POWER SYSTEM LOAD VARIATIONS AND FREQUENCY CONTROL.

by

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ABSTRACT.

A hybrid real-time power systems simulator has been designed and built over the last few years in the Power Systems Section at Imperial College. One of its main purposes is its use as a research tool in the development and proving of new digital control algorithms suitable for implementation on process control computers being installed in the central and area control rooms of many power systems.

The first part of this thesis describes the development of a digital load simulation. It is a three part model including simulation of load characteristics (changes with frequency and voltage), trend changes and random fluctuations. Analysis of recordings made by the C.E.G.B. on their network was carried out to obtain parameters about the short term behaviour of loads, and these parameters were used in designing the random fluctuations part of the load simulation. Details of the implementation and behaviour of the load model are included in the thesis.

Use was made of the simulator to study methods of measuring the area power frequency response characteristic (K) and a new method of estimating K for small frequency deviations using the system's normal fluctuations was developed. Real power systems have a non-linear frequency response characteristic primarily due to governor deadband effects. The governor deadbands on the simulator are small but the system still shows a non-linear frequency response characteristic.

Two Automatic Generation Control algorithms similar to those in current use were implemented. These were compared with algorithms that were developed using a non-linear estimate of K as their frequency bias. The advantages and disadvantages of the various algorithms are discussed.

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CONTENTS.

	Abstract	1.
	Acknowledgements	2.
	Contents	3.
	List of symbols	6.
1.	Introduction.	8.
1.1.	Economic and Social Forces on the Electricity Supply Industry.	8.
1.2.	Centralised Digital Control.	9.
1.3.	Power System Simulation.	10.
1.4.	Interconnection and Automatic Generation Control.	11.
1.5.	Original Contributions in this Thesis.	13.
2.	Hybrid Power System Simulator.	14.
2.1.	Analogue Simulation Section.	17.
2.1.1.	Representation of Generation.	17.
2.1.2.	Load Units.	19.
2.1.3.	Other System Components.	20.
2.2.	Signal Measurement and Interfacing.	20.
2.3.	The Digital Computer.	23.
2.4.	Standard Software.	24.
2.4.1.	Operating Systems.	24.
2.4.2.	Programming Languages.	27.
2.4.3.	Utilities.	27.
2.5.	Special to Project Software.	28.
2.5.1.	System Support Software.	28.
2.5.2.	Data Acquisition Software.	30.
2.5.3.	Logging and Monitoring Software.	31.
2.5.4.	Simulation and Control Programs.	32.
3.	Load Behaviour.	33.
3.1.	Trend Changes.	33.
3.2.	Load Characteristics.	34.
3.3.	Random Load Variations.	34.
3.3.1.	Models Based on the Poisson Process.	36.
3.3.2.	Models Based on the Random Walk Process.	38.
3.3.3.	Direct Modelling as a Markov Process.	39.

3.3.4.	Model Using Low Pass Filtering of Random Numbers.	40.
3.3.5.	Discussion of Models of Random Load Behaviour.	43.
4.	Experimental Analysis of Random Fluctuations of Power System Loads.	44.
4.1.	Spectral Density of Random Fluctuations.	44.
4.2.	Previous Analyses of Random Fluctuations of Power System Loads.	46.
4.3.	Analysis of Measurements made at Sundon Substation.	47.
4.3.1.	DREAM Recordings at Sundon Substation.	47.
4.3.2.	Analysis of One Hour Records.	49.
4.3.3.	Analysis of Ten Minute Records.	49.
4.3.4.	First Differenced Data.	63.
4.3.5.	Conclusion.	66.
5.	Power System Simulator Load Model.	68.
5.1.	Algorithm for Load Model.	68.
5.2.	Implementation.	70.
5.3.	Supporting Software.	75.
5.4.	Experimental Results and Conclusion.	75.
6.	Area Frequency Response Characteristic (K)	78.
6.1.	Definition of Area Frequency Response Characteristic.	78.
6.2.	System Load and Generation Capacity Formula for K.	78.
6.3.	Governor Deadband and Non-linearity of K.	81.
6.4.	Measurement of K by System Tests.	83.
6.5.	Measuring K from System Fluctuations.	85.
6.5.1.	Gain Identification from Standard Deviations.	85.
6.5.2.	Identification of K.	87.
6.6.	Frequency Response Characteristic of the Power System Simulator.	89.
6.7.	Conclusions.	97.
7.	Automatic Generation Control (AGC).	98.
7.1.	Definition of AGC	98.
7.2.	Tie Line Bias Control	98.
7.3.	Performance Criteria	100.
7.3.1.	Frequency Performance	100.
7.3.2.	Power Interchange Performance	101.
7.3.3.	Generator Control Action.	101.
7.3.4.	Area Control Error (ACE) and its Integral (IACE)	102.

7.3.5.	Mutual Aid Criterion (MAC)	103.
7.3.6.	Inadvertent Energy Interchange (II) and Time Deviation (TD)	103.
7.3.7.	Assessment of Control Criteria	104.
7.4.	Present Problems Associated with AGC	104.
7.5.	Methods of Improving AGC	106.
7.6.	Non Linear Frequency Bias	107.
7.7.	Implementation of AGC Algorithms on Simulator	111.
7.7.1.	Simple Tie Line Bias Algorithm.	111.
7.7.2.	Error Adaptive Control Computer Algorithm	113.
7.7.3.	Non Linear Frequency Bias Algorithm	116.
7.7.4.	AGC Support Software	116.
7.8.	Comparison of AGC Algorithms	118.
8.	Conclusion	124.
8.1.	Original Contributions	124.
8.1.1.	Spectral and Time Series Analysis of Power System Variables.	124.
8.1.2.	Load Simulation	125.
8.1.3.	Estimation of K	126.
8.1.4.	Non-linear Frequency Bias for AGC	126.
8.2.	Power System Simulator Project	126.
8.2.1.	Power System Simulator Analogue Section	127.
8.2.2.	Digital Computer and Software	128.
8.2.3.	Future Studies of Control Algorithms	129.

APPENDICES:

A	– Sample Data Signals and Digital Filtering	130.
A1	– Sample Data Signals	130.
A2	– Introduction to Z-Transform	131.
A3	– Introduction to Digital Filters	131.
A4	– Non-Recursive Filters	132.
A5	– Recursive Filters	133.
B	– Statistical, Time Series and Spectral Density Analyses	135.
B1	– Statistical Properties	135.
B2	– Cross Correlation	136.
B3	– Stationary Signals	136.
B4	– Time Series Analysis	137.
B5	– Spectral Density Function	140.
C	– Tie Line Unit	143.

References 147.

LIST OF SYMBOLS.

ACE	–	area control error.
B	–	frequency bias.
E [...]	–	expected value.
G (f)	–	spectral density function.
Ip	–	phase current.
Iq	–	quadrature current.
II	–	inadvertent energy interchange.
K	–	area frequency response characteristic.
K_G	–	power frequency characteristic of generation.
K_L	–	power frequency characteristic of load.
N	–	number of samples in a data record.
P	–	power.
P (...)	–	probability.
P_C	–	connected generation capacity.
P_G	–	generated power.
P_L	–	load power demand.
P_T	–	tie line power flow.
R (τ)	–	autocovariance function.
S (τ)	–	structure function.
T	–	data record length (time).
TD	–	time deviation.
V	–	voltage.
f	–	frequency.
fo	–	nominal frequency.
f (t)	–	function of time.
t	–	time.
x_i	–	i th sample of x.
y_i	–	i th sample of y.
Z	–	Z- transform.
ΔP_T	–	tie line power flow error.
ΔP_G	–	change of generation.
Δf	–	change of frequency or frequency error.
Δt	–	sample period.
δ (t)	–	Dirac or impulse function.
ρ (τ)	–	autocorrelation function.

σ – standard deviation.

σ^2 – variance

τ – time lag.

1. INTRODUCTION.

1.1. ECONOMIC AND SOCIAL FORCES ON THE ELECTRICITY SUPPLY INDUSTRY.

During this century the demand for electricity in the industrialised nations has grown from almost zero to its present level. The use of electricity in the U.K. was 3,923 kwh per person per annum in 1975 [1], about half of the comparable usage in the U.S.A. Associated with the increased demand is an increasing reliance on electricity, since modern industrial society has been built on an assumed availability of electricity for industrial uses, water and sewerage pumping, lighting, food preservation, traffic control, rail transport etc. Large scale failures of electricity in urban areas of industrialised nations have grave consequences, as has been shown by the 1973-74 miners' strike in the U.K. and the 1965 and 1977 power failures in New York.

The period from 1974-76 saw a rise in the price of oil by a factor of 3-4, thus drastically altering the fuel economics of the world and causing considerable problems. Much discussion has followed about the world's energy reserves and efforts to conserve them. Although the level of energy reserves is debatable the increase in the cost of all fuels has affected the economics of electric power generation.

Mankind is a natural part of the environment of the earth. However, it has developed the ability to make large and rapid alterations to the environment, many of which are later discovered to be detrimental. A realisation of this has led to the so called "environmentalist movement" which has applied pressure to governments to regulate pollution of all forms. These controls have restricted the expansion of the power utilities, increased costs and created system security problems.

Society is demanding more electricity with greater reliability of supply but with as little increase of cost as possible. The costs of the fuel and the plant have increased and stricter controls have been placed on plant construction and operation. In an effort to satisfy the demands within these constraints the electricity supply

industry has increased its efficiency and is attempting to increase further its better use of fuel and plant.

Control equipment for power plant is cheap when compared with the capital cost of new generation or transmission equipment. Any method of increasing efficiency which reduces fuel costs or any improvement of control systems that will enable power systems to be operated nearer their limits, without loss of security, is worth investigating. The Central Electricity Generating Board (C.E.G.B.) in the U.K. spends on average £M 4.2 per day on fuel [2], and the new Drax B 2000 MW coal fired power station will cost about £M 600 [3]. When set against these sums, considerable expenditure on research to improve our understanding of the behaviour and the ability to control any part of a power system can be well justified.

It is recognised that our knowledge of system behaviour and control is inadequate because of the difficulty in explaining observed phenomena on power systems. Two recent conferences [4,5] have been held in the U.S.A. under the sponsorship of the Energy Research and Development Administration (ERDA) and the Electrical Power Research Institute (EPRI) to discover current problems and highlight areas where research is needed. Also CIGRE (International Conference on Large High Voltage Electric Systems) and the Institute of Electrical and Electronic Engineers (IEEE) have subcommittees involved in setting standards, identifying problems and publicising solutions.

1.2. CENTRALISED DIGITAL CONTROL.

Once the number of interconnected power stations in a system exceeds 3 or 4, a central control probably becomes necessary. These central controls are responsible for load dispatching, system configuration, security and stability as well as operational planning. As power systems have become larger and the technology more complex the amount of information needed in the control room has increased.

Central control rooms were first established in the 1920's.

Through the 1940's and 50's the main facilities were a mosaic wall diagram equipped with signalling and metering, teleprinters and telephones. Where the utility was operating tie lines it may have had an analogue automatic generation control unit. However, by the mid 1960's the amount of information required in the control room was beginning to swamp the display methods in use. Most utilities by this time had experience of digital computers which were used for planning studies, forecasting and accounting. The petro chemical industry had made some use of computers for monitoring and control, and the power utilities saw the digital process control computer as the solution to their problems. Initially the computer systems were only used for system monitoring, usually with visual display units. As experience was gained new facilities were added for system supervision. These included state estimation (data validation), on-line load flow, security analysis and short circuit analysis. Dy Liacco in references 6 and 7 discusses the problems and requirements of system control centres, the different types of facilities possible and also gives details of systems implemented.

The latest development is the closing of the control loop, with the computer directly controlling system plant. Many American utilities have transferred their automatic generation control from the analogue dispatcher onto the digital computer [6,7] and some Japanese utilities have implemented on-line reactive power/voltage control [6,7]. Research is continuing into the improvement of existing systems and the development of new ones.

1.3. POWER SYSTEM SIMULATION.

The primary objective of a power system is to provide the consumer with a continuous supply of electricity at a stated frequency and voltage, within specified limits, and at an economic price. Continuity of supply is very important and this forces power system's operation personnel to be conservative. Power system tests and changes of operational procedure must be carefully considered before being carried out so as to minimise the threat to system security.

Obviously any new control technique must be extensively tested before it can be implemented on the power system. This creates a need for power system simulation and has led to the development of the Power System Simulator at Imperial College. Development of a simulator requires measurement of the behaviour of parts of a power system, design of a mathematical model and parameter fitting. Normally, to model a component of a power system completely, would involve too complex a model so a simpler model is developed which represents the component's behaviour under certain operating conditions, or over certain time periods. The Power System Simulator is a real time hybrid simulator designed to simulate the neo-steady state or long term dynamics of a power system and operates in the 1s to $\frac{1}{2}$ hr. time scale.

Chapter 2 of this thesis describes the hybrid power system simulator, which is a special purpose analogue digital computer. This description includes an outline of the analogue section, interfacing unit, digital computer, system software and the special simulator software.

The load simulation used on the simulator was developed by the author. This model consists of three parts: load characteristics (changes with frequency and voltage), trend changes and random fluctuations. Chapter 3 is a critical literature survey of the previous models of these three components. Analysis of data records of the CEGB system were carried out primarily to develop a random fluctuation model and these are described in Chapter 4. The algorithm of the load model developed, its implementation and behaviour in the simulator are discussed in Chapter 5.

1.4. INTERCONNECTION AND AUTOMATIC GENERATION CONTROL.

Electric Power Utilities discovered that by connecting themselves together with tie-lines they could reduce their costs. This is due to two factors; the opportunity to buy and sell electricity between themselves in order to minimise costs and the ability to share spinning reserve and thus reduce the costs of standby equipment and to increase security.

Tie lines connecting control areas are often weak compared with the capacities of the areas and the power flows in the tie lines must be carefully controlled so as not to overload them. Also energy interchange between control areas is organised as contracts which specify energy interchange and power level limits. Power flow in a transmission line is a function of the relative phase angles at its ends, and as phase angle is the time integral of frequency, changes of power are affected by frequency differences. Control must be exercised over frequency and tie line power flows to operate as interconnected systems and this is known as Automatic Generation Control [8] (AGC) or Load Frequency Control (LFC).

The changes of power and frequency on a power system can be related by the use of a system parameter the Area Frequency Response Characteristic (or Power Frequency Characteristic). This parameter, which is important in AGC, is normally assumed to be constant for long periods and is measured by special system tests. Chapter 6 discusses the Area Frequency Characteristic (K) and it is shown that it is a function of the frequency variations. A method of estimating the system K for small frequency variations from the system's natural fluctuations is described and the results of tests on the Power System Simulator given.

Historically, various methods of frequency control have been employed by interconnected power systems. However, today most utilities use a form of Tie Line Bias Control. This involves evaluating a system performance criteria, with dimensions of power, from the frequency error and the algebraic sum of the tie line errors. A proportional plus integral controller is then used to minimise this criteria by altering the speeder gear settings of some of the generators that are under control. The method of control varies, but the most common is a raise/lower pulse system. Tie line bias control is discussed in Chapter 7, along with the operating problems associated with present methods of frequency control. Two currently used AGC algorithms have been implemented and the performance of these is compared with an AGC algorithm developed using a variable value of K. Use of a variable value of K reduces the amount of control action.

1.5. ORIGINAL CONTRIBUTIONS IN THIS THESIS.

The author has been responsible for the design and implementation of the software for the digital section of the simulator. A modular design has been used and efforts have been made to maintain simple interfaces between modules. As the simulator is a research tool under development, without a final specification, a high degree of flexibility must be maintained. It is this lack of a final specification and the need for flexibility that differentiates this system from a conventional process control software system. However, the design concepts used are similar, and similar engineering trade offs have to be made.

Time series and Fourier analysis has been widely used for signal analysis and has been applied to the analysis of power system frequency. There is no mention in the literature of the application of these techniques to system voltages and only limited application to power flows. The results from the Fourier analysis definitely shows that the spectral characteristics of the variations of power system variables can be divided into three parts. High and low frequency sections are white noise of different magnitude and the middle section has a magnitude inversely proportional to the square of the frequency. The frequency of the transition from one section to another varies for different system variables, frequency and voltage being the extremes. These frequencies of transition relate to composite system time constants and the dominant time constants vary for different variables.

A three part load model for real time power system simulation has been developed. The part of the model relating to random fluctuations is based on the results of the statistical analysis carried out on the data made available by the CEGB.

Consideration of the area frequency characteristic of a power system and its variations with frequency error has led to two developments. The first is a method of estimating the small frequency deviation value of the frequency characteristic from the natural fluctuations of the system. Secondly, a method of AGC using tie line bias control with a non-linear frequency bias has been implemented on the simulator and some of its advantages are discussed.

2. HYBRID POWER SYSTEM SIMULATOR.

A number of methods of simulating part or whole of the dynamics of a power system have been used in the past. Three of these in particular are:-

(a) Network analyser.
(b) Analogue simulation.
(c) Digital computer modelling.

Probably the most general of these techniques is that of dynamic modelling on a digital computer. However, at the present state of the art, models using step-by-step integration techniques are very time consuming. Digital computer models are best for dealing with slow time constant processes, such as boiler models and secondary control including automatic generation control. The faster responding system components such as turbines, generators, governor and automatic voltage regulators are better modelled by analogue techniques. Steady state power flows can be obtained on a network analyser, where the network is represented by passive electrical components.

The power system simulator at Imperial College uses all these three techniques (Figure 2.1). Transmission lines are represented by single phase lumped π representation, transformers by transformers and circuit breakers by relays. The turbogenerator sets with their primary control equipment are simulated electronically and are interfaced to the network by power amplifiers. A digital computer provides simulation of loads, boilers and secondary and higher control loops. This is interfaced to the rest of the model via Analogue to Digital (A/D) and Digital to Analogue (D/A) converters.

This hybrid solution is regarded as an effective use of the advantages of each technique. There are a few parts of the system where it is difficult to decide which technique is the most suitable and generally in these cases the most flexible solution has been used.

The simulator is divided into two physical parts, which are situated on separate floors of the Electrical Engineering Department (Figure 2.2). One part contains all the analogue simulation, both by network analyser and operational amplifier

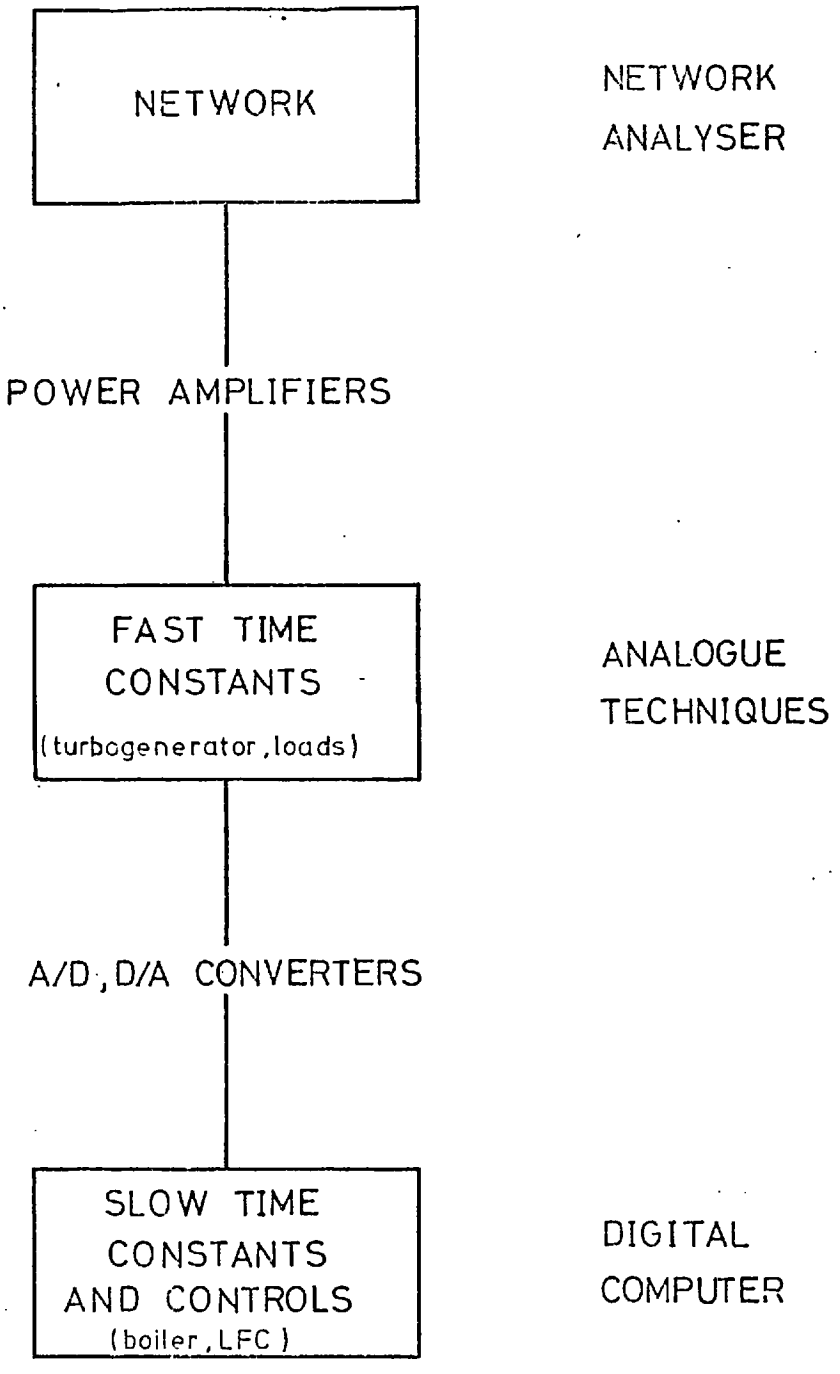


FIGURE 2.1 . COMPROMISE OF SIMULATION TECHNIQUES

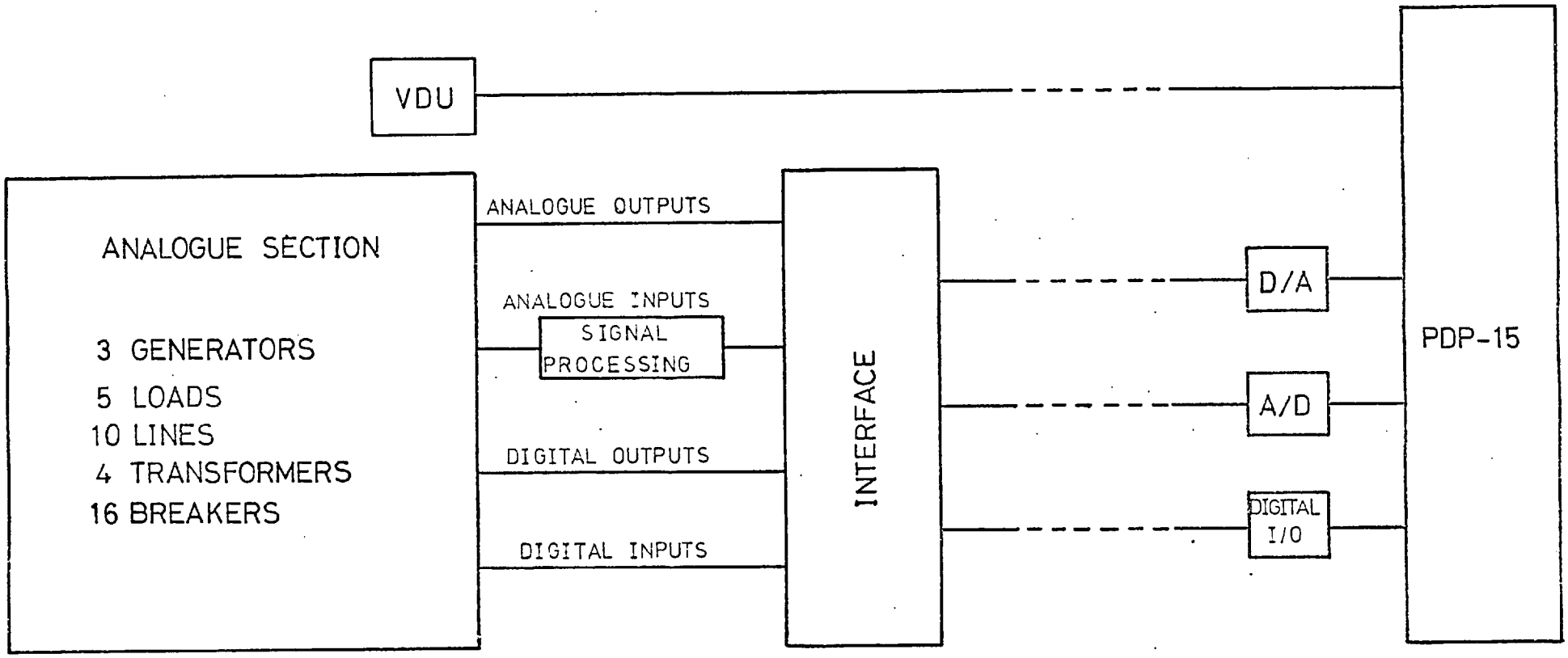


FIGURE 2.2 . SIMULATOR BLOCK DIAGRAM

techniques, and termed the analogue simulation section, plus an interface unit. This is connected by two multicore cables, one for digital and one for analogue signals, to the computer. The interface unit includes metering and multiplexing but not the A/D and D/A converters. A PDP-15 computer comprises the digital part of the simulator.

2.1. ANALOGUE SIMULATION SECTION.

The power system simulator at Imperial College is based upon the Central Electricity Generating Board's "Power System Model" [9] although many of the original concepts have been changed and the circuits brought up to date[10,11,12,13]. Most of this work has been carried out by Drs. Sheldrake [14] and Giles [15].

One of the main features of the system is that the network frequency is continuously variable between 48 and 52 Hz, the exact frequency being dependent upon the instantaneous power balances of the system. A single phase representation of the three phase system is used with a per-unit base voltage of 20V RMS and base current of 30 m.amps RMS.

2.1.1. REPRESENTATION OF GENERATION [10,11,12,13,14,15].

Space is available in the model for six generator units, although at present only three have been constructed.

A generator unit can be represented by an E.M.F. behind its synchronous reactance, the magnitude of the E.M.F. being determined by an Automatic Voltage Regulator (AVR) and the frequency by the turbine and speed governing system. A block diagram of a whole generator unit is shown in figure 2.3.

A constant amplitude sinusoidal voltage signal is produced by a voltage controlled oscillator (VCO). To improve the frequency stability of the device, feedback is applied, via a frequency voltage

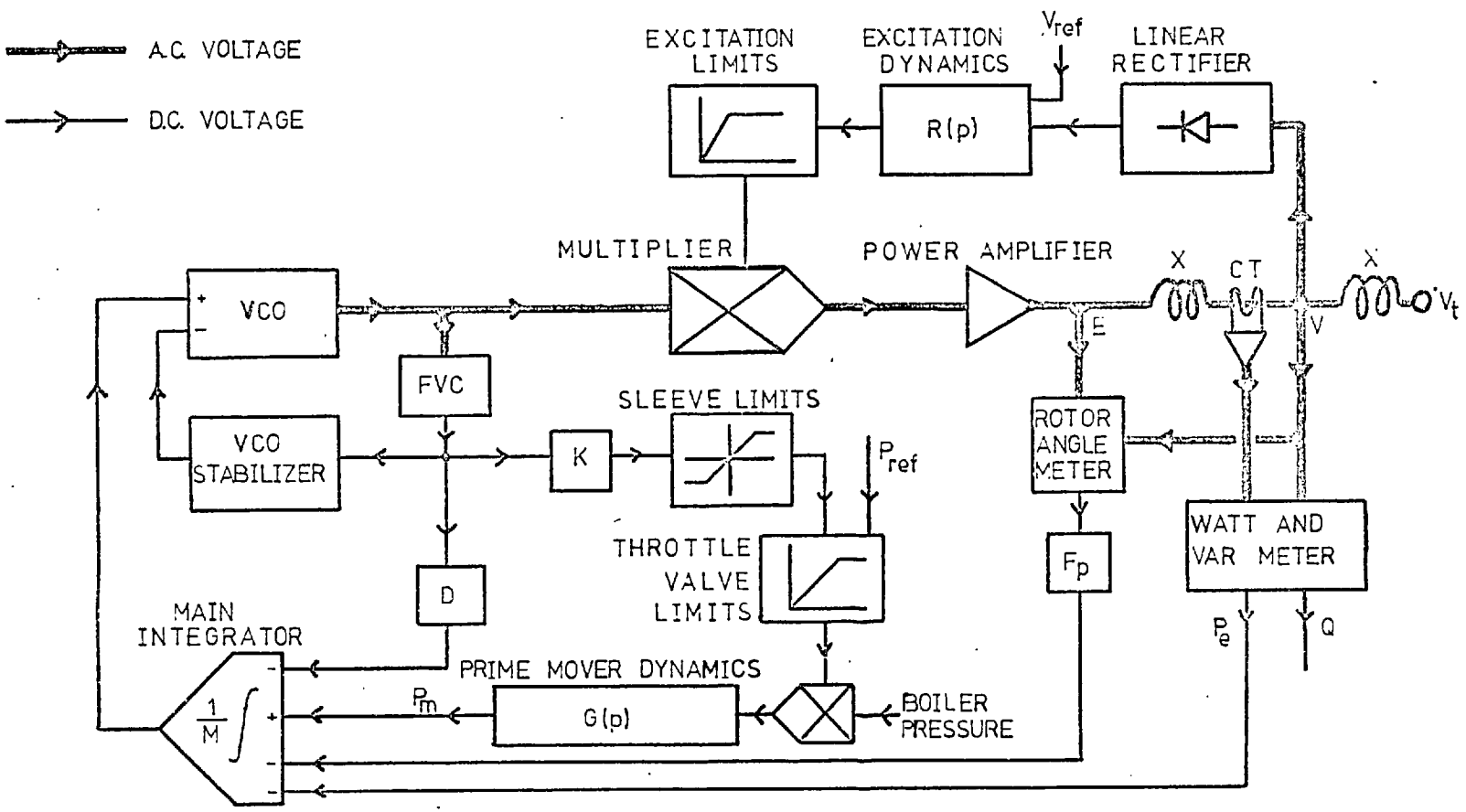


FIGURE 2-3 · BLOCK DIAGRAM OF GENERATOR UNIT

converter (FVC). The sinusoidal signal from the VCO is amplitude modulated by the AVR using an analogue multiplier and then amplified by a power amplifier to give E, which is the generated E.M.F. The terminal voltage is passed through a linear rectifier before being applied to the AVR. The excitation system includes a dynamics unit where typical AVR transfer functions R(s) are represented.

The output from the FVC is used to provide the shaft speed of the machine for governor simulation. K represents the steady state droop of the governor control and a further analogue unit applies the limits to the sleeve movement: 47.8 - 52.2 Hz in this simulation. The governor position and the speeder gear setting then determine the throttle valve position, which has a maximum limit. Valve position and boiler pressure are multiplied and then fed to a unit where prime-mover dynamics are represented. The boiler pressure signal is supplied manually or from the computer. Pm the mechanical shaft power is the output of the prime-mover dynamics unit.

The main integrater represents the mechanical equation of motion

$$(Ms + D)f + Fs\delta + Pe = Pm$$

where the first term includes the inertia of the rotating system and the friction and windage losses, Pe represents the electrical power output, and the term $Fs\delta$ represents the electromagnetic damping of the rotor circuits derived from the power slip characteristics.

A second method of representing the generator involves the use of Park's equations to build a 2-axis machine representation [15]. This has a number of advantages over the synchronous reactance model including accuracy and size [14].

2.1.2. LOAD UNITS [15].

The model contains five load units which represent the bulk supply points from the transmission to the distribution network. Originally the load units were conceived as programmable sinks of power and sinks or generators of reactive power. However, these were found to be unstable and the load units built were programmable sinks of in-

phase current and sinks or generators of quadrature current.

Control of the reference values of phase and quadrature current can be either manual or by computer. These values are compared with a signal fed back from the output via the current resolver, integrated and used to control amplitude modulators. The phase and quadrature currents are added and output to the system via a power amplifier. A block diagram of the system is shown in figure 2.4.

2.1.3. OTHER SYSTEM COMPONENTS.

A lumped nominal π representation of transmission lines is used which simulates 132 Kv double circuit overhead lines. Voltage and current transformers are provided at each end of the transmission lines. The same instrumentation is used on the four tap-changing transformers.

Circuit breakers are represented by electromechanical relays switched either manually or by digital outputs from the computer. The statuses of the circuit breakers are available to the computer as digital inputs.

A tie line to an infinite busbar which can be used to represent an interconnection to a power pool is available. Accurate metering of the real and reactive power flows on the tie line is provided. This is the only piece of hardware designed by the author and is described in Appendix C.

Any network configuration within the capacity of the equipment may be created by patching on the network panel.

2.2. SIGNAL MEASUREMENT AND INTERFACING.

The load and generator units include their own measurement circuits which process the A.C. signals. Phase and quadrature currents and voltage are measured by the load units. Four of the following six

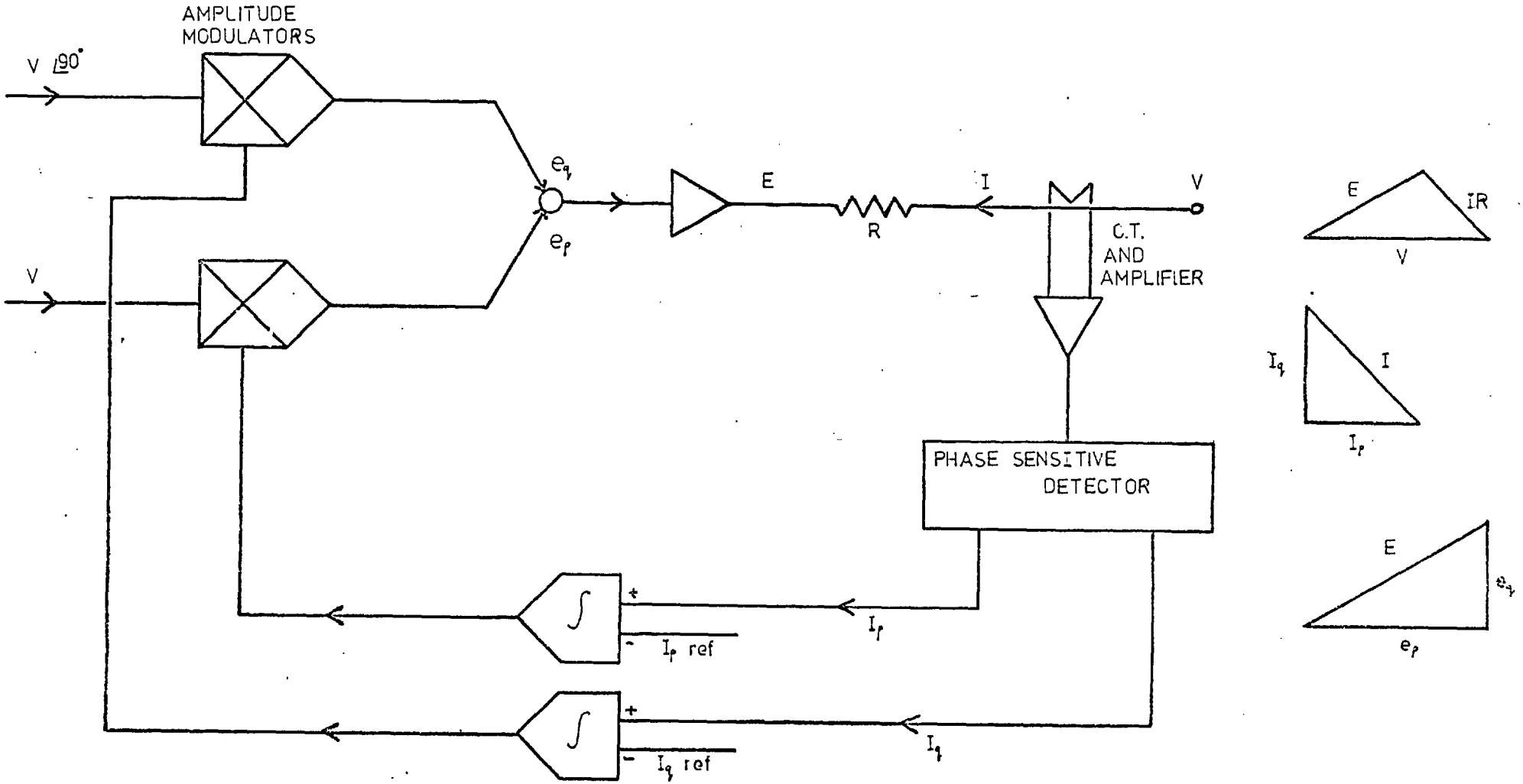


FIGURE 2·4 · BLOCK DIAGRAM OF LOAD UNIT

measurement signals are available from the generators:

(i) reference voltage.
(ii) reference power.
(iii) electrical power output.
(iv) reactive power output.
(v) throttle valve position.
(vi) rotor angle.

Only transducers are built into the transmission line and transformer models. These transducer leads are brought out to the interface unit. In the interface section are A.C. signal processing units for measuring voltage, phase angle, real and reactive power and a unit for frequency measurement. The frequency measurement produces frequency as a 12 bit count.

The interface section consists of a control unit which sets the analogue and digital multiplexers and demultiplexers 16 . 96 analogue input * channels are multiplexed onto 6 lines to the A/D converter and 64 analogue outputs are demultiplexed from 4 channels from the D/A converter. 32 of the analogue outputs are stored in zero order holds. Sample holds are not used for analogue inputs as the signals change only slowly.

Four words of digital inputs, 64 bits at 16 bits per word, are available and are multiplexed to the digital input/output unit. A status discrepancy check is made on the digital inputs and a status bit set on a discrepancy, indicating a bit change. Control of the interface can be manual, but is normally from the digital computer. Data and control instructions are distinguished by the state of the most significant bit of an 18 bit word sent from the computer via the digital input/output unit.

On the front of the interface unit is a patching panel to connect raw data to signal processing and metering units, to connect processed data to the multiplexers and control signals from the demultiplexers to the equipment they control. A few set point potentiometers and meters are provided on the panel with manual control switches for the interface.

* The terms input and output are relative to the computer in all cases.

2.3. THE DIGITAL COMPUTER.

In the early 1960's the PDP-15 range of computers was developed by the Digital Equipment Corporation (DEC) from its PDP-9 computer range. The computer used as part of the simulator is a PDP-15 /20 which would just classify as a minicomputer; however, it is larger than most modern minicomputers as it is built mainly using discrete component technology. The computer hardware is well described in the DEC manuals [17,18].

The machine uses an 18 bit word length and has a core cycle time of 0.8 ms, but with an add time of 1.6 ms. Only a single accumulator exists although there is also an index register and a limit register. Hardware multiply and divide are provided by the extended arithmetic unit using its quotient register.

All data and control transfers between peripherals, the central processor and memory are controlled by the input/output processor, which is an autonomous subsystem of the PDP-15 computer. Control logic and registers necessary to transfer up to 18 bits of parallel data on a common bidirectional input/output bus are contained in the input/output processor. The cycle time of this processor is 1 ms.

Operator communication with the computer is via the console panel and the console teletype. The console panel provides access and control over virtually every part of the computer. A Tektronix graphic and character storage display parallels the console teletype.

Main memory consists of 24k words of core memory, supported by two fixed head disks with 250k words of storage each and an access time of 20 ms. The other file based peripheral system is a twin Dectape unit.

A real time clock and an automatic priority interrupt (API) system are connected into the input/output processor. These options are essential for real time process control operation. The real time clock provides the time reference for scheduling. Priority Interrupt, the PDP-15's normal interrupt system, has only a single interrupt, which is software decoded, and is inadequate for process control type

requirements. The API system provides 4 hardware and 4 software priority levels and 32 interrupt lines.

Communications with the analogue section of the Power System Simulator is via the A/D converter, the D/A converter and the digital input/output unit. The A/D converter and multiplexer unit type AF01 has a variable accuracy, and a 10 bit accuracy is used. This gives a conversion time of 18 ms and an accuracy of 0.1% [19]. 10 bit accuracy is also used by the D/A converter type AA05 [20]. The digital input/output unit was designed and built in the department [21,22]. It can operate under program control or using direct memory access, but for the Power System Simulator program control is used.

Two other peripherals exist, a high speed serial printer and a second Tektronix display which is situated by the analogue section of the model.

2.4. STANDARD SOFTWARE.

A large amount of standard software is available from the computer manufacturers. This includes operating systems, assembler, compilers and utility programs which are all described in the relevant DEC manuals.

2.4.1. OPERATING SYSTEMS.

The main operating system used on the Electrical Engineering Department's PDP-15 computer is DOS-15 (Disk Operating System) [23]. This, however, is not suitable for multiprogramming or extensive real time operation.

A real time operating system is obviously required for the simulator project with the basic facilities that

(1) Programs can be scheduled on a time or event basis including the use of interrupts, with priorities so that more important programs might be executed first.

(ii) Input and output must be possible from programs without knowledge of what other programs are doing.

(iii) All programs must be able to access common data which must be protected from use while it is being updated.

(iv) The set of active programs must be changeable in real time.

At the time this was considered RSX Phase 1 (referred to as RSX) was the cheapest operating system with these features available [24].

RSX is a real time monitor system designed for handling real time information in a multiprogramming environment (ref 25 and 26). It has a modular construction which allows it to be configured to make best use of the hardware resources available.

Like most real time operating systems RSX uses an interrupt priority system to carry out multiprogram execution. The API system provides the interrupts for the operating system and the real time clock gives the system a time reference. RSX does not have a foreground/background facility or roll in/roll out. All programs are run in the foreground in predefined core area, there is no relocation hardware and once in core a task must be run to completion.

The operating system's facilities include scheduling, input/output supervision, resource allocation and operator communication. There are no facilities for editing, assembling, compiling or task building and these must be done under the Advanced Monitor operating system.

Configuration of RSX involves specifying core memory size, clock frequency, peripherals, partitions and common area. Partitions are areas in which the program tasks are run and common areas are used for inter-program communication. Some area must be left for system and system program communication. Peripheral handlers are installed for the standard peripherals available. Figure 2.5 shows how the core memory is divided into sections for use.

Advanced Monitor is the predecessor of the DOS-15 operating system and its use is described in reference 27. Task building is carried out under Advanced Monitor.

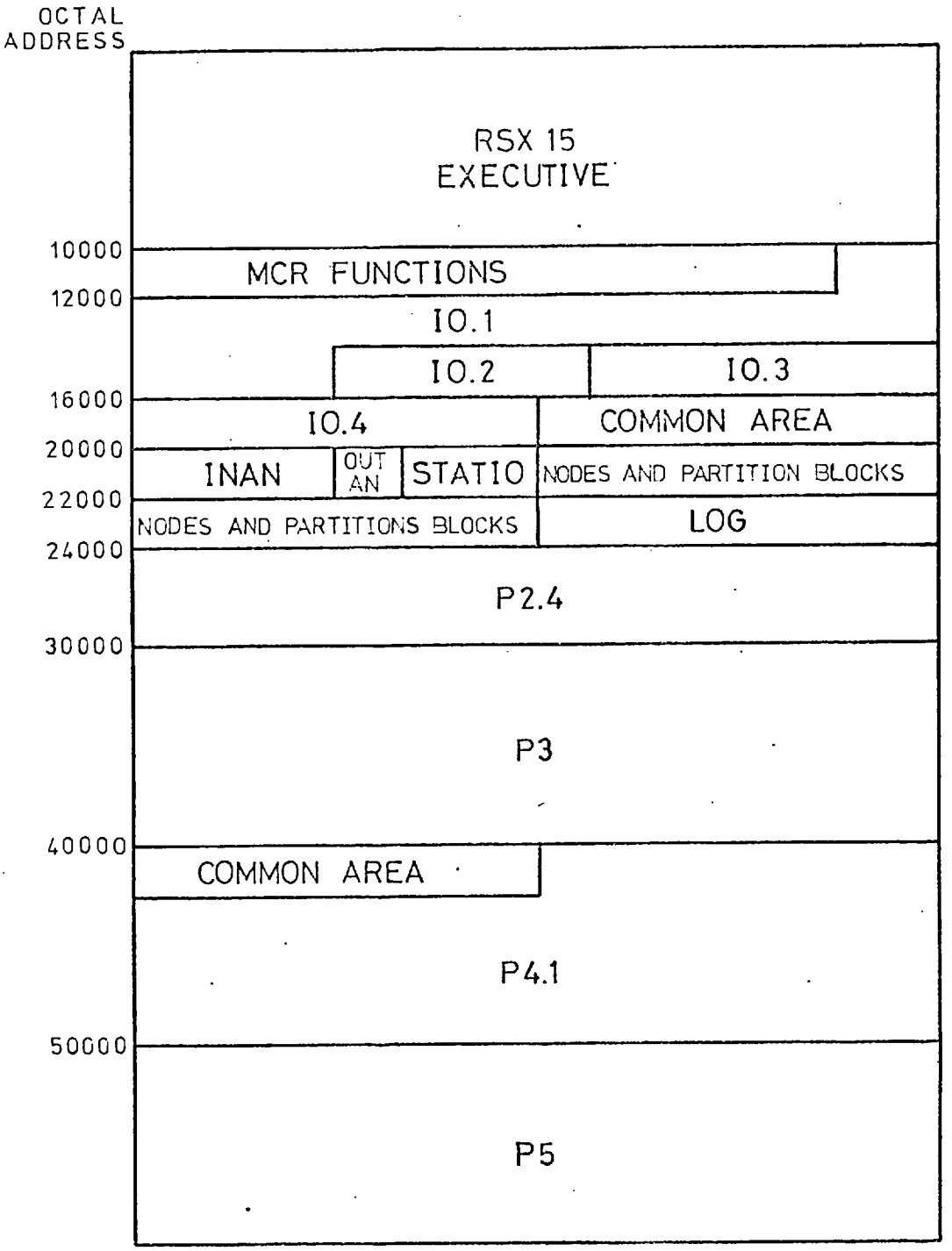


FIGURE 2.5 . CORE MAP

2.4.2. PROGRAMMING LANGUAGES.

Two programming languages can be used for writing programs run under RSX, Macro-15 (the PDP-15's symbolic assembler) and Fortran IV.

The assembler is machine dependent and can exploit all the facilities of the machine. It can be used for writing code efficient in execution time and memory usage; however, writing long, complex or mathematical programs in assembler is complicated and time consuming.

Fortran IV is a well known high level language, designed for scientific programming. It is not a very suitable language for real time operation [28]. The implementation on the PDP-15 is poor being sub-ANSI standard and the code is inefficient in memory usage.

A compromise must be made when writing programs between ease of programming and maintenance and efficiency in the use of computer resources; the language used depends upon this compromise. Normally programs directly controlling computer hardware or being executed more than twice a second are written in Macro-15 and the rest in Fortran IV.

2.4.3. UTILITIES.

A number of utilities exist for use under Advanced Monitor including a text editor and a peripheral interchange program. However, the main utility of interest is the Task Builder. This takes the relocatable binary code produced by the Macro-15 assembler and Fortran IV compiler and combines it with library routines from the system and user libraries to form a fixed binary task. The partition for task execution, its common area usage and default priority are fixed at task building.

The system library contains the Fortran language subroutines for input/output, floating point arithmetic, mathematical operations etc. and the subroutines for generating operating system requests. A small user library consists of useful subroutines collected and

written by the author and includes routines for paging of devices and random number generation.

2.5. SPECIAL TO PROJECT SOFTWARE.

Software for the power system simulator project can be divided into four categories; these are system support, data acquisition, logging and monitoring, and the rest which include simulation, control and analysis programs and would be regarded as directly part of this research project.

2.5.1. SYSTEM SUPPORT SOFTWARE.

This consists of utilities which are not supplied by the computer manufacturer but are required by the project. Two extra programs were written and are described below.

The computer system used has a Centronics 101 high speed serial printer for which no standard RSX phase 1 peripheral handler exists. However, a peripheral handler for the printer had been written by Jorgen Pihl of the Tandem Accelerator Laboratory, Uppsala in Sweden, to operate under a later version of RSX. A copy of this handler was obtained from the Digital Equipment Users Association DECUS and the handler modified for use under RSX phase 1. This works very well and a copy of the modified program was returned to DECUS.

Writing a real time process control system requires a knowledge of machine loading. A monitor consul routine USE was written to measure the amount of processor time remaining available in the system. It does this by operating at the lowest priority level and measuring the real time taken to execute a routine of known execution time.

Table 2.1. shows some of the results obtained by this routine. The table lists a number of the system tasks including the

TABLE 2.1. USE OF COMPUTER RESOURCES.

Name.	Partition	Residency	Frequency of Execution	Processor Usage
RSX	-	Core	-	3%
ANIN2	INAN		100 ms	12%
ANOUT	OUTAN		400 ms	1%
DIGIN	STATIO		200 ms	v.small
SIMLD(manual loads)	P2.4	Core	1 s	1%
(auto loads)				3½%
(random fluctuations)				9½%
BOIL1 (2 generators)	P4.1	Core	400 ms	16%
PRNT2	P3	Disk	3 s	3½%
LOG3 (64 samples /½s)	LOG	Core	-	2%
AGC1	P3		3 s	3%
AGC2	P3		3 s	4%
AGC3	P3		3 s	4%
AGCM	P3		3 2	3%

operating system, indicating the area in core they use, whether they are core or disk resident, their frequency of execution and their real time processor usage.

2.5.2. DATA ACQUISITION SOFTWARE.

This is the software responsible for data transfer between the digital computer and the analogue simulation section. It consists of five programs; an analogue input program ANIN2, an analogue output program ANOUT, a digital input program DIGIN and start and stop programs.

ANIN2 is a further development of the program ANIN described by Mogridge [26]. It has been modified by the addition of a smoothing or low pass filter and is described in reference [29]. The program reads the system frequency and 96 analogue inputs using the A/D converter. These values are then stored in a common area in core. Interrupt programming is used for efficiency and the task is permanently in core. Each analogue value is read once every 100 ms and filtered using the equation:

$$Y_k = 0.875\, Y_{k-1} + 0.125\, X_k$$

where Y_{k-1} = analogue value stored by last pass of program

X_k = analogue value read from analogue to digital converter.

Y_k = filtered analogue value.

The coefficents were chosen so that multiplication and division could be done in integer arithmetic using shift and add instructions as fast execution of the equation is needed as it is evaluated almost a thousand times a second. A digital filter of the type used has an exponential impulse response with a time constant of 0.75 s.

The analogue output program is described in reference [26]. It outputs the analogue values from the computer via the D/A converter to the analogue simulation section every 400 ms. The program is core resident.

Digital inputs are brought into the computer by the program

DIGIN which is described in reference 30 . This program executes every 200 ms and checks the status bit. If this is set, indicating a status discrepancy, the program searches for the bit or bits that have changed. The core copy of the digital input statuses is updated and a message printed on the serial printer. This program is also core resident.

Two other programs GO and STOP are associated with the data acquisition system. GO is used to initialise the system by setting initial conditions and scaling constants and then starting all the data acquisition and simulation programs. Use of GO saves much time over initalising the system manually. STOP stops execution of the data acquisition and simulation routines.

2.5.3. LOGGING AND MONITORING SOFTWARE.

Three techniques of logging/monitoring are used by the simulator project.

The first, which is a strictly monitoring technique, uses the Tektronix displays. It is designed to use the display by the analogue simulation section of the model although it can use either. A selection of different displays are available upon operator request. Each display shows time, system frequency, and will also show some specific system measurements e.g. generator 1 performance or system voltages. The display is strictly alpha-numeric, but the response is rapid, less than 10 s for any display. DISPLA is the master program controlling the display package. Each separate display is produced by a subroutine and extra subroutines can easily be added as required. Overlay programming is used to reduce core memory requirements, so that only one display subroutine is in core memory at any one time.

Use is made of the serial printer for monitoring/logging. PRNT2 prints the time, frequency and the values of 15 analogue inputs or outputs in per-unit values. A program PRNT2S prints a heading for the printout and schedules PRNT2 to run every 3s.

Logging of data for later computer analysis was done

originally on Dectape[26]. However, this proved unreliable and the logging program was completely rewritten to log results on to the disk. The present version LOG3 logs 64 words of data normally including time, system frequency and analogue input and output values on to disk store every 0.5 s. It would involve only minor modifications to the program to alter the frequency of sampling or number of words of data recorded. Two words of the common area NETWRK are used to store the disk address of the data log which contains a 20 minute record. Using these address words the data log can be read for printout or analysis. Special analysis programs can be written to evaluate system performance or statistical data such as mean, variance or time series functions. One program exists for printing out sections of the data record on the serial printer, called ANAL03, and prints a heading followed by as many lines of data as required. Each data line includes time, system frequency and up to 15 other data values which can be scaled in per-unit. The other data analysis programs will be described in the sections where their use is mentioned.

2.5.4. SIMULATION AND CONTROL PROGRAMS.

These programs consist of the implementations of the algorithms that have been developed during the research, and the programs that support them. Two simulation programs are in common use, one for load simulation which is described in Chapter 5 and one for boiler simulation developed by Tsiganis. These are supported by various initialisation and parameter setting routines. There are also various routines connected with the work on power frequency characteristic identification and load frequency control. These are also described later in the thesis.

Tsiganis, as part of the research for his doctorate, has been developing real time simulation algorithms for conventional and nuclear power station boiler equipment. He has also done work on simulation of hydro plant using the generator simulations available on the power system simulator. The implementations of these algorithms provide a good compromise between accuracy and machine usage for the real time simulation of boiler dynamics[31].

3. LOAD BEHAVIOUR.

Load behaviour has been studied extensively for a number of different reasons. A major one is for load forecasting: in the long term for system planning, in the medium term for maintenance planning and in the short term for generation scheduling [32]. Study of the effect of alteration of frequency and voltage on loads has been examined for stability, short circuit and load reduction studies [33]. Automatic generation control (load frequency control) studies and other system operation problems have encouraged some study of very short term variations of load.

The power system model operating in the time range of 1s to ½ hour involves the problems of load changes due to customer switching and variations of voltage and frequency. Load forecasting is rarely regarded as meaningful over a period of less than 5 minutes as trends over shorter time periods tend to be random. Thus for the purposes of load modelling for the power system simulator the behaviour can be divided into three parts:

1. Trend changes.
2. Load characteristic (variation with voltage and frequency)
3. Random variations.

3.1. TREND CHANGES.

Most power utilities have a recognisable daily load cycle. This is used as the basis for predicting load throughout the day. Other factors such as day of the week, time of year, weather etc. are allowed for. Predictions are made for 5 - 15 minute intervals. Over the period considered with the power system simulator, complex representation of longer term effects is unnecessary. The ability to set varying rates of change of load at 5 or 10 minute intervals is, however, useful. These changes, however, can reasonably be represented as linear changes of demand.

3.2. LOAD CHARACTERISTIC.

Every piece of electrical equipment exhibits its own load characteristic or variation of real and reactive power with variation of voltage and frequency [34]. For individual items of equipment the characteristics over a wide range of operating conditions are known or can be obtained. It is normal in power system studies to be faced with a mixed load - a load consisting of many different individual loads. Some attempts have been made to evaluate the characteristic of a load area from its individual parts [35], but this method usually breaks down because the composition of the load is rarely known.

The other method of finding the load characteristic, i.e. the load at a bulk supply point on the transmission network, is to measure it. This is not too difficult in the region near the nominal voltage and frequency, but almost impossible for the regions entered only during fault conditions, because of operational problems of intentionally entering these regions.

As the power systems simulator is designed to study neo-steady state behaviour it can be assumed that the frequency and voltage remain close to their nominal values.

It is generally assumed that [36]

$$\left(\frac{Pa}{Pr}\right) = \left(\frac{Va}{Vr}\right)^{n}$$

(where Pa and Pr are the powers consumed by a load and Va and Vr are their respective busbar voltages with n a constant)

giving $P \propto V^{n}$

$$\frac{\partial P}{\partial V} = n V^{(n-1)}$$

Assuming that V is small i.e. V is always close to 1.0 per unit then

$$V^{(n-1)} \approx 1.0$$

especially if n is between 0 and 2 which is normally the case

$$\frac{\partial P}{\partial V} \simeq n \qquad \text{for } V \simeq 1{\cdot}0 \text{ per unit}$$

Similar results can be shown for $\frac{\partial P}{\partial f}$, $\frac{\partial Q}{\partial V}$ and $\frac{\partial Q}{\partial f}$

which can all be represented by constants for near normal operating conditions.

Concordia [33] discusses estimates made internationally of nominal linear characteristics of power system loads. He also discusses more complex representations for load characteristics further from nominal and gives an extensive bibliography.

In the U.K. the Central Electricity Generating Board have made measurements of some of their load characteristics particularly those based upon voltage variations. However, when measuring the variations of reactive power with voltage they use a different measurement.

The approximation

$$\frac{\partial Q}{\partial V} = \frac{\Delta Q}{\Delta V} \times \frac{V}{Q} \qquad \ldots\ldots (3.1)$$

is the more commonly used formula for deriving the variation of reactive power with voltage. If, however, the reactive power level is low due to high power factor this can be misleading and Kozlowski, Rudzinski and Levy [37] argue that

$$\frac{\partial Q}{\partial V} = \frac{\Delta Q}{\Delta V} \times \frac{V}{P}$$

is a more accurate measure. The author has used the first approximation of 3.1.

3.3. RANDOM LOAD VARIATIONS.

Load variations, as seen at the bulk supply points, from the transmission to the distribution network, or seen as the total system load is the sum of the behaviour of many users. The individual loads are of different sizes and are either switched independently or in some specific but unknown sequence with other loads. Simulation of this situation without some assumptions would be extremely complex, if not impossible.

The task of developing a load model could be done by identification from system measurements, with choice of one of the many different classes of suitable models to fit the data. However, a theoretical study can indicate which types of models have physical justifications and which parameters can then be fitted.

Developing a theoretical model for load variations requires first a decision as to what simplifying assumptions can be made to produce a model not too complex. Once the basic model is evolved its characteristics are evaluated and then probably compared with measured behaviour. The model may then be modified to simulate more accurately the measured behaviour. However, the complexity and the accuracy of the model must be weighed against the necessary accuracy and computational requirements.

3.3.1. MODELS BASED ON THE POISSON PROCESS.

Lehman in 1953 (ref 38) developed a simple model of load variations based on the use of the Poisson process, a technique that had already been used in telephone exchange load studies. In 1954 Fortet [39] further developed models using the Poisson process.

A Poisson process consists of independent events that occur randomly in time[40,41,42] . If m is the average number of events occurring in a defined period of time the probability of K events occurring in that period is defined as

$$P(k) = \frac{m^k}{k!} e^{-m}$$

Adopting an arbitrary time origin, then

$n(t)$ = number of events in interval (o, t), $t \geqslant o$ can be defined Thus $n(t)$ is nondecreasing and varies in unit steps. Also $N(t)$ can be defined as

$$N(t) = E[n(t)]$$

where $E[\ldots]$ indicates the expected value

such that $N(t)$ is also nondecreasing and in general has a derivative,

$$m(t) = \frac{\partial N(t)}{dt} \geqslant 0$$

which is the mean density at t on the distribution curve.

For a stationary process

$m(t) = \text{constant} = m$

All the models based upon the Poisson process assume that

(i) The power consumed P (t) is a stationary process.

(ii) Individual consumers act independently.

(iii) The time τ_i at which consumers switch on is a Poisson process.

(iv) The individual power consumed at time t is a random function of t, R (t - τ) which only depends on (t - τ). The various individual powers are independent of each other and of the switching time distribution.

$$R(\tau, t) = 0 \quad \text{for} \quad t < \tau$$
$$R(\tau, t) = U \quad \text{for} \quad \tau < t < t + V$$
$$R(\tau, t) = 0 \quad \text{for} \quad t < \tau + V$$

These assumptions about the behaviour of consumers are then taken to the stage where manageable models are derivable by limiting the behaviour of U and V. Lehman proposes the model that has

$U = u_o$ for all loads

and V is derived from an exponential probability distribution function such that

$$P(V < t) = 1 - e^{-\frac{t}{T}} \qquad (T > 0)$$

$$\text{or} \quad P(V = t) = \frac{1}{T} e^{-\frac{t}{T}}$$

where P (....) indicates probability.

This means that τ has a mean duration of T and the expected power demand is

$$E[P] = M u_o T$$

It can then be shown[38,39] that

$$\text{autocovariance} \qquad R(\tau) = m u_o^2 T \exp\left(\frac{-\tau}{T}\right)$$

$$\text{giving} \qquad R(0) = m u_o^2 T$$

and the spectral density

$$G(\omega) = \frac{m u_o^2 T^2}{\pi} \cdot \frac{1}{1 + T^2 \omega^2}$$

A second model discussed by Fortet [39] and also by Bolton [42] assumes that u may take a number of discrete values u_k each with probability P_k and that again V is derived from an exponential probability distribution function giving

$$\text{Expected power} = E[P] = m \sum p_k u_k T_k$$

$$\text{autocovariance} = R(k) = m \sum p_k u_k \exp\left(\frac{-\tau}{T_k}\right)$$

$$\text{and spectral density} = G(\omega) = \frac{2m}{\pi} \sum p_k \frac{u_k^2 T_k^2}{1 + T_k^2 \omega^2}$$

It is interesting to note that both these models describe Markov processes.

3.3.2. MODEL BASED ON A RANDOM WALK PROCESS.

The random walk process is commonly used for modelling physical processes in nature. Brownian motion is the term used to describe the ceaseless irregular motion of a small particle or molecule immersed in a liquid or gas. This can be modelled in 1, 2 or 3 dimensions by a random walk process [41].

Let L_k define the displacement of a particle after the k th step such that

$$L_k = X_1 + X_2 + \ldots\ldots + X_k$$

where $X_1, X_2, \ldots\ldots X_k$ are independent random variables with a common distribution X

and $L_o = 0$

It is normally assumed that $E[X] = 0$ which results in

$$E[L_k] = 0$$

$$E[L_k^2] = k\, E[X^2]$$

Waddington [43,44,45], and Levy and Myerscough [46] have modelled the variations of the load of the C.E.G.B. with this process. The distribution of X is assumed to be normal with

$$E\ [X^2] = \sigma_x^2$$

Considering the Structure Function or Mean Square Deviation (see section B4)

$$S(k) = \frac{1}{n} \sum_{i=1}^{n} (L_{i+k} - L_i)^2$$

then

$$S(k) = k^2 \sigma_x^2$$

The random walk process has a total memory back to the initial value which results in the autocovariance function being a function of the length of the series. Thus the process is not weakly stationary and the autocovariance function is meaningless. This process is also a Markov Process.

3.3.3. DIRECT MODELLING AS A MARKOV PROCESS.

Trybula [47] evaluated the autocovariances of the power demand on a number of power systems in the COMECON countries. The results obtained could not be explained by the Poisson models of Lehman and Fortet so direct modelling of the load fluctuations by Markov processes was used. Three models were developed having two, three and four load states respectively.

The simplest model allows for a load to absorb either zero power or a fixed power Z at time t. $\zeta(t)$, the demand process, is stationary with independent increments. Letting the zero power state be represented by state 0 and the Z power state by state 1 and considering the process $\zeta(t)$ for $0 \leqslant t \leqslant \infty$ the probability $P_{ij}(\tau)$ that $\zeta(t+\tau) = j$ if $\zeta(t) = i$ is given by

$$P_{ij}(\tau) = P(\zeta(t+\tau) = j \mid \zeta(t) = i) \qquad (i,j = 0,1)$$

and if τ is very small

$$P_{01} = \frac{\tau}{T_o} + O(\tau)$$

$$P_{10} = \frac{\tau}{T_1} + O(\tau)$$

where T_0 and T_1 denote mean duration of the 0 and 1 states and $O(\tau)$ is an arbitrary quantity such that

$$\lim_{\tau \to 0} \frac{O(\tau)}{\tau} = 0$$

This describes a stationary process whose autocovariance is

$$R(\tau) = \frac{T_0 T_1 z^2}{(T_0 + T_1)^2} \cdot \exp\left(-\frac{T_0 + T_1}{T_0 T_1} |\tau|\right)$$

which is a decreasing first order exponential.

If the load reaches full power after some time delay it is described by a three state model where

$$\zeta_2(t) = \begin{cases} z \text{ if } \zeta_1(t) = z_1 \text{ for } t-T \leq \tau \leq t \\ 0 \text{ in the other case.} \end{cases}$$

where T is greater than zero and fixed.
Visually this may be shown as in figure 3.1 and gives the autocovariance shown in figure 3.2, where the first part is a single exponential and the second part a combination of two exponentials.

A further more complex model can be considered in which the load can also demand the power Z_2 for a period T. The power demand is shown in figure 3.3.and the autocovariance in figure 3.4.

Adding in different proportions of these three types of load demands can produce an infinite number of different total load behaviours which can then be used to simulate many types of total load autocovariance function.

3.3.4. MODEL USING LOW PASS FILTERING OF RANDOM NUMBERS.

This model was first used by de Mello et al [48] and later by Taylor and Creesap [51] for simulation studies of automatic generation control. The specifications for this model describe it as providing rapidly varying components with no sustained frequency spectrum whose bandwidth exceeds that of effective automatic generation control.

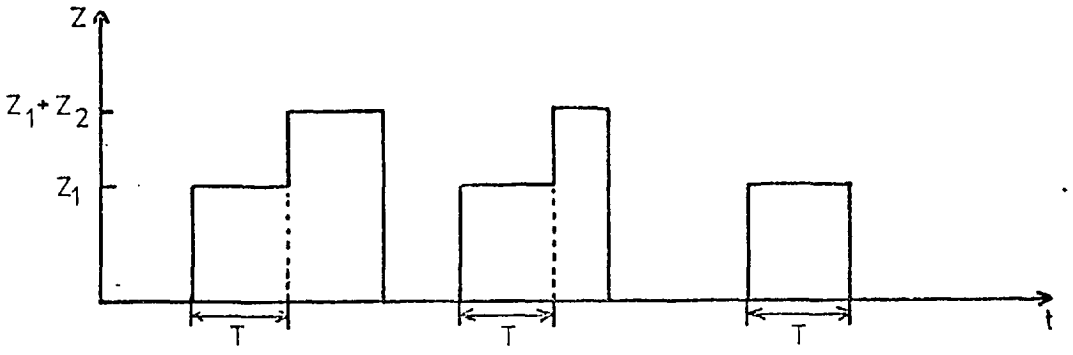


FIGURE 3.1 . INDIVIDUAL LOAD DEMAND FOR THREE STATE MARKOV MODEL

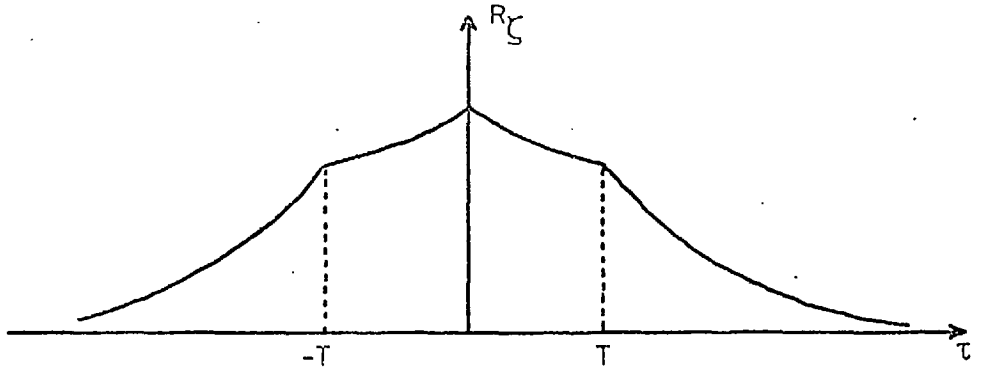


FIGURE 3.2 . AUTOCOVARIANCE FOR THREE STATE MARKOV MODEL

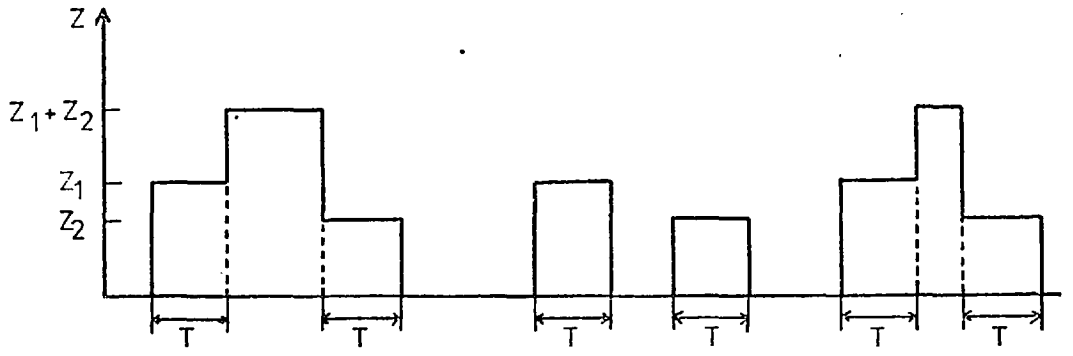


FIGURE 3.3 . INDIVIDUAL LOAD DEMAND FOR FOUR STATE MARKOV MODEL

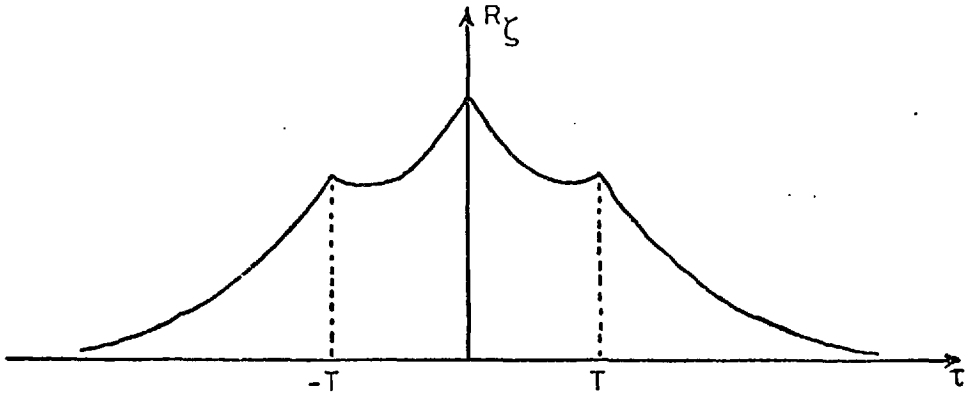


FIGURE 3.4 . AUTOCOVARIANCE FOR FOUR STATE MARKOV MODEL

Implementation of the model is by first order digital filtering (see A5) of numbers drawn randomly from a normal distribution. This gives the output an autocorrelation function that is identical to the impulse function of the filter and this is exponential. The output of this model, as explained by the First Arc Sine Law [50] can, for considerable periods of time, remain away from the zero value. To combat this, the result was forced to zero at random intervals.

3.3.5. DISCUSSION OF MODELS OF RANDOM LOAD BEHAVIOUR.

Only two of the four model types are easily implementable on a digital computer. These are the Random Walk Model and the Low Pass Filtering of Random Numbers Model. Both involve taking numbers randomly from a normal distribution and will thus have impulse autocorrelations of their first difference or serially differenced data.

The Low Pass Filtering of Random Numbers Model, the simpler Poisson Process Model of Lehman's involving a single individual load size and the simplest Markov Process Model having two load states all have an exponential autocorrelation function. As the mean variance and autocorrelation function describe the random load variations as accurately as the data allows (the spectral density and autocorrelation functions are directly transformable, see B5) the easiest model to implement should be used, i.e. the Low Pass Filtering of Random Numbers Model.

Fortet's Poisson Process Model involving many different individual load sizes and Trybula's three and four state Markov Process Models obviously describe the real state, as it is imagined, more accurately. However, in modelling what is a comparatively small effect, (it is shown in section 4.3 that the standard deviation of the load is not more than 2% of its value) these models are too complex for use in real time simulation.

4. EXPERIMENTAL ANALYSIS OF RANDOM FLUCTUATIONS OF POWER SYSTEM LOADS.

Although this research has been primarily concerned with random fluctuations of the power system loads, any analysis of the measurement of power system variables tends to reveal the behaviour of all parts of the system. The effects due to the various components must therefore be identified. This tends to reveal other information about the system not specifically sought, and to obscure the information required for load model development.

4.1. SPECTRAL DENSITY OF RANDOM FLUCTUATIONS.

Fortet [39] showed that in many cases the spectral density of a random function is proportional to the inverse of the square of the frequency.

The spectral density is defined in terms of the autocorrelation by the Fourier transform (B5).

$$G(f) = 2\int_0^\infty \rho(\tau)\cos 2\pi f\tau \, . \, d\tau$$

where $G(f)$ - spectral density
$\rho(\tau)$ - autocorrelation
f - frequency
τ - time lag

Integrating by parts gives

$$G(f) = \left[\rho(\tau)\frac{\sin 2\pi f\tau}{\pi f}\right]_0^\infty - \frac{1}{\pi f}\int \dot{\rho}(\tau)\sin 2\pi f\tau \, . \, d\tau$$

where $\dot{\rho}(\tau) = \frac{d\rho(\tau)}{d\tau}$ and $\ddot{\rho}(\tau) = \frac{d^2\rho(\tau)}{d^2\tau}$

and integrating again

$$G(f) = \left[\rho(\tau)\frac{\sin 2\pi f\tau}{\pi f} + \dot{\rho}(\tau)\frac{\cos 2\pi f\tau}{2\pi^2 f^2}\right]_0^\infty - \frac{1}{4\pi^2 f^2}\int_0^\infty \ddot{\rho}(\tau)\cos 2\pi f\tau \, . \, d\tau$$

Assuming $\rho(\infty) = \dot{\rho}(\infty) = 0$

$$G(f) = \frac{\rho'(0)}{2\pi^2 f^2} \quad \frac{1}{4\pi^2 f^2} \int_0^\infty \rho''(\tau) \cos 2\pi f \tau \; . \; d\tau$$

under very general conditions

$$\lim_{f \to \infty} \int_0^\infty \rho(\tau) \cos 2\pi f \tau \; . \; d\tau = 0$$

giving

$$G(f) = \frac{\rho'(0)}{2\pi^2 f^2}$$

$\tau = 0$ is a point of symmetry of the autocorrelation function and if $\rho'(\tau)$ exists for $\tau = 0$

$$\rho'(+0) = \rho'(-0) = 0$$

but frequently there is a discontinuity of $\rho(\tau)$ at $\tau = 0$

$$\rho'(+0) = -\rho'(-0) < 0$$

and in this case

$$G(f) \approx \frac{\rho'(+0)}{2\pi^2 f^2}$$

$$G(f) \propto \frac{1}{f^2}$$

or $\log_{10} G(f) = -2 \log_{10} f + C$

Remembering that the model of interest was of a stationary process and had an exponential autocorrelation, then

$$\rho(\tau) = \exp(-\lambda|\tau|)$$

where $\lambda = \frac{1}{T_c}$

T_c = time constant of autocorrelation

Then

$$G(f) = 2 \int_0^\infty \exp(-\lambda\tau) \cos 2\pi f \tau \; . \; d\tau$$

becomes from tables [52]

$$G(f) = \frac{2\lambda}{\lambda^2 + 4\pi^2 f^2}$$

which shows that for $2\pi f > \lambda$

$$G(f) \propto \frac{1}{f^2}$$

The $2\pi f = \lambda$ point should show as a meeting point of two asymptotes on the graph of log of spectral density to a base of log of frequency. At this point the time constant of the autocorrelation is related to the frequency by the equation

$$Tc = \frac{1}{2 \pi f} \qquad \ldots\ 4.1.$$

4.2. PREVIOUS ANALYSES OF RANDOM FLUCTUATIONS OF POWER SYSTEM LOADS.

Analysis has been carried out using time series or spectral density techniques on data records of power system loads of length 1 minute to a few hours. Gaden first published the results of load studies in 1952 [53]. However, the results he published in 1955 [54] are more comprehensive. The 1 minute and 7 minute records used were recorded in 1952 and were of the power demand of the town of Lausanne with a mean load of about 25 MW. Only the spectral densities of the records have been published and these show a slope of -2 on the log spectral density versus log frequency plot that is described in section 4.1.

Rudinski in 1962 analysed three records of 7, 9 and 10 minute lengths with 1s sample period. These recorded in 1959 at Sittingbourne Substation which had a mean load of about 30 MW. An internal report of the Central Electricity Research Laboratories [55] shows the autocorrelations and the spectral densities. The autocorrelations are damped oscillatory functions first crossing the axis with a time lag of 40 - 50s, and recrossing with time lag of about 120s. A minimum value of about - 0.3 is attained. Log of spectral density versus log of frequency plots show a slope of -2 although there is slight evidence of levelling off, below 0.03 Hz.

During the late 60's Waddington [43,44,45], carried out a series of studies on the total system load and system frequency of the C.E.G.B. Records of 1 hour and 3 hours were used and the mean square deviation functions (section B4) were calculated. These were straight lines and from these results the Random Walk Model (section 3.3.2) was derived. If the process is regarded as stationary the autocorrelation function can be deduced (section B4) and would be a slowly decaying linear function.

Trybula [47] shows in his paper discussing Markov Process Load Models, four autocovariances obtained for power system loads in COMECON countries. These are from records of a length of a few to a dozen minutes and are presumably of total utility load. The autocovariances remain positive, but decay to less than a tenth of their initial value after a time lag of 25s. However, the decays are not steady and some oscillation is shown.

The difference between the results of Waddington with an almost linear time series response and Rudinski and Trybula with rapidly decaying autocovariance responses is noticeable. Different record lengths and sampling periods are used and these may be the cause of the discrepancies.

4.3. ANALYSIS OF MEASUREMENTS MADE AT SUNDON SUBSTATION.

4.3.1. DREAM RECORDINGS AT SUNDON SUBSTATION.

During the period 28th April - 2nd May, 1976, the System Technical Branch of the C.E.G.B. was involved in the field evaluation of the DREAM (Digital Recording and Measuring) Equipment. This involved recording measurements at the Sundon 400 Kv Substation.

The DREAM equipment records up to six variables at 1000 samples/ s in two different modes [56].

(i) Continuous recording for 4 min. 50s and a pause for 10s, repeated four times. (Total run time: 20 mins.)

(ii) Record 0.2s every 2s for 2 hours.

Sampling frequency is controlled by a radio clock locked onto the 60 KHz MSF signal at Rugby.

For the field evaluations of the DREAM equipment four inputs were connected to the blue phase current transformers on the Cowley, Elstree 1, Grendon 1 and Wymondley feeders, one to a blue phase voltage transformer and the sixth to a D.C. reference. A number of recordings were made using both recording modes.

Data recorded by the second mode (i.e. recording for 0.2s every 2s) was preprocessed by the System Technical Branch to evaluate the frequency from the voltage signal, RMS voltage, RMS feeder currents and RMS three phase real and reactive powers on the feeders over the 0.2s sample period. In these calculations the three phases were assumed to be balanced. This resulted in a 2 hour data record with a 2s sample period.

Three records of the preprocessed data were made available to the author for analysis. These were

G 0 9	3.35 - 5.35	2nd May, 1976 (Sunday)
G 1 5	4.15 - 6.15	29th April, 1976 (Thursday)
G 2 0	10.36 - 12.36	28th April, 1976 (Wednesday)

Each 2 hour record contained 3600 samples and each sample included time, frequency and busbar voltage. Record G 0 9 included the real and reactive power flows on the Elstree 1 and Grendon 1 feeders and records G 1 5 and G 2 0 the real and reactive power flows on all the four metered feeders.

The *error* of the voltage transformer which was a wound type of class AL was specified as $\pm$ 0.25% in the normal operating range. Class C current transformers used have an *error* of $\pm$ 1% between 10 - 125% of their rated current. Linearity for these transducers is not specified but would be expected to be good enough to register changes of 1%.

DREAM equipment converts the analogue signal from the voltage and current transformers to digital values using a 15 bit plus sign A/D converter which gives a resolution of 0.003% and an overall *error* of 0.01%.

Estimates of the *errors* of the preprocessing algorithms were as follows:

Frequency	-	$\pm$ 0.2%	
Voltage	-	$\pm$ 0.01%	
Current	-	$\pm$ 0.01%	
Real Power	-	$\pm$ 0.5%	Power factor > 0.5
Reactive Power	-	$\pm$ 0.5%	Power factor < 0.5

A problem associated with the accuracy of the results is that of aliasing. This occurs when signals are present whose frequencies are above the Nyquist limit (section A1). For 2s sampling the Nyquist limit is 0.25 Hz. Evaluation of the sample value over 0.2s attenuates frequencies above 5 Hz.

Simple sample data theory assumes that samples are taken over an infinitely short period. This is impossible if digital sampling of A.C. signals to give the RMS value is used.

Sundon substation is close to the electrical centre of the C.E.G.B. power system network. One of the main north-south feeders of the network is a twin circuit line from Cottam to Sundon via Grendon where a small amount of power is transferred to the lower voltage network. The Grendon 1 line is one of these circuits. Elstree is a 275 Kv substation, which forms a node of the outer London ring and supplies the North West London load. The 275/400 Kv transformers are at the Elstree substation. Power flows in the Elstree 1 feeder should behave in a similar manner to the power demand at the Elstree substation. Cowley and Wymondley are east-west feeders whose use depends upon the network configuration.

There are static and synchronous compensators at Sundon substation. A synchronous compensator is also present at Elstree and there is evidence from other analysis of the data collected that these compensators may be setting up an oscillation on feeders in the area. During recordings G 0 9 and G 1 5 120 MVA of shunt reactance was connected at Sundon and during all the tests the synchronous compensator was absorbing up to 30 MVA of reactive power.

4.3.2. ANALYSIS OF ONE HOUR RECORDS.

The data records were divided into two one hour records for analysis. This reduced the computing requirement and increased the number of records for comparison. These results are described in detail in references 57 and 58 .

Initially the data was analysed for mean, standard deviation, cross correlation of real and reactive powers with voltage and frequency and the real and reactive power on each feeder. A test of stationarity of the records was made and time series analysis using both mean square deviation and autocorrelation functions carried out. Finally, the spectral density was calculated and the time series and spectral density functions plotted. The techniques used are described in Appendix B.

The data records were then filtered using a second order high pass Butterworth digital filter with a cutoff at 0.011 Hz (91s period) and the tests repeated. A second order Butterworth filter was chosen because it was a suitable compromise between sharpness of cut off and complexity, it had a flat passband and its poor phase characteristics would not effect the results. Initial tests had indicated that the spectrum of the data had less "power" in the region of 0.011 Hz, but this later proved false. The power density of the spectrum is governed by the inverse square law (section 4.1) up to a frequency of about 0.4 Hz. As the use of the filter was an attempt to isolate the short term behaviour, of the order of 1 minute, the 0.011 Hz cut off was considered reasonable.

The dispersion, defined as the standard deviation divided by the mean value of the unfiltered data, was used as a measure to compare the fluctuations of the data. Table 4.1 shows the average values for the variables analysed for both the filtered and unfiltered cases. In general the mean values of the Cowley real power and Wymondley reactive power flows were small (less than 10% rated value) thus distorting the dispersion measure. The values for unfiltered power flows were in the range 1.5 - 5.5% and for filtered power flows 0.25 - 1.5%. Voltage and frequency, the controlled variables on a power system, show much smaller variations. It is interesting to note that of the real power flows Grendon 1 has the largest fluctuations and Elstree 1 the smallest. This is to be expected when it is remembered that Grendon 1 is a main system interconnection and carries synchronising power, whereas Elstree 1, in the main, supplies a load.

It can be seen from Table 4.1 that these dispersions are of comparable order to the absolute accuracies of the measurements. However, it must be remembered that voltage and current transformers

TABLE 4.1. AVERAGE VALUES OF DISPERSIONS FOR ONE HOUR RECORDS.

	Absolute Values	Filtered Values
Frequency	9.45×10^{-4}	9.01×10^{-5}
Voltage	1.63×10^{-3}	3.06×10^{-4}
Elstree 1 power	0.0235	0.0024
Elstree 1 vars	0.0300	0.0101
Grendon 1 power	0.0566	0.0146
Grendon 1 vars	0.0420	0.0122
Cowley power	-	-
Cowley vars	0.0290	0.0103
Wymondley power	0.0189	0.0046
Wymondley vars	-	-

TABLE 4.2. INTERSECTION POINTS FOR ASYMPTOTES ON SPECTRAL DENSITY IN DECIBELS VERSUS LOGARITHM OF FREQUENCY PLOTS.

	Frequency in Hz.	Cycle Period in seconds
Frequency	0.113	9.1.
Voltage	0.041	28.1.
Elstree 1 power	0.093	11.0.
Elstree 1 vars	0.049	20.9.
Grendon 1 power	0.085	12.5.
Grendon 1 vars	0.079	16.4.
Cowley power	0.085	11.8.
Cowley vars	0.048	21.6.
Wymondley power	0.079	12.9.
Wymondley vars	0.021	47.3.

have a good linear response over their normal operating limits. Thus, as measurements of a similar value are being considered, the accuracy used in assessing the standard deviation, time series and spectral density functions is dominated by the accuracy of the preprocessing algorithms.

Cross correlation values for unfiltered data are very inconsistent [58], and it is reasonable to assume that there is no significant correlation. The results for filtered data are more consistent falling between $\pm$ 0.3 and indicating no correlation. This result was unexpected. As the frequency is derived from the voltage signal and real and reactive power are partly derived from the voltage signal it may be argued that the lack of correlation is due to interdependence. However, it is considered that this type of effect would cause spurious correlation rather than the lack of it. Lack of correlation of the Grendon 1 real and reactive powers with each other and with voltage and frequency may be explained by the fact that the real power flows are dependent upon the differences between phase angle in different parts of the system and the reactive power flows upon voltage differences. An explanation for the lack of correlation on the Elstree 1 line is that consumer switching of loads of different power factors totally obscures the very small load changes due to small fluctuations in voltage and frequency.

Any finite length record is strictly non-stationary. However, it is normally hoped that the record will be of a stationary or weakly stationary process. No accurate measurement can be made of stationarity, but use of the stationarity test (section B3) does give an indication of the presence of long term trends. Consideration of the three sets of results (i.e. for 6, 12 and 30 slices) from the stationarity tests and examination of the number of variables that have all results in the 0-5% and 95-100% probability bands shows that if the results contain no long term trends then the number should be less than 10% of the total. For the unfiltered data 40% of the variables have all the results of their stationarity tests in these bands. It can be reasonably assumed that the data records are not even of weakly stationary processes. Naturally the results for the filtered data show that trend and slow variations are absent.

The mean square deviation functions of the unfiltered data

records are mainly linearly increasing functions similar to figure 4.1. Some functions show indications of levelling off. All the mean square deviation functions of the filtered data rise rapidly to level off at twice the variance of the record. There is normally an overshoot on the rise, with the peak after a time lag of about 40s.

Autocorrelation functions of the unfiltered data decay slowly and often linearly like figure 4.2. None of the functions decay to exponential -1 (≈ 0.37) in less than 100s time lag. There is considerable variation between the plots and it is difficult to draw any conclusions from them. The autocorrelation functions of the filtered data records decay rapidly as shown in figure 4.5. After an overshoot the value varies randomly around the zero.

Some of the time series functions are very noisy, a problem more noticeable on the analyses of voltage and reactive power flow records. This noise appears to be due to a signal of about 0.256 Hz, at which frequency there is a spike on the spectral density plots. However, analysis of other data records from the DREAM recordings at Sundon, by the System Technical Branch of the C.E.G.B. indicate that this is aliasing caused by a signal, above the Nyquist limit, of 1.28 Hz. It can be shown that the apparent frequency is related to the real frequency by the equation

$$fr = \frac{a}{b} fa$$

where fr - causal frequency above Nyquist limit
fa - apparent frequency
a, b - integers.

The spectral density was plotted in decibels to a base of both frequency and logarithm of frequency. Figure 4.3. shows a typical plot of spectral density to base of frequency and shows that most of the energy is in the low frequency end of the spectrum. Filtered data records have most of this low frequency power removed which shows up in their plots.

Study of the plots of spectral density in decibels to a base of logarithm of frequency shows a slope of -2 (-20 dB's per decade). However, the slope levels out at the higher frequencies to give an almost white noise response (fig. 4.4). Asymptotes were drawn by

FIGURE 4.1 . STRUCTURE FUNCTION ELSTREE 1 POWER ABSOLUTE
10.36-11.36 28/4/76

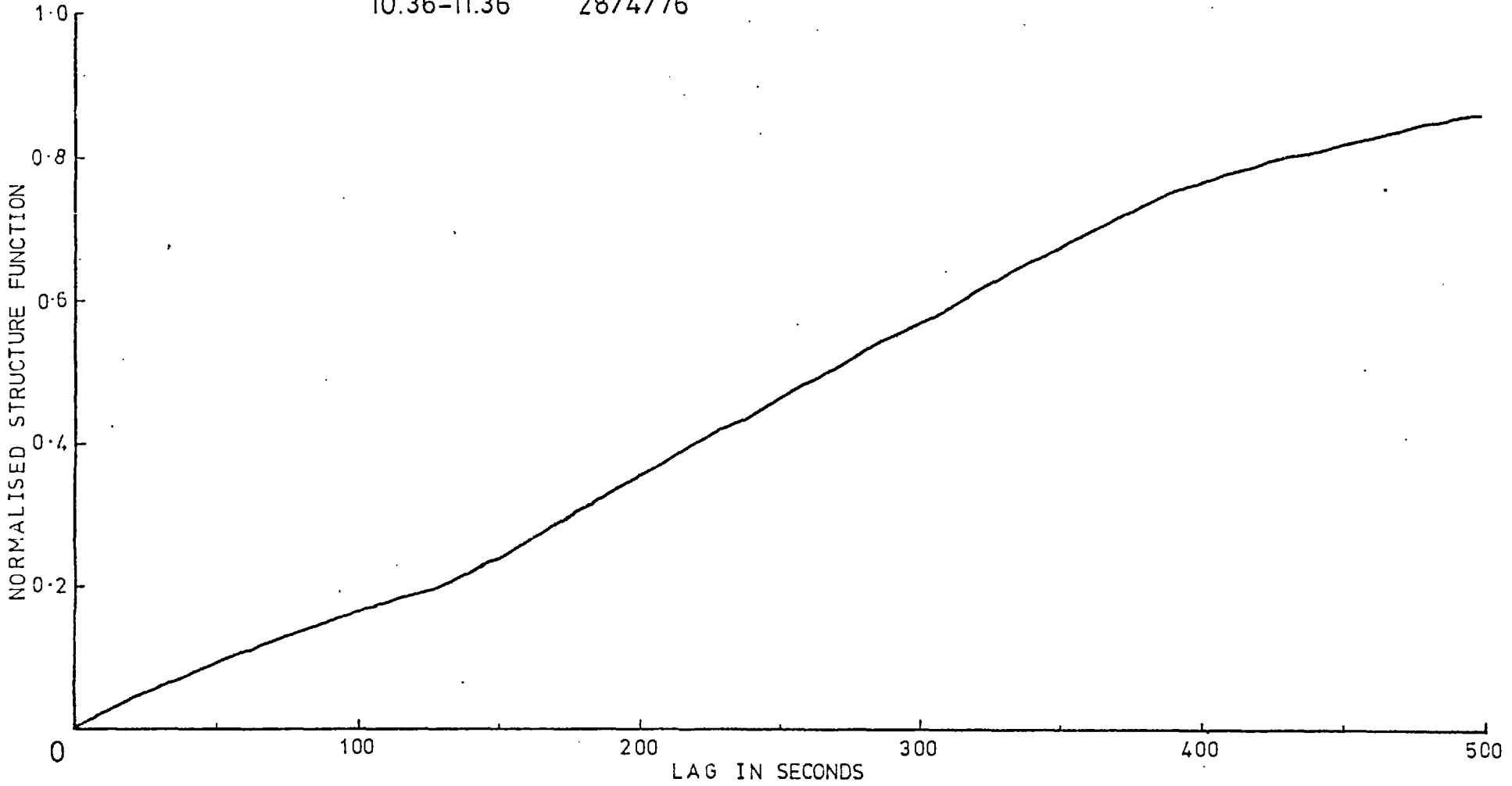


FIGURE 4.2 . AUTOCORRELATION ELSTREE 1 POWER ABSOLUTE
10.36–11.36 28/4/76

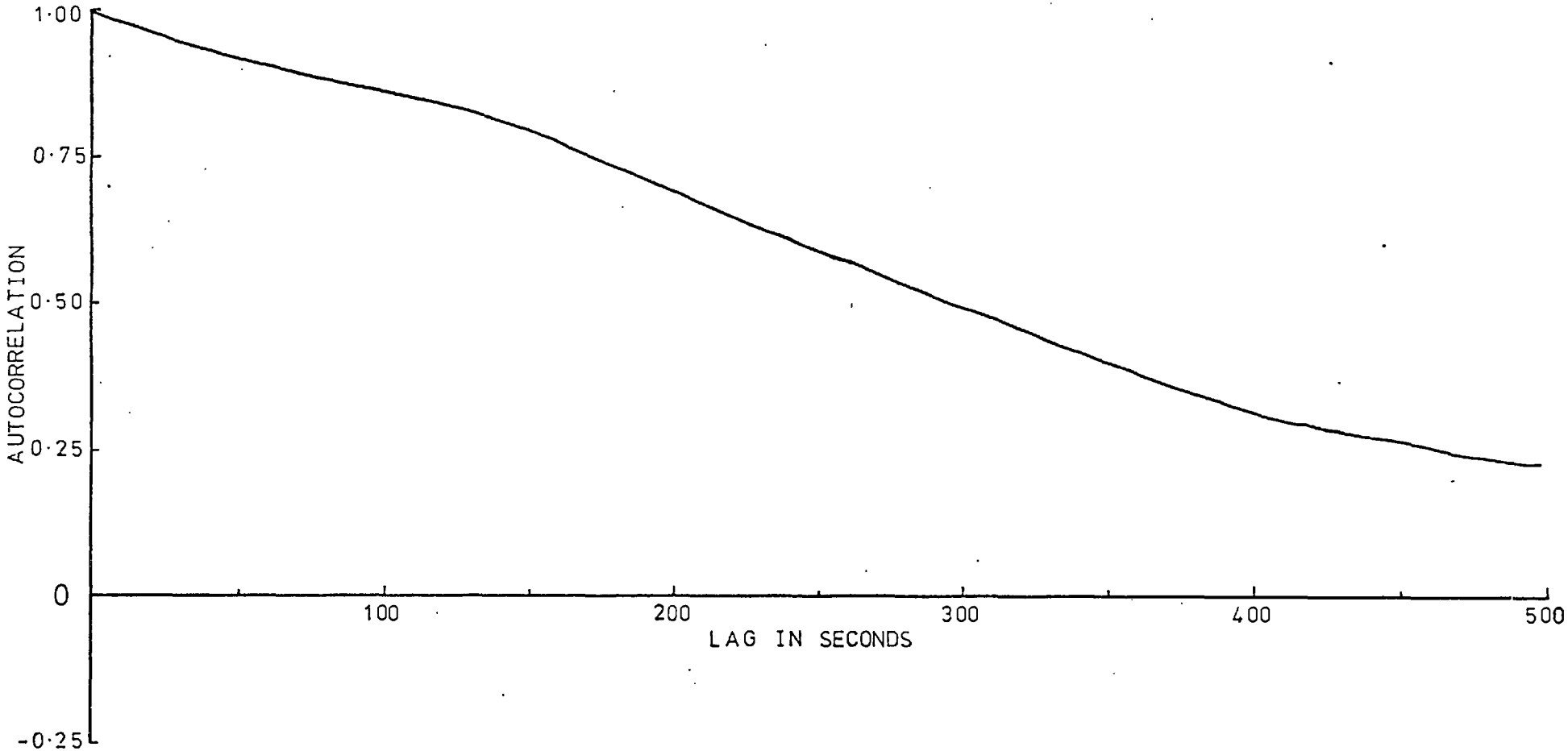


FIGURE 4.3 . SPECTRAL DENSITY ELSTREE 1 POWER ABSOLUTE
10.36-11.36 28/4/76

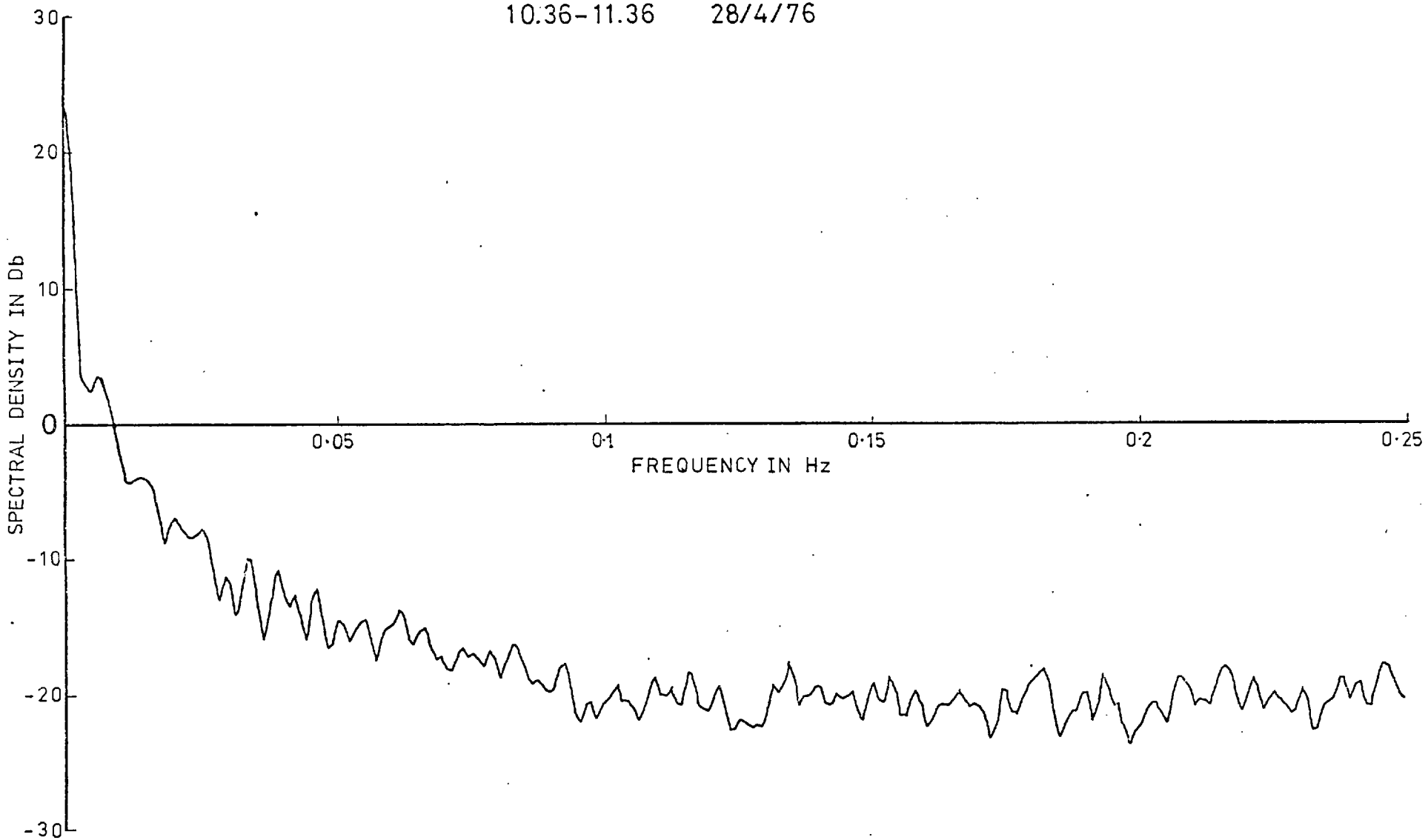


FIGURE 4.4 . SPECTRAL DENSITIES SYSTEM FREQUENCY AND VOLTAGE ABSOLUTE
10.36–11.36 28/4/76

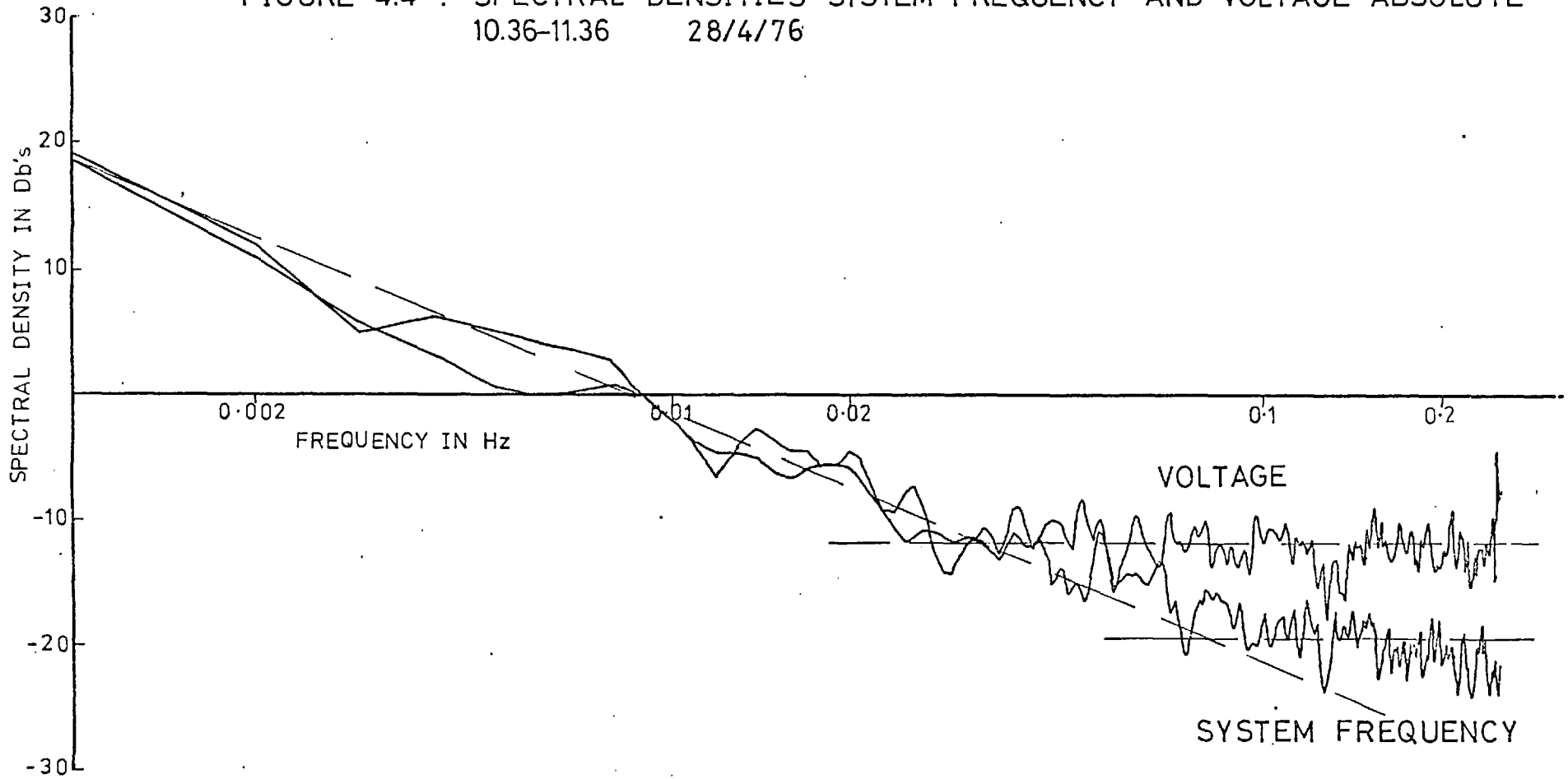
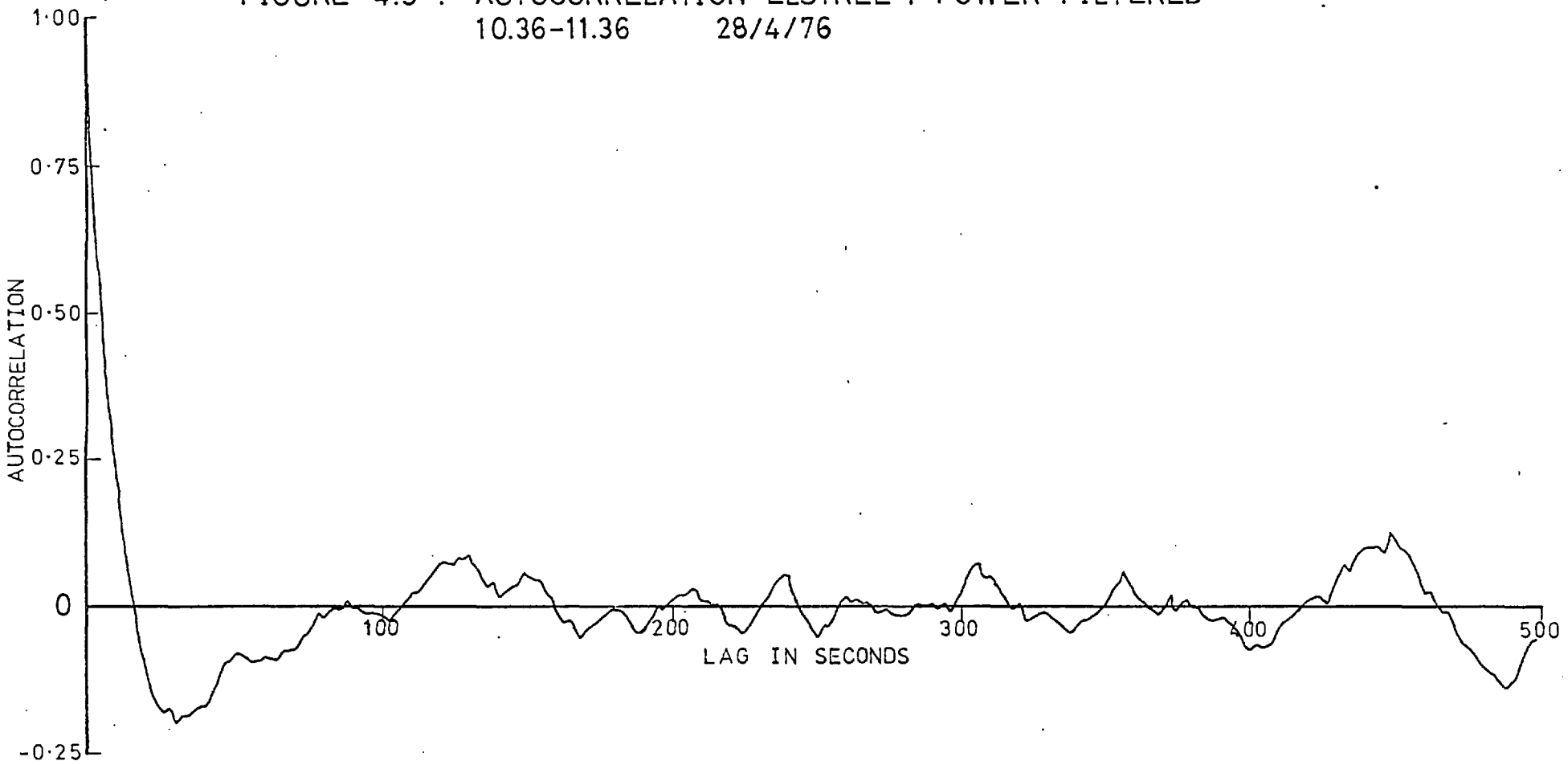


FIGURE 4.5 . AUTOCORRELATION ELSTREE 1 POWER FILTERED
10.36-11.36 28/4/76



visual estimation for the flat and -2 sloped sections of the plots, and the frequencies at the intersection points recorded. Table 4.2 shows the average frequencies of the intersection points and their corresponding cycle times for each of the variables. The cycle times for the system frequency intersection points are lower than those for voltage; real and reactive power flows fall between with the real power flow intersection points having shorter cycle times than the reactive power flows. One explanation of this is the effect of the signal to noise ratio. However, this was rejected since voltage, an originally measured variable, should have the highest signal to noise ratio and thus the smallest cycle time at the intersection. A more likely explanation is that at this point the component dominating the system response changes. The lower frequency effect is probably caused by the load, whilst on the system frequency and real power plots the higher frequency effect is a conglomerate of system and generation plant effects. Bowdler et al [59] list many of the C.E.G.B. system time constants and a combination of governor, reheat and system inertia time constants could cause this effect. On the voltage and reactive power plots the observed effect probably involves the time taken by tap-changers on transformers to change their setting.

4.3.3. ANALYSIS OF TEN MINUTE RECORDS.

The results of the one hour record analyses were similar to those of Waddington [43,44,45] and different from those of Rudzinski [55] and Trybula [47]. Waddington had used one hour or longer record lengths, but Rudzinski and Trybula had used record lengths of around 10 minutes.

Tests were run on 5, 10 and 15 minute data records. The results of the 5 minute record analyses showed that they were noisy, the spectral density plots indicating the absence of some frequencies. Although the 15 minute records were less noisy than the 10 minute records, the stationarity tests indicated a higher probability of trends being present. Thus it was decided to use 10 minute data records for short record tests.

A complete set of tests was run on the 10 minute records.

The statistical results were similar to those of the unfiltered one hour records. Dispersions are slightly smaller than those of the one hour records with the values for the power flows in the range 1-5%. There is no correlation between the real and reactive power flows or between them and voltage and frequency.

About half the data records have all results from the stationarity tests in the bands 0-5% or 95-100%. This is a larger proportion than in the one hour records, because a trend in a 10 minute record may be an oscillatory signal in a one hour record. Any record that has some of its stationarity test results outside these bands probably does not have any signals of period greater than 2 minutes.

Most of the mean square deviation functions rise steadily, levelling out to a value of twice the variance of the data record. The rise times vary considerably. All the autocorrelation functions decay steadily, two thirds decaying to less than exponential -1 in less than 100s time lag. Spectral density plots to base of frequency shows that there is considerable power in the low frequency end of the spectrum. A slope of -2 is present on the central section of the plots of the spectral density in decibels to a base of logarithm of frequency, but at high, and on many, at the low frequencies the plots level out. At the higher frequencies this is identical to the effect on one hour records. The low frequency effect is caused by the absence of trends in the records.

Many of the autocorrelation functions appear to approximate an exponential function (e.g. fig. 4.6) and two methods were used to estimate the time constant of these exponentials. The first was to measure the time lag at which the autocorrelation decayed to exponential -1 (fig. 4.6). Where the autocorrelation function was noisy a visual approximation to the mean value of the autocorrelation in the area around exponential -1 was used. Over half the plots of the spectral density in decibels to a base of logarithm of frequency show some levelling off at the lower frequencies. This usually involves only two to four points. However, it is possible to draw asymptotes to the -2 and zero slope sections and find the frequency at the intersection (fig. 4.7). From this frequency the time constant is evaluated using equation 4.1. Where a result was obtained by the second method the two results showed considerable agreement, within 25%

FIGURE 4.6 . AUTOCORRELATION ELSTREE 1 POWER ABSOLUTE
5.25-5.35 2/5/76

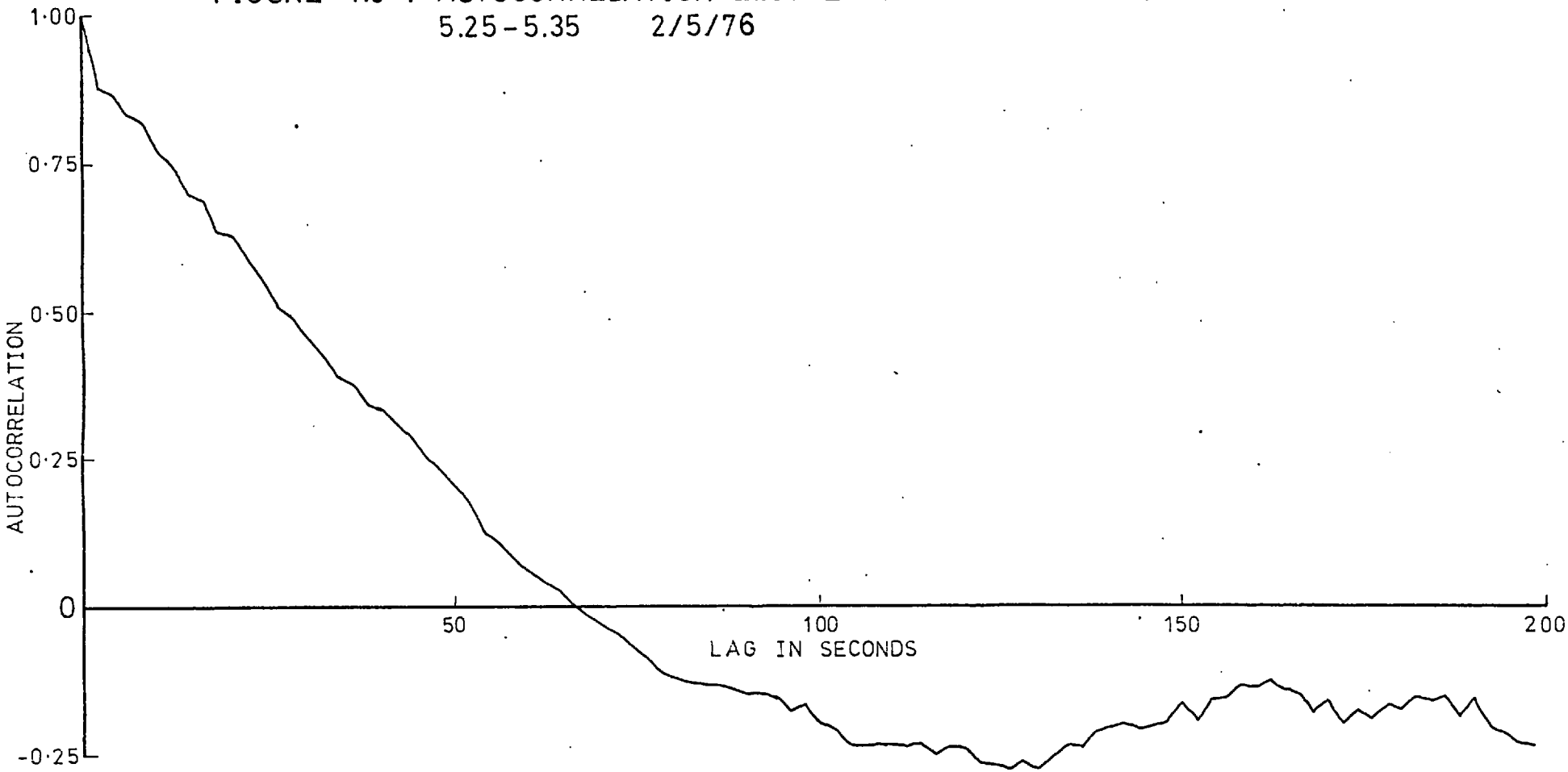
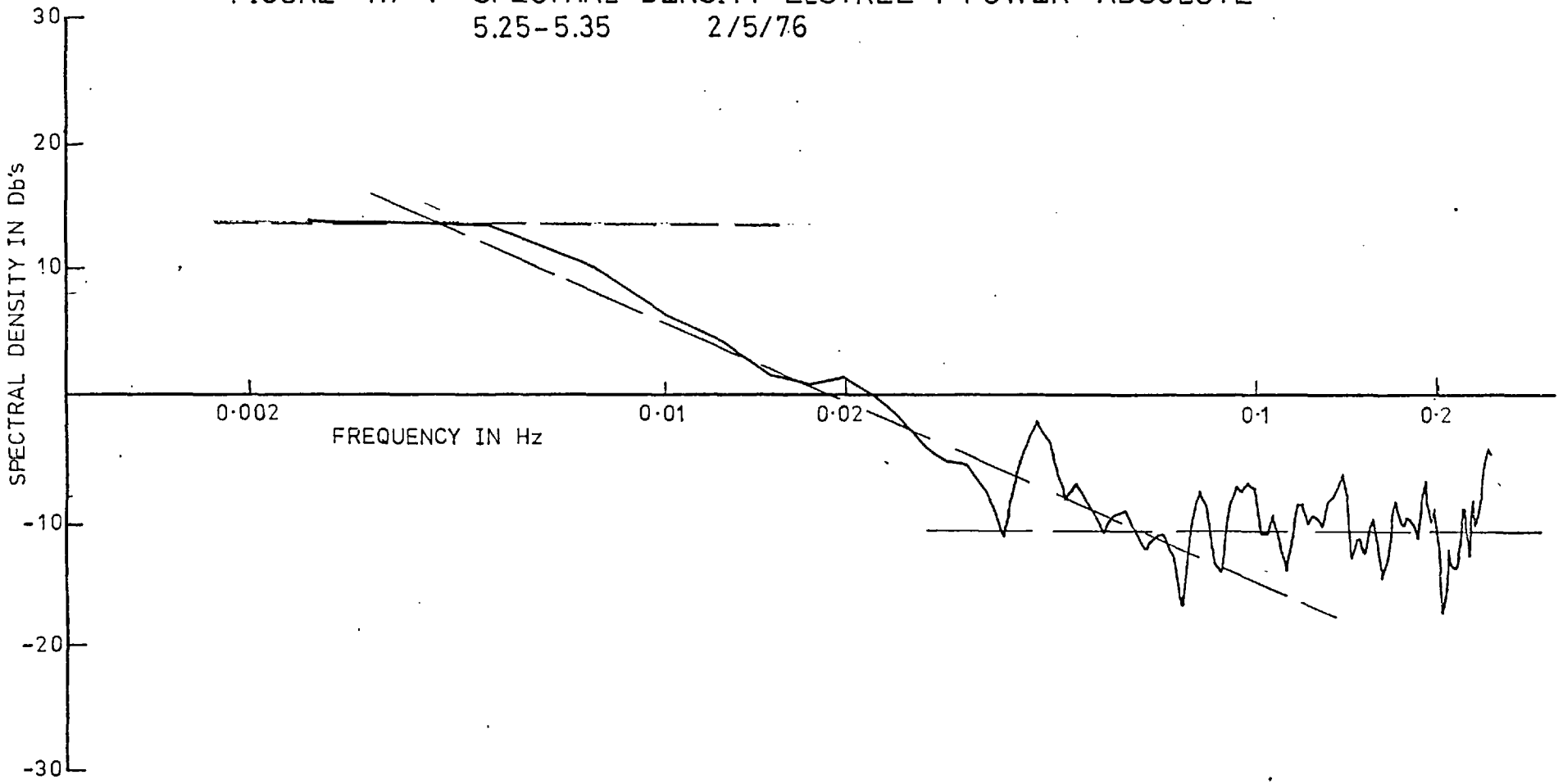


FIGURE 4.7 . SPECTRAL DENSITY ELSTREE 1 POWER ABSOLUTE
5.25-5.35 2/5/76



in 60% of the cases, considering the crudity of the tests. It was found that in general the longer time constants were associated with those records whose stationarity test results were in the ranges 0-5% and 95-100%. These time constants were ignored and the remainder averaged for each variable. These results are shown in Table 4.3 along with the overall average time constant which was 47s.

4.3.4. FIRST DIFFERENCED DATA.

First differencing of a data record involves forming a record of the difference between consecutive data values, i.e.

$$\dot{y}_k = y_{k+1} - y_k$$

where $\dot{y}_k$ - first differenced value.

The first difference data records were evaluated for the first hours of the G09, G15 and G20 recordings, and for six sets of 10 minute data records, two from each recording.

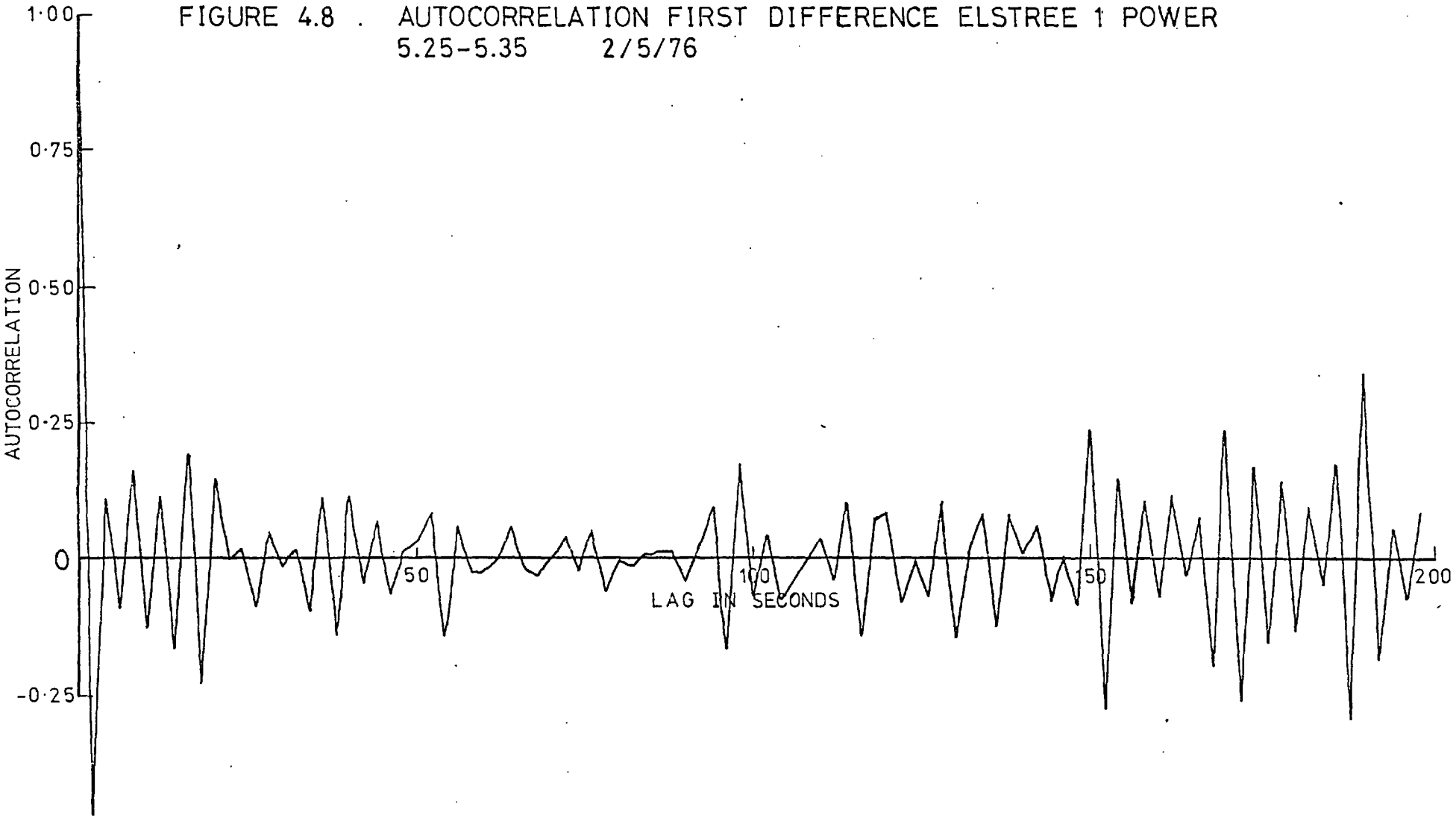
The data records were analysed using the same tests used on the other types of data records. The mean values were very small, the power flows being less than 0.05 MVA. An assumption of stationarity of the data records seemed more reasonable, from the results of the stationarity tests, for these records than any other sets of records analysed.

The zero time lag value of the autocorrelation function is, of course, 1. All the autocorrelation function plots have a negative value for the first time lag value, usually in the range -0.2 to-0.6 with a mean of -0.42. The behaviour of the rest of the function falls into one of two categories. One category, which is the smaller and consisting mainly of autocorrelations of voltage and reactive power flows, contains autocorrelation functions which are oscillatory, crossing the zero axis between consecutive time lag values. This oscillatory behaviour is an aliasing effect and has the same cause as similar effects mentioned previously. All the rest of the autocorrelation functions have values normally between $\pm$ 0.1 and rarely outside $\pm$ 0.2 for time lags greater than one sample period. Figure 4.8 shows a typical plot of an autocorrelation function of this later type.

TABLE 4.3. TIME CONSTANTS OF AUTOCORRELATIONS OF 10 MINUTE RECORDS IN WHICH TREND VARIATIONS ARE ABSENT.

	Time constant in seconds.
Frequency	35
Voltage	28
Elstree 1 power	54
Elstree 1 vars	47
Grendon 1 power	39
Grendon 1 vars	105
Cowley power	34
Cowley vars	56
Wymondley power	48
Wymondley vars	23
Mean value	47

FIGURE 4.8 . AUTOCORRELATION FIRST DIFFERENCE ELSTREE 1 POWER
5.25-5.35 2/5/76



Despite the consistent negative value of the first time lag value the assumption that the first differenced data consists of uncorrelated random numbers is a reasonable approximation.

4.3.5. CONCLUSIONS.

The results of the analyses of the one hour records are similar to those obtained by Waddington [43,44,45] whereas the results of the 10 minute record analyses are similar to those of Rudzinski [55] and Trybula [47]. There is obviously a relationship between the record length and the decay rate of the autocorrelation function. Rudzinski [60] has found that for a stationary or weakly stationary process there is a relationship between the "apparent time constant" of a near exponential autocorrelation, the "real time constant" and the record length. This to a first approximation is

$$\frac{1}{Tr} = \frac{1}{Ta} + \frac{1}{Tn}$$

where Tr - real time constant
Ta - apparent time constant
Tn - record length

The direct effect of the record length on a 100s time constant autocorrelation function obtained from a 10 minute record is less than 15%. This is too small to explain the results observed. A better explanation of the observed results is the presence of trend or very low frequency variations. Longer record lengths generally contain more energy in the low frequency end of the spectrum than the short record lengths.

A model for the simulation of random load fluctuations can be derived from these results. Two theoretical models were considered as suitable for real time simulation, the Random Walk Model and the Low Pass Filtering Model. The results from the one hour records would be better simulated by the Random Walk Model whereas the 10 minute records by the Low Pass Filtering Model. To simulate the short term random fluctuations the second model seems more appropriate.

The Low Pass Filtering Model of the random load fluctuations

requires two parameters to describe its behaviour; the standard deviation and the filter time constant. From the results of the analysis of the Sundon Recordings it was decided to use a standard deviation of 2% of mean value. The average value of the measured autocorrelation time constants for the ten minute records with no trends present was 47s. A value of 40s was used for the filter time constant, partly because the value measured was larger than that obtained by Rudzinski [60] and Trybula [55] and partly because it was felt that not all the records including variations with a frequency of less than 0.01 Hz had been excluded.

Although the first time lag value of the autocorrelation function of the first differenced data is not insignificant, it has been assumed to be. This is one of the less justifiable assumptions of the model used. Cox and Jenkins [61] discuss a method of identification from differenced data record autocorrelations. Using their techniques a model of the form

$$y_k = y_{k-1} + x_k + ax_{k-1}$$

where y – output of the model.
x – input, uncorrelated random numbers.
a – coefficient of about 0.15.

could be derived to fit the results of the first differenced data autocorrelations obtained from the DREAM recordings. This model is nonstationary and has a linear mean square deviation of the form

$$S(k) = (2a + k(1 + a))\ \sigma^2 \qquad k \neq 0$$

where k – time lag.
σ^2 – variance of x

With this behaviour it is considered that the model is more suited to longer time period modelling than is required for random fluctuation modelling.

The modelling of the parts of the load simulation was completed by the choosing of the Low Pass Filtering Model and its parameters to model the random fluctuations. This part could now be integrated with the trend and load characteristic models to form the complete simulation.

5. POWER SYSTEM SIMULATOR LOAD MODEL.

The load units in the power system simulator's analogue section are described in section 2.1.2. They absorb phase current and absorb or generate quadrature current according to manually or computer set reference values. A real power system load does not have a constant current characteristic and a digital computer algorithm was implemented to vary the phase and quadrature current reference signals to make the load unit imitate the characteristics of a typical bulk supply point supplying the distribution network.

5.1. ALGORITHM FOR LOAD MODEL.

A division of the load model into three sections as described in section 3 was used. The model was designed so that trend loads could be specified by the operator or other programs and would be implemented by the model. Two parameters are used to specify a trend the target load and the rate of change of load. The target load is the value of phase current that the load unit should eventually absorb and the rate of change of load is the amount of change of load that should be made each second towards the target level. Once the phase current reaches the target level it remains there until the target is altered.

When the load is switched from manual to computer operation it has a phase angle defined by its phase and quadrature current values. While the load is in manual operation a record of the power factor is kept by the simulation program and this value is used in computer operation to alter the quadrature current relative to the trend changes in phase current. There is no evidence that over load changes the phase angle remains constant, in fact from the Sundon results the random variations in real and reactive power are uncorrelated. However, as there is no data available, and each bulk supply point probably has a different phase angle load relationship, this is as reasonable an assumption as any and more reasonable than constant quadrature current which is the only more easily programmed solution.

Once the modifications to the current values have been made for trend changes, the random fluctuation variations are added. Separate fluctuation figures are used for phase and quadrature currents. The model used for these is the Low Pass Filtering Model that was judged the most suitable for this task (Section 4.3.5.). A filter time constant of 40s was used and the output has a standard deviation of about 2% of the current value.

The final change to the current values is to modify them to allow for the values of the system frequency and load busbar voltage. Here modifications must be made to the currents not the powers. Remembering from section 3.2 that

$$P \propto V^n$$

where P - real power

V - busbar voltage

n - characteristic $\approx \frac{\partial P}{\partial V}$

then dividing by voltage [62]

$$\frac{P}{V} \propto \frac{V^n}{V}$$

so that $Ip \propto V^{n-1}$

where Ip = phase current

Then $$\frac{\partial Ip}{\partial V} = \frac{\partial P}{\partial V} - 1$$

Similarly for the $\frac{\partial Iq}{\partial V}$ characteristic.

Values of load characteristics can be altered on line by the operator, but normally the default values are used, and these are the values recommended by Concordia [33].

$$\frac{\partial Ip}{\partial V} = 0$$

$$\frac{\partial Ip}{\partial f} = 1.5.$$

$$\frac{\partial Iq}{\partial V} = 0.8.$$

$$\frac{\partial Iq}{\partial f} = -1.5.$$

5.2. IMPLEMENTATION.

The computer simulation program is controlled by three switches for each load unit. These are available as digital inputs to the computer; one is the circuit breaker which indicates whether the load is connected to the system; the second is the auto/manual control which indicates whether the reference phase and quadrature currents are set manually or by the computer and the third indicates if the random fluctuations are required.

A hierachical structure is used in the simulation. The highest level (fig. 5.1.) which is programmed in assembler deals with each load in turn. It reads the status of the circuit breaker and auto/manual switches of a load unit and if the circuit breaker is open the load is ignored. The phase angle of the load is evaluated, and it and the phase current magnitude recorded, if the load is connected to the system but under manual control. When the load is connected to the system and under computer control the next level of the program is called.

The second level of the program consists of a Fortran subroutine which carries out the main tasks of load simulation (fig.5.2.). On entry the subroutine obtains the busbar voltage and system frequency and evaluates the modifications that these will entail. It then calculates the load change required by target and rate change values. If the random fluctuations are required these are calculated by use of subroutines which form the third level of the program, but the actual modifications are incorporated at the second level. Finally the modifications for voltage and frequency are carried out and the result output. The subroutine then returns to the main program having kept a record of the phase current magnitude after target and rate change corrections.

Three routines are used to evaluate the random fluctuations. The first produces random numbers between 0 and 1. It is an assembler routine devised by Lambert [63] and produces pseudo-random numbers. These numbers are fed to another routine which alters the distribution to a normal distribution with mean of zero and variance of 1. The

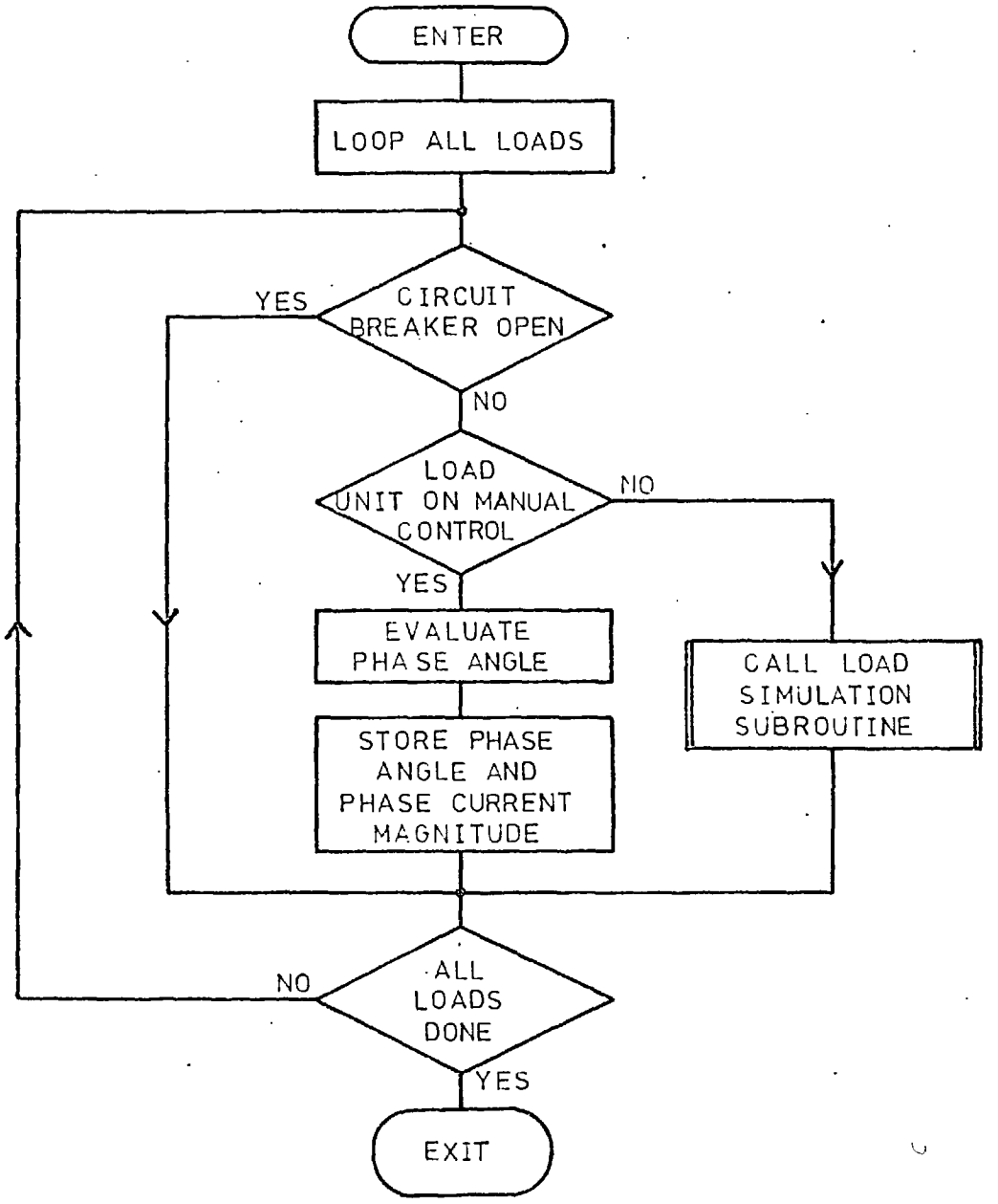


FIGURE 5.1 . FLOWCHART OF TOP LEVEL OF LOAD SIMULATION PROGRAM

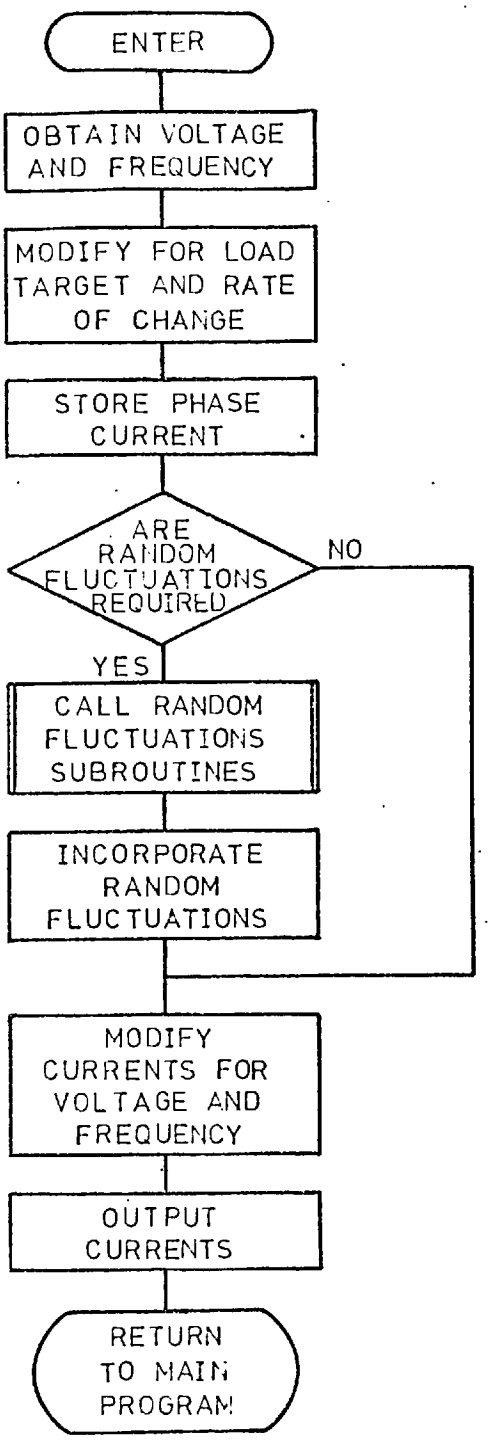
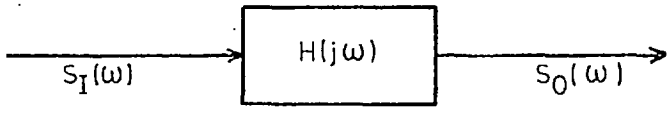


FIGURE 5.2 . FLOWCHART OF SECOND LEVEL OF LOAD SIMULATION PROGRAM

algorithm used in this routine was devised by Wetherill [64] and is implemented in Fortran. Finally the random numbers are filtered using a first order recursive digital filter.

The filter routine has to remember the previous output and an array of 10 floating point numbers is used to store the values. Before filtering the random numbers must be scaled to give an output with the correct standard deviation. The relationship between the standard deviation of the normally distributed random numbers and the output of the digital filter is derived as follows

Consider the system



where $S_I(\omega)$ - spectrum of the input.

$H(j\omega)$ - transfer function of the filter.

$S_0(\omega)$ - spectrum of the output.

The input is uncorrelated Gaussian White Noise

$$R_I(\tau) = \sigma_I^2 \, \delta(\tau)$$

$R_I(\tau)$ - autocovariance of the input.

σ_I^2 - variance of input.

$\delta(\tau)$ - Dirac function.

A first order recursive digital filter of unity D.C. gain is of the form

$$y_n = a\, y_{n-1} + b\, x_n$$

where x_n - the input at period n

y_n - the output at period n

a - $\exp(-\lambda)$

b - $(1 - a)$

$$\lambda \quad = \quad \frac{1}{T_c}$$

T_c – time constant of filter.

whose transfer function is

$$H(j\omega) \quad = \quad \frac{b}{j\omega + \lambda}$$

$S_I(\omega)$ = Fourier transform of $R_I(\tau)$

$$= \quad \int_{-\infty}^{\infty} \sigma_I^2 \; \delta(t) \; \exp(-j\omega\tau) \; . \; d\tau$$

$$= \quad \frac{\sigma_I^2}{2\pi}$$

$$S_O(\omega) = \quad |H(j\omega)|^2 \quad S_I(\omega)$$

$$= \quad \frac{b^2}{(\omega^2 + \lambda^2)} \cdot \sigma_I^2$$

The autocovariance of the output

$$R_O(\tau) \quad = \quad \frac{1}{2\pi} \int_{-\infty}^{\infty} S_O(\omega) \quad \exp(-j\omega\tau) \quad . \quad d\tau$$

$$= \quad \frac{\sigma_I^2 \, b^2 \exp(-\lambda\tau)}{2\lambda}$$

output variance = σ_O^2 = $R_O(0)$

$$\sigma_O^2 \quad = \quad \frac{\sigma_I^2 \; b^2}{2\lambda}$$

$$\sigma_I \quad = \quad \frac{\sigma_O^2}{1 - \exp(-1/T_c)} \sqrt{\frac{2}{T_c}}$$

For σ_0 = 2% and Tc = 40s,

then σ_I = 0.181.

and thus the random numbers are scaled by a factor of 0.18.

5.3. SUPPORTING SOFTWARE.

Default values of load target, rate of change of load and load characteristics for all the loads are set by the program GO before it starts the data acquisition and simulation programs. The values can be altered by the operator by the use of the program LDPAR which is normally controlled from the monitor console.

The values of load target and rate of change of load can be altered at regular intervals e.g. every minute, by a program LDTARP which reads the values from the paper tape reader. This routine is useful for setting predefined load patterns during tests, especially load frequency tests.

Analysis of the behaviour of the loads was carried out using a series of programs that access the data records stored on the disk by LOG3 (section 2.5.3). These include ANAL01 which lists sections of the record, ANAL02 which calculates the autocorrelation and spectral density of a variable and ANAL07 which calculates cross correlations.

5.4. EXPERIMENTAL RESULTS AND CONCLUSIONS.

Tests were carried out to check that load simulation operated in the way intended. This involved operating the load simulation with the load units and the rest of the system.

Initial tests of trend behaviour and load characteristics show that the load simulation behaved as expected. The phase and quadrature currents are slightly lower than the computer output values

probably due to a voltage drop on the cables from the computer to the analogue simulation section of the model.

Two sets of tests were run to evaluate the behaviour of the random fluctuations. The power system was set up with two generators and four loads and for the first test the tie line to the infinite bus was used. LOG3 was used to record the behaviour of the system and the data records analysed for standard deviation, autocorrelation and spectral density. A ten minute record length with 0.5s sampling was used for calculating these values.

The design standard deviation was 2% of the mean value, the measured values were between 1.3% and 2.5% of the mean value with an average of 1.8%. Figure 5.3 shows two of the autocorrelation functions obtained. The decay rates of the autocorrelation function vary with the value decaying to exponential -1 in between 17 and 59s time lag with a mean of 33s. This is less than the design time constant of 40s.

Spectral density plots show that most of the power is in the low frequency end of the spectrum. Plotting logarithm of spectral density to a base of logarithm of frequency shows the slope of -2 with no evidence of levelling off at the high or low frequencies. This is probably because the values metered are the current flows to the loads, not the flows in the transmission network.

The load simulation behaves as expected, and in a similar manner to the measured power flows in the transmission lines. There is a variation in the autocorrelation functions of the load simulation similar to those found in the analysis of power flows measured with the DREAM equipment.

This load model was considered satisfactory for the purpose for which it was designed. Use of the model is made for frequency control studies discussed in the next part of this thesis.

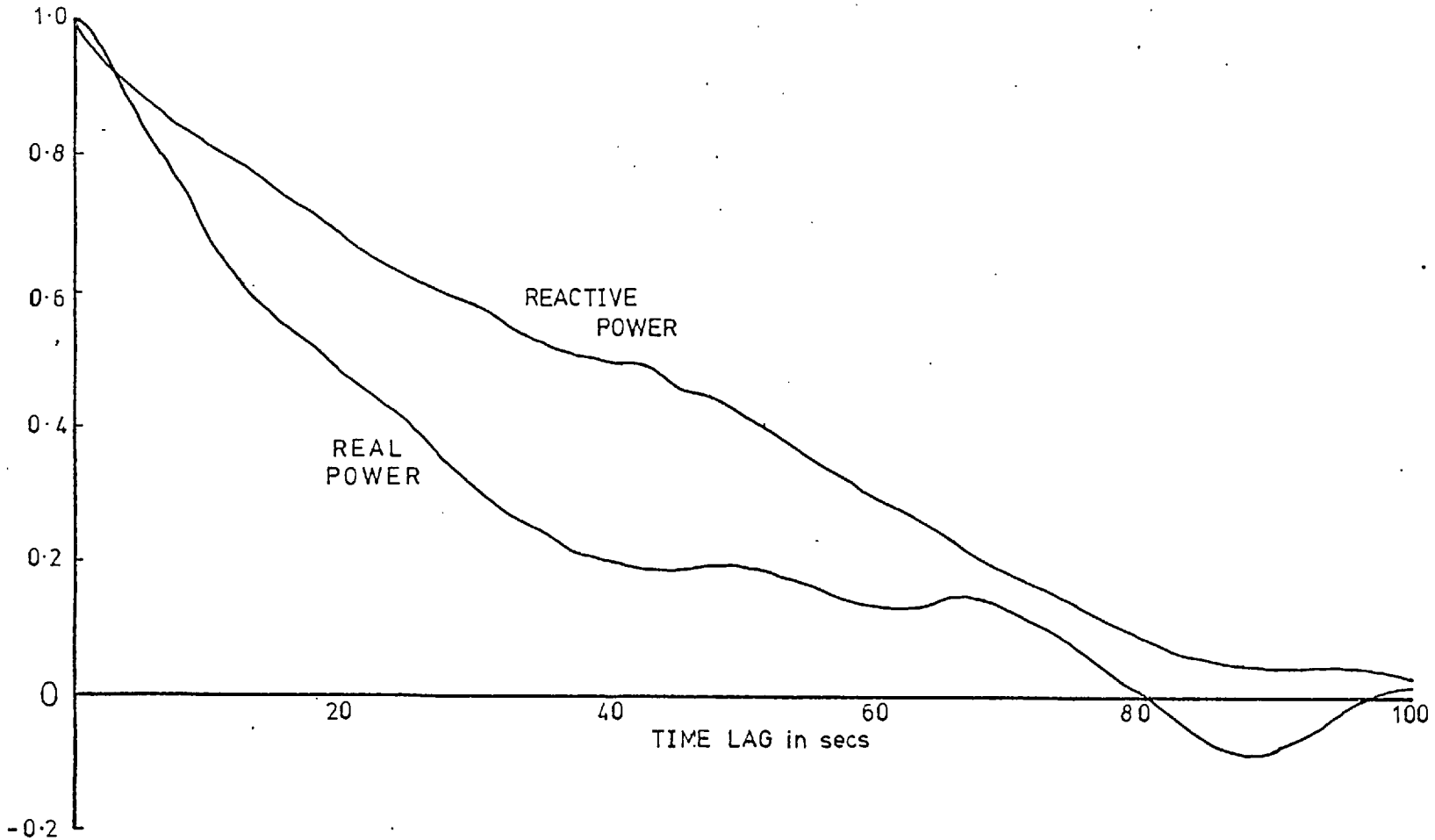


FIGURE 5.3. AUTOCORRELATIONS OF LOAD SIMULATION

6. AREA FREQUENCY RESPONSE CHARACTERISTIC (K).

6.1. DEFINITION OF THE AREA FREQUENCY RESPONSE CHARACTERISTIC.

The Area Frequency Response Characteristic K, also known as the Power/Frequency Characteristic, is defined in IEEE Standard 94 [8] as

"For a control area, the sum of the change in total area generation caused by governor action and the change in total area load, both of which result from a sudden change in system frequency, in the absence of automatic control action ".

The main use of K is in frequency control which involves estimating the change in power generation to correct the frequency deviation. In utilities operating tie lines the problem is more complex, as is discussed in Chapter 7, but the solution still requires a knowledge of K.

Following a change of frequency K is a function of two factors, the load and the generation changes. The frequency behaviour of the load has been discussed in Chapter 3. Frequency changes are not instantaneous due to system inertia so that all but large induction motor load changes will be almost instantaneous with the frequency changes. However, generation changes in response to frequency changes are caused mainly by governor action. Bowdler et al [65] estimate that the average response time to governor action of reheat plant on the CEGB system is 9s. This time delay in generation change is important when measuring the value of K.

6.2. SYSTEM LOAD AND GENERATION CAPACITY FORMULA FOR K.

From the definition, the equation

$$K = \frac{\Delta P_G}{\Delta f} + \frac{\Delta P_L}{\Delta f} \qquad \ldots\ldots (6.1)$$

can be written where

Δf - change of frequency.

ΔP_G - change of generation.

ΔP_L - change of load.

The change of load with frequency over the narrow range of normal operation can be assumed to be almost linear (Chapter 3), so that the second term of 6.1 can be written as

$$\frac{\Delta P_L}{\Delta f} = \frac{q\, P_L}{fo}$$

where q is a constant

fo is the nominal frequency

and P_L is the total load.

For a flyball governed steam turbine, assuming no deadband and making other simplifying assumptions Davies et all [66] show that the first term of 6.1 can be written as:

$$\frac{\Delta P_G}{\Delta f} = \frac{2fo}{(a - fo^2)} \quad (cP_C - P_G)$$

where P_G is a total generation

P_C is connected generating capacity.

a, c are constants (based on governor parameters)

For power balance $P_G \approx -P_L$, neglecting losses, so

$$K = \frac{2c\, fo}{a - fo^2} P_C - \left(\frac{2\, fo}{a - fo^2} - \frac{q}{fo} \right) P_G$$

and as fo is a constant

$$K = mP_C - nP_G \qquad \ldots\ldots (6.2)$$

As the generators on the system are different and governors vary, m and n estimated from power system tests.

Tests on the CEGB system in 1953 [66] showed that

$m = 0.8$

and $n = 0.6$

When the Cellerhead tests were carried out in 1967 these values had change [67] to

$m = 0.86$

$n = 0.62$

However, in their report Blair et al [67] had considerable reservations over the value of this equation which they call an empirical formula. The proportion of part loaded plant has decreased in recent years reducing the proportion of nominal spare generation connected to the system. Spare capacity costs money as modern plant is most efficient at full load, and efforts have been made to maintain security with reduced spare. Equation 6.2's sensitivity, this is the change in K for small changes of m and n, increases as the spare capacity, the difference between P_C and P_G, decreases. Also m and n are partly defined by the effective system governor characteristics and these change with system loading, as older plant only used during high demand periods has different characteristics from more modern plant, m and n vary with the system loading. As the accuracy of K is more critical at the lower levels of spare capacity, more complex methods may now have to be used for operational evaluation of K.

One factor that Blair et al [67] did not allow for is that the derivation of equation 6.2 assumes that all system generating plant is subject to governor control. This is no longer true of CEGB plant where base load and nuclear powered turbogenerators in particular are subject to overriding pressure control. Adding this factor to equation 6.2 an equation of the form

$$K = aP_{RC} - bP_G + cP_{NG} \quad \ldots\ldots (6.3)$$

where P_{RC} - connected regulating generation capacity.
P_G - total generation.
P_{NG} - generation from non regulating plant
and a,b,c - constants.

can be derived. This equation's coefficients will be more difficult to estimate, but the results should be more accurate. Coefficient estimates can be made from the results of system tests for which the proportion of non regulating generation was known. A disadvantage of this method is that coefficient estimation would involve a considerable number of tests.

The Method of Synthesis of calculating frequency changes following loss of generation or similar incidents has been developed by Blair et al [67]. This involves dividing generation and possibly load into a number of type categories where all the plant in one category acts in a similar manner. The response of each category to frequency

change is evaluated and the responses of all the categories summed. Loss of a generator causes voltage changes on the system and the load change caused by this is added to the lost generation and from this and the system response the frequency change is calculated. This method has the advantage of accuracy, but it requires some computation, considerable knowledge of the system state and some engineering judgements and these factors may make it too complex for operational use.

6.3. GOVERNOR DEADBAND AND THE NON-LINEARITY OF K.

The previous analysis assumes that K is a function of total generation and total load alone which is a simplification. K is also a function of the frequency deviation, which is due primarily to the deadband of the turbine governors. Both the American Standards [68] and the British Standards [69] specify the maximum deadband for the governors on large steam turbines (> 30 mw) as 0.06% (0.0006 p.u.) or 0.03 Hz for a 50 Hz system and 0.036 Hz for a 60 Hz system. The British power system has a maximum normal frequency error of $\pm$ 0.2 Hz [70], six times larger than the deadband. However, large continental systems, such as the UCPTE network in Western Europe and the interconnected systems in North America, have much smaller frequency variations. A normal maximum frequency error of $\pm$ 0.02 Hz is reported for the North Eastern interconnection in the U.S.A. [70] and the Western U.S. system has a standard deviation of system frequency of 0.005 - 0.01 Hz [51].

Within the governor deadband area there will be no response from the generator to a change of frequency. Governor deadbands vary within the maximum specified limit, and their centrepoint settings will probably be different. However, the value of K for small frequency variations (less than 0.06%) can be expected to be smaller than for larger frequency variations. Cohn [71] feels that the K value for a decrease in frequency will be smaller than for an increase in frequency as fully loaded sets will be unable to increase generation. There appears to be no experimental evidence of this, which may be due to generating sets short term overload facility.

Figure 6.1 shows the response characteristic for the Union

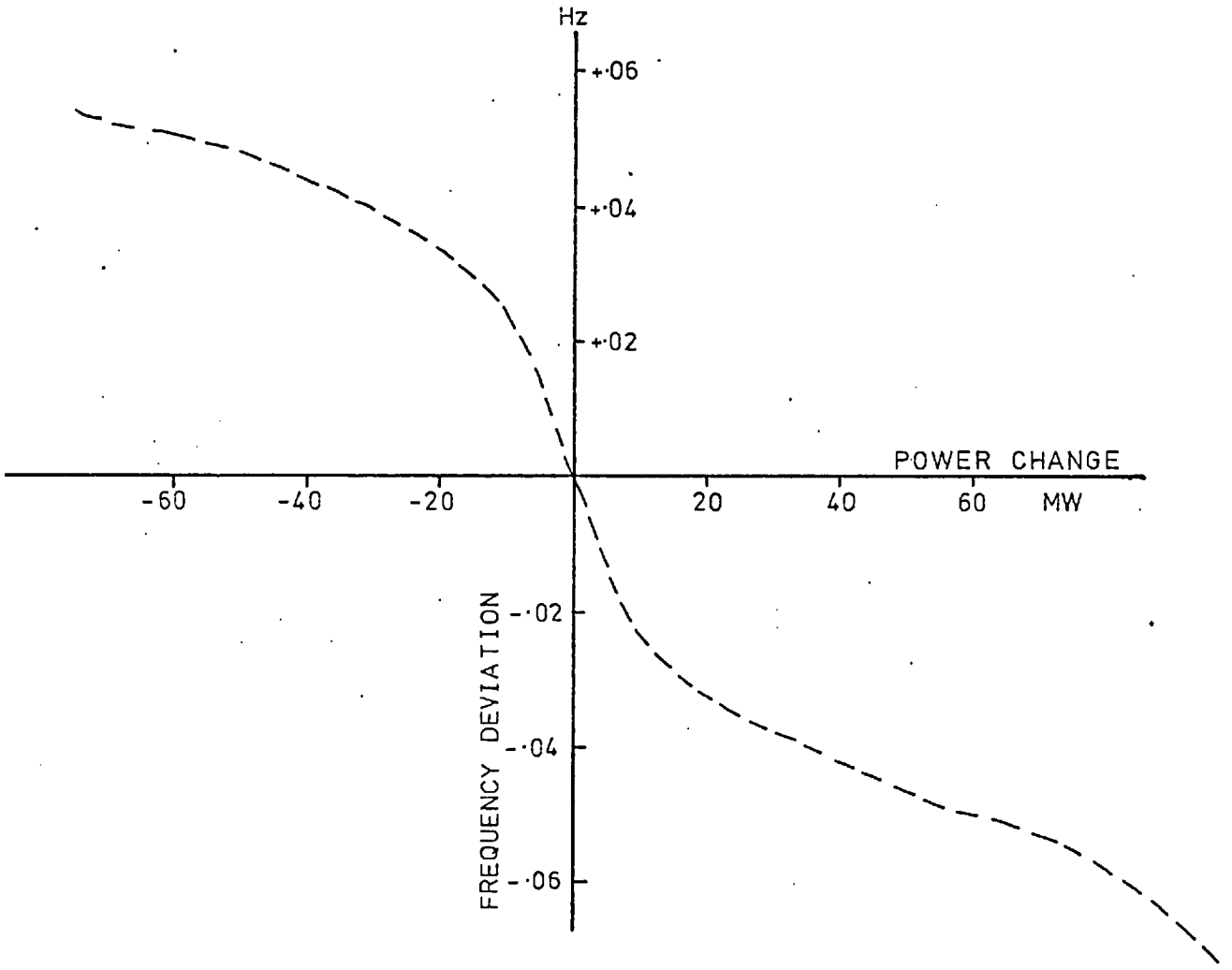


FIGURE 6.1 . UNION ELECTRIC AREA FREQUENCY RESPONSE CHARACTERISTIC

Electric Power System in the U.S.A. which is taken from reference 71. This characteristic, which is time dependent, includes a load response of 8% /Hz, a governor deadband of 0.02 Hz on average with governor droop of 5% outside deadband. The results are similar to those postulated above and could be accurately simulated by a three segment approximation.

Governor characteristics on the CEGB are typically 4% droop with 0.03 Hz deadband [68,72], although these vary with plant loading, plant age and time since recalibration. The load response is 2% /Hz [65] and the system capacity is 56.4 GW [2]. Frequency variations on the CEGB system are larger than those experienced on continental systems [70] like the North American interconnections, so, although a similar shape of area frequency response can be expected as that on the Union Electric System, though of course with different scaling, this plot could be centred about any equilibrium frequency. The non linearity of K is far less important on the CEGB system because the normal frequency variations are larger.

6.4. MEASURMENT OF K BY SYSTEM TESTS.

One method of measuring K on a power system is to create a system disturbance and measure the system response. On an isolated power system this can be done by tripping a generator or by splitting the system by tripping out a transmission line. Where a utility operates tie lines, opening of the final tie line to isolate the system can be used as the disturbance. On a large system, generator trips are not uncommon and considerable information can be gathered from the normal system metering. However, most utilities set up a series of system tests every five to ten years.

The response of a system to a generator trip will be similar to that of figure 6.2, although the magnitude of the frequency change will depend upon the loading of the generator and the K of the system. Initially the frequency drops rapidly reaching a minimum after 2 - 3s and then rises, levelling out to a pseudo stationary value 6 - 12s after the incident. Frequency behaviour after this is affected by the behaviour of boilers on thermal plant, AGC, power plant control

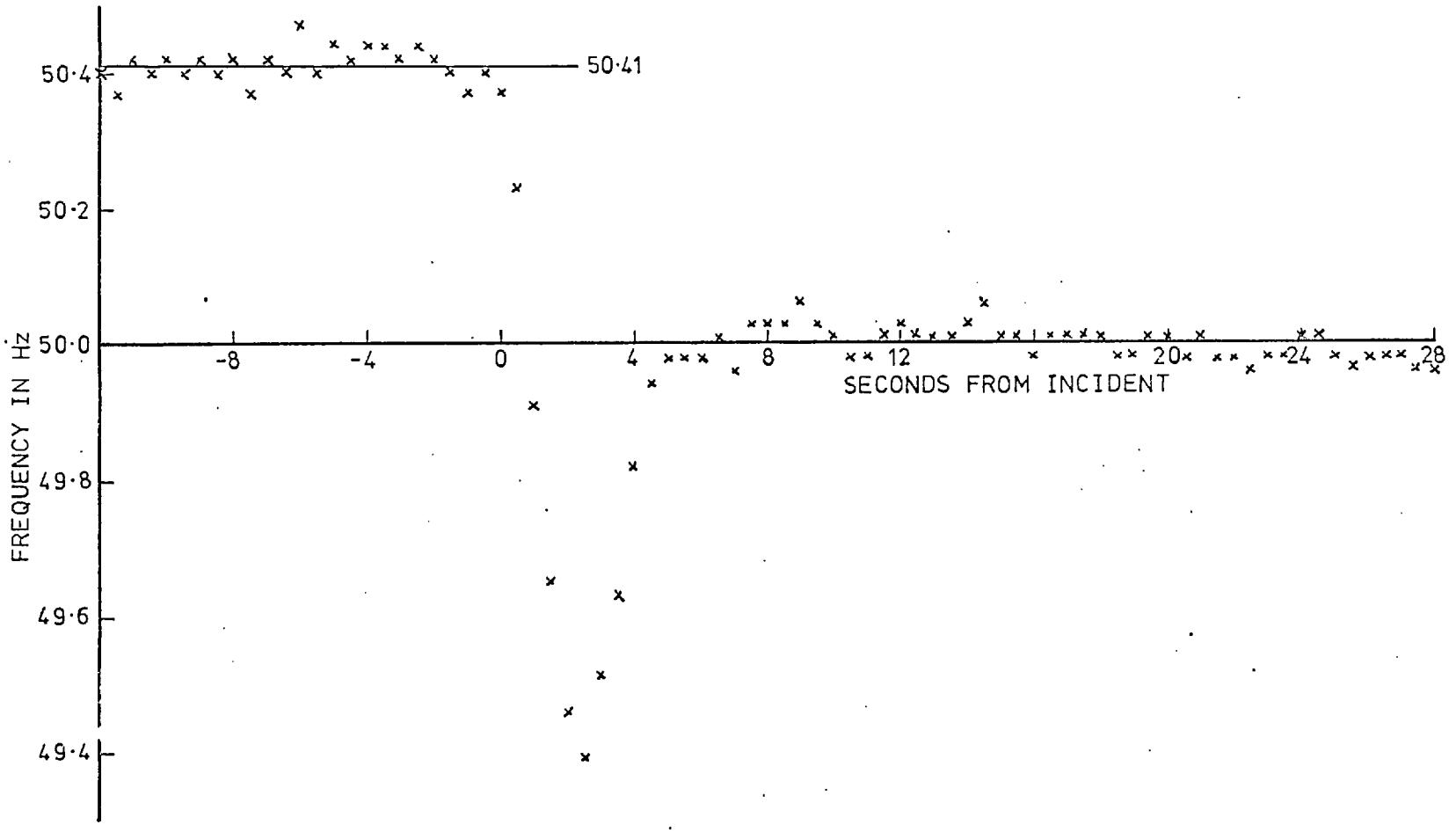


FIGURE 6.2 . FREQUENCY BEHAVIOUR FOLLOWING STEP INCREASE IN LOAD
(POWER SYSTEM SIMULATOR K TEST 3)

and manual intervention. K is evaluated from the frequency difference between the pre-trip value and the pseudo steady state condition. Davies et al [66] recommend averaging the frequency over the 10s preceding the trip and 5 to 20s after the trip to evaluate the frequency change. Consideration must be given to the time aspect of the frequency response of the system in choosing averaging periods. During the Cellerhead tests on the CEGB system, an average of 9s was needed for the system to reach the pseudo steady state and this state was maintained for an average of 50s. A fall in boiler pressures is responsible for the end of the pseudo steady state which follows a disturbance causing a drop in frequency.

6.5. MEASURING K FROM SYSTEM FLUCTUATIONS.

6.5.1. GAIN IDENTIFICATION FROM STANDARD DEVIATIONS.

The system test method of measuring the K of a power system involves intentionally disturbing the system with a significant disturbance. This disturbance must be large enough so that the response to it is much greater than the normal system fluctuations. However, if an input and an output can be identified it is possible to measure approximately the K of the system from the system's normal fluctuations by statistical methods.

Consider the system shown in figure 6.3 where x is the random fluctuations of the input, y the output's fluctuations and μ is noise.

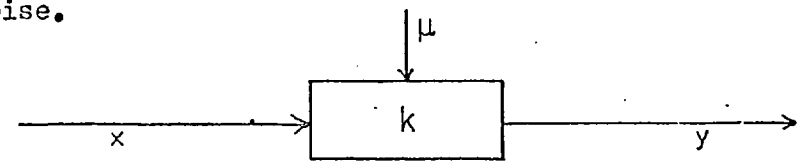


Figure 6.3 : System with Gain and Noise.

If x and μ are assumed to have a Gaussian distribution and zero mean, then

$$y = kx + \mu$$

y also has a Gaussian distribution and zero mean. Let σ_x , σ_y and

σ_y be the standard deviations of x, μ and y, then

$$\frac{\sigma_y}{\sigma_x} = \frac{\sqrt{\sum (y_i)^2}}{\sqrt{\sum (x_i)^2}}$$

where x_i and y_i are the i th samples of x and y

$$\frac{\sigma_y}{\sigma_x} = \sqrt{\frac{\sum (kx_i + \mu_i)^2}{\sum (x_i)^2}}$$

$$= \sqrt{\frac{k^2 \sum (x_i)^2 + 2k \sum (x_i . \mu_i) + \sum (\mu_i)^2}{\sum (x_i)^2}}$$

Now if x_i and μ_i are uncorrelated random fluctuations of zero mean, given by

$$\sum (x_i . \mu_i) = 0$$

then

$$\frac{\sigma_y}{\sigma_x} = \sqrt{\frac{k^2 \sum (x_i)^2 + \sum (\mu_i)^2}{\sum (x_i)^2}}$$

$$= \sqrt{\frac{k^2 \sigma_x^2 + \sigma_\mu^2}{\sigma_x^2}}$$

$$= \sqrt{k^2 + \left(\frac{\sigma_\mu}{\sigma_x}\right)^2}$$

and provided that $\frac{\sigma_\mu}{\sigma_x} < k$

$$\frac{\sigma_y}{\sigma_x} \approx k$$

It should be noted that the more obvious relationship

$$k = \frac{1}{n} \sum \left(\frac{y_i}{x_i}\right)$$

is unusable as x and y are random fluctuations with zero mean and although not uncorrelated the result of their ratio can be either very large (if not infinite) or very small, causing numerical problems.

The transfer function of the system need not be solely a gain function, but may also involve a time delay. Provided the sample record is long relative to the time lag, the gain of the system is still calculable.

6.5.2. IDENTIFICATION OF K.

K is the gain relating the frequency and power changes on a power system. It is the sum of the steady state load and generator responses to changes in frequency, i.e. from equation 6.1.

$$K = K_G + K_L$$

where $K_L = \frac{\Delta P_L}{\Delta f}$ = power frequency characteristic of the load.

$K_G = \frac{\Delta P_G}{\Delta f}$ = power frequency characteristic of the generation.

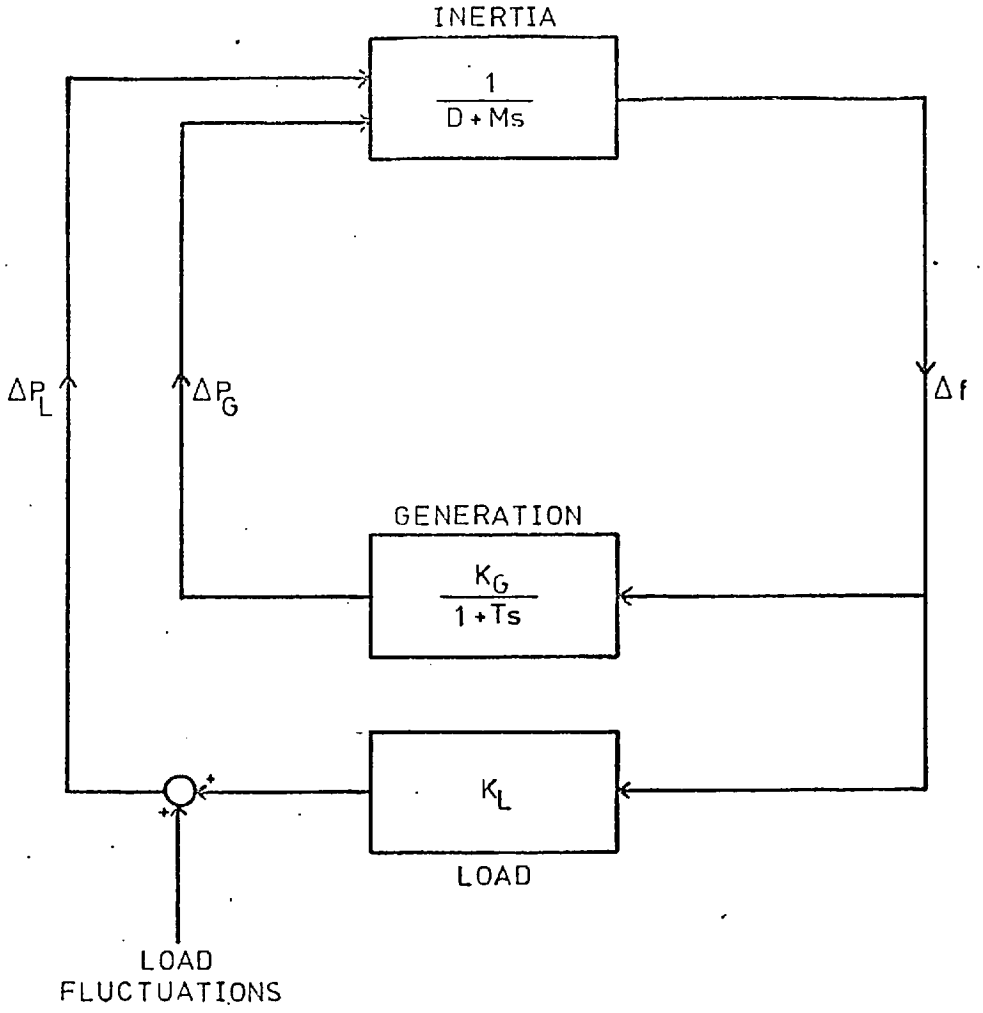
Figure 6.4 shows a simplified block diagram of the power frequency loop of a power system.

Although the load contributes to K the generation is more responsive to variations of frequency.
Typically

K_G = 0.5 x part loaded generation capacity/Hz.

K_L = 0.03 x load/Hz.

Also the total load on a power system is always subject to random variations, which may have an underlying trend, as customers switch individual loads. These fluctuations are usually considerably greater than those due to frequency variations. Load fluctuations due to switching have a standard deviation of about 1½% of load (Section 4.3.2) and for a system having large frequency variations, with a standard deviation of 0.1 Hz, are about 5 times as significant as frequency



D - SYSTEM DAMPING
M - SYSTEM INERTIA
Δf - CHANGE OF FREQUENCY
ΔP_G - CHANGE OF GENERATION
ΔP_L - CHANGE OF LOAD
K_G - GENERATION FREQUENCY RESPONSE
T - GENERATION TIME CONSTANT
K_L - FREQUENCY RESPONSE OF LOAD

FIGURE 6.4 . BLOCK DIAGRAM OF POWER FREQUENCY RELATIONSHIP

induced load changes. Thus figure 6.4 can be simplified further to figure 6.5 whose steady state behaviour is described by

$$\Delta P_G = K_G . \Delta f$$

$$D.\Delta f = \Delta P_L + \Delta P_G$$

where ΔP_G - change in generation.
Δf - change in frequency
ΔP_L - change in load
D - system damping.

Using the technique described earlier it should be possible to identify the value of K_G from

$$K_G = \frac{\sigma_{\Delta P_G}}{\sigma_{\Delta f}}$$

Although this does not identify the system K it does give an estimate of its primary component, the effective governor gain of the system.

Any variations of the tie line power can be ignored as they can be treated as a change in the load. ΔP_G is not only altered by governor action, but also by the scheduling of generation both manually and using AGC. These actions are equivalent to an increase in the noise of the system. If the standard deviation of the generation changes due to scheduling exceeds that due to governor action the ratio of the standard deviations will be more an estimate of the gain of the scheduler than of the governors. However, steady changes of generation will only have a very small effect on the method as only the mean values and not the standard deviations of ΔP_G and Δf are affected.

6.6. FREQUENCY RESPONSE CHARACTERISTIC OF THE POWER SYSTEM SIMULATOR.

A series of system tests was performed on the power system simulator to evaluate K by conventional techniques. The system configuration used is shown in figure 6.6, with the boiler and load simulations operating, but no random load fluctuations or A.G.C. included. As there are only two generators on the system a generator

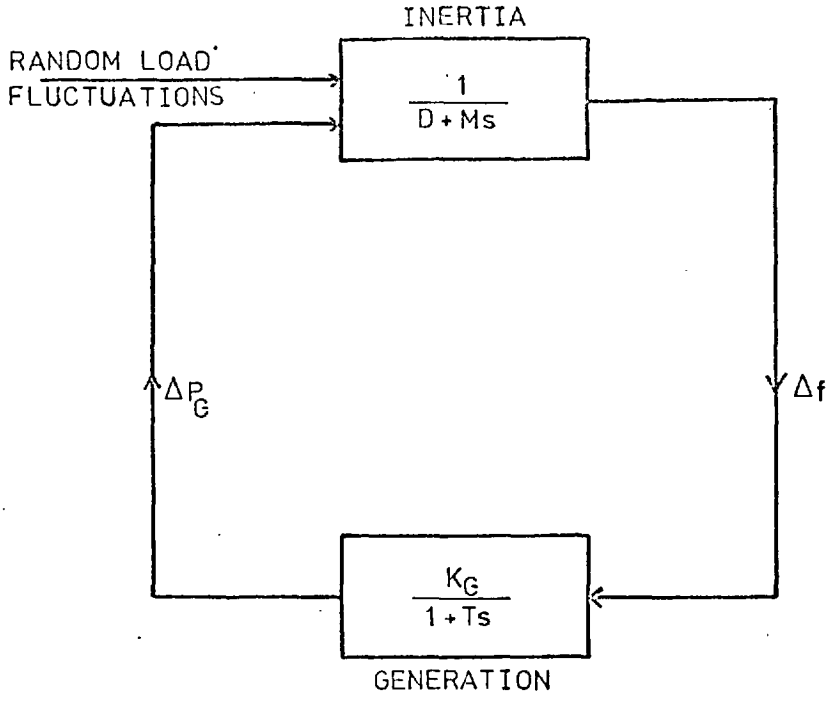
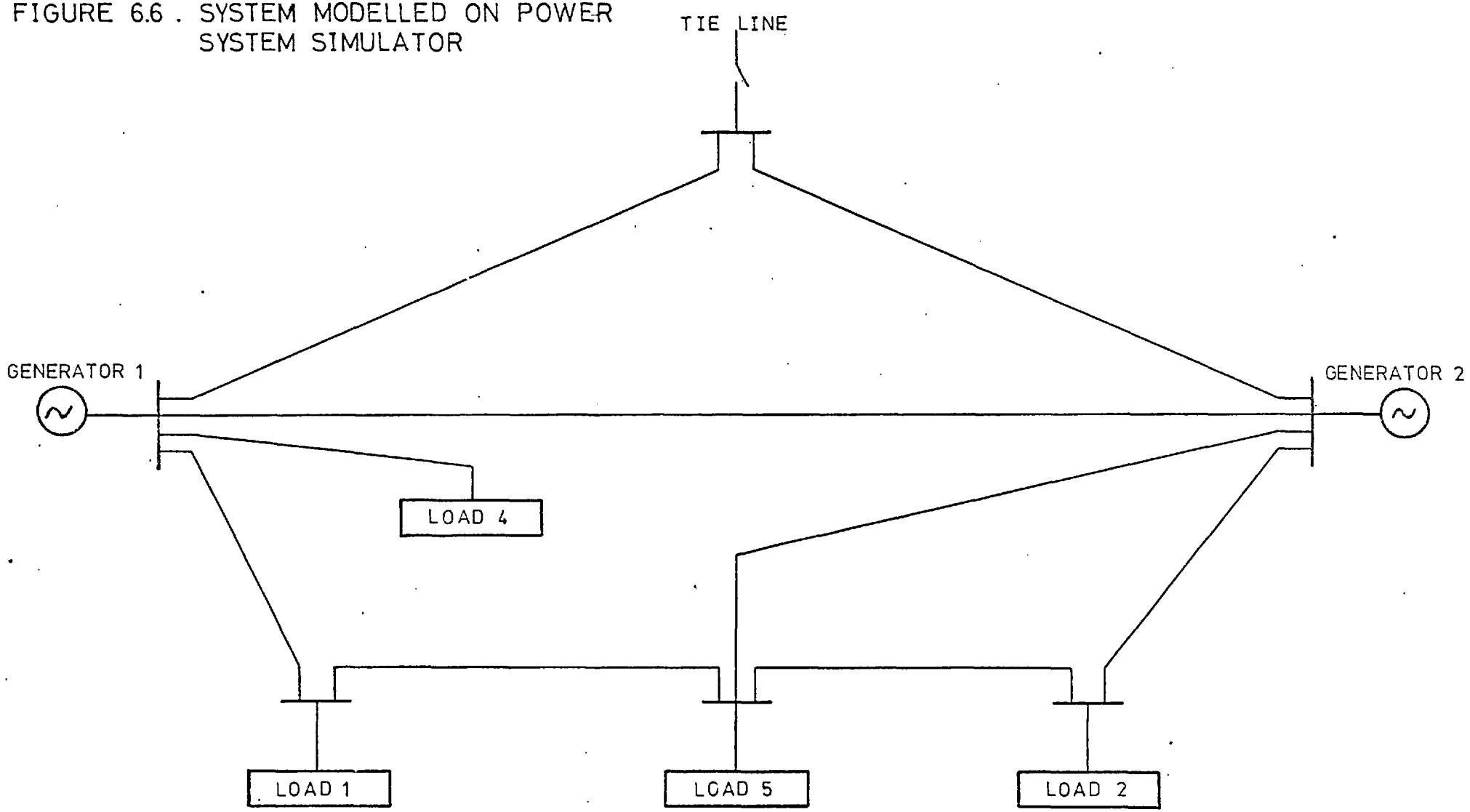


FIGURE 6.5 . SIMPLIFIED BLOCK DIAGRAM OF POWER FREQUENCY RELATIONSHIP

FIGURE 6.6 . SYSTEM MODELLED ON POWER SYSTEM SIMULATOR



trip would not yield reasonable results, so step changes of load and tie line trips were used to provide system disturbances. On a real system large planned load changes are not normally possible, but the method can be used in the same manner as generator trips.

The tests were carried out by allowing the system to attain an equilibrium state and then applying the disturbance. A computer logging program was used to record the system behaviour with a sampling time of ½s, and from this record a plot of the frequency for 10s before and 20s after the event was drawn. Figure 6.2 shows one of these plots. From the plots the time to reach the pseudo-steady state was estimated. The power change was evaluated for each test, and the frequency change calculated from the mean frequency for the 10s preceding the event and the 14s after reaching the pseudo steady state. Table 6.1 shows a summary of the results where the frequency change was greater than 0.1 Hz. Plots of change of frequency against change of power are shown in figures 6.7 and 6.8.

Considering those tests resulting in frequency changes of greater than 0.1 Hz (table 6.1) it can be seen that K is in the range 0.45 - 0.67. However, further study shows that for each individual cause of the disturbances there is a high degree of consistency, e.g. for load 1 the values of K are in the range 0.45 - 0.51. Disturbances caused by loads 1 and 2 give smaller values of K than the others. Loads 1 and 2 are closely connected to the generators and the generator AVRs reduce the steady state voltage changes caused by the incidents and this is probably the prime cause of the difference. The mean value of the results is K = 0.55. However, a more sensible mean, that of the average value for each cause of a disturbance is 0.59. There is no evidence of any difference in K values calculated from power excess or deficit tests.

The system K was smaller than expected, as a value nearer 1.0 was anticipated because the governor droops were thought to be around 4% (i.e. K = 0.5). Individual generator tests, involving tripping the generator with resistive load from the system, showed that the governor droops were just under 4½%, but that the boiler simulation had a small amount of steam storage which resulted in the following K's for the generators:-

TABLE 6.1. RESULTS OF SYSTEM TESTS ON POWER SYSTEM SIMULATOR.
(TESTS WITH FREQUENCY CHANGES OF MORE THAN 0.1 Hz ONLY)

Test	Step Change	Power Change in P.U.	Frequency Change in Hz.	K P.U.Power/Hz.	Time to pseudo steady state in s
1	Load 1	- 0.3	- 0.610	0.49	10
2	Load 1	+ 0.3	+ 0.590	0.51	10
3	Load 1	- 0.2	- 0.410	0.49	6
4	Load 1	+ 0.2	+ 0.400	0.50	8
5	Load 1	- 0.1	- 0.220	0.45	5
6	Load 1	+ 0.1	+ 0.220	0.45	4
7	Load 1	+ 0.1	+ 0.208	0.48	7
8	Load 2	- 0.2	- 0.350	0.57	6
9	Load 2	+ 0.2	+ 0.360	0.56	7
10	Load 2	+ 0.1	+ 0.181	0.55	6
11	Load 4	+ 0.1	+ 0.158	0.63	6
12	Load 5	+ 0.1	+ 0.149	0.67	5
13	Tie Line	- 0.256	- 0.385	0.66	6
14	Tie Line	- 0.088	- 0.155	0.57	4
15	Tie Line	- 0.083	- 0.135	0.61	4

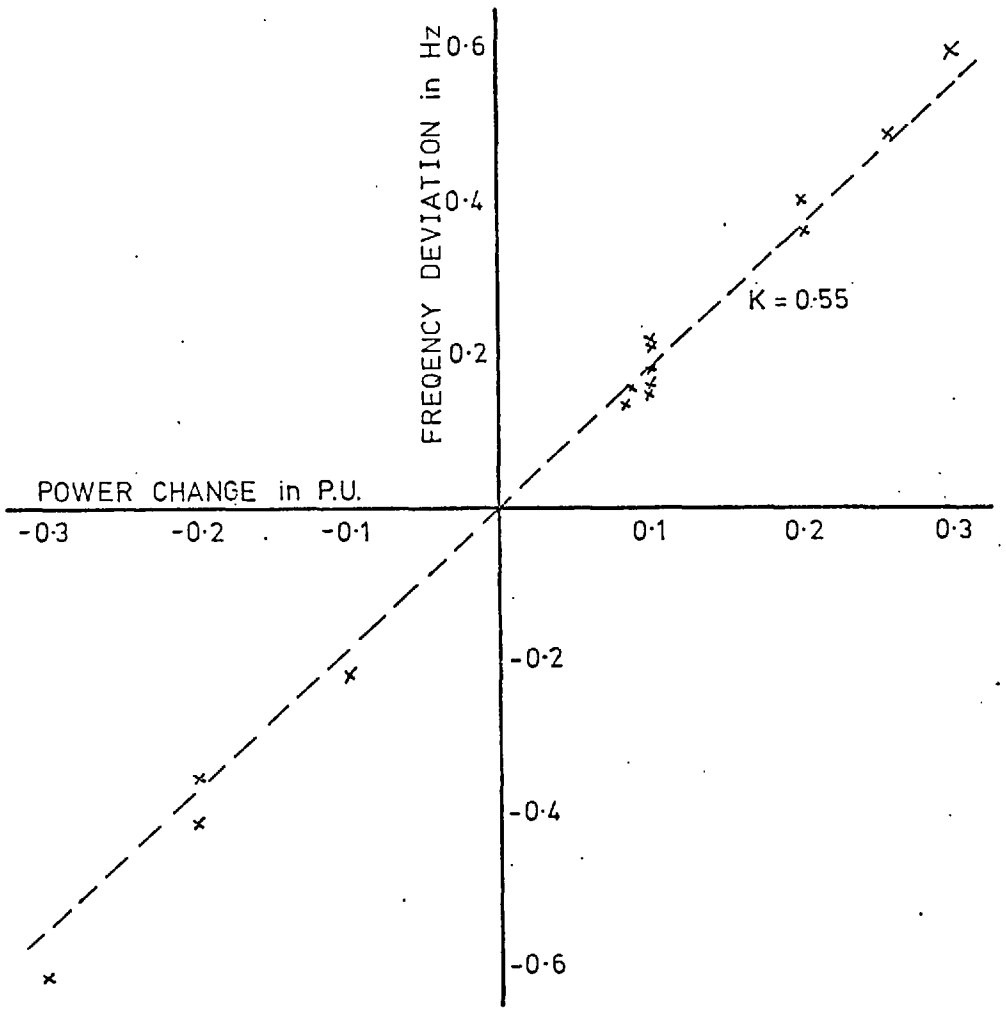


FIGURE 6.7 . RESULTS OF SYSTEM STEP CHANGE TESTS WITH A FREQUENCY CHANGE OF MORE THAN 0·1 Hz

Generator 1	K	= 0.31
Generator 2	K	= 0.32

The load has a frequency change of 3% of load per Hz (section 5.1), and as the test system had a load of 1.2 p.u. then

Load	K	= 0.036

The net result for this system is a theoretical K of 0.665, slightly larger than the value measured, but within the range of measurements of the system K.

The value of the ratio of the standard deviations of changes of frequency and generation were calculated from a series of records. One or more of the load units provided random load fluctuations for these tests, and some tests also had trend changes of load. During none of the tests did the standard deviation exceed 0.05 Hz. A record length of 5 min and a sample period of 5s were used in evaluating the standard deviations.

Figure 6.8 shows the results of the system tests where the frequency change was less than 0.1 Hz and the results of the fluctuation tests. Results obtained from the two sets of tests are similar, for frequency changes of less than 0.04 Hz the system tests give a mean value of K of 0.52 and the mean value of K from the fluctuation tests is 0.47. Both sets of results are subject to some degree of scattering. In the case of the system tests this is due to the difficulty in obtaining very stable conditions on the model as the simulated system is small with low inertia and is subject to small fluctuations. These are partly due to the time lag in the application of the load's frequency response, and partly to other modelling errors. The scatter of the results of the fluctuation tests has been discussed previously (section 6.5.1).

The generators were not designed with a specific governor deadband, but it was known that small governor deadbands did exist due to offsets in the operational amplifiers particularly in the governor simulation. As the test system used on the simulator has two similar generators the plot of the frequency change against power change will be of similar shape to the governor characteristics. Extrapolating

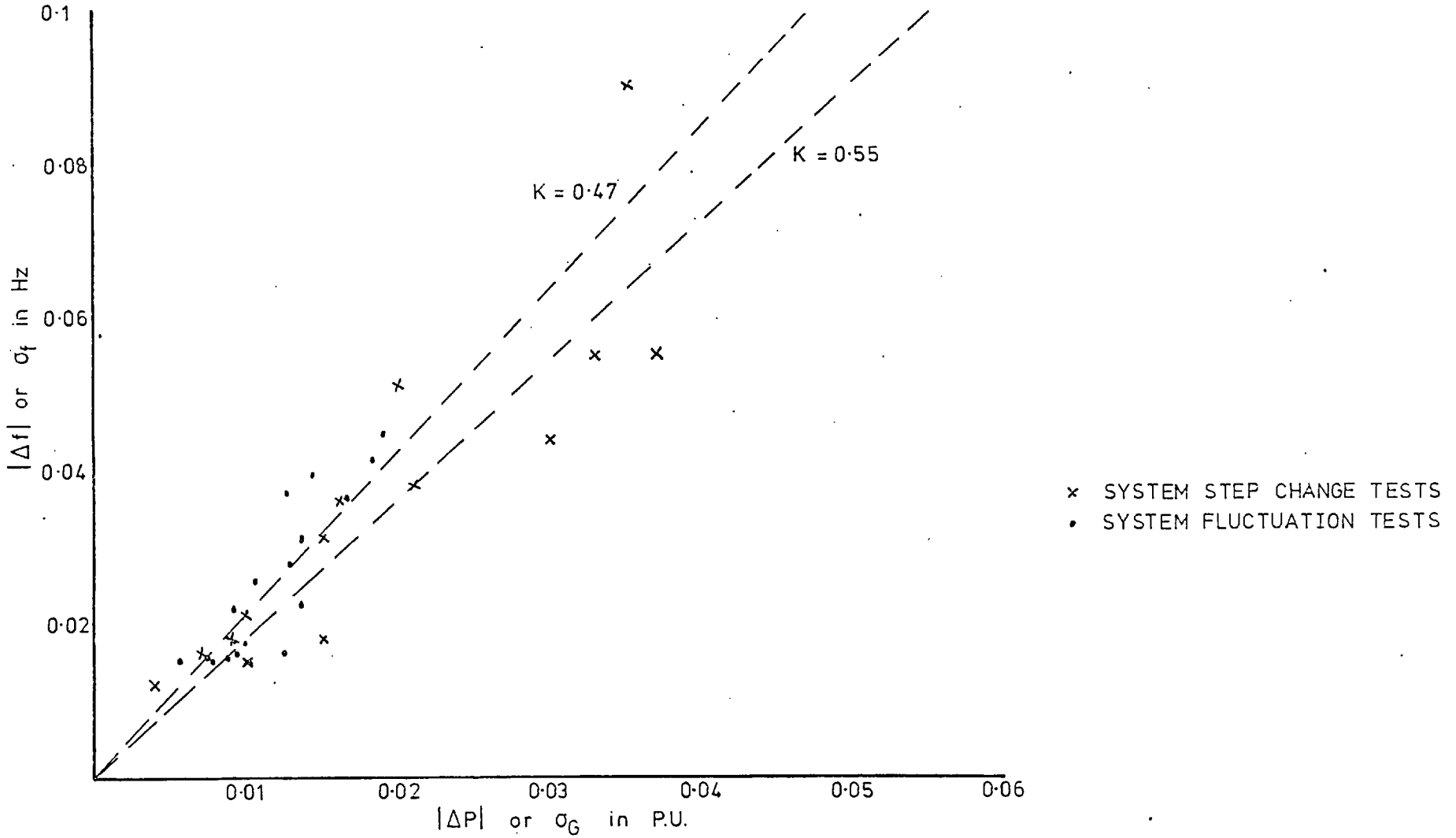


FIGURE 6·8 . RESULTS OF SYSTEM STEP CHANGE AND FLUCTUATION TESTS TO EVALUATE FREQUENCY RESPONSE CHARACTERISTIC

from the points in figure 6.8 that have very small frequency deviations i.e. < 0.02 Hz, one can estimate the governor deadbands as $0.005 - 0.007$ Hz. Unfortunately, there are no simulator results for frequency deviations of less than 0.01 Hz mainly due to these deadband effects. However, the effect of this small deadband in producing a non-linear area frequency characteristic can be seen.

6.7. CONCLUSION.

A method of estimating the area frequency response of a power system for small frequency fluctuations using the natural disturbances on the power system has been developed. It can be seen that there are problems associated with the technique in that it is upset by generator scheduling. However, it does not require the application of intentional disturbances and uses measurments, available at a control centre, of total generation and frequency.

The presence of a non-linear area frequency response characteristic , of the form postulated, has been shown for the power system simulator. However, the non-linearity is not as evident as that on the Union Electric Power System; the ratio of the large frequency error response to small frequency error (< 0.04 Hz) response on the simulator is 1.2 and on the Union Electric System 2. This difference is due to the smaller governor deadbands on the simulator.

7. AUTOMATIC GENERATION CONTROL (A.G.C.)

7.1. DEFINITION OF AGC.

Automatic Generation Control (AGC) sometimes known as Load Frequency Control (LFC) has the primary aim of ensuring that at any instant the energy being supplied by the generators is equal to the energy demanded by the loads including the losses. It is defined in IEEE Standard No.94 [8] as:

"The regulation of the power output of electric generators within a prescribed area in response to changes in system frequency, tie line loading, or the relation of these to each other, so as to maintain the scheduled system frequency and/or the established interchange with other areas within predetermined limits".

Control of frequency and tie line power flows has been a problem since utilities were first interconnected. Interconnection has the advantages that it produces the most economic generation and has the ability to share reserve generation. Historically, various methods of AGC were used, one popular one being the use of constant net interchange control by all but the largest control area, this being on constant frequency control. These techniques are still used in some countries such as West Germany, but now most power interconnections use some form of Tie Line Bias Control.

7.2. TIE LINE BIAS CONTROL.

Tie line bias control is the most commonly used form of AGC today. A system performance criterion, the Area Control Error(ACE), is defined as

$$ACE = \Delta P_T - B.\Delta f \qquad \ldots\ldots\ldots (7.1)$$

where ΔP_T = tie line power flow error

Δf = frequency error

B = frequency bias setting

This value is then minimised using a proportional plus integral controller which also minimises the integral of the ACE, called the IACE.

The advantage of tie line bias control over earlier frequency control methods, such as constant frequency control (where the tie line power flow errors are ignored) and constant tie line control (where the frequency error is ignored) is that it performs the following functions [73] if all areasin a power pool are using it:-

1. Causes each area to absorb its own local load changes.

2. Determines the steady state response of an area to a remote load change, after the initial governor response and pending absorption of the change by the remote area.

3. Causes each area to do its share of system frequency control.

The steady state response to a remote load change is specified by the frequency bias setting. Normally the relationship between the frequency bias setting and the K of each control area is agreed between all power pool members. Cohn in reference 73 discusses this in detail but, in summary, if B = K then for a distant load change the ACE is zero and the local area supports the distant area through governor response to frequency change only. Where B < K the ACE is negative and support to the remote area is reduced by the AGC and in the situation where B > K the ACE is positive and the AGC increases the support to the distant area. In the past various values of B were used, mainly affected by the strength of the tie lines. Minimal control action occurs when B = K, but as discussed in chapter 6 K is variable. B is often chosen to be equal to the largest anticipated value of K [71] so that the frequency deviations caused by disturbances outside the local control area are not exacerbated, without imposing excessive control action on the generators.

Once the ACE has been calculated it is fed to a proportional plus integral controller which minimises the ACE and over time the IACE.

$$\text{Thus} \qquad G = (C_1 \times ACE) + C_2 \int_0^t ACE \, dt.$$

The lead time of the controller will be in the range 50 - 100s. De Quervain and Frey [74] use a lead time of 62.5s for the controller in a tie line bias control example; however, the value chosen for a control area will be a function of the size of the system and its load variations.

The generation change is allocated according to economic criteria, which are calculated by analogue or digital methods to minimise the generation costs within security constraints. Where the utility has hydro-electric capacity, these sets are normally used for AGC, as their response is rapid and the cost of generation change is low. Most generating sets used for AGC are controlled by a pulse system; a pulse of specific length indicates fast or slow, raise or lower. Some modern systems have been constructed where a set point generation value is sent to a local generation controller [75]. In carrying out generation allocation the physical limitations of the plant, specifically maximum capacity and maximum rate of change of generation, must be taken into account.

7.3. PERFORMANCE CRITERIA.

The value and performance of AGC can be assessed in terms of a number of performance criteria. Each criterion quantifies a different facet of the performance of the system and a judgement must be made in assessing the overall value of the various techniques.

7.3.1. FREQUENCY PERFORMANCE.

The standard deviation of the frequency deviation can be used to measure the quality of frequency control [76] by

$$\sigma_f = \sqrt{\frac{1}{T} \int_0^T (f - f_o)^2 \, dt}$$

where f - frequency.

f_o - scheduled frequency.

7.3.2. POWER INTERCHANGE PERFORMANCE.

Quality of control can be characterised by the standard deviation of the net power interchange deviation [76].

$$\sigma_{P_T} = \sqrt{\frac{1}{T} \int_o^T (P_T - P_{TO})^2 \, dt}$$

where P_T - power interchange.

P_{TO} - scheduled power interchange.

7.3.3. GENERATOR CONTROL ACTION.

Excessive generator control action causes wear on the control equipment. CIGRE [76] propose two measures: the standard deviation of the regulating power

$$\sigma_\omega = \sqrt{\frac{1}{T} \int_o^T (P - P_o)^2 \, dt}$$

and the standard deviation of the rate of change of generation

$$\sigma_v = \sqrt{\frac{1}{T} \int_o^T \left(\frac{dP}{dt}\right)^2 \, dt}$$

where P is the instantaneous power supplied by the generators and P_o is the scheduled power supply.

Another measure that may be used is the mean of the absolute power variation speed.

$$= \frac{1}{T} \int_0^T \text{ABS} \left| \frac{dP}{dt} \right| .dt$$

This is a measure of the actual control action and could be measured by summing the length of the raise and lower pulses sent from the master controller.

7.3.4. AREA CONTROL ERROR (ACE) AND ITS INTEGRAL (IACE).

The ACE is the measure of the instantaneous ability of a control area to match its load and generation and is given by equation 7.1.

A number of meagures of the effectiveness of the AGC can be defined from the ACE. One proposal is the standard deviation of the ACE [76].

$$\sigma_{ACE} = \sqrt{\frac{1}{T} \int_0^T (ACE)^2 \quad dt}$$

However the ACE should be first filtered to avoid including the rapid fluctuations.

Measurement of the longer term performance of the control can be made using the IACE where

$$IACE = \int_0^T ACE \quad dt$$

This is an important criterion, and according to Ross and Green [77] the most important performance criterion for AGC as it is a measure of a control area's ability to meet its load commitments over a longer time period.

7.3.5. MUTUAL AID CRITERION (MAC).

This criterion [77] is a measure of the extent to which individual control areas in an interconnected power system contribute to the frequency control of the interconnection

$$MAC = \int_0^T (C.\Delta f.\ \Delta P_T)\ dt$$

where C is a constant to give the result in units of energy.

If Δf and ΔP_T have different signs then the MAC is negative and the area is contributing to the maintenance of the system frequency and if they have the same sign then the MAC is positive and the area is hindering the maintenance of the system frequency.

7.3.6. INADVERTENT ENERGY INTERCHANGE (II) AND TIME DEVIATION (TD)

The inadvertent energy interchange as a function of the normal AGC parameters is

$$II = \frac{1}{3600} \int_0^T \Delta P_T\ dt \qquad \text{in MWh}$$

and the time deviation

$$TD = \int_0^T \left(\frac{f - fo}{f} \right) dt \qquad \text{in seconds}$$

Both terms are also measured by other means, for example, energy meters on tie lines and by crystal or atomic clocks to determine the time error.

If a power system has a time deviation, the individual utilities in the interconnection may have "intentional inadvertent energy interchanges" because the utilities have supported the system frequency. These interchanges are

$$II\ (\Delta f) = \frac{1}{3600} \int_0^T B. \Delta f \ dt \quad \text{in MWh}$$

$$II\ (TD)' = \frac{K.\ (TD)}{3600} \quad \text{in MWh}$$

7.3.7. ASSESSMENT OF CONTROL CRITERIA.

The assessment of the control criteria of AGC depends upon whether they are regarded from the point of view of the utility or from the viewpoint of the whole interconnection. Each utility wishes to minimise its costs so minimum control action is important, as is maintaining the tie line loadings at a level that avoids infringing contractual agreements. Most power systems in Europe and North America must avoid time deviations as this tends to upset consumers who use synchronous clocks.

Considering the whole interconnection, the important criteria are time deviation and inadvertent energy interchange. IACE is a measure of the local sum of these errors and MAC gives an indication of the extent to which the utilities are contributing to the overall control of the interconnection.

A number of performance criteria were measured to assess the performance of AGC algorithms on the Power System Simulator. These included mean and standard deviation of ACE, frequency deviation and tie line power flow error and the mutual aid criteria. Generation control action was measured by counting the number of control pulses of each type sent to each generator. The importance of the various criteria was dependent upon the purpose of the test being run.

7.4. PRESENT PROBLEMS ASSOCIATED WITH AGC.

The problems associated with AGC are at a number of levels. Cohn [71] remarks that an economic assessment of the required level of frequency control has never been made. If frequency is allowed to

wander time deviations may occur. Western industrialised nations aim for a zero time deviation over 24 hours, partly because of the large number of synchronous electric clocks in use. In Russia, where this type of clock is less common, time deviations are a regular occurrence.

Time deviations and inadvertent energy interchanges are a problem if, as at present, the aim is to maintain these at zero. Two causes of these deviations are metering errors on tie lines and frequency metering error. Analysis of this type of error and correction procedures are discussed in references 78, 79 and 80. Some interconnections now employ automatic time deviation correction at low rates of change, others correct manually.

Another problem associated with AGC which has been reported in the U.S.A. [71, 81] and in Australia [83], is of oscillations of the system frequency. A short term oscillation usually with a peak to peak magnitude of about 0.01 Hz and a cycle time of 60 - 90s is observed, often superimposed on a long term oscillation with a cycle time of hours and frequency variations of up to 0.05 Hz.

The frequency bias term B is normally set to be the largest anticipated value of K. This should give the best overall frequency response since if B is less than K the AGC can act in a manner that increases the frequency error. However, as explained in section 6.3, K is non linear and smaller for small frequency deviations due to governor deadband effects. For small frequency deviations the AGC overcorrects the error causing system oscillations or "hunting". Another partial explanation given is the effect of the time delay in changing generation, particularly when this is associated with periodic loads.

A final problem associated with AGC is the cost of regulation. Often older, more expensive plant has to be run out of merit order to carry out regulation as more efficient modern plant does not respond fast enough. Improved AGC algorithms might require slower response. Also control action costs money and any reduction in control action would therefore be welcomed.

7.5. METHODS OF IMPROVING AGC.

Methods of improving AGC fall into two categories. The first involves improving the present method of tie line bias control by making small modifications to, and increasing the complexity of, the algorithm. The second approach is to design a completely new control scheme using modern control theory. In the long term the second method will probably provide the best solution, but at present only improvements to the tie line bias control method have been implemented.

Reddoch [82] provides a good summary of the approach to AGC using modern control theory which involves developing a realistic system model with both deterministic and stochastic load components. A performance criterion is specified and some optimal or sub optimal control strategy developed. The problems at present besetting this approach are the large amounts of computation involved, and the difficulties of developing a model of sufficient realism. Although this approach has attracted considerable interest it will be some time before operations personnel are convinced of its value.

The methods of correcting time deviations and inadvertent energy interchanges have been discussed in the previous section. These often involve altering the target frequencies of the whole interconnection or some of its areas from nominal or altering target tie line power flows.

Considerable interest has been shown in the use of adaptive control techniques for both the controller and generation allocation sections of the AGC system [84]. Some systems have already been implemented using these methods, in particular the General Electric and Leeds and Northrup (L & N) systems. These systems incorporate logic which assesses the probability that control action is required and adjusts the controller gain suitably. The systems are based on similar concepts [82], but more has been published about the L& N system [77, 85, 86] and this is briefly described below.

The L & N system is a complete digital computer based AGC system with evaluation of the ACE by conventional methods, a proportional plus integral controller, a generation allocation program

and an economic dispatch program [85, 86]. However, the main difference from previous tie line bias control systems is the Error Adaptive Control Computer (EACC) section. The EACC is connected as shown in figure 7.1. It is not in the control loop, but monitors the error signals, calculates the probability that action is required and adjusts the controller gain.

A basic assumption of the EACC concept is that it is unnecessary for AGC to follow rapid small random fluctuations of load and thus frequency. Checks are carried out to evaluate the probability of AGC action being required. These involve checking the length of time since the ACE changed sign, the sign relationship between the ACE and its integral and the magnitude of the ACE. Account can also be taken of time deviation and inadvertent energy interchange errors. The gain of the controller is altered usually between 0 and 2 according to the probability of AGC action being required. EACC, like the AGC controller, needs to be tuned to suit the particular system, and, although approximate estimates of parameters can be found, operational tuning is required to give the best results.

The generation allocation section of the L & N AGC system uses the Pointer Count Down Controller. This determines the participation of a generator according to its present and economic loading and its rate of change of generation limits. Economic considerations can be overridden when the ACE is large.

It can be seen that considerable effort has been put into the improvement of AGC. This should in time yield improvements, but system operations personnel must be convinced of the security of the new control methods. Small changes to existing methods meet less resistance as they are more easily understood by operators.

7.6. NON LINEAR FREQUENCY BIAS.

The area control error is defined by equation 7.1., i.e.

$$ACE = \Delta P_T - B. \Delta f$$

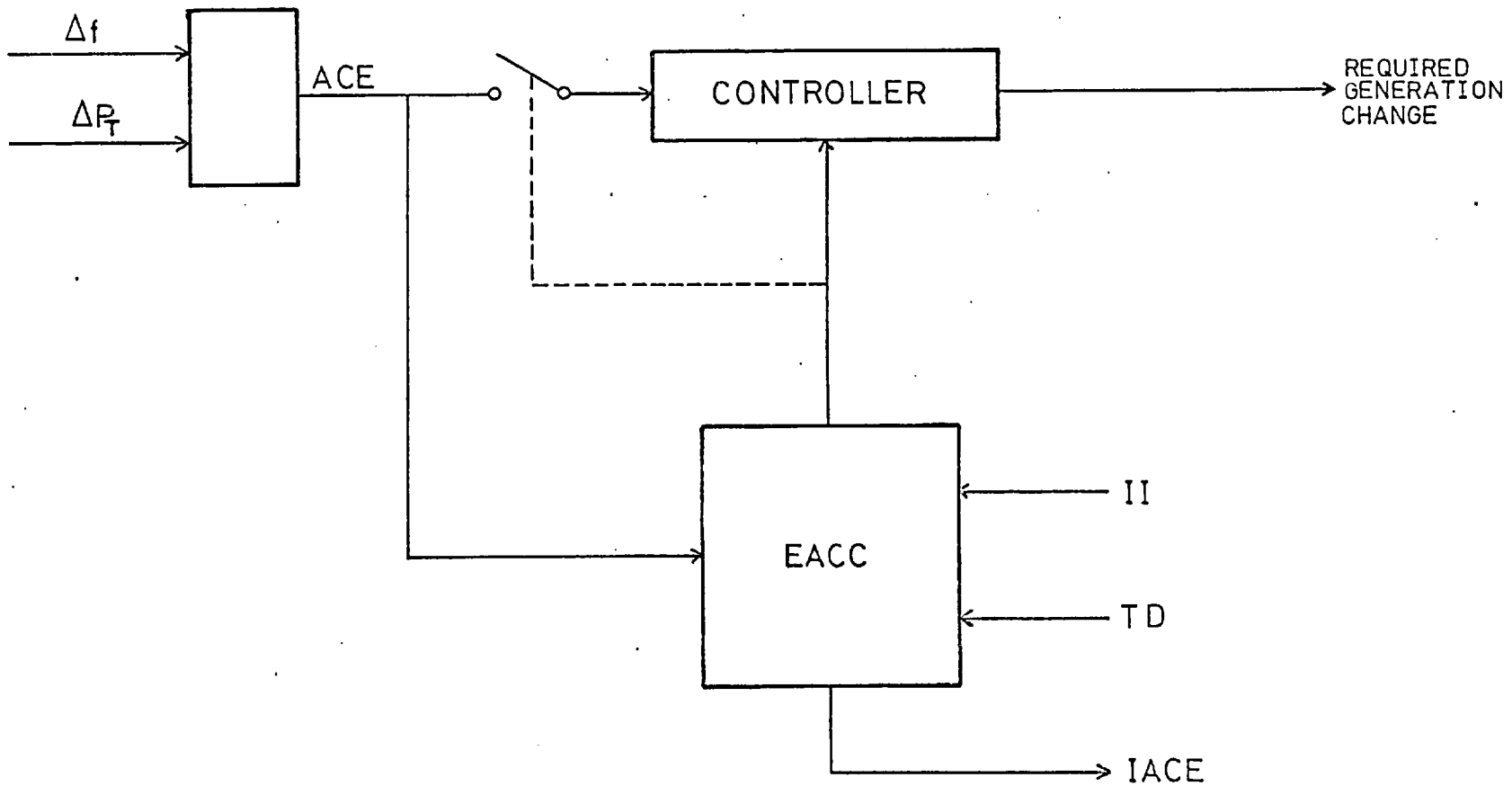


FIGURE 7.1 . BLOCK DIAGRAM SHOWING CONNECTION OF EACC TO AGC

where ΔP_T - tie line error

Δf - frequency error.

B - frequency bias.

However, the generation imbalance for the control area is

$$\Delta P_T - K.\Delta f$$

where K - area frequency response characteristic for frequency error Δf

There are three causes of differences between the ACE and the generation imbalance of the control area:

error in measurement of ΔP_T

error in measurement of Δf

difference between B and K

It has been shown that K varies with system loading and also with frequency error.

A knowledge of the actual generation imbalance in the local control area is the best basis for evaluating the control response. Even if it is desired to support another control area in difficulties when there is a large frequency deviation, a knowledge of the local state and the true level of support is useful.

Small frequency deviations cause all control areas in an interconnected system to respond by altering their generation to correct the error. If the error is small and, as is common for small frequency deviations, all areas are using a B value considerably larger than the K value for that situation, "over control" occurs and an oscillatory or damped oscillatory response results. For small ACE values it is probably better to correct in an overdamped manner then in an underdamped manner, although of course for large deviations rapid response and correction is important.

The effect of the EACC is to reduce the response for small errors and increase that for large errors. Results from the implementation of EACC are good but it is a method designed to reduce response to small random and oscillatory load changes. The use of a non-linear B, copying the non-linear K of the system, where the value

for small frequency deviations is B = K and for large frequency deviations B $\geqslant$ K, should help the control. Slightly different aims are set for AGC during large and small frequency deviations; for large deviations rapid correction to within more reasonable limits is required whereas for small deviations, slower correction without overshoot is the aim.

Implementation of AGC on digital computers enables algorithms to be incorporated which are logic rather than analogue based. The digital computer is suited to the use of algorithms which involve choice of alternatives and thus an algorithm using a non-linear B consisting of a series of linear approximations to K is feasible.

Two factors need to be noted about this method. The first is that the integral of the ACE should be separately calculated or else the non-linear B will result in time deviation errors being caused. If the integrals of tie line power flow errors and frequency error are calculated separately and then combined using some mean or weighted mean of K to transform the frequency error to power units, this would be effective. The two integrals can then also be easily corrected using the measurements of energy interchange errors and time deviation available. Secondly, non-linear frequency bias and EACC are not incompatible, although alterations would have to be made to the EACC response to small errors.

Adaptive control using a value of B = K, where K is estimated on-line, to evaluate the ACE is an interesting idea. The K value estimated would be related to the K in the preceding few minutes and not related to the present value. As K is a function of the frequency deviation, which can change quickly, the sole use of an on-line estimation of B would cause problems due to the underestimation of K during the early stages of large frequency deviations. If on-line estimation was used only for small frequency deviation values of B in a non-linear frequency bias algorithm it might be valuable. However, estimation of K in a system with AGC is extremely complex as is mentioned in section 6.5.

7.7. IMPLEMENTATION OF AGC ALGORITHMS ON THE SIMULATOR.

All the AGC algorithms implemented were based on the tie line bias control concept. These were:

1. Simple tie line bias.
2. EACC
3. Non-linear frequency bias

Much of the programming used was common to all the algorithms e.g. the generation allocation. A common main routine was used in all the programs which evaluates the tie line error and calls subroutines to execute the other parts of the algorithm (figure 7.2.)

7.7.1. SIMPLE TIE LINE BIAS ALGORITHM.

The main routine in the AGC calls three subroutines of which the first, SACE, evaluates the area control error. For simple tie line bias control this involves the use of equation 7.1. to evaluate the area control error (ACE).

A value of 0.65 was used for B, which is slightly larger than the mean value of K measured for the simulator system and is approximately the largest of the measured values obtained.

A proportional plus integral controller is included in the second subroutine. The integral part of the controller was implemented by keeping a running sum of the ACE, which is effectively IACE. A controller with a 100s lead time was used

$$G = (A \times ACE) + (C \times IACE)$$

where G - generation change required
A - proportional coefficient = 1
C - integral coefficient = 0.01

Generation changes required were allocated by a third subroutine ALLOG. Each of the generators had five control states, fast raise, slow raise, no change, slow lower and fast lower and the system was similar in effect to the pulse control system used on many

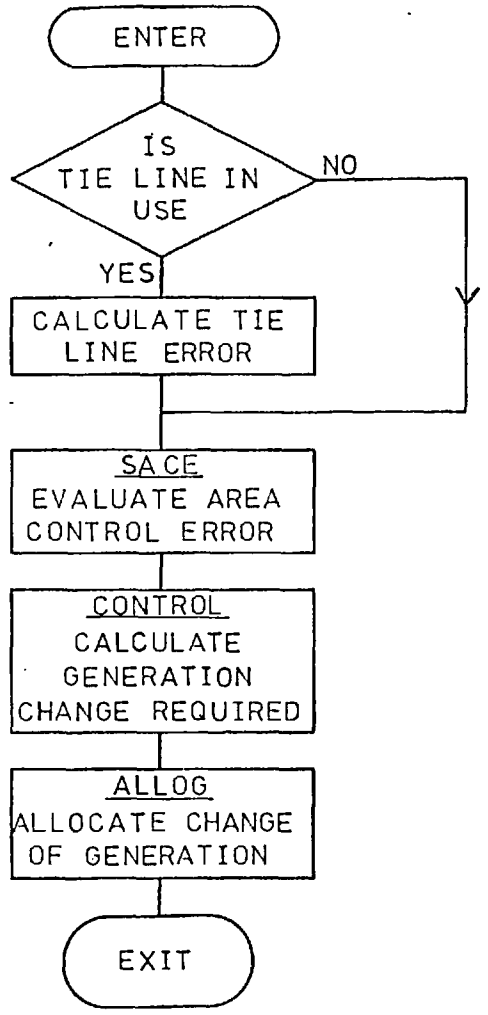


FIGURE 7.2 . FLOWCHART OF MAIN ROUTINE FOR AGC PROGRAMS

power systems. Fast control action results in a generation change equivalent to 15% of capacity per min and slow control to 7½% of capacity per min. These are fast control rates for thermal plant. The change of generation required was obtained from the controller and the generators were cyclically assigned generation changes as shown in figure 7.3. Each generator in turn was instructed to change generation until either all the generators had received instructions or the required generation change had been allocated. During the next run of the AGC program the allocation subroutine gave commands to the next generator in the cycle first.

7.7.2. ERROR ADAPTIVE CONTROL COMPUTER ALGORITHM.

In implementing this algorithm the same main, area control error evaluation (SACE) and generation allocation (ALLOG) routines were used. The EACC was built into the controller routine thus altering the gain of the controller.

Three separate sections were used to see if the ACE was significant. The first two checks involved algebraically summing the ACE and its integral up to a maximum value, and if the sign remained constant and the magnitude greater than a certain value for more than a specified period then the gain of the controller was altered from zero. Only the magnitude of the ACE was considered in the third check and if this was large, a large gain was used by the controller. Values used in the EACC are shown in table 7.1. below and a block diagram showing the implementation of the EACC is shown in figure 7.4.

Table 7.1. EACC: Parameters for 3s Scheduling.

Section	MAX IACE in p.u.	ERROR MAGNITUDE in p.u.	Time Period in s	Gain
1.	0.003	0.0036	24	0.75
2.	0.006	0.009	12	1.00
3	0	0.015	1	1.50

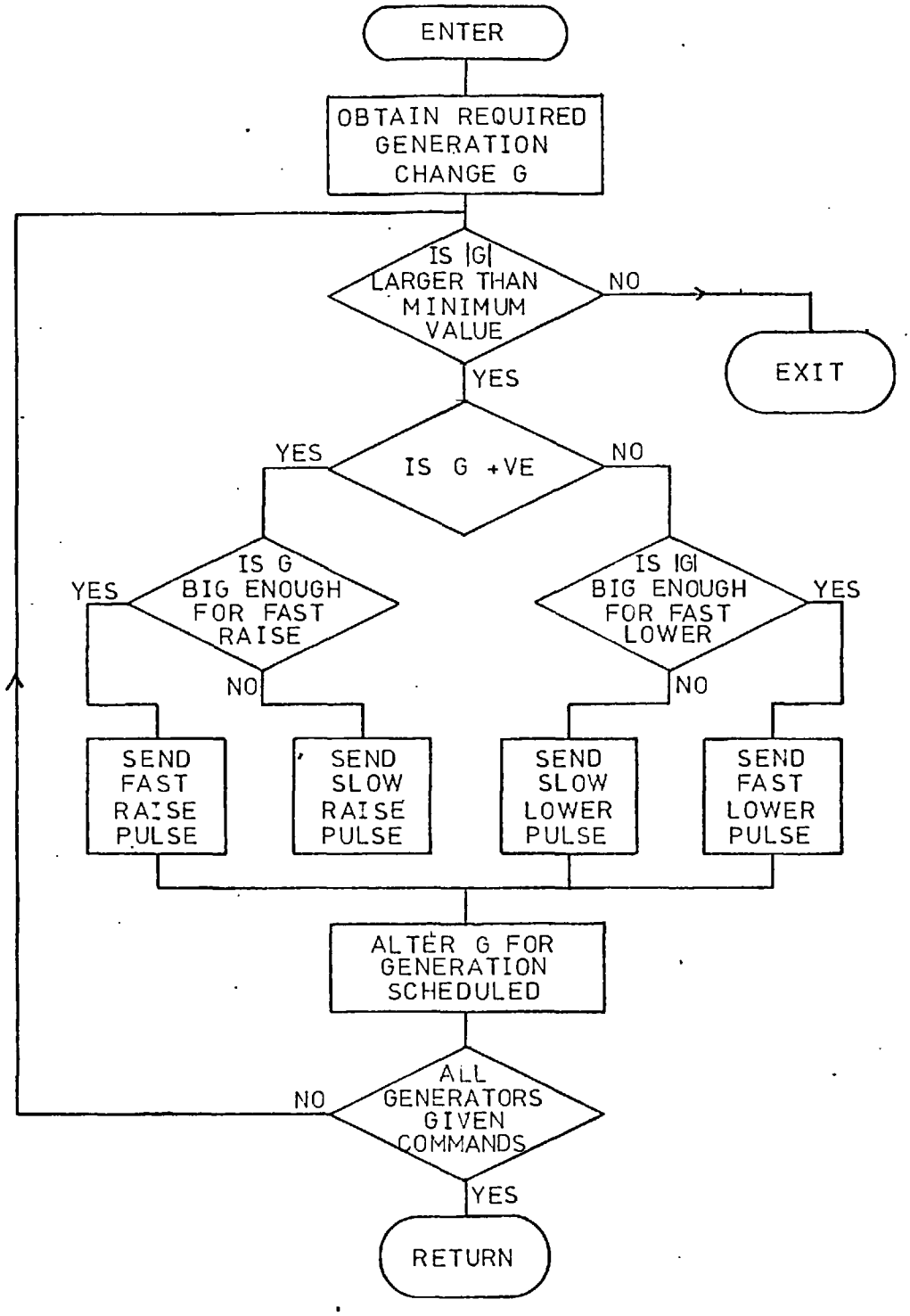


FIGURE 7.3 . FLOWCHART OF GENERATION ALLOCATION SUBROUTINE ALLOG

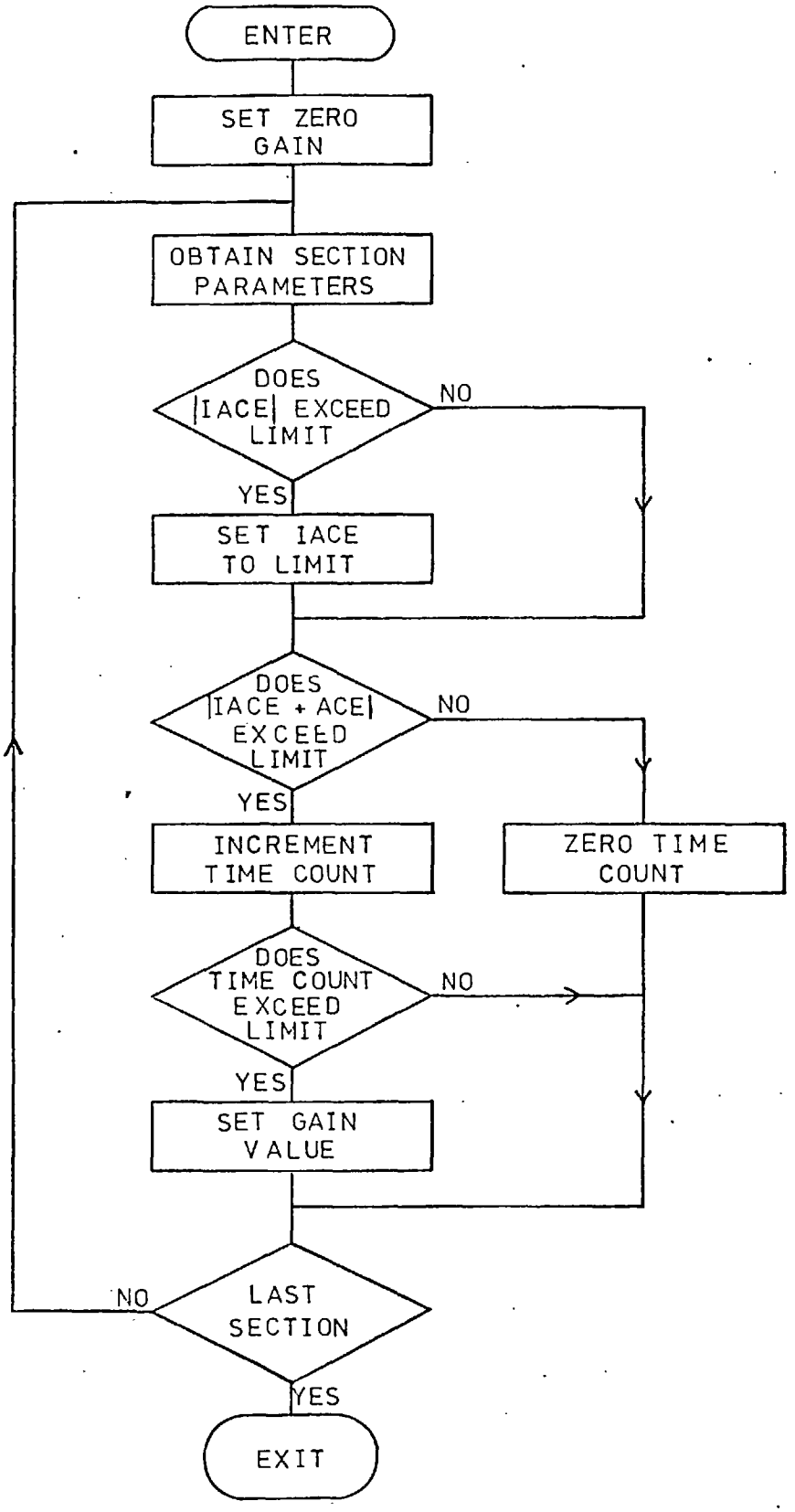


FIGURE 7.4 FLOWCHART OF IMPLEMENTATION OF EACC

The controller whose gain was altered by the EACC was included in the same subroutine. It had the same lead time as the simple controller, but unless set by the EACC the default gain was zero.

7.7.3. NON-LINEAR FREQUENCY BIAS ALGORITHM.

This algorithm was the same as the simple tie line bias algorithm except in the manner in which the ACE was calculated. A non-linear value of B was used which consisted of three linear segments in each half of the power frequency plane. Constant B values were used for large and small frequency deviations, with a smooth transition between the two as shown in figure 7.5 and listed below:-

Δf - frequency deviation

$|\Delta f| \leqslant 0.025$ Hz $\quad B = 0.4$

$0.05 > |\Delta f| > 0.025$ Hz. $\quad B = (10 \times |\Delta f|) + 0.15$

$|\Delta f| \geqslant 0.05$ Hz. $\quad B = 0.65$.

These values were chosen from a study of the measurements of system K discussed in section 6.6. The large frequency deviation value of B was just less than the largest measured value of K for the system, and the same as the value used in the other two AGC programs. A slightly smaller value of B than the mean value of B obtained for small frequency deviations was used.

7.7.4. AGC SUPPORT SOFTWARE.

A series of support programs were developed to work in conjunction with the AGC programs. Most of these programs were associated with the analysis of the behaviour of the AGC system.

The first AGC support program was the initialisation program IAGC. This initialised various common locations used for AGC

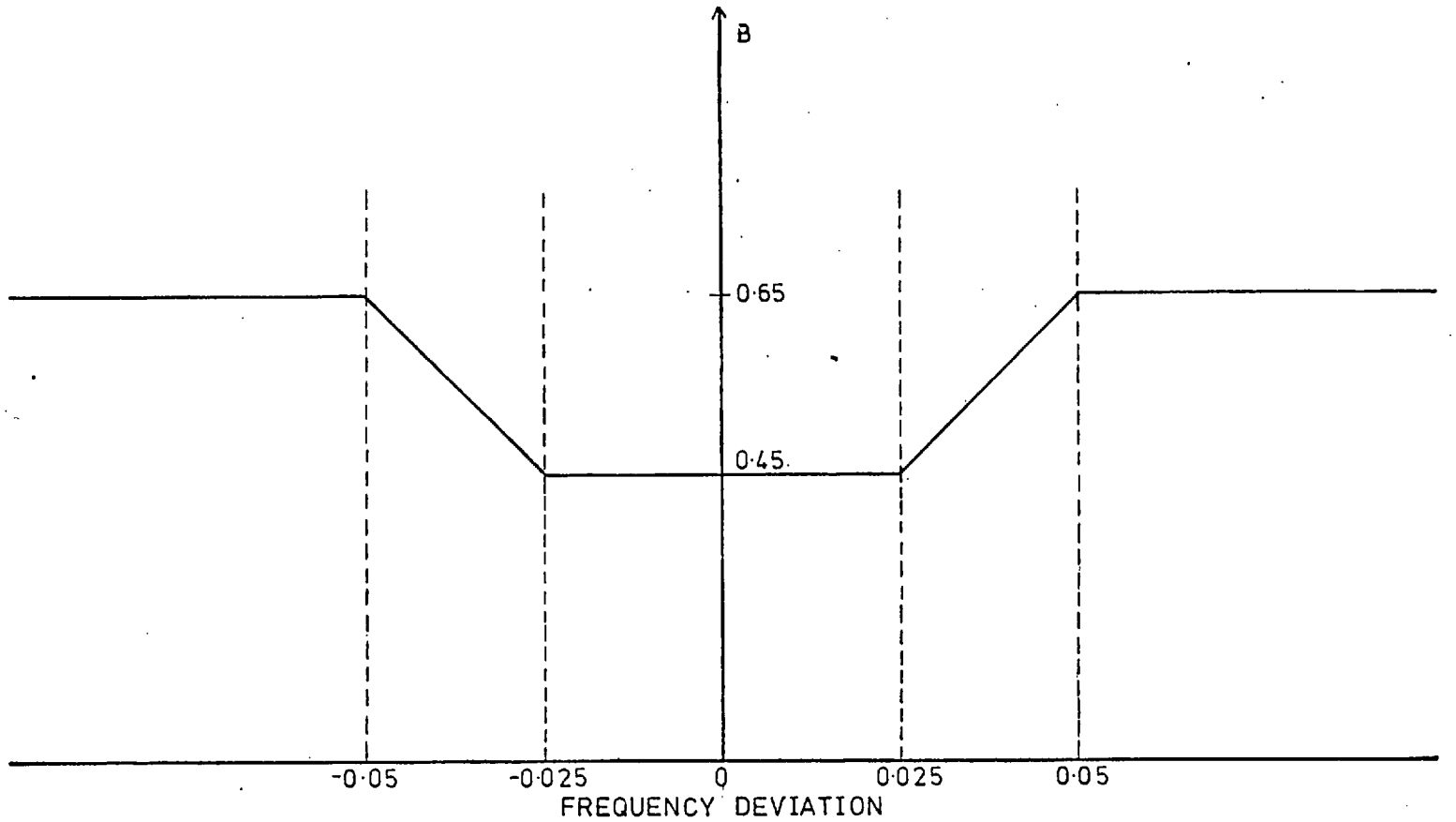


FIGURE 7·5 . PLOT OF NON-LINEAR FREQUENCY BIAS

and AGC analysis. It then started the analysis program, the monitoring program and an AGC program at a specified scheduling frequency. Information as to the AGC program to be used and its scheduling frequency, along with other information, was provided by interactive communication with the operator via the teletype.

Every 1s the AGC analysis program AGCA was executed. It evaluated the ACE and its integral, the frequency deviation and the tie line error. These four values were output as analogue outputs so that they could be recorded with a chart recorder. A running sum of the various values and their squares was kept for 20 mins. These values could then be accessed by the AGCAP, a task which then evaluated and output various AGC performance criteria including mean and standard deviation of ACE, frequency and tie line error and the generation commands which had been issued. The performance of the AGC could also be monitored by a program which ran at the same frequency as the AGC program called AGCM and this output the values of power generation, loads, frequency and generator commands to the serial printer.

7.8. COMPARISON OF AGC ALGORITHMS.

Two tests were set up to compare the behaviour of the three different AGC algorithms. Both tests involved the frequency control of the isolated area system shown in figure 6.6 with the tie line open. The only alternative available to operating as an isolated system was to connect the system to the infinite bus which followed the frequency of the national grid. As the main point of comparison between the AGC programs was the treatment of frequency deviations, the isolated system test was felt to be the better test for the algorithms.

The first test used on the algorithms involved using AGC to maintain the nominal frequency while the load characteristics and random load fluctuations were operating, but with the target load values kept constant. This was effectively subjecting the system to small load variations, a situation in which the non linear frequency bias algorithm should prove most effective. Table 7.2 shows the results of this test for the three AGC programs and the results for no AGC.

TABLE 7.2 : AGC OF RANDOM LOAD FLUCTUATIONS

Test	AGC Program	σ_f	Generator Control Pulses				
			Fast Raise	Slow Raise	No Action	Slow Lower	Fast Lower
1	None	0.0970	-	-	800	-	-
2	1	0.0374	282	46	165	58	249
3	1	0.0374	280	46	158	51	265
4	2	0.0387	239	6	349	0	206
5	2	0.0412	234	4	353	1	208
6	3	0.0332	228	51	251	56	214
7	3	0.0332	199	72	279	58	192

AGC PROGRAMS 1 - Simple Tie Line Bias

2 - EACC

3 - Non-linear Frequency Bias

Results from the second test are shown in table 7.3. This test involved large load changes caused by trend load changes with the random fluctuations superimposed. The load changes are quite sharp being as large as 0.4 p.u./min on a mean load of 1.2 p.u. and with a maximum of 1.4 p.u. and a minimum of 0.8 p.u.

During the tests the AGC programs were scheduled at 3 s. This resulted in the smallest change of generation requested being 0.00375 p.u. per execution of the AGC program. Assuming a mean K of about 0.5 this indicates that frequency deviations of less than 0.0075 Hz cannot be controlled.

Inspection of the results shows that AGC is effective giving a reduction by a factor of about 3 in the standard deviation of the frequency deviations; slightly more for large load variations and less for small load variations. Comparing the different algorithms and taking the simple tie line bias as the base, table 7.4 summarises the results. These results are evaluated by taking the mean for the test and using a negative sign for value reduction. Generator control action is calculated by giving twice the weighting to a slow pulse than to a fast pulse.

The program using EACC is very effective in reducing generator control action and in improving frequency control for large load variations. This is probably due to the known ability of the EACC to follow trend changes of load because of its overcontrol for large values of ACE. For small load variations frequency control is not as good as the simple tie line bias method, because the algorithm ignores very small ACE errors rather than over-controls them.

Non-linear frequency bias has a good effect on the results for the small load variations, reducing frequency deviations and generator control action. The results for larger load changes are not as good, with slightly poorer frequency control, due probably to the slightly lower response at the start of a trend load change.

The non-linear frequency bias algorithm does have advantages over the conventional algorithm. However, although not often required, the large deviation response of the system is very

TABLE 7.3 : AGC OF LARGE LOAD CHANGES

Test	AGC Program	σ_f	Generator Control Pulses				
			Fast Raise	Slow Raise	No Action	Slow Lower	Fast Lower
1	None	0.1723	-	-	800	-	-
2	1	0.0557	280	56	175	44	245
3	1	0.0500	285	26	258	21	210
4	2	0.0500	266	16	294	4	220
5	2	0.0458	267	26	271	11	225
6	3	0.0574	288	41	187	47	237
7	3	0.0529	277	26	272	26	199

AGC PROGRAMS 1 - Simple Tie Line Bias

2 - EACC

3 - Non-linear Frequency Bias

TABLE 7.4. SUMMARY OF AGC TEST RESULTS.

	AGC Progam	σ_f		Generator Control.	
small load changes	1	0.0374	-	1177	-
	2	0.0400	+ 7%	893	- 24%
	3	0.0332	- 11%	952	- 19%
large load changes	1	0.0529	-	1094	
	2	0.0479	- 9%	1006	- 8%
	3	0.0552	+ 4%	1071	- 2%

AGC Programs
1 - Simple tie line bias
2 - EACC
3 - Non linear frequency bias

important. From these tests it can be deduced that a combination of EACC and non-linear frequency bias control would be the most effective. The parameters used in the EACC for small errors would need modification with unity gain and possibly increased sensitivity. Obviously all the algorithms benefit from fine tuning in the operational situation and care must be taken in fitting the non-linear bias.

8. CONCLUSION.

8.1. ORIGINAL CONTRIBUTIONS.

The author feels that the original contributions to the field of power systems analysis and operation described in this thesis are:-

1. Furtherance of the use of time series and spectral analysis techniques in the analysis of power system variables.

2. Development of a load model suitable for load simulation in the neo-steady state region and particularly for real-time studies.

3. Development of a method of estimating the area frequency response of a system for small frequency variations from normal system fluctuations.

4. Evaluation of a method of improving AGC for small disturbances using a non-linear frequency bias.

Although this thesis reports most of the work carried out by the author during his studies, it is naturally biased towards reporting that part of the work which is original or has other points of interest. This obscures the efforts put into work in support of the continuing research and use of the power system simulator, particularly in the area of design and implementation of supporting software.

8.1.1. SPECTRAL AND TIME SERIES ANALYSIS OF POWER SYSTEM VARIABLES.

The aim of the analysis of the power system variables, in particular the real and reactive power flows, was to develop a model of the random load fluctuations. A model, the Low Pass Filtering Model, was used for the load simulation requirements, and suitable

parameters obtained from the analysis. This analysis also led to the development of a model for longer term probabalistic load modelling.

Although the main objective of the analysis was the development of a random load fluctuations model, other interesting information was also revealed. The inverse square relationship between spectral density and frequency was known and some evidence of the termination of this giving white noise at high frequencies for system frequency analysis had previously been obtained. Analysis confirmed this change of characteristic for all the system variables, but showed that the frequency of the change varied. This is due to different time constants dominating the behaviour of different system variables. The dominant time constant in the case of the voltage is the tap changers on the transformers, but for system frequency it appears to be a composite time constant.

A similar low frequency change was found, but this is less definite and may be due to load effects or slow system time constants such as manual frequency control. Further analyses of this type with data collected at different points on the system may lead to a better understanding of the shape of the spectral densities and possibly to methods of identifying system parameters.

8.1.2. LOAD SIMULATION.

Development of the load simulation was directed at the requirements of the power system simulator. However, the model developed could be used for completely digital simulation studies. In developing digital simulation for AGC studies a load simulation is necessary and with small modifications the model developed could be used. Simulation for AGC studies will probably require power rather than current output values and an increase in the frequency of execution would also improve the simulation of the frequency response of the loads.

8.1.3. ESTIMATION OF K.

The area frequency response characteristic, K, is an important system parameter. A method of estimating K from the normal system fluctuations has been developed, with the advantage that it does not require large disturbances to be applied to the system. Application of this method to a real power system is feasible provided almost all the generator power injections are available every 3 - 5s, which is not uncommon on modern power systems. Obviously there are factors that may upset the method and will need further consideration: for example, real data is not a "snapshot" of the system. However, this technique requires further investigation on a real system.

8.1.4. NON-LINEAR FREQUENCY BIAS FOR AGC.

The problems of over control of power systems by AGC causing system hunting are discussed in section 7.4. Use of a non-linear frequency bias, similar in form to the non-linear K, should improve control for small frequency deviations, by giving a more accurate estimate of the true system imbalance. Obviously, the ideal would be some method of estimating the K for small frequency deviations on-line and introducing adaptive control to this section of the tie line bias control. The large frequency deviation value of frequency is less critical, provided it is larger than the current large frequency deviation K.

8.2. POWER SYSTEM SIMULATOR PROJECT.

Continuation of the power system simulator project should yield useful results in the development and initial testing of system control algorithms. A number of problems have and will be encountered with the system and these are discussed in the next section and some possible solutions proposed. Also some suggestions are offered for areas in which further investigation might be fruitful.

8.2.1. POWER SYSTEM SIMULATOR ANALOGUE SECTION.

One of the main limitations of the power system simulator is the small size of the systems it is possible to represent. A particular problem is the shortage of generator units. There is room in the simulator for six generator units, but for much work four would be adequate and an improvement on the present situation. A new generator unit design is not necessary as that designed by Giles [15] is reasonably compact and effective [10].

The study of AGC was limited by a number of system factors. These included the shortage of generator units, the lack of an effective method of representing the rest of a power system interconnection and limitations in the pulse control system. It should be possible to build a unit to represent the rest of a power system interconnection. Analogue representation of the system with reheat generation, governor, machine and AGC could be constructed and the output fed to a voltage controlled oscillator. The unit should be built with the possibility of easily altering the K of the system, the ability to produce distant disturbances equivalent to loss of generation or load changes and the possibility of disconnecting the AGC. This unit could be constructed to fit into one of the unused generator positions.

Thought should be given to redesigning the pulse control units. These units integrate the control pulses sent to the generator to evaluate a local power reference signal. Relays were originally used to stop the integration of noise on the transmission lines. However, the relays are not reliable enough for the frequent switching operations. Also the voltage range of the units is not suitable and should be altered.

Maintenance and calibration will be a problem to which there may be no easy solution. However, all future equipment should be designed so that calibration is as easy as possible and that the units are reasonably insensitive to alterations of power supply voltages.

8.2.2. DIGITAL COMPUTER AND SOFTWARE.

The PDP-15 computer is now eight years old and further modifications or additions to it appear unlikely. Every effort should be made to use its facilities to the full, particularly those which show high reliability such as processor, main memory and disk units. At this stage any change of computer would cause considerable difficulties as the software is very system dependent. Also 18 bits is an unusual computer word length and any other machine is likely to be 16 bits, producing further conversion problems.

Present processor usage is about 47% with a heavy but sensible selection of system tasks running. This is not excessive and for a research system up to 70% usage should be reasonable. All the frequently executed programs, i.e. less than 2s scheduled programs, have probably been implemented, although further generator units requiring boiler simulation will increase the loading by 6% per unit. If sensible use is made of priority and scheduling so as to maintain an even processor loading there should be no major problems. The disk situation is even better with the second disk only being used for large data logs, and it seems highly unlikely that disk storage will provide any constraints. Unfortunately, the situation regarding main or core memory is not as encouraging and in the present configuration partition P3 is used by all the disk based programs.

Consideration of the use of core requires comment on the large core requirements of the display program. This infrequently run program requires 4 K words of core virtually permanently. The display system is now becoming essential as the complexity of the overall system increases. A further problem is that the increase in the number of generator units to 4 would result in an increase in demand for common area for the boiler programs. If a 1 K word common area was created in P3 (see figure 2.5) for use of boiler simulation it would free the $\frac{1}{2}$ K word common area used at present. An assembler task capable of communicating with the visual display could be written to fit into this area and used to request display tasks made from the subroutines of the present display program DISPA. This would mean that the partition P5 used at present by DISPA could also be used by other character I/O programs such as PRNT2 and AGCM. The

P3 partition, now only 3 K words in length, could be reserved solely for control programs, which, having no character I/O, tend to be smaller. Implementation of these changes should relieve the present core congestion.

8.2.3. FUTURE STUDIES OF CONTROL ALGORITHMS.

There is still considerable scope left for work on AGC and the simulator is a useful tool in designing and initially testing AGC algorithms. Further study and modifications to the tie line bias concept of control may be useful and AGC using modern control theory should be investigated. The proposed modifications to the power system simulator would make these studies more realistic.

Care must be taken in studying longer term control or optimisation problems such as economic dispatch. It is difficult to assess how viable the simulator is as a tool for studying control loops whose frequency of execution is more than 5 mins.

Previously, studies of state estimation have been carried out using the simulator. Further work in this area including configuration verification and bad data identification may be useful. Another field which might be studied is voltage/var control; however, small extensions to the hardware to include reactive power compensation and automatic control of tap changing transformers would probably be needed for this purpose.

The power system simulator is a useful tool for research into the problems associated with the development and implementation of secondary control of power systems. It highlights problems that it is difficult to appreciate from a mathematical study or digital simulation, and which might not have been otherwise recognised until implementation on a real system was attempted.

APPENDIX A - SAMPLE DATA SIGNALS AND DIGITAL FILTERING.

A1. SAMPLE DATA SIGNALS [88].

The Dirac (δ) function is defined such that it describes a pulse of infinite power, infinitely short duration and unit energy. It is also known as the Delta function or Impulse function.

$$\delta(t - t_o) = 0 \quad \text{for} \quad t \neq t_o$$
$$= \infty \quad \text{for} \quad t = t_o$$

$$\int_{-\infty}^{\infty} \delta(t)\, dt = 1$$

Consider a function f (t) multiplied by the Dirac function

$$f(t_o) = \delta(t - t_o)\ f(t)$$

Suppose a series of Dirac functions exist

$$\delta(t),\ \delta(t - t_1),\ \delta(t - t_2)$$

such that $t_1 = \Delta t$

$t_2 = 2.\Delta t$ etc.

and these are multiplied by the function f (t) to give a series of spikes representing the values of the function f (t) at specified points. These can be termed samples of the function f (t) separated by a period Δt.

Normally it is assumed that the data is sampled at a constant frequency and that the sample time is infinitely short. In practice this is not achievable although efforts are made to make it a reasonable approximation.

The sampling frequency used is a function of the highest frequencies present in the continuous signal. This relationship is expressed in the sampling theorem:

"A continuous signal which contains no significant frequency components above f Hz may in principle be recovered from its sampled version, if the sampling is less than $\frac{1}{2f}$ s. "

This limit of half the sampling frequency is sometimes

termed the Nyquist limit. Normally continuous signals are filtered to remove higher frequencies from the signals before digitising. This avoids aliasing problems.

A2. INTRODUCTION TO Z - TRANSFORM [87,88]

The Z - transform is a transform designed to deal with sample data systems in the frequency domain and is the equivalent of the Laplace transform for sample data,

$$Z = \exp(sT)$$

and the Z transform of a discrete signal f (k) is F (z)

$$F(z) = \sum_{k=0}^{\infty} f(k) \quad Z^{-k}$$

Z can be thought of as a time shift with Z^{-j} being a time delay of j sample periods in the same way that e^{-jwt} is a time delay of T seconds. Transfer functions can be derived in terms of Z transforms and poles and zeros in the complex Z-plane found.

A3. INTRODUCTION TO DIGITAL FILTERS. [87,88]

A filter is any device or processor which is frequency selective. Normally the term is used to describe a system which transmits a certain range of frequencies (passband) and rejects others (stopband). Analogue filtering is well known in electronic engineering, but sampled data or digital filtering has been developed since digital computers have become widely available.

An ideal filter is one which passes the desired frequencies with no attenuation and completely attenuates undesired frequencies. This involves an instantaneous cutoff in the frequency band, a requirement that is impossible. The more complex a filter the sharper the cutoff. However, often other characteristics can be traded for sharper cutoff, e.g. phase response. This is the phase shift caused

by the filter across the frequency spectrum and in many applications is important.

Digital filtering can be carried out by two methods. The first in the frequency domain involves taking the Fourier transform of the signal record, operating on the frequency record and then transforming back to the time domain. Obviously this technique cannot be used in real time as the complete data record must be available. The technique involves considerable computer memory requirements but has a sharp cut off. Filtering can also be carried out in the time domain and this is the more commonly used technique.

Time domain digital filter behaviour can be studied in both the time and frequency domains. In the time domain impulse and step responses can be studied. The poles and zeros of the filter in the Z plane can be plotted and these used to derive the magnitude frequency plot and phase frequency plot.

Two methods of implementing time domain filters are available, non recursive and recursive filters. The difference is that recursive filters use the previous outputs of the filter, whereas non recursive filters only use input values.

A4. NON-RECURSIVE FILTERS.

The generalised form of the non-recursive digital filter is

$$Y_N = \sum_{k=o}^{N} A_k \cdot X_k$$

where Y = output
X = input
A = coefficients.

and the simplest form is the moving average filter. One example used in this thesis is

$$Y_k = 0.23\, X_{k-1} + 0.54\, X_k + 0.23\, X_{k+1}$$

which is used for smoothing evaluated functions. If this was used in

real time the output would have to be the K + 1 th time value.

Another non-recursive digital filter used is the Hanning Window filter, which belongs to the group of filters including Rectangular, Hamming and Blackman Window Filters[88]

$$Y_k = \frac{X_k}{2} \left[1 + \cos \left(\frac{k}{N} \right) \right]$$

where N is the record length.
This filter would not be used in real time as the complete data record is required. Use is made of this filter (section B5) for weighting the autocorrelation function before transformation to the spectral density to reduce noise.

A5. RECURSIVE FILTERS.

A generalised form of the recursive digital filter is

$$\sum_{e=o}^{M} A_{M-e} \cdot Y_{M-e} = \sum_{k=o}^{N} B_{N-k} \cdot X_{N-k}$$

where X - input
Y - output
A, B - coefficients.

If M is zero the filter is non-recursive, if greater than zero then initial values of Y must be known or a start up transient will be experienced if these are estimated.

Butterworth and Chebyshev Filters[88] are two types of filters which can be implemented efficiently as recursive filters to give a good approximation to ideal bandpass and bandstop filters. Both types can be implemented at any order, the greater the order the sharper the cutoff, but the greater the number of terms and the complexity. The Chebyshev filter has a sharper cutoff at any particular order, but has a ripple in the bandpass sections.

An N th order Butterworth Filter has a squared magnitude function

$$|H(j w)|^2 = \frac{1}{1 + \left(\frac{w}{w_o}\right)^{2N}}$$

for the low pass implementation with cutoff frequency w_o. This type of filter is implementable as low or high pass, bandpass or bandstop filter and is normally serially realised as second order sections. Using subroutines described by Ackroyd [88] a computer program was written to design and plot the responses of Butterworth Digital Filters.

One filter that has been used in the project for different tasks is a first order low pass recursive filter which has the form

$$Y_k = A\,Y_{k-1} + B\,X_k$$

where X - input.
Y - output.
A, B - coefficients.

This filter is very easy to implement and is used for smoothing input data (section 2.5.2) and is also used in load simulation (section 5.2). It has an exponential impulse response whose time constant T_f is

$$T_f = \frac{-1}{\ln A} \quad \text{sample periods.}$$

Usually the filter is programmed for unity D.C. gain with

$$A + B = 1.$$

APPENDIX B - STATISTICAL TIME SERIES AND SPECTRAL DENSITY ANALYSES.

B.1. STATISTICAL PROPERTIES [40]

The two main statistical characteristics of a data record are its mean and standard deviation. These are defined for the purpose of this thesis as

$$\text{Mean} = \bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i \qquad \ldots\ldots (B1)$$

where x_i is the i th value of the N samples making up the record.

$$\text{Sample Variance} = \sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2 \qquad \ldots\ldots (B2)$$

and Standard Deviation = σ = $\sqrt{\text{sample variance}}$

(Normally standard deviation is defined as the root of the variance, rather than the sample variance)

$$\text{Variance} = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2$$

However for large N (i.e. > 35) there is no significant difference between the true and sample variances.

A further measure, the dispersion is defined as

$$\text{Dispersion} = \frac{\sigma}{|\bar{x}|} = \frac{\text{standard deviation}}{\text{mean}} \qquad \ldots (B3)$$

which describes the proportional size of the variations. When this measure is being used on detrended or otherwise modified data the mean of the pretransformed data should be used.

B.2. CROSS CORRELATION[40]

Instantaneous cross correlation is a measure of the relationship between two variables. The numerical result of the analysis

$$\text{Instantaneous Cross Correlation} = \frac{\sum_{i=1}^{N} (x_i - \bar{x}).(y_i - \bar{y})}{N \times \sigma_x \times \sigma_y} \quad \ldots\ldots (B4)$$

where σ_x is the standard deviation of x

σ_y is the standard deviation of y

is in the range + 1 to − 1. Normally a value greater than 0.7 or less than − 0.7 is considered a significant degree of correlation.

Cross correlation can also be carried out as a time series where a delay of a sample period or more between cause and effect is expected.

B.3. STATIONARY SIGNALS[40,87,90,91]

A stochastic process is described as "strictly" stationary if none of its statistics is affected by a shift in time origin. The term "weakly stationary" is used to describe a rather larger group of processes only some of whose statistical properties, including mean, standard deviation, autocorrelation and spectral density functions, are time independent.

Many signal analysis techniques assume that the process being analysed is stationary and also may assume that it is ergodic (a tighter restriction discussed in references 40 , 87 and 91). It is never possible to decide with certainty if a process is stationary without examining a record of infinite length. A process that has a beginning and an end is theoretically not stationary, but if the record length is long compared with the period of the lowest frequency spectral components then it can reasonably be supposed to be "weakly" stationary over most of its lifetime.

There are a number of tests that can be applied for the probability of a non-stationary process. One is a trend test using the method of counting "reverse arrangements" or "inversions" [90,91] This method assumes initially that the record is stationary. The record is divided into equal slices whose mean square values can be calculated. A reverse arrangement is defined as occurring when a 'term', that is the mean square value of a 'slice', is less than an earlier term. It is possible to calculate the probability of having C or less inversions in a stationary record. If there are n slices in the record then there are N! possible permutations. The number of possible inversions varies from

$$0 \text{ to } (N + (N-1) + \ldots\ldots\ldots + 3 + 2)$$

There are a number of permutations that have a specific number of inversions, and knowing the number of permutations for each number of inversions, the probability of C or less inversions can be evaluated, and these values are summarised in Table B1 for 6, 12 and 30 slices.

If a signal is found to have a trend, removal of this may be possible. A simple linear trend can be approximated by a least squares fitting and removed. It would also be possible to postulate a quadratic or larger order polynomial trend or even an exponential or sinusoidal trend, to fit the curve to the data and then remove. However, this is rather complex on a long data record.

Another technique for trend removal or data smoothing is digital filtering. This technique can be used to remove certain frequencies from a data record, be they high or low frequencies. Removal of low frequency signals should instil some degree of stationarity upon the data.

B.4. TIME SERIES ANALYSIS.

Time series analysis is a technique for studying the way the present value can be expected to be related to the previous sample values, or the way future sample values can be expected to be affected by the present sample value.

One method of time series analysis is known as the

Table B1 : Distribution of Reverse Arrangements for a Random Series.

6 Slices		12 Slices		30 Slices	
C	P	C	P	C	P
0	0.001	12	0.002	136	0.002
1	0.008	14	0.004	144	0.004
2	0.028	16	0.010	152	0.010
3	0.068	18	0.022	160	0.021
4	0.136	20	0.043	168	0.040
5	0.235	21	0.058	176	0.072
6	0.360	22	0.076	180	0.094
7	0.500	23	0.098	184	0.121
8	0.640	24	0.125	188	0.152
9	0.765	25	0.155	192	0.188
10	0.864	26	0.190	196	0.228
11	0.932	27	0.230	200	0.274
12	0.972	28	0.273	202	0.298
13	0.992	29	0.319	204	0.323
14	0.999	30	0.369	206	0.349
15	1.000	31	0.420	208	0.375
		32	0.473	210	0.402
		33	0.527	212	0.430
		34	0.580	214	0.458
		35	0.631	216	0.486
		36	0.681	217	0.500
		37	0.727	218	0.514
		38	0.770	220	0.542
		39	0.810	222	0.570
		40	0.845	224	0.598
		41	0.875	226	0.625
		42	0.902	228	0.651
		43	0.924	230	0.677
		44	0.942	232	0.702
		45	0.957	236	0.749
		46	0.969	240	0.792
		48	0.984	244	0.831
		50	0.993	248	0.864
		52	0.997	252	0.893
		54	0.999	256	0.917
		66	1.000	260	0.937
				264	0.953
				272	0.975
				280	0.988
				288	0.995
				296	0.999
				435	1.000

Structure Function (ref. 92) or Mean Square Deviation (ref. 94) and is defined

$$S(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} (f(t+\tau) - f(t))^2 \quad \text{.... (B5)}$$

where τ is the time lag and f (t) is the function of time.

For discrete data this becomes

$$S(k) = \lim_{N \to \infty} \frac{1}{2N} \sum_{i=-N}^{N} (f(i+k) - f(i))^2 \quad \text{.... (B6)}$$

An advantage of this method of time series analysis is that it does not assume that the record is of a weakly stationary process.

Consider the expansion of equation (B.5)

$$S(\tau) = \lim_{T \to \infty} \left[\frac{1}{2T} \int_{-T}^{T} (f(t+\tau))^2 dt + \frac{1}{2T} \int_{-T}^{T} (f(t))^2 dt - \frac{1}{T} \int_{-T}^{T} (f(t+\tau) \cdot f(t))^2 dt \right]$$

If the record is of a stationary process then by definition

$$\int_{-T}^{T} (f(t+\tau))^2 dt = \int_{-T}^{T} (f(t))^2 dt$$

from which it can be shown that

$$S(\tau) = 2\sigma^2 - 2\rho(\tau)$$

where $\rho(\tau)$ is the autocovariance

The equation used in calculating the structure function is

$$S(\tau) = \frac{1}{N-p} \sum_{i=1}^{N-p} (x_{i+p} - x_i)^2 \quad \text{.... (B7)}$$

where $p \cdot \Delta t = \tau$

Δt = sample period

N = total number of samples.

Dividing the structure function by twice the variance gives a scaled value termed the "normalised structure function".

Normalised Structure Function = $S_n(\tau)$

$$S_n(\tau) = \frac{S(\tau)}{2\sigma^2}$$

The autocovariance of a stationary process is defined as

$$R(\tau) = \lim_{N\to\infty} \frac{1}{2T} \int_{-\infty}^{\infty} f(t).f(t+\tau) \quad \text{.... (B8)}$$

and for discrete data the sample autocovariance is defined as

$$R(k) = \lim_{N\to\infty} \frac{1}{2N+1} \sum_{i=-N}^{N} (x_i - \bar{x}).(x_{i+k} - \bar{x}) \quad \text{.... (B9)}$$

for a stationary process with sample mean value of $\bar{x}$

Sometimes a running mean is used instead of the mean of the total record.

It can be shown that

$$R(o) = \sigma^2$$

and the variance can be used to normalise the function giving the autocorrelation.

$$\text{autocorrelation} = \rho(\tau) = \frac{R(\tau)}{\sigma^2} \quad \text{.... (B10)}$$

Computer calculation of sample autocovariance can be done using the equation

$$\rho(p) = \frac{1}{N-p} \sum_{i=1}^{N-p} (x_i - \bar{x}).(x_{i+k} - \bar{x}) \quad \text{.... B11)}$$

B.5. SPECTRAL DENSITY FUNCTION [40,87,89,93]

The Wiener-Khintchine Theorem states that the autocorrelation function R (τ) of x (t) and the Power Density

Function G (f), where f is frequency, constitute a Fourier Transform pair

$$G(f) = \int_{-\infty}^{\infty} R(\tau) . \exp(-j 2\pi f \tau) . d\tau$$

$$R(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} G(f) . \exp(j 2\pi f \tau) . df$$

If x (t) is real then R (τ) is real and symmetric about $\tau = 0$, therefore

$$G(f) = 2 \int_{-\infty}^{\infty} R(\tau) . \cos(2\pi f \tau) . d\tau \qquad \ldots\ldots (B12)$$

Transforming to the discrete data form the integration can be carried out by a Discrete Fourier Transform (DFT) or a Fast Fourier Transform (FFT). The Fast Fourier Transform is more efficient, but more complex and has some limitations on record length.

In the discrete time domain the autocorrelation function can be replaced by the autocovariance function,

Using the Discrete Fourier Transform

$$G(p) = \rho(0) + 2 \sum_{q=1}^{M-1} \rho(p) . \cos \frac{pq}{M} + \cos \rho(M) . \cos p \qquad \ldots\ldots (B13)$$

where M is the maximum number of autocovariance lags and

$$\text{frequency} = \frac{p}{2 . M . \Delta t}$$

Practically, Spectral Density estimates are subject to excessive sample variance and require smoothing. This can be carried out on the spectral density estimate using a window filter e.g.

$$G(p) = 0.23 . G(p - 1) + 0.54 . G(p) + 0.23 G(p + 1) \ldots (B14)$$

or by weighting the autocovariance function. A Hamming filter of the form

$$\rho(\tau) = \frac{\rho(\tau)}{2} \left[1 - \cos \frac{\tau}{\tau_{max}} \right] \qquad \ldots\ldots (B15)$$

minimises the contributions of the larger lags. The Fourier transform of the weighted autocovariance leads to a smoothed version of the spectral density estimate.

The resultant spectral estimate in the frequency band

$$0 \rightarrow \frac{1}{2.\Delta t} \quad \text{Hz}$$

has increments of $f = \frac{1}{2\ M\ .\Delta t}$ Hz

APPENDIX C - TIE LINE UNIT.

Tie lines between power systems are accurately metered as the power flows and energy exchanges are the subject of contractual agreements. The accurate metering of power flows on the tie line between the system and the infinite busbar must be simulated and for this purpose the tie line unit was built.

Real and reactive power are measured by the tie line unit and a target power flow can also be specified for automatic generation control studies. Two analogue multipliers are used to evaluate the real and reactive power flows.

The inputs to the multiplier measuring real power are the tie line line to ground voltage and the current. Voltage is measured using a resistor divider and the signal buffered through an operational amplifier. Measurement of current is by use of a 9.2 : 1 ratio transformer with a 10Ω load across the secondary. The voltage across the resistor is multiplied by 10 by the buffering operational amplifier circuit. The buffered signals are fed into a MC 1494L analogue multiplier[95] which gives a signal proportional to the real power as output. This is buffered by an operational amplifier circuit which is also used to remove D.C. offset before the signal is filtered to provide a steady output signal. All operational amplifiers used are MC 741 or equivalent. Calibration involves scaling of the two inputs and the offset of the output, and the method is described in the analogue multiplier application notes[95].

Reactive power is measured in the same manner as the real power except that the voltage is shifted through 90°. Power supplies required are ± 15v which are available from the simulator power supplies. The target power flow signal is supplied by a multiturn potentiometer switchable between ±10v and ground. All the output signals produced are metered on the front panel and are available on the front panel as well as via a connector which fits into the signal sockets on the analogue section of the simulator. Figure C1 shows the layout of the front panel, C2 the real power measuring circuit and C3 the reactive power measuring circuit.

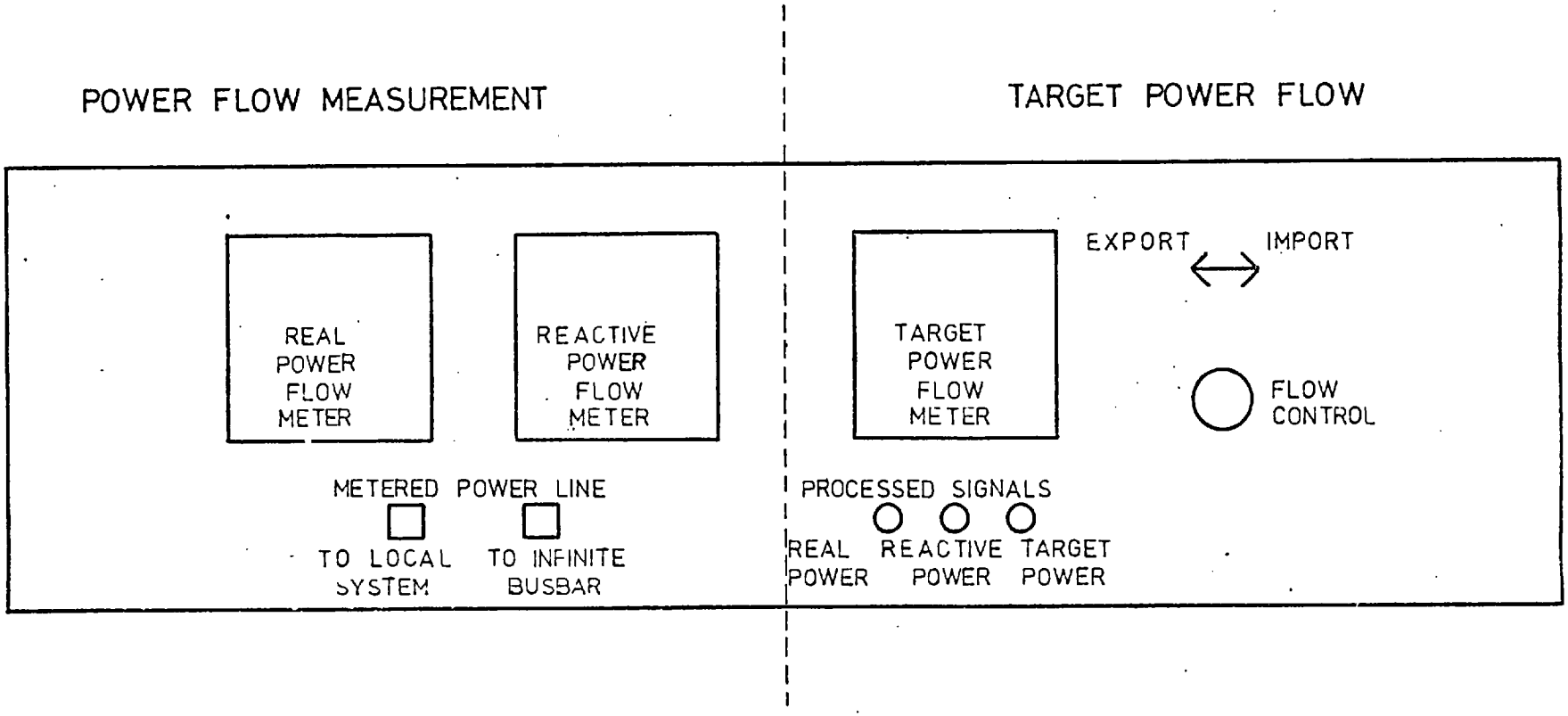


FIGURE C1. FRONT PANEL OF TIE LINE UNIT

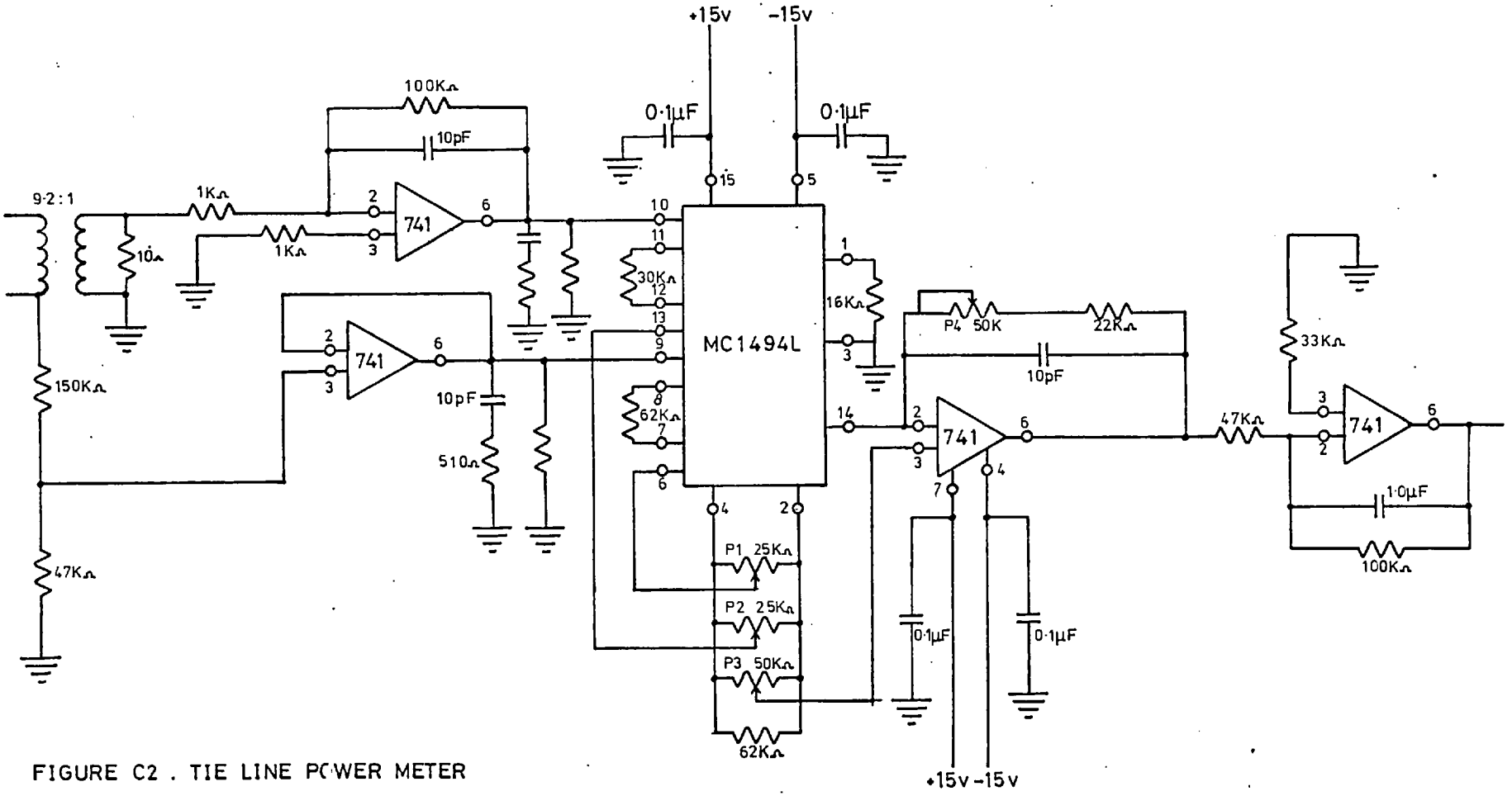


FIGURE C2 . TIE LINE POWER METER

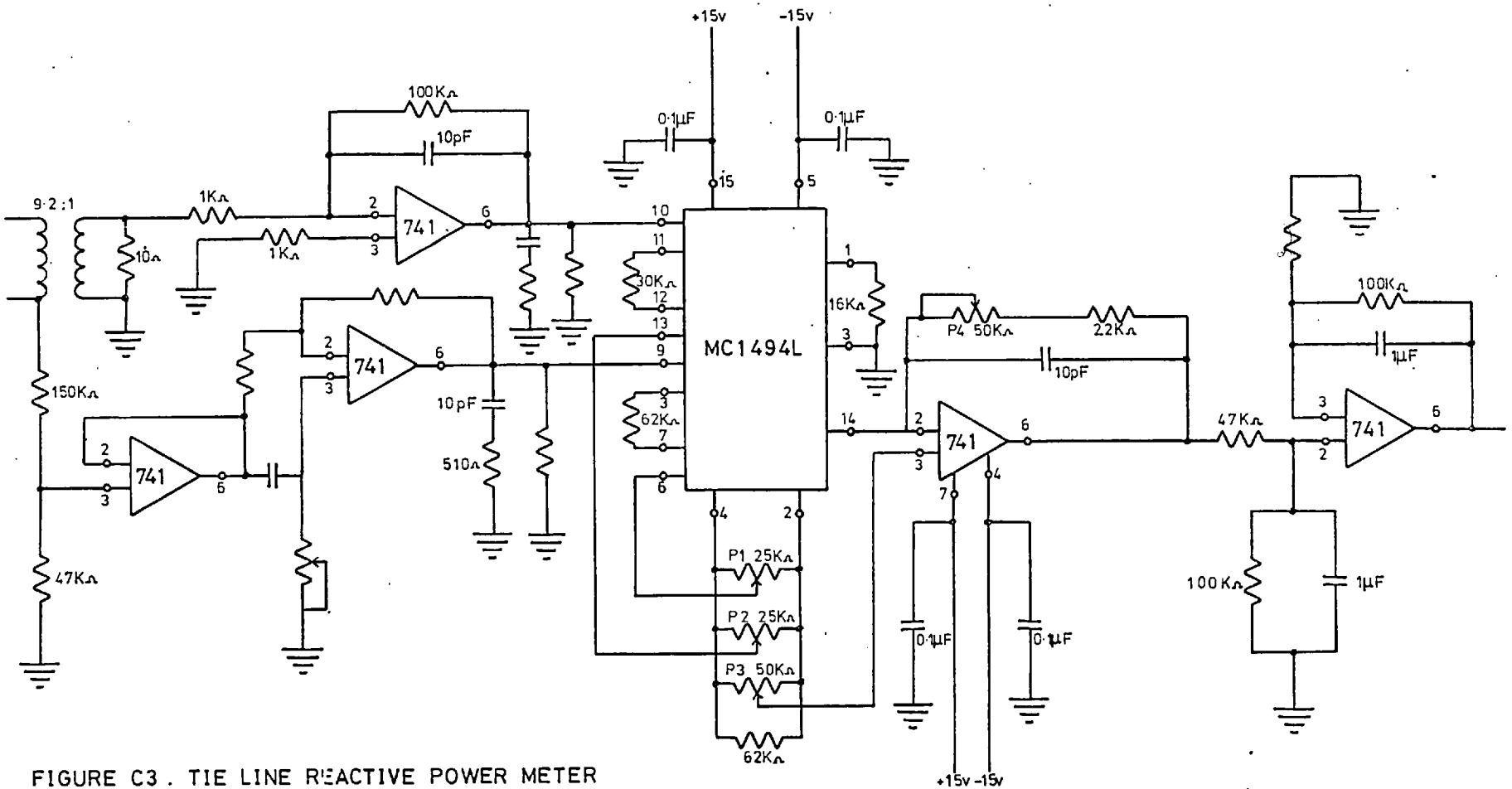


FIGURE C3 . TIE LINE REACTIVE POWER METER

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