Paper 2

# PROCESS DYNAMICS IN ELECTRIC UTILITY SYSTEMS

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## ABSTRACT

An overview of the subject of Process Dynamics and Control in Utility Systems is the subject of this paper. Utility systems are characterized by dynamics of very high order covering not only a wide spectrum of dynamic effects in electrical, electromechanical and thermo-mechanical processes, but also a very high dimensionality of interacting elements and interacting variables within elements.

Power system dynamic problems are described and classified under major areas of electrical machine and system dynamics, system governing and generation controls, and prime-mover-energy supply system dynamics and controls. One unifying discipline involved in all areas is the technology of dynamic simulation and control analysis.

Included are discussions of the problem of process modeling, control design and of factors which have affected approaches and relative emphasis given to dynamics in the different areas of the Electric Power System process.

## INTRODUCTION

Process dynamics in electric utility systems cover a very wide spectrum of phenomena and a wide range of disciplines. Rapidly developing technologies of dynamics and control applicable to many of these diverse areas and diverse equipments of the power system are stimulating application of common concepts and methods of analysis and control. A strong unifying factor in the treatment of dynamics among the various processes is the computer as a calculating tool and as a control device.

Some interesting similarities and contrasts in methods of approach, in emphasis, and in the importance of dynamics in the various areas of the power system process are apparent to those who have been active in many areas of utility systems dynamics. These matters are explored in this paper which attempts to describe the power system process from the point of view of dynamics and control. Of necessity, the coverage of such a vast subject cannot be exhaustive and will no doubt reflect the author's eclectic judgment on points of emphasis.

## THE PROCESS

### Spectrum of Dynamic Effects

To the control systems engineer, the power system process can be described as in Figure 1, identifying its many systems and subsystems in the familiar pattern of several closed loops nested within one another.

The dimensions and complexity of power system dynamics can well be appreciated when one realizes that there are hundreds of interacting elements such as generators with their prime movers, energy supply systems and controls, and that the mathematical representation of each element generally involves many interdependent variables, described by sets of high order, nonlinear differential equations. In its simplest form, the power system comprising a single prime-mover, generator and load is a complex process. Add to this the effects of interconnecting large numbers of units within systems and of interconnecting entire power systems from Coast to Coast, and one can appreciate the dimensionality of the overall process!

This high dimensionality of the problem makes it important to use skill in the choice of simplifying assumptions aimed at cutting down size and complexity to suit the needs of the particular situation. An intimate knowledge of the process physics and the orders of magnitude of basic effects is fundamental to the task of cutting down the problem to a workable size.

With reference to Fig. 1, power system dynamic effects of prime interest to instrumentation and control engineers can be conveniently categorized as belonging predominantly in one of the following areas:

1. Electrical machine and system dynamics
2. System governing and generation controls
3. Prime-mover-energy-supply system dynamics

In the area of electrical machine dynamics, a prime concern is the ability of the power system to operate with synchronism through severe credible disturbances. The emphasis of representation is on the network power flow and machine inertial relations. As excitation and prime-mover energy controls are made to play more active roles, the need for more detail in their representation increases.

Problems that fall under the category of system governing are concerned with the frequency behavior of overall systems and power flow between systems. Considerable lumping or equivalencing is justified in the representation of networks and electrical machines, while more detail is preserved in individual prime movers including gross energy supply system effects (boiler pressures, hydraulic heads), their governor systems and supplementary controls.

The third category, that of prime-mover energy supply systems, is concerned with such details as combustion, feedwater and temperature controls in the case of fossil steam prime-mover complex or a number of flow and pressure controls in the case of Nuclear Plants. In this category, the turbine can be represented as a variable orifice and its dynamics are practically instantaneous relative to the many other pressure, flow and temperature effects of the plant multi-variable process.

As shown in Fig. 2, the principal phenomena under the various categories fall in different spectra of duration of main effects. Also indicated in Fig. 2 are the important areas at the extremes of the duration spectra which will not be covered in this paper, but which deserve mention since they represent important areas of activity that may also be classified under the subject of dynamics.

One of these is the important and distinct area of electrical system transients concerned with overvoltage studies. Prediction of the overvoltage levels resulting from switching transients and lightning surges is vital in insulation coordination design and proper application of overvoltage protection measures to ensure reliable power systems. The nature of the process dynamics in this area spans durations of microseconds and milliseconds and the need for a high degree of refinement and fidelity of representation of very high frequency phenomena has made the most practical method of study that of direct measurement on electrical scaled models of the system. Specialized laboratories with models of transmission lines, transformers, reactors, lightning arresters and switches are devoted to study of transient overvoltage performance of systems. The digital computer is beginning to find application in this field as its computing capability grows to the point where it is practical to solve digitally the very high order equations of traveling waves in distributed parameter systems.(1)(2)

The other extreme in the duration spectrum involving hours, days and weeks concerns problems of management of energy resources, typically water and nuclear fuel. The nature of storages in these processes classifies them as dynamic and the techniques of simulation and prediction involve dynamic equations. The nature of the time duration in these processes is such that automatic control is usually not involved but rather the implementation of operating decisions and schedules implemented manually(3)(4) in response to results of sophisticated nonlinear programming techniques.

The field of dynamics will be discussed in the three areas of principal interest to the field of instrumentation and control. These areas were identified as Electrical Machine and System Dynamics, System Governing and Generation Controls, and Prime-Mover-Energy-Supply System Dynamics and Control.

In discussing the subject, it is helpful to list some considerations on the importance of dynamics and on aspects of modeling and control analysis. Practices in the three areas mentioned above will be viewed and contrasted against the backdrop of these considerations.

## Importance of Dynamics

Engineering account of dynamics can be for one or more of the following reasons:

(1) As an important aspect of the basic system design involving the configuration of major equipment.

(2) In evaluations and syntheses of the overall system design where trade-offs exist between major apparatus and control system equipment required to meet given performance criteria.

(3) In design of control systems necessary for the successful operation of individual pieces of apparatus (turbine controls, excitation controls, boiler controls, etc.) in the power system environment.

(4) In development of real time plant and system simulators for educational or operator training purposes.

The importance given to dynamics and indeed the different approaches dealing with dynamics which have evolved in the several areas can often be related to the speed of the pertinent effects relative to the speed of human reaction; i.e., relative to the ability of the process to be controlled manually. The economic impact of possible damage to equipment or curtailment of customer service that could result from inadequate system design or lack of proper control is often a major incentive. In some cases, regulatory bodies concerned with safety have played a major role in determining the extent to which dynamics are factored in design studies. Another important factor is, of course, the analyticity, or the ease with which the process physics lend themselves to mathematical treatment and simulation.

## Modeling and Control Analysis Aspects

Since the problem of prediction is fundamental to analysis of dynamic effects and inseparable from the problem of application of controls, several general points should be made on methods and techniques of simulation of power system dynamics. Although the block diagram of Figure 1 clearly shows interdependence of every system and subsystem on each other, it is very seldom that all areas need be considered simultaneously in equal detail. Depending on the particular phenomenon of concern, various simplifications can be made to represent the less important and less relevant effects.

The need to zoom in on the relevant and blot out the irrelevant is not only one of economics of computation, but also one related to limitations of human data-gathering capability. In spite of the enormous expansion in computing capability, one is still faced with limitations in the capability of the human brain to absorb results and to feed in the correct input data. Hence, no matter how powerful the computing capability, it is important to solve the problem with the right degree of detail in the representation of relevant effects and a justifiable amount of simplification in the less important effects.

Opportunities for simplifications arise on several counts:

(a) One concerns the duration of effects and the resolution in time over which the effects are of significance. For instance, where electrical system transient stability phenomena over a second or two are the primary effects under investigation, it is not necessary to represent boiler transients which develop over several minutes. Again for this same problem, the other end of the spectrum of extremely fast transients such as switching transients of high frequencies need not be represented, allowing corresponding simplifications in the basic equations.

Similarly in the simulation of pressure-flow-temperature dynamics for boiler control studies, the pressure propagation effects at the velocity of sound are not significant, justifying the deletion of fluid inertia terms which give rise to these effects.

(b) The range of variables may allow simplifications. For instance, in normal power system transients where frequency excursions are small, the simplifying assumption of constant speed in the generated voltage equations and constant frequency for the network impedance parameters is perfectly justified. However, for load rejection conditions where the generator might undergo a significant speed transient, this assumption is no longer valid and for these problems one needs to represent speed as a variable. Additional peculiarities of the rejection case involve the need to represent saturation effects in transformers and reactors because of the possible range of voltage excursions. Another example in the difficult nonlinear thermo-mechanical process of steam generation concerns the modeling simplifications and linearization techniques applicable for treatment of small changes about a load point. These would not be valid for large changes such as for the case of a turbine trip.

(c) Other opportunities for simplification involve the number of elements of a kind that needs to be represented. It is surprising how many problems can be solved and how many concepts can be developed with the study of the case of the single machine against infinite bus. Usually the greater the detail of a given effect that is to be studied, the more advisable it is to reduce the dimension of the system by considering a limited number of like elements. There are a few fundamental effects that cannot be studied better on a one- or five-machine system representation than on a 100-machine representation. This is particularly true in the study of detailed control effects.

In the area of control analysis, one general observation is that little practical use has as yet been made of modern optimal control theory which seems to have grown out of proportion to the needs of real-life problems. Such theory has evolved much too often around hypothetical and unreal problem postulations engineered to be mathematically viable and tailored to fit the theory. While general control concepts have been extremely useful, by far most attempts at control design in the real-life environment have been through simulation and educated trial and error.

## ELECTRICAL MACHINE AND SYSTEM DYNAMICS

In the planning of electrical generation-transmission systems, study of dynamics has played a dominant role in the sense that the system design must withstand the test of continuous synchronous operation through abrupt and severe contingencies such as are occasioned by electrical faults and by the changes in network conditions that result from action necessary to clear the faults. The phenomena of concern determining the success or failure of the system to meet performance criteria usually spans a period of one to two seconds and seldom more than 5 seconds. The speed of the basic phenomena is therefore such that the system must be designed to cope with the disturbance criteria without manual intervention. The dominant system parameters with major influence on performance are:

(1) Generator characteristics - principally reactance and inertia.

(2) Network strength; i.e., transmission reactance under normal and contingency conditions.

(3) Switching devices, their number, deployment and speed of actuation.

(4) Protective relaying.

Until recently, the options to the system planner in configuring the system to meet desired reliability criteria were generally limited to these basic parameters and the technology of dynamics used in this area was basically one of large-scale simulation of the electrical system to test its ability to sustain shocks imposed by faults.

## Dynamic Simulation Methods - Electrical Systems

The simulation methods were often unique to this industry and evolved over the years from the use of scaled models of the network (a-c network analyzers) in the 30's and 40's to the use of large-scale digital computer programs today.

Figure 3 describes the basic process dynamics which can be compared to those of a large system of masses interconnected by nonlinear springs. The masses are analogous to the machine inertias and the springs are analogous to the nonlinear power-angle relations of the network against impressed machine internal voltages with phase angles related to individual generator rotor positions.

In its simplest form, the basic dynamics involve the second order differential equation of each machine (swing equations) relating accelerating power to speed and speed to angle (Fig. 3). Limitations of calculating tools forced the adoption of approximations such as that of representing machines as constant voltage sources behind equivalent machine reactances.

The computation problem was basically one of solving the network power flow relations given the machine voltages and rotor angle positions. The network analyzer (scaled model of the network) permitted instantaneous solution of such power flows based on manually inputed values of generator voltages and angles. The dynamic solution was then executed by step-by-step numerical integration of measured accelerating power (mechanical shaft power, assumed constant, less measured electrical power) to yield speed, and integration of speed to yield angle. Machine voltages with new angles were then impressed on the network to give new readings of power flow for the next time interval. The step-by-step process was repeated until it could be concluded from the shape of the transient whether the system met the disturbance criterion or not (Fig. 4). In this method of solution (used till the late 50's), the simultaneous algebraic power flow relations were solved by the scaled model and the integration of the system states (two per machine) was done by hand calculation. Solution of electrical system dynamics by these methods generally required limiting the size of the problem to less than 40 machines and neglecting such effects as excitation controls, prime-mover controls and nonlinear current/voltage relations of loads.

The advent of the mechanical differential analyzer and then the electronic analog computer did not offer attractive alternates to the a-c network analyzer method of solution since the basic computation burden was still that of solving the network power flow; i.e., a large number of simultaneous algebraic equations coupling the system states (machine angles) through trigonometric functions which would have required a very large number of nonlinear elements such as resolvers and multipliers.

Analog computers, however, have been used extensively in specialized studies of machine dynamics and excitation controls. Here the problem could be reduced to that of one or two machines with the network reduced to minor proportions while the nonlinear dynamic representation of machine and excitation system is considered in great detail. As an example, Figure 5 describes the elements to be considered in solving for the dynamics of a single machine undergoing load rejection.(5)

Beginning in the mid-1950's, digital computers found exponentially growing applications in all areas of electrical machine and system dynamics. With development of numerical methods of network load flow solution, the a-c network analyzer has been replaced completely by the digital computer. Likewise, numerical methods of differential equation solution implemented digitally made it possible to solve not only the dynamics of the rotor inertial equations, but also to extend the representations to include variations in internal machine fluxes in response to demagnetizing action of armature currents and in response to voltage control action of excitation systems. Prime-mover representations including governor and turbine dynamics have been included. Not only has the representation of the dynamics of each generating unit been extended considerably from the simple second order dynamics of a-c network analyzer days (current programs sport between 10th order and 20th order nonlinear models for each machine and controls), but also the number of machines has increased from the 20 to 40 of a-c network analyzer days to several hundred considered in modern programs.

It is axiomatic that the size and complexity of representations tackled in this area always seem to tax the limit of capability of the latest computing machines. Such capability has been increasing by orders of magnitude every few years and one is faced today with the problem of the capacity of the human brain to absorb a mass of results and to feed in the correct masses of input data. The proper management of the fantastic computing capability to be used in the right manner considering the problem requirements and limitations of the vital human element is one of today's unsolved challenges in the area of electrical system dynamics.

## Control Effects - Switching Logic

Although one often associates the discipline of dynamic analysis with that of control design, it has been characteristic of the area of electrical system dynamics that relatively little control analysis has been involved in the very large number of dynamic studies continually taking place in this area. This is because the basic problem being studied concerns the ability of the system to withstand major disturbances, and the parameters at play have for the most part involved the configuration of major equipment. Questions such as, "Is an additional transmission line, switching station, etc., needed to meet the reliability criteria?" are determined by simulation runs, exercising an orderly trial-and-error procedure where the options are usually limited to discrete cases defined by feasible configurations of equipment.

In recent years, several factors have been pointing towards more dependence on excitation and prime-mover controls for overall system reliability. These factors are:

(1) Continually increasing ratings of new gen-

erating sources with a lowering of inertias and raising of per unit reactances tend to encroach on inherent stability margins.

(2) Increasing load demands to be served by transmission whose utilization and relative loading must be maximized in order to make best use of limited rights of way and the large investment involved.

(3) Pooled operation and planning places increased dependence of interconnections between large systems. The capacity and, therefore, investment requirements in these interconnections as dictated by transient stability often can be much larger than might be dictated from steady-state load-carrying capacity considerations. Provision of required degree of reliability by alternate control means can be economically very attractive.

(4) Rapid and extensive advancements in computational capability and techniques of large system dynamic simulation have made it possible to engineer controls and to evaluate the potential benefits in their proper application.

(5) Technological advances in excitation control, turbine energy control, power thyristor development and application have made it possible to implement with hardware the theoretical concepts developed in engineering simulation studies.

A possible role of controls in enhancing the dynamic performance of electrical systems is in the use of discrete switching logic using the principle of counteracting disturbances(6)(7)(8) such as the temporary closing of turbine valves for a period of a few seconds, or the temporary switching of braking resistors. The temporary switching of series capacitors has also been suggested. This bang-bang type action can be programmed to offset, in part, the shock of faults.

Although normal speed governing action in turbines is too small to affect the phenomena of power system transient stability, modern turbine speed control systems have the capability of fast valve shut-off (in fractions of a second) provided for the control of overspeed under load rejection conditions. With specially designed logic, this capability can be used to advantage to provide a sharp and temporary decrease in turbine power upon detection of an abrupt loss in electrical power output such as occurs during faults.

Fig. 6 illustrates an equivalent single generator driven by a reheat machine connected to a large power system through a step-up transformer and transmission system used for parametric studies on alternate means of providing an adequate design to meet given disturbance criteria such as a 3-phase fault subsequently cleared by switching off a line section.

The options are, transmission strength as measured by prefault and post-fault transfer reactances, excitation system type and response and the use of fast valving such as is done by rapid shut-off of intercept valves followed by their subsequent reopening after a short time delay. The action of the excitation types considered in response to the disturbance are shown in Fig. 7, while the response of shaft power due to the "fast valving" action (abrupt closure of turbine intercept valves followed by their reopening) is illustrated in Fig. 8. The results of a parametric study wherein a computer was programmed to make repetitive stability runs in search for the value of post fault reactance for which stability was just marginal are shown on Fig. 9, where the effectiveness of various design measures can be evaluated in terms of the amount of post fault reactance (translatable into transmission strength) which these measures can offset.(9) Fig. 10 illustrates the transients following a temporary fault which did not cause instability.(7)

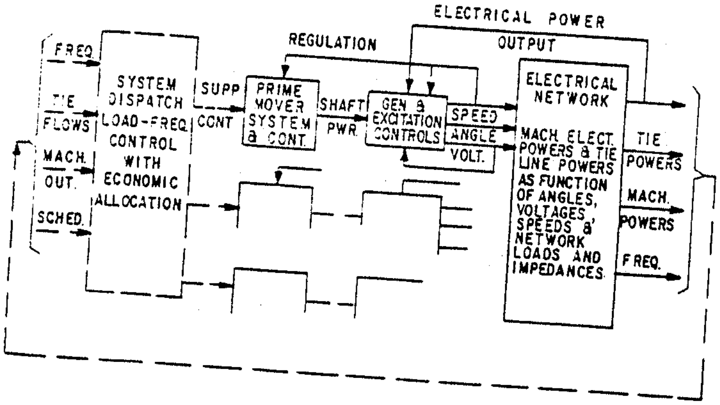
In the foregoing, the problem was one of providing first swing transient stability. This is a highly nonlinear dynamic problem and the basic concern is to provide sufficient restoring forces to cancel out relative machine accelerating energies so as to limit excursions of relative machine angles as needed to preserve synchronism. From a control standpoint, the engineering analysis involves a great deal of highly nonlinear dynamic simulation but relatively little control system design technology. Complex switching logic strategies have generally not found application for the following reasons:

(1) Since power systems are under constant evolution, control strategies should withstand the tests of a constantly changing and evolving network. This requirement generally acts as a wet blanket on schemes which are precisely tailored to, and sensitive to a particular generation-transmission configuration.

(2) The same characteristic of an evolving power system makes it desirable to apply local control measures which are dependent on local measurements and which need not rely on complex strategies based on processing of remote quantities. Often the measures in question are not expected to come into play more than once or twice a year, and if changes in strategies must be made every couple of years or so, the theoretical benefits of the scheme may be offset by the probability of malfunction during implementation and testing. Such malfunctions could easily result in more outages than the scheme was designed to offset.

<u>Control Effects - Continuous</u>

Another important aspect of power system dynamics concerns its behavior in the linear, small perturbation mode referred to as steady-state or dynamic stability. In this mode, traditional linearized control analysis methods are applicable and much useful knowledge has been derived with the use of



SCHEMATIC OF POWER SYSTEM AND CONTROLS
FIG. 1

POWER SYSTEM PROCESS DYNAMICS
DURATION OF PRINCIPAL EFFECTS

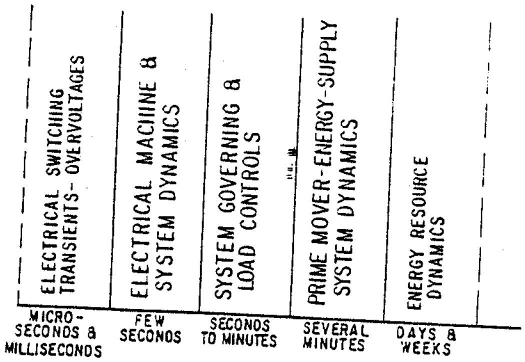
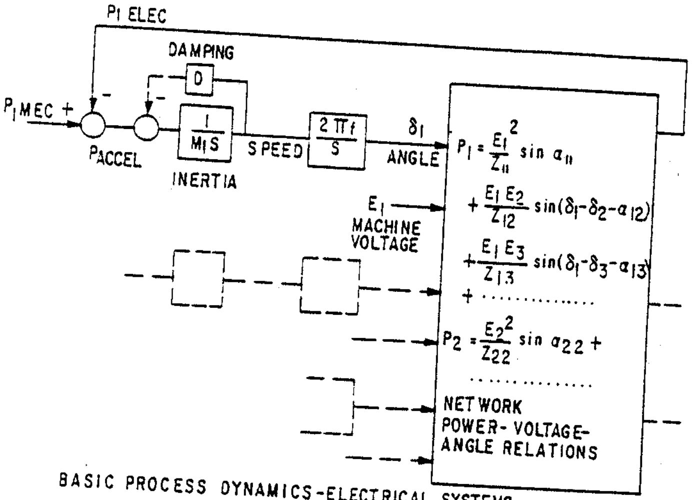
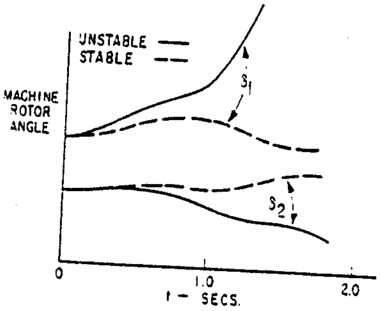


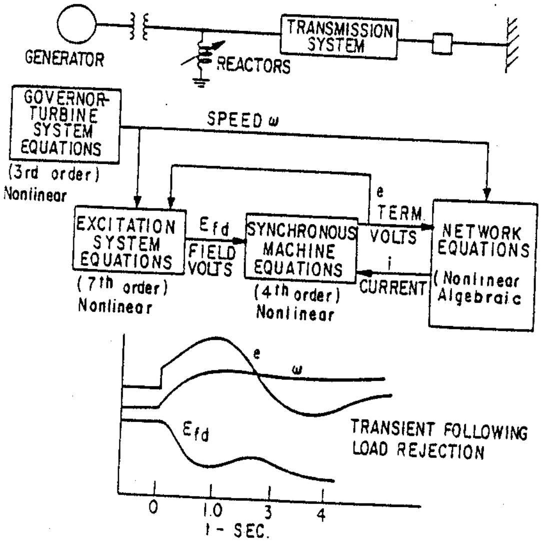
FIG. 2



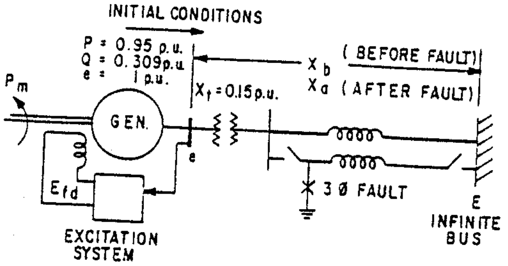
BASIC PROCESS DYNAMICS-ELECTRICAL SYSTEMS
FIG. 3



MACHINE ROTOR ANGLE TRANSIENTS FOLLOWING ELECTRICAL FAULT TEMPORARY
FIG. 4



DYNAMICS OF LOAD REJECTION
FIG. 5



SCHEMATIC OF SYSTEM INVESTIGATED
PARAMETERS: FAULT CLEARING TIME
BEFORE FAULT REACTANCE
AFTER FAULT REACTANCE
EXCITATION RESPONSE
TURBINE ENERGY CONTROL
MACHINE INERTIA
FIG. 6

frequency response techniques and simulation methods applied to typical generalized prototype power system configurations.(10)(11)

One way of describing stability limits of generating units is as shown in Fig. 11 which contains loci of machine operating points in the P-Q plane, with the machine at constant terminal voltage. The curves mark the limit of stable operation, the points in the plane to the left of the curves being stable and those to the right of the curves denoting unstable operating conditions.

The curves give no information on the type of instability associated at a particular point. For instance, the type of instability phenomena associated with hand control of excitation is related to lack of steady-state synchronizing power coefficient, and instability in this case, following a small torque disturbance, is characterized by a gradual unidirectional drift of the machine angle as shown in Fig. 12a.

This lack of steady-state synchronizing torque coefficient of the machine at the hand control limit can be neutralized with a slow-acting, low-gain voltage regulator-excitation system and the stable operating region is now typically as shown by curve "C" on Fig. 11. With a continuously acting voltage regulator, the limit of stability is usually not reached through lack of synchronizing torques, but rather due to a lack of damping torques, and for this case, the nature of the instability following a small torque disturbance is as shown on Fig. 12b.

It has been known for many years(12) that voltage regulators, while curing the synchronizing torque problem can contribute negative damping to the machine angle-torque dynamic process, a process which is basically oscillatory.

As the gain and response of voltage regulation is increased, a point is soon reached where instability of the form of Fig. 12b occurs at operating points well within the region that would otherwise have been stable under hand control. Curve "B" on Fig. 11 illustrates this effect.

These dynamic phenomena have been analyzed by a number of linear systems techniques such as Routh's criterion,(12) Nyquist's criteria,(11) root locus,(13) and by analog computer simulation.(14) Considerable insight is also derived by looking at the feedback closed-loop nature of the problem and by use of frequency response techniques.(15)

Although voltage regulators can have adverse effects on damping of intermachine and intersystem oscillations, in the majority of situations the benefits of voltage regulators through their effect on synchronizing torques have far outweighed the adverse effects on damping. These benefits are usually obtained with relatively low response voltage regulator-excitation systems.

Previously mentioned trends in equipment and system designs are placing increasing dependence on voltage control to offset effects of higher per unit reactance. Naturally, increasing attention must also be given to the problem of combating the effects of voltage control on damping.(15)

The use of special stabilizing signals in excitation control to provide a significant amount of damping to intermachine and intersystem oscillations has been the subject of many investigations, but it has not been until recently that the theories have been put to practice.(17)(18)

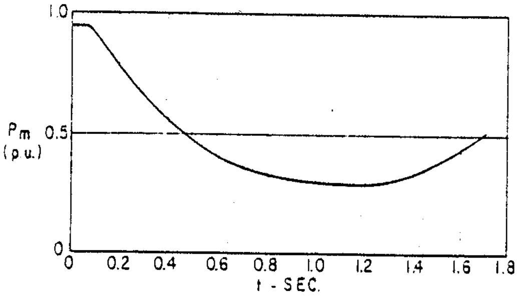
The stabilizing signals derived from speed or some related machine variable can be used to transiently offset the voltage regulator reference with the object of producing torques in phase with speed (damping torques) (Fig. 13). To accomplish this, the signal must be processed through a phase advancing (lead) network designed to offset the lags in the regulator-exciter-generator-flux loop for the frequency range of interest. Techniques of analysis in search for the shape of the phase-advancing network must consider the range of operating conditions encountered by typical machines in power systems. A key point in the design of the shaping network is that it provides a reasonable degree of phase lag cancellation over the region of frequencies of oscillation which a machine is likely to encounter in the power system environment.

The number of frequencies of oscillation that a machine can exhibit is very large, being related to the number of machines in the rest of the system. Usually only a few modes are excited and these are very much a function of the particular disturbance. The spectrum of these frequencies falls generally within the range of from approximately 0.2 Hz to 2 Hz due to the range of parameters that are normally encountered in power systems.

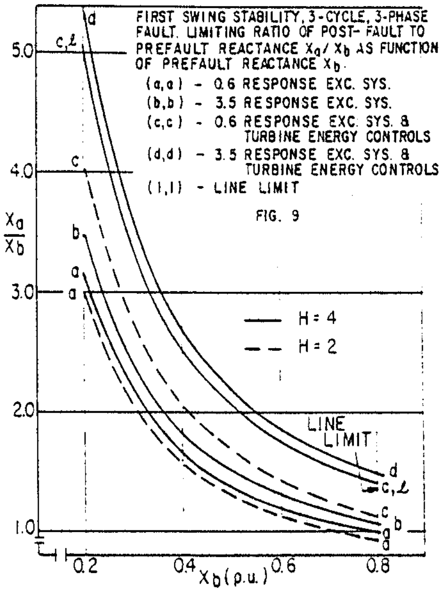
Figure 14(15) shows the effectiveness of providing damping through supplementary excitation control for a high initial response excitation system on an equivalent machine simulating generation in a close-knit power system supplying local load and tied to a large neighboring system through a tie line of size small relative to the system. The speed oscillations shown would, of course, also be accompanied by power oscillations across the tie. The loading conditions are such that, without the use of supplementary stabilizing, the system is dynamically unstable.

Stabilizing signals can also be used with slower-action conventional exciters. Due to the greater lags in the response of machine flux to changes in voltage reference, the amount of lead compensation that must be used is considerably greater than is the case for the thyristor or equivalent high initial response systems.

Poorly damped electrical systems sometimes have adverse effects on auxiliary systems within the power plant. A number of auxiliary devices such as pumps driven by a-c motors respond to frequency swings, and conditions can arise where the system induced frequency swings in the order of 0.2 Hz can cause sustained oscillations in flows, especially in the feedwater cycle. They may also adversely affect the dynamic performance of industrial plants whose processes may exhibit resonant frequencies in these ranges.



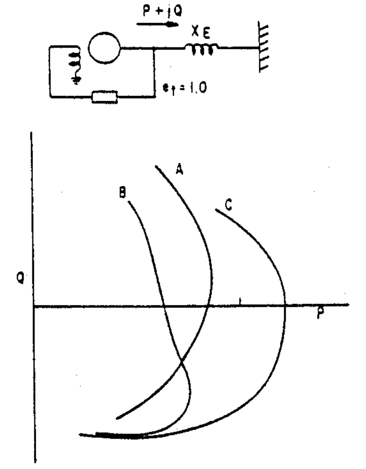
RESPONSE OF TURBINE SHAFT POWER
RAPID INTERCEPT VALVE ACTUATION
FIG. 7



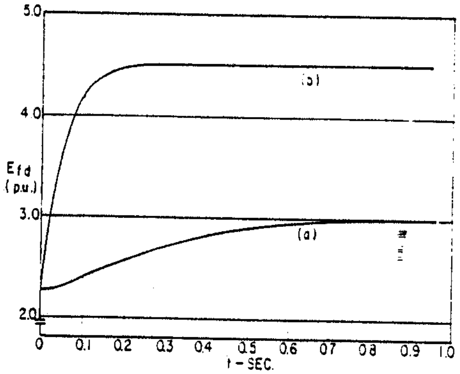
FIRST SWING STABILITY, 3-CYCLE, 3-PHASE FAULT. LIMITING RATIO OF POST-FAULT TO PREFAULT REACTANCE $X_a/X_b$ AS FUNCTION OF PREFAULT REACTANCE $X_b$.

(a,a) - 0.6 RESPONSE EXC. SYS.
(b,b) - 3.5 RESPONSE EXC. SYS.
(c,c) - 0.6 RESPONSE EXC. SYS. & TURBINE ENERGY CONTROLS
(d,d) - 3.5 RESPONSE EXC. SYS. & TURBINE ENERGY CONTROLS
(l,l) - LINE LIMIT

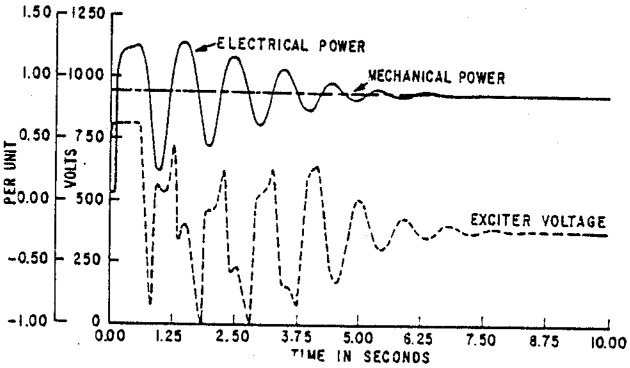
FIG. 9



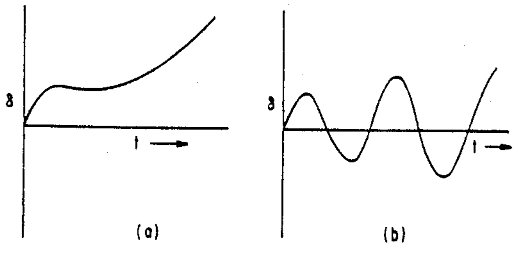
DYNAMIC STABILITY REGIONS
(a) MANUAL VOLTAGE CONTROL (CONSTANT $E_{fd}$)
(b) TIGHT VOLTAGE CONTROL
(c) MODERATE RESPONSE VOLTAGE CONTROL
FIG. 11



EXCITATION SYSTEM VOLTAGE RESPONSES
(a) CONVENTIONAL SYSTEM, 0.6 RESPONSE, 130% CEILING
(b) HIGH INITIAL RESPONSE SYSTEM - 3.5 RESPONSE, 200% CEILING
FIG. 8



MACHINE OSCILLATONS FOLLOWING 3-PHASE FAULT.
HIGH INITIAL RESPONSE EXCITER WITH SPEED STABILIZING
FIG. 10



(a) (b)

RESPONSE OF ANGLE FOLLOWING SMALL TORQUE DISTURBANCE
(a) LACK OF SYNCHRONIZING TORQUE
(b) LACK OF DAMPING TORQUE
FIG. 12

## SYSTEM GOVERNING AND GENERATION CONTROLS

### Governing or Primary Speed Controls

Beyond the first few instants in which dynamic effects are governed primarily by machine inertias and network synchronizing coefficients, the mechanism of maintaining system speed involves the bringing into balance of prime-mover shaft powers with electrical load demands.

For the case of constant prime-mover power (blocked governors) this balance is obtained by virtue of the change in connected load with frequency (typically load changes between 1 and 2% for a 1% change in frequency). For the more usual case of active governors, the frequency deviations acting through the turbine governing mechanisms produce changes in prime-mover power, and the final frequency change following a disturbance or load change is primarily a function of the equivalent governor regulation which is usually considerably more effective than the load characteristic in limiting the extent of the frequency dip. The changes in prime-mover power occur with varying degrees of lags depending on the response characteristics of the prime mover system. Since governing systems are proportional control systems, the complete elimination of frequency error must be done by slower integral control action known as supplementary control or load frequency control.

The emphasis of representation for this range of phenomena is on the prime mover, and the process dynamics are often represented as shown on Fig. 15, where the electrical network is simplified considerably by considering the generators as one equivalent source with a composite inertia whereas the identity of prime movers is preserved in more detail. Typical responses of the prime-mover shaft power to control action are shown on Fig. 16 for the case of the reheat turbine.(19) Since power is proportional to steam flow in the various turbine stages, the response of power follows closely that of steam flow which gets established very rapidly (fraction of a second) in the high pressure turbine, but more slowly through the intermediate and low pressure turbines due to the charging time (several seconds) of the reheater and steam lead volume. Although the assumption of constant boiler pressure is often made, the effect of limited boiler storage can be significant as shown in Fig. 16.

In most conventional steam units, changes in generation are initiated by turbine control valves and the boiler controls respond with necessary control action upon sensing changes in steam flow and boiler pressure. Energy is transiently drawn from or put into boiler storage since the inputs to the boiler are relatively slow in relation to the speed with which a turbine valve can move.

In the case of once-through units, their response has been very much a function of the method and philosophy adopted in the coordination of controls of the boiler turbine unit.(20)(21)(22)(23) By assigning the turbine control valves the task of continuous boiler pressure regulation in addition to their normal role of supplying load demands, a radical change in prime-mover response characteristics can result depending on the relative weight given to the pressure control function relative to the MW control function. Fig. 17 describes this variation in prime mover responses that can occur depending on the gain in the cross-coupling between pressure and MW control loops.

The subject of prime-mover system response is of particular significance under conditions of isolated system operation which can occur in the course of a major disturbance. Fig. 18 illustrates the effects of having generation with dissimilar response characteristics in an isolated system subjected to a sudden load unbalance.

Another interesting and important area concerns the dynamics of hydro generation. Because of water inertia effects, the hydro turbine exhibits an initial reversal in response which washes out to the final value with the characteristic water starting time. This peculiar response characteristic has made it necessary to use transient droop characteristics in governors for hydro turbines. This feature, in essence, cuts down the transient gain of the regulating loop so that hydro generation exhibits its slower short-term (measured in seconds) response capability than steam generation.

A pertinent observation at this point is that proper attention to optimizing the control performance of individual units as determined by criteria of isolated operation can often be ignored entirely since, in parallel operation with a very large system, the stability of governing is provided by the composite effects of many other units. When, however, the practice of ignoring these requirements is extended to a large proportion of the units, problems can arise such as experienced several years ago in predominantly hydro systems which experienced instances of frequency instability (in the order of 0.07 Hz) due to improper adjustment of governors.(24)

### Supplementary Generation Controls(25)(26)

If the mechanism of changing generation to match loads is left to the primary speed control or governing action, the only way a change in generation can occur is for a frequency deviation to exist. Restoration of frequency to rated value requires manipulation of the speed/load reference, known as generation control or supplementary control.

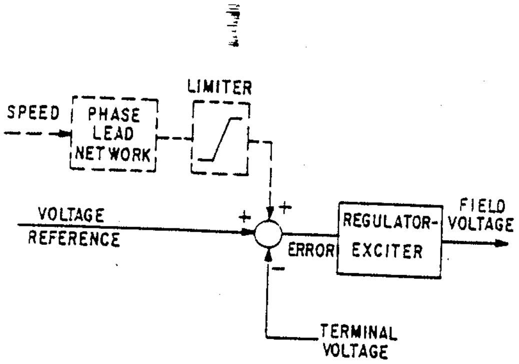
Generation control in a given area has the following objectives:

(1) Matching area generation changes to area load changes.

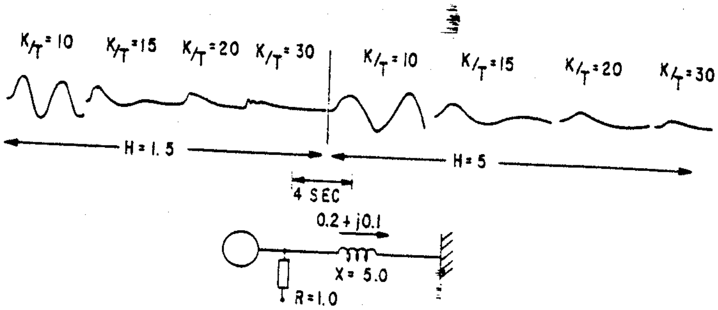
(2) Distributing these changes among generators so as to minimize operating costs.

Meeting the first of these objectives is known as supplementary control. Addition of the second objective is labeled supplementary control with economic allocation.

In isolated systems, frequency deviation is the only index of mismatch between generation and connected



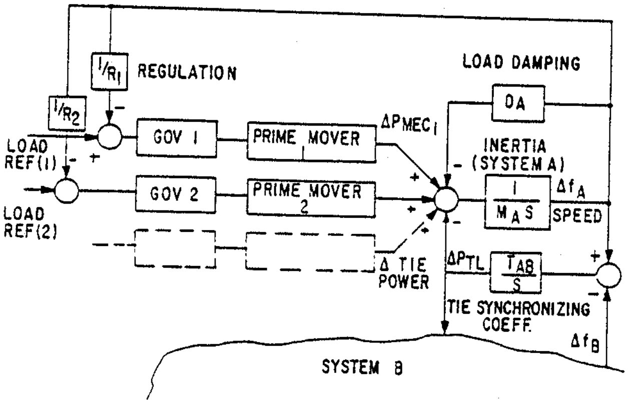
EXCITATION SYSTEM WITH SUPPLEMENTARY STABILIZING
FIG. 13



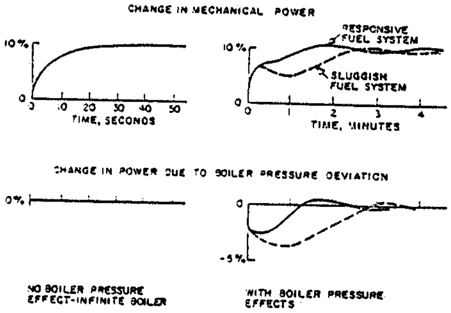
SPEED DEVIATION OF STEAM GENERATION FOLLOWING SMALL STEP DECREASE IN MECHANICAL TORQUE. EFFECT OF STABILIZING WITH SPEED DERIVED SIGNAL.

REGULATOR-EXCITER GAIN = 25
EXCITER TIME CONSTANT = 0.05 SEC.
STABILIZING FUNCTION $= \frac{K_s(1+S/8)^2}{(1+T_s)(1+S/20)^2}$, T = 3 SEC.

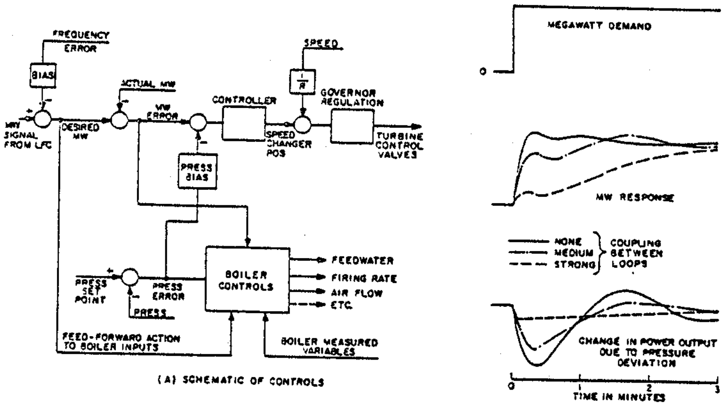
FIG. 14



SYSTEM REPRESENTATIONS FOR GOVERNING AND LOAD CONTROL STUDIES
FIG. 15



REHEAT TURBINE MECHANICAL POWER RESPONSE TO STEP CHANGE IN LOAD REFERENCE
FIG. 16



(A) SCHEMATIC OF CONTROLS

(B) RESPONSE CHARACTERISTICS

COORDINATED BOILER-TURBINE CONTROL USED ON SOME ONCE THRU UNITS
FIG. 17

load, and supplementary control or reset action operates on this deviation to restore balance.

In the more usual case of interconnected system operation, a mismatch between load and generation in a given area results in deviations of tie flows and frequency. In the usual case of areas interconnected to others which are part of a very large power pool, frequency deviations are very small, and the basic effect of a load change in an area is felt as a deviation in the tie flow between the area and neighboring systems.

Keeping in mind the basic objective of supplementary control the restoration of balance between area load changes and area generation changes, this basic objective is met when control action restores frequency deviation and tie line deviation to zero.

The objective of achieving noninteraction between control efforts in interconnected areas lead to the use of the area control error (ACE) made up from tie line deviation added to frequency deviation weighted by a bias factor, providing each area with approximate intelligence as to the location of the load change.

This concept, also known as "tie-line bias load frequency control," is based on the philosophy that supplementary control in a given area should correct for load changes in that area but should not be acting to supply load changes in the other area beyond the contribution made by virtue of frequency deviation through its area regulating characteristic.

Fig. 19(19) shows typical phenomena with the load change being initially supplied by the interconnecting ties and then being gradually satisfied by the area generation through supplementary control action.

## New Functions in Modern Generation Control Systems

The area of automatic dispatch or automatic generation control has evolved rapidly from the days when the function was performed manually, to the days of simple analog systems and to the present trend to sophisticated direct digital control.

Fig. 20 sketches the evolution of systems from the simple single pulsing controller to the use of direct digital control made possible with the advent of the modern digital process control computer and recent great improvements in data transmission and communication equipment. Practice is almost universal in new systems of developing the control logic, including considerations of economic allocation, at the central location called the dispatch center.

In addition to the area control error, unit MW loadings are telemetered to the central location where supplementary control and economic allocation logic develops the desired generation and control action for the individual units.

In the past, the amount and type of control logic that could be provided, and indeed the motivation for a particular control philosophy, was to some extent influenced by the practical constraints of analog hardware implementation. With the use of digital computers this is no longer the case since it is a simple matter to accommodate with control software almost any degree of logic that may be desirable. This new freedom from hardware constraints in the implementation of control logic makes it a simple matter to implement a wide range of strategies.

The concept of generation control has evolved rapidly from the simple function of minimization of Area Control Error to the addition of the function of economic allocation of generation and simultaneously the minimization of control effort.

An interesting application of digital control logic is in the provision of nonlinear filtering logic to minimize unnecessary and ineffective control action. It is characteristic of load frequency control systems that the control error contains random components with frequencies considerably higher than the closed loop response bandwidth of generation control. Control action in response to these random components does not reduce ACE but merely imposes an unnecessary wear and tear on governor motors, turbine valves and other plant equipment.

The conventional approach with linear filtering accomplishes noise reduction at the expense of speed of response. Nonlinear digital logic can be designed to preserve the response capabilities for large and sustained error signals while rejecting control action for the small and high frequency (nonsustained) components of error.(20)

Another function of modern digital generation controls is to account for rate of change limits in machines including time varying constraints such as are imposed by considerations of thermal stresses in steam units.

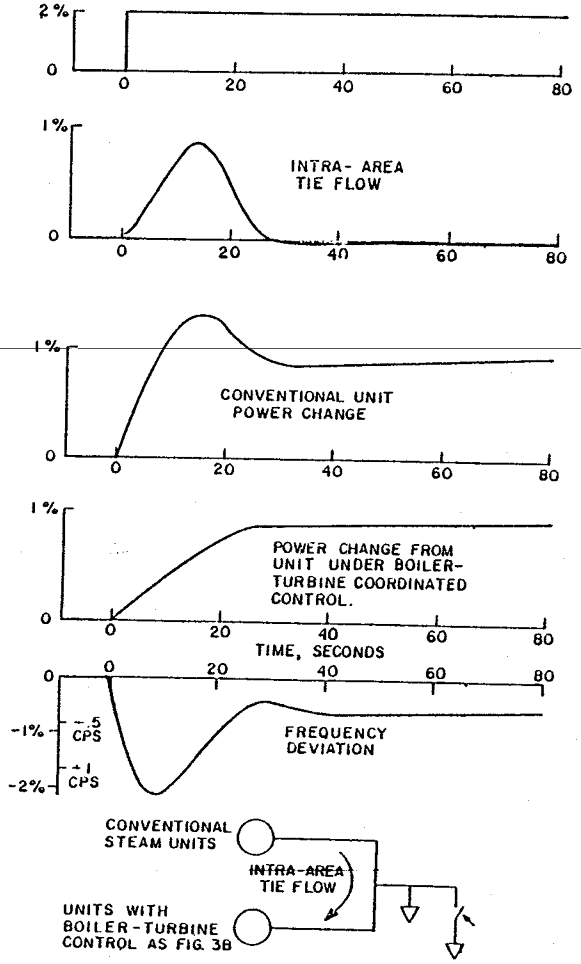
As system control centers take on added responsibilities for monitoring and maintaining security of systems, the function of generation control will also include the task of sudden reallocation of generation as may be dictated by security considerations such as the avoidance of loading constraints in the transmission system.

## PRIME-MOVER ENERGY SUPPLY SYSTEM DYNAMICS

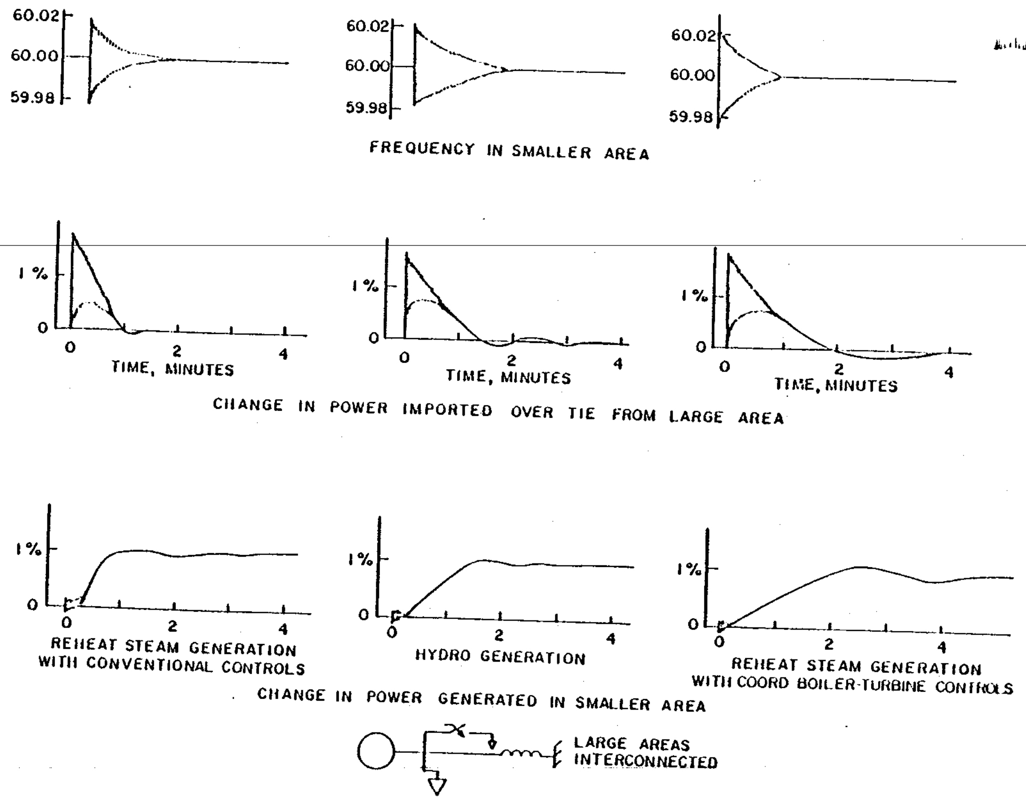
Perhaps one of the most challenging areas in the field of dynamics and control lies within the foundaries of the large modern power plant. Industry approaches to the problem of dynamics and control have been quite different in the area of fossil-fired plants as compared with what was needed to make the modern nuclear plant a reality.

### Fossil-Fired Plants

The process of thermal energy conversion is characterized by very high order dynamics. Fossil plants evolved over the years from a process that was controlled largely manually to one that today requires very complex multi-variable controls. The complexity of the process dynamics discouraged analytical approaches. The process was slow enough to admit



LOAD CHANGE ON ISOLATED AREA
FIG. 18



EFFECT OF LOAD INCREASE IN AREA TIED TO MUCH LARGER INTERCONNECTION
FIG. 19

operation under manual control and its evolution occurred over decades when the technology of dynamics and control was largely an art. Hence, the development of plant controls has been largely an evolutionary process of closing a loop here, adding an improvement there - a process that has relied largely on extrapolation of past experience and experimentation on site.

Within the last decade, several developments have given new thrusts and opened new opportunities for major improvements in the control of plants. These are:

(1) Computational capability has expanded many billions of times making it possible to simulate the very complex process dynamics, a step that is essential in the engineering of controls.

(2) Major improvements have occurred in control hardware capable of performing complex computational and logic functions.

(3) Rapid advancements in control technology which provide the bases for complex multivariable control system design.

Concurrently, the need for sophistication in control design and proper account of process dynamics has increased manyfold due to the adoption of large generating unit sizes which typically are ten times the ratings of units of twenty years ago. Along with increased sizes, there have been increases in design pressures and temperatures closer to the limits of materials.

Although there is growing recognition that transient duty and the quality of control of plant variables have a direct correlation with plant availability, there appears to be much room for improvement of plant controls through the use of modern approaches of engineering the sytem through simulation. Much too often the added costs of such approaches are weighed against the costs of the control hardware rather than against the costs of the total plant whose performance and availability are directly affected.

## Boiler-Turbine Simulation

Fig. 21 schematically describes a typical boiler-turbine process.(29) The process dynamics are characterized by the distributed nature of thermal and fluid storage in various sections. The process of fluid flow and heat transfer is highly nonlinear as can be noted from the simplified set of equations in Fig. 22 describing the finite difference approximation to the process physics equations which are nonlinear partial differential equations. The set applies to one heating section. To place the overall task in proper perspective, a typical boiler must be represented by 20 to 30 such sections whose equations must be solved simultaneously.

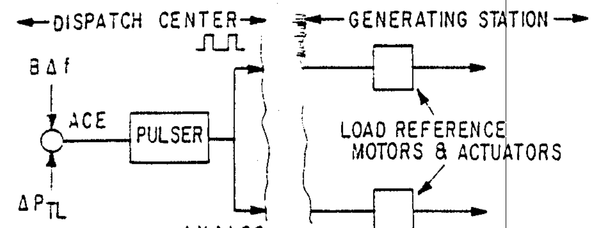
The subject of simulation of the boiler-turbine process in a fairly comprehensive manner gained industry attention in 1958 with the publication of a paper(30) on the design of noninteracting controls for a marine boiler. Analog computer simulation was used requiring adoption of linearization techniques. Since that time, many attempts have been made(31,32,33,34,35) at simulation of utility boiler turbine units with varying degrees of success. The rapid advancements in digital techniques made it natural to tackle the huge computation task digitally. The digital computer also made it possible to describe the process in nonlinear form, whereas such approaches on analog facilities would have required hundreds of multipliers and function generators, much beyond the capacity of the largest conceivable facility.(35)

Unlike analog techniques for the solution of differential equations which can be classifed as almost standard, the solution of such equations by means of digital computers involve use of numerical techniques of which there are many and, no doubt, many still to be developed. A given problem can be solved with different numerical techniques to yield essentially the same result. It is quite easy, however, to consume a hundred times as much computer time solving the governing equations one way as compared with what might be required solving them another way. Several approaches have been taken with the use of digital computers in this area. A powerful method has been the use of linearization techniques similar to those used with analog computation and with the solution of the resulting set of linear differential equations by state space matrix formulations.(31)

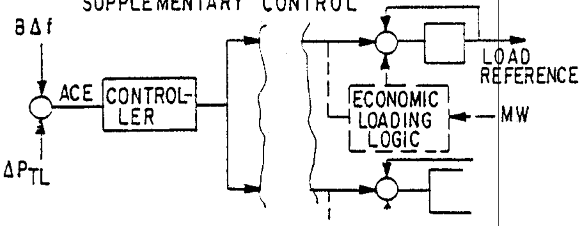
Another interesting application has been the use of the digital computer to calculate linearization parameters for use in analog computer representations.(33)

Unique methods of digital simulation have been developed(35) to model the process, preserving its nonlinear nature. The need for solution in nonlinear form can be appreciated from Fig. 23 which describes the fluid properties along the heating path of typical once-through boilers. Another incentive for the nonlinear treatment of the process relates to the needs of control design wherein the real challenge lies in providing for proper logic through large disturbances which result in additional nonlinearities due to such factors as valves and dampers hitting limits.

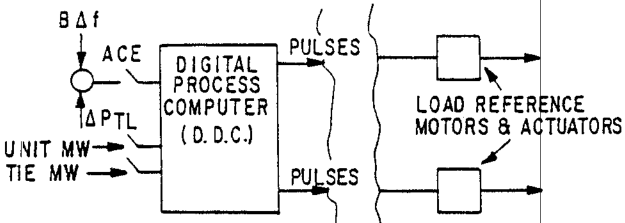
Fig. 24(35) describes a very effective technique of solution where the sets of equations describing pressure-mass flow phenomena are solved nonsimultaneously with the equations which yield the temperature profile. The temperature profile is solved by techniques of modeling of heating sections derived by visualizing the continuous flow process as a sequence of pulsations whereby the volume of a given section is filled instantaneously with fluid at inlet conditions; after residing in the volume for a time equal to the residence time, the fluid is instantaneously to the next volume. The visualization of flow in terms of such discrete pulsations permits solution of the fluid temperature at the discrete instant of expulsion, as a closed form transition algorithm operating on the inlet temperature, accounting for the heating during the residence period.



ANALOG SUPPLEMENTARY CONTROL

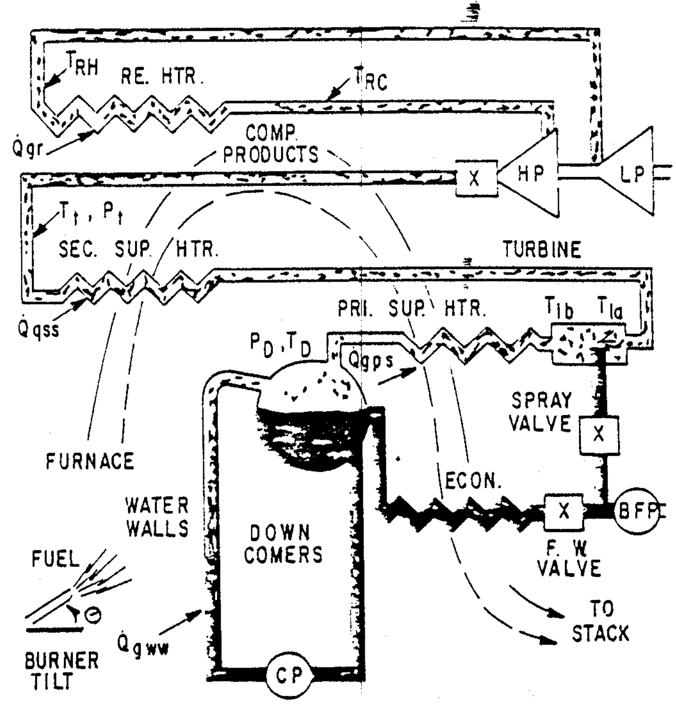


ANALOG SUPPLEMENTARY CONTROL WITH ECONOMIC ALLOCATION

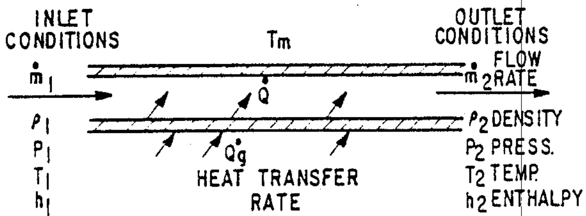


DIGITAL LOAD FREQUENCY CONTROL WITH ECONOMIC ALLOCATION

EVOLUTION OF GENERATION CONTROL SCHEMES
FIG. 20



SCHEMATIC OF BOILER-TURBINE PROCESS
FIG. 21



MASS BALANCE

$$\dot{m}_1 - \dot{m}_2 = V \frac{d}{dt}\left[\frac{\rho_1+\rho_2}{2}\right]$$

ENERGY BALANCE

$$\dot{m}_2 h_2 - \dot{m}_1 h_1 + V\frac{d}{dt}\left[\frac{\rho_1 h_1 + \rho_2 h_2}{2} - \frac{P_1+P_2}{2J}\right] = \dot{Q}$$

PRESSURE DROP

$$F_1 - F_2 = \frac{2f}{(\rho_1+\rho_2)}\left(\frac{\dot{m}_1+\dot{m}_2}{2}\right)^2$$

HEAT TRANSFER

$$\dot{Q} = K\left(\frac{\dot{m}_1+\dot{m}_2}{2}\right)^{0.8}\left(T_m - \frac{T_1+T_2}{2}\right)$$

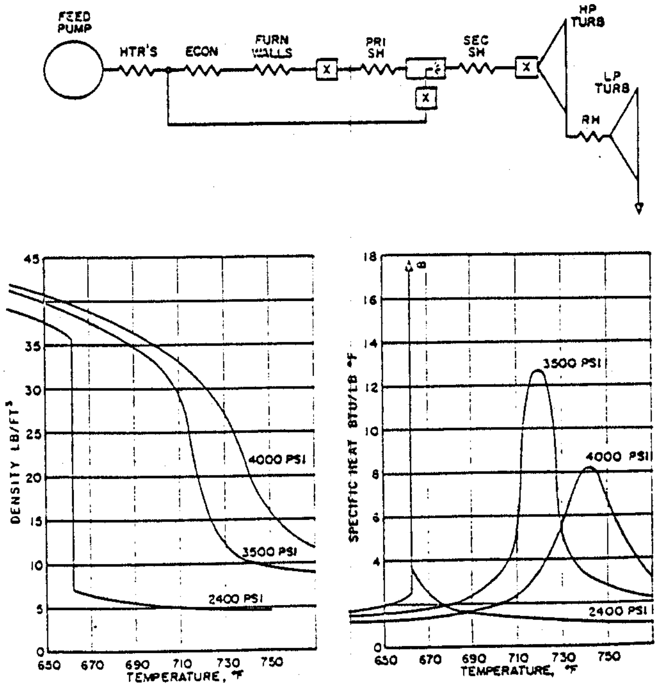
METAL TEMP.

$$T_m = \frac{1}{MC}\int(\dot{Q}_g - \dot{Q})\,dt$$

STEAM TABLES

$$\rho_2 = f_1(P_2, h_2)$$
$$T_2 = f_2(P_2, h_2)$$

EQUATIONS FOR HEATING SECTION
FIG. 22



ONCE THROUGH BOILER PROCESS
VARIATION OF FLUID PROPERTIES AS FUNCTION
OF PRESSURE AND TEMPERATURE
FIG. 23

The problem of modeling of heating sections is a very important ingredient of the overall plant dynamic simulation. Significant contributions have been made in this area in all digital approaches(32,35,36) and special analog computer approaches(37,38)

Figs. 25 and 26(32) illustrate the degree of success that can be achieved in predicting by simulation the boiler process dynamic characteristics. They also illustrate the slow time response nature of process dynamics in this area.

Simulation by empirical approaches and tests is also most useful and plays a big role even when a large part of the process is modeled from mathematical description of the process physics. For instance, the response characteristics of subsystems such as that of a pulverizer, or hydraulic coupling, etc., are usually described by appropriate lags and deadtimes generally derived from tests rather than analysis.

It is encouraging that industry contributions continue to be made in the area of modeling and in the very important area of documenting test response data.(39,40)

## Control Design

Plant dynamics are of prime interest for design of controls. The synthesis of a control configuration for a complex process such as just described presents a real challenge to the control engineer. Attempts to automate the design process by optimization theories of modern control methodology have not been practical because the process is highly nonlinear, the control logic must recognize constraints such a valves at limits, etc., and the information available from the process generally involves much fewer states than the order of the system. The most practical approach will continue to be the use of simulation in interactive process whereby the engineer develops a design by an orderly process of trial and evaluation.

The options of accomplishing a given control function are many and the mix of feedforward, feedback, cross-coupling for noninteraction, and adaptive features that are used requires a strong element of creativity and judgment. Such difficult questions as sensitivity of the configuration to variations in process characteristics, reliability versus complexity, etc., must be carefully weighed.

Typical modern boiler-turbine control systems have been configured as large operational amplifier analog type systems with hundreds of elements such as described in Fig. 27. Also shown in Fig. 27 is the next evolutionary step in configuring the control system with digital computers rather than analog operational amplifier type systems. This step, already taken in some pioneering applications, promises major benefits to the plant control function. Digital control permits use of practically unlimited control logic, including such functions as nonlinear and adaptive control. Sophistication is often discouraged in the case of analog controls since it invariably involves more components, and complexity must be weighed against its effect on reliability. In the digital machine complexity, when needed, it is easily implemented in software and has no significant effect on reliability.

The digital approach opens many opportunities for the user to implement his philosophy of controls and to adapt the function through software to his particular needs. These same opportunities were not present in the case of analog systems in which new functions meant added hardware and circuitry changes.

## Nuclear Plants

Dynamics have been a most important part of the design of nuclear plants which have taken giant steps based on engineering predictions rather than gradual evolution from one existing size plant to the next.

The requirements of regulatory bodies have also played a strong role in requiring extremely complex dynamic simulations to assure that proper safeguards are designed into the plant to cope with numerous contingencies. Process dynamics include complexities of core flux analysis and fuel element thermal transients. The basic steam dynamics have been somewhat simpler than is the case for the fossil plant because steam conditions are generally limited to saturation.

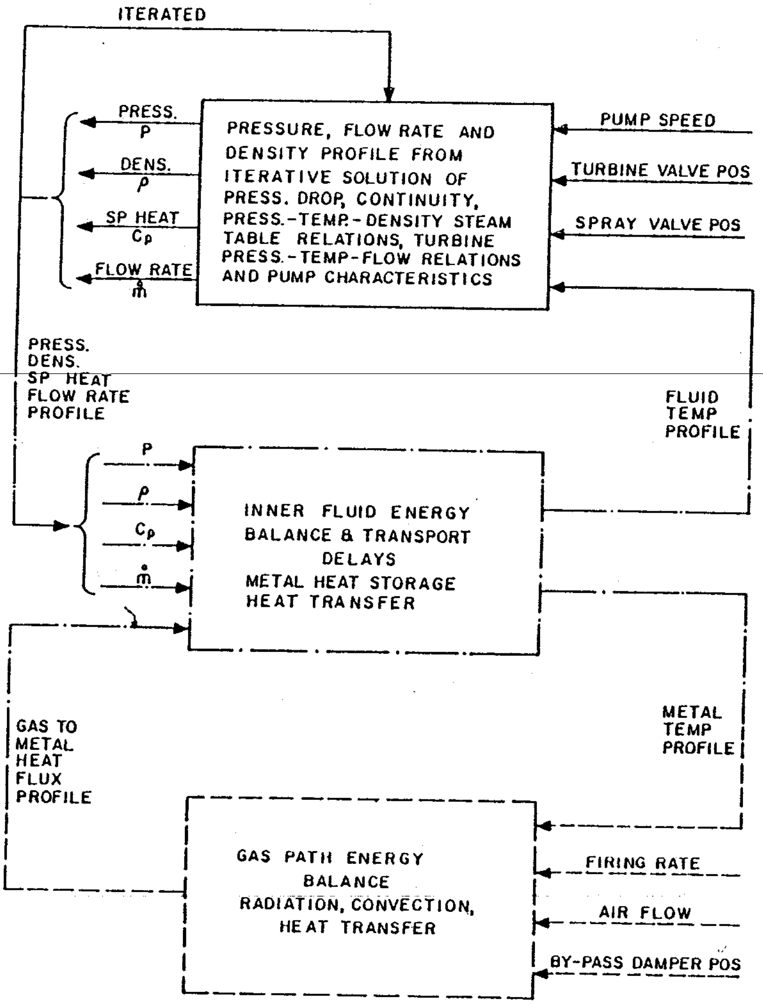
The role of dynamics in the nuclear plant has been brought to light in some exciting applications such as those involving the use of plant simulators for operator training.(41) Here the operator interface of several hundred meters, recorders, controllers, switches and buttons, indicating lights and annunciators is preserved as in the real plant. The plant, however, is simulated by a digital computer with appropriate programs and input/output interface to perform dynamically as close to the real plant as is practical. Although the need for such facilities for operator training has been critical in the case of nuclear plants, similar approaches could well be justified to provide operator training in the case of fossil-fired plants. To date, simulators for the latter have been made up of analog hardware with associated limitations in size, complexity and maneuverability.

## CONCLUSIONS

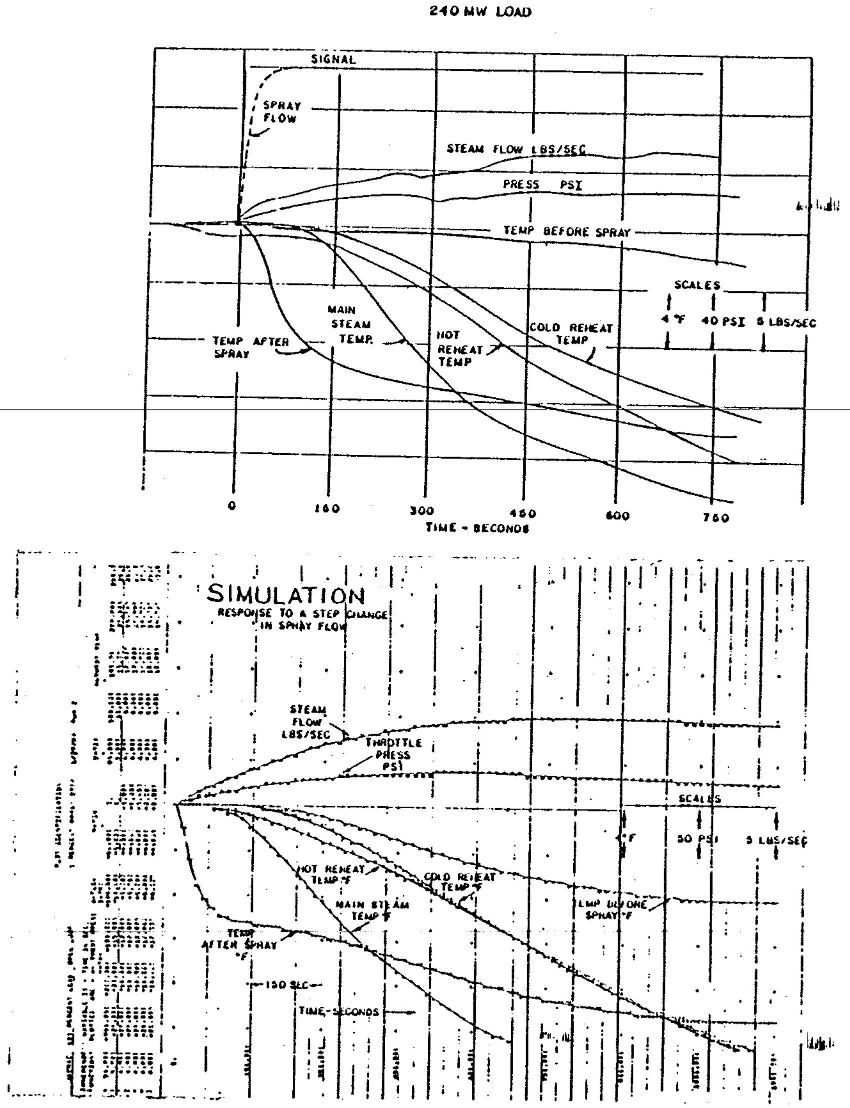
An overview of process dynamics in electric utility systems is a task that would require volumes to do it justice.

In this paper, we have attempted to cover the subject of necessity in a rather superficial manner. Process dynamics were categorized in three major areas, that of the electrical system and machine dynamics, system governing and generation controls, and power plant dynamics and control.

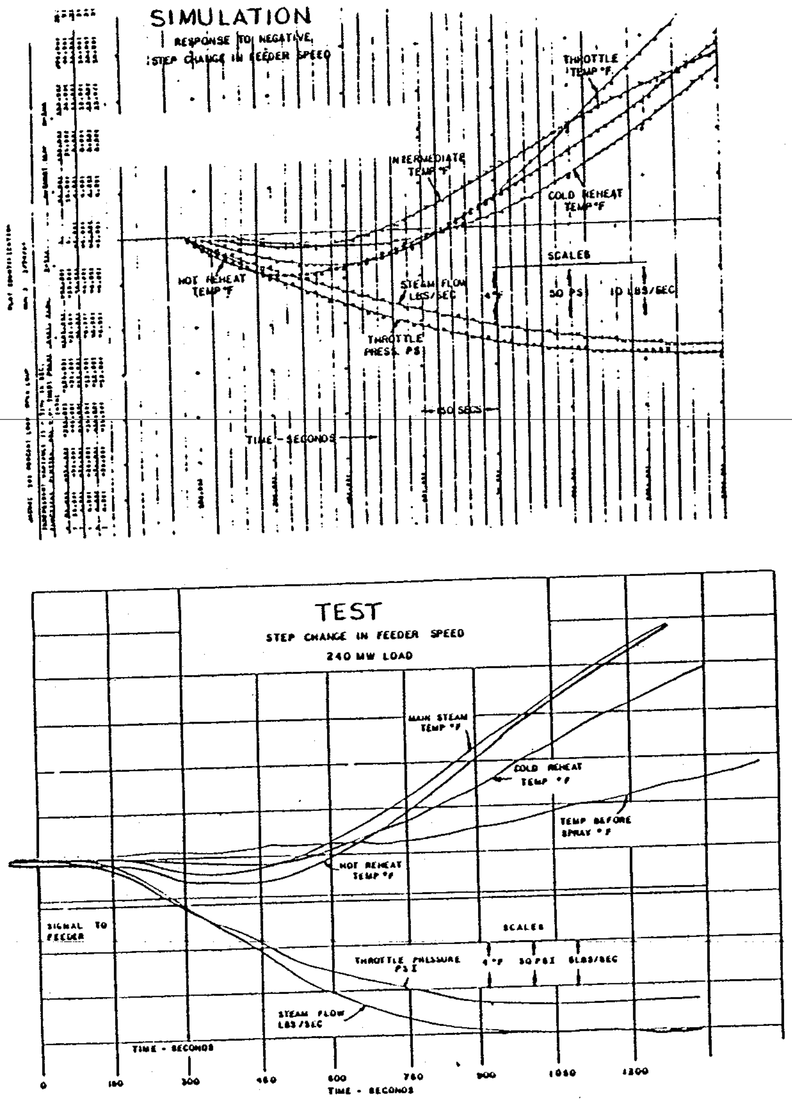
Some observations on the importance and emphasis given to dynamics in these areas attempt to relate current approaches to factors that explain them. The role of control technology as part of the discipline of dynamics is also touched on in the several areas discussed.



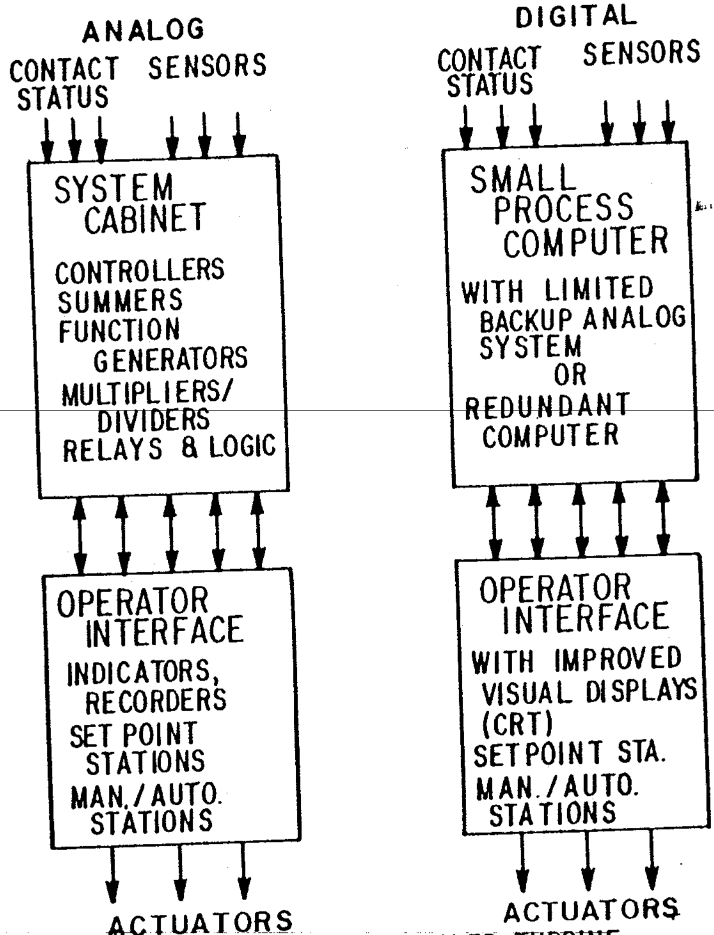
PROBLEM SOLUTION DIAGRAM
FIG. 24



SIMULATION VS. TEST RESULTS
2400 PSI DRUM TYPE BOILER
FIG. 25



SIMULATION VS. TEST RESULTS
2400 PSI DRUM TYPE BOILER
FIG. 26



CONFIGURATIONS OF BOILER-TURBINE
CONTROL SYSTEMS
FIG. 27

We are left with the distinct conviction that the digital computer as a calculating tool in dynamic analyses and as an on-line control device has opened many opportunities for new approaches to the design of overall power systems. As the control of dynamic effects is attempted in the several areas, one realizes that disciplines must interact and interface. For instance, the use of fast valving on turbines for power system stability raises the impact of such actions on the design of turbine controls and energy supply system control areas that have until recently been somewhat uncoupled from the fast dynamics of electrical transients.

By far, the most important aspect of the task is the development of indepth knowledge of the process dynamics and associated modeling techniques.

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