MICROPROCESSOR GOVERNORS FOR HYDRO-TURBINE GENERATORS

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Doctor of Philosophy

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ABBREVIATIONS

A/D	Analogue to Digital (converter)		
ADP1	First Adaptive Microprocessor Governor		(7.9.78)
ADP2	Second Adaptive Microprocessor Governor		(10.10.78)
CEGB	Central Electricity Generating Board		
CMOS	Complementary Metal Oxide Semiconductor		
CPU	Central processing unit		
D/A	Digital to Analogue (converter)		
DD	Double Derivative (governor)		$T_2 = T_4 = 0.2$
DDO	" " "		$T_2 = T_4 = 0$
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DDHI2	" " "	" "	(10.10.78)
DDLOW1	" " "	low band	(7.9.78)
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DDMID1	" " "	mid band	(7.9.78)
DDMID2	" " "	" "	(10.10.78)
DEC	Digital Equipment Corporation		
DECUS	DEC User Society		
DOS	Disk Operating System		
ILS	Isolated Load Simulator		
I/O	Input/Output		
LSB	Least Significant Bit		
MPU	Microprocessor unit		
MSB	Most Significant Bit		
MW	Megawatts		
NSHEB	North of Scotland Hydro-Electric Board		
TD	Temporary Droop (governor)		
U/V	Ultra Violet (recorder)		
VCO	Voltage Controlled Oscillator		

SYMBOLS

When a symbol is repeated twice, once in upper case then in lower case (e.g. Y, y) this signifies the same quantity. The upper case form relates to the quantity in the frequency domain whilst the lower case form implies the time domain.

a	Constant - partial fraction representation of governor
A	Constant - partial fraction representation of governor
A_{cv}	Control valve area (m^2)
A_p	Cross sectional area of conduit (m^2)
a_v	Sonic wave velocity (m/s)
b	Constant - partial fraction representation of governor
B	Constant - partial fraction representation of governor
b_p	Permanent droop
b_t	Temporary droop gain constant
c	Constant - partial fraction representation of governor
C	Constant - partial fraction representation of governor
C_d	Discharge coefficient
C1 - C7	Coefficients in simple analogue plant simulation
d	Per unit temporary droop output position - mechanical TD governor
DFR	Narrow band frequency
e_n	Load self regulation factor (ILS)

FR1	Narrow band frequency
FR2	Wide band frequency
g	Acceleration due to gravity (m/s^2)
G_1	Transfer function - 3rd order TD governor representation
G_2	Transfer function - 2nd order TD governor representation
G_3	Transfer function - simplified 2nd order TD governor representation
h	Per unit deviation of turbine head
H	Per unit turbine head
H_{mv}	Head at main valve (m)
H_p	Line pressure head (m)
H_R	Reaction head (m)
H_v	Turbine velocity head (m)
I	Rotational inertia (Kgm^2)
I_B	Generator Current - Blue phase
I_R	Generator Current - Red phase
J, j	Per unit internal governor parameter
K	Constant
K_1	1st derivative gain constant - DD governor
K_2	2nd derivative gain constant - DD governor
K_L	Loss factor in simple analogue plant simulation
k_n	Isolated Load Simulator constant
K_p	Feedback lever ratio gain factor - mechanical TD governor
$1/K_s$	Main servo time constant - mechanical TD governor
LL	Per unit Load Limit demand.

m	Per unit deviation of turbine torque
M	Per unit turbine torque
MW	Per unit Megawatt demand
n	Per unit deviation of turbine speed
N	Per unit turbine speed
N_r, n_r	Per unit speed reference
N_s, n_s	Per unit speed
P_L	Per unit total load power (ILS)
P_m	Per unit turbine power (ILS)
P_o	Per unit balancing load power demand (ILS)
ps	Per unit pilot servo position - mechanical TD governor
pv	Per unit pilot valve position - mechanical TD governor
q	Per unit deviation of turbine flow
Q	Per unit turbine flow
Q_T	Turbine volumetric flow rate (m^3/s)
Q_V	Volumetric flow rate (m^3/s)
r_i	Inner radius of turbine blades (m)
r_o	Outer radius of turbine blades (m)
R, r	Per unit internal governor parameter
SP1 - SP5	Various speed used during run-up - Frequency Transducer
SVO, svo	Per unit main servomotor output
SYNC	Main breaker status open/closed - Frequency Transducer
t	Time (s)
T	Sampling interval (s)
$T_{1/10}$	Time to settling band of 1/10 (s)
T_2	1st derivative, lag time constant - DD governor (s)

T_4	2nd derivative, lag time constant - DD governor (s)
T_a	Generator inertia time constant (s)
T_b	Time constant within simplified TD governor representation
T_c	Time constant within simplified TD governor representation
T_d	Temporary droop time constant (s)
T_p	Pilot valve time constant - mechanical TD governor (s)
T_s	Main servo time constant - separate hydraulic actuator(s)
T_w	Water starting time constant (s)
T_y	Main servo time constant - mechanical TD governor (s)
U, u	Per unit governor input i.e. speed error
V,v	Per unit internal governor parameter
VDET	Input signal detected - Frequency Transducer
V_{in}	Resultant measured voltage used as input to frequency transducer
V_o(FR)	Frequency reference
V_o(LL)	Load limit demand
V_o(MW)	Megawatt demand
V_{RY}	Generator voltage measured between red and yellow phase
V_{YB}	Generator voltage measured between yellow and blue phase
X	Per unit governor lag output
Y,y	Per unit governor output
YA, ya	Per unit component part of governor output (partial fraction representation)
YB, yb	Per unit component part of governor output (partial fraction representation)
YC, yc	Per unit component part of governor output (partial fraction representation)
z	Per unit deviation of turbine gate position
Z	Per unit turbine gate position

α	Constant	
ΔA	Per unit deviation of control valve area	
ΔP	Per unit power disturbance	(ILS)
ΔW	Per unit deviation of power	
$\Delta \tau$	Per unit torque disturbance	(ILS)
η	Turbine efficiency	
ρ	Density of fluid	(Kg/m^3)
ω	Angular velocity of turbine	(rad/s)
$\dot{\omega}$	Angular acceleration of turbine	(rad/s^2)
ω_o	Normal rated speed	(rad/s)
τ	Developed turbine torque	(Kgm^2/s^2)
τ_r	Normal rated torque	(Kgm^2/s^2)
τ_L	Load torque demand	(Kgm^2/s^2)
τ_o	Per unit balancing torque demand	(ILS)
τ_m	Per unit turbine torque	(ILS)

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SUMMARY

The aim of the work described within this thesis was to investigate the use of a microprocessor in the field of speed governing of a hydro-turbine generator. By applying the methods of interactive, real time simulation studies, microprocessor governors having characteristics of existing mechanical or electro-hydraulic governors were developed and tested. Following on from these successes a novel adaptive microprocessor governor was implemented. Each of these microprocessor governors was proven by using them to control a real time digital simulation of a hydro-turbine generator. Finally, one of the 32.5 MW generator units of Sloy Power Station was successfully controlled by all the microprocessor governors produced. The adaptive governor proved itself superior to conventional governors, being exceptionally responsive with the generator connected to the National Grid Distribution System, while retaining stability over the full operating range during simulated isolated load conditions.

INTRODUCTION

Over a period of some years the Department of Electronics and Electrical Engineering at Glasgow University and the North of Scotland Hydro Electric Board (NSHEB) have been jointly pursuing investigations into improved speed governing of hydro-turbine generators. Most of this work has centred around Sloy Power Station on Loch Lomondside. The NSHEB provided the facilities at Sloy to measure the characteristics of the existing English Electric governors and more importantly they allowed experimental governors to be tested on one of the 32.5 MW hydro generator sets.

Many of the governors in use at present are of the Temporary Droop (TD) type. They offer very good stability when controlling a Francis Hydro-turbine generator which is supplying a load that is isolated from the National Grid. This governor type, however, displays a very slow speed of response when it is required to pick up load. Typically the speed of response is characterised by a dominant lag with a time constant of the order of three minutes. The work carried out at Glasgow University has been aimed at producing governors, specifically for Francis turbines, which provide a fast speed of response (in the range 10-30 seconds for the dominant lag) when the generator is connected to the National Grid. This fast speed of response was not to jeopardise the overall stability of the governor and hydro-turbine generator system during conditions of isolated load.

A previous project investigated the use of analogue electronics for determining the governor characteristics. This current project, however, was made possible by the new technologies which are able to provide comprehensive digital processing power in the form of the economical microprocessor. Assuming the feasibility of microprocessor governors then there are obvious advantages to be gained over their analogue counterparts. For example, the drift characteristics of analogue electronics due to non-ideal and ageing components does not exist in the digital domain. The digital computer also lends itself to the application of sophisticated algorithms.

Thus it was the aim of this project, which commenced in October, 1975, to produce and test on site, firstly a microprocessor governor with already proven characteristics, and secondly to develop an adaptive microprocessor governor to provide yet a better speed of response over existing governor types. Much of the work presented within these pages has been reported in Reference 1. (A copy of this Reference is contained in Appendix A.) A secondary aim of this project was to provide an accurate real time digital simulation of the plant characteristics at Sloy. The advantages to be gleaned from a purely digital simulation are repeatability and transportability of the simulation.

There are ten Chapters to this thesis. The first gives a general introduction to the various characteristics of different types of hydro electric schemes. The generating scheme at Sloy is also described. Chapter 2 provides an overview of governing strategies to the present day while Chapter 3 details the models of the hydro electric plant which were used during simulation studies. A description of the methods of simulation along with the findings of some of these studies is presented in Chapter 4.

As a result of the various projects associated with Sloy a comprehensive site test facility has been developed at Sloy power station. The author's involvement with the production of this interface equipment was limited mainly to the commissioning of the electronics. However, a full understanding of its operation was required, not only for commissioning purposes, but also to enable the proposed microprocessor to communicate sensibly with these facilities. Chapter 5 presents an overview of this interface equipment, and additional information may be found in Reference 2. (This Reference is also contained within Appendix A)

The development of the microprocessor governors can be found in Chapter 6 and some additional aids that were devised to ease the on site investigations at Sloy Power Station are detailed in Chapter 7. Chapters 8 and 9 contain the results from the major trials conducted on site. Finally, the conclusions and recommendations arising from this work are given in Chapter 10.

The claim for originality with this work lies with the application of a microprocessor as a speed governor on an actual hydro electric power installation and more importantly, the successful application of an adaptive microprocessor governor in 1978.

(A number of the figures throughout the thesis are the results of simulations or site tests. Appendix G lists the associated data for the results shown on these figures.)

CHAPTER 1 - GENERAL ASPECTS OF HYDRO-ELECTRIC INSTALLATIONS

1.1 Introduction

The electricity generating industry in the United Kingdom is obliged to provide for its customers a 50 Hz supply to within $\pm$ 0.5 Hz and to a tolerance of $\pm$ 6% of the stated voltage. For the period 1976/77 (Reference 3) this was achieved throughout Britain (excluding Northern Ireland) by the use of 253 power stations of various types, some statistics of which are shown in Table 1.

Station Type	No. of Stations	Aggregate output capacity MW	Electricity generated GWh
Steam	132	55,865	214,564
Nuclear	11	5,080	36,917
Gas Turbine	28	2,292	929*
Oil Engine	9	118	-
Conventional Hydro-electric	70	1,284	3,330
Pumped storage	3	1,060	1,313
All	253	65,699	256,553

* Note: The electricity generated by oil engine stations is included within the figure for gas turbine stations.

Table 1.1 United Kingdom (excluding Northern Ireland) Public supply power stations capacity and total electricity generated.

From these figures it can be seen that the installed capacity of hydro-electric power, including pumped storage, is slightly less than 3.6% of the total, and that the total electricity supplied by hydro means was 1.8% of the total.

According to the CEGB (Reference 4), during a typical day the consumer demand falls between the hours of midnight and 0600h, and rises to a peak through the day. If supply and demand were not matched the system frequency would exceed the allowable limits. The correct balance is reached by starting and stopping generators and adjusting their individual outputs which generally results in the frequency being $\pm$O.1Hz of nominal.

In order to maintain the integrity of the supplied electrical power there must be a proportion of the generating plant operating as spinning spare reserve (i.e. running, but not fully generating), so that compensating action may result as soon as any change of system frequency is detected. It is not feasible to use nuclear plant for this purpose, it is costly to operate gas turbines, and it is undesirable to have steam plant utilised for spinning spare reserve due to the lost revenue through operating at lower efficiency.

Although, at present, hydro plant contributes a small percentage of the total requirements in the U.K., it is extremely useful for assisting the total generation system over the peak demand periods of the daily load cycle. And now with the ever increasing capacity of pump-storage plant (i.e. Cruachan (400 MW), Foyers (300 MW), Ffestiniog (260 MW), Dinorwic (1800MW) (still under construction) and the proposed Craig Royston (3200 MW) scheme on Loch Lomond) further advantages of hydro power will be realised. For example, when consumer demand is low and consequently electricity is cheap, pumped storage plants can replenish their upper reservoirs by pumping from their lower reservoirs and if, while in this mode of operation, some other generation loss occurs, the pumping can be immediately stopped until alternative generators are brought into service.

Additionally, the relatively fast start up time of hydro sets aids the system after the tripping of any large generating plant. As an example, Ffestiniog can donate its 360 MW within 55s, and with special design, pumped-storage stations could be used to generate all the required emergency power by coming on line as generation plant within 10s. When the Dinorwic pumped-storage scheme becomes operational in the early 1980's, it may be capable of this fast start up time. It could be achieved by motoring the machines in readiness for emergencies, but with the turbines de-watered by the use of compressed air so that losses are reduced to a minimum.

Compared with the two minute start up time of gas turbines, hydro plant now offers a much improved response time to large grid disturbances. There is a disadvantage, however, with these very fast acting machines. The fast speed of response is achieved at the expense of stability on isolated load. (Reference 5)

Hydro plant offers a more economical solution to providing spinning spare reserve than does steam powered generating systems. Although the efficiency of hydraulic turbine-generators tends to fall off at low loads, as illustrated in Figure 1.1 there is no fixed heat loss irrespective of load setting as occurs in steam power-generating equipment. Thus if a fast acting hydro plant with isolated load stability can be achieved then all desirable operational characteristics of a hydro-turbine generating system will have been met.

It is the aim of this project to produce a governor which has a fast speed of response (of the order of 10-30 second dominant lag), but one which still maintains stable operation under isolated load conditions.

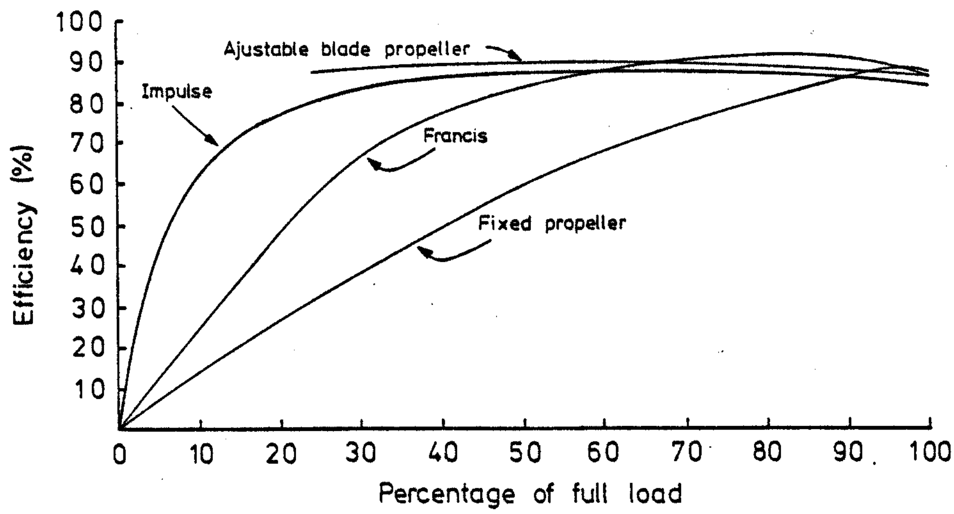


Fig. 1.1 Efficiency characteristics for various types of turbines

1.2 Types of Hydraulic Turbines

Hydraulic turbines may be grouped in two general classes. Firstly, there is the impulse (or Pelton) type which derives its power from the kinetic energy of a high velocity jet which acts on a small part of the circumference at any instant. Secondly, there is the reaction type which develops power from the combined action of pressure and velocity of water that completely fills the runner and water passages. The reaction type is further sub-divided into two groups: the Francis (sometimes referred to as reaction) and the propeller. The fixed blade and adjustable blade propeller types create yet another division within the propeller turbines.

Comparison of the efficiency characteristics (Figure 1.1) of the various types of turbines reveals a marked difference in their performance. There is, however, a more fundamental reason for choosing any particular type of turbine. The head of water between the reservoir and the turbine generally determines which turbine type should be used. The three types of turbines are commonly associated with the following ranges of head:-

a) Impulse turbine	800 ft and up
b) Francis turbine	50-800 ft
c) Propeller turbine	15-100 ft

The geography of the land has dictated that the Francis turbine predominates throughout the hydro installations of Britain and in particular at Sloy Power Station. Consequently the governor studies of this project have centred round this type of turbine. In addition, the successful development of a fast, stable governor for these turbines would be directly applicable to the large pumped storage schemes, since the Francis turbine is the only suitable type for reversible use.

The salient features of the operation of a Francis turbine are presented in the following paragraphs.

Surrounding the Francis turbine is a casing or flume round which the water flows with a relatively low velocity. Guide vanes round the entire circumference of the casing direct the water flow into the runner, and then the blades of the turbine deflect the flow into an axial direction so that the exhaust water is discharged through the draft tube and thence to the lower reservoir. The scroll or spiral casing guiding the water is designed with the cross-sectional area reducing uniformly around the circumference from a maximum at the entrance to very nearly zero at the tip. This reduction results in the water flowing smoothly at an almost constant velocity around the casing, producing uniform distribution of water to all parts of the runner and a nearly uniform pressure arcund the entire casing.

A large proportion of the power developed in the Francis runner is due to the pressure difference acting on the front and back of the runner buckets (Reference 6) with additional power being produced by the dynamic action due to the velocity of the water. The draft tube also contributes to the available power due to the suction created by the vertical column of water below the runner and because the outlet of the draft tube is larger than the throat just below the runner, thus utilising a part of the kinetic energy of the water leaving the runner blades.

1.3 The Loch Sloy Development

Having discussed briefly the general aspects of hydro-electric installations, it is now appropriate that a more detailed description of the Loch Sloy hydro-electric scheme be presented, since it was for this power station that simulations and new governors were designed. The reason for focusing on Sloy was that the NSHEB in conjunction with the Department of Electronics and Electrical Engineering at Glasgow University had agreed to provide on-site facilities for the testing of new governors.

Throughout the following discussion it may be useful to refer to the photographs of Plates 1 to 6 which show various aspects of the Sloy development. Figure 1.2 presents a simplified diagram of the Sloy pipeline system.

The construction work at Sloy began in 1945 but before this there had been several schemes proposed to transform this geographically favourable site into a source of hydro-electric power. Among them were plans to produce a plant with a total generating capacity of 360 MW, and one which would have made the Loch Sloy Power Station the first in the United Kingdom to provide pumped-storage. At that time the use of a single runner for both generation and pumping

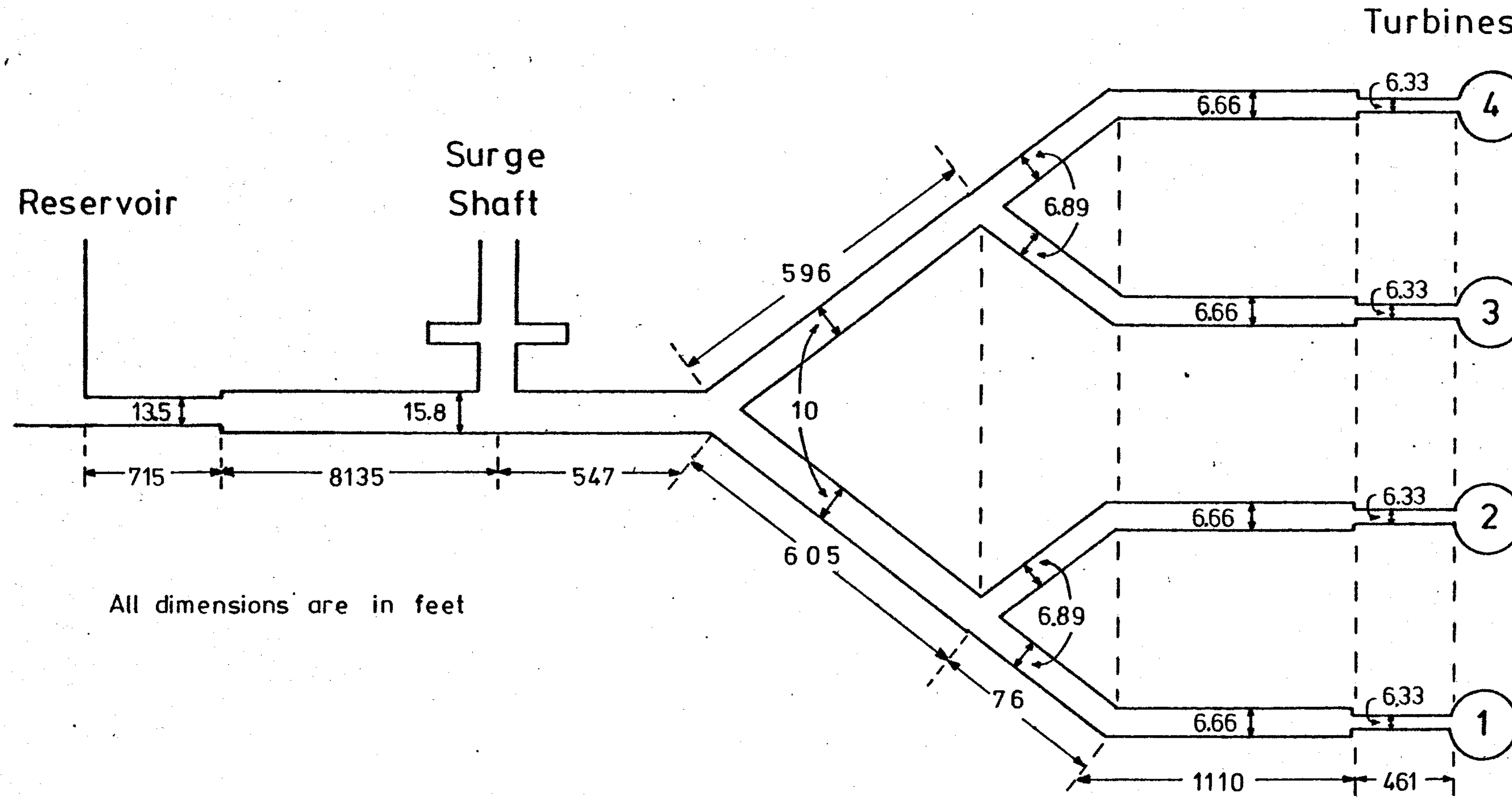


Fig. 1.2 Pipeline arrangement for Sloy Power Station

was not sufficiently advanced so the proposed pumped-storage scheme would have used a double runner, one at each end of the generator/motor and dedicated either to pumping or generating. However, this proposal was dropped and the final choice of power station was that of a peak-load station with a total rated capacity of 130 MW from four machines.

Loch Sloy was originally a small and natural loch situated in the steeply sided valley between Beinn Dubh and Ben Vorlich, approximately 2 miles (3.22 km) west of Loch Lomond. The initial height of the loch above sea level was 782 ft (238.4 m) but was further increased by 153 ft (46.6 m) due to the dam built to create a reservoir. Thus the reservoir elevation is 935 ft (285 m) resulting in a gross head of 910 ft (277.4 m) to the power station, since the station site is itself at an elevation of 25 ft (7.6 m).

The natural catchment area of Loch Sloy was 6.5 sq. miles (16.8 sq.km) but by virtue of an extensive aqueduct system this was increased to 31.3 sq. miles (81sq.km).

The reservoir dam, pictured in Plate 2, is a buttress type dam with two of the spaces between buttresses covered over by reinforced concrete slabs on the downstream side in order to form a spillway over the site of the original outlet. Rising from the top of the dam can be seen the intake tower which accommodates the gates, screens and operating gear controlling the flow (2,200 cu ft/s (62.3 m^3/s) at full load) into the tunnel through the mountain leading to the pipelines beyond. The tower itself is about 205 ft (62.5 m) high from sill to roof and at the foot of the tower lies the outlet pipe of diameter 13 ft 6 in (4.1 m) passing under the dam. This main tunnel slopes down from the foot of the dam and proceeds for 1.8 miles (2.9 km) through the mountainside south of the peak of Ben Vorlich until it emerges at the head of the pipeline on the hillside above Loch Lomond. During its travel the tunnel changes its form and diameter several times. For 715 ft (218 m) the tunnel is 13.5 ft (4.1 m) in diameter and is steel lined in this section where the rock cover is limited. After this the tunnel shape changes to a horse shoe shape having an area of 192 sq ft (17.8 m^3) and is lined with unreinforced concrete to provide a smooth surface for the water flow. The length of this section is 8,682 ft (2,646 m) and after this the tunnel bifurcates into two separate tunnels with a welded steel plate lining 10 ft (3 m) in diameter embedded in concrete. These two tunnels travel for 600 ft (183 m) before they emerge as pipes entering the valve house. One important feature of the tunnel system has not as yet been mentioned but cannot be ignored and this is the surge shaft which is situated 1,000 ft (304.8 m) back up the tunnel from the valve house. The diameter of the surge shaft is 26 ft (7.9 m) and the overall height is about 275 ft (83.8 m), with an expansion chamber at the top. Just above the roof of the tunnel there are two expansion chambers each about 120 ft (36.6 m) long and of a cross-section similar to that of the main tunnel. This elaborate surge shaft ensures that the water level will not fall to the roof of the tunnel when load is thrown on to the station and the reservoir is low, and conversely, the shaft provides temporary storage space when load is thrown off.

The valve house itself, as the name implies, contains four butterfly valves 7 ft (2.13 m) in diameter, which can be individually shut in the event of accident causing excessive discharge, or simply in order to enable inspection or repair.

If a pipe has been emptied then the means of refilling it is by use of a hand-operated sluice valve allowing flow into the main pipe via a 10 in (25.4 cm) bypass pipe. Another feature just downstream of the main valve is an anti-vacuum valve which is designed to prevent dangerous vacuum conditions within the pipe; and it also provides for the entry or discharge of air during the emptying or filling of the pipeline.

The valve house marks the position of the second bifurcation of the two pipes, resulting in four 6.89 ft (2.1 m) pipes beginning their descent down the surface of the hillside. The diameter of the pipelines changes twice, reducing to 6.66 ft (2.03 m) and then to 6.33 ft (1.93 m) before finally reaching the power house approximately 1,650 ft (502.9 m) away.

At the entrance to each of the spiral casings there is a main valve of the cylindrical balanced type with an inlet diameter of 76 in (1.93 cm) and outlet size of 60 in (1.52 cm). A similar type valve of 28 in (71.1 cm) is situated directly in line with the main valve further along the spiral casing. This is the relief valve and it is connected to the governor such that it will open if the governor action exceeds a certain rate of closure. As the fastest designed closure rate for the governor is 2 seconds for full stroke the relief valve is an essential part of the system, for without it, there would undoubtedly be disastrous consequences from the resultant pressure wave in the pipeline. After any relief valve action reclosure is achieved slowly by means of the timing dashpot or if the governor reopens the guide vanes, then the relief valve closes proportionately.

Sitting on the last pipeline anchor block immediately behind the machine hall are the four 11/132 KV transformers, which are cooled by water, pumped from the tailrace. The machine hall contains four vertical shaft reaction turbines whose normal running speeds are 428 rpm and each runner drives a 32.5 MW (0.95 power factor) generator. These 11 KV alternators are directly coupled to the turbine with the thrust-bearing situated above the rotor and this bearing supports the weight of the rotor and also the hydraulic thrust from the turbine runner, amounting to a total of 235 tons (238.7 tonnes). Two further bearings exist to guide the shaft, the upper guide being an integral part of the thrust-bearing, and the lower guide sits just below the rotor. The bracket supporting the lower guide bearing also provides a seat for the air operated brakes which bear on the under side of the rotor when the set is being shut down.

An additional shaft, again directly coupled to the main shaft above the rotor, drives the main and pilot exciters. The pilot exciter is self excited and supplies the field of the main exciter at constant voltage. The output of the main exciter in turn is directed to the alternator through a main field circuit breaker.

There is also an auxiliary house set comprising of a Pelton wheel turbine attached to a 450 KW generator. The discharge from the turbines exits via draft tubes leading to the tailrace and thence to Loch Lomond. (Reference 7)

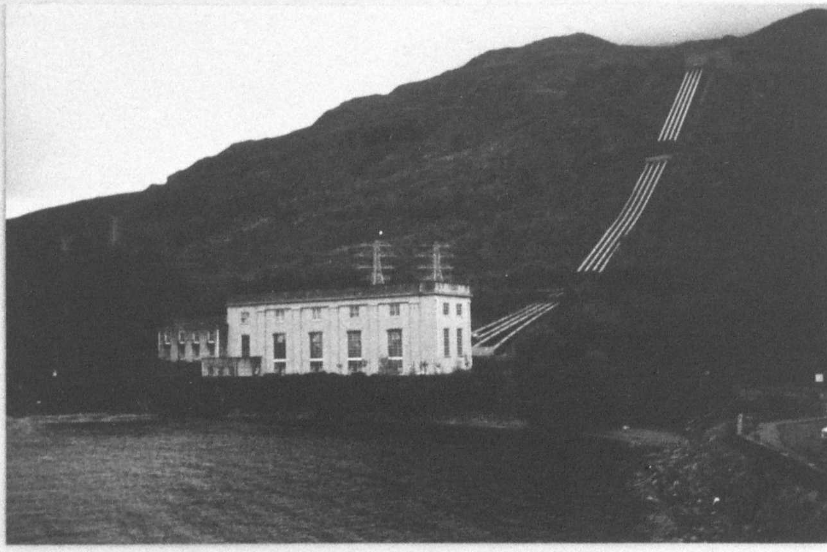


Plate 1. Sloy Power Station

Plate 2. Loch Sloy Dam

Plate 3. Pipeline from valve house to machine hall

Plate 4. Pipeline from machine hall to valve house

Plate 5. Four 11/132KV transformers at rear of machine hall

Plate 6. Machine hall

CHAPTER 2 - REVIEW OF GOVERNING

2.1 Introduction

The age of speed governing dates back to the eighteenth century when James Watt applied the centrifugal governor to his steam engines. Since then the mechanical governors have been much improved providing amplification and stability of control through mechanical and hydraulic means. (Reference 8) Surprisingly, though, the flyballs of the Watt governor continue to give service as the speed sensing element of many modern mechanical governors.

With the emergence of the electronic age a new breed of governor has surfaced. Electronic governors now offer greater flexibility to the designer of a governing system since the control strategy may be contained within the confines of a single printed circuit board of electronic components. It is thus easier to modify the control or incorporate more sophisticated control by simply changing the electronic circuitry.

The use of the microprocessor for governing should enable even more ambitious control schemes to be realised, particularly in the provision of non-linear or adaptive algorithms.

The prime objective of the speed governor is to maintain the speed of the machine under its control as close as possible to the desired speed. The governor must compensate for speed changes brought about by load variations on the machine. This regulating action should be quickly implemented but is invariably constrained due to certain characteristics of the system being governed. The governing of a Francis hydro-turbine generator is further hampered by the fact that such a system is inherently unstable when controlled by a purely proportional type of governor. This arises because the water column leading to the turbine cannot accelerate instantaneously when the guide vanes open after a demand in load. In fact, when the guide vanes open, the head at the turbine momentarily drops which produces a drop in the available input power. This initial drop in power is contrary to the demanded increase. Hence the hydro-turbine is not a simple machine to control, and requires a sophisticated control algorithm in the governor to provide stable operation.

An additional requirement of the governor is to provide load sharing amongst many power generating units. This is achieved by including, what is termed, permanent droop in the governor.

The mechanical Temporary Droop (TD) governor provides the necessary features to control a hydro-turbine generator by producing an output which correctly positions the guide vanes of the turbine for a given input.

The following sections outline the progress to date from mechanical to electronic governors as applied to hydro-turbine generators. Equations defining the characteristics of the various governors are presented. There have been suggestions of how governor performance can be improved, largely related to the tuning of existing governors, and some of these are also mentioned.

2.2 The Mechanical TD Governor

References 9 to 14 and some of the texts of the bibliography describe, amongst other topics, the component parts and completed forms of mechanical governors. As a resume and as a means of illustrating the equations describing such governors, the following example is presented.

The main features of a mechanical governing system are shown in Figure 2.1. The method of operation of this system may be described, for a drop in speed from nominal, as follows:-

i) The drop in speed is detected by the flyballs which is translated into an upward movement of the pilot valve.

ii) As a consequence of the pilot valve and servo movements the distribution valve moves down directing the oil flow to the main servo in such a way as to open the main servo, and thus increase the water flow to the turbine.

iii) For load sharing in a multi machine environment, a signal proportional to the main servo output is fed back to the governor input. This is called the permanent droop and typically lies in the range 3-6%.

iv) The spring and dashpot feedback arrangement is also activated by the main servo movement so as to provide a stabilising influence to the governor action. If the governor was used to control a turbine without this feedback then the only major feedback signal to the governor input would be the turbine speed which, when compared with the speed reference, gives the speed error to drive the governor. This would result in a totally unstable system.
This situation is alleviated by introducing this second feedback mechanism from the main servo output to speed signal. The mechanism operates in a temporary way through the spring and dashpot feedback shown in Figure 2.1. This temporary droop feedback is characterised by a gain (typically in the range 20-100%) and a relaxation time constant (typically in the range 2.5-25s).

v) Once the original change of speed has been corrected

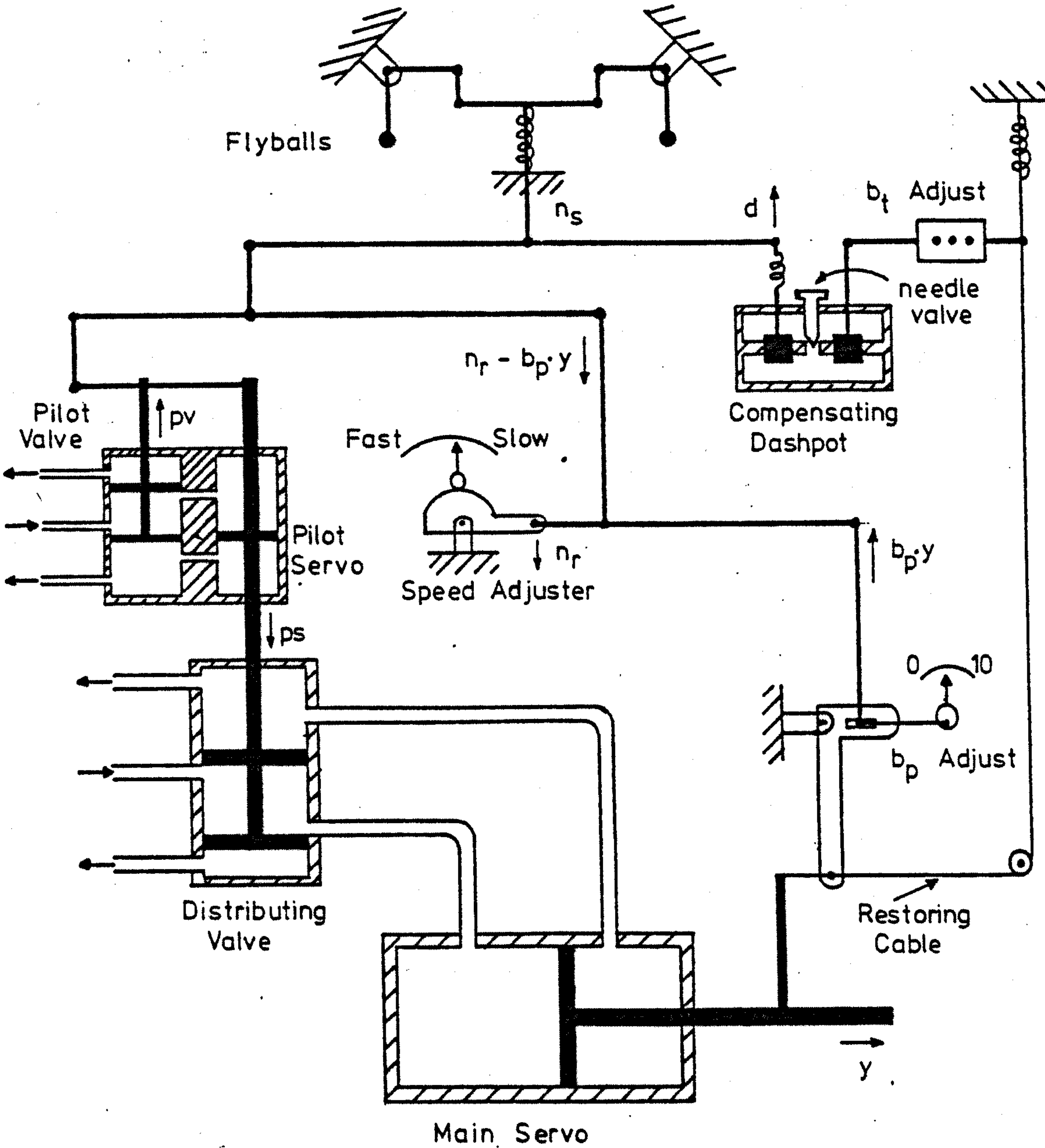


Fig. 2.1 Simplified Mechanical and Hydraulic Governor Representation

and the temporary droop mechanism has relaxed to its steady state value then the complete governor is in its steady state condition again.

In order to relate the governor of Figure 2.1 to subsequent electronic versions it is convenient to consider the governor in its transfer function representation. This has already been done by Ramey(14) but the salient features of his analysis are repeated here for convenience. Referring to Figure 2.1 the transfer function of the pilot valve and servo is:-

$$\frac{ps}{pv} = \frac{K_p}{1 + T_p \cdot s} \qquad \text{equ. 2.1}$$

where K_p is a gain factor relating to the feedback lever ratio and T_p is a time constant relating to valve port areas and K_p.

The transfer function for the distribution valve and the main servo is:-

$$\frac{y}{ps} = \frac{K_s}{s} \qquad \text{equ. 2.2}$$

where $1/K_s$ is a time constant determined by the port areas of the distribution valve and main servo. Combining equations 2.1 and 2.2 gives

$$\frac{y}{pv} = \frac{1}{T_y \cdot s(1 + T_p \cdot s)} \qquad \text{equ. 2.3}$$

where $T_y = K_p K_s$

The transfer function for the temporary droop mechanism, assuming that the flow of dashpot fluid through the needle valve is proportional to the dashpot pressure, is:-

$$\frac{d}{y} = \frac{b_t . T_d . s}{1 + T_d . s} \qquad \text{equ. 2.4}$$

where b_t, the temporary droop, relates to the choice of pivot position for the lever connected to the input piston and T_d, the reset time, is determined by the needle valve.

A system of floating levers is used to sum the various input signals with the feedback signals, namely speed reference, measured speed, permanent droop and temporary droop. The pilot valve input can thus be expressed as:-

$$pv = n_r - n_s - b_p . y - \frac{b_p . T_d . s}{1 + T_d . s} . y \qquad \text{equ. 2.5}$$

Re-arranging and combining with equations 2.3 and 2.4 then the governor transfer function is obtained

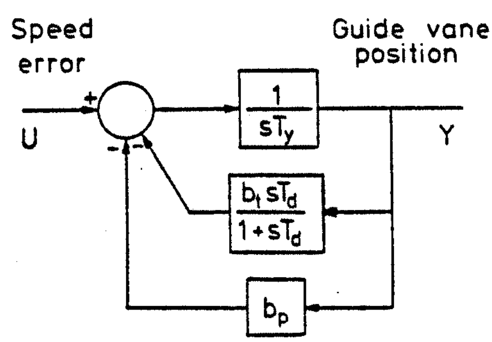
$$\frac{y}{n_r - n_s} = G_1 = \frac{\frac{1}{b_p} . (1 + s . T_d)}{\frac{T_p . T_d . T_y}{b_p} . s^3 + \frac{T_y . (T_p + T_d)}{b_p} . s^2 + \left[\frac{T_y}{b_p} + \frac{T_d . (b_p + b_t)}{b_p}\right] . s + 1}$$

$$- \quad \text{equ. 2.6}$$

In modern equipment the pilot valve time constant, T_p, can be made very small and can therefore be neglected so that the transfer function reduces to

$$G_2 = \frac{\frac{1}{b_p}\cdot(1 + s.T_d)}{\frac{T_y.T_d}{b_p}\cdot s^2 + \left[\frac{T_y}{b_p} + \frac{T_d.(b_p + b_t)}{b_p}\right]\cdot s + 1} \qquad \text{equ. 2.7}$$

Equation 2.7 exactly represents the transfer function of the traditional Temporary Droop Governor which is illustrated in block diagram form in Figure 2.2.



Transfer function

$$\frac{Y(s)}{U(s)} = \frac{1 + sT_d}{b_p(1+1/b_p((b_p+b_t)T_d+T_y)s+(T_yT_d/b_p)s^2)}$$

Figure 2.2 Traditional Temporary Droop Governor

Equation 2.7 can be closely approximated to the simpler transfer function:-

$$G_3 = \frac{\frac{1}{b_p}\cdot(1 + sT_d)}{(1 + T_b s)(1 + T_c s)} \qquad \text{equ. 2.8}$$

where $T_b = \dfrac{T_y + T_d.(b_p + b_t)}{b_p}$ and $T_c = \dfrac{T_y.T_d}{T_y + T_d.(b_p + b_t)}$

Reference 14 gives typical parameter values and provides bode plots of equations 2.6 and 2.8, and for the values chosen, the gain of the approximation of equation 2.8 matches well, up to a frequency of 1.6 Hz, while the phase agrees well to 0.48 Hz. Governing frequencies for this type of governor in a hydro plant are a good deal lower than these limiting frequencies and so the approximation of equation 2.8 does not assume too much. In fact equation 2.8 correlates well with the findings of experiments carried out on two of the governors at Sloy Power Station (Reference 15). The resultant transfer function of the governor estimated by experiment was

$$\frac{\frac{1}{0.03}\cdot(1 + 16.s)}{(1 + 160.s)(1 + s)}$$

The governor type of Figure 2.1 is the Temporary Droop Governor which is commonly used in hydro stations using Francis runners. The stabilising influence of the temporary droop mechanism could alternatively be achieved by utilising a signal proportional to the rate of change of speed. This signal would then be applied to the input of the governor along with the speed signal. The form of the resultant controller is that of an accelerometer governor.

2.3 Previous Investigations into Governor Performance

There have been various studies performed which have dealt with the measurement of existing governor settings, improvement of these settings and the stability of a governed system with these settings. This section documents some of these studies with particular attention being paid to mechanical governors of the temporary droop type due to their predominance.

On some types of mechanical governors there are no calibration marks on the mechanism for temporary droop, b_t, and dashpot relaxation time, T_d. Consequently techniques (References 16, 17, 18, 19) have been used to determine the settings of these parameters. The methods include static and dynamic tests and determination of the governor performance through the use of a transfer function analyser.

The optimisation of the governor constants b_t and T_d has been the topic of discussion by many authors some of whom are given in the References 16, 20, 21, 22, 23, 24, 25, 26. The starting point in all cases is a mathematical model of the governor and system being governed. These models are generally highly linearised and involve many concessions in moving from the real world. For example, the most obvious assumptions made may be listed as follows:-

i) Small disturbances thus providing a basis for linearisation of all components around an operating point.

ii) Purely resistive load with instantaneous voltage regulation. The power then becomes independent of speed, i.e. there is no load self regulation. Disturbances are generally applied as constant torque variations rather than power thus eliminating the small variation with speed associated with a constant power disturbance.

iii) The turbine efficiency is assumed to be constant for small variations of speed, head and gate opening.

iv) No governor non-linearities i.e. no hard limits, lags or hysteresis, and ignoring the pilot valve time constants.

v) The permanent droop is often neglected.

vi) The mechanical inertia of all rotating loads is neglected.

Once the form of the model has been developed the coefficients need to be defined for the particular system of interest. The governor parameters may be determined by static or dynamic methods and the plant parameters such as water starting time, T_w, and machine inertia time constant, T_a, may be deduced from manufacturer's data and model tests.

With these simplified models the techniques of Bode and Nyquist may be applied in order to investigate the stability of the overall system.

Such stability checks can thus be made before and after the optimum governor settings have been applied. Stein (Reference 16) has documented the conditions which were considered to give optimum performance for the temporary droop governor. The criterion used by plant specialists for optimum performance dictated that the regulation of frequency after a disturbance should be damped to within one tenth of the final steady value after approximately four fluctuations of frequency. Associated with this response is the time taken to reach this settling band i.e. $T_{1/10}$. Stein has listed the relationships between

$T_{1/10}$, $b_t + b_p$, and T_d and the plant parameters T_w and T_a for optimum governor performance. These are repeated below for convenience.

Damping Time $T_{1/10}$	=	$6T_w$
Total frequency droop $b_t + b_p$	*	$2.6T_w/T_a$
Dashpot time constant T_d	=	$6T_w$

Variations of these optimum relationships have appeared in the literature and other methods altogether have been proposed for determining the optimum governor settings. For example, Ransford et al (Reference 21), again using a simple linearised model, proposed a method of determining the optimum governor settings by searching for the condition which minimised the speed error after a disturbance.

The English Electric governors which control the hydro-turbine generators at Sloy Power Station are of the Temporary Droop type. Their grid connected speed of response, which is characterised by the governor's dominant lag, is of the order of 3 minutes. Attempts by Bryce (Reference 27) to improve the grid connected speed of response of the Sloy governors, while retaining isolated load stability, did not produce a governor which was significantly faster. Thus Bryce moved on to investigate more sophisticated governors of the types mentioned in the following section.

The vast majority of the problems associated with mechanical governors are now becoming dated due to the adoption of electronic governors which eliminate the problems of non-linearities within the governors, unless such non-linearities are included on purpose. Additionally, the governing strategies have changed with a resultant improved grid connected speed of response. However, the previous studies of optimum governor performance relating to the old Temporary Droop governors no longer hold for these new governors.

As will become apparent from this present study, some of the simplifications previously made in the mathematical analysis cannot be tolerated now as the governor's speed of response is forced to the limit. Such relations as efficiency, servomotor position to flow, servomotor to wicket gate backlash and artificially imposed servomotor rate limits must be considered in determining the governor constants.

2.4 Electronic Governing

The first electronic governing system (of the Temporary Droop type) to be commissioned was at Rydboholm Power Station in Sweden in 1944. (Reference 28) Asea was responsible for this development and according to their more up to date literature (Reference 29) the benefits in using electronics for governing may be summarised as follows:-

i) High accuracy of measurement of frequency and long term stability of the electronic frequency transducer.

ii) Long term stability of governor control parameters.

iii) Accurate calibration of the control parameters.

iv) No inherent governor non-linearities.

v) Greatly increased flexibility and potential since transducers are available to measure power, flow, head and many more, thus enabling such variables to be taken into consideration for the governing strategy.

vi) The easy inclusion of desirable facilities such as load limiting, output rate limiting, direct loading of machine by by-passing the governor lag, and permanent droop relating directly to power output.

vii) Greater feasibility of supervisory control of several governors within a power station.

Electronic governors have the advantage of working at low power levels but this in itself necessitates the use of an electro-hydraulic amplifier to condition the governor output signal to produce the required driving force needed to operate the guide vanes. For example, the governor at Sloy, on which the work of this project was carried out, had to be able to move the main servo piston a distance of 0.36 m at a force of 0.22 MN as a result of an electrical input changing from 0 to 10 volts DC. In terms of a transfer function this electro-mechanical position servomotor can be made look like a first order lag having a time constant as low as 0.1s. This allows the electronics to contain all the characteristics of the governing strategy without having to be over concerned about the main servomotor.

There have been several governor types implemented in electronic form. The Temporary Droop governor, as illustrated in Figure 2.2, has been used in electronic form at Beechwood Generating Station, New Brunswick (Reference 30) and more recently has been the subject of experiment at Sloy Power Station, Scotland. (References 27,31)

As mentioned before, the Temporary Droop and Accelerometer governor types are essentially identical in function. Combining the two, however, produces a new governor type as shown in Figure 2.3 on the following page.

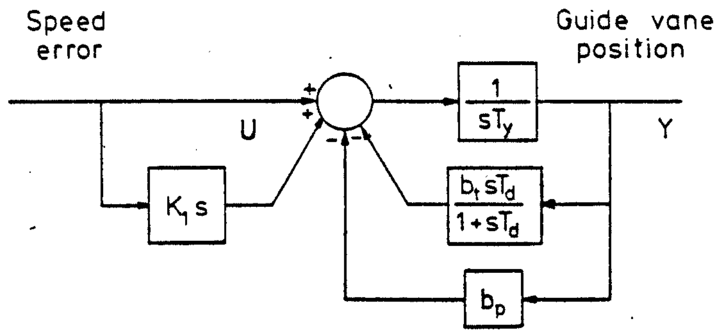


Figure 2.3 Combined Temporary Droop and Accelerometer type of Governor

This type of governor has been implemented (References 29, 32) and, as a result, an improved grid connected speed of response (whilst retaining isolated load stability) has been achieved compared with the Temporary Droop governor.

Bryce (Reference 27) investigated this type of governor for the Sloy Power Station. It was found that the dominant lag could be reduced by a factor of four relative to the Temporary Droop governor. Although the isolated load stability was retained the resulting amplitude of the limit cycles (due to the guide vane linkage backlash) were unacceptably large, so this type of governor was abandoned for use at Sloy.

The most promising new type of governor of recent years is that proposed by Schleif (References 33, 34, 35) the form of which is illustrated in Figure 2.4.

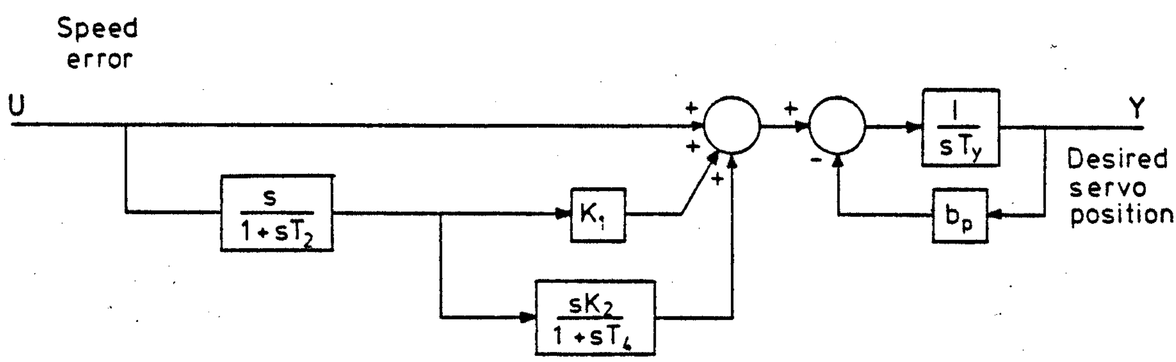


Figure 2.4 Double Derivative Governor

This governor has been given the title of Double Derivative Governor by virtue of the first and second order derivatives acting on the frequency error input. This derivative action replaces altogether, the stabilising influence previously assigned to the Temporary Droop (dashpot) mechanism. Assuming a much improved control of the main servomotor, thus eliminating control valve and servo non-linearities, then the governor of Figure 2.4 is capable of fast but stable performance. This has been demonstrated by Bryce et al (References 27, 31) on a 32.5 MW turbine at Sloy Power Station where the dominant time constant of the governor was reduced to 33s. Schleif (Reference 33) also indicates that the governor parameters may be changed for better operation at speed no load where the water time constant is of a lower value than that of full load operation. These parameter changes effectively produce a new governor more suitable for easy synchronisation of the machine to the grid.

It should now be clear that electronic governors offer superior control over their mechanical predecessors. Moreover, with the ease of interfacing and transmission of signals over long distances the electronic governors lend themselves to co-ordinated control from the power station level up to total power system level.

The advantage of flexibility with electronic governing has already been mentioned and one aspect of its versatility is highlighted by Wuhrer (Reference 36). The approach adopted here is one of modularity where there are separate plug in modules for derivative, integral and other desirable actions. Thus any one of the previously mentioned governors, or even some of the future, may be easily obtained by plugging in the appropriate modules to the specially designed backplane.

This present study is concerned with investigating the feasibility of using a microprocessor as a speed governor. If this new, cheap form of digital processing, applied to this application, becomes a viable proposition then there will be greater opportunity for even more sophisticated control schemes. Wozniak (Reference 37) has suggested one such scheme in which the parameters of the governor are changed as a function of the load level in order to give optimal transient response at a particular load level.

CHAPTER 3 - MODELS FOR USE IN SIMULATION

3.1 Introduction

The various simulations carried out during this project required that mathematical models be available to represent the real system. The major functions associated with a hydro-electric generating plant are illustrated in Figure 3.1.

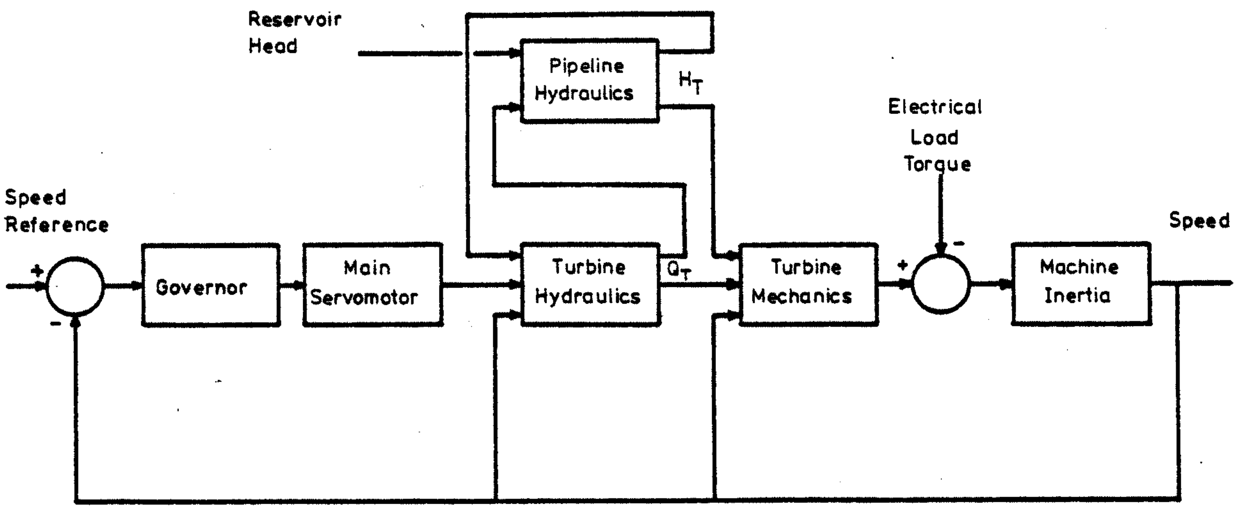


Figure 3.1 Main features of a Hydro-Generating System

There have been many suggestions put forward on how to model such a system, some of which may be found in References 14, 38, 39, 40, 41, 26, and 27 and in some of the texts of the bibliography. The different methods involved have had slightly different objectives in mind but nevertheless all the methods are based upon the same principles and differ, mainly, by the degree of accuracy of representation.

The following sections partition the system into several major areas for discussion, namely,

a) Governor and main servomotor
b) Impulse model representation of turbine
c) Impedance representation of pipelines
d) Wood's representation of pipelines
e) Turbine hydraulic characteristics
f) Turbine mechanical characteristics
g) Generator inertia

The model representations which have been chosen resulted due to the ease with which they could be adapted for use, in the digital simulation package which is described in Chapter 4. Additionally, the accuracy of the resultant simulation models was to some extent limited through the need to develop real time simulations.

3.2 Governor and Main Servomotor

Although the object of the project was to produce a working governor it was also necessary to simulate the governor for development and test purposes. The governor, in a mathematical form, was, in any case, the most convenient means of description since it was directly compatible with the form required by the proposed microprocessor governor.

There were two types of governors that were modelled.

These were the Temporary Droop (TD) and the Double Derivative (DD) types, both of which have been presented in the previous Chapter.

The main servomotor characteristics are very often hidden within the overall governor characteristics especially in the mechanical types. On the new electronic governors, however, the main servomotor becomes an entirely separate entity through necessity. The servomotor output must provide the driving force to operate the guide vanes of the turbine. However the electronic governor output which becomes the input to the servomotor mechanism is typically a DC voltage in the range 0-10 V (representing 0 to full stroke of the main servomotor). With the servomotor having to supply forces of the order of 0.22 MN then it can be seen that the gain of the servomotor must be high.

The model of the main servomotor which was used throughout this project uses the simple transfer function between governor drive (y) to servo output (svo) as shown below,

$$\frac{svo}{y} = \frac{1}{1 + sT_s} \qquad \text{equ. 3.1}$$

In all simulations a direct correspondence between servomotor output position and guide vane control valve position was assumed.

3.3 Classical Transfer Function of Impulse Turbine

In developing the transfer function for this simple model the authors of References 25, 42 and 31 assumed that the entire head at the main valve is discharged across the control valve. Although true for Pelton wheels it is not strictly true for Francis turbines since there is a reaction head developed as the water passes through the runner passageways. The turbine torque output is a function of head, flow and speed. The turbine flow is a function of gate position, head and speed. However, for small perturbations about an equilibrium condition the turbine may be represented by the following linearised equations.

$$q = \frac{\partial q}{\partial h} h + \frac{\partial q}{\partial n} n + \frac{\partial q}{\partial z} z \qquad \text{equ. 3.2.}$$

$$m = \frac{\partial m}{\partial h} h + \frac{\partial m}{\partial n} n + \frac{\partial m}{\partial z} z \qquad \text{equ. 3.3.}$$

where the variables are all per unit deviations with the following meaning:-

q = flow

h = head

n = speed

z = gate position

m = torque

The partial derivatives of equations 3.2 and 3.3 may be obtained, for a particular turbine, from the performance curves of the turbine. To model the turbine over its complete operating range would however necessitate the storage of a large amount of data or the construction of complex functions for each of the partial derivatives relating them to the operating point at any particular time.

With the aid of some simplifications, however, the well known impulse turbine relation can be obtained.

Firstly, an ideal lossless turbine is described by the equations:-

$$Q = ZH^{\frac{1}{2}} \qquad \text{equ. 3.4}$$

$$M = QH/N \qquad \text{equ. 3.5}$$

where the per unit variables have the following meanings:-

Q = flow

Z = gate position

H = head

M = torque

N = speed

Secondly, the water inertia effect relating incremental head (h) and incremental flow (q) is given by

$$h = -(T_w s).q \qquad \text{equ. 3.6}$$

where T_w is the water starting time.

Thirdly, the following relations can be obtained from equations 3.4 and 3.5 if the turbine is assumed to be operating at rated speed and head for the condition of full load.

$$\frac{\partial q}{\partial z} = 1.0 \qquad \text{equ. 3.7} \qquad \frac{\partial q}{\partial h} = 0.5 \qquad \text{equ. 3.8}$$

$$\frac{\partial m}{\partial z} = 1.0 \qquad \text{equ. 3.9} \qquad \frac{\partial m}{\partial h} = 1.5 \qquad \text{equ. 3.10}$$

And finally, if the effect of speed in equations 3.2 and 3.3 is ignored then the two resulting equations when combined with equations

3.6 to 3.10 gives,

$$\frac{m}{z} = \frac{1 - T_W s}{1 + 0.5T_W s} \qquad \text{equ. 3.11}$$

which is the classical representation of the impulse turbine. This form was used extensively in simulation studies.

Agnew (Reference 43) has provided a more accurate representation of the turbine characteristics than that of equation 3.11. Equation 3.11 assumes an impulse type of runner in which all the head of the control valve is converted to kinetic energy within the high velocity fluid which eventually strikes the runner buckets. Agnew takes into account the reaction head developed within the runner of a Francis turbine and also includes the impedance effects of the pipeline. His resulting relation for a turbine operating near full load is given in equation 3.12.

$$\Delta W = \left[\Delta A - \left(\frac{1-\alpha}{\alpha}\right)n\right]\left[\frac{1 - sT_w}{1 + s(T_w/2\alpha)}\right] \qquad \text{equ. 3.12.}$$

where the variables in per unit deviation form have the following meanings:-

ΔW = power

ΔA = control valve area

α is a dimensionless constant which depends on the head and the control valve design.

The Francis turbine coupled with its associated pipeline produces a system which is inherently non linear because of the inertia of the water column leading to the turbine. Although equation 3.12 offers a better solution to that of equation 3.11 for the case of a Francis turbine neither of the representations were at all suited for investigating the effect of large disturbances to the system. Consequently a more complex model was developed in preference to these highly linearised representations. In addition, a complex model with a more explicit representation of the component parts of the system would allow for the inclusion of non linearities associated with parts of the real hydro-turbine generator system. These larger models included explicit pipeline representations, models for which are described in the following sections.

3.4 Hydraulic Impedance Method

This method of representing pipeline characteristics was not used in this project. It operates in the frequency domain and is therefore unsuitable for use in real time simulations. However, it is worth a brief mention since a comprehensive computer program in the files of the NSHEB provided a reference impedance chart of the penstock system at Sloy. A section of this chart may be found in Figure 4.5 and 4.6 where it is compared against the results of simulations based on Wood's method of pipeline modelling.

A detailed discussion of the hydraulic impedance method may be found in the text of the bibliography by Streeter and Wylie. However the brief summary given by Jarvis (Reference 44) is worth noting.

The impedance method for categorising steady-oscillatory flow in pipelines is analagous to electrical transmission line theory. The impedance at a point in a hydraulic network is defined as the ratio of the oscillatory component of head to the oscillatory component of flow. If the impedance at one end of a conduit is known then it is possible to determine the impedance at the other end of the conduit, or at intermediate points between the two. By starting at a system boundary where the impedance is known then the impedance at various points of interest throughout a complex network of conduits can be constructed as a function of frequency. Having established these impedance relationships at the chosen points of interest it is possible to calculate the head and flow variations at these points in relation to the amplitude at the excitation point.

3.5 Wood's Pipeline Equations

Wood (Reference 45) has provided a simple means of simulating the effects of unsteady flow in pipelines. The starting point for his analysis calls on the partial differential equations representing momentum and continuity. Thus, neglecting small terms, the basic equations are,

for momentum $$\frac{\partial Q_v}{\partial t} = -gA_p \frac{\partial H_p}{\partial x} - f(Q_v) \qquad \text{equ. 3.13}$$

and for continuity $$\frac{\partial H_p}{\partial t} = \frac{-a^2}{gA_p} \frac{\partial Q_v}{\partial x} \qquad \text{equ. 3.14}$$

where the variables and constants have the following meaning:-

Q_v	=	Volumetric flow rate
H_p	=	Line Pressure head
a	=	sonic wave velocity
g	=	acceleration due to gravity
A_p	=	Cross sectional area of conduit

The function $f(Q)$ represents a loss term in the pipeline and for turbulent flow this viscous term is given closely by,

$$f(Q_v) = KQ_v^2 \qquad \text{equ. 3.15}$$

where K is a constant.

A pipe or a section of a pipe may be visualised as in Figure 3.2

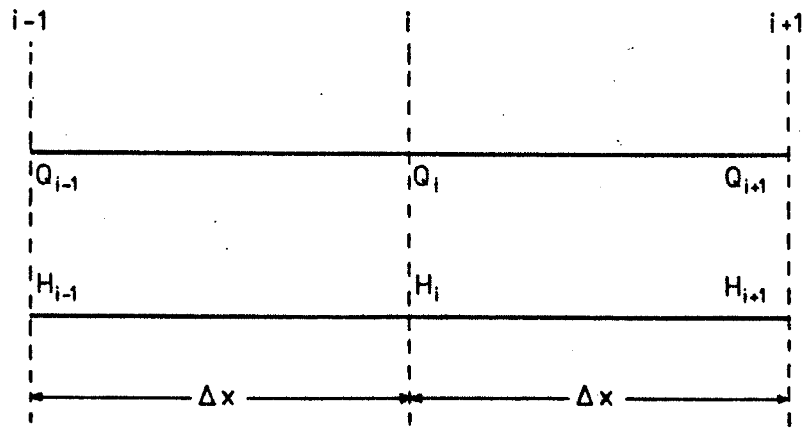


Figure 3.2 Finite difference form for liquid transmission line

The spatial derivatives of Q and H at the central point of the pipe section may be approximated to the following first order finite difference equations.

$$\frac{\partial Q_i}{\partial x} = \frac{Q_{i+1} - Q_{i-1}}{2\Delta x} \qquad \text{equ. 3.16.}$$

$$\frac{\partial H_i}{\partial x} = \frac{H_{i+1} - H_{i-1}}{2\Delta x} \qquad \text{equ. 3.17.}$$

Further equations describing the conditions at the pipe boundaries are required and these can be obtained by using a second order polynomial interpolation leading to equations 3.18 to 3.21.

$$\frac{\partial Q_{i-1}}{\partial x} = \frac{-3Q_{i-1} + 4Q_i - Q_{i+1}}{2\Delta x} \qquad \text{equ. 3.18.}$$

$$\frac{\partial Q_{i+1}}{\partial x} = \frac{3Q_{i+1} - 4Q_i + Q_{i-1}}{2\Delta x} \qquad \text{equ. 3.19.}$$

$$\frac{\partial H_{i-1}}{\partial x} = \frac{-3H_{i-1} + 4H_i - H_{i+1}}{2\Delta x} \qquad \text{equ. 3.20.}$$

$$\frac{\partial H_{i+1}}{\partial x} = \frac{3H_{i+1} - 4H_i + H_{i-1}}{2\Delta x} \qquad \text{equ. 3.21.}$$

By suitable substitutions into equations 3.13 and 3.14 four equations can be obtained namely,

$$\frac{\partial (H_p)_i}{\partial t} = \frac{-a^2}{2gA_p\Delta x}\left((Q_v)_{i+1} - (Q_v)_{i-1}\right) - f\left((Q_v)_i\right) \qquad \text{equ. 3.22.}$$

$$\frac{\partial (H_p)_{i+1}}{\partial t} = \frac{-a^2}{2gA_p\Delta x}\left(3(Q_v)_{i+1} - 4(Q_v)_i + (Q_v)_{i-1}\right) - f\left((Q_v)_{i+1}\right) \qquad \text{equ. 3.23.}$$

$$\frac{\partial (Q_v)_{i-1}}{\partial t} = -\frac{gA_p}{2\Delta x}\left(-3(H_p)_{i-1} + 4(H_p)_i - (H_p)_{i+1}\right) \qquad \text{equ. 3.24.}$$

$$\frac{\partial (Q_v)_i}{\partial t} = -\frac{gA_p}{2\Delta x}\left((H_p)_{i+1} - (H_p)_{i-1}\right) \qquad \text{equ. 3.25.}$$

Thus equations 3.22 to 3.25 can be used to represent the dynamics of a single pipe section. It is necessary, though, to provide these equations with two pieces of information, namely H_{i-1} and Q_{i+1} These are provided by adjoining pipe sections or as a result of one of several possible boundary conditions (e.g. a reservoir or a control valve). Very often, as in this study, the viscous loss term, f(Q), is so small that it can be neglected.

The sonic wave speed depends on the physical nature of the conduit. The penstock system at Sloy Power Station contains both rock tunnels and steel pipelines and the values of wavespeed used were those given by Bryce (Reference 27).

i.e.	for rock tunnels	a	=	4140 ft/s	(1262 m/s)
	and for steel pipes	a	=	3616 ft/s	(1102 m/s)

3.6 Turbine Hydraulic Characteristics

To satisfy equations 3.22 to 3.25 at the turbine end of the penstock then the flow at the turbine must be defined in terms of its characteristics. The discharge at the turbine is often regarded as obeying the relationship below.

$$Q_T = A_{cv} C_d \sqrt{2gH_v} \qquad \text{equ. 3.26.}$$

where the variables have the following meaning:-

Q_T	=	Turbine flow
H_V=	=	Turbine velocity head
A_{cv}	=	Current Control Valve area
C_d	=	Discharge Coefficient
g	=	acceleration due to gravity

This relationship relates to the flow resulting at an orifice of a given area due to a pressure head. Here the entire pressure head present on the upstream side of the turbine is converted to kinetic energy on the downstream side, having what is termed, a velocity head. For impulse turbines the relation is fairly accurate; however it does not take into account the reaction head found in Francis turbines. This reaction head may be represented by

$$H_R = \frac{(r_o^2 - r_i^2)}{2g} \omega^2 \qquad \text{equ. 3.27.}$$

where

H_R	=	Reaction head
r_o	=	outer radius of turbine blades
r_i	=	inner radius of turbine blades
ω	=	angular velocity of turbine

Thus in the mixed flow machine, such as the Francis turbine, the head at the main valve, H_{MV}, which represents the total energy available, is converted to torque in the turbine due to the velocity head and the reaction head.

i.e. $H_{mv} = H_v + H_R$ equ. 3.28.

Consequently the velocity head is no longer simply the head at the main valve so the equation representing turbine flow can be modified to take account of this reduced velocity head.

$$Q_T = A_{cv} C_d \sqrt{(2gH_{mv} - (r_o^2 - r_i^2)\omega^2)} \qquad \text{equ. 3.29.}$$

3.7 Turbine Mechanical Characteristics

The power transfer in a turbine is the rate of change of work done to or by the working fluid. In the case of a pump the power required is the time derivative of the work done on the fluid, where the work done relates to moving a certain mass of fluid against the force of gravity through a given head. For a turbine the same relation holds but the energy transfer is in the opposite direction.

Thus $P = \rho g Q_T H_T \eta$ equ 3.30

where

P	=	power output of turbine
ρ	=	density of fluid
g	=	acceleration due to gravity
Q_T	=	Volumetric flow rate through turbine
H_T	=	head across turbine $(=H_{MV})$
η	=	turbine efficiency

The torque output of the turbine is therefore,

$$\tau = \frac{\rho g Q_T H_T \eta}{\omega} \qquad \text{equ. 3.31}$$

where ω is the angular velocity of the turbine. An efficiency relationship had been developed by Bryce (Reference 27) and was incorporated into the simulation but it was often found to be more convenient to use the simple efficiency factor by inserting a value appropriate to the operating point of the machine.

3.8 Machine Inertia

Once the torque output developed by the turbine is known, the demanded torque of the load is deducted and the resultant error torque accelerates the turbine/generator. This then allows the speed of the generator to be calculated, i.e.

$$\tau - \tau_L = I \dot{\omega}$$

$$\therefore \omega = \frac{1}{I}\int(\tau - \tau_L)\,dt \qquad \text{equ. 3.32.}$$

where

τ	=	developed turbine torque
τ_L	=	load torque demand
I	=	rotational inertia
ω	=	angular velocity
$\dot{\omega}$	=	angular acceleration

Equation 3.32 may be expressed in per unit form where

$$n = \frac{\omega}{\omega_o} = \frac{1}{T_a} \int \frac{(\tau - \tau_L)}{\tau_r}\, dt \qquad \text{equ. 3.33.}$$

where

ω_o = rated speed

τ_r = rated torque

T_a = turbine/generator inertia time.

CHAPTER 4 - SIMULATION STUDIES

4.1 Introduction

The main objective of the overall project was to produce a governing strategy in a microprocessor which would have obvious advantages over governors that had been developed in the past. In order to be able to discern a good governing strategy from one that was indifferent, if not abysmal, then simulation studies had to be carried out. One of the aims during these types of simulations was to optimise the particular governor's performance. However, another necessity for conducting simulation studies was for verification of actual governing equipment which would subsequently be taken and tested on the real plant at Sloy. This second type of simulation involved interfacing prototype governor equipment to the computer which simulated in real time the remainder of the hydro-turbine generator system.

During a previous project (Reference 27) an EAI 231/640 hybrid computer had been used for simulating the system at Sloy. Through no other reason than old age this computer was becoming unreliable and the arrival of a replacement was not imminent. It was therefore desirable that an alternative method of simulation was adopted. As a result of another project (Reference 46) carried out at the Department of Electronics and Electrical Engineering at Glasgow University, a simulation package running on a DEC PDP 11/45 digital computer was available. This provided an interactive method of simulation with the further option of attaching external equipment to the computer. Thus the two aforementioned simulation requirements could be satisfied with this digital simulation package and so this means of simulation was used. Since most of the simulation package was written in FORTRAN then there was the further advantage of this system having the potential portability of not only the package but also the models being simulated.

4.2 Simulation Package

This software package was developed during a previous project but for clarity during subsequent discussions a brief overview of the package and how the user interfaces to it will be presented here. The salient features of the package may be conveniently described under the following headings.

a) Package facilities

b) User written routines and available utilities

c) Real time operation.

a) Package facilities.

The user would set up a simulation run by answering questions during a dialogue session with the computer. The type of integration method to be used was chosen from one of the following: Euler; Modified Euler; 3rd order Runge Kutta; 4th order Runge Kutta; 4th order, variable step Runge Kutta; a user supplied integration method. Once the integration method had been chosen then the user entered the parameter values appropriate to the method in use. (e.g. integration interval and total time for simulation, since time was always the independent variable). The results of a simulation could be directed to one of three, if not all, media, namely, printer; x/y plotter; mass storage disk. The user could also select timed output which synchronised the simulation to real time or a multiple thereof. The simulation could be requested to automatically rerun and if so, decisions on parameter changes could be included in a terminal section (TERM) which will be described in the next section. Finally, the package asked if the user wished to input the initial conditions. If a negative reply was given to this question then it was assumed that the initial conditions had been set up in the initialisation (INIT) routine, which will also be described in the next section.

b) User routines and available utilities.

There were four routines that the user could supply with two of them being essential. These were MODEL, INIT, TERM and EXT. The last in the list was a routine that the user supplied if an alternative integration method to those already mentioned was required.

Both MODEL and INIT were essential user supplied routines. MODEL contained the FORTRAN statements representing the system dynamics. A set of first order differential equations was used to represent the system being modelled. Non-linearities and forcing functions were also included in this section. The definition of coefficients and variable initialisation was carried out in the INIT section which also allowed communication with the user via the console during the dialogue session.

The optional terminal section, TERM, could be called at the end of a simulation. This section might contain some re-definition of parameters before an automatic re-run of the simulation, thus enabling, say, an optimisation procedure to be carried out automatically.

There was a library of utilities available which could be used within the MODEL section. Included were limit, step, delay, analogue input and output. For the simulations to be discussed the author had to include two further functions, namely, rate limits and hysteresis (i.e. backlash).

c) Real time operation

This facility was available so that external equipment could be attached to the computer to enable real time interactive simulations. For example, as was the case during this project, governors were initially tested by using a simulation of, not only the system being governed but also the governor. Once a suitable governor had been produced it would be translated for operation in the microprocessor. After this separate entity was operational it would be connected to the PDP 11/45 via analogue to digital (A/D) and digital to analogue (D/A) converters. During such an operation the simulation in the PDP 11/45 would consist only of the system being governed and the external microprocessor actually governed the simulation.

4.3 System Models

The previous chapter has detailed the origin of the various building blocks that were considered for the purposes of simulation work. There were several different simulation models constructed which used a combination of the following blocks:-

a) Temporary Droop governor
b) Double Derivative Governor
c) 'Sampled' Double Derivative Governor
d) Main servomotor lag
e) Generator Inertia
f) Simple Impulse Turbine model
g) Single pipe section + turbine characteristics
h) 3 pipe sections + turbine characteristics

Sections d) and e) were always present in a simulation with the governor being a choice of a), b) or c) or an external governor linked to the simulation of the plant. One of the sections f), g), or h) was chosen to represent the hydraulic and turbine characteristics. Section f) was used extensively during the initial stages of the project but was later superseded by g) then h). However both g) and h) were also well used. The representation described in h) was found to give a very good representation of the plant but it became apparent that the time taken to compute the equations, given a suitable integration interval , became excessive for real time operation. Hence h) was used for the testing and tuning of governor ideas and g) was used when the final microprocessor hardware was connected to the simulation for test purposes.

The listing contained in Appendix B is an example of one of the MODEL routines which was devised. This MODEL was built up from sections a), b), c), d), e) and h) with one of the three governor types being chosen during the dialogue stage. Figures 4.1 and 4.2 provide simple block diagram representations of the Simple Impulse model and the Pipeline with Turbine Characteristics model, both with governors.

As previously mentioned the models used first order differential equations to represent the dynamic sections. This was how the governors within these simulations were produced. These types of governors were considered as 'continuous'. Alternative governors could be used within the simulations and these were termed 'discrete' since they were difference equation governors similar to the actual microprocessor governors. The justifications in differentiating between 'continuous' governors and 'discrete' governors were twofold. Firstly, the 'continuous' governors were generally computed using a higher order of integration method than the backward Euler method used for the 'discrete' case. Secondly the 'discrete' governors were evaluated using an integration interval of 0.1s (since this was the integration interval which was practical with the actual microprocessor) whereas the 'continuous' governors, and the model

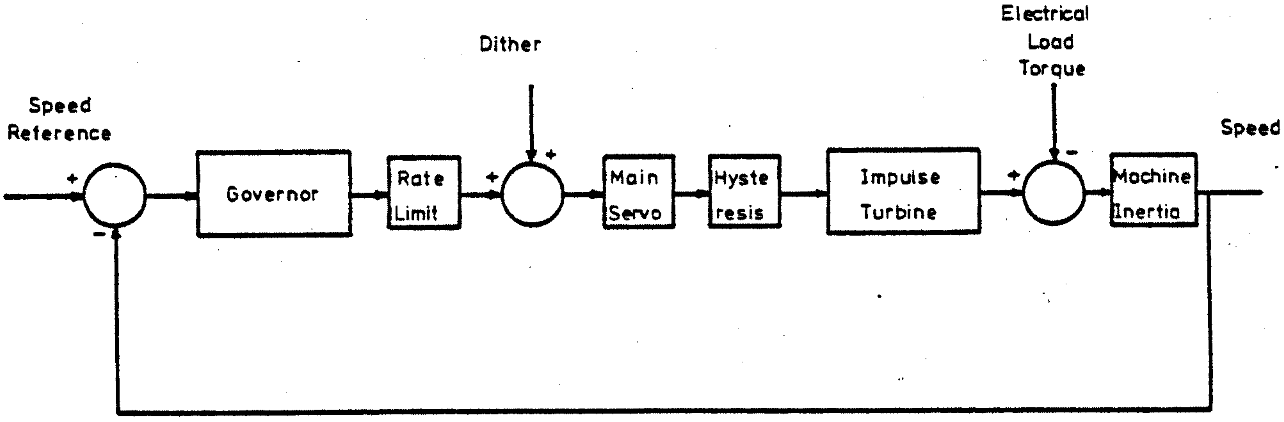


Figure 4.1 Simulation with Simple Impulse Model

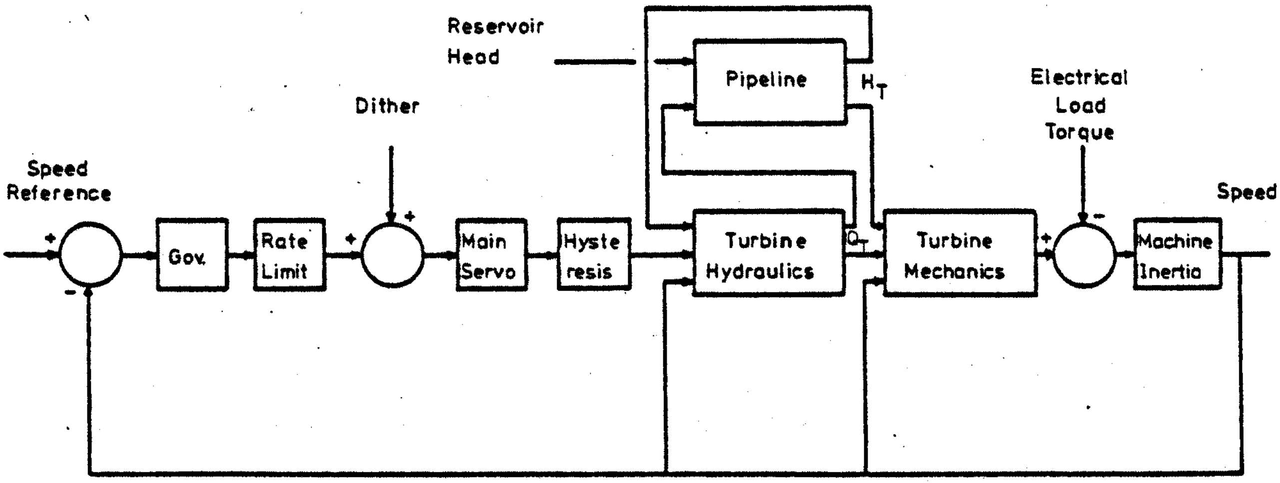


Figure 4.2 Simulation with Pipeline and Turbine Characteristic Models

of the plant, were generally computed to an order of accuracy higher than that of the 'discrete' governor. In other words, the model of the plant would appear 'continuous' to the 'discrete' governor and comparison of the two types of governors would reveal a 'continuous'-'discrete' relationship.

4.4 Initial Simulation Experiments

The digital simulation package facility and the models of the various parts of a hydro-turbine generating system were brought together to produce the working simulations. The first step in using these simulations was to verify their correct operation. This section shows how the models of the pipelines were verified and also introduces the non-linearities that were included in the simulations. Subsequent simulation studies dealt mostly with investigations into the performance of different governors. The results of these governor related simulations are presented in Chapter 6 and some additional information may be found in Chapters 8 and 9.

a) Pipeline Model frequency response

Wood's (Reference 45) method of representing pipe sections was thought to be a suitable method simulating the pipeline system at Sloy. The set of first order differential equations that resulted from this representation was extremely convenient for use in the simulation package.

The two pipeline simulations that were developed represented a single pipe section and a triple pipe section. The single pipe model replaced the complex pipeline system by assuming a single uniform pipe from the surge shaft to the turbine of Set No. 3. This is illustrated in Figure 4.3. The overall length of the pipe remained at 2790 ft (850 m) but since the diameter of the pipeline reduced in size on its journey towards Set No. 3 then a weighted average for pipe cross sectional area was computed with a resultant equivalent diameter of 9.791 ft (2.98 m). Similarly, since this single pipe section was replacing several sections, some of which were rock tunnel and the rest steel lined, then a weighted value of wave speed, equal to 3831 ft/s (1167.7 m/s) was used.

The triple pipe section model that was developed is illustrated in Figure 4.4. The first pipe section (a) lies between the surge shaft and the first main bifurcation of the Sloy system. The first of two pipes leading from this bifurcation is a stub section (b) representing the pipes leading to the turbines of Sets No. 1 and 2 which are assumed to be off. The other section (c) of the bifurcation leads to the turbine of Set No. 3. The pipe section to the turbine of Set No. 4 is ignored. Each of the pipe sections of Figure 4.4 had the parameter values as listed in Table 4.1.

Pipe Section	Length		Equivalent Diameter		Wave Speed	
	ft	(m)	ft	(m)	ft/s	(m/s)
(a)	547	(166.7)	15.8	(4.8)	4140	(1261.8)
(b)	2252	(686.4)	9.49	(2.89)	3756	(1144.8)
(c)	2243	(683.6)	7.64	(2.33)	3755	(1144.5)

Table 4.1 Pipe parameter values for 3 section model

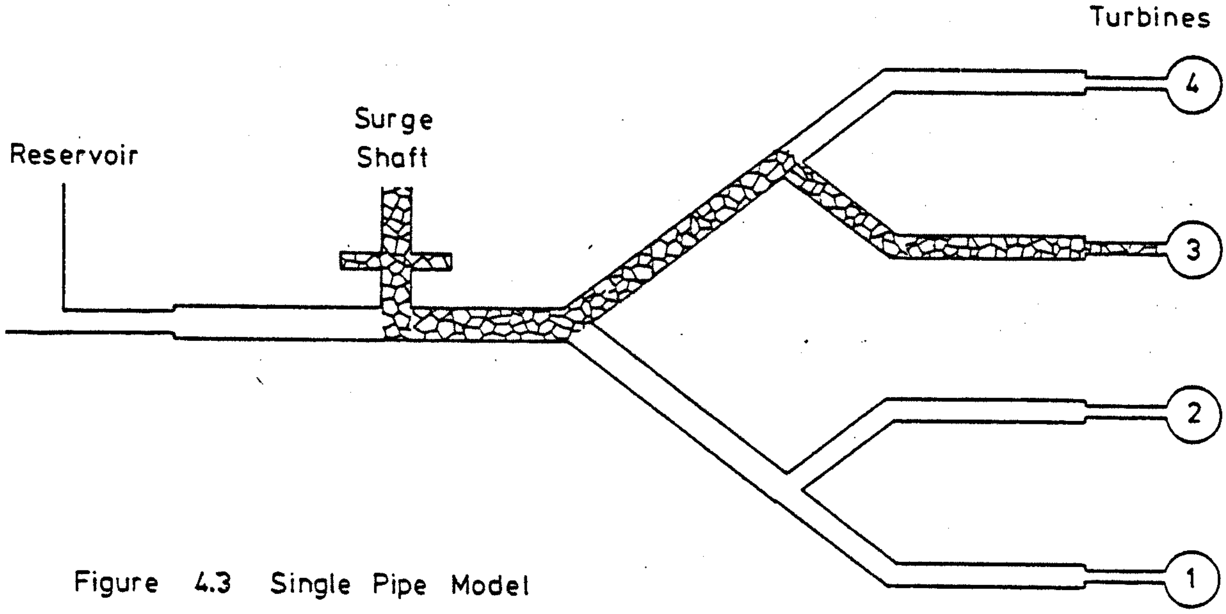


Figure 4.3 Single Pipe Model

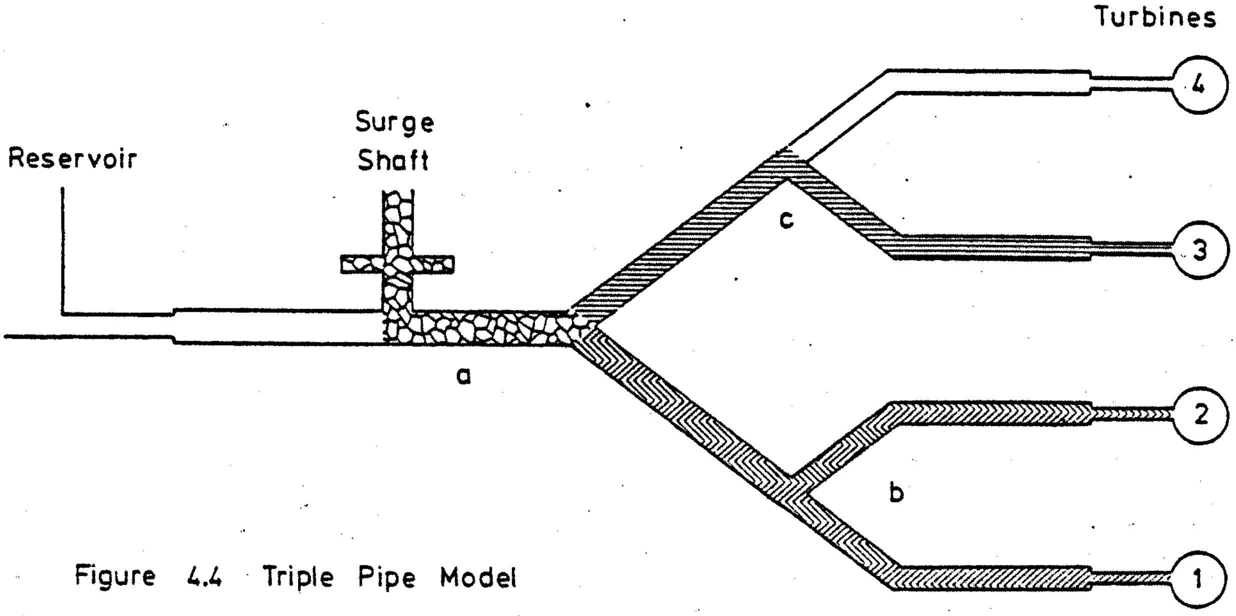


Figure 4.4 Triple Pipe Model

Section (a) is an existing pipe length and so its parameters remain unchanged from actual values. As section (b) represents varying diameter pipes in series and in parallel an equivalent cross sectional area was computed which resulted in a similar pipe volume for the single pipe which replaces the actual pipe configuration. An identical procedure was observed in calculating an equivalent cross sectional area for section (c) but in this case there are no parallel pipe sections. For both sections (b) and (c) a weighted value of wave speed was calculated as before.

Having constructed these two models verification of their correct operation and of their accuracy in emulating the actual pipeline was required. To verify correct operation impedance charts for the two pipeline models were constructed. The impedance chart obtained from experiment on the single pipe model is shown in Figure 4.5. This graph was constructed simply, by carrying out multiple simulation runs in which the turbine end of the pipeline was excited sinusoidally. The resultant fluctuations of flow and head were plotted out and interpreted by hand for each frequency of test. Also shown on Figure 4.5 are the three lower impedance peaks which were obtained from an impedance chart constructed by the NSHEB for the condition where Sets No. 1, 2 and 4 are off and only Set No. 3 is running. As frequency increases the three peaks shown on the NSHEB chart correspond to the three fundamental reflections from the surge shaft, Sets No 1 and 2, and Set No 4. The model of the single pipe section should correspond to the reflection from the surge shaft, but due to the nature of the model there are two resonant peaks. However the lower of these two peaks matches well with the lowest peak of the NSHEB chart.

A similar comparison between the NSHEB impedance chart and model results is displayed in Figure 4.6 for the 3-pipe section

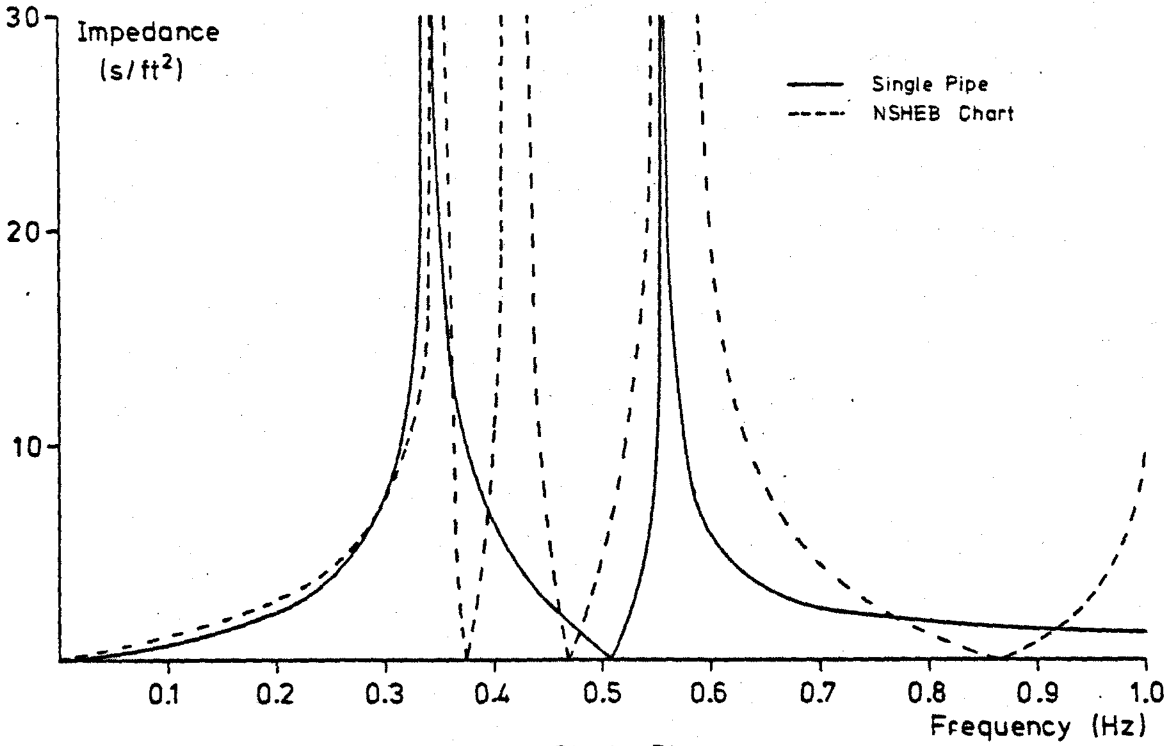


Figure 4.5 Impedance Chart for a Single Pipe

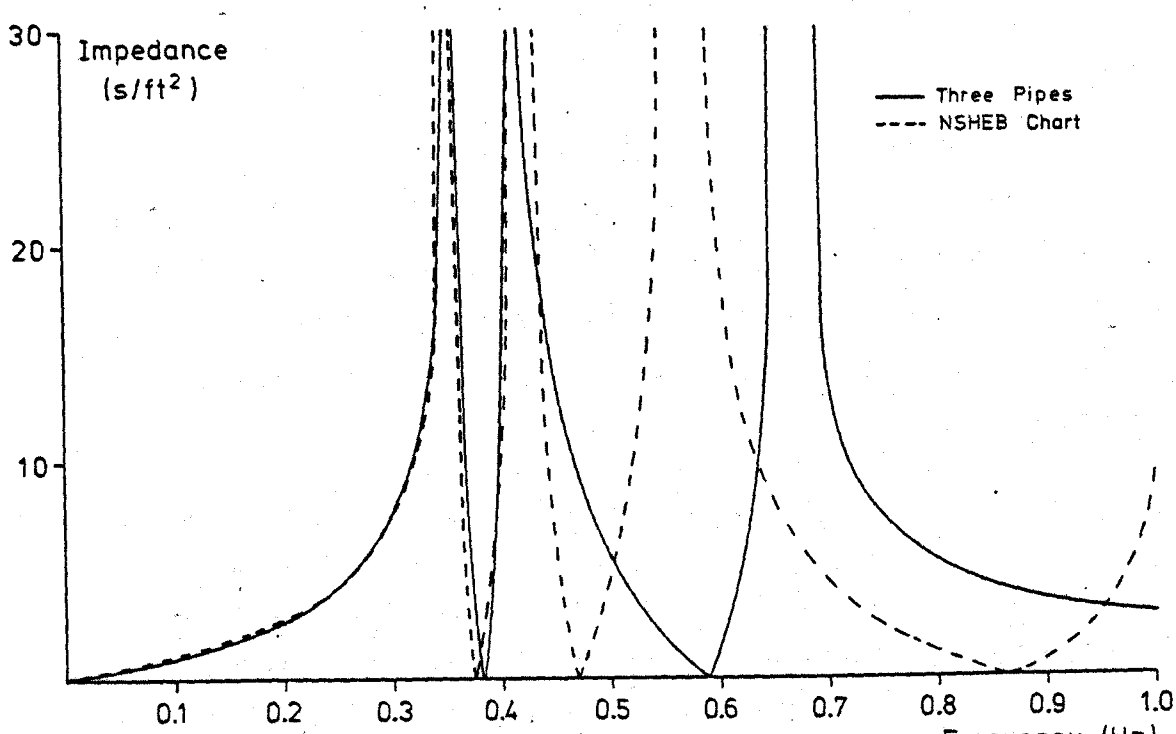


Figure 4.6 Impedance Chart for Three Pipes

model. The upper resonance peak contains several resonances within its envelope. These additional peaks are not shown because it was not easy to accurately measure these points using the simple method for obtaining the impedance chart of the models. However the overall appearance of this chart for the three pipe section model matches well with the NSHEB impedance chart which is also pictured on Figure 4.6. This match is obtained even without considering the extra pipe section to Set No. 4.

In both the single and triple pipe models the lowest resonance peak matches extremely well with the lowest peak on the NSHEB chart. This is the resonance of greatest interest since the loop gain of the governing system must fall below unity before this lowest resonance peak in order to retain overall stability. Thus, although it is useful to check the models against higher resonances it is only essential that the lowest resonance be modelled.

As reasonable results were obtained using the single and three pipe section models no further extension of the pipeline model was considered. Additionally, as each pipe section introduces another four first order differential equations it was not desirable to expand the simulation size much further due to the increased time required for computation. During subsequent simulation studies relating to the tuning of the governor the three pipe section model was used extensively. However due to the size of this model the single pipe model was employed when real time interactive simulations were carried out with the actual microprocessor governor.

b) Introduction of Non-linearities into the Simulation

The three functions LIMIT, HSTRSS and RATLIM were used in the simulation studies to introduce the major non-linearities of the system.

LIMIT provided a means of introducing hard limits to the span of the variable. Typically, this was used to limit the governor output which in real life would be limited by the microprocessor governor algorithm or saturation of amplifiers in the analogue governor. The main seromotor output was also limited, corresponding to the maximum mechanical movement of the actual servomotor.

The HSTRSS function was later applied to the output of the main servomotor in order to imitate the backlash that exists between the main servomotor mechanism and the guide vanes around the spiral casing. This backlash is the primary cause of limit cycling.

Finally, RATLIM was used to simulate the protective rate limits built into the system at the governor output. Two of the parameters of RATLIM allowed the user to set different upward and downward rate limits which was essential since in practice the upward rate limit was much slower than the downward. The hydraulic system at Sloy was designed so that the fastest upward rate limit is 22s for full stroke and the fastest downward rate limit is 2s for full stroke. As will be shown in Chapter 9 the inclusion of these rate limits has a detrimental effect on the system stability which is increasingly noticeable as the size of disturbance to the system rises.

CHAPTER 5 - DESCRIPTION OF INTERFACE/CONTROL RACK AND SITE FACILITIES

5.1 Introduction

The site facilities to be described existed on Set No. 3 at Sloy Power Station and were a consequence of a previous project. The first set of facilities were re-designed by Dr. D. J. Winning of Glasgow University, in consultation with Mr. A. G. Marshall of the NSHEB. The author's involvement with the new design was largely connected with the commissioning of the equipment in the laboratory and on site. It is appropriate, however, to present an overview of the resultant test facilities and also to highlight some of the difficulties which had to be overcome during the commissioning stage and which had not been previously foreseen.

Throughout the following discussion reference to Figure 5.1 and to the photographs of Plates 7 to 11 may prove useful.

Figure 5.1 presents an overall schematic diagram of the Control and Interface Rack. A more detailed functional description of the Control and Interface Rack may be found in Appendix C.

Plate 7 illustrates the entire Control and Interface system whilst Plate 8 also includes the recording equipment i.e. the Rack containing signal conditioning and the U/V recorder and the Digital Data logger. Plates 9 to 11 give different views of the old and new governor actuators.

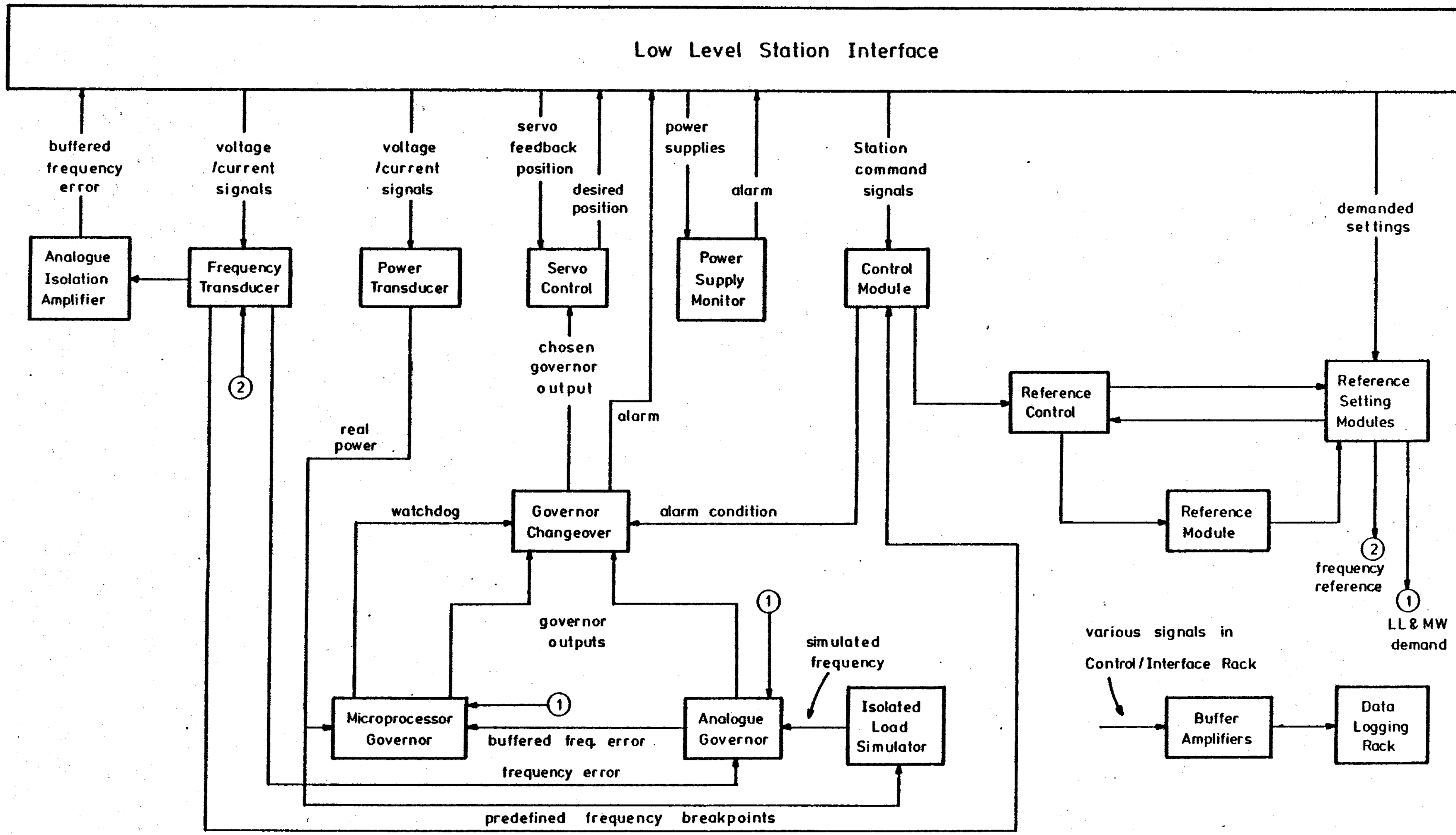


Figure 5.1 Schematic of the Control and Interface Rack

The purpose of this equipment was to allow new governor types, in microprocessor form, to be quickly and easily interfaced to the turbine/ generator. The resultant electronics may be divided into two different major functions. Firstly, there was the Interface Rack and secondly the Control Rack. Each of these two units may be described by further sub-dividing their functions as listed below.

1. The Interface Rack

    a) Low level station interface
    b) Frequency Transducer
    c) Main Servo Controller
    d) Power Transducer
    e) Power Supply Monitor
    f) Analogue Isolation Amplifier
    g) Buffer Amplifiers

2. The Control Rack

    a) Control Module
    b) Reference Control Module
    c) Reference Module
    d) Reference setting Modules (FR, MW, LL)
    e) Analogue Governor Module
    f) Governor Changeover Module
    g) Microprocessor Governor Module
    h) Isolated Load Simulator Module

In order to be able to actually move the guide vanes a high pressure (3000 psi) servo actuator had been attached in parallel with the existing low pressure (300 psi) mechanical governor actuator. This modification to the station governor had been implemented during a previous project (Reference 27) and remained unchanged throughout this project.

Each of the two hydraulic actuators had oil bypass systems which allowed one actuator to become slave to the other. By this means it was an easy and quick (3 mins) move to disable the old governor and install the high pressure actuator, and vice versa. (Reference 47)

Finally, once all the aforementioned components had been brought together into a working system, some means of recording the results of experiments conducted using this comprehensive site facility was required. Two methods were employed namely U/V recordings and Digital Data logging.

5.2 The Interface Rack

The purpose of the Interface Rack was to provide a mechanism of interfacing the station logic signals (110V DC) to the Control Rack logic signals at TTL levels (5V DC). Additionally, measurements of the generator's terminal voltage and current were required in order to supply the necessary low level analogue signals ($\pm$ 10V DC) to the frequency and power transducers and the power supply monitor. The component parts of the Interface Rack are described in greater detail in the following paragraphs.

a) Low level station interface

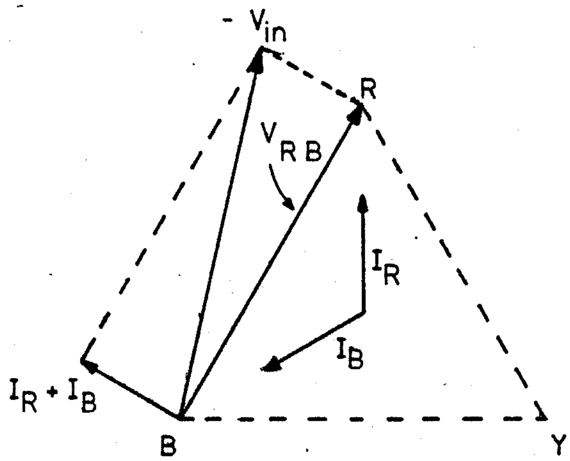
Within the logic interface there was the facility for allowing the input and output signals to be simulated on switches. The third position on these switches was the normal setting which connected the station signals through to the Interface Rack. The inclusion of these switches greatly eased the commissioning of the equipment and also allowed total system tests to take place before some of the less important station functions had been connected through to the Interface Rack.

The lowest section of Plate 7 shows these switches. The electronics which did the actual signal conditioning between the station and the remainder of the Interface Rack and the Control Rack was located behind the panel containing the switches and the 110V DC relays.

For incoming signals the 110V DC was fed to the input of an opto-isolator via a noise reducing filter. The output of the opto-isolator was made directly compatible with TTL logic. Outgoing TTL signals were similarly directed to the input of an opto-isolator, the output of which, after being suitably buffered, controlled the 110V DC supply to a relay coil. The switch contacts of the relay provided the connections to the station.

b) Frequency Transducer

The means by which the governor obtained its frequency signal was through monitoring the frequency of both the generator's terminal voltage and current. By using the combination of generator current and voltage signals as shown in Figure 5.2 a measure of the frequency generated was obtained even for most fault conditions.



Signals measured

V_{RY}

V_{YB}

I_R

I_B

Figure 5.2 Phasor Diagram showing Frequency Transducer input signal for 3 phase balanced load at unity power factor.

Figure 5.2 shows the resultant of the voltage signals and the resultant of the current signals measured for the conditions of a 3 phase balanced load at unity power factor. As can be seen the resultant current signal leads the resultant voltage signal by 90°. Thus a resultant input signal is guaranteed even under the conditions of a 3 phase short circuit. During such a situation the lagging current of the short circuit would be in phase with any voltage signal that remained, thus ensuring a resultant input signal for the frequency transducer to operate upon.

Figure 5.3 is a block diagram representation of the complete transducer. Once the input signal has been filtered to reduce the effects of noise the resultant signal is routed in two separate directions. One leads to a full wave rectifier and integrator, the output of which, VDET, indicates that there is a sufficiently large input signal for correct operation of the transducer. When running up the turbine from standstill the residual magnetism in the rotor is sufficient to produce the necessary input signals to the transducer during the run up sequence of the turbine. The second route for the filtered input signal results in a squared-up signal, at TTL levels, representing the input frequency. In order to obtain a DC level proportional to the frequency input the period of the incoming signal is measured using a 24 bit binary counter which is clocked at a frequency of 1 MHz. The necessary logic is provided which strobes the period count into a 24 bit latch at the end of each period. Simultaneously, the counter is reset ready to measure the subsequent period. The outputs of the latch are directed to various logic circuits and two D/A converters. The two D/A outputs provide a wide band frequency signal and a narrow band frequency signal respectively. Calling these signals frequency is perhaps not correct since it is in fact the period of the incoming signal that is being monitored. The wide band frequency signal, FR2, is in fact highly non linear but this does not matter since this signal is only used to detect fixed speeds

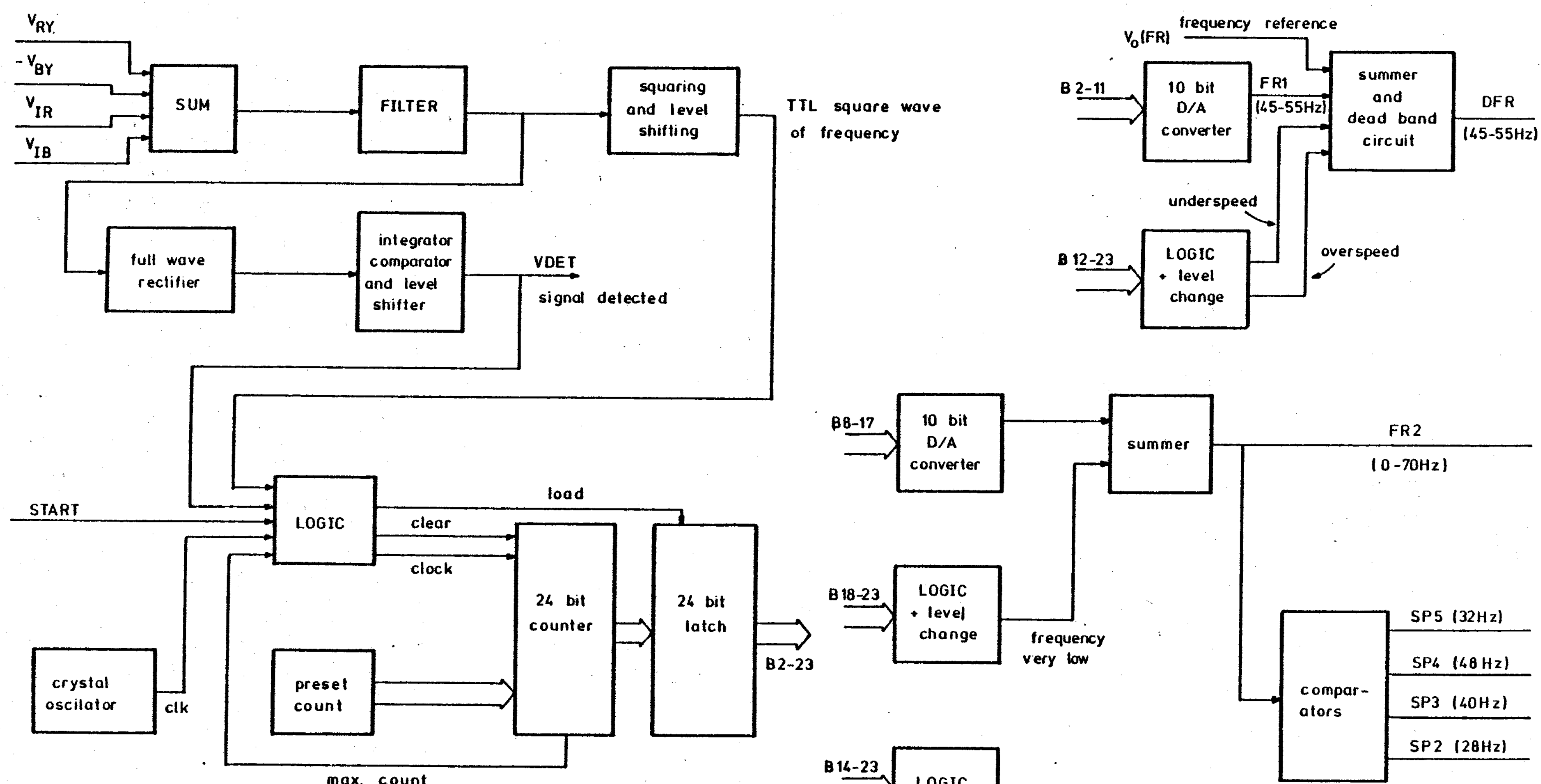


Figure 5.3 Block diagram of the Frequency Transducer

which are previously chosen by comparator settings. These speeds, SP1 to SP5 are used in the run up sequence as will become apparent during the discussion of the Control Rack.

The narrow band frequency signal, DFR, again is not truly frequency but within the narrow band is sufficiently accurate as can be seen from Figure 5.4 which shows the ideal relationship and the actual transducer relationship for input transducer count to resultant output voltage representing frequency. The $\pm$ 1V output of DFR represents $\pm$ 5 Hz around 50 Hz. As can be seen from Figure 5.4, the method used for measuring the period results in an accurate measurement of frequency of 50 Hz. The 10 bit accuracy of the D/A used for DFR provided a resolution of 0.01 Hz at 50 Hz.

Also provided is a frequency reference signal, Vo(FR), which has its source in the Control Rack and is used by the auto synchroniser and the operator. The normal range of the DFR signal is $\pm$ 1V as mentioned before but in the event of overspeed or underspeed, greater than 55 Hz or less than 45 Hz respectively, the DFR signal is stepped to 15V with the appropriate sign in order to initiate immediate action by the governor, even through the dominant lag of the governor.

Finally, the last feature of the frequency transducer is a deadband circuit which allows a deadband of up to $\pm$1 Hz around 50 Hz. This facility was included so that the Isolated Load Simulator (described in Chapter 7) could provide a simulated frequency to the governor in parallel with the system frequency, without the system frequency influencing the results. If, however, a system fault occurred which took the system frequency outside the deadband then corrective regulating action would be taken by the governor.

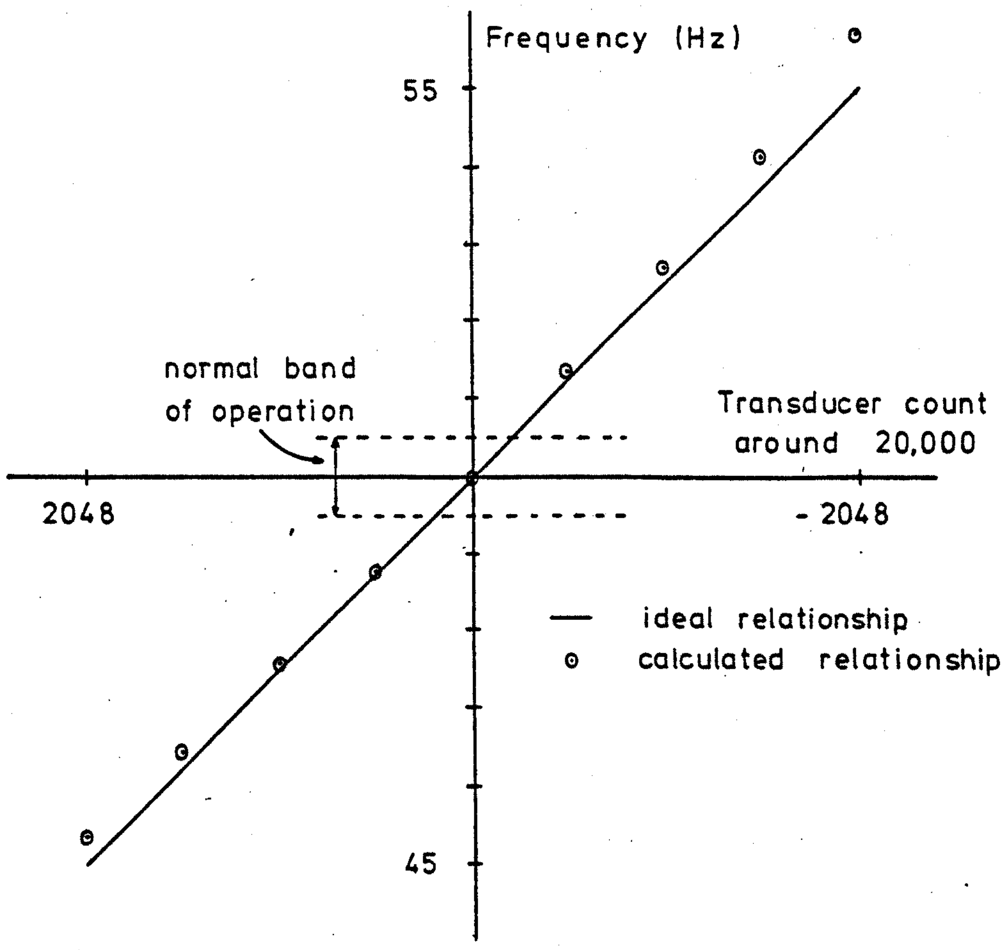


Figure 5.4 Frequency Transducer error around 50 Hz
(i.e. 20ms = a transducer count of 20,000)

c) Main Servo Controller

This unit provided the necessary position feedback control so that the main, high pressure, servomotor could be positioned correctly as requested by an input voltage signal in the range 0 - 10V representing 0 - 100% servo movement. The input signal was compared with a feedback signal from a Linear Variable Differential Transformer type transducer which was attached to the body of the servomotor. The resultant error signal was suitably amplified, converted to a current signal and then fed to the MOOG control valve which directed the high pressure oil to the appropriate oil circuit. The electronics of the controller also contained a gain control to enable the control loop to be set up so that a dead beat type of response was achieved by a suitable choice of loop gain.

d) Power Transducer

This unit calculated both Real and Reactive Power using the two wattmeter method. Electronic multipliers were used to form the products $V_{RY}.I_R$ and $V_{BY}.I_B$. The sum of these two products gave a measure of the Real Power which, with suitable scaling, provided a DC output voltage from 0 - 10V, corresponding to a power of 0 - 30 MW. The difference of the two products resulted in a similar type of signal representing the Reactive Power.

e) Power Supply Monitor

This unit was provided to monitor all the low voltage supplies (i.e. +5V, ±15 V, and ±15V for the Analogue Isolation Amplifier) and also the 230 V AC input to the Interface/Control Rack. As reliable operation could not be guaranteed if any of these supplies failed, it was the Power Supply Monitor's job to provide the appropriate alarm so that the Station protection system could run the set down safely. Although not part of the Power Supply Monitor's function it is appropriate to mention here that a similar type alarm would be raised due to the failure of the 110V DC to the Interface/ Control Rack. This happened automatically since the relaxed position of one of the 110 V relays generated the alarm.

f) Analogue Isolation Amplifier

Several of the functions on the Control Rack were duplicated on the panel in the Control Room. These are listed below:

i) Raise/lower desired Megawatts
ii) Raise/lower load limit
iii) Raise/lower frequency reference
iv) Set Megawatts
v) Display narrow band frequency

(The setting of Megawatts was done approximately since the actual machine power was not monitored here. The desired Megawatts was assumed to be proportional to main servo position.)
Excepting v), the signals involved in i) to iv) are all logic signals and so the necessary isolation between Station and Interface/ Control Rack was dealt with in the opto-isolators of the Interface Rack. However, the narrow band frequency was an analogue signal in the range $\pm$ 10V so an Analogue Isolation Amplifier was included to provide the required isolation.

g) Buffer Amplifiers

Many of the signals generated within the Interface/Control Rack were to be recorded during the tests that were to follow once the system was operational. The Buffer Amplifiers not only provided simple buffering but in some cases included gain and offset conditioning. The resultant output signals were passed on to the recording equipment.

5.3 The Control Rack

It was the responsibility of the Control Rack to coordinate the input signals from the Station, provide the run-up sequencing, closed loop governing action and a set of controls to interface to the operator. Additionally test governors could be easily included into the system for evaluation purposes. The Isolated Load Simulator was an extra facility outwith the normal overall control but it proved to be very useful, eliminating the necessity to arrange system splitting tests in order to check out the closed loop governor response.

A more detailed description of the operation of each of the modules in the Control Rack is given in the following sections.

a) Control Module

Input signals from the Station were coordinated within this module so that orderly run-up and run-down sequences were observed. Additional input signals (the speeds SP1 - SP5) from the frequency Transducer were also included in the control of these sequences. If certain speeds were not reached within predetermined times then the run-up was aborted by the Control Module. However if conditions were normal then further speed signals would eventually enable functions such as engaging the Automatic Voltage Regulator (AVR). The five speeds and their associated functions are listed below:

SP1	(0.25 Hz)	Breakaway
SP2	(28 Hz)	Run-up OK
SP3	(40 Hz)	Pull back guide-vanes
SP4	(48 Hz)	Engage AVR
SP5	(32 Hz)	Governor Drive OK

Outputs from the Control Module were passed to the Reference Control Module.

b) Reference Control Module

This module took the inputs from the Control Module and produced the correct control of the Reference and Reference Setting Modules during run-up sequences. A thumbwheel switch allowed a choice of up to eight different preset Megawatt settings to be set up. This facility was repeated on the Control Room Panel and enabled the operator to set a desired loading to be automatically assumed on completion of a run-up sequence. It was also possible during normal running of the generator, to select a suitable Megawatt setting and then to initiate this loading by executing a "Set Megawatts" instruction.

c) Reference Module

Comprising of mainly CMOS multiplexers and reference voltage levels this module operated as slave to the Reference Control Module producing appropriate reference outputs to the three Reference Setting Modules. All the reference voltages were derived from a voltage regulator with individual control of each reference being accomplished by individual linear preset potentiometers. Adjustment of these potentiometers was achieved from the front panel of the module.

d) Reference Setting Modules (Frequency (FR), Megawatts (MW), Load Limit (LL))

These three, essentially identical, modules provided a means of defining the Frequency Reference signal, $V_o(FR)$, the Megawatt signal, $V_o(MW)$, and the Load Limit signal, $V_o(LL)$ respectively. Three methods of operation were available. Firstly, local to the module was a raise/lower switch which allowed the chosen signal to be ramped up or down at a preset rate which was adjustable by means of a linear preset potentiometer. The second method was identical to the first except that the raise/lower control was remote from the module residing on the Control Room Panel. The final mode of operation was a tracking mode in which the output from the module ramped towards a given reference value. On reaching the desired value a feedback signal was returned to the Reference Control Module which in turn cancelled the tracking command it initially requested. The third method was used extensively during the run-up sequence.

Two types of outputs were provided from these modules. Since the output values were originally derived from an 8 bit binary counter it was a simple matter to provide a digital output representation for use in the microprocessor governor. This digital count was further directed to an 8 bit D/A converter then to a first order lag to smooth out the individual transitions of the D/A output. The resultant analogue signals were required in the analogue governor and frequency transducer.

e) Analogue Governor Module

The fundamental purpose of this module was to provide the double derivative governing function during normal operation of Set No. 3 at Sloy. Its complexity was further increased however by the inclusion of the load limit function and other control functions, some of which had not been foreseen at the initial design stages. Reference to Figure 5.5 during the following discussion should provide a better understanding of the operation of the governor module.

Two frequency signals were taken into this module. One was the normal frequency error signal derived from the Reference frequency and the system frequency signals. The second was a test input which was generally used in conjunction with the Isolated Load Simulator (ILS). The composite input signal was then subjected to a rate limit circuit which was designed to respond more rapidly than changes of frequency, which would be limited by

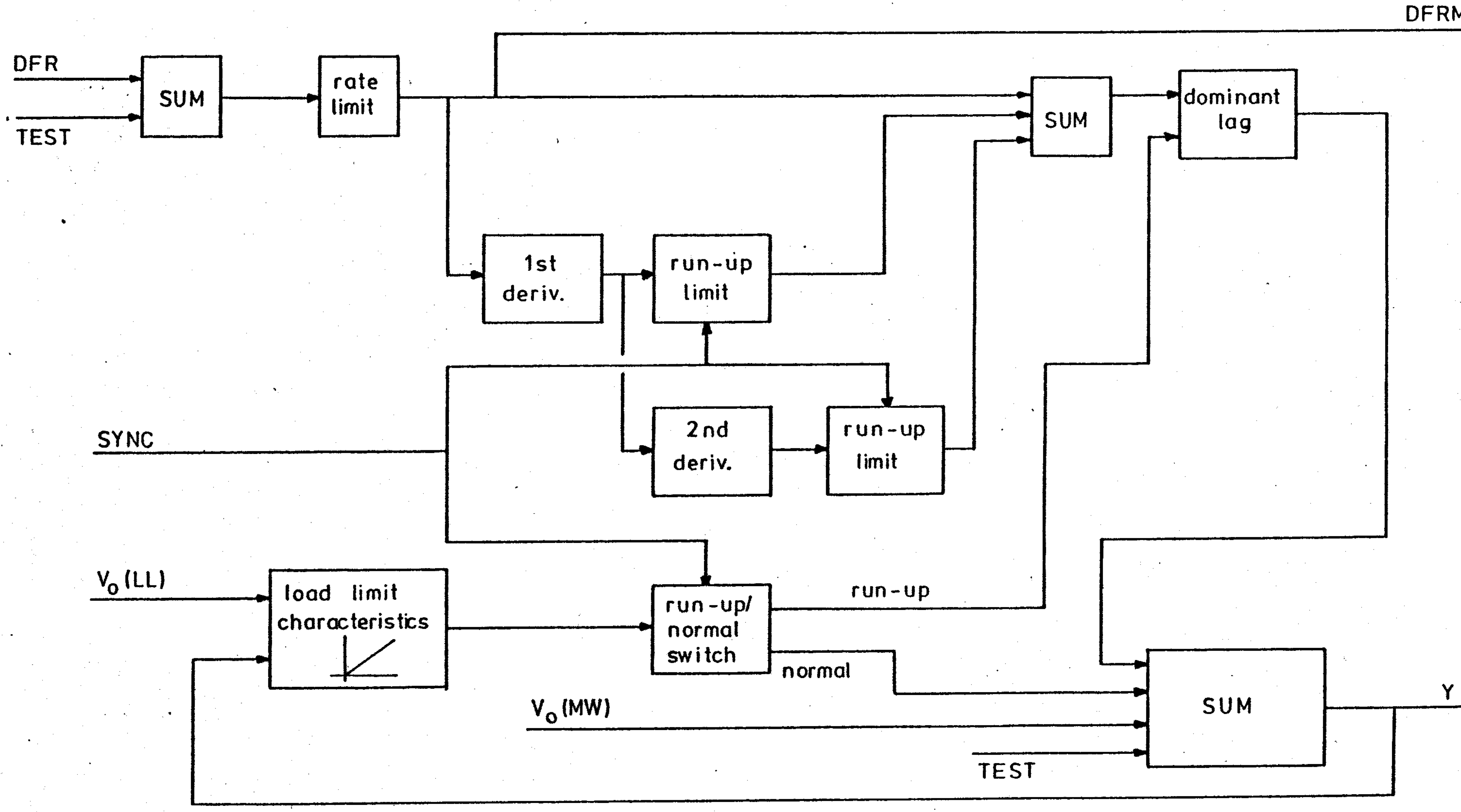


Figure 5.5 Block diagram of the Analogue Governor Module

the machine inertia. Thus the rate limit circuit provided a means of filtering noise. The resultant signal was used by the Microprocessor Governor as its frequency error signal. As can be seen in Figure 5.5 this signal was also routed to the proportional and first and second derivative functions of the analogue governor. The sum of these three outputs were fed to the dominant lag component of the governor. The final governor output was added to the desired Megawatt signal V_O(MW) thus producing an overall governor drive output. Figure 5.5 shows two further complications to the total governor system. Firstly there were two limit circuits controlling the outputs of the first and second derivatives. These were only operational during the run-up phase of operation, hence their dependency on the SYNC (main breaker status) signal. The necessity for these limits was due to the nature of operation of the frequency transducer. The normal output from the transducer was ± 1V representing ± 5 Hz around 50 Hz; however during run-up the transducer stepped from a large negative value to -1V when the frequency reached 45 Hz. This step was amplified greatly through the derivative functions with the result that the governor output headed towards zero very rapidly. Consequently the derivative action was not eliminated, but greatly reduced during this mode of operation.

The second control feature of the governor module relates to the load limit facility. The load limit operated by comparing the desired limit with the actual governor output. The one sided load limit characteristics provided a greatly amplified error signal if the actual output became greater than the desired value. This error signal was used to correct the output. The optimum position for this corrective action is at the dominant lag section because the corrective action has the effect of swamping the lag characteristics if load limit operation is required, but allows immediate governing action out of the load limit if the frequency error signal so decrees. This was exactly what happened during the run-up sequences since the value of the desired Megawatt (MW) signal followed the Load Limit signal, V_o(LL). However, during normal operation, when say the Load Limit was set below its maximum value, the following undesirable circumstance could arise if the Load Limit acted on the governor lag. It was possible that the Load Limit could be lifted thus releasing the governor lag from the limiting condition even although the frequency error input was still requesting further output from the governor lag. Consequently the output of the governor would have to rise at a rate determined by the dominant lag of the governor rather than following the Load Limit signal directly. For this reason the swamping action of the Load Limit was switched from the dominant lag to the final summing amplifier by use of the SYNC signal after run-up was complete. The disadvantage now is that the Load Limit condition will not be released immediately if the frequency error indicates that it should. Instead, a delay will occur due to the dominant lag characteristics before the Load Limit condition is released.

The last feature of the governor module was a test input which directly affected the final governor output signal. This test input was used to inject signals during the dither experiments.

f) Governor Changeover Module

Both governor outputs from the Analogue and Microprocessor Governors were inputs to the Changeover Module. A manual choice of which governor had control was available. There was also an automatic safety feature which could have been selected. By using the Analogue Governor as a reference the Microprocessor (or test) Governor output was compared with the Analogue Governor output and if there was a large discrepancy an alarm was set and the Analogue Governor could be automatically reselected.

This safety mechanism could also be activated if a watchdog signal from the Microprocessor Governor failed.

No matter which governor was operational the chosen output was directed via rate limit circuits which had adjustable rates for both increasing and decreasing signals. For reasons of safety to Station equipment these rates were not set below the following:

(a) Upward Rate - 22s for full stroke

(b) Downward Rate - 2s for full stroke.

g) Microprocessor Governor

This provided similar facilities to those of the Analogue Governor and is explained in detail in Chapter 6.

h) Isolated Load Simulator

This unit provided a means of simulating isolated load conditions by monitoring load power and generating a simulated frequency to be fed to the governors. Chapter 7 explains the Isolated Load Simulator in detail.

5.4 Data Logging Equipment

Two methods of recording site test data were employed, thus providing a certain amount of redundancy. Firstly there was a twelve channel ultra violet (U/V) recorder and secondly there was a microprocessor based, sixteen channel, digital data logger. The common source of data input to both of these systems was from within the module containing the buffer amplifiers.

Before being recorded on the U/V recorder, incoming signals were patched through to individual signal conditioning units. Each of these units was capable of implementing gain and offset changes to the inputs. Switches set the gain and offset by a preset calibrated amount while potentiometers allowed for continuous vari ation of these controls. Once conditioned, the signals to be recorded were passed over to the U/V recorder. Fixed references could be momentarily applied to each of the channels of the U/V recorder to enable easy identification of any one channel. Additionally a sequencer could be set in motion which applied this reference, in turn, to each of the channels.

The digital data logger was based upon an Altair 8800B Microcomputer System with a floppy disk unit. Additional to the normal system was a board containing a 12 bit analogue to digital converter and a sixteen input, single ended multiplexer. Before the analogue signals were passed to this data acquisition board the signals were subjected to analogue filters to minimise the effect of noise. The software required for collecting the data was provided by Dr. H. Davie of the Department of Electronics and Electrical Engineering at Glasgow University. The section of program controlling the dialogue with the operator was written in BASIC. The initial dialogue defined the number of channels (up to sixteen) and, specifically, which channels would be recorded. The choice of sampling interval was also chosen at this point and was dependent on the number of channels that were being monitored and the proposed length of time over which data would be collected, since the data was stored in the microcomputer's memory during the test. After termination of a test the acquired data would be stored within a file on the floppy disk. Due to the time critical nature of the section of program that actually dynamically recorded the data, this part of the software was written in the assembly language of the microcomputer which was based on the Intel 8080 microprocessor.

Additional related software, prepared by the author, was associ ated with the plotting of the results obtained. Two methods were available. Firstly another BASIC program could be run on the

Microcomputer system and this allowed the plotting of the results by using a Tektronix 4662 Interactive Plotter attached to one of the serial I/O lines of the microcomputer. This method was used on site to verify that the information acquired on the digital data logger system was sensible. Only sample plots were made on site since the U/V recordings gave an immediate indication (and subsequent backup) of the validity of each test as it happened.

Further programs were developed for off site manipulation of the digital data. Software was developed which enabled the site test data on the microcomputer's floppy disk to be transferred along a serial link to a PDP 11/45 computer. This not only duplicated the data for safety reasons, but also allowed a more sophisticated program for the Tektronix 4662 Plotter to be run on the PDP 11/45. Illustrations of the types of plots produced can be found in Chapters 8 and 9 where site test results are displayed.

5.5 Description of a Run-up Sequence

In order to initiate a run-up sequence from a standstill position the operator throws a single switch. After essential services have been switched on, such as the governor oil pump, the main valve opens. Once the spiral casing of the turbine has filled with water the Control/Interface Rack gives the "go" signal. The Control Module initiates the opening of the guide vanes which ramp up to approximately 24% of full opening at a rate of 2.3% full travel per second. The guide vanes remain at 24% for about 11 seconds after which (SP3 reached) they ramp down to 22% until the frequency increases to such a point that conventional governing action takes place. This sequence of events is illustrated in Section 2 of Chapter 8. If, having initially opened the guide vanes to 24%, the turbine does not "breakaway" (i.e SP1) within 15 seconds then the Control Module automatically initiates a logical run-down sequence. Similar action is taken if, after successfully reaching "breakaway", a speed equivalent to 28 Hz is not reached 1 minute after "breakaway". Assuming the run-up is proceeding logically then the AVR is switched in at 48 Hz (SP4).

During the sequence up to this point the operator could have chosen a desired loading which the set would take up as soon as the run-up sequence was completed. If the operator does not choose a loading then a default setting is assumed to ensure that the generator does not motor when connected to the grid system.

A fter the AVR is operational the auto-synchroniser synchronises the generator with the grid system by manipulation of the frequency reference, and then closes the main breaker at the appropiate moment. With the closing of the breaker the Load Limit lifts to 105% and the frequency reference signal resets to zero (i.e. 50 Hz). The last step in the run-up sequence occurs when the main inlet valve reaches its fully open position. At this point the set is automatically loaded to the predefined level defined by the operator as previously described. This would complete the run-up sequence after which the operator would have normal control of the raise/lower controls of the three Reference Setting Modules.

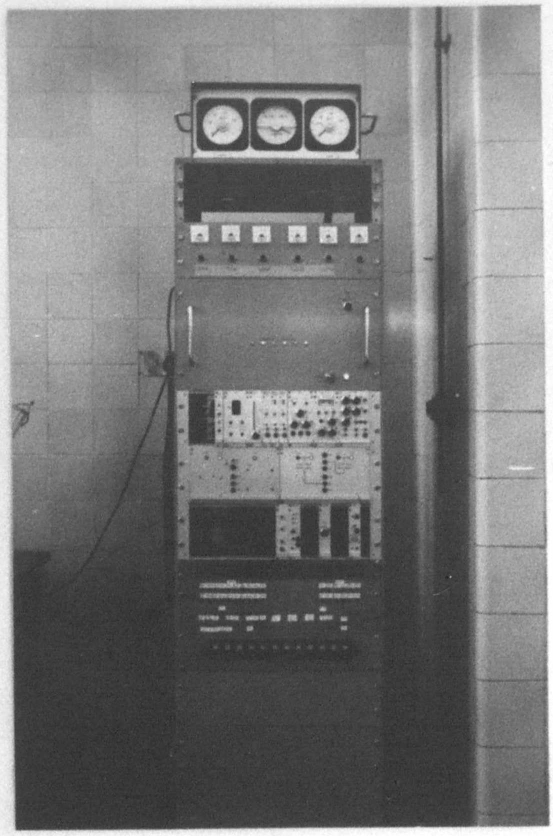


Plate 7. Control and Interface Rack

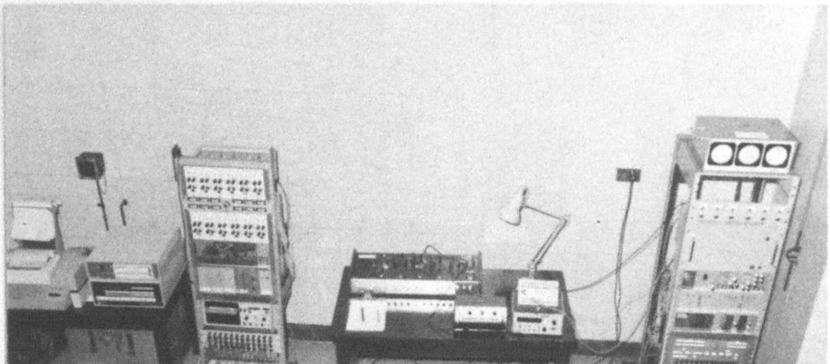


Plate 8. Experimental control and recording equipment

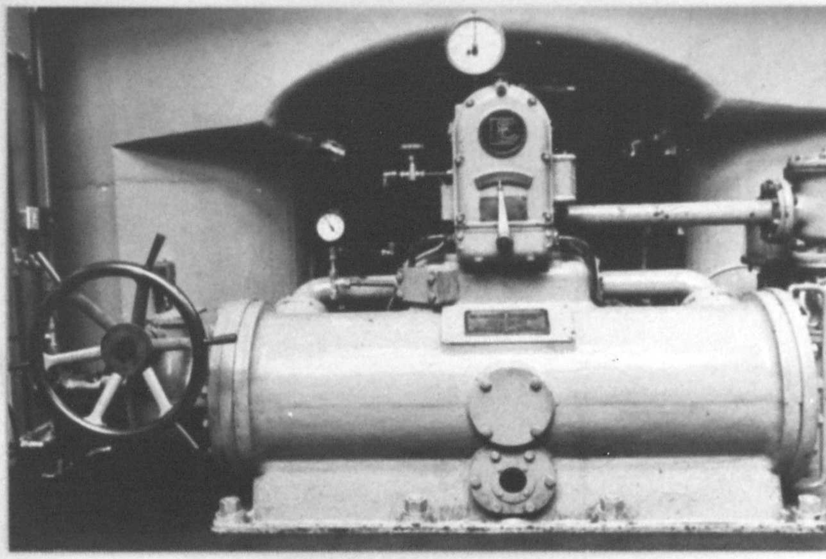


Plate 9. English Electric Governor of Set No. 4 at Sloy

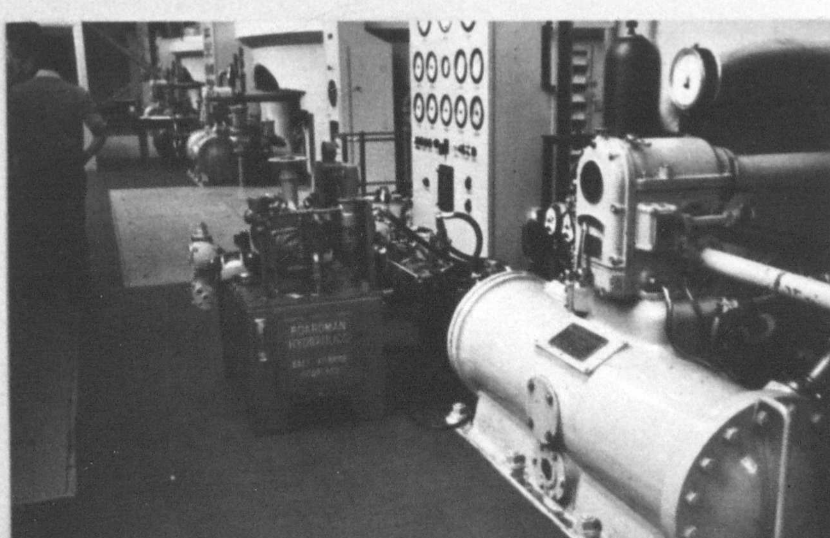


Plate 10. Experimental governor hydraulics of Set No. 3 at Sloy

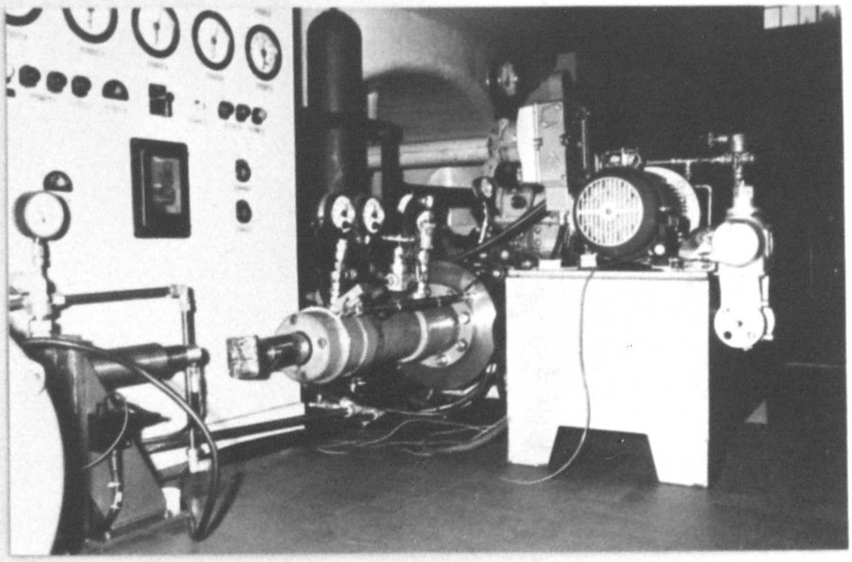


Plate 11. High pressure hydraulic actuator

CHAPTER 6 - THE MICROPROCESSOR GOVERNOR

6.1 Introduction

The microprocessor governor took on many different guises as it developed from its initial form as a Temporary Droop (TD) governor running in an Intel 8008 Central Processing Unit (CPU) and then advancing to the later and more powerful Intel 8080 CPU within the Altair development system. With this hardware transition the governor was also changed from the TD form to a Double Derivative (DD) type. Further features were then added to the governor, such as Load Limit (LL) and Set Megawatts (SMW) before the entire governor was finally realised using the Intel single board computer, the SBC 80/10, working in conjunction with an Analog Devices data acquisition board, the RTI 1200.

It was with this project, concerning the use of microprocessors as speed governors, that the Department of Electronics and Electrical Engineering at Glasgow University started to build up facilities associated with microprocessors. The equipment initially available consisted of an evaluation system built around Intel's 8008 CPU by DEC (Reference 48). This system consisted of a backplane, a monitor switch panel, 8008 processor card which had an instruction cycle time of around 20 microseconds, 2K of Random Access Memory (RAM) and a line frequency clock. After adding power supplies, an extra 1K of RAM, an 8 bit input and an 8 bit output port, the system was ready for programming

The software available for this system consisted of an assembler, a floating point package and a basic monitor. As the assembler was not particularly powerful then, using the Department's DEC PDP 11/45 minicomputer, a cross-assembler was prepared for the 8008 instruction set and at a later date a corresponding cross-assembler for the instruction set of the 8080 was produced (Reference 49). Thus the procedure for preparing and running programs was of the following general form. Firstly, the source programs (in assembly language format) were edited on the PDP 11/45. Then the cross-assembler was put to work and, assuming a successful assembly, a paper tape copy of the resultant binary code was punched. This DEC DOS formatted tape was subsequently taken to the microprocessor and loaded into the microprocessor unit (MPU) via a teletype. By using a special loader program with checksum error detecting facilities, the chance of the paper tape being read incorrectly and undetected was reduced. At one time, when the bulk of the microprocessor system was such that the MPU could be easily transported to the PDP 11/45, the binary load module was down-loaded directly from the PDP 11/45 using a parallel (byte size) interface. This method of loading took a fraction of a second compared with minutes for the reading in of paper tapes.

6.2 Floating Point Package

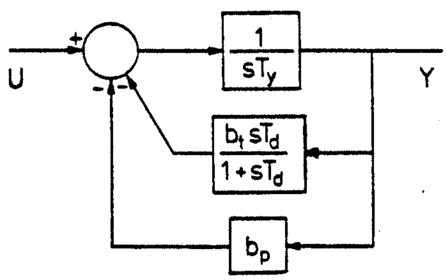
Having become familiar with the equipment and their operating procedures, attention was directed towards the production of a governor routine which would operate in the 8008 MPU, since this was, initially, the only available microprocessor system. The first component of the software which was required was a set of routines to perform basic arithmetic. The decision was made to use a floating point package instead of a package operating on integers and the reasons for this were twofold. The floating point package would eliminate the problems of scaling and overflow that would have been associated with integer arithmetic. Also the existence of a library of floating point routines and functions in the DECUS (DEC User Society) library made the development of a mathematics package unnecessary. Unfortunately the DECUS routines were supplied on paper tape in binary load module form. This implied the use of the complete package, without choice of origin, where only a few selected routines were required. For this reason the author wrote a disassembler (Reference 50) in FORTRAN to run on the PDP 11/45. The binary paper tapes were used as input to the disassembler resulting in an assembly language listing of the floating point routines as output, After tracing through the listing, the appropriate routines were extracted and with the addition of a couple of extra sections a working floating point package was produced. The limited facilities thus produced could be called as subroutines from the main governor program. Appendix D. explains the usage of these subroutines.

6.3 TD Governor in Difference Equation Form and Operational Feasibility in the 8008 MPU

The first microprocessor governor to be developed was that of a Temporary Droop (TD) type. Since this was the type of governor that already existed at Sloy then a reference governor was readily available. The TD governor was also a lower order system and had longer time constants than other types of governors and would therefore not take up so much computation time. This was an important consideration when dealing with the slow 8008 microprocessor. Additional input/output facilities were constructed for this microcomputer so that communications with the PDP 11/45 could be achieved via an 8 bit parallel interface, with handshaking signals. This communications link served two purposes; firstly it was used to down load binary modules produced from the cross-assembler, and secondly, it was used to transfer data during real time simulations with the PDP 11/45.
The data transfer should ideally have been through A/D (analogue to digital) and D/A (digital to analogue) converters since this was to be

the means by which the microprocessor would communicate with the hydro turbine interface at Sloy Power Station. However these converters were not available for the microprocessor at this time, so for initial proving tests the parallel interface was used.

The implementation of the TD governor, the block diagram of which is shown in Fig. 6.1, was achieved using difference equations, after once having reduced the transfer function into partial fractions (Reference 51).

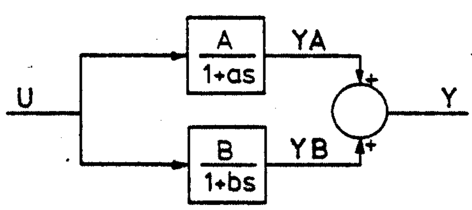


Transfer function

$$\frac{Y(s)}{U(s)} = \frac{1+sT_d}{b_p(1+1/b_p((b_p+b_t)T_d+T_y)s+(T_yT_d/b_p)s^2)} \qquad \text{equ. 6.1}$$

Fig. 6.1 Temporary droop governor and transfer function

The partial fraction representation of the TD governor is illustrated in Fig. 6.2.



Transfer function

$$\frac{Y(s)}{U(s)} = \frac{A}{1+as} + \frac{B}{1+bs} \qquad \text{equ. 6.2}$$

Fig 6.2 Partial fraction representation of the TD governor.

For equivalence between these two representations then the constants in the partial fraction case must adopt the following values.

$$a = 2T_yT_d/[((b_t+b_p)T_d+T_y)+\sqrt{(((b_p+b_t)T_d+T_y)^2-4b_pT_yT_d)}]$$

$$b = 2T_yT_d/[((b_t+b_p)T_d+T_y)-\sqrt{(((b_p+b_t)T_d+T_y)^2-4b_pT_yT_d)}]$$

$$A = \frac{a-T_d}{b_p(a-b)}$$

$$B = \frac{b-T_d}{b_p(b-a)}$$

It is now a simple matter to produce a representation of these first order lags in difference equations.

Taking $\dfrac{YA(s)}{U(s)} = \dfrac{A}{1+as}$

implies $YA(s).(1+as) = A.U(s)$

which in the time domain may be written as

$$ya(t) \pm a\,\frac{dya(t)}{dt} = A\,u(t)$$

If this continuous waveform is sampled regularly at intervals of T seconds then the output ya(t) may be represented at intervals T, by ya(nT) where t=nT (and n is an integer value). Taking the definition of the derivative of ya(t),

$$\frac{dya(t)}{dt} = \lim_{h\to 0} \frac{ya(t)-ya(t-h)}{h}$$

then an approximate value of this derivative can be calculated from

$$\left(\frac{d\,ya(t)}{dt}\right)_{t=nT} \doteqdot \frac{ya_n - ya_{n-1}}{T} = \frac{\Delta ya_n}{T} \qquad \text{equ. 6.3.}$$

which becomes more and more precise as the sampling interval is decreased. (Subscripts n and n-1 imply values taken at times nT and (n-1)T respectively.

For convenience, it is appropriate to mention here how the second derivative is obtained, since it will be required in future representations of governors in discrete form.
Thus for any variable y

$$\frac{d^2y(t)}{dt^2} = \frac{d}{dt}\left(\frac{d\,y(t)}{dt}\right) \doteqdot \frac{1}{T}\left(\frac{\Delta y_n}{T} - \frac{\Delta y_{n-1}}{T}\right) \qquad \text{equ. 6.4}$$

$$= \frac{1}{T^2}\left(y_n - 2y_{n-1} + y_{n-2}\right)$$

However, returning to the present governor representation, equations 6.2 and 6.3 combine to give the following set of first order difference equations

$$ya_n = \frac{a}{a+T}\, ya_{n-1} + \frac{AT}{a+T}\, u_n$$

$$yb_n = \frac{b}{b+T}\, yb_{n-1} + \frac{BT}{b+T}\, u_n$$

$$y_n = ya_n + yb_n$$

These equations require only multiplication and addition routines to solve them. They have the added advantage of being difference equations in Backward Euler form which is a stable integration technique no matter what the integration step length.

During simulation, as mentioned before, the 8008 communicated with the PDP 11/45 by transmitting data along an 8 bit wide I/O system. The data transmitted was the governor input from the PDP 11/45 and the governor output to the PDP 11/45. Four 8 bit bytes were required to represent each of these quantities and since the floating point formats of the two machines were different it was necessary to include conversion routines in the PDP 11/45, to translate from one format to the other.

The sampling interval used in this first governor was set at 0.5secs. This was not the ideal choice but was determined by the speed of computation of the 8008. However the sampling rate was fast enough to give some reasonable results proving the feasibility of a microprocessor governor.

Fig 6.3 is a trace of a real time simulation with the PDP 11/45. This is a step response to a load demand change from 100% - 90% FL. While the microprocessor emulated the governor the PDP 11/45 simulated the main servo, a simple impulse representation of the hydraulic system, and a generator. The entire simulation process may be visualised as in Fig. 6.4. Table 6.1 gives details of the parameters for this simulation.

Both frequency and governor output have been plotted as a function of time. Additionally, the responses for two different microprocessor sampling intervals (i.e T = 0.5s and T = 1.0s) are given. Observation of the traces at the different sampling intervals illustrates the resultant decrease in stability as the sampling interval period is stretched. Although the trace with the 0.5 second sampling

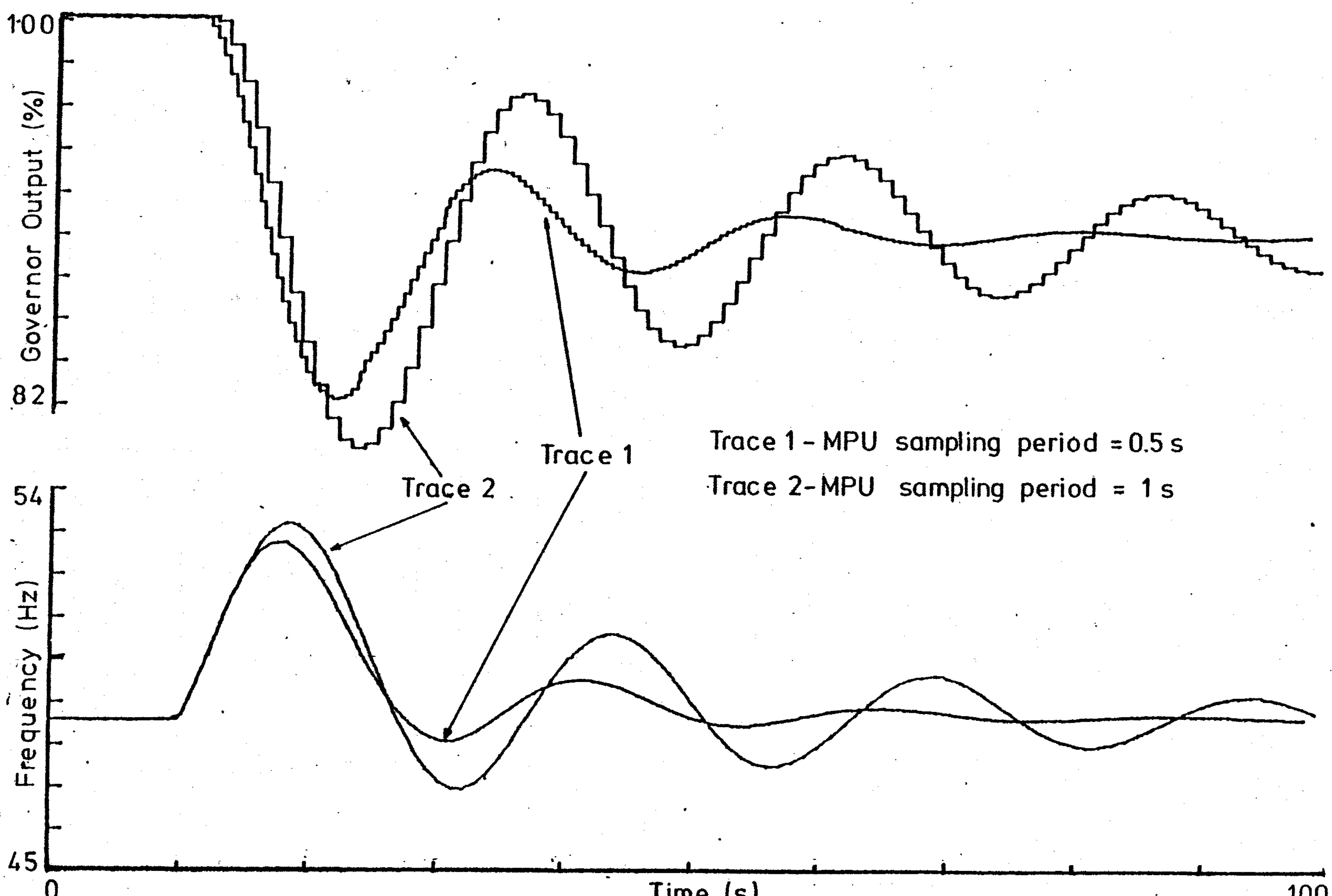


Figure 6.3 Interactive PDP 11 - Microprocessor (8008) TD Governor simulation

interval gives a reasonable response for the TD governor the 8008 was stretched to its limit. Thus if any additions were required to the governor or a more complex algorithm desired (e.g. the Double Derivative governor) then the 8008 would not be a suitable choice of microprocessor.

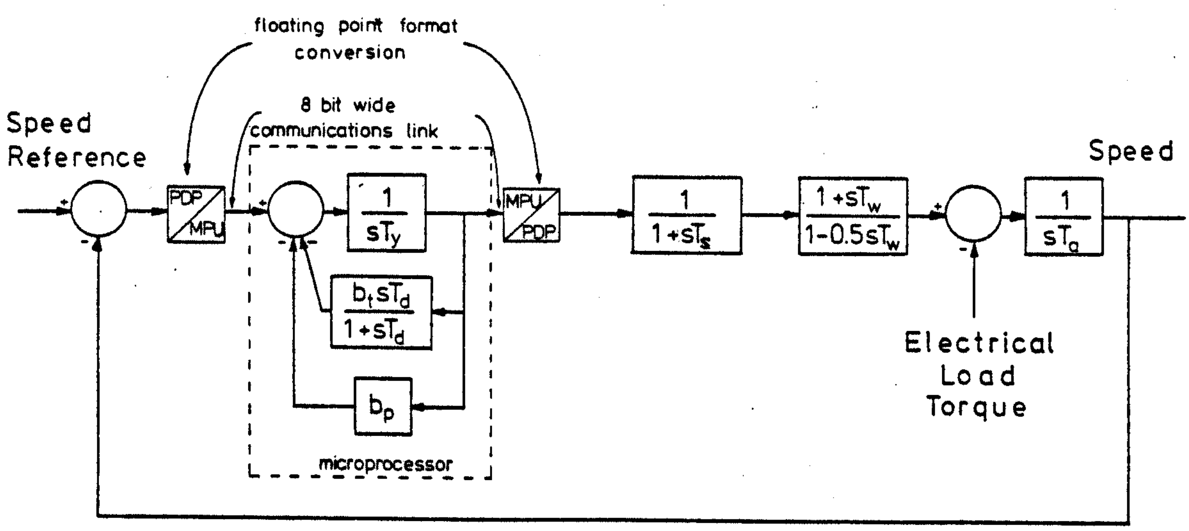


Figure 6.4 Representation of interactive simulation between PDP 11/45 and 8008 MPU

Parameter	Value
T_y	1.0s
T_d	16.0s
b_t	0.5
b_p	0.03
T_s	0.2s
T_w	1.1s
T_a	7.0s
Frequency Ref.	50 Hz
Load Torque	100%–90%

Table 6.1 Parameter values for interactive simulation between the PDP 11/45 and the 8008 MPU.

6.4 DD Governor in Difference Equation Form and its Operation in the Altair 8800B

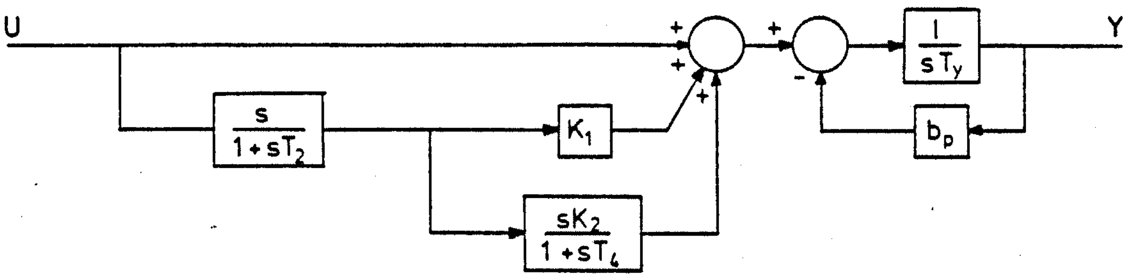
Although the 8008 governor had proved successful, it was clear that a higher performance microprocessor was required if a more accurate and more sophisticated governor was to be produced. It has also been shown that a Double Derivative (DD) type of governor gives more rapid control yet retains stability under isolated load conditions. (Reference 27) Consequently the next microprocessor governor to be implemented was of the DD type and had the 8080 CPU at its heart.

Initial work with the 8080 CPU was carried out using an Altair 8800B microcomputer system which provided not only a more powerful processor but also much more in the way of development aids than did the 8008 based system. The microprocessor used in the Altair was the Intel 8080 which is an order of magnitude faster than the 8008 and has an extended repertoire of instructions. The 8080 was further supported by 32K bytes of RAM, a floppy disk and interface, and PROM (Programmable Read Only Memory) programming facilities. The software support came in the form of a BASIC interpreter. Although the BASIC language was not used to produce governor routines it was used to provide the software for the data logging facility and the plotting routines which were discussed in the previous chapter. The BASIC interpreter operated too slowly to allow the governor routines to be computed in real time therefore the governor programs had to be written in assembly language.

As there was little software support at assembly language level for this system the procedure for governor routine production remained the same as before. However an important addition to the governor facilities was implemented by the author, namely A/D and D/A converters and an independent, stable, real time clock. These three items were contained in a separate unit from the MPU and were interconnected via 8 bit I/O ports. The A/D was of 12 bits accuracy and the D/A, 10 bits. The clock consisted of a 1 MHz crystal oscillator divided down to form a low frequency clock with a period of 100ms.

The input converter, which dealt with the frequency error signal, was set up in its bipolar mode. It was arranged that ± 10V was equivalent to $\pm 5\%$ of nominal frequency. The output converter, in unipolar mode, was arranged such that 0 - 10V represented 0 - 100% governor output.

Reduction of the DD transfer function, shown in Fig. 6.5, into difference equations was again initially achieved by the use of partial fractions.

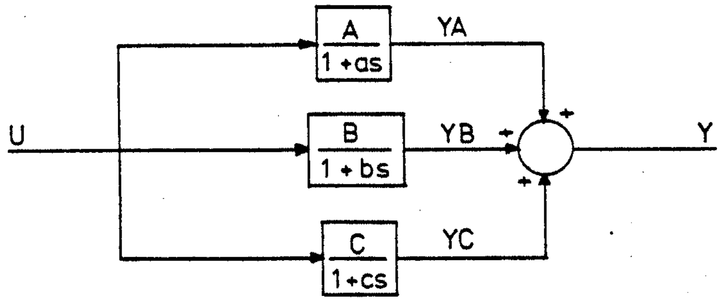


Transfer function

$$\frac{Y(s)}{U(s)} = \frac{1}{b_p + sT_y}\left(1 + \frac{sK_1}{1 + sT_2} + \frac{s^2K_2}{(1+sT_2)(1+sT_4)}\right)$$

Figure 6.5 Double Derivative Governor and transfer function.

Fig. 6.6 contains the block diagram and transfer function of the partial fraction representation of the DD governor.



Transfer function

$$\frac{Y(s)}{U(s)} = \frac{A}{1 + as} + \frac{B}{1 + bs} + \frac{C}{1 + cs}$$

Figure 6.6 Partial fraction representation of DD Governor

In order that this partial fraction representation be identical to that of the DD governor then the constants must assume the following values.

$$a = \frac{T_y}{b_p} \qquad A = \frac{1}{b_p}\left(1 - \frac{b_p K_1}{T_y - b_p T_2} + \frac{b_p^2 K_2}{(T_y - b_p T_2)(T_y - b_p T_4)}\right)$$

$$b = T_2 \qquad B = \frac{K_2}{(T_2 b_p - T_y)(T_2 - T_4)} - \frac{K_1}{(T_2 b_p - T_y)}$$

$$c = T_4 \qquad C = \frac{K_2}{(T_4 - T_2)(T_4 b_p - T_y)}$$

Thus this representation of the DD governor may be expressed in difference equations as follows,

$$ya_n = P_1\, ya_{n-1} + P_2\, u_n \qquad \text{where} \qquad P_1 = T_y/(b_p T + T_y)$$

$$P_2 = A.T/(b_p T + T_y)$$

$$yb_n = P_3\, yb_{n-1} + P_4\, u_n$$

$$P_3 = T_2/(T + T_2)$$

$$yc_n = P_5\, yc_{n-1} + P_6\, u_n$$

$$P_4 = B.T/(T + T_2)$$

$$y_n = ya_n + yb_n + yc_n$$

$$P_5 = T_4/(T + T_4)$$

$$P_6 = C.T/(T + T_4)$$

As a refinement to this governor, it was thought that the time constants T_2 and T_4 were unnecessary. They are only included to reduce the bandwidth of the signals reaching the first and second derivatives, in order to minimise the effects of noise. However the effect of sampling the input signal provides a bandwidth limitation similar to that which is desired. A further benefit in omitting T_2 and T_4 was a saving in computation time since the complexity of the algorithm is slightly reduced.

Thus with both T_2 and T_4 equal to zero the transfer function for the DD governor becomes,

$$\frac{Y(s)}{U(s)} = \frac{1}{b_p + sT_y}\left(1 + sK_1 + s^2K_2\right)$$

and in the time domain

$$b_p\, y(t) + T_y \frac{dy(t)}{dt} = u(t) + K_1 \frac{du(t)}{dt} + K_2 \frac{d^2u(t)}{dt^2} \qquad \text{equ. 6.5.}$$

By using equations 6.3 and 6.4 the difference equation form of equation 6.5 may be written as

$$\begin{aligned} y_n = \frac{T_y}{b_pT + T_y} \cdot y_{n-1} &+ \left(\frac{T}{b_pT+T_y}\right)\left(1 + \frac{K_1}{T} + \frac{K_2}{T^2}\right) \cdot u_n \\ &- \left(\frac{T}{b_pT+T_y}\right)\left(\frac{K_1}{T} + \frac{2.K_2}{T^2}\right) \cdot u_{n-1} \\ &+ \left(\frac{T}{b_pT+T_y}\right) \cdot \frac{K_2}{T^2} \cdot u_{n-2} \end{aligned}$$

Both types of DD governor were implemented in the Altair MPU and performed quite satisfactorily. Three independent checks were made on the correct operation of the microprocessor governor. These rigorous checks were carried out using the governor containing the constants T_2 and T_4.

Firstly, the analytical open loop step response of the DD governor transfer function was compared with an actual step response of the microprocessor governor. The value of the input step resulted in the output of the governor settling from 10% to 90% of full output swing. This ensured that neither the input A/D nor output D/A converters reached their saturation levels. The output response was recorded on an X/Y recorder in sweep mode.

Both analytical and actual responses are traced in Fig. 6.7. The initial spike, due to derivative action, is smaller in the microprocessor case and this may be due to several factors, i.e rate of the X/Y recorder, switch contact bounce and the MPU sampling process. However, on the whole, the MPU response is very similar.

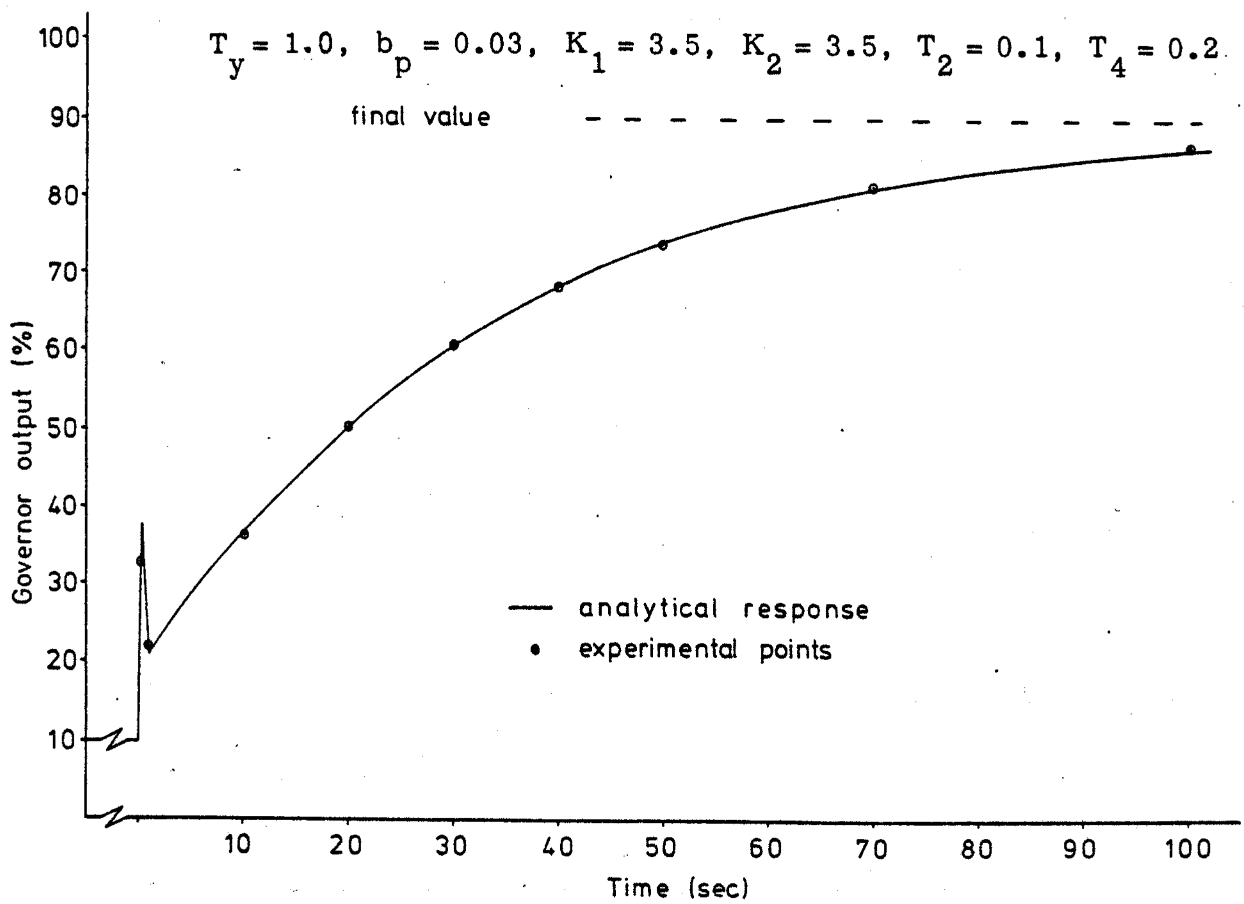


Figure 6.7 Analytical and experimental step responses of the DD governor

The next test on the microprocessor was to compare the analytical frequency response with the actual MPU frequency response. Fig. 6.8 gives this comparison over an appropriate frequency range. Agreementwasvery close until the effects of sampling (T now 0.1s) became important.

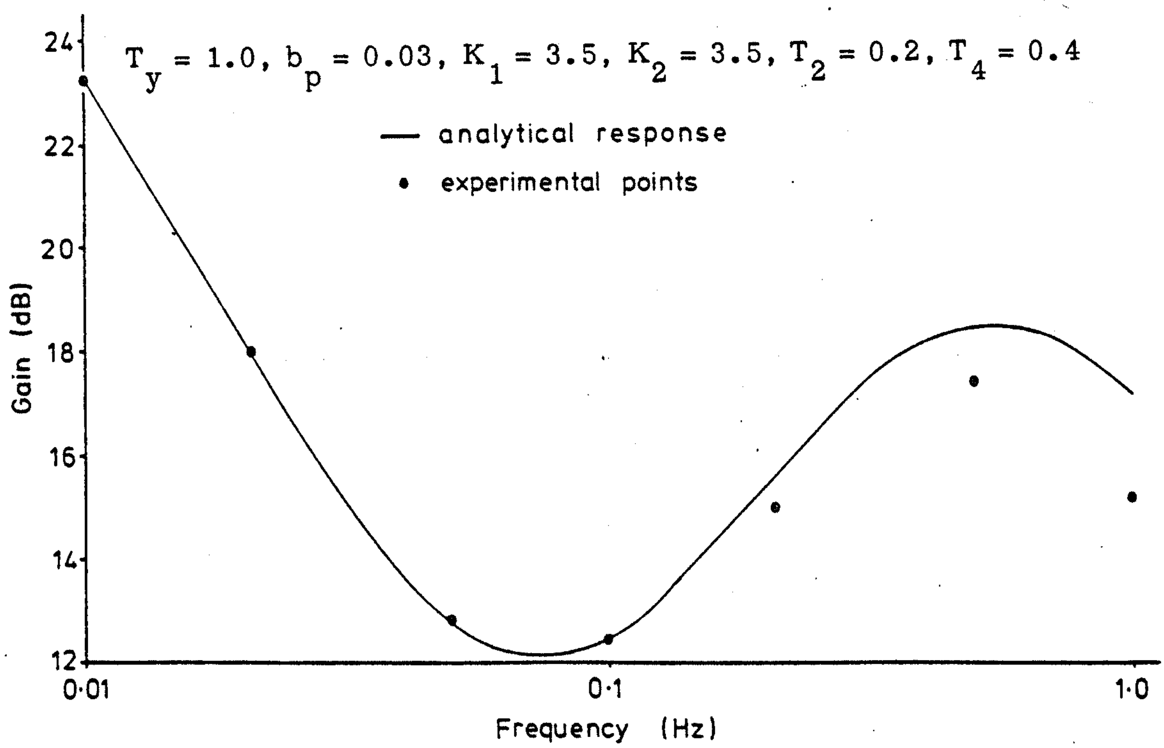


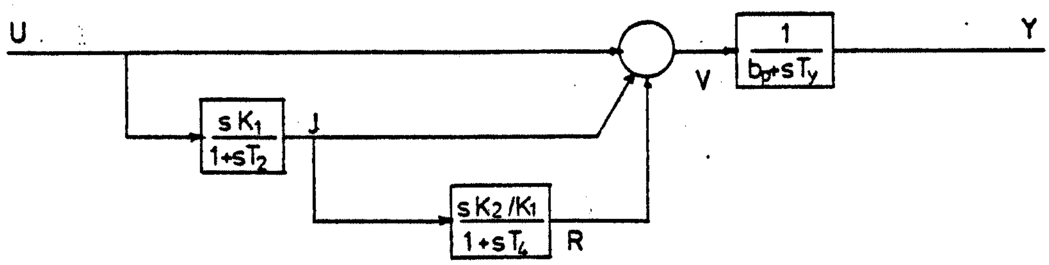
Figure 6.8 Frequency response of the DD governor

The final test consisted of a closed loop response with the PDP 11 real time simulation. The real time simulation with the MPU was compared with simulation results which were obtained by simulating both governor and system within the PDP 11. These results were in excellent agreement.

6.5 Final Form of DD Algorithm used in the Microprocessor Governor.

Although the partial fraction representation and the type with $T_2 = T_4 = 0$ are both quite correct, neither of these representations was used. Several factors were responsible for this. For example in the partial fraction method it is not permissible for $T_2 = T_4$. Additionally it was later discovered from experience on site that ignoring T_2 and T_4 led to unacceptable levels of system noise being fed through the governor causing a noticeable juddering movement on the main servo. Thus T_2 and T_4 were finally included in the governor and through observations at Sloy, minimum acceptable values of $T_2 = T_4 = 0.2$sec. were chosen.

The final form of algorithm employed is illustrated in Fig. 6.9 and a set of equations describing the system is listed.



System equations

$$J + T_2\dot{J} = K_1\dot{U}$$

$$R + T_4\dot{R} = K_2/K_1\,\dot{J}$$

$$V = U + J + R$$

$$Y = (V - T_y\dot{Y})/b_p$$

Figure 6.9 Final form of the DD algorithm used

The equivalent set of equations in difference form is listed on the following page

$$j_n = P_1\ j_{n-1} + P_2(u_n - u_{n-1})$$

$$r_n = P_3\ r_{n-1} + P_4\ (j_n - j_{n-1})$$

$$v_n = u_n + j_n + r_n$$

$$y_n = P_5 \cdot v_n + P_6 \cdot y_{n-1}$$

where

$$P_1 = T_2/(T+T_2) \qquad \text{equ. 6.6}$$

$$P_2 = K_1/(T+T_2) \qquad \text{equ. 6.7}$$

$$P_3 = T_4/(T+T_4) \qquad \text{equ. 6.8}$$

$$P_4 = K_2/K_1/(T+T_4) \qquad \text{equ. 6.9}$$

$$P_5 = T/b_p/(T+T_L) \quad (\text{where} \quad T_L = T_y/b_p) \qquad \text{equ. 6.10}$$

$$P_6 = T_L/(T+T_L) \qquad \text{equ. 6.11}$$

The one disadvantage in this representation compared with the partial fraction form is the extra arithmetic involved i.e two additional subtractions.

6.6 Transfer of MPU Governor to Intel SBC 80/10

With the governor algorithm now working satisfactorily in the microprocessor, attention was now directed towards some refinements required in order that the microprocessor could be interfaced to the hydro-turbine generator at Sloy Power Station.

Much of the hardware in the Altair was unnecessary for the governing function so an Intel SBC 80/10 single board computer replaced the Altair for the final site governor. The SBC 80/10 contains its own 8080 CPU, 4K of PROM space, 1K of RAM, 48 lines of parallel I/O, a serial communication link and a bus system to communicate with additional expansion boards.

The final software for the governor and floating point algorithm fitted into 3K of the 4K PROM space and approximately 160 bytes out of the 1024 bytes of RAM were used as working space.

Originally the SBC 80/10 communicated with the previously mentioned A/D, D/A converters and clock system by using some of the parallel I/O lines. This was later tidied up with the introduction of the Analog Devices RTI 1200 data acquisition board. This contains a 12 bit A/D converter with a 16 line multiplexer, 2 D/A converters, and a real time clock. The board simply plugs into the same bus system of the SBC 80/10 with the necessary registers of the RTI 1200 becoming part of the normal memory space of the SBC 80/10.

6.7 Addition of Set Megawatts (MW) and Load Limit (LL).

The MW and LL functions were added to the governor algorithm to enable easier control of the generator under certain conditions. Their positions within the governor are shown in Fig. 6.10.

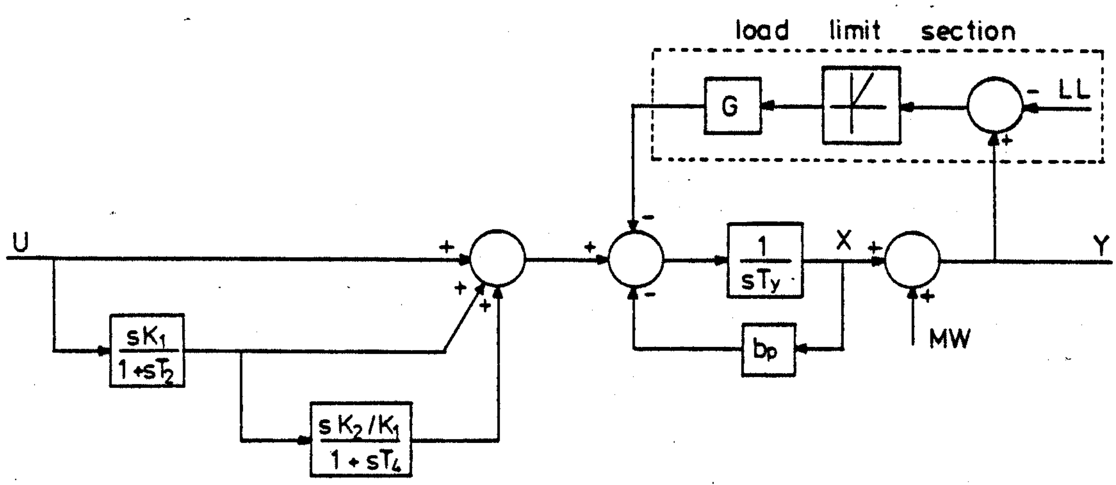


Figure 6.10 DD Governor with MW and LL functions

Ignoring the LL section, the MW control merely allows instant setting of the guide vanes when grid connected, thus giving instant megawatt output change. The alternative approach for a desired megawatt change is to shift the frequency reference, but this does not result in an instant response at the guide vanes due to the dominant lag of the governor.

The LL control is one sided such that if the governor output is below the load limit then normal governing action prevails. However, if the governor output rises above the LL then the LL control operates in such a manner as to keep the output approximately equal to the LL. This is a useful function, again when grid connected. The operator may wish a constant megawatts output no matter what the grid frequency is doing. To achieve this he simply sets the LL to the desired position then raises the frequency reference which will then take the governor output up till it hits the limit.

The LL is also useful during the run up sequence of the turbine before connection to the load.

Both the MW and LL functions are improvements to the governor which provide the operator with a means of quickly achieving conditions which would otherwise take some time.

In practice both signals are rate limited to avoid damage to the turbine and pipeline. The source of these signals is the control rack (Chapter 5) and are derived from 8 bit up/down counters. Thus the microprocessor sees two 8 bit signals through its parallel I/O lines. It is a simple matter to deal with the MW signal, which is added to X (previously the final governor output) resulting in the new governor output.

The method for coping with the LL signal is somewhat more complex. An additional variable has to be calculated namely the steady state value of the output corresponding to the current input. This will be called XDC.

If Y (=X + MW) is tending to be greater than LL then Y is fixed to be equal to LL. Meanwhile X is allowed to drift as if there was no limit condition being enforced. If the input now changes such that the output comes out of the LL of its own volition then Y is no longer preset. However if the input changes and the computed value of Y still remains above the LL but XDC + MW indicates that Y should be out of the LL, then X is preset to LL-MW. This allows Y to immediately come out of the LL rather than waiting for X to reduce through the effect of the dominant lag.

A similar limiting algorithm prevents the output from falling below zero.

There were additional difficulties encountered in implementing the LL and these are outlined in Appendix E. There was a practical problem encountered on site with the MW and LL controls. As previously mentioned these two signals were controlled by 8 bit up/down counters. Zero to full count of these counters becomes approximately equivalent to 0 to 10V representing 0 - 100% main servo movement. Thus the Least Significant Bit (LSB) of the counters implies 0.39% servo movement, and even these minute steps caused the actual servo to noticeably step as the MW or LL were raised or lowered. This stepping motion of the servo was deemed unacceptable, and it was not a feasible proposition to change the 8 bit up/down counters for ones of higher precision. Fortunately, a solution was achieved within the software of the governor routine, and this is described below.

The real time clock on the RTI 1200 interrupted the CPU every 10ms (not 100ms as was the case before) so to achieve a 100ms sampling interval the clock service routine had to count 10 interrupts before declaring the end of the sampling interval.

The governor output converters were of 12 bits precision where the LL and MW input signals were of 8 bits. That is, if the MW or LL input demands were routed directly to the governor output then these 8 bit signals would occupy the upper 8 bits of the 12 bit D/A converter of the output. If the 4 LSBs of the output could be built into the movement of the MW and LL signal, then the stepping problem on the servo would be eliminated. This was achieved as follows.

The clocking period of the MW and LL counters was approximately every 180ms. As the MPU looked at these two signals every sampling interval (i.e. every 100ms) then the MPU would never see a change greater than 1 LSB. Furthermore, if the MPU output was updated, due to any MW or LL demand, by 1 LSB in 12 every interrupt (i.e every 10ms) then it would only take 160ms to catch up with the actual 8 bit MW and LL signals.

This simple form of linear interpolation between adjacent counts of the MW and LL values was how the servo stepping problem was overcome. Fig. 6.11 gives a simplified pictorial representation of the aforegoing description.

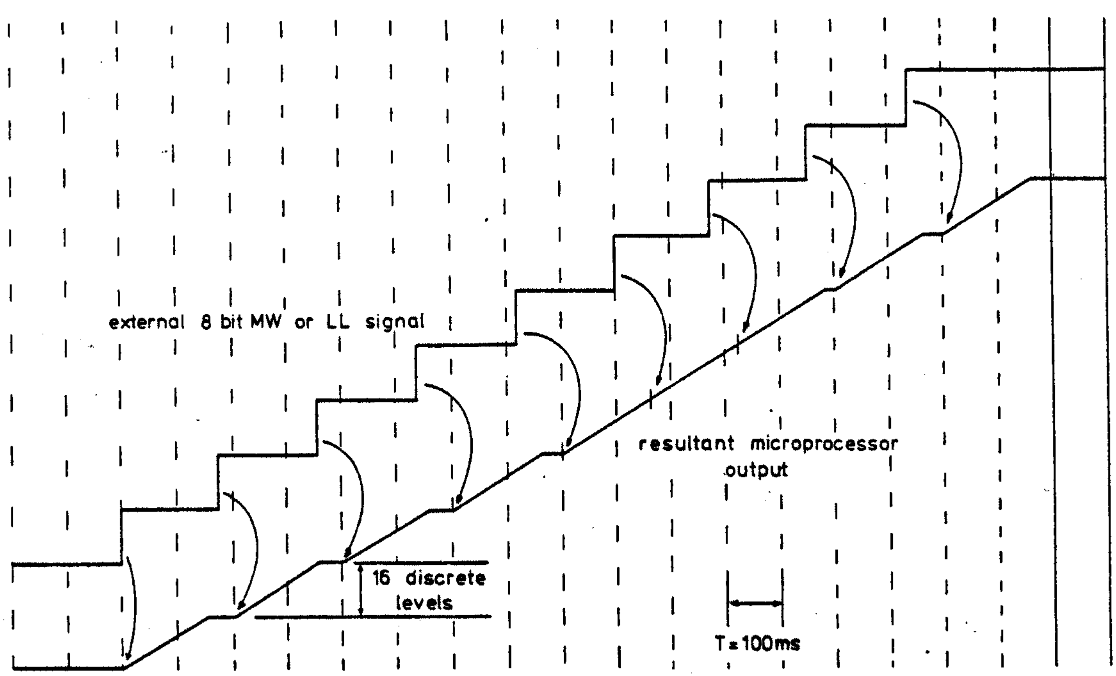


Figure 6.11 Linear interpolation of MW and LL signals within the MPU governor routine

6.8 Multiple Governors out of One

It should be appreciated that the characteristics of the DD governor are defined by the constants $P_1 - P_6$ in equations 6.6 to 6.11. To be able to investigate noise problems, which could not be simulated, it was desired that several different DD governors (the difference being in the values of T_2 and T_4) should be contained within the MPU routine. The change over between governors should also be easily implemented.

The solution here was to store the constants $P_1 - P_6$ in consecutive locations within memory. Then different sets of constants would follow similarly after these first constants. At the beginning of each sampling interval, depending on switch settings into an I/O port, a set of constants would be chosen by selecting the start address of the set involved. Subsequent references to any of the constants within the set were indexed relative to the selected start address. This method of switching between constants, whether through observing external switch settings or by some software logic, provided a means of producing bumpless transfers when switching to a different governor type.

Not only were different DD governors selected by this means but it was also possible to define values of $P_1 - P_6$ which represented a TD governor.

The TD governor may be obtained from the DD governor equations by comparing the transfer functions of the two governors whose transfer functions follow.

$$\frac{Y}{U} = \frac{1 + sT_d}{s^2(T_y T_d) + s(T_y + b_p T_d + b_c T_d) + b_p}$$

TD governor transfer function

$$\frac{Y}{U} = \frac{1}{b_p^1} \cdot \frac{(1+sT_2)(1+sT_4) + K_1 s(1+sT_4) + K_2 s^2}{s^3 T_2 T_4 T_L + s^2 (T_2 T_4 + T_L (T_2+T_4)) + s(T_2+T_4+T_L)+1}$$

$$\text{where } T_L = \frac{T_y^1}{b_p^1}$$

DD governor transfer function

Lettinq $K_2 = 0$, $T_4 = 0$, $b_p^1 = b_p$ then

$$T_d = T_2 + K_1$$

$$b_p^1 T_L T_2 = T_y T_d$$

$$b_p^1 (T_2 + T_L) = (T_y + b_p T_d + b_c T_d)$$

So given the constants for the TD governor, corresponding values of K_1, T_2, T_L may be obtained with the result that the DD governor becomes a TD governor.

In the station governor at Sloy Power Station the TD constants were $b_t = 0.25$, $T_d = 16.0$, $T_y = 0.3$, $b_p = 0.03$ and the corresponding DD constants are approximately $K_2 = T_4 = 0$, $T_2 = 1.0108$, $K_1 = 14.9892$, $Ty^1 = 4.74867$, $bp^1 = 0.03$.

6.9 Adaptive Governor Algorithm

The function of the governor being developed here was one in which rapid response to grid frequency changes would be achieved without loss of isolated load stability.

The operating point of least stability of the turbine is at full load. Simulation studies found that a reduction of the dominant time constant below 33.3 secs was undesirable. However it was shown that stability with shorter dominant lags was feasible at reduced working loads. This was the basis on which the adaptive governor was developed.

An arbitrary choice of three operating bands were chosen for initial studies. The breakpoints between the different bands were at 40% and 70% of full load. The resultant governor constants for each of the bands provided dominant lags of 10, 20 and 33.3 seconds.

In order to implement the switching from one band to the next an extra analogue signal was connected to the RTI 1200 data acquisition board. This signal was the measured generator megawatts which was available from the interface rack. Partial elimination of noise on the megawatt input was accomplished by two methods. Firstly, the MPU read and stored megawatt values every interrupt then averaged the previous ten readings at the beginning of every sampling interval (this cleanup procedure was also applied to the frequency error input into the MPU). Secondly, the software subjected the averaged result to a first order lag, with the emerging result being used to perform the band switching.

The first order lag served another function other than that of noise reduction. While the generator was at a steady state within a band then benefit would arise from the band settings for small disturbances within the band. During a large disturbance, though, in which a rising band change occurred, greater benefit could be gleaned by delaying band switching by use of the lag. The retardation of switching from faster low band constants to more sluggish, higher band constants could result in a speedier pick up of load while grid connected. As always, though, the condition of isolated load stability was to be observed.

Fig 6.12 illustrates a simulated grid connected response to a frequency step equivalent to 10% to 90% servo movement. Comparison is made between TD, DD (33.3s dominant lag), DD adaptive and DD (10s dominant lag) governor responses. In the case of the DD adaptive governor three different time constants were used for the megawatt input control lag (i.e 0.1, 5.0, 10.0).

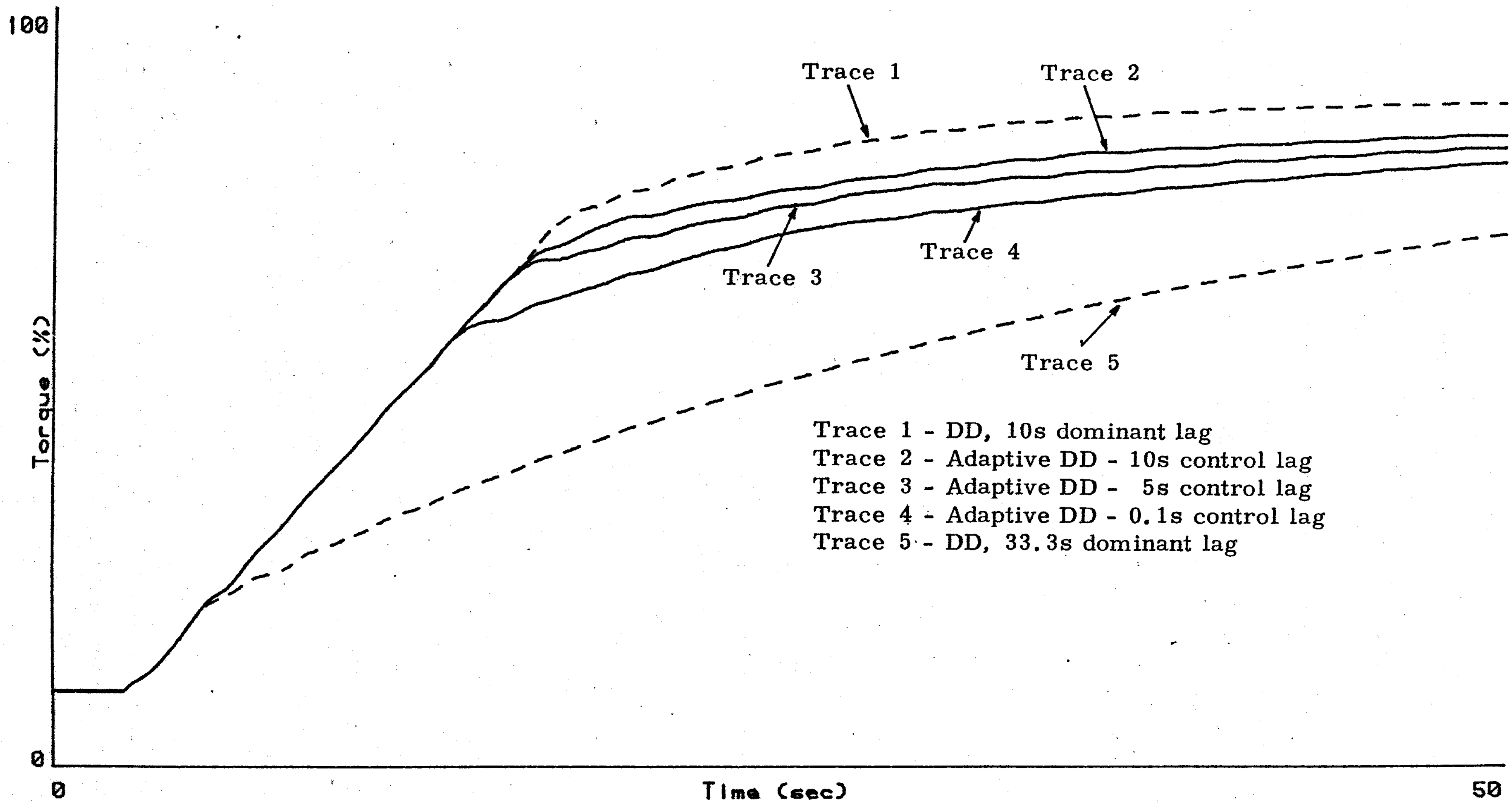


Figure 6.12 Grid connected simulation - 10% - 90% disturbance

As can be seen from the simulation results of Fig. 6.12 the DD 10s lag produces the fastest response and on the whole, rises up on the built in protective rate limit at the governor output. A simply proportional governor would give the fastest response but like the 10s DD governor the condition of isolated load stability would be lost. For a reference to aim for, though, the 10s DD governor provides a reasonable target.

Comparing the responses of the adaptive governors, it is clear that further return on speed of response would only be obtained for a greatly increased control lag over the maximum of 10s as shown. Accompanying such a long lag would be loss of stability on isolated load. Consequently, a control lag of 10s was adopted for use in the final adaptive governor. Furthermore, this combination proved to be stable under isolated load as indicated in the simulation results of Figs. 6.13 and 6.14 which compare the responses of the DD (33.3s) non adaptive and the DD adaptive governors for input steps equivalent to 35% - 75% full load. The frequency swing in these results would not be tolerated on the actual generator but then the disturbance is unrealistic in the first place. The point of Figs. 6.13 and 6.14 is merely to illustrate that the adaptive governor remains almost as stable as the DD (33.3s) governor.

Another result of interest is the comparison shown in Figs 6.15 and 6.16. Fig 6.15 compares the DD (33.3s) governor with the DD (10s) (i.e. adaptive low band) governor in the high band of operation. The instability of the low band adaptive constants is clear. Fig. 6.16, on the other hand, indicates the improved response of the adaptive low band constants over the DD (33.3s) constants when operating within the low band.

The final form of the governor algorithm used is listed in Appendix F. There are ten different sets of governor constants included. Each set may be called upon for use by means of switches connected to

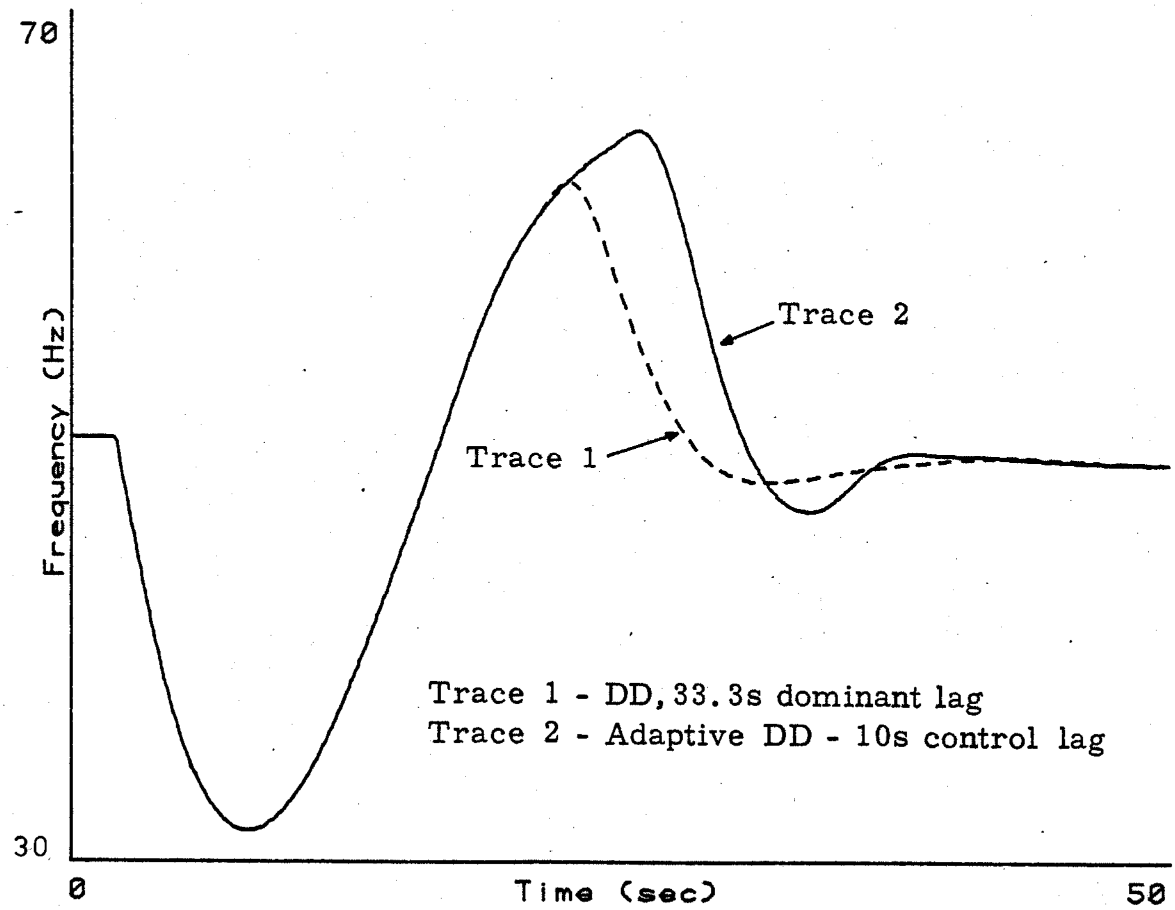


Figure 6.13 Isolated load simulation - 35%-75% dist

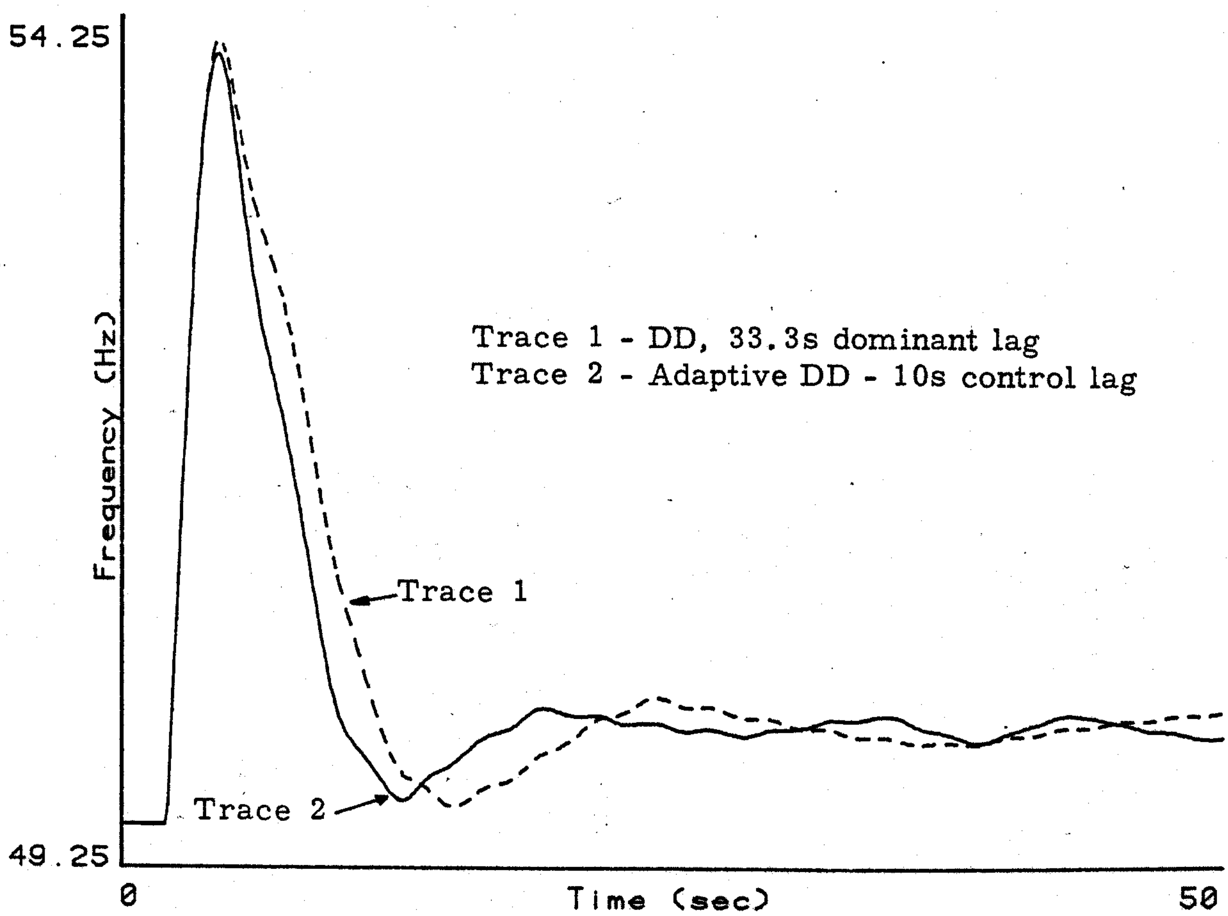


Figure 6.14 Isolated load simulation - 75%-35% dist

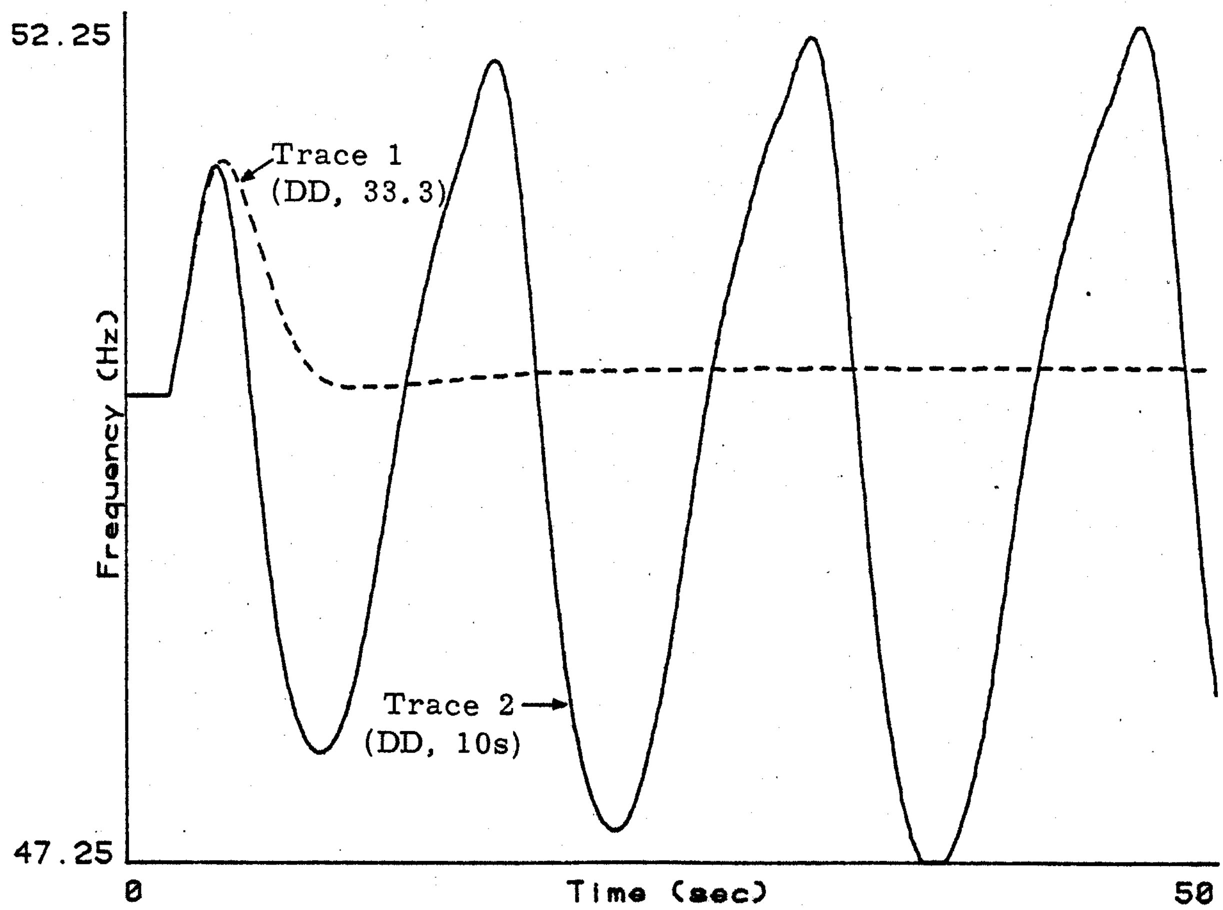


Figure 6.15 Stability of governors - 100%-90% dist

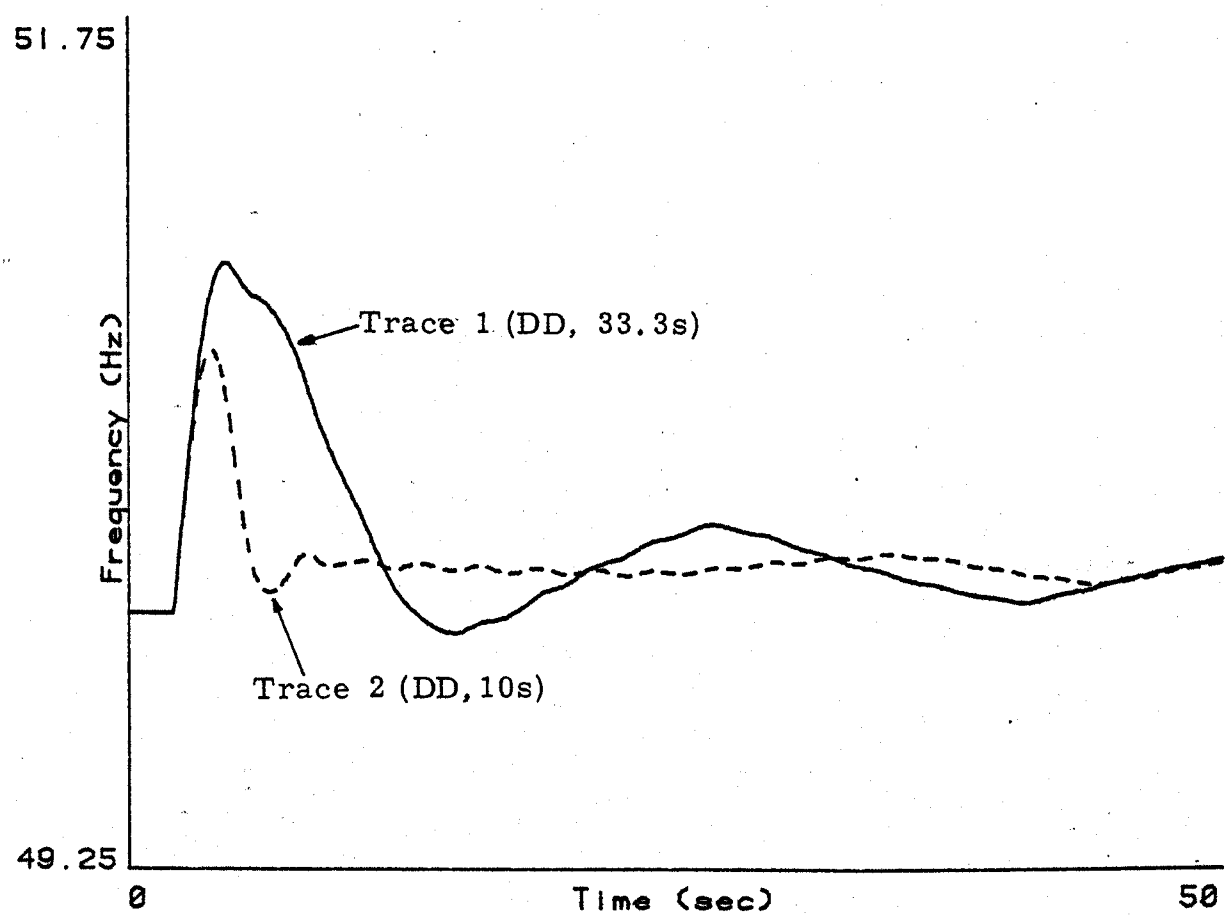


Figure 6.16 Stability of governors - 40%-30% dist

one of the I/O ports. Additionally there are two groups of 3 sets within the 10 that may be invoked so as to produce an adaptive governor. Thus there are 12 possible governors currently written into the software of Appendix F.

Table 6.2 provides a summary of these 12 different governors while Table 6.3 lists the constants associated with these governors.

Governor Description	Abbreviation
1 Standard Temporary Droop Governor for use throughout the complete operating range.	TD
2 Initial Double Derivative governor with $T_2 = T_4 = 0$ and for use within the complete operating range.	
3 Initial Double Derivative governor with $T_2 = T_4 = 0.1$ and for use within the complete operating range.	DDO
4 Initial Double Derivative governor with $T_2 = T_4 = 0.2$ and for use within the complete operating range.	DD
5 First Adaptive Low Band Double Derivative governor for use within the band 0 - 40% full load.	DDLOW1 (7.9.78)
6 First Adaptive Mid Band Double Derivative governor for use within the band 40 - 70% full load.	DDMID1 (7.9.78)
7 First Adaptive High Band Double Derivative governor for use within the band 70 - 100% full load.	DDHI1 (7.9.78)
8 Second Adaptive Low band Double Derivative governor for use within the band 0 - 40% full load.	DDLOW2 (10.10.78)
9 Second Adaptive Mid Band Double Derivative governor for use within the band 40 - 70% full load.	DDMID2 (10.10.78)
10 Second Adaptive High Band Double Derivative governor for use within the band 70 - 100% full load.	DDHI2 (10.10.78)
11 First Adaptive Double Derivative Governor for use within the complete operating range. Comprises of the combination of governors 5, 6 and 7.	ADP1 (7.9.78)
12 Second Adaptive Double Derivative Governor for use within the complete operating range. Comprises of the combination of governors 8,9 and 10.	ADP2 (10.10.78)

Table 6.2 Governor Descriptions and Abbreviations

Governor	Constants						
	T_2	T_4	K_1	K_2	bp	Ty	Dominant Lag (s)
1 TD	1.0108	0	14.9892	0	0.03	4.7486	160
	i.e. Temporary Droop Constants of bt = 0.25; Td = 16.0; Ty = 0.3; bp = 0.03						
2 DDO	0	0	3.5	3.5	0.03	1.0	33.3
3 DDO1	0.1	0.1	3.5	3.5	0.03	1.0	33.3
4 DD	0.2	0.2	3.5	3.5	0.03	1.0	33.3
5 DDLOW1	0.2	0.2	1.8	0.8	0.03	0.3	10.0
6 DDMID1	0.2	0.2	2.5	1.8	0.03	0.6	20.0
7 DDHI1	0.2	0.2	3.0	2.3	0.03	1.0	33.3
8 DDLOW2	0.2	0.2	0.8	2.0	0.03	0.3	10.0
9 DDMID2	0.2	0.2	2.0	3.0	0.03	0.6	20.0
10 DDHI2	0.2	0.2	3.0	2.8	0.03	1.0	33.3

Table 6.3 Constants used within the different governors

Note (i) The first adaptive governor (7.9.78) is obtained by combining governors 5, 6 and 7.

The second adaptive governor (10.10.78) is obtained by combining governors 8,9 and 10.

(ii) The dominant lag refers to Ty/bp except in the case of the TD governor. In this case the dominant lag corresponds to that documented by Agnew.

i.e Previous tests on the mechanical governor on site revealed a transfer function of approximately

$$\frac{1 + 16s}{0{\cdot}03\,(1 + 160s)(1 + s)}$$

6.10 Tuning of Governor Parameters

When simulation studies had shown that it was possible to reduce the dominant lag of the governor at reduced loads it became necessary to find the best parameter values for the governor for these different lags. As the permanent droop, bp, must be defined at 3%, and Ty is used to define the dominant lag, then the parameters associated with the first and second derivatives provided the only means of improving the quality of the governor's response. The derivative time constants T_2 and T_4 have been discussed before and have been given fixed values. Thus the derivative gain constants K_1 and K_2 emerge as the only parameters available for use in optimising the performance.

In order to find the best values of K_1 and K_2 the following procedure was adopted.

Slight adjustments were made to one or other of K_1 and K_2. The new step response of the system was then observed and if the adjustment provided an improvement in response then the parameter was further altered in the same direction. If the initial adjustment did not improve the response then the parameter was moved in the opposite direction. Once no further improvement could be made with the one parameter the other parameter was adjusted similarly. A return to the first parameter would then follow and so on until an acceptable response was eventually found. For the adaptive governor three operating bands were arbitrarily chosen (1 - 40%, 40 - 70% and 70 - 100% full load) and were assigned their own dominant lags (10, 20 and 33s respectively). By simulation, these smaller dominant lags had been found to be acceptable within their own operating bands, since the system stability improves as the load power decreases.

The governor constants K_1 and K_2 were optimised by the aforementioned method for each of the bands. The optimisation was carried out at the top of the respective bands since this is the point of worst stability within a band. The results of this band optimisation is shown in Figures 6.17a to d. Figure 6.17a shows the response in the top band using the original governor constants. Figure 6.17b repeats 6.17a but with the optimised constants which demonstrates a marked improvement. Figures 6.17c and d show the optimised responses within the mid (20s lag) and low (10s lag) bands respectively. The constants obtained here were used in the first adaptive governor.

This method of tuning K_1 and K_2 is similar to an automatic optimisation technique based on sensitivity analysis as described by Winning et al (Reference 52). Unfortunately, there was not sufficient time to investigate this technique fully.

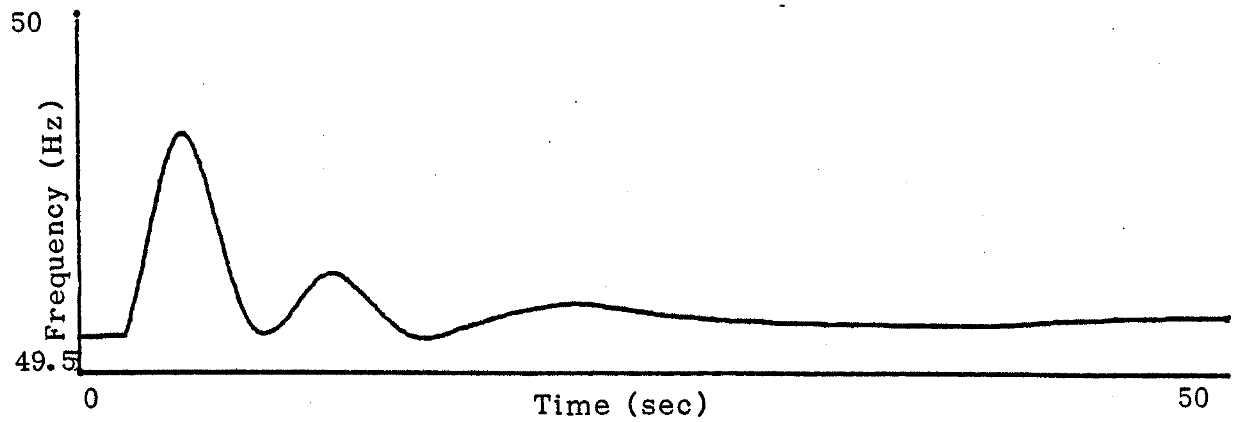


Figure 6.17 (a) Standard DD Governor - 100%-90% disturbance

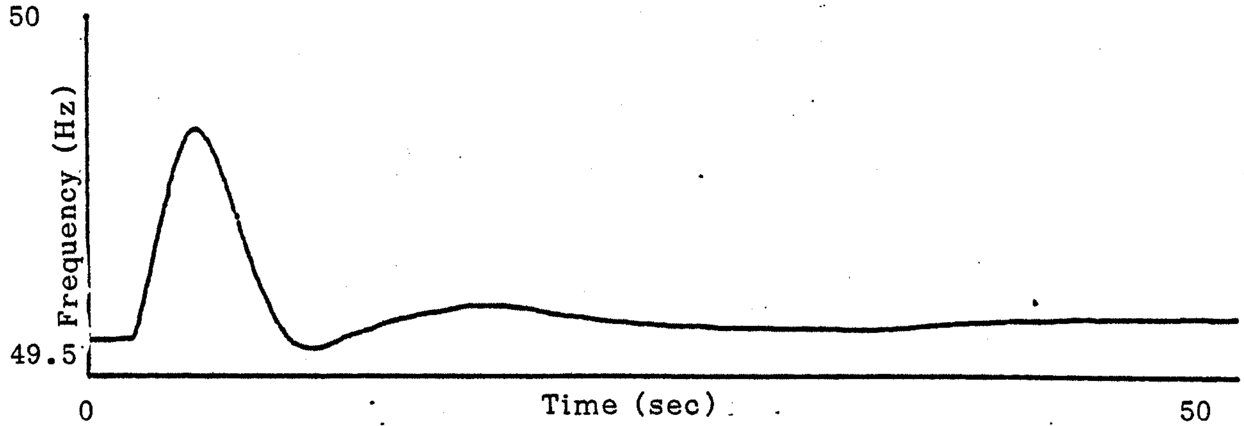


Figure 6.17 (b) DDHI1 Governor - 100%- 90% disturbance

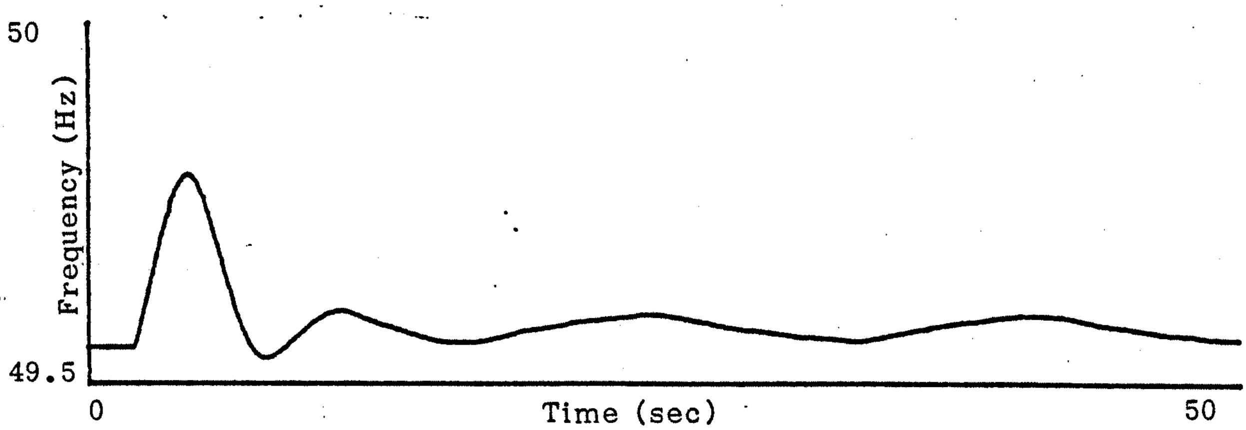


Figure 6.17 (c) DDMID1 Governor - 70%-60% disturbance

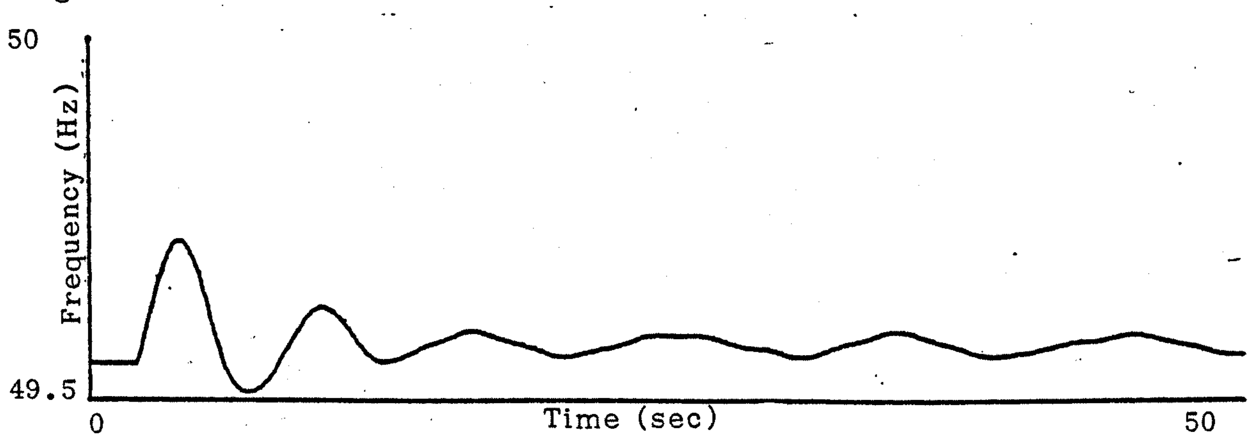


Figure 6.17 (d) DDLOW1 Governor - 40%-30% disturbance

CHAPTER 7 - ON SITE AIDS

7.1 Introduction

Two minor developments proved to be very useful. The first was an analogue simulation for on site verification of the interface, control and microprocessor equipment before attempting a link up with the actual generating plant. The other aid was the isolated load simulator.

7.2 Simple Analogue Model of the Plant

This model represents the main servo, pipeline and turbine characteristics, and the generator inertia. The reason for producing such a model was to enable the Control and Interface Rack and the experimental governor to be fully integrated and tested before proceeding with any investigations on the real hydro-turbine generator. With this simulation all important functions of the test equipment, including simulated run-ups, could be verified without endangering the actual plant.

The block diagram of Fig. 7.1 shows the features of the simple plant model used.

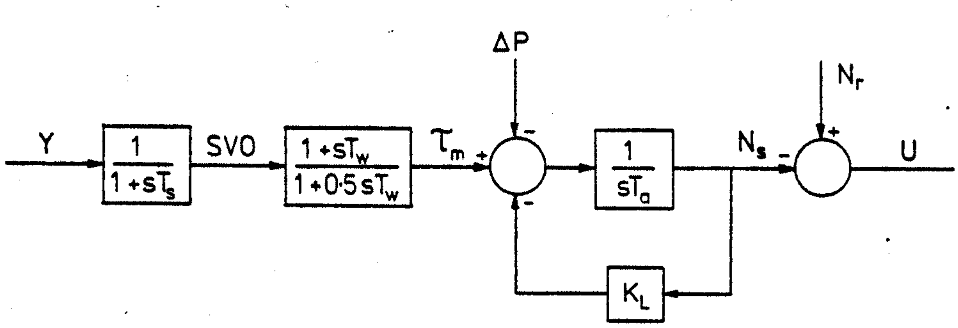


Figure 7.1 Simple model of Plant

The input to this model was the chosen governor output from the control rack. Two outputs were available from the model. The first output was a suitably scaled signal which could be connected directly to the frequency error input of the control rack. The second output was arranged to feed the VCO (voltage controlled oscillator) input of a sine wave oscillator. The output frequency of the oscillator could then be routed to the test input of the frequency transducer of the interface rack. So by this method the frequency transducer was included in the test loop, and it was possible to simulate a complete run up sequence. A small loss factor (K_L) was included in the generator inertia section to allow for speed no load losses, and hence to facilitate the simulation of the run up test.

The model was implemented on a small analogue tutor which provided portability, such that the same tutor could be used in the laboratory and on site. Fig. 7.2 illustrates the patch diagram used on the analogue tutor.

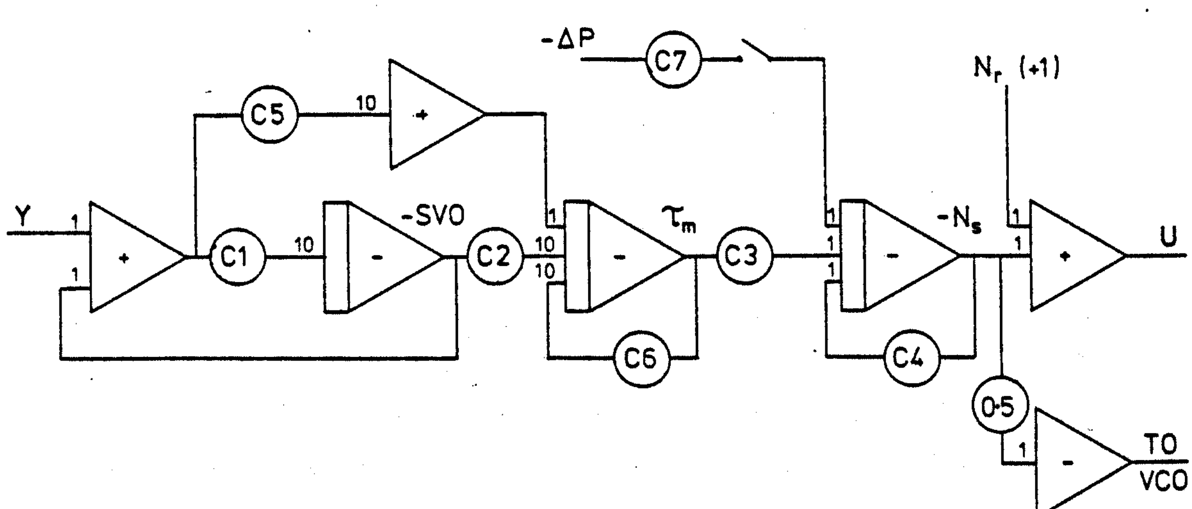


Figure 7.2 Patch diagram of simple Plant model

The settings for the coefficient potentiometers C1 to C7 for associated system parameters are tabulated in Table 7.1. There are two conditions listed i.e full load and speed no load. Approximate values of the water time constant T_w are taken to be 1.1 and 0.2, respectively. In the speed no load case the loss factor used was 14%. This would appear to be rather high but it gave a reasonable run up performance compared with the response of an actual run up. The loss factor is simply ignored in the full load case.

Coefficient	Equivalence	Coefficient Value	
		Full load	Speed no load
C1	$0.1/T_s$	0.5	0.5
C2	$0.2/T_w$	0.18	1.0
C3	$1/T_a$	0.14	0.14
C4	K_L/T_a	0	0.02
C5	$0.2/T_s$	1.0	1.0
C6	$0.2/T_w$	0.18	1.0
C7	$1/T_a$	0.14	0.14

Table 7.1 Coefficient values for analogue model

In the analogue tutor one machine unit was equivalent to 10V. It was arranged that one machine unit was equivalent to the 100% settings of Y, SVO, τ_m and N_s = 50 Hz. As the tutor was capable of allowing its amplifiers to rise to about 1.4 machine units before saturation occurred, then there was little chance that overloading would be a problem under normal operating conditions.

7.3 Isolated Load Simulator (ILS)

The use of the Isolated Load Simulator was pursued in order to avoid the time consuming and costly exercise of arranging actual isolation of the Sloy Power Station from the National Grid. Such a test was necessary so that the closed loop response of the speed governor could be observed. This proves, or otherwise, that the governor responds stably under the conditions of isolated load.

The ILS was basically a subsystem of the analogue model as is evident from the block diagram of Fig. 7.3. This shows the ILS as simply representing the turbine/generator mechanical inertia.

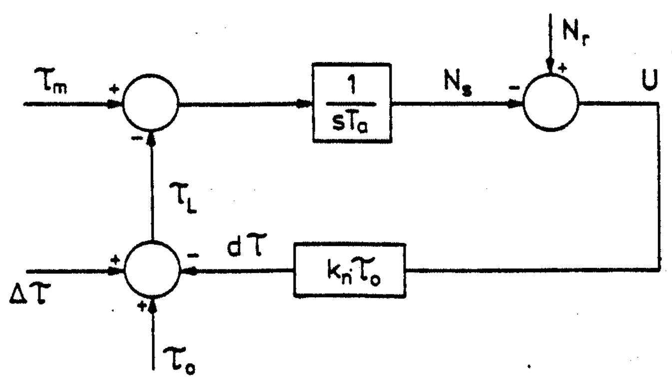


Figure 7.3 Isolated Load Simulator

Here k_n is taking into account some form of load self regulation factor, but note that this is not the properly defined load self regulation factor, e_n, which relates to load power and not torque. It will be shown later that an approximate relationship exists between k_n and e_n such that the torque variables, $\Delta\tau$ and τ_o, of Fig. 7.3 may be regarded as representing their corresponding power variables.

Schleif (Reference 53) first put forward the ILS as a means of field testing and optimising governor settings. The use of the ILS in this current study was merely to check the results of simulation studies without the mammoth task of organising actual isolated load tests. Through the application of the ILS some apparently small, yet significant, inaccuracies in the PDP 11 digital simulation were brought to light.

When the ILS was being used the generator remained tied to the grid. However deadband was introduced into the frequency transducer which was monitoring system frequency. The frequency error signal from the ILS was then fed to the governor module, thus providing a synthesised isolated load frequency signal. Should the actual grid frequency have varied significantly though, then the frequency transducer deadband limits would have been violated and normal governing operation would have ensued.

The turbine output torque was derived from the measured megawatt output of the generator. As the grid frequency fixed the speed of the turbine then power became proportional to torque. The generator electrical characteristics were ignored since the time constants here were much shorter than those involved with the governing of the set.

To balance the machine torque, τ_m, a simulated load, P_O, is generated within the simulator, and small load disturbances ΔP, may be injected into the system.

In the ILS of Schleif no account was taken of the turbine and load self regulation. However, here, as with Causon (Reference 54), a load self regulation factor, e_n, is included.

The self regulation factor is defined as being the percentage change in power for a given per unit change in speed. A glance at Fig. 7.3 will make it clear that τ_o and $\Delta\tau$ cannot represent power quantities directly and that k_n is not the self regulating factor as defined, since these quantities make their way to the torque summing junction without consideration of the necessary speed factor. A more accurate representation may be drawn as in Fig. 7.4, and here P_O and ΔP represent power and e_n is the load self regulation factor.

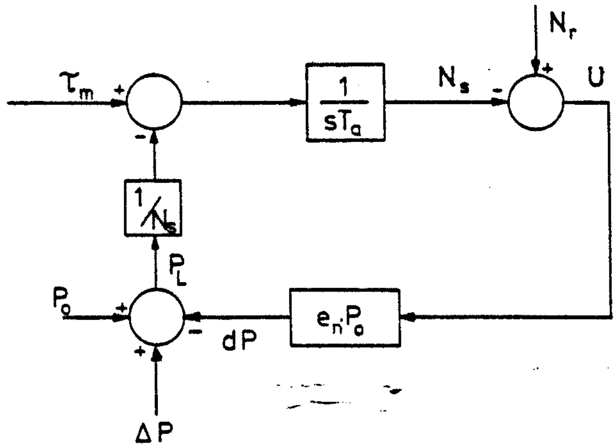


Figure 7.4 True representation of the self-regulation of the load

However the diagram of Fig. 7.3 can be approximated to that of Fig. 7.4 by taking account of the following considerations, in which all variables are normalised.

Firstly, e_n is the frequency dependence of the load, i.e

$$e_n = \frac{dP/P_o}{U/N_r}.$$

where dP = change of load power due to speed change,

P_o = nominal power at N_r

U = speed deviation

N_r = normal speed

Assuming operation at normal frequency then $N_r = 1$

thus,

$$dP = P_o \, e_n \, U$$

So taking into account the frequency dependence of the load and ignoring the small disturbance, ΔP, the load power may be expressed as

$$P_L = P_o + dP$$
$$= P_o(1 - e_n U)$$

(The -ve sign in this expression takes into account that the speed deviation, U, is defined throughout the thesis as $N_r - N_s$. This implies U will be negative when the speed is high. The governors were responsible for dealing with the this inversion.)

The load torque, though, is given by

$$\mathcal{T}_L = \frac{P_L}{N_s} = \frac{P_L}{N_r + U} = \frac{P_L}{1 + U}$$

and using the first order approximation of the Binomial series

$$\mathcal{T}_L \approx P_L\ (1 - U)$$

and substituting for P_L then

$$\mathcal{T}_L \approx P_o\ (1 - e_n U)(1 - U)$$

By, again, using a first order approximation

$$\mathcal{T}_L \approx P_o\ (1 - (e_n - 1)U)$$

In the representation of Fig. 7.3, if small disturbances, $\Delta\mathcal{T}$, are ignored, then

$$\mathcal{T}_L = \mathcal{T}_o(1 - k_n u)$$

so clearly, simulated power steps may be applied if the constant $k_n = e_n - 1$, thus equivalencing $\mathcal{T}_o$ to P_o without introducing a speed term.

In order to simulate load power disturbances the additional signal ΔP was applied to the power summing junction. To calculate dP then ΔP should really be added to P_o to give,

$$dP = e_n(P_o + \Delta P)$$

To simplify the ILS, however, dP was always calculated as

$$dP = e_n P_o$$

This is a reasonable approximation, since ΔP will not be very significant relative to P_o when working close to full load. The error will be greater at lower loads, but here the effect of load self regulation becomes less significant anyway.

The complete circuit diagram of the ILS is given in Fig. 7.5 and a brief description of how it was used follows.

Firstly, parameters that were constant were set up on their respective potentiometers. i.e $1/T_a$ and k_n. SW5 allows k_n to become negative to cater for the situation where $e_n < 1$, since $k_n = e_n - 1$. SW4 would start in the balanced condition. Note that this reduces the integrator section to a first order lag of gain 0.07 and time constant 0.47s. This allows the integrator output to quickly track the desired balanced input of zero. With SW4 in this position the output of the ILS is also disconnected from the frequency test input of the governor.

With SW1 closed and SW2 open the machine power should be balanced by the potentiometer, P_o. $P_o(k_n)$ would now be set to the same as P_o. A choice of magnitude and sign of disturbance could then be set up on Δ P. By switching SW4 to operate the integrator would be returned to its normal operational state and the output of the ILS could be connected into the governor. Assuming the machine power and P_o had been balanced properly, then the switching of SW4 to operate would not cause any disturbance into the governor since, at balance, the synthesised frequency error output from the ILS will be zero.

By use of SW2 the chosen disturbance Δ P can be introduced into the system.

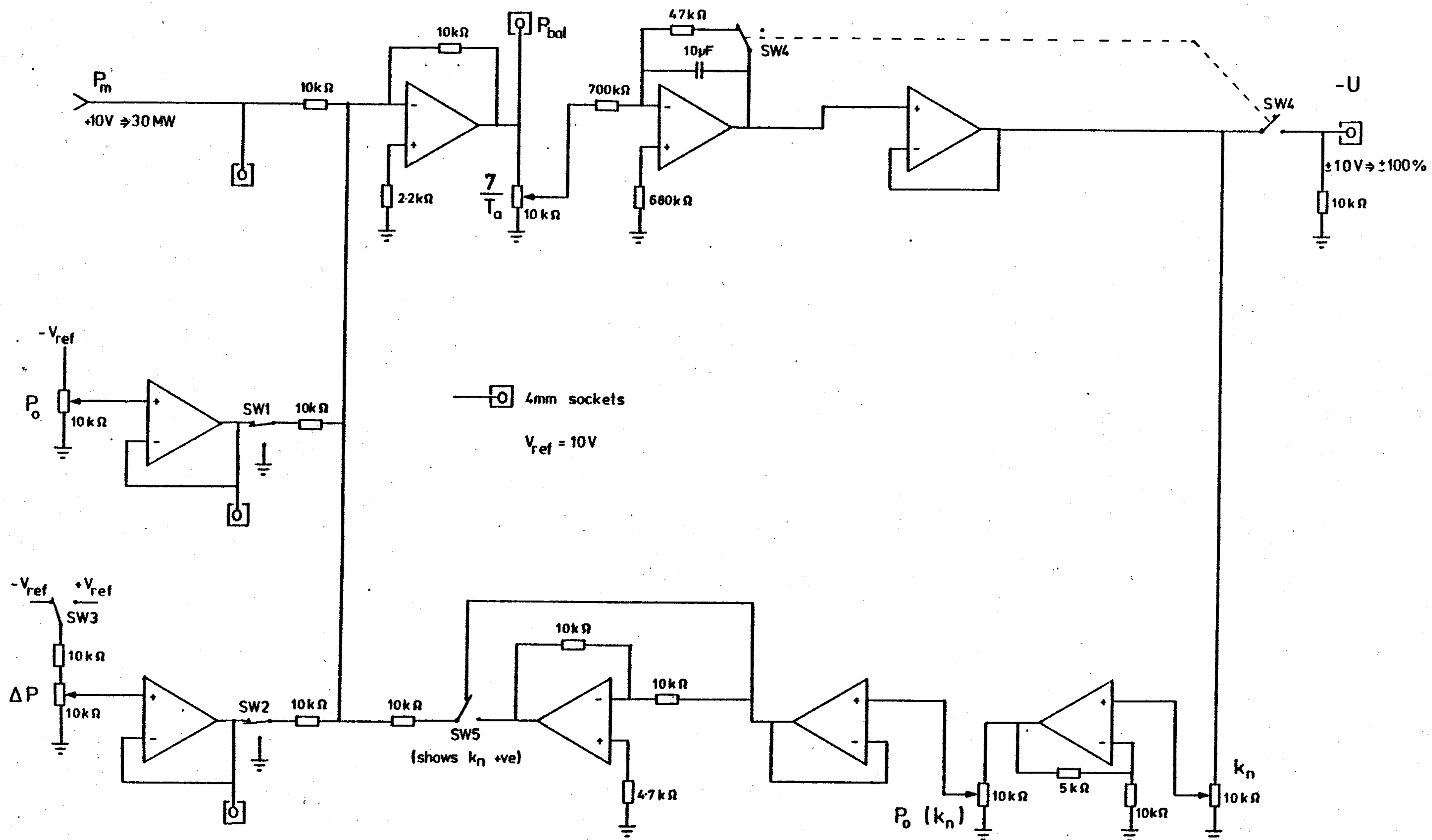


Figure 7.5 Circuit diagram of the ILS

Many of the experiments carried out with the ILS used a value for $k_n = 0$ (i.e $e_n = 1$). This is equivalent to saying that the self regulation factor is one percent change in power per 2 Hz deviation in frequency from 50 Hz. This figure was reported by Ashmole et al (Reference 5) as being a realistic self regulation factor for the British power system network.

CHAPTER 8 - INITIAL SITE TESTS - Discoveries Thereof and Subsequent Amendments to the Simulation.

8.1 Introduction

The following two chapters present the prominent results which were obtained during the three major sets of site trials of this project.

This chapter contains the results of the first site tests which were conducted on June 22nd, 1978. The purpose of this trial was to verify the correct operation of the Control and Interface Rack, the data recording equipment and the ILS. It was also the first application of the MPU governor to the actual hydro-turbine generator.

Chapter 9 collates the results of tests performed on September 7th and October 10th, 1978. The experiments within these tests were predominantly concerned with the performance of the MPU Adaptive governor.

Another important product of the first site tests was the recording of limit cycles due to the backlash of the guide vane linkages. These results helped to corroborate the existence of the nonlinear function which exists between servo position and actual megawatts generated. This is probably due to the machine efficiency or a nonlinear correspondence between servo position and guide vane area opening, or a combination of both factors.

Additionally, up till this point the digital simulation did not include a representation of the ILS, but did in fact look more like a system in real isolation. It was only when the limit cycle results from simulations and site tests were compared that this difference was fully appreciated. The differences between real isolated load and simulated isolated load stem from the fact that when the isolated load simulator is in use the generator is tied to the grid system, thus fixing the speed of rotation of the turbine. The net result here is that the frequency dependence of the turbine and of megawatt output is totally eliminated even although the simulated frequency of the ILS may be changing quite substantially. The following two equations, extracted from Chapter 3, should help to clarify where the frequency dependence of the turbine and megawatts lies.

$$Q_T = A_{cv} C_d \sqrt{(2gH_{mv} - (r_o^2 - r_i^2)\omega^2)}$$

$$\tau = \frac{\rho g Q_T H_T \eta}{\omega}$$

ω in both these equations will be fixed when using the ILS where, in fact, they should be allowed to vary with the simulated frequency. However both effects have a self regulating influence and therefore could be included into the value of k_n in the ILS.

Further experiments carried out during this first day of tests were (a) the investigation into the use of dither to eliminate limit cycling, (b) the observation of the noise filtering effect of T_2 and T_4 of the microprocessor governor and finally, (c) some step tests were conducted with the various governors at different loads.

Throughout this chapter the parameters of the different governors adopt the following values. The only varied parameters are T_2 and T_4 in the microprocessor DD governor but unless otherwise stated $T_2 = T_4 = 0.2s$.

Analogue DD governor $T_2 = T_4 = 0.2$, $K_1 = K_2 = 3.5$, $T_y = 1.0$, $bp = 0.03$

Microprocessor DD " $T_2 = T_4 = 0.2$, $K_1 = K_2 = 3.5$, $T_y = 1.0$, $bp = 0.03$

Microprocessor TD " $b_t = 0.25$, $T_d = 16.0$, $T_y = 0.3$, $bp = 0.03$

8.2 Simulated and Actual Run-ups

By making use of the simple analogue model, which was described in Chapter 7, the correct operation of the Control and Interface Rack, the governors, the main servo motor and the recording equipment was verified. This was done with the main valve shut so that the spiral casing remained dewatered and hence the turbine did not move when the main servo opened the guide vanes. The necessary speed signal for the frequency transducer was obtained from an oscillator whose VCO input was driven by the analogue computer. This arrangement has been described previously in Chapter 7.

The results of this simulated run up, which was carried out using the microprocessor TD governor, are illustrated in Fig. 8.1 in which the variables frequency and actual servo position are displayed.

The run up strategy is easily observed from Fig. 8.1. The Control Rack commands the servo to open the guide vanes to approximately 24% of full travel at a rate of around 2.3% full travel per second. Having remained at 24% for about 11 seconds the guide vanes are pulled back to 22% where they remain until the frequency forces the governor to take conventional regulating action.

The success of the simulated run up gave the necessary confidence to try an actual run up of the turbine. Again, the microprocessor TD governor was selected to control the run up and the complete success

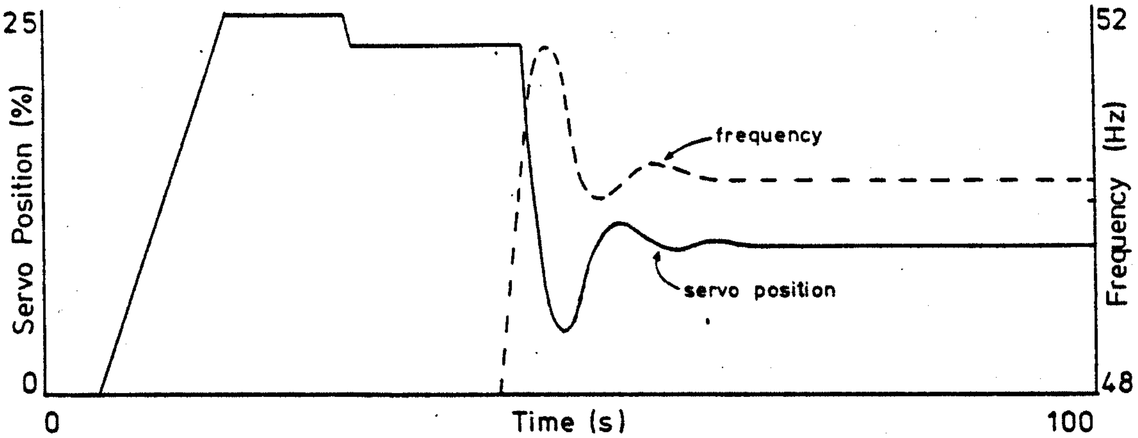


Fig. 8.1 Simulated run up using the microprocessor TD governor

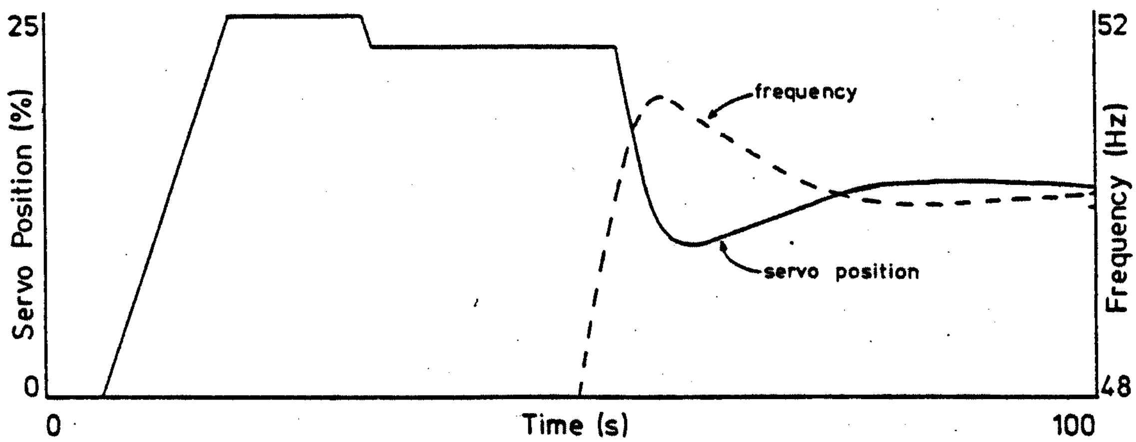


Fig. 8.2 Actual run up using the microprocessor TD governor

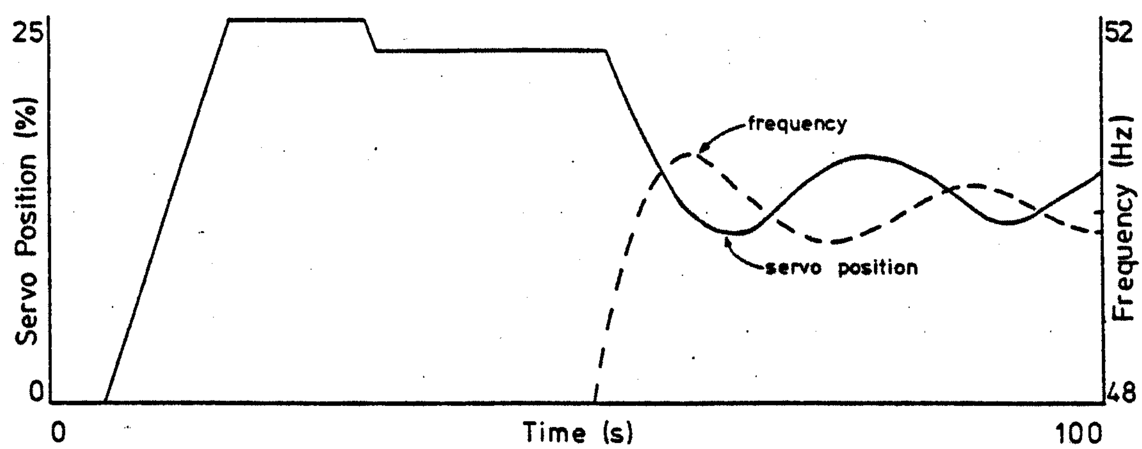


Fig. 8.3 Actual run up using the analogue DD governor

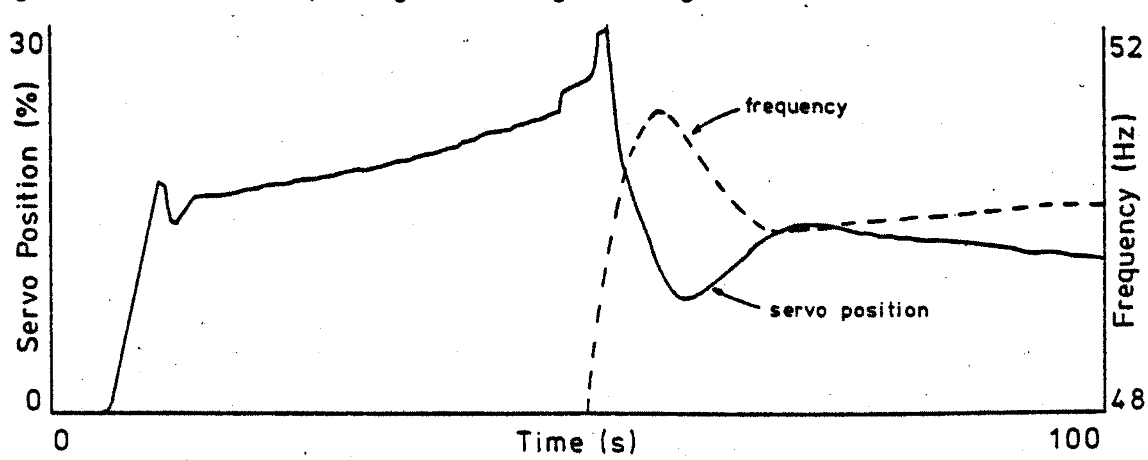


Fig. 8.4 Actual run up using the Station mechanical TD governor

of this test is confirmed in the traces of Fig. 8.2. The results shown here are of the same general form as the previous test, but there are two slight differences which are worth pointing out. Firstly, the initial overshoots of frequency and servo position during the actual run up (Fig. 8.2) are quite substantially less than those during the simulated run up (Fig. 8.1). This demonstrates that the simple impulse model representation of the turbine gives rather pessimistic (i.e less stable) results relative to the actual system response. The second noteworthy difference between the two run-ups is that the simulated model response eventually settles to a steady state level, whereas the real system shows the beginnings of limit cycling. This is, of course, due to the fact that there was no attempt to model the guide vane linkage backlash in the simple analogue computer model.

Throughout this first set of site tests there were several run-up sequences recorded using different governors. Figs 8.3 and 8.4 show two more such run-ups, the former utilising the analogue DD governor and the latter using the existing station, mechanical TD governor. From Fig. 8.3 it can be seen that the DD governor also produces limit cycling but at a higher frequency than the TD governor. By comparing Figs 8.1 to 8.3 with Fig. 8.4 it is apparent that the electronic governor control equipment provides a much tidier run-up sequence than does the hydraulic based run-up gear that exists around the mechanical governor at present.

8.3 Limit Cycle Observations

a) Run-up sequences to synchronisation.

As simulation results had predicted, the TD governor would be better than the DD governor for synchronising the generator to the grid. The reason for this is due to the different limit cycles produced by each of the governors. The TD governor produces long period, low amplitude limit cycles, where, on the other hand, the DD governor limit cycles are of shorter period and generally of larger amplitude. The resultant greater rate of change of frequency with the DD governor can only make the job of synchronising more difficult.

These two situations are compared in Figs 8.5a to d and Figs. 8.6a to d. The former set of traces is an auto run-up sequence using the analogue DD governor. The second set of results show a similar test using the microprocessor TD governor.

It is clear that the TD governor synchronises much more smoothly than the DD governor. In fact in the two cases illustrated the TD governor synchronises after about 33 sec. of the initial frequency overshoot and within one period of the transient oscillation. However the DD governor takes about 56 sec. to synchronise from the initial frequency overshoot and by that time more than two periods of transient oscillation have been completed.

Figs 8.6a to d show more than the sequence to synchronisation. As soon as synchronisation has been achieved the SYNC (synchronisation) signal directs the Control Rack to lift the load limit signal to its maximum. Once the run-up sequence is complete (i.e. once the main inlet valve is fully open) the SG (Start Generate) signal automatically loads the set to the desired value as chosen by the operator. Figure 8.6 shows further load increases. These were demands made manually with the RAISE MW control on the Control Rack.

b) Use of dither to eliminate limit cycles.

The analogue DD governor provided the facility of allowing a signal to be added to the final governor output. With use of a signal generator a sine wave was injected into this input of the

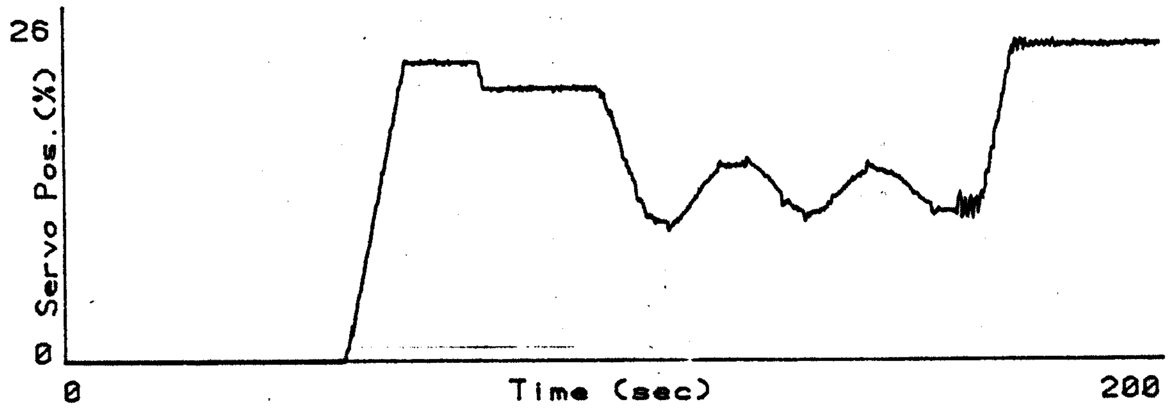


Figure 8.5(a) Auto run-up, Anal. DD Gov.(Servo Pos.)

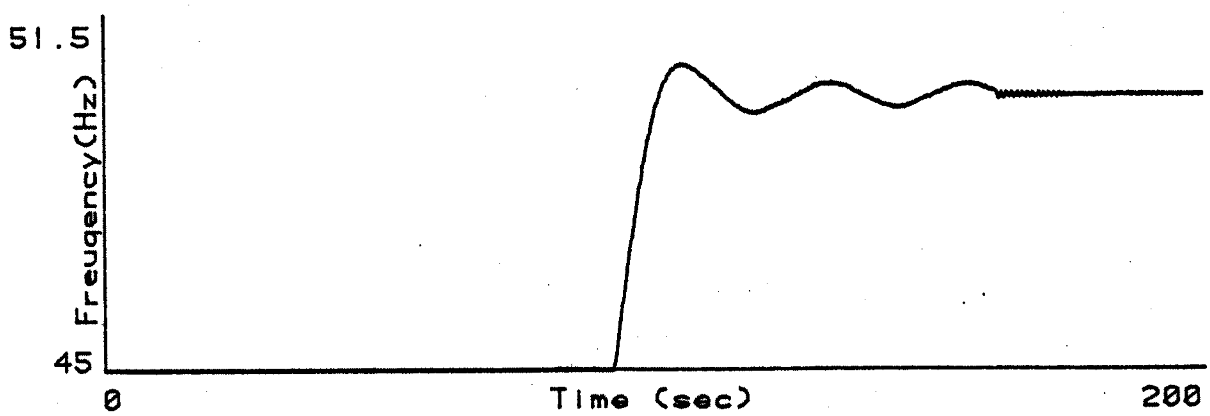


Figure 8.5(b) Auto run-up, Anal. DD Gov.(Frequency)

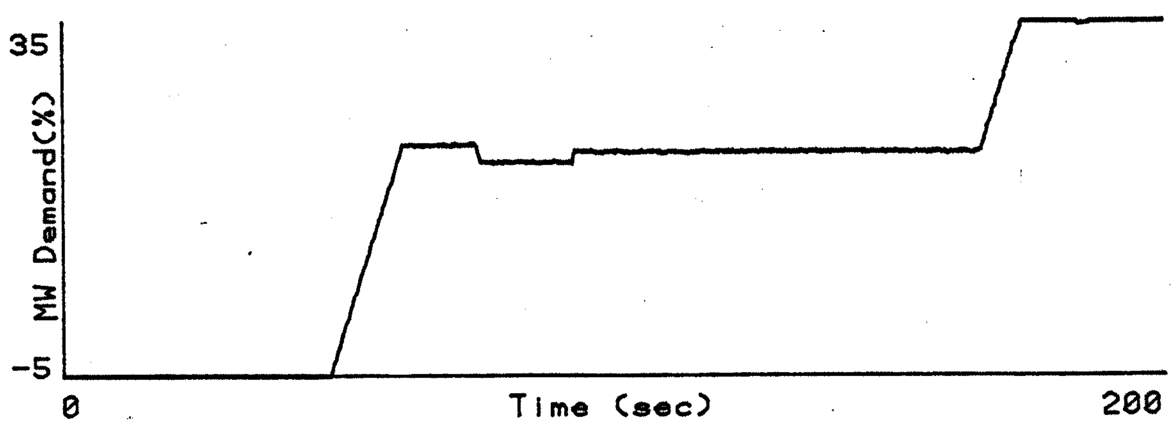


Figure 8.5(c) Auto run-up, Anal. DD Gov.(MW Demand)

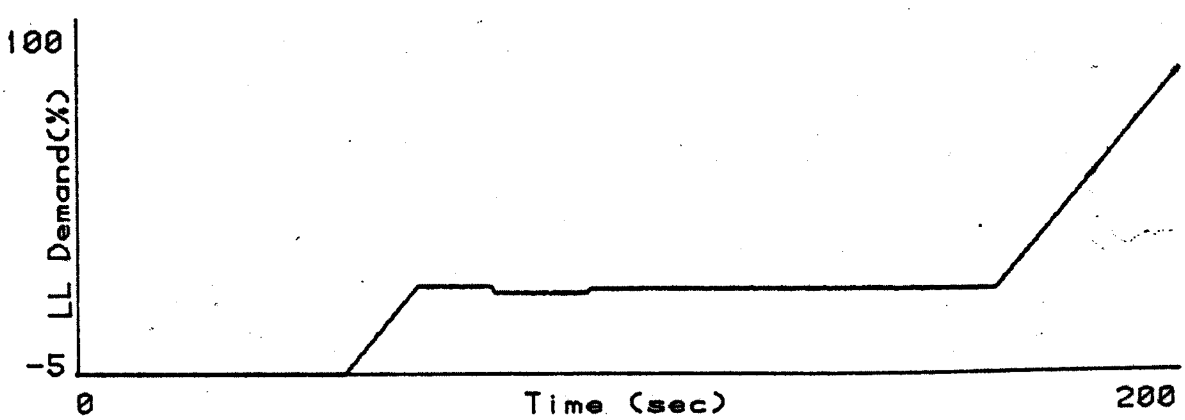


Figure 8.5(d) Auto run-up, Anal. DD Gov.(LL Demand)

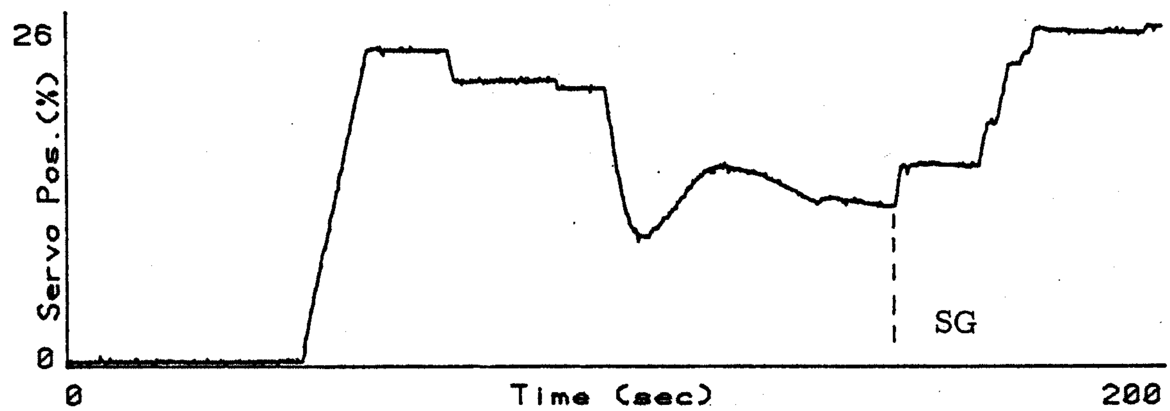


Figure 8.6(a) Auto run-up, micro TD Gov.(Servo Pos.)

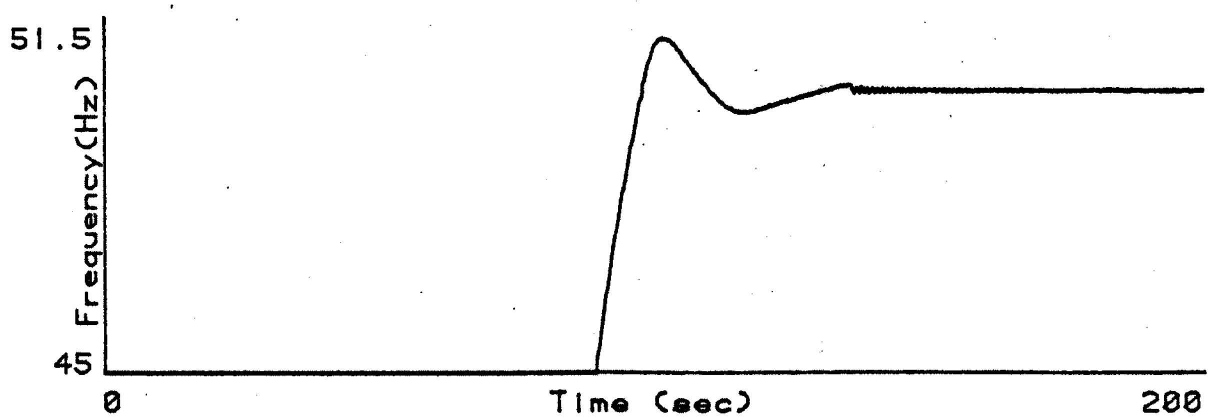


Figure 8.6(b) Auto run-up, micro TD Gov.(Frequency)

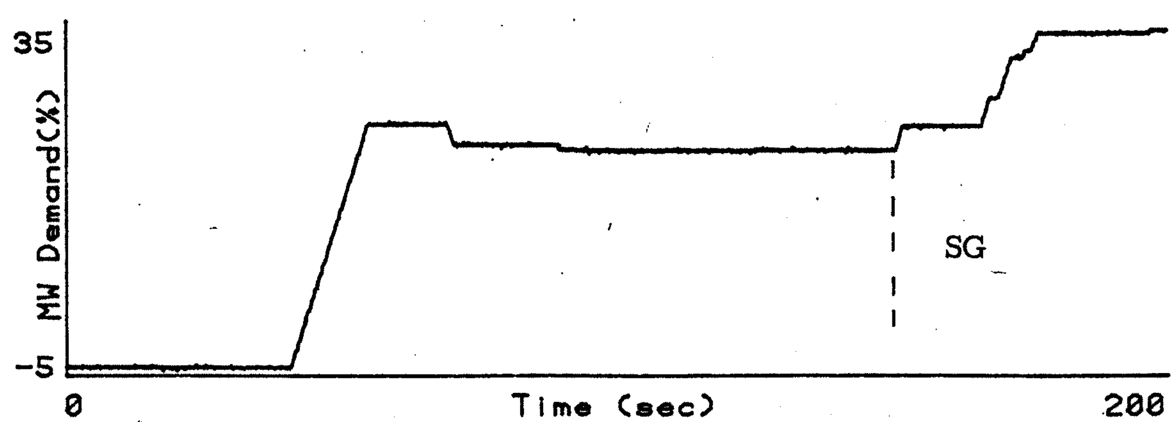


Figure 8.6(c) Auto run-up, micro TD Gov.(MW Demand)

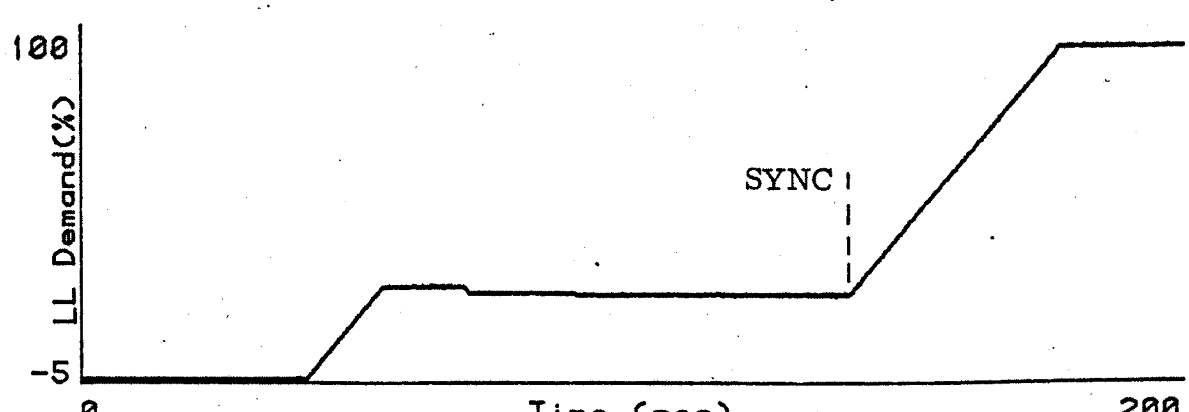


Figure 8.6(d) Auto run-up, micro TD Gov.(LL Demand)

governor. The purpose of this experiment was to investigate the use of dither to eliminate limit cycling. A dither frequency of 1 Hz was chosen since this frequency was high relative to the frequencies associated with the limit cycles and also 1 Hz was not going to hit one of the resonant frequencies of the pipeline. As the peak to peak amplitude of the dither was increased towards 1% of the full servo movement the limit cycling had nearly disappeared. By the time the dither amplitude had reached 1.48% peak to peak the limit cycling had completely disappeared. These measurements were taken from the linear position transducer of the main servo mechanism.

Thus the backlash in the servo mechanism had a value lying between 1% to 1.48% of full servo movement. With a value of 1.48% dither applied at the main servo it was found extremely easy to synchronise the generator to the grid. This would, therefore, be a solution to the problem of trying to synchronise using the lively DD governor. However it is not a very convenient way of doing so, since the constant application of this type of dither would very quickly wear down the servo mechanism. It would be possible, though, to switch out the dither after synchronisation had been achieved.

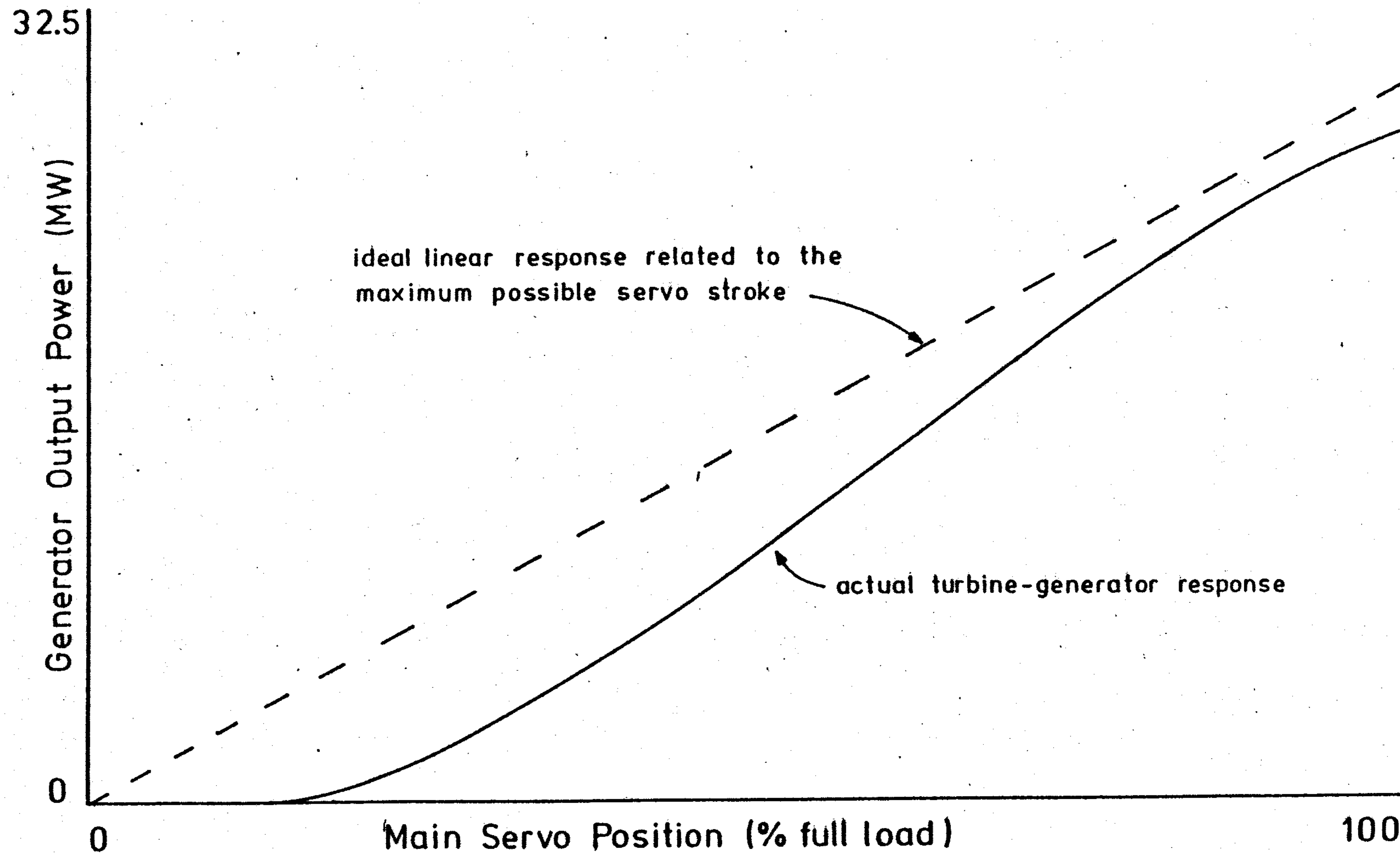
However, since the bumpless transfer from the TD microprocessor governor to the DD microprocessor governor was so easy to implement, the extra software effort involved in providing dither was rejected in favour of the good synchronising characteristics of the TD governor. Thus it was arranged in the microprocessor governor that the TD constants could be used for the run-up sequence to synchronisation. After synchronisation the change of state of the SYNC signal into the governor could be used to direct the microprocessor to the DD constants.

c) Limit cycle comparisons

From the results about to be presented, it became obvious that there existed several discrepancies between computer simulations, isolated load simulator results and the actual machine results. These differences were first appreciated by the consideration of the limit cycle results displayed in Table 8.1. This table collates the results of the limit cycle experiments carried out on Set No. 3 at Sloy. During each experiment both U/V recordings and digital recordings were taken. The tabulated results are the average values of all recordings collected during each experiment.

The first problem to be noted is that the limit cycles for true speed no load conditions are quite substantially different from those obtained using the ILS at low load. It had been thought that the ILS at as low a load as possible, would have closely represented actual speed no load. In an attempt to clarify the obvious inaccuracy of this statement the value of k_n in the ILS was varied. The results of Table 8.1 do show that by increasing k_n the period of the limit cycles can be extended towards the desired values at speed no load. However the resulting values of k_n become so ridiculous that this line of reasoning had to be abandoned.

To solve this problem, further studies were carried out on the digital simulation using the single pipe model. The various parameters that were investigated included the servo hysteresis (backlash), turbine efficiency and reservoir head. As a result of these investigations and in conjunction with the results of another test performed on Set No. 3 at Sloy, a gain factor was introduced into the forward path of the digital simulation. The additional test mentioned was a plot of output megawatts versus main servo position (as measured on the linear transducer of the high pressure servo). This plot is shown in Fig. 8.7 which was traced for increasing megawatts. Due to the guide vane linkage backlash a slightly different



Note:- Full stroke here is approximately 90% of the maximum possible stroke.
The high-low pressure servo connector block inhibits the upper 10%movement.

Figure 8.7 Megawatts versus Servo Position curve results when the same variables are plotted for decreasing megawatts. It should also be appreciated that this curve will shift for different levels of the reservoir head, since megawatts output is directly proportional to the head of the turbine.

The findings of the digital simulation studies are listed in Table 8.2. There were two goals to aim for with these simulation studies. (Reference should be made to both Table 8.1 and Table 8.2)

i) At high load - Using the DD governor

The original digital simulation results (Table 8.2, Section 1) predicted limit cycles of period 25.8s and amplitude 0.2 Hz. Actual site results using the ILS (Table 8.1, Section 3) provided a corresponding limit cycle period of 18.02s and amplitude 0.24 Hz. The problem here was to reduce the limit cycle period of the simulation.

ii) At low load - Using the DD governor

The ILS is ignored in both simulation and actual tests. The original digital simulation results (Table 8.2, Section 3) predicted limit cycles of period 30.36s and amplitude 0.134 Hz. Actual site tests (Table 8.1, Section 1) indicate limit cycles of 65.49s and amplitude 0.15 Hz. The problem here was to increase the limit cycle period of the simulation.

In ii) simulation results were carried out at 10% of full load. The simulation does not allow for speed no load losses, hence 0% servo position is equivalent to 0 MW output. The 10% full load operating point in the simulation was chosen since the servo position, at speed no load on the actual turbine/generator sits at approximately 13.5% whereas the water flow rate has an actual value between 6% and 10% of the full load flow rate. Thus 10% full load is a fair compromise for use in the simulation studies.

System Configuration	Governor	Value of k_n in ILS	Limit Cycles	
			Period (s)	Amplitude p-p (Hz)
1) Machine at speed no load	Station TD	-	172.8	0.20
	Micro TD	-	175.2	0.24
	Micro DD	-	61.18	0.16
	Analogue DD	-	65.49	0.15
2) Machine grid connected (at 1.5MW i.e 4.5% full load) using ILS i.e. approx speed no load	Analogue DD	0	37.47	0.30
	Analogue DD	1.5	41.95	0.25
	Analogue DD	3.0	45.4	0.20
	Micro DD	1.5	35.05	0.29
	Micro TD	1.5	110	0.31
3) Machine grid connected (at 25 MW i.e 75% full load) using ILS	Micro TD	1.5	None	None
	Micro TD	0	None	None
	Micro DD	1.5	None	None
	Micro DD	0	18.02	0.24

Table 8.1 Limit Cycle characteristics for set No. 3 at Sloy for a mean head of 261.5m (858 ft).

Simulation Configuration	Gain Factor	Servo Hysteresis(%)	Turbine Efficiency	Reservoir Head (pu)	Limit Cycles	
					Period (s)	Amplitude (Hz)
1) DD governor, no ILS	1	1.4	1	1	25.8	0.20
representation (i.e true	1	1.6	1	1	25.5	0.23
isolated load).Operating	1	1.6	0.9	1	26.5	0.23
point = 74% full load	1	1.6	0.9	0.9	28.15	0.23
2) DD gov, ILS represented	1	1.6	1	1	20.3	0.32
(i.e. frequency dependence	1	1.4	1	1	20.3	0.28
of turbine and torque out	1	1.4	0.9	1	21.1	0.29
74% full load						
3) DD gov, No ILS	1	1.4	1	1	30.36	0.134
representation (i.e.	0.5	1.4	1	1	38.08	0.134
true isolated load)	0.1	1.4	1	1	73.75	0.099
10% full load	0.17	1.4	1	1	59.32	0.098
TD governor	0.17	1.4	1	1	161.9	0.116

Table 8.2 Simulation results of limit cycles (Simulation model was a single pipe representation)

Initial attempts in achieving i) are shown in Table 8.2, Section 1. Firstly the value of hysteresis was increased. This had little effect on the period but it did increase the amplitude. Secondly the values of efficiency and head were decreased and both alterations had the same effect, namely increasing the limit cycle period. Success in i) was finally gained (Table 8.2, Section 2) when the frequency dependence of the turbine and torque was eliminated from the simulation thus emulating the effect of the ILS.

In the case of ii) the arrival at an explicable solution took somewhat longer. From the results in Table 8.2, Section 1, it can be seen that the effect of reducing the efficiency and the head was to increase the period of the limit cycles. The alteration of these two parameters was almost equivalent to a simple gain change within the control and system loop. Section 3 of Table 8.2 show the results of introducing such a gain factor into the system. It was the DD governor which was studied initially and it is apparent that the target figure of 61.18s (Table 8.1, Section 1) for the limit cycle period is very nearly reached (59.32s) for a gain factor of 0.17. Further encouragement was gained when it was noted that the limit cycles for the TD governor in the real and simulated cases were also approaching agreement when using this gain factor value of 0.17. The only problem now was to justify this exceptionally low value of gain.

The answer lies in the graph of Figure 8.7, which is a plot of megawatt output versus servo position for Set No. 3 at Sloy Power Station. The general shape of this graph is 'S' shaped, with the top and bottom section levelling out quite substantially. The gain factor of 0.17 indicating a similar gradient on the curve of Figure 8.7 is by no means ridiculous when the lower portion of this curve is observed. An accurate measurement from the results of the graph of Figure 8.7 was not possible for this particular region due to the additional confusion introduced into the original trace because of limit cycling. Figure 8.7 is a best estimate of the original trace.

It can be seen, though, from Fig. 8.7 that the curve progresses into a more sensible, semi-linear form very rapidly with increasing load away from the speed no load position.

8.4 The effect of the DD governor time constants T_2 and T_4 on noise observed at the main servo.

After the simulated run-up sequence of Fig. 8.1 was complete the main servo was held constant at approximately 14% full load. Different governors were switched into operation, and for each, U/V recordings were taken of the actual servo position. Both the analogue and microprocessor governors with $T_2 = T_4 = 0.2$s provided relatively noise free performance. The microprocessor governor with $T_2 = T_4 = 0.1$s produced results which made the servo noticeably judder. Not surprisingly, the microprocessor governor in which $T_2 = T_4 = 0$ made the servo judder quite unacceptably.

Thus, for future governor tests it was decided that the value of $T_2 = T_4 = 0.2$s should be adopted for best elimination of noise without too great a degradation in overall performance.

8.5 Step tests at various load settings

The following tests were performed simply to ensure that the governors, and in particular the microprocessor governor, retained stability for small disturbances around various mean load settings. The disturbances were applied as step deviations to the demanded torque signal of the ILS. Tests were carried out at both low and high loads, but of greater importance were the results of the high load tests, since the system is less stable at high loads. For this reason only the high load results are displayed here.

Figs. 8.8a and b illustrate the results for the microprocessor TD governor of a 6% (of 30 MW) step up from a mean power level of 25.1 MW then back down again.

Figs 8.9a and b is a repeat of the above test but using the microprocessor DD governor. The mean power level started at 24.4 MW.

In both these tests the machine inertia time constant was set at 7s and the self regulation constant, k_n, was set at 1.5. This value of k_n is of course too high but was set so at the time of this test because the relation between e_n and k_n was not fully appreciated at this time. However the comparison of the results in Figs. 8.8 and 8.9 is still valid.

The tests were to confirm stability, and they do, but more than this is displayed. The other interesting feature of these results is the faster settling time of the DD governor compared with the TD governor.

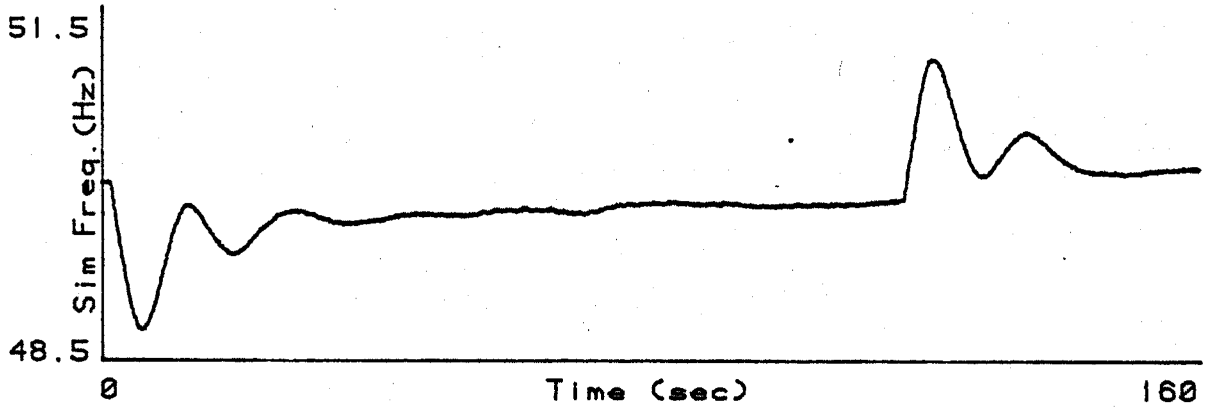


Figure 8.8(a) ILS step, micro TD Gov.(Sim. Freq.)

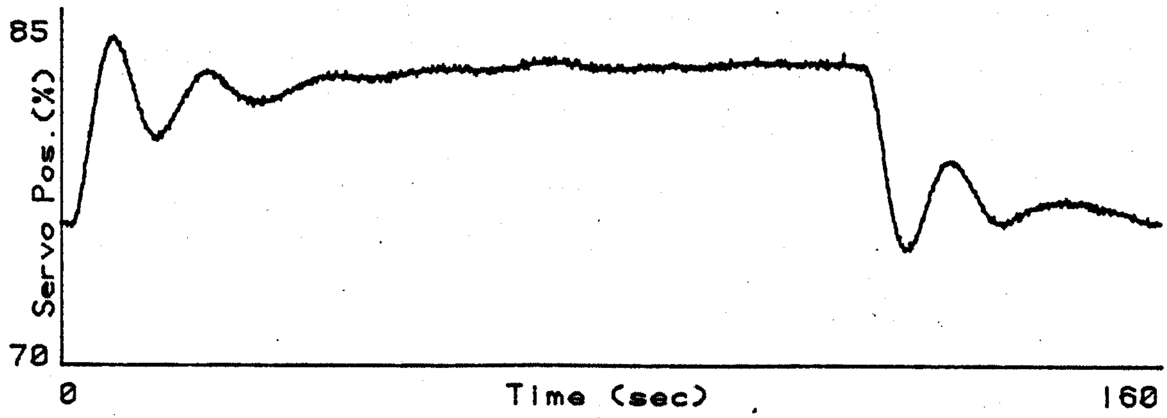


Figure 8.8(b) ILS step, micro TD Gov.(Servo Pos.)

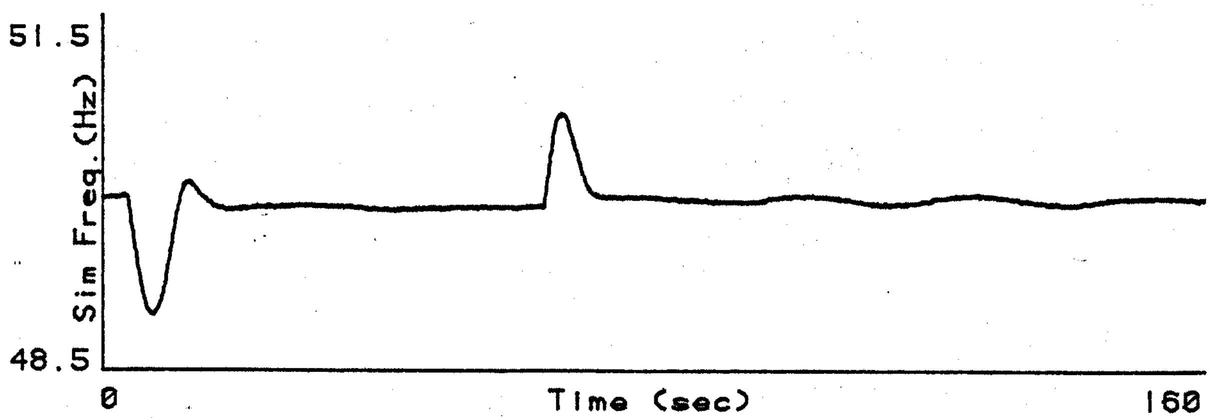


Figure 8.9(a) ILS step, micro DD Gov.(Sim. Freq.)

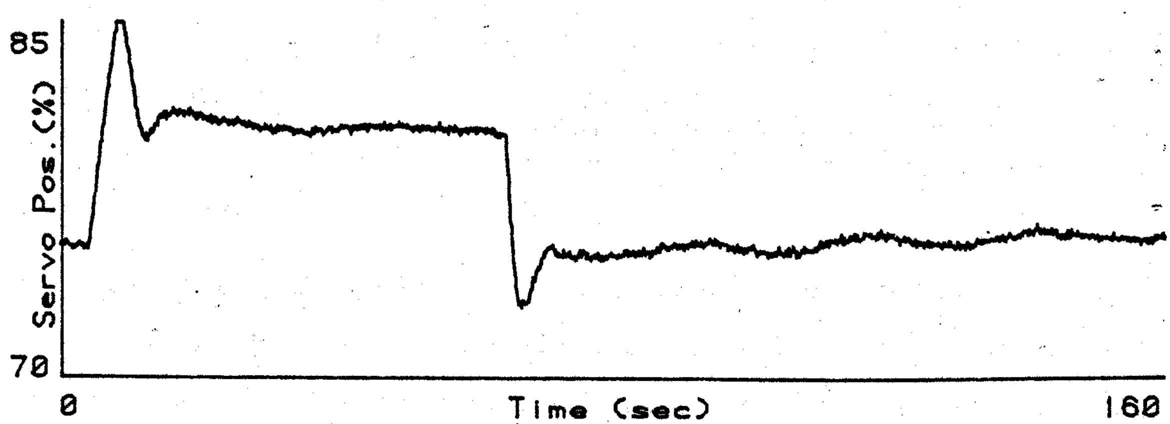


Figure 8.9(b) ILS step, micro DD Gov.(Servo Pos.)

CHAPTER 9 - FINAL SITE TESTS

9.1 Introduction

The results contained within this chapter were the consequence of site tests which were conducted on two separate occasions, namely 7th September and 10th October, 1978.

The purpose of the tests of 7th September was to test the Adaptive Microprocessor Governor, the philosophy of which was explained in Chapter 6.

As previously explained in Chapter 6, the Adaptive Microprocessor Governor had been devised such that a faster grid connected response would be achieved while still retaining conditions of stability under isolated load. The three chosen bands (0 - 40%, 40 - 70%, and 70 - 100%, being equivalent to 0 - 13.2 MW, 13.2 -23.1 MW and 23.1 - 33 MW) were each assigned their own DD governor constants for optimum performance.

The experiments which were carried out on this governor are listed below.

1) Grid connected responses to step input disturbances of the frequency signal. Separate tests were observed for steps across single band boundaries, and for steps across both boundaries.

2) By using the ILS, the intention here was to observe the isolated load stability of the Adaptive Governor when subjected to load disturbances within the individual bands, and also for disturbances that resulted in the band boundaries being crossed.

As will become apparent, the investigations of 7th September were not wholly successful. However, after consideration of these first results with the Adaptive Microprocessor Governor and subsequent simulation studies, the Governor was ammended and further site tests were conducted on 10th October. Basically a repeat of the experiments of 7th September, the results taken on 10th October proved to be much more successful, thus proving the credibility of the Microprocessor Adaptive Governor.

Throughout this chapter the governors will be referred to using the abbreviated forms as listed in Table 6.2. The actual constants applicable to the various governors may be found in Table 6.3.

9.2 Grid Connected Responses of 7th September 1978.

Preparations for these tests consisted of the usual checks of the Control and Interface equipment, governors and servo system by using the simple analogue computer simulation of the plant. All checks made, Set No. 3 was run up to normal speed and synchronised to the Grid after which the breaker was closed thus connecting the generator on to the power distribution system.

Initial grid connected tests consisted of applying small steps to the frequency reference signal, such that small power steps across governor band boundaries were achieved. Sufficient confidence was gained through the results of these experiments to merit further, larger steps to be investigated.

A mean power level of 3.3 MW was chosen as a starting point. This value ensured that the Adaptive Governor would settle down to its low band constants. A 2.4% step was then applied to the frequency reference input which should have resulted in a final change of 80% in the servo position output. This would be sure to take the Adaptive Governor into its high band of operation.

This type of experiment was repeated several times using the following different governors - Temporary Droop (TD), Double Derivative, 33.3s (DD), Low Band Double Derivative, 10s (DDLOW1) and Adaptive (ADP1).

The results of these four tests are traced in Figs. 9.1a and b. The first graph illustrates the four responses of the servo position to the step disturbance in frequency reference, whereas Fig. 9.1b shows how the actual machine output power responded.

The initial reaction to these results was one of great encouragement. It is quite apparent that the ADP1 governor was very little slower than the DDLOW1 governor, which has a 10s dominant lag but is not stable outside the low band under isolated load conditions. The DD governor is noticeably slower than both the aforementioned governors, and the traditional TD governor simply cannot compete with any of the others when speed of response is the dominant criterion.

Further study at a later date of the responses of Fig. 9.1 revealed other factors of interest some of which were to become significant for future tests. These factors are listed below.

a) It was observed that the main servo appeared to be hitting its top end stop for this value of frequency reference disturbance.

b) After one or two of these large disturbances the oscillations of the surge shaft to reservoir became particularly noticeable on the megawatt output signal. This phenomenon was noticed at the time of the trials by observation of the dial indicating spiral casing pressure for Set No. 3.

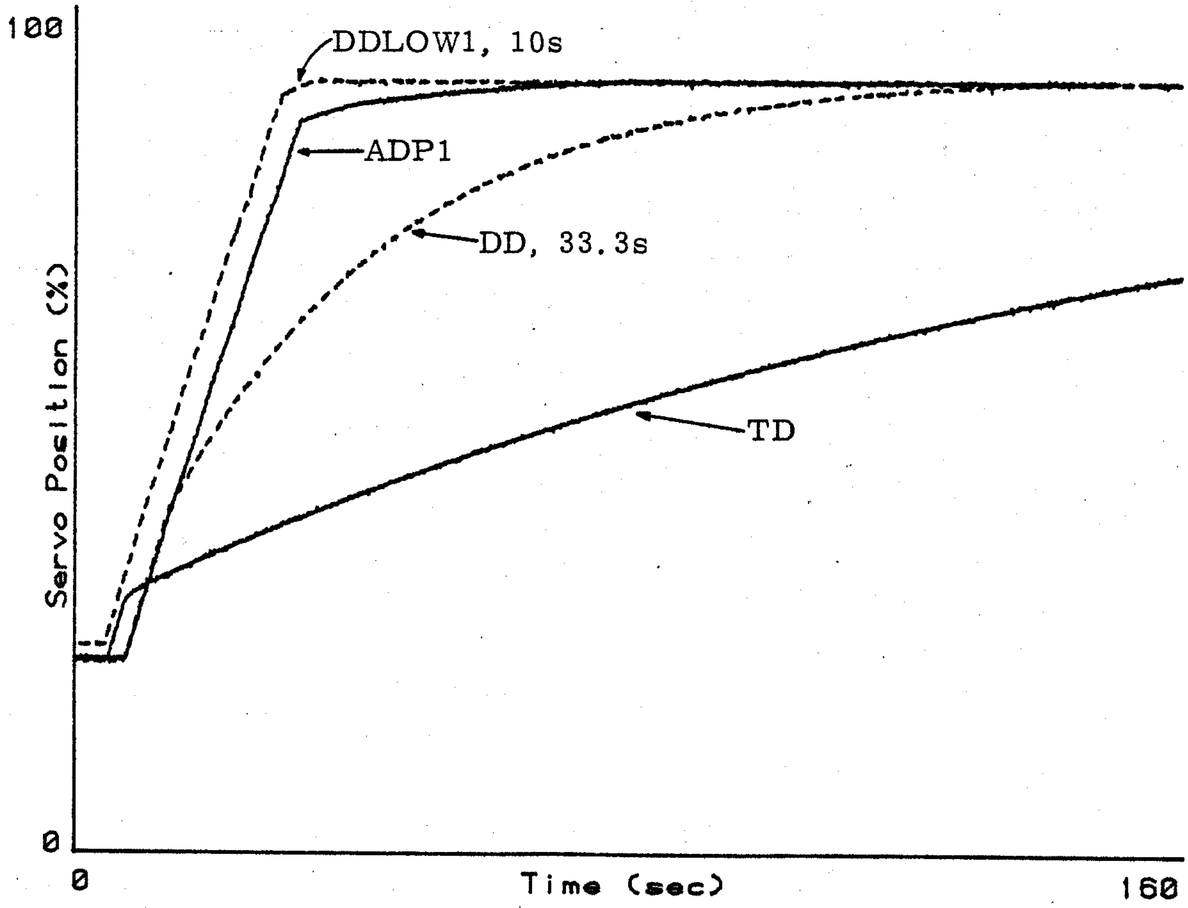


Figure 9.1(a) Grid connected gov response (Servo Pos)

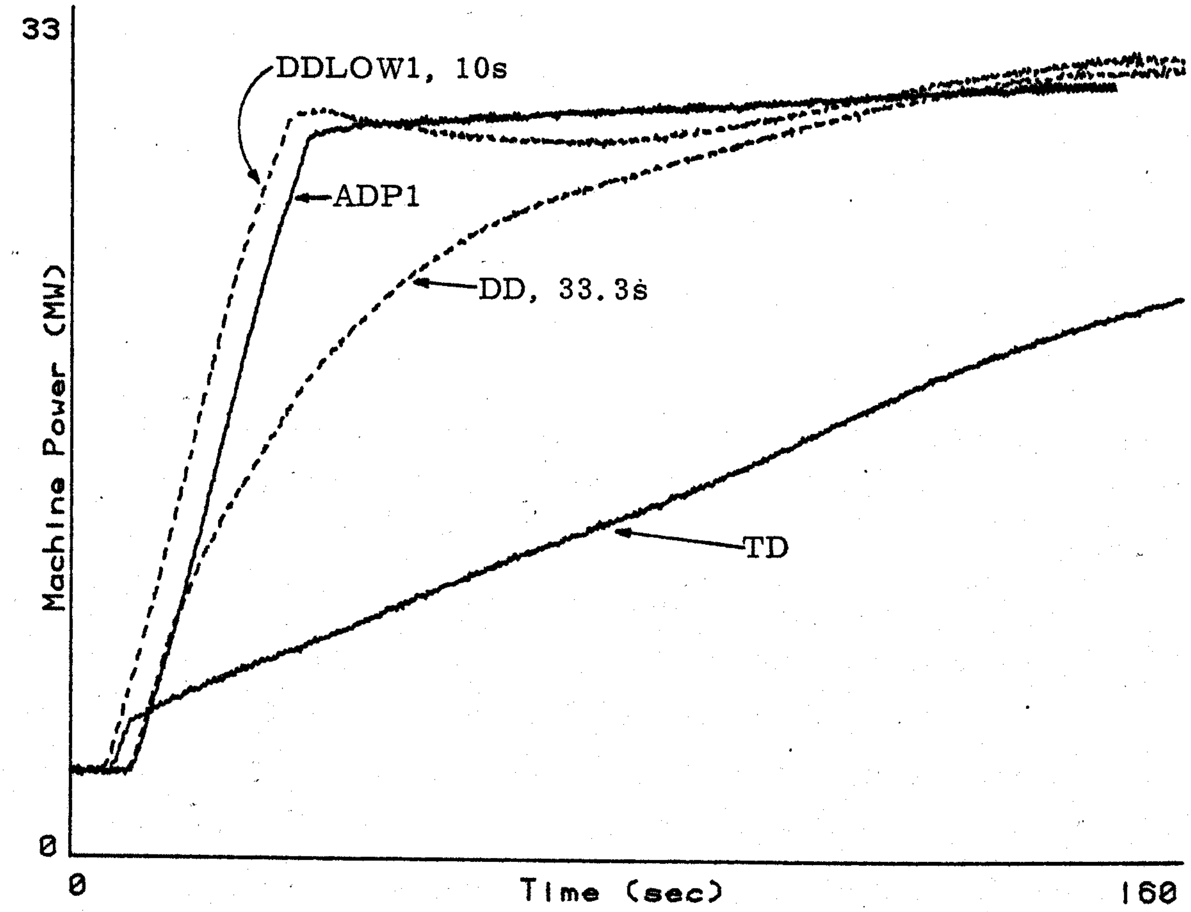


Figure 9.1(b) Grid connected gov responses (Power)

c) Measurement of the initial ramp increase of servo position produces a ramp rate of 40s for full scale travel of the main servo. The expected rate was around 22s for full scale, which was the value that had been set up in the analogue circuits of the Governor Changeover Unit of the Control Rack. Subsequent investigations into this problem revealed that the 40s rate limit was as it should be since it had been included as a hydraulic rate limit in the high pressure servo oil circuit when initially commissioned several years ago.

9.3 Step Responses on Simulated Isolated Load (7th September, 1978)

The purpose of the next set of tests was to confirm simulation results that showed the ADP1 Governor would remain stable under isolated load.

The proposed method of test here was to apply step disturbances which would test the Adaptive Governor constants within their respective operating bands. Subsequent step tests would shift the operating point across a band boundary thus testing the Adaptive Governor across band boundaries.

The first experiment with the ADP1 Governor using the ILS was a test on the DDLOW1 Governor constants. The generator was set to output a mean power of 11 MW (i.e. top of low band range). With $k_n = 0$ (i.e $e_n = 1.0$) and $T_a = 7.0$s set by the appropriate dials of the ILS, the ILS was connected into the governing loop thus simulating isolated load. The system was to be allowed to settle before any stimulus was applied to the load demand of the ILS. However a steady state condition was not reached and the ILS had to be disconnected from the system before any damage resulted from the unstable cycling which was produced. This instability is illustrated in the site results of

Figures 9.2a to c.

There were only two variables that were accessible on site for the purposes of experimentation. They were k_n and T_a of the ILS. Stability was achieved in the low band, for example, for the conditions where $k_n = 1.5$ and $T_a = 7.78s$ or $k_n = 0$ and $T_a = 8.75s$. This was hardly a satisfactory solution to the problem but it did show that the limit of stability was not too far out of reach.

The mid and high band governors, in their respective bands did not suffer from the same problem as the low band. The relatively successful results of the DDMID1 governor are shown in Figs. 9.3a to c. This test was started at a mean power level of 20 MW (i.e. close to the top of the mid band, the least stable operating point of the band) and $k_n = 1.5$. A 1.8 MW increase in load demand was applied followed by a 1.8 MW decrease. This was repeated for $k_n = 0$, and although less stable for the lower k_n the system remained stable overall.

Figs 9.4a to c illustrate the governor responses in the high band. Unfortunately these tests were only conducted for $k_n = 1.5$. However a useful comparison is shown in the results which were conducted from a mean power level of 24.4 MW. The first 1.8 MW increase followed by a similar decrease, shows the response of the standard DD governor while the second 6% increase-decrease resulted from the operation of the DDHI1 governor. As can be seen from Figs. 9.4a to c there is little to choose from the two governors but, if anything, the DDHI1 governor is marginally better.

The DDLOW1 governor results using the ILS were disappointing but what was more disturbing was the inconsistency with the simulation studies. The low band instability was the main worry, however there was also a noticeable degradation in the stability going

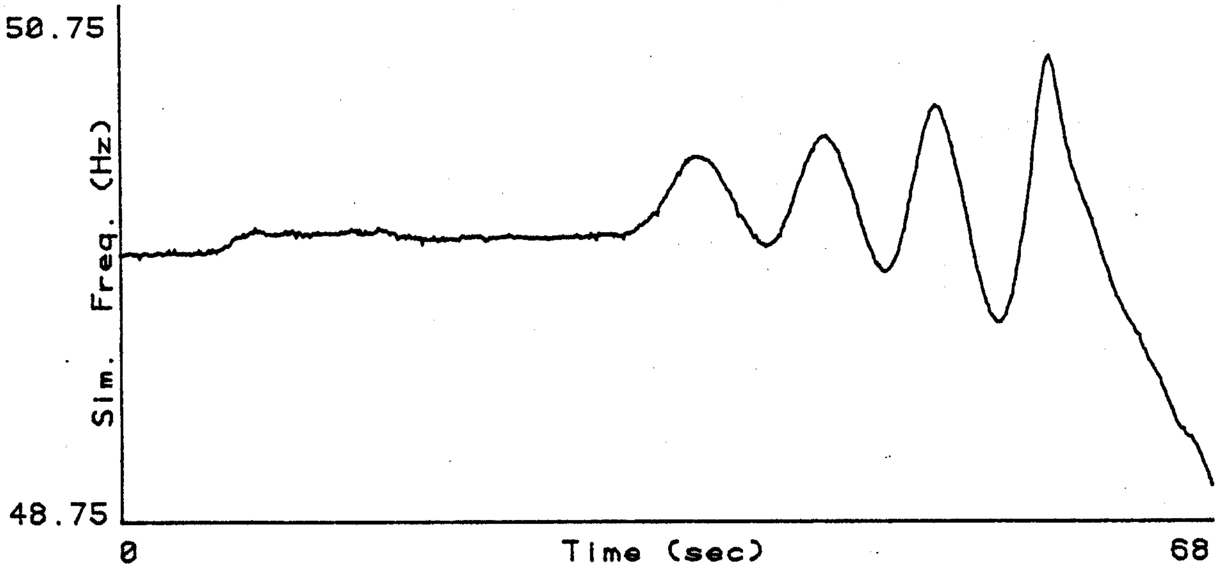


Figure 9.2(a) DD low band test with ILS (Sim. Freq.)

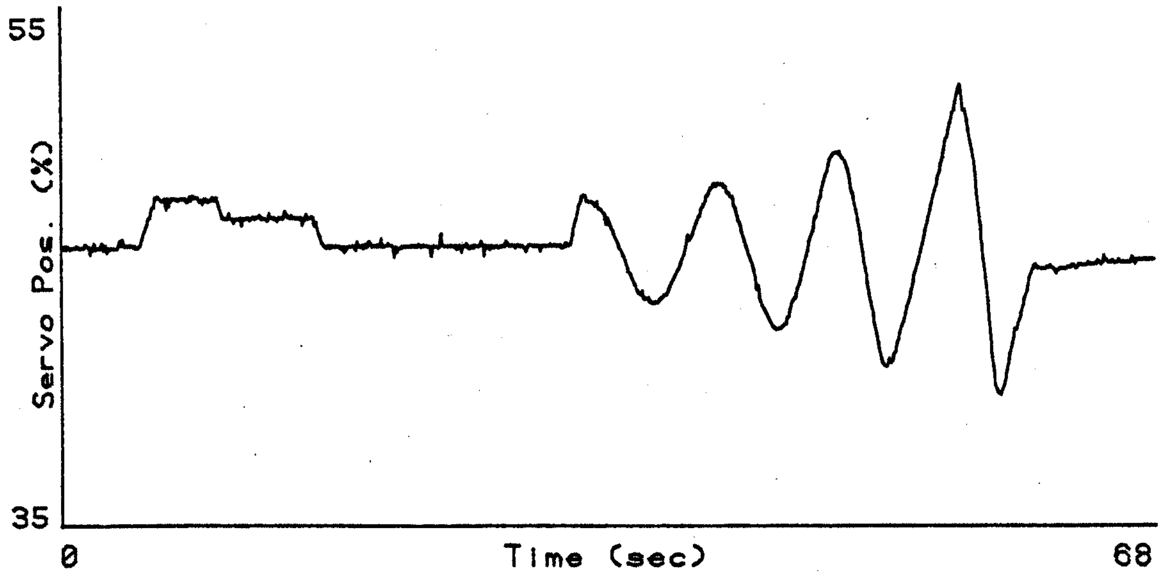


Figure 9.2(b) DD low band test with ILS (Servo Pos.)

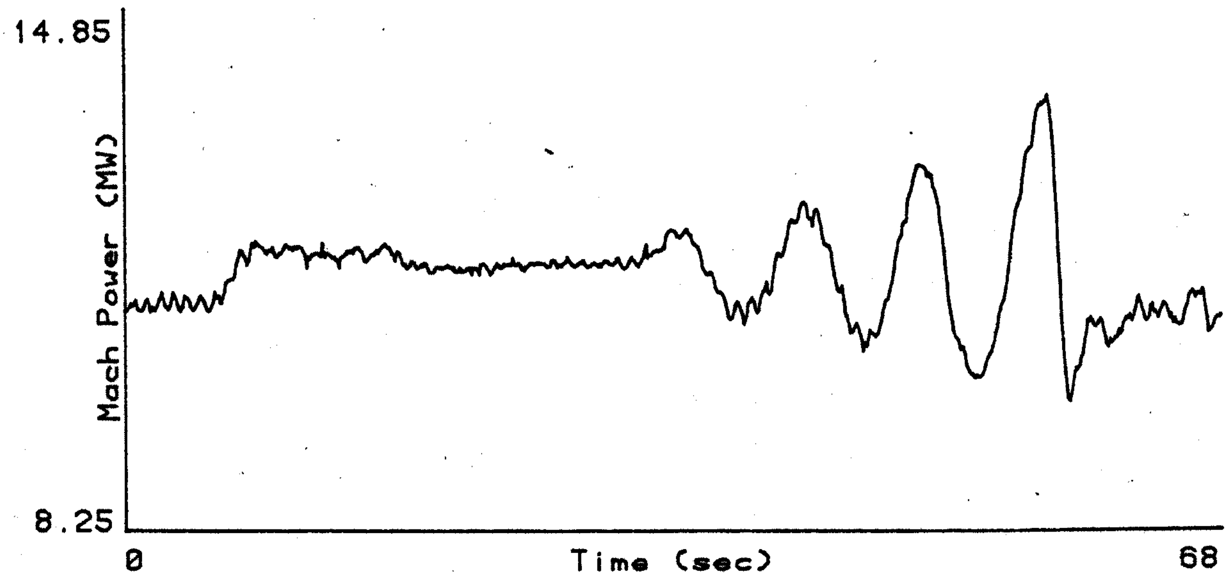


Figure 9.2(c) DD low band test with ILS (Mach. Power)

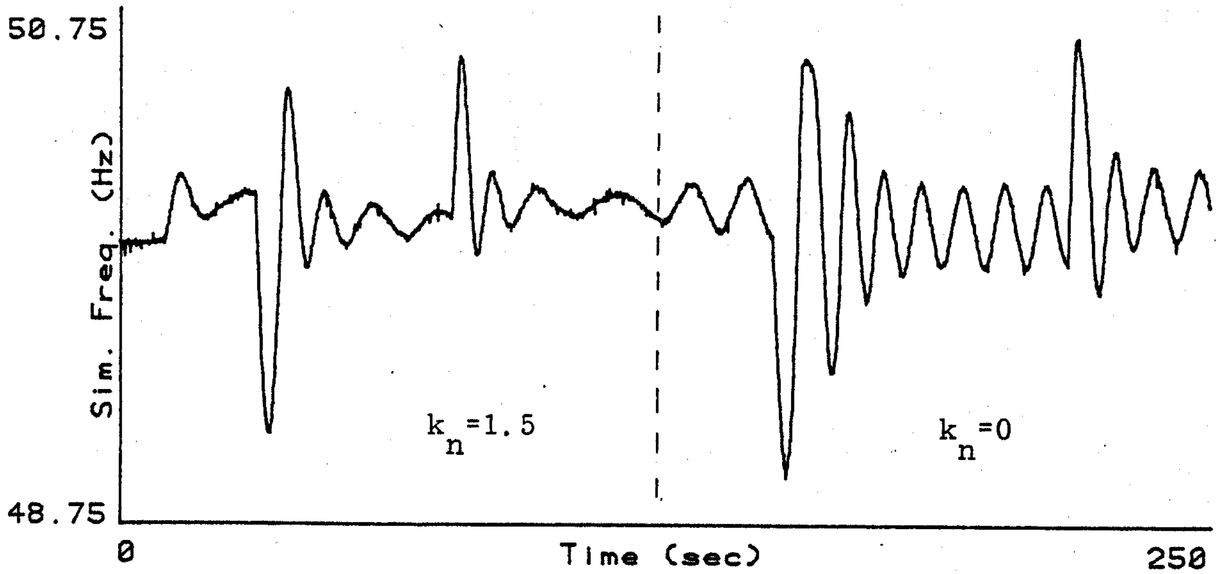


Figure 9.3(a) DD mid band test with ILS (Sim. Freq.)

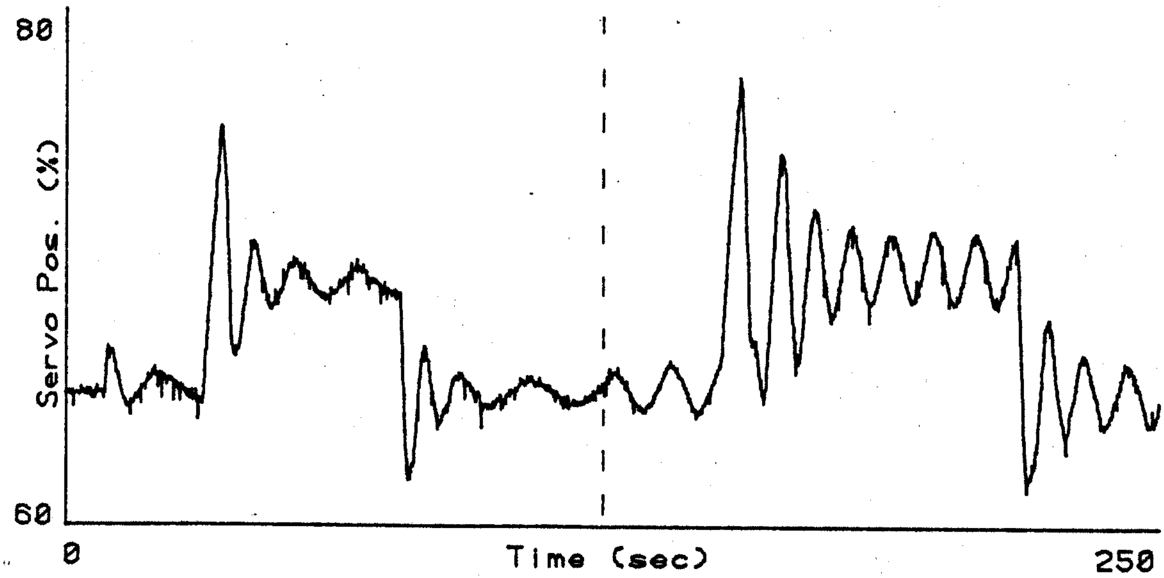


Figure 9.3(b) DD mid band test with ILS (Servo Pos.)

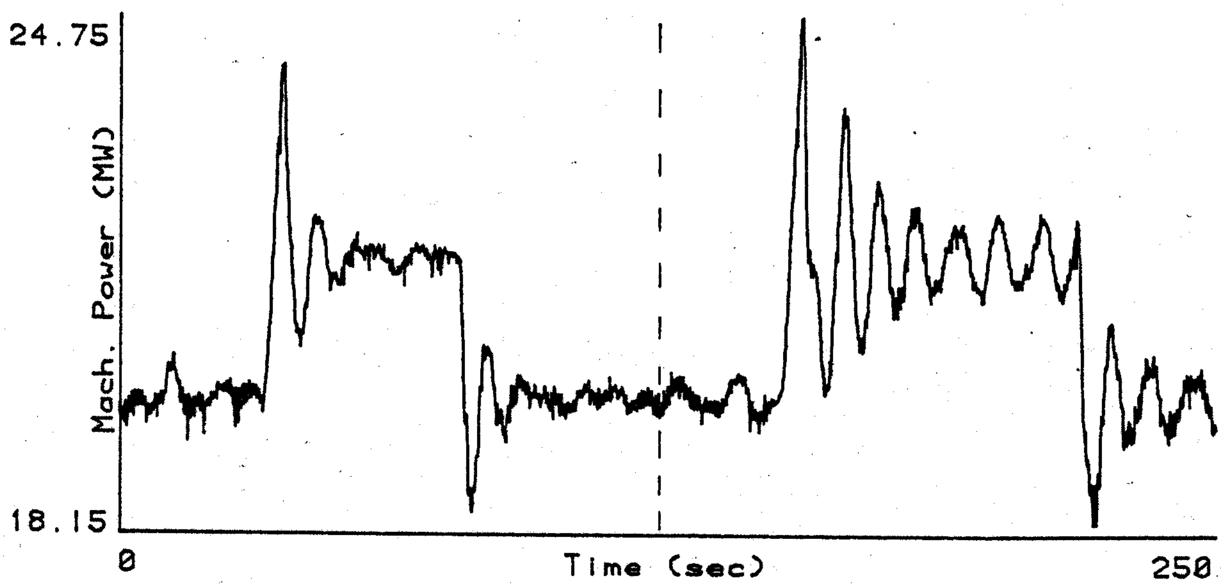


Figure 9.3(c) DD mid band test with ILS (Mach. Power)

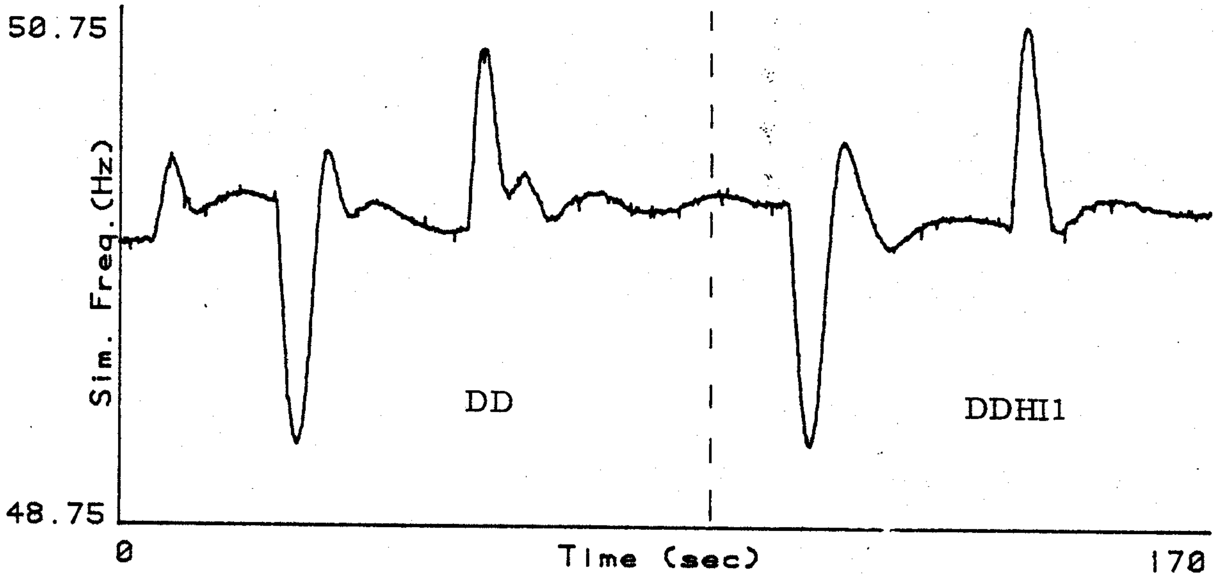


Figure 9.4(a) DD high band test with ILS (Sim. Freq.)

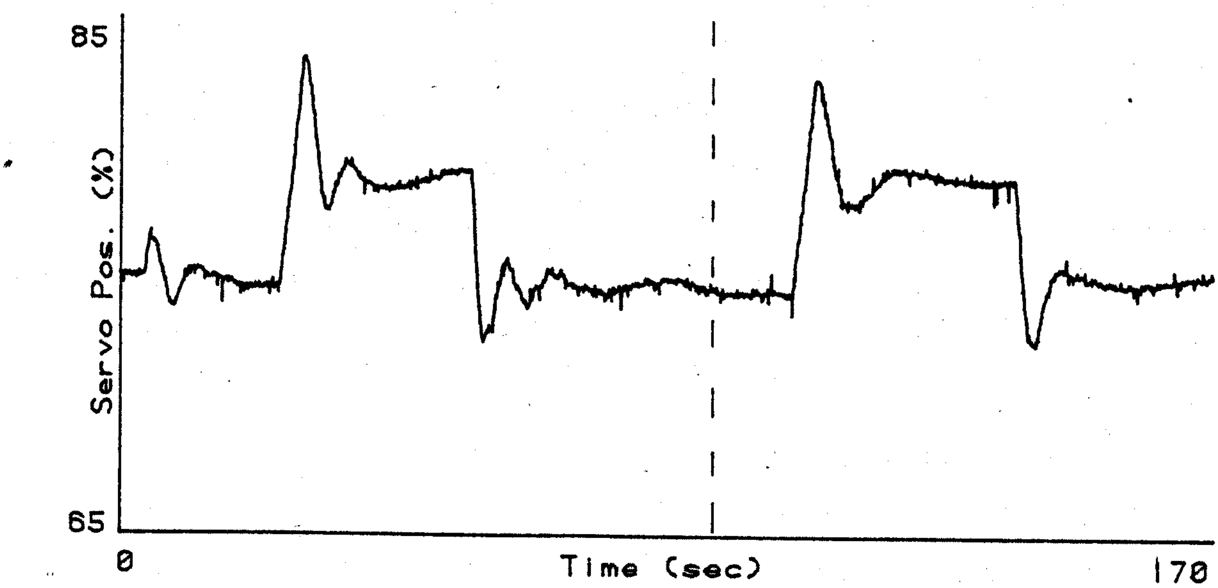


Figure 9.4(b) DD high band test with ILS (Servo Pos.)

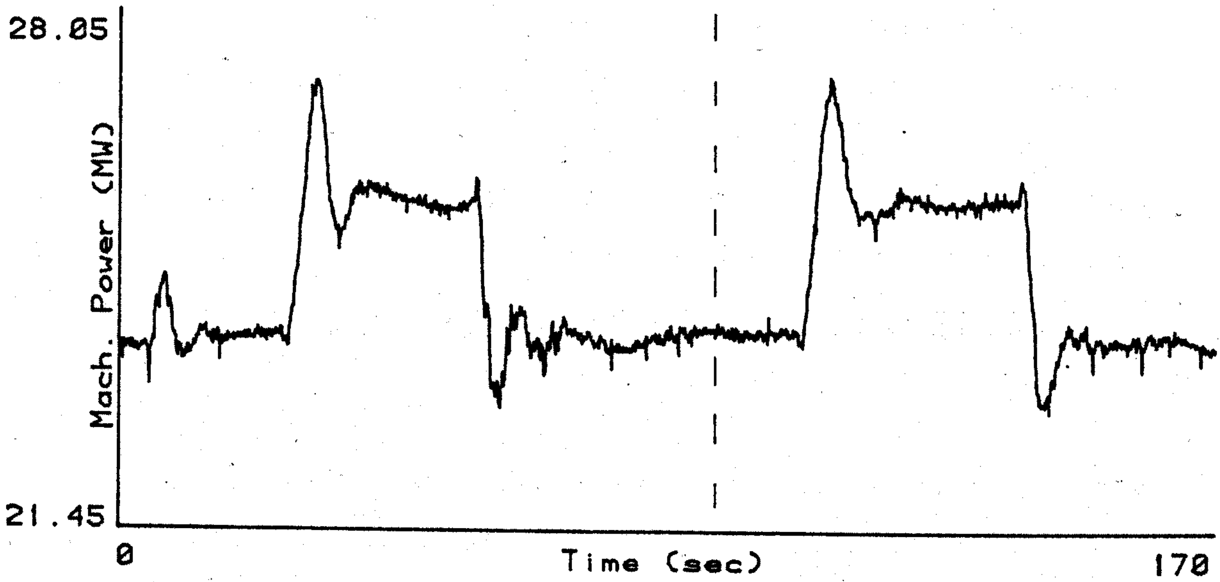


Figure 9.4(c) DD high band test with ILS (Mach. Pow.)

from simulation to site results, even for the governors that retained overall stability.

9.4 Analysis of First Tests of the Adaptive Governor

After studying the results of the 7th September, 1978 and performing further digital simulations the causes for the failure of the DDLOW1 Governor were ascertained.

As previously mentioned, the existence of the hydraulic 40s rate limit was brought to light as a consequence of these tests. This was not the cause of the instability with the DDLOW1 governor but was partly to blame for the pessimistic results obtained on site while operating in the mid and high bands. Further simulations were therefore performed with an upward rate limit of 40s and a downward rate limit of 4s on the governor output.

The source of the instability problem is to be found in the trace of Megawatts versus Servo Position in Fig. 8.7 of Chapter 8. When optimising the constants for the governors in each band the top of each band had been used as the worst case operating point in the respective bands. A unity, linear relationship had been assumed for Servo Position to Megawatts. The linear approximation is fairly acceptable especially since the top ends of the low and mid bands certainly lie on the most linear portion of Fig. 8.7. This is perhaps not a valid statement for the upper end of the top band, but as the gain drops off at this point then the linear assumption is likely to produce results with an additional safety margin.

Regarding the unity gain relationship, however, this was not a valid assumption. A closer look at Fig. 8.7 revealed that the gain reached a maximum of approximately 1.36. Providing the simulation with this gain (by utilising the gain factor previously mentioned in the limit cycle studies of Chapter 8) and including the 40s rate limit produced simulation results which were very similar to the instability recorded on site. Figs. 9.5a to d show the results of an interactive digital simulation in which the actual microprocessor governor (DDLOW1) was offered up to a single pipe type model of the plant. The only disturbance to the overall simulation was a mismatch in the initial conditions. This is a similar situation to that found when the ILS is switched into operation on the site equipment. Comparing the response of the frequency traces in Fig. 9.2a and Fig. 9.5a shows that the simulation can reproduce a similar type of instability as that obtained on site. Note, too, as the diverging oscillations increase the governor output rises and falls along the built in protective rate limits. The period of the diverging oscillations in the simulation are somewhat longer than those of the site results. This is probably due to the influence of the relief valve which was certainly active on site, but is not modelled in the simulation.

The low band constants were re-optimised using a simulation containing the gain of 1.36 and the rate limit of 40s. The final choice of governor constants (DDLOW2) were implemented in the microprocessor and this was then connected up to the PDP 11/45 again. The results of this simulation were quite stable compared to those of Fig. 9.5.

As an additional test to the stability of these new low constants an interactive simulation was performed in which the load demand change from 35% to 40% was applied in the form of a step change. The subsequent response is shown in Figs. 9.6a to d. The source of limit cycling can also be seen on these plots in which the servo output signal is shown after it has been subjected to hysteresis (i.e. backlash).

Similar optimisations were carried out in the mid and high bands. Figs. 9.7 to 9.10 are the results of further interactive simulations

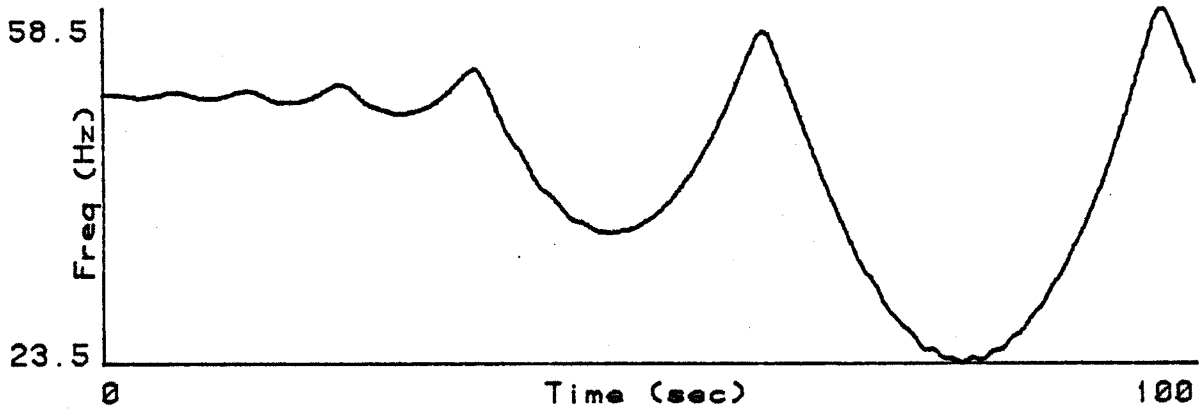


Figure 9.5(a) Simulation of instability (Freq)

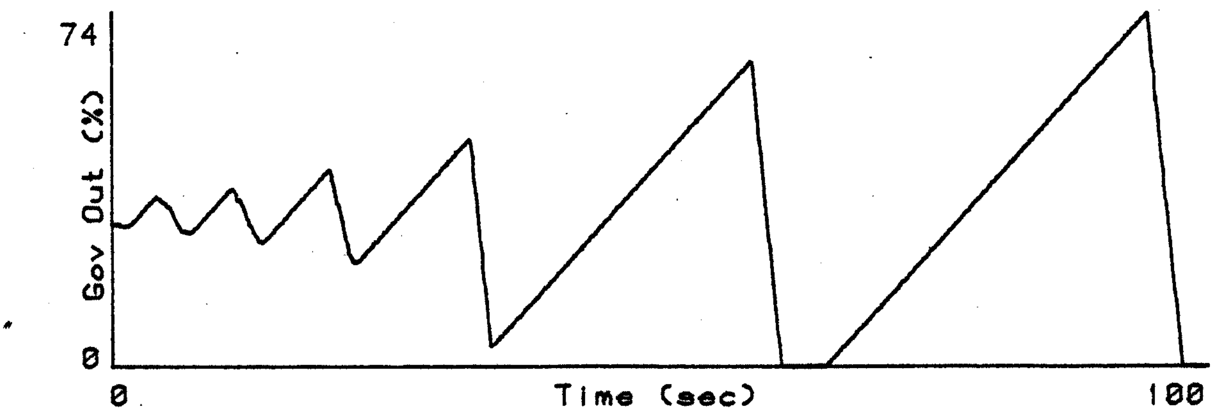


Figure 9.5(b) Simulation of instability (Gov Out)

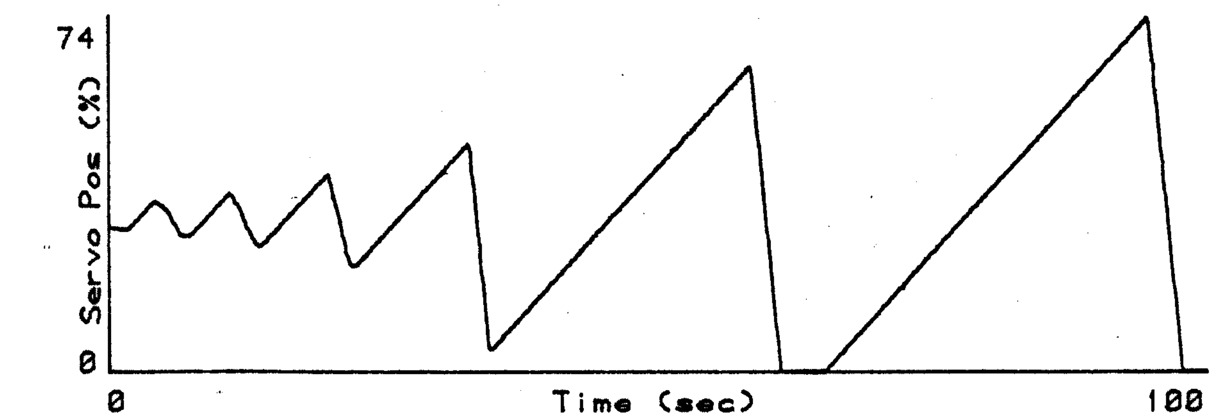


Figure 9.5(c) Simulation of instability (Servo Pos)

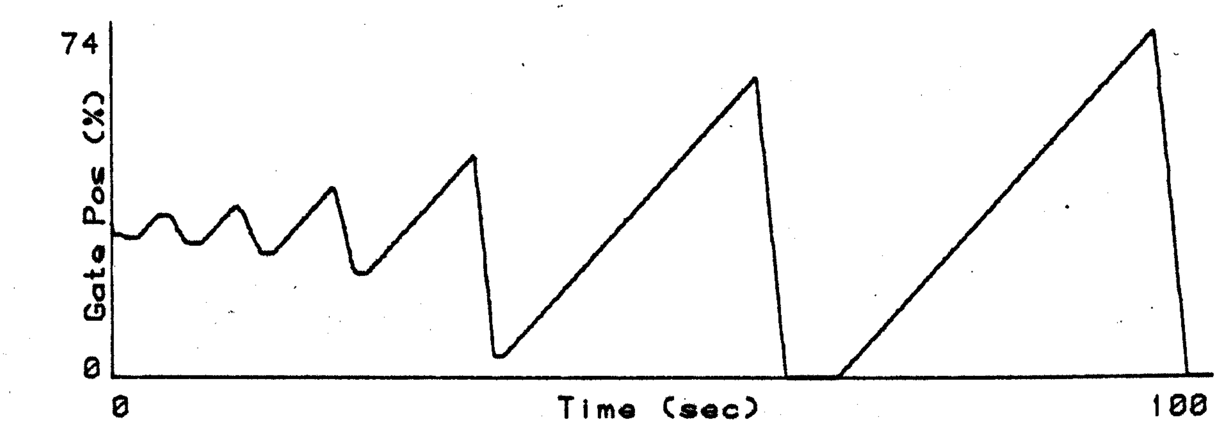


Figure 9.5(d) Simulation of instability (Gate Pos)

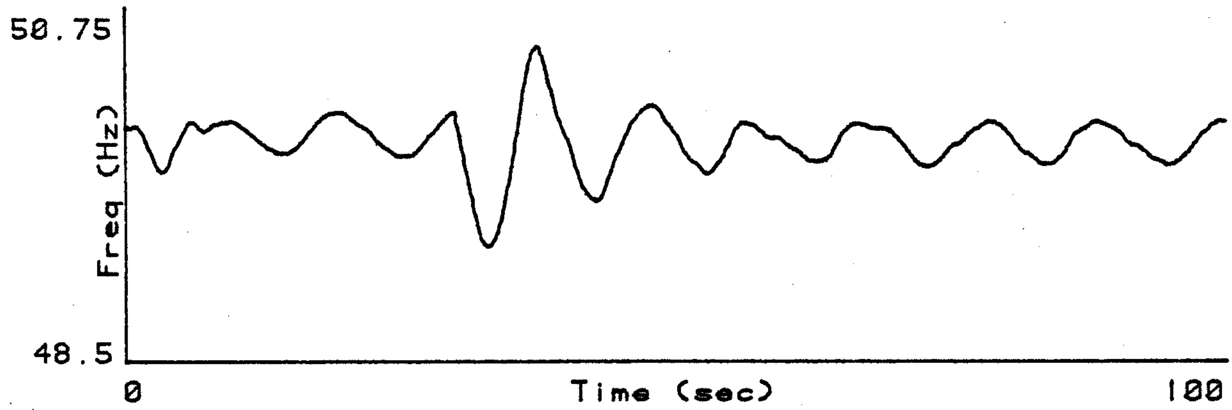


Figure 9.6(a) Re-optim low band constants (Freq)

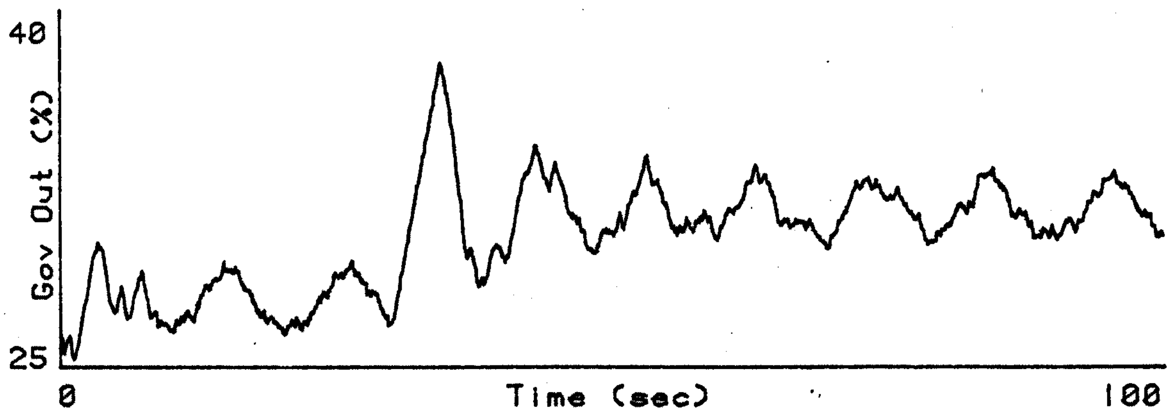


Figure 9.6(b) Re-optim low band constants (Gov Out)

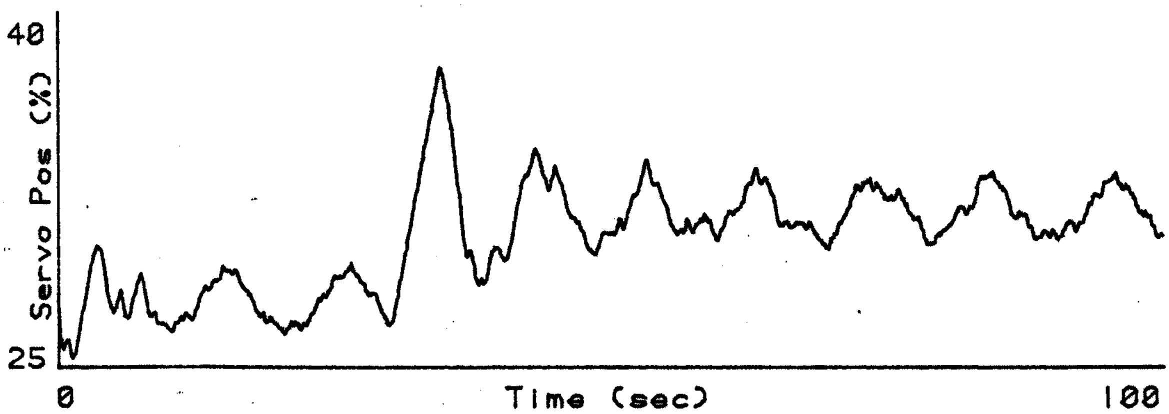


Figure 9.6(c) Re-optim low band constants (Servo Pos)

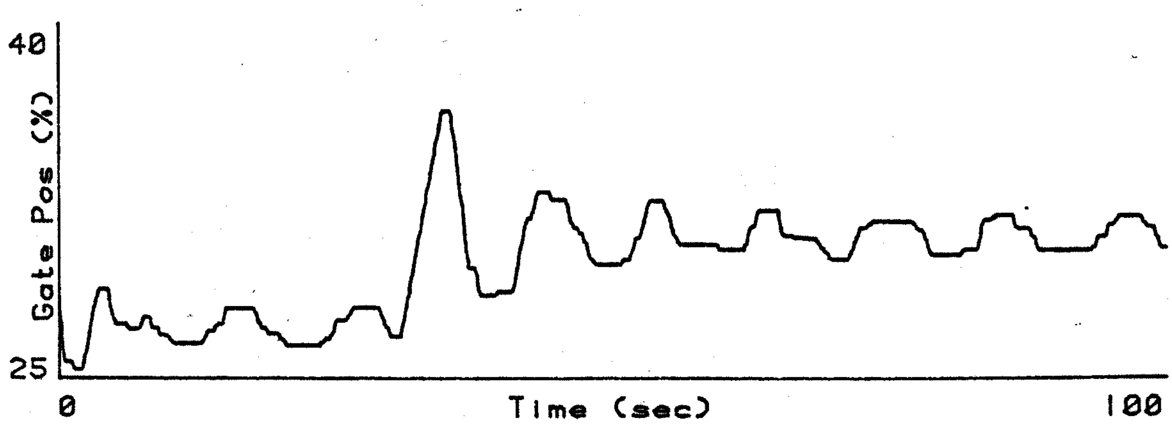


Figure 9.6(d) Re-optim low band constants (Gate Pos)

between the microprocessor and the PDP 11/45.

Figs. 9.7a and b and Figs. 9.8a and b illustrate the mid band governor step responses (45% - 50% full load with a gain factor of 1.36) before and after re-optimisation respectively.

The old high band responses to a step from 90% to 95% full load, with a gain factor of 1, are reproduced in Figs. 9.9a and b while the improved high band governor constants respond as shown in Figs. 9.10a and b.

From the simulation results just mentioned it is quite apparent that an improvement had been made by the re-optimisation of the governor constants in each of the bands. However while carrying out these simulations with the corrected model further possible problems were discovered.

Having optimised the governor constants in the low band, step tests were carried out to ensure retention of stability. It turned out that stability was conditional on the size of the disturbance due to the non-linearity introduced by the rate limit. For example Figs. 9.11 to 9.14 are the results of digital simulations at the top of the low band (entirely within the PDP 11/45 using the 'sampled' governor representation). The disturbance in Fig. 9.11 was 33% - 40% full load, in Fig. 9.12 it was 34% - 40% full load, and in Fig. 9.13 it was 35% - 40% full load. Thus for steps greater than 6% at the top of the low band, instability is sure to result. The response displayed in Fig. 9.14 however was for a step disturbance of 30% - 40% full load. There was one difference in this simulation, however, and this was a reduction of the governor output rate limit from 40s to 22s rate limit which is the minimum specified rate allowed for the hydraulic system at Sloy. Thus, removal of the 40s hydraulic rate limit and the inclusion of a 22s rate limit as implemented in the Control Rack electronics would be permissible with

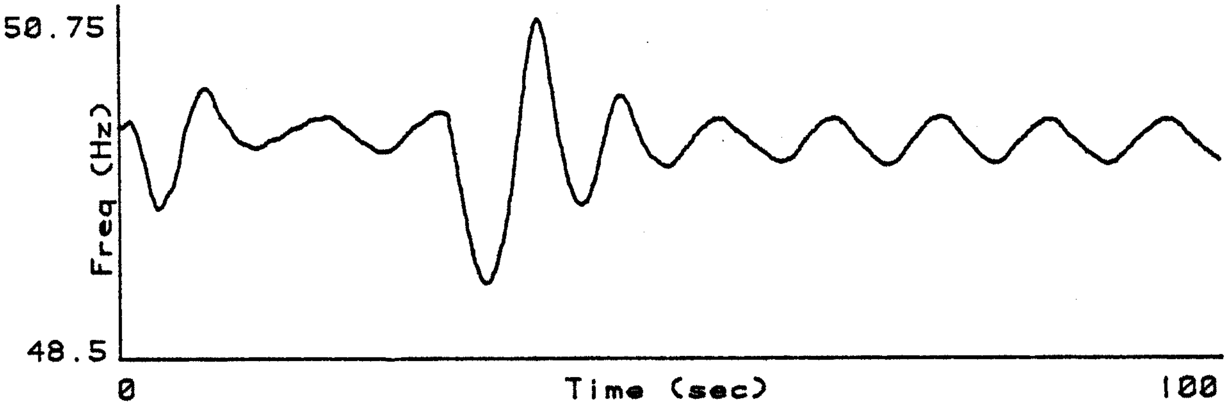


Figure 9.7(a) Initial mid band constants (Freq)

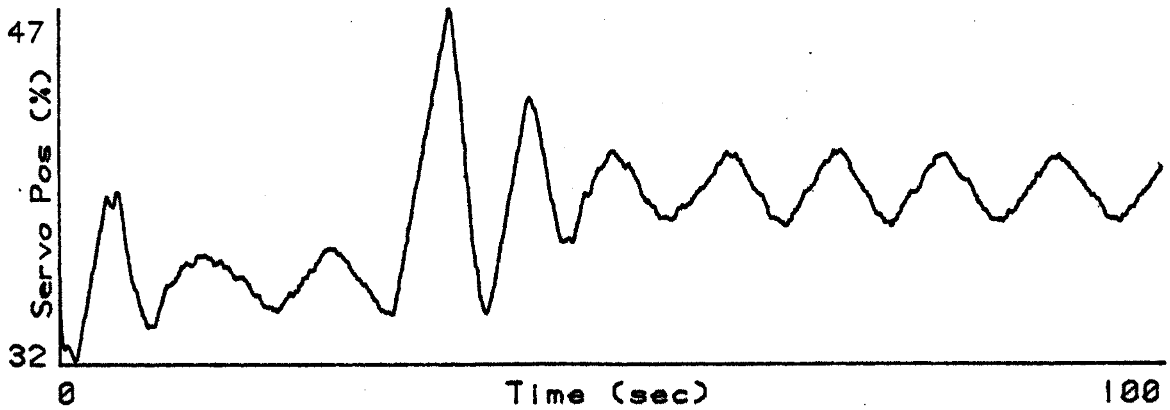


Figure 9.7(b) Initial mid band constants (Servo Pos)

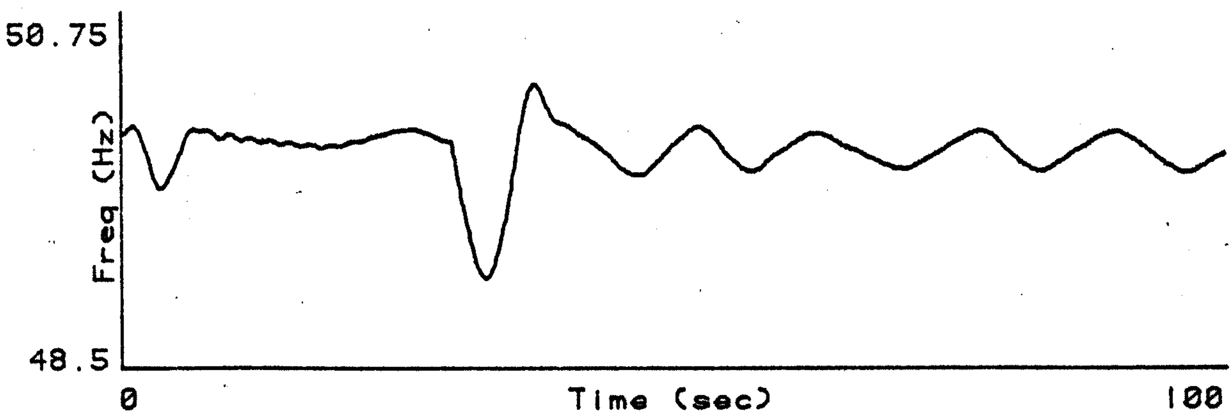


Figure 9.8(a) Re-optim mid band constants (Freq)

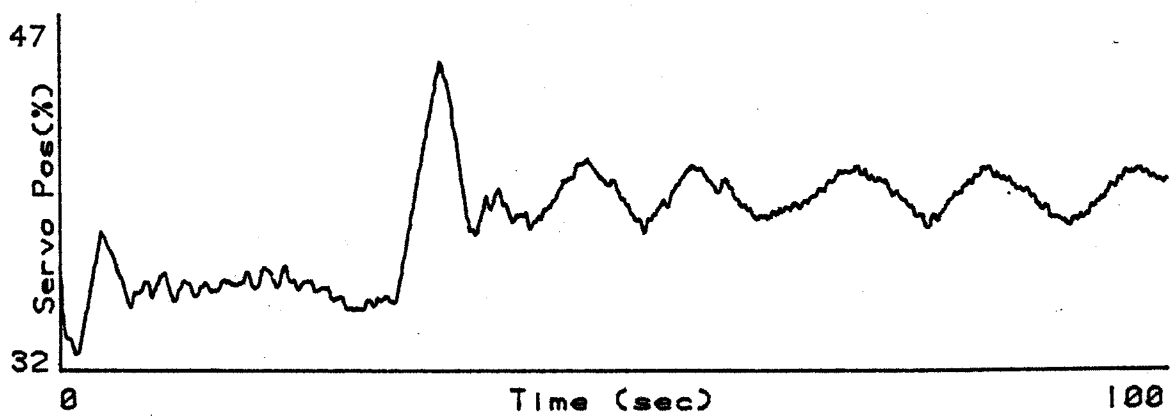


Figure 9.8(b) Re-optim mid band constants (Servo Pos)

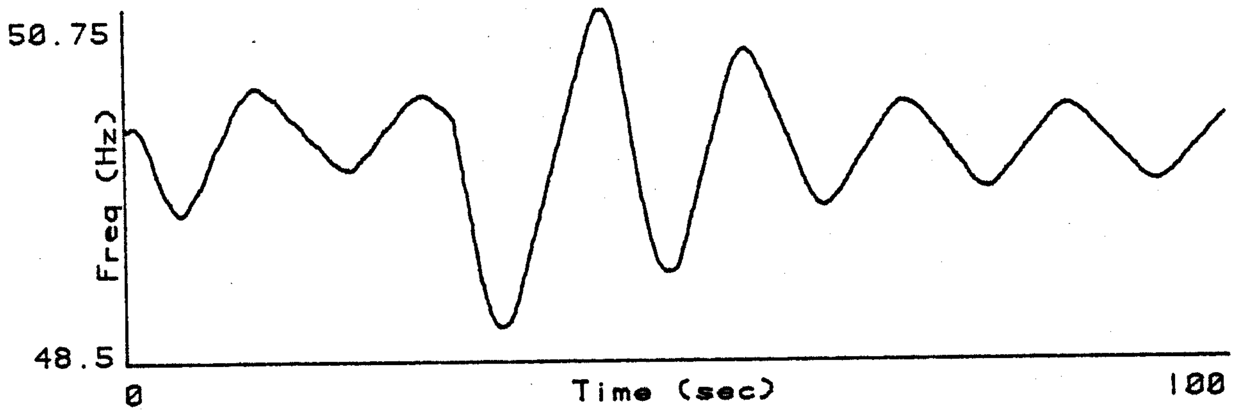


Figure 9.9(a) Initial high band constants (Freq)

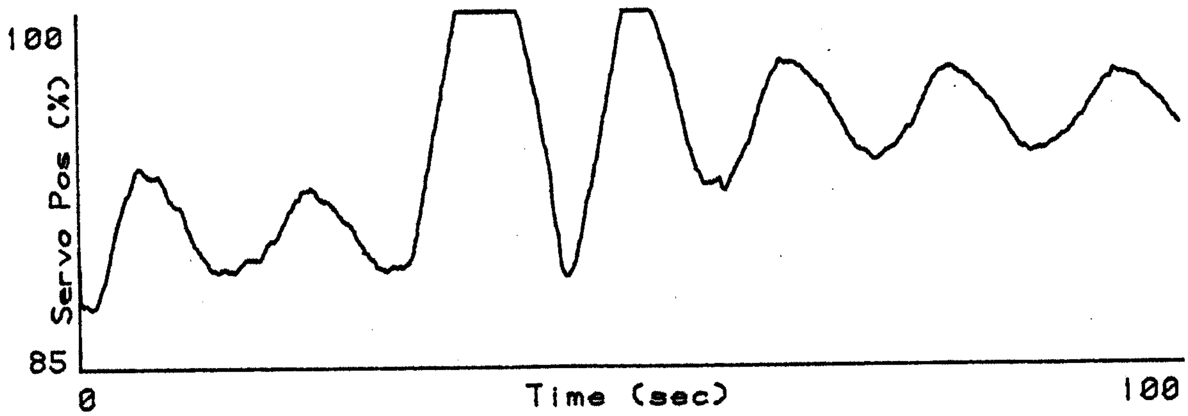


Figure 9.9(b) Initial high band constants (Servo Pos)

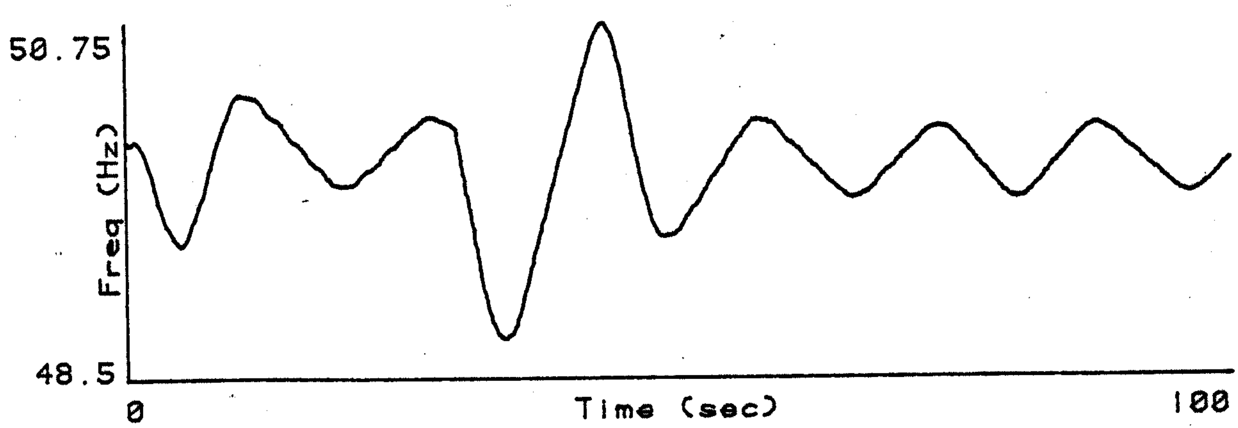


Figure 9.10(a) Re-optim high band constants (Freq)

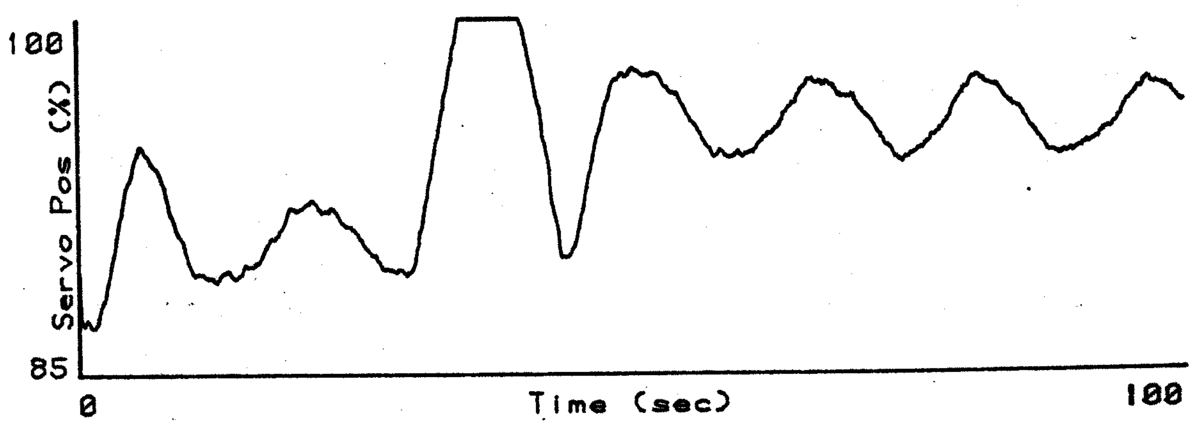


Figure 9.10(b) Re-optim high band constants (Srv Pos)

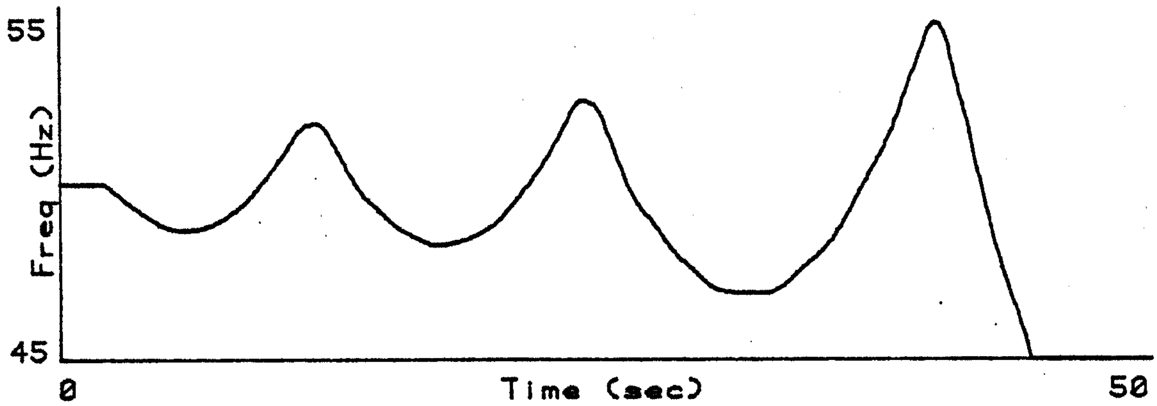


Figure 9.11 7% low band step - Rate limit=40s

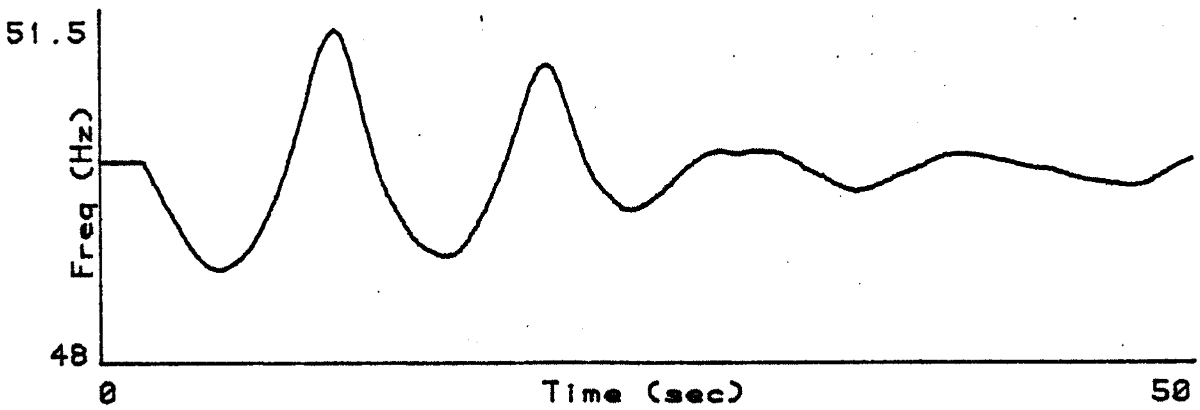


Figure 9.12 6% low band step - Rate limit=40s

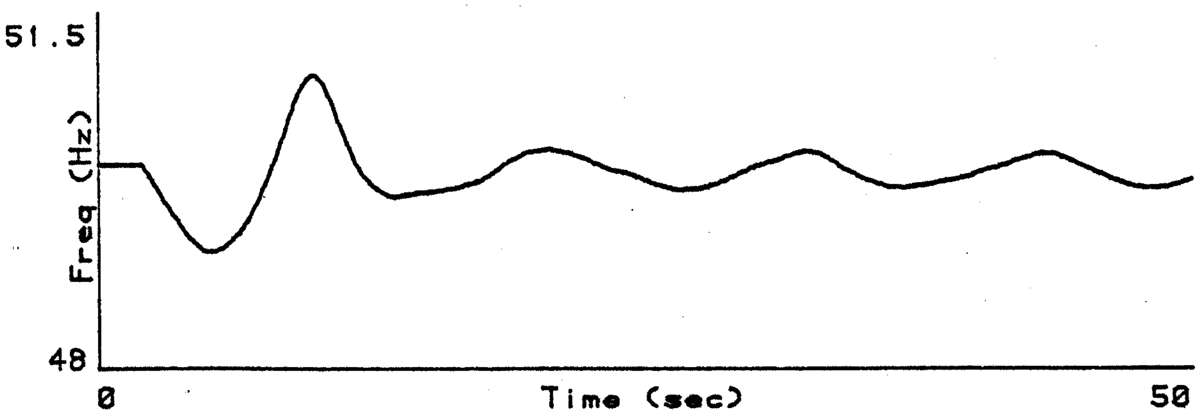


Figure 9.13 5% low band step - Rate limit=40s

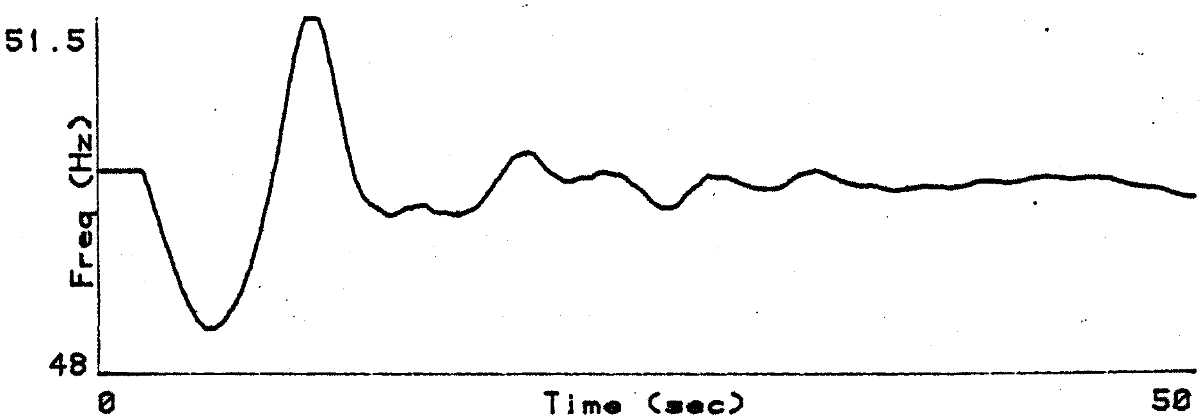


Figure 9.14 10% low band step - Rate limit=22s

the benefit of added stability to large disturbances.

A similar problem was encountered in simulation studies carried out at the top of the mid band. Again, instability was the result for increasing step disturbances (but not for decreasing disturbances). However the previous actual site results in the mid band did not display this instability. The reason is most likely a dropping off of the gain in Fig. 8.7 (MW versus SP) towards the top of the mid band, whereas the simulation studies had been carried out with a fixed gain of 1.36. Additional simulations using lower gain factors confirmed stable operation.

9.5 Final Site Tests using the Re-optimised Adaptive Governor

It had been noticed in the results of 7th September, 1978 that the main servo had hit its end stop during the large disturbance, grid connected tests. Thus it was arranged for the similar tests of 10th October, 1978 to contain a slightly smaller disturbance in the frequency error signal in order to avoid the servo saturating. The mean reservoir head during these last trials was 922.6 feet (281.2m).

The purpose of these tests was twofold. Firstly the isolated load stability of the updated Adaptive Governor was to be confirmed and secondly the grid connected response to frequency changes was to be observed.

(a) Adaptive Governor Stability under ILS conditions.

During all the following ILS experiments $k_n = 0$ and $T_a = 7s$. A mean power output level of 13.2 MW was set up (i.e the top of the low band). Initially, using the DDLOW2 governor (i.e. the new low band settings) the ILS was switched into operation.

Stable limit cycling was observed and to verify the previously obtained results a switch to the DDLOW1 governor (i.e. the old low band settings) was made, resulting in diverging oscillations building up very rapidly. This sequence of events is presented in Figs. 9.15a and b.

The DDLOW2 governor was reinstated and a 1.5 MW decrease from 13 MW was followed by a 1.5 MW increase. The resulting step responses are shown in Fig. 9.16a and b. Both these disturbances were adequately controlled by the DDLOW2 governor, although the step down was much smoother than the upward step due to the large rate limit during the increasing movement of the servo.

The next experiment involved the ADP2 governor whose performance was monitored for an approximate step of 1.5 MW across the low-mid band boundary (i.e. from 12.3 MW to 14 MW then back down again). The success of this test is shown in Figs 9.17a to c. The points at which the Adaptive governor actually changed from its lower band constants to its middle band constants are also marked.

Following the low to mid band transition the new mid band constants, DDMID2, were put to the test at both the low and top end of the mid band range. Starting at 14.8 MW, a 1.5 MW step upwards to 16.3 MW was implemented followed by a similar step down. The results of this procedure are shown in Figs. 9.18a and b. To complete the mid band experiments the mean power level was shifted to 23 MW. A 1.5 MW step down was complemented by a 1.5 MW return step, after which a repeat performance was observed but this time 1.8 MW steps were used. Figs. 9.19a and b display the associated results. Although the responses prove the test successful it can be seen that the last step upwards is becoming less stable, which links up well with the predicted simulation results, where it was found that the main

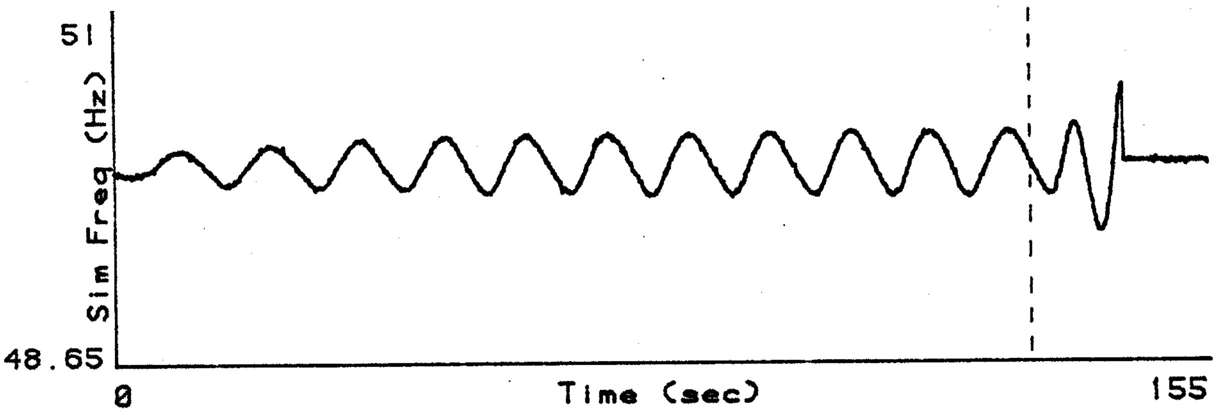


Figure 9.15(a) ILS, old/new low band test (Sim Freq)

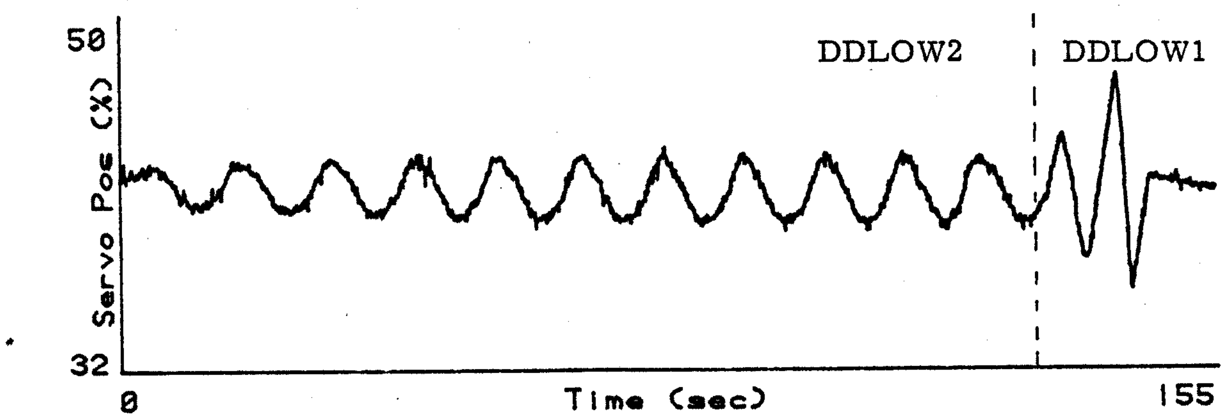


Figure 9.15(b) ILS, old/new low band test (Servo Pos)

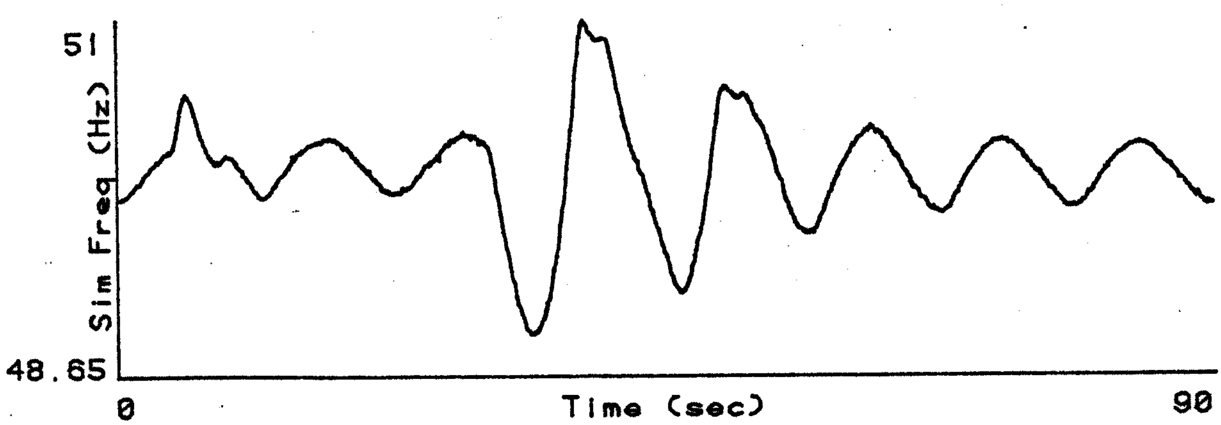


Figure 9.16(a) ILS, new low band steps (Sim Freq)

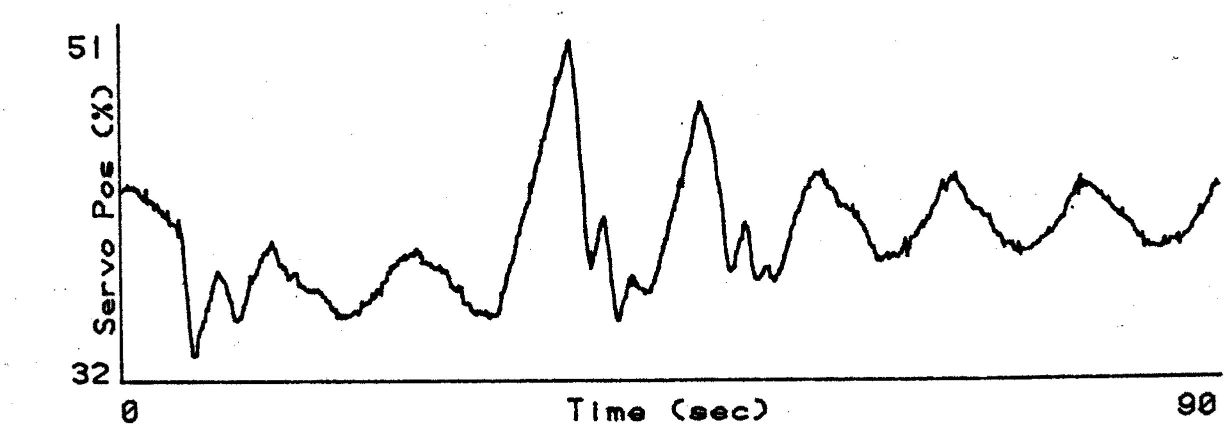


Figure 9.16(b) ILS, new low band steps (Servo Pos)

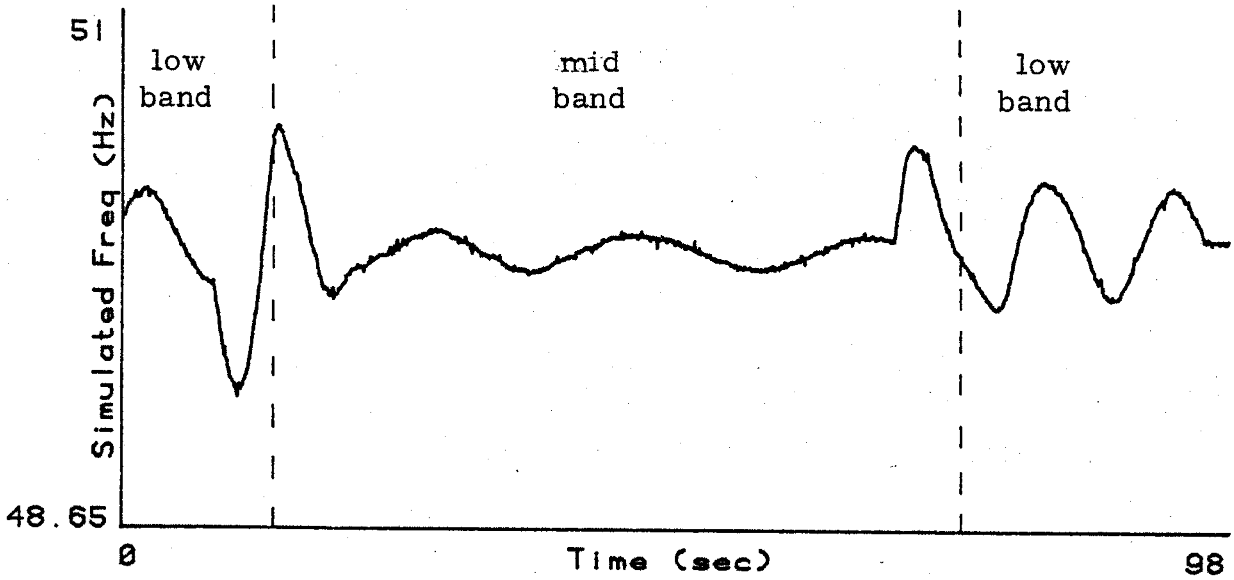


Figure 9.17(a) ADP2, low-mid band steps (Sim Freq)

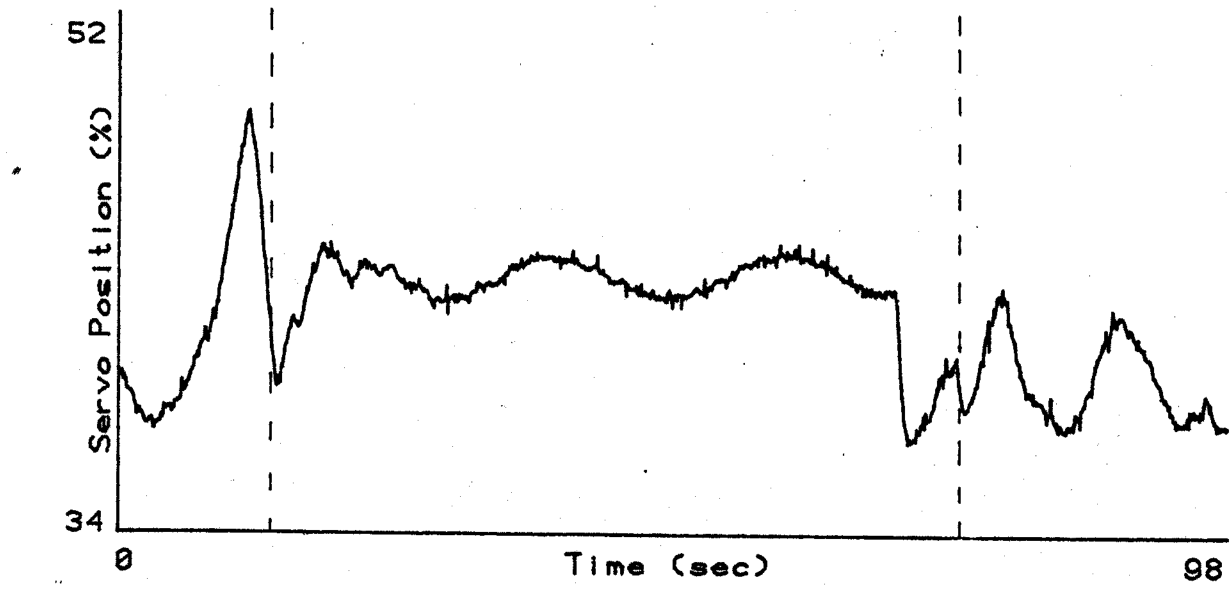


Figure 9.17(b) ADP2, low-mid band steps (Servo Pos)

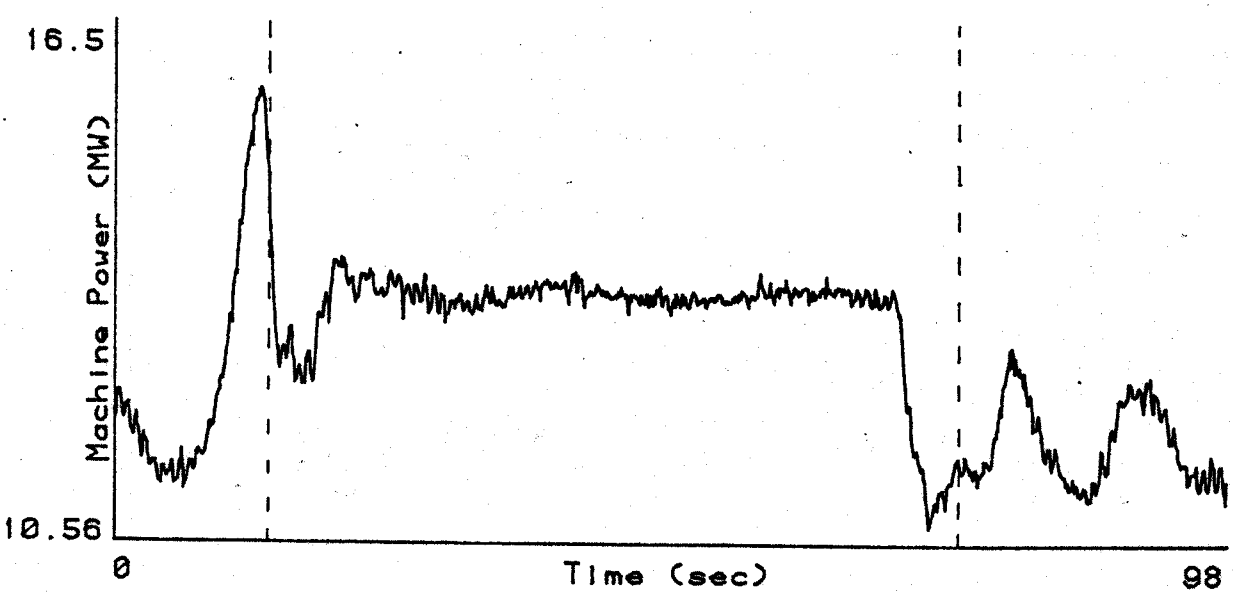


Figure 9.17(c) ADP2, low-mid band steps (Power)

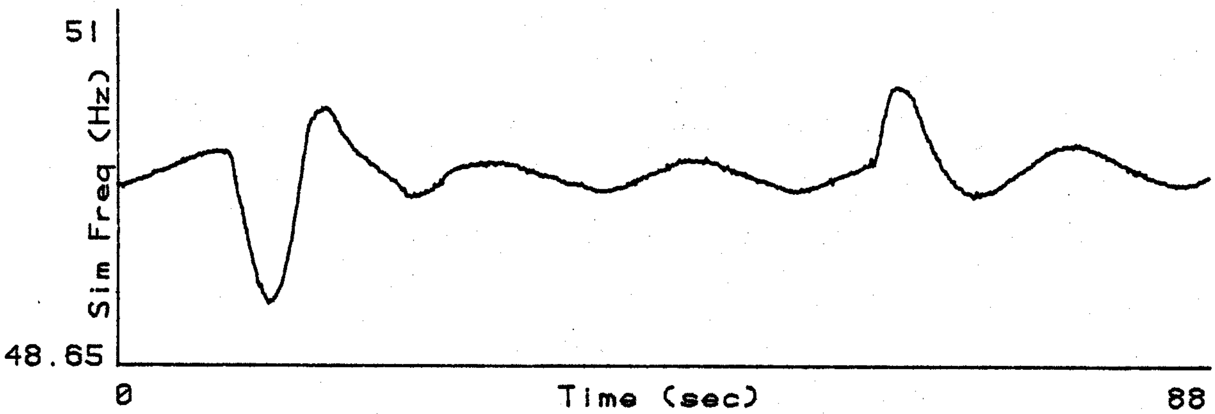


Figure 9.18(a) DDMID2 steps, bot-mid band (Sim Freq)

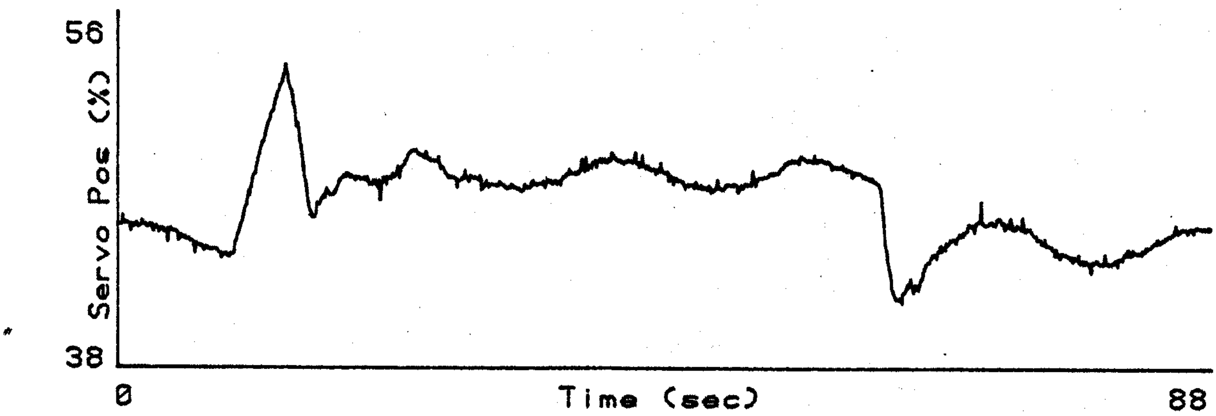


Figure 9.18(b) DDMID2 steps, bot-mid band (Servo Pos)

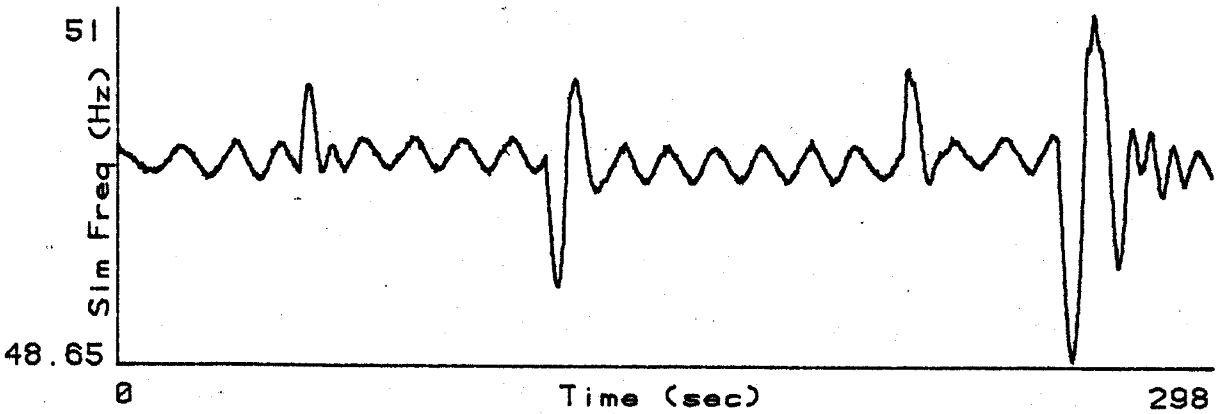


Figure 9.19(a) DDMID2 steps, top-mid band (Sim Freq)

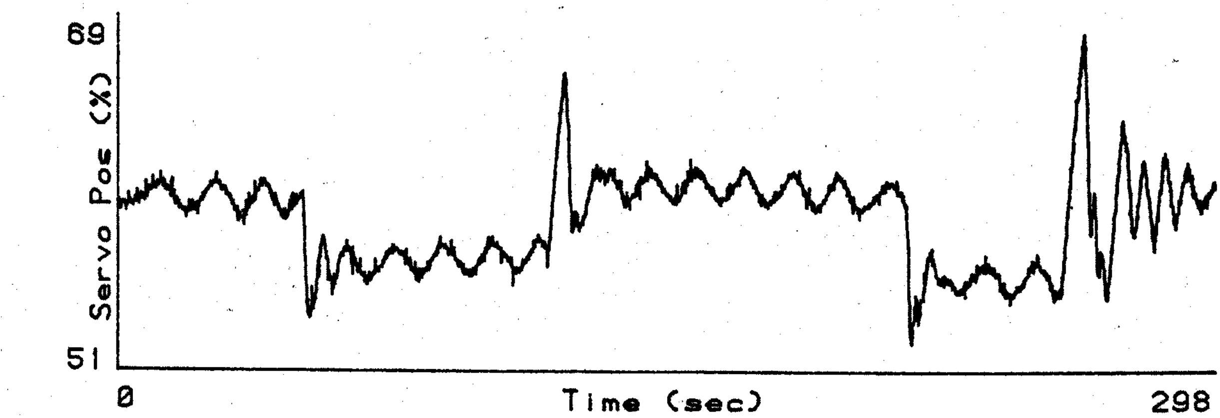


Figure 9.19(b) DDMID2 steps, top-mid band (Servo Pos)

servo rate limit was the predominant factor in this instability for the given governor constants. Figs 9.20a and b provide the results of the behaviour of the system to disturbances which took the operating point across the upper band boundary. The ADP2 governor was in operation for these transitions from 22.4 MW to 24.1 MW and back again. Also marked are the points at which the Adaptive governor changes its constants.

The final closed loop test using the ILS was the recording of step responses in the upper band of operation using the DDHI2 governor constants. (Figs. 9.21a and b) Starting from 29.7 MW a 1.5 MW step down was controlled very well, while a 1.5 MW increase was once again hindered by the slow upward servo rate limit. However, stability was still achieved. With this test over all the experiments under simulated isolated load were complete. Every one of the tests had been quite successful thus corroborating the predictions of the improved simulation model.

(b) Adaptive Governor Grid Connected Response.

As previously mentioned the main servo had saturated at its top limit during the large disturbances of 7th September, 1978. To avoid this happening again the equivalent experiments carried out on 10th October, 1978 were arranged such that the frequency error step would result in the main servo travelling from 10% Full Scale to 80% Full Scale. This ensured that both band boundaries were still crossed. Figs. 9.22a and b show the Power and servo position responses for the TD, DD, ADP2 and DDLOW2 governors which provide results similar to those obtained during the trials of 7th September, 1978, except that this time the simulated isolated load stability had also been achieved.

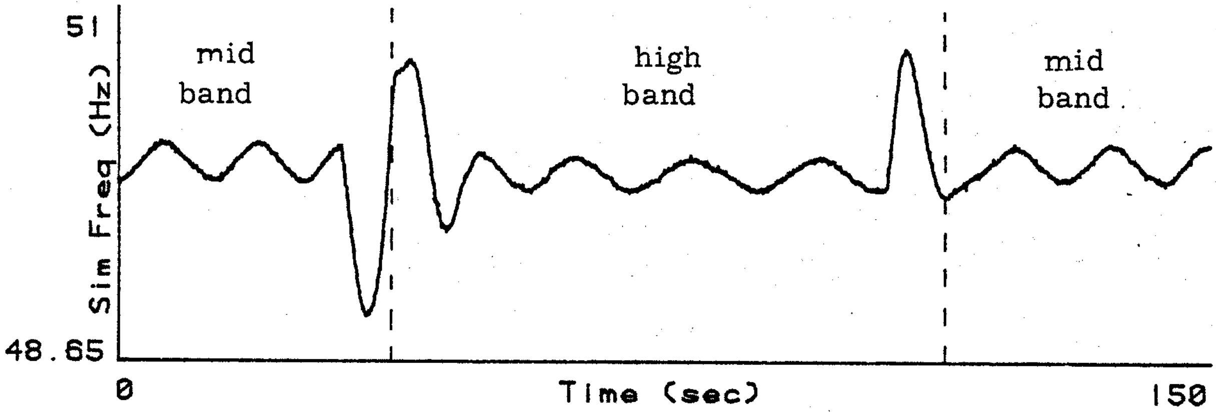


Figure 9.20(a) ADP2, mid-high band steps (Sim Freq)

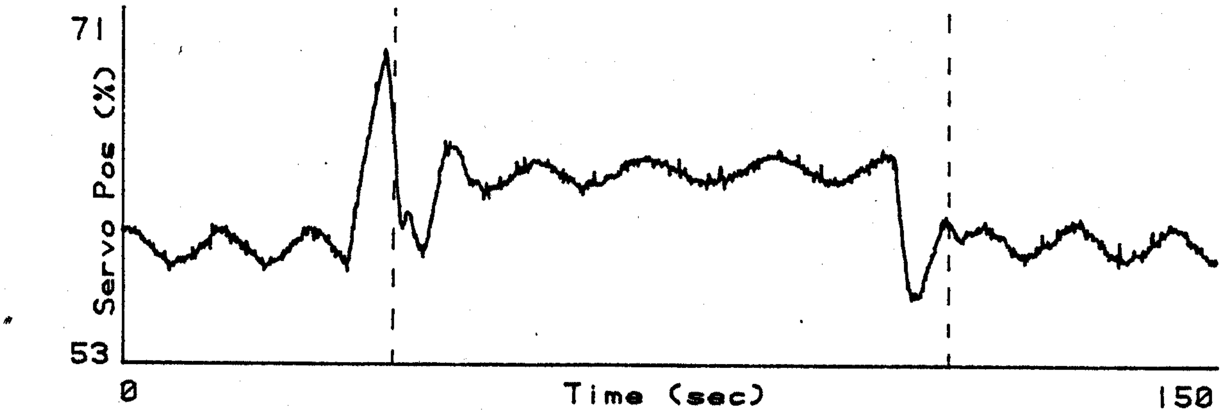


Figure 9.20(b) ADP2, mid-high band steps (Servo Pos)

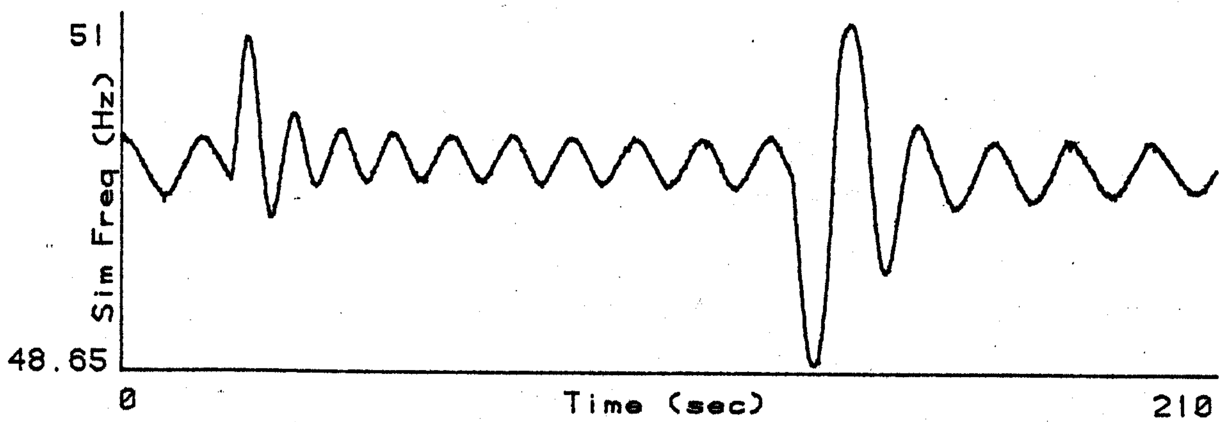


Figure 9.21(a) DDHI2, new high band steps (Sim Freq)

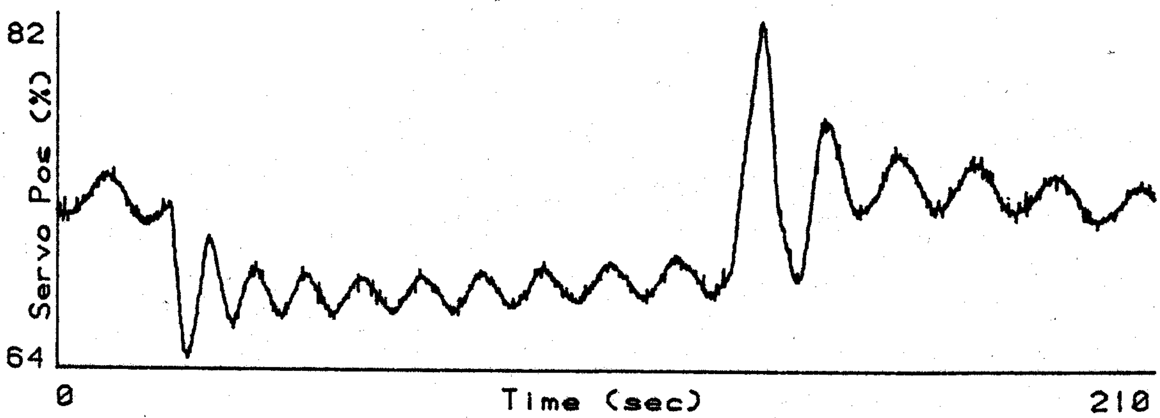


Figure 9.21(b) DDHI2, new high band steps (Servo Pos)

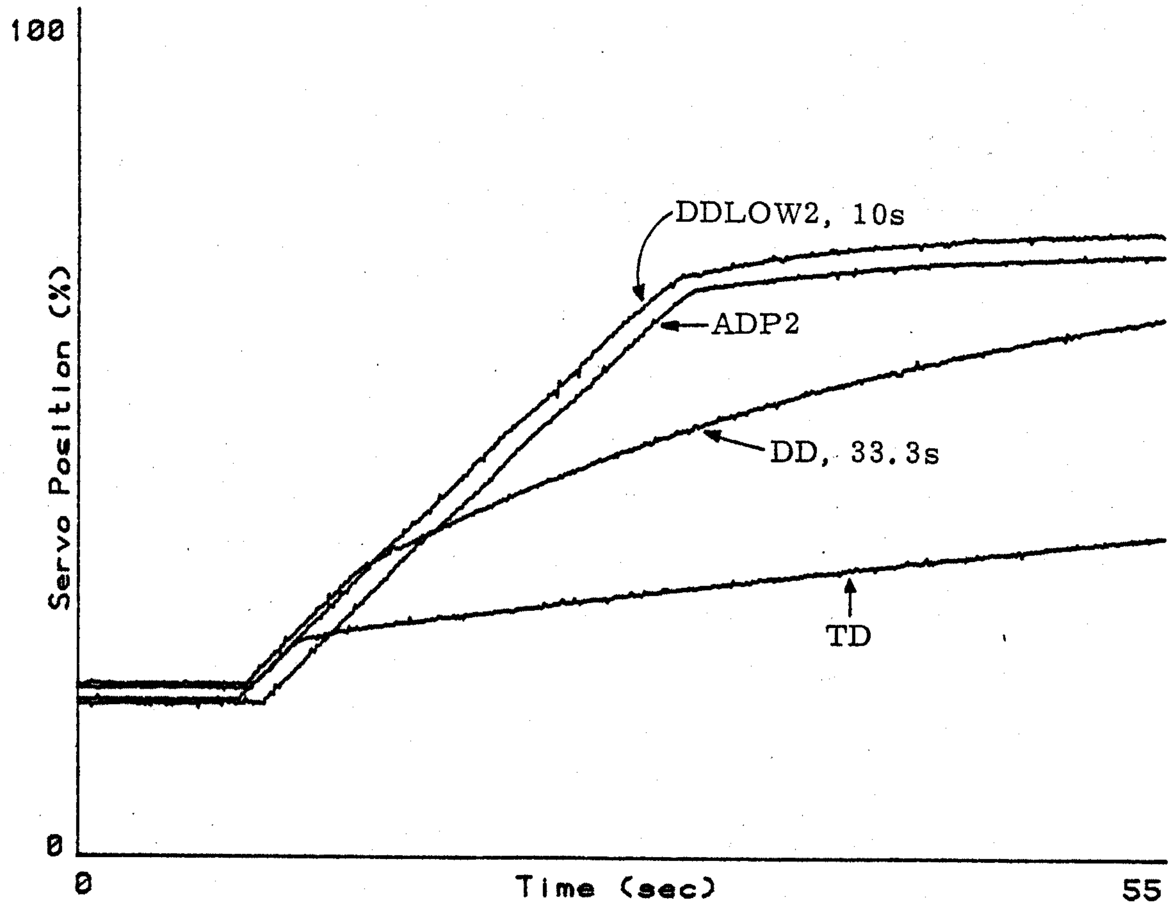


Figure 9.22(a) Grid connected gov responses (Servo)

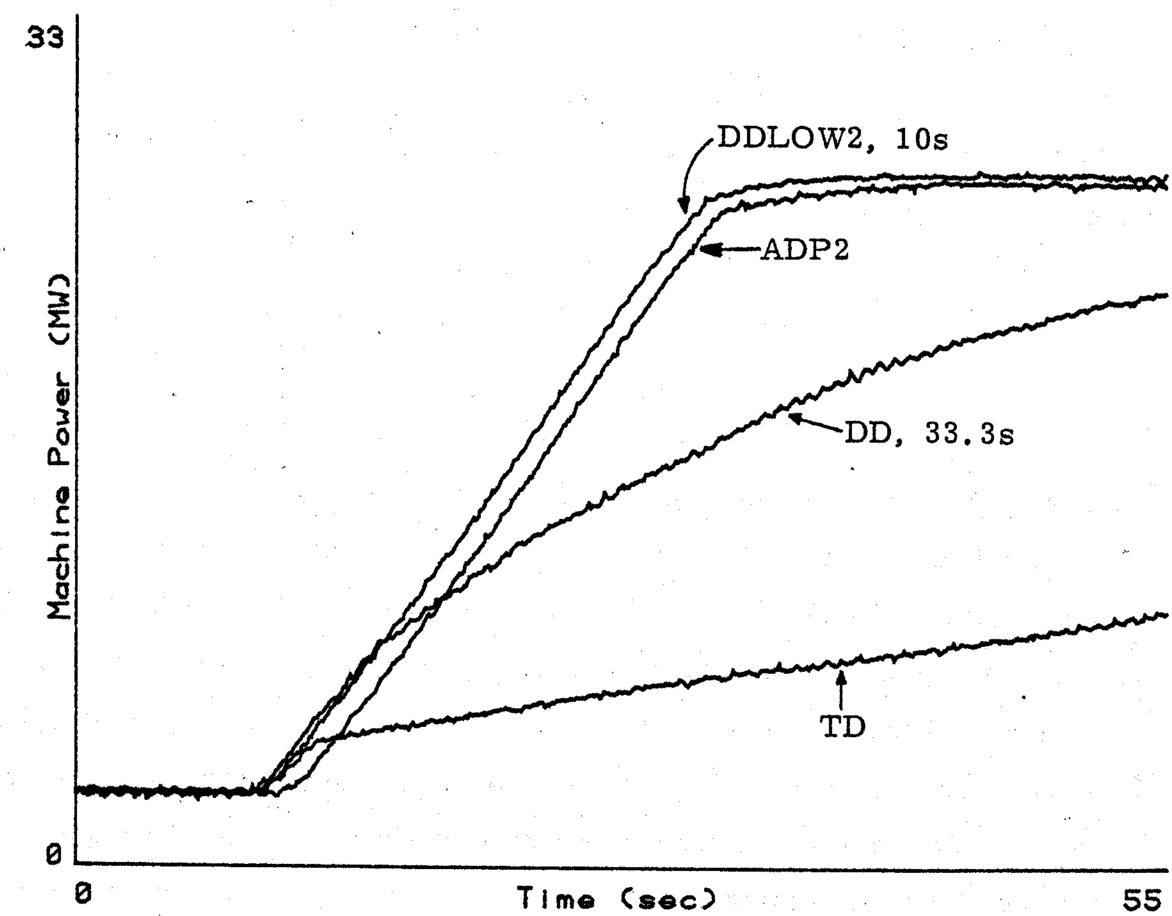


Figure 9.22(b) Grid connected gov responses (Power)

CHAPTER 10 - CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

The work of this project has shown, quite convincingly, that a microprocessor governor is a highly feasible proposition. Moreover, a considerable improvement in the speed of response of the governor, with retention of system stability, has been achieved with an easily implemented adaptive governor algorithm. Such a governor could, perhaps, prove to be very useful in large pumped-storage schemes. At present large hydro plants of this type aid the control of system frequency by being able to donate their generating capacity very rapidly. However the governors that achieve this fast response rate would not provide suitable stability if the pumped-storage plant had to supply an isolated load. With this new adaptive governor it might be possible to meet both constraints of speed of response and isolated load stability. It must be noted, though, that the margin of stability of this new governor type is not as high as its very conservative predecessors. Thus the governor must be tuned for the most pessimistic operation conditions to ensure stability under all likely conditions.

The digital simulation of the Sloy system has proved to be an adequate representation of the real plant. Two important features of the real system, however, were omitted. These were the surge shaft and the relief valve. Ignoring these elements of the hydraulics did not significantly detract from the validity of the model. The three minute oscillations resulting from the operation of the surge shaft obviously did not appear in any of the simulation results where, of course, they were quite apparent from actual site results. The natural frequencies of the system which were likely to cause problems as a result of control actions were of much higher frequencies than those associated with the surge shaft, and, as a result, there were no difficulties discovered in not modelling the surge shaft. Ignoring the relief valve merely aided the production of governors with greater stability than was obvious through simulation studies alone. The reasoning for this lies with the fact that the relief valve has a stabilising influence when the governor closes the guide vanes rapidly. During such a manoeuvre, which happens at load rejections or during governor action with a fast acting governor, the relief valve opens in order to divert some of the water flow away from the closing guide vanes. This action relieves any large pressure build up in the pipeline resulting in an overall stabilising influence in the control.

The use of the Isolated Load Simulator was, indeed, of great benefit during the testing of new governors. By simply simulating the machine inertia, isolated load conditions could be observed without going to the expense of very time consuming system splitting tests.

10.2 Recommendations

Microprocessors are appearing in many varied applications from the low cost, mass produced consumer products, such as washing machine controllers, through to the low volume, specialised items such as distributed digital control systems. On projects of any significant size it is essential that the appropriate development aids are available, otherwise there will be a disproportionate amount of time spent in tracing problems. The level of programming has to be carefully considered as well. It is often quoted that a programmer will write between five and ten lines of correct code in a day, no matter what level of programming is involved. Thus a high level language should be used if possible since each line of a high level language program will relate to several lines of assembly level programming.

The present governor, which is written in assembly language, uses approximately 70% of the available time for the necessary computations. As the floating point package is not particularly efficient then it is quite conceivable that the governor could be written in a high level language and still meet the time constraints. If a more efficient software package did not prove satisfactory then the use of a hardware floating point board would certainly resolve the problem. Such a floating point board would be between one and two orders of magnitude faster than a software floating point package.

The existing adaptive governor might be improved if there were more than three bands of operation. Alternatively a continuous function could be developed which would relate the governor parameters to load level. It might also be advantageous to take into account other station variables such as turbine flow and head. For example, as the reservoir head falls the turbine head follows, bringing the turbine operation to a reduced point of stability due to the necessary increase in flow for a given output power. Normally the governor parameters would have to be tuned for the lowest condition of stability, namely, the lowest head condition. This leaves the governor optimised for low heads but not high heads, thus correcting action could be achieved by monitoring turbine head. This would have the added advantage of including compensation for surge shaft oscillations.

The governor studies to date have concentrated on only one out of four of the turbines being operational. As more of the turbines are brought on line the stability margin for governing is reduced because the effective water starting time increases. It is clear that a marginally stable governor tuned for only one set operational would meet difficulties as other sets were brought into use. The alternative solutions are either to reduce the responsiveness of the existing governor or to investigate the possibility of some kind of hierarchical control which would have to influence each of the governors' parameters depending on how many sets were operating and on their load levels.

If any of these aforementioned areas of work were investigated it would be necessary to radically change the digital simulation to take into account other sets being operational, and probably to include a model of the surge shaft. The increased complexity of such a simulation would undoubtedly increase computation time such that real time simulations with the existing computer would be impossible. This would not pose any great problems, however, if actual microprocessor governors were required to be verified against the digital simulation since the microprocessor governor could be suitably time scaled for such tests. As a first step to improving the simulation, though, the non linearities of servo position through to flow, and machine efficiency could be included as continuous functions.

Most of the recommendations mentioned above are directed to the improvement of the governors and simulations orientated around Sloy Power Station. It is unlikely though that the existing governors at Sloy and similar older power stations would be replaced with new up to date governors. Where these new governors might be most applicable is in the future pumped-storage schemes. Therefore further governor studies should be concerned with the specific needs of pumped-storage installations.

The technique of optimising the governor parameters for any given load would benefit through the adoption of some automatic optimisation technique. This would be a very useful exercise if the application of adaptive governors of the type presented here was pursued.

As previously mentioned the Isolated Load Simulator was a great asset to the test facilities. The Simulator was unfortunately never verified against actual system splitting tests, so it would be beneficial if such a comparison could be arranged during a future series of tests.

APPENDIX A

"Microprocessor-based Adaptive Water Turbine Governor"

and

"Controller Testing Facility on a 32.5 MW Water Turbine"

APPENDIX A

This appendix contains a paper entitled,

"Microprocessor-based Adaptive Water Turbine Governor"
by
D. FINDLAY, H. DAVIE, T. R. FOORD, A. G. MARSHALL,
D. J. WINNING.

This paper was submitted to the IEE in December, 1979 to be considered for publication in the Proceedings. It has been accepted by the IEE, however publication has been postponed while the IEE consider whether or not to publish a second paper as a companion paper. This second paper is also included in this appendix and is entitled,

"Controller Testing Facility on a 32.5 MW Water Turbine"
by
D. J. WINNING, A. G. MARSHALL, D. G. E. FINDLAY,
K. H. AITKEN, N. F. GRANT.

MICROPROCESSOR-BASED ADAPTIVE WATER TURBINE GOVERNOR

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T.R. Foord, B.Sc., Ph.D., C.Eng., F.I.E.E.,

A.G. Marshall, B.Sc.,

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MICROPROCESSOR-BASED ADAPTIVE WATER TURBINE GOVERNOR

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Replace paragraph 2, page 17 with:

Associated with this equipment is a prototype controller and analogue double derivative governor based on the design developed in earlier work. The controller is responsible for generating the appropriate input signals shown in figure 2 for both governors. These input signals

f - frequency error

y_s - servo set point

y_L - load limiter set point

are continuously supplied to the analogue and microprocessor governors which both continuously generate the desired servo position signal y. A switch and balance indicator on the controller permit the selection of the output of one of the governors as the set point for the closed-loop servomotor controller. This moves the servomotor to the position demanded by the selected governor using a position feedback signal derived from the servomotor.

Abstract

Conventional governors of water-turbine-generator sets can be set up to provide either stability when supplying an isolated load or rapid response when connected to a large, predominantly thermal, system. In this paper, an adaptive microprocessor-based governor is described which goes some way to satisfying both requirements. Results are given for tests on a 32.5 MW turbine-generator.

1. INTRODUCTION

The U.K. electrical grid system utilises largely thermal generation, together with about 4% of conventional and pumped storage hydro generation. To ensure that sudden demands for electrical power can be met or that unexpected plant loss can be rapidly replaced, it is necessary to have a certain amount of plant connected to the system but only partially loaded. The load margin of this plant provides a spinning spare reserve which must be capable of very rapid and sustained increase in output in response to the drop in system frequency following the demand disturbance.

Conventional hydro and pumped-storage plant have the potential to be used effectively in this way but suffer one disadvantage. The governor is often set up so that stability is preserved on the infrequent occasions that the generator is called upon to supply load in an isolated part of the system which contains little or no thermal plant. However, when the hydro plant is connected to a large, stable thermal system, the governor controls the output power of the hydro plant in response to frequency changes in the thermal system and has little influence on total system stability. In this role, the hydro governor with settings which give stable isolated operation, has a somewhat sluggish response to frequency disturbances and hence does not fulfil its full potential for spinning spare.

If on the other hand, the governor is set up to provide very rapid response to system frequency changes when grid-connected, the stability of the generating unit on isolated load is lost. The choice of stability or speed of response is one which is made on the basis of system consideration and Ashmole et al (1) suggest that for a pumped-storage scheme a compromise should be used which provides system stability when it is run in conjunction with a relatively small thermal system (10 times the capacity of the pumped-storage plant). In the North of Scotland, however, adverse weather conditions/

conditions can cause system 'islanding' in an otherwise secure system and so the governors must be set up to permit the sets to supply isolated loads.

With a view to improving the grid-connected response whilst maintaining isolated-operation stability, a programme of work has been carried out at The University of Glasgow in collaboration with the North of Scotland Hydro-Electric Board. This resulted in a stable governor (2) in which the dominant time constant in the power response to frequency disturbance was reduced substantially. However, even with this substantial improvement, the potentially high rate of response of the turbine was still not realised and work has continued to improve this further and to study the interaction between these improved governors and a thermal system with a view to the design of governors for large pumped storage installations in the future.

The earlier work has shown that conventional linear governors would be inadequate to meet the requirement for a governor which was flexible enough to provide stability together with a high speed of response. In consequence it was decided to experiment with governors whose structure and/or parameters varied with changing plant conditions. The investigation of these adaptive governors would clearly involve complex, changeable hardware and so the decision was made to use a microprocessor-based system. This offered the potential, which has subsequently materialised, of making rapid structural or parameter changes by changes in program. At the inception of the project, it also appeared possible that a microprocessor system might provide a cost-effective operational governor; trends in microprocessor costs and complexity and the rapid development of high-level programming languages have wholly confirmed this prediction.

2. GOVERNOR DESIGN

In an electrical power network, momentary imbalance between demanded electrical power and prime mover power will result in acceleration of the generators and hence a change in system frequency. This change in turn/

turn is detected by the speed governors fitted to all generating sets and these cause appropriate changes in prime mover powers in an attempt to restore power balance in the system. In a water turbine, the governor senses shaft speed or terminal frequency (which is equal to shaft speed if the generator remains in synchronism with the system to which it is connected and ignoring the relatively high frequency inter-rotor transients). The governor output acts upon the water control valve through a hydraulic servomotor.

There are many different possible forms for the governor. Old designs, many of which are still in operational use, are entirely mechanical in construction and use flyballs to sense change of frequency. Modern governors are fully electronic and allow greater flexibility for change. Whatever physical form the governor takes, its operation is most readily understood in terms of its overall transfer function. Thus the very widely used "temporary-droop" governor may be represented by the block diagram shown in figure 1 for which the transfer function is:

$$\frac{y}{f} = -\frac{1 + sT_d}{b_p\left[1 + \frac{1}{b_p}\left\{(b_p + b_t)T_d + T_{yt}\right\}s + \frac{T_{yt}T_d}{b_p}s^2\right]} \qquad (1)$$

where y is the servo position, f is the frequency error and b_p, b_t, T_d and T_{yt} are the permanent droop, temporary droop, damping time constant and servo time constant respectively (3). Governors of this type are characterised by a relatively slow response to a sudden change of frequency but give stable isolated operation.

The double derivative governor used in previous work (2, 4) is shown in figure 2 and includes, in addition to the normal governing functions, a servo set-point control and a load limiting circuit. The transfer function of the governing section alone, assuming the load limiting circuit is inactive (i.e. that $y_L > y$) is:

$\frac{y_1}{f}$

$$\frac{y_1}{f} = -\frac{1}{b_p\left(1 + s\frac{T_y}{b_p}\right)}\left[1 + K_1\frac{s}{1 + sT_1} + K_2\frac{s^2}{(1 + sT_1)(1 + sT_2)}\right] \qquad (2)$$

where b_p and T_y are the permanent droop and servo time constant respectively, K_1 and K_2 specify the amount of first and second derivative used and T_1 and T_2 are filtering time constants for the derivatives.

In both governors, the response to a step change in frequency is given by an initial, relatively fast, transient followed by an exponential rise in servo position, the time constant of which dominates the response. The time constants of these dominant lags are given by:

$$\text{Temporary droop } T_L \approx \frac{T_d(b_t + b_p)}{b_p} \qquad (3)$$

$$\text{Double derivative } T_L = \frac{T_y}{b_p} \qquad (4)$$

The dominant lags for the existing mechanical temporary droop governor at Sloy Power Station, and the double derivative governor described in the earlier publication,(2) were approximately 160s and 30s respectively; both governors gave stable isolated operation.

A feature which has proved useful in giving added versatility to the microprocessor based governor described in section 3, is that the double derivative transfer function reduces to that for the temporary droop governor when appropriate parameter values are chosen. For equivalence it is necessary for $K_2 = 0$. If, in addition, b_p is taken to be the same for both then T_1, T_y and K_1 for the double derivative governor are quadratically related to b_t, T_d and T_{yt} for the temporary droop governor.

In the double derivative governor shown in figure 2, there are

three/

three set points: the frequency set point f_s which is used to synchronise the generator, the servo set point y_s which, in a rate limited form is used in the run-up sequence and for rapid and precise loading, and the load limiter set point y_L which is also used during the run-up and to provide an artificial ceiling for the servo position for operational purposes.

The load limiting action is obtained by feeding the difference between the desired servo position y and the load limiter set point y_L through a one-sided circuit and a high gain, G, to the input of the servo set point. Should y exceed y_L, a large signal is fed back and this reduces y_1 and hence y with a very short time constant. When y_L is greater than y, the one-sided circuit ensures that no signal is fed back and hence that the load limiter is inactive.

The so-called servo time constant T_y in the double derivative governor is in fact implemented as part of the governor and so the output from the governor, y in figure 2, is the <u>desired</u> servo position.

Stabilisation of the governed turbine supplying near to full power to an isolated load, demands a large value of the dominant time constant T_L. However, at lower values of isolated load, stabilisation is possible with lower values of T_L due to the fact that the water column in the pipe is now moving at a lower velocity and it is the momentum of this water which dominates the dynamics of the system controlled by the governor. The variation of the optimum controller settings with load is utilised in the adaptive governor described below.

3. MICROPROCESSOR GOVERNOR

3.1 Development

Preliminary studies of the applicability of microprocessors to the governing of hydro-turbines commenced in 1975. Initially a microprocessor system based on the early Intel 8008 microprocessor was used. Assembly/

Assembly language programs for this processor were cross-assembled on a PDP11 computer (5) and the resultant machine code was transferred into and run from read/write memory (RAM) in the microprocessor system. Real time implementations of temporary droop-like governors were carried out in conjunction with a digital simulation of the remainder of the hydro-plant (see section 4).

These initial studies confirmed the marginal adequacy of the 8008 processor in implementing simple governors of the temporary droop type; however its processing speed was not sufficient to cope with the more complex transfer function of the double derivative type of governor and its faster time constants. Around this time a new generation of more powerful microprocessors became available from several different manufacturers, and after a comparative study it was decided to continue the governor work using the Intel 8080 microprocessor. The chief motivation behind this selection was that the 8080 contained as a sub-set of its instruction set, the full instruction set of the 8008. Hence all of the governor programs for the 8008 could, after re-assembly, be run on the 8080.

As previously, programs for the 8080 microprocessor were written in assembly language and cross-assembled on a PDP11 computer. The initial testing of these programs was carried out on an 8080 - based general purpose microcomputer. The machine code output from the cross-assembler was transferred from the PDP11 and stored on the microcomputer's floppy disk. Thereafter it could be loaded down into the microcomputer's read/write memory, tested, and quickly amended as necessary to obtain the desired function. In this manner double derivative governor strategies were examined and tested against real time digital plant simulations with the analogue interface equivalent to that used on-site.

For all on-site governing of the real hydro-turbine, an 8080-based Intel SBC 80/10 single board computer was used along with a second board containing/

containing all of the analogue I/O and the real time clock. Once the governor program had been fully tested on the microcomputer, minor adjustments were made to it to enable it to run on the SBC 80/10 with its different I/O arrangements, and the machine code was written into U-V erasable programmable read only memory chips (EPROM's), which were transferred to the SBC 80/10. This produced a non-volatile governor program which immediately ran on powering up the SBC 80/10 system. When site trials showed up possible areas for improvement on the governing strategies, these EPROM's could be erased and new programs could be written into them.

3.2 Algorithms and Software

In the microprocessor governor the differential equations of governors described in section 2 were solved using the first order numerical integration method, Backward Euler. The short computation time of this simple method permitted a rapid updating of the integrated variables, so producing a quasi-continuous output. Backward Euler has also the advantage that it is numerically stable for all integration intervals. The derivation of the difference equations for the double derivative governor is given in the Appendix.

At each fixed increment of time (the integration interval) the past and present values of input, intermediate and output variables were used in the equations of the Appendix to compute the new value of the output variable. This value was transferred to the digital/analogue converter at the end of the interval and the procedure was repeated at each subsequent interval.

All computations in the microprocessor involving these difference equations were carried out using real, floating point arithmetic in preference to integer arithmetic. This removed the need to scale variables and/

and minimised the probability of numerical overflow. The penalty to be paid for this approach is the relatively slow speed of floating point number computations. Typically, floating point operations on the 8080 require several milliseconds and a single evaluation of the three difference equations described in the Appendix required approximately 50 ms. An integration interval of 100 ms was used, thus permitting some other processing computations to take place and still leave a satisfactory margin.

In order that the difference equations should produce an accurate solution of their associated differential equations, the integration interval T should normally be much less than any of the time constants in the differential equations. The values of T_1 and T_2 (0.2s, 0.2s) used in the earlier analogue governor clearly did not conform to this requirement. However, since these are merely the time constants of noise reducing lags which are associated with the differentiators, their exact value is not critical. Simulation studies suggested that factors of two changes in these constants made little difference to the operation of the governor.

Synchronisation of the governor program with real time was carried out using a crystal controlled clock which interrupted the processor. As a check on the correct synchronisation of the program, a single bit of digital output was set at the beginning of each integration interval and reset at the end of each evaluation of the difference equations provided the time to carry out this evaluation did not exceed the integration interval. An external hardware watchdog timer was attached to this single bit and if a high-low-high cycle was not completed once per integration interval, then this fault condition could initiate a turbine and generator shut-down sequence.

All of the governor types tested were of the general form described in the Appendix. Load limiting and servo position setting facilities as described in section 2 were also incorporated. With a suitable/

suitable selection of parameters this could produce either temporary droop or double derivative governors and on-site trials were carried out with a range of pre-computed parameter settings selectable via switches as described in section 3.3. Table 1 lists the sets of parameters which could be employed to produce one of the following:

1. a temporary droop governor equivalent to the existing station mechanical governor;
2. a double derivative governor equivalent to the electronic analogue governor of the previous studies;
3. an adaptive double derivative governor whose operation is outlined below.

With the generator operating at low load, a short dominant lag (T_L) in the double derivative governor can provide isolated load stability and give the desired fast response when grid connected. However, as the load increases, successively larger dominant lags are required, as well as adjustments to the first and second derivative multipliers K_1 and K_2, to ensure isolated load stability. Thus the adaptive governor operated with 3 sets of parameters, the appropriate set being selected by the measured generator output power. The low-band parameters (see table 1) operated from 0 to 40% of full load, the mid-band parameters from 40% to 70% and the high-band parameters operated from 70% to full load (32.5 MW). The parameter settings in each band were predetermined from computer simulations to provide as short a dominant lag as was compatible with isolated load stability at the worst operating point in the band (usually the highest load setting).

To prevent instability in the adaptive process when the load is near to the band boundaries and to further enhance the speed of response of the adaptive/

adaptive governor, the measured power signal was fed through a first order lag - the adaptive time lag - implemented within the microprocessor, before activating the parameter changes. Thus, if a sharp drop in frequency was observed with the generator running at low load as spinning spare, the load would pick up rapidly with this adaptive lag holding back the transitions to the more sluggish mid and high-band settings. A value of 10 seconds for the adaptive time lag was selected after simulations to ensure isolated load stability yet provide an enhanced speed of response to grid frequency disturbances.

The complete microprocessor governor program including the three selectable governor types listed in table 1 along with the necessary floating point routines was contained in 3 k bytes of programmable read only memory and used a few hundred bytes of read/write memory.

	Type	K_1	K_2	T_1	T_2	T_y	b_p	$T_L = T_y/b_p$
1	Temporary Droop	14.99	0	1.01	0	4.75	0.03	158.3
2	Double Derivative	3.5	3.5	0.2	0.2	1.0	0.03	33.3
3	Adaptive: 0-40% band	0.8	2.0	0.2	0.2	0.3	0.03	10.0
	Adaptive: 40-70% band	2.0	3.0	0.2	0.2	0.6	0.03	20.0
	Adaptive: 70-100% band	3.0	2.8	0.2	0.2	1.0	0.03	33.3

Table 1 Governor Parameters for Double Derivative Structure

3.3 Hardware

The microprocessor system used for all site trials is shown in figure 3. The 80/10 Single Board Computer was connected via the system bus to a second board containing analogue input/output channels and a crystal controlled real time clock capable of interrupting the CPU. The microprocessor governor was connected in parallel with an analogue governor (see section 4.6) both being supplied at all times with all inputs. The output of the required governor was then selected by switch.

The analogue frequency error signal produced by a hardware frequency transducer was transferred to the microprocessor via one channel of the input A-D convertor while the desired servo position signal was transferred via one output D-A converter to the electro hydraulic servo controller which positioned the water control valve appropriately (see section 4.6). Servo set point and servo limit set point signals (see section 2) were present in both analogue and digital forms in the interface equipment and were read into the microprocessor system via 8 bit parallel digital input ports.

Additional inputs to the microprocessor but not to the analogue governor were:

(i) an analogue signal proportional to the electrical power being generated by the hydro turbine;

(ii) the state of user-adjustable switches;

(iii) the SYNC signal present when the generator circuit breaker was closed.

The power signal was used in the adaptive form of the microprocessor governor while the switches were used to select the particular governor type under investigation. A governor program for a typical site trial contained several governor types with a range of parameter settings. At each integration/

integration interval the switches were scanned and the appropriate governor type was selected. This was a further major advantage of the microprocessor governor over the analogue governors as rapid, bumpless transitions between governor types could be simply achieved. Transition between types could also be made on the basis of the SYNC signal so that one governor, typically the temporary droop, could be used for run-up control while another was used subsequently.

4 PLANT SIMULATIONS AND SITE-TEST FACILITIES

4.1 General

The hydro plant controlled by the governor system is highly non-linear in the following major ways:

(i) the water column dynamics change with water flow and hence with load;

(ii) the turbine efficiency is a non-linear function of load;

(iii) the water flow is a non-linear function of servo position;

(iv) backlash exists in the linkages between the hydraulic servo-motion and the water control valve (guide-vanes).

Thus, whilst classical control system design techniques can be used to give approximate settings, extensive on-site tests and/or accurate simulation studies are necessary to ensure that the governor design takes account of the departures in the plant from linear behaviour. To obviate much of the time-consuming and expensive site-tests and to provide design tools for future stations, simulations have been developed at a number of levels.

In earlier governing studies (2, 6) a hybrid simulation of the plant was used but the problem size and set-up and operating difficulties lead to the use of digital simulations for most of the work described here. -

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In order to test not only the philosophy but also the operational hardware of the governor prior to control of the real turbine, simulation was used, not only at the design phase, but also in conjunction with the governor and with progressively greater amounts of plant and equipment on site. These simulation facilities are now briefly described.

4.2 Off-line digital simulation

In this part of the work, a full simulation of turbine, pipeline and servo systems incorporating the non-linearities described above was combined with a simulation of the proposed governing system. The Real Time Interactive Simulation Package (11), a FORTRAN based system developed at Glasgow University for the simulation of continuous systems, was used for these studies which were performed on PDP11, Prime 400 and GEC 4070 computers at various times. The pipeline system model included a branch to an adjacent generator and used the method of representing the water column dynamic proposed by Wood (7). The turbine model was that used by Bryce et al (6) and included an efficiency characteristic. The servo system model included a non-linear servo/effective control valve area characteristic and backlash.

This simulation was used interactively and the governor was tuned to give stable responses at various load levels.

4.3 Real-time digital simulation

Having designed the structure and chosen the parameters of a governor using the off-line simulation, the governor was implemented on the microprocessor system and this was connected to a digital simulation on the PDP11 computer of the remainder of the plant. The plant simulation accepted a 'desired servo position' signal from the governor; the output from the simulation, which was fed to the governor, was the frequency error. Since these are the essential interface signals with the real-plant and since the digital simulation was synchronised to run in real-time, the microprocessor-based site-governor was subjected to realistic overall tests in the laboratory without risk to plant.

4.4/

4.4 Portable, plant simulation

Initial tests on-site were conducted using a simple analogue model of the plant consisting of the standard simple turbine and penstock model (4) and the rotational inertia equation of the generator together with a linear loss-torque/speed equation which ensured that the servo opening of this model at nominal speed matched that of the real plant.

The input to this simulation, see figure 4, was derived initially from the 'desired servo position' signal from the governor and the servo was disconnected. The simulation output signal (turbine speed) was fed to a voltage-controlled-oscillator which in turn fed the frequency transducer in place of the normal signal derived from the generator voltage transformer. In this way, the governor was connected to the turbine controller and the remainder of the plant, providing an overall check of the governor and its inter-connection with station equipment.

Following preliminary checks on system function, the servo was connected with the turbine de-watered and the input to the simulation was derived from actual servo position. Using this system, simulated run-up tests were performed including all the station equipment except the turbine-generator unit itself. Only very occasionally did these tests fail to reveal problems which subsequently appeared with the turbine-generator in-service.

4.5 Isolation Simulation

In earlier work (2) the governor stability was checked with the generator supplying an isolated load. However, the risk to consumer supply, and the management and cost of such isolated load tests, militated against their continued use on a routine basis and so the technique of Simulated Isolation described by Schleif (8), Causon (9) and Brown and Willing (10) was adapted for this programme of work.

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In this technique, with the generator connected to the Grid, (see figure 5) a signal proportional to the electrical output power of the generator is fed to the Isolation Simulator as an approximation to turbine mechanical torque output F_m. This is compared, in the Simulator, with the (assumed) electrical torque F_e and the difference, the accelerating torque F_a, is fed to an integrator with a time constant T_m equal to the mechanical time constant of the turbine generator unit. The integrator output is simulated frequency f_{ms} from which the nominal frequency f_o is subtracted leaving the frequency error, f. This simulated error is fed to the governor in place of the normal frequency error.

The electrical torque F_e is derived from estimated load power P_{Lo} and any injected disturbance load power ΔP_L (e.g. test step) using the system power self regulation factor e_n in the equation:

$$F_e = \frac{P_L (1 + e_n \cdot f)}{f_{ms}} \qquad (5)$$

This structure involves one multiplier and one divider, a level of complexity which is not justified by the use of the simple approximation to system load/frequency behaviour given by the power self regulation factor. Using the fact that

$$f_{ms} = f_o + f \qquad (6)$$

where f_{ms} is the system frequency, f_o is the set or nominal frequency (= 1 p.u.) and f is the (small) frequency error, all in per unit, the binomial expansion of $\frac{1}{f_o + f}$ gives a simplified expression for F_e of

$$F_e = P_L (1 + k_n \cdot f) \qquad (7)$$

where $$k_n = e_n - 1 \qquad (8)$$

Additionally, if $\Delta P_L . k_n . f$ is assumed small compared to $P_{Lo} . k_n . f$,

the/

the torque equation further simplifies to:

$$F_e = P_{Lo} + \Delta P_L + P_{Lo} . k_n . f \tag{9}$$

The system as implemented is shown in figure 6. To make the system operationally satisfactory, the switched gain G around the integrator and the output switch have been added. With this ganged switch in the position shown, the output is connected to ground, and the integrator is converted to a short time constant, first order lag which thus rapidly follows the BALANCE signal, the measure of balance between F_m and F_e.

The normal system frequency into the governor is passed through a dead-band of typically $\pm$ 0.3 Hz, temporarily inserted to ensure that normal system frequency excursions do not interfere with the operation of the Isolation Simulator whilst still affording protection under fault conditions. The simulated frequency error from the Simulator is injected into the governor at the same point as the normal frequency signal.

The system is put into service by adjusting the ganged pair of P_{Lo} potentiometers (with ΔP_L set to zero, the feed back gain switched in and the output switched off) until F_e equals the value of F_m derived from the turbine and the BALANCE signal is zero. The position of the ganged switch is then changed, removing the integrator feedback and connecting the system output.

Testing on the system is accomplished by injecting load disturbance signals to ΔP_L and observing simulated frequency error and servo position.

Discrepancies between the behaviour of the full plant simulation and that of a simulation of the plant with the Isolation Simulator were found to be due to the fact that the turbine torque incorporates a speed dependent term which is active in the true isolation case and inactive when isolation is only simulated. Notwithstanding this limitation, the transient behaviour differed little between the two cases.

4.6 Site-Test Facilities

The earlier work culminated in tests on a 32.5 MW water turbine at Loch Sloy Power Station on Loch Lomond in Scotland. Since the time of these tests, the temporary test facilities have been formalised and the Experimental Site Test Facility for water turbine controllers has been rebuilt. In this, an electro-hydraulic servo system was added to the same mechanical linkage as the original servomotor and either can be used to operate the water control valve. The Experimental Facility also includes all interfaces with the Power Station Control Room, automatic control scheme and protection, and contains transducers for frequency, power and reactive power. The system has been designed to permit rapid changeover between the existing station governor and governors and controllers being tested in the Experimental Facility so that operational use of the generating set is not restricted.

Associated with this equipment is a prototype controller and analogue double derivative governor based on the design developed in earlier work. The controller was responsible for generating the appropriate input signals for the analogue and microprocessor governors, both of which are continuously supplied with all input signals. A switch and balance indicator on the controller permit the selection of the output of one of the governors for servo control.

5 RESULTS

5.1 General

A series of simulation studies resulted in governor designs which were finally subjected to site tests on the water turbine Experimental Facility. The results presented here were all produced during the tests on this 32.5MW unit.

The monitoring facilities which exist as part of the Experimental Facility at Sloy include a 12 channel Ultra-Violet (U-V) recorder and a 16 channel/

channel microprocessor-based data recording system. The U-V recorder provides immediate records for analysis and is used in conjunction with highly flexible offset and gain amplifiers which permit the steady component of signals to be offset by a calibrated amount and the remaining signals to be amplified by a continuously variable and calibrated amount. These records also form a back-up, which however has not yet been required, for the data recording system.

The data recording system incorporates a 16 (single-ended) channel, 12 bit accuracy, data acquisition system and the results are stored on floppy disk. The software developed for this project also permits on-site plotting of data on a digital X-Y recorder for accurate assessments of test results. Software usually used off-site includes programs to produce fully annotated results for reports and to transfer the results for comparison purposes to the PDP11 mini-computer used for the simulation studies.

5.2 Run-up Tests

Since the microprocessor governor was fully integrated with the experimental controller and with the station auto-sequencing equipment, fully automatic run-ups were performed with the governor in service. Using test switches, different governor types could be selected for the run-up. Figure 7 shows the run-up with the Temporary Droop governor.

The experimental controller generates the Servo Set Point Signal y_s and Servo Load Limit Signal y_L (see figure 2) and the following sequence of events take place (the numbers refer to figure 7):

Before 1: Auto run-up has started auxilliaries and opened Main Inlet Valve.

1 - 2: y_s and y_L are raised simultaneously from -5% to approximately 25% to give breakaway; servo position y is the sum of y_s and the governor output which is highly positive but is limited to not greater than y_L and so is equal to y_L once y_L rises above 0%, the lower limit of servo travel.

3: A set speed (approximately 30 Hz) is reached and servo position is/

position is reduced to approximately 21% to provide a better transient response at near synchronous speed.

4: Governor action giving negative governor output causes y to be pulled back below y_L.

4 - 5: Frequency transient includes start of limit cycling with long period. Frequency reference is adjusted to prepare generator for synchronising.

5: Circuit breaker is closed and controller raises limiter y_L to 105%.

5 - 6: Auxilliaries transferred to Unit board.

6: Auto run-up complete, controller starts loading set by increasing y_s to setting selected during run-up.

7: Manual loading of set takes place using control of y_s.

Run-up is performed using the Temporary Droop Governor, one of the types implemented in the microprocessor system, in order to permit easier synchronisation using the power station automatic synchroniser which is set up for the normal station temporary droop governors. The limit cycle behaviour of frequency is present with all governors including the mechanical type and is due to the backlash in the control-valve linkages. With the double derivative governor, the amplitude of these limit cycles is smaller but an accompanying shorter period makes automatic synchronising more difficult. Insertion of a dither signal (1.5%) peak-to-peak,1 Hz) into the servo system has been found to eradicate this limit cycling. Injection of dither by the microprocessor governor when the circuit breaker is open, is being investigated as an alternative means of achieving rapid synchronising.

5.3 Grid-connected Tests

The new governors developed in this work have become progressively faster in response to disturbances in frequency when connected to the Grid and the results of a series of tests conducted to demonstrate relative speed of response is/

is shown in figure 8. The existing station Temporary Droop Governors have a dominant time constant of approximately 160s and curves (i) of figure 8 show the response of the Unit with the microprocessor equivalent to the station Temporary Droop Governors to a test step reduction of frequency of 0.97 Hz.

The work previously described (2) produced a double derivative governor with a 33s dominant time constant and curves (ii), figure 8, show the significant improvement over the Temporary Droop Governor. The response rate is limited intially by the rate limit on the servo system (set to provide protection for the pipeline) but after about 15% travel at this rate, the servo opening rate becomes limited by the governor dominant 33s time constant; the full potential of the Unit is still not being realised.

The adaptive governor yields the responses given by curves (iii) of figure 8. The servo response is very close to the ideal of continuous rate-limited travel. As the power increases, the action of the adaptive time constant means that the governor remains in each band even after the power has increased above the top of the band. As a result, the lower band and hence faster, governors are used for longer than the transition of the power signal through the bands would imply.

5.4 System-connected Tests using Isolation Simulator

The adaptive governor was also subjected to a series of tests with the generator synchronised to the Grid but with the Isolation Simulator in service. The tests were conducted at various load levels and consisted of the injection of 5% step changes in simulated electrical load. k_n was set to zero for these tests, giving a value of e_n of 1.0 (see equation 8).

When the distrubance power resulted in the total power crossing the boundary of an adaption band, adaption from one set of constants to another took place during the transient. These and all other tests resulted in stable governor operation and the results of the tests in which adaption band/

band boundaries were crossed are presented in figure 9 and 10. In each of these figures a 5% step rise in load is followed by a 5% step reduction in load and the point of adaption can be seen in each case.

In figure 9, the transition is from the top of the low band to the bottom of the mid-band, and the low band governor is clearly only lightly damped at this load level. This however represents the worst possible point from stability considerations over the whole operating regime of the governor. At this point, the non-linear power/servo stroke curve reaches its maximum gain value, this is the governor band with the shortest dominant time lag and hence is the least stable band and the water flow rate is at its highest value within this band. In the continuing programme of work on this governor, the possibility is being investigated of inversely characterising this non-linear curve within the governor.

6. CONCLUSIONS

A microprocessor-based adaptive water turbine governor has been developed and has been successfully used on a 32.5MW turbine under conditions of run-up, grid connected operation and operation with a simulation of isolated load. The use of an adaptive technique permits stable operation with isolated load together with a rate of power response to system frequency disturbances limited only by operational constraints on servo rate.

Governors of this type could be applied to conventional hydro or to pumped storage stations. In the U.K., their use with large pumped storage schemes, especially in areas where system 'islanding' is possible, could mean rapid response rates but with stability on isolated or near-isolated load conditions.

The use of a microprocessor means that governing strategies can be readily changed to meet evolving system needs. Although the present governor uses assembly language programs which are relatively complex, new governors are under development as part of this project, which use FORTRAN and a higher level Continuous System Simulation Language to define the control action. The program defining the governor will then be written in a language which is close to the engineering definition of the governor and will also be similar to part of the simulation program used to design the governor initially.

Governing is the most complex part of the turbine controller which includes run-up control and the operator interface. Work is also in hand to integrate these functions with the governor in a single microprocessor-based system.

7. ACKNOWLEDGEMENTS

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9 APPENDIX

A DIGITAL REPRESENTATION FOR A DOUBLE DERIVATIVE GOVERNOR

The differential equations of the double derivative governor shown in figure 2, assuming that load limiting is inactive (i.e. $x_L = 0$), are:

$$\dot{x}_1 = (-x_1 + K_1 \dot{f}) / T_1 \qquad (10)$$

$$\dot{x}_2 = (-x_2 + \frac{K_2}{K_1} \dot{x}_1) / T_2 \qquad (11)$$

$$\dot{y}_1 = -(b_p y_1 + f + x_1 + x_2) / T y \qquad (12)$$

The backward Euler method is given by:

$$v^n = v^{n-1} + T\dot{v}^n$$

where T is the integration interval, v^n is the value of the integrated variable v at the nth integration interval and $\dot{v}^n$ is the derivative of v^n

Using this method for equations 10, 11 and 12 gives:

$$x_1^n = C_1 x_1^{n-1} + C_2 (f^n - f^{n-1}) \qquad (13)$$

$$x_2^n = C_3 x_2^{n-1} + C_4 (x_1^n - x_1^{n-1}) \qquad (14)$$

$$y_1^n = C_5 y_3^{n-1} - C_6 (f^n + x_1^n + x_2^n) \qquad (15)$$

with

$$C_1 = \frac{T_1}{T + T_1} \qquad C_2 = \frac{K_1}{T + T_1}$$

$$C_3 = \frac{T_2}{T + T_2} \qquad C_4 = \frac{K_2}{K_1(T + T_2)}$$

$$C_5 = \frac{T_y}{T_y + b_p T} \qquad C_6 = \frac{T}{T_y + b_p T}$$

In/

In practice only an approximate solution of the discrete equations above is obtained in real time since the value of output due at time nT can only be output at time nT plus the computation time for the three equations. This results in the introduction of a pure delay equal to the computation time which in the presently described governors was effectively the integration interval T.

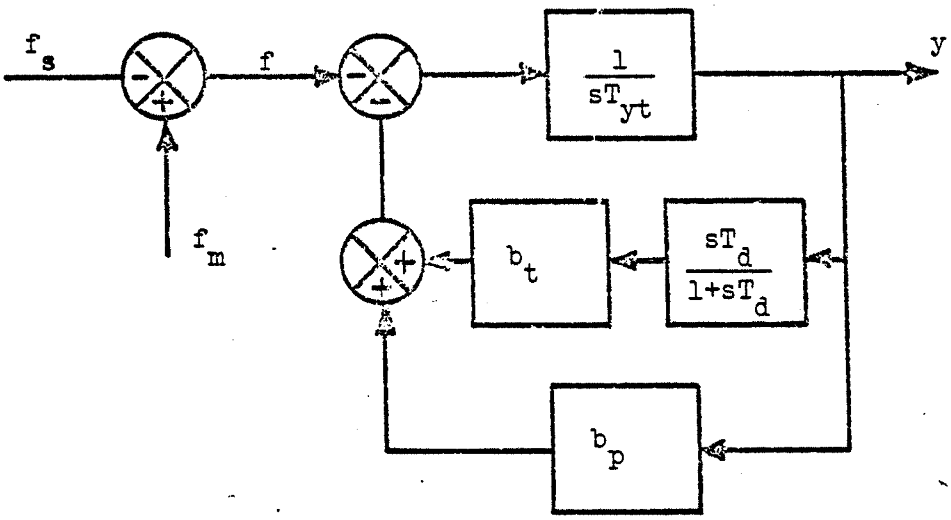

Figure 1 Temporary Droop Governor

f_s = frequency set point

f_m = measured frequency

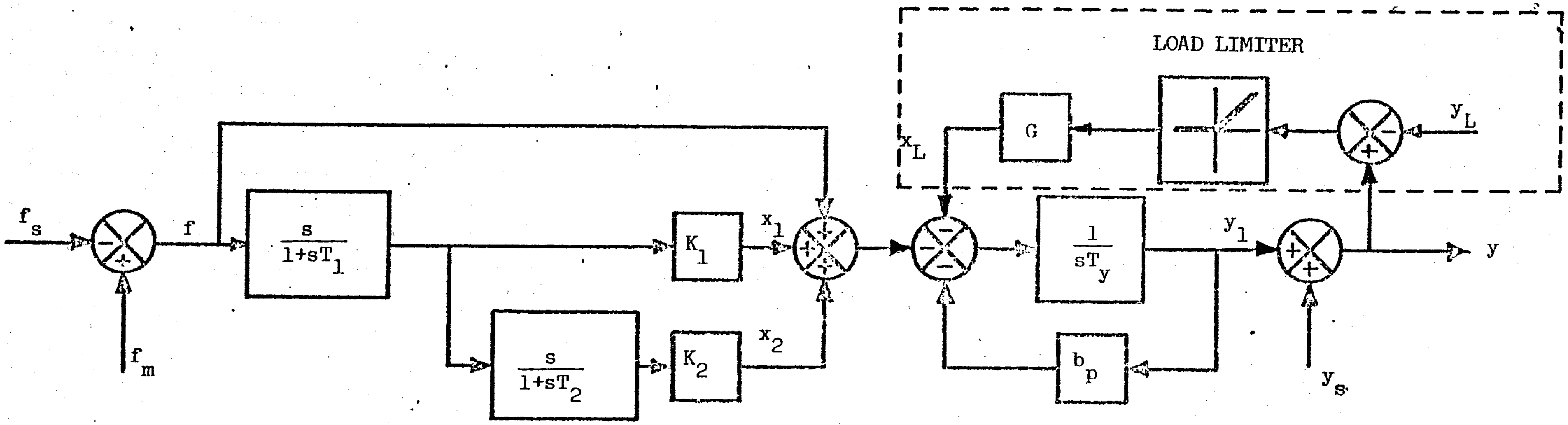

Figure 2

Double Derivative Governor
f_s = frequency set point
y_s = servo set point
y_L = load limiter set point

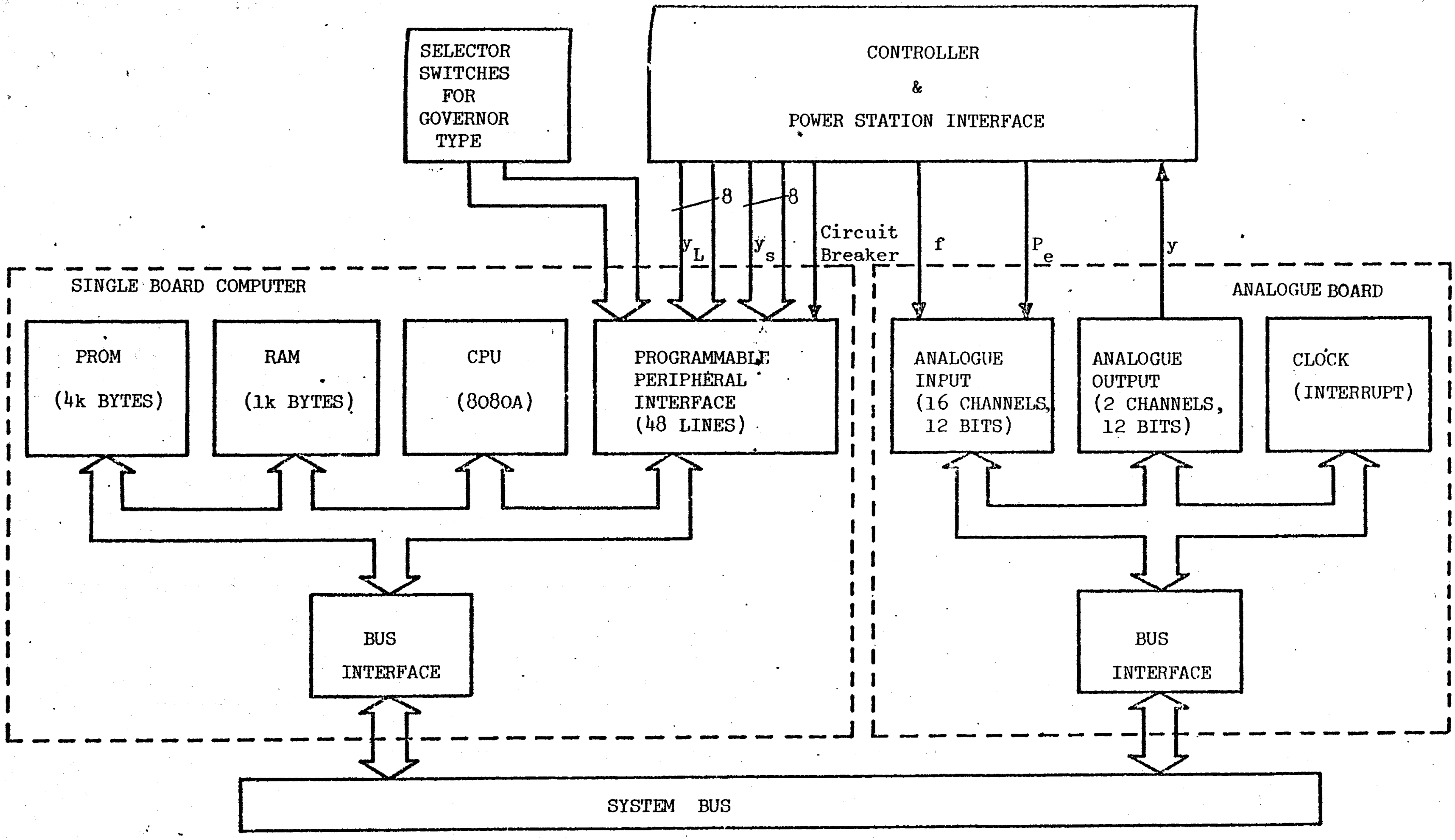

Figure 3 Microprocessor System

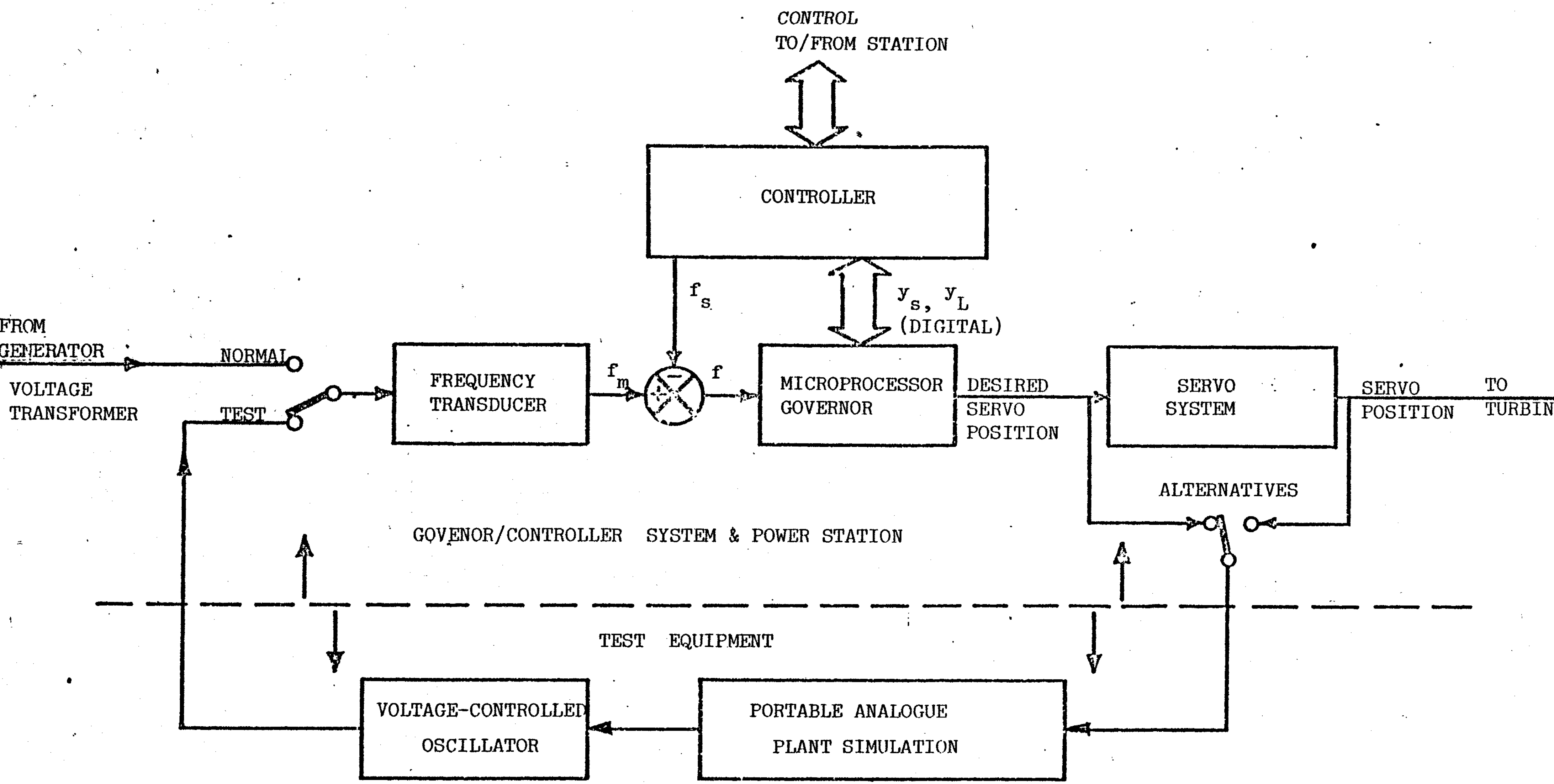

Figure 4 Use of portable analogue plant simulation

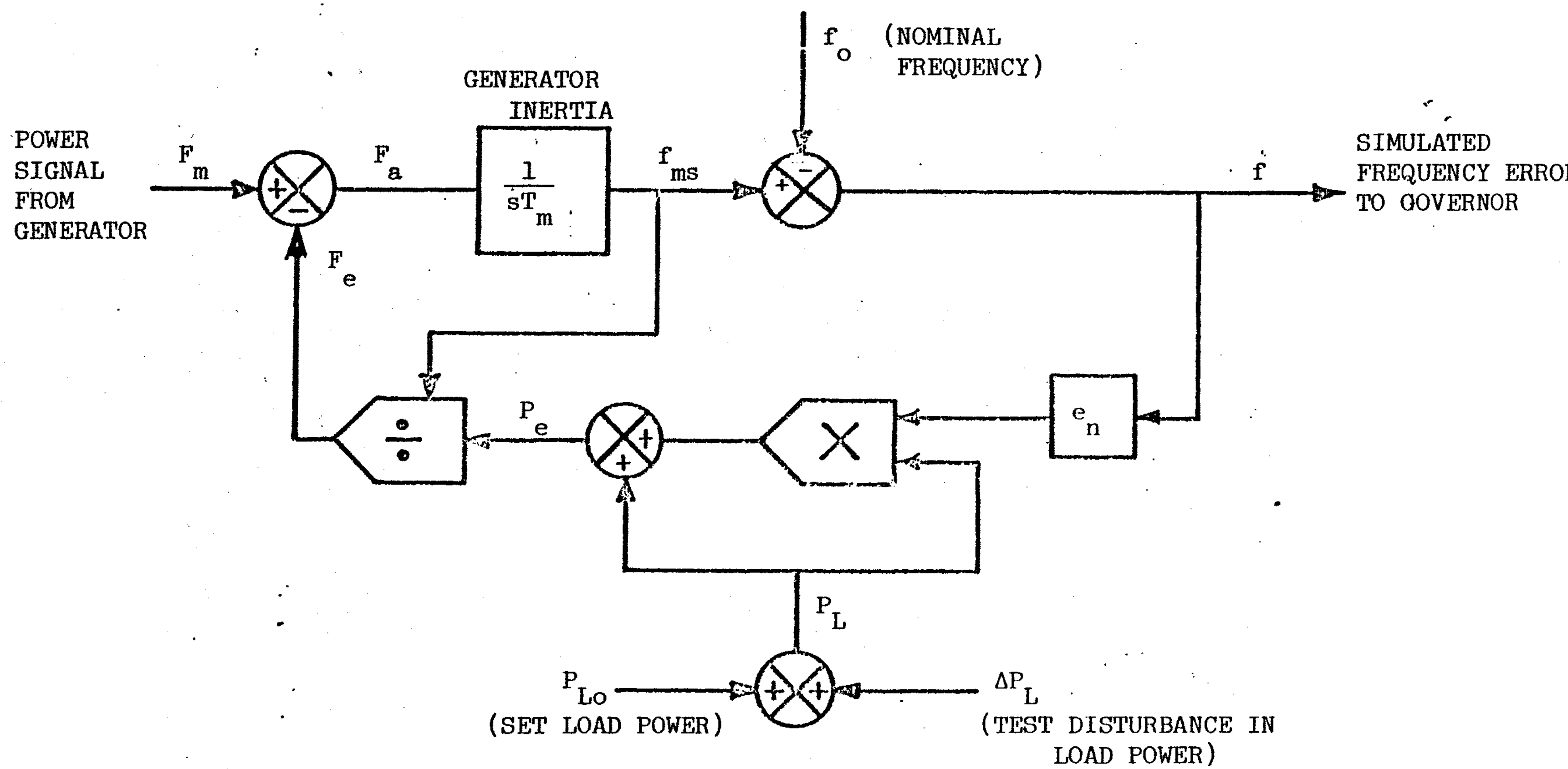

Figure 5 <u>Full simulation of isolated load</u>

e_n = Load power self regulation factor

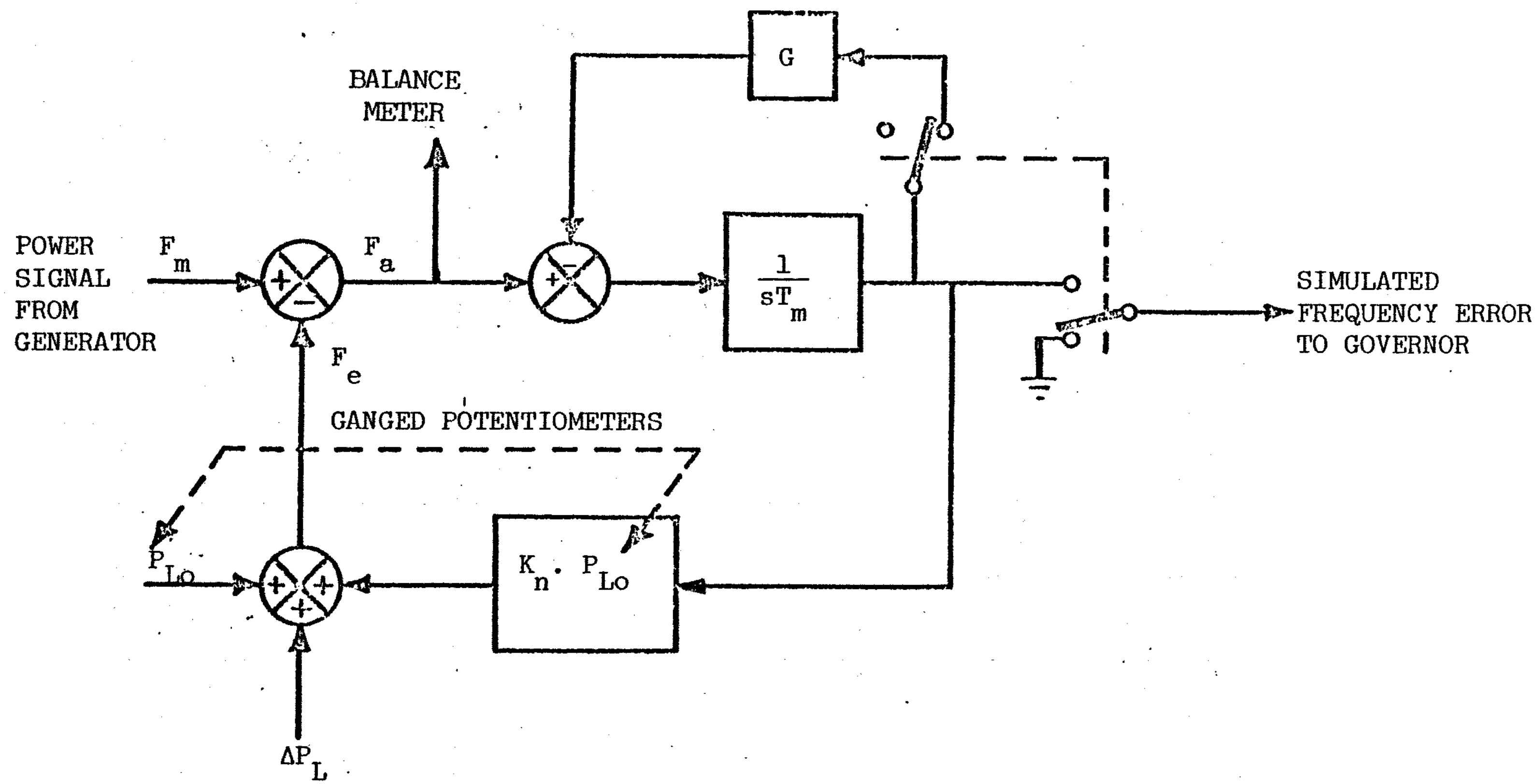

Figure 6 Simplified simulation of isolated load - used in system ($K_n = e_n - 1$)

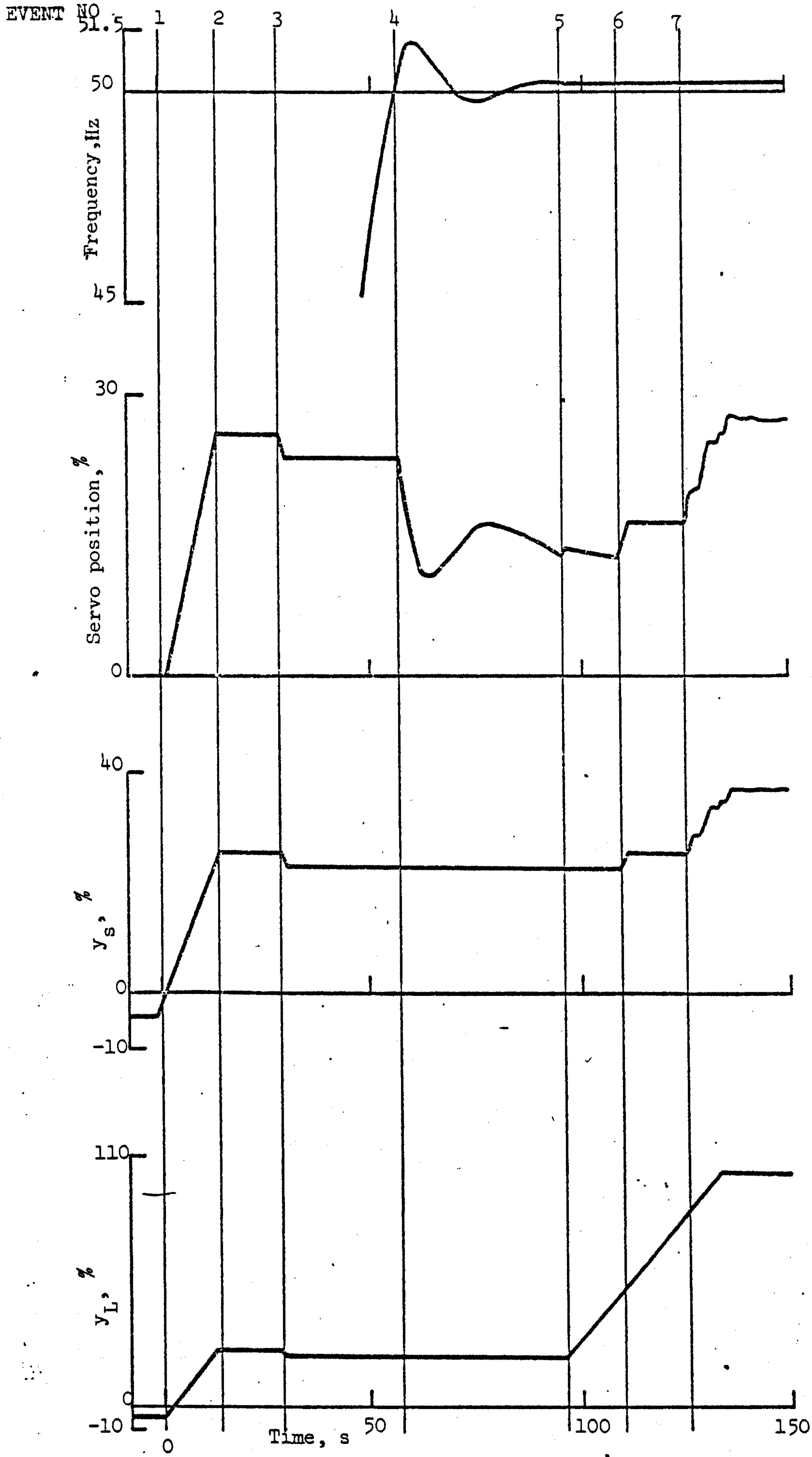

Figure 7 Run-up sequence

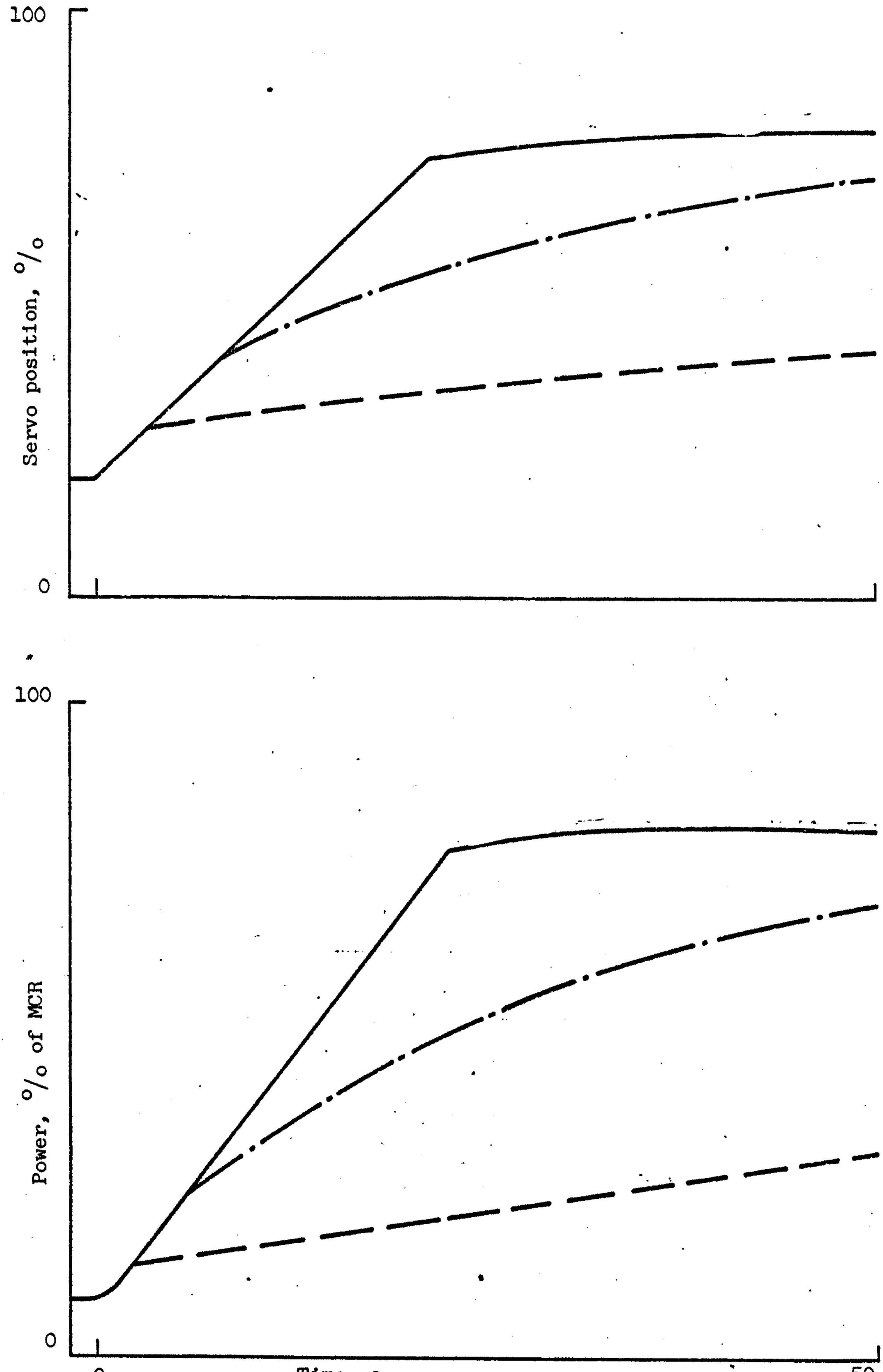

Figure 8 <u>Response of governors to 0.97 Hz step drop in frequency, grid connected</u>

(i) — — — Temporary droop (T_L = 160s)
(ii) —·— Double derivative (T_L = 33s)
(iii) ——— Adaptive double derivative.

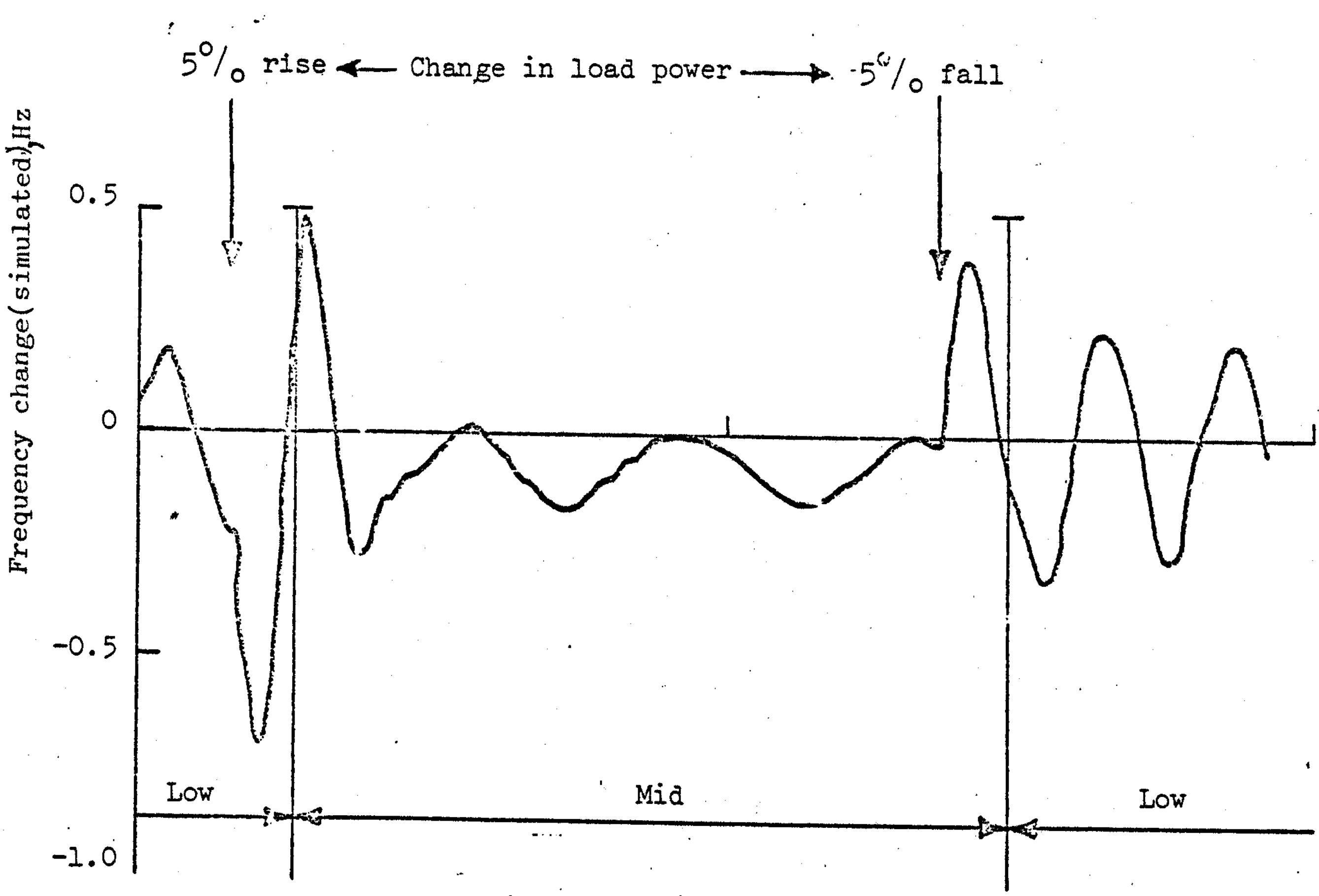

Figure 9. Governor adaption between low and mid-bands

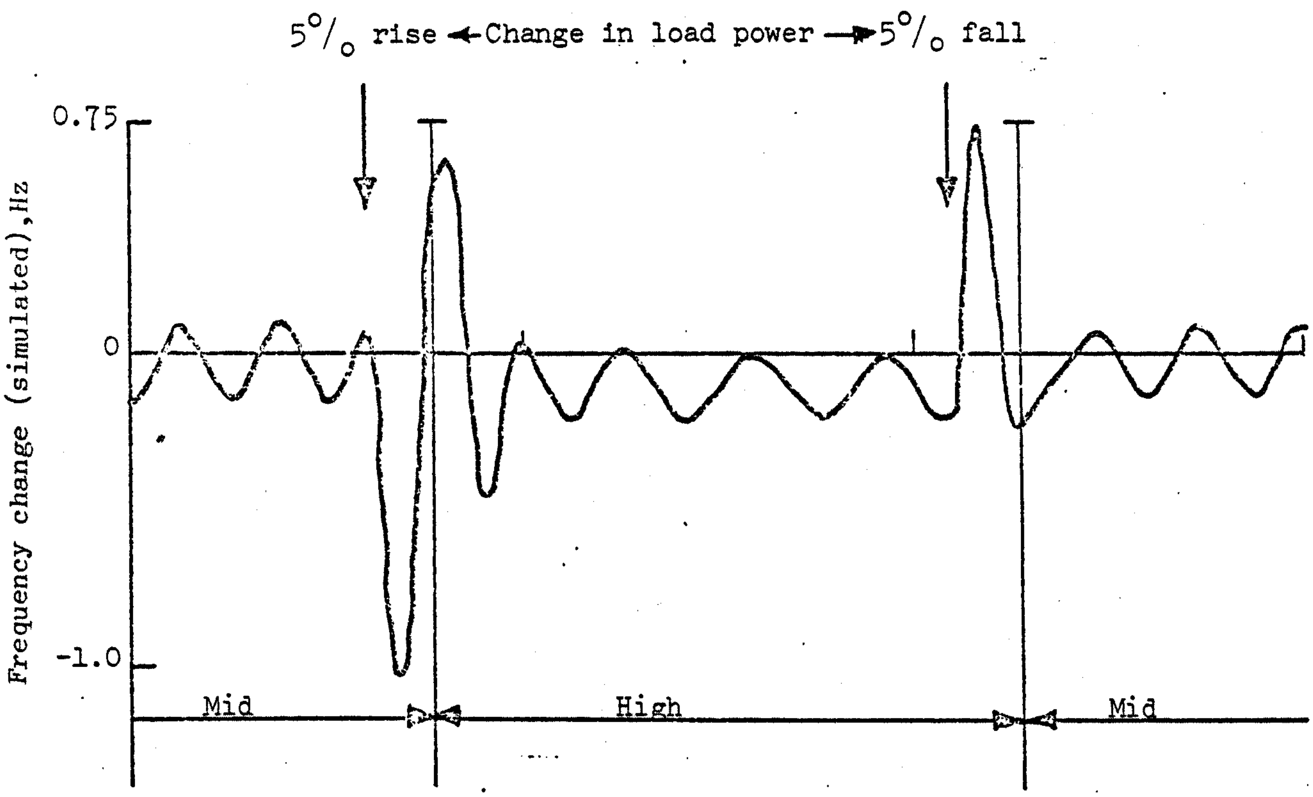

Figure 10. Governor adaption between mid and high-bands

CONTROLLER TESTING FACILITY ON A 32.5 MW WATER TURBINE

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ABSTRACT

As part of a collaborative programme of work betwen University and Industry on the control of hydro generating units supplying power to the U.K. national grid, equipment has been installed on a 32.5 MW unit which permits the testing of new controllers in a realistic, operational environment. A central feature of this equipment is that it permits the generating unit to be returned quickly to operational use with its existing controller. Full integration with the power station operator's controls, automatic control scheme and protection, permit the controllers under test to be evaluated under normal operational conditions. The test equipment, which includes a new, independent, high-pressure servomotor, is described as is the way in which typical controllers are used with it. The main features of the way in which the collaborative work has ben carried out are also discussed.

CONTROLLER TESTING FACILITY ON 32.5 MW WATER TURBINE

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1.0 INTRODUCTION

1.1 History of collaborative research

Collaborative research on various aspects of power systems has been carried out over a period of 13 years between the University of Glasgow and the North of Scotland Hydro-Electric Board and, during the last seven years, the work has concentrated on the study of water turbine control systems. Within a general framework laid down by the Board; the University has formulated a number of specific projects each aimed at improving the understanding of the way in which existing turbine controllers operate or at improving the design with a view to providing controllers for future conventional or pumped-storage hydro generating units. This policy has enabled the University to set each project at an appropriate level for a post-graduate student working for a higher degree while at the same time following the Board's research programme.

It was decided at an early stage of the investigations, to carry out studies at Loch Sloy Power Station on the shore of Loch Lomond some 40 miles north of Glasgow. This was sufficiently close to the University Laboratories to permit parallel studies at the power station on the real plant and in the Laboratories on computer models without significant loss of time in travel between the two locations. The whole scheme was also extremely well documented[1] and this meant that the data necessary for the proposed studies was likely to be readily available. The early work was concerned with the analysis and modelling of the pipeline, tunnel and turbine systems[2] and with improved governor designs[3]. A prototype electronic governor including an additional servomotor was installed and tested[4] which gave much better power response to frequency disturbances when grid-connected than the original governor, whilst still preserving stability when supplying an isolated load.

Since then, the work has been concerned with improving further still the characteristics of the governors[5] and with developing a turbine controller which is used not only in governing but also in the run-up and loading of the unit. To permit this and future work to proceed unhindered by the need to rebuild the entire experimental equipment in the power station each time a new controller is designed and constructed, a "Controller Testing Facility" has been installed which rationalises the experimental equipment and provides a tool for controller and governor testing. This paper describes this Facility.

1.2 General description of Sloy plant

The experimental equipment is installed on one of the four 32.5 MW hydro generating units at Loch Sloy Power Station. Water for the power station is supplied from a reservoir at a head of about 265 m (varying depending on reservoir level) through a single 2750 m rock tunnel, two 180 m concrete lined tunnels and finally four 360 m steel pipes. A surge shaft is situated at the junction of the rock and concrete tunnels. The turbines are high head Francis machines running at 428.6 rpm producing a nett output of 33.9 MW. Control of the water flow into the turbine is provided by a water control valve consisting of 24 guide vanes arranged around the periphery of the runner. This control valve is positioned by the main servomotors of the controllers through two links and a ring which simultaneously moves all of the guide vanes. There is a main inlet valve on the pipeline side of the control valve which is either fully open or fully closed and since it is capable of closing against full flow, it serves as a means of isolating the turbine from the pipeline, which is completely independent of the control valve.

1.3 Original controller

The original controller consists of an English Electric governor of the mechanical hydraulic dashpot type and a hydraulic "gradual-start" mechanism which controls the turbine during run-up and permits remote control. It has a main servomotor of 43 cm diameter and 35 cm stroke which can exert a force of 20 tonne. The speed sensitive element is a mechanical hydraulic pendulum and great care was taken in its design to avoid the effects of friction. This governor has a temporary droop characteristic and is described in detail in reference 6.

2.0 EXPERIMENTAL EQUIPMENT

2.1 General

Attempts were made to use the original controller in early tests on the plant which sought to identify its characteristics. This approach was found to be unsatisfactory since the injection of test signals was seriously restricted by the need to use a mechanical transducer. In addition, it proved impossible to add new characteristics to this existing system. It was therefore decided to supplement the existing controller on one of the station generating units with an experimental controller and the necessary equipment to permit either of them to be selected for service using a rapid and simple changeover procedure. Since the Loch Sloy station is not designed to run continuously throughout the year, this arrangement had the advantage, in general, of permitting the experimental work to take place during normal breaks in operational service of the unit. From the plant operator's point of view this is most important as the primary purpose of the generator is to provide a public electricity supply. At the same time the experimental work was able to proceed relatively unhindered by the operational requirements of the electricity supply system.

Figure 1 shows the general arrangement of the experimental facilities. A new high-pressure hydraulic servomotor system has been installed on the end of the original servomotor and mechanically connected to it. Electrical connections are made through a selector switch which selects one of the controllers. This switch is mounted on a marshalling cubicle where isolation links are provided to permit the experimental equipment to be entirely disconnected from the power station plant. By this means, work can continue on the experimental equipment when the generator is running and supplying power to the grid, with no risk to the operational plant.

Cables connect the marshalling cubicle and the controller cubicle, in which all signals to and from the power station are connected through signal conditioning equipment, which is permanently installed, to the controllers/governors, which change as the development work proceeds and which are moved between the power station and the University Laboratory. The signals between this conditioning equipment and the controller/governor are all at standard logic system and operational amplifier voltage and impedance levels and are available on plugs or sockets. Thus all controllers operate to a well-defined and unchanging interface, require no special interface equipment (e.g. relays or power amplifiers), and can be rapidly installed in the station. This provides not only the obvious advantage of simplyfing controller design, but also means that controllers can be connected to the station simulation in the University Laboratory.

Final checks on new controllers can be made prior to implementaion on the actual generating unit using the rudimentary simulation facilities provided in the controller cubicle. For these checks, the isolating links can be left open and hence there is no connection to the station apart from a power supply.

Steps have been taken in designing the experimental equipment to ensure that in the event of component failure, the generating unit is shut-down using the same orderly method as that used under similar circumstances for the original controller. An important consideration, however, in the design philosophy of both controllers is that a water turbine, unlike a steam turbine, can withstand for several minutes, the overspeed caused by loss of electrical load with full water flow through the turbine. Thus, even with total controller failure, time exists to close the main water inlet valve (cf. steam emergency stop valve). It is therefore unnecessary to provide parallel redundancy in the controller system.

2.2 Power supply arrangements

The principal items within the controller cubicle for signal conditioning and simulation are shown in Figure 2. The controller is designed so that failure in its essential parts will result in orderly shutdown of the plant. The source of power for the equipment is 240V A.C. derived from one of three sources and all of which are passed through interference filters. During preliminary commissioning, totally isolated from station operational supplies, the test supply is taken from an auxiliary supply. During normal operation, the station common services supply or the generator unit supply is used.

The filtered A.C. supply is used to derive regulated 5v and $\pm$15V D.C. supplies which are used within the signal conditioning equipment and are available together with the 240V A.C. at the controller interface. Each of the supplies is monitored for voltages above and below those at which the remainder of the equipment will operate. In addition a watchdog timer (retriggerable monostable) is used to monitor a pulse train derived from a microprocessor governor or controller if one is present. If all the power supply voltages are within tolerance and if the watchdog timer is operating correctly, a 110V relay is energised and its contacts are used to provide an indication of healthy system supplies. Power supply failure has the same effect in the station protection as low hydraulic oil pressure (see section 4.0, Protection and Alarms).

The 110V D.C. supply for the cubicle is normally derived from the station battery through an interference filter but during testing can be derived from the A.C. supply.

2.3 Control signals

Various control signals into the cubicle are derived from 110V D.C. signals in the station. Each passes through a selector switch which permits use of the incoming signal, or of a continuous on or continuous off. It then passes through an optical isolator and a driver logic gate and is presented to the controller interface as a logic level signal. The selector switch can be used to disconnect an incoming signal and to simulate it locally for test purposes. The input unit also contains an indicator for each channel and these together with the selector switches permit rapid and simple commissioning of new controllers. Similar switches and indicators are provided on the outputs which take logic signals from the controller and drive relays, also through optical isolators, to give clean contacts for use in station circuits.

2.4 Servo controller

The servo controller normally has a closed loop proportional action and is contained entirely within the interface equipment. This positions the servomotor to the "desired servo position" given by the value of the signal from the governor and the controller. The electro-hydraulic servovalve which controls the servomotor has an integral action and the system thus has zero steady state error. A linear variable differential transformer (LVDT) position transducer connected directly to the servomotor is used to provide a highly robust, reliable and stepless position feedback.

The servo position signal is transmitted to the controller across the interface. Should it be necessary for the controller/governor to exercise direct control over the servovalve, the feedback loop in the servo controller can be broken and "desired servo position" signal would then be used for the different function of driving the electro-hydraulic servovalve directly. Facilities have also been provided to move the servomotor even when there is no 240V A.C. supply by using the 110V battery supply in a "servo local controller" module to drive the servovalve directly. Additionally, mechanical bias within this valve results in the servomotor slowly closing the guide vanes of the water turbine when it receives no electrical signal.

2.5 Frequency transducer

The turbine speed input to the governor is obtained from the frequency of the phasor combination of two generator phase-phase voltages and two currents. The combination is such that 90 degrees lagging, balanced currents will add in phase with the resultant voltage signal and provides a frequency signal even during a zero impedance, three phase fault on the generator terminals. The use of two voltage and two current signals means that there is a measure of redundancy in the system.

The transducer is designed to operate with very low values of generator terminal voltage and will give normal output at and above rated speed of the turbine even with total loss of generator excitation current.

The transducer measures the period of the A.C. signal with a resolution of one part in 20,000 at 50 Hz. It uses a crystal controlled oscillator to give an accurate, sensitive and stable signal with a very fast transient response. The transducer makes available to the controller at the interface the following signals:

a 24 bit digital signal proportional to the period of the A.C. signal;

an analogue signal covering the frequency range 0 to 70 Hz;

an analogue signal covering the range 45 to 55 Hz;

six logic signals which indicate attainment of certain speeds, the values of which can be set by potentiometers in the transducer.

This method of speed measurement is relatively inexpensive and it was chosen to give operational experience of its performance and to avoid the considerable problems which would have been posed by the necessity of fitting an additional tachometer to the generator shaft. The frequency of the terminal voltage and the turbine speed differ only as a result of generator rotor transients at a frequency (approximately 1 Hz) which is attenuated adequately by relatively slow water turbine governors. With faster water turbine governors, this difference could impose a limitation on the use of terminal frequency as a measure of turbine speed. However, this limit has not yet been reached although its effects have been noticed.

2.6 Power and reactive VA transducer

The two wattmeter method for three wire, unbalanced systems is used to give a power signal. The reactive VA signal provided is valid only during balanced conditions but is derived in the same way as that used for station control room indications.

2.7 Analogue simulator

Included in the controller cubicle is a rudimentary turbine simulator used to permit almost complete system checkout in the station environment but without water being supplied to the turbine. This simulation takes as an input signal, either the desired or measured servo position and simulates in a simple but adequate method, the servo system, the turbine and pipeline and the turbine and generator inertia, and gives a voltage proportional to frequency signal as output. This signal is used to drive a voltage controlled oscillator and the resulting A.C. signal (test frequency) is supplied as input signal to the frequency transducer as an alternative to the normal signal derived from the generator terminals via the voltage and current transformers.

2.8 Monitoring

Monitoring of tests is done using digital data logging with ultra-violet recording as a back up. Analogue voltages from the signal conditioning equipment (eg servo position,frequency or power) and from the controller (e.g. desired servo position) are buffered before output to the monitoring equipment in order to reduce the possibility of faults in the monitoring equipment affecting controller functions. The buffer amplifiers are contained in the controller cubicle.

3.0 EXPERIMENTAL SERVOMOTOR SYSTEM

The experimental controllers use a 207 bar hydraulic servomotor system to position the water control valve of the turbine, the whole system being shown in figures 3 and 4. This new servomotor is fitted to the end of the original 14 bar servomotor and three valves (A, B and C in Figure 3) are fitted to permit one or other of the servomotors to exercise control at any time.

Figure 4 shows the physical arrangement of the two servomotors. At the bottom, the original controller gradual-start mechanism is fitted at the end of the new servomotor which is in turn connected to the original servomotor through the rectangular-section spacer-block. The new pump, reservoir and contactor can be seen at the bottom right.

The 207 bar system shown in Figures 3 and 4, uses a swash plate pump to supply the high pressure oil to two 35 litre hydraulic accumulators which act as a pressure reservoir. Fluctuations in pump pressure are thus prevented from reaching the servomotor and sudden demands for oil, as for example in an emergency closing of the water valve, are taken from the accumulators and not from the pump. Sufficient energy is stored in the accumulators to enable the water control valve to be fully opened or closed several times without the pump running. This latter feature provides safety in the event of pump or electrical supply failure.

The electropneumatic valve E and non-return valve D are used to isolate the servomotor from the supply and to prevent the accumulators from leaking high pressure oil whilst the generator and pump are shut down. In normal service, high pressure oil is distributed to the ends of the servomotor by an electrohydraulic servovalve F. The flow rate is approximately proportional to current in the coil of the servovalve and the direction of servomotor travel is determined by the direction of the current. Oil from the other end of the servomotor returns to the hydraulic system reservoir.

When the original controller is required for service, valve E is closed, depressurising the experimental servomotor system and valve A is open permitting free exchange of oil between its ends and making it totally inactive. The bypass valve C in the station controller is closed and valve B is opened giving the original servomotor control of the turbine water control valve.

When the experimental controller is in service, the oil supply must still be available to provide lubrication for the original controller which is still mechanically connected to the turbine shaft. Bypass valve C is opened and valve B is closed to disable the original servomotor and prevent the original governor head from exhausting its oil supply through the bypass to drain. Bypass valve A is closed. The A.C. supply to the experimental equipment oil pump motor is derived from the original oil pump motor supply which has to run to provide lubrication. The contactor for the experimental equipment pump is closed only when the electrical changeover switch selects the experimental controller.

To ensure that, in the event of controller failure, it is still possible to close the water control valve and hence render the generating unit safe, an emergency close solenoid dump valve G is fitted. This valve, which corresponds to an equivalent valve in the original controller, is operated by the station protection, venting one end of the distribution spool in the electro-hydraulic servovalve directly to drain. This forces the distribution of oil to the closing side of the servo motor irrespective of any current signal from the controller.

4.0 PROTECTION AND ALARMS

The experimental equipment is fully integrated with the station protection and alarm schemes. Low oil pressure switches on the servomotor hydraulic system (see figure 3), supply alarm and protection signals, the alarm setting being somewhat higher than the trip setting. The alarm is annunciated in the control room and the trip has the same effect as low oil pressure in the original controller hydraulic system. A fall in oil pressure below the trip setting will result in operation of the trip relay which initiates the closing of the turbine main water inlet valve and operation of the emergency close solenoid dump valve D. It also starts battery operated generator and turbine lubrication pumps and after the guide vanes are fully shut, opens the generator circuit breaker.

The power supplies in the experimental equipment are monitored and connections are made to the protection equipment so that power supply failure produces the same trip effect as low oil pressure.

The phasor combination of voltages and currents used by the frequency transducer is monitored and if it is lost, a "governor drive" fail trip takes place. The action is the same as would occur if the drive shaft carrying the turbine speed signal to the original governor was broken. If the drive fail occurs when the generator circuit breaker is open, the controller closes the guide vanes at the normal shutdown rate. If the circuit breaker is closed, the generator trip relay operates and the sequence of events is as described above.

The experimental controllers control and monitor the turbine run up procedure and if the unit fails to reach certain speeds within preset time limits, the guide vanes are closed at the normal shutdown rate and an alarm is annunciated.

High temperature of the oil in the hydraulic system also provides an alarm which again is annunciated in the control room.

5.0 DESK CONTROLS

The controls normally available to the control engineer on the unit control desk include:

speed reference:	raise/lower
voltage reference:	raise/lower
circuit breaker:	open/close
automatic sequence control:	start/stop

An additional panel has been fitted to the desk to provide necessary controls required by the experimental equipment. The additional controls include:

power:	raise/lower & set value & execute set value
load limiter:	raise/lower
control:	auto unload and stop/reset

The experimental controllers which have been implemented have a speed reference similar to the original controller but also have a servo set point control. Both governors act upon the difference between measured and reference speed. The output of the original governor is the desired servo position. The output of the governing part of the experimental controller is added to the servo set point to give a desired servo position. If this signal exceeds the load limiter set point, which is set by the desk control or the run up logic, a signal is fed back to the governing part of the controller which reduces its output until the desired servo position equals the limiting value.

With the original controller is use, the method of controlling generator output power when the generator is connected to the grid is to vary the speed reference. Output power responds with the dominant time constant of the governor which is a few minutes. In the experimental controller, the servo set point is varied giving a very rapid and precise control over power because the dominant lag is bypassed. The power raise or lower control is used to adjust the servo set point.

A rudimentary load controller for the generator is provided in the experimental controller which is currently in service. In this, the servo positions corresponding to eight load power values at a given reservoir level are stored in the controller. The "power: set value" control will select one of these power values and operation of the "power: execute set value" control will cause the servo reference to be moved to the corresponding servo position. A load controller is under development which will set the electrical output power directly and which will improve the response rate of changes in reference which is restricted in the current version, by the requirement of not opening the turbine relief valve.

The station auto control scheme provides automatic starting and synchronisation of the generating unit and also automatic disconnection from the grid and stopping; loading and unloading are done when the original controller is in service by the control engineer. When the experimental controller is in use, operation of the "power: execute set value" control at any time after the start control is operated results in fully automatic loading of the set after the end of the starting sequence.

In a future controller it is intended to implement an automatic unloading scheme which will reduce to zero the real power and the reactive VA and then initiate the stop sequence. This function is at present done manually. The "auto unload and stop" control will initiate this and it will be possible to arrest the action at any time before the circuit breaker is opened by operating the "reset" control.

6.0 CONCLUSIONS

The Controller Testing Facility has been successfully installed on an operational hydro electric generating unit and has permitted tests to be carried out with novel controllers in a real operating environment. In earlier work[4], the equipment was used in a series of system splitting tests to demonstrate the suitability of a double derivative governing characteristic for both isolated system operation and when connected to the grid. Testing of this new characteristic on a real system established rather more conclusively than would have simulation tests alone, its ability to control the generating unit.

More recent work using the testing facility has shown the advantage of enhancing the double derivative governor by making it stepwise adaptive[5]. The performance of this adaptive governor has been assessed in simulated isolation tests in which as much as possible of the real system is included without actually splitting the supply system and thereby placing consumer's supplies at risk.

The testing facility and controllers have now been developed to the point at which they are undergoing assessment under normal operational conditions with the generating unit supplying power to the grid.

The test equipment has also permitted frequency response and other tests to be carried out on the Sloy hydraulic system. This has enabled a comprehensive simulation of the power station and one of its turbines to be constructed which was used to check theoretical work on the characteristics of these systems. The importance to controller design of an accurate simulation of the plant has been found, particularly in relation to the various non-linearities which are frequently not included in conventional controller design. The techniques used in simulating the Sloy unit are applicable to other plant.

The testing facility provides an important method of investigating and confirming the performance of novel governing and control characteristics for new or existing conventional hydro or pumped storage plant. Characteristics giving optimum frequency control performance can thereby be specified for plant to be installed in the future which, in the case of pumped storage plant, would be likely to be rated at about 400MW.

The construction of in situ test equipment has been of considerable benefit to the University in providing a test bed for ongoing work and one which has been readily available over a period of some years. It has accustomed University staff and post-graduate students to the realities of an industrial environment enabling them to design controllers which are not only theoretically satisfactory but which are capable of controlling real plant. It has also stimulated the interest of the power station engineers in the work and their suggestions have assisted in ensuring that the controllers designed would be satisfactory in operational service.

It is also perhaps of some general interest to note that the way in which the collaborative work has been carried out has ideally suited the requirements of a University group where one of the main constraints is to provide projects at a level suitable for post-graduate students who rarely have industrial experience after the award of a first degree. The definition by the Board of broad objectives of its research plan, leaving the University to make detailed proposals, the committment of a Board Engineer, who has taken a very close and detailed interest in the work and the provision and ready access to the generating unit at Sloy have all contributed to the benefits derived by both the University and the Board from the work.

7.0 ACKNOWLEDGEMENTS

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In particular, thanks are due to the late A.M. Cochran of the North of Scotland Hydro Electric Board and T.R. Foord of Glasgow University with whose encouragement and interest the work was commenced and to G.W. Bryce and to P.W. Agnew who carried out the initial work.

The financial and engineering support received from the North of Scotland Hydro-Electric Board, and the continuing access to operational plant have been central to the work described above and are gratefully acknowledged. Thanks are due to the staff of Sloy/Awe Generation Group, in particular to I. Phillipson and A.L. Grant, without whose co-operation and help the work could not have been carried out.

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Thanks are due to Professor Lamb of the Department of Electronics and Electrical Engineering, University of Glasgow for laboratory facilities.

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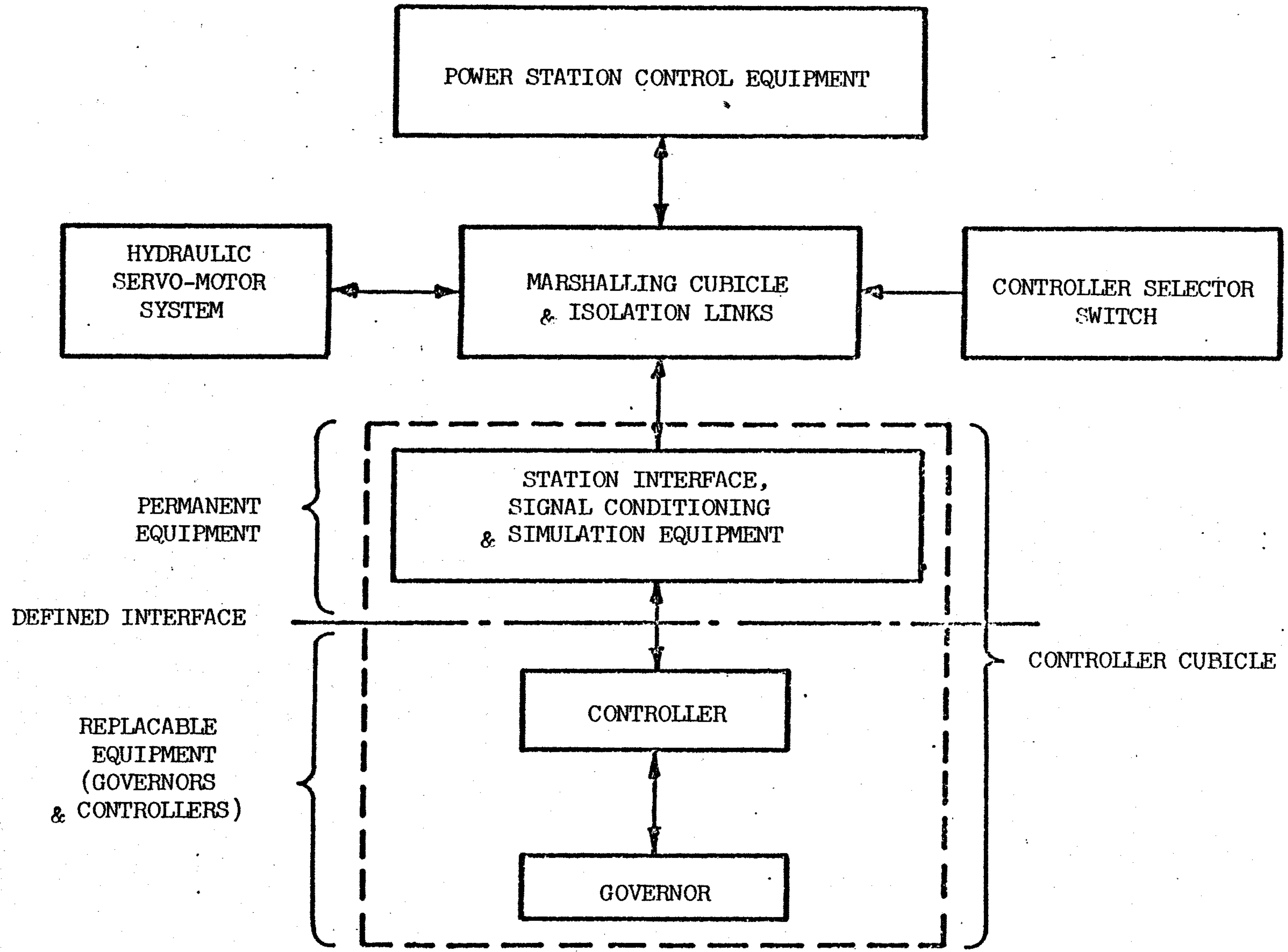


Figure 1. General arrangement of experimental equipment.

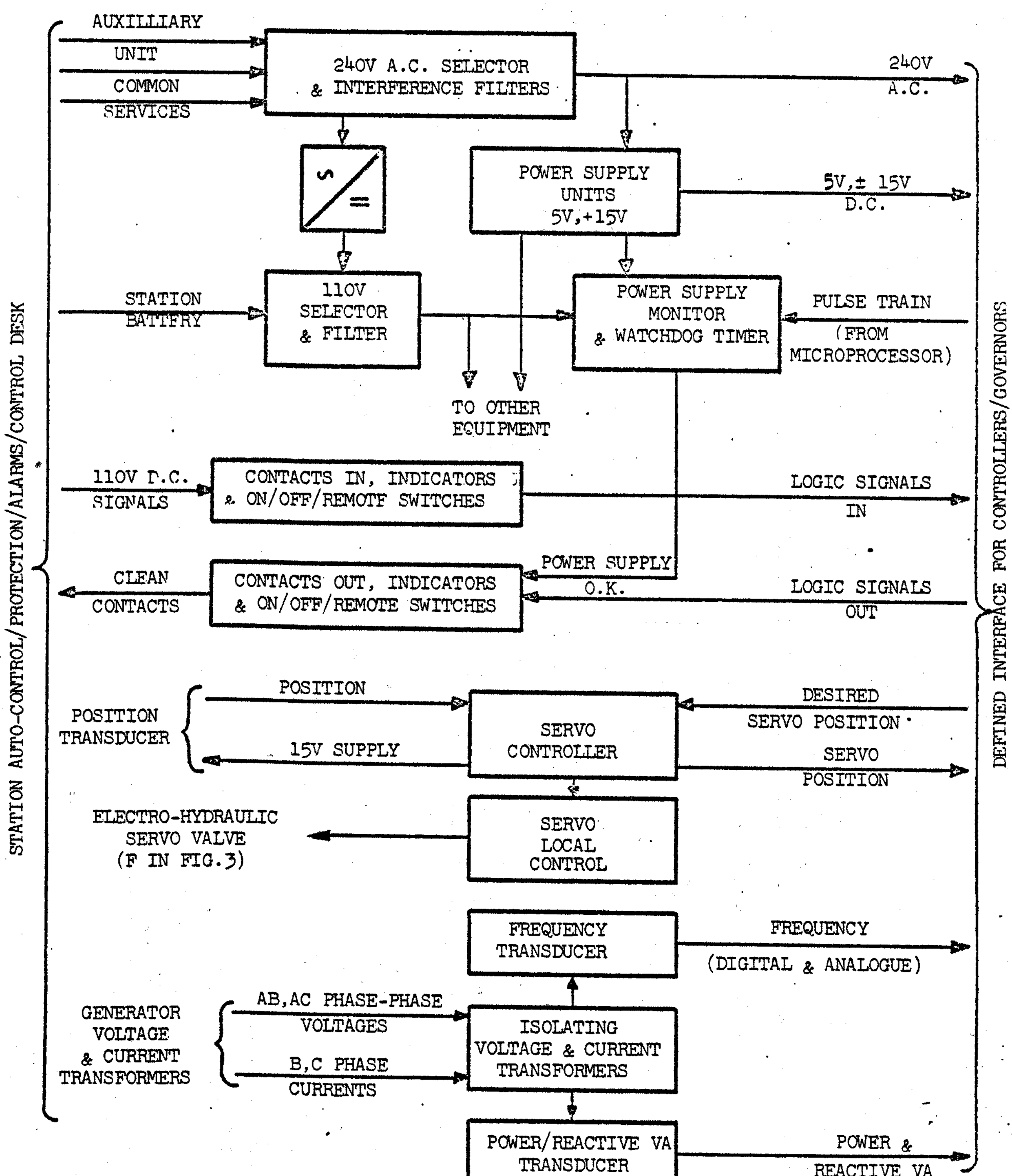


Figure 2. Principal elements of Station Interface
(Buffer amplifiers, meters for monitoring purposes
& simulation facilities are also included)

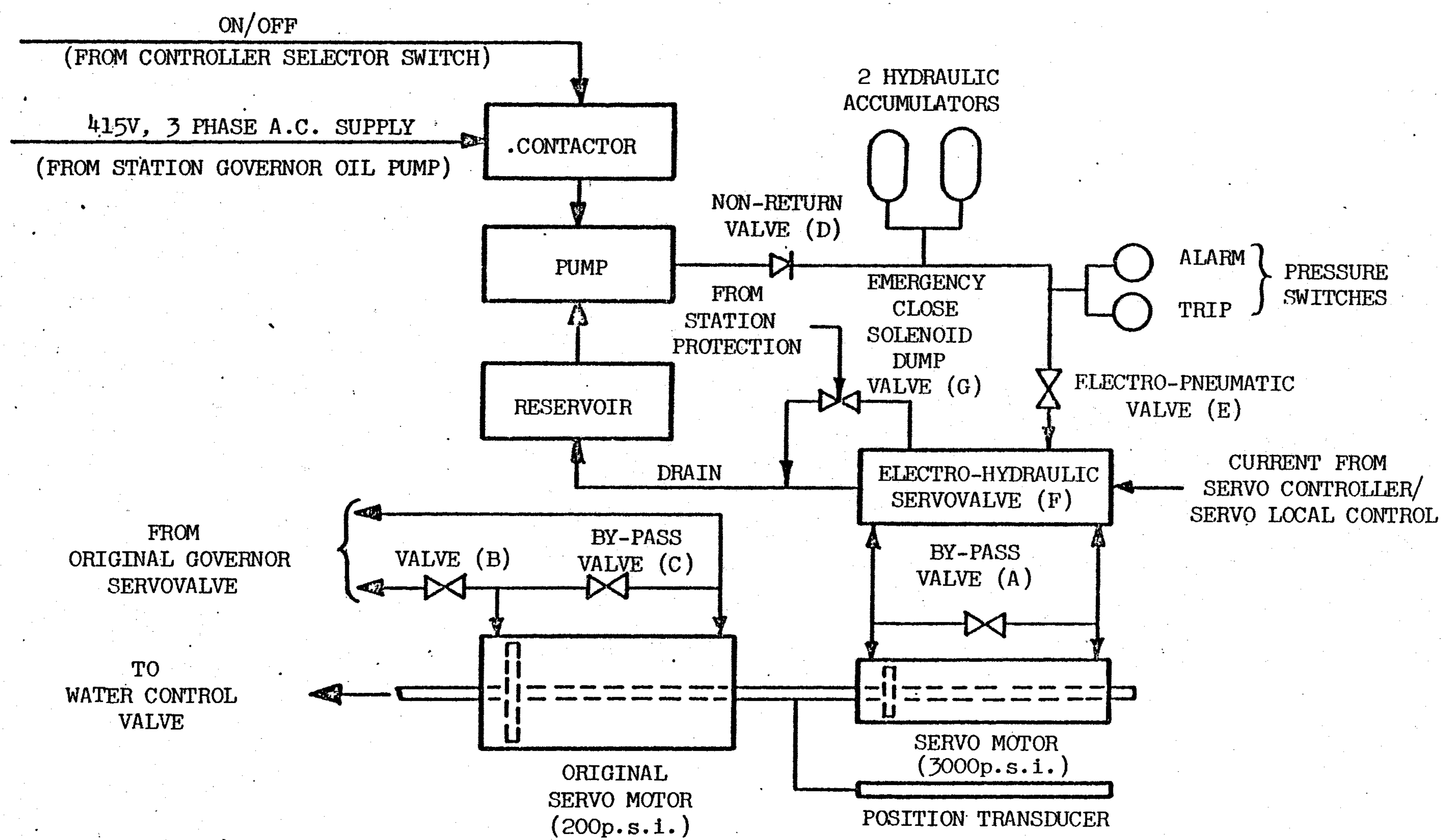
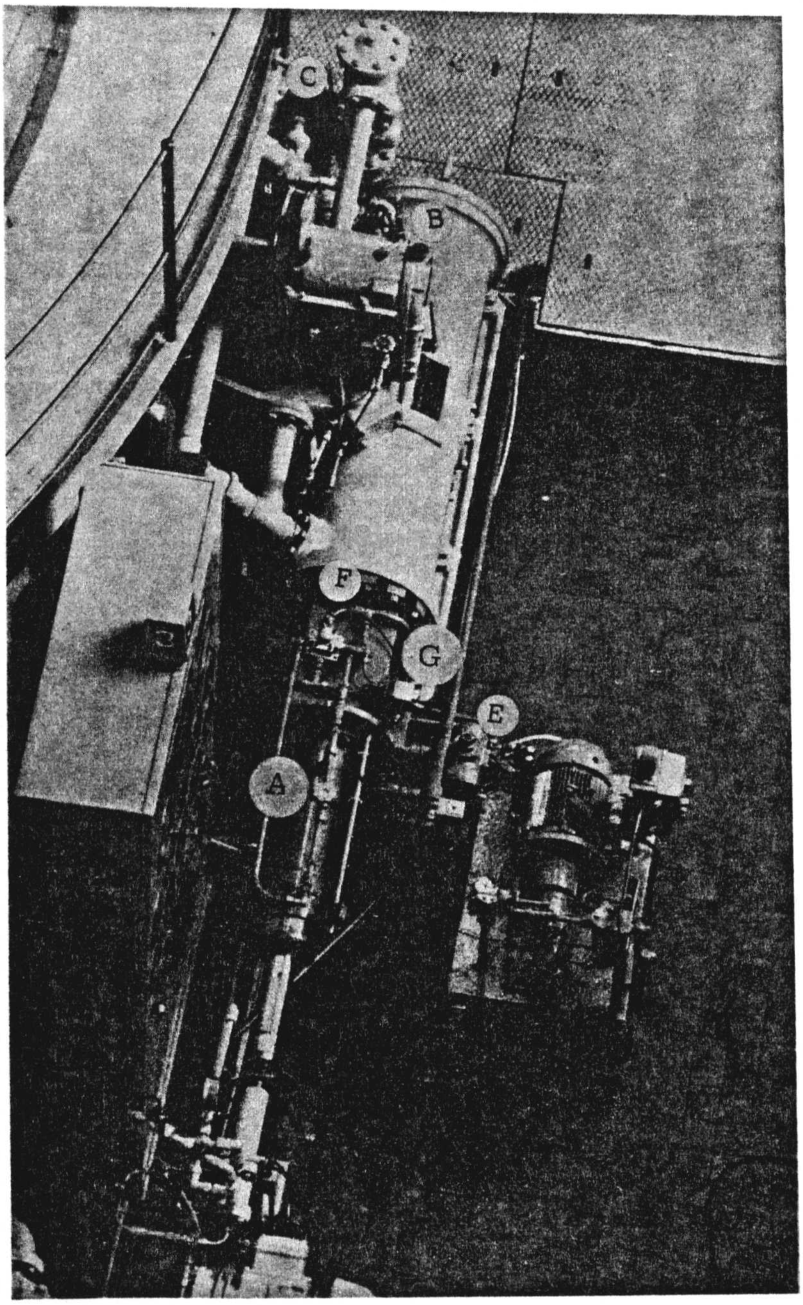


Figure 3. General arra ngement of hydraulic servo-motor system.



A. By pass Valve

B. Valve

C. By pass Valve

D. Non-return Valve (not visible on photograph)

E. Electro-pneumatic Valve

F. Electro-hydraulic Servovalve

G. Solenoid Dump Valve

Fig. 4 High and Low Pressure Hydraulic Servomotors

APPENDIX B

Example of a MODEL Routine

```
C   DFMD25.FOR   23-MAY-77       U/20-AUG-78
C   ----------   ---------       -----------
C
C   THIS MODEL REPRESENTS A PIPELINE,TURBINE AND
C   D.D. GOVERNOR. THE FIRST SECTION OF THE PIPELINE
C   EXTENDS FROM THE surge shaft  TO THE FIRST BIFIRCATION.
C   THE PIPES TO SETS ONE AND TWO ARE LUMPED INTO ONE
C   SINGLE STUB SECTION. THERE IS THEN ANOTHER SINGLE
C   PIPE SECTION LEADING TO SET NO. 3.
C   THE STUB SECTION TO SET NO. 4 IS IGNORED.
C
C   THE GOVERNOR CAN EITHER BE IN DIFFERENCE EQUATION
C   FORM OR BE 'CONTINUOUS'.
C   THE GOVERNOR OUTPUT MAY BE SUBJECTED TO RATE LIMITS,
C   AND A DITHER SIGNAL CAN BE ADDED TO THIS RATE LIMITED
C   OUTPUT.
C   BACKLASH, IN THE FORM OF HYSTERESIS, PLACED BETWEEN THE
C   MAIN SERVO OUTPUT AND ACTUAL GATE POSITION IS OPTIONAL.
C
C   THE GOVERNOR DERIVATIVE CONSTANTS AND LAG CHANGE WITH LOAD
C   FOR THREE DIFFERENT LOAD SETTINGS.
C
      SUBROUTINE MODEL(X,DX,T,M)
C
      REAL LIMIT
C
      DOUBLE PRECISION TIME ,H,TIM,ST,STEMP
C
      DIMENSION X(20),DX(20),DAT(40)
      DIMENSION VARX(2),VARY(2)
      DIMENSION VX(3),VY(3)
C
      REAL KA,KB,KC
C
      COMMON/BLK1/T3,T4,XK1,XK2,BP,TY
      COMMON/BLK2/SETF,F2,T9,E1,E2,T8,T2,TA
      COMMON/BLK3/HR,TS1,TS2,T10,KTEST,QT,KEFFIC,EFFIC
      COMMON/BLK4/KA,KB,KC,FA,FB,FC
      COMMON/BLK5/VARX,VARY,PP1,PP2,VX,VY,RLT,RLB,KNOISE,NOISE
      COMMON/BLK6/GOVOLD,BN1,CN1,GVOLD,KDIG,ST,TIM,GVIN,GVOUT
      COMMON/BLK7/KDITH,DITH,FR,KGN,GN,KEN,EN
      COMMON/BLK8/TLAG
      COMMON/BLK9/REFOLD,DXREF,KSYNC
C
      COMMON/H/MESSER,TIME,H

C
      COMMON/V/DAT
C
      X(14)=LIMIT(0.0,1.0,X(14))
      VARX(1)=X(14)
      X14=HSTRSS(VARY,VARX,PP1,PP2)
```

```
C
        QA3=X(5)+X(9)
C
C***PIPE SECTION-SURGE SHAFT TO FIRST BIFIRCATION
C
        DX(1)=FA*(3.0*HR-4.0*X(3)+X(4))
        DX(2)=FA*(HR-X(4))
        DX(3)=KA*(X(1)-QA3)
        DX(4)=KA*(-3.0*QA3+4.0*X(2)-X(1))
C
C***PIPE SECTION-STUB TO SETS ONE AND TWO
C
        DX(5)=FB*(3.0*X(4)-4.0*X(7)+X(8))
        DX(6)=FB*(X(4)-X(8))
        DX(7)=KB*X(5)
        DX(8)=KB*(4.0*X(6)-X(5))
C
C***PIPE SECTION-FIRST BIFIRCATION TO SET NO.3
C
        DX(9)=FC*(3.0*X(4)-4.0*X(11)+X(12))
        DX(10)=FC*(X(4)-X(12))
        DX(11)=KC*(X(9)-QT)
        DX(12)=KC*(4.0*X(10)-3.0*QT-X(9))
C
C***TURBINE CHARACTERISTICS
C
        IF(KTEST.EQ.0) GOTO 20
C
C***OPEN LOOP-GUIDE VANES STEP RESPONSE
C
        X(13)=1.0
        SQ=SQRT(54400.0*X(12)-20568.948*X(13)**2)
        QT=5.436786E-3*STEP(TS1,TS2,T10)*SQ
        IF(KEFFIC)200,200,30
C
C***CLOSED LOOP
C
20      IF(KSYNC.EQ.0) GOTO 24
        X(13)=1.0
        GOTO 21
24      IF(KEN.EQ.0) GOTO 21
        FREQ=1.0
        GOTO 22
21      FREQ=X(13)
22      CONTINUE
C
        QT=5.436786E-3*X14*SQRT(54400.0*X(12)-20568.948*FREQ**2)
        QT=QT*GN
        IF(KEFFIC.NE.1) GOTO 200
30      QOT=X(13)/QT/11.298691
        IF(QOT.LE.0.25) GOTO 40
        FN=227.3-228.4*QOT
        GOTO 50
40      FN=(QOT*(QOT*(-111.3*QOT+69.9)-16.27)+1.608)*1.0E3
50      TMD=X(12)*FN*1.566432E-3
```

```
          GOTO 201
200       TMD=X(12)*QT*EFFIC/FREQ
201       CONTINUE
C
C***ELECTRICAL AND GOVERNOR CHARACTERISTICS
C
          REF=STEP(SETF,F2,T9)
          GOVIN=REF-X(13)
          DX(13)=(TMD-(STEP(E1,E2,T8)*(1+EN*(-GOVIN))))/TA
          IF(KSYNC.EQ.1) DX(13)=0.0
C!!!
          POW=STEP(E1,E2,T8)/X(13)
          IF(KSYNC.EQ.1) POW=TMD
          DX(18)=(POW-X(18))/TLAG
          IF(M.EQ.0) GOTO 350
C!!!
          IF(X(18).LT.0.7) GOTO 300
          XK11=XK1
          XK22=XK2
          TYY=TY
          GOTO 350
300       IF(X(18).LT.0.4) GOTO 310
          XK11=2.5
          XK22=1.8
          TYY=0.6
          GOTO 350
310       XK11=1.8
          XK22=0.8
          TYY=0.3
350       CONTINUE
C!!!
          IF(KDIG.EQ.1) GOTO 499
C
C***CONTINUOUS GOVERNOR
C
          DXGVIN=-DX(13)
          DX(15)=(GOVIN+XK11*X(17)+X(16)-BP*X(15))/TYY
          DX(16)=(XK22*(DXGVIN-X(17))/T3-X(16))/T4
          DX(17)=(DXGVIN-X(17))/T3
          GVOUT=X(15)
          GOTO 500
C
C***SAMPLED GOVERNOR
499       IF(M.EQ.0) GOTO 500
          GVIN=GVIN+GOVIN
          TIM=TIM+H
          STEMP=ST*0.99
          IF(TIM.LT.STEMP) GOTO 500
          TIM=0.0
          GVIN=GVIN*H/ST
C         GVIN=GOVIN
          GVOUT=GVOLD
          BN=T3*BN1/(ST+T3)+XK11*(GVIN-GOVOLD)/(ST+T3)
          CN=T4*CN1/(ST+T4)+XK22/XK11*(BN-BN1)/(ST+T4)
          TL=TYY/BP
```

```
      EN=GVIN+BN+CN
      GVOLD=TL*GVOLD/(ST+TL)+ST*EN/(ST+TL)/BP
      GOVOLD=GVIN
      GVIN=0.0
      BN1=BN
      CN1=CN
C
500   CONTINUE
      IF(KDITH.EQ.0) DITH=0.0
      ADD=DITH*SIN(2.0*3.14159*FR*T)
      VX(1)=T
      VY(1)=GVOUT
      GOVOUT=RATLIM(VX,VY,RLT,RLB)
      GOVOUT=GOVOUT+ADD
      DX(14)=(GOVOUT-X(14))/T2
C
C
      IF(M.EQ.0) GOTO 10
C
      DXREF=(REF-REFOLD)/H
      REFOLD=REF
C

      DAT(1)=T
C TIME
      DAT(2)=TMD
C TURBINE TORQUE
      DAT(3)=X(13)
C FREQUENCY
      DAT(4)=X(14)
C SERVO OUTPUT
      DAT(5)=QT
C TURBINE FLOW
      DAT(6)=X(12)
C TURBINE HEAD
      DAT(7)=X(1)
C FLOW A1
      DAT(8)=X(2)
C FLOW A2
      DAT(9)=X(3)
C HEAD A2
      DAT(10)=X(4)
C HEAD A3
      DAT(11)=X(5)
C FLOW B1
      DAT(12)=X(6)
C FLOW B2
      DAT(13)=X(7)
C HEAD B2
      DAT(14)=X(8)
C HEAD B3
      DAT(15)=X(9)
C FLOW C1
      DAT(16)=X(10)
C FLOW C2
```

```
      DAT(17)=X(11)
C HEAD C2
      DAT(18)=X(15)
C CONTINUOUS GOV. OUT
      DAT(19)=X(16)
      DAT(20)=X(17)
      DAT(21)=X14
C HYST. SERVO OUT
      DAT(22)=FN
      DAT(23)=QOT
      DAT(24)=GVOUT
C GOV. OUT
      DAT(25)=GOVOUT
C GOV. OUT WITH DITHER IF REQUESTED
C
10    RETURN
      END
```

APPENDIX C

Functional Description of the Control and Interface Rack

APPENDIX C - Functional Description of the Control and Interface Rack

This appendix contains the functional description of the Control and Interface Rack which was developed and installed at Sloy Power Station. This functional description attempts to summarise the functions of each of the modules within the Rack and also indicates the interdependence of these modules. The flow of information between modules is from left to right i.e. inputs to a module entering from the left and outputs emanating from the right.

The functional description follows in Figure C.1.

FIGURE C.1

FUNCTIONAL DESCRIPTION OF THE SITE FACILITIES EXISTING ON SET NO. 3 AT SLOY

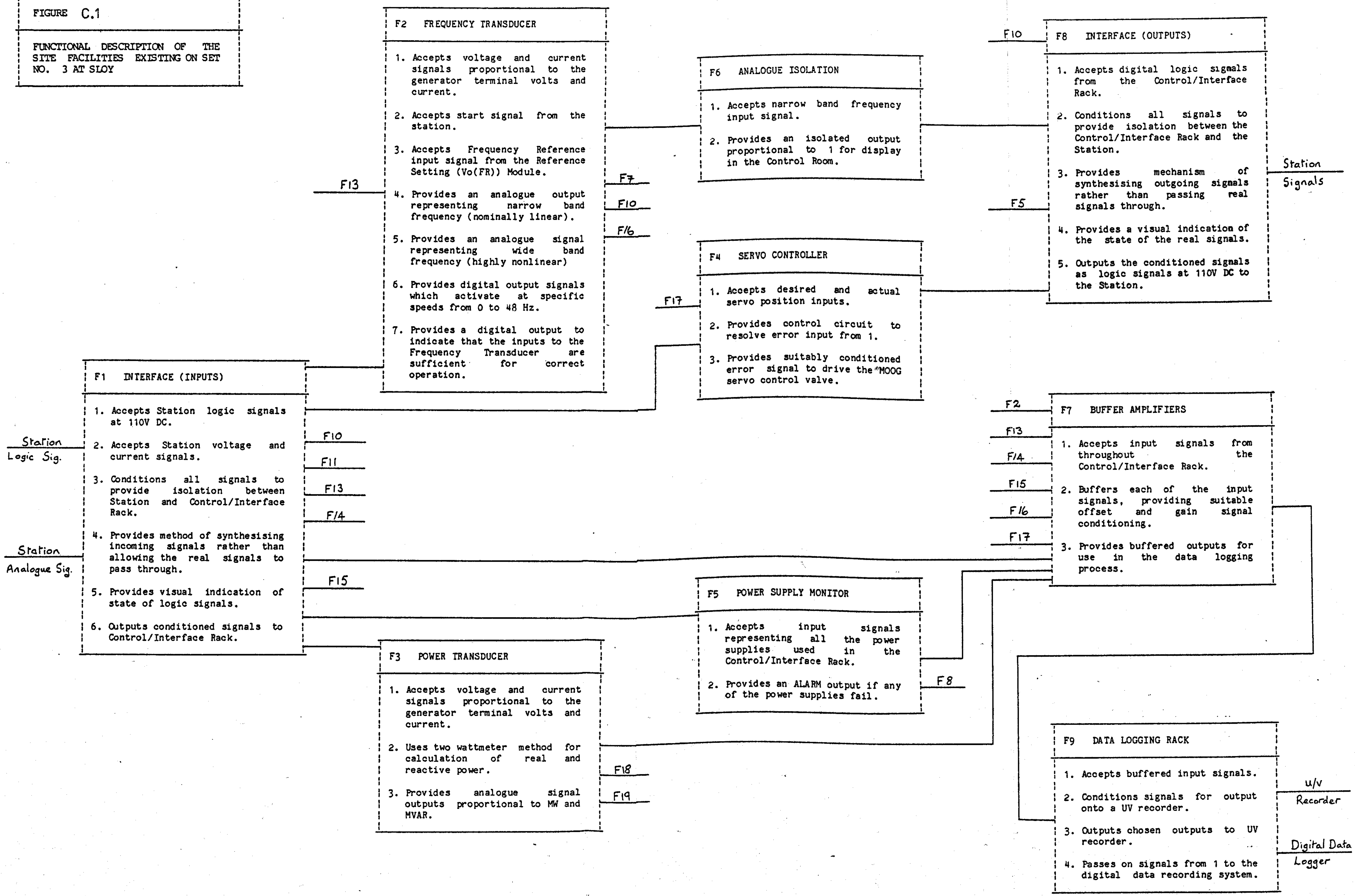


FIGURE C.1 contd.

FUNCTIONAL DESCRIPTION OF THE SITE FACILITIES EXISTING ON SET NO. 3 AT SLOY

F12 REFERENCE MODULE

1. Accepts reference choice inputs from the Reference Control Module.
2. Allows for adjustment of the reference signals.
3. Provides outputs to the Reference Setting (FR,MW,LL) Modules to provide the tracking MODE of operation with a target reference.

F10 CONTROL MODULE

1. Accepts start,main breaker closed, and start generate signals from the Station Interface.
2. Accepts digital speed and Frequency Transducer confidence signals from the Frequency Transducer.
3. Provides the necessary sequencing control to enable a logical run-up sequence. and supervisory control.
4. Generate appropriate control outputs for use in the Reference Control Module.
5. Generates ALARM signal.

F11 REFERENCE CONTROL MODULE

1. Accepts control inputs from the Control Module.
2. Accepts raise/lower and inband feedback inputs from the Reference Setting (FR,MW,LL) Modules for cancelling of tracking MODE.
3. Accepts desired "MW" inputs from the Station Interface.
4. Allows for remote or local setting of desired "MW".
5. Provides MODE control outputs destined for the Reference Setting Modules.
6. Provides outputs which choose the correct reference values in the Reference Module.

F14 REFERENCE SETTING (MW)

1. Accepts external raise/lower command inputs from the Station Interface.
2. Accepts MODE and Reference input signals.
3. Allows for local raise/lower control.
4. Allows adjustment of the raise/lower rate.
5. Provides control feedback output signal to cancel tracking MODE.
6. Provides one analogue and 8 digital outputs representing the current desired "MW" setting.

F15 REFERENCE SETTING (LL)

1. Accepts external raise/lower command inputs from the Station Interface.
2. Accepts MODE and Reference input signals.
3. Allows for local raise/lower control.
4. Allows adjustment of the raise/lower rate.
5. Provides control feedback output signal to cancel tracking MODE.
6. Provides one analogue and 8 digital outputs representing the current desired "LL" setting.

F13 REFERENCE SETTING (FR)

1. Accepts external raise/lower command inputs from the Station Interface.
2. Accepts MODE and Reference input signals.
3. Allows for local raise/lower control.
4. Allows adjustment of the raise/lower rate.
5. Provides control feedback output signal to cancel tracking MODE.
6. Provides one analogue and 8 digital outputs representing the current desired "FR" setting.

F16 ANALOGUE GOVERNOR MODULE

1. Accepts narrow band frequency signal from the Frequency Transducer for calculation of the current desired servo position.
2. Accepts a test frequency input which is added to the narrow band frequency input signal (used with ILS when frequency deadband set in Frequency Transducer).
3. Accepts an analogue input representing the current desired "MW" value.
4. Accepts an analogue input representing the current desired "LL" value.
5. Accepts a test analogue input which is added to the desired servo position (used for dither experiments).
6. Provides a desired servo position output in accordance with the inputs in 1,2,3,4 and 5.
7. Provides a rate limited output of the narrow band frequency signal

F17 GOVERNOR CHANGEOVER MODULE

1. Accepts desired servo position from the Analogue Governor.
2. Accepts desired servo position from the Microprocessor Governor.
3. Accepts watchdog signal from the Microprocessor Governor.
4. Provides a rate limited desired servo position output which is a choice of 1 or 2 depending on front panel switches.
5. Provides autochangeover mechanism from Microprocessor to Analogue Governor output if 1 and 2 disagree greatly.
6. Provides an ALARM output if the watchdog signal fails or the autochangeover mechanism operates.

F18 MICROPROCESSOR GOVERNOR

1. Accepts rate limited narrow band frequency from the Analogue Governor Module for calculation of current desired servo position.
2. Accepts megawatt signal from the Power Transducer to determine which governor band is applicable when using the Adaptive Governor.
3. Accepts 8 digital inputs which indicate which governor is operational.
4. Accepts 8 digital inputs which represent the current desired "MW" value.
5. Accepts 8 digital inputs which represent the current "LL" value.
6. Provides an analogue desired servo position output in accordance with the inputs provided in 1,2 3,4 and 5.
7. Provides a digital watchdog output signal to indicate continuing operation of the Microprocessor Governor.

F19 ISOLATED LOAD SIMULATOR

1. Accepts MW input signal from the Power Transducer.
2. Simulates Machine Inertia and provides for an adjustable load self regulation factor.
3. Provides controls to adjust the following:
   a. Machine Inertia.
   b. Load Power Balance.
   c. Load Power Disturbance.
   d. Self Regulation Factor.
4. Outputs a simulated frequency error signal.

APPENDIX D

Description of the floating point package

APPENDIX D - Description of the floating point package

a) General format of the package.

This software was written in such a way that most of the code could be stored in read only memory space. A small section of read/write (RAM) memory is necessary for use as scratch pad working space. This area of RAM contains the two operands of any calculation, i.e. the Floating Accumulator (Fl.Acc.) and the Floating Operand (Fl. Op.) The result of any calculation is always left in the Fl.Acc.

The Fl.Acc and Fl.Op each occupy five bytes. The first byte represents the exponent, and being of 2's complement form this gives a range of 2 * * (+127) to 2 * * (-128). The remaining four bytes form the mantissa although the accuracy is always taken to three bytes. The mantissa is also of 2's complement form.

When called upon to perform an arithmetic operation the package will assume that both the Fl.Acc. and Fl. Op. are normalised, i.e both mantissas are in the range, $1 > \text{mantissa} \geq \frac{1}{2}$.

If the user wishes to place a value in either the Fl.Acc or Fl.Op. then two precautions must be observed. Assuming three byte mantissa accuracy then the fourth byte of the mantissa should be zeroed, and the mantissa should be normalised, unless a subsequent call to the normalisation routine is made. Additionally, in multiplication, addition and subtraction operations, the Fl.Op. will most likely be corrupted from its original value so it will have to be given a new value before the next operation.

b) Subroutines of the package.

Table D1 lists the subroutines of the package and gives a description of their functions.

Subroutine Call	Function
FNORM	The mantissa resident in the Fl.Acc. is normalised to within the range $1 > \text{mantissa} \geq \frac{1}{2}$, and the exponent is adjusted accordingly.
FMULT	The Fl. Acc. and Fl.Op. are multiplied together and the normalised result is left in the Fl. Acc.
FLAD	The Fl .Op. is added to the Fl.Acc and the result is normalised and left in the Fl.Acc.
FLSU	The Fl.Op. is subtracted from the Fl.Acc. and the result is normalised and left in the Fl.Acc.
ACNEG	The content of the Fl.Acc. is negated.
OPNEG	The content of the Fl.Op. is negated.

Subroutine Call	Function
FIX	The floating point content of the Fl. Acc. is fixed to a 2's complement integer of sixteen bits. This result is left in the two MS bytes of the Fl. Acc. mantissa. For floating point values less than ½ a zero result is returned. For values greater than 2 * * 15 -1 a result of 2 * * 15 - 1 is returned. Similarly -2 * * 15 is returned for initial values less than -2 * * 15. (After returning from this routine the carry bit will be set if an overrange condition occurred).
FLOAT	The two MS bytes of the Fl.Acc mantissa are assumed to contain a 16 bit, 2's complement integer. This integer is normalised and the Fl.Acc. exponent adjusted appropriately, leaving the floating point representation of the integer in the Fl.Acc.

Table D1

APPENDIX E

Load Limit Algorithm

APPENDIX E - Load Limit Algorithm

For clarity, the diagram of Fig. 6.10 is repeated here in Fig. E.1.

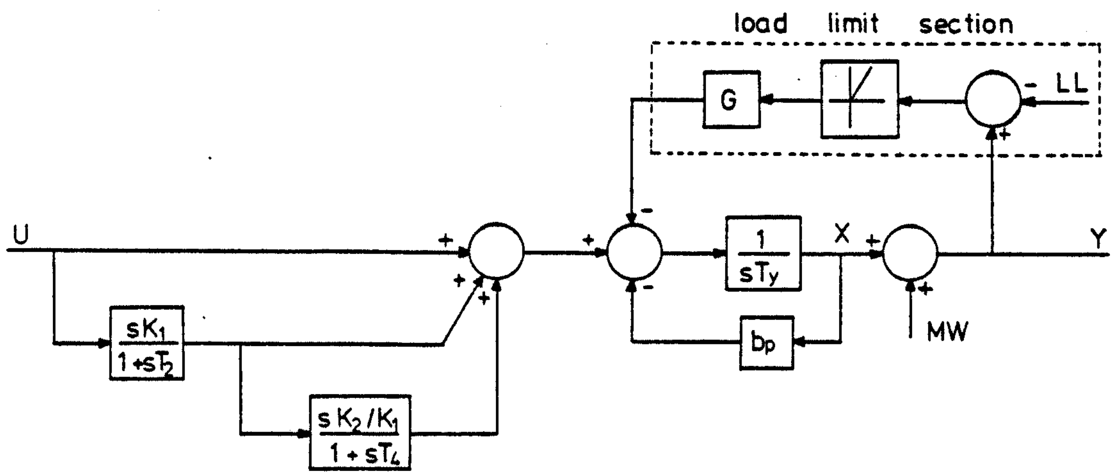


Figure E.1 DD governor including SET MW and SET LL controls

An analogue governor module would very nearly ape the block diagram representation of Fig. E.1. The gain element, G, following the one sided transfer characteristic of the LL loop, would adopt a large value such that, assuming Y > LL, the resultant error signal, Y - LL, would be greatly amplified. This large signal would swamp all others at the summing junction so as to force Y towards the desired value given by LL.

This can be further clarified by considering the final part of the governor as shown in Fig. E.2. For simplicity the MW summing junction has been omitted and it is assumed that Y > LL so that the limiter is operational.

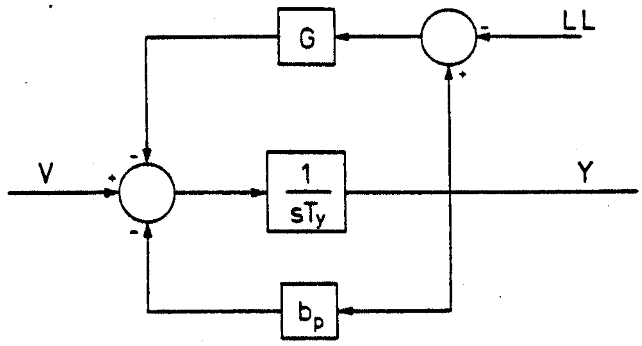


Figure E.2 Output section of DD governor with LL operational

The transfer function for this system is

$$Y(sT_y + b_p + G) = V + G.LL$$

but with G very large then G >> bp and G.LL >> V so the transfer function becomes

$$Y = \frac{1}{1 + sT_y/G} LL$$

This is a first order lag of unity gain and time constant T_y/G. Take, for example, $T_y = 1.0$ and $G = 100$ then the time constant is very short at 0.01s.

This analogue technique could have been copied in the microprocessor governor but it was thought that digital techniques would lend themselves to a simpler solution. This turned out not to be strictly true, but the end result in the digital domain had an additional feature that the analogue equivalent could not have easily included. Namely, the prevention of a false exit from the LL condition due to the nature of the double derivative action.

In the following discussions the step responses shown in the diagrams follow the same pattern - an initial spike then an exponential drift towards a steady state. Each breakpoint in this response occurs at consecutive sampling intervals but for simplicity vectors connect the series of samples as shown in Fig. E.3. In the actual MPU governor this first order hold construction of the output is replaced by the simpler zero order hold.

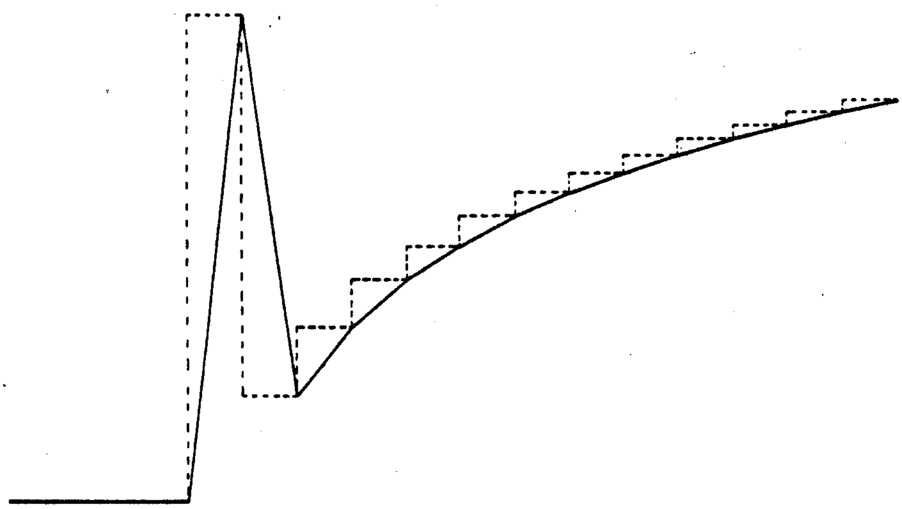


Figure E.3 Zero order and first order hold constructions of the DD governor step response

For convenience the equations, in difference form, for the DD governor are repeated here

$$j_n = P_1 \, j_{n-1} + P_2 (u_n - u_{n-1})$$

$$r_n = P_3 \, r_{n-1} + P_4 (j_n - j_{n-1})$$

$$v_n = u_n + j_n + r_n$$

$$x_n = P_5 \, v_n + P_6 \, x_{n-1}$$

$$y_n = x_n + m w_n$$

In the MPU governor the simplest way to obey a LL condition, if it existed, would be to limit x_n by assigning it the value given by the LL - MW.

This practice would be quite adequate apart from the situation depicted by Fig. E.4. Here are shown two separate governor output responses to a step input. One is the correct response but the other illustrates the drastic effect on the output by implementing the LL through presetting of the algorithm parameter x_n. It is on the subsequent sampling interval when things go wrong after the preset value of x_n has become the past value x_{n-1}, and so influences the present calculation of y_n.

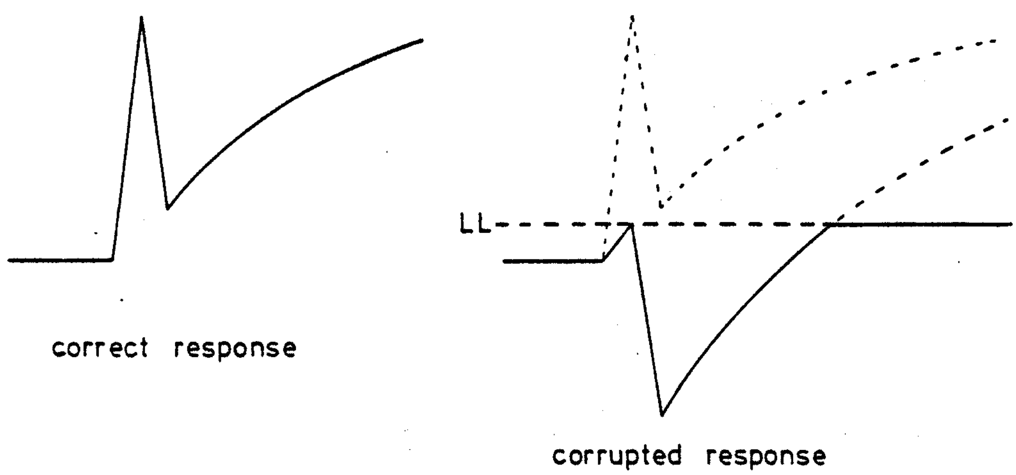


Figure E.4 Effect on step response through a direct presetting LL algorithm

The second attempt at solving this problem takes advantage of the fact that x_n is the floating point value of the governor output. The actual output that the real world sees is an analogue signal derived from a 12 bit integer equivalent of y_n. Here it is the 12 bit integer that is limited if a LL condition exists. As x_n remains unchanged then the floating point algorithm will drift on upwards past the limit, although the outside world will not perceive this.

To aid recovery from this limit situation an additional signal is computed, which is

$$xdc_n = \frac{u_n}{b_p} \quad \text{so } ydc_n = xdc_n + mw_n$$

This represents the final steady state value of the output due to the frequency error input, u_n.

Thus if y_n is still in the limit but ydc_n indicates that the limit constraints are no longer valid then a single setting of x_n is implemented such that x_n is set to LL - MW. Therefore the output y_n is positioned on the limit, ready to emerge, rather than having to wait for x_n to catch up with u_n demands through the governor's dominant lag.

Fig E.5 and Fig. E.6 attempt to clarify the above for the conditions of an upward step into the limit and a downward step out of the limit, respectively.

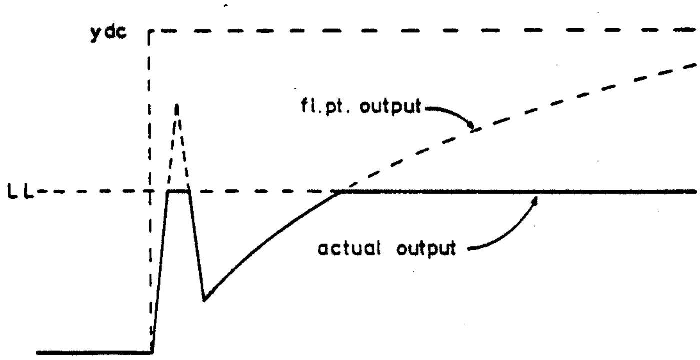


Figure E.5 Step response into the LL incorporating a simple ydc estimate

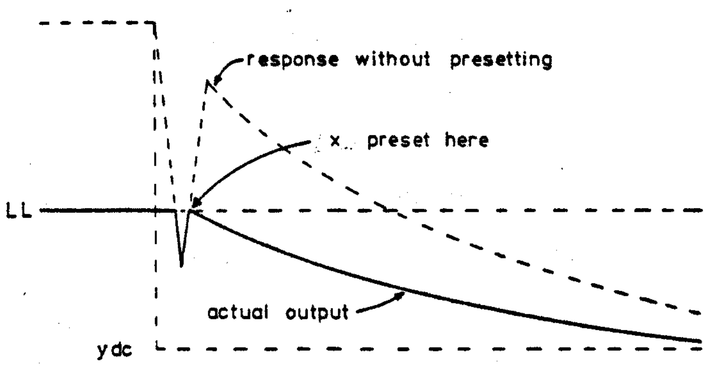


Figure E.6 Step response out of the LL incorporating a simple ydc estimate

In the final governor algorithm all but one of the different governors uses this form of limiting. The one governor which proved difficult to satisfy by this method was the DD (33.3s) type in which $T_2 = T_4 = 0$.

The peculiarity of this governor is the fact that the initial spike at the output, due to a step at the input, overshoots the final value. The danger here is false presetting of x_n as Fig. E.7 illustrates. The LL is positioned between ydc_n and the maximum of the output peak with the result that the output is preset to the LL after its rise to the peak. The subsequent falling edge drops an additional amount given by the difference between the peak maximum and the LL.

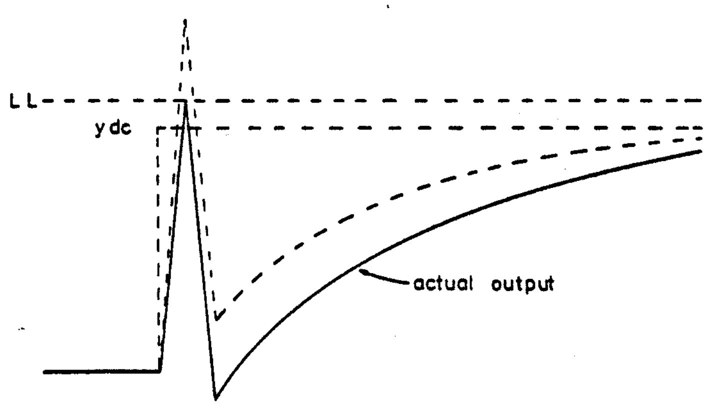


Figure E.7 False presetting of y_n due to output peak rising above ydc_n

The problem was overcome by giving xdc a hint of the characteristics of the real output. By adding a small amount of first order derivative action to xdc the steady state value of the output could be made to follow the governor output over transient phases.

Thus the expression for xdc_n becomes,

$$xdc_n = \frac{u_n}{b_p} + K_{dc}\frac{(u_n + u_{n-1})}{T}$$

In the case where $T_2 = T_4 = 0$ and $T = 0.1$s then the governor output overshoots the steady state value by approximately 16% of u_n/bp, when a step is applied at the input. For the derivative section of xdc_n to compensate for this deficit then K_{dc} must take on a value of approximately 0.533.

APPENDIX F

Listing of Microprocessor Governor in its Final Form

```
;*************************************************************************
;*************************************************************************
;**                                                                     **
;**              DFGOVN.SBC      24-AUG-77       U/03-OCT-78            **
;**              ----------      ---------       -----------            **
;**                                                                     **
;**       RUNS IN THE INTEL SBC 80/10 MPS                               **
;**       FOR USE WITH THE ANALOGUE DEVICES RTI-1200 DATA AQUISITION    **
;**       BOARD. ANALOGUE CH.0 IS USED FOR FREQUENCY ERROR INPUT,       **
;**       CH.1 IS USED FOR POWER INPUT AND DAC.1 IS USED FOR            **
;**       THE GOVERNOR OUTPUT.                                          **
;**                                                                      *
;**       ALGORITHM, IN DIFFERENCE EQUATIONS , WHICH REPRESENTS         **
;**       A DOUBLE DERIVATIVE GOVERNOR                                  **
;**       8 BIT LOAD LIMIT AND SET MW SIGNALS ARE READ                  **
;**       IN AND PROCESSED.                                             **
;**       VARIOUS DIFFERENT GOVERNOR PARAMETERS MAY BE SELECTED BY A    **
;**       SUITABLE CHOICE OF THE SWITCH SETTINGS WHICH ARE CONNECTED TO **
;**       PORT 3. THE THREE BAND ADAPTIVE GOVERNORS ARE SELECTED BY THIS **
;**       MECHANISM.                                                    **
;**       THE ADAPTIVE GOVERNORS DECIDE WHICH SET OF ITS THREE SETS OF  **
;**       GOVERNOR PARAMETERS TO USE BY MONITORING THE MACHINE POWER.   **
;**       THE DECISION IS MADE AFTER SUBJECTING THE POWER MEASUREMENT   **
;**       TO A FIRST ORDER LAG.                                         **
;**                                                                     **
;**       AS THE LL AND MW SIGNALS CONSIST OF THE TOP 8 BITS OF THE 12 BIT**
;**       OUTPUT, IT WAS FOUND THAT CHANGES IN THE LL OR MW SIGNALS     **
;**       RESULTED IN AN OVER COURSE RESPONSE AT THE OUTPUT.            **
;**       TO OVERCOME THIS, THE ROUTINE NOW OUTPUTS DURING EVERY INTERRUPT**
;**       (10 PER INTEGRATION CYCLE) INCREMENTING OR DECREMENTING BY 1 LSB**
;**       IN 12 TO ANY DEMAND OF CHANGE BY THE LL OR MW.                **
;**       IN ADDITION AN ATTEMPT HAS BEEN MADE TO TRY TO REDUCE THE NOISE **
;**       AT THE INPUT BY SAMPLING THE INPUT EVERY INTERRUPT, THEN TAKING **
;**       AN AVERAGE VALUE AT THE BEGINNING OF EVERY INTEGRATION CYCLE. **
;**                                                                     **
;**       SYSTEM EQUATIONS                                              **
;**       ----------------                                              **
;**                                                                     **
;**       B(N)=P1*B(N-1)+P2*(U(N)-U(N-1))                               **
;**       C(N)=P3*C(N-1)+P4*(B(N)-B(N-1))                               **
;**       E(N)=U(N)+B(N)+C(N)                                           **
;**       X(N)=P5*E(N)+P6*X(N-1)                                        **
;**        AND FOR USE IN DETERMINING THE LL CONDITION                  **
;**       XDC(N)=P7*U(N)+P8*(U(N)-U(N-1))                               **
;**       IF X(N)+MW-LL AND XDC(N)+MW-LL ARE +VE THEN Y(N)=LL AND X(N)  **
;**       IS LEFT ALONE.                                                **
;**       BUT IF X(N)+MW-LL IS +VE AND XDC(N)+MW-LL IS -VE THEN Y(N)=LL **
;**       AND X(N)=LL-MW.                                               **
;**       SIMILARLY, IF X(N)+MW < 0 AND XDC(N)+MW < 0 THEN Y(N)=0 AND   **
;**       X(N) IS LEFT ALONE.                                           **
;**       BUT IF X(N)+MW < 0 AND XDC(N) > 0 THEN Y(N)=0 AND X(N)=0      **
;**                                                                     **
;**       THE CONSTANTS P5 AND P7 AND THE VALUE OF X(N-1) ALL           **
;**       INCLUDE THE OUTPUT SCALING FACTOR OF 10/11*2**12.             **
```

```
;**      THE VALUE OF THE CONSTANTS ARE GIVEN BY:-                          **
;**                                                                         **
;**      P1=T2/(T+T2)                                                       **
;**      P2=K1/(T+T2)                                                       **
;**      P3=T4/(T+T4)                                                       **
;**      P4=K2/K1/(T+T4)                                                    **
;**      P5=T/BP/(T+TL)*10/11*2**12                                         **
;**      P6=TL/(T+TL)                                                       **
;**      P7=1/BP*10/11*2**12                                                **
;**              WHERE TL=TY/BP                                             **
;**      P8 IS ONLY NON ZERO IF THE GOVERNOR OUTPUT CAN OVERSHOOT ITS       **
;**      FINAL VALUE DUE TO EXCESSIVE D.D. ACTION, AS CAN HAPPEN, FOR       **
;**      EXAMPLE, IN THE D.D. GOV. FOR WHICH T2=T4=0.                       **
;**      IN THIS CASE P8 TAKES ON A VALUE WHICH ALLOWS THE PREDICTED        **
;**      DC VALUE TO FOLLOW THE ACTUAL GOVERNOR OUTPUT OVER THE INITIAL     **
;**      DISTURBANCE OF A TRANSIENT, THUS REDUCING THE POSSIBILITY OF       **
;**      FALSELY PRESETTING THE OUTPUT OF THE FL.PT. ALGORITHM.             **
;**                                                                         **
;**      P1-P7 ARE CONSTANTS CONTAINING THE SAMPLING                        **
;**      PERIOD, T. - REFER TO DFKONN.FOR FOR VALUES                        **
;**      P1TD-P8TD ARE CONSTANTS USED BEFORE AND UP TO SYNCHRONISATION.     **
;**      THEY ALTER THE GOVERNOR CHARACTERISTICS FROM A D.D.                **
;**      GOV. WITH DOMINANT LAG OF 33.3,20, OR 10SECS OR TO A T.D. GOV.     **
;**      WITH A DOMINANT LAG OF 160 SECS.                                   **
;**      U(N)[GOVIN] IS THE FREQUENCY DIFFERENCE AT TIME N                  **
;**      Y(N)[GOVOUT] IS THE PILOT SERVO MOTOR OUTPUT AT TIME N             **
;**                                                                         **
;**      ORDER OF EVENTS:-                                                  **
;**      ----------------                                                   **
;**                                                                         **
;**      INPUT U(N) - CALCULATE -WAIT FOR END OF                            **
;**      SAMPLING PERIOD -OUTPUT Y(N)- REPEAT.                              **
;**                                                                         **
;****************************************************************************
;****************************************************************************
;
;
;               DESCRIPTION OF I/O CONTROL SIGNALS
;               ----------------------------------
;
;        INPUT SIGNALS
;        -------------
;
;        SYNC (BIT 5-PORT 3)-SIGNAL IS HELD LOW DURING
;          RUN UP THEN BROUGHT HIGH AFTER SYNCHRONISATION.
;
;        SEE INPUT: FOR FURTHER DETAILS OF THE USE OF PORT 3 INPUT LINES.
;
;        OUTPUT SIGNALS
;        --------------
;
;        WATCH DOG TIMER (BIT 0-PORT 6)-THIS SIGNAL INDICATES CORRECT
;          CYCLIC OPERATION OF THE MPS. IT IS SET AT THE BEGINNING OF THE
;          THE ALGORITHM AND RESET AT THE END OF THE ALGORITHM.
;
```

```
;
;       28 LINES OF I/O HAVE BEEN FREED DUE TO THE INCLUSION OF THE
;         RTI-1200. HOWEVER, THE I/O PORTS ARE CONFIGURED IN EXACTLY
;         THE SAME WAY AS IN DFGOVX.SBC WHICH MEANS THAT THE
;         I/O TERMINATORS REMAIN THE SAME FOR BOTH GOVERNOR ROUTINES.
;
;                           I/O TERMINATORS
;                           ---------------
;
;PORT   DIRECTION         LOWER 4 BIT SOCKET        UPPER 4 BIT SOCKET
;----   ---------         ------------------        ------------------
; 1     INPUT (J41-42)     A1-INTEL 8226            A2-INTEL 8226
; 2     INPUT              A6-SBC 902                A5-SBC 902
; 3 LOW INPUT              A3-SBC 902
; 3 UP  INPUT                                        A4-SBC 902
; 4     OUTPUT             A7-7408                   A8-7408
; 5     INPUT              A21-SBC 902               A11-SBC 902
; 6 LOW OUTPUT             A10-7408
; 6 UP  OUTPUT                                       A9-7408
;
;
;
PORT1   =344    ;(E4) SET MW SIGNAL.
PORT2   =345    ;(E5) NOT USED
PORT3   =346    ;(E6) LOWER 4 BITS-NOT USED
;               ;     UPPER 4 BITS-(MSB)BLANK-BLANK-SYNC-BLANK
CTLPL1  =347    ;(E7) PARALLEL I/O DEVICE 1-CONTROL REGISTER.
;
PORT4   =350    ;(E8) NOT USED
PORT5   =351    ;(E9) LOAD LIMIT SIGNAL.
PORT6   =352    ;(EA) LOWER 4 BITS-BLANK-BLANK-BLANK-WATCH DOG(LSB).
                ;     UPPER 4 BITS-NOT USED
CTLPL2  =353    ;(EB) PARALLEL I/O DEVICE 2-CONTROL REGISTER.
;
;       RTI-1200 REGISTERS
;       ------------------
;
ADCLO   =177775 ;ADD. OF LOWER BYTE OF ADC DATA - READ
STATUS  =177774 ;ADD. OF RTI STATUS REGISTER    - READ
CNVCMD  =177773 ;ADD. OF CONVERT COMMAND REG.   - WRITE
MUXADR  =177772 ;ADD. OF MULTIPLEXER REG.       - READ/WRITE
GNSEL   =177771 ;ADD. OF GAIN SELECT REG.       - READ/WRITE
DAC1LO  =177766 ;ADD. OF LOWER BYTE OF DAC1     - WRITE
DAC2LO  =177764 ;ADD. OF LOWER BYTE OF DAC2     - WRITE
SETUP   =177760 ;ADD OF RTI SETUP REGISTER      - WRITE
;
;       FLOATING POINT ROUTINE ADDRESSES
;       --------------------------------
;
ACNEG   =6213   ;ADD. OF ROUTINE TO NEGATE FL. ACC.
FLAD    =6512   ;ADD. OF ROUTINE TO ADD FL. OP. TO FL. ACC.
FLMY    =6000   ;ADD. OF ROUTINE TO MULTIPLY FL. ACC. BY FL. OP.
FLOAT   =7350   ;ADD. OF ROUTINE TO FLOAT UPPER 2 BYTES OF FL. ACC.
FLSU    =6575   ;ADD. OF ROUTINE TO SUBTRACT FL. OP. FROM FL. ACC.
FIX     =7506   ;ADD. OF ROUTINE TO FIX FL. ACC. TO A 16-BIT INT.
```

```
FNORM   =6057   ;ADD. OF ROUTINE TO NORMALISE FL. ACC.
;
;       RAM MEMORY USAGE:
;       -----------------
;
;       FLOATING POINT REGISTER AND PARAMETER ADDRESSES
;       -----------------------------------------------
;
EX1     =36100  ;ADD. OF FL. OP. EXPONENT
EX2     =36105  ;ADD. OF FL. ACC. EXPONENT
HY2     =36106  ;ADD. OF MS BYTE OF FL. ACC.
LW2     =36110  ;ADD. OF LS BYTE OF FL.ACC.
POINT   =36123  ;ADD. FOR ADD. OF AN INDIRECT CALL
SIGN    =36130
;
;       GOVERNOR ROUTINE PARAMETER AND BUFFER SPACE
;       -------------------------------------------
;
XN1     =36140  ;ADD. OF FL. GOV. OUTPUT (AT T=N-1)
UN1     =36144  ;ADD. OF FL. GOV. INPUT (AT T=N-1)
BN1     =36150  ;ADD. OF FL. INTERNAL GOV. VARIABLE (AT T=N-1)
CN1     =36154  ;ADD. OF FL. INTERNAL GOV. VARIABLE (AT T=N-1)
STORE   =36160  ;ADD. OF TEMPORARY FL. STORAGE AREA
XFN     =36164  ;ADD. OF DC. GOV. OUTPUT (16-BIT INTEGER)
UPOINT  =36166  ;NOT IN USE
K       =36170  ;NOT IN USE
PPOINT  =36171  ;POINTS TO CHOSEN GOV. CONSTANTS
STATIN  =36173  ;NOT IN USE
TIMCNT  =36174  ;HOLDS 10MS COUNT LEFT IN INTEG. INTERVAL
XNDC    =36175  ;NOT IN USE
MWOLD   =36201  ;CURRENT MW SIGNAL FOR OUTPUT
XN      =36203  ;CURRENT GOV. OUTPUT (INTEGER) FOR OUTPUT
LLOLD   =36205  ;CURRENT LL SIGNAL FOR OUTPUT
MWLL    =36207  ;STORAGE FOR MW-LL (INTEGER)
DIRMW   =36211  ;DIFFERENCE; DEMANDED MW-OUTPUT MW
DIRLL   =36213  ;DIFFERENCE; DEMANDED LL-OUTPUT LL
BUFPNT  =36215  ;POINTER TO INPUT BUFFER IN USE
BUFADD  =36216  ;ADD. POINTER TO INPUT BUFFER IN USE
BUF1    =36220  ;INPUT BUFFER 1
BUF2    =36244  ;INPUT BUFFER 2
CUROUT  =36270  ;CURRENT TOTAL OUTPUT MW+XN
LIMEX   =36272  ;INDICATES WHICH LIMIT CONDITION EXISTS
UDIFF   =36300  ;FREQ. INPUT DIFFERENCE U(N)-U(N-1)
;
PWOUT   =36304  ;FL. POINT LAGGED POWER INPUT; PWOUT(N-1)
PWBFAD  =36310  ;ADD. POINTER TO POWER BUFFER IN USE.
PWBFPT  =36312  ;POINTER TO POWER BUFFER IN USE
PWBF1   =36313  ;POWER BUFFER 1
PWBF2   =36337  ;POWER BUFFER 2
;


        ORG 0                   ;POWER ON RESET VECTOR
;
```

```
        DI
        JMP     PROG
;
        ORG 70                  ;SBC 80/10 INTERRUPT VECTOR
;
        PUSH    PSW             ;SAVE REGISTERS
        PUSH    B
        PUSH    D
        PUSH    H
        JMP     SERVIC          ;GOTO INTERRUPT SERVICE ROUTINE
;
        ORG 100                 ;START OF MAIN PROGRAM

;INITIALISATION OF CONSTANTS IN AREA OF RAM.
;
PROG:   XRA     A
        MVI     B,273           ;ZERO LOCATIONS EX1 TO UN.
        LXI     H,EX1
MOVE1:  MOV     M,A
        INX     H
        DCR     B
        JNZ     MOVE1
        MVI     A,1             ;INITIALISE BUFFER SPACE AND POINTER.
        STA     BUFPNT
;!!!
        STA     PWBFPT
;!!!
        LXI     H,BUF1
        SHLD    BUFADD
;!!!
        LXI     H,PWBF1
        SHLD    PWBFAD
;!!!
        LXI     H,POINT
        MVI     A,315           ;CODE FOR 'CALL' TO POINT IN FL.PT.PKG.
        MOV     M,A
        LXI     H,POINT+3
        MVI     A,311           ;CODE FOR 'RET' TO POINT IN FL.PT.PKG.
        MOV     M,A
;
;
;SBC PARALLEL PORT INITIALISATION.
;
        MVI     A,233           ;MODE 0-INPUT FOR-
        OUT     CTLPL1          ;PORTS 1,23.
        MVI     A,202           ;MODE 0-OUTPUT FOR PORTS 46-
        OUT     CTLPL2          ;MODE 0-INPUT FOR PORT 5
;
;INITIALISATION OF STACK POINTER,CLOCK AND WATCH DOG.
;
        LXI     SP,40000        ;TOP OF FIRST 16K.
        XRA     A               ;CLEAR WATCH DOG SIGNAL
        OUT     PORT6
        MVI     A,12            ;INITIALISE COUNT FOR NO. OF-
        STA     TIMCNT          ;10MS PERIODS PER SAMPLING INTERVAL.
```

```
        XRA     A
        STA     MUXADR          ;SELECT ADC CH.0.
        STA     GNSEL           ;SELECT ADC GAIN OF 1.
        LDA     STATUS          ;CLEAR STATUS.
        MVI     A,3
        STA     SETUP           ;START THE CLOCK.
        EI
;       CALL    TIMUP           ;WAIT FOR ONE SAMPLING INTERVAL.
;
;
;BEGINNING OF GOVERNOR ROUTINE.
;
;
INPUT:  MVI     A,1             ;CONTROL REG. 2-
        OUT     CTLPL2          ;SETS WATCH DOG
        IN      PORT3           ;TEST STATE OF SYNC SIGNAL
        MOV     B,A
        ANI     40
        JZ      SYNLAG          ;PORT 3; BIT 5 LOW-T.D. CONSTANTS.
        MVI     A,100
        ANA     B
        JZ      DD01            ;PORT 3; BIT 6 LOW-D.D.(T2=T4=0.1) CONSTANTS.
        MVI     A,20
        ANA     B
        JZ      DD00            ;PORT 3; BIT 4 LOW-D.D.(T2=T4=0) CONSTANTS.
;!!!
        MVI     A,200
        ANA     B
        JZ      ADPT            ;PORT 3; BIT 7 LOW-ADAPTIVE D.D. CONSTANTS.
        MVI     A,1
        ANA     B
        JZ      DDPWL           ;PORT 3; BIT 0 LOW-LOW BAND ADAPTIVE.
        MVI     A,2
        ANA     B
        JZ      DDPWM           ;PORT 3; BIT 1 LOW-MID BAND ADAPTIVE.
        MVI     A,4
        ANA     B
        JZ      DDPWH           ;PORT 3; BIT 2 LOW-HIGH BAND ADAPTIVE.
;!!!
        LXI     H,P102
        SHLD    PPOINT
        JMP     INMW            ;PORT 3; ALL HIGH-D.D.(T2=T4=0.2) CONSTANTS.
;!!!
ADPT:   CALL    ADAPT
        JMP     CHOOSE
DDPWL:  LXI     H,LW1DD
        SHLD    PPOINT
        JMP     CHOOSE
DDPWM:  LXI     H,MD1DD
        SHLD    PPOINT
        JMP     CHOOSE
DDPWH:  LXI     H,HI1DD
        SHLD    PPOINT
CHOOSE: IN      PORT3           ;CHOOSE OLD(1-SEP-78) OR NEW(2-OCT-78)
        ANI     10              ;SET OF ADAPTIVE CONSTANTS.
```

```
        JNZ     INMW            ;PORT 3; BIT 3 HIGH-OLD CONSTANTS.
        LHLD    PPOINT          ;PORT 3; BIT 3 LOW -NEW CONSTANTS.
        LXI     D,140
        DAD     D
        SHLD    PPOINT
        JMP     INMW
;!!!
DD00:   LXI     H,P100
        SHLD    PPOINT
        JMP     INMW
DD01:   LXI     H,P101
        SHLD    PPOINT
        JMP     INMW
SYNLAG: LXI     H,P1TD          ;IF SYNC LOW THEN USE
        SHLD    PPOINT          ;T.D. CONSTANTS.
INMW:   IN      PORT1           ;INPUT SET MW
        CMA                     ;COMPENSATE FOR INVERTING BUFFERS.
        MOV     L,A
        XRA     A
        MOV     H,A
        DAD     H               ;SHIFT HL 4 PLACES LEFT
        DAD     H
        DAD     H
        DAD     H
        XCHG
        LHLD    MWOLD           ;DEFINE DIRECTION OF MOTION OF MW
        CALL    NEG
        DAD     D
        SHLD    DIRMW           ;STORE MW DIRECTION
        IN      PORT5           ;INPUT LL SIGNAL
        MOV     L,A
        XRA     A
        MOV     H,A
        DAD     H               ;SHIFT HL 4 PLACES LEFT
        DAD     H
        DAD     H
        DAD     H
        XCHG
        LHLD    LLOLD           ;DEFINE DIRECTION OF MOTION OF LL
        CALL    NEG
        DAD     D
        SHLD    DIRLL           ;STORE DIRECTION
;
;
;BEGINNING OF FLOATING POINT ALGORITHM
;
;

;!!!
ALG:    LDA     BUFPNT          ;SUM THE LAST 10 INPUTS AND POSITION
        LXI     H,BUF1
        LXI     D,BUF2
        CALL    SUM
;!!!
        CALL    FNORM           ;IN THE FL. ACC. FOR NORMALISATION.
```

```
        XRA     A
        LXI     H,HY2
        ADD     M
        JP      SCALE
        LDA     EX2             ;IF FREQUENCY INPUT IS LOW I.E. <-10/8V
        CPI     20              ;THEN SET THE GOV.OUTPUT TO 1/BP AS IF
        JM      SCALE           ;THE FREQUENCY WAS =-10V, SO THAT WHEN
        LXI     D,XNHI          ;THE FREQUENCY COMES WITHIN RANGE, I.E.
        LXI     H,XN1           ;>-1V, THE STEP FROM -VE TO -1V WILL NOT
        CALL    FTRANS          ;PROPAGATE THROUGH THE D.D. ACTION AND
                                ;GIVE A LARGE SWING OF THE GOVERNOR OUTPUT
SCALE:  LXI     D,KIN
        LXI     H,EX1
        CALL    FTRANS
        MVI     M,0
        CALL    FLMY            ;SCALING INPUT
        LXI     H,EX1
        LXI     D,UN1
        CALL    FTRANS          ;UN1 TO FL.OP.
        MVI     M,0
        LXI     D,EX2
        LXI     H,UN1
        CALL    FTRANS          ;UPDATE UN1
        CALL    FLSU            ;UN-UN1
        LXI     D,EX2
        LXI     H,UDIFF         ;UDIFF=UN-UN1
        CALL    FTRANS
        LXI     D,EX1
        LHLD    PPOINT
        LXI     B,4
        DAD     B
        XCHG
        CALL    FTRANS          ;P2 TO FL.OP.
        MVI     M,0
        CALL    FLMY            ;P2*(UN-UN1)
        LXI     D,EX2
        LXI     H,STORE
        CALL    FTRANS          ;STORE=P2*(UN-UN1)
        LXI     D,EX1
        LHLD    PPOINT
        XCHG
        CALL    FTRANS          ;P1 TO FL.OP.
        MVI     M,0
        LXI     D,BN1
        LXI     H,EX2
        CALL    FTRANS          ;BN1 TO FL.ACC.
        MVI     M,0
        CALL    FLMY            ;P1*BN1
        LXI     D,STORE
        LXI     H,EX1
        CALL    FTRANS          ;STORE TO FL.OP.
        MVI     M,0
        CALL    FLAD            ;P1*BN1+P2*(UN-UN1)
        LXI     D,BN1
        LXI     H,EX1
```

```
        CALL    FTRANS          ;BN1 TO FL.OP.
        MVI     M,0
        LXI     D,EX2
        LXI     H,BN1
        CALL    FTRANS          ;UPDATE BN1
        CALL    FLSU            ;BN-BN1 (BEFORE UPDATE OF BN1)
        LXI     B,14
        LHLD    PPOINT
        DAD     B
        LXI     D,EX1
        XCHG
        CALL    FTRANS          ;P4 TO FL.OP.
        MVI     M,0
        CALL    FLMY            ;P4*(BN-BN1)
        LXI     D,EX2
        LXI     H,STORE
        CALL    FTRANS          ;STORE=P4*(BN-BN1)
        LXI     D,CN1
        LXI     H,EX2
        CALL    FTRANS          ;CN1 TO FL.ACC.
        MVI     M,0
        LXI     B,10
        LHLD    PPOINT
        DAD     B
        LXI     D,EX1
        XCHG
        CALL    FTRANS          ;P3 TO FL.OP.
        MVI     M,0
        CALL    FLMY            ;P3*CN1
        LXI     D,STORE
        LXI     H,EX1
        CALL    FTRANS          ;STORE TO FL.OP.
        MVI     M,0
        CALL    FLAD            ;P3*CN1+P4*(BN-BN1)
        LXI     D,EX2
        LXI     H,CN1
        CALL    FTRANS          ;UPDATE CN1
        LXI     D,BN1
        LXI     H,EX1
        CALL    FTRANS          ;BN TO FL.OP.
        MVI     M,0
        CALL    FLAD            ;BN+CN
        LXI     D,UN1
        LXI     H,EX1
        CALL    FTRANS          ;UN TO FL.OP.
        MVI     M,0
        CALL    FLAD            ;UN+BN+CN (=EN)
        LXI     D,EX1
        LHLD    PPOINT
        LXI     B,20
        DAD     B
        XCHG
        CALL    FTRANS          ;P5 TO FL.OP.
        MVI     M,0
        CALL    FLMY            ;P5*EN
```

```
        LXI     D,EX2
        LXI     H,STORE
        CALL    FTRANS          ;STORE=P5*EN
        LXI     D,EX1
        LHLD    PPOINT
        LXI     B,24
        DAD     B
        XCHG
        CALL    FTRANS          ;P6 TO FL.OP.
        MVI     M,0
        LXI     D,XN1
        LXI     H,EX2
        CALL    FTRANS          ;XN1 TO FL.ACC.
        MVI     M,0
        CALL    FLMY            ;P6*XN1
        LXI     D,STORE
        LXI     H,EX1
        CALL    FTRANS          ;STORE TO FL.OP.
        MVI     M,0
        CALL    FLAD            ;P5*EN+P6*XN1
        LXI     D,EX2
        LXI     H,XN1
        CALL    FTRANS          ;UPDATE XN1
        LXI     D,UN1
        LXI     H,EX1
        CALL    FTRANS          ;UN1 TO FL.OP.
        MVI     M,0
        LXI     D,EX2
        LHLD    PPOINT
        LXI     B,30
        DAD     B
        XCHG
        CALL    FTRANS          ;P7 TO FL.ACC.
        MVI     M,0
        CALL    FLMY            ;P7*UN
        LXI     D,EX2
        LXI     H,STORE
        CALL    FTRANS          ;STORE=P7*UN
        LXI     B,34
        LXI     H,PPOINT
        LXI     D,EX1
        DAD     B
        XCHG
        CALL    FTRANS          ;P8 TO FL.OP.
        MVI     M,0
        LXI     D,UDIFF
        LXI     H,EX2
        CALL    FTRANS          ;UN-UN1 TO FL.ACC.
        MVI     M,0
        CALL    FLMY            ;P8*(UN-UN1)
        LXI     D,STORE
        LXI     H,EX1
        CALL    FTRANS          ;STORE TO FL.OP.
        MVI     M,0
        CALL    FLAD            ;P8*(UN-UN1)+P7*UN
```

```
        CALL    FIX
        LHLD    HY2
        XCHG
        MOV     L,D
        MOV     H,E
        SHLD    XFN                 ;16 BIT STEADY STATE OUTPUT TO XFN
        LXI     D,XN1
        LXI     H,EX2
        CALL    FTRANS              ;XN1 TO FL.ACC.
        MVI     M,0
        CALL    FIX                 ;FIX FLOATING POINT OUTPUT.
;
;
;END OF DOUBLE DERIVATIVE GOVERNOR ALGORITHM.
;
;
        LHLD    HY2                 ;LOAD DE WITH CURRENT 16 BIT VALUE OF X(N)
        MOV     E,H
        MOV     D,L
        XCHG
        CALL    MAGTST
        MOV     H,B
        MOV     L,C
        SHLD    XN                  ;SAVE THE CURRENT MAGTESTED OUTPUT
;
;
;BEGINNING OF LL DETERMINATION ROUTINE.
;
;
        LHLD    LLOLD               ;COMPUTE MW-LL.
        CALL    NEG
        XCHG
        LHLD    MWOLD
        DAD     D
        SHLD    MWLL                ;SAVE MW-LL.
        XCHG
        LHLD    XN
        XCHG                        ;XN TO REG. D AND E: MW-LL TO REG. H AND L.
        DAD     D                   ;COMPUTE X(N)+MW-LL
        XRA     A
        ADD     H
        JP      EXLIMH              ;JUMP TO ROUTINE WHICH EXECUTES A HIGH L.L.
        LHLD    MWOLD
        DAD     D                   ;COMPUTE X(N)+MW.
        XRA     A
        ADD     H
        JP      NOLIM               ;OUTPUT X(N)+MW IF IN RANGE-
                                    ;ELSE EXECUTE A LAD LIMIT OF ZERO-
                                    ;ON OUTPUT.

EXLIML: MVI     A,-1
        STA     LIMEX
        LHLD    XFN
        CALL    MAGTST
        LHLD    MWOLD
```

```
        PUSH    H               ;STORE MW
        DAD     B               ;XFN+MW
        XRA     A
        ADD     H
        POP     H               ;RETURN MW
        JM      LEAVE
        JMP     PRESET
;
EXLIMH: MVI     A,1
        STA     LIMEX
        LHLD    XFN
        CALL    MAGTST
        LHLD    MWLL
        PUSH    H               ;SAVE MW-LL FOR USE IN PRESET.
        DAD     B               ;XFN+MW-LL
        XRA     A
        ADD     H
        POP     H               ;RETURN MW-LL
        JP      LEAVE

PRESET: CALL    NEG             ;NEGATE HL GIVING LL-MW (OR -MW),
                                ;SINCE X(N)=LL-MW UNDER LIMIT CONDITIONS
        XCHG
        MOV     L,D
        MOV     H,E
        SHLD    HY2
        CALL    FLOAT           ;FLOAT LL-MW, RESCALE AND STORE AS-
                                ;CURRENT VALUE OF X(N).
        LXI     D,EX2
        LXI     H,XN1
        CALL    FTRANS
        JMP     LEAVE

NOLIM:  MVI     A,0
        STA     LIMEX
LEAVE:  MVI     A,0             ;RESET WATCH DOG SIGNAL. (PORT 6-BIT 0 RESET)
        OUT     CTLPL2
        CALL    TIMUP
;
;
;SWAP OVER TO THE OTHER INPUT BUFFER WHILE THE CURRENT INPUT
;BUFFER DATA IS PROCESSED.
;
;
        XRA     A               ;SWAP FREQUENCY BUFFER SPACE
        LXI     H,BUFPNT
        ADD     M
        JM      BUFF2
        MVI     M,-1
        LXI     H,BUF2
        SHLD    BUFADD
        JMP     OUTPU
BUFF2:  MVI     M,1
        LXI     H,BUF1
        SHLD    BUFADD
```

```
OUTPU:  NOP
;!!!
        XRA     A               ;SWAP POWER BUFFER SPACE.
        LXI     H,PWBFPT
        ADD     M
        JM      PWBUF2
        MVI     M,-1
        LXI     H,PWBF2
        SHLD    PWBFAD
        JMP     OUPU
PWBUF2: MVI     M,1
        LXI     H,PWBF1
        SHLD    PWBFAD
OUPU:   NOP
;!!!
;
;
;STORE THIS CURRENT INTEGRATION CYCLE'S MAGTESTED OUTPUT
;TO AWAIT OUTPUT TO DAC1.
;
;
        LHLD    MWOLD
        XCHG
        LHLD    XN
        DAD     D
        SHLD    CUROUT          ;CUROUT=XN+MW
;
        JMP     INPUT
;
;END OF GOVERNOR ROUTINE.
;
;!!!
;*********************************************************************
;*********************************************************************
;
;
;ROUTINE WHICH ASSIGNS THE GOVERNOR CONSTANTS DEPENDING ON
;THE OPERATIONAL POWER OF THE MACHINE.
;THE CURRENT MACHINE POWER IS MEASURED AND THEN SUBJECTED TO
;A FIRST ORDER LAG.
;THE LAGGED POWER:  PWOUT=G/(1+sTp)*(Pin*10)
;WHERE Tp IS THE LAG TIME CONSTANT AND
;WHERE G COMPENSATES FOR THE SUMMING OF 10 VALUES OF INPUT
;POWER, Pin (Pin = 1 MEASURED VALUE ONLY). THE RESULT IS TOO
;LARGE BY A FACTOR OF 2**14 DUE TO THE ADC INPUT. THUS POWER BAND
;COMPARISONS ARE CARRIED OUT AT THIS LEVEL.
;THE DIFFERENCE EQUATION FORM OF THE POWER LAG IS:
;
;PWOUT(N)=(G*T/Tp*(Pin*10)+PWOUT(N-1))*Tp/(T+Tp)
;
ADAPT:  LDA     PWBFPT
        LXI     H,PWBF1
        LXI     D,PWBF2
        CALL    SUM             ;SUM THE LAST 10 INPUTS AND
        CALL    FNORM           ;NORMALISE THE RESULT.
```

```
        LXI     D,PWKIN
        LXI     H,EX1
        CALL    FTRANS
        MVI     M,0
        CALL    FLMY            ;(Pin*10)*G*T/Tp
        LXI     D,PWOUT
        LXI     H,EX1
        CALL    FTRANS
        MVI     M,0
        CALL    FLAD            ;(Pin*10)*G*T/Tp+PWOUT(N-1)
        LXI     D,PWLAG
        LXI     H,EX1
        CALL    FTRANS
        MVI     M,0
        CALL    FLMY            ;((Pin*10)*G*T/Tp+PWOUT(N-1))*Tp/(T+Tp)
        LXI     D,EX2           ;PRODUCE A LAGGING POWER SIGNAL IN
        LXI     H,PWOUT         ;INTEGER FORM WHERE 30MW = 2**14
        CALL    FTRANS          ;AND SO 100% POWER = 2**14*33/30.
        CALL    FIX
        LHLD    HY2
        MOV     E,H
        MOV     D,L
        XRA     A
        ADD     D
        JM      HIRNG
        LXI     H,-7209.        ;TEST FOR PWOUT <40% AND IF SO
        DAD     D               ;USE LOW BAND CONSTANTS.
        XRA     A
        ADD     H
        JM      LOWRNG
        LXI     H,-12616.       ;TEST FOR 40%< PWOUT <70% AND IF SO
        DAD     D               ;USE MID BAND CONSTANTS.
        XRA     A
        ADD     H
        JM      MIDRNG
HIRNG:  LXI     H,HI1DD         ;USE HIGH BAND CONSTANTS IF
        SHLD    PPOINT          ;PWOUT > 70% OR IF PWOUT HAS BEEN
        MVI     A,3             ;EVALUATED AS NEGATIVE.
        OUT     PORT4
        RET
MIDRNG: LXI     H,MD1DD
        SHLD    PPOINT
        MVI     A,2
        OUT     PORT4
        RET
LOWRNG: LXI     H,LW1DD
        SHLD    PPOINT
        MVI     A,1
        OUT     PORT4
        RET
;!!!
;*********************************************************************
;*********************************************************************
;
;
```

```
;ROUTINE TO TEST IF A16 BIT SIGNED INTEGER WILL OVER OR UNDER FLOW
;DUE TO THE NUMBER 4096 (DEC).IF SO THE INTEGER IS REDUCED OR
;INCREASED APPROPRIATELY
;ENTER THE ROUTINE WITH THE INTEGER IN REG. HL, AND
;THE RESULT IS RETURNED IN REG. BC.

MAGTST: MOV     B,H
        MOV     C,L
        XRA     A
        ADD     B
        JP      TMAG
        LXI     H,-D4096
        DAD     B
        XRA     A
        ADD     H
        RM
        LXI     H,+D4096
        DAD     B
        MOV     B,H
        MOV     C,L
        RET
TMAG:   LXI     H,+D4096
        DAD     B
        XRA     A
        ADD     H
        RP
        LXI     H,-D4096
        DAD     B
        MOV     B,H
        MOV     C,L
        RET
;
;
;**********************************************************************
;**********************************************************************
;
;
;ROUTINE TO DETECT END OF SAMPLING INTERVAL
;
TIMUP:  LXI     H,TIMCNT          ;CHECK IF SAMPLING PERIOD
        XRA     A                 ;ALREADY OVER.
        ADD     M
        JZ      ERR1              ;IF SO THEN ERROR CONDITION.
        JM      ERR1
WAIT:   XRA     A                 ;WAIT FOR END OF SAMPLING PERIOD
        ADD     M
        JNZ     WAIT
        MVI     A,12              ;RE-INITIALISE NO. OF 10MS COUNTS
        MOV     M,A
        RET
;
ERR1:   DI
        MVI     A,7
        OUT     CTLPL2
```

```
        HLT
;
;
;***********************************************************************
;***********************************************************************
;
;
        ;DFTRAN.ALT     27-JAN-77       U/17-FEB-77
;
;
;THIS ROUTINE TRANSFERS A FL. PT. NO. (4 BYTES)
;FROM AN EFFECTIVE SOURCE ADD. TO AN EFF. DESTINATION
;ADD.
;BEFORE ENTERING THE ROUTINE PLACE SOURCE ADD.
;IN REG. D  E AND DEST. ADD. IN REG. H  L
;ROUTINE RETURNS WITH H  L CONTAINING ADD. OF
;5TH DEST. BYTE
;
FTRANS:MVI      B,4
NBYTE:  LDAX    D
        MOV     M,A
        INX     D
        INX     H
        DCR     B
        JNZ     NBYTE
        RET
;
;
;***********************************************************************
;***********************************************************************
;
;
;INTERRUPT SERVICE ROUTINE.
;THE CLOCK COUNT IS UPDATED DURING EVERY INTERRUPT.
;THE GOVERNOR OUTPUT IS UPDATED WITH RESPECT TO THE MW AND LL
;SIGNALS, AND A FREQUENCY ERROR SAMPLE IS TAKEN AND STORED.
;
;
SERVIC:LDA      TIMCNT          ;DECREASE PRESENT SAMPLING INTERVAL
        DCR     A               ;BY 10MS.
        STA     TIMCNT
;
;THE FIRST READ STATUS IN ROUTINE AIO WILL CLEAR THE TIME MARK BIT.
;
;!!!
        MVI     B,0             ;READ CURRENT FREQUENCY INPUT AND STORE
;!!!
        CALL    AIO             ;IT INTHE BUFFER SPACE IN USE.
        XCHG
        LHLD    BUFADD
        MOV     M,E
        INX     H
        MOV     M,D
        INX     H
        SHLD    BUFADD
```

```
;
;!!!
        MVI     B,1             ;READ CURRENT POWER INPUT AND STORE
        CALL    AIO             ;IT IN THE BUFFER SPACE IN USE.
        XCHG
        LHLD    PWBFAD
        MOV     M,E
        INX     H
        MOV     M,D
        INX     H
        SHLD    PWBFAD
;!!!
        XRA     A
        LHLD    DIRLL           ;FIND DIRECTION OF MOVEMENT OF LL
        ADD     H
        JM      SUBLL           ;GOTO SUBLL IF LL TO GO DOWN.
        ORA     L
        JZ      CHKMW           ;LEAVE LL IF NO MOVEMENT.
        DCX     H               ;ELSE DECREASE LL ERROR BY 1
        SHLD    DIRLL
        LHLD    LLOLD           ;AND INCRAESE THE LL BY 1
        INX     H
        SHLD    LLOLD
        JMP     CHKMW
SUBLL:  INX     H               ;LL DECREASING SO DECREASE LL ERROR BY 1
        SHLD    DIRLL           ;AND THEN DECREASE THE LL BY 1
        LHLD    LLOLD
        DCX     H
        SHLD    LLOLD
CHKMW:  XRA     A               ;FIND THE DIRECTION OF MOVEMENT OF MW
        LHLD    DIRMW
        ADD     H
        JM      SUBMW           ;GOTO SUBMW IF MW TO GO DOWN
        ORA     L
        JZ      CONT            ;LEAVE MW IF NO MOVEMENT.
        DCX     H               ;ELSE DECREASE THE MW ERROR BY 1
        SHLD    DIRMW           ;AND THEN INCREASE THE MW SIGNAL BY 1
        LHLD    MWOLD
        INX     H
        SHLD    MWOLD
        LHLD    CUROUT          ;INCREASE THE CURRENT GOV. OUTPUT BY 1
        INX     H
        SHLD    CUROUT
        JMP     CONT
SUBMW:  INX     H               ;MW DECREASING SO DECREASE MW ERROR BY 1
        SHLD    DIRMW           ;AND DECREASE THE MW SIGNAL BY 1
        LHLD    MWOLD
        DCX     H
        SHLD    MWOLD
        LHLD    CUROUT          ;DECREASE THE CURRENT GOV. OUTPUT BY 1
        DCX     H
        SHLD    CUROUT
CONT:   LDA     LIMEX           ;FIND OUT WHICH LIMIT CONDITION EXISTS
        ANA     A
        JM      LOWLL
```

```
        JZ      NOLL
;
;OUTPUT A HIGH LL UNLESS CUROUT COMES OUT THE LIMIT
;THEN OUTPUT CUROUT.
HIGHLL: LHLD    LLOLD           ;LIMEX=1 SO HIGH LL IN OPERATION
        CALL    NEG
        XCHG
        LHLD    CUROUT
        DAD     D
        XRA     A
        ADD     H
        JP      LIMOUT
        LHLD    CUROUT
        XRA     A
        ADD     H
        JM      UNDFLO          ;CHECK FOR CUROUT DROPPING BELOW ZERO-
        JMP     PUTOUT          ;IF SO LIMIT OUTPUT TO ZERO.
UNDFLO: LXI     H,0
        JMP     PUTOUT
LIMOUT: LHLD    LLOLD
PUTOUT: SHLD    DAC1LO
        JMP     ENDINT
;
;
;OUTPUT A LOW LL UNLESS CUROUT COMES OUT THE LIMIT
;THEN OUTPUT CUROUT.
LOWLL:  XRA     A               ;LIMEX=-1 SO LOW LL IN OPERATION
        LHLD    CUROUT
        ADD     H
        JM      OTLM
        XCHG
        LHLD    LLOLD
        CALL    NEG
        DAD     D
        XRA     A
        ADD     H
        XCHG
        JM      OUTCUR
        LHLD    LLOLD
        JMP     OUTCUR
OTLM:   LXI     H,0
OUTCUR: SHLD    DAC1LO
        JMP     ENDINT
;
;
NOLL:   LHLD    CUROUT          ;LIMEX=0 SO NO LL
        XRA     A
        ADD     H
        JP      PTOT
        LXI     H,0
PTOT:   SHLD    DAC1LO
;
;
ENDINT: POP     H               ;RESTORE REGISTERS
        POP     D
```

```
        POP     B
        POP     PSW
        EI
        RET
;
;
;*********************************************************************
;*********************************************************************
;
;
;ADC INPUT ROUTINE WHICH AUTOMATICALLY SELECTS THE CORRECT
;GAIN AND PRESENTS THE 15 BITS OF DATA IN REGISTERS DE
;IN REVERSE ORDER.
;ENTER THE ROUTINE WITH THE CHANNEL TO BE READ IN REG.B
;
AIO:    XRA     A
        STA     GNSEL
;!!!
CONVB:  MOV     A,B             ;INITIATE A CONVERSION ON CH.
        STA     MUXADR
        STA     CNVCMD
;!!!
ADSTAT: LDA     STATUS          ;CHECK  ADC STATUS
        RLC
        JNC     ADSTAT          ;CHECK FOR EOC BIT=1
        ANI     60              ;MASK
        JNZ     ADJUST          ;CHECK FOR 2 MSB'S=00B
                                ;I.E. MOST -VE NO.
        CPI     60
        JZ      ADJUST          ;CHECK FOR 2 MSB'S=11B
                                ;I.E. MOST +VE NO.
        LDA     GNSEL
        CPI     3
        JZ      ADJUST          ;CHECK FOR GAIN=8
        INR     A               ;INCREASE GAIN ONE STEP
        STA     GNSEL
        JMP     CONVB
ADJUST: LDA     GNSEL
        LHLD    ADCLO           ;READ DATA
        SHLD    DAC2LO          ;OUTPUT CURRENT INPUT FOR OBSERVATION.
SHIFT:  CPI     3
        RZ
        INR     A
        DAD     H               ;SHIFT DATA LEFT ONE PLACE.
        JMP     SHIFT
;
;
;*********************************************************************
;*********************************************************************
;
;
;ROUTINE WHICH NEGATES THE 16 BIT INTEGER IN REG. H AND L.
;
;
NEG:    MOV     A,L
```

```
        CMA
        MOV     L,A
        MOV     A,H
        CMA
        MOV     H,A
        INX     H
        RET
;
;
;************************************************************************
;************************************************************************
;
;
;ROUTINE TO SUM THE LAST 10 VALUES OF FREQUENCY ERROR OR POWER INPUT.
;BUFPNT IS USED TO POINT TO THE BUFFER SPACE WHICH IS NOT CURRENTLY
;IN USE FOR INPUT.
;THE SUM IS ACCUMULATED IN THE FL. ACC. AND THE EXPONENT IS SET TO
;2**23. A CALL FNORM IS SUBSEQUENTLY REQUIRED IN ORDER TO NORMALISE
;THE FL. ACC.
;AVERAGING THESE INPUTS (I.E. DIVIDING BY 10) SHOULD BE INCORPORATED
;INTO THE FL. INPUT SCALING FACTOR.
;ENTER THE ROUTINE WITH THE BUFFER POINTER IN REG.A-
;-THE ADDRESS OF BUFFER 1 IN REG. H AND L-
;-THE ADDRESS OF BUFFER 2 IN REG. D AND E.
;
;
SUM:    ANA     A
        JM      TOT
        XCHG
TOT:    PUSH    H
        LXI     H,EX2           ;CLEAR FL. ACC.
        XRA     A
        MVI     B,5
ZFLAC:  MOV     M,A
        INX     H
        DCR     B
        JNZ     ZFLAC
        MVI     B,12
NEXTFR: LXI     H,HY2+2         ;START OF SUMMING LOOP.
        XTHL
        MOV     E,M
        INX     H
        MOV     D,M
        INX     H
        XTHL
        XRA     A
        ADD     D
        JP      PLUS
        MVI     C,-1
        JMP     MINUS
PLUS:   MVI     C,0
MINUS:  MOV     A,E
        ADD     M
        MOV     M,A
        DCX     H
```

```
        MOV     A,D
        ADC     M
        MOV     M,A
        DCX     H
        MOV     A,C
        ADC     M
        MOV     M,A
        DCR     B
        JNZ     NEXTFR
        MVI     A,27                    ;LOAD FL. ACC. EXPONENT WITH
        DCX     H                       ;APPROPRIATE VALUE.
        MOV     M,A
        POP     H
        RET
;
;
;**********************************************************************
;**********************************************************************
;
;
;FREQUENCY ERROR INPUT IS IN THE RANGE +-10% = +-1VOLT
;AND ABOVE THESE LIMITS IT STEPS TO +-10VOLTS GIVING
;A HIGH GAIN CHARACTERISTIC OUTWITH THE CENTRAL LINEAR
;REGION.
;THE INCOMING SIGNAL IS ALSO OF THE WRONG SIGN, THUS
;KIN IS APPROPRIATELY NEGATED.
;AS THE FREQUENCY ERROR INPUT IS SUBJECTED TO AUTOMATIC
;GAIN RANGING WITHIN THE RTI-1200, THEN THE DIGITAL INPUT
;SIGNAL CONSISTS OF 15 SIGNIFICANT BITS. KIN IS ADJUSTED
;APPROPRIATELY.
;AN AVERAGE INPUT VALUE IS DERIVED BY SUMMING THE PAST 10 INPUTS
;(1 PER CLOCK INTERRUPT).
;THE DIVISION BY 10 IS INCORPORATED INTO KIN.
;
KIN:    DB 357,231,231,232      ;-1.0/10.0/(2**14) = -0.000006
KBACK:  DB 365,106,146,146      ;11/(10*2**12) = 0.000269
XNHI:   DB 21,171,66,116        ;1/BP*10/11*2**12 = 124121.218750
;!!!
PWKIN:  DB 367,101,211,67       ;G*T/TP= 0.001
PWLAG:  DB 0,176,273,220        ;TP/(T+TP)= 0.990099
;!!!
;
;ALGORITHM CONSTANTS FOR THE FOLLOWING PARAMETER VALUES,
;I.E. DOUBLE DERIVATIVE GOVERNOR WITH 33.3 SEC. LAG.
;T2=T4=0.0 - K1=K2=3.5 - BP=0.03 - TY=1.0 - T=0.1
;
P100:   DB,0,0,0,0              ;0.0
P200:   DB 6,106,0,0            ;35.0
P300:   DB 0,0,0,0              ;0.0
P400:   DB 4,120,0,0            ;10.0
P500:   DB 11,134,317,376       ;371.249878
P600:   DB 0,177,235,376        ;0.997009
P700:   DB 21,171,66,116        ;124121.218750
P800:   DB 3,125,107,256        ;5.33
;
```

```
;ALGORITHM CONSTANTS FOR THE FOLLOWING PARAMETER VALUES,
;I.E. DOUBLE DERIVATIVE GOVERNOR WITH 33.3 SEC. LAG.
;T2=T4=0.1 - K1=K2=3.5 - BP=0.03 - TY=1.0 - T=0.1
;
P101:   DB 0,100,0,0              ;0.5
P201:   DB 5,106,0,0              ;17.5
P301:   DB 0,100,0,0              ;0.5
P401:   DB 3,120,0,0              ;5.0
P501:   DB 11,134,317,376         ;371.249788
P601:   DB 0,177,235,376          ;0.997009
P701:   DB 21,171,66,116          ;124121.218750
P801:   DB 0,0,0,0                ;0.0
;
;ALGORITHM CONSTANTS FOR THE FOLLOWING PARAMETER VALUES,
;I.E. DOUBLE DERIVATIVE GOVERNOR WITH 33.3 SEC. LAG.
;T2=T4=0.2 - K1=K2=3.5 - BP=0.03 - TY=1.0 - T=0.1
;
P102:   DB 0,125,125,125          ;0.666667
P202:   DB 4,135,125,125          ;11.666666
P302:   DB 0,125,125,125          ;0.666667
P402:   DB 2,152,252,252          3.333333
P502:   DB 11,134,317,376         ;371.249878
P602:   DB 0,177,235,376          ;0.997009
P702:   DB 21,171,66,116          ;124121.21875
P802:   DB 0,0,0,0                ;0.0
;
;ALGORITHM CONSTANTS FOR THE FOLLOWING PARAMETER VALUES,
;I.E. TEMPORARY DROOP GOVERNOR WITH 160 SEC. LAG.
;I.E. bt=0.25, bp=0.03, Td=16.0, Ty=0.3
;T2=1.0108 - T4=0 - K1=14.9892 - K2=0 - BP-0.03 - TY=4.74867 - T=0.1
;

P1TD:   DB 0,164,172,15           ;0.909975
P2TD:   DB 4,153,363,324          ;13.494057
P3TD:   DB 0,0,0,0                ;0.0
P4TD:   DB 0,0,0,0                ;0.0
P5TD:   DB 7,116,135,143          ;78.364792
P6TD:   DB 0,177,353,117          ;0.999369
P7TD:   DB 21,171,66,116          ;124121.21875
P8TD:   DB,0,0,0,0                ;0.0
;!!!
;
;ALGORITHM CONSTANTS FOR THE FOLLOWING VALUES,
;I.E. DOUBLE DERIVATIVE GOVERNOR WITH 33.3 SEC. LAG,
;T2=T4=0.2 - K1=3.0 - K2=2.3 - TY=1.0 - T=0.1
;
HI1DD:  DB 0,125,125,125          ;0.666667
HI2DD:  DB 4,120,0,0              ;10.0
HI3DD:  DB 0,125,125,125          ;0.666667
HI4DD:  DB 2,121,307,34           ;2.555555
HI5DD:  DB 11,134,317,376         ;371.249878
HI6DD:  DB 0,177,235,376          ;0.997009
HI7DD:  DB 21,171,66,116          ;124121.21875
HI8DD:  DB 0,0,0,0                ;0.0
;
```

```
;ALGORITHM CONSTANTS FOR THE FOLLOWING VALUES,
;I.E. DOUBLE DERIVATIVE GOVERNOR WITH 20.0 SEC. LAG,
;T2=T4=0.2 - K1=2.5 - K2=1.8 - TY=0.6 - T=0.1
;
MD1DD:  DB 0,125,125,125         ;0.666667
MD2DD:  DB 4,102,252,252         ;0.333332
MD3DD:  DB 0,125,125,125         ;0.666667
MD4DD:  DB 2,114,314,314         ;2.40
MD5DD:  DB 12,115,60,227         ;617.518433
MD6DD:  DB 0,177,134,371         ;0.995025
MD7DD:  DB 21,171,66,116         ;124121.21875
MD8DD:  DB 0,0,0,0               ;0.0
;
;ALGORITHM CONSTANTS FOR THE FOLLOWING VALUES,
;I.E. DOUBLE DERIVATIVE GOVERNOR WITH 10.0 SEC. LAG,
;T2=T4=0.2 - K1=1.8 - K2=0.8 - TY=0.3 - T=0.1
;
LW1DD:  DB 0,125,125,125         ;0.666667
LW2DD:  DB 3,137,377,377         ;5.999999
LW3DD:  DB 0,125,125,125         ;0.666667
LW4DD:  DB 1,136,320,230         ;1.481482
LW5DD:  DB 13,114,316,303        ;1228.922607
LW6DD:  DB 0,176,273,220         ;0.990099
LW7DD:  DB 21,171,66,116         ;124121.21875
LW8DD:  DB 0,0,0,0               ;0.0
;
;ALGORITHM CONSTANTS FOR THE FOLLOWING VALUES.
;I.E. DOUBLE DERIVATIVE GOVERNOR WITH 33.3 SEC. LAG.
;T2=T4=0.2 - K1=3.0 - K2=2.8 - BP=0.03 - TY=1.0 - T=0.1
;
HI1DD1: DB 0,125,125,125         ;0.666667
HI2DD1: DB 4,120,0,0             ;10.0
HI3DD1: DB 0,125,125,125         ;0.666667
HI4DD1: DB 2,143,216,70          ;3.111111
HI5DD1: DB 11,134,317,376        ;371.249878
HI6DD1: DB 0,177,235,376         ;0.997009
HI7DD1: DB 21,171,66,116         ;124121.21875
HI8DD1: DB 0,0,0,0               ;0.0
;
;ALGORTIHM CONSTANTS FOR THE FOLLOWING VALUES,
;I.E. DOUBLE DERIVATIVE GOVERNOR WITH 20 SEC. LAG.
;T2=T4=0.2 - K1=2.0 - K2=3.0 - BP=0.03 - TY=0.6 - T=0.1
;
MD1DD1: DB 0,125,125,125         ;0.666667
MD2DD1: DB 3,152,252,252         ;6.666666
MD3DD1: DB 0,125,125,125         ;0.666667
MD4DD1: DB 3,120,0,0             ;5.0
MD5DD1: DB 12,115,60,227         ;617.518433
MD6DD1: DB 0,177,134,371         ;0.995025
MD7DD1: DB 21,171,66,116         ;124121.21875
MD8DD1: DB 0,0,0,0               ;0.0
;
;ALGORITHM CONSTANTS FOR THE FOLLOWING VALUES,
;I.E. DOUBLE DERIVATIVE GOVERNOR WITH 10 SEC. LAG.
;T2=T4=0.2 - K1=0.8 - K2=2.0 - BP=0.03 - TY=0.3 - T=0.1
```

```
;
LW1DD1: DB 0,125,125,125        ;0.666667
LW2DD1: DB 2,125,125,125        ;2.666667
LW3DD1: DB 0,125,125,125        ;0.666667
LW4DD1: DB 4,102,252,252        ;8.333332
LW5DD1: DB 13,114,316,303       ;1228.922607
LW6DD1: DB 0,176,273,220        ;0.990099
LW7DD1: DB 21,171,66,116        ;124121.21875
LW8DD1: DB 0,0,0,0              ;0.0
;!!!
;
;*************************************************************************
;*************************************************************************
;
        .END
```

APPENDIX G

Simulation and Site Test Data

APPENDIX G - Simulation and Site Test Data

This Appendix contains all the pertinent data for the simulation and site results which are displayed throughout the thesis. The variables of the simulations were normalised to correspond with the actual values given below.

Frequency	50 Hz = 44.8 rad/sec
Reservoir head	850 ft
Control valve area	3.44 ft^2

These values imply the following normal working conditions:-

Flow	506 ft^3/sec
Power at 0.91 efficiency	33 MW

The values of the following constants are also listed.

C_d	0.8
r_o	3.57 ft
r_i	1.58 ft

Due to the mechanical linkage between the low and high pressure servo units the main servo could only move through 90% of its full travel. The electronic governor outputs were so arranged that their 100% output value took the servo to its maximum actual limit (i.e. 90%). Thus the results collected with the microprocessor based data logging system were corrected to provide results which reflected the true 100% travel of the servo.

The tables of data that appear in the remaining pages of this appendix relate to particular figures of the thesis as indicated. The data shown gives the constants used in the simulations which were performed on the PDP 11/45, the constants used in the microprocessor governors and the conditions of the generator system at Sloy Power Station during the various trials that were carried out there. The tables relating to simulations also indicate which model was used and whether or not an internal governor or an external microprocessor governor was used.

Figure 6.3 Interactive PDP 11 - Microprocessor (8008) T.D. Governor Simulation

(simple impulse model + microprocessor governor)

Plots of frequency versus time
and servo position versus time

Trace 1 Integration interval of 0.5 sec
Trace 2 Integration interval of 1.0 sec

PARAMETER	PDP 11 SIM.	MICROPROCESSOR
T_y		1.0
T_d		16.0
b_t		0.5
b_p		0.03
T_s	0.2	
T_w	1.1	
T_a	7.0	
Frequency Ref	1.0	
Torque demand before step	1.0	
Torque demand after step	0.9	

	TRACE 1	TRACE 2
Integration interval	0.5	1.0
Integration method	Euler	Euler

Figure 6.12 Grid connected simulation - 10%-90% disturbance

(3 pipeline + internal 'continuous' governor)
(no governor output limit)

Plots of Servo position versus Time

Trace 1 Fixed DD dominant lag of 10 sec
Trace 2 Adaptive governor with power lag of 10 sec
Trace 3 Adaptive governor with power lag of 5 sec
Trace 4 Adaptive governor with power lag of 0.1 sec
Trace 5 Fixed DD dominant lag of 33.3 sec

PARAMETER	PDP 11 SIMULATION VALUE				
	TRACE				
	1	2	3	4	5
K_1	1.8	3.0	3.0	3.0	3.0
		2.5	2.5	2.5	
		1.8	1.8	1.8	
K_2	0.8	2.3	2.3	2.3	2.3
		1.8	1.8	1.8	
		0.8	0.8	0.8	
T_y	0.3	1.0	1.0	1.0	1.0
		0.6	0.6	0.6	
		0.3	0.3	0.3	

	All Traces
T_2	0.2
T_4	0.2
b_p	0.03
T_s	0.1
T_a	7.0
Servo hysteresis (%)	1.4
Servo rate limit up (sec)	22.0
Servo rate limit down (sec)	4.0
Reservoir head	1.0
Efficiency (%)	100.0
Guide vane gain factor	1.0
Freq. Ref. before step	1.003
Freq. Ref. after step	1.027
Integration interval (sec)	0.05
Integration method	RK4

Figure 6.13 Isolated load Simulation - 35%-75% disturbance

(3 pipeline + internal 'continuous' governor)
(no governor output limit)

Plots of Servo position versus Time

Trace 1 Fixed DD dominant lag of 33.3 sec.
Trace 2 Adaptive governor with power lag of 10 sec.

PARAMETER	PDP 11 SIMULATION VALUE	
	TRACE	
	1	2
K_1	3.0	3.0
		2.5
		1.8
K_2	2.3	2.3
		1.8
		0.8
T_y	1.0	1.0
		0.6
		0.3
	Both Traces	
T_2	0.2	
T_4	0.2	
b_p	0.03	
T_s	0.1	
T_a	7.0	
Servo hysteresis (%)	1.4	
Servo rate limit up (sec)	22.0	
Servo rate limit down (sec)	4.0	
Reservoir head	1.0	
Efficiency (%)	100.0	
Guide vane gain factor	1.0	
Freq. Ref.	1.0105	
Torque before dist.	0.35	
Torque after dist.	0.75	
Integration interval (sec)	0.05	
Integration method	RK4	

Figure 6.14 Isolated load Simulation - 75%-35% disturbance

(3 pipeline + internal 'continuous' governor)
(no governor output limit)

Plots of Servo position versus Time

Trace 1 Fixed DD dominant lag of 33.3 sec.
Trace 2 Adaptive governor with power lag of 10 sec.

PARAMETER	PDP 11 SIMULATION VALUE	
	TRACE	
	1	2
K_1	3.0	3.0
		2.5
		1.8
K_2	2.3	2.3
		1.8
		0.8
T_y	1.0	1.0
		0.6
		0.3
	Both Traces	
T_2	0.2	
T_4	0.2	
b_p	0.03	
T_s	0.1	
T_a	7.0	
Servo hysteresis (%)	1.4	
Servo rate limit up (sec)	22.0	
Servo rate limit down (sec)	4.0	
Reservoir head	1.0	
Efficiency (%)	100.0	
Guide vane gain factor	1.0	
Freq. Ref.	1.0225	
Torque before dist.	0.75	
Torque after dist.	0.35	
Integration interval (sec)	0.05	
Integration method	RK4	

Figure 6.15 Stability of governors at 90% full load.

(3 pipeline + internal 'continuous' governor)
(no governor output limit)

Plots of Servo position versus Time

Trace 1 Fixed DD dominant lag of 33.3 sec.
Trace 2 Fixed DD dominant lag of 10 sec.

PARAMETER	PDP 11 SIMULATION VALUE	
	TRACE	
	1	2
K_1	3.0	1.8
K_2	2.3	0.8
T_y	1.0	0.3
	Both Traces	
T_2	0.2	
T_4	0.2	
b_p	0.03	
T_s	0.1	
T_a	7.0	
Servo hysteresis (%)	1.4	
Servo rate limit up (sec)	22.0	
Servo rate limit down (sec)	4.0	
Reservoir head	1.0	
Efficiency (%)	100.0	
Guide vane gain factor	1.0	
Freq. Ref.	1.03	
Torque before dist.	1.0	
Torque after dist.	0.9	
Integration interval (sec)	0.05	
Integration method	RK4	

Figure 6.16 Stability of governors at 30% full load.

(3 pipeline + internal 'continuous' governor)
(no governor output limit)

Plots of Servo position versus Time

Trace 1 Fixed DD dominant lag of 33.3 sec.
Trace 2 Fixed DD dominant lag of 10 sec.

PARAMETER	PDP 11 SIMULATION VALUE	
	TRACE	
	1	2
K_1	3.0	1.8
K_2	2.3	0.8
T_y	1.0	0.3
	Both Traces	
T_2	0.2	
T_4	0.2	
b_p	0.03	
T_s	0.1	
T_a	7.0	
Servo hysteresis (%)	1.4	
Servo rate limit up (sec)	22.0	
Servo rate limit down (sec)	4.0	
Reservoir head	1.0	
Efficiency (%)	100.0	
Guide vane gain factor	1.0	
Freq. Ref.	1.012	
Torque before dist.	0.4	
Torque after dist.	0.3	
Integration interval (sec)	0.05	
Integration method	RK4	

Figure 6.17 (a) to (d)

(3 pipeline + internal 'continuous' governor)

Plots of Frequency versus Time

(a) Standard DD Governor - 100%-90% disturbance

(b) DDHI1 Governor - 100%-90% disturbance

(c) DDMID1 Governor - 70%-60% disturbance

(d) DDLOW1 Governor - 40%-30% disturbance

PARAMETER	PDP 11 SIMULATION VALUE			
	PLOT			
	(a)	(b)	(c)	(d)
K_1	3.5	3.0	2.5	1.8
K_2	3.5	2.3	1.8	0.8
T_y	1.0	1.0	0.6	0.3
Frequency Ref.	1.03	1.03	1.021	1.012
Torque demand before step	1.0	1.0	0.7	0.4
Torque demand after step	0.9	0.9	0.6	0.3

	Figures 6.17 (a) to (d)
T_2	0.2
T_4	0.2
b_p	0.03
T_s	0.1
T_a	7.0
Servo hysteresis (%)	1.4
Servo rate limit up (sec)	22.0
Servo rate limit down (sec)	4.0
Reservoir head	1.0
Efficiency (%)	100.0
Guide vane gain factor	1.0
Integration interval (sec)	0.05
Integration method	RK4

Figure 8.8 (a) and (b)

Site tests at Sloy Power Station
(Test Number - SLT018)

Plots of Simulated Frequency versus time
and Servo Position versus time

(a) ILS step, micro TD governor (Simulated Frequency)
(b) ILS step, micro TD governor (Servo Position)

Date of test	22-JUN-78
Mean loch level (ft)	858.3
Mean power at start of test (MW)	25.1
Frequency transducer deadband (Hz)	0.3
ILS Machine inertia constant, T_a (sec)	7.0
ILS load self regulation constant, k_n	1.5
ILS disturbance (% of 33 MW)	6%up;6%down

Figure 8.9 (a) and (b)

Site tests at Sloy Power Station
(Test Number - SLT017)

Plots of Simulated Frequency versus time
and Servo Position versus time

(a) ILS step, micro DD governor (Simulated Frequency)
(b) ILS step, micro DD governor (Servo Position)

Date of test	22-JUN-78
Mean loch level (ft)	858.3
Mean power at start of test (MW)	24.4
Frequency transducer deadband (Hz)	0.3
ILS Machine inertia constant, T_a (sec)	7.0
ILS load self regulation constant, k_n	1.5
ILS disturbance (% of 33 MW)	6%up;6%down

Figure 9.1 (a) and (b)

Site tests at Sloy Power Station
(Test Number - SLT107,8,9,10)

Plots of Servo Position versus time
and Megawatts versus time

(a) Grid connected governor responses (Servo Position)
(b) Grid connected governor responses (Megawatts)

Date of test	7-SEP-78
Mean loch level (ft)	888.3
Mean power at start of test (MW)	3.3
Frequency transducer deadband (Hz)	0.3
Frequency Ref. step disturbance (Hz)	1.2

Figure 9.2 (a) to (c)

Site tests at Sloy Power Station
(Test Number - SLT113)

Plots of Simulated Frequency versus time
and Servo Position versus time
and Machine Power versus time

(a) DD low band test with ILS (Simulated Frequency)
(b) DD low band test with ILS (Servo Position)
(c) DD low band test with ILS (Machine Power)

Date of test	7-SEP-78
Mean loch level (ft)	888.3
Mean power at start of test (MW)	11
Frequency transducer deadband (Hz)	0.3
ILS Machine inertia constant, T_a (sec)	7.0
ILS load self regulation constant, k_n	0
ILS disturbance (% of 33 MW)	none

Figure 9.3 (a) to (c)

Site tests at Sloy Power Station
(Test Number - SLT124)

Plots of Simulated Frequency versus time
and Servo Position versus time
and Machine Power versus time

(a) DD mid band test with ILS (Simulated Frequency)
(b) DD mid band test with ILS (Servo Position)
(c) DD mid band test with ILS (Machine Power)

Date of test	7-SEP-78
Mean loch level (ft)	888.3
Mean power at start of test (MW)	20
Frequency transducer deadband (Hz)	0.3
ILS Machine inertia constant, T_a (sec)	7.0
ILS load self regulation constant, k_n	1.5 and 0
ILS disturbance (% of 33 MW)	6%up;6%down 6%up;6%down

Figure 9.4 (a) to (c)

Site tests at Sloy Power Station
(Test Number - SLT123)

Plots of Simulated Frequency versus time
and Servo Position versus time
and Machin Power versus time

(a) DD high band test with ILS (Simulated Frequency)
(b) DD high band test with ILS (Servo Position)
(c) DD high band test with ILS (Machine Power)

Date of test	7-SEP-78
Mean loch level (ft)	888.3
Mean power at start of test (MW)	24.4
Frequency transducer deadband (Hz)	0.3
ILS Machine inertia constant, T_a (sec)	7.0
ILS load self regulation constant, k_n	1.5
ILS disturbance (% of 33 MW)	6%up;6%down 6%up;6%down

Figure 9.5 (a) to (d)

(single pipeline + microprocessor governor)

(a) Simulation of instability (Frequency)
(b) Simulation of instability (Governor Output)
(c) Simulation of instability (Servo Position)
(d) Simulation of instability (Gate Position)

PARAMETER	PDP 11 SIM.	MICROPROCESSOR
K_1		1.8
K_2		0.8
T_y		0.3
T_2		0.2
T_4		0.2
b_p		0.03
T_s	0.1	
T_a	7.0	
Servo hysteresis (%)	1.4	
Servo rate limit up (sec)	40.0	
Servo rate limit down (sec)	4.0	
Reservoir head	1.0	
Efficiency (%)	95.0	
Guide vane gain factor	1.36	
Freq. Ref.	1.012	
Torque before dist.	0.4	
Torque after dist.	0.4	
Integration interval (sec)	0.02	
Integration method	Euler	

Figure 9.6 (a) to (d)

(single pipeline + microprocessor governor)

(a) Simulation with re-optimised low band governor constants (Frequency)
(b) Simulation with re-optimised low band governor constants (Governor Output)
(c) Simulation with re-optimised low band governor constants (Servo Position)
(d) Simulation with re-optimised low band governor constants (Gate Position)

PARAMETER	PDP 11 SIM.	MICROPROCESSOR
K_1		0.8
K_2		2.0
T_y		0.3
T_2		0.2
T_4		0.2
b_p		0.03
T_s	0.1	
T_a	7.0	
Servo hysteresis (%)	1.4	
Servo rate limit up (sec)	40.0	
Servo rate limit down (sec)	4.0	
Reservoir head	1.0	
Efficiency (%)	95.0	
Guide vane gain factor	1.36	
Freq. Ref.	1.0105	
Torque before dist.	0.35	
Torque after dist.	0.4	
Integration interval (sec)	0.02	
Integration method	Euler	

Figure 9.7 (a) and (b)

(single pipeline + microprocessor governor)

(a) Simulation with initial mid band governor constants (Frequency)

(b) Simulation with initial mid band governor constants (Servo Position)

PARAMETER	PDP 11 SIM.	MICROPROCESSOR
K_1		2.5
K_2		1.8
T_y		0.6
T_2		0.2
T_4		0.2
b_p		0.03
T_s	0.1	
T_a	7.0	
Servo hysteresis (%)	1.4	
Servo rate limit up (sec)	40.0	
Servo rate limit down (sec)	4.0	
Reservoir head	1.0	
Efficiency (%)	95.0	
Guide vane gain factor	1.36	
Freq. Ref.	1.0135	
Torque before dist.	0.45	
Torque after dist.	0.5	
Integration interval (sec)	0.02	
Integration method	Euler	

Figure 9.8 (a) and (b)

(single pipeline + microprocessor governor)

(a) Simulation with re-optimised mid band governor constants (Frequency)

(b) Simulation with re-optimised mid band governor constants (Servo Position)

PARAMETER	PDP 11 SIM.	MICROPROCESSOR
K_1		2.0
K_2		3.0
T_y		0.6
T_2		0.2
T_4		0.2
b_p		0.03
T_s	0.1	
T_a	7.0	
Servo hysteresis (%)	1.4	
Servo rate limit up (sec)	40.0	
Servo rate limit down (sec)	4.0	
Reservoir head	1.0	
Efficiency (%)	95.0	
Guide vane gain factor	1.36	
Freq. Ref.	1.0135	
Torque before dist.	0.45	
Torque after dist.	0.5	
Integration interval (sec)	0.02	
Integration method	Euler	

Figure 9.9 (a) and (b)

(single pipeline + microprocessor governor)

(a) Simulation with initial high band governor constants (Frequency)

(b) Simulation with initial high band governor constants (Servo Position)

PARAMETER	PDP 11 SIM.	MICROPROCESSOR
K_1		3.0
K_2		2.3
T_y		1.0
T_2		0.2
T_4		0.2
b_p		0.03
T_s	0.1	
T_a	7.0	
Servo hysteresis (%)	1.4	
Servo rate limit up (sec)	40.0	
Servo rate limit down (sec)	4.0	
Reservoir head	1.0	
Efficiency (%)	95.0	
Guide vane gain factor	1.0	
Freq. Ref.	1.027	
Torque before dist.	0.9	
Torque after dist.	0.95	
Integration interval (sec)	0.02	
Integration method	Euler	

Figure 9.10 (a) and (b)

(single pipeline + microprocessor governor)

(a) Simulation with re-optimised high band governor constants (Frequency)

(b) Simulation with re-optimised high band governor constants (Servo Position)

PARAMETER	PDP 11 SIM.	MICROPROCESSOR
K_1		3.0
K_2		2.8
T_y		1.0
T_2		0.2
T_4		0.2
b_p		0.03
T_s	0.1	
T_a	7.0	
Servo hysteresis (%)	1.4	
Servo rate limit up (sec)	40.0	
Servo rate limit down (sec)	4.0	
Reservoir head	1.0	
Efficiency (%)	95.0	
Guide vane gain factor	1.0	
Freq. Ref.	1.027	
Torque before dist.	0.9	
Torque after dist.	0.95	
Integration interval (sec)	0.02	
Integration method	Euler	

Figure 9.11 7% low band step - Rate limit = 40s

(3 pipelines + internal 'sampled' governor)

Plot of Frequency versus time

PARAMETER	PDP 11 SIMULATION
K_1	0.8
K_2	2.0
T_y	0.3
T_2	0.2
T_4	0.2
b_p	0.03
T_s	0.1
T_a	7.0
Servo hysteresis (%)	1.4
Servo rate limit up (sec)	40.0
Servo rate limit down (sec)	4.0
Reservoir head	1.0
Efficiency (%)	95.0
Guide vane gain factor	1.36
Freq. Ref.	1.0099
Torque before dist.	0.33
Torque after dist.	0.4
Integration interval (sec)	0.05
Integration method	RK4

Figure 9.12 6% low band step - Rate limit = 40s

(3 pipelines + internal 'sampled' governor)

Plot of Frequency versus time

PARAMETER	PDP 11 SIMULATION
K_1	0.8
K_2	2.0
T_y	0.3
T_2	0.2
T_4	0.2
b_p	0.03
T_s	0.1
T_a	7.0
Servo hysteresis (%)	1.4
Servo rate limit up (sec)	40.0
Servo rate limit down (sec)	4.0
Reservoir head	1.0
Efficiency (%)	95.0
Guide vane gain factor	1.36
Freq. Ref.	1.0102
Torque before dist.	0.34
Torque after dist.	0.4
Integration interval (sec)	0.05
Integration method	RK4

Figure 9.13 5% low band step - Rate limit = 40s

(3 pipelines + internal 'sampled' governor)

Plot of Frequency versus time

PARAMETER	PDP 11 SIMULATION
K_1	0.8
K_2	2.0
T_y	0.3
T_2	0.2
T_4	0.2
b_p	0.03
T_s	0.1
T_a	7.0
Servo hysteresis (%)	1.4
Servo rate limit up (sec)	40.0
Servo rate limit down (sec)	4.0
Reservoir head	1.0
Efficiency (%)	95.0
Guide vane gain factor	1.36
Freq. Ref.	1.0105
Torque before dist.	0.35
Torque after dist.	0.4
Integration interval (sec)	0.05
Integration method	RK4

Figure 9.14 10% low band step - Rate limit = 22s

(3 pipelines + internal 'sampled' governor)

Plot of Frequency versus time

PARAMETER	PDP 11 SIMULATION
K_1	0.8
K_2	2.0
T_y	0.3
T_2	0.2
T_4	0.2
b_p	0.03
T_s	0.1
T_a	7.0
Servo hysteresis (%)	1.4
Servo rate limit up (sec)	22.0
Servo rate limit down (sec)	4.0
Reservoir head	1.0
Efficiency (%)	95.0
Guide vane gain factor	1.36
Freq. Ref.	1.009
Torque before dist.	0.3
Torque after dist.	0.4
Integration interval (sec)	0.05
Integration method	RK4

Figure 9.15 (a) and (b)

Site tests at Sloy Power Station
(Test Number - SLT200)

Plots of Simulated Frequency versus time
and Servo Position versus time

(a) ILS, old/new low band test (Simulated Frequency)
(b) ILS, old/new low band test (Servo Position)

Date of test	10-OCT-78
Mean loch level (ft)	922.6
Mean power at start of test (MW)	13.2
Frequency transducer deadband (Hz)	0.3
ILS Machine inertia constant, T_a (sec)	7.0
ILS load self regulation constant, k_n	0
ILS disturbance (% of 33 MW)	none

Figure 9.16 (a) and (b)

Site tests at Sloy Power Station
(Test Number - SLT201)

Plots of Simulated Frequency versus time
and Servo Position versus time

(a) ILS, new low band steps (Simulated Frequency)
(b) ILS, new low band steps (Servo Position)

Date of test	10-OCT-78
Mean loch level (ft)	922.6
Mean power at start of test (MW)	13
Frequency transducer deadband (Hz)	0.3
ILS Machine inertia constant, T_a (sec)	7.0
ILS load self regulation constant, k_n	0
ILS disturbance (% of 33 MW)	5% down;5%up

Figure 9.17 (a) to (c)

Site tests at Sloy Power Station
(Test Number - SLT202)

Plots of Simulated Frequency versus time
and Servo Position versus time
and Machine Power versus time

(a) ADP2, low-mid band steps (Simulated Frequency)
(b) ADP2, low-mid band steps (Servo Position)
(c) ADP2, low-mid band steps (Machine Power)

Date of test	10-OCT-78
Mean loch level (ft)	922.6
Mean power at start of test (MW)	12.3
Frequency transducer deadband (Hz)	0.3
ILS Machine inertia constant, T_a (sec)	7.0
ILS load self regulation constant, k_n	0
ILS disturbance (% of 33 MW)	5% up;5%down

Figure 9.18 (a) and (b)

Site tests at Sloy Power Station
(Test Number - SLT203)

Plots of Simulated Frequency versus time
and Servo Position versus time

(a) DDMID2 steps, bottom of mid band (Simulated Frequency)
(b) DDMID2 steps, bottom of mid band (Servo Position)

Date of test	10-OCT-78
Mean loch level (ft)	922.6
Mean power at start of test (MW)	14.8
Frequency transducer deadband (Hz)	0.3
ILS Machine inertia constant, T_a (sec)	7.0
ILS load self regulation constant, k_n	0
ILS disturbance (% of 33 MW)	5% down;5%up

Figure 9.19 (a) and (b)

Site tests at Sloy Power Station
(Test Number - SLT204)

Plots of Simulated Frequency versus time
and Servo Position versus time

(a) DDMID2 steps, top of mid band (Simulated Frequency)
(b) DDMID2 steps, top of mid band (Servo Position)

Date of test	10-OCT-78
Mean loch level (ft)	922.6
Mean power at start of test (MW)	23
Frequency transducer deadband (Hz)	0.3
ILS Machine inertia constant, T_a (sec)	7.0
ILS load self regulation constant, k_n	0
ILS disturbance (% of 33 MW)	5% down;5%up 6%down;6%up

Figure 9.20 (a) and (b)

Site tests at Sloy Power Station
(Test Number - SLT205)

Plots of Simulated Frequency versus time
and Servo Position versus time

(a) ADP2, mid-high band steps (Simulated Frequency)
(b) ADP2, mid-high band steps (Servo Position)

Date of test	10-OCT-78
Mean loch level (ft)	922.6
Mean power at start of test (MW)	22.5
Frequency transducer deadband (Hz)	0.3
ILS Machine inertia constant, T_a (sec)	7.0
ILS load self regulation constant, k_n	0
ILS disturbance (% of 33 MW)	5% up;5%down

Figure 9.21 (a) and (b)

Site tests at Sloy Power Station
(Test Number - SLT206)

Plots of Simulated Frequency versus time
and Servo Position versus time

(a) DDHI2, new high band steps (Simulated Frequency)
(b) DDHI2, new high band steps (Servo Position)

Date of test	10-OCT-78
Mean loch level (ft)	922.6
Mean power at start of test (MW)	29.4
Frequency transducer deadband (Hz)	0.3
ILS Machine inertia constant, T_a (sec)	7.0
ILS load self regulation constant, k_n	0
ILS disturbance (% of 33 MW)	5% down;5%up

Figure 9.22 (a) and (b)

Site tests at Sloy Power Station
(Test Number - SLT207,8,9,10)

Plots of Servo Position versus time
and Megawatts versus time

(a) Grid connected governor responses (Servo Position)
(b) Grid connected governor responses (Megawatts)

Date of test	10-OCT-78
Mean loch level (ft)	922.6
Mean power at start of test (MW)	3.3
Frequency transducer deadband (Hz)	0.3
Frequency Ref. step disturbance (Hz)	0.97

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