GENERAL REVIEW OF THE CONTROL PROBLEMS IN POWER SYSTEMS

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1.1 Introduction:

In this chapter the overall picture of power system control is presented. In subsequent chapters the particular analytical models required for analysis and design are given as well as the specific study of typical power system problems.

The problems associated with the control of an electric power system fall broadly into two categories: firstly, those problems associated with the off-line analysis, design and optimization of settings of regulators and controllers; and secondly, the actual operating problems associated with the on-line implementation of the results of the analytical, synthesis and optimization calculations.

The first group of problems requires the consideration of system models suitable for analytical study and the tools available to the investigator. The second group of problems leads to hardware considerations - communication systems, instrumentation and monitoring devices, data handling and processing equipment, decision making devices and computers and the regulating and control gear itself.

The purpose of this set of notes is to deal with the first group of problems in an attempt to illustrate the background of control theory required by the engineer in the power system field and to point the way toward the areas where a concentration of effort is required to meet new needs. Consideration is given to the models with which the investigator must deal, the actual problems of a control nature which must be faced and the analytical tools which are available and under development for attacking these problems.

1.2 The Power System from a Control Engineer's Point of View

An electric power system consists basically of a set of generating units or sources with their associated prime moving, controlling and protective equipment, a set of energy absorbing elements or loads and the complex network of transmission lines, transformers, switches, etc. necessary to interconnect the energy sources and sinks satisfactorily. The prime function of the control systems in a power network is to automatically maintain a balance between the real and reactive power supplies and demands in such a way as to maintain optimum system performance. From the customer's point of view this performance is judged in terms of the quality of voltage and frequency levels maintained and service continuity; while from the supplier's viewpoint, the judgement is largely one of operating facility and economics.

In the common control theory terminology the power system can be considered to be a high order interacting multivariable process, basically nonlinear with time varying coefficients, subject to pseudo-random disturbing variables. The control philosophy which has been generally adopted to cope with the control of this system is that of a hierarchial type of structure (See Figure 1.1). In the overall control structure there are individual

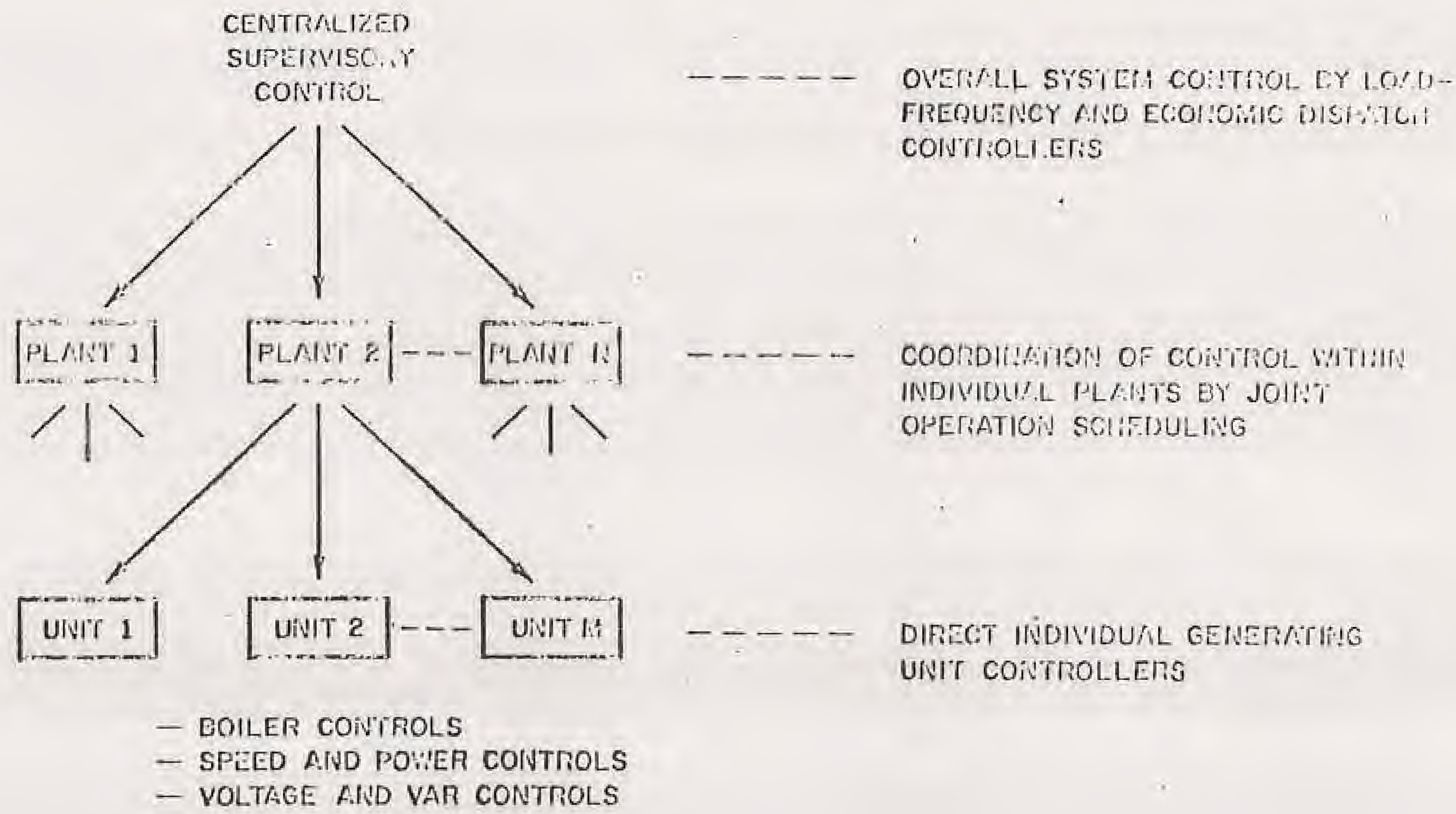


Figure 1.1 Hierarchial control scheme for power system control

controllers operating directly on specific system elements such as boilers, turbines, exciters and so on at the single unit level. Usually there is some overall plant controller which coordinates the actions of closely related units. The plant controllers in turn receive supervising direction from area controllers. Again the area control actions are coordinated by master controllers which maintain desired conditions over a multiple area interconnected power pool. To date, the control devices at the lower levels in this structure have been predominatly analog devices. These are being replaced in some instances by digital devices as the more complex supervisory control structure evolves. On-line digital controls at the area and interconnected system levels are well established in the industry. On-line digital monitoring and data collection are common at all levels in the structure.

The factors which enter into the problems of dynamic control of frequency and voltage in an electric power system can be summarized in terms of a number of mathematical relationships. In general these are nonlinear differential equations and cannot be solved completely as they stand, however, they do provide insight into the main features of the control problems. Basically there are three sets of relationships: those which describe the real and reactive power flows in the static part of the electric network and connected loads, those which describe the behaviour of the generating units with their prime movers and exciters, and those which describe the controllers at the various levels in the control structure.

1.3 Real and Reactive Power Flows in the Network

Real power and var flows through the static network from the generating points to the load points are governed by the principles expressed in Equations (1.1) and (1.2), for a system containing n generating units.

$$P_{ei} = \sum_{j=1}^{n} E_i E_j Y_{ij} \cos(\delta_{ij} - \delta_i + \delta_j) \tag{1.1}$$

$$Q_{ei} = \sum_{j=1}^{n} E_i E_j Y_{ij} \sin(\delta_{ij} - \delta_i + \delta_j) \tag{1.2}$$

where P_{ei} and Q_{ei} are the real and reactive powers injected into the network at the ith node.

$E_i\angle\delta_i$ and $E_j\angle\delta_j$ are the voltages at the ith and jth nodes.

$Y_{ij}\angle\theta_{ij} = (G_{ij} + jB_{ij})$ is the transfer admittance between the ith and jth nodes.

In an operating system the real and reactive power injections (P_{ei} and Q_{ei}) into the network at the supply points and the pattern of power and var flows through the network are set to provide for adequate supply to the consumers without overloading any of the system components. During normal operation the actual levels of the voltage and frequency variables vary from the base or average values and the whole system is maintained in a state of dynamic equilibrium about the operating point by the coordinated action of all the system control elements. The control actions are actually exercised on the system from manual or automatic supervisory controllers by way of set point adjustments on the controllers on individual generating units, through tap settings on magnitude and phase shifting transformers, by switching of lines and compensating static elements such as reactors and capacitors and by synchronous condensor action. The voltage magnitudes at the nodes (E_i, E_j) vary with the generator excitation levels, the transformer voltage tap settings and the pattern of power and var flows through the network. The δ angles change with generator prime mover shaft torque variations with changes in system power and var flow patterns and with changes in settings of phase shifting transformers. The transfer admittances between nodes (Y_{ij}) vary with network switching and with changes in connected customer loads. In general the customer loads are nonlinear, being sensitive to the frequency and voltage of the source which supplies them.

1.4 The Generating Units and Their Prime Movers and Exciters

The control characteristics of the generating units and their associated prime movers and exciters can perhaps best be illustrated by way of a signal flow graph representation of the relationships which exist. Such an illustration appears in Figure 1.2. The mathematical expressions for the links connecting the variables are complex in that they contain transcendental and trigonometric functions of variables, products of variables and nonlinearities due to physical system characteristics. In general it is possible to represent these complex expressions in mathematical terms. The Park DQO Two-Axis transformation is usually employed with the synchronous machine to remove some of the complexities of the machine representation. For small signal quality and stability studies the linearized approximations of the actual equations valid in the region of a specific operating point are satisfactory.

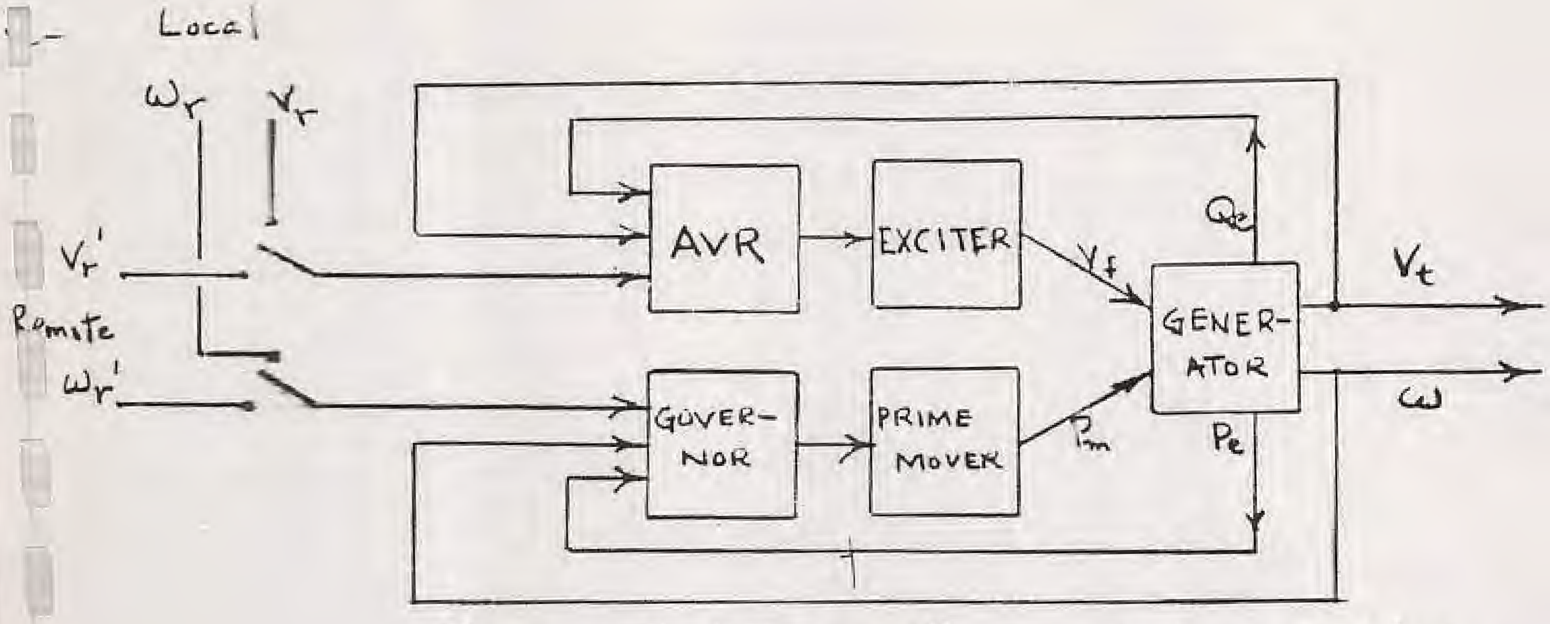
The frequency response characteristic of the common types of hydraulic turbines have been measured in the field by Oldenburger[3]. For most installations the water(compressibility) can be neglected. It has been demonstrated that so far as the electric system is concerned the transfer function of a steam plant is dictated by the turbine itself since the time constants of the steam generator are significantly long and for dynamic speed control operation the steam source to the turbine can be assumed to be infinite. On major system disturbances the actual performance of the steam supply system may be significant and should not be dismissed without consideration. The control and optimization of a high performance steam generator is a major problem in its own right.

The exciters of most units in service today are rotating dc generators of the conventional separately excited type or high power rototrols or amplidynes. The trend is now to install static SCR controlled rectifier power supplies for exciters to provide for faster and more trouble-free operation.

1.5 The System Controllers

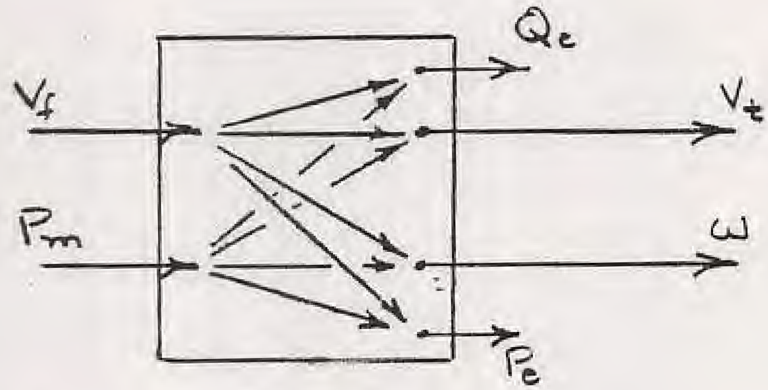
The controllers which directly affect the quality of the electrical supply can be classified in terms of:

i) the individual generating unit governors, voltage regulators and boiler controls.



Basic control loops of a single machine

(a)



Generator Model

(b)

Figure 1.2

ii) the area controllers which control the energy interchange between connected areas (4)

iii) the economic dispatch controllers which schedule generation in accordance with cost criteria.

1.5.1 The individual unit controllers

The actuation of the wicket gates on a hydraulic turbine or the steam valves on a steam turbine requires a considerable effort; the speed or frequency sensing problem on the other hand requires very sensitive instrumentation. To embody both of these requirements in a single governor unit requires a combination of techniques. In older governors, the mechanical Watt-type fly-ball unit was used for speed sensing. This was coupled through a mechanical-hydraulic transducer to a hydraulic power amplifier thence to the final actuator. In more recent governor designs the fly-ball speed sensor has been replaced by an electrical frequency sensor of either the resonant frequency or pulse rate counting type. An electro-hydraulic transducer is used to couple to the hydraulic power gain stage. With the mechanical-hydraulic governor, two mode P-I control is available. Derivative action is possible although the speed sensing is in many cases not accurate or smooth enough to make this practical. With electrical speed or frequency sensing however it is possible and practical to make use of three mode P-I-D control with its inherent advantages.

The tendency in the most recent installations is to go to all-electronic automatic voltage regulators with high gain SCR exciters. This results in a fast, trouble-free excitation system but has caused trouble due to second order effects. It has been found that excessively high gain in the voltage control loop will cause a negative damping effect in the speed control loop. Speed error signal coupling from the speed control loop into the voltage control loop is required to stabilize against this. Up to the time this second order effect caused difficulty the speed control and voltage control systems were considered to be independent and controller designs were founded on this basis. This is obviously no longer adequate.

The control of the combustion process in a high performance fossil-fuel plant is a complex operation. The various system parameters are highly interactive; however for the purposes of description the control systems can usually be considered as the separate functional sub-systems: combustion control, feedwater control and steam temperature control.

In a thermo-nuclear station the usual steam control problems are present and the combusion control problem is replaced with a reactor reactivity control problem.

During normal operation it is often advantageous to have several generators in one station share the variations in real and/or reactive power demand in accordance with some prearranged schedule. This is usually arranged by using a "joint-operation" scheme for the governors and voltage regulators, whereby those individual unit controllers are interconnected to insure harmonious operation. If this is done then the summation of all the controllers in such a plant constitutes a plant controller.

1.5.2 Area controllers

The function of area controllers is to control the generation in interconnected areas to cause each area to adjust its own generation to follow its own load changes. The total generation within each area is matched to the total area load plus or minus scheduled energy interchange with adjacent areas. This operation is achieved through the supervising action of set point adjustment of individual generator load (governor) controllers.

To illustrate the action of such a controller consider the area control signal produced as a result of a system disturbance. It is

$$\boxed{\Delta G = k_f \Delta f + k_t \Delta P_{te}}$$

where ΔG is the change in generation called for by the area controller.

This provides set point information for the unit governors in the system;

Δf, the frequency deviation in the area;
ΔP_{te}, the deviation away from scheduled area import or export over tie lines;
k_f and k_t are regulating coefficients.

The control signal ΔG is used to adjust governor settings in the area to restore frequency and tie-line flows to scheduled values.

1.5.3 Economic dispatch controllers

Economic dispatch can be applied to the generators of one area or on a multiple-area basis; the decision is really one of management not of technical feasibility. The object of the economic dispatch control is to allocate generation amongst the various participating generators such that the minimum cost of delivered power is achieved. Cohn(7) shows that the optimizing problem is solved when all generators are operating at the same incremental cost values for delivered power. This is expressed mathematically by the equation

$$\lambda = \frac{\dfrac{dF_n}{dP_n}}{1 - \dfrac{\partial P_L}{\partial P_n}}$$

where λ is the incremental cost of power delivered for the area.

$\dfrac{dF_n}{dP_n}$, the incremental generation cost for source n.

$\dfrac{\partial P_L}{\partial P_n}$, the incremental transmission loss for source n.

$(1 - \dfrac{\partial P_L}{\partial P_n})$ is the incremental fraction of power delivered.

At the present time on-line analog, digital or hybrid computer control systems are available to determine and achieve optimum generation allocation. These controllers use stored data such as thermal generator heat rates, fuel costs and transmission loss coefficients and on-line measured data such as tie-line flows, generation levels at the plants to evaluate the λ's. On the basis of these evaluations set point data is transmitted to individual generator governors to readjust individual outputs to achieve minimum cost of operation.

1.6 The Control Problems

The control problems which exist with power systems centre around the more general problems of

i) optimizing system performance with existing hardware as it now exists in actual systems; and
ii) synthesizing extensions to existing systems and wholly new systems to cope with increased future demands.

The risks due to poor judgement in either of these general areas involve vast sums of money so it is essential that reliable analytical tools be made available to predict the performance of control concepts and systems long before they are put into practice.

1.6.1 System identification

The models referred to in this chapter and developed more fully in subsequent chapters represent the general forms of the models which exist; however, a large amount of system field testing is required to determine the definite numerical models which exist in operating systems. Due to the complexity of interconnections which exist and the inherent nonlinearities of most elements, this testing must be done in every system. Only then can the investigator be assured that the analyses he makes on that particular system are really meaningful. Two types of models are required: the large signal models which contain all the nonlinearities, etc. encountered during major system disturbances, and small signal, or linear models which hold for small disturbances near normal conditions.

Recent advances in computing methods have made it possible to analyse larger systems but these analyses are meaningful only in so far as the models truly represent the actual system under study. Numerical methods have been developed to study larger disturbances in large systems, matrix methods using state space techniques have been found useful for small signal studies.

The items which require particular field study for identification at the present time are the generating units themselves and the characteristics of composite loads. Staged tests using step response and frequency response methods can be used in some instances for identification purposes but in general no standards have been developed by the industry for tests on operating systems and no test equipment is available specifically for this application. The use of statistical correlation methods for system identification offers a number of advantages and should be investigated further.

1.6.2 Stability measures

The question of system stability is solved by the method of numerical integration of the nonlinear differential equations for large disturbances or by application of the Routh Hurwitz Criterion, eigenvalue methods or other linear system techniques for small disturbances. In the latter category the methods are adequate; however, in the former, the question of stability can be answered although doing so by direct integration of the equations is a lengthy process. Some progress has been made in the application of the Liapunov Direct Method to analysis of stability of the nonlinear system but a considerable amount of work is required in this area before the method can be said to be of practical value. Up to the present time no Liapunov function has been found which can include all of the nonlinear effects which are significant in determining overall stability in a multimachine system.

In the case of stability assessment in the presence of large disturbances the tendency in the past has been to design systems to cope with some arbitrarily established criterion such as the worst possible disturbance. If faster stability assessment could be made it should be possible to approach the design from a probability point of view and thereby establish more reasonable and consistent design criteria. This approach requires more knowledge of the stability measures as well as the adaptation of probability methods to the particular situation.

1.6.3 Controller synthesis

In the past, voltage and frequency controllers for generating units have been synthesized on the assumption that the two control loops were independent and non-interacting. Such is not the case as has been demonstrated with the introduction of fast acting static AVR's. Stop-gap measures such as using a speed error signal in the AVR have been used to overcome the difficulty; however, it would appear that a new approach to the regulator design problem using multivariable control concepts might be fruitful. At least the criteria for the design of the cross coupling elements could be specified more logically than at present.

1.6.4 Optimization of controller settings

Due to the nonlinear characteristics of the controlled system it is not possible to specify an "optimum" set of controller parameters. With the advent of on-line digital monitoring it is possible to continuously up-date controller settings to maintain optimum dynamic performance as operating conditions change. Virtually no work has been done in this area specifically applicable to the overall power system problem; although a considerable amount of research has been directed toward the optimization of settings on an individual unit. The settings for speed governors on hydro generators has received considerable attention(9) and methods have been developed to provide good response to single step disturbances. Ganesan(10) has shown that the optimum setting for a single disturbance may not be the most satisfactory for a more realistic pseudo-random disturbance. Ganesan has further shown that the performance of a linear system and its controller subjected to pseudo-random disturbances can be readily analyzed using a Markov process to represent the disturbance. This method is applicable to any linear system but is particularly useful in the evaluation of the quality of performance of voltage and frequency controllers.

In the case of area controllers, the policy at the present time is to base the settings on considerations of steady-state operation. It has been shown[d] that this is not adequate for dynamic operation and that more detailed criteria are required especially where mixed thermal and hydro generation is used in an interconnected system.

In overall system planning, methods have been developed[11] which will allow for the development of generation and transmission facilities on a consistent reliability basis. Similar techniques could be adapted to provide consistent reliability in the actual operating system. This would require the factoring in of reliability criteria into the conomic dispatch control and would require "on-line" data handling and control.

1.7 Conclusions

In this chapter an attempt has been made to outline the types of control problems which exist in an electrical power system and to focus attention on some of the particular areas which require concentrated study and development at the present time. In general terms these problems require further original development of methods of analyzing large complex systems and the adaptation of existing on-line computer control and optimization techniques to particular power system cases.

In subsequent chapters of these notes, detailed developments of pertinent analytical models are given and typical analytical and synthesis procedures are illustrated.

References

1. S.Y. Chang: "Multivariable Models for an Electric Generator", M.Sc. Thesis, University of Saskatchewan, 1969.

2. K. Stanton: "Estimation of Turboalternator Transfer Functions Using Normal Operating Data", Proceedings, I.E.E., Vol. 112, No. 9, September, 1965.

3. R. Oldenburger and J. Donelson: "Dynamic Response of a Hydroelectric Plant", A.I.E.E. Transactions, Paper No. 62-167.

4. T.E. Harras and R.J. Fleming: "Stability Limits for Hydraulic Turbine Governors", Transactions, E.I.C., Vol. 10, No. C-3, June, 1967.

5. F.S. Heeley: "Generator Exciter Systems - An Historical Review", Proceedings, C.E.A., Montreal, March, 1969.

6. T.H. Lee, O.W. Hanson and R.J. Fleming: "Automatic Voltage Regulator Studies", Proceedings, C.E.A., Montreal, March, 1969.

7. N. Cohn" "Automatic Control of Power Systems", I.E.E.E., International Convention Record - Part 12, 1966.

8. O.I. Elgerd and C.E. Fosha, Jr.: "Optimum Megawatt-Frequency Control of Multi-Area Electric Energy Systems", I.E.E.E., Paper No. 69-TP 658-PWR.

9. T.E. Harras: "Optimum Adjustment of Hydro Generator Governors", Ph.D. Thesis, University of Saskatchewan, 1968.

10. K. Ganesan and R.J. Fleming: "Speed Governor Adjustment for Optimum Frequency Control with Pseudo-Random Load Disturbances", Paper submitted for I.E.E.E. Winter Power Meeting, 1970.

11. R. Billinton: "Power System Reliability Evaluation", Ph.D. Thesis, University of Saskatchewan, 1967.