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Power Systems

Electric Power Systems and Plants

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TECHNICAL SESSION
40

Organized by
Naczelna Organizacja Techniczna w Polsce

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FOURTH CONGRESS OF THE INTERNATIONAL FEDERATION OF AUTOMATIC CONTROL
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ON-LINE CONTROL OF VOLTAGE AND REACTIVE POWER FLOW IN ELECTRIC POWER SYSTEMS

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1. Introduction

During the past decade, Japan has made a remarkable progress in economic development and supply and demand of electric power have grown with that. As electric power becomes satisfactory in its quantity, "the quality of electricity" has been required. "The quality of electricity" means chiefly frequency and voltage.

A lot of methods and apparatuses have been developed for the automatic control of frequency and active power and today we can see large-scale computer control systems including AFC (Automatic Frequency Control) and ELD (Economic Load Dispatch). Automating system voltage contrl/var dispatch, however, have hardly been considered.

Up to now voltage and reactive control have been done by using automatic voltage tegulators (AVR) of generators and synchronous condensers, tap changers under load (TCUL), shungtcapacitors (SC) and shunt reactors (SR) being located at various points and operated manually or with conventional automatic apparatuses. Therefore, it was quite difficult to get a co-operative control of these devices in electric power systems. Automatic voltage-reactive power controller (AQC) was developed to solve such difficulty. Several AQC's have been installed by Japanese electric utilities and now they are being operated with very satisfactory effects.

2. Voltage control/var dispatch

2.1 The purposes of automatic control of voltage and var

The main purposes of voltage and var control (V-Q control) are:

(1) to maintain reasonable system voltage

(2) to reduce transmission losses by dispatching var rationally

(3) to operate automatically several kinds of devices under an unified logic

On the other hand voltage and var have been controlled with

SC·SR, AVR and TCUL locally and with unsophisticated methods. But as electric power systems grow, it has become difficult or even impossible to control system voltage and var in such manner. In order to control the variables with an unified logic automatic control systems have been required.

2.2 The problem formulation of V-Q control

V-Q control problem could be broken down into two levels, that is, optimizing level and feed back level. The control systems of the feed back level are operated with desired value settings determined by optimizing level.

The optimizing level problem, referring to Fig 1, could be described as follows.

Minimize transmission losses L under constraints

$$V_{min} \leq V \leq V_{max}$$
$$Q_{min} \leq Q \leq Q_{max} \quad (1)$$
$$N_{min} \leq N \leq N_{max}$$
$$Y_{min} \leq Y \leq Y_{max} \quad (2)$$
$$E_{min} \leq E \leq E_{max}$$

where V : controlled voltage at the secondary busses of substations (1 X n vector, where n is the number of busses whose voltage would be controlled)

Q : controlled var flowing through transformers (1 X n vector)

N : winding ratios of transformers having TCUL (1 X n vector. 1 will be the entry when a transformer has no TCUL)

Y : admittances of SC·SR's connected at the busses (1 X n vector)

E : the voltage of generators connected to the busses (1 X n vector)

At the feed back level, referring to Fig 2, the problem is described as follows:

$$y = G \cdot x \quad (3)$$
$$x = F \cdot (u - y) \quad (4)$$

where u : disturbances of voltage and var (1X n vector)

x : manipulated variables of SC, SR, AVR and TCUL (1X n vector)

y : deviations from ideal values (1X n vector)

F : transfer function matrix of the controllers

G : characteristic constant matrix of the controlled system

Nonlinear blocks might be inserted between F and G because SC.SR and

TCUL would be manipulated discretely while AVR would be continuously controlled. If we take y for small deviations from the ideal values of V and Q, then the entries of the matrix G can be reduced to constants.

Concreletely,

$$\Delta V_k = \sum_j A_{nkj} \Delta N_j + \sum_j A_{qkj} \Delta Y_j + \sum_j A_{gkj} E_j \qquad (5)$$

$$\Delta Q_k = \sum_j B_{nkj} \Delta N_j + \sum_j B_{qkj} \Delta Y_j + \sum_j B_{gkj} \Delta E_j \qquad (6)$$

A and B in equations (5), (6) are the elements of G, and they are called "system characteristic constants". The suffix n, q, g mean TCUL, SC·SR, and generator respectedly, also kj means a small change at point k after manipulation of a device j. Approximate values of system characteristic constants are determined by using only impedances of the system. One can comparatively easily calculate them with an AC board or a digital computer.

An example of the characteristics of SC·SR, AVR and TCUL are shown in Fig 3. The slopesof the lines are identical to the system characteristic constants. It is of importance that the slopes of SC·SR & AVR and the slope of TCUL are opposite in signs..

2.3 Comparison of centralized and decentralized control systems

There are two different approaches to the automatic V-Q control problem; centralized and decentralized.

Centralized control system is done by means of DDC with a large-scale digital computer. In this case feed back control level might be cut out.

By adopting it, one can easily control and supervise the total condition of the controlled power system. But for this system a high speed digital computer with large memories would be needed because of a plenty of on-line computation. Even if the computer is used on a time-sharing basis, the computation for V-Q control must occupy a lot of time and memories. Data communication systems are essential to the centralized control and if the computer or communication system are out of order, V-Q control system will lose the whole functions.

The values of voltages vary with places and var losses at transmission are big and the control effects of devices are limited to the neighboring area. It is, therefore, not only possible but even desirable to do V-Q control locally. This is the basic philosophy of the decentralized control system. A special purpose controller (AQC) takes care of local V-Q control and a central computer could be added to the system to determine the ideal V and Q values and transmit them to the controllers at substations. In this system even if the computer, communication systems, or some of controllers would not work or would not exist, the rest of the controller would not have to stop control function. The computation time for V-Q control in this system is supposed to be pretty short in comparison with the centralized system. The central computer, therefore, can be occupied chiefly for other pourposes such as ELD, AFC etc.

3. AQC system

V-Q control system proposed here is called AQC system. AQC system is a kind of the decentralized control system mentioned above. The system is based upon the concept of hierarchy of controller (AQC) and computer. If consists of Unit AQC, Block AQC and Central AQC (a digital computer). The functions, variables to be controlled, devices to be manipulated, the location of installation of each AQC are shown in Fig 4. It goes without saying that AQC system could be modified in accordance with the variety of utility systems.

3.1 Unit AQC

Unit AQC is the controller which controls the secondary voltage and reactive power flow through the transformer at a high voltage substation by operating SC·SR, TCUL at the substation and AVR at local power stations. The setting values of V and Q are given by a higher level controller.

The description on unit AQC in details will be found in Chapter 4.

3.2 Block AQC

Block AQC determines settings of unit AQC.

The algorythm of the control is based upon Lagrange's multiplier method. Block AQC is usually a small size digital computer for process control but could be an analog type controller, and it is installed at EHV substation.

3.3 Central AQC

Central AQC is a digital computer installed at Central Dispatching

Center and the computer is shared by quite a few functions including V-Q control.

Central AQC determines the optimal voltages and var dispatch among EHV subsystems.

The algorythm[3] used in it is based upon Lagrange's multiplier method and multi-level technique.

4. Unit AQC

Generally speaking two variables out of three, V_1, V_2 and Q (the primary and secondary voltage and var flow through transformer) are controllable by manipulating SC·SR & AVR and TCUL. Although usually it seems sufficient to control V_2 and Q, AQC mentioned here could control three variables when possible.

4.1 The role of devices

As the fundamental principle of AQC system is based on local control, AQC determines which device is to be operated according as the disturbance is brought in the subsystem or not.

Generator and SC·SR are reactive power sources, while TCUL is regarded as an equipment for regulating the balance of reactive power between outside and inside of the subsystem.

With this in mind we can easily decide how to distinguish between the devices in their usage. When the disturbance results from inside cause, AQC gives control signal to SC·SR and AVR to control inside variable and to prevent the influence from spreading to the outside of the subsystem. For the disturbance due to outside cause, AQC would operate TCUL to prevent the var dispatch inside the subsystem from being disturbed.

On the other hand each device has its control characteristics shown as Fig 3 and Table 1. A generator is considered just like SC·SR in its characteristics though it can generate var continuously. The co-operative control scheme of SC·SR and AVR is shown as Fig 5.

4.2 Controlled variables and control patterns

If a condition is satisfied, then three variables are controllable.

Let the dead band of the controlled variables be

$$\Delta V_{1min} \leq \Delta V_1 \leq \Delta V_{1max}$$
$$\Delta V_{2min} \leq \Delta V_2 \leq V_{2max} \quad (7)$$
$$\Delta Q_{min} \leq Q \leq \Delta Q_{max}$$

V_2 must be always controlled and the condition all the three variables are controllable is shown as follows; (See Appendix 2)

$$\Delta V_{1min} + x_1 \Delta Q_{min} \quad \Delta V_1 + x_1 \Delta Q \quad \Delta V_{1max} + x_1 \Delta Q_{max} \qquad (8)$$

where x_1 is the impedance seen from the high voltage bus.

It is assumed in the discussion below that V_1 and V_2 are controlled variables and Q too, if possible. The control patterns are illustrated in Fig 6.

5. An application example of AQC

Several AQC's have been installed in actual utility systems and they are supposed to be integrated into total AQC system in future. Let us look at the results of AQC installation.

An AQC was installed at Minami-Osaka substation by Kansai Electric Company, Osaka in December 1965.

We have done a few experiments as shown below. First of all AVR's setting was fixed.

Case 1 Controlling V_2 with SC•SR automatically (TCUL was fixed)

Case 2 Controlling V_2 with TCUL automatically (SC•SR are manually operated as scheduled)

Case 3 Controlling V_2, V_1 and Q with AQC (A few different values were given as dead bands and time constants)

The results of the experiments are shown in Fig 7, 8 and Table II. From these we can say:

(1) There are little difference among Case 1, 2 and 3 so far as V_2 control is concerned and in every case V_2 is remained nearly within the dead band except a small part in Case 1.

(2) As for Q control they are much different and AQC showed its effectiveness for this purpose.

(3) V_1 control is impossible by other cases than Case 3 and actually V_1 control are obtained effectively.

(4) The more precise V-Q control is needed, the more frequently the devices are manipulated. Now look at the AVR's effect. In this experiment the frequencies of SC•SR was reduced to 60% by operating AVR at a thermal power station.

6. Summary

A V-Q control system called AQC system is proposed. It consists of Central, Block and Unit AQC. As a first step the authors developed the Unit AQC and it was proved to be powerful for automatic V-Q control through series of field experiments.

As a next step, high speed digital computer is considered to be introduced as Central and Block AQC.

References (All written in Japanese)

(1) J. Baba, S. Hayashi, K. Ishida: "Automatic Voltage-Var Controller", Denki Hyoron (Electrical Review) 52, 2 (Dec. 1967) & 53, 2 (Feb. 1968)

(2) J. Baba, S. Hayashi, K. Ishida: "On line Control of Voltages and Reactive Power Flows in Electric Utility Systems", Mitsubishi Denki Giho 41, 5 (May 1967)

(3) J. Baba, S. Hayashi, K. Ishida: "Optimum Allocation of Reactive Power Source", Preprints, 1968 Joint Electrical Engineering Meeting, Tokyo

Appendix 1

Control characteristics of SC·SR and TCUL.

We consider V-Q control with SC·SR and TCUL at a substation shown in Fig 1.

1) Control effect of SC or SR

Let us define variable names as shown in the parantheses in Fig 1, where V, E mean voltage, Q: reactive power and X: impedance.

Provide E_s and E_g are constant, we obtain

$$\Delta Q = \Delta Q_c + \Delta Q_g \quad (9)$$

$$x_1 \Delta Q + x_2 \Delta Q_g = 0 \quad (10)$$

where,

$$x_c \gg x_1 x_2$$

$$\Delta V_2 = -x_1 \Delta Q$$

Then,

$$\Delta V_2 = -x_1 \frac{x_2}{x + x_s} \Delta Q_c$$

$$\Delta Q = \frac{x_2}{x_1 + x_2} \Delta Q_c \quad (11)$$

2) Control effect of TCUL

In the same manner as 1)

$$\Delta Q = \Delta Q_g \quad (12)$$

$$x_1 \Delta Q + x_2 \Delta Q_g = \Delta E \quad (13)$$

$$\Delta V_2 = \Delta E - x_1 \Delta Q \quad (14)$$

where ΔE is voltage change by operating TCUL.

$$\Delta V_2 = \frac{x_2}{x_1 + x_2} \Delta E$$

$$\Delta Q = \frac{1}{x_1 + x_2} \Delta E \quad (15)$$

3) Determination roles of the devices

From (11) and (15) we come to a conclusion that it is the best to operate

SC or SR if $\Delta V_2 \times \Delta Q < 0$

TCUL if $\Delta V_2 \times \Delta Q > 0$

If $\Delta V_2 \times \Delta Q = 0$, either SC(SR) or TCUL will do.

In actual operation there can be allowable errors (dead bands) and we can take ΔV_2, ΔQ for the deviations from the errors, not from accurate ideal values.

Appendix 2

Relationship between V_1 and Q when V_1, V_2 and Q have their feasible solutions in allowable bands.

Looking at Fig 1 we obtain

$$\Delta Q = -\frac{1}{x_1 + x_2}(\Delta E - x_2\Delta Q_c + \Delta E_g - \Delta E_s)$$

$$\Delta V_1 = \frac{x_1}{x_1 + x_2}(\Delta E - x_2\Delta Q_c + \Delta E_g + \frac{x_2}{x_1}\Delta E_s) \quad (16)$$

$$\Delta V_2 = \frac{x_2}{x_1 + x_2}(\Delta E + x_1\Delta Q_c - \frac{x_1}{x_2}\Delta E_g - \Delta E_s)$$

Supposing V_2 must be controlled at any time, we need the relationship between V_1 and Q when all of three variables can be controlled at the same time.

$$\Delta Q_{min} < (-\frac{1}{x_1 + x_2})(\Delta E - x_2\Delta Q_c) + (-\frac{1}{x_1 + x_2})(\Delta E_g - \Delta E_s) < \Delta Q_{max}$$

$$\Delta V_{1min} < \frac{1}{x_1 + x_2}(\Delta E - x_2\Delta Q_c) + \frac{1}{x_1 + x_2}(\Delta E_g + \frac{x_2}{x_1}\Delta E_s) < \Delta V_{1max} \quad (17)$$

In order that a set of feasible solution exist,

$$\Delta Q_{min} < (-\frac{1}{x_1 + x_2})(\Delta E - x_2\Delta Q_c) + (-\frac{1}{x_1 + x_2})(\Delta E_g - \Delta E_s) < \Delta Q_{max}$$

$$\Delta V_{1min} < \frac{x_1}{x_1 + x_2}(\Delta E - x_2\Delta Q_c) + \frac{x_1}{x_1 + x_2}(\Delta E_g + \frac{x_2}{x_1}\Delta E_s) < \Delta V_{1max} \quad (18)$$

Now we obtain

$$\Delta V_{1min} + x_1 \Delta Q_{min} < \Delta E_s < \Delta V_{1max} + x_1 \Delta Q_{max} \quad (19)$$

Since

$$\Delta E_s = \Delta V_1 + x_1 \Delta Q \quad (20)$$

Thus,

$$\Delta V_{1min} + x_1 \Delta Q_{min} < \Delta V_1 + x_1 \Delta Q < \Delta V_{1max} + x_1 \Delta Q_{max} \quad (21)$$

Table I The cause of disturbance and the device which should be operated

Sign of $\Delta V \cdot \Delta Q$	Cause of disturbance	Device which should be operated
$\Delta V \cdot \Delta Q < 0$	inside	AVR, SC·SR
$= 0$	not to be determined	AVR, SC·SR or TCUL
> 0	outside	TCUL

Table II Numbers of operations

times/day

	TCUL			SC·SR			Remark
	up	down	total	SC(on)	SC(off)	total	
Case 1	-	-	-	14	12.5	26.5	V_2-SC
Case 2	19	19.3	38.3	11.0	10.0	21.0	V_2-TCUL
Case 3-(1)	19.5	20.0	39.5	21.5	22.5	44.0	T=90S ΔQ=+20MVAR
Case 3-(2)	27.5	22.5	50.5	22.5	24.0	46.5	T=30S ΔQ=+20MVAR
Case 3-(3)	15.5	16.0	31.5	10.0	10.5	20.5	T=90S ΔQ=+43MVAR

1) The numbers show average values

2) Ideal value and dead band of V_2 were fixed and $\Delta V_2 = +0.8\%$

3) T is Time constant

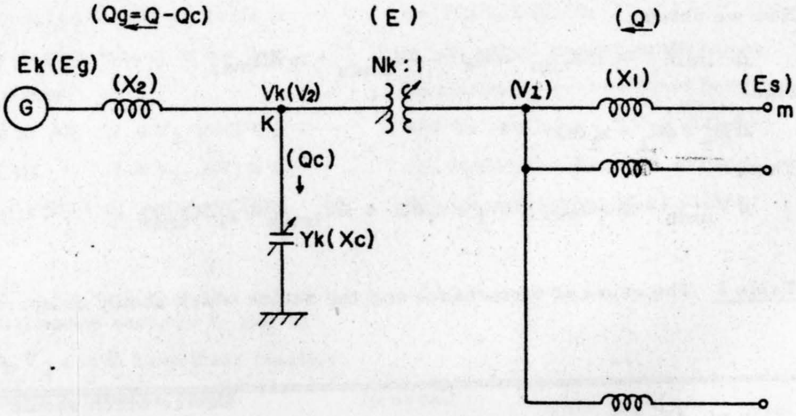

Fig. 1. Typical model system for V-Q control (Optimizing level)

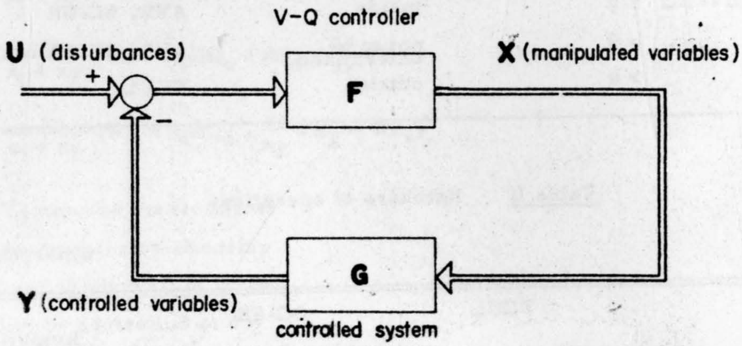

Fig. 2. Block diagram of V-Q control (Feedback level)

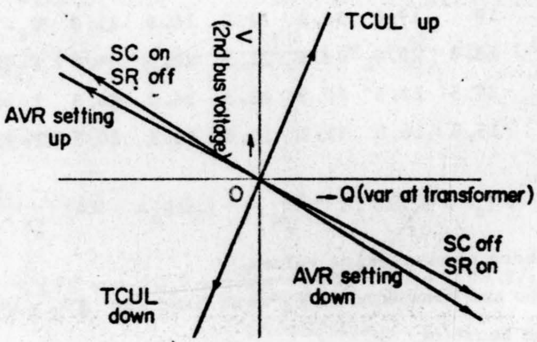

Fig. 3. Control characteristics of AVR, SC.SR and TCUL

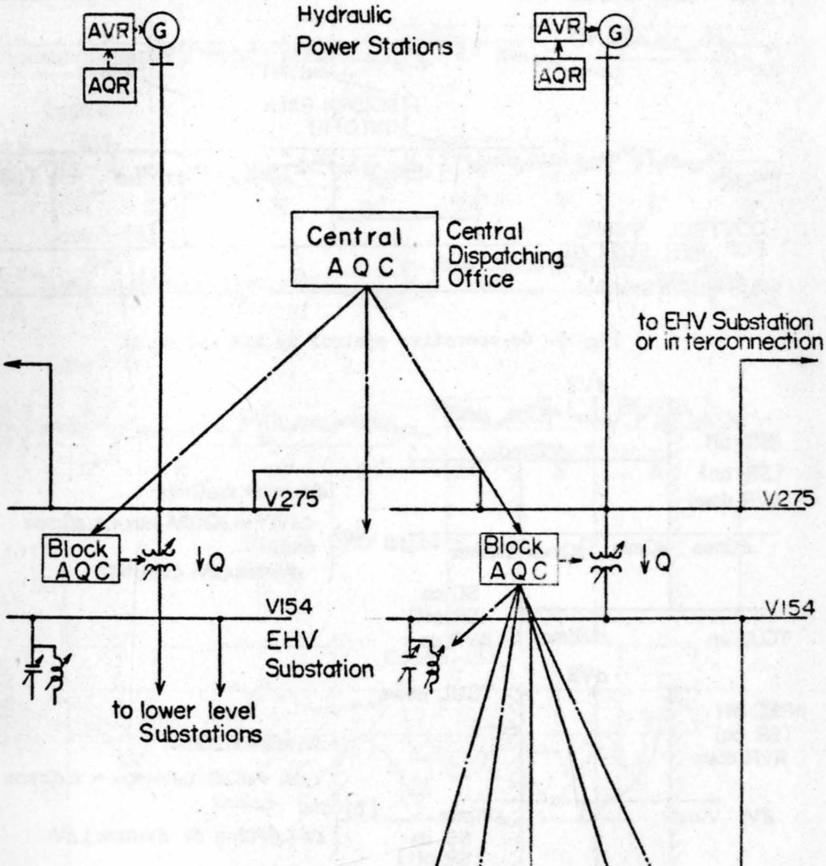

Fig. 4. Hierarchy of AQC system

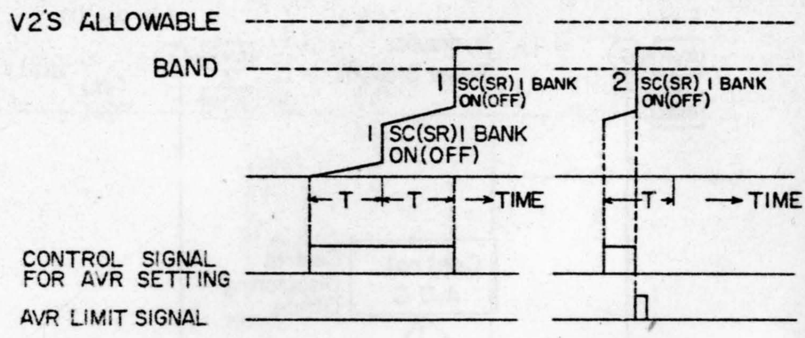

Fig. 5. Co-operative control by AVR and SC.SR

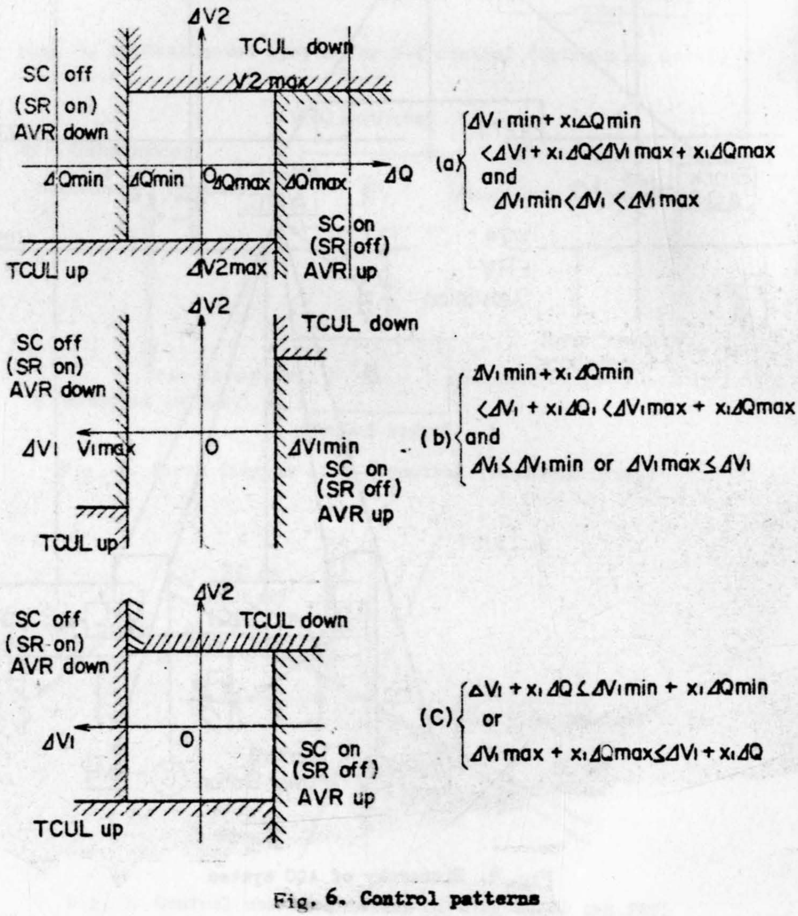

Fig. 6. Control patterns

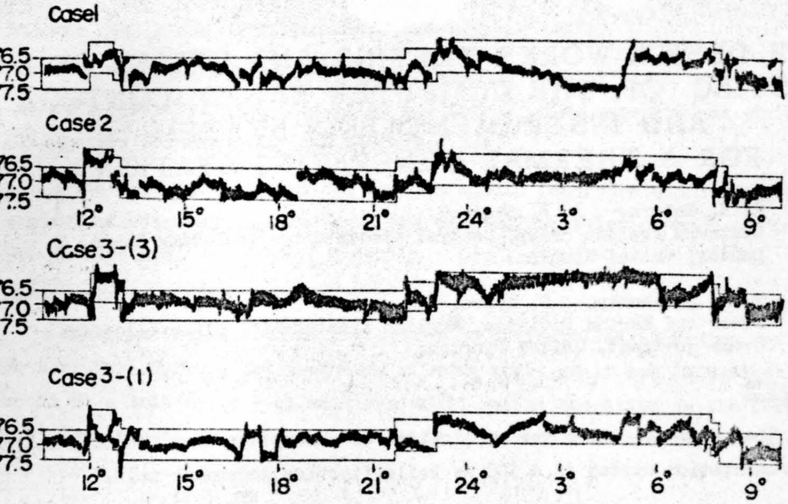

Fig. 7. 77KV voltage chart

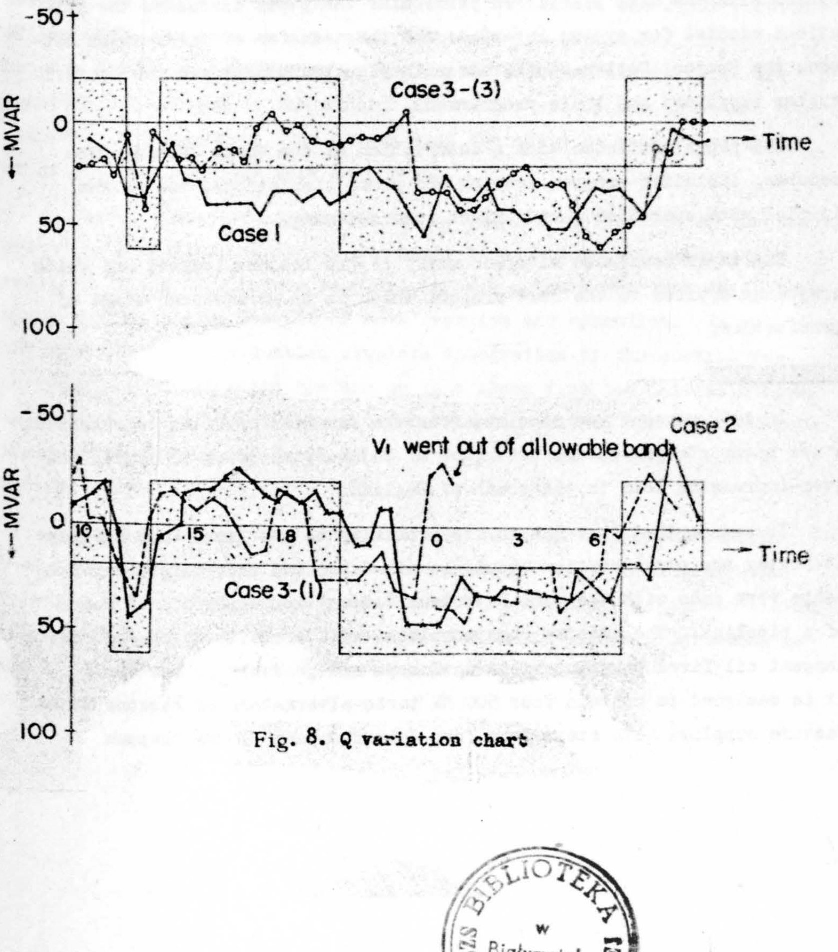

Fig. 8. Q variation chart

THE DESIGN WORKS TESTING AND INITIAL SITE TESTING OF THE COMPUTER BASED CONTROL AND INSTRUMENTATION SYSTEM FOR A THERMAL GENERATING STATION

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SYNOPSIS

The paper describes the application of a computer based control and instrumentation system to a 500 MW boiler/turbine generator unit.

It appraises the facilities offered by such a system and discusses the design and programming methods adopted for the integration of the system with the main plant. In particular the paper discusses the solutions adopted for system interface and the transfer of information between the Project Design Staff, the main plant suppliers and the control system suppliers and their programmers.

The paper continues with a description of the Works Testing procedures, including program testing and plant simulations, and of the initial site operation during plant commissioning.

The paper concludes with a summary of the lessons learned and which are being applied to the next project which is in an advanced stage of manufacture.

INTRODUCTION

In 1962 consent was received from the Minister of Power to construct a new power station on the west bank of Southampton Water to supply the ever-increasing load in the south of England.

It was decided that due to its proximity to the local Esso refinery at Fawley the power station should be oil-fired and accordingly arrangements were made with the Esso Petroleum Company to supply oil by means of a pipeline. The station when completed will probably be one of the largest oil fired power stations in Europe and probably in the World. It is designed to contain four 500 MW turbo-alternators of Parsons manufacture supplied with steam from four John Thompson/Clarke Chapman boilers with steam conditions of 2,400 psig at 540°C.

The station will consume over 2 million tons of oil a year from the adjacent refinery. Also installed are four 17.5 MW capacity gas turbo-alternators for emergency and peak load use.

The CEGB decided that the station should incorporate unit computer control of start-up and shut-down and on-load operation on each of the 500 MW machines.

SYSTEM DESCRIPTION

As initially conceived the system to be installed at Fawley was to be used for start-up and shut-down of each unit, as it was thought this would be a relatively easy task and would assist operation as the forecast load factor necessitated two shift operation from the time of commissioning.

The correction of plant faults and abnormalities was not really considered at this time but as soon as work commenced on the project it became immediately obvious that this would constitute the major portion of the work. As soon as alternative actions are considered the matter becomes extremely complicated by the number of permutations which are possible, as opposed to the straight forward start-up and shut-down procedures. A decision on this aspect must therefore be made at an early stage in order to allow work to proceed.

Due to these considerations the detailed investigation of the plant operating procedures which was necessary to establish the information required by the programmers resulted in some quite major changes to the plant systems to the benefit of both erection and operation. In addition the investigation has enabled complete integration of the control requirements into the plant systems to take place from the initial stages. In the majority of cases the required data is measured directly. Relatively little inferred data is used, contrary to the situation when a control scheme is added to a plant at a later stage.

Further, standardisation of the measuring units has been sought both from a maintenance and spares viewpoint and also to simplify the input to the analogue scanners where the large majority of inputs are in the ranges 1 - 5 mA or 0 - 100 mV. This also simplifies programming as the amount of scaling and linearising is greatly reduced.

The basic design of the English Electric system adopted for Fawley has been described previously (1) and consists of a data gathering system covering 1200 analogue and 1800 digital points feeding a KDF7 computer provided with a drum backing store. This computer drives the cathode ray tube displays for the operator and 900 plant outputs plus several analogue outputs.

CONTROL METHOD

Initially the method of plant control was based on the time dependency of the various operations to be performed with some major plant dependencies in addition. This meant that the start-up operations were analysed on the basis of the time at which specific operations were to be performed with due attention to major relationships in the pattern of plant operations.

For this method the plant was divided into 7 main plant operational groups which could operate independently of each other, time being the common factor. During discussions with the design and operating staff and the main plant manufacturers, it became evident that this concept should be modified in the interests of achieving a rapid start-up and the safety and interlock requirements of the plant.

The method finally adopted was to consider each main plant group separately. The various groups are tied together by plant operational dependencies such that before any item is started, the necessary plant 'for that item' is in operation. By this method all the various plant conditions that could exist at any stage of operation were adequately and logically considered and the following operations determined by the state of plant currently existing.

This allowed all operations to take their natural time to complete and the fact of their completion was the signal for subsequent actions to commence. Time was still retained as one of the checks on the system such that each operation was given a limiting time for completion. Completion within this time was accepted as correct, provided completion checks had been received. No plant response on the expiration of the limit time was taken as a plant failure and alternative plant configurations were sought. If plant safety was jeopardised by such response failure shut-down routines were entered to safeguard the plant.

The method allowed each major plant item or group to be considered on its own merits by determination of the conditions to be fulfilled prior to its start-up and the conditions requiring a trip of the plant item. Further routines were necessary to integrate several plant items or groups on the same basis until eventually the whole unit operation was specified.

INFORMATION TRANSFER

To achieve the necessary degree of integration of plant information it was necessary to consider each plant group independently. Consideration of the operational effect of the plant groups on the entire unit operation was also necessary. To ensure this a strict control of information transfer between the various parties involved was necessary and of vital importance.

At the outset of the project joint working parties consisting of

project design staff

station operation staff

main plant manufacturers

and control system manufacturers and programmers

were set up to ensure all parties were cogniscant of the various problems and could bring their individual expertise to bear on the solution of the problems raised. Similarly a strictly controlled procedure of information presentation to all parties was established.

The strategy of plant control was first outlined on Master Flow Sheets. Such sheets showed the plant items to be controlled, the dependence of each operation on previous operations and the operations allowed to proceed following completion. Based on these Flow Sheets, the tactics of dealing with each plant item was shown on Detail Flow Sheets. These sheets, which are numerous, laid down the method of operation of the plant item and detail alternative actions. A third set of sheets detailed the Remedial Actions to be followed in the case of faults.

This set of data detailed the procedures to be followed from a plant point of view. They were then integrated, plant group by plant group into comprehensive operational statements on Plant Control Logic Diagrams. These sheets detail the whole of the operations related to the groups into which the plant has been divided under all conditions such as start-up, shut-down and fault conditions. The method also allowed the system designers to see the extent and implications of control actions without complicating the program layout of overtaxing higher level programs. It was from these sheets that the operational program was written using a specially developed language known as Plant Auto Code which allowed direct translation of the logic diagrams into program (2). In certain instances it was necessary to supplement the information given on the Master and Detail Flow sheets by written information where particularly complex plant operations were being undertaken.

During this development it was realised that the individual operations to be performed on each plant item were simple, involving such operations as closing a contactor, opening or tripping a contactor etc. The majority of such operations can be covered by 6 or 7 standard routines (i.e. close contactor, close contactor for given period of time or until certain conditions had been fulfilled, trip contactor,etc.). These standard routines were therefore used wherever possible, the appropriate parameters being fitted into a blank standard program.

This method of program design lead to a flexible method of program operation and allowed the state of the plant to dictate the operations to be performed next. It also allowed individual plant items to be modified in their operation as found necessary on site without major program re-organisation or re-allocation, as each individual plant item has its own program.

WORKS TESTING (HARDWARE)

During manufacture of the system it was essential that confidence should be built up in the equipment, such that the various parties involved were satisfied that the equipment would perform the desired functions in the desired manner with the reliability specified. To this end a comprehensive testing procedure was adopted. Equipment for the system was assembled from standard modules using standard printed circuit boards. This allowed custom built systems to be designed and manufactured for individual power station requirements, whilst still retaining a family resemblance between all equipment manufactured by English Electric in this and other industries.

Prior to assembly into modules each printed circuit board was tested both statically and dynamically. As modules were fabricated they were further tested to ensure compatability with the manufacturing specifications. As whole units were assembled such as analogue and digital scanners they were functionally tested to ensure complete operation and compliance with the various specifications. Similarly the various peripheral equipment and the central processor were tested as standard production units.

Following the satisfactory completion of the unit tests the whole system was connected up together using the interconnecting cables to be installed at site and a further series of tests performed to prove entire equipment.

WORKS TESTING (SOFTWARE)

From what has been stated previously it is evident that the software for the project may be segregated into two distinct portions. The first of these covers the software necessary for the operation of the computer system as a system, and includes such facilities as the executive routine, the director programs, scanning programs, and other housekeeping routines. The second covers that software which is special to the project and includes such programs as the plant control logics, alarm analysis programs and other plant orientated programs.

To test the first of these portions a bureau machine was used in an off-line mode as is current practice. The second portion was prepared and coded and checked for obvious errors of logics and coding by off-line methods. Fuller testing could not be carried out at this stage until the system hardware was complete and operational. Having performed all the possible off-line coding and tape checks the program was then used for a considerable period in the works systems test.

SYSTEMS TESTING IN WORKS

The purpose of these tests, having completed the individual unit tests, is to ensure that the various sections of hardware operate together as a system and perform in accordance with the relevant specifications and the required levels of reliability. In the systems test all individual inputs and outputs from the scanners and output suite of the system were connected to the marshalling cubicles which act as the interface between the control system and the plant, and are provided with disconnecting type terminal blocks.

Initially a series of hardware tests was performed to ensure the correct functioning of the entire system. Firstly, each input was checked to determine it was correctly located in the system and that the basic accuracy specification of the equipment was being met. Secondly, the system was operated using the standard housekeeping routines of the computer system to establish the correct performance of the whole. This involved checking that the routine facilities for data acquisition and control functions were correct and were capable of routing the various inputs and data to the correct peripheral device in the correct manner. In addition, limit checks were performed on power supplies etc., to ascertain that operation was within specification. Speed and timing checks were performed for the same purpose. When all these tests had been satisfactorily completed the system was in a satisfactory state to accept the operational program for plant control. Prior to commencing the testing of this feature a plant simulator was connected to the marshalling cubicles to allow simulation of the whole of the plant both from an input and an output point of view. Having proved that the simulator had been correctly connected and was functional, the operational program was fed into the computer.

The first stage of program testing consisted of following through step by step the plant logic diagrams. This was done by initiating a start up from the operators control panel, observing the output signals generated by the computer in the output section of the simulator. The plant responses to these requests were then fed back into the system by manually setting the appropriate inputs on the simulator, so achieving a complete operation of the plant step by step. Obviously this procedure was not performed on the whole program at one time; tests were performed plant section by plant section. In addition to checking the program operation by this method, the displays of information and print out of data were simultaneously verified.

Having shown that the plant control logics were basically correct for start up and shut down by the above method, various fault conditions were next simulated by manual modification of the simulated input pattern and the computer system response verified as just described. It is obviously impossible to check every route through the plant control logics by this method. However, the most likely routes were so checked. Further checks were carried out on the system by Monte Carlo methods and the initiation of the fault condition and the computer system response noted. The Monte Carlo methods were interesting in that two types of problems were shown up. It was expected that some of the situations presented to the logics were so exotic that it gave faulty answers.

It was found however that other simpler situations which were more feasable showed that errors existed in the logics due to unexpected links between events which had not been detected during previous checking. These were subsequently analysed and discussed with plant experts to determine their validity. By these means it was possible to ensure that as far as practically possible the system behaved in a manner which was correct and not likely to impose severe problems in the plant nor cause plant damage when the system was installed at site.

The procedure outlined above took some four months of full time testing in the works by both engineers and programmers, and in the authors' opinion is absolutely essential if a system such as this is to be installed and commissioned at site with any degree of confidence. It is the authors' considered opinion that for such a system to have any chance of success, it is essential that tests such as have been outlined above are performed and allowed for in the planning of a project and that the evident lack of trouble subsequent to installation has in great measure been due to this thorough works testing procedure. The method of control program testing was aided by the structure of the plant control programs.

Before despatch to site the whole equipment was subjected to a stringent 400 - hour soak test to ascertain that the system was in a fit state for installation.

INSTALLATION AND INITIAL PLANT COMMISSIONING

Following the stringent and lengthy system testing described above, the system was dismantled, refurbished and despatched to site. Prior to despatch the initial installation planning had been done at site to ensure that the site was in a satisfactory state to accept the equipment. Marshalling cubicles had been on site for some time to enable plant cabling to proceed. On arrival at site the equipment was installed in its permanent location and connected up using the interconnecting cables utilised during the Works Test to minimise interference and other problems. On completion of installation the Works hardware tests were repeated to ensure the system was in an acceptable state and had not suffered damage during transportation to site. Having established that the system was satisfactory it was prepared for operation to assist the commissioning of the main plant.

Inputs were made available in groups to the marshalling cubicles which were then checked from transducer through the computer system to output to determine the correctness of connections, accuracy of measurement etc.. Following these checks the appropriate plant logic program for the particular plant item was fed into the computer for use during commissioning. Initially, this program was used in its 'shadowing' mode as the initial plant commissioning was performed. In such cases actual plant operations are performed by the operator but the computer system, although not able to perform these specific operations, still shadows the operator actions to prevent plant damage or dangerous conditions arising. Subsequently the plant was operated under the full control of the computer program to prove full integration of the system and plant.

At the time of writing (July 1968) this phase of the commissioning is proceeding and several plant items have been successfully commissioned using this procedure, excepting turbine run-up and boiler burner ignition, and it is planned that the first machine with its boiler and auxiliaries will be fully commissioned by the end of 1968. It is hoped that this operation and the achievement of full commercial operation will be described in the next paper in this series.

LESSONS TO BE LEARNED FROM PROJECT

In bringing such a project to a satisfactory conclusion it is inevitable that several of the problems solved could, with hindsight have been dealt with more effectively. It is also evident that some of the features which have proved successful would also benefit from reappraisal. The object of the following paragraphs is to highlight some of these matters.

Initially it was realised that the control system should be an integral part of the station design philosophy and that it was necessary to concentrate on operational problems at an early stage which impose on all parties a discipline not previously found necessary. To achieve success in a computer installation of this type it is absolutely essential that an expert team be set up comprising the station designers, plant contractors, control systems equipment supplier and programmers both from the user and the supplier. This enables all parties to be fully involved during all phases of the project from conception through manufacturing and testing to commissioning.

Another area requiring detailed attention is that of documentation relating to plant design criteria and operational limitations to ensure that this type of information may be freely available to the whole of the project team. The method adopted in this project of preparing master and detailed flow charts supplemented by descriptive matter on special plant items and procedures, whilst operating with success, requires careful consideration and streamlining for future projects.

The sensible and satisfactory solution that emerged was the preparation of logic diagrams by the operating staff of the Generating Board which are then checked by the control system programmers and translated into computer logic diagrams. This ensures that many missing items of information are detected by the engineers preparing the data and these can be obtained before handing over to the programmers. Such a procedure gives the programmers a clearer indication of the pattern of plant operation and eliminates wasted effort in reworking logics and in determining the operation of particular logics which has not been checked for some time. It is also obvious that, as the engineers become more experienced in this type of work, the logic diagrams they produce approximate more closely to the computer logic diagrams. Certain plant operations such as turbine run up and the burner pattern to be used in pressure raising cannot reasonably be written in logic form. For these a sophisticated program is necessary, written using a user code or nmemonics.

By these procedures it is possible for every party to be kept fully informed of the operational pattern determined for each item of plant. It also allows the logics to be checked by the main plant contractors to ensure that no operational or design criterion has been violated in the formulations of the mode of operations. Further this method of operation allows adequate consideration to be given at the appropriate time to the effects of plant failures and loss of information to the control system.

The conception and design of the control system and its constituent electronic modules requires careful consideration to ensure that standard, adequately proven modules can be used in the formulation and fabrication to reduce the custom built equipment necessary. Similarly the various interfaces between the plant and the control system, mainly in connection with transducers, control outputs for the operation of switchgear and contactors, require careful and detailed consideration.

These facets of system design will ensure that viable and economic systems of proved reliability and performance can be made available. While these features will reduce to some extent the time spent on unit tests in the works, it is not envisaged that they will significantly effect the time necessary for Works System test to prove the integration of hardware and software prior to installation on site. In the next few years, however, it is foreseen that program development will take significant steps forward, both in the direction of methods of proving on-line software and in the formulation of on-line control languages which are problem orientated to that of power station control and not merely algorithms for generalised problems.

ACKNOWLEDGEMENT

The authors wish to acknowledge the permission of C.E.G.B. and E.E. Company to publish this paper. They would like to place on record their appreciation of the help and assistance received from their colleagues associated with the project. They also acknowledge the help and advice given by the main plant contractors and their staffs.

It is evident that a project of this nature cannot be brought to fruition without the co-ordinated help and assistance of a large number of people, and the authors would like to take this opportunity of thanking everyone who has taken part in this project, and without whose assistance and co-operation it would not have reached the present stage of successful completion.

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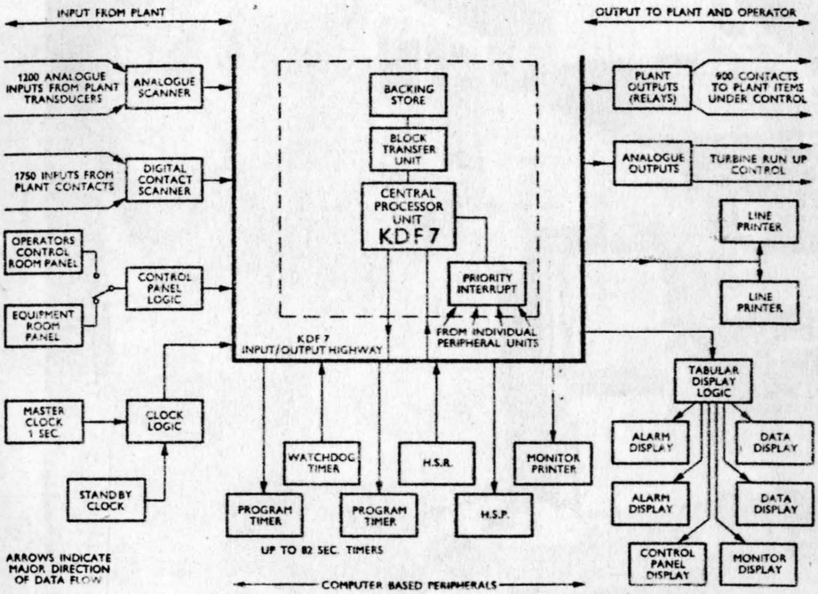
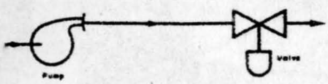
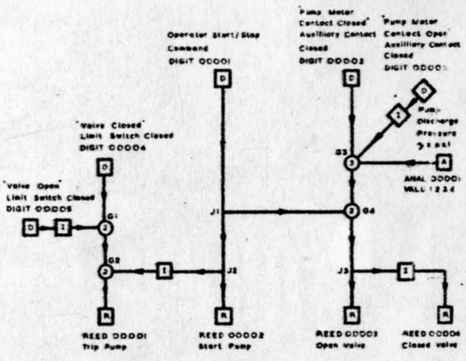


Fig. 1 - Block schematic of computer based control and instrumentation system



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GATE00002 INTO REED00001;
DIGT00004 INTO GATE00001;
DIGT00005 INVT GATE00001;
DIGT00002 INTO GATE00003;
DIGT00003 INVT GATE00003;
GATE00003 INTO GATE00004;
GATE00004 INTO JUNC00003;
JUNC00003 INTO REED00003;
JUNC00003 INVT REED00004;
GATE00001 INTO GATE00002;
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GATE00001 VALU 2;
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GATE00003 VALU 3;
GATE00004 VALU 2;

ANAL00001 VALU 1234;
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Fig. 2 - Example of plant control logic diagram and plant auto code statement

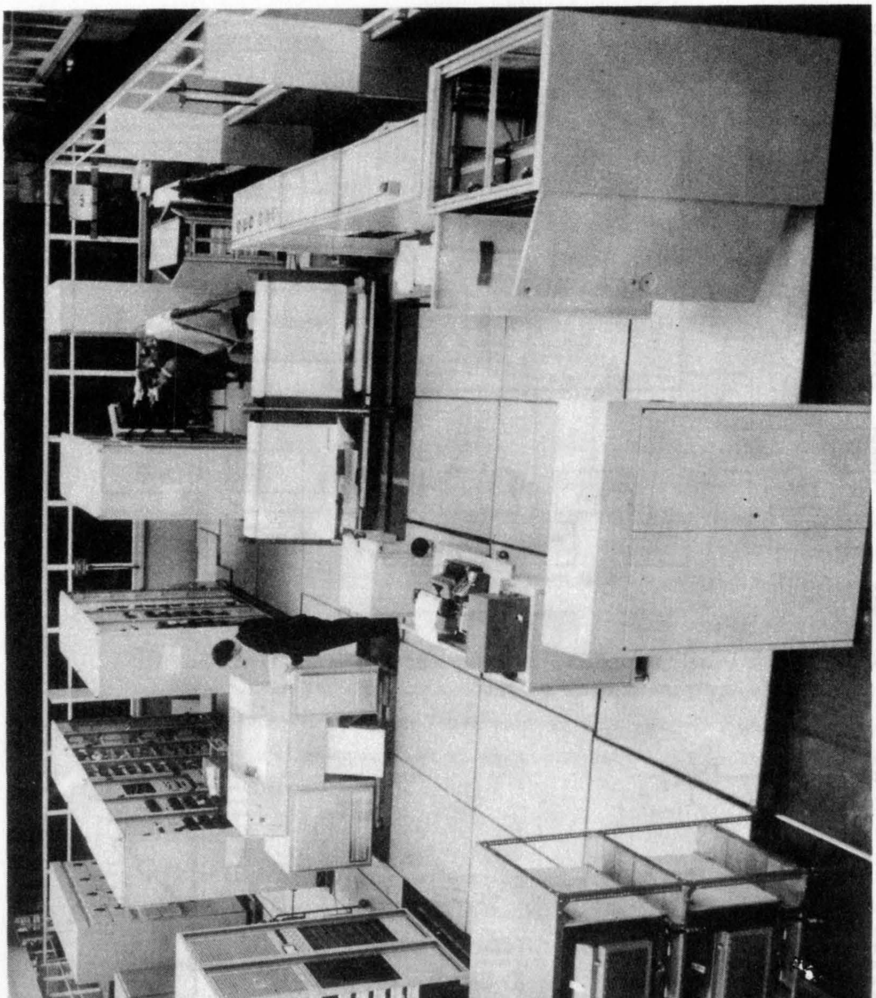

Fig. 3 - Equipment under-going systems test.

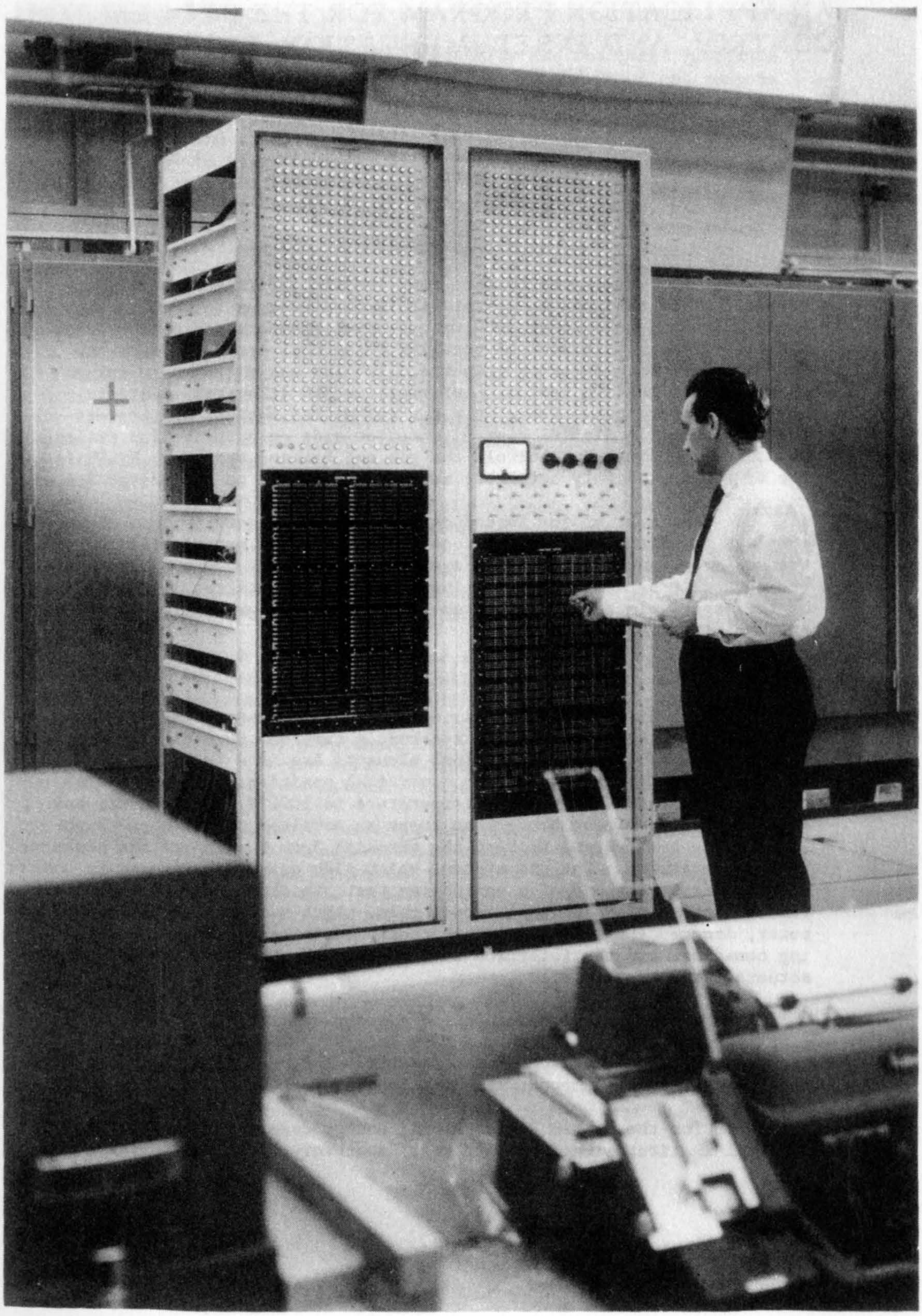

Figure 2. HTLTR Control Room

AN APPLICATION PROGRAM FOR THE PROGRAMMED CONTROL AND INSTRUMENTATION SYSTEM OF A NUCLEAR REACTOR

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INTRODUCTION

The High Temperature Lattice Test Reactor (HTLTR)* at Richland, Washington was designed to operate at temperatures up to 1000°C with nuclear power levels under 2000 watts. Fuel elements and control rods are dispersed in a lattice of parallel holes that are bored into the ten-foot cube of moderating graphite. The low nuclear power requires an electrical heating system, that supplies 384 kilowatts to attain the high temperature. There is a gas system for cooling and preventing oxidation. A digital control computer aids an operator for nuclear operation and directly controls the gas and heating systems. HTLTR is one of the most highly automated reactor facilities in the United States.

The remainder of the Introduction gives brief descriptions of the complete facility, the control room, and the system program for the programmed measurement and control system. Development and evaluation of the control program for the heating system are emphasized in the body of the paper, since the gas system control program was patterned after it.

THE REACTOR FACILITY

Figure 1 is a cut-a-way drawing of the test reactor facility. In the center of the figure is the reactor, a ten-foot cube of graphite. The heaters, control rods, and fuel elements are in a horizontal position, and the safety rods are in a vertical position. The horizontal heaters will raise the reactor temperature to 1000°C. The reactor has an insulated steel enclosure that traps an envelope of nitrogen (supplied by the gas system) to keep the graphite from burning at the high test temperatures. The gas system, which also supplies nitrogen to cool the reactor at the end of a particular test, is shown beneath the reactor floor. At the right is the control room, which houses the control computer, independent analog safety circuits, data recording and displaying consoles, and the interface between the computer and the process actuators and transducers.

The reactor rests on insulation supported by the water-cooled cement floor of the reactor room. More insulation is placed around the top, sides, front and back of the reactor. A five foot square test core, which may be removed, runs the length of the reactor.

*Operated for the United States Atomic Energy Commission by Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, Washington.

REACTOR CONTROL ROOM

The computer system for the HTLTR facility has the three functions of recording, indicating and controlling. One of the important reasons for computer control or processes is that the computer can elimate the drudgery of recording process information from indicating dials onto data sheets, and the task of examining and storing strip chart records. The computer in the HTLTR facility allows the operator to request typewriter logs of selected process variables for immediate access records and magnetic tape logs for historical, computer-retrievable, records, The computer continuously displays on a three-color cathode ray tube (CRT) the current values of process variables that are important for routine operation.

All the analog instrumentation and digital equipment are in the control room, which is pictured in Figure 2. The third wall of cabinets, which is not visible, contains the process-computer interface and a multichannel analyzer for time-of-flight measurements. Three devices in the control room particularly show the extent to which a computer can be used to perform complex operations: (1) the three-color display unit; (2) two wide range flux measuring units; and (3) two wide range resistance measuring circuits.

The three color (blue, green, red) alphanumeric display unit selects binary coded decimal data from a fixed computer core area by stealing memory cycles. It generates twenty-six alphabetic and ten numeric characters as well as the minus sign and the period in three colors. Only 140 core locations are needed to display 420 characters (including space and color change indicators) in a 20 by 21 character matrix.

Each flux measuring unit consists of a current-to-voltage amplifier and a voltage-to-frequency converter. Full scale ion chamber currents of 10^{-10} to 10^{-4} amperes are converted with 12 gain ranges that are computer controlled. Also, two calibration inputs of 10% of full scale and zero may be selected under programmed control. A computer program determines the zero offset for the units, calibrates them at 10%, finds the proper ranges, and then automatically keeps them in the proper ranges.

The identical resistance measuring circuits, which are in two ADC channels, provide precise temperature measurements to 400°C in the reactor core. The computer is programmed to select the correct range from the ten ranges in each channel. A calibration program periodically checks one channel and types the results on the logging typewriter.

HTLTR SYSTEM PROGRAM

A complete program for a programmed measurement and control system consists of several smaller programs of two general types: (1) the Monitor is composed of those programs that operate the part of the system interfaced to the physical plant, and that schedule all programmable reactions to plant and operator actions; (2) application programs are all those programs that satisfy the measurement and control needs for a specific system. Every program making up the system program was coded in machine language to save memory. At HTLTR the programmed system performs the following functions:

(1) measures neutron flux and calculates reactor period and power;

(2) controls the reactor heating system and maintains a desired temperature;

(3) controls the gas system;

(4) detects the on-off or open-closed status of mechanical devices such as flow detectors, valves, and doors (this status is indicated by digital inputs called "watch channels");

(5) measures the positions of all horizontal control rods every 0.1 second and completes the operator initiated-computer executed movements (all movements must proceed according to operational safety requirements); monitors and displays the vertical rod status (a vertical rod may be completely out of the reactor, completely into the reactor, or somewhere between the two extremes);

(6) logs, displays, and stores analog and digital data in meaningful form that will be easy to read by the operations and physics personnel;

(7) scrams the reactor under certain emergency conditions defined by the safety requirements;

(8) services the command typewriter and performs actions in response to the commands.

HEAT SYSTEM CONTROL

Although all the functions performed by the computer involved interesting problems, this paper will stress the designing, coding and evaluating of the routines to perform function (2), control of the heat system. The first specification for the heat control program was: its completion had to coincide with the completion of the physical structure. This was a valid criterion, because we were trying to show that a programmed control and measurement system could have the same characteristics as a conventional analog system, as well as, much greater flexibility. Since the purchase and installation of conventional instrumentation could coincide with completion of the plant, the programs had to meet the same deadlines. Design of the control program started before the reactor heating system was completed, so the measured characteristics for the heating system were not initially available. The distributed nature of the heating system, its multitude of inputs and outputs, its mixture of different materials, and its non-linearity over its operating range resulted in a process that could be completely described only with direct measurements.

Because of the lack of a good mathematical model of the process, conventional design methods were not used. Rather, the control program was designed in two stages: first, when the system was incompletely specified, a general algorithm was designed to meet the operating requirements and then coded for the control computer; second, after construction, measurements were made on the completed system in order to refine the original general algorithm.

FIRST DESIGN STAGE

As part of the first stage of designing the heater system control, it was necessary to determine the required system operation and to obtain a preliminary description of its dynamic characteristics. Information about the dynamic response of the system and the required operating characteristics could then be used to formulate a general form of the control program.

General System Characteristics

Four separate electrical circuits (identified as top, side, bottom and core) supply electrical energy to heater elements in the graphite moderator of the nuclear reactor. Saturable reactors in each electrical circuit control the power over a continuous range that is approximately 100 per cent of the total available power to a circuit. The saturable reactors are controlled from the computer by signals whose values are determined from readings of thermocouples, which are in the graphite moderator.

Figure 3 depicts the locations of the heater elements and the thermocouples. The heaters are parallel graphite rods that extend from the front to the rear face of the reactor, and the thermocouples (as shown grouped with heater circuits in part (b) of Figure 3), are positioned in planes which are perpendicular to the lengths of the heater elements. Because the heater elements extend from the front to the rear faces, and there is no control along their length, heater control can be considered in only two dimensions. Although the bus bars for each heater circuit supplied four or eight heating elements in parallel, there was control of electrical energy only to the bus bar. The electrical current divided equally among the elements if they had equal resistance. In an attempt to compensate for possible unequal temperatures measured from the heater elements, the averages of a set of thermocouples near each of the four heater circuits was taken as the output of the heater circuit. For example, the temperatures measured by the thermocouples labeled "T" in part (b) of Figure 3 were averaged to produce one temperature that was taken as the output for the top heater circuit. Averaging also reduced the noise, since the variance of the random variable could be divided by the number in the average to obtain the variance for the average.

Because of the complexity of the heating system, an accurate description of its dynamic response could be determined only from direct measurements. Of course, these would have to wait until the construction was complete. An inaccurate, but useful, description was obtained from basic ideas of heat transfer, and was used to surmise the general nature of the system. In other words, an exact solution to the control problem could not be found, but it was very likely that a class of solutions could be found which contained the exact solution. A common method of modeling distributed systems is by lumped circuit approximations.[1] The reactor was considered a homogeneous mass of heat conducting material, which could be modeled with an electrical network of resistors, which were analogous to resistance to heat flow, capacitors, which were analogous to thermal capacity, and current sources, which were analogous to heat energy inputs. The voltages would correspond to temperatures. Ground would be the ambient temperature, so a resistor to ground could simulate heat loss. No physical model of the heating system was made, but the transfer functions exhibited by such a model were simulated on a hybrid computer in the second stage in the design of the control program.

General Form of the Control Program

At the time the design for the control program was started, there were available reports about successful applications of control computers in which the control algorithm was a discrete approximation of a conventional analog controller with proportional, derivative and integral modes.[2,3] This type of digital controller was used for the heat system, but with arithmetic and logic additions that would meet the specifications for the system. With the assumption that the sampling intervals could be made negligible compared to the system time constants, the digital controller's response would be equivalent to that of an analog controller.[4] The resistor and capacitor model of the heating system indicated that a proportional-plus-integral controller could be stable in a single loop even if the heating process was not self-regulating. The continuous controller equation,[5] (1), and the discrete approximation equation, (2), are shown below,

$$m(t) = K_P \left(e(t) + K_I \int e(t)\, dt\right), \tag{1}$$

where, $m(t)$ = the manipulated variable,

$e(t)$ = the feedback error,

K_p = the proportional constant,

K_I = the integral constant.

$$M_n = K_p \left(e_n + K_I \sum_{i=1}^{n} e_i * T\right), \tag{2}$$

where, M_n = the manipulated variable at the n^{th} sampling instant,

e_n = the feedback error at the n^{th} sampling instant,

T = the sampling interval.

At every sampling interval, the summation indicated in the latter equation was performed in the automatic control mode.

It might have been possible to compensate for interactions between the heater circuits and their associated sets of thermocouples by providing 16 controllers, one for each possible transfer function relating the four inputs and four outputs. Besides being complex, a further disadvantage to this approach was the shortage of memory. Instead of 16 controllers, one controller for each of the four main transfer functions was used. Interaction was compensated for by adjusting the controller parameters K_p and K_I in the actual heating system. Adjusting these parameters in the completed system will be discussed as the second design stage for the control program, after the control program is described in more detail.

The general design of the control program continued with the determination of a set of criteria for the system and then the modification of equation (2) to attempt to meet them. A problem in defining specifications for the system was caused by the initial lack of understanding of computer programming by physicists and operators. That is, the requirements for system operation that were discussed with the operators and physicists had to be translated into terms that were appropriate for programming. These design features are discussed below.

Because of the large number of application programs and the limited core memory, each program had to be as short as possible and still meet its essential requirements. The gas system control and alarm programs were to run simultaneously with the heat system control and alarm program because of their close dependency; cooling gas and cooling water flow throughout the reactor were monitored and loss of flow could cause the heat control program to shut off the heaters or request emergency gas cooling.

Heat energy was supplied by the heater circuits so the electrical power to each of the four heater circuits was considered as the four inputs to the heating system. The transformers for two heater circuits were rated at 64 Kilowatts and 128 Kilowatts for the other two. This problem of different ranges of inputs was solved by normalizing the feedback error to a range of -100 to +100 per cent and normalizing the control signal to a range of 0 to 100 per cent. (Normalizing the control calculations allowed the same basic controller form to be used in the gas system where the measured variables were pressure, flow and blower motor current.)

To keep the reactor moderator blocks from cracking because of nonuniform expansion during large temperature increases, an approximately uniform heating rate was required throughout the graphite. Once the average reactor temperature was near the setpoint, a temperature variation of a few degrees was allowed. The control program allowed the operator to set a maximum output from each of the heater circuits. Thus, for large feedback errors, where an uneven heating rate was likely, the operator could limit the outputs to provide uniform heating. The heater power was determined by the controller equation for values less than the operator-set maximum. In the attempt to achieve a zero temperature gradient in the reactor core, the program was designed to allow the operator to shut off the core heaters, while the control program regulated the top, side and bottom heaters. (During evaluation tests on the completed reactor, it was discovered that the heat loss from the front and back faces could not be supplied from the regulating heaters. This error is mentioned to show that a programmed system could be altered considerably, if necessary, without requiring an additional capital investment. Room had been allowed in the program for this possibility.)

Several response criteria could be summarized by stating that a response similar to a deadbeat response[6] was necessary. This was decided because the heat-transfer analysis showed possible time constants on the order of hours. A control program like equation (2) would give zero steady-state error. However, when the process disturbance was a setpoint change, an overshoot would very likely result with this equation.[7] In an attempt to eliminate an overshoot because of integral action, provision was made for the operator to eliminate the integral action when he made a large setpoint change ("large" had to be defined as experience was gained with the system). The subroutine for summing the increments of the integral term was designed to clamp any results with a magnitude greater than 100 per cent at 100 per cent. This eliminated windup in the integral action. An additional clamp was made after the proportional and integral terms were summed so that the control signal was in the range of 0 to 100 per cent.

When the temperature of graphite is varied over a range of 1000°C, its electrical and heat-transfer properties change widely. (Preliminary calculations had shown a possible increase in the heat-transfer time constants by a factor of 7 over the temperature range of 1000°C.) Also, it was suspected that the mode of heat loss from the graphite surface, whether by convection cooling or radiation, might also affect the linearity of the system. It was realized that the nonlinear operation would require a compromise between response time and overshoot over the operating temperature. This meant the controller constants would probably have to be adjusted for no overshoot with the longest time constants, and then the heating system would respond much slower than it was capable of at the lower temperatures that gave shorter response times. Logic was introduced that would select one of two sets of controller parameters depending on average reactor temperature.

An additional feature of the control program allowed individual manual control of the heater circuits. Also, during preliminary tests of the heater system, a delay of approximately 10 seconds was found between the output of a zero control signal and the return of heater power to its lowest value. To prevent opening the heater breakers with a load, a programmed delay was introduced between a zero control signal and a breaker-open command.

A simplified flow chart of the heat control program is shown in Figure 4.

SECOND DESIGN STAGE

The second stage in the controller design consisted of refining and evaluating the control program with a model and the actual system. With eight controller parameters in an interacting system and estimated response times of hours, adjusting the parameters would have taken an unreasonably long time in real time. For this reason a hybrid computer model of the heating system and control computer was made and time-scaled for faster-than-real-time response. The dynamic response of the real system was measured to obtain transfer functions for the model. The controllers on the model were then adjusted to compensate for interaction.

System Model

Step response tests in the heating system were made, and the results were time-scaled 3000 times faster for modeling on the hybrid computer. For the tests, the reactor was heated to a temperature above the desired operating point, and then all heaters were shut off until steady-state conditions were reached. Steady-state was an (approximate) exponential decrease that was approximately the same for all four outputs of the heating system. At the particular temperature examined, the exponential decrease was approximated by a linear decrease. Once the system was at steady-state, a step input of power (approximately 25% of full scale) was applied to one of the heater circuits, and the temperature averages of the four parts of the heating system were recorded. This procedure was repeated for each of the four heater circuits until all 16 input-output response curves were obtained. Since steady-state in this case was a linear temperature decrease, the original response data was modified by adding the negative of the decreasing temperature ramps to each response curve. Delays and slopes were fit to these curves and the dynamic response of the system was simulated with the digital delays and analog integrators of the hybrid computer. The response tests were conducted and analyzed as if the system was linear, because small changes about an operating point were made. The results of this step function test would be approximately correct only near one operating point. A more complete analysis of the system would require step response tests at several temperatures over the whole operating range of the heating system.

Control Program Refinement and Evaluation

The use of a hybrid computer model was justified for two reasons: (1) there would be no chance of wrecking the heating system during the tests because of failure in the hardware or instability in the control program; (2) considerable experimenting time could be saved by running the model faster than real time. There were four parts to the hybrid computer model: (1) the control program, (2) the system model, (3) the evaluation program, and (4) the hybrid computer operating programs.

Only the essential features of the control program were modeled. Alarms and the gas system were not included. The system modeling was just routine amplitude and time scaling. A unique feature of the digital delays was the movement of only two computer words at each sampling instant. The memory for a delay was organized as a circle with an input and an output pointer. The length of the delay was determined by the sampling rate and by the distance between the input and output pointers. The hybrid computer operating programs allowed control of both the digital and analog computers from the analog console; entry of program parameters via the digital computer operator's console; and typing of data from the evaluation routines. Although the above mentioned parts of the hybrid computer model were rather complex, they were also routine for the most part.

Time scaling the model allowed experiments to run faster, but adjusting the four sets of control parameters to compensate for interactions was time consuming. Much of the adjustment of the control program was simplified with the use of an evaluation program in the hybrid operating system. The nature of the evaluation program can be explained by considering one of the four sets of control parameters (proportional and integral gains.) and an evaluation criterion, the integral of the absolute value of the error multiplied by time (ITAE). During a computer run to choose the best set of parameters (the best set of parameters gave a minimum ITAE value) several evaluation intervals of equal duration were automatically cycled on the computer. The operator could set parameters in the evaluation routine that defined the number of steps and their size through which the controller gains automatically changed. At the start of each evaluation interval a step input was automatically applied. After one gain of the pair was cycled through its range the other gain was cycled. The value of the fixed gain was always chosen as the value that gave the best performance during the evaluation steps when it was the gain that was varied. Bekey[8] calls this method of optimizing "hill climbing".

Several programming features made this "hill climbing" program practical. It was made rather simple for the hybrid computer operator to intervene during the computation to change the number of evaluation steps, their size for each controller gain, and the starting gain values. The operator could thus perturb the gain values when a minimum ITAE value was found to determine if it was a local or a global minimum. When identical step inputs were applied for identical control parameter values, the digital computer calculated ITAE values that differed by a few tenths of a per cent. An adjustable dead band was set around the ITAE value so that changes due to noise could be ignored. The method of determining the "best" response to a step input was more complex than a simple "hill climbing" problem because of the interaction among the four heater parts. Four ITAE values were calculated as if there was no interaction, and interaction was accounted for in the logic to determine an improved ITAE value. System response was considered improved if at least one ITAE value had decreased, and no ITAE values had increased. Even though the four proportional gains and then the four integral gains were stepped through their range of values simultaneously, the fact that each of the eight gains had individually adjustable step sizes and starting values made it possible to search a large part of the eight dimensional evaluation space.

CONCLUSIONS

Evaluation tests on the hybrid simulation and on the real heating system showed that most design goals, that were evaluated, were met. The effect of two sets of control parameters, which were to compensate for system non-linearity, was not evaluated, because the system was not tested initially over a wide enough temperature range. It is hoped that this can be done in the future. Tests on the real system and the model showed that the core-heaters would have to be on to maintain a desired operating temperature. This was a design error and is mentioned to show that a software change would be possible that could give different control characteristics without an addition to the capital investment.

Hybrid simulation of control systems is a necessity where the system response is too slow or too fast for testing the system directly. An additional argument in favor of simulation is: there is no possibility of harming the real system if the controller model became unstable.

Digital computers should be used for control and data handling on systems that are not well defined or that will be changed to obtain different experimental conditions. The most important feature for the system program in such a facility is modularity, so that specific functions may be deleted or added without rewriting the rest of the program.

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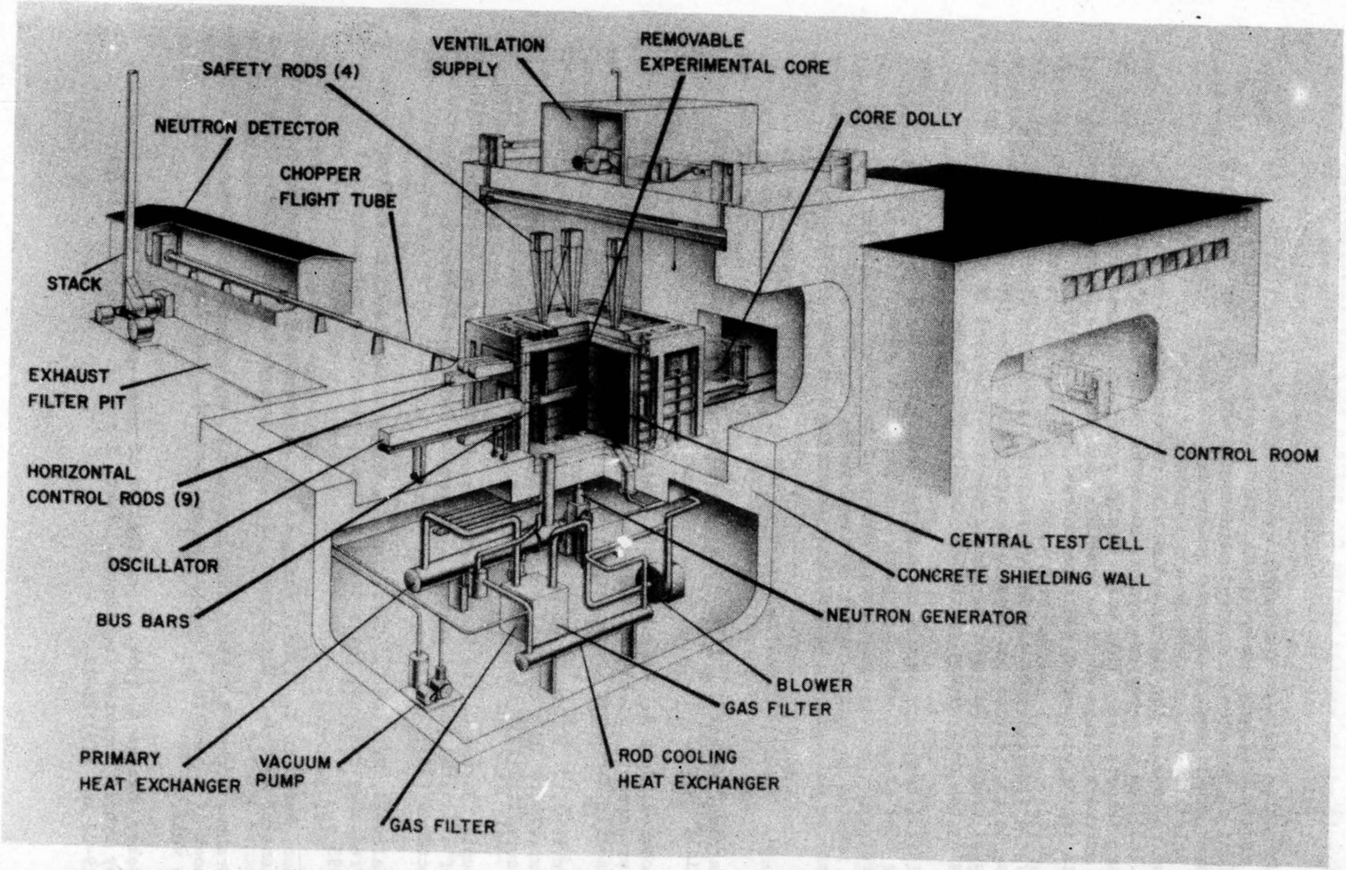

Figure 1. High Temperature Lattice Test Reactor (HTLTR)

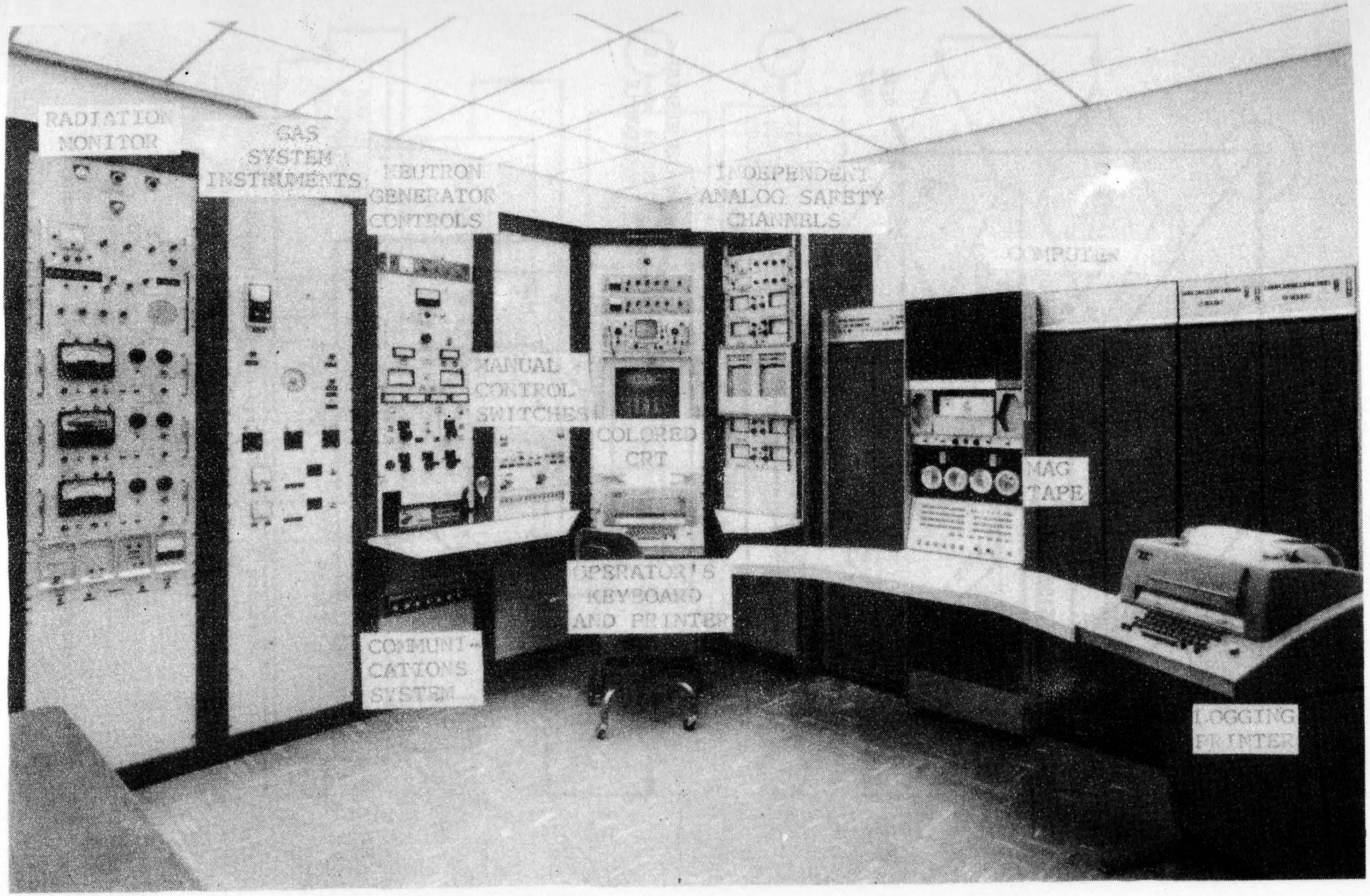

Figure 2. HTLTR Control Room

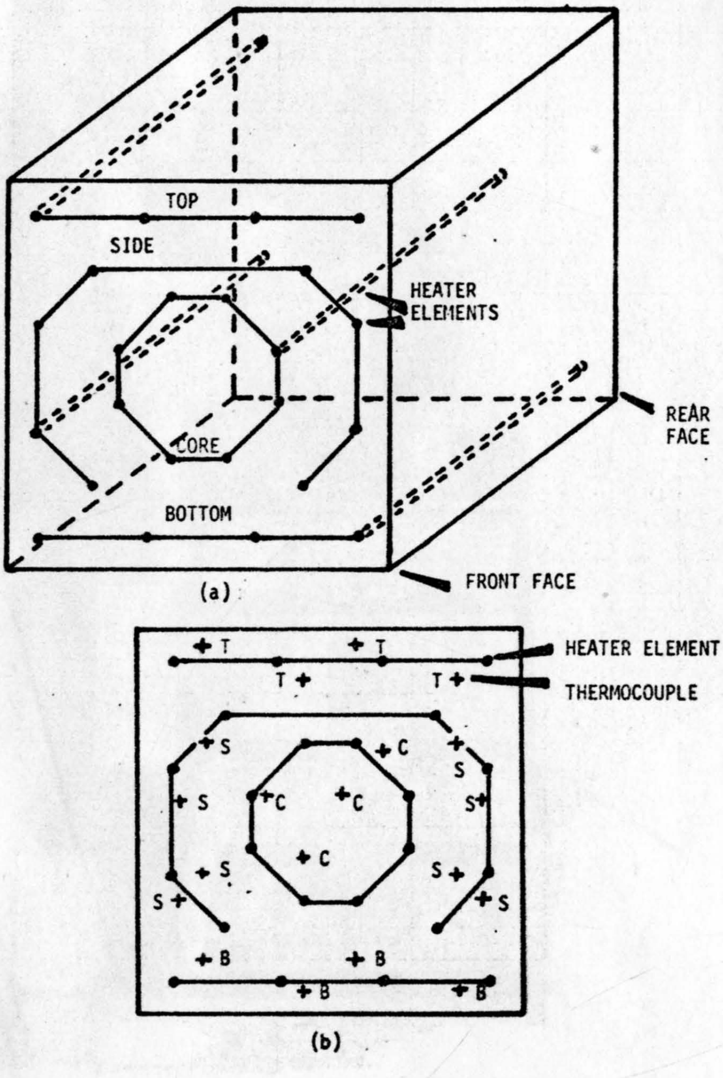

Figure 3. Pile Heaters and Thermocouples

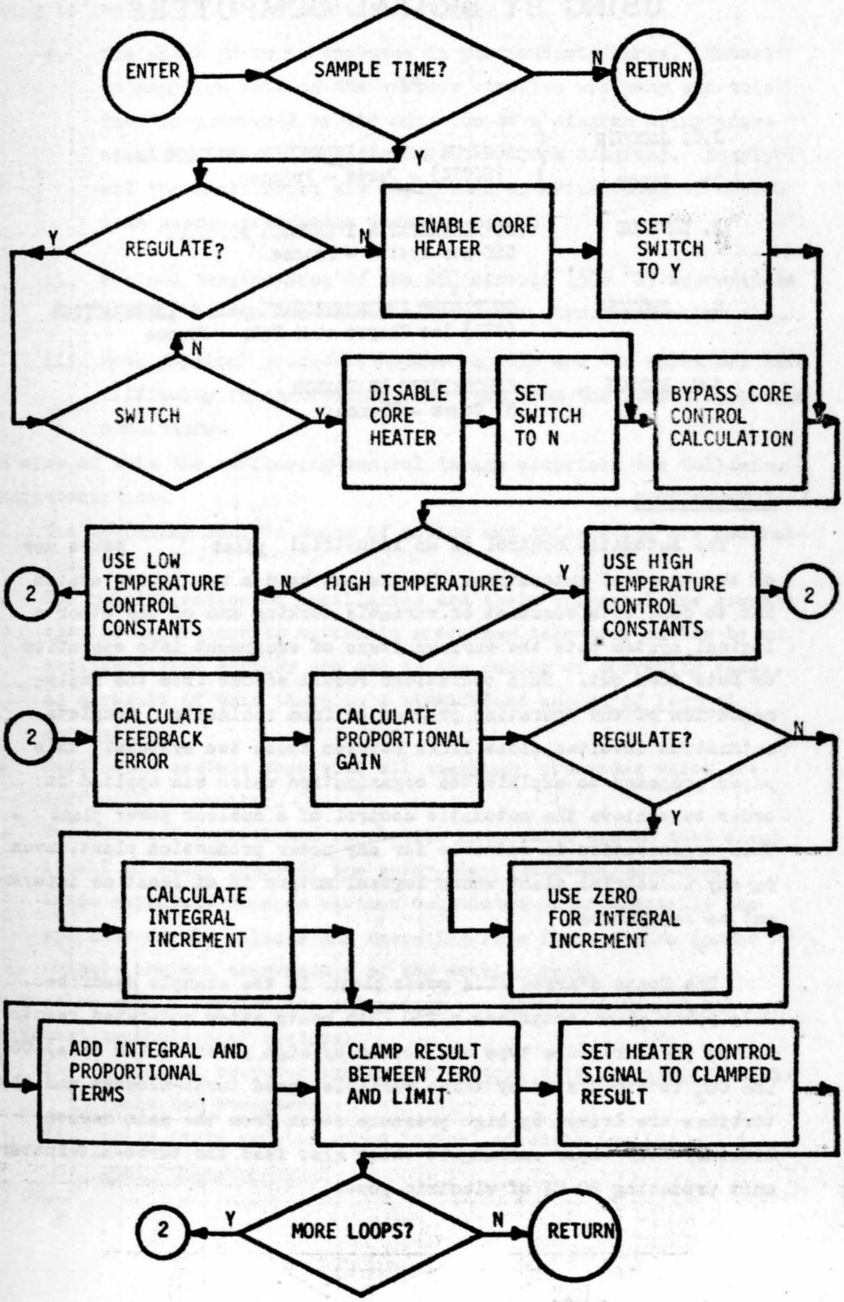

Figure 4. Flow Chart of the Heat Control Program

AUTOMATIC CONTROL OF AN INDUSTRIAL PLANT USING BY DIGITAL COMPUTERS

by

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1 INTRODUCTION

The automatic control of an industrial plant makes use of two types of automatons. On the one hand a regulation system has to cope with constant or variable working and on the other a logical system puts the various items of equipment into operation or cuts them out. Such operations result either from the implementation of the operation program or from incidents. Complete automation involves close links between these two systems. This paper proposes to explain the organization which was applied in order to achieve the automatic control of a nuclear power plant. This organization is suitable for any power production plant, even for any industrial plant where logical action is at least as important as regulation.

The Monts d'Arrée EL.4 power plant is the example described. This power plant comprises a 250 MWth heavy water moderated reactor of the pressure tube type and cooled by high pressure (60 bars) CO_2. The CO_2 is circulated by three variable speed turbo-blowers and the turbines are driven by high pressure steam from the main carbon dioxide/water vapor exchangers which also feed the turbo-alternator unit producing 80 MW of electric power.

The control of this plant poses a number of problems owing to its own intrinsic characteristics:

i. The plant ~~is~~ to be operated is particularly large. Mutual interaction between the various circuits are many and this fact is increased by the adoption of a diagram using universal equipment (as opposed to the block diagram). Nearly all the ancillaries are duplicated or triplicated to ensure that energy production does not cease.

ii. Nominal temperatures of the CO_2 circuit (500 °C) approximate closely to the top values allowed for structural materials.

iii. Some physical processes envolve rapidly and the operators have difficulty in controlling them even from the lowest operation conditions.

In view of this, the monitoring-control design comprises the following characteristics:

1. The operating staff's means of action and information are centralized.
2. The multiplication of ancillaries and their universal use gives special importance to automatic emergency take-over action by an ancillary from another one and to the number of operating cases. As a result of this there is a significant amount of logical automation.
3. Regulation systems cope with all transient processes which are difficult to monitor.
4. The combined logical and regulation automation system must adapt itself to every phase of the power plant (start-up, shut-down) large amplitude changes whether calculated or accidental); the operator merely selects the operating rate instructions (power output, maximum temperature of the cooling gas).

To resolve such a problem, the automation was divided into several different technological systems:

i. a digital computer system for central data processing built round two computers,
ii. solid state modular wired logical circuits (called solid stat logic circuits)

iii. electronic analogue regulation circuits.

Those units of equipment obviously work in close relation. The role assigned to each one results from decisions which may seem arbitrary in some cases when they are examined separately from the general context of the design and from the date when the options were taken. We shall mention them briefly after we have explained the monitoring-control system of the Monts d'Arrée nuclear power plant and before specially and fully describing the structure of programmed automatic control fed to the computers.

2. MONITORING-CONTROL ORGANIZATION

2.1 DESCRIPTION OF THE FUNCTIONAL DIVISION

The monitoring control organization is based on a functional division of the plant. This division calls upon the ideas of functions, assemblies and sub-assemblies which must be defined:

i. starting with the plant as a whole the first divisional step is the function. All the equipment and circuits which help to maintain a physical parameter to its instructional value or to complete a given "service" are grouped together in a function. A case in point is all the equipment needed to cool the reactor and which is therefore attached to the cooling flow parameter. An example of service is the distribution of electric power to the motors, valves, etc.

ii. within a given function, the division is taken a step further by defining the systems which are themselves attached to a physical parameter or to a service which now only concern the sole function under consideration.

iii. finally, within each assembly, sub-assemblies are defined which are attached to a physical parameter or to a service which only concern the one system to which they belong. Actuators and measurements of the installation make up the sub-assemblies.

At a given moment each of the divisional levels (installation, function, assembly and sub-assembly) is distinguished by its state (which varies discontinuously) and by the value of the physical parameter attached to it (varying continuously). The state of each level is defined in relation to the service achieved (i.e. the possibility of making the corresponding physical parameter reach a value within the operating nominal range) and to the program of operation.

a) in relation to the service achieved, the state can only reach three or four discontinuous values : the non-available state for the automaton (marked 00), not in use available state for the automaton (marked 01) and the in use state (marked 11) which may sometimes be split into two states when actual putting into use time is long in relation to the physical parameter concerned. In this case there are two states: in stand by (marked 10) and effectively in use (also marked 11) which is distinguished by actual operation (for example: a slow starting pump actually working but not delivering for state 10 and pump actually delivering into the line for state 11).

b) in relation to the program of operation, for each level there is the present state (marked EA), feasible state (marked ER - potential operation allowing for present state) and requested state (marked ED) either by the automaton or by the operator himself.

c) likewise the present state of the physical parameter is tied to the requested state (instruction) emitted by the operator or by the automaton and compared to threshold values below or above which regulation is no longer possible.

Having agreed on these definitions, it can be stated that automating the installation is tantamount to organizing the functional links existing within each level of the division (installation, functions, assemblies and sub-assemblies) and between these levels. On the one hand there is the regulation automation that continuously copes with the physical parameters and on the other, the change of state automation which puts the units of equipment into use or cuts them out as and when required. The above concepts are shown on the outline diagram to which details will be added later when the actual structure of the automatic system is described.

From this diagram it will be seen that the structure of change of state automation closely resembles that of the regulation automation: ED acts as the instruction, EA the measurement, etc. We shall see later on that the analogy can be stretched to include the determination of ED in "closed loop" and in "open loop", taking into account the ER's of the level concerned and of the other levels, as well as the values of the physical parameters.

2.2 DEVELOPMENT OF MONITORING CONTROL GEAR

The functions of the wired equipment (solid state logic circuit, analogue regulators) and the programmed equipment (central data processing computer system) in the case of the Monts d'Arrée EL.4 power plant are as follows:

i. central regulation as well as logical automation at the level of functions and assemblies are entrusted to the computers which also process most of the data,

ii. sub-assemblies level automation is carried out by solid state relays.

iii. regulation of sub-assemblies, systems and functions is entrusted to analogue equipment.

This choice takes the following mandatory conditions into account, should the computers be stopped or fail:

i. maintain the operating rate reached

ii. enable the plant to be stopped in complete safety with the remaining controls and data.

The equipment layout is shown on the block diagram of figure 2 which also shows the layout of controls and information on the console and the indicator board (respectively called the main block and subsidiary block). These controls only occur at the functional division level, excluding all individual control by actuators (except of course the emergency safety actuators; control rods, turbine starting electric valves).

From the main block console, the operator fixes the operating rate by the power and temperature instructions. He also has access to the controls at function and assemblies level. All these instructions and controls are accepted by the computer which then sends out its logical orders to the solid state relays and its instructions to the analogue regulation. From the subsidiary block, the operator can also deal manually with the main regulation loops instructions. He is provided with information by printers and teleprinters, and by the conventional indicators and recorders for the data accepted by the analogue regulation loops.

3. PROGRAMMED AUTOMATION DESCRIPTION

3.1 COMPONENTS

Programmed automation manages the three plants assembly, Function, and System" levels by associating the "States" defined in the preceding section to each of these levels.

The automation structure is shown on figure 3. Before describing it in detail, with the help of examples taken from the automated system used at the Monts d'Arrée EL.4 power plant.., we shall review the precise definitions of each state represented.

3.1.1. Plant level

Requested state of plant by operator GO

This represents the value selected by the operator to indicate on the program the desired operating rate. For example, this results in the coupling of instructions for the characteristic parameters of the plant: power PO and maximum temperature of the cooling gas Θo.

Feasible state of the plant GL

For the moment, this gives a limit value GL for the characteristic parameters of the plant taking into account the limitations GLi imposed by the feasible state of each function.

Requested state of plant by program GD

For each characteristic parameter this results from sorting values GO and GL (for example selecting the lesser of these values. This sorting results in an individual instruction point for each loop of the general regulation.

The organization of automated regulation which comprises cascade loops is outlined for the record on figure 3. In order that the physical parameters of the plant, may reach their instruction point, each function must have a perfectly determined state.

3.1.2 <u>Function level</u>

The job of the change of state automation is to meet the requirements of regulation automation by bringing into use or cutting out the requisite ~~systems~~. assemblies

<u>Requested state of function by the program: ED Function</u>

This is the <u>number</u> of systems of the function to be brought into use so that the operating instruction point which distinguishes this function is maintained or reached.

This number of systems is defined by thresholds from measurements representing the top possibilities of the ~~systems~~ assemblies in operation which we call "management criteria".

Hence, in the case of a turbo blower, when the speed of a machine in use reaches a given level (or when a valve opens), a request is sent out to bring a further machine into use. These "management criteria" TS also intrinsically take into account any causes of fluctuation (change in the output instruction, alteration in the steam pressure conditions, in the volume of gas...).

It is on this level that the continuous and progressive requests from regulation give rise to intermittent automated action.

<u>Feasible state of the function: ER Function</u>

For each function a "feasible state" ER is computed which represents:

i. the number of ~~systems~~ assemblies actually in use (ER = EA) associated with this function

ii. or, the number of ~~systems~~ assemblies associated with this function which can be brought into use in a very short time when faced with the rapid change in the monitored physical parameter (ER > EA).

The feasible states of the functions form as many management constraints which enforce GLi limit values on the characteristic parameters of the plant. For example, a maximum cooling limit is set by the number of turbo blowers in operation; therefore, for a given gas temperature there is an operational power limit. The limit value GL forming the feasible state of the installation results from the sorting of all the GLi's.

3.1.3. ~~Systems~~ Assemblies level

Requested state by the program: ED System

The requested state ED of the ~~system~~ assembly is computed from the requested state of the function of which it forms part, from the awareness of the order in which the various ~~systems~~ assemblies of this function must be brought into use, and the present state of each system of the function.

In this way, an overall demand (ED Function) defining the amount of equipment to be brought into use is transformed at this level into a particular request for each ~~system~~ assembly.

This request will be achieved by sending successive orders to the actuators.

Present state: EA Assembly

The present state EA of the ~~system~~ assembly results from the immediate analysis of the various logical or analogue physical criteria which define this state (position of actuators and measurement values).

3.2. FUNCTIONING OF PROGRAMMED AUTOMATION

In order to describe how programmed automation functions, we shall examine on figure 3 the cascade of updating of the various components and the actions they entrain, from selecting the request of the operator GO, up to sending elementary orders to be carried out. The diagram shows:

i. for each function: an individual management loop,

ii. for the plant : a single management loop.

3.2.1. Management of a function

The analysis of the management criteria of the function produces the requested state ED function (number of ~~systems~~ assemblies to go into operation);

i. according to the present state of each system forming the function and of the selection of a starting up order, the management of the function computes the requested states. for each system of the function,

ii. the execution of this request is ensured by the effective order to start up these systems or to stop them,

iii. the orders thus transmitted to a ~~system~~ assembly modify its present state. The new state is up-dated by analysing the measurements and by signals.

iv. the random variations of the present state of a ~~system~~ assembly start actions on two levels:

a) at function level, this action copes with failures by ensuring that a ~~system~~ assembly will automatically take over from another one in order to maintain the requested state of the function,

b) at power plant level, a modification of the feasible state ER Function up dates the GLi limitation associated with this function, as a result of which there is a possible change GL processed in the management programs of the power station described above.

3.2.2. Managing the plant

The updatings of the management limitations GLi stem from the alterations in the feasible states ER Function. They cause a predetermined variation in the feasible state of the plant GL.

The sorting between the operator GO request and this new value GL possibly causes an alteration in the requested state ED plant GD. New instruction points are transmitted to the regulation automation of each function.

If the new GL value is correctly pre-determined, the equipment in each function is likely to bring the physical parameters to their new respective instruction points.

3.2.3: Example

The reactor can be cooled by three turbo-blowers. Let us assume that the operating rate, allowing for the power, temperature, steam pressure and gas volume figures, requires two turbo-blowers. Should a failure cause a turbo-blower to stop, everything else being equal, two possibilities could occur:

i. the third turbo-blower is on stand by: the management program of the function sends the coupling orders. The feasible state of the function does not change, nor does the feasible state GL of the plant ... The operating rate is not affected.

ii. the third turbo-blower is not available. The feasible state of the function resulting from this situation alters the feasible state of the plant .... The management program of the plant ... modifies the operating power instruction to make it compatible at a given temperature, with one turbo-blower operation. The contingency gives rise here to an alteration in the operating rate (power reduction).

The main features of such an organization are therefore as follows:

i. permit starting, shutting down, and changes in the operating rate of the plant to take place as from the sole selection of CO,

ii. bring equipment into use only when required by the physical criteria of management linked with each function and not as from a rigid sequential program,

iii. not to link a management level to another except through stored "states" since an analysis is only triggered off when there is a change in the value of one of these states,

iv. ensure that the rate is maintained by the separate management of each function and conversely to ensure the safety of the plant by fitting the rate to the management limitations.

ORGANIZATION OF PROGRAMS

Figure 4 shows how the programs and sub-routines of the computer are articulated to achieve the automated working just described.

We notice the four management levels, i.e. Installation, Functions, assemblies and Sub-assemblies, as well as the various state associated to them.

Each state is represented in the computer by the contents of a store. These various state stores are available for use at any time by any program. These stores act here as interfaces between the automation programs which are filed in the following manner:

i.	analytical sub-routine	random starting
ii.	function management sub-routine	random starting
iii.	GLi selection sub-routine	random starting
iv.	program RED	cyclic
v.	program DEA	cyclic

4.1. ANALYTICAL SUB-ROUTINE

An analytical sub-routine is executed when a signal changes of state or when a measurement or the result of a computation is compared with a threshold. It updates the contents of the state stores by testing the values of any one of the four following categories:

i. state of a assembly criterion

ii. occurrence of a assembly criterion

iii. function management criterion

iv. operator requirement.

In some cases the test of these values may result in the sending of safety orders whose execution cannot be deferred.

The following table gives the analytical sub-routine:

Level	Reason for starting	Storage updated	Action required
Plant	Operator requirement	GO	Deferred analysis of storage GO by cyclic program DEA
Function	Management criteria	ED function	Management sub-routine
Assembly	State criteria	EA Assembly	management sub-routine
	Incident criteria	EA Assembly	management sub-routine - safety order
	Operator requirement	ED Assembly	Deferred analysis of storage ED system by cyclic program RED

4.2. MANAGEMENT SUB-ROUTINE OF A FUNCTION

Like the analytical sub-routine that is only executed when a change of state of an elementary information appears, the management sub-routine is only executed when there is a change in the contents of one of the two stores EA Assembly or ED function.

Such a sub-routine plays a vital part in the organization of automation since it achieves the following:

a) assemblies level
   i. immediate take-over action from a assembly by another following an incident at assemblies level by direct order transmitted to the sub-sequences,
   ii. updating of the ED required state store of each function system taking into account its present state EA, the overall required state ED function, selection and operator requests.

b) Function level

   preparation and up-dating of the feasible state ER of the function.

c) Power plant level

   preparation and up-dating of the GLi limitation. If this limitation changes in value, it also requests the execution of the GLi selection sub-routine.

4.3 GLi SORTING ROUTINE

It up-dates the feasible state of the plant GL by computations made on the various GLi values.

When the safety of the installation requires G3 (new GL value to be met which is lower than present state) this sub-routine immediately alters the requested state GD.

4.4. PROGRAM RED (Completion of requested states)

This cyclic program compares the present state EA and the requested state ED of each system at regular intervals (about every twenty seconds) and deduces from it the succession of sub-sequence tables (or lists) which must be executed to meet the request.

4.5. PROGRAM DEA (Starting, Changing, shutting down)

The role of this program is twofold:

- first start up the power house systems before the reactor is raised to full power. This result is obtained by open lopp up-dating of the requested state ED of some functions
- compute the instruction points defining the reactor's operating rate at start-up, power change and shut-down, allowing for:
  i. the request of operator GO
  ii. the present state of the plant
  iii. the feasible state GL
  iv. certain constants (dynamic restriction, etc.)

It computes the instruction point GD and transmits the instructions for each loop to the automated regulation.

5. EXECUTION OF AUTOMATED PROGRAM

In the automated system of the Monte d'Arrée power plant about 4,000 binary in puts signals and 1,000 analogue in puts have to be scanned. The automated program ensures that about 140 binary orders are transmitted to the sub-systems and about ten instructions to the analogue regulation loops. It is designed around two CAE 530 computers of 24,000 words core-memory each, in conjunction with two 200,000 word drums. The two systems are linked for emergency take-over, with one system doing all the processing. Apart from its automated function, the computer in use naturally processes analogue and digital data, monitors burst cans and does some computations.

The main features of automation programming are:

1) Modular working

Each sub-routine is an independent unit, which up-dates a store and lets another specialized sub-routine analyse the effect of the change of state of that store.

Hence it is quite easy to modify the "in use" state criteria of a system by altering the conditions which define such a state. Only the corresponding sub-routine will be altered, the balance of the string remaining valid.

2) Repeatability

The identical sub-routines organization is to be found at all levels of division (analytical, managerial and cyclic sub-routines).

3) Brevity

At each sub-routine is given a well defined part, it is short (about 30 to 100 words of 18 digits per sub-routine).

4) Language

Twenty special instructions are sufficient to program all these sub-routines. The instructions thus elaborated define the "machine language".

5) Easy coding

Modular division on the one hand and the easy writing of operational block diagrams on the other, make it possible to switch over directly from the block diagram to the program with the "machine language".

6) Ease of modification

Program alterations are made possible whilst processing in real computer time and thus enable the automated system to be adjusted rapidly as testing of and alterations to mechanical equipment proceed.

6. CONCLUSION

For most circuits and at a time when the rise in power trials are not yet completed, the Monts d'Arrée EL.4. power station is operating, utilizing the possibilities offered by the automated system just described.

For the record, this system can be extended without difficulty to include additional levels of management:

i. downwards by entrusting the computer with the management of sub-routines, an idea which was not envisaged when EL.4 was developed,

ii. upwards by attaching the requested state GO to the characteristics of the network.

This organization is particularly interesting in the case of universal equipment, as the functional links between circuits and the configurations are thus numerous. In the case of the block diagram (where links between the equipment of one same circuit are rigid) this organization could be streamlined to a considerable extent.

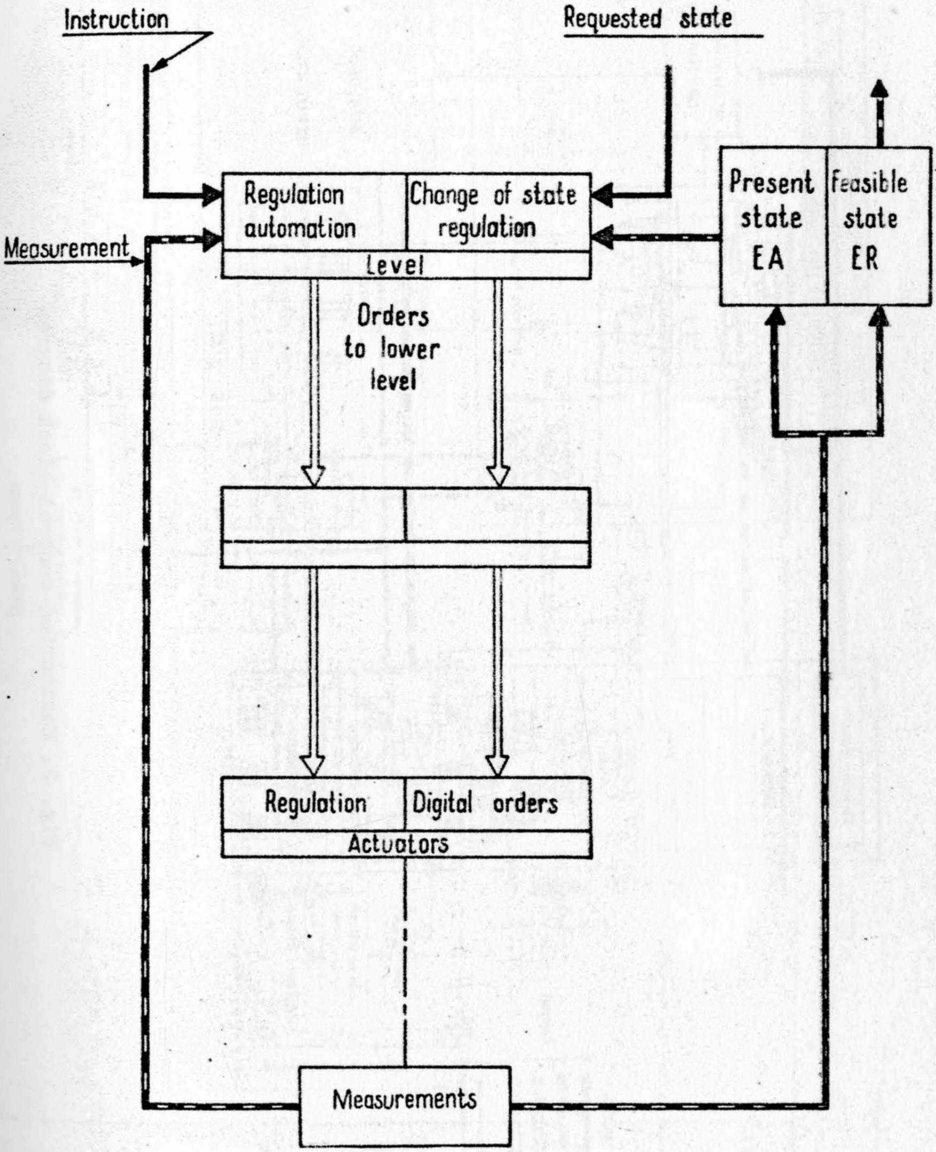

Fig. 1. Outline structure of automated system

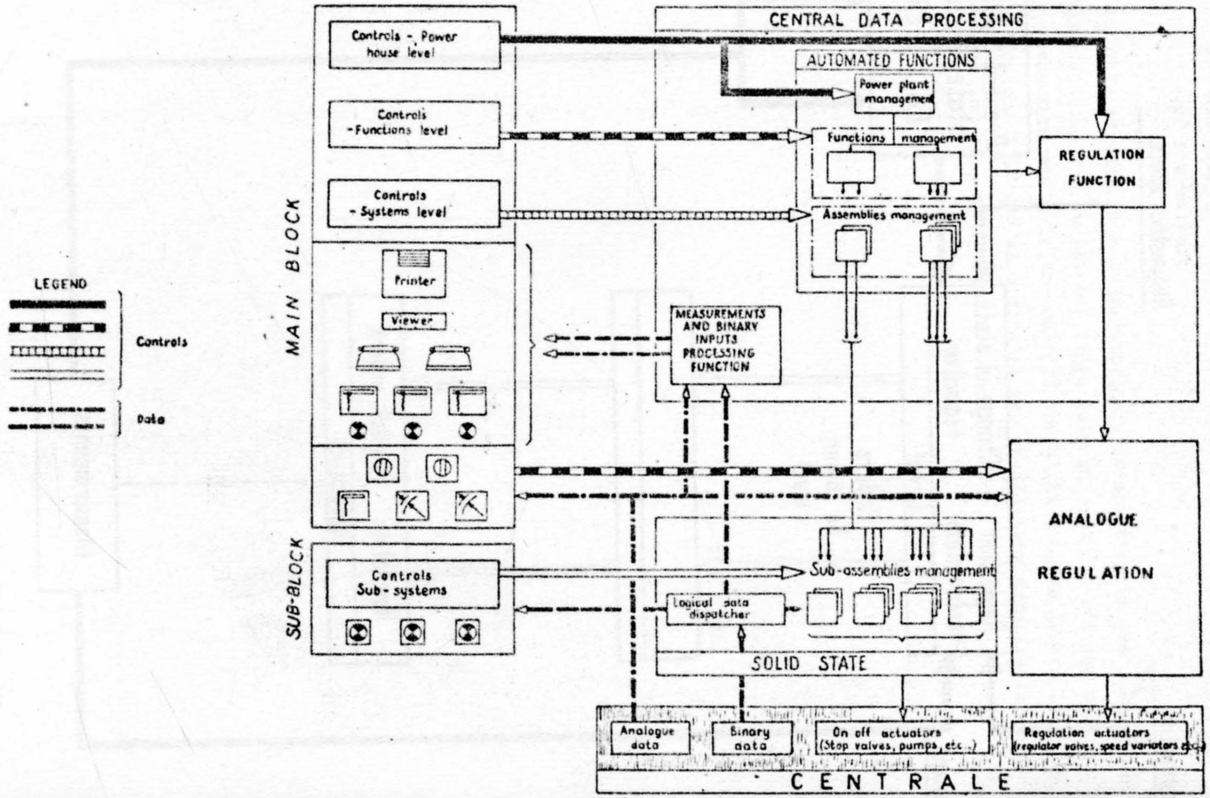

Fig. 2. Monitoring-control block diagram

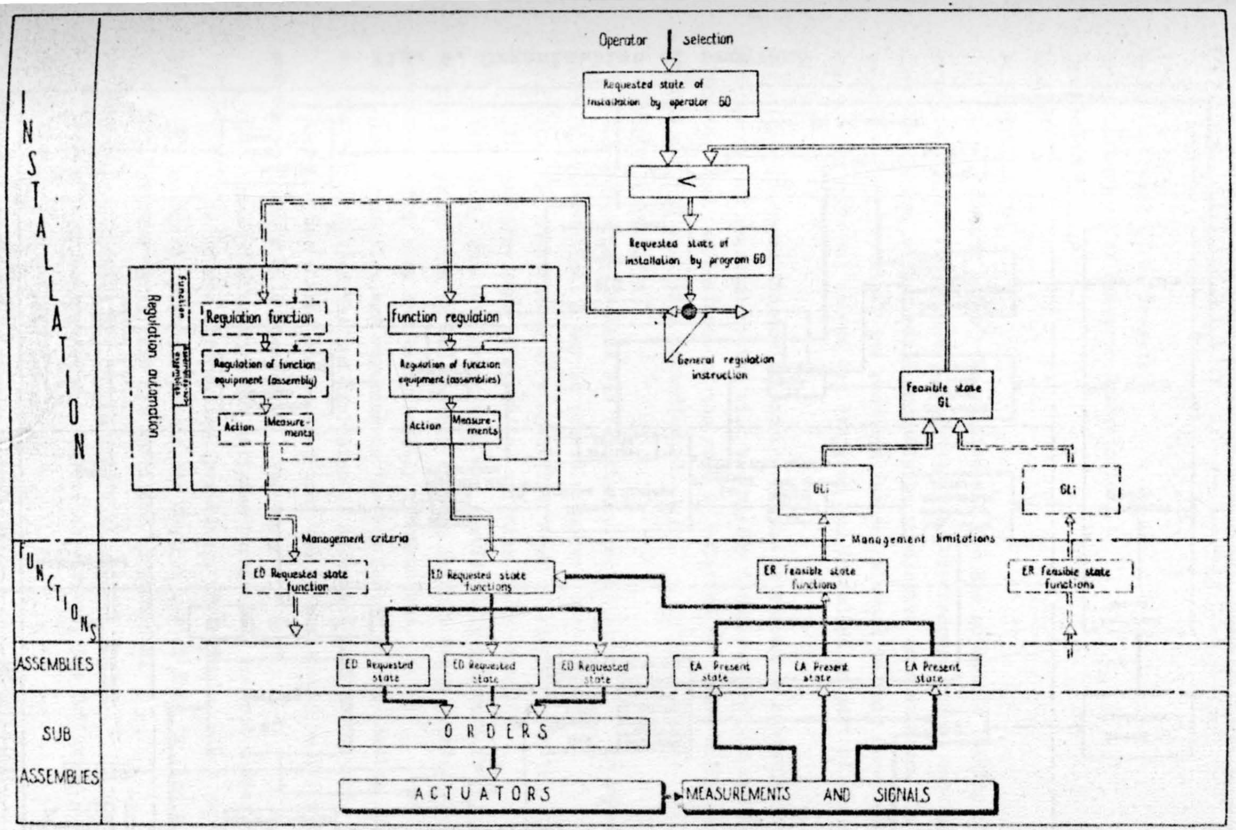

Fig. 3. Programmed automation sructure

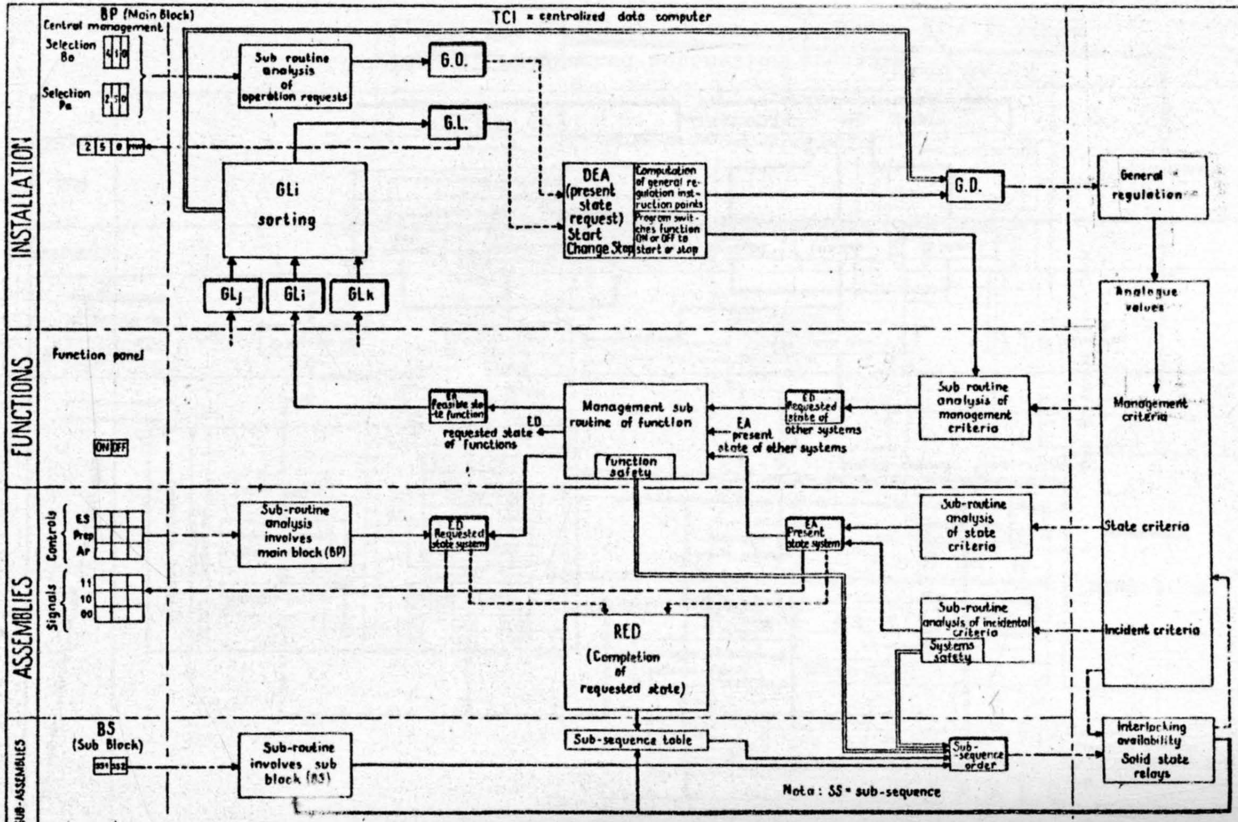

Fig. 4. Organization of programs

AN EXPERIMENT IN THE AUTOMATIC CONTROL OF POWER GENERATION IN A LIMITED AREA OF THE C.E.G.B.

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1. Introduction

In an earlier paper[1] the requirement for the automatic loading of the generating plant on the C.E.G.B. system was foreshadowed and it was indicated that the control system would probably be predictive in character. In order to clarify the technical and economic issues relevant to this development a limited experimental scheme was designed and installed on part of the C.E.G.B. system.[2]

In this paper the design aspects of the experimental installation will be discussed, the physical system will be briefly described and the results examined. The implications of the work in relation to future fully automatic control schemes will then be indicated.

2. Control Objectives

The design requirement was for the automatic loading of the generating plant in as economical a way as possible subject to:-

(a) the maintenance of a specified level of system security* and
(b) the provision of specified spinning spare capacity.

Control of reactive generation was specifically excluded from the scheme as was switching[2] and it was further limited in only being required to load generators after they had been manually synchronised.

Load prediction was regarded as the key factor of the loading operation and the design called for the inclusion of automatic load prediction.

Emphasis was placed on the fact that the scheme should be fully automatic and the operator's role (see Fig. 1) was to:-

(a) update the constraints defining permissible control action in the light of new information (regarding, for example, plant capability)
and (b) to initiate action should the control system fail to find a loading pattern satisfying the specified constraints.

3. Design Requirements for the Experimental Control System

From a consideration of the control objectives, the following guide lines to the design were settled:-

---

* defined as the loss of any double circuit high voltage line or the loss of the largest load being carried on an individual generator

(1) the system would be predictive in character requiring load predictions to be made (see Fig. 2) at:-

1.1 2 hours ahead - for use in the loading program

1.2 30 minutes ahead for advising stations of expected load changes and for the main reversionary control mode

1.3 a few minutes ahead for use in the actual loading operation

(2) it would be a digital system to give the required flexibility

(3) it would execute load changes directly on the turbines

(4) it would be a cyclic system i.e. the required loadings of all machines would be instructed at regular time intervals

and (5) the periodic time of the loading cycles should be as long as possible consistent with the economic operation of the system.

4. The Selected System Design

The system design finally selected for experimental assessment is shown schematically in Fig. 3.

It comprised a central digital process control computer whose main function was to generate the loading instructions, these being transmitted in digital form at regular time intervals of t* minutes to the power stations. The instructions were accepted at the stations by machine controllers which loaded the turbo-generators in accordance with these instructions.

4.1 Loading Calculations

The loading calculations[3] followed the C.E.G.B. practice of merit order loading,[1] spinning spare being allocated to the most uneconomic plant, generally by running sufficient of this at 75% M.C.R.[+] to make up the requirement. Security checks based on group limits were incorporated into the loading calculations. (The group limits defined the permissible power flows into, or out of, selected groups of stations and load points).

A second loading calculation was made every 30 minutes in which security was more carefully examined by a set of d.c. load flow calculations. The resulting 30 minute target outputs were displayed at the stations and stored for use in the reversionary mode (see Section 6.5).

4.2 Loading of Plant

The machine controllers interpolated linearly between the digital instructions to give continuous desired values for the generator outputs, these being controlled by feedback loops as shown in Fig. 4. By this means control to within $\pm\frac{1}{2}$% of the instructed values was achieved.

The machine controllers also contained frequency loops which could bias the desired value, in accordance with the deviations of frequency from 50 Hz.

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* variable from 1 to 10 + maximum continuous rating

Two power/frequency characteristics shown in Fig. 5 could be selected as required; if the first were chosen the set would regulate with a linear droop* which could be preset between 1 and 10%, otherwise the second characteristic gave no response for normal frequency deviations but a 4% characteristic should these become excessive.

5. The Experimental Installation

5.1 The Test Area

The control scheme was installed in part of the Board's system covering the South West corner of England.

The installed generating capacity totalled some 1800 MW and the bulk of this plant, in three coal and three oil-fired stations was directly controlled.

In selecting the area the essential requirement was that it could be electrically isolated from the main system so as to enable the performance of the frequency control system to be examined. This choice did, however, result in the experiment being carried out on old plant not typical of the large units currently being installed. All the controlled sets were within the 30 to 60 MW range and the boiler plant was almost entirely manually controlled.

5.2 The Control Hardware

The control hardware installed for the experiment comprised:-

(1) a Ferranti Argus 200 computer
(2) an operators console
(3) interposing equipment
(4) a telecommand system and
(5) 31 machine controllers

This was additional to the existing telemetry system which supplied the computer with data (line-flows, switch positions, station outputs, etc.).

The computer had a data store of 16,384 12 bit words and a program store with a capacity of 10,240 instructions.

The operator's console (see Fig. 6) provided facilities for the operator to monitor the performance of the control system, the principal medium being two cathode-ray tube displays.[4]

Two typical machine controllers are shown in Fig. 7 and the operators panel for insertion of constraints in Fig. 8. The controllers contained comprehensive protective systems to guard against all credible control system and associated plant failures.[5]

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* defined as the ratio of the percentage frequency change to the corresponding power change (expressed as a fraction of M.C.R.)

5.3 The Control Programs

The principal computer programs were those associated with the loading of plant, the assessment of security and communication between the computer and operator through the control console and display equipment. The relative magnitude of each task is shown in Table 1.

Table 1

Principal Programs

Program	No. of Instructions
Network calculations	2400
Plant loading	2300
Console	1700
Display interpreter	1350
Input (analogues and a paper tape)	800
Supervisor	500
Data logging	500
Load prediction	300
Telecommand	250
Minor special routines	100

5.3.1 Loading

The plant loading program followed the following steps:-

(i) it first calculated the required generation G(t) at the end of the next t - minute interval from the expression

$$G(t) = L(t) + K_1 \; \Delta f(o) + K_2 \int_{\infty}^{o} \Delta f(\tau) d\tau \; + P_T(t)$$

where L(t) is the predicted load, $\Delta f(\tau)$ is the frequency error at time τ, $P_T(t)$ is the required area export and K_1, K_2 are program constants.

(ii) it then allocated to each generator the minimum load $\overset{*}{a}_i(t)$ found from the (t + 30) calculation (see below).

(iii) starting with the cheapest generator it increased each output $x_i(t)$ in turn as much as possible without violating $\sum x_i(t) \leq G(t)$ or any generator, station or group constraint.

(iv) it then calculated the total spare capacity. If it exceeded the required spare the allocation found in (iii) was accepted as the set of generator targets, if not it proceeded to step (v).

(v) it then increased the spare, generally by transferring load from one generator to a more expensive one and then returned to step (iv).

This program only minimised the cost at the instant (t), whereas what was required was a minimisation over all time i.e., the problem can be expressed as minimising the integral:-

$$\int_{o}^{T} \left[\sum c_i x_i(t) \right] dt$$

where c_i is the incremental cost of generator i and the x_i are subject to satisfying all the constraints on the generating plant and transmission system over the time interval (0, T).

Whilst this minimisation was not practicable an approximate solution was found by constraining the calculation by one carried out for time (t + 30), this again being constrained for one for time (t + 60).

5.3.2 Network calculations

All network calculations used the d.c. approximation to the nodal equations of the network. The nodal equations are YV = I

where Y is the nodal admittance matrix

V is a vector of nodal voltages

and I is a vector of nodal currents

All elements Y, V and I are real and currents are taken to be numerically equal to real power flows. The admittance matrix was found by inverting the impedance matrix Z, which was permanently stored.

The matrix Z was built up initially from a single node, by adding new nodes and branches. Changes in the network throughout the day were specified to the computer as actual changes in switch and isolator positions, automatically telemetered into it, as they occurred, or inserted manually as projected changes. Z was then updated by suitably adding or removing nodes and branches.[3]

5.3.3 Security Checking

The first step in predictive security checking was to allocate the predicted load to load points; for this purpose 'load ratios' measured every 15 minutes were used.

The calculation of the power flows resulting from the loss of one or more branches was then calculated by leaving the branches in service but injecting into (or removing from) their terminal nodes suitable currents.[3]

6. Experimental Results

The experimental results will be discussed under the three topics of automatic prediction, load dispatching and frequency control.

6.1 Automatic Load Prediction

Two methods of automatic load prediction were developed,[6] both utilising only past and current load data.

The first method[7] depended on the spectral decomposition of the past load record into a long term trend and a residual component. It proved promising in off-line tests but was unacceptable on-line, as the prediction errors, particularly at the time of the peak evening demand, were excessive, due mainly to random measurement errors.

The second approach sought to exploit directly the general similarity that exists in the load profiles of successive days. It therefore used the previous day's load curve, this being scaled by a factor depending only on current load (for weekends the previous week's data was used). Its performance was superior to that of the correlation method and, in particular, it significantly reduced the errors at the evening peak, as can be seen in Fig. 9. This shows the r.m.s. errors for the two methods for predictions 2 hours ahead.

A corresponding improvement for shorter prediction periods was achieved.

A relationship between the variance var (t) of the prediction error (for the scaling method) and the time t hours ahead of the event was established as:-

$$\mathrm{var}(t) = a + bt \qquad t > 0.1$$

Numerical values of a and b for the best fit of this model to the test area data were 57 MW^2 and 267 MW^2/hour respectively, taken over the daily load cycle when the load varied between 700 and 1700 MW.

6.2 Load Dispatching

The first questions to be answered[8] stemmed from the emphasis on prediction in the control system design and related to the effectiveness of the system security checks and the usefulness of the predicted station loadings.

6.2.1 Predictive Security Checking

The security of the system was predictively checked half hourly. In the event the system could be insecure, as a result of two factors,

(a) errors in the predicted line flows

and (b) errors in the estimated changes in the line flows

resulting from all line faults included in the security requirement.

It was shown that errors of the first kind would be of major significance and their magnitudes were therefore experimentally determined. The data, for a typical day's operation in parallel with the main system, is shown as a histogram in Fig. 10b and gave errors in predicted line flows, of 8.3 MW r.m.s. for lines inside the area and 15.6 MW r.m.s. for those crossing the boundary. For an insecurity to have arisen the error in the prediction would have had to exceed the margin of about 50 MW between the overload trip setting and the maximum permitted post fault line flow adopted in the security calculation. The ratio of about 6:1 between this margin and the internal line flow r.m.s. error showed a negligible risk of unknown insecurity.

6.2.2 Prediction of Station Loads

A typical histogram of the departures of station output from the 30 - minute targets is shown in Fig. 10a. The r.m.s. error was 13 MW, i.e. about 4% of the average station capacity and this was found quite acceptable both when the stations were following these targets under the reversionary mode of operation and for broad guidance when following the t-minute targets.

However, the variations in output called for between successive t-minute targets did present operational problems. The corresponding t-minute target errors were about 2% r.m.s. for 5 minute dispatching and again this was considered very satisfactory.

6.2.3 Control Ratio

It became clear early in the experiment that the total amount of load-changing was considerably in excess of that normally experienced under manual control. This was quantified as a control ratio defined as:-

$$\text{Control ratio} = \frac{\text{Sum of changes in generator outputs (regardless of sign)}}{\text{net change in generation being instructed}}$$

Under manual control this ratio is nearly unity whereas under automatic control it varied widely during the day. For example, during a typical morning load rise, it was about 1.4 but later rose in two half hour periods to 5.8 and 3.4.

These high values arose from the assiduous attempts of the computer to maintain spare on the system precisely at the minimum specified level in the most economical way and relatively small changes in the dispatched load were accompanied by considerable reallocations of generation.

The apparent economic gains thus achieved were, in practice, probably offset by increased operating costs at the stations. An upper limit to this ratio of 2 would appear reasonable and some modification to the rules defining the loading procedure are needed to achieve this.

6.2.4 Constraints

In the design stage the constraints thought adequate to define plant capability were maximum and minimum generation, maximum step change in output and maximum rate of change of output, these being defined for each set.

These were found to be insufficient in practice. Under range operation the station capability was often limited to the regulation that could be made by only one boiler. Station constraints, similar to the set constraints were therefore included. Forbidden loading zones, where the governing systems hunted were also found essential.

The loading rates were found to be critically dependent on the warning received at the stations. At the start of the experiment no warning of t-minute loading was given and loading rates much below those used under manual control had to be adopted. It was subsequently shown that between one and two minutes warning was adequate to restore the original rates and this was incorporated. This need for warning is not primarily associated with physical plant lags but with the necessary communication, under range operation, between the several boiler operators before any action is initiated.

6.2.5 Cost Savings

The cost savings arising from the increased frequency of load dispatching possible under automatic control, was assessed from an off-line simulation exercise, as sufficient time was not available to enable a statistically significant comparison with manual control to be made by a prolonged, direct experiment in the field. The necessary cost data was, of course, obtained through the experiment.

Using the simulation the optimum dispatch* was found for a typical day's operation and also the incremental costs for meeting load changes at each level of demand through regulation (on the sets free to respond) were established. The cost penalty for dispatching only at t-minute intervals was then calculated from the product of the prediction error for time t-minutes ahead and the differential cost between regulation and optimum dispatch. This calculation showed that a dispatch period less than 15 minutes (corresponding to a prediction error of 2½%) must be used if the cost penalty was not to exceed 0.2%. If the prediction errors under manual dispatching, as deduced from the observed frequency fluctuations, are taken as about twice this value, i.e. 5% the direct cost savings attributable to automatic control are about 0.2% of operating costs.

A very significant observation supporting the view that real cost savings are likely under automatic control is shown in Fig. 11. The outer boundaries 'a' and 'b' show the range of costs, against total generation, averaged for a few days running under normal automatic control. The narrowing of the range, shown in the shaded area was achieved by displaying additional information to the control engineer, notably which constraints were being invoked.

Coupled with any cost savings credited to the automatic system, were, of course, other benefits such as more consistent and improved security and better allocation of running spare capacity.

6.3 The Performance of the Frequency Control System

In the system design provision was made for the control of frequency by the inclusion of frequency terms in the digital algorithms to remove the slower fluctuation (see Section 5.3.1), leaving the faster fluctuations to be removed by the analogue frequency loops.

Several topics for investigation were thus raised:-

(1) the possibility of interaction between these two mechanisms

(2) the stability and performance of the analogue frequency loops

(3) the extent to which the number of machines chosen to regulate could be reduced and

(4) the rules governing the selection of machines to regulate.

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* this assumes continuous matching of the dispatched load to demand

6.3.1 Interaction between the Digital and Analogue Systems

This topic was studied analytically by Jenkin[9] and Farmer[10] who concluded that a fairly simple stability criterion existed provided that the load dispatching cycle was not repeated more frequently than about every thirty seconds; this being

$$\frac{K_2T_o}{2} - K_1 < K_f; \quad K_1 < K_f; \quad K_2 > 0$$

where K_1 and K_2 are effectively the 'gains' of the digital frequency and time error control loops (see Section 5.3.1) and K_f is the gain of the analogue control system.

It is clear from these conditions that if improvements in frequency control are required these must be achieved by increasing the gain of the analogue system; (possibly followed by increasing the digital gain); any attempt to achieve it purely by stiffening the digital system will only lead to instability.

6.3.2 The Stability and Performance of the Analogue Loops

In view of this the stability limits of the analogue loops were investigated.[11] Preliminary studies showed these to depend in a non-linear manner on:-

(1) the net gain settings of the frequency and power loops of all the regulating sets

(2) the total inertia of all generators

and (3) the net gain of the primary governors of all the generators.

The predicted stability boundary is shown in Fig. 12, and this was confirmed experimentally by increasing the loop gains until the instability was reached.

The consequences of exceeding the stability limit were minimised by the inclusion of rate limits on the analogue loops. The resulting bounded frequency oscillations were then typically as shown in Fig. 13.

6.3.3 The Quality of Frequency Control

The quality of frequency control was assessed from frequency recordings made during isolated operation of the test area.[11]

The effectiveness of the analogue loops in controlling the random fluctuations of frequency was measured during periods of steady load, the r.m.s. deviation being about 5×10^{-3} Hz compared with six times this value under manual control. This corresponds to a range of variation under automatic control of about 0.02 Hz.

The gain of the analogue loops during the morning load rise, when the digital system was calling for high rates of loading simultaneously on a number of sets, was reduced to about half the expected value. This was no doubt because many sets were being held at their rate limits by the dispatching system and were thus unable to regulate, at any rate in the upward direction. Generally the response was consistent with that to be expected only from the sets part loaded at a steady value.

6.4 Grid Control Facilities

The data flow through the operator's console, at the Grid Control Centre was examined for two purposes:-

(a) to show up any shortcomings in the facilities

(b) to clarify the operator's task under automatic control, this being

(1) to enter changes in plant constraints

(2) to apply constraints for any insecurities not covered by the group limits

(3) and to enter estimated load or generator values when the telemetering system or automatic load prediction were suspected of being in error.

This data was entered into the computer through a keyboard containing a small display unit.[4] The principal usage of the keyboard was found to be informing the computer of (a) generator states (on average 3 times per hour) (b) actual outputs or maximum load (4 times per hour) and (c) asking for the area load (twice per hour).

The main display system was able to draw any one of the 50 different characters (up to a total of 3900 characters) anywhere on either of two CRT screens within a matrix of 80 x 64. The data formats were stored in the computer as a special display language (Disc),[12] the three most used displays being (a) the 30-minute targets (8 times per hour), (b) the t-minute targets (4 times per hour) and (c) computer anomalies (5 times per hour). Comparatively little attention was focussed on the security of the network.

6.5 Reversionary Modes and Equipment Reliability

The equipment installed was designed to be highly reliable but automatic reversionary modes were provided to cater for such failures of control or telecommunications equipment as might occur. The main facility to help in reversion consisted of a set of manual setters on the control console which could be used to send 30-minute targets when the computer was out of commission.

The expected patterns of reversion for the principal faults, in increasing order of severity, are shown in Table 2.

During the experiment all these types of reversion were tested. They were found to be very effective in dealing with these situations; in particular the operators found that they could control the system very conveniently through the manual setters for prolonged periods.

The reliability of the equipment generally proved to be very high.[13] Fault rates for the total installations at the Grid Control Centre showed an expectancy of one fault every 7 days, whilst the figure for the machine controllers was about one fault every year.

Table 2

Principal Reversionary Modes

Failure	Items Affected	Reversionary Mode
One machine controller	One set	Manual control of the set to the stored 30-min. target, thereafter to telephone instructions.
One telecommand link	All sets in one station	Automatic reversion to stored 30-min. targets, thereafter manual control.
Interposing equipment	Possibly more than one station	Automatic reversion to stored 30-min. targets. Thereafter 30-min. targets computed automatically and set manually on the console.
Minor computer defect	All stations	Automatic reversion to stored 30-min. targets.
Major computer defect	All stations	For about 2 hours 30-min. targets already computed and printed out set manually on the console. Thereafter reversion to full manual control.
Telemetering equipment	Some data	Values inserted manually, obtained by telephone or estimated.

7. Future Possible Developments

Experience with the control system has indicated some areas where useful technical changes or developments could be made, particularly in:-

(1) reducing the work load on the operator at the Grid Control Centre,

(2) reducing the control activity at the stations (i.e. the control ratio),

and (3) reducing the constraints on generator load changes (mainly imposed by boiler plant) by suitable control action.

The first would be considerably helped by the automatic transmission of data relating to plant capability directly from the station into the central computer. This would halve the operator's work load immediately. Significant improvements could also be made in the console facilities, e.g.

(a) the simplification of the operation of the keyboard,

(b) the removal from the displays of irrelevant data (e.g. fixed data),

(c) the selective marking of data to bring it to the operator's attention,

(d) the automatic estimation of data during telemeter faults.

Reductions in the control ratio could probably best be achieved by using in the loading program dynamic incremental generating costs that more truly reflect the implications of carrying out load changes than do the present static costs. The development of methods for generating dynamic costs is, in itself, a major programme of work as these should properly take into account, both the reduction of efficiency during load changes and the cumulative effect of load cycling on plant life and availability. This aspect becomes more important as increasing amounts of nuclear plant are installed characterised by high capital and low fuel costs.

Some expedients such as reducing the frequency of instruction or elaborating the rules incorporated in the load program could help in reducing the control ratio.[8]

At the stations full use was not made in the manipulation of the boilers of the predicted information available. This stemmed, no doubt, from the difficulties of range operation, the general lack of automatic boiler control and the inadequate display of this information.

The direct injection of the predictions into the automatic boiler control system of a modern unit and the analysis of the display problem in this context are the lines of attack proposed here. Some work has already been started on the improvement in regulating capability resulting from the optimised feed-forward control of the boiler.

The other major change visualised in the stations is a shift from individual machine controllers to station controllers, these being flexible digital systems,[5] capable of taking account of both unit and station constraints and able to update the central computer directly, as mentioned above.

8. Conclusion

The control system that has been described was found to have operational potentialities which qualify it as a satisfactory basis for the application of fully automatic control on the C.E.G.B. system, as and when this should prove desirable and necessary.

The emphasis on prediction was shown to have been justified and this feature should be retained in any future designs as it enabled the desired level of security to be achieved at minimum cost, taking full account of the known plant constraints. It also enabled a highly flexible loading program to be developed.

The major shortcoming was a lack of appreciation of the operational problem that would arise at the stations in matching steam production to the load changes imposed on the turbogenerators. As has been said this aspect must receive proper attention in the future, bearing in mind the differences between modern stations and those used in the experiment.

Finally, the lack of a clear demonstration in the experiment of the expectation of substantial economic benefits from the application of full automatic control should not be taken as too discouraging. This is to be expected when an automatic system is compared with a highly developed manual control technique carried out by skilled operators. That the automatic system was more consistent in discharging its task and that it freed the men from routine work to concentrate on future problems is not in doubt.

9. Acknowledgements

The authors wish to acknowledge the contribution made to the project by Mr. J.A. Roberts and their many other colleagues both at C.E.R.L. and in the South Western Region of the C.E.G.B. The paper is published by permission of the Central Electricity Generating Board.

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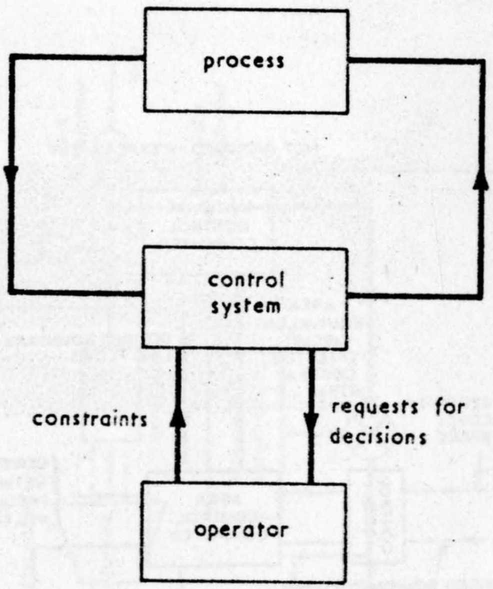

Fig. 1. The operators role

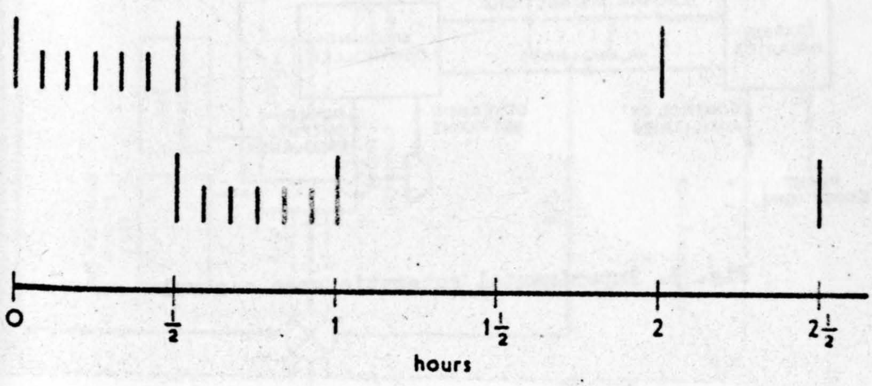

Fig. 2. Load prediction for 2 1/2-hour cycles

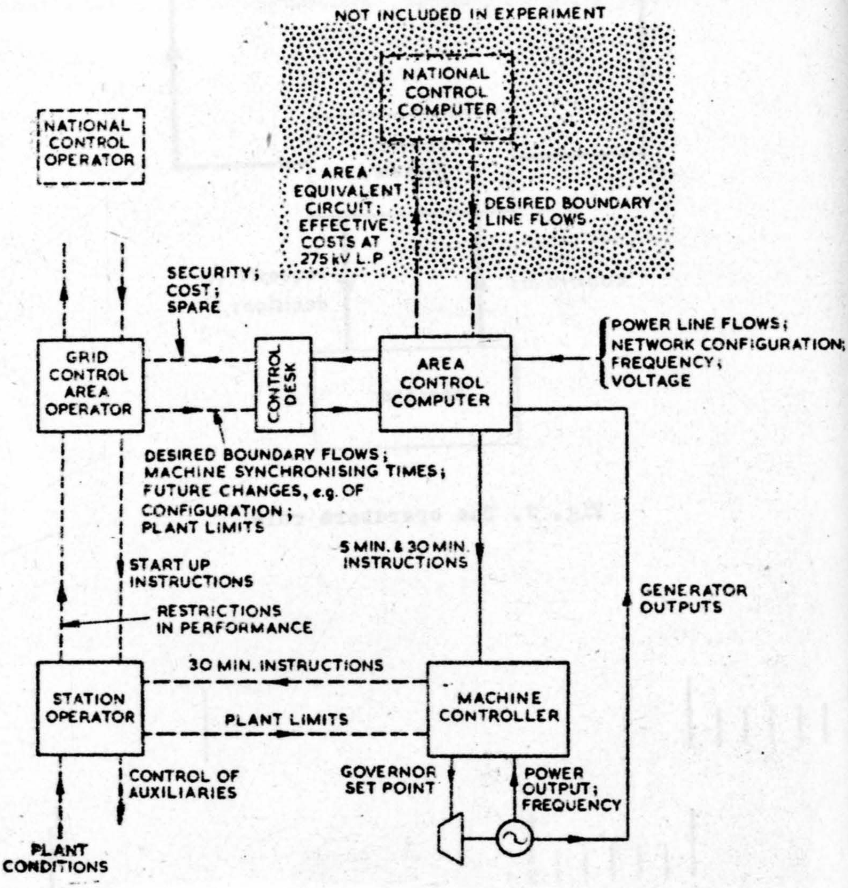

Fig. 3. Experimental automatic area control

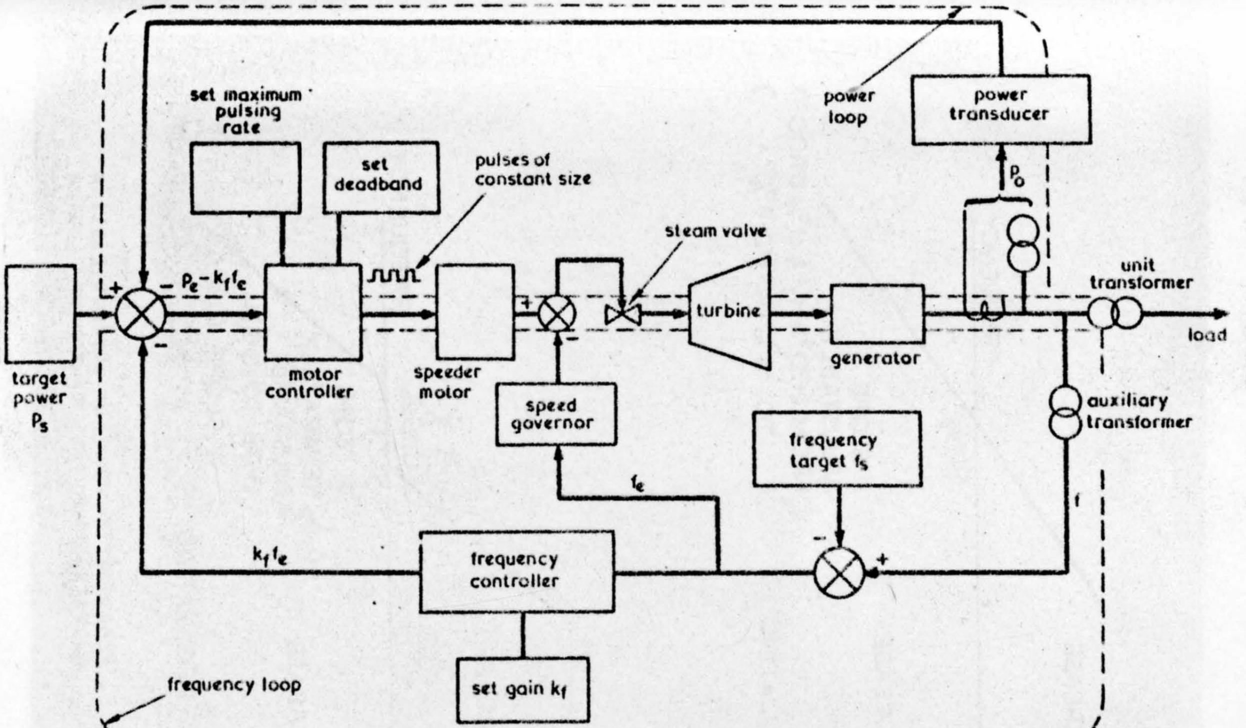

Fig. 4. Schematic of a machine controller

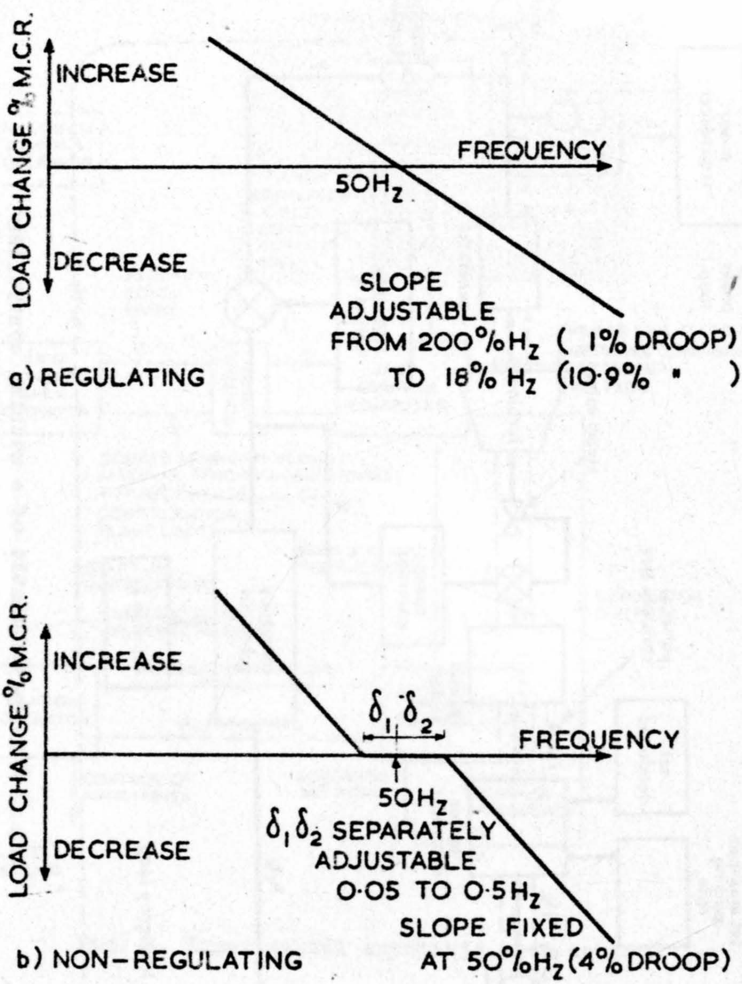

Fig. 5. Frequency controller characteristics
a/ regulating b/ non-regulating

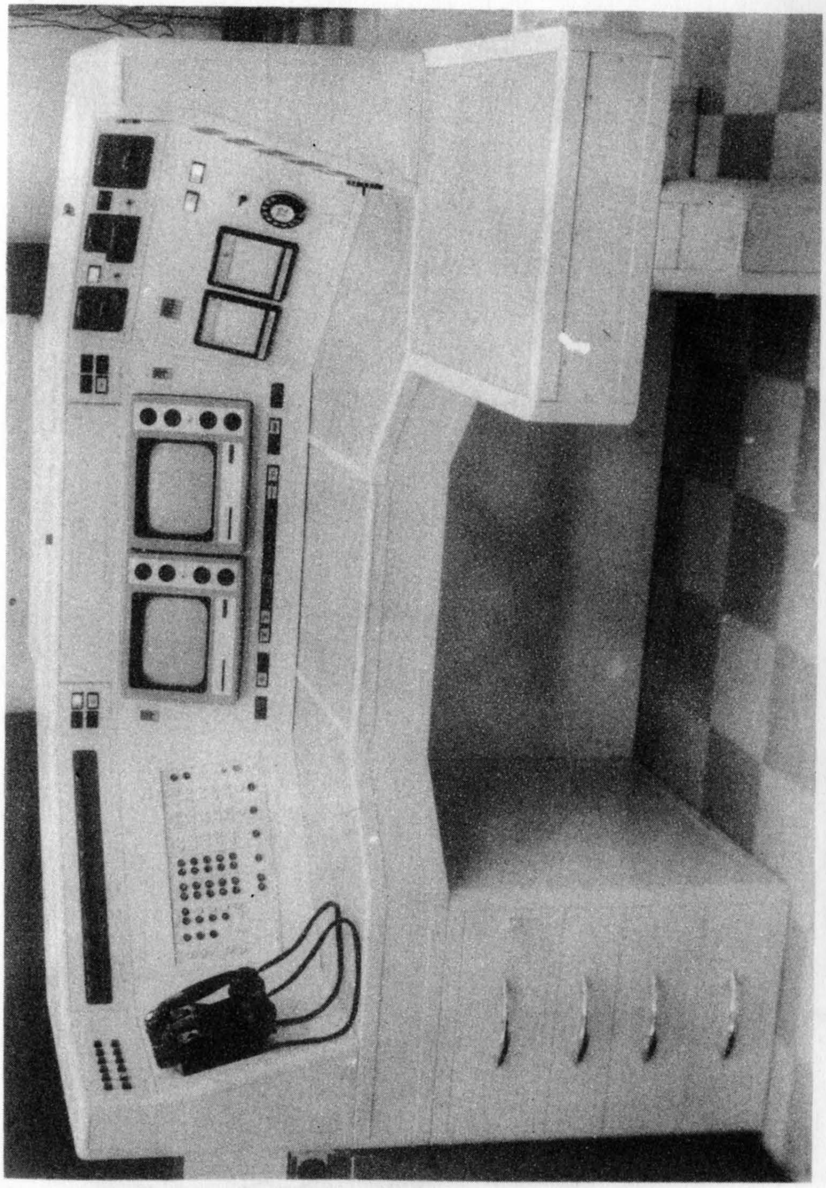

Fig. 6. The operators console at the Grid Control Centre

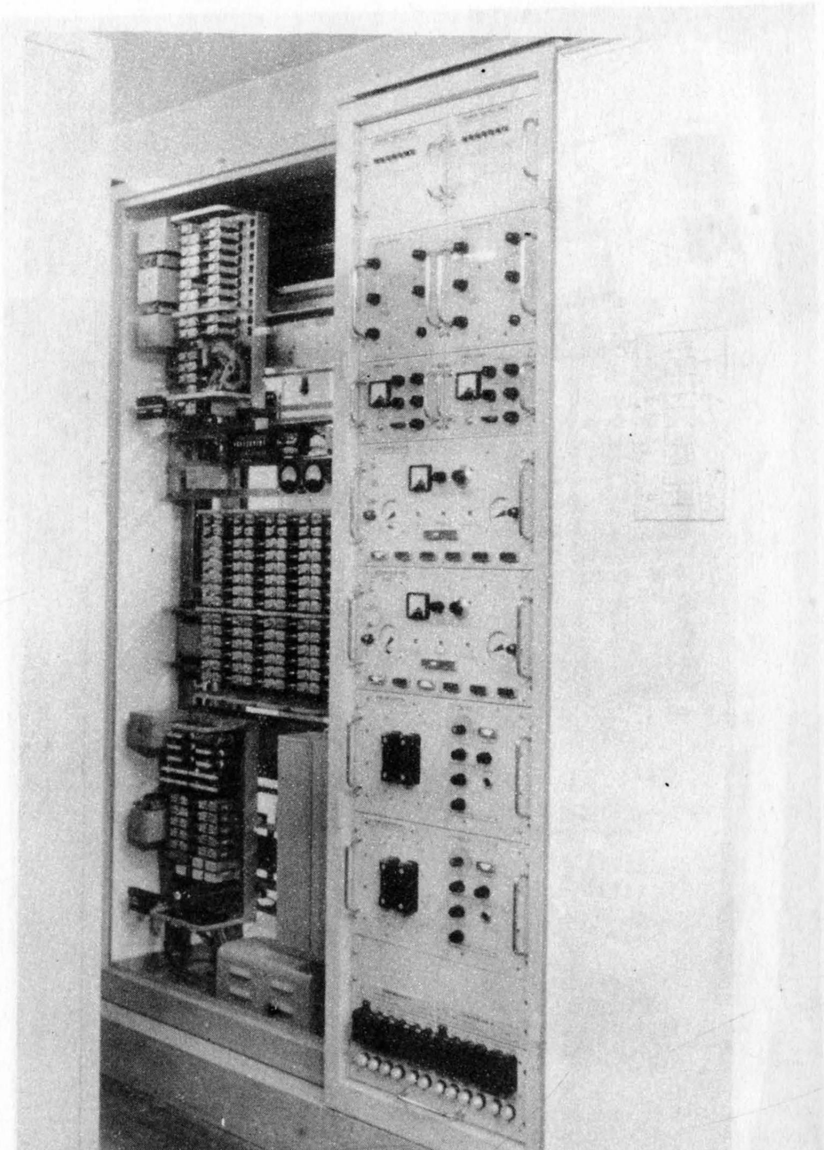

Fig. 7. Two controllers and the telecommunications cubicle

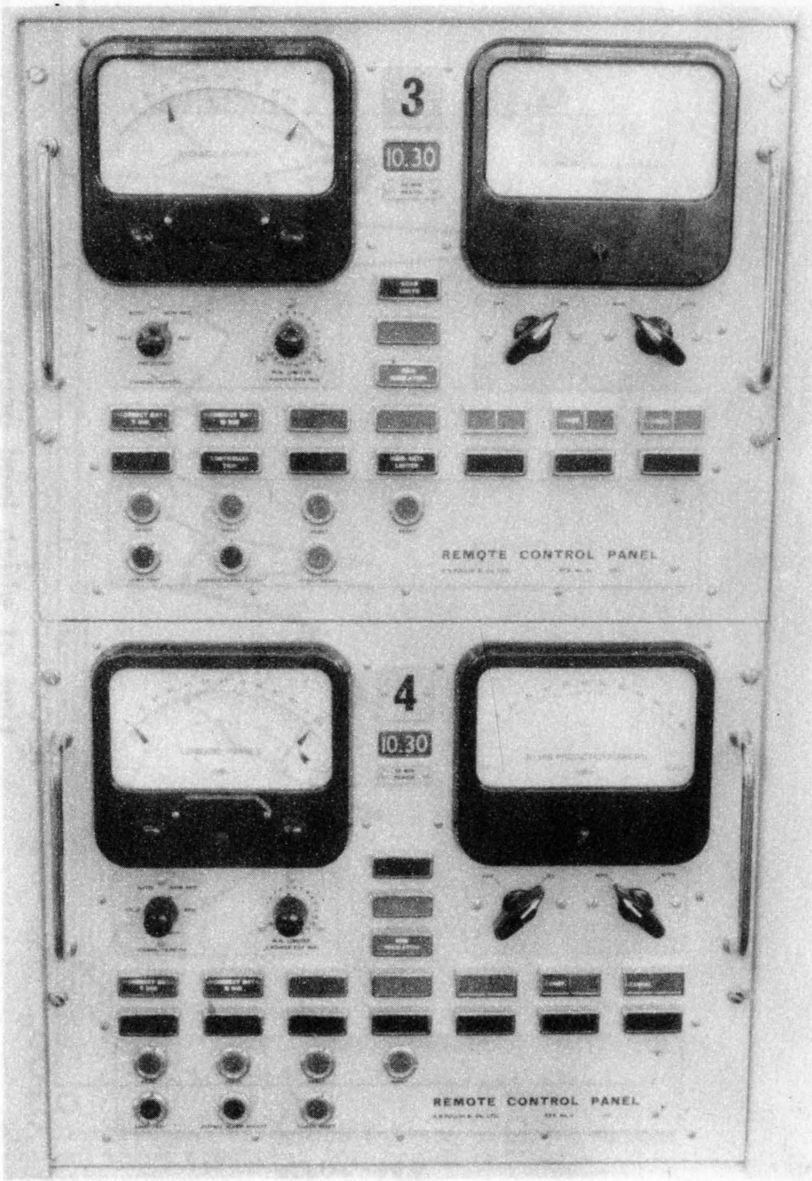

Fig. 8. The remote control panel for a machine controller

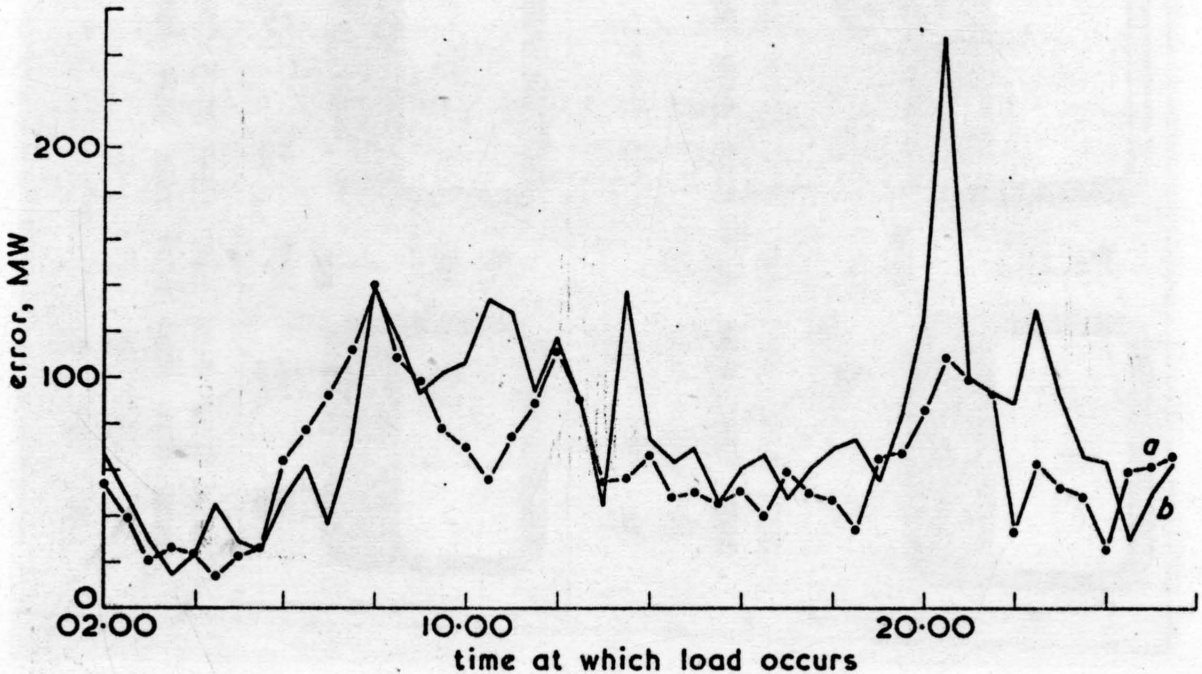

Fig. 9. RMS errors comparing correlation and scaling methods for 2 hours ahead

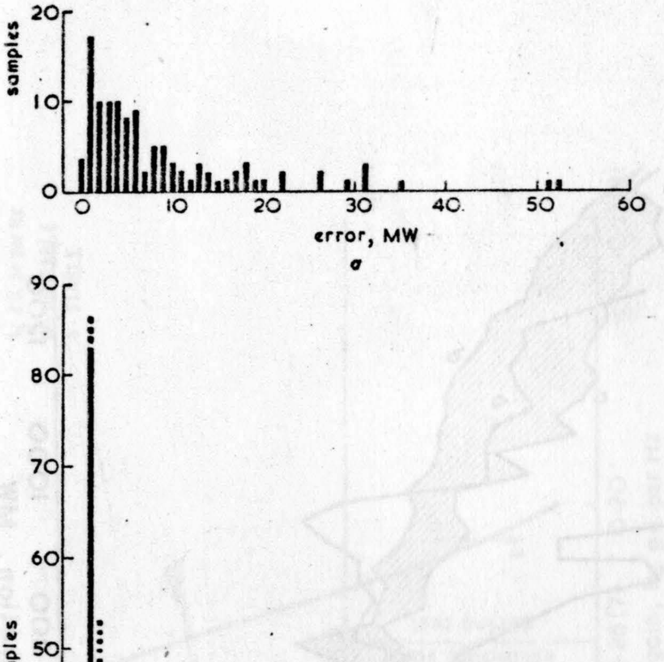

Fig. 10. Distribution of errors between measured values and those predicted 40 minutes before

a/ for power station outputs
b/ ——— for circuits inside the test area
- - - - - - - for circuits crossing the test area boundary

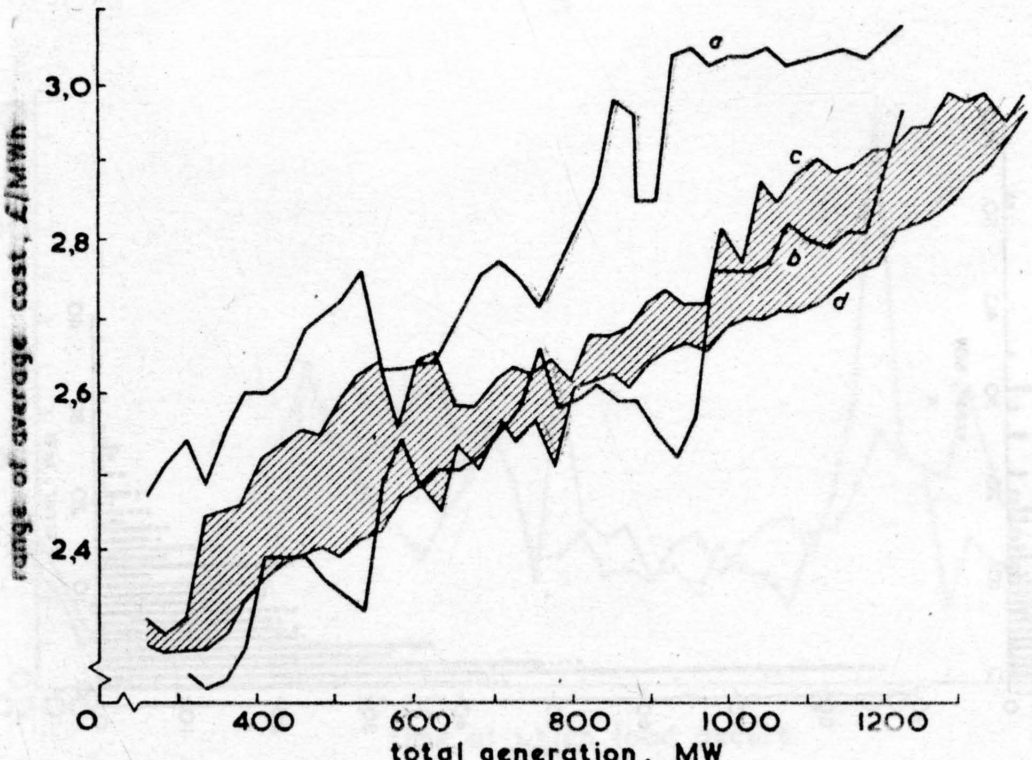

Fig. 11. The effect on the incremental cost range of displaying more information to the operator, under automatic control

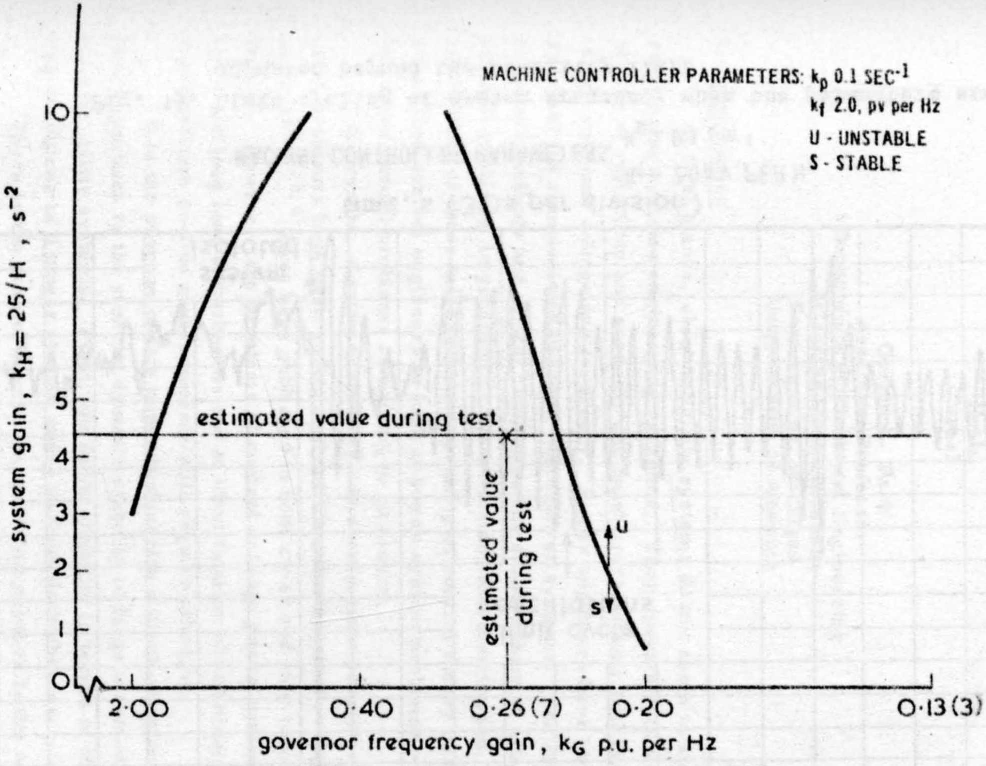

Fig. 12. South Western test system stability boundary

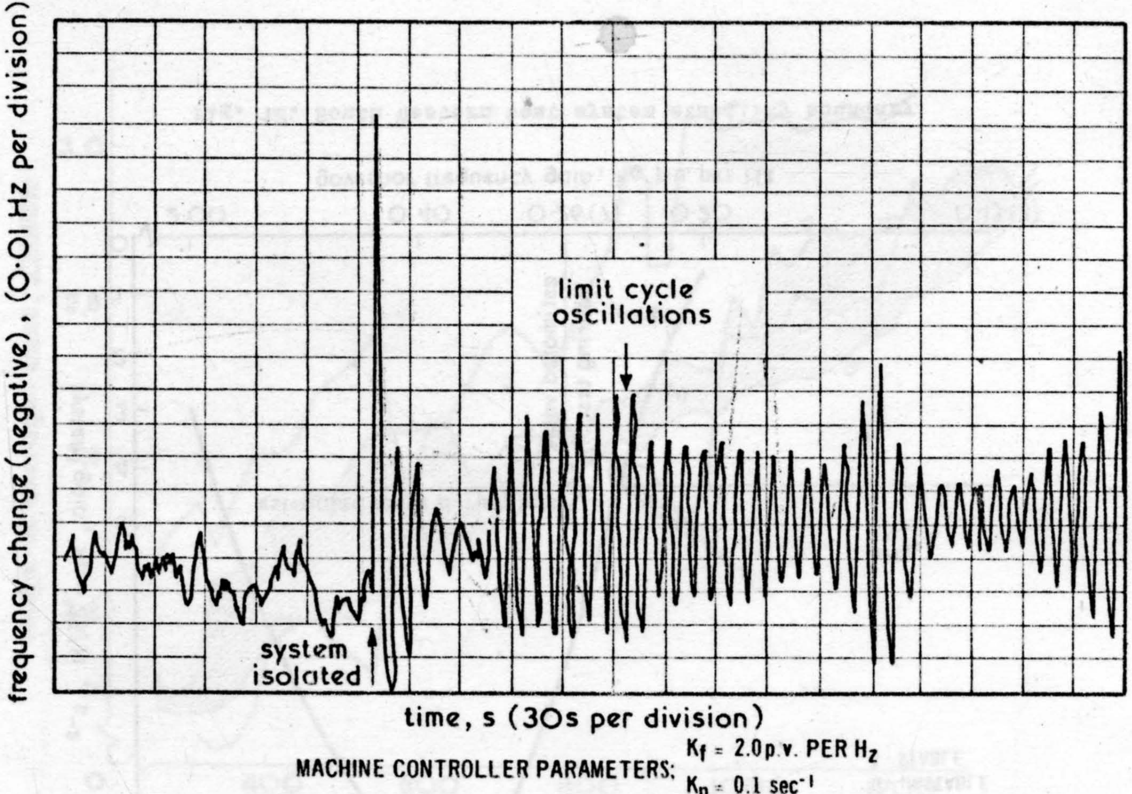

Fig. 13. Limit cycling of system frequency when the parameters are adjusted beyond the stability limit

ANALYSIS OF DYNAMIC STABILITY OF A POWER SYSTEM UNDER DETERMINISTIC LOAD CHANGES

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I. Introduction

At first glance, electric utility systems do not seem to suggest challenging systems engineering problems. They operate with a high degree of reliability and economy and most users assume that the output is at a constant voltage and frequency. Power engineers have long been aware of the complexities of large-scale power systems. The advent of matrix methods and digital computers has enabled them to attack difficult problems in generation, transmission, and distribution.[1] The availability of these tools and the popularity of control theory has also stimulated control engineers to look at power system problems - and there are enough problems remaining to go around.

At present, electrical stability and steady-state economic dispatch problems have been well-posed and essentially solved. Computer analyses[1, 2, 3, 4] have been published in both areas and only refinements remain. However, the problems of control of large power systems under large and long load disturbances and of identification of interconnected systems from on-line measurements still require attention.

It is the purpose of this paper to describe a block-diagram simulation approach to the study of dynamic stability of large steam-driven electric utility systems. First, we define stability in terms of the operating conditions of a power system under various disturbances.

There is the case of severe transmission network faults which change the electrical configuration of the network and the load. During and after the fault, all the generators must be kept synchronized or be removed by protective relays. This can be called the electrical transient stability problem where the angles $\theta_i(t)$ of all machine shafts must return to values determined by the post-fault load. This problem in Lagrange stability has been effectively solved[1] and the programs have been available for some time and are in daily use.[4, 5]

Another case of importance is when a large load disturbance does not cause a network change and does not exceed the spinning reserve of the system. Such a load change is distributed among the generators of the system as follows:

(1) Load distribution which is directly proportional to the synchronizing torques of the turbogenerators, according to the location of the changes occurring within the system. This distribution is associated with electro-magnetic transients occurring over relatively short time intervals in synchronous machines.

(2) Load distribution which is directly proportional to the kinetic energy of the rotating masses of the turbogenerators of the system and the rotating masses of the consumers' drives. Coverage of the load increase derived from this kinetic energy results in frequency changes.

(3) Load distribution which is due to the action of the individual speed governors of the generating units.

(4) Load distribution which is due to the action of centralized frequency and tie line control.

(5) Load distribution which is due to the steam-generation behavior (boilers) and which is of extreme importance in the case of very large load changes.

In this study, the model used includes only the physical phenomena described in (2) and (3) and not of (1). The inclusion of (4) and (5) would would be straightforward if simple input-output dynamic models were available for the dispatch computer and the boilers. Boiler models have been developed[6, 7] but as yet they do not reduce to tractable block equivalents. The electromagnetic transient state (1) is accounted for in fault stability studies. The torque changes due to load disturbances are usually less than those due to faults so we make the assumption, which must be verified in every case, that the system is stable during the epoch of electromagnetic transients (about 1 second). Until boiler and load-frequency controller models are included, the effects of a continued load disturbance are not accurately modeled since we assume constant steam pressure and no action from supplementary generation controls.

Thus the main goal of this study is to obtain an adequate and relatively simple mathematical model for predicting frequency and active load transients which accompany sudden load or generation changes. With the assumption of constant boiler pressure the time interval of relevance is from about 1 to 30 seconds after the load impact. These time periods of load distribution are illustrated in Fig. 1. We discuss the behavior of the frequency and power during the 1 to 30 second interval using the term "dynamic stability."

The transfer-function block diagram model has proven very useful in control system analysis and simulation where some of the system components are in cascade. This is the case in power systems where the governor controls the steam valve to the turbine which in turn drives the alternator. The electrical load can be accounted for in terms of torques on the alternator shaft. Kirchmayer[2] successfully utilized this approach for the study of several machine systems so the authors have extended his approach to a ten machine system. The models are derived in Sections II and III and are valid under the assumptions listed above and in those sections.

Once the block model is derived for a ten-machine system, it is simulated using the COBLOC language for the CDC 3600 computer. The simulation results include time plots of active power and frequency deviations at the various plants and on the equivalent tie-lines. The behavior of these variables roughly agrees with typical measured system behavior except for damping. A similar simulation program written for the IBM 360-40 computer is in regular use at Consumers Power Company Jackson, Michigan, for studying dynamic stability of future systems configurations of the Michigan Power Pool.

II. Derivation of Block Model for One Equivalent Plant

The model we have chosen, essentially as described by Kirchmayer,[2] includes the significant time constants of the turbines and governor system aswell as a nonlinearity to account for unit saturation. The model is essentially a mechanical one where shaft torque and angle are the fundamental variables so that the loads are represented in terms of torques. The stator reactances are included in the transmission and distribution network equivalent. The voltage regulator is ignored since a well-designed feedback regulator keeps the stator voltage nearly constant in the face of non-catastrophic load changes and usually does not degrade dynamic stability.[8]

The Laplace transform operator s appears in the transfer function used in this model but an equivalent model using a set of first-order differential equations (so called "state" equations) could be used and in fact were used by the investigators to verify the results of the transfer-function model. The complete block model for one equivalent plant is shown in Fig. 2. The concept of equivalent plants is used because several generator units, feeding the station bus in parallel, with identical parameters can be combined into one equivalent generator.

The simplicity of the transfer-function model is both a blessing and a disadvantage. It admits a measurable input-output description of the dominant dynamics of a complex subsystem but the detailed interaction of the components in the subsystem is obscured.

Governor Steam-Valve Block

For example, the governor, hydraulic amplifier, and motor-driven steam valve forms a complex subsystem requiring many intercoupled non-linear differential equations for an accurate mathematical model. Nevertheless, an adequate input-output description can be developed using a two-term transfer function, representing the governor and valve response as first-order lags, cascaded into a limiter which limits at the power corresponding to the maximum steam flow. This model is adequate in the sense that the response characteristics of this model and of the real system are close.

The transfer function, where x is the relative valve position before limiting, is

$$\frac{\omega_o(s)}{x} = \frac{K_1}{(1 + sT_1)(1 + sT_3)}$$

Here the gain constant K_1 is the reciprocal of the regulation coefficient or speed droop (change in shaft velocity per unit change in load) and T_1 and T_3 are the time constants which represent the dominant dynamics of the governor and the steam valve and its driving hydraulic servo. Typical values for T_1 and T_3 are 250 and 200 ms. T_3 in recent plants with high-speed valves may be on the order of 50 ms.

Turbine Steam-Dynamics Block

Changes in shaft torque produced by changes in steam flow acting on the turbine can be approximated by the transfer function

$$\frac{L}{x'}(s) = \frac{1 + K_2T_5s}{(1 + sT_4)(1 + sT_5)}$$

where T_5 is a time constant (about 10 seconds) used to approximate the pure time delay for steam to charge the reheater section of the boiler and the connecting piping. K_2 is the reheat coefficient which equals the proportion of torque developed in the high-pressure section of the turbine which is approximately equal to one minus the fraction of steam reheated. Thus when there is no reheat, $T_5 = 0$ and the transfer function reduces to a single lag

$$\frac{L}{x'}(s) = \frac{1}{1 + sT_4}$$

where T_4 (about 300 ms) represents the first-order response of shaft torque to a change in steam valve relative position x'.

In this block, the transfer function description represents the furthest departure from reality. A realistic model includes energy and momentum equations, the effect of propagation of disturbances in the steam flow between boiler and condensor, pure time delays, and the effect of limited steam supply when the steam valve is suddenly opened and kept open. These factors limit the approximate model above to describing small (about 20%) load changes lasting less than 30 seconds.

Instead of adding more linear terms, a better model requires a fresh start including these effects as well as boiler and auxilary behavior. Attempts towards such a description have been published[6, 7] but much work remains and the complete plant model will then be much more complex.

Alternator Dynamics

Here the effective moment of inertia of the turbine-alternator as well as the damping, primarily due to the connected load-frequency characteristic, are easily described in terms of torques on the turbine shaft. Since torque is proportional to power times frequency and since frequency changes are small, we assume torque proportional to active power (the system power factor is high). The torque equation is

$$L_T(s) - L_L(s) = Ms\omega(s) + D\omega(s)$$

where L_T is the torque produced by the turbine and L_L represents the load and synchronizing torques of other machines in the system. This equation leads to the summer followed by the transfer function

$$\frac{1}{Ms + D}$$

shown in Fig. 2.

Thus the single-loop block diagram (the top half of Fig. 2) is a simple representation of the dominant dynamics of a steam-driven generating plant on an incremental basis. The effects of load and interconnections with other plants are considered in the next section.

III. Isolated Systems Model

A number of single plant models are interconnected to represent a large isolated power system. The additional work required involves representing the synchronizing torques between generators and the load. The block diagram for the interconnection reduces to an integrator after each frequency ω_i to get relative machine angle θ_i and a subtractor and coefficient T_{ij}, which is proportional to the synchronizing torque between equivalent generators. The load configuration is accounted for in the T_{ij} and the existing load-flow and network reduction programs are used to find these coefficients. A load-flow program which reflects estimated peak load conditions in 1970, is used with a network reduction program which yields an equivalent interconnection network between generator busses. The resulting bus loads are converted to shunt impedances using the expressions

$$R_i + jX_i = \frac{(MW_i)(E_i^2)}{(MW_i)^2 + (MVAR_i)^2} + j\frac{(MVAR_i)(E_i^2)}{(MW_i)^2 + (MVAR_i)^2}$$

where E_i is the per unit bus voltage, MW_i the active load of the i^{th} unit in per unit, and $MVAR_i$ the reactive load in per unit. Now the synchronizing torque coefficients can be calculated as

$$T_{ij} = \frac{(E_i)(E_j)}{Z_{ij}}$$

where Z_{ij} is the equivalent per unit impedance between the i^{th} and j^{th} equivalent generators and E_i and E_j are the per unit voltages behind synchronous reactance at the corresponding plants. Note that in this calculation the relative machine angles are assumed small since the synchronizing torque is, in general,

$$L_{ij} = \frac{(E_i)(E_j)}{Z_{ij}} \sin(\theta_i - \theta_j) .$$

Furthermore, we assume the load is as described by the load-flow program and load changes are represented by torque changes ΔL at one or several generators.

There is no accurate method included to represent other systems interconnected with the system under study other than to reduce all their dominant generators into the model. Attempts were made to terminate the system at the interties with an equivalent machine with a very large M. Further work on representing interconnections between large systems has begun and will be discussed in Section VI.

IV. Simulation Technique and Results

The system chosen for study included the ten dominant equivalent machines of the Consumers Power Company system. The synchronizing torque coefficients were calculated using the Westinghouse Engineering Service Programs for the load-flow and network reduction based upon estimated 1970 peak load conditions. From these, a table of per unit synchronizing torque coefficients and equivalent tie-line impedances was collected. The approximate per unit time constants, inertias, damping constants, maximum powers, and regulation coefficients were obtained from the Governor Representation sheets in the technical file for each unit. A load disturbance was simulated by introducing a 200 MW (two per unit) change in generation at one unit and readout was desired for

(a) The angular velocity (and thus frequency) deviations on the equivalent turbogenerator shafts.

(b) The deviations of the active power generation on the equivalent turbogenerator shafts.

(c) The deviations of the equivalent tie-line active power flow.

This block model (obtained for an isolated operation of the Consumers Power system), although extensive, could still be simulated using a large analog computer facility. On the other hand, in future studies this model will be extended by adding the neighboring power systems, thereby increasing the dimensionality, so that even the largest of analog computers can not handle it. Because of this the analog computer solution was not attempted. Instead, a digital simulation based on the analog computer approach was chosen.

There are a number of simulation programs available for obtaining solutions for systems represented as a block diagram or analog computer diagram, each of them written for a particular manufacturer's computer. The Michigan State University CDC 3600 uses such a program called COBLOC, which is an easily programmed and powerful hybrid simulator.

The use of COBLOC is described elsewhere[9] and its application to this problem is described in detail in a research report[10] which also includes the patching program, the per unit constants, and plots for each equivalent generator. We note only that the program requires about 250 punched cards and is easily extended to more than 30 machines when a sufficiently large computer is available. The patching diagram for one plant is shown in Fig. 3 - the relation of this diagram to Fig. 2 is immediate.

Obviously a complex simulation generates much data so only a few typical outputs are shown. The ten generators are listed in Table 1 with some parameters obtained from the plots. The 200 MW load increase was introduced at Campbell 1 and the effects there and at Karn 1 are shown in Figs. 4-7. The complete results were studied by Consumers Power Company engineers who felt that, except for the highly oscillatory behavior in frequency and tie-line power, the data described expected system behavior.

The reason for the underdamped oscillations is being investigated - the real system is more heavily damped (see Section IV). One factor is that the damping given in the machine file does not include dynamic load damping and slip damping. Sample runs including slip damping show much less oscillation. In any case, the model is now in use by Consumers Power Company engineers for planning future system expansion.

V. Measurement Techniques for Verification of Response Data

The power and frequency recorders used in most control centers are too slow to record in detail dynamic transients and oscillographs for studying voltage transients cycle by cycle generate too much paper. What is needed to observe frequency and active power transients over the relevant time period is a device measuring frequency, to an accuracy of $\pm$ .005 Hz and precision of .001 Hz, averaged over several cycles. Also needed is active power averaged over the same number of cycles to $\pm$ 1% accuracy. Finally, portability and a digital readout format were deemed important. An instrumentation system, see Fig. 8, meeting these requirements was designed by Karl Andrews of Consumers Power Company. The apparatus, mounted on a lab cart, averages active power from a Hall-effect wattmeter, and frequency, measured by gating a precision high-frequency oscillator to a counter, over six cycles (about 100 ms) and prints out decimal numbers on a paper tape. The power number is related to active power by a constant, and the frequency number divided into 6×10^6 yields the frequency. This process is repeated automatically every 200 ms.

Thus the printed record of power and frequency has five entries every second.

Sample measurements on the Michigan Power Pool system yield time plots that look much like the simulation output except that the real system oscillates at 2 Hz and the damping is greater. However, the data reveal that the system is always "swinging" about the center values indicated on the control center meters - in fact, swings as much as 20% are regularly observed. This phenomena was anticipated and is discussed in Section VI.

VI. Extensions to Pumped Storage and Interconnection Modeling

Once the basic block model is formulated, several useful extensions are possible and are under investigation:

(1) The Michigan Pool will operate a pumped storage plant on Lake Michigan which will provide about 1800 MW of peaking power by the early 1970's. Water will be pumped up to a reservoir at night and will flow back to the lake through the generators at peak hours. The six 375 MW synchronous motor-generators will be the dominant load during the night so a block model for these pumps and their transmission system has been introduced into the COBLOC model of the system to study the dynamic stability after short duration line faults occur. The model includes inertia of the wheel, shafts and rotor, and water as well as the dominant electrical parameters.

(2) At present, the number of plants included is limited by the memory capability of the 3600 computer used. A fourteen-plant model of the Michigan Power Pool is the largest simulation presently possible with this computer.

(3) Measurements with the apparatus described in Section V reveals as expected that the load on a power system is random and can be described with a stochastic time series. Considerable effort has been devoted to modeling the effect of interconnections by utilizing the statistical correlation between measured power and frequency to give an equivalent plant with varying parameters. This approach has been used to model individual machines[11] and should result in a more realistic simulation. Furthermore, the COBLOC model now developed can be excited with a random load signal with statistical properties similar to the real load yielding response data closer to reality.

VII. Conclusions

The transfer-function block model is shown to be a compatible model for the study of dynamic stability in large power systems. The assumptions needed to obtain this model, while too loose for electrical stability studies, do not seriously affect the model for electrically stable systems of fixed configuration until the time that boiler response affects the steam flow. Existing load-flow and network reduction programs are utilized to characterize the electrical load and interconnections. The COBLOC model is programmed directly from the block model and extensions to random load and pumped storage are direct. The lack of adequate recorders forced the development of an accurate portable power and frequency meter which is useful for other system measurements.

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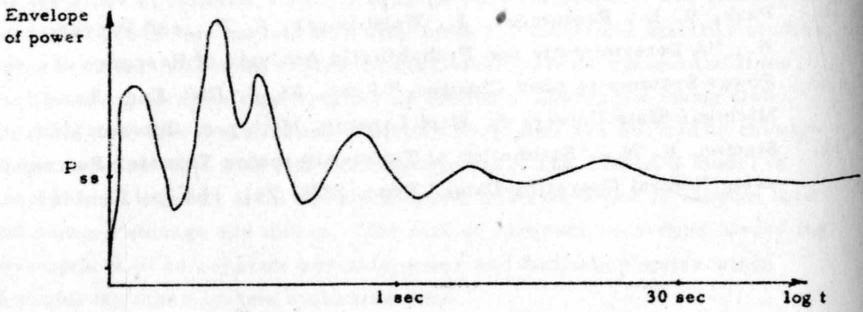
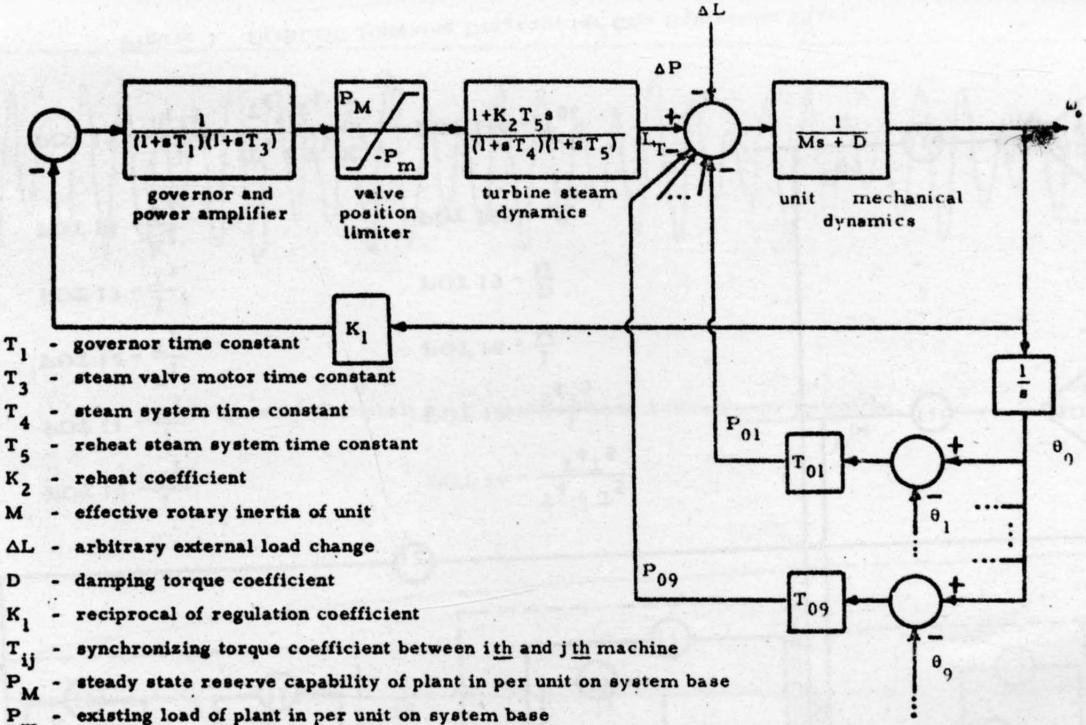


Stability Definition	Transient Stability	Dynamic Stability	Steady State
Load Distribution	Synchronizing Torques and Inertias	Inertia and Control Loops	Dispatch Computer and Boilers

Figure 1. Definition of Stability Corresponding to Load Distribution Characteristics

Equivalent Turbogenerator	Pickup Rate	Steady State Deviation (at 30 sec)	Average Steady State Frequency Deviation (at 30 sec)
Campbell 1	5.71 MW/sec	6.31 MW	-0.384 cps
Campbell 2	7.27	1.22	-0.372
Cobb	23.85	34.01	-0.366
Karn 1	5.82	12.34	-0.384
Karn 2	--	3.71	-0.379
Morrow	13.9	15.20	-0.387
Weadock W	15.22	35.61	-0.380
Weadock B	11.41	27.27	-0.379
Whiting 1 and 2	6.04	18.50	-0.376
Whiting 3	4.21	9.01	-0.381

Table 1. Parameters Obtained from Plots



T_1 - governor time constant

T_3 - steam valve motor time constant

T_4 - steam system time constant

T_5 - reheat steam system time constant

K_2 - reheat coefficient

M - effective rotary inertia of unit

ΔL - arbitrary external load change

D - damping torque coefficient

K_1 - reciprocal of regulation coefficient

T_{ij} - synchronizing torque coefficient between i th and j th machine

P_M - steady state reserve capability of plant in per unit on system base

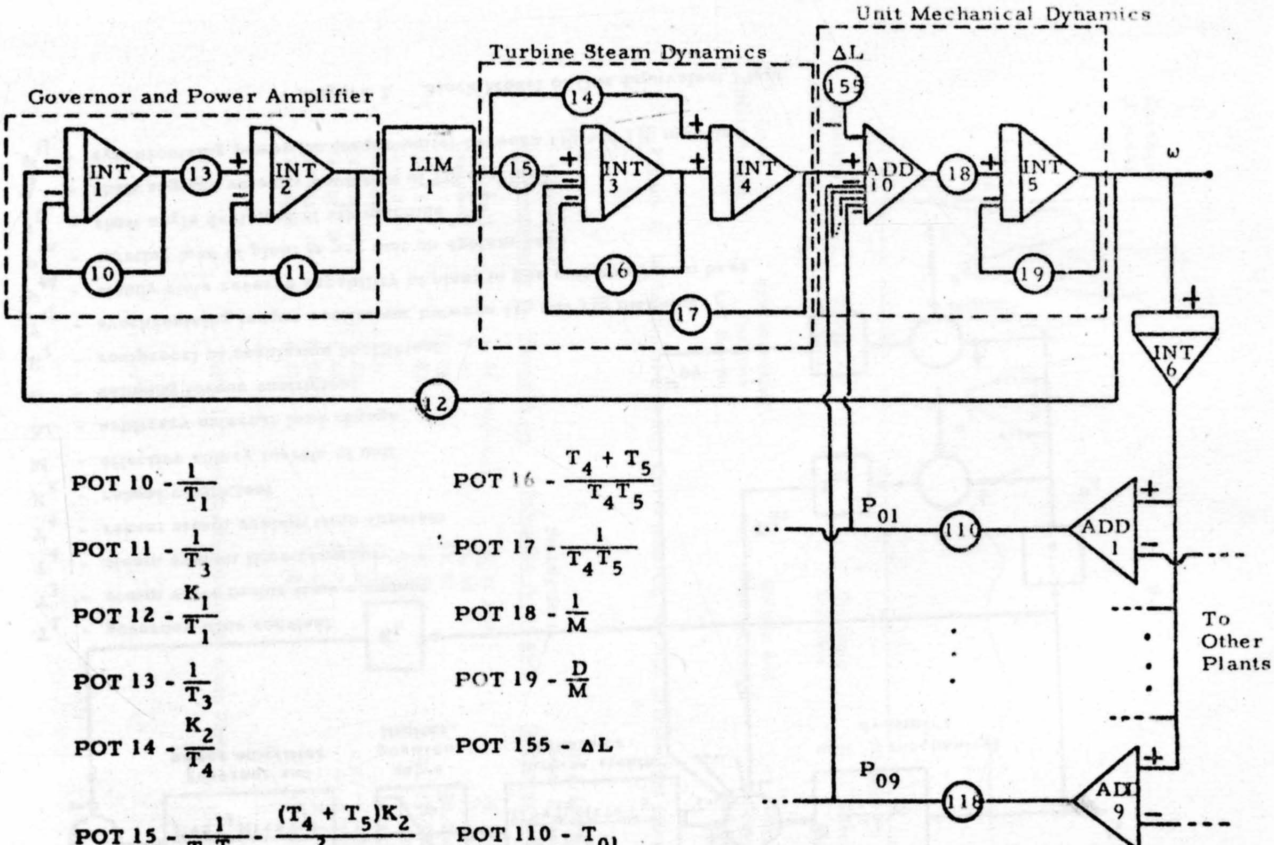
P_m - existing load of plant in per unit on system base

θ_i - shaft angle deviation of i th machine

ω_i - shaft angular velocity deviation of i th machine

P_{ij} - synchronizing power (in torque units) between i th and j th machine.

Figure 2. Block Model of One Equivalent Plant



POT 10 - $\frac{1}{T_1}$

POT 11 - $\frac{1}{T_3}$

POT 12 - $\frac{K_1}{T_1}$

POT 13 - $\frac{1}{T_3}$

POT 14 - $\frac{K_2}{T_4}$

POT 15 - $\frac{1}{T_4 T_5} - \frac{(T_4 + T_5)K_2}{T_4^2 T_5}$

POT 16 - $\frac{T_4 + T_5}{T_4 T_5}$

POT 17 - $\frac{1}{T_4 T_5}$

POT 18 - $\frac{1}{M}$

POT 19 - $\frac{D}{M}$

POT 155 - ΔL

POT 110 - T_{01}

Figure 3. COBLOC Patching Diagram for One Equivalent Plant.

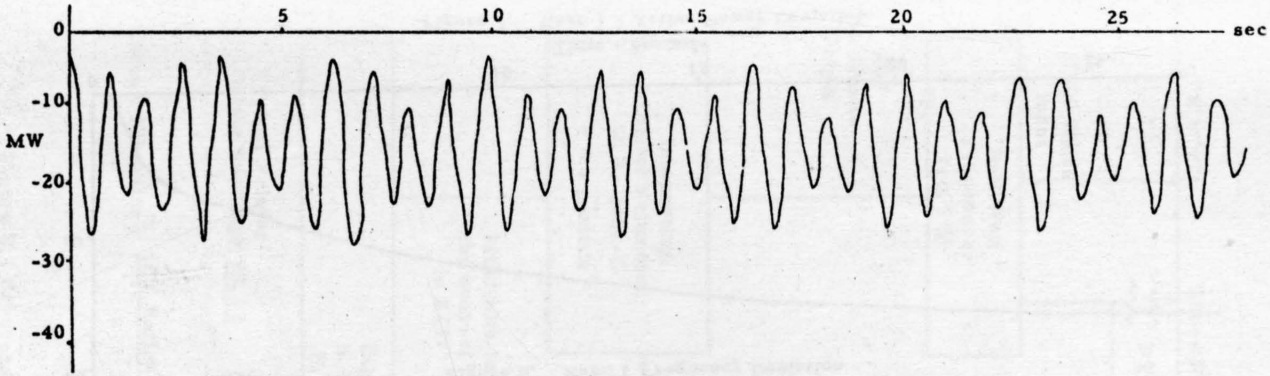


Figure 4. Campbell 1 - Karn 1 Tie-Line Active Power Deviation

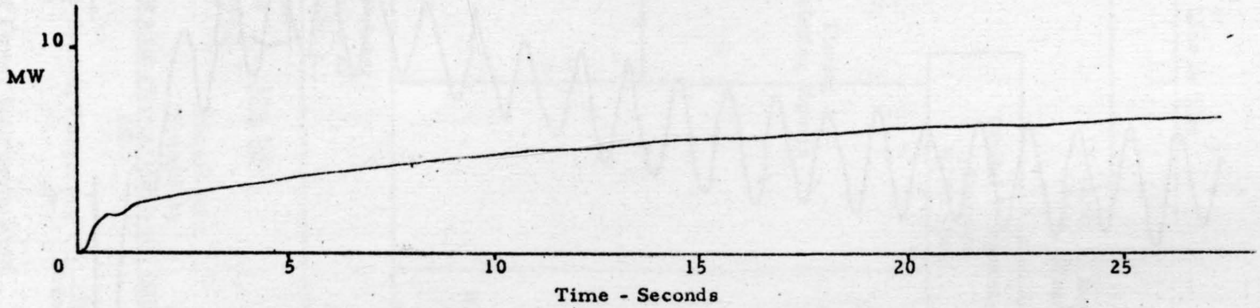


Figure 5. Campbell 1 - Active Power Deviation

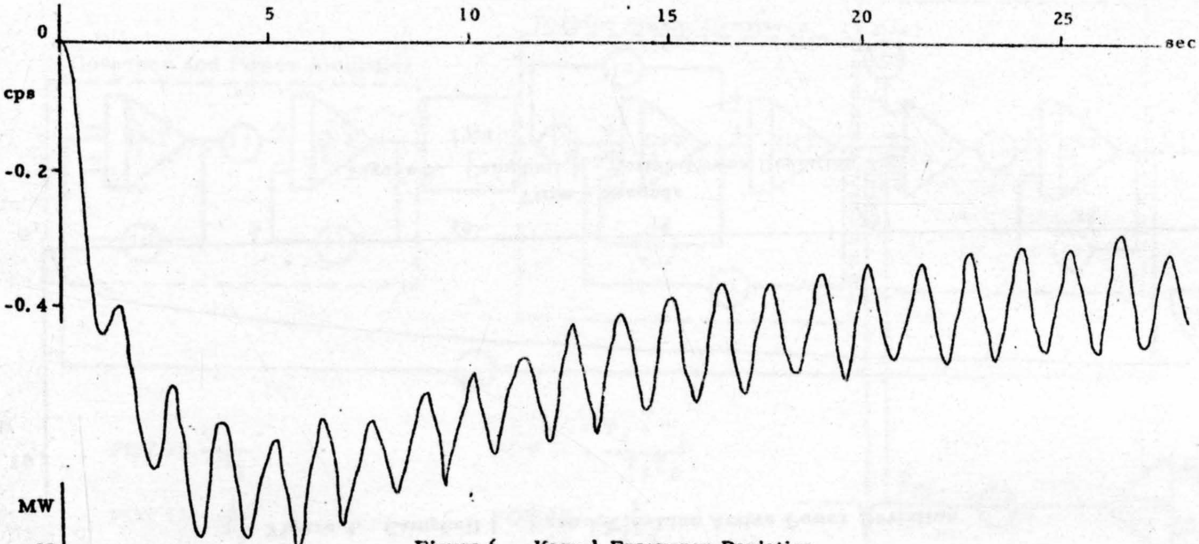


Figure 6. Karn 1 Frequency Deviation

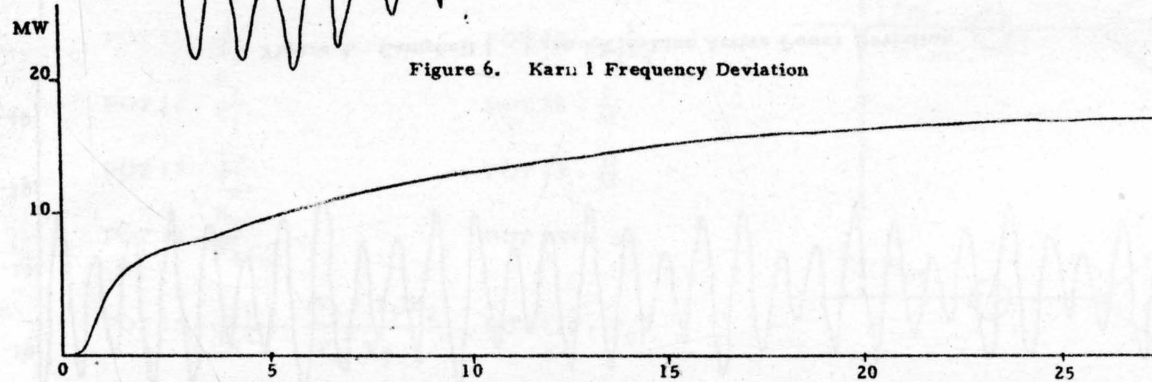
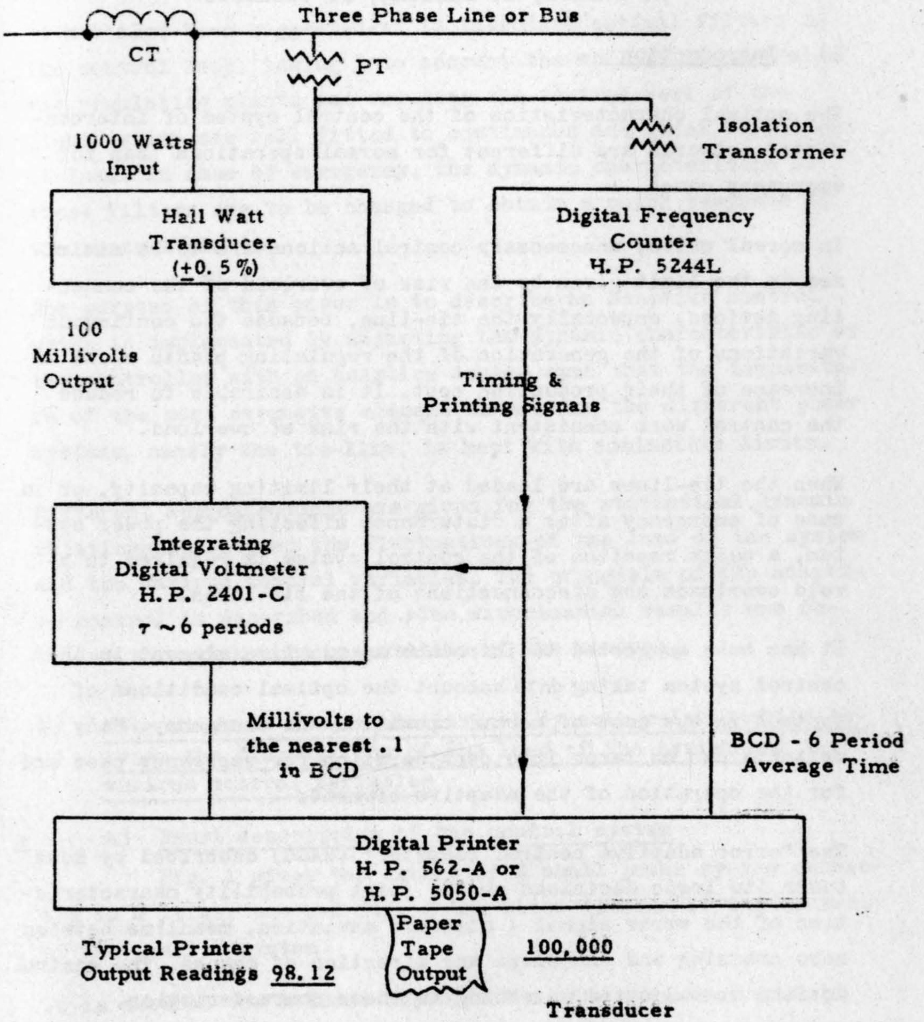


Figure 7. Karn 1 - Active Power Deviation



$$\text{Circuit Kilowatts} = \frac{(\text{CT Ratio})\,(\text{PT Ratio})\,(\text{Transducer Secondary Watts/Millivolt})\,(\text{Printer Millivolt Reading})}{1000}$$

$$\text{System Frequency} = \frac{6,000,000}{\text{Printer Reading}}$$

Figure 8. Frequency and Power Instrumentation

ADAPTIVE CONTROL OF INTERCONNECTED POWER SYSTEMS

M. Cuénod, A. Durling, P. Valisalo

1) Introduction

The optimal characteristics of the control system of interconnected networks are different for normal operations than for emergency cases.

In normal cases, unnecessary control actions are to be minimized in the limit given by the risk of overload of the connecting devices, especially the tie-line, because the continuous variations of the generation of the regulating plants cause an increase of their production cost. It is desirable to reduce the control work consistent with the risk of overload.

When the tie-lines are loaded at their limiting capacity, or in case of emergency after a disturbance affecting the power system, a quick reaction of the control system is required to avoid overloads and disconnections of the tie-lines.

It has been suggested to introduce an adaptive element in the control system taking into account the optimal conditions of control in the case of normal operation and emergency. Many criteria can be taken into consideration for emergency case and for the operation of the adaptive element.

The "error adaptive control computer" (EACC) described by Ross [1] bases its logic decisions on the joint probability characteristics of the error signal : standard deviation, meantime between zero crossing and the slope and direction of change. The control actions are adjusted according to these characteristics.

The "logic adaptive process for control and security in interconnected power systems" described by Couvreur [2] takes as the criterion the slope and the magnitude of the control signal, the power exchange and the frequency deviation. These characteristics are used to provide safe actions by bringing into operation quick starting units, load shedding, or changing the bias of tie-line control.

It has also been suggested[3,4] to introduce optimal filters in the control loop, taking into account the ability to control of the regulating plants and reducing the control work of the plants which are well fitted to continuous and quick variations of load. In case of emergency, the dynamic characteristic of these filters are to be changed to obtain a quick response of the control plants.

The purpose of this paper is to describe an adaptive control which is implemented by adjusting the dynamic characteristic of the controller with an adaptive device such that the temperature of the most expensive element connecting the different power systems, namely the tie-line, is kept with admissible limits.

Different approximations are given for the statistical dynamic relationship between the fluctuations of the load of the system and the various control variables. The principle of the adaptive control is described and some experimental results are obtained through hybrid computation of the control.

2) Determination of the statistical dynamic relationships between the fluctuations of the load of the system and the various control variables

a) Short description of the control system

Fig. 1 gives the scheme of a small power system connected to a larger one and fig. 2 the block diagram of the control of the smaller system.

It is assumed for a first approach that the frequency is kept constant by the large system and the statistical characteristics of the load fluctuations Q of the small system, with regard to the mean load of the power system, for a given time interval of observation can be described by the autocorrelation :

$$A_Q(\theta) = \sigma_Q^2 \, e^{-|\theta|/T_Q}$$

where σ_Q^2 = mean square value of the load fluctuation Q

T_Q = time constant of the "variability" of the load fluctuation

It is also assumed that the response curve $\gamma_{P_i\tau}$ of the temperature τ of the cable after a change of the exchanged power P_i is exponential with time constant T_τ :

$$\gamma_{P_i\tau}(t) = K_m \left(1 - e^{-t/T_\tau}\right)$$

where Km = the steady state temperature **variation.**

The transfer functions of the **various control variables** with regard to a variation of the load Q of the **system** are :

$$G_{QP_i}(s) = \frac{sT_r(sT_a + 1)}{s^2 T_r T_a + sT_r + 1}$$

$$G_{QP}(s) = \frac{1}{s^2 T_r T_a + sT_r + 1}$$

$$G_{Q\tau}(s) = \frac{sT_r(sT_a+1) \; K_m}{(s^2 T_r T_a + sT_r + 1)(sT_\tau + 1)}$$

with P_i = interchanged power

P = power of the regulating plant

T_r = time constant of the control system

T_a = time constant of the regulating plant

b) <u>Analytical determination of the autocorrelation of the control variables</u>

The auto-correlations of the control variable were evaluated by the relation

$$A_P(\theta) = \int_0^\infty A_Q(u+\theta) A_g(u) du + \int_0^\infty A_Q(u-\theta) A_g(u) du$$

where $A_g(\theta)$ is the auto-correlation of the systeme impulse response

$$A_g(\theta) = \int_0^\infty g_{QP}(t)\, g_{QP}(t+\theta)\, dt$$

the autocorrelation functions are normalized with respect to the time constant T_Q.

In annex the analytic expression of the autocorrelation function and the meansquare value of the various control variables are given in a special case where $T_a = 0$.

Figures 3a, b and c give these autocorrelation functions as a function of the relative value of the system time constant T_r/T_Q and figure 4 gives the meansquare values σ_P^2/σ_Q^2, $\sigma_{\dot{P}}^2/\sigma_Q^2$ and σ_τ^2/σ_Q^2 versus T_r/T_Q. These curves allow the selection of the control time constant T_r to obtain desirable performance and a prescribed σ_τ^2 for given values of σ_Q^2 and T_Q.

3) Principle of the adaptive control

Many criteria can be formulated for the adaptive control of power exchange, taking into consideration the control signal, the temperature of the tie-line, the exchange power variations and the frequency. The adaptive control discussed in this paper consists of adjusting the time constant of the integral element of the controller, according to these criteria. The adjustment can be made either continuously or in discrete steps.

a) Adaptive control according to the magnitude of the control signal

The time constant of the controller T_r can be modified in discrete steps, according to the magnitude of the control signal. Fig. 5 shows a control signal and three regions corresponding to different magnitudes of the signal.

Region A is the total range of the regulating power fluctuations.

Region B corresponds to the effective regulating region given by the capacity of the controller or by the limitations of the telemetering devices.

Region C is a narrow region around the meanvalue of the region A.

The limits of this band will be specifically defined in each case.

In interval 1 , the control signal is kept within the narrow band C, for which a large value of T_r is chosen, exerting minimal control work. This corresponds to a slow regulating effect which reduces the control work. In interval 2, the control signal y is in region D and T_r is set at an intermediate value. In interval 3, y is in the upper limit of the admissible region and the minimum value of T_r must be used to maintain the control signal in the regulating band, thus insuring that the cable temperature does not become excessive.

b) Adaptive control according to the temperature

Under normal conditions, with relatively quick variations of the power exchange P_i, the temperature of the cable is approximately proportional to the square of the mean value of P_i, over a given interval if constant voltage is assumed. The allowable standard deviation of the cable temperature fluctuation is approximately

$$\sigma_\tau^2 = \sigma_{\tau max}^2 \left(1 - \left(\frac{P_i}{P_{imax}}\right)^2\right)$$

where P_{imax} is the steady state value of the power exchange corresponding to the maximum allowable temperature τ_{max}. Fig. 6a shows the relationship between the temperature τ and the interchange power P_i, and fig. 6b shows the relationship between σ_τ^2 and P_i : when the mean value of the power interchange is small, the control can be slow, because large fluctuations of the temperature are admissible. When the mean value of P_i is near P_{imax}, the control must respond quickly (small T_r) to reduce the temperature fluctuations.

c) Adaptive control according to the power exchange variations

Computation of the power density spectrum or autocorrelation of the exchanged power fluctuationsover a specific period can be used to institute a control action.

It is necessary to identify the difference between normal fluctuations and variations due to perturbations on the system. The derivative of the exchanged power fluctuation over an interval proceeding control action as a criterion for adjusting the controller time constant. In normal operation, the mean value of the derivative is small, and in cases of emergency, the mean value increases to initiate a change in the time constant.

d) Adaptive control as a function of frequency deviation

Under actual conditions, the frequency of the interconnected system is not constant. Frequency perturbation can be considered as an emergency condition and compensated for by reducing the bias of the tie-line control, to prevent overload due to operation with poor frequency control. Also decreasing the time constant of the controller improves the frequency characteristics of the system. The present study considers only systems in which the frequency can be considered constant.

The integration of the fluctuation with a modified time constant can be approximated by integrating the fluctuations over a variable period and adjust the control action by varying the interval of integration ; a large interval of integration corresponding to a large integration time constant.

4) Experimental results of the adaptive control obtained by hybrid computation

Fig. 7 shows a sample of the stochastic function of the different control variables of the system for different values of the time constant T_r. Fig. 8 gives the corresponding autocorrelation functions of these variables.

Fig. 9 gives an example of the adaptive control, according to the magnitude of the control signal (Fig. 9a and 9b, without adaptive control and Fig. 9c and 9d, with the adaptive control.)

Fig. 10 gives an example of the adaptive control as a function of the mean value of the interchanged power. It can be seen that, when the mean value is high, the magnitude of the fluctuation of the interchanged power is reduced, and vice-versa.

Fig. 11 gives an example of the adaptive control after a perturbation causing a step change of the power exchanged.

With an adaptive control, the interchanged power comes back to its set point value much quicker than without adaptive control which reduces the temperature variation.

5) Conclusion

The problem of adaptive control of a power system is connected to the problem of the overload protective devices of the tie-lines and must be coordinated with these devices. The use of a "Thermal model" of the line, taking into account the thermal inertia of its cable provides a safety base which is consistent with the proposed adaptive control. Both means give the possibility to combine the safety of the transmission and a complete use of the capacity of the tie-line. This is true if other criteria are not considered such as voltage drop, dynamic stability and so on. Due to the increasing number of the links in tie-line, the "bottle neck" of the power exchange will be in many cases the risk of overload of the tie-line, because the distribution of the load between parallel links is not well defined, leading to a higher risk of overload.

The proposed adaptive system attempts to increase the reliability of the interconnected system and, in some case, to save the expenses of a new tie-line. It can be combined with other methods like load shedding and must be coordinated with appropriate protective devices.

Annex

Auto-correlation function and mean square value of the various control variables

$$\frac{A_Q}{\sigma_Q^2} = e^{-|\delta|}$$

$$\frac{A_{P_i}}{\sigma_Q^2} = \frac{t_r}{t_r^2-1}\left(t_r e^{-|\delta|} - e^{-\frac{|\delta|}{t_r}}\right) \quad (t_r \neq 1)$$

$$\frac{A_P}{\sigma_Q^2} = \frac{1}{t_r^2-1}\left(t_r e^{-\frac{|\delta|}{t_r}} - e^{-|\delta|}\right) \quad (t_r \neq 1)$$

$$\frac{A_\tau}{\sigma_Q^2 K_m} = \frac{t_r^2}{t_r^2-1}\left[\frac{1}{t_\tau^2-1}\left(t_\tau e^{-\frac{|\delta|}{t_\tau}} - e^{-|\delta|}\right) - \frac{1}{t_\tau^2-t_r^2}\left(t_\tau e^{-\frac{|\delta|}{t_\tau}} - t_r e^{-\frac{|\delta|}{t_r}}\right)\right] \quad (t_r \neq 1)$$

$$\frac{\sigma_{P_i}^2}{\sigma_Q^2} = \frac{t_r}{1+t_r}$$

$$\frac{\sigma_P^2}{\sigma_Q^2} = \frac{1}{1+t_r}$$

$$\frac{\sigma_\tau^2}{\sigma_Q^2 K_m} = \frac{t_r^2}{(t_r+1)(t_\tau+1)(t_\tau+t_r)}$$

with $t_r = \frac{T_r}{T_Q}$, $t_\tau = \frac{T_\tau}{T_Q}$, $\delta = \frac{\theta}{T_Q}$

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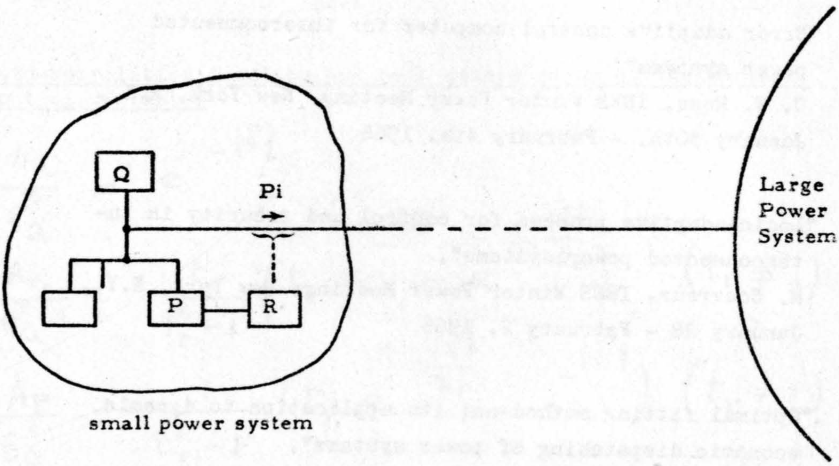


Fig. 1 Scheme of a small power system connected to a large one.

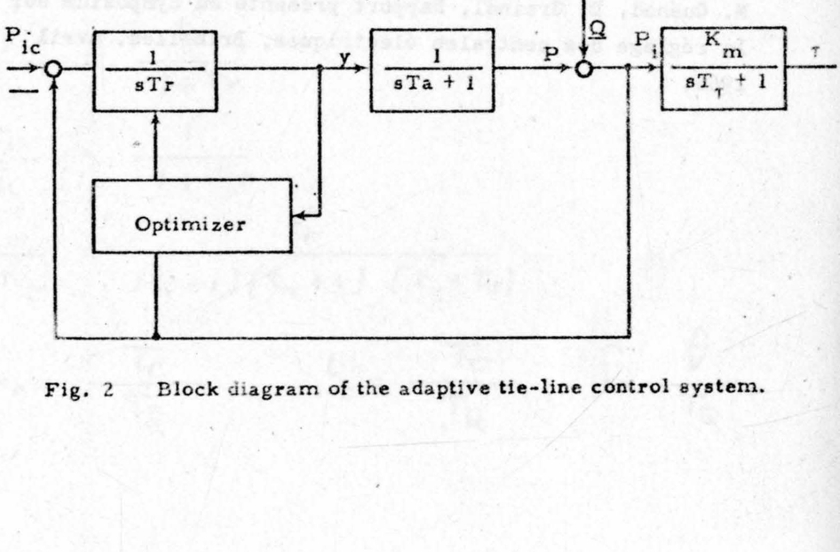
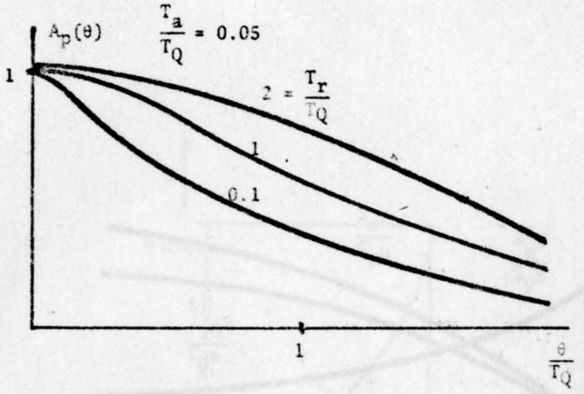
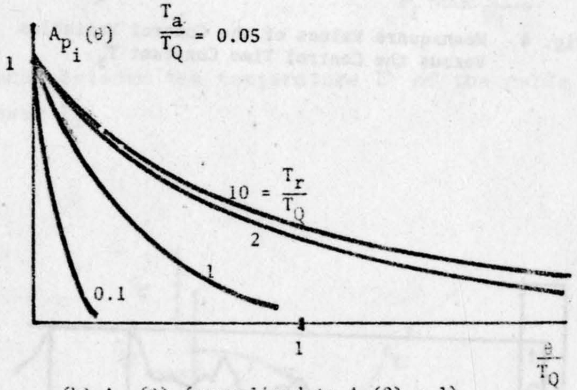


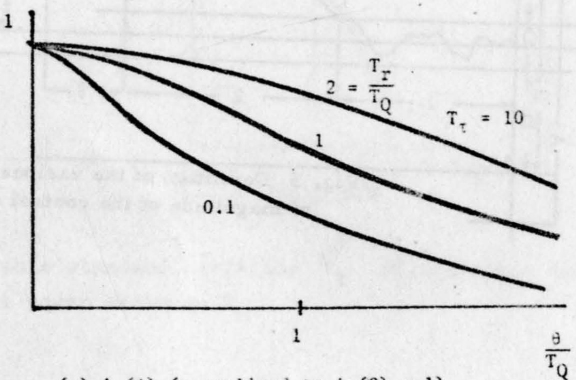
Fig. 2 Block diagram of the adaptive tie-line control system.



(a) $A_p(\theta)$ (normalized to $A_{p_i}(0) = 1$)



(b) $A_{p_i}(\theta)$ (normalized to $A_p(0) = 1$)



(c) $A_\tau(\theta)$ (normalized to $A_\tau(0) = 1$)

Fig. 3 Auto-correlations of the Output of the Regulating Plant P, of the Interchange Power P_i and the Temperature τ of the Cable

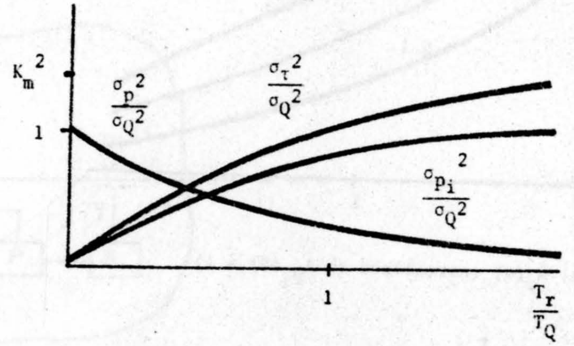


Fig. 4 Meansquare Values of the Control Variables Versus the Control Time Constant T_r

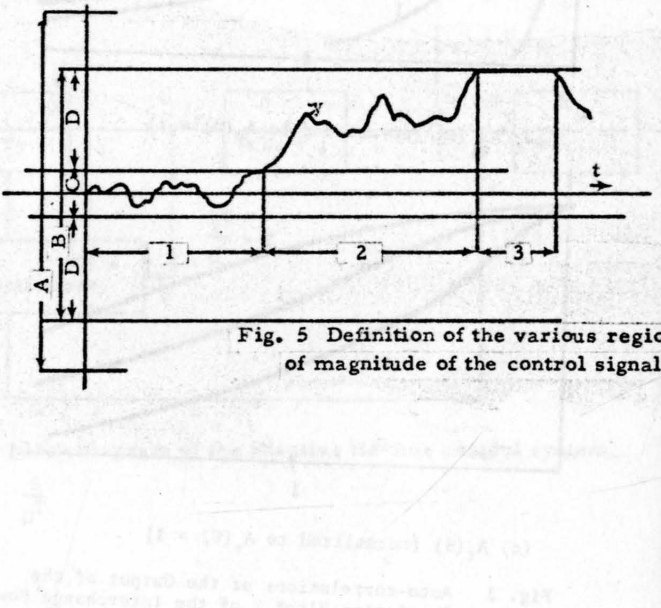
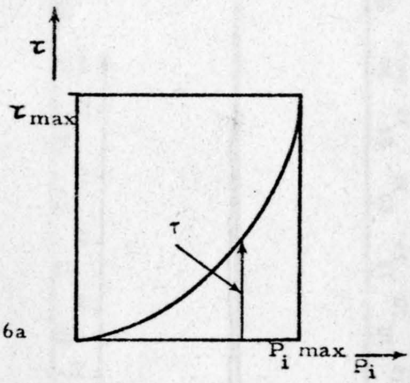


Fig. 5 Definition of the various regions of magnitude of the control signal y.



Relationship between the temperature τ of the cable and the interchange power P_i

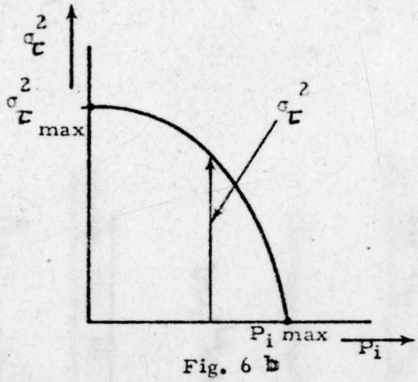
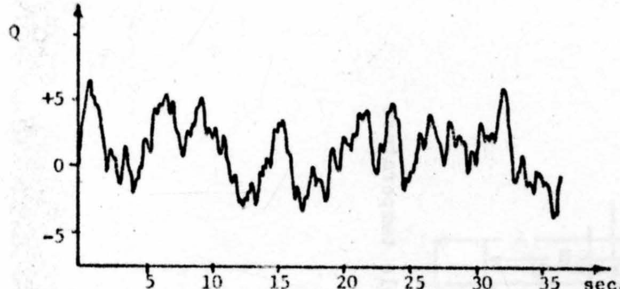


Fig. 6 b

The allowable standard deviation σ_{τ}^{2} of the cable temperature versus the power exchange P_i



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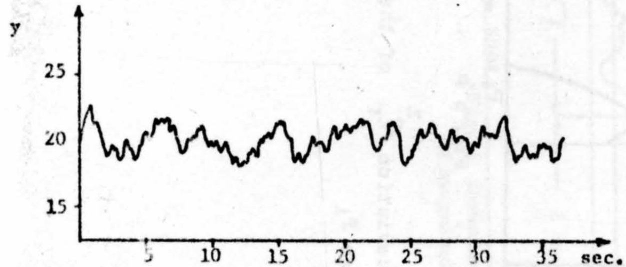

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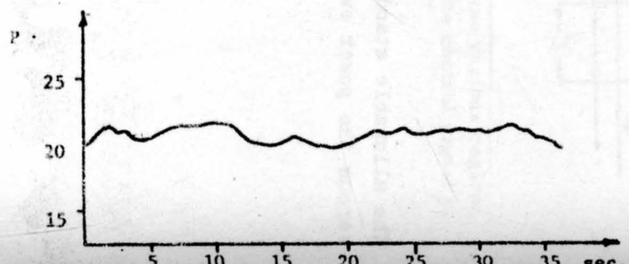

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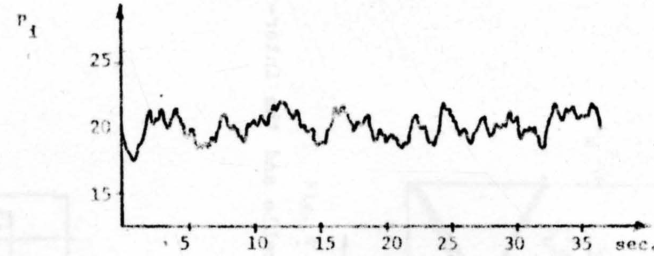

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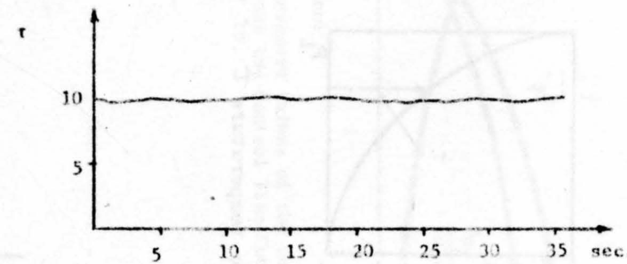
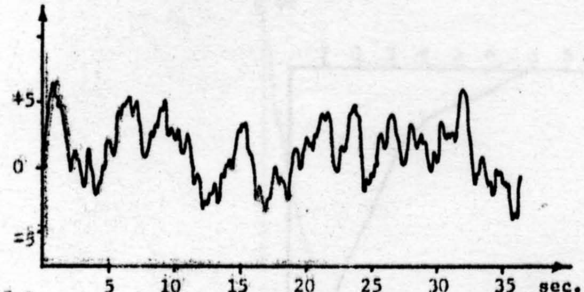


7 Λe

Fig. 7Λ. Sample of stochastic functions obtained by the simulation for $T_r = 2$ and $T_a = 0$



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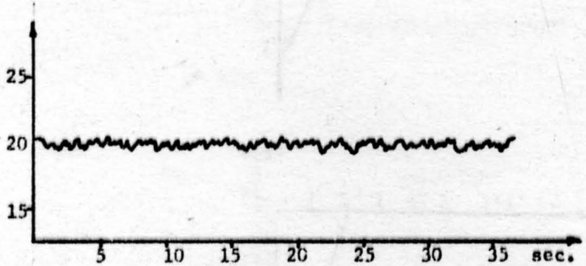

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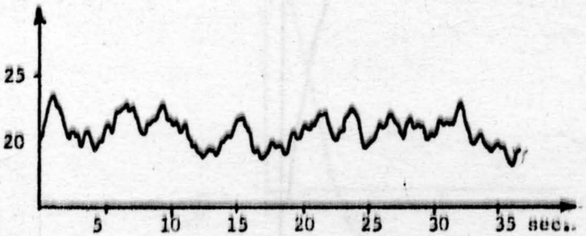

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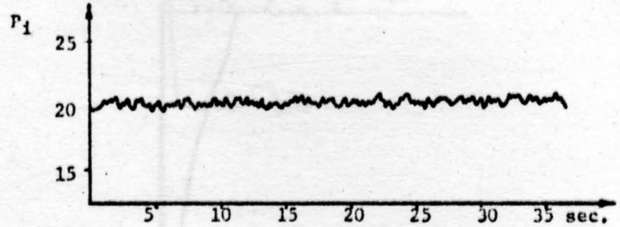

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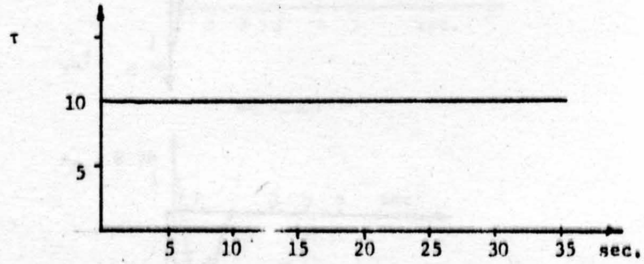


7 Be

Fig. 7B. Sample of stochastic functions obtained by the simulation for $T_r = 0.1$ and $T_a = 0$.

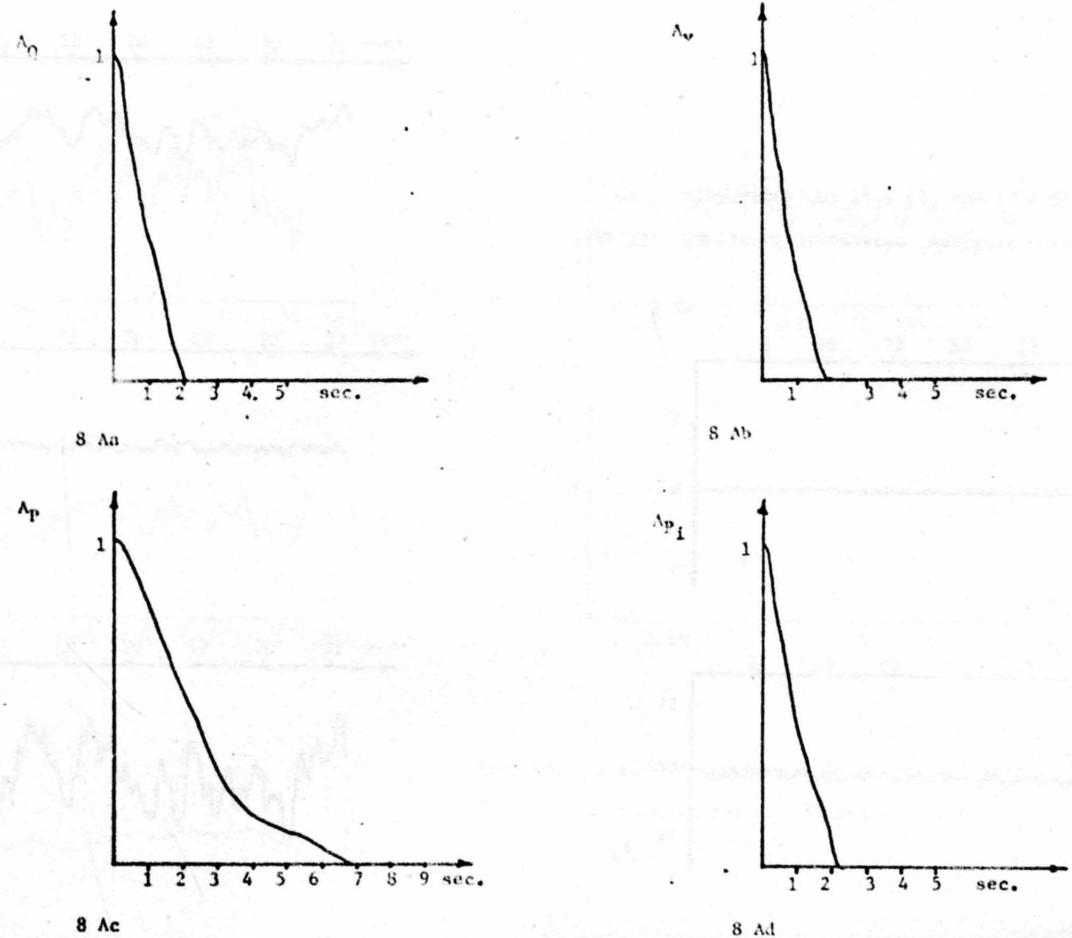


Fig. 8A. Autocorrelation function of the various control variables with $T_r = 2$ and $T_a = 0$

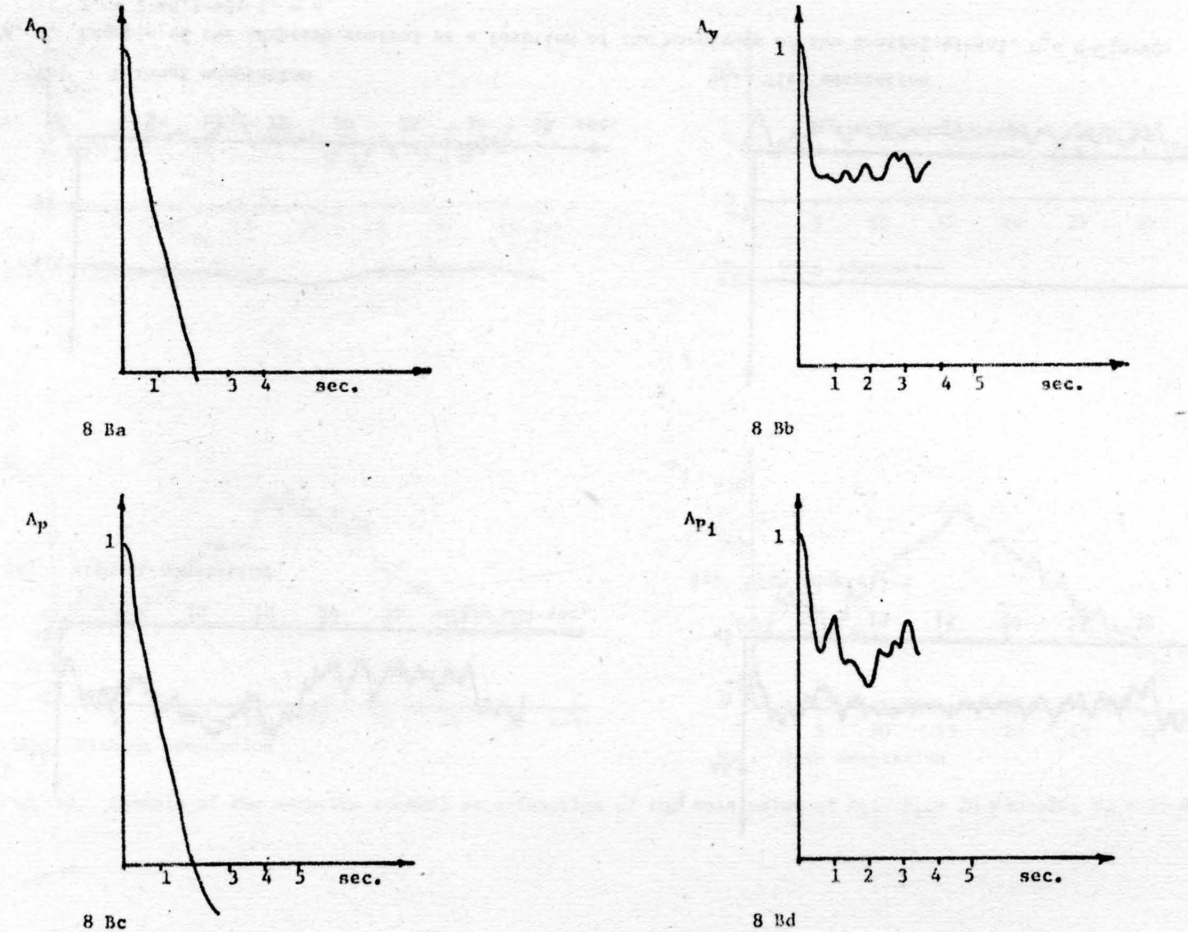
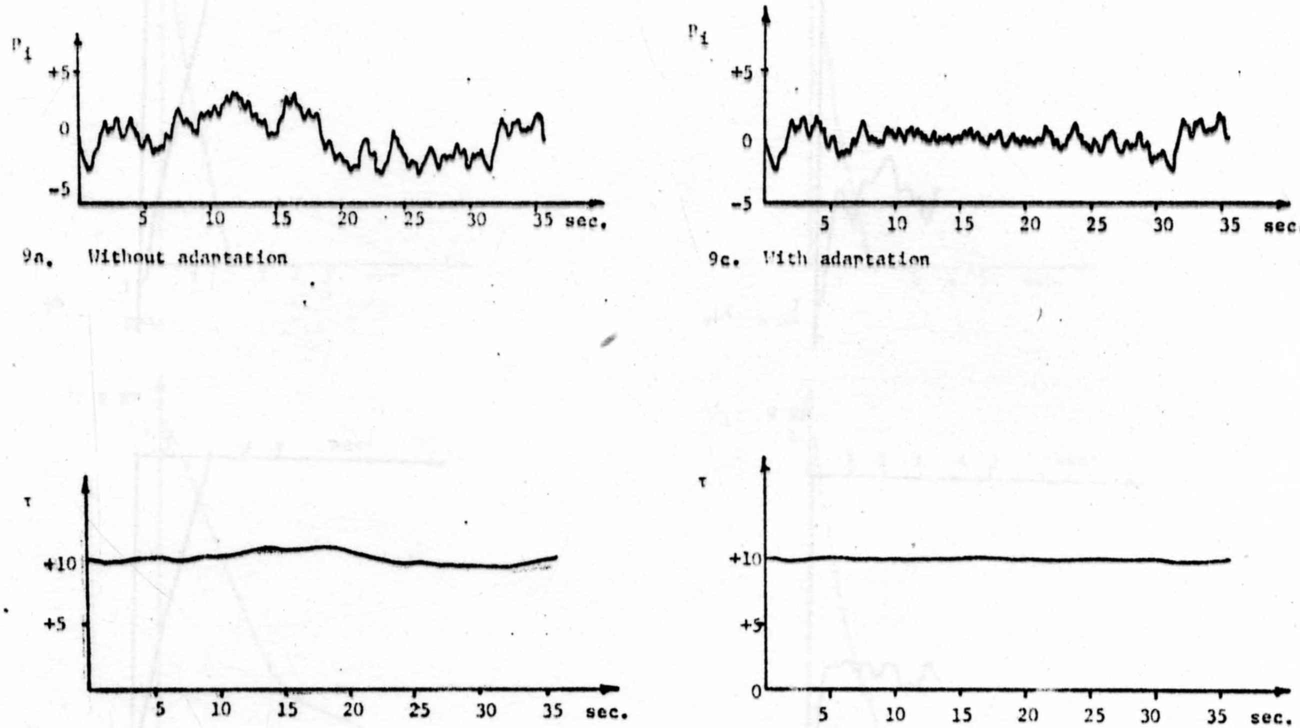


Figure 3B. Autocorrelation function of the various control variables with $T_r = 0.1$ and $T_a = 0$



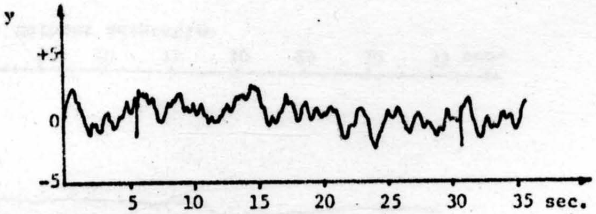
9a. Without adaptation

9c. With adaptation

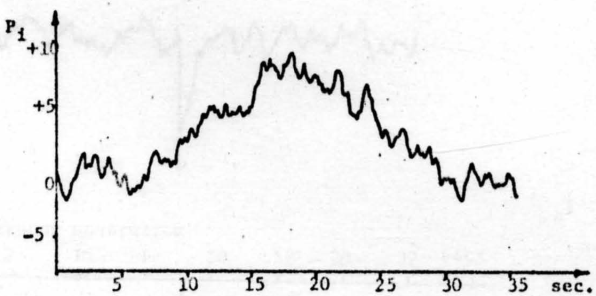
9b. Without adaptation

9d. With adaptation

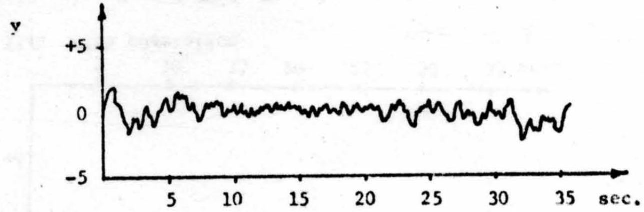
Fig. 9. Example of the adaptive control as a function of the magnitude of the control signal. $Q_m = 0 \to 10 \to 0$; $T_r = 2 \to 0.1 \to 2$; $T_\gamma = 4$



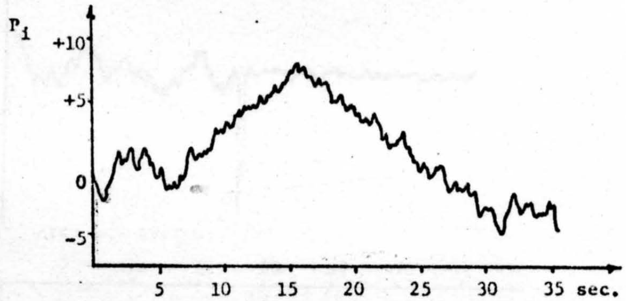
10a. Without adaptation



10b. Without adaptation



10c. With adaptation



10d. With adaptation

Fig. 10. Example of the adaptive control as a function of the mean value of P_i. P_{ic} = 20→30→20; T_r = 2→0.1→2.

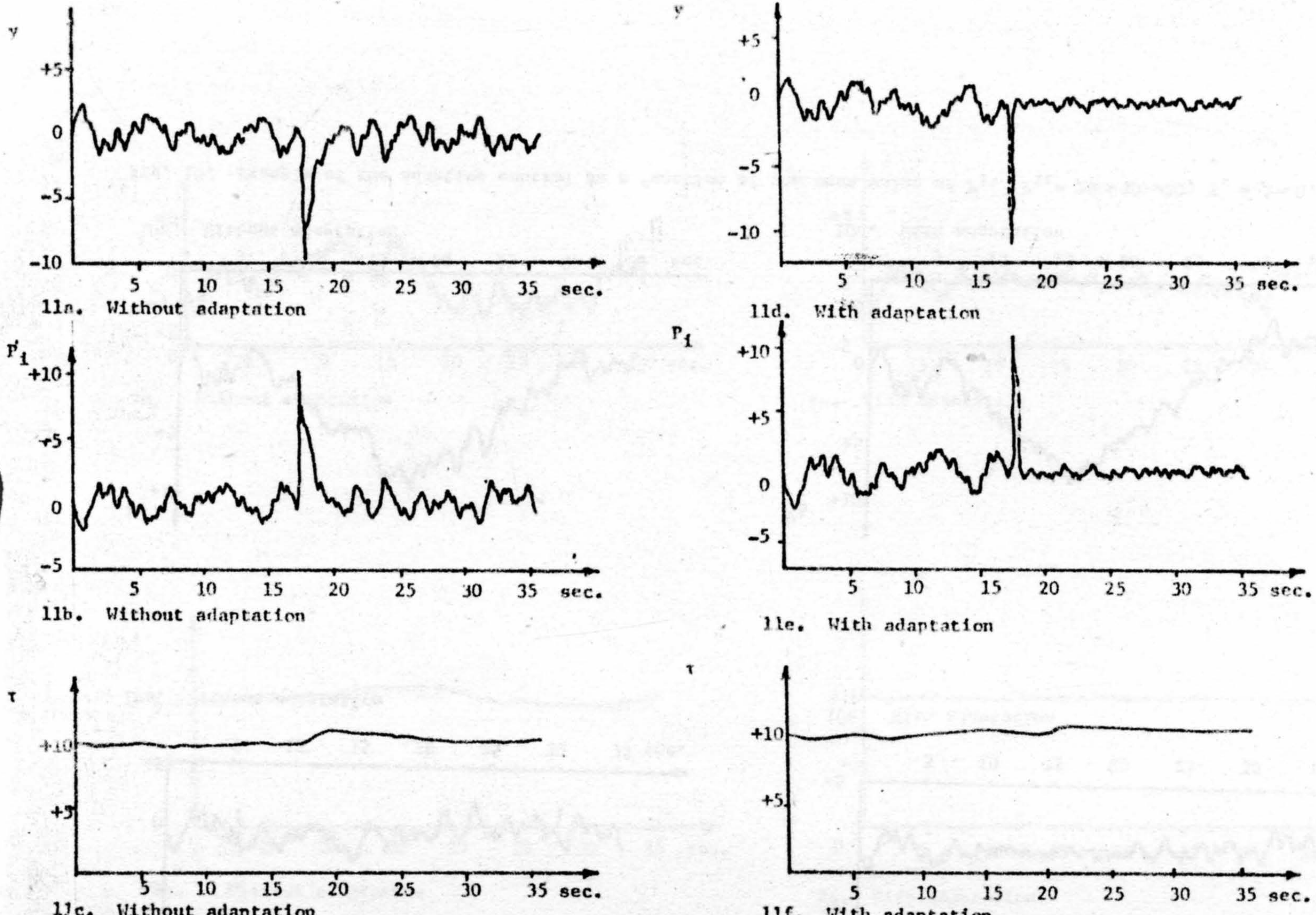


Fig. 11. Example of the adaptive control to a step change. O_m = 0→10 step; T_r = 2→0.1; T_I = 4.