to various electrical limitations which may exist or because of certain operating requirements which take precedence over the desire for optimum operating efficiency. These limitations and requirements are not represented in the coordination equations as given in equations (8), and hence the solution of these equations may or may not be within the bounds imposed on a given system by electrical capabilities and other restrictions. In such cases, the optimum efficiency condition will only be approximated in practice since any operational requirements for modifying the ideal pattern of generation allocation will certainly have to be observed. Thus, what has been referred to as the "economic allocation of generation" becomes in truth "the allocation of generation on an economic and operational basis" when put into practice. Of course, any computerized scheme for applying the coordination theory to system operation will have to include provisions for satisfying any electrical limitations or other restrictions which may present themselves from time to time.

Finally, it may be mentioned that several modifications of the basic coordination theory presented on the preceding pages have been

developed. Most of these have been simplifications which are applicable in certain restricted cases -- discussion of such special methods and of their range of applicability will be found in the technical literature. (71) Other investigations have resulted in alternate methods of deriving the coordination equations. (58) Also, coordination methods have been developed for use with predominantly hydroelectric systems. (72-76) For the purposes of this study, however, it will be sufficient to work with the general coordination equations (as given earlier) for a predominantly thermoelectric system.

In the years following the first introduction of the coordination equations of the type given in equations (8), many improvements and refinements in the techniques of application of these equations were introduced. Even as early as 1951, general-purpose electronic computers had already been foreseen as future tools for the solution of the coordination equations. Actually, it was only shortly after the first introduction of the coordination equations in 1949 that the use of automatic digital calculators, such as the IBM 602A or 604, was mentioned for the numerical calculation of generation schedules including the effect of transmission losses. Indeed, the solution of a system of n simultaneous, nonlinear, partial differential equations (such as the coordination equations for an n -source system) is such a formidable task that one might very well be immediately led to think in terms of such handy subterfuges as the use of electronic computers.

The application of electronic computers to the solution of the coordination equations will be mentioned again at a later point. For the present, it will be assumed that some means of solution is available,

whether it involves a general-purpose or special-purpose electronic computer, some form of punched-card business machine, a network calculator, or some alternative "brute-force" method.

Solution of the coordination equations for a particular value of total system load will then indicate the proportions in which the system's various generating plants should be loaded for minimum operating cost at the given total load. The solution may be repeated for any desired number of representative total load conditions, and the results may be presented as curves of generator loading versus system load, i.e., each plant will have a curve indicating the load which it should assume at each value of total load in order to satisfy the previously mentioned criteria for economic operation. Such a family of curves is generally known as a set of precalculated economic dispatch curves.

These curves may then be applied directly to the economic scheduling of generation as long as the operating conditions for which they were derived continue to prevail. They are "precalculated" curves because they are based on predicted operating conditions rather than on those operating conditions actually existing at the time of scheduling. Nevertheless, insofar as the conditions for which they were derived remain approximately correct, they are very useful as an aid to the system dispatcher, and at the time of their introduction they served to open up new possibilities in the quick determination of the proper economic loading patterns.

Generally, the system dispatcher will prepare generation schedules for the following day on the basis of predicted loads for each hour of the daily load cycle by referring to the precalculated dispatch curves

to determine the indicated apportionment of load among the system's plants which corresponds to the total load forecast for any given hour of the next day. This procedure introduces substantial savings in operating economy since it incorporates an analytically defined method for considering the presence of transmission losses and their effect in modifying the optimum distribution of generation.

The use of precalculated dispatch curves, however, does not represent a panacea or cure-all for the complex problem of allocating generation economically. Any one family of dispatch curves is based on a number of fixed quantities which include specific values of fuel costs and production costs, the assumed availability of units, the scheduled dispatch of power over interconnections, and other specified operating conditions. But fuel costs vary with time and geographical location; the subsidiary production costs vary with labor and maintenance costs and with fluctuations in the costs of supplies; the availability of generating units is altered by forced outages and by planned outages for repairs and maintenance; tie-line power flows vary as interconnection transactions are modified and as daily and seasonal fluctuations in demand occur.

In order to permit economic dispatch at all times it is necessary to provide numerous families of dispatch curves which will consider all practically possible combinations of these variables. As the extent of interconnections increases and as power systems become more widespread, these variables become more influential, and the required number of sets of precalculated dispatch curves mounts rapidly.

A large number of precalculated curves is objectionable because

the system operator is often uncertain which curves should be used and because he becomes confused in attempting to interpolate between non-applicable curves. Also, the preparation of so many precalculated families of dispatch curves is a very laborious and time-consuming task. Moreover, it is generally necessary to revise the curves about every six months in order to keep pace with changing conditions and with modifications in system configuration due to the construction and installation of new transmission lines, generating plants, and substation load centers. Clearly, the entire matter can quickly get out of hand, and the value of precalculated dispatch curves is often drowned in a sea of related problems and complications.

Of course, it is true that precalculated dispatch curves are extremely useful on systems of limited extent whose variations in operating conditions are more restricted, whose interconnection transactions are less frequent, and whose fuel (or production) costs vary together across the system. But the continuing trend toward the integration of small systems to build large interconnected systems and power pools operating over extensive areas of varied geographical, climatic, and economic characteristics soon made it clear that a more sophisticated and more widely applicable means for scheduling generation was urgently needed. Furthermore, it must be remembered that in addition to having to correctly select and apply the large volume of information contained in the numerous sets of dispatch curves, the load dispatcher and the chief system operator are also concerned with such problems as observing the established electrical limitations related to normal and emergency equipment ratings, spinning reserve requirements,

plant thermal characteristics, service continuity, voltage regulation, reactive power limitations, stability limitations, and others.

Finally, for all the good that the precalculated dispatch curves based on predicted conditions do in providing the operators with a framework within which to operate, it is still necessary to maintain continuous contact with actual load and frequency conditions and to modify the original generation schedules to meet these requirements and other unexpected emergency situations as they arise during each day's operation. For example, existing conditions may differ from anticipated conditions because of the unexpected loss of a generator; because of unexpected limits on generation due to wet coal, or leaks in boiler, superheater, or economizer tubes, or clogged or dirty condensers, etc.; because of emergency changes in the power flow over the tie-lines; because of unforeseen changes in the power supply to non-conforming loads; and because of the many other unexpected situations which continuously confront the operator of a large power system.

The increasing complexity of power system operation and the commensurately larger burden on the system operators were factors which contributed to the search for a better means of scheduling generation. More influential, perhaps, was the realization that despite the substantial savings which resulted from the use of precalculated dispatch curves, even greater savings would be obtained if it were possible to develop a procedure for continuously maintaining the system in the economic balance dictated by the pertinent coordination equations. This would require elimination of the error resulting from the discrepancy between predicted and actual conditions.

It is true that, as the years passed, various methods for calculating and preparing generation schedules using electronic computers were developed (77-79), and these incorporated important refinements over the earlier methods of references 37 and 68. They materially reduced the drudgery of preparing numerous families of dispatch curves, but still this had little effect in alleviating the demands made of the system operators. Thus, in spite of these advances, it was still felt that a new method for continuously assigning generation on an economic basis was seriously needed.

Such a method would free the system operators of much routine work and make them more completely available for important decisions and closer scrutiny of the operating practices. It would also pay big dividends in boosting operating economy and thus affording increased savings. These conditions created a need for a computing device which could be used directly in the dispatching office to show the correct dispatch at all times, and the realization of this goal later led to the introduction of automatic control systems which continuously provide for the economic allocation of generation together with the maintenance of system frequency and scheduled net interchange.

An example of a specialized computer located in the load dispatcher's office for the sole purpose of aiding him in preparing up-to-date generation schedules is the transmission loss penalty factor computer. (80,81) This is an analog device that computes the previously discussed penalty factors of equations (11). Upon selection of a particular power source, the computer calculates the corresponding penalty factor, and in this manner all of the penalty factors K_n are made

immediately available. These calculated penalty factors are then used to modify the adjustment of the previously described incremental fuel cost slide-rule in order to account for the presence of transmission losses. Readings derived from the slide-rule provide the dispatcher with the necessary information to economically assign generation.

Though the method is not automatic in that it still depends on a human operator link to translate the calculated data into actual practice, it does overcome many of the objections to the earlier approach using precalculated curves. The speed of the computer enables changes in operating conditions to be quickly reflected in the pattern of generation allocation, and thus the discrepancy between anticipated and existing conditions is largely eliminated. However, some time is consumed in carrying out an iterative process of adjustment between the computer readings and the slide-rule settings in order to achieve convergence on the desired generating schedule. Nevertheless, the use of this method on one system was claimed to have resulted in yearly savings of the order of \$150,000 when compared with the use of a scheduling method which included no consideration of the presence of transmission losses.

Elimination of some of the manual steps included in the computer and slide-rule method leads to another load dispatching computer designed specifically for use by the system dispatcher in his office. In this approach, the slide-rule is discarded and the incremental production cost characteristics are obtained from function generators or from some form of electrical analog of the incremental production cost curves. Further analog-type circuitry properly combines the cost characteristics with the penalty factors (computed by the penalty factor computer

as before) to yield the incremental cost of delivered power λ_n from each of the n sources.

Though previously only a single value λ of the incremental cost of delivered power was mentioned, it is entirely reasonable that n distinct values of this cost should exist when the system is not at its optimum condition of generation allocation. Operation of the equipment requires that the dispatcher continuously modify his generation assignments in order to approach as closely as possible a condition in which the computed values of λ_n from all of the n sources are equal to a single value λ . Use of the computer is facilitated by additional circuitry which calculates the average of the existing λ_n values; then, the dispatcher simply compares each plant's λ_n with the prevailing λ_{average} and accordingly assigns generation so that each individual λ_n will approach λ_{average} as closely as electrical limitations and other restrictions permit. A load dispatching computer of this general type was introduced on the Southern Company system in 1954. (82)

Some consideration should be given to the type of input data required by load dispatching computers of the kind just mentioned. Calculation of penalty factors, of course, requires that the incremental transmission losses be known, and these are found from equation (5). Therefore, the prevailing values of P_n , or of the variable power source loadings, must be supplied to the computer. Similarly, once the P_n values are specified, the incremental production costs are found from the cost curve analogs. Thus, the basic input data required for the operation of a load dispatching computer of this type is a list of the prevailing source loadings.

The loading schedule which is then indicated by the computer as the optimum pattern of generation allocation may be modified by the operator in order to meet operating requirements related to local area protection, spinning reserve, voltage support, and other restrictions on system and equipment operation. On the other hand, in automatic dispatching computers, most of these operational limitations must be represented in the computer itself, as will be seen later. In either case, however, it is important that all loading changes and other changes in operating conditions be immediately fed back into the computer in order to maintain a continuing correspondence between the computer operation and the existing system conditions.

Several basic aspects of the operation of load dispatching computers placed in dispatching offices as aids to up-to-date generation allocation have been presented in order to permit some understanding of the manner in which such computers are able to overcome many of the limitations of the precalculated loading curves. Numerous improvements in the design and utilization of such specialized dispatching office aids have evolved in recent years (83-90), but the details of these installations will not be mentioned here. It is more important to realize that these specialized load dispatching computers do not themselves represent the ultimately desired method of obtaining economic system operation.

Once a means is developed for computing generation schedules which include allowances for transmission losses and which are essentially up to date in all respects (i.e., applicable to existing conditions), it becomes desirable to curtail the heavy dependence on human

participation in the transfer of calculated operating data into actual practice. A means of automatically implementing the computer-indicated operating conditions would reduce time delays caused by speed and volume limitations on human implementation; it would increase fuel economy through the elimination of human errors and inaccuracies; and it would enable savings in operating man-hours. Of course, these comments refer to automatic economic dispatching systems, and systems of this more advanced nature will be further considered in the next chapter.

At this point, however, attention will be restricted to the application of analog and digital computer methods to the solution of the basic coordination equations, since these equations are the essence of any dispatching scheme (whether it employs a specialized load dispatching computer or a complete automatic economic dispatching system).

Although the preceding chapter pointed out that the problem of preparing a transmission loss formula is essentially digital in nature, this should not also imply that the use of transmission loss formulas will in turn require the utilization of predominantly digital techniques. One of the more important applications of transmission loss formulas is in the coordination equations, and the load dispatching computers just mentioned effectively solve these equations using only analog methods. Actually, the coordination equations may be solved using either analog or digital techniques, and similarly, transmission loss formula applications may be either digital or analog in nature. Indeed, since the coordination equations include an incremental transmission loss formula, succeeding discussions of analog and digital approaches

to the solution of the coordination equations will imply that many of these approaches are also suitable for use with the various transmission loss formula applications.

It is perhaps well to briefly consider just what is meant when analog and digital computer methods are mentioned for the solution of the coordination equations. Analog methods will involve either a direct-analog approach in which the coordination equations whose solutions are desired are directly represented by electrical circuits whose governing equations are of an analogous form or they will involve an indirect-analog approach employing electronic differential analyzer techniques. (14, 91, 92) Digital methods of solution will employ determinants and manual matrix manipulations in the very elementary cases, and in the more general situations, the matrix manipulations and other operations will be performed by electronic digital computers. Alternatively, a technique combining both analog and digital characteristics, such as the use of digital differential analyzers, might be employed. (15, 16) Both analog and digital methods (or combinations thereof) are entirely feasible for the solution of the coordination equations, i.e., the use of any of these methods will afford solutions of the coordination equations.

A somewhat more subtle question, however, considers the relative merits of the analog and digital approaches. (83) Of course, the choice between alternate approaches is often largely dependent on the particular application in view and on economic considerations. For example, where specialized digital load dispatching computers are installed in the dispatching offices as aids in the economic allocation of generation, it is usually difficult to justify the heavy expenses involved

in maintaining a digital computer continuously on stand-by while actually only using it intermittently for rapidly performed calculations. On the other hand, a special-purpose analog computer for the same application would generally be less expensive, and hence more readily justified economically. Yet, if precalculated schedules were considered acceptable and if a digital computer could be rented for short intervals, then the digital method would probably appear more attractive than the analog method for this particular application.

However, beyond the economic considerations pertinent to each application, there remain certain inherent attributes of analog and digital computers which should be evaluated in the light of the specific application in mind before a final selection is made.

For example, digital computers are primarily information-handling devices by nature. They offer the attributes of "memory" or "storage" and "decision-making" or "automatic sequencing" (7) and they are consequently of great value in information-processing systems requiring data storage and the ability to select between alternate information-flow paths or data processing procedures on the basis of internal information and without human intervention. Digital computers are well suited to the handling of very large amounts of data and particularly to data used repetitively in precise arithmetic calculations. Finally, the concept of a "stored program" for digital computers makes available general-purpose computers of enormous flexibility in the sense that they may be applied to many, many different problems.

On the other hand, whereas digital computers are well adapted to the handling of numerical data of a completely random nature, analog

computers are better suited to the handling of data which follows natural physical laws (often expressed by differential equations) or which can be described in equation form. And whereas the computational accuracy of digital computers can be made almost whatever is desired, the accuracy of an analog computer will depend upon the inherent accuracy of its component parts and upon the accuracy with which the variables can be measured both in obtaining the output data and in supplying the input problem data. Since the analog computer is in essence a device for the solution of physical systems by the construction of a mathematical model of the system, it is admirably suited to the solution of problems requiring the simulation of physical systems. However, analog computers depend on "wired-in programming" and do not permit automatic program modification; nor do they afford the storage and decision-making possibilities of the digital computer.

Finally, the digital differential analyzer offers a combination of some of the advantages of both the analog and digital computer, while overcoming some of their individual limitations. (Conceivably, the digital differential analyzer could very effectively be applied to the economic coordination problem, although as yet little announced progress has been made in this direction.)

From the above remarks it should be evident why analog computers have been so widely used for the solution of the economic coordination problem at the level considered in this chapter (i.e., where a computer is placed in the dispatching office as a specialized dispatching aid), for in addition to the economic advantage, it is obvious that the coordination problem at this level can better utilize the analog computer's

special attributes rather than those of the digital computer. In other words, where attention is restricted to the so-called specialized load dispatching computers which have been considered on the preceding pages as an intermediate step between the use of precalculated schedules and the use of automatic dispatching systems, analog methods have generally been found more feasible in view of the relative cost of digital computers and because the requirements for information-handling and computational accuracy have not been sufficient to warrant the use of digital techniques.

Nevertheless, the economic considerations pertinent to each application will still have to be reviewed as new applications arise, and perhaps more important, the characteristics and peculiar attributes of the analog and digital methods will also need to be re-evaluated for each new application in light of their relative importance to the problem at hand. In cases where the benefits to be derived from the use of automatic economic dispatching systems are important enough to justify the incorporation of these more refined systems, the analog-versus-digital question becomes more involved. The following chapter will consider automatic dispatching in greater detail and will investigate more thoroughly the use of digital and analog techniques both in these systems and in meeting the requirements of other power system control functions.

PART II

Chapter 3

LOAD-FREQUENCY CONTROL, AUTOMATIC DISPATCHING, AND OTHER COMPUTER SYSTEM FUNCTIONS

Considerable attention has been devoted to the many aspects of the important problem of securing the optimum economic operation of power systems. The factors which influence the economic allocation of generation among the power plants of a system have been investigated, and the desired relationships among the incremental production costs and incremental transmission losses have been established. Preliminary discussions of the application of analog and digital computer methods to the solution of the economic coordination equations have been included.

The problem of economic operation is at the heart of any control system for power system operation, and it is only proper that this topic be thoroughly explored. Further consideration of the application of analog and digital computer methods to power system control, however, will have to be undertaken on a broader level. It will be necessary to treat such applications in terms of the several control functions of interest in power system operation rather than simply in terms of the function of economic operation. To this end, the various control functions in question should be discussed.

The basic law of supply equalling demand, which is so debated in other circles, must continuously be satisfied in the operation of electric power systems. The principle of the conservation of energy requires

that the total generation of energy on any power system be at each instant completely absorbed in its loads, its transmission losses, and a net outward flow of power over the interconnections with adjacent systems (where the net tie-line flow is inward, this is viewed as additional generation). Moreover, the loads on a power system are in a continuously fluctuating state -- it has been said that the only normal state of a power system is an abnormal one! Since the transmission losses and interconnection flows will not automatically adjust themselves in such a manner as to exactly compensate for all load fluctuations, the conservation of energy requirement will have to be met through compensating frequency fluctuations unless some satisfactory means of continuous generation control is provided. Of course, random frequency fluctuations are not permissible, and therefore it has become necessary to introduce load-frequency control in the operation of power systems.

The evolution of acceptable load-frequency control methods has been a long and gradual process. (93-100, 35) Although the history is a fascinating one, there is little justification for reviewing at this time the various developments which have led to today's advanced methods of load-frequency control. Instead, suffice it to say that the shortcomings of the flat-frequency, flat-tie line, and selective-frequency methods of load-frequency control used in many early installations have eventually led to their rejection where today's extensive integrated power pools are concerned. For smaller, isolated power systems, some of the earlier methods are still useful, but where it is necessary to both control system frequency within narrow limits and hold tie-line power flows at scheduled levels, the principle of tie-line bias control has found universal acceptance.

Although the complete theory of tie-line bias load-frequency control is somewhat involved, it may be said that the method is very effective in meeting the prime requirement for satisfactory control of frequency and net interchange on integrated systems. This requirement is that each area of an interconnected network modify its own generation to absorb its own load changes. The fact that the load changes are absorbed will permit an essentially constant system frequency, and the fact that these changes are met (i.e., compensated for) in the same area in which they occur will permit the tie-line power flows to remain at the scheduled levels. During each period of readjustment, and until the indicated reassignments of generation have been realized, the tie-line flows are altered, however, while each area in the pool contributes an appropriate share (determined by the bias* chosen) of the necessary regulating action that will accelerate the recovery of the afflicted area. These tie-line schedule deviations are unavoidable, and they are not entirely objectionable if the changes are steady rather than fluctuating and if the normal schedule is promptly restored as the afflicted area acts to compensate for the load change which it suffered. In short, tie-line bias is the most effective method known for controlling system frequency and net interchange on integrated power systems.

The concept of individual areas within a power system which separately adjust their total generation in order to meet their own load swings is an interesting one. Exactly what constitutes an "area" and

*Area "bias" values, expressed in Mw/0.1 cycle, for power systems in the United States have generally fallen in the range of one-half to two per cent of the spinning capacity on the line in that area.

just how many areas will exist within a given interconnected system will depend largely upon the system's geography, the overall network configuration, and the extent of interconnections between the various groups of neighboring stations and load centers. In effect, the boundaries of an area are so determined as to permit it to satisfy the requirement that it absorb its own load changes through adjustments in its own generation. An area may be of any size, but it must operate as a single entity insofar as the allocation of generation changes to accommodate load changes is concerned.

A given power system may be either a single-area system or a multiple-area system according to the dictates of the above definition of an area. On a single-area interconnected system, the whole interconnection is one area, which implies that because no one part of the interconnection is solely responsible for adjusting generation to meet its own load changes, the tie-line power flows within that area are neither scheduled nor controlled. Therefore, the generation allocation problem is reduced to a question of determining where on the interconnection it is most economical to absorb the next load increment, and this may be done without any regard for where the change occurred. On multiple-area interconnections, however, it is obvious that tie-line power flows must be scheduled and controlled if a fixed net interchange between the several areas is to be maintained. The generation allocation problem then has two aspects: First, the required change in generation to meet a given load change must be allocated to the area in which the load change occurred; then, once the generation change is assigned to the proper area, it is desirable to allocate this generation requirement

among the power plants in that area in the most economical manner. Clearly, these considerations will have to be incorporated in the design of an automatic dispatching system which is to be used on a multiple-area system. Also, it may be noted in passing that automatic dispatching systems will generally be found more frequently applicable to the large multiple-area interconnections than to the smaller single-area systems.

There are two limitations on economic system operation which pertain to operating functions that are of greater importance than achieving the optimum economic allocation of generation. The first of these is related to load-frequency control. The requirements of proper load-frequency control will not conflict with the theoretical economic loading of generators as long as it is possible to change the load on any unit at any desired rate. But, of course, there is a practical limit on how rapidly any given machine can pick up or drop load, and though this restriction becomes less serious whenever there are several machines which can be simultaneously called upon to absorb the load swings, it must still be considered. Thus, when load swings on the system occur very rapidly, there will be instances in which even several machines will not offer enough latitude to permit the load swings to be absorbed in accordance with the principles of incremental loading, and therefore it will become necessary to assign part of the load swing to units which are not at that time prepared to economically participate in meeting the new generation assignments. On many systems, situations of this type, which require that economic generation allocation be temporarily overlooked in favor of the more important function of load-

frequency control, will develop every morning and evening during load build-up and drop-off.

The other limitation on economic system operation concerns service reliability. A prime function of an electric utility is the production of electric energy at the lowest cost consistent with the obligation of maintaining continuity of service. And to the essential need for service continuity may be added the desire for high-quality service. Considerations of this nature may, for instance, require that units be kept in service in remote parts of a system to provide voltage support during off-peak hours, although it may not be economical to do so. Similarly, where one generating station is connected to the rest of the system by only one transmission line, it might be desirable to maintain a certain amount of spinning reserve in this area even though this may be contrary to the pattern of generation allocation indicated for maximum operating economy. In a sense, load-frequency control is also directly related to service reliability and service quality. Such control is responsible for continuously matching generation to load demand and hence makes an important contribution toward service continuity; also, it is concerned with maintaining constant system frequency and therefore is essential to high-quality service.

In summary, the various operating practices which are necessary to insure continuous electric service of a high quality (in terms of voltage fluctuations, frequency deviations, etc.) will always take precedence over any effort at economic operation. Only once these requirements have been met, and only insofar as they continue to be satisfied, will it be possible to consider the most economical means

of supplying the generation needed to meet the existing demands.

Clearly, automatic economic dispatching systems will have to satisfy the various operating requirements of an electric utility system in the order of their relative importance, as outlined above.

A tie-line bias load-frequency control system operates in such a manner as to first determine the "area requirement" (or the change in net generation needed in an area in order to permit a stable frequency and a fixed net interchange) of a given area in terms of the prevailing system frequency, the existing net interchange with other areas, and the bias value selected for that area.* The system then must do whatever is necessary to reduce or eliminate the area requirement, and the degree of accuracy with which each area maintains its area requirement equal to zero will be a measure of its operating competence as a participating member of the interconnection. If the area requirement is zero, no change in total generation is desired, but if the area requirement is a positive or negative value, the total generation must be increased or decreased accordingly. Whatever the case, the required total generation should be distributed among the area's stations and units in the most economical manner, provided that any operating requirements pertaining to continuity or quality of service are also satisfied.

Essentially, the function of an automatic dispatching system is to receive the order for more generation, less generation, or no change in generation (as indicated by the load-frequency control equipment in

* By definition, Area Requirement = (Actual Net Interchange - Scheduled Net Interchange) \pm Bias (Actual Frequency - Scheduled Base Frequency).

terms of an area requirement) and then apply the principles embodied in the coordination equations to execute this order in the most economic fashion subject to any restrictions imposed by the requirements of service continuity and quality. The previously considered load dispatching computers for use in the dispatcher's office as an aid to economic operation served only to indicate how a given total generation could be economically supplied. How much total generation is required was determined by an entirely independent load-frequency control system. The restrictions imposed by the requirements for service continuity and quality were partially represented in the computer and partially introduced by the operator himself. Implementation of the computed results was effected via a human link (the operator) between the computer output and the power system.

On the other hand, an automatic dispatching system weds the computer to the load-frequency control system and thereby reduces human participation to a minimum. Computed results are immediately implemented by the integrated dispatching and load-frequency control equipment and will consequently be followed more accurately (and with less time lag) by the power system. Automation of the dispatching procedure also overcomes the human limitations on the number of operations which may be performed simultaneously. Of course, because the automated system must reduce human interference to a minimum, it is necessary to devise some means of representing in the dispatching computer a wide range of operating restrictions such as those which would reflect the greater importance of service continuity and quality -- and other similar considerations -- over the desire for economical operation.

Some consideration of the manner in which such restrictions are introduced and of the value of analog and digital methods for such purposes would seem appropriate; however, it will first be necessary to describe a typical automatic dispatching system more completely.

It has been stated that information regarding the prevailing net interchange is needed in order to compute the area requirement. This will generally require that each of the tie-line power flows be telemetered to the centrally located dispatching office and fed into a totalizing circuit which will yield an indication of the net inward or outward flow. Application of the coordination theory will also require that the prevailing outputs of all those generating stations represented in the transmission loss formula be known at the dispatching office. In short, the loadings of all tie-lines, all regulating stations, and the major generating stations will generally be transmitted to the dispatching office via direct wire, carrier, or microwave channels. This information constitutes a large portion of the input information required by an automatic economic dispatching system. As far as the area requirement computing circuits are concerned, the only additional information needed (beyond specification of the appropriate bias value) is the prevailing system frequency, and this will be metered locally and supplied to the computing circuits in a suitable form. These comments cover all of the variable inputs whose existing values must be continuously supplied to the automatic dispatching system.

An automatic economic dispatching system will thus include the necessary telemetering equipment to continuously gather such information as is needed for economic dispatching and for load-frequency control

but which is not otherwise available locally. In addition, the system will consist of the load-frequency control equipment, the computer which solves the coordination equations, and the necessary control interconnections between these major components. Of course, there are many automatic dispatching systems available today (101-113), but upon close examination it may be seen that these are actually almost all alike as far as a functional analysis is concerned. However, the actual design details vary widely. Two typical automatic dispatching systems may be mentioned briefly.

One of the earliest systems placed in operation was the Southern Company's "Early Bird." (103-105) Although this was initially used simply as a load dispatching computer of the type considered in the preceding chapter, it was later converted to automatic operation. The "Early Bird" now operates to distribute the area requirements of the system among the various generating plants in the most economical fashion. This is accomplished through impulse-routing circuits. The tie-line bias control computes the area requirements and sends out appropriate "raise generation" or "lower generation" signals for each area. These signals, or impulses, are routed to those stations which are at that time best qualified to increase or decrease generation, as determined by comparison of the prevailing incremental costs of delivered power of the various stations with the existing λ_{average} for the system. The impulse routing is accomplished by electronic relays whose operation is governed by the λ_n values which form the outputs of the "Early Bird" computer. The computer's outputs are fed to electronic relays which act -- much as traffic controllers -- to block or

pass the raise and lower impulses in such a manner that no station having a λ_n above the existing λ_{average} can receive raise impulses and no station having a low λ_n can receive lower impulses. In this fashion, it is possible to superimpose the requirements of economic operation on the load control system's operation.

The "Early Bird" is a fully automatic dispatching system. It is a closed-loop computer-control system in which the power system itself is included in the feedback loop; i.e., the computer outputs govern the load control system's operation, the power system parameters are adjusted via the load control, and the resulting power system behavior in terms of various telemetered quantities is then fed back into the computer to be analyzed -- this cycle is repeated continuously as the "Early Bird" optimizes the system operation. Human intervention in the dispatching procedure is kept to a minimum. It is evident that the real heart of the "Early Bird" system is the computer, for it is there that all the control information is gathered and operated on to develop outputs which will guide the power system operation.

Another automatic dispatching system of interest has been developed by the Westinghouse Electric Corporation. (106-108) Since this system differs somewhat from the "Early Bird," it will be reviewed here in order to permit a fuller understanding of the functional operation of typical automatic dispatching systems. The integration of the load-frequency control and economic dispatching functions is more complete in the Westinghouse system. In this system, an area requirement signal is developed through computing circuits which meter system frequency and the net interchange. This signal drives a fast-acting servo

device which causes the generating stations to follow the system load swings as they occur. The signal simultaneously drives a slow-acting servo device which continuously indicates the prevailing incremental cost of delivered power. The slow-acting servo's output may then be used to modify the earlier, rapidly determined allocation of generation in such a manner as to permit optimum economic operation.

The Westinghouse system illustrates well the previously mentioned need to satisfy the existing load demand and frequency requirements before attempting any application of the economic loading principles. For instance, when rapid load swings occur, these will be immediately followed by the generating stations, as required by the fast-acting servo. Generally, this initial allocation of generation to meet sudden changes in system demand will not be the most economic allocation, and the slow-acting servo is then called upon to gradually return the system to an economic balance. Meanwhile, of course, further load swings may occur, and the fast-acting servo will continue to follow these swings as soon as they occur. Yet, whatever the sequence of load fluctuations, the slow-acting servo will follow the total system demand and will continue to gradually force a return of the system to the economic operating condition corresponding to the then-existent total demand. With such a system, it is possible to consistently keep the existing generation distribution very close to the ideally desired optimum condition of generation allocation. Unless load swings are infrequent, some residual error will persist, however, for it is necessary to choose the time constants of the control system in such a manner as to avoid over-compensation and "hunting."

At this point, the general picture of how automatic dispatching systems function should be clear. As far as the computer output control commands which "tell" the system what generation changes are needed are concerned, these will usually be transmitted to the generating station via the load-frequency control equipment, and it is not necessary to consider the details of how this is done. It may be noted, however, that the generation allocation may be accomplished directly in terms of the individual unit incremental rates, or instead simply in terms of the overall station incremental rates. In the latter case, each station will receive a station requirement signal, and this will then have to be allocated among that station's units according to the unit incremental rates. Thus, one difference between these two approaches is the location at which (and the form in which) the station or unit incremental rates must be known and represented in computing circuits. On many systems, generation allocation directly in terms of individual unit incremental rates will afford appreciable gains in dispatching accuracy. In either case, the preceding discussions have shown that the computer which is located in the dispatching headquarters and which is given the task of directing the automatic economic dispatching procedures must include representations of many operating parameters and must properly coordinate large amounts of information. The operation of this computer clearly merits further investigation.

Those computer inputs which may vary continuously and which must therefore be continuously metered and supplied to the computer have been considered earlier. The remaining inputs are those which are of a semi-permanent nature, i.e., those which will occasionally

change in discrete steps and which may be left fixed except for occasional resetting by the system operator. Among the inputs of this type are those which provide necessary information regarding various power system parameters and others which introduce operational restrictions of the type considered earlier.

Inspection of the coordination equations will reveal some of the additional inputs required. One of the most obvious of these is the group of incremental fuel rates for all the generating stations or units. This group of inputs must be provided in a high-accuracy form and in such a manner as to permit selection between the various cost curves in order to cover all possible combinations of units in a station and all unit operating modes. The accuracy and flexibility of this group of inputs is an important consideration, for frequently the cost of an automatic economic dispatching system cannot be justified unless the system representation in the computer is accurate and complete enough to permit taking full advantage of the computer's potential for providing minimum-cost system operation. (114)

Another input of interest is the fuel cost which is to be applied to the heat rate curves in order to permit coordination on a cost basis. It is necessary to include provision for changing the fuel cost multiplier whenever the cost of fuel changes. Also, on certain systems, two (or more) fuel costs may be used at the same station and special provisions are necessary in such cases. For example, for a generating unit burning two types of fuel having different prices, the selection of the appropriate fuel cost multiplier will be made on the basis of which fuel is to be varied as a function of load.

Associated with the specification of the proper cost characteristics and fuel prices is the stipulation of which units are in service and which are off the line. In this connection, certain operating restrictions and computational considerations frequently require that additional inputs be supplied to indicate which units are in their variable ranges and which must be held at fixed loadings. Alternatively, such information may often be supplied in the form of high and low limits on each unit's output -- the high limits will refer to the maximum generation ratings of the units and the low limits to the minimum generations considered practical. Exactly how information regarding operational limitations should be supplied will depend largely on the form in which a given computer is designed to receive it, and since the same information may often be conveyed in different forms, it is not possible to enumerate just which inputs are required unless a specific computer is considered. Also, the extent of the operational limitations which may be anticipated will vary from one power system to the next, and hence the same computer may require somewhat different types of inputs when applied to different systems. In short, regarding computer inputs which represent power system operational limitations, it is sufficient to mention here that provision must be made for adequately representing all pertinent operational limitations which may be expected on the system in question.

Another important group of inputs includes the transmission loss formula coefficients. These are also of a semi-permanent nature, as the coefficients will normally need to be modified only when major transmission system changes are made; however, the flexibility of the

computer is improved if some means is provided for quickly and easily changing the coefficient values whenever necessary. Finally, in addition to all the previously cited inputs, it is necessary to specify the appropriate bias value for each area of a system, plus the desired frequency and net interchange values to be held by the load-frequency control.

Nearly all of the automatic economic dispatching systems used up to now have employed analog rather than digital computers. The manner in which the various inputs considered above are handled by an analog computer may be briefly considered. The incremental fuel rate curves, for example, may be represented in an electrical analog using an externally loaded slidewire potentiometer. The adjustable external loading permits a curve to be represented by a number of properly oriented and readjustable straight-line segments, and where the potentiometer tap is servo-positioned to correspond to the particular power source loading, the voltage "picked-off" represents the associated incremental cost of generating power. Various means of adjustment are incorporated in order to permit changes in cost characteristics and different combinations of units in each station.

Inputs reflecting fuel costs, unit operating limits, transmission loss formula coefficients, bias values, desired frequency and desired net interchange, and other semi-permanent conditions needed for the dispatching procedure are usually represented by simple switches, standard potentiometer circuits, mechanical limits, and other common analog techniques and circuits. The computers themselves employ standard techniques including the use of servo-positioners, operational amplifiers, transformer-resistance matrices (e.g., for transmission

loss formula representation), and other conventional analog computer equipment.

There is no real problem in developing analog computers of various designs and operational characteristics for use in an automatic dispatching system. Analog methods lend themselves well to the solution of the coordination equations, the system's transmission loss formula is conveniently represented analog-wise, and the variable and semi-permanent inputs are easily handled. Since there is no real stumbling block in the development of analog computers for automatic dispatching systems, it is not important to consider here the design details of any of the computers presently available. Instead, it will simply be assumed that standard analog techniques, and possibly some modifications of these, will be sufficient for meeting any of the requirements which may appear in the development of automatic dispatching computers of the types which have been considered. In other words, the functions which have been mentioned can be accomplished with analog devices and there is no need to investigate the more minute details of how this is done.

Of greater interest will be a consideration of why analog methods should or should not be used and of which techniques (analog or digital) are most suitable for representing information and for performing the various operations in a more comprehensive control system which is concerned with certain functions beside automatic economic dispatching but which does incorporate an automatic dispatching system of the type that has been described.

Of course, the automatic dispatching system functions can be realized in terms of digital methods also. Indeed, a digital dispatching

and load control computer is presently being readied for installation on a metropolitan power system (115), and this will mark the first step in what may well be a developing trend toward the wider acceptance of digital techniques in power system operational control systems. As mentioned in the preceding chapter, digital computational techniques can certainly be used to solve the coordination equations, and they are also readily applied to the evaluation of transmission loss formulas. In fact, all dispatching system inputs of an on-off, high-low, "this-or-that" nature, i.e., those inputs of a bi-stable character, may be readily handled by digital computer methods. Even incremental production cost curves may be suitably represented in the digital computer, and fuel costs can be specified digitally just as well as by having an operator set a multi-position switch in an analog computer. The requirements for digital computer application to automatic dispatching become more demanding, however, when the continuously varying inputs are considered.

It must be remembered that the basic problem is to control an analog system (the electrical power system). This requires that analog information be taken from the power system, presented to the digital computer in digital form, analyzed and processed by the computer in order to yield output information in digital form, and then delivered in analog form to the power system for implementation. Clearly, such inputs as system frequency, power source loadings, and net interchange will have to be continuously supplied to the computer via analog-to-digital conversion devices. Similarly, output information prepared by the computer to indicate the desired form of system control and operation

will have to be delivered to the system via digital-to-analog conversion devices. This need for analog-to-digital and digital-to-analog conversion equipment, and the fact that such devices have only recently become available in a practical and reliable form, have no doubt been influential factors in restricting the earlier development of automatic dispatching systems to the predominant use of analog techniques.

An important distinction between the analog and the digital computer lies in the fact that the size (and consequently, to some extent at least, the cost) of an analog computer is usually roughly proportional to the complexity and extent of the calculations that are to be performed, whereas the digital computer shows a relatively small size increase beyond the initial equipment as the complexity and extent of the problem to which it is applied increases. Many of the earlier automatic dispatching systems called for computing facilities in a size range in which the analog computer was considerably less expensive than a digital computer of equivalent capacity. Considering then the additional cost of extensive analog-to-digital and digital-to-analog conversion equipment, the cost of a digital installation became considerably greater than the cost of a comparable analog installation. The obvious question which resulted concerned the advantages which a digital system might offer.

Essentially, there are two prime characteristics generally attributable to digital computers. One is speed of computation and the other is accuracy. However, the computational speed of a digital computer can hardly be looked upon as an advantage over the use of an analog computer, for in truth the analog machine -- as, in effect, an electrical

system whose behavior is analogous to that described by the mathematical equations which define the problem at hand -- will instantly readjust itself to continuously yield a solution to the coordination problem as the input parameters are varied. Thus, the "computational time" of an analog computer is a somewhat nebulous quantity and cannot be effectively evaluated. For all practical purposes, the analog computer produces an immediate solution, although it is true that servo devices and other electrical or electronic components will have small, inherent time delays.

On the other hand, the digital computer does have a very definite computational time which can be readily evaluated, and of course, this time is invariably very short in relation to whatever alternative, non-computerized procedures may exist for achieving the desired solution. In fact, the digital computer's unique capacity for processing information at extremely rapid rates is essential to the successful application of such machines to automatic dispatching problems, since a large volume of computations must be carried out to determine a new set of generation assignments each time the operating conditions change. However, it should also be noted that there is a limit to how fast a power system can respond to changes requested by the computer, and it would be pointless to perform calculations showing what changes are desired many times faster than the speed with which the indicated changes can be implemented -- this question of relative speeds is closely associated with the need to provide for time constant compatibility in order to avoid continued "hunting" and overcorrection, as mentioned earlier.

In conclusion, then, it may be seen that the factor of computational speed is one which, if anything, favors the analog computer, although it does not on the other hand hinder the application of digital computers to automatic dispatching, provided that the latter are able to meet the minimum computational speed requirements of such applications (and, for today's state of the art, these requirements are not particularly demanding).

The accuracy of the digital computer also merits consideration. There is no question of digital accuracy overshadowing analog accuracy -- digital methods definitely offer a greater potential for high-accuracy calculations. In many applications, the accuracy of digital methods is sufficient to justify their greater expense when compared with similar analog devices. However, as yet it has not been possible to supply all of the input information required by an automatic dispatching system with sufficient accuracy to justify performing the necessary computations on the high accuracy level possible with digital computers. There is some question of the practicability of performing calculations with an accuracy far greater than that inherent in the input data upon which these calculations are based, although many will offer the argument that the almost unlimited precision available in the digital computer will at least insure that no accuracy will be lost in operating on the input data.

One fundamental group of inputs which have as yet been limited in the accuracy with which they may be specified is the group of incremental fuel rates for all the generating stations and units. Before the days of widespread interest in economic dispatching, there had never

been sufficient justification for attempting to secure high-accuracy data on incremental fuel rates. But as the importance of economic dispatching has become more widely recognized, and as the value of increased accuracy in such operations has become more obvious, greater efforts have been made to obtain high-accuracy data representing incremental fuel rates. It appears quite likely that in time all of the input information needed for automatic dispatching will be made available in high-accuracy form. In any case, the fact that the input data has not in years past been available with great accuracy has no doubt been another important factor in restricting the earlier development of automatic dispatching systems to the analog field.

It is evident, then, that the two fundamental characteristics of the digital computer, computational speed and accuracy, have not as yet proved advantages which might result in a swing from analog to digital computers for automatic dispatching systems. This statement, however, is probably more accurate in terms of the circumstances prevailing during recent years rather than in terms of the present state of the art. For as progress in the accuracy with which the necessary input data may be specified continues to be made, the accuracy capabilities inherent in the digital computer will no doubt tend to bring it into greater favor for such applications. Significant developments are also being made in the field of analog-to-digital and digital-to-analog conversion devices, and it is expected that further progress in this field will make available continually more reliable and more accurate conversion devices suitable for a wider range of applications at a reduced cost per installation. As such advances are made, and as a growing computer

technology begins to permit reductions in the cost of digital computer installations, it is possible that the additional savings obtainable from the use of higher-accuracy digital methods will gradually permit justification of the generally increased cost and complexity of digital systems for automatic economic dispatching.

On the other hand, it also possible that even when such advances occur, it will still be difficult to justify digital systems. Many of the analog systems now used do not offer too much room for improvement in terms of the accuracy with which the ideally desired loading condition is approached, and hence the additional savings obtainable from such improvements might be too small to justify even those digital systems of reduced cost.

The other possible justification for the wider use of digital computers in automatic dispatching is one which was lacking at the time the first automatic dispatching systems were developed, and which therefore served -- in a negative fashion -- to further restrict the earlier efforts at automatic dispatching to the field of analog computers. This expected justification now appears to hold perhaps greater appeal than the prospect of increased savings resulting from high-accuracy computations and control. It is concerned with the expected trend toward more comprehensive computer systems for power system operation, control, and possibly "administration."

As an expanding computer technology continues to permit more and more computer applications to power system needs and problems, and as the needs of a growing power industry continue to make it more receptive to the benefits to be derived from the introduction of advanced

computer-control philosophies, it becomes interesting to consider the coordination and integration of many of these applications for the development of a comprehensive computer system designed to perform many of the electric utility system functions of control, operation, and administration.

For example, once information regarding transmission losses and power flows is available in a computerized dispatching system, it would appear that the computer might be adapted to incorporate procedures which would be designed to accumulate and properly correlate various types of data needed in handling the inter-area or inter-company billing and energy accounting requirements (116, 117) mentioned earlier in connection with the application of transmission loss formulas. The primary input information would be the telemetered interconnection power flows, and the computer itself would store information relating to sales and contracts between operating companies plus incremental production cost and transmission loss data for use in a continuing procedure for energy accounting and the determination of power pool savings. Conceivably, such techniques could greatly facilitate and improve the billing and energy accounting functions which are so essential to orderly utility management and good inter-company relations. Similarly, other functions associated with transmission loss formula derivations, with loss formula up-dating (e.g., coefficient adjustments) to maintain agreement with existing conditions, with the up-dating of incremental cost data on the basis of test results and other input information, with the use of linear programming techniques for the optimum scheduling of maintenance, and with various types of statistical

compilations, operational records, performance calculations, etc., may be found compatible with the automatic dispatching functions in a comprehensive computer system designed to provide integrated control, operational, and administrative information. Another illustration of the type of function which such a comprehensive computer system might perform would be the preparation of continuously up-dated load duration curves (or at least the data from which such curves could be drawn) on a monthly, yearly, and cumulative basis. Of course, digital methods are inherently more suitable for simple, repetitive calculations and data-processing duties of the types listed here.

It is very difficult to surmise just which of the functions suggested above would prove economically justifiable, and since economic justification will almost certainly be required, most of these functions presently lie entirely within the realm of conjecture. That most of them will merit continued consideration and will in one manner or another eventually be subjected to thorough economic analyses appears quite likely, particularly since much of the information needed for the realization of these functions is already required in most of the modern automatic dispatching systems anyway. The development of such comprehensive computer systems would then, in one sense at least, amount to nothing more than the extension of the capabilities of today's automatic dispatching systems to take better advantage of much of the currently available information through the introduction of more comprehensive and more ambitious information-processing and data-manipulation provisions. Just how far such extensions should be carried will have to be determined in each individual case on the basis of thorough

economic studies of the benefits available with such comprehensive systems, and the importance and variety of such benefits will no doubt be found to differ somewhat from utility to utility. Consequently, the character, complexity, and degree of sophistication of such computer systems would presumably vary from company to company. That such systems will in one form or another gradually find economic and operational justification, however, does not seem entirely unreasonable, and it would appear that an evolutionary trend toward their wide acceptance will follow the first concrete indications that such justification does indeed exist.

It is evident that most of the subsidiary functions suggested for the comprehensive computer system under consideration would clearly call for the utilization of the specialized capabilities of a digital computer. Whether in some cases portions of this computer system might be of an analog nature, resulting in a composite analog-digital system, is rather difficult to forecast. However, as such systems are conceived and put through the early design phases, it is probable that thought will be given to the possibility of interconnected analog and digital sections; indeed, some of the contrasting characteristics of analog and digital computers often lead them to be considered as mutually complementary devices. The fact remains, however, that if comprehensive computer systems of this type are to be assembled, then a definite requirement for at least some digital computing equipment will exist, and therein lies the other previously mentioned possible justification for the development of a trend toward the wider use of digital computers in automatic dispatching systems.

Though it is difficult to predict the exact form in which and time at which such comprehensive computer systems as those considered above might gain widespread recognition and acceptance, it does seem entirely reasonable that such recognition and acceptance could eventually result. And when the trend toward such acceptance begins, the case for digital computers in power system control will certainly be considerably strengthened, inasmuch as digital techniques will be essential to certain phases of the operations suggested for the proposed comprehensive computer system.

Indeed, it is not even necessary that great progress toward the development of a comprehensive computer system be made before digital computers begin to appear more attractive for power system operation and control systems. Any movement toward comprehensive computer systems will certainly be an evolutionary one, and during the developmental phases of such a movement it will be desirable to experiment with different approaches, new applications, and novel techniques. If a general-purpose digital computer of adequate size were already operating in an automatic dispatching system, its programming flexibility and general adaptability to different problems would be very useful in such experimental evaluations.

Situations of this type may very well have a catalytic effect in stimulating a transition from analog to digital methods in the design of automatic dispatching systems.

Whether the swing from analog to digital methods will go so far as to result in the use of digital methods to the complete exclusion of analog methods is debatable and not suited to a thorough investigation

at this time. In general, any mention of trends toward the application of digital methods to certain problems will not here imply automatically that this will also lead to the complete rejection of analog computing techniques in such applications. As mentioned earlier, analog and digital methods will often be found mutually complementary.

The following chapter will summarize the current activity in the control and operation of central stations using digital computer techniques, and this review of what is happening in a closely allied field will carry strong implications regarding the trend suggested above as pointing ever more surely toward the wider use of digital methods in computer systems for power system operation and control. Indeed, the thought that computer control systems for power system operation and for central station operation may ultimately be linked to provide an integrated computer system for overall power system control has direct bearing on the above discussion of the current trends in the field of automatic dispatching systems.

Meanwhile, in view of the preceding, the use of analog techniques is generally indicated for computer systems concerned only with the basic automatic dispatching functions, except that forward-looking system engineers will no doubt hope to experiment with digital computers in such applications from time to time and that the increasing complexity of automatic dispatching systems or the previously mentioned accuracy considerations may soon become significant enough to deprive the analog system of much of its current economic advantage.

In any case, the outstanding conclusion at this point is the fact that computer systems for economic dispatching are now an established

trend in the electric power industry (118-122) and that the currently existing systems are but the forerunners of a whole family of optimizing computer systems for all purposes in which economy plays an important role.

PART III

THE FUTURE OF POWER SYSTEM CONTROL

The foregoing study has been primarily concerned with the application of analog and digital computer methods to power system control on a system-wide operational level. This topic has been given thorough consideration, but it will be possible to view the preceding comments in better perspective if attention is briefly focused on other recent developments in power system control. One of the outstanding developments which has recently appeared on the horizon is computerized central station control and operation.

The economic and operational benefits mentioned in Part I as stimulants toward the increased utilization of computer methods in the operation and control of power systems are valid for both system control and central station control applications. Of course, different factors will have varying degrees of influence in the two fields of application, but both fields stand to benefit from the increased use of computers for essentially the same reasons.

As a basis for discussion of computerized central station control, it is noted that plant operation involves the following four functions:

1. data collection
2. manipulation of this data to provide the desired information in a useful form, i.e., data reduction
3. correlation of this information to yield the required operating decisions

4. implementation of these decisions to achieve the desired control action.

A present-day plant accomplishes some of these functions through the use of many automatic "sub-loops" which consider only individual items such as the control of combustion, feed water, steam temperature, the turbine-generator governor, generator voltage regulation, coal pulverizer air temperatures, generator hydrogen pressure and temperature, lubricating oil temperatures, and many others. The important point, of course, is that these sub-loops operate independently of one another and that they therefore do not form an integrated system for plant operation. Coordination of these sub-loops, equipment monitoring, and the operation of infrequently used equipment are functions assigned to the human plant operator.

In such a plant, decisions related to equipment starting and stopping and to operational readjustments are dependent upon data gathered by visual equipment inspection, hand-logged readings, and human scanning of indicating and recording instruments. The data reduction and other phases (listed above) of plant operation are also performed by humans. As was stated earlier, however, such efforts will often be hampered by inherent human limitations on accuracy and the volume of work which may be accomplished in a given time and by the further limitations on human sensing and reaction. For example, the data collection and reduction functions may only be performed with limited accuracy by humans, and the time required for such functions will also be considerably greater when they are realized by humans rather than by automatic means. Furthermore, operating and performance data and other information derived continuously in the course

of plant operation will not be made available early enough to correct conditions of poor economy of operation -- and other deviations from ideal operation -- until long after these conditions first appear.

Considerations of this type have led to the recent introduction of computerized equipment for scanning, logging, and results-computation. (123-136) Several installations of this type have been realized. In general, such equipment is basically concerned with scanning any desired number of operating variables (e.g., temperatures, pressures, flows, voltages, power, BTU, amperes, etc.) at the rate of several points per second and providing an alarm when predetermined limits are exceeded; logging any desired number of operating variables at preset intervals (from, say, five minutes to several hours) or whenever called for; computing "results" such as net unit heat rates, the optimum unit heat rate for existing conditions, net plant heat rate, steam and water enthalpies for heat balances, boiler efficiency, condenser performance, heat-exchanger performance, turbine-generator performance, averages of steam pressures and temperatures, integrations of gas flows, feed flows, and kilowatt-hours, plus many others at selected intervals or "on demand."

These scanning, logging, and results-computation functions are accomplished by computer systems with considerably greater accuracy, reliability, speed and degree of completeness than could ever be expected from humans. The computed results are immediately available to the human operators to guide them in their efforts to obtain optimum performance from the equipment under their supervision, and the safety of humans and plant equipment is improved as off-normal conditions

and potential trouble-spots are quickly detected and pinpointed.

At this point it is of interest to note the three classifications into which plant data may be grouped:

1. operating data
2. performance data
3. historical data.

Operating data serves as a guide for service continuity and for the safety of equipment and men; i.e., it indicates the ability to alter load, the status of plant equipment, any approach to structural, mechanical or thermal limits on equipment operation, and other conditions that may impose limitations on load or the rate of change of load or that may require shutdowns. Performance data indicates the efficiency of operation and provides information to determine which part of the plant is not performing at or near the optimum condition. Historical data is of no immediate use but is collected and held for later studies, long-term analyses, maintenance requirement predictions, and other purposes.

Operating information is thus related to the function of equipment monitoring and requires the continuous scanning of operating variables in a rapid and reliable manner to determine any approach to preset (fixed or variable) operating limits. Performance data requires the accurate acceptance of numerous inputs and then considerable computation and data reduction to obtain meaningful information indicative of heat rates, boiler efficiency, condenser performance, etc. Historical data requires the accurate recording at established intervals -- and in a permanent, readily stored form -- of specific information such as averages, maximum and minimum values, etc.

This classification of plant data facilitates analysis of the requirements of computer systems for central station operation and control and is of interest also in that it permits a better understanding of what central station computer systems will involve. It is evident that the monitoring and results-computation computer systems (MARC systems) considered above offer significant advantages in the collection and utilization of each of the three classifications of plant data listed above. The development and application of MARC systems, however, is only a stepping-stone toward the more ambitious goal of power plant automation.

Having applied computer methods to the first two of the four items listed earlier as functions necessary to the operation of a power plant, attention is naturally drawn to the possibility of accomplishing the remaining two functions through computerized means. In effect, this would require that the control "loop" be closed to permit the computed results to be automatically evaluated and interpreted and then implemented without human interference. In other words, an automatic power plant would be realized. (132, 137-142) Such a plant would utilize computer methods to apply operating, performance, and historical data derived from scanning, logging, results-computation and other equipment to the coordination of the previously mentioned sub-loops in order to develop an integrated system capable of reliably, safely, and efficiently starting up, running, changing load on, and shutting down a power plant without human intervention.

It should be emphasized that the automatic power plant is no longer a topic suited only for dreamy-eyed conjecture, as many would

be inclined to believe. On the contrary, the author's company* is presently designing and constructing such a station for the Louisiana Power and Light Company. This station, known as "Little Gypsy," is scheduled for trial operation in January, 1961. (143) It is expected that this will become the world's first fully automatic power plant, and the computer-control system employed there will be known as a steam-power automation and results-computation computer system (SPARC system).

Part of the justification for the automation of power plants will no doubt be found in the reduced likelihood of operating errors which is expected in the automated plant (as compared with the human operation of power plants). This viewpoint is derived from the fact that the automated plant will be operated on the basis of calmly considered and carefully evaluated procedures chosen in advance rather than in accordance with the hastily conceived methods decided upon by an operator working under pressure or emergency conditions. Moreover, the greater sensitivity and faster reaction time of the computer-control will permit the station to be operated much closer to actual equipment operating limits for higher overall efficiency (and yet with unprecedented safety). It is also conceivable that the plant equipment will be treated better by the computer than by a human operator, inasmuch as the computer will start, operate, change load on, and stop equipment in accordance with a previously prepared and accepted program which will require that specific conditions be satisfied both before proceeding to the next step of the program and during the execution of that step. In addition, the computational

*Ebasco Services Incorporated, New York, N. Y.

accuracy and the decision-making abilities of the digital computer will further permit increased operating economies through the more precise (relative to the human operator) determination of what equipment combinations are needed to meet specific demands and of exactly how this equipment should be operated. Finally, all the operating, performance, and historical data available in the MARC system will also be available in the automatic power plant -- not to mention the manpower savings related to the collection and utilization of this data.

Considerations of this same type have led computer-control systems to be considered for the automation of many complex processes in several major industries. (144-148) Indeed, the embryonic field of computerized industrial process control is among the more fascinating, more challenging, and more promising of the dynamic fields of technological activity that have in recent years appeared on the engineering horizon. Although many formidable problems must still be resolved, it is a field that has captured the imaginations of many engineers, and with the advent in recent years of highly reliable, solid-state digital computers, the ultimate goals set for on-line computer process control have steadily come within closer reach.

Exactly what course the further development of this field will take in the years ahead is difficult to predict, but a conservative viewpoint would at least envision the continuing application of ever more refined and more sophisticated computer-controls to a steadily broadening variety of process control functions. As long as economic and operational justification exists (and -- often for reasons very similar to those that have guided the electric power industry toward computerized

operation of power systems and central stations -- such justification does not seem to be lacking in many industries even today), and as technological obstacles are gradually overcome, the presently foreseen trends will almost certainly be realized in the years ahead.

Although at present the production of electric energy in steam-electric stations is looked upon as a process within itself, it is entirely reasonable that the overall task of both producing electric energy and delivering electric energy to the load centers should come to be viewed as a single all-inclusive process. Certainly the coordinated control and operation of two such closely interrelated functions would appear to be a sensible approach to the overall problem of electric utility system operation and control.

An analysis of the requirements of computerized central station control and operation lies beyond the scope of the present study, but even at this point it is fairly evident -- and a review of the current technical literature will immediately confirm this -- that the automation of power plants will definitely call for the use of digital computers. If the expected movement toward the integration of power system operation and central station operation is indeed realized in the years ahead, the fact that digital computers will be used almost exclusively for power plant operation will have further bearing on the previously considered question of whether analog or digital methods are preferable for the automatic dispatching systems of tomorrow.

It thus appears that the field of computerization of power system control hardly remains static long enough to permit any lasting conclusions, and consequently this study can hope to accomplish no more

than a survey of what is being done in this field, of why this has been done, and of what appear to be the developing trends for the future of the field. In other words, the discussions and arguments put forth in Part II must be viewed within the context of a dynamically developing setting which is continuously undergoing modification, and although they are considered accurate for the time and state of the art to which they apply, they should not be taken to represent an immutable set of conclusions that will hold for tomorrow's circumstances. The present comments regarding the future of power system control are put forth in part to emphasize this point.

In concluding this peek at what tomorrow will bring, the integrated computerization of both system and station operating functions may be considered further. It has been seen that presently available automatic dispatching systems are capable of economically assigning load to generating units on the basis of existing conditions. The central station automation systems of the future must be made compatible with these dispatching systems in order that signals for load changes received at the various stations may be immediately and automatically implemented in the most effective manner possible. The previously considered comprehensive computer systems will likewise be developed with an eye on their expected compatibility with the plant automation computer systems of tomorrow. Ideally, the two systems should become mutually complementary, and inasmuch as the basic interdependence of system and station operating procedures appears unquestionable, it is possible to risk the conclusion that the two automation trends now in sight will indeed prove entirely compatible. Certainly, the best efforts of all concerned

will be applied toward the realization of this objective, and the advances currently noted in the areas of systems engineering and computer technology should contribute heavily toward the attainment of this goal.

As an example of what the integration of these two types of computer systems might involve, it is expected that automatic dispatching systems will eventually be developed to the point where it will be possible to predict forthcoming load changes on the basis of weather predictions, statistical data on previous load demand fluctuations, and similar information. Such computerized dispatching systems would then prepare generation schedules for economically meeting the anticipated load demand variations, and a tie-in between the dispatching and station control systems would permit the station control computer systems to prepare plant equipment for forthcoming generation requests in advance of the commands from the dispatching system. (149) In fact, there are those who ultimately envision the application of a single master computer to the supervision of an entire power system, though subordinate computer systems would no doubt be required for the plant automation functions at each individual station. In short, it can only be definitely stated that the future will bring whatever advances economic or operational justification, technological capabilities, and man's imagination permit. And from today's vantage point, it appears that the future will bring many advances in the area of power system control computerization. (150, 151)

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