

U N I V E R S I T Y O F L O N D O N

Imperial College of Science and Technology
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THE CONJOINT USE OF A NETWORK ANALYSER AND
ANALOGUE COMPUTER FOR STUDIES OF THE AUTOMATIC
GOVERNING AND REGULATING OF POWER SYSTEMS

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Doctor of Philosophy in Engineering

by

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ABSTRACT

A physical model has been developed to facilitate automatic control studies in multi-machine power systems. The continuing growth in size and complexity of modern power systems increases the necessity to impose widespread schemes of automatic control to fulfill all operating criteria.

The basic requirements of power system control are outlined and a proposed scheme is described. The development of analytical techniques is surveyed and the present limitations and difficulties discussed. An analogue computer study of a control system applied to a single turbo-alternator was carried out using a model based on linear transfer functions.

The preliminary study revealed the need for a fuller approach with provision for an adequate representation of the relevant characteristics of boiler constraints, governor mechanisms, turbines, alternators, transmission lines and loads in a multi-machine system. The complexity of such a study, even with comparatively simple representation of individual elements, outgrows the capabilities of an analogue computer. The merits of the conjoint use of a conjugate network analyser and analogue computer are then discussed.

The schematic layout of the network analyser, analogue computer and auxiliary equipment is described, with circuit details of the latter. The capabilities of the model are outlined and a representative study presented. Other potentialities of the equipment are also mentioned.

It is concluded that the conjoint use of a network analyser and analogue computer promotes a clear physical understanding of the dynamics of a power system so that the equipment has value as a research and design tool or as a teaching and training aid. The flexibility of the entire model enables a power system to be simulated with economy and speed.

'The philosopher may be delighted with the extent of his views, the artificer with the readiness of his hands, but let the one remember that without mechanical performance profound speculation is but an idle dream, and the other that without theoretical prediction dexterity is little more than a brute instinct.'

Samuel Johnson

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LIST OF SYMBOLS

(All powers are per unit of rated machine output in
MW; time constants in seconds.)

P_o	: Alternator output power
P_l	: Alternator input power
P_p	: Scheduled power
P_F	: Power demand from frequency control loop
P_e	: Control power error signal
P_x	: Power change per pulse (Pulsecontrol of speeder motor)
P_M	: Power output represented by speeder motor shaft position
P_g	: Power signal from governor
P_s	: Total steam power input to turbine
P_2	: Power at H.P. turbine outlet (shaft torque + steam)
P_3	: Power at I.P. turbine outlet (shaft torque + steam)
P_4	: Power at L.P. turbine outlet (shaft torque)
K_1	: Proportion of total steam power converted to shaft torque by H.P. stage
K_2	: Proportion of total steam power converted to shaft torque by I.P. stage
K_3	: Proportion of total steam power converted to shaft torque by L.P. stage
F_M	: Machine speed (c.p.s.)
F_M	: Machine speed error
F_s	: System standard or target frequency
F_o	: Actual system frequency (at time $t = 0$)

$F_e (F_o)$	: System frequency error
F	: System frequency (at time t)
K_4, K_5	: Turbo-alternator transfer function coefficients
K_6	: Gain of frequency control loop
K_7	: Derivative coefficient of output power
K_8	: Governor speed droop constant
K_9	: Velodyne gain
K_{10}	: Pulse frequency coefficient
T_1	: Turbine H.P. stage time constant
T_2	: Turbine reheat time constant
T_3	: Turbine I.P. stage time constant
T_4	: Turbine L.P. stage time constant
T_5	: Governor mechanism time constant
T_6	: Speeder motor time constant
T_7	: Wattmeter time constant
T_8	: Frequency meter time constant
z	: Damping ratio for machine rotor oscillations
ω_n	: Machine natural frequency in radians/sec.
f_n	: Machine natural frequency in radians/sec.
T_d	: Damping torque coefficient
H	: Machine inertia constant KWsec/KVA
E	: Excitation voltage behind machine transient reactance
E_1	: Infinite busbar voltage
E_T	: Machine terminal voltage
X_e	: External reactance on machine base
x'	: Machine transient reactance

ρ	:	$\frac{d}{dt}$
δ	:	Machine rotor angle (between E and E_1)
P_B	:	Base load power generation
P_{o1}	:	Power generated by controlled non-reheat sets
P_{o2}	:	Power generated by controlled reheat sets
P_L	:	System load power (maximum)
K_{11}	:	Proportion of system load supplied by base generation
K_{12}	:	Proportion of load capable of supply by controlled non-reheat sets
K_{13}	:	Proportion of load capable of supply by controlled reheat sets
K_{14}	:	System load coefficient (proportion of maximum)
P_5	:	Fraction of system load supplied by Base generators
P_6	:	Fraction of system load supplied by controlled non-reheat sets
P_7	:	Fraction of system load supplied by controlled reheat sets
P_8	:	Actual system load
P_{P1}	:	Programmed Power to non-reheat sets
P_{P2}	:	Programmed Power to reheat sets
K_{15}	:	Frequency characteristic of load
K_{16}	:	System frequency/load incremental coefficient

Any departures from the above definitions are locally specified in the text.

CHAPTER 1

INTRODUCTION

1. MANUAL CONTROL OF POWER SYSTEMS

1.1 General - The C.E.G.B. System.

In order to outline the background of the work described and discussed here, it is appropriate at the outset to explain briefly the contemporary configuration and method of operation of the electricity supply system of the Central Electricity Generating Board (C.E.G.B.).

In the U.K., the C.E.G.B.'s system is the largest under unified control in the world. At the present time (early 1965) the system is manually controlled and sophisticated techniques have evolved to achieve a high degree of security and economy. Since the scheme of operation is typical of modern practice, a few notes will be of general interest as well as providing the particular starting point for the work which follows. The details are abstracted from information sheets and standing orders issued to Control Engineers responsible for System and Power Station Operation. The author gathered the material during a period of field experience in C.E.G.B. Power Stations and Grid Control rooms.

The C.E.G.B. is responsible for the generation of electricity in England and Wales, which it supplies in bulk to the Area Boards, who, in turn, are responsible for supplying electricity to the ultimate consumers.

The National Grid System comprises the generating stations, 275 kV and 132 kV lines and cables with their associated switchgear, and the transforming stations where the supplies are given to the Area Boards. At 1st April, 1963, there were 234

generating stations in commission, containing 1,058 sets with a total effective capacity of 31, 683 MW. There were 3,529 miles of 275 kV overhead line, 9,266 miles of 132 kV overhead line, and shorter lengths of lower voltage lines and cables.

The capacity of the generating sets range up to 300 MW, with steam pressures up to 2,350 p.s.i. and temperatures up to 1,050°F.

The cost of fuel to generate a unit of electricity at a coal-fired station (including transport, handling and preparation) varies from about 0.35 d. to more than 4.0 d. depending on the thermal efficiency of the set and the cost of heat delivered to the station. At a nuclear station the cost is about 0.2 d.

The primary purpose of the 132 kV Grid was to interconnect stations to pool spare generating capacity. Interconnection has allowed spare capacity to be reduced to 10%. Prior to interconnection the national average was about 42%.

Interconnection covers risks of delays in commissioning plant, variations in availability, and errors in long term load estimation. The capacity of interconnection required is a function of the size of an Area and the national total.

With the increase in total capacity of the national system and the consequent increase in interconnection capacity required the 132 kV system became inadequate because of the number of lines required, and the 275 kV Supergrid system was developed. The 132 kV double circuit line has a capacity of about 200 MW, whereas a 275 kV double circuit line has a capacity of 1,000 MW, and consequently makes better use of a wayleave.

The 275 kV system also provides facilities for bulk transfer of energy from stations remote from load centres, and also from coal producing areas to areas where because of high transport cost coal is expensive.

1.2 System Operation.

The responsibility of the System Operation Organisation is to direct the output of the Board's generating stations to meet the Area Boards' demands for electricity with security and economy. For operational purposes the country is divided into eight Grid Control Areas each with a Grid Control Room. Each Control Room has direct communication with all power stations and transforming stations in the Area, and directs the output of these power stations.

Area Control.

The Grid Control Engineer has a list of the cost of production at each station in his Area (the Merit Order Schedule) and loads stations according to their costs. The low cost stations (high merit) are run continuously at full available output and the lower merit stations are brought on load as required to meet the varying demand for electricity. By this means the maximum number of units are generated at the low cost stations and the minimum number of units at the higher cost stations.

The Area Control Engineers are also responsible for all switching on the 132 kV and lower voltage circuits within their Areas and for ensuring the safety of men carrying out maintenance work on these circuits.

National Control.

Although the high voltage system is divided into eight Control Areas for operational purposes it is an interconnected network, and many lines cross Grid Control Area boundaries. To a large extent 275 kV lines are inter-area lines. It is therefore necessary to co-ordinate the operation of the eight Control Areas, and this is done by National Control.

National Control have a supervisory control of all switching on main 132 kV transmission lines, whether inter-area or internal to an Area. Area Controls receive permission to switch out lines, and report their return to service.

The 275 kV system is basically inter-area, and National Control issues direct instructions for all switching.

National Control also direct the transfer of energy between Areas.

Inter-Area Transfers.

Originally generating plant was installed in each Area to meet the local demand. Even under these conditions the cost of production varied considerably in the Areas, and although all plant might be required to meet the peak demand it was economical at other times to shut down high cost plant in one Area and import from lower cost plant in another Area.

With the development of the interconnected system it became possible to concentrate stations in the coal producing areas. As a result the Midlands, East Midlands, Yorkshire and North Eastern Divisions tend to have a surplus of generating plant and are planned to export at peak.

Inter-area transfers already result in a reduction in total fuel cost of some £3 million per year.

Economic Operation.

To meet the demand for electricity at minimum fuel cost it is necessary to predict the demand accurately to ensure: (i) that adequate generating plant is on load to meet the demand, and (ii) that too much plant is not put on load as this will cause additional and unnecessary no load losses.

Steam driven generating plant (which predominates in the C.E.G.B. system) requires from one to two hours for starting up and bringing up to full output (a longer time is required if the plant has been shut down for more than about twelve hours) and it is therefore necessary to plan the generating programme some hours in advance.

The day is divided into seven periods of relatively steady demand. Three hours in advance of the start of a period each Area estimates its local demand and assesses the local plant which is required to meet that demand. It then quotes to National Control the average cost of the 40 MW of lowest merit plant which will run to meet the demand (the decremental cost) and the average cost of the next 40 MW of plant which it has available (the incremental cost).

National Control considers these costs, and if the decremental cost of one Area is higher than the incremental cost of another a transfer is instructed. Maximum economy is obtained when all decremental costs are equal, that is, when the cost of the lowest merit plant running in each Area is the same.

In practice there will be substantial differences in the costs quoted by different Areas, and transfers of 500 MW or more may be required before a balance in costs is established. The magnitude of the economic transfers for the different periods can be forecast with some accuracy, and in fact basic transfers are issued to all Areas in advance and the incremental and decremental quotations are made from these basic transfers.

The economic transfer programmes are issued to the Areas by National Control, and the Area Controls instruct their stations on the plant required to be on load to meet the programme, and the output required from that plant.

In the event the estimated demand in an Area may not be presented and the Area may have output available at a lower cost than it quoted in advance. To ensure that advantage is taken of such conditions Areas quote to National Control each half-hour the actual incremental and decremental costs, and, when appropriate, transfers are adjusted.

Transfers of energy between Areas involve losses on the transmission lines, and account is taken of these losses by inflating the costs of an exporting Area by a suitable percentage when determining the economic transfer.

Economic transfers may be limited by the capacity of the transmission system. There is always the possibility of a fault occurring on a circuit, and the transfers are therefore limited to the capacity of the transmission system under the worst foreseeable outage conditions.

Demand Estimating.

The demand for electricity varies throughout the day, but follows a consistent pattern because consumers in the mass have regular habits. A substantial proportion of the demand for electricity is, however, made up of lighting and space heating, both of which are influenced by atmospheric conditions.

The lighting demand is naturally associated with hours of darkness, but can be influenced during normal daylight hours by cloud cover, visibility and precipitation. The variation in natural daylight can vary the demand by as much as 1,200 MW from one day to another.

The space heating demand varies with effective temperature, which is a compound of present air temperature, air temperature over the preceding 22 hours, humidity and wind speed. The response to change in temperature depends on the time of day and on the temperature level, for example, at 9.00 a.m. a variation in effective temperature of 1°C from 0°C would cause a demand variation of some 430 MW, whereas a variation of 1°C from 10°C would only cause a demand variation of 300 MW.

The demand varies from day to day throughout the year due to the changing hour of sunset and the seasonal variations in temperature.

Weather forecasts for all parts of the country are provided by the local Meteorological Offices each day at 05.00, 08.30, 12.00, 15.00 and 20.00 hours, and estimates of demand are made by adjusting the normal pattern to these conditions.

1.3 Frequency Control and Policy.

The one common factor on an interconnected system is the frequency. The C.E.G.B. endeavour by their normal methods of load despatching to maintain the system frequency at 50 c.p.s. The statutory obligation imposed on the Board is to maintain the frequency within $\pm 1\%$ (between 49.5 and 50.5 c.p.s.) and analysis shows that this is achieved within a tolerance of $\pm 0.1\%$ (i.e. between 49.95 and 50.05 c.p.s.) for 85% of the time. Thus it is clear that a high standard of manual control is maintained.

The frequency of the system only remains at 50 c.p.s. so long as supply and demand are exactly matched i.e. if the steam power input to the turbines is exactly equal to the consumers' demand (plus electrical and mechanical losses). Should they not be matched then any surplus or deficit of generation is thrown onto the stored rotational energy of the system (in the turbogenerators and consumers' rotating machinery) and the frequency rises or falls.

Without automatic frequency control it is necessary for the Area Controls to constantly adjust their generation to meet their demand plus or minus the inter-area transfers required whilst maintaining the frequency at 50 c.p.s. The basic frequency line is therefore the responsibility of the load despatching engineers in the eight Grid Control Areas who are instructing the loads to be carried by the generating stations. These instructions are based on anticipation, from previous experience, of the minute to minute load trend and this anticipation backed by sophisticated methods of load estimation results in the frequency line remaining very close to 50 c.p.s.

However it is clearly impossible to estimate consumer demand to a second and there will always be moments when generation and load are not matched. Thus continual frequency variations must be expected and it is the responsibility of the Area Control Engineer (and to a lesser extent the National Control Engineer) to ensure that deviations from 50 c.p.s. are halted and reduced as quickly as possible. The present instruction is that when the frequency rises above or falls below 50 c.p.s. the loading engineers in the Grid Control Areas must decrease or increase their generation by 2% of the area generation per $\frac{1}{10}$ c.p.s. deviation. Experience has shown that this percentage gives the optimum frequency control. National Control may also bias the inter-area transfers to correct the frequency.

When sudden loads (due to faults or outage trips) are thrown on the system unexpectedly there is no generation picking up to meet it and the load increase can only be met initially from the stored rotational energy of the system. The resultant fall in speed is sensed by the turbine governors which operate to increase steam supplies until balance is achieved and the frequency stabilises at a level slightly below 50 c.p.s. To cope with such emergency contingencies it is necessary to have generating plant with reserve capacity on the bars operating with free governor action. Such nominal 'spinning reserve' is 600 MW in the day and 280 MW at night. In practice, the reserve exceeds 600 MW between peaks as there is generally insufficient time to shut down plant and restart it.

It has been assessed statistically and proved in practice that if the spinning reserve falls below 200 MW the frequency cannot be satisfactorily controlled and will tend to fall. The provision of spinning reserve is treated as a national matter and its allocation is adjusted as necessary by National Control.

Electric Time.

The C.E.G.B. has no statutory obligation to maintain accurate electric time. However the high standard of frequency control enables this to be done and the National Control Engineer, who is largely responsible for clock control, works to a maximum variation of ± 10 sec. from Greenwich time. (A deviation of the frequency by only 0.2% from 50 c.p.s for one hour will result in a gain or loss of 7 seconds).

Faced with a deviation of electric time from standard the National Control Engineer will bias the transfers between Grid Control Areas (the algebraic sum of which is normally zero) so as to create a deficit or surplus of generation in the country. The former will result in a fall in frequency which would be necessary to correct a fast clock and the latter, vice versa. A standing instruction is issued to the G.C.A.'s that they must make no attempt to correct frequency deviations if these are within 0.1% of 50 c.p.s. (between 49.95 and 50.05 c.p.s.) and in such a direction as to reduce the clock error.

C.E.G.B. outlook.

At first glance it may be thought that as the Board's system develops in size it will become easier to regulate since load variations can be met from a greater reserve of stored energy

and plant capacity. Unfortunately this is not the case since the continual quest for increased efficiency and decreased capital costs is resulting in the system becoming 'lighter' both mechanically and thermally. Larger outputs are being obtained from smaller rotors with a resultant decrease in the mechanical Moment of Inertia. High pressures and temperatures have led to the development of fast circulation P.F. fired boilers, and these have a smaller thermal inertia than the older type stoker fired boilers.

Will automatic frequency control be adopted in the future? Possibly so, but there is no economic justification at present when such good control is maintained manually (the picture may change in future), although it is significant that the growth of specialised electronic equipment requiring fixed standards is promoting an increasing number of enquiries about frequency variation. From the Board's point of view it may be no economic justification will ever exist to install such equipment per se unless it be as part of a completely automated system centrally controlled by a digital computer.

In some parts of the Continent and the U.S.A. where automatic frequency control is used there has been the incentive of power exchanges with neighbouring systems over limited interconnection and (apart from the recent development of High Voltage D.C. transmission) this can only be done by accurate control of frequency if stability is to be maintained. Furthermore these countries often have a proportion of hydro plant which with very low running costs and fast regulating

characteristics is ideally suited for such control. Neither of these factors is applicable to the C.E.G.B.'s system.

1.4 Voltage and Reactive Power Control.

The Area Boards have a statutory obligation to maintain the voltage at the consumers' premises within $\pm 6\%$ of the figure they state to be their standard. Since the Area Boards buy all their supplies from the Generating Board (although they have powers to generate their own) it is necessary to ensure that correct voltage levels are maintained at the points of transfer between the C.E.G.B. and Area Board systems.

Thus satisfactory voltage control must be maintained on the C.E.G.B.'s 132 kV and 275 kV systems, for although a limited measure of voltage control can be given to transformers at a bulk supply point (by tap-changing) this would be totally inadequate if large variations on the primary volts were experienced.

Voltage level and control is analogous to frequency level and control in that it is primarily determined by basic design and the installation of supervisory equipment to correct deviations. The analogy can be taken one step further since while the frequency will only remain constant if the demand and supply of electrical energy (real power) are matched, so voltage levels will only remain constant if the demand for reactive power is matched to its supply. A shortage (or surplus) of reactive power is more localised in its effect on the system than a shortage of real power. The former will simply cause a drop in volts at the particular point whereas the latter will cause a drop in frequency of the entire system.

If the consumers' demand were met by generation nearby there would be little problem attached to control of system volts. Economic considerations however dictate that as far as possible generation is located on coalfields and power transferred electrically to load centres 100 miles or more away. The transmission of both real and reactive power (particularly the latter) gives rise to a voltage drop caused by resistive and inductive losses in the equipment through which the power is flowing.

The extent of this drop has to be controlled and corrected for not only, as mentioned above, have accurate levels to be maintained to the Area Boards but more importantly from the C.E.G.B.'s point of view, if the system volts are allowed to fall at large load centres then widespread instability can result. This aspect of operation known as voltage instability is one of the most important problems facing system control engineers.

Voltage instability is a form of steady state instability.¹ The basic equation for the transfer of power over an overhead line (or for the output of an alternator) is

$$P = \frac{E V \sin \delta}{X}$$

where E is the driving voltage, V the receiving voltage, δ the phase angle between E and V, and X the circuit reactance between E and V. If V gradually falls and P, E and X remain constant, then δ must increase. If δ increases beyond the steady state limit (90° in this simple case) the power transmitted must fall. But this power is being produced by mechanical means and the

steam input to the turbines cannot be reduced immediately. Therefore there is a surplus of power which will accelerate the machines at the sending end of the line and synchronism is lost. This is steady state instability. It could have been caused by a fall in E or increase in X . When however it occurs due to a fall in V it is usually referred to as voltage instability.

As the amount of real and reactive power transmitted over an overhead line increases so the volts at the receiving end fall (because of resistive and inductive losses along the line). It is possible to calculate this fall and if receiving end volts are plotted against real power transmitted, for different lengths of line and different amounts of reactive power transmitted, then a nest of curves which will be sine functions can be drawn. For each line length and power factor of transmitted load there is a value of receiving end volts at which the power transmitted is a maximum. If the volts fall below this figure the power falls; synchronism is lost. On the 275 kV circuits from the Midlands to the Southern parts of this country synchronism would be lost at loads well below the thermal ratings of the lines if the power factor lagged below unity and there was no regulating plant at the receiving end to keep the volts up.

Thus consumer reactive demands should be generated at the load centre and not transmitted. Plant should be available at the receiving end to generate additional power so that the reactive demands of the lines are compensated. Additionally further reserves of reactive generation must be held so that

these can be used in the event of fault or other conditions which could cause abnormally high line loadings and consequent high reactive losses.

The day to day operating policy of National Control states what reactive power reserves must be held by importing Grid Control Areas at their Supergrid points under different loading conditions. These values have been found by Computer study and allow 275 kV to be maintained at these points under onerous fault conditions.

At time of peak loads these reserves can be held largely on older generating plant. Such plant is a heritage of the pre-nationalisation era when in general it was policy to build power stations near load centres. Off peak, however, and increasingly on peak these reserves will be met now by synchronous compensators - which are simply synchronous motors idling on the system with the ability to both absorb or produce reactive power as required (by altering their excitation). Static shunt capacitors to generate reactive power are installed both at 275/132 kV transforming stations where heavy imports are taken and at points close to the load to compensate for the reactive requirements of inductive machinery (by the Area Board or consumer). No series capacitors are installed yet in this country to improve the stability and power carrying capability of long high voltage lines. If generators are run asynchronously, by removing the field, a large degree of MVA absorption occurs because the excitation must be provided by the stator - but this type of operation is not used on the C.E.G.B.'s system although field trials have been carried out to investigate its possibility.

Voltage Levels.

Transmission voltages are defined by two values. One is the nominal network voltage (the design voltage), the other is the upper limit of working voltage. The latter is generally 110% of nominal but may not always be reliable because of atmospheric conditions. The difference between these figures denotes the measure of normal permissive network regulation. On the C.E.G.B.'s system the values are 275 to 300 kV and 132 to 145 kV.

National Control issue a weekly instruction to the Grid Control Areas stipulating the voltage levels to be maintained at their 275 kV substations at different times of the day. This policy is based on anticipated load flows and the effect these will have on voltage levels. The Grid Control Areas in turn are expected to regulate the volts on the 132 kV system so that acceptable voltage levels are held here without appreciable deviation from the stated 275 kV levels. The determination of the voltage profile of the 275 kV system is a complex exercise and it is done by digital computer. At times of heavy load transfer sending end 275 kV system volts will be as high as 295 kV. At times of light load transfer the trend is completely reversed and now the load despatching points in the Midlands will be held down to 275 kV in order to maintain the receiving end points in the Southern Areas below 300 kV.

2. AUTOMATIC CONTROL OF POWER SYSTEMS

2.1 The Need for Automatic Control.

Automation may be described as the extension of man's faculties which integrates all the sensing, thinking, and decision making elements. In this respect something more than mere mechanisation and simple automatic control is implied. An explanation, if not a definition, of automation has been given by Sir Leon Bagrit:²

'Automation is a concept through which a machine system is caused to operate with maximum efficiency by means of adequate measurement, observation and control of its behaviour.'

There are three major elements, which Sir Leon has termed the 3 'c's: Communication; Computation; Control. It is implicit that there is feedback round the system so that optimisation in one sense or another may be achieved without human intervention.

In any organisation as large and as complex as an existing electricity supply undertaking (e.g. that of the C.E.G.B.), automation can come only by a process of evolution. Over a period of years it must be compatible with existing methods of manual operation and control - such as those described in the previous Section and by Gunning.³ Interest in automatic control has been shown in America, Australia, Belgium, Canada, France, U.K., Germany, Japan, Russia and Sweden, as well as other industrially advanced countries. In many of these it is now an established and essential feature of system operation, and in

others it is in an advanced experimental stage. The methods adopted differ according to the particular technical and operational problems that have to be solved and are more usually of an ad hoc nature suited to individual plant and local system conditions. Unfortunately, in many of these cases, detailed quantitative data is hard to come by. Much of the technical literature is essentially only qualitative.

Although most of the material discussed here is concerned with the special features and problems of applying automatic control to the C.E.G.B.'s system, with due regard to future planned expansion, the work is relevant to the problems and needs of large power systems everywhere. As described in Section 1 and elsewhere,⁴ the present pattern of generation and transmission involves control at three main levels:

- i. The National Control Centre in London exercises general supervision over
- ii. Eight Grid Control Centres, each dealing with a specific area of England and Wales. The Grid Control Centres give instructions to the
- iii. Generating Stations and switching centres.

Such a three-level hierarchy of control would indeed be appropriate to any scheme of power system operation and not only to that developed by the C.E.G.B.

The need for computer aids and automatic control exists at all three levels and arises from the growing complexity of the system and its plant. Human operators are no longer able, without the aid of computers, to take account of all the

information available to them, nor can they act sufficiently quickly and accurately in emergencies. Calculations of system security, system stability and optimisation of line flows are becoming too complex to be undertaken manually by other than very approximate methods and there is a need for using refined computer techniques in load prediction. These calculations are usually performed 'off-line' at present and hence do not strictly qualify as automation.

In the case of security assessment, a new special purpose computer being installed by the C.E.G.B. at National Control incorporates direct input of information via telemetry links from appropriate measuring points on the system. Output information shows which lines are in danger of being overloaded, and it is left to the operator to take the decision as to the action required. This he does on the basis of his experience and his knowledge of plant availability, predicted loads, etc. It is possible, in principle, for a computer to do much the same thing, and the piece of equipment now known as the 275 kV security assessor might, in such circumstance, become a component of a fully automated system. However, computers are not yet in use on-line in control centres, and where installed for plant control the usual procedure is to revert to manual operation in the event of any unusual circumstance. Nevertheless, the above example of security assessment illustrates an important point, namely that any computer aided control system now being developed should be sufficiently flexible to be compatible with automation if the transition is to proceed smoothly and without wholesale obsolescence of equipment.

The daily routine at Grid Control Centres includes the following tasks:

- i. Load prediction
- ii. Decision on what plant should run (plant ordering)
- iii. The allocation of load to running plant (plant loading)
- iv. Checking network security at all times;

and one can foresee an automated system in which they are all performed by computer. The major economy which should result is in optimum plant ordering, for, once this has been done, there remains little flexibility in the loading, which results from short-term prediction.

In power systems in general the control problem is to match total system generation to total system demand and to obtain the requisite total from available system sources with such allocation among them as fulfils system operating criteria.⁵

The important operating criteria are security and economy combined at all times with the obligation to maintain statutory frequency and voltage within the prescribed limits.

These criteria imply the control of available power stations and interconnection networks to meet the existing and anticipated demand for power, the governing of the steam supply to the turbines to maintain correct frequency and suitable sharing of load, the regulating of the excitation of alternators to maintain correct voltages and suitable sharing of reactive voltamperes, the continuous assessment and safeguarding of the ability of the system to withstand faults, and the systematic programming

of plant loadings to achieve maximum economy of operation. An idea of some of the typical operating factors and the way in which they interact and conflict is gained from Fig. 1 which summarises the situation at National and Area control levels.

Ultimately, whatever system of overall control is developed, a loading schedule reaches the power stations, and a certain demand is made of each generating unit, which may be termed the programmed power. It is envisaged that completely automatic system control may be developed in the U.K. by about 1970, and that each turbo-alternator set will then receive a sequence of programmed power demands at intervals of the order of 1 to 5 minutes. These instructions would be carried by a data transmission system which is self-checking and based on binary coded pulses.

The final stage of the system control problem consists of imposing the desired loading on the generating plant by automatically adjusting the set points and gains of the governing and regulating equipment. Any proposed scheme of automatic control must possess inherently the ability to preserve stability and security at all times and especially in the event of sudden faults and unexpected disturbances.

2.2 Power Station Control Requirements.

Automation in Power Stations has already progressed further than at other levels of the system. It is now quite practicable for a small hydro-electric set or diesel or gas-turbine generator to be started up, synchronised and brought on load under automatic control from some remote point. The prime reason for so doing is that the stations may be left unattended.

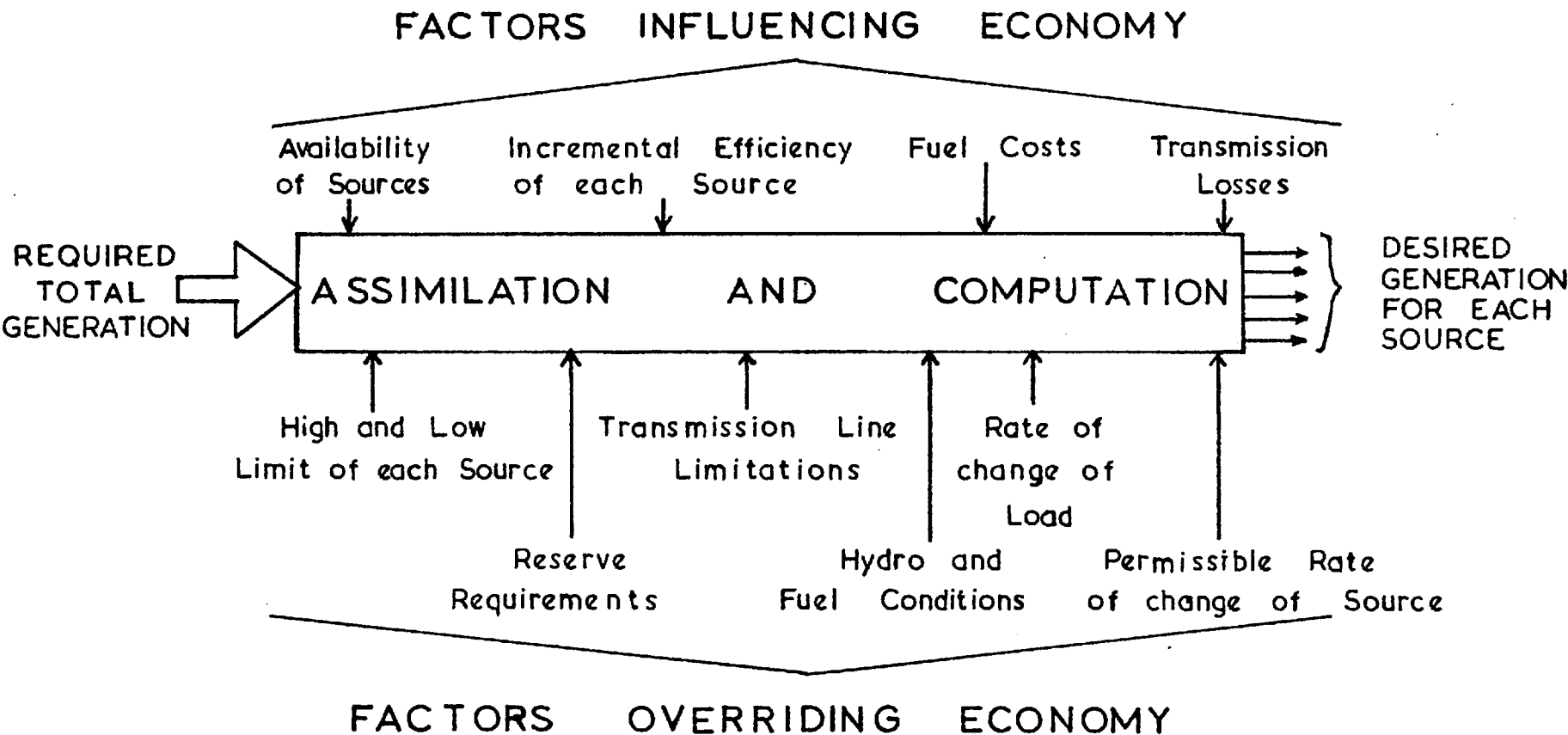


FIG. 1. THE CONTROL PROBLEM

There is no question of operating large thermal power stations unmanned. In these the need for automation arises from the complexity of the plant and the large amount of data to be taken into account in running it efficiently. At Northfleet, for example, there is a comprehensive Panellit system of automatic boiler/turbine instrumentation enabling each unit to be run up and operated from a control desk. At West Thurrock, rapid start up under computer control is expected to result in more economic operation. The programme to be followed by the computer will depend on the initial plant conditions. Some 200-300 analogue inputs and about 1,000 yes/no signals require to be monitored, and each stage of the running-up procedure is initiated just as quickly as plant-design restrictions permit.

Once on load, the basic function of the boiler control scheme is to maintain the desired steam output pressure and temperature as accurately as possible in the face of all disturbances, while the boiler itself is operated safely and with maximum efficiency. The greatest advantage of the automatic control system is its correct and speedy reaction to unanticipated changes in demand. Given a steady steam supply at constant temperature and pressure, control can then be transferred to the governor mechanism which controls the admission of steam to the turbine, thus building up load to meet and subsequently follow the programmed power signals. The next section of this chapter discusses the design requirements of the feedback loops applied to turbo-alternator sets to enable them to follow automatically the programmed power signals.

The design of the Power Station control system must be such that optimum speed of response and stability exists for all types of generating units: e.g. whether incorporating reheat or non-reheat steam turbines, or of low or high inertia constant; and for pulsed or continuous speeder motor control. Since each set is an integral part of the national Grid System, its performance must be such that the stability and frequency response of the System is satisfactory in response to sudden load changes under maximum and minimum plant conditions and different proportions of controlled sets on the System.

3. A PROPOSED CONTROL SYSTEM FOR AUTOMATIC PLANT LOADING

3.1 General Principles.

In the first place it will be advantageous to summarise the part played by the primary regulation i.e. the mechanical governor gear, in the present system of manual dispatching of generation. There are two essential factors:

i. At all times the load is determined by the consumers and must be exactly balanced by generation. Consequently the total output of electrical energy from the generators must exactly balance the load, including system losses and station auxiliaries, in the steady state.

It follows that any permanent change in load can only be met by a corresponding change in energy input to the turbines. Thus a small increase of load first results in a fall of speed, as the change is initially met from the stored kinetic energy of the rotating machines. The speed change in turn causes an increase in energy input to the turbines, through the operation of the governor gear, to re-establish a balance between generation and load. When balance has been reached there will be a resultant change in speed proportional to the load change (known as the regulation). Thus a load change causes a permanent change in the speed of the turbines and consequently in system frequency. Random changes of load occur continuously and are reflected in continuous random changes in system frequency. The net effect of such load changes over a period of time may be predominantly of one sense (i.e. a net increase or decrease), and the resultant change in frequency

may be sufficiently large to call for manual correction. In this event, one or more stations will be instructed to increase or decrease load according to the sense of the frequency error and this leads to the second important factor:

ii. Suppose an increase of generation is called for. As this adjustment is carried out the frequency will rise, the rotational stored energy will increase, and as the frequency rises the remaining generators will shed load by governor action resulting, at the end of the adjustment, in the same dispatched load as before but at a higher frequency. This factor is fundamental to all control, whether manual or automatic.

It should be noted that the sequence of events described in (ii) is strictly true only if the load is wholly resistive, since the component of load consisting of rotating machinery will be somewhat frequency sensitive, but the effect can be neglected at this stage as the rate of change of load with frequency is always very small compared with the rate of change of generation due to governor action.

From the above discussion it is clear that load dispatching and frequency control requirements eventually demand the adjustment of the steam input to the regulating turbo-alternator sets. In order to avoid expensive modification to the turbine control equipment, it is desirable that the control signals operate through the medium of the existing governor gear, possibly by feeding controlling pulses into the speeder motors. However, in Sweden the mechanical governors have been largely replaced by electrical types in order to achieve better

frequency control, and such a governor is discussed by Moran,⁶ who also surveys some British developments in mechanical turbine regulators.

3.2 The Control Loops.

The proposed control system is composed of two fundamental feedback loops which will be termed respectively:

- i. The Power Feedback Loop; enabling a set to maintain its
programmed load
- ii. The Frequency Control Loop; enabling compensating corrections
to be made for errors in system
frequency.

These two loops must be considered in conjunction with the governor loop which is an integral part of existing governor mechanisms. A block diagram showing these loops in relation to the overall system is shown in Fig. 2.

It is now appropriate to summarise the design requirements of these loops. Most of the observations which follow in the next three sections, (3.3 to 3.5), are derived directly from the author's knowledge of the proposed C.E.G.B. system control project, and from information kindly supplied by C.E.G.B. workers.

3.3 The Power Feedback Loop.

A power feedback loop is necessary in order that each generator can maintain its programmed load. It is hardly possible to maintain sufficiently accurate power output by just fixing the main throttle valve at a predetermined position corresponding to that output since, besides the difficulty in determining this position due to a non-linear relationship

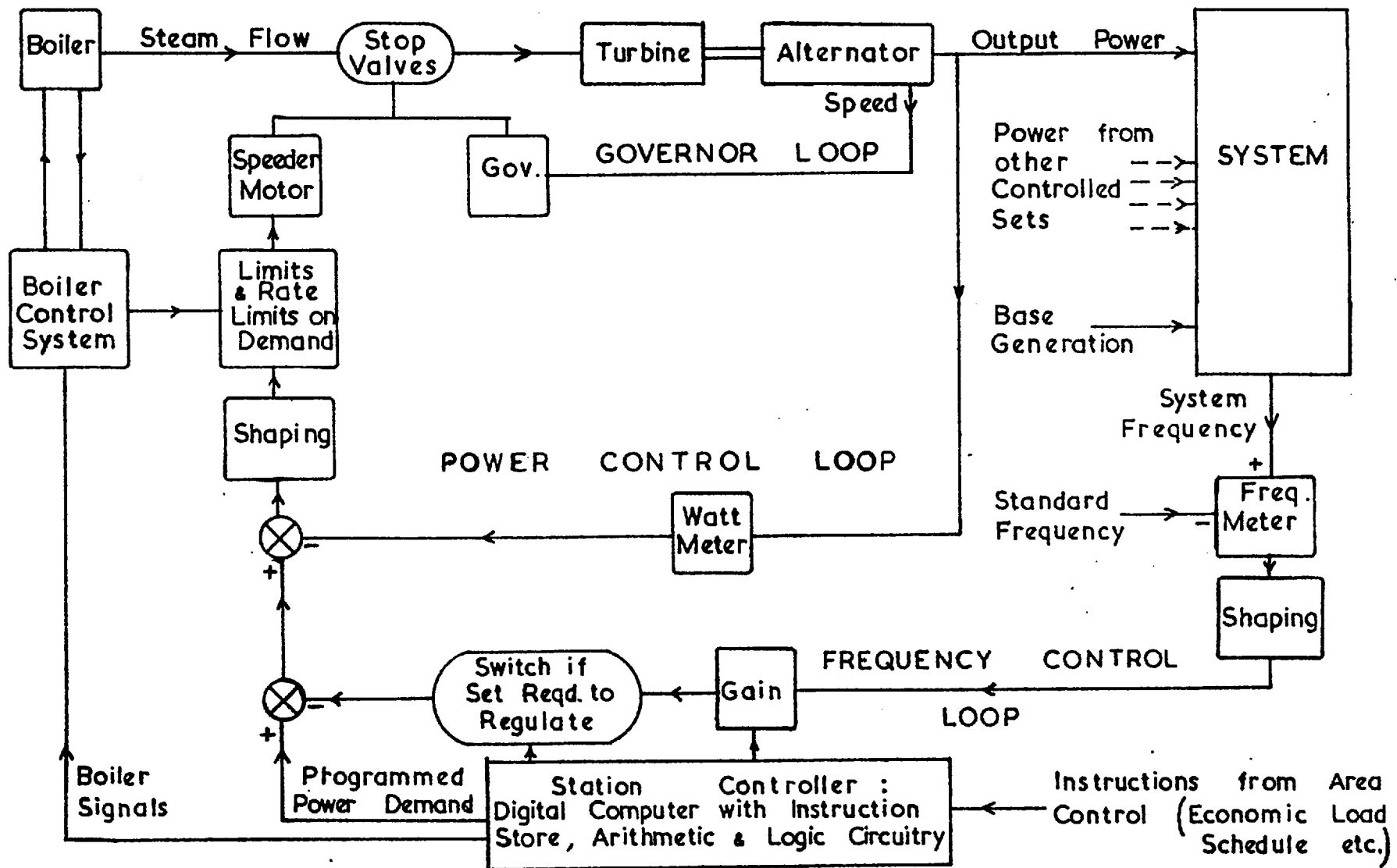


FIG. 2. PROPOSED CONTROL SYSTEM

between power output and valve position, the power output will vary considerably for a fixed valve position due to variation in steam conditions, machine power factor, machine voltage, etc.

The equipment for receiving loading instructions through data transmission links from the Grid Control Centres may be termed the 'Station Controller' - see Fig. 2. These instructions would probably be received at a basic rate of one per half-hour, the distribution of load having been economically optimised. In addition, it is probable that intermediate instructions would be transmitted every few minutes, involving the latest estimate of load, obtained by an extrapolation method. The station controller would include a digital store for these instructions and simple computing circuitry to produce a continuous value of demanded power for each generator.

The logical manner in which to complete the transfer of power demand to a generator is to measure its output power and employ the power feedback loop to enable a power error function to be calculated which can actuate the speeder-motor when it is non-zero. This gives accurate loading of power demands on each generator. It also has the effect of overriding the governor action, for if the governor tries to close the steam valve, thus decreasing the generator power output, the power feedback loop opens it again via the speeder-motor. Thus if the proposed power feedback loops are applied, the present method of frequency control by governor action cannot be used. Consequently, the provision of an additional frequency control loop becomes imperative.

Type of Device	Possible Manufacturer or Designer	Estimated Accuracy	Estimated Cost	Approx. Time Const. (T_7)	Output	Remarks
Pure Electronic Multiplier	PACE Chatterton etc.	Depending on cost 1%	£500+	As required	As required	Needs auxiliary supply
Hall Effect Multiplier	AEI Blackburn	2%	£20+	As required	100 mW max.	Needs output amplifier
Servo Type Multiplier	Solartron	cost 1%	£200+	0.1 sec	As required	Needs aux. supply and maintenance
Thermoverter	Bristol	1%	£200	0.2 sec	100 mW max.	Needs output amplifier
Integrating Wattmeter with Feedback loop	E.E. Co.	Probably 1%	£200	Better than 0.1	As required	Needs auxiliary supply
Integrating Wattmeter with 66 $\frac{2}{3}$ RPM contacts	Ferranti	1%	£10	5 secs	ABC contacts	
Integrating Wattmeter with 1200 RPM output		1%	£100	0.5 sec	ABC contacts	Needs auxiliary supply
I cos ϕ rectifier bridge		5%	£10	As required	As required	Does not measure true watts
Indicating Wattmeter with variable inductance attachment	Brown-Boveri	Probably 2%	£50	0.5 sec	Variable Frequency	Needs auxiliary supply
Indicating Wattmeter with digitising disc	G.E.C.	Depends on design	£100	0.5 sec	Digital	Needs auxiliary supply

TABLE 1

TYPES OF POWER SENSING DEVICE (C.E.G.B. Sources)

The necessary features of the power feedback loop are:

i. Accuracy.

High accuracy in the power measuring equipment is unnecessary as discrepancies between programmed power and actual power will be absorbed by the frequency control loop and by the intermediate loading instructions from the Grid Control computer. A figure of 2% maximum error for the power sensing device would seem to be satisfactory and easily attainable with the devices currently on the market - see Table 1. Table 1 also includes estimated costs and approximate time constants for comparison.

ii. Response time.

The overall time constant of a steam turbo-alternator set varies between about 1 sec. for a non-reheat turbine to over 11 secs. for a reheat set, thus any action taken to increase the load will not result in appreciable load change for at least one second.

If it is required to check the fall of system frequency in the event of loss of a large set, it may be necessary to include a differential term in the loop. The actual speed of response and shaping required could be evaluated from a simulation of the proposed system.

iii. Emergency conditions.

A worst emergency condition is when a large set trips out when the system load is a minimum. The electrical load formerly carried by the large set is suddenly transferred to other machines whose outputs will then exceed the programmed levels for that instant. The power feedback loop will then

tend to cause valve operation to worsen the situation and so promote the rate of fall of system frequency. The simplest expedient would be to incorporate a sensing device for detecting the emergency condition and breaking the power feedback loop to revert to governor control, or to do this if the frequency error exceeded a specified value. Alternatively, a fast enough acting frequency control loop might be able to cope with emergencies successfully.

3.4 The Frequency Control Loop.

The purpose of the frequency control loop is to compare the system frequency with a standard frequency and apply a correction to the programmed power signal to compensate for frequency error.

The frequency control loop can incorporate proportional, integral and differential terms and these will now be considered under separate headings:

Proportional Term.

It is appropriate first to list the factors which determine the accuracy to which the frequency needs to be controlled:-

- i. There is a statutory requirement (in Britain) to maintain the system frequency within ± 0.5 cycles/sec. of 50 c.p.s.
- ii. Present policy of the C.E.G.B. is that the frequency should be kept within ± 0.2 cycles/sec. of 50 c.p.s.
- iii. The economic cost of maintaining frequency within a given limit of error requires assessment.
- iv. The economic cost of allowing frequency to deviate from 50 c.p.s. should also be assessed, and compared with (iii).

Of these factors, (i) fixes an absolute limit of error for the design of the control system, while the limit of ± 0.2 cycles/sec. in (ii) will be taken as the working value since this has been laid down by the C.E.G.B. as an aid to certain industrial consumers. The economic cost of maintaining frequency within a given limit, (iii), depends on the cost of installing the extra control equipment required and on the extra running cost involved in keeping frequency constant. This extra cost arises from possibly having to run plant out of merit order and the increased running cost of individual plant due to unsteady operating conditions in trying to make generation follow load closely.

The extra cost of allowing frequency to deviate from 50 c.p.s., (iv), is because station auxiliaries, optimised to run at 50 c.p.s., become less efficient at some other frequency.

The spare plant which must be carried by the system to maintain system load in the event of sudden outage of largest set need only be a small percentage of the total generation, and would be selected with due regard to economic operation, or merit order, in general being the sets with the ^{next} highest generation costs. Thus if the 'spinning reserve' generators were running at 90% full load, 10% load is available for an emergency. The figure of 10% is typical of the estimated safe sudden load increase which can be achieved by modern plant. These needs for economy and safety in the use of spare plant capacity account for the regulation switch and gain factor incorporated in the frequency control loop of Fig. 2, operated by the station controller.

Now let $D\%$ = inverse of proportional frequency control loop gain, or speed droop characteristic, defined as the: percentage change in system frequency required for full-load change in power output. Then for fully loading all spare plant due to sudden loss of generation (e.g. outage of a large 550 MW set), the frequency fall of the system equals the proportion by which spare plant generation is increased $(10\%) \times \frac{D}{100}$.
i.e. for 0.2 c.p.s. limit of frequency fall,

$$\% \text{ frequency change} = \frac{0.2}{50} \times 100 = 10 \times \frac{D}{100}, \text{ or } \underline{D = 4\%}.$$

Thus 4% is the maximum speed droop maintaining the system frequency within ± 0.2 c.p.s. A better value of 2% speed droop would maintain the system frequency within ± 0.1 c.p.s under the condition of loss of generation of largest set and could be used in future design studies, although the actual value would vary according to the various machines' ability to accept sudden load increases. It may be noted that the system frequency stability in the event of loss of generation equivalent to the spare plant running at that time is independent of the total system load.

The above evaluation of a limiting value of $D\%$ assumes that the frequency control is fast acting enough to prevent the system swinging transiently outside its steady state value. It is also assumed that the sets on full load take no regulating action and that the frequency dependence of the load can be neglected, whereas both of these would in fact tend to improve frequency stability.

The following specifications can be made for the proportional frequency control loop term:

- i. Set on full-load: no load variation for frequency variations 49.8-50.2 c.p.s. 4% droop outside this region.
- ii. Set not on full-load: variable speed droop in range 1% to 5% to be present according to set's ability to accept sudden load change.

Thus only the sets not on full-load assist in system frequency control unless the frequency due to special circumstances is forced outside the specified limits of 49.8-50.2 c.p.s.

Integral Term.

In acting on a frequency error, the proportional control does not reduce this error completely to zero, but ends up with a resultant smaller error which is inversely proportional to the feedback gain of the loop. The resultant error from an individual disturbance must be kept as small as possible in order that errors from a series of disturbances do not accumulate and exceed the permissible limit. In consequence, it is necessary to schedule load variation from the national or grid control centres to correct for steady state errors. The required generation change ΔP has to be estimated from the steady state frequency error Δf , using the Power/Frequency Characteristic appropriate to the particular power system. The Characteristic for the British system is discussed in a paper by Davies, Moran and Bird⁷ which gives the steady state relation between frequency change Δf and change ΔP in load or generation as

$$\Delta P + K. \Delta f = 0$$

where K is the Power/Frequency Characteristic of the system, depending on governing and load conditions, which is constant for each set of plant and load conditions. The formula deduced for K from the results of tripping tests is

$$K = 0.80 P_T - 0.60 P_L$$

where P_T = Turbine plant capacity on busbars

$$P_L = \text{Load}.$$

The present method of manual control (in the U.K.) consists of continuously revising estimates of load, using these relations, and sending out instructions sufficiently quickly to stop the frequency drifting outside the limits. The method could be incorporated in the dispatching process of programmed power. However, this method is unsatisfactory in the following respects:

- i. The equation for K is of uncertain accuracy and highly empirical.
- ii. Data transmission errors may occur in trying to make scheduled power equal to generated power, both in outgoing and incoming information.
- iii. A quantization error will always exist due to the finite number of pulses used to transmit information. This could be reduced by sending more pulses.
- iv. The system is sensitive to breakdowns in any part of it.
- v. Sets may not be able to take up scheduled generation with complete accuracy.

These difficulties could be overcome, and the need for short-term load prediction eliminated, by making use of an integral term in the frequency control loop. The frequency errors existing at all instants would be integrated with respect to time and the integral used as the regulating instruction.

The disadvantage of including an integral term in the frequency control loops, besides the additional expense, is the problem of load slip between different machines due to integrator drift. This difficulty can be overcome by arranging that integrators only work on sets not on full load and are reset when sets reach full load or are taken off load completely. Hence no set would then run on integrator control for more than a day since the daily load pattern prevents any set being used as spare during both maximum and minimum load conditions. Thus the generator load slip due to integrator drift need never reach an excessive value.

Differential Term.

Some improvement in the speed of system response to sudden large load changes might be achieved by including a rate of change of frequency term. The probable improvement in response would be marginal, however, since the system deceleration under conditions of tripping of large sets is limited by the combined machine inertias, and records show these to be of the same order as the accelerations present in random system frequency fluctuations. To maintain control stability it would thus be necessary to include lags in the differential term - thus destroying its function of improving the rate of machine response to large system disturbances.

In various countries the control schemes used differ in the combinations of proportional, derivative and integral action used and in the means employed to implement the control instructions. In France, for example, the use of pure integral control is known as load-phase regulation, load-phase-energy regulation or load-energy regulation according to whether the integrated quantity is frequency error, frequency error plus transfer error or simply transfer error. Note that 'load' here refers to the output from the regulating sets. Again, in the United States some systems employ proportional-plus-derivative control⁸, based on frequency error and transfer error, whilst others use pure integral, integral-plus-proportional or fringe control⁹.

The merits of using integral action are well appreciated so that its incorporation in control schemes is becoming almost universal. An interesting feature of some American systems is that the automatic control is used, not only to trim small load fluctuations, but also to control continuously the main changes of generation required to meet the daily load cycle¹⁰.

3.5 Physical Form of Control Devices.

It is now appropriate to include a few notes on some of the control devices which are basic to any proposed system of automatic governing and regulating of power systems.

i. Meters for the Frequency Control Loops.

The frequency error will be translated by the frequency control loop into a power demand which must be applied to the turbine steam valves. All that is necessary is to add this demand to the programmed power signal on the sets which are to

regulate at any given time, as shown in Fig. 2, so that a total power demand is injected into the power feedback loop.

It is possible to use either a central frequency meter and transmit a frequency error signal to all power-stations, or each station can have its own frequency meter. The former alternative would require continuous transmission of a signal and hence a transmission system of its own. The second scheme needs a larger number of meters but would probably be cheaper. There is moreover a gain in security with the second scheme. If the system splits in two, the frequencies in the two parts will diverge sharply. The second scheme provides a frequency error for each part of the system. Hence the provision of separate frequency meters would be preferable. A suitably accurate meter is the British precision frequency meter described by Moran⁶. This has an accuracy of ± 0.001 c.p.s. and also delivers the integral of frequency error in a drift-free manner as a shaft position.

The type of loop shaping and the value of gain would have to be varied for different sets. This is because different sets would be chosen to regulate at different times and each has its own characteristic, which varies with different operating conditions. Thus the composition and performance of the loop is continuously changing. However, in all circumstances, the loop must be known to be stable. The simplest technique might be to design special shaping for each set so that each set with shaping forms a unit with the same performance within known limits as any other.

This would result in degradation of the performance of faster sets by shaping to be similar to that of slower sets. The latter have a natural frequency of the order of 1 c.p.s. - see Table 2, (in Chapter 2). This figure forms an upper bound to the overall speed of operation, but there are two reasons why the overall loop might be slower: concerned with obtaining a uniform predictable performance:

- a. As the working condition of each set varies, so will its transfer function (power output/power input), and this change will be most pronounced in the region of the natural frequency.
- b. The transfer functions accurate up to the natural frequency could be quite complicated, whereas if only a slow frequency range were of interest a simple lag approximation might suffice.

For both these reasons the design of a satisfactory loop to operate over a lower frequency range which avoids machine natural frequencies (say 0-0.2 c.p.s.) would be easier.

ii. Speeder Motor Control.

The 'speeder motor' is traditionally so called because it is directly linked to the turbine steam valve, in addition to the governor, and is used to admit steam initially to run the turbo-alternator set up to synchronous speed. Subsequently, the speeder motor is operated to admit more or less steam to advance or retard the rotor angle and control loading.

Various methods of speeder motor control which might be suitable when applying automatic control to existing machines are as follows:

- a. Continuous control using existing speeder motor.
- b. Continuous control using a velodyne system either with the existing speeder motor or new special velodyne motor.
- c. Pulsed control of speeder motor using
 - (a) Pulse frequency proportional to error
 - (b) Pulse width proportional to error
 - (c) Pulse height proportional to error.

Of these methods, a., c(b) and c(c) are unsuitable because of the very high loop gain needed to keep the control error represented by speeder motor stiction down to a reasonable value. This high loop gain needed would make these systems too unstable. Only methods b. and c(a) are worthy of further consideration:

Velodyne System (method b.)

It may be possible, with this system, to use the existing speeder motor in some cases. A tacho generator would be connected to the speeder motor shaft. The armature is continuously supplied and the field of the motor is driven via a high gain amplifier. Thus the motor is rapidly accelerated until its speed, represented by the T.G. voltage, matches the applied voltage.

Special precautions would be needed to guard against amplifier failure driving the motor against its stop.

Pulsed Control (method c(a))

In this system the pulse frequency is proportional to error signal. The pulses are made of constant voltage and duration, their size being determined by the minimum pulse size required for reliable and consistent speeder motor operation and the

control accuracy needed. One method of generating the pulses is to integrate the error signal and pulse the speeder motor when the integrator reaches a certain value. The integrator would be made to reset when the speeder motor is pulsed.

This scheme has the advantage that no alteration need be made to the existing speeder motor arrangement.

4. TECHNIQUES OF ANALYSIS

Having so far in this chapter discussed the general performance requirements of a scheme for automatic control of plant loading and system frequency, this section will proceed to survey the techniques available to facilitate the design of specific schemes and to enable their relative suitability to be assessed.

4.1 Network Analysers.

Network analysers have proved to be useful tools for the solution of power system problems. They represent transmission systems by the interconnection of the equivalent circuits of their component parts - all voltages, currents and impedances being converted to values which are proportional to the actual values. The analysers may work on d.c. or a.c., but in the former there is normally no adjustment of individual generator and motor voltages and nothing to correspond to phase differences of voltages. Nevertheless d.c. analysers are often suitable for fault studies arising from short circuits. The a.c. analyser is the most commonly used for load studies and for the study of the effects of changes in a system. The first modern type of a.c. analyser was built by the General Electric Co. and M.I.T. in 1929 and there was rapid evolution thereafter. Fifty analysers in use in North America, together with technical data about each, are listed by Gross.¹¹

In analysers, the representation is steady-state so that transient investigations and the plotting of rotor swing curves must be carried out using step-by-step processes. Only the dynamic equation of motion for each rotor in the system is normally solved and electrical representation of machines is simplified. As a design technique for stability and control studies, the basic analyser procedure is tedious, chiefly on account of the volume of associated calculations. Only with the associated use of a digital computer can such studies be completed in a reasonable time.

A good account of the uses and capabilities of network analysers is given by Stevenson¹² (Chapter 8, p. 171-178). A comparative discussion of the use of analysers, computers and model systems has been recently set out by Dineley and Humpage.¹³

4.2 Micro-systems.

The modelling of a power system, using specially designed micromachines and micronetworks, is a research and design technique which has not so far been as widely employed in Britain as elsewhere. Important installations have been described in France, by Robert¹⁴, and in Russia by Venikov¹⁵ and Kostenko¹⁶. In Britain some of the work carried out with Micro-machines at Imperial College has been described by Adkins¹⁷.

Micro systems are energised from a 3-phase power supply and normally operate in association with an a.c. busbar, assumed 'infinite' for study purposes. The technique is the most realistic, but uses expensive equipment and consumes a large amount of power. However, it is the best approach to advanced

machine studies which require detailed representation of a single machine. Some studies where transient electrical effects are significant, for example pole-slipping, asynchronous running and resynchronisation, are difficult to handle by most computer techniques because of the continuous and protracted nature of the changing conditions. Since the micromachine is a continuously running model, it lends itself readily to investigations of this sort.

For multi-machine system studies the problem still remains of modelling adequately the steam or hydro conditions, turbine and governor characteristics, automatic voltage regulators, transmission lines and all constraining factors. The inflexibility of any particular micro-machine can be significant if a range of per-unit parameters for different types of machine in a system must be considered. Relevant variable parameters would be power output, inertia constant, reactance, field time constant, etc. Micro-systems have the disadvantage that they themselves suffer from the same difficulties encountered in operating an actual system.

4.3 Digital Computers.

The mathematical methods developed for studies of load flow and transient stability are mostly based on the use of the network analyser, and it is in this connection that the speed of computation attainable by modern digital computers was first appreciated. Programmes can enable the network load flow itself to be computed at each stage of a step-by-step stability study, so that it becomes possible to dispense with the network analyser.

Unparalleled numerical accuracy is inherently achieved by digital computers once a correct programme has been formulated. The computer is able to make selections from several possibilities and hence optimise designs.

But in view of the fundamental requirement to maintain a physical understanding of the power system, when changes to the basic system are being made, it is necessary to carry out preliminary studies on a network analyser or analogue computer before the problem can be intelligently formulated for digital computation.

The digital approach can, in itself, hardly be appropriate to basic investigations. An analogue, or simulator, approach is more suitable, because the logical steps in the solution need not be stated at the outset. A passage from an article by Adkins¹⁸ is very relevant:

'The role of the model is to help formulate the equations for the process under investigation, since although the behaviour of the equipment must still be known, the physical model can be brought into use as soon as this is clear while a mathematical model requires much more detailed knowledge.'

Two further comments on the digital computer technique for the type of power system analysis discussed in this Thesis are:

- i. The programmes formulating the mathematical representation of all the elements of the system, and formulating the solution procedure, will be numerous and lengthy, containing many sub-routines and loops. The problem of detecting and eliminating all errors is formidable. It would in all cases be necessary to ascertain that a computer output indicative of instability in a particular case,

for example, was in fact indicative of physical instability to be expected in the power system, and not merely a result of mathematical instability arising from an unsuitable solution process or undetected programming error.

Some reliable and comprehensive method for proving the correctness of a programme would be an absolute necessity. Check conditions and results in the computer study would have to be compared with similar conditions and results in the real power system, or when this is impracticable, in a power system model. Thus we establish the need for a model, since it is seldom possible to experiment arbitrarily with an actual power system, while the problem under study may, in any case, involve a modified or developed configuration and new, unproven, machines and devices.

ii. The important and justifiable claim that the degree of accuracy inherent in the digital method cannot be approached by any other technique should be discussed in the present context.

Although the electrical parameters of machines, transformers, transmission lines, etc. are sometimes known with fair certainty, the same cannot be said for the corresponding mechanical and thermodynamic data. There is, for example, a general ignorance of the precise transient behaviour of boilers, valve mechanisms, steam turbines, governors and automatic voltage regulators. Manufacturers usually have a good qualitative idea of the performance of their products, which they have often developed empirically, but they often have very little detailed quantitative knowledge. This situation has evolved partly from the practice of merely ensuring, when commissioning tests are done, that the

plant meets the overall working specifications within the required efficiency margin.

At best, data on time delays, dead-bands, non-linearities, etc. is usually correct to 10%, but sometimes even the order of magnitude of a parameter is uncertain. Thus, until more comprehensively instrumented and controlled tests are carried out for the purpose of elucidating plant dynamic performance, the use of the digital computer technique for system control studies would appear to be too sophisticated, although it will undoubtedly become more relevant to enlightened technological progress.

4.4 Analogue Computers.

Analogue computers have become well established as computing aids in a wide variety of scientific problems. The equations which describe many physical systems are not amenable to classical methods of analysis due to inherent non-linearities. Others may be difficult and tedious to solve because of general complexity, or because solutions of the same equations are required with many values of physical constants. This is particularly so, for example, in optimising control system design, where insufficient initial information exists to enable the constants to be chosen directly. In such cases as this, it is desirable to set up a model, or analogue, of the system to be studied. These generalised comments are directly applicable to the discussion of suitable techniques for control analysis in power systems, which incorporate a wide variety of physical plant.

An electronic analogue computer is a system model in which the physical variables are represented as voltage variations, mathematical operations on these variables being performed using direct-coupled high gain feedback amplifiers, whilst the coefficients (physical constants) multiplying the variables are set up on continuously variable attenuators (potentiometers). The most suitable applications for these computers are those in which the independent variable is time, both transient and steady state solutions being readily obtainable from the analogue. Advantages of the analogue computer technique are that programming is much simpler than in the digital case and that a closer appreciation of the physics of the problem is gained rather than a preoccupation with the mathematics. Overall errors less than 1% can be achieved on modern analogue computers, which is an order of accuracy adequate for practically all design studies concerned with power-system dynamics.

Transient stability problems in power systems are especially amenable to d.c. electronic analogue computation, and many recent papers on these studies by Aldred, Miles, Shackshaft et al. have appeared.^{19,20,21,53}

An analogue computer study of the control scheme of Fig. 2 applied to a single turbo-alternator was developed from linear transfer functions, and forms the subject of Chapter 2.

4.5 Hybrid Simulators.

Several techniques have been described for obtaining automatic plots of rotor swing curves in transient stability studies using a network analyser in which the generator units are driven dynamically

by some kind of servo-mechanism. Early papers are those of Kaneff, Adamson et al.^{22,23} The development promotes the versatility of the network analyser for dynamic investigations and eliminates the tedium of numerical calculation mentioned in 3.1.

It is a natural sequel to prefix an analogue computer to the servo-mechanisms, or conversion units, which supply the network analyser so that prime-mover dynamics, control device characteristics, etc. can be readily simulated also. The use in this way of a d.c. analogue computer combined with an a.c. network analyser for transient stability studies has been recently described by Dineley.²⁴ Such combined systems can be termed hybrid simulators, and the potential exists for achieving high flexibility.

The design and use of a suitable hybrid simulator for automatic governing and regulating studies in multi-machine systems forms the subject of Chapters 3 and 4.

5. CLASSICAL THEORY OF THE ELECTRICAL MACHINES

Any study of power system performance will inevitably centre on the electro-dynamic behaviour of the generators and motors in the system. The history and development of the theory of the electrical behaviour of the machines is long and still highly controversial. This section contains brief notes on modern general machine theory and then an account of the assumptions and limitations.

5.1 Notes on General Machine Theory.

Of the many papers which have been published on the theory of synchronous machines, two of the most important classical works are those of Park.^{25,26} A reference frame can be chosen, and a transformation applied, which converts the general machine equations into a form suitable for simulation by an analogue computer.^{19,20,21,24} The equations describing synchronous machines, and which are applicable to all modes of operation, including derivation and transformations, are presented in detail by Adkins.²⁷

The general equations express field and terminal voltages in terms of circuit currents as products with R , L , M , $\frac{d}{dt}$ and $\mathcal{V}$ coefficients, where $\mathcal{V}$ is the machine speed. The method of application of the theory is by the sequence:-

current $\longrightarrow$ m.m.f. $\longrightarrow$ flux $\longrightarrow$ voltage; thus the procedure is:

- i. Work out the m.m.f. which would be created by each current in turn, in each winding separately.
- ii. Sum m.m.f.'s from all currents, work out the resultant flux, hence the induced e.m.f. for each coil.

iii. Superimpose the current-voltage relation for each coil.

In the per-unit notation it is supposed that:-

Unit current creates unit m.m.f.

Unit m.m.f. establishes unit flux, ψ .

Unit $\frac{d\psi}{dt}$ generates unit e.m.f.

5.2 Assumptions and Limitations of the Idealised Theories.

The general theory arises in the first instance from the following assumptions:

- i. Saturation is neglected (assume that there is a linear relation between m.m.f. and flux on any axis).
- ii. Product terms are ignored (to linearise the equations).
- iii. Harmonics are assumed to be zero (none are generated by the field).
- iv. Flux distributions are sinusoidal.

Practical considerations involve the following points:

- i. Sinusoidal m.m.f. distribution assumes round rotors. In practice, synchronous saliency substantially affects steady-state operating conditions.
- ii. Saturation of the iron circuits results in non-linearity of ideal equation parameters. Detailed work is thus necessary to allow adequately for variable leakage and transient and sub-transient reactances. These factors greatly complicate a computer study.
- iii. Amortisseur circuits are difficult to represent. The computation of these equations involves a study of machine geometry, depth of flux penetration and variation of permeability. Thus a rigorous theoretical analysis of damping is difficult.

Several workers have used the general theory in machine stability studies and good accounts of these have been given by Aldred,²⁰ Miles²¹ and Shackshaft.²⁸ In traditional studies, the following assumptions are usually made:

(a) Transient Stability.

- (i) No transient saliency ($x_q' = x_d'$)
- (ii) Constant flux linkages
- (iii) No damping torque
- (iv) Constant mechanical input torque
- (v) Stability is determined by first swing of machine, including those with longest period.

(b) Steady-State Stability.

- (i) No synchronous saliency ($x_q = x_d$)
- (ii) Constant field current
- (iii) No inertia effects.

Hence these theoretical approaches are inadequate for detailed studies when governors and voltage regulators are effective, or for the behaviour of the system after the first swing and until final steady state is reached.

Since a more elaborate analysis results in extensive calculations, it becomes desirable to restrict the study to that of a single machine connected through a reactive tie-line to an infinite source (or sink). This is of value for general investigation, or for a remote generator attached to a large system by a long transmission line. But the analysis is cumbersome for the case of an extensive, heavily loaded network with several generators of the same order of magnitude.

For power system control studies, the operational characteristics of the machines, as seen by the system, are of fundamental importance in multi-machine investigation. Such characteristics can be deduced quantitatively from full-scale tests on individual machines. If the machines are envisaged as a.c. voltage sources behind black boxes, test results can allow consideration to be given to a means of simulation for studies using models. Thus for load flow studies, an a.c. voltage source behind an impedance representing synchronous reactance produces results of satisfactory accuracy. For transient stability studies, the synchronous reactance in the black box is replaced by the transient reactance. It is the author's contention that the e.m.f./black-box concept is the appropriate analogy for the purpose of carrying out studies of the automatic governing and regulating of power systems. The only alternative is to start with the idealised theoretical approach and incorporate detailed modifications to account for practical performance. It is suggested that this approach is cumbersome and unnecessary.

CHAPTER 2

ANALOGUE COMPUTER STUDY

1. EVALUATION OF SYSTEM TRANSFER FUNCTIONS

1.1 General.

In the following sections approximate evaluations are made of the transfer functions of a typical steam turbine, its governor and speeder-motor gear, of the electrodynamics of the alternator and power system, and of the necessary feedback elements for the proposed control system described in Chapter 1 (Sections 3.1 - 3.5). These transfer functions are reduced to a simple linear form so that a mathematical model of the overall system can be developed which is not initially too complex in nature. Time delays, for example, are represented by simple time constants.

The justification for basing design studies on a comparatively simple mathematical model is that if the desired performance and stability are achieved with this, then the perturbing effects of non-linearities and constraints can be subsequently studied individually and in combination using appropriately more sophisticated transfer functions. Efforts can then be made to compensate the control loops accordingly and to include shaping and smoothing elements where desirable. Ultimately, as fully comprehensive a model as possible would have to be studied, but a preliminary, simplified design study will enable the basic features of the behaviour of the control system to be appreciated.

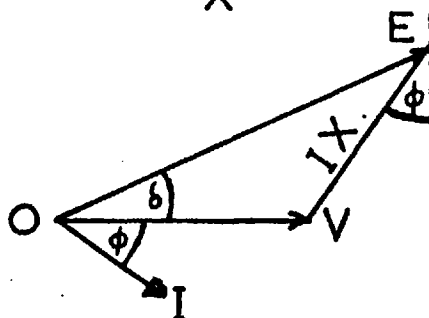
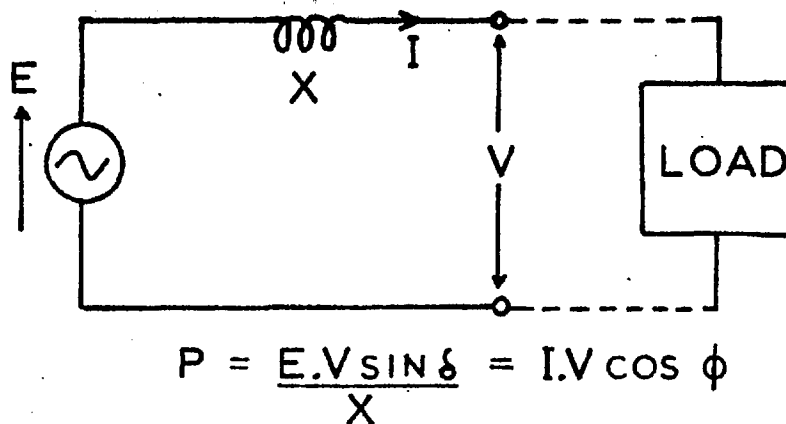
It is desirable to clarify the concept of system stability. Traditionally there are two natural types of stability in power systems: steady state and transient. Steady state stability is concerned with small or gradual load changes and can be tested by

means of a small disturbance. Transient stability is that which deals with large or sudden changes and is tested by means of a large disturbance. These two aspects of stability in power systems are discussed and analysed in great detail by Crary,¹ among others. In general it can be considered that the simple linear mathematical model of the system enables the steady state stability to be precisely determined. When the inherent non-linearities are incorporated in the model, the transient stability can be assessed.

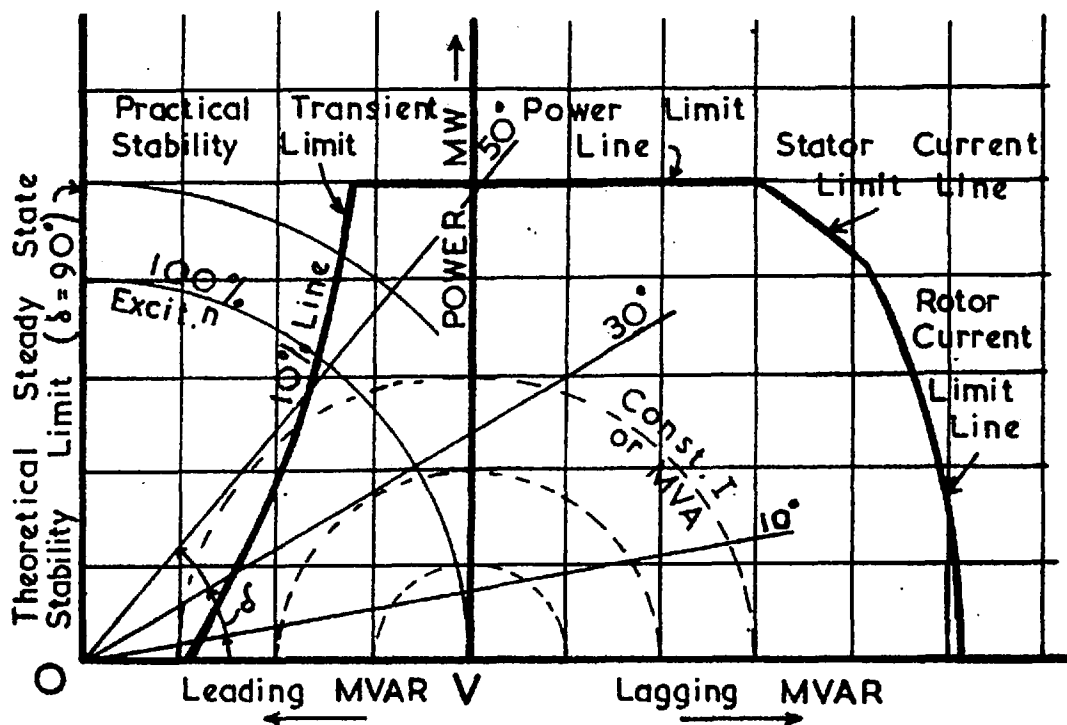
The standard, but often pessimistic definition of stability boundary in electric power systems has traditionally been based on the simple equal-area criterion.¹ This concept assumes, among others, four factors, each of which may be invalid when control devices are effective (such as governors and fast-acting automatic voltage regulators):

- i. Constant flux linkages between the field and armature systems of the generator
- ii. Constant power input to the generator
- iii. First-swing stability is the criterion of overall stability
- iv. Pole-slipping cannot be curtailed.

These conventions demonstrate that the generator output limit prescribed by the requirement of stability in transient conditions is usually less than the steady-state power limit. A generator operating chart is a convenient way of showing all the operating limits of a generator and a typical example is shown in Fig. 3. Such a chart is normally available to all Control Engineers responsible for controlling generators manually on the C.E.G.B. system.



3 a. VECTOR DIAGRAM



3 b. TYPICAL OPERATING CHART (C.E.G.B.)

FIG. 3. SIMPLE OPERATING CONDITIONS

It has been demonstrated recently that fast-acting automatic voltage regulators can permit operation in the dynamic stability region beyond the steady state limit, allowing stable operation at large rotor angles.²⁹ Such regulators can automatically produce changes of excitation during a transient period to assist in keeping the rate of change of electric power output with rotor angle positive, the stability limit not being reached until this rate of change of electric power becomes negative. These techniques are well known abroad, where schemes are often designed to incorporate 'forced excitation' to increase transient stability limits, and Kostenko¹⁶ describes such a system in the U.S.S.R. Some computer studies are described by Aldred and Shackshaft.⁵³

If an alternator loses synchronism either due to loss of excitation or following system disturbances of any kind, it is normal practice on the C.E.G.B.'s system to disconnect it immediately. However, it is known from full scale tests that, under certain conditions and for a limited period, it is permissible to leave the machine connected to the system until some action can be taken to bring it back into synchronism. Such tests in Britain in 1960 are described by Chalmers,³⁰ while combined studies on micro-machines and analogue computer at Imperial College are described by Malik.³¹

It has further been demonstrated that conventional velocity-actuated governors generally assist stability by regulating the input power so as to diminish rotor oscillations. Sophisticated governors can perfectly well be specially developed for the large turbo-alternators now coming into use which would take maximum advantage of the contribution these devices may make

to system stability. An admirable range of studies to ascertain these possibilities is described by Dineley and Kennedy.³²

The developments described above show that the preliminary conventional simplifications are nowadays replaced by a generator whose excitation is increased or decreased as the terminal voltage falls or rises and whose input power is reduced or increased as the difference between input and output powers tends to increase or reduce the generator angular velocity. The equal area criterion of stability³³ is still applicable to these changed conditions as long as the power/rotor-angle curve is modified in accordance with the changes in excitation and input power, but important differences in the dynamic performance of the generator begin to appear. A survey of these considerations is given in a paper by Dineley and Kennedy³⁴ wherein the concept of synchronous generator stability is examined. This paper concludes that overall stability cannot with certainty be assessed from the first rotor swing, and modern computational aids which can take cognisance of the effects of control devices should be used for the calculation of generator stability. The computation should be extended to cover several rotor swings until it is clear that they are being steadily diminished so that an ultimately stable rotor angle will be reached.

This criterion of stability is adopted in the studies described in this Chapter.

1.2 Turbo-Alternator.

The turbo-alternator unit as a whole is a rotating device for converting steam input power into electrical output power. It has inertia, which results in stored kinetic energy at

synchronous speed, experiences mechanical and electrical damping torques and is subject to losses. For the present purpose of studying power control in conditions of steady state stability, the following simplifying assumptions can be made:

- i. Mechanical power input to the prime mover is approximately equal at all times to the electrical power output of the alternator, thus ignoring electrical and mechanical losses;
- ii. the set runs at, or very near, steady synchronous speed, so that power is equivalent to torque, or 'torque-balance' exists.

With these simplifications the electro-mechanical performance of the turbo-alternator may be supposed to obey the elementary relation:

$$P_o + K_4 \cdot \frac{dP_o}{dt} + K_5 \cdot \frac{d^2 P_o}{dt^2} = P_1$$

or

$$\frac{P_o}{P_1} = \frac{1}{1 + K_4 \cdot p + K_5 \cdot p^2} \cdot 1$$

If we set

$$K_4 = \frac{2z}{\omega_n}$$

$$K_5 = \frac{1}{\omega_n^2}$$

then z is the damping ratio for small machine oscillations and ω_n is the machine natural frequency. In response to a step input of P_1 , we get:

$$\frac{P_o}{P_1} = 1 - e^{-\omega_n z t} \left\{ \cos \omega_n \sqrt{1 - z^2} \cdot t + \frac{z}{\sqrt{1 - z^2}} \cdot \sin \omega_n \sqrt{1 - z^2} \cdot t \right\}$$

which describes the normal, damped oscillatory response to small power disturbances.

The natural frequency of machines, ω_n , on the system depends on machine inertia, system reactance, machine reactances, etc. Data regarding the natural frequency of machines on which suitable tests have been carried out is given in Table 2. It can be seen that the natural frequency of these particular sets is reasonably constant and independent of set size or H constant.

The damping term in Crary¹ Vol. II, p. 283, is given as $e^{-\frac{T_d \cdot t}{4H}}$, where T_d is the coefficient of damping torque and varies with machine constants and system conditions. Values of T_d are shown in Table 2, and are found to be reasonably constant (about 10) except in the cases of sets at Stella North and Goldington where the damping is considerably greater, but in neither case were the system conditions normal for the tests. For the mathematical model a value of z is required, and such values are listed in Table 2 for the machines listed. In order that the designed control system can be considered stable for all machines it is proposed to adopt here the smallest value for z likely to be found in practice and this will represent the least stable machine. It is therefore proposed to use a value of $z = 0.05$ in the present study.

Hence, with $z = 0.05$

$$\text{and } \omega_n = 8.5,$$

$$\text{we get } K_4 = \frac{2z}{\omega_n} = 0.0118,$$

$$K_5 = \frac{1}{\omega_n^2} = 0.014,$$

and the transfer function for the turbo-alternator becomes:

$$\frac{P_o}{P_1} = \frac{1}{1 + 0.0118p + 0.014p^2}.$$

Local Frequency		Damping		Date of Test	Type of Test
Set	Rads/Sec $\omega_n = 2\pi f_n$	Coeff. T_d	Ratio $z = T_d / 4H\omega$		
Hig	10.3	12	0.103	1961	Fault Throwing
Wil	8.5	11	0.088	1961	Fault Throwing
Dra	8.6	9	0.049	1961	Fault Throwing
Don	8.2	9	0.056	1961	Fault Throwing
Sta	10.0	11.5	0.093	1961	Fault Throwing
Gol	9.7	17.5	0.085	1960	Fault Throwing
Ste	8.7	21.2	0.131	1958	Short Circuiting High Impedance Link
Cli	7.9	10	0.054	1956	Fault Throwing with High System Impedance

T A B L E 2

TYPICAL TURBO-ALTERNATOR SETS

(on from C.E.G.B. Sources)

1.3 Steam Conditions and Governor System.

When a load disturbance occurs on the power system, there is a difference in input and output power across the turbo-alternators. Thus $P_a = P_1 - P_o$, where P_a is the accelerating power, and we have:

$$P_a = P_1 - P_o = M.p^2\delta + K_d.p\delta$$

In some published works dealing with the elementary transient stability of synchronous generators it is conventionally assumed, when solving this equation for the disturbance in rotor angle δ , that the mechanical power input to the generator remains unchanged during the transient disturbance being investigated, i.e. P_1 remains constant. This is the case, for example, in the paper of Aldred and Doyle.¹⁹ Other workers, however, have assumed a variable input power, and described a transfer function to represent the turbine and governor.^{20,21,35,28} The latter treatment is appropriate here, since we are concerned with load dispatching and frequency control studies in which governor and steam turbine action are very relevant over periods of several seconds.

It is well known from the thermodynamics associated with steam cycles that for maximum efficiency the supply temperature should be as high as possible, and the rejection temperature should be as low as possible.

$$(\text{In the Carnot cycle, efficiency} = \frac{T_1 - T_2}{T_1},$$

where T_1 = absolute temperature at which heat is supplied
and T_2 = absolute temperature at which heat is rejected.)

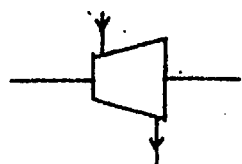
Superheating in the boiler results in a final steam temperature, T_1 , which is limited by the properties of the materials from which

the superheater, piping, valves, steam chest and inlet blades are constructed. For ferritic steels the present limit is about 1,050°F.

To obtain full benefit from high steam conditions it is necessary to use large turbines. This is partly because the extra cost of the high temperature components is offset by a general saving in the number of components per MW and partly because losses become proportionately smaller.

On large turbines of 100 MW and over it is economic to increase the cycle efficiency by using external reheating. This is one way of partially overcoming temperature limitations. By returning partially expanded steam to a reheater, the average temperature at which heat is added is increased. A rigorous treatment of turbine conditions would require representation of each set of turbine blading - there may be 10-20 sets per pressure stage.

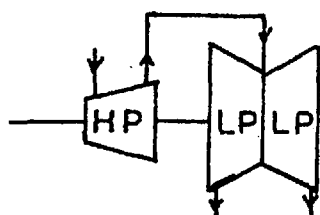
The complexity of steam turbines has become considerable over recent years as a result of the continuous trend towards increasing unit power and efficiency.³⁶ Thus steam conditions at the turbine stop valve are nowadays typically of the order 2350 p.s.i.g. 1050°F³⁷ and the large quantities of steam flowing under these conditions necessitate the expenditure of appreciable power to move the controlling valves. Turbines have several cylinders and Fig. 4 shows various typical arrangements and illustrates the way in which the modern turbine has evolved. Although most multi-cylinder turbines drive a single shaft-'tandem-compound', a two shaft design, 'cross-compound' is sometimes preferred. The reason may be the turbine house layout, limited generator size, or the need to run the low pressure shafting at half-speed.



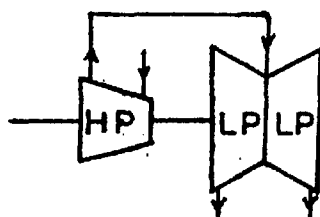
20 MW
1 CYLINDER
1 EXHAUST

HP = HIGH PRESSURE
IP = INTERMEDIATE "
LP = LOW "

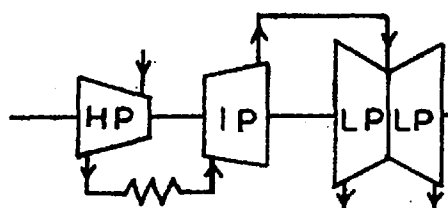
—W— = REHEATER



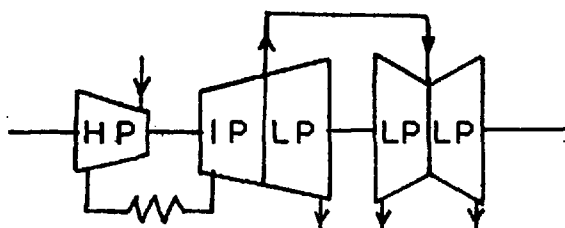
30 MW
2 CYL.
2 EX.



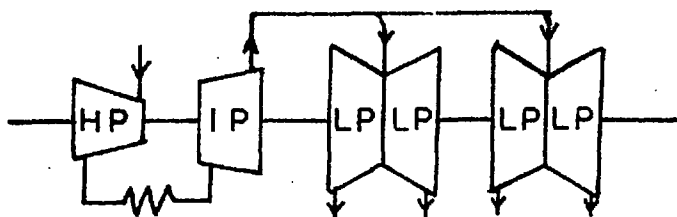
60 MW
2 CYL.
2 EX.



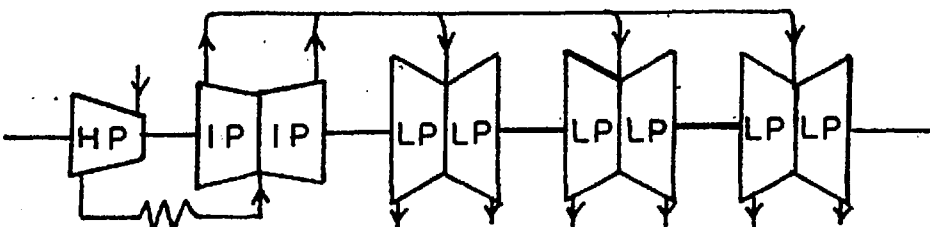
120 MW
3 CYL.
2 EX.
REHEAT



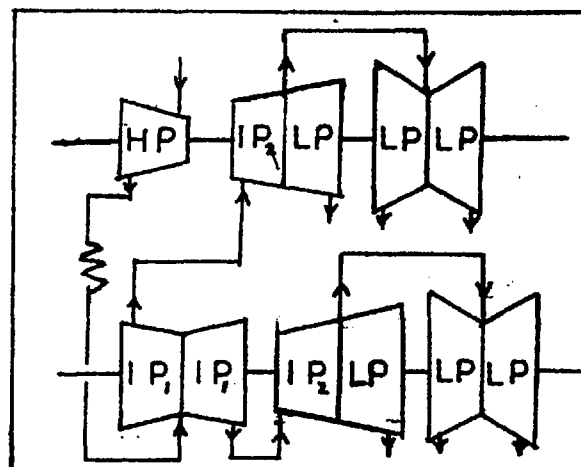
200 MW
3 CYL.
3 EX.
REHEAT



350 MW
4 CYL.
4 EX.
REHEAT



500 MW
5 CYL.
6 EX.
REHEAT



PROPOSED 550 MW
CROSS-COMPOUND

FIG. 4. TYPICAL TURBINE LAYOUTS

The majority of publications on the control and operation of reheat turbines in recent years have appeared in America. Thus the C.E.G.B. Technical Information Service lists 28 references in the period 1948-1955, 15 of which are A.I.E.E. or A.S.M.E. papers. Since 1955 some interesting German and Russian papers have appeared, notably those of Zickuhr³⁸ (Jan, 1956), Galperin³⁹ (Sept, 1959), Veller⁴⁰ (Oct, 1960), Kirillov and Ivanov⁴¹ (Oct, 1961).

Kirillov and Ivanov observe that during the last decade steam reheating has been widely employed in steam turbine power plants, the turbines operating not only as main prime movers but also being used to maintain network frequency. This has had a wide application in Europe where it is often convenient for highly economic plants with reheating not to shut down during periods of light loading. Consequently the operating conditions of reheat turbine control systems become complicated and the question of control stability and the nature of the transient performance become important.

In reheat turbines a large part of the working medium accumulates in the reheater and in its incoming and outgoing pipework. The accumulation of steam in this part of the plant fundamentally alters the dynamics of regulation. This accumulation of steam in the reheater of turbines has different effects on stability and transient performance depending on the reheater size and steam parameters. Therefore it is essential to have a picture of the dynamic characteristics and control performance of reheat turbines for various steam parameters and different sizes of reheaters. Simple transfer functions are used in the discussion

and the idea is put forward of using valves after the reheater for improving throttling.

Galperin³⁹ points out that large and highly stressed turbines cannot withstand the additional stresses imposed by overspeed and permissible deviations from the normal speed rating should not exceed 2-3% (compared to 10% limits acceptable on earlier turbines).

New and more exacting demands thus arise in regard to governor design. The delay in loading the medium and L.P. stages (which develop 70-75% of the installed power), caused by intermediate superheating, sharply reduces the governing rate of the turbo-generators and power system. This effect has been examined by Concordia⁴² using an analogue computer with simple transfer functions.

Galperin³⁹ and Veller⁴⁰ carry out a critical discussion of practical governing systems, such as the hydraulic types with various compensating arrangements. Galperin also suggests that the actuating element and first stage of amplification in the governor system should be replaced by an electrical system.

A full description of a typical steam-turbine governor of the form widely used on modern sets has been given recently by Dineley and Powner.⁴³ The separate stages of a complete governor are:

- i. the actuating mechanism which detects the speed changes
- ii. the oil servo-mechanism which transfers the signal of detected speed change to the throttle-valve operating mechanism
- iii. the throttle valves and their actuating mechanism, controlling the steam input to the turbine.

Dineley and Powner reduce each stage to a gain term associated with a simple time constant and quote an overall transfer function of the form:

$$\frac{\text{Throttle valve position}}{\text{Turbine speed}} = \frac{G_1 \cdot G_2 \cdot G_3}{(1 + pT_1)(1 + pT_2)(1 + pT_3)}.$$

They consider that the longest delay occurs in the oil servo-system, and set $T_2 = 0.5$ secs.

Earlier workers, such as Shackshaft,²⁸ have also used simple time delays to represent governor action. The values used by Shackshaft were based on field test results at Goldington Power Station in May, 1960. He put $T_1 = 0$, $T_2 = 0.1$ secs, $T_3 = 0.188$ secs and observed that the governor valve closed in 0.2 secs after a 30 MW rejection test. Shackshaft makes the further point that this time (of 0.2 secs) is typical for a 30 MW set, though it is not very important in view of the much longer time constant of the turbine, which he quotes as 0.49 secs.

Further details and remarks about governing gear are given in 'Modern Power Station Practice',⁴⁴ p. 36 et seq. Protective devices are always incorporated to guard the turbine against such operational dangers as overspeeding, oil pressure failure, excessive vibration, excessive temperature differentials, etc. Thus provision is made for rapid closing of the stop valve by emergency tripping. In reheat turbines a considerable quantity of steam is entrained in the reheater and its piping, and in the event of loss of load this steam could accelerate the rotor to a dangerous extent. This is prevented by intercept valves controlled by the governor, with overriding control by a secondary governor

or anticipatory gear in some cases. In addition it is necessary to include emergency relief valves in the reheater piping, in order to safeguard the reheater and high pressure turbine against excessive pressure. This is illustrated in Fig. 5.

From all the above information and papers about steam turbines and governors, it might appear that formulation of transfer functions is straightforward. This is not the case, since there is a distinct lack of numerical data backed up by full-scale test results. The remarks made in Chapter 1, section 4.3. concerning accuracy of available data deserve further elaboration here. Some manufacturers have said that they do not know the transient time delays and non-linearities of steam turbines and governor gear, since 'they have never been asked', i.e. such data has not hitherto appeared in specifications. Few manufacturers in this country have facilities for full-scale tests on boilers, turbines and governor gear at full load at their own factories and laboratories. The G.E.G.B., on the other hand, have, in past years, been unwilling and almost continuously unable to conduct controlled and fully instrumented tests in power stations, mainly because of general plant shortage and transmission network weakness on a heavily loaded system.

The planning and design of satisfactory control schemes for enlarged power systems of the future, which are stable and secure, of necessity demand the knowledge of transient and dynamic characteristics of all incorporated plant, (See also the observations of Chapter 1, section 4.3.ii.). There are signs that awareness of this problem is leading to the execution of more system and power-station tests, and this trend is to be commended.

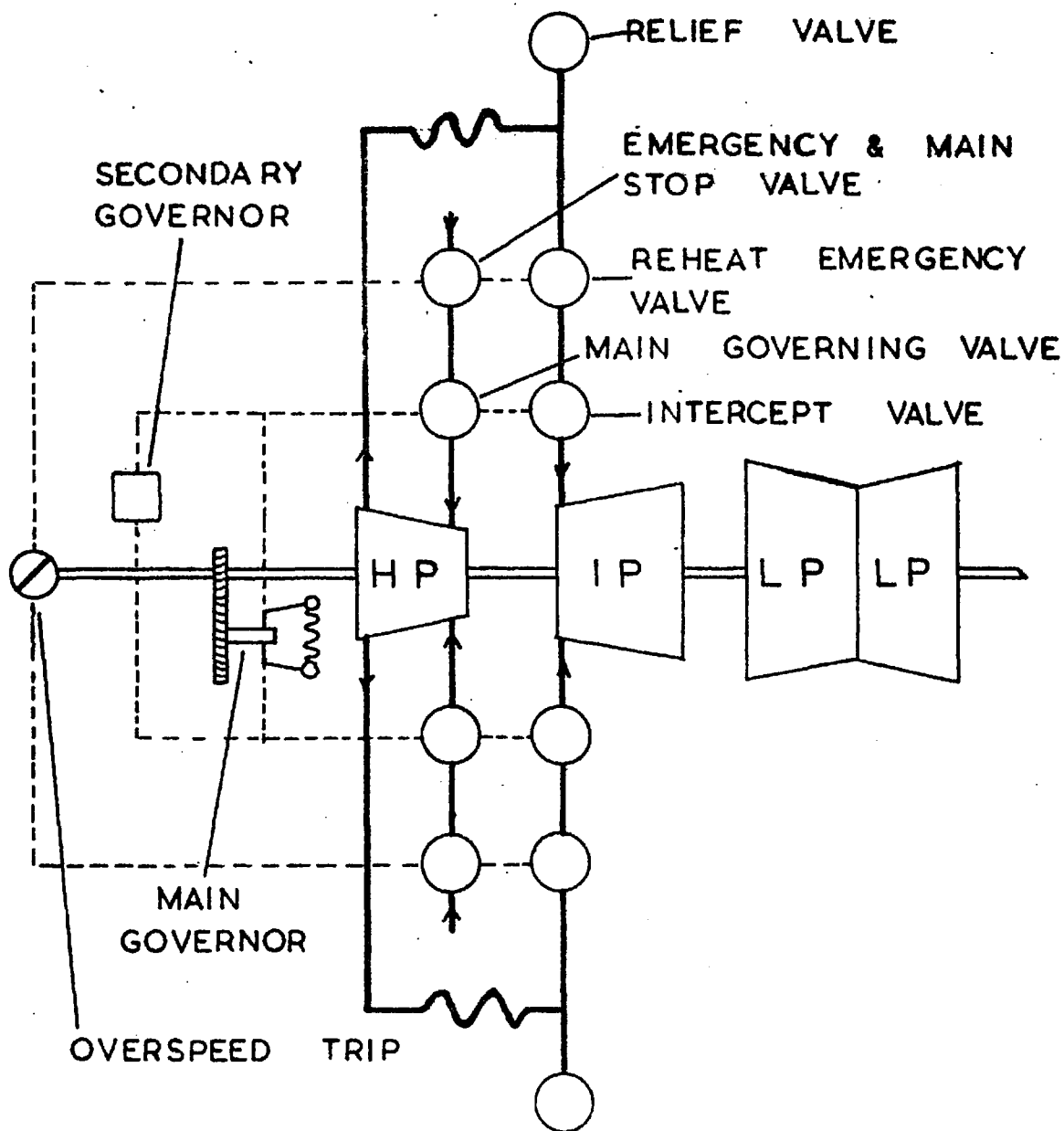


FIG. 5. REHEAT TURBINE VALVE ARRANGEMENT
(‘MODERN POWER STATION PRACTICE’)

Meanwhile, some simple transfer functions can be formulated here when the following assumptions are made:

- i. Under steady conditions of normal running, the operation of the governor is such that the steam admitted to the turbine is a linear function of the speed of the turbine throughout the governor's working range.
- ii. The movement of the governor mechanism may be represented by a simple single time lag.
- iii. The boiler provides a source of steam at constant pressure and temperature so that the steam power reaching the turbine is proportional to the stop valve position.
- iv. The efficiency of the turbine does not change over the small range of speed in which it is normally required to operate.
- v. The delays in each stage of the turbine, and in the reheat cycle when it exists may each be represented by simple time constants.

Thus the combined equations for steam power flow may be written:

$$\text{Governor response} \quad P_g = \frac{K_g \Delta F_M}{1 + p \cdot T_5}.$$

$$\text{Stop Valve} \quad P_s = P_M - P_g.$$

$$\text{Turbine H.P. Stage} \quad P_2 = \frac{P_s}{1 + pT_1}.$$

$$\text{Turbine I.P. Stage (after reheat)} \quad P_3 = \frac{P_2}{(1 + pT_2)(1 + pT_3)}.$$

$$\text{Turbine L.P. Stage} \quad P_4 = \frac{P_3}{1 + pT_4}.$$

These transfer functions appear in the block diagram of Fig. 6. K_1 , K_2 , K_3 are the proportions of total steam power P_s converted to shaft torque by each stage of the turbine. A typical turbine would have:

H.P. Stage	$K_1 = 0.3$
I.P. Stage	$K_2 = 0.5$
L.P. Stage	$K_3 = 0.2$

showing that 70% of the total mechanical power delivered to the alternator is developed in the I.P. and L.P. stages.

Equivalent time constants would be of the order:

H.P. Stage	$T_1 = 0.2$ secs
Reheat cycle	$T_2 = 3 \rightarrow 15$ secs (=0 for non-reheat sets)
I.P. Stage	$T_3 = 0.2$ secs
L.P. Stage	$T_4 = 0.4$ secs

By comparison, Shackshaft²⁸ lumped all turbine time constants together as $T = 0.49$ secs (non-reheat); and Dineley and Powner⁴³ put $T = 0.5$ secs.

For the centrifugal governor, K_g represents the speed droop constant, and for 4% droop, or 2 c.p.s. droop in 50 c.p.s., the power change would be 1 p.u. when $K_g = 0.5$ (F_M is in c.p.s.).

The overall effect of delays in the hydraulic system will be lumped as a time constant $T_g = 0.2$ secs.

1.4 Speeder Motor.

For velodyne operation (Chapter 1, section 3.5.ii.)

in which the motor is continuously actuated by the power error signal P_e , it will be assumed that a simple lag due to inertia and friction is of the order: $T_6 = 0.1$ secs. In practice there

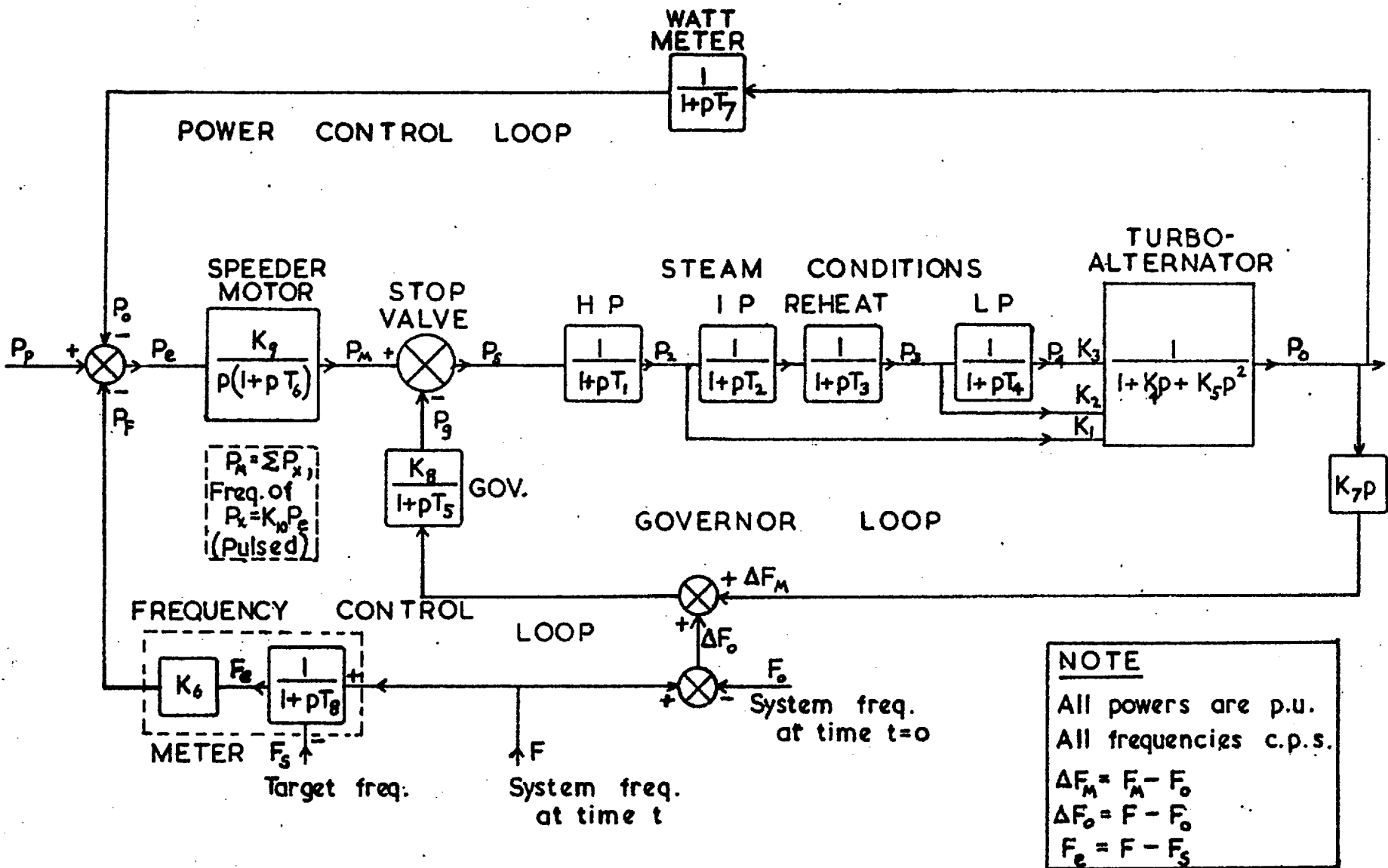


FIG. 6. BLOCK DIAGRAM OF TURBO-ALTERNATOR AND CONTROL LOOPS

is some backlash and a certain dead-band, which would be useful, in fact, in preventing perpetual hunting after the minimum P_e had been achieved.

There is also a rate limit on speeder motor operation, since typically, the linkage cannot drive a stop valve from fully closed to fully open in less than 30 secs. This could be represented as a rate of integration limit in deriving the motor position, assumed analogous to the steam power admitted to the turbine. Hence the transfer function for the velodyne speeder motor is:

$$P_M = \frac{K_9 \cdot P_e}{p(1+pT_6)},$$

where K_9 is the control gain.

For pulse control, the error signal P_e determines the frequency and sign of a pulse train of constant width, constant height pulses. These pulses would be of adequate magnitude and duration to overcome motor stiction. Thus, pulse frequency

$$= K_{10} \cdot P_e,$$

where K_{10} is the control gain, and motor position P_M is given by

$$P_M = \sum P_x,$$

where P_x is the change of steam power per pulse.

1.5 Measuring Devices.

The variety of devices available for use in the power feedback loop were listed in Table 1. Their time constants, T_7 in Fig. 6, can be as low as 0.01 secs rising to 5 secs for the cheaper types. It would be desirable to study the effect of different values of T_7 in this range in order to assess the

maximum time constant permissible to maintain stability while also keeping the cost of the meter to a minimum. Initially, values of T_7 will be considered in the range:

$$0.1 < T_7 < 0.5 \text{ secs.}$$

The frequency meter described by Moran⁶ has a time constant of approximately 0.05 secs = T_8 . The gain factor K_6 in the frequency control loop of Fig. 6 can be set to represent speed droops in the range 1% to 5%, as discussed in Chapter 1, section 3.4.

1.6 Machine Speed Variations due to changes in Power Output.

The vector diagram for the current and voltages present in the alternator, where resistances are negligible compared with machine reactances, and for the case of generation at unity power factor, is shown in Fig. 7a, where

E = Excitation voltage behind machine transient reactance

E_1 = Infinite busbar voltage

δ = angle between E and E_1 in p.u. quantities

X_e = external reactance on machine base

X' = machine transient reactance on machine base

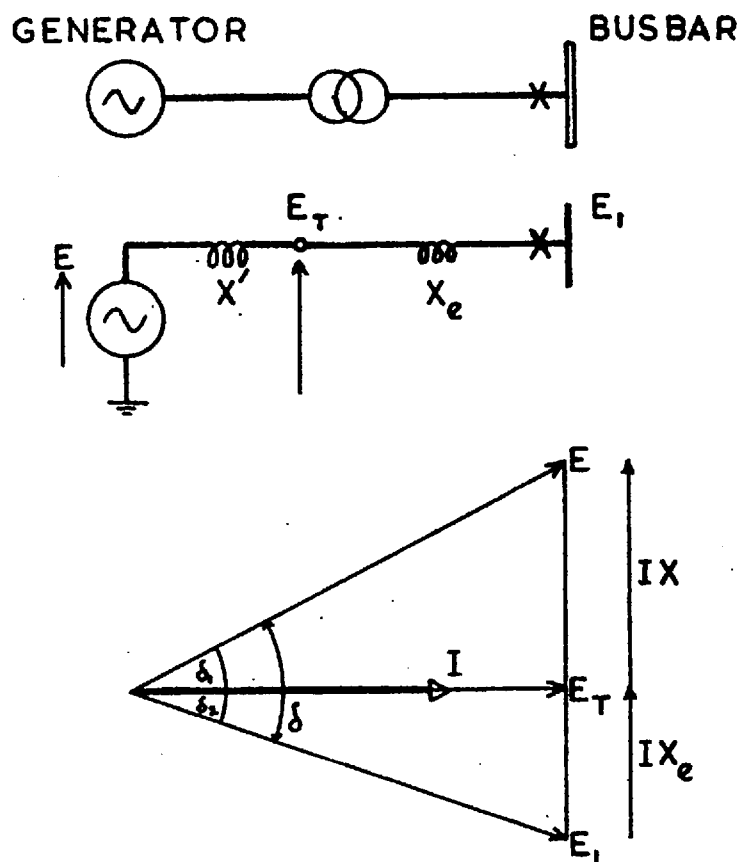
E_T = machine terminal voltage (= 1 p.u. on machine base)

The equation for power transfer is¹

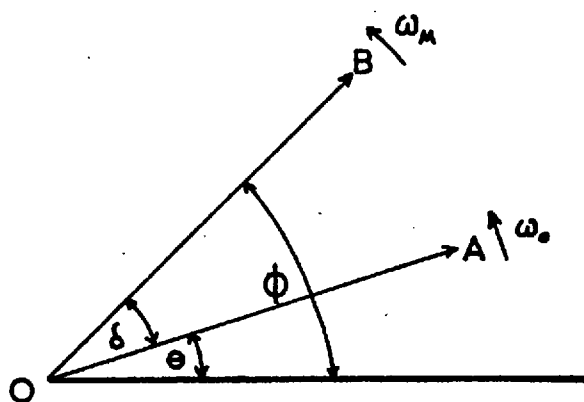
$$P = \frac{E \cdot E_1 \sin \delta}{(X_e + X')}.$$

The speed vectors are shown in Fig. 7b. OA represents the system vector such that system frequency (at the busbar) is given by

$$F_o = \frac{\omega_o}{2\pi}, \text{ or } \omega_o = 2\pi F_o.$$



7.a. POWER TRANSFER (UNITY P.F.)



7. b. SPEED VECTORS

FIG.7. MACHINE VECTOR DIAGRAMS

For the system, $\theta = \omega_o t$ (where $\theta = 0$ when $t = 0$).

$$\begin{aligned}\text{For the machine, } \phi &= \theta + \delta = \omega_o t + \delta \\ &= 2\pi F_o t + \delta,\end{aligned}$$

so machine speed at time t is

$$\omega_M = \frac{d\phi}{dt} = \frac{d}{dt} (2\pi F_o t + \delta) = 2\pi F_o + \frac{d\delta}{dt},$$

$$\text{i.e. } \omega_M = 2\pi F_M = 2\pi F_o + \frac{d\delta}{dt},$$

$$\text{whence } F_M = F_o + \frac{1}{2\pi} \cdot \frac{d\delta}{dt}.$$

$$\text{Hence, machine speed error } \Delta F_M = F_M - F_o = \frac{1}{2\pi} \cdot \frac{d\delta}{dt}.$$

Now from the power transfer equation above,

$$\frac{dP}{dt} = \frac{EE_1 \cos \delta}{(X_e + X')} \cdot \frac{d\delta}{dt},$$

$$\text{whence } \frac{d\delta}{dt} = \frac{(X_e + X')}{EE_1 \cos \delta} \cdot \frac{dP}{dt}.$$

Substituting this value for $\frac{d\delta}{dt}$ in equation for ΔF_M gives

$$\Delta F_M = \frac{1}{2\pi} \cdot \frac{(X_e + X')}{EE_1 \cos \delta} \cdot \frac{dP}{dt},$$

which relates machine speed variations to changes in power output.

For the machines at present on the C.E.G.B.'s system, X' varies between 0.2 and 0.3, on machine base (Shackshaft²⁸ quotes $X' = 0.232$ for a 30 MW set at Goldington and Scott, Casson, Chorlton and Banks⁴⁵ quote $X' = 0.228$ for a 200 MW set at High Marnham). X_e is the sum of the transformer and external reactance and is generally between 0.15 and 0.2. The upper limits will be taken, since these represent the modern machines and the least stable conditions.

Referring again to Fig. 7a,

$$\begin{aligned}\delta &= \tan^{-1} X_e + \tan^{-1} X' \text{ (at unity p.f.)} \\ &= \tan^{-1} 0.2 + \tan^{-1} 0.3 \\ &= 29^\circ\end{aligned}$$

$$\therefore \cos \delta = 0.875.$$

$$\begin{aligned}\text{Also, } E_1 E_2 &= \left\{ \sqrt{1 + X_e^2} \right\} \cdot \left\{ \sqrt{1 + X'^2} \right\}, \text{ since } E_T = 1 \text{ p.u.} \\ &= (\sqrt{1 + 0.04}) \cdot (\sqrt{1 + 0.09}) = 1.07.\end{aligned}$$

Hence the p.u. form of the equation for ΔF_M becomes:

$$\Delta F_M = \frac{1}{2\pi} \cdot \frac{(0.3 + 0.2)}{1.07 \times 0.875} \cdot \frac{dP}{dt} = 0.085 \frac{dP}{dt}.$$

Thus in Fig. 6 the machine speed error is related to variations in output power by the transfer function:

$$\Delta F_M = K_7 P_o,$$

where $K_7 = 0.085$.

1.7 System Parameters.

Fig. 8 shows the schematic diagram for a power system in which selected proportions of controlled sets provide frequency control while the base load sets are running steadily at full output. The spinning reserve generation available in the controlled sets must be adequate to maintain the system load balance in the possible event of outage of one or more of the largest sets due to tripping under unexpected fault conditions. The necessary amount of spinning reserve at any time will have been estimated in advance, as discussed in Chapter 1, section 1.3 and section 3.4.

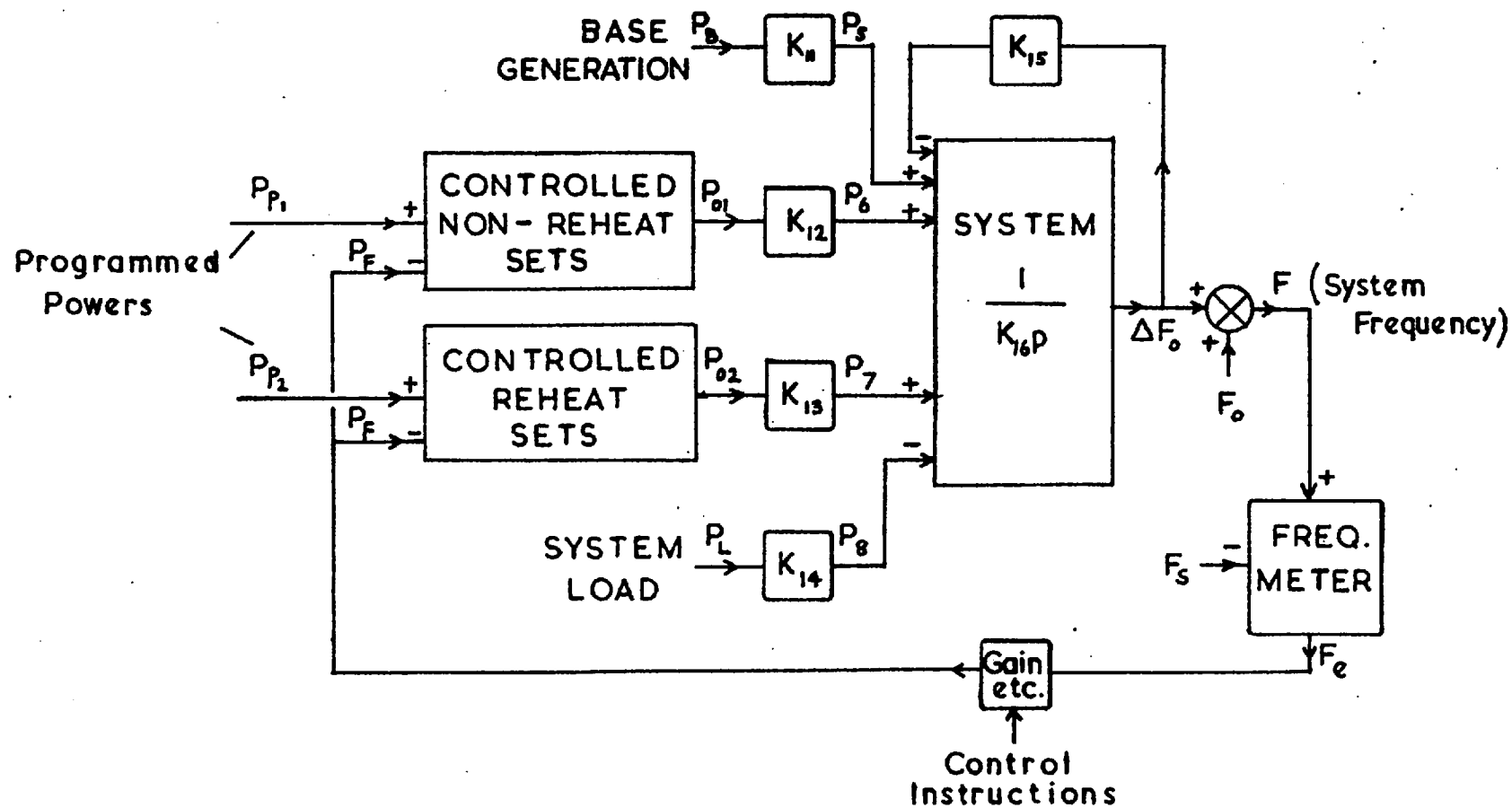


FIG. 8. BLOCK DIAGRAM OF POWER SYSTEM

Suppose E is the total stored energy in KWsec/KVA in the system and P_e is the p.u. load balance error at any instant. Let F be the system frequency at the instant considered, and let suffix o denote time zero, when P_e also is zero. Then the approximate relations may be written:

$$E = E_o \cdot \frac{F^2}{F_o^2}$$

$$\therefore \frac{dE}{dt} = \frac{2E_o F}{F_o^2} \cdot \frac{dF}{dt},$$

and $\frac{dE}{dt} = -P_e.$

For small errors in F , $\frac{F}{F_o} \approx 1$, hence

$$\frac{2E_o}{F_o} \cdot \frac{dF}{dt} = -P_e$$

$$\therefore F = -\frac{F_o}{2E_o} \int P_e \cdot dt + \text{const.}$$

If $F = F_o$ ($= 50$ c.p.s.) at time $t = 0$, then subsequent system frequency at time t due to load errors may be written

$$F = F_o - \frac{1}{K_{16} \cdot P} \cdot \Delta P,$$

where $\Delta P = P_5 + P_6 + P_7 - P_8 - K_{15} \Delta F_o.$

In the above, $K_{16} = \frac{2E_o}{F_o}$ and K_{15} is the frequency dependence of the load. Present C.E.G.B. estimates are that $E_o = 3.5$ KWsec/KVA for the system as a whole, and that 1 c.p.s. rise in frequency results in an increase of load of 2%. These values have been deduced from system tests, and there is some published material

on Power/Frequency characteristics of the British Grid System by Davies, Moran and Bird.⁷ Since $F_o = 50$ c.p.s., we have

$$K_{16} = 0.14.$$

and $K_{15} = 0.02 (F - F_o)$, and constitutes a negative feedback effect round the system -- See Fig. 8.

1.8 Summary of Transfer Function Constants.

With reference to Figs. 6 and 8, the list of constants evaluated in the above sections is as follows:

<u>Turbine</u>	$K_1 = 0.3$	$T_1 = 0.2$ secs	$T_4 = 0.4$
	$K_2 = 0.5$	$T_2 = 0$ or 3-15	
	$K_3 = 0.2$	$T_3 = 0.2$	
<u>Alternator</u>	$K_4 = 0.0118$	(assumptions: $z = 0.05$, $\omega_n = 8.5$	
	$K_5 = 0.014$	$X_e = 0.3$ p.u., $X' = 0.2$ p.u.)	
<u>Governor</u>	$K_8 = 0.5$ (for 4% droop)	$T_5 = 0.2$	
<u>Speeder motor</u>	$K_9 =$ control gain of velodyne operation		$T_6 = 0.1$
	$K_{10} =$ control gain of pulsed operation		
<u>Wattmeter</u>	T_7 variable, range 0.1 $\rightarrow$ 0.5		
<u>Frequency Meter</u>	$K_6 =$ gain of frequency control loop, in range		
	0.4 $\rightarrow$ 2.0		
	$T_8 = 0.05$		
<u>System</u>	K_{11} : proportion of base load generation		
	K_{12} : controlled non-reheat sets (as proportion of		
	total generation)		
	K_{13} : controlled reheat sets (as proportion of		
	total generation)		
	K_{14} : system load demand		

K_{15} : frequency dependence of load = 0.02

K_{16} : 0.14 (assumptions: $E_o = 3.5$ KWsec/KVA

$F_o = 50$ c.p.s.)

1.9 Notes on tests at Brachead Power Station.

As a result of liaison between the University of Glasgow and the South of Scotland Electricity Board a series of Generator performance trials was carried out at Brachead Power Station (on the Renfrew side of Glasgow) in October, 1964. The author was fortunate to be invited to attend the trials as an observer from Imperial College.

The trials were conducted on a 60 MW A.E.I. machine to investigate its transient behaviour with special reference to constructing an adequate mathematical model of the turbine, alternator and ancillary control equipment. In the tests, the performance of turbine main and secondary governing systems, generator excitation system and alternator damping effects, together with turbine behaviour was measured, to ascertain the contributions made by these factors to the resynchronising ability of a modern turbo-generator when synchronism has temporarily been lost.

From the analysis of the results further light should be thrown on the mechanism whereby current flowing in the rotor body contributes to restoring torque. It is also hoped that useful information relating to the basic characteristics of the A.V.R. desirable for stability conditions will be obtained together with similar information relating to governor characteristics.

The arrangement of the system during the trials was such as to create as strong an electrical connection to the Grid as possible to simulate infinite busbar conditions. The test machine was connected via a series reactor. There were two series of trials: the first being essentially of a steady-state nature involving small excursions from a steady operating condition; the second involved pole slipping of the machine's rotor system.

A wide range of electrical and mechanical quantities were recorded using an ultra-violet recorder (for electrical quantities, by S.S.E.B.), a photographic Duddell recorder (for mechanical quantities, by A.E.I.), and a multi-channel Ampex magnetic tape recorder (electrical and mechanical quantities, provided by Glasgow University, operated by the author).

Governor tests were conducted by injecting step and sinusoidal changes into the turbine governing system at the first oil relay. The governor system is normally part of a closed loop system but the method of introducing the changes was such as to make it open loop. The force due to current flowing in an electric coil situated in a strong fixed magnetic field acted against a spring and injected mechanical movement into the speeder gear system. Position control devices were fitted to both sleeve and governor spindle and a simple electrical compensating circuit ensured that movement of the sleeve was controlled by the coil such that the relative movement between sleeve and spindle followed an electrical disturbing signal to within a time constant of 0.01 seconds. A low frequency signal generator was used as a source of step and sinusoidal electrical disturbing signals. The control

device and associated amplifier were constructed by Glasgow University. During governor tests the A.V.R. was inoperative.

A.V.R. tests comprised the injection of step and sinusoidal signals into the A.V.R. reference circuit with the machine at various loads and power factors. In some cases, large amplitude rotor swings were deliberately induced, including pole slipping.

At the time of writing, some of the photographic records have been received from A.E.I. An example is shown in Fig. 9.

Measurements show that the overall time constant of the governor mechanism is approximately 0.2 secs.

Time constants in the steam turbine stages appear to be of the order 0.2 - 0.5 secs.

These values help to confirm some of the transfer function constants listed in the last section.

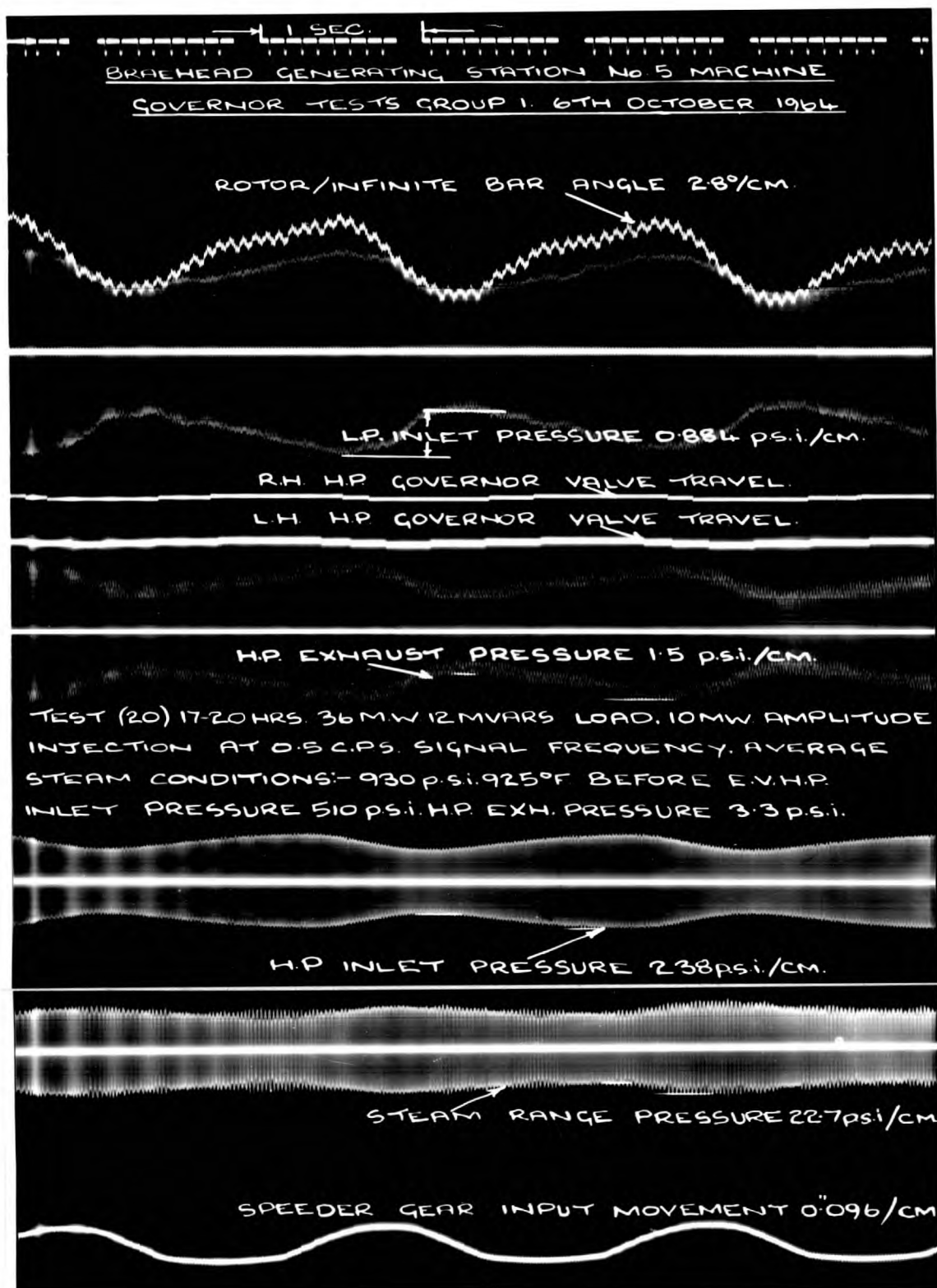


FIG. 9. EXAMPLE OF BRAEHEAD RESULTS

2. DEVELOPMENT OF AN ANALOGUE

2.1 Advantages of Analogue Study.

The complexity of the mathematical model of Fig. 6 is such that attempts to study control stability by traditional numerical methods would be onerous. Nevertheless, such methods would be feasible to a limited extent - Jacovides,⁴⁶ for example, gives a copious account of his use of the Nyquist criterion of stability based on frequency response analysis to examine the steady state stability of an alternator connected by a transmission line to an infinite bus and provided with a regulator. This work is valid only for small disturbances and does not make provision for the existence of any non-linear functions.

Again, the processes of pole-zero analysis⁴⁷ soon become intractible, since an attempt to calculate the closed-loop poles of the turbo-alternator-governor loop results in the need to solve a 7th order equation in p . Even although the aid of digital computers may be enlisted to facilitate the numerical work in frequency-response or pole-zero analysis, these methods are inappropriate when the desire and need arises to carry out further studies on the effects of non-linearities, constraints, and more elaborate representations of transfer functions.

For the above reasons it is deduced that the simplifying advantages of an analogue computer study are apparent here. The reader is referred to the comments on analogue computers in Chapter 1, section 4.4.

The Solarton Minispace, shown at 'A' in Fig. 10, is a small general purpose analogue computer. It comprises ten drift corrected D.C. amplifiers, each of which may be used for summing, sign reversal, or integrating. Also incorporated are 24 potentiometers, a patching panel, computer control facilities and built-in power supplies. The technical specifications of importance are summarised below:

<u>Input and Feedback Resistors:</u>	100K Ω and 1M Ω 0.1%, wire-wound.
<u>Feedback Capacitors:</u>	0.1 and 1 μ F, 0.5%
<u>Reference Potentiometer:</u>	10 turn helical, 0.1% linearity
<u>D.C. Amplifiers</u> (Type AA261.2)	<u>D.C. gain</u> $> 30 \times 10^6$; $> 10 \times 10^3$ at 100 c.p.s. <u>Drift</u> $< 100 \mu$ V (long term) (referred to summing junction) typically 20 μ V per day <u>Noise:</u> typically 100 μ V
<u>Unity Integrator Drift</u>	$< 100 \mu$ V/sec (1 μ F and 1M Ω)
<u>Bandwidth</u> (3db)) (with 1M Ω feedback))	16 Kc/s at X10 gain 9 Kc/s at X100 gain
<u>Typical Safe Capacitance Loading</u>) (with 1M Ω feedback resistor))	10,000 pF at O/P with 250 pF at summing junction
<u>Output</u>	$> \pm 100$ V into 20K Ω or 10K Ω
<u>H.T. consumption</u>) (and max. at ± 100 V O/P))	+300V at 20mA (31mA) -300V at 19mA (25mA)

In order to extend the range of the equipment, a group of ten summing amplifiers with patch panel and ten associated potentiometers, built into an extension unit -- 'B' in Fig. 10, was linked with the Minispace. The additional amplifiers have the



FIG. 10. ANALOGUE COMPUTATION EQUIPMENT

same specifications as above. The construction and circuitry of the extension unit is described by Hammons.⁴⁸

2.2 Operational Amplifier Functions.

The use of operational D.C. amplifiers in the simulation of transfer functions is a well established technique and has been treated exhaustively by many writers, representative of the best of whom are Korn,⁴⁹ Johnson⁵⁰ and Fifer.⁵¹ For completeness here a brief review of the elementary principles follows:

i. D.C. Amplifier with generalised forward and feedback impedances (Fig. 11a).

The amplifier input impedance is high, so the current into the amplifier is assumed to be zero.

∴ Summing currents at input node:

$$\frac{V_1 - \epsilon_g}{Z_1} + \frac{V_2 - \epsilon_g}{Z_2} + \dots + \frac{V_n - \epsilon_g}{Z_n} + \frac{V_o - \epsilon_g}{Z_f} = 0$$

also, $V_o = -\alpha \epsilon_g$, hence

$$\frac{V_1}{Z_1} + \frac{V_2}{Z_2} + \dots + \frac{V_n}{Z_n} = -\frac{V_o}{Z_f} - \frac{1}{\alpha} \left(\frac{V_o}{Z_1} + \frac{V_o}{Z_2} + \dots + \frac{V_o}{Z_n} + \frac{V_o}{Z_f} \right)$$

If α is very large, terms multiplied by $\frac{1}{\alpha}$ in the bracket may be neglected, and then

$$V_o = - \left(V_1 \cdot \frac{Z_f}{Z_1} + V_2 \cdot \frac{Z_f}{Z_2} + \dots + V_n \cdot \frac{Z_f}{Z_n} \right)$$

Depending on the value of α the number of inputs is limited, since the effective amplifier loop gain and accuracy of the computation is decreased as the value of the forward path impedances paralleled is decreased.

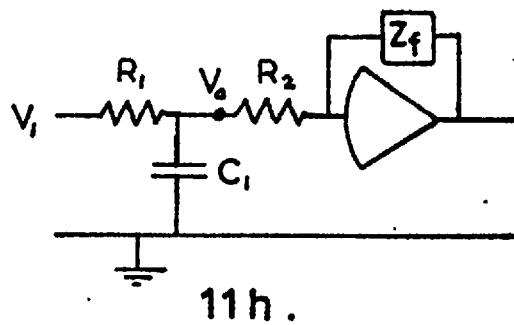
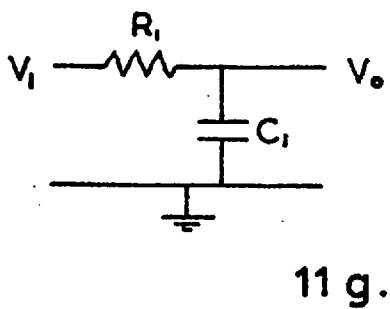
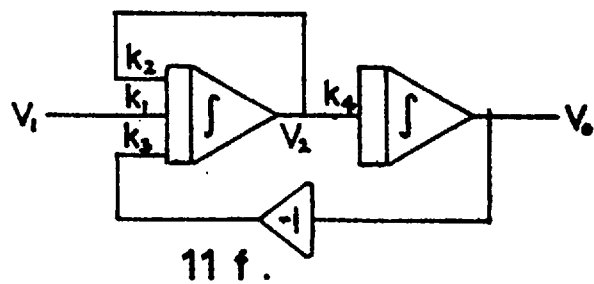
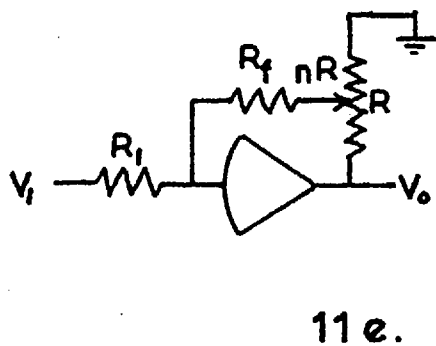
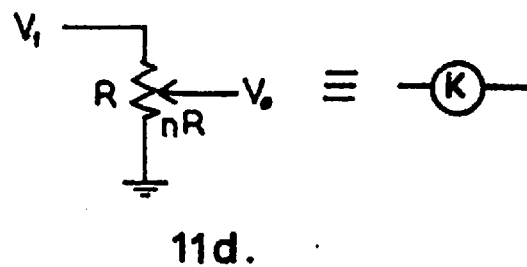
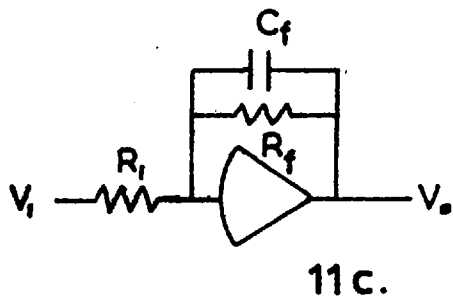
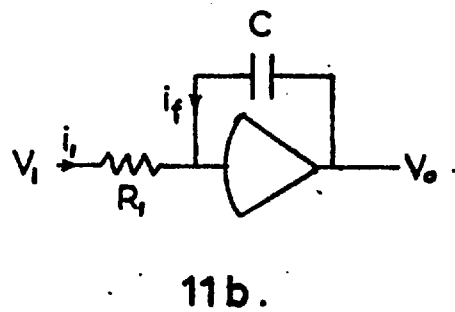
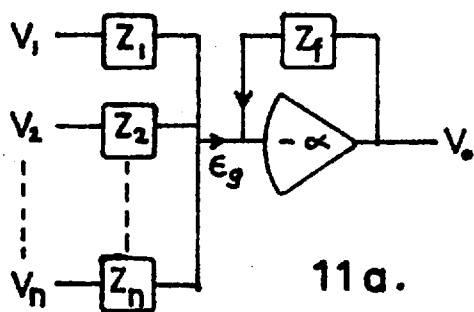


FIG.11. OPERATIONAL AMPLIFIER FUNCTIONS

Note that V_o , V_1 , etc. are required to be of similar orders of magnitude; also, since α is very large, ϵ_g is always vanishingly small. Thus the summing node is termed a virtual earth.

ii. Sign reversal.

Put $Z_1 = Z_f = R$ and remove all other forward impedances.

Then
$$\frac{V_o}{V_1} = -1,$$

for scale change,
$$\frac{V_o}{V_1} = - \frac{R_f}{R_1}.$$

iii. Summing.

All impedances in Fig. 11a are made pure resistances:

$Z_f = R_f$, $Z_1 = R_1$, etc.

$$\therefore V_o = - \left(V_1 \cdot \frac{R_f}{R_1} + V_2 \cdot \frac{R_f}{R_2} + \dots + V_n \cdot \frac{R_f}{R_n} \right)$$

All inputs are added in proportions depending on respective forward path resistance.

iv. Integrating (Fig. 11b).

In this case the feedback impedance is capacitative.

Thus
$$Z_f = \frac{1}{pC}; \quad Z_1 = R_1$$

$$\therefore \frac{V_o}{V_1} = - \frac{1}{pCR_1}; \quad \text{which represents an integration with respect to time.}$$

alternatively

Assume $\epsilon_g = 0$; then $i_1 = \frac{V_1}{R_1}$, $i_f = C \cdot \frac{dV_o}{dt}$

and
$$i_1 + i_f = 0$$

$$\therefore \frac{V_1}{R_1} = - C \cdot \frac{dV_o}{dt},$$

integrating:

$$V_o = \frac{1}{CR_1} \int_0^t V_1 dt.$$

v. Simple lag, or 1st order time constant (Fig. 11c).

$$\text{Total feedback impedance } Z_f = \frac{\frac{R_f}{pC_f}}{R_f + \frac{1}{pC_f}} = \frac{R_f}{1 + pC_f R_f}$$

$$Z_1 = R.$$

$$\therefore \frac{V_o}{V_1} = - \frac{R_f}{R_1} \cdot \frac{1}{1 + pC_f R_f}.$$

Thus time constant = $C_f R_f$; scale change = $\frac{R_f}{R_1}$.

vi. Multiplication by k ($k < 1$) (Fig. 11d).

Neglecting forward path loading of following amplifier on potentiometer of Fig. 11d:

$$V_o = nV_1.$$

vii. Dividing by k (Fig. 11e).

Neglecting loading of R_f on potentiometer,

$$\frac{V_o}{V_1} = - \frac{1}{n} \cdot \frac{R_f}{R_1}.$$

viii. 2nd Order time constant (Fig. 11f).

$$\text{In this circuit, } V_2 = - \frac{1}{p} (k_1 V_1 + k_2 V_2 - k_3 V_o),$$

$$V_o = - \frac{1}{p} k_4 V_2.$$

$$\text{Eliminating } V_2: -\frac{1}{k_4} \cdot pV_o = -k_1 \frac{1}{p} \cdot V_1 + \frac{k_2}{k_4} \cdot V_o + k_3 \frac{1}{p} \cdot V_o$$

$$\text{Rearranging: } \frac{V_o}{V_1} = \frac{k_1}{k_3 + \frac{k_2}{k_4} \cdot p + \frac{1}{k_4} \cdot p^2}.$$

which is of the general, 2nd order form:

$$\frac{V_o}{V_1} = K \cdot \frac{1}{1 + Ap + Bp^2},$$

where $A = \frac{k_2}{k_3 k_4}$, $B = \frac{1}{k_3 k_4}$, scale change = $\frac{k_1}{k_3}$.

The operational amplifier circuits described above are capable of representing all the transfer functions of Figs. 6 and 8.

2.3 Passive Network Functions.

In order to economise on operational amplifiers it is possible to use R-C networks to represent time constants. Thus the simple network of Fig. 11g has the transfer:

$$\frac{V_o}{V_1} = \frac{1}{1 + pT},$$

where

$$T = R_1 C_1.$$

This relation only holds provided that the output is on open circuit, or when V_o is applied to a very high impedance. Thus it is not possible to cascade directly a number of these elements to represent a series of simple time delays. However, it is possible to connect the passive R-C network of Fig. 11g to the input resistance of an operational amplifier, and its transfer function is then modified to the form:

$$\frac{V_o}{V_1} = \frac{R_2}{R_1 + R_2} \cdot \frac{1}{1 + pT} \text{ (see Fig. 11h),}$$

where

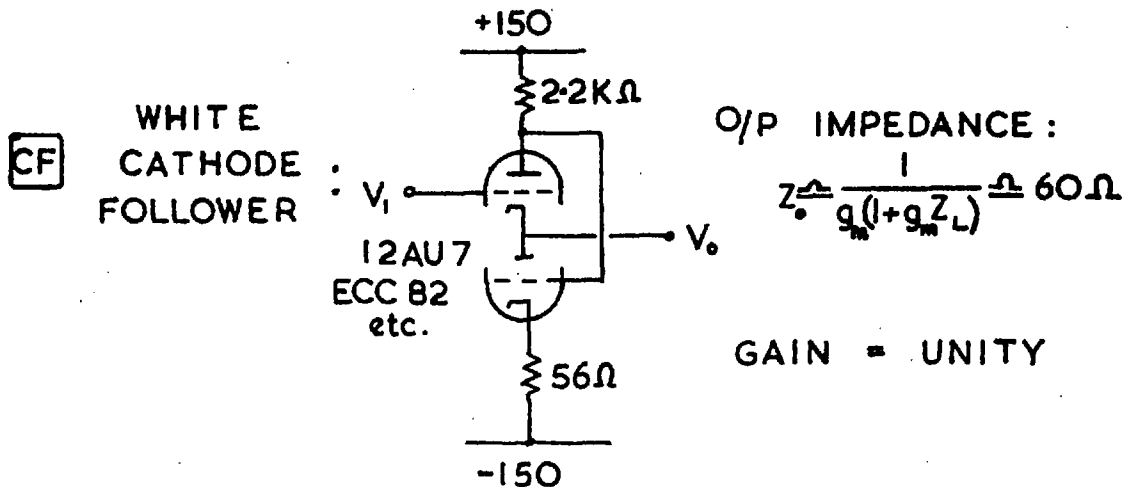
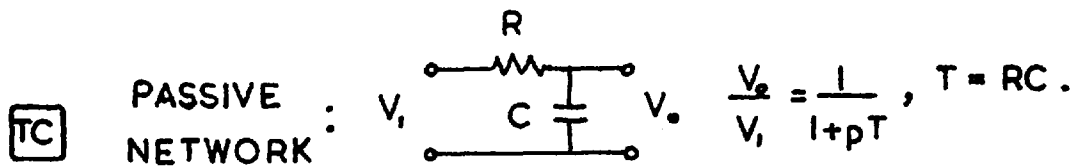
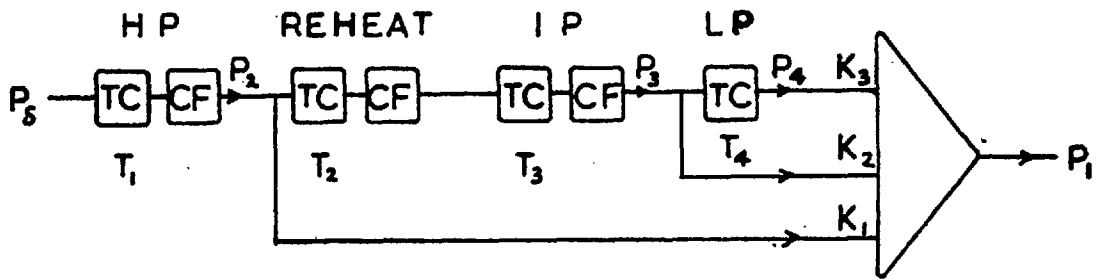
$$T = \frac{CR_1 R_2}{R_1 + R_2}.$$

Note that there is a scaling reduction $\frac{R_2}{R_1 + R_2}$, but this can be corrected at the operational amplifier (by suitable choice of Z_f , or by use of arrangement in Fig. 11e).

The representation of all the transfer functions of Figs. 6 and 8 by operational amplifiers would require twelve integrators and ten summers. Additional amplifiers are also needed in the speeder motor pulsing circuit, for function generation and for other auxiliary circuits such as output drives for pen-recorders (at 'E' and 'F' in Fig. 10). For studies of both reheat and non-reheat sets under simultaneous control in a system, the basic number of amplifiers quoted above would be doubled.

If passive R-C circuits are used to represent all time constants, it is possible to use cathode-follower buffers after those circuits which are required to supply elements other than ordinary inputs to succeeding operational amplifiers. Such a scheme for representation of the turbine is shown in Fig. 12a. Where necessary, each time-constant network is followed by a White Cathode Follower, which has a very high input impedance and offers negligible loading. The White Cathode Follower also possesses an exceptionally low output impedance for the supply of other circuits. Both positive and negative going wavefronts are transmitted faithfully, and this feature together with an output impedance some 11 times less than that of a conventional simple cathode follower makes it particularly suitable. Further discussion of the White Cathode Follower may be found in Farley's book,⁵² p. 105.

The cathode-follower circuit shown in Fig. 12a is direct coupled, and requires a stabilised power supply of $\pm 150\text{V}$, 10mA . Using passive networks wherever possible, the operational amplifier requirement for an analogue of Fig. 6 reduces to three integrators and five summers. However this analogue configuration was found to have two disadvantages:



$$i_a = 10 \text{ mA} ; v_a = 130 - 140 \text{ V} ;$$

$$\mu = 18.5 ; g_m = 2.55 \text{ mA/V} ; r_a = 7 \text{ K}\Omega .$$

FIG. 12a. TURBINE ANALOGUE USING PASSIVE NETWORKS AND CATHODE FOLLOWERS

i. High stability power supplies must be available for the White Cathode Followers, but the circuits have a tendency to drift nevertheless. These drifts, although usually slight, were often sufficient to create appreciable difficulties when attempts were made to set up accurate steady-state initial conditions in the analogue.

ii. When the effect of varying a time constant over two or three decades is under study, as in the cases of meters and control devices in the feedback loops for example, it was somewhat troublesome to repeatedly interchange the appropriate R-C elements.

2.4 The Adopted Analogue.

Ultimately, a compromise was achieved in which only those time constant elements, which could be conveniently followed by operational amplifiers, were represented by passive networks. The complete analogue circuit is given in Fig. 12b. The time constant networks were mounted on panel 'C' in Fig. 10. When it was desired to study the effect of varying a time constant, the appropriate passive network was replaced by an operational amplifier circuit in which the time constant could be readily varied by changing potentiometer settings.

Fig. 12b does not show the auxiliary circuits used for generating P_p functions, or for providing outputs for driving the pen recorders. These circuits were simple, however. The analogue was run in real time, and the scaling of voltage levels was:

$$1 \text{ p.u. power} = 50\text{V}$$

$$1 \text{ c.p.s. frequency} = 50\text{V}$$

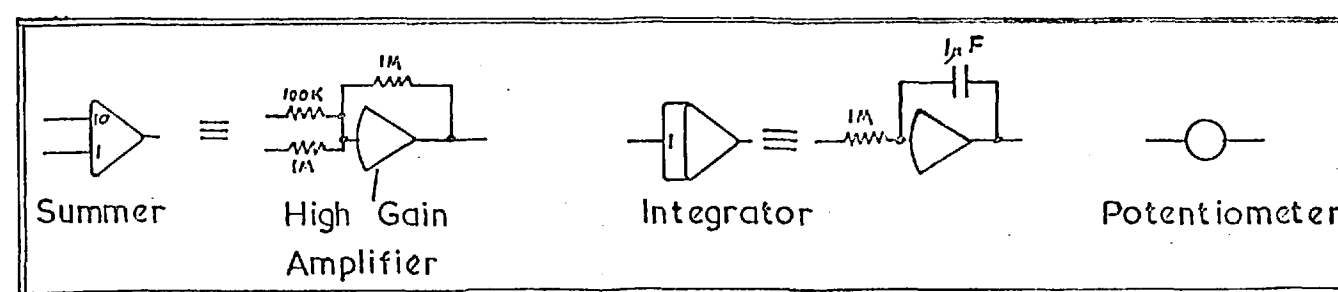


FIG. 12b. CIRCUIT DIAGRAM OF ADOPTED ANALOGUE

2.5 Pulse Generator.

In order to study the effects of pulsed control of the speeder motor, a pulse generator is required, and a satisfactory device was developed as shown in Fig. 13. The required output is a train of pulses of constant amplitude and width having sign and frequency determined by the sign and magnitude of P_e . The sign of the output is determined by the Carpenter relay R_1 , depending on the sign of P_e . The error signal P_e also controls a motor, whose speed is linearly proportional to the magnitude of P_e , and which is geared to a cam which closes a contactor once per revolution. This contactor causes relay R_2 to operate through a summing amplifier. The relay R_2 supplies the leading edge of the pulse to the output, and at the same time releases an integrator circuit, the ramp output of which reduces the voltage holding R_2 , via the summing amplifier, until R_2 opens. The output then falls to zero and the integrator is reset, leaving the circuit conditions ready to repeat the cycle when the next closure of the contactor occurs.

The pulse generator described thus produces output pulses of adjustable height and width at a rate proportional to the amplitude of P_e , and with sign equal to that of P_e . The motor and gear train are shown below 'D' in Fig. 10. The motor power supply and control unit is to the right of 'D' and below 'E'.

2.6 Summary and Discussion of Analogue Studies.

Many scores of analogue runs were carried out with the adopted circuit of Fig. 12b. Results were recorded on paper rolls from a two-track Evershed and Vignoles ink pen recorder, at 'E' in Fig. 10, and from a Philips four-channel recorder at 'F'.

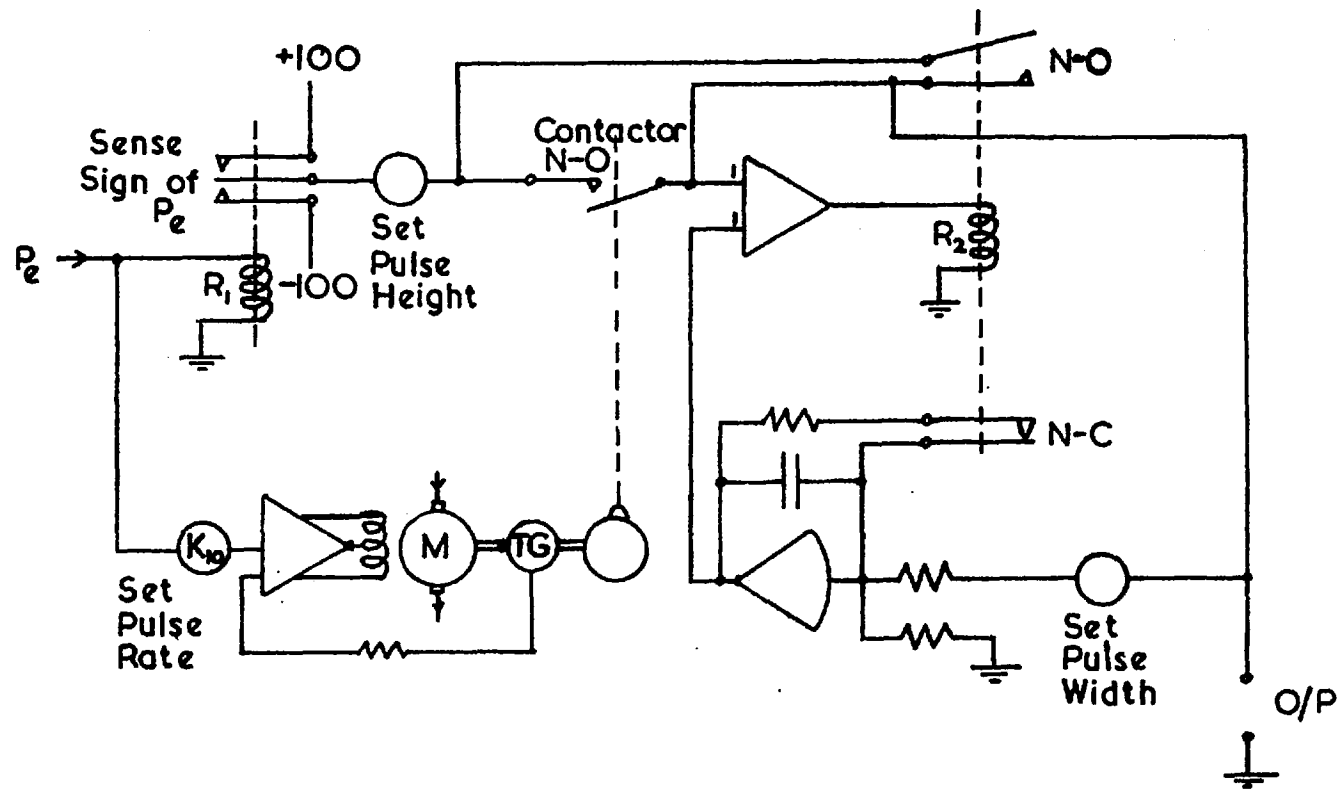


FIG.13. PULSE GENERATOR

The experimental studies can be considered in two groups:

- i. Response of individual turbo-alternator sets to programmed power signals and ramp frequency error inputs.
- ii. Frequency deviation of the system, and individual turbo-alternator stability, in the event of step changes of total system load.

The studies covered wide ranges of control gains and time constants, and different proportions of controlled sets on the system. The effects of some simple limits were also assessed, such as:

- i. The maximum boiler output being limited to 1 p.u. steam power.
- ii. The existence of a maximum practicable rate at which existing speeder motors can operate the governor valves.

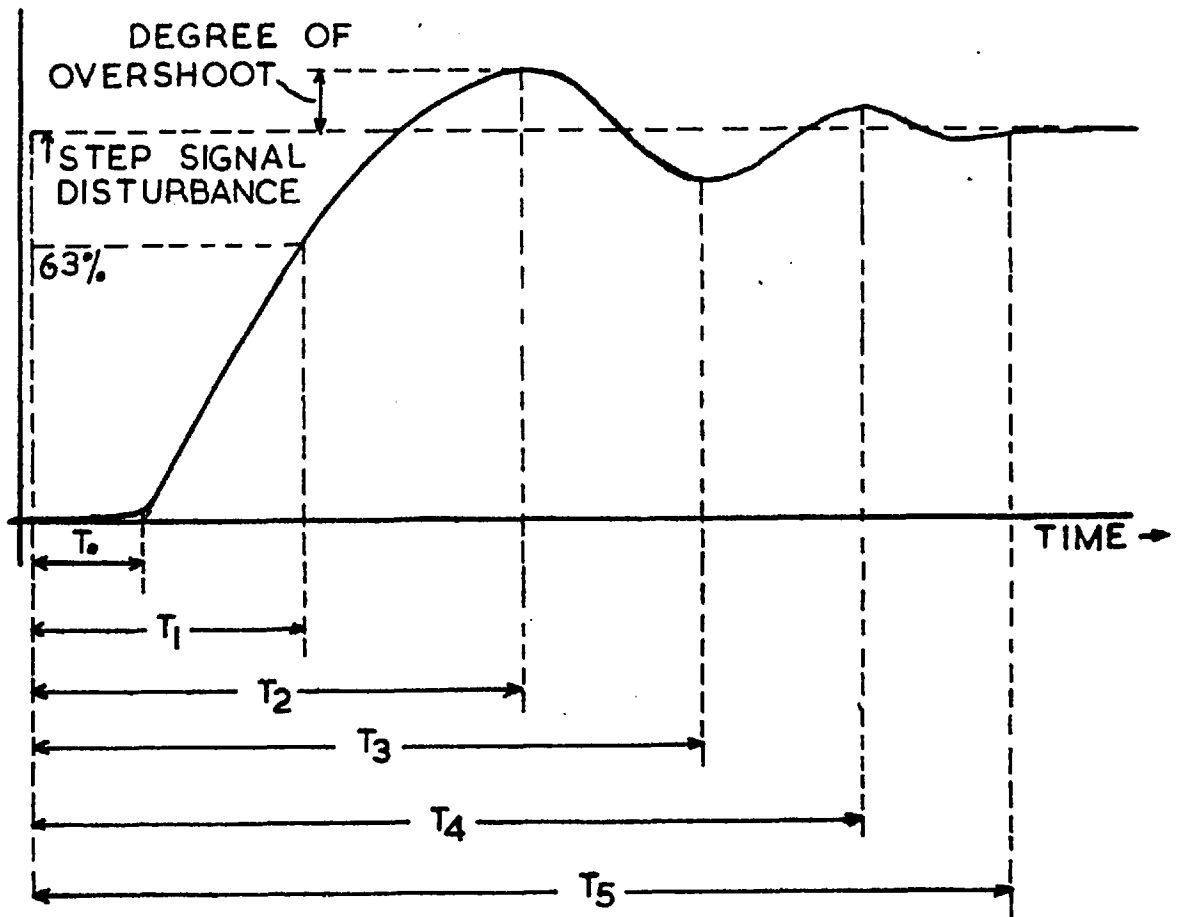
Of the many studies conducted to clarify the overall picture only those are presented here which best illustrate the significant findings to be discussed. The terminology used in the analysis is elucidated by Fig. 14.

2.6.1 Behaviour of Individual Sets.

The tests on individual sets enable the basic performance and stability of the control loops to be assessed. The system simulation to the right of the chain-link line in Fig. 12b was omitted.

Step Changes in Programmed Power.

Fig. 15 shows the response of reheat and non-reheat sets to step increases of 0.1 p.u. in programmed power when the sets are initially running at a steady output of 0.9 p.u.



T_0 = Initial Delay

T_1 = Time to reach 63% of step change = "TIME CONST."

T_2 = Time to reach maximum of disturbance

T_3 = Time to undershoot pre-set level, and with

T_4 , gives a measure of major frequency of response

T_5 = Time to reach steady state conditions

FIG.14. ANALYSIS TERMINOLOGY

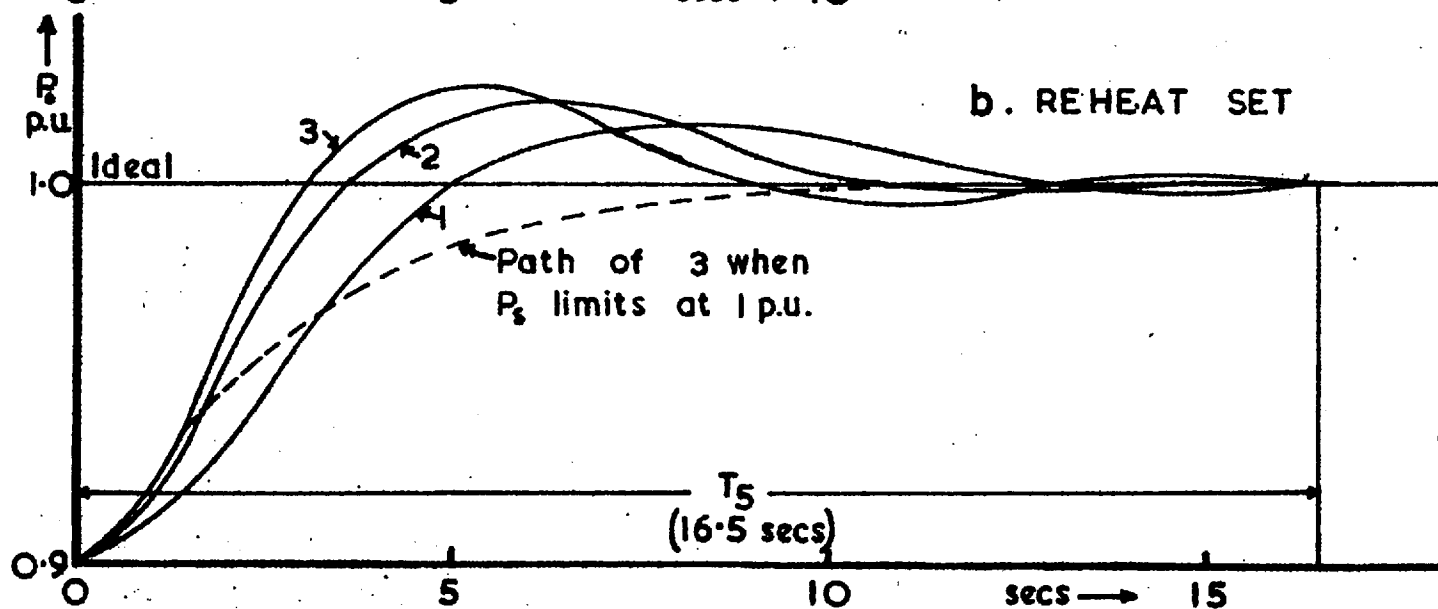
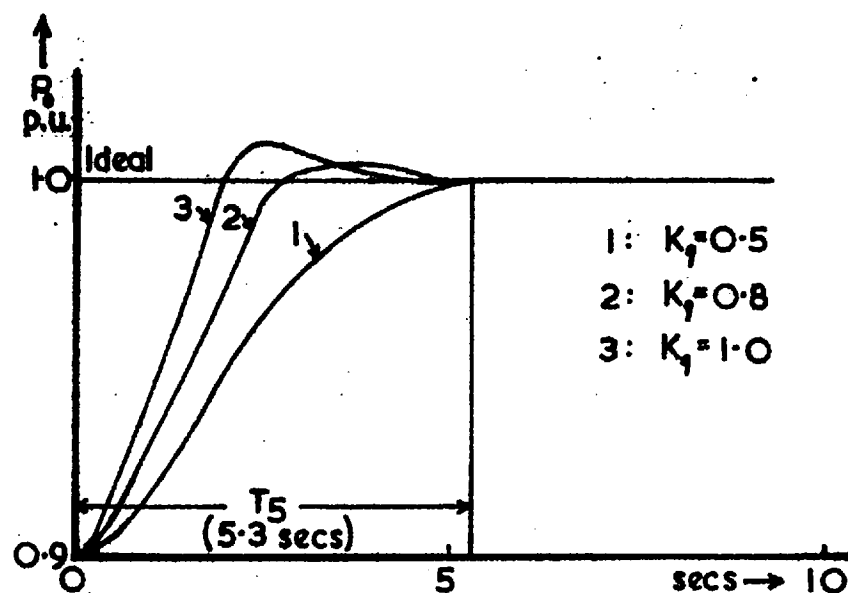


FIG.15. STEP RESPONSE OF INDIVIDUAL SETS

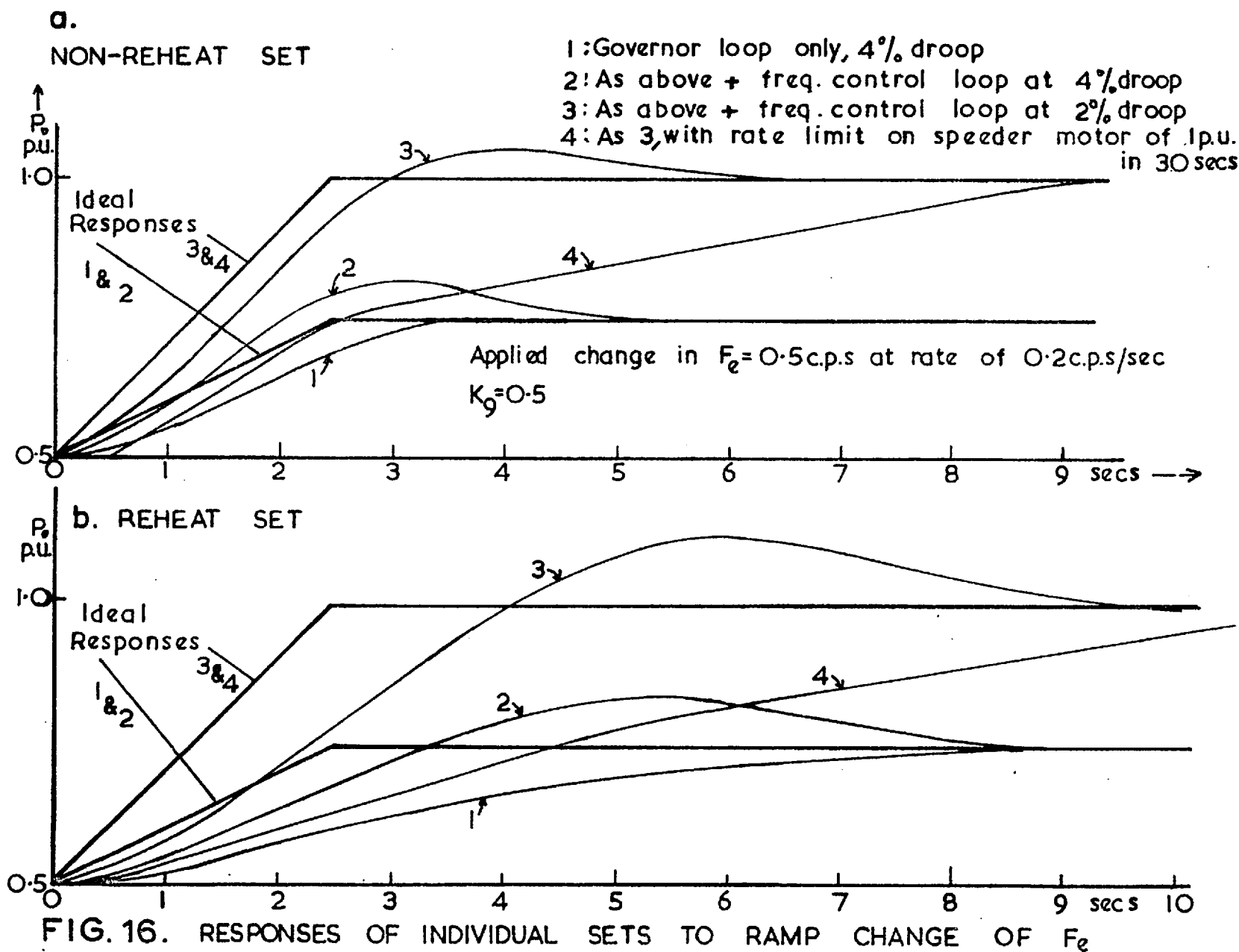
This test might correspond to the worst emergency conditions on the system when the sudden loss of a large set is detected and it is necessary to take up the equivalent generation immediately on the spinning reserve sets (each with 10% spare capacity).

Responses are shown for three values of velodyne control gain of the speeder motor. The behaviour is stable within the full range of gain, having shorter rise times T_1 (see Fig. 14) when K_9 is high, accompanied by higher degrees of overshoot in P_o . The time to reach steady state, T_5 , is seen to be independent of the values of K_9 taken. The transient response of reheat sets is more oscillatory than for non-reheat, and this effect worsens with increasing K_9 .

Ramp Frequency Error.

Fig. 16 shows the changes in power output developed when a ramp frequency error signal is applied to the governor gear and frequency control loop.

The sudden loss of a large set on the system results in an initial linear fall of system frequency F_o , since the frequency error becomes a simple integral of load unbalance (see section 1.7). The machine governors will pick up this ramp change directly, as all machines slow down together, while the frequency control loops on regulating sets will respond to the frequency meter signals. This mode of control would be effective if the programmed power schedule discussed above failed to detect the sudden loss of generation, or was not designed to do so. Clearly the ramp frequency error disturbance is the most severe



frequency disturbance that would be experienced by the control loops in practice.

The deployment of error signals appropriate to the analogue model is shown in Fig. 6. It can be seen in Fig. 16 that good responses are obtainable for frequency control loop gains of 4% and 2% droop. The time taken to reach steady state is again longer for reheat sets than for non-reheat.

The existence of a speeder motor rate limit (0 to 1 p.u. in 30 secs) caused the response to be smoother and slower. These limits were set up in the analogue by fitting biased diodes around the appropriate operational amplifier.

From these analogue studies it can be concluded that the performance of individual sets fitted with the proposed control loops will be satisfactory. The situation studied would correspond to that of a single set being equipped with automatic control and linked to the system in the ordinary way. Ignoring frequency control requirements, it would appear that individual sets can be readily loaded to programmed power levels. Regulation can be successfully applied through the frequency control loop.

In all cases, the behaviour of reheat sets is seen to be more oscillatory than the non-reheat types. This phenomenon is undoubtedly due to the relatively high time lag in the reheat cycle (set at 3 secs in the tests of Figs. 15 and 16). These oscillations could be reduced by including damping or suitable phase advance networks in the control loops. The optimum design of the control loops would have to be matched to each turbine. Alternatively, better control might be achieved by extending

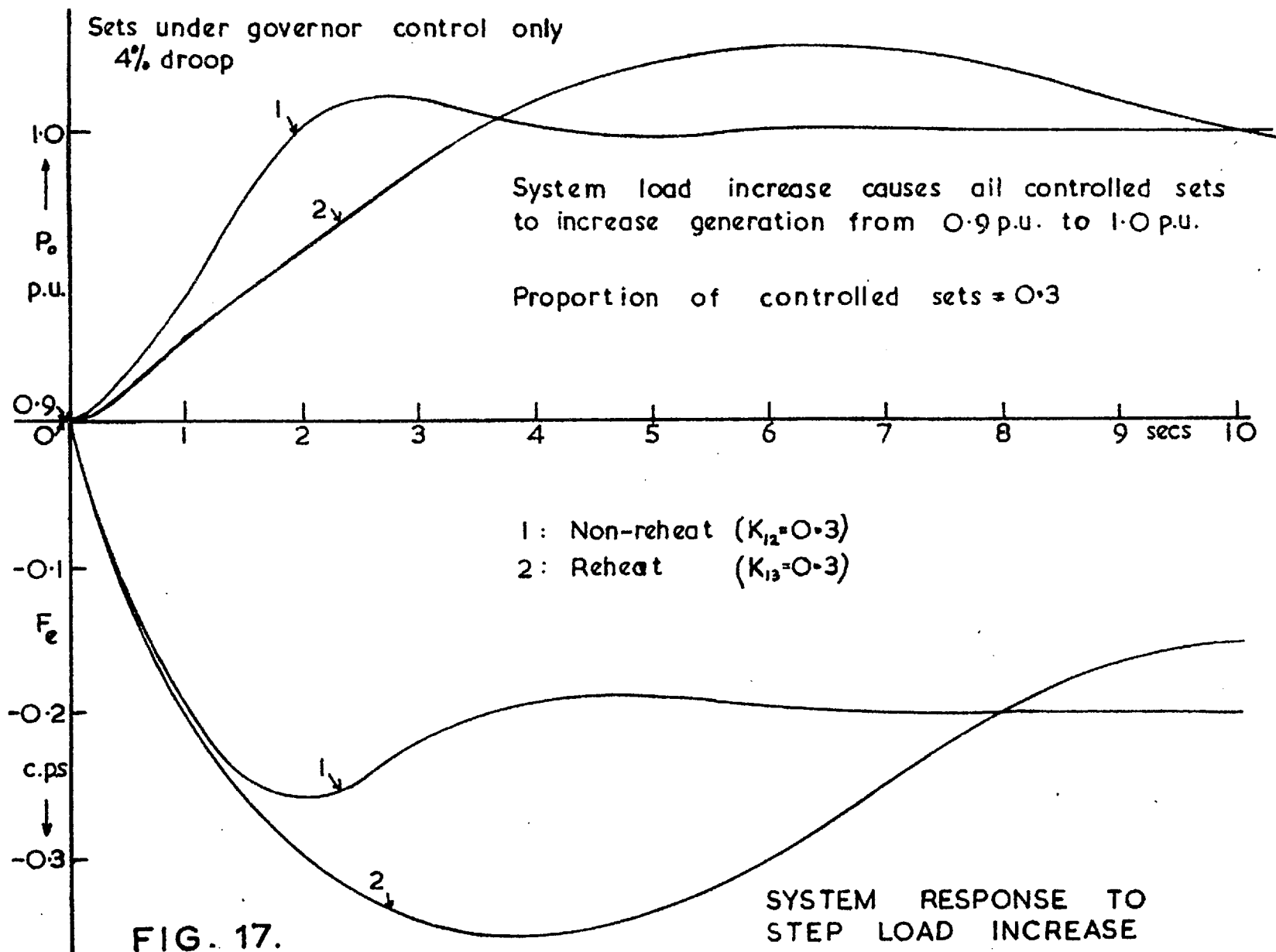
governing action to the intercept valves immediately prior to the I.P. stage (see Fig. 5). These possibilities would be the basis of further analogue studies of particular reheat turbines.

2.6.2. System Response.

In these tests, step changes in system load (set by K_{14} - see Fig. 8) were made after steady state conditions had been set up with all power levels constant and balanced and the system frequency correct at 50 c.p.s., so that frequency error $F_e = 0$. The subsequent variations in system frequency and in the power output levels of the controlled sets were then recorded.

Fig. 17 shows the system behaviour when the regulating sets are on free governor control without the presence of automatic control loops. This represents the present state of a system which is manually operated, and is a basis for comparison with automatic control performance. Results are shown for the two cases: (1) regulation by non-reheat sets, and (2) regulation by reheat sets. In each case the proportion of total generation being carried by regulating sets, K_{12} and K_{13} in Fig. 8, is 0.3, the remaining generators operating at constant (base-load) output power throughout. The system load change was such that all the regulating sets, formerly each running at 0.9 p.u. power output, are subsequently brought up to 1 p.u. power by governor action. It is seen that performance with regulation by non-reheat sets is good (confirmed by existing operational knowledge), but when reheat sets are regulating, the response is much more oscillatory.

Figs. 18 and 19 show the system response with non-reheat and reheat regulating sets respectively when all control



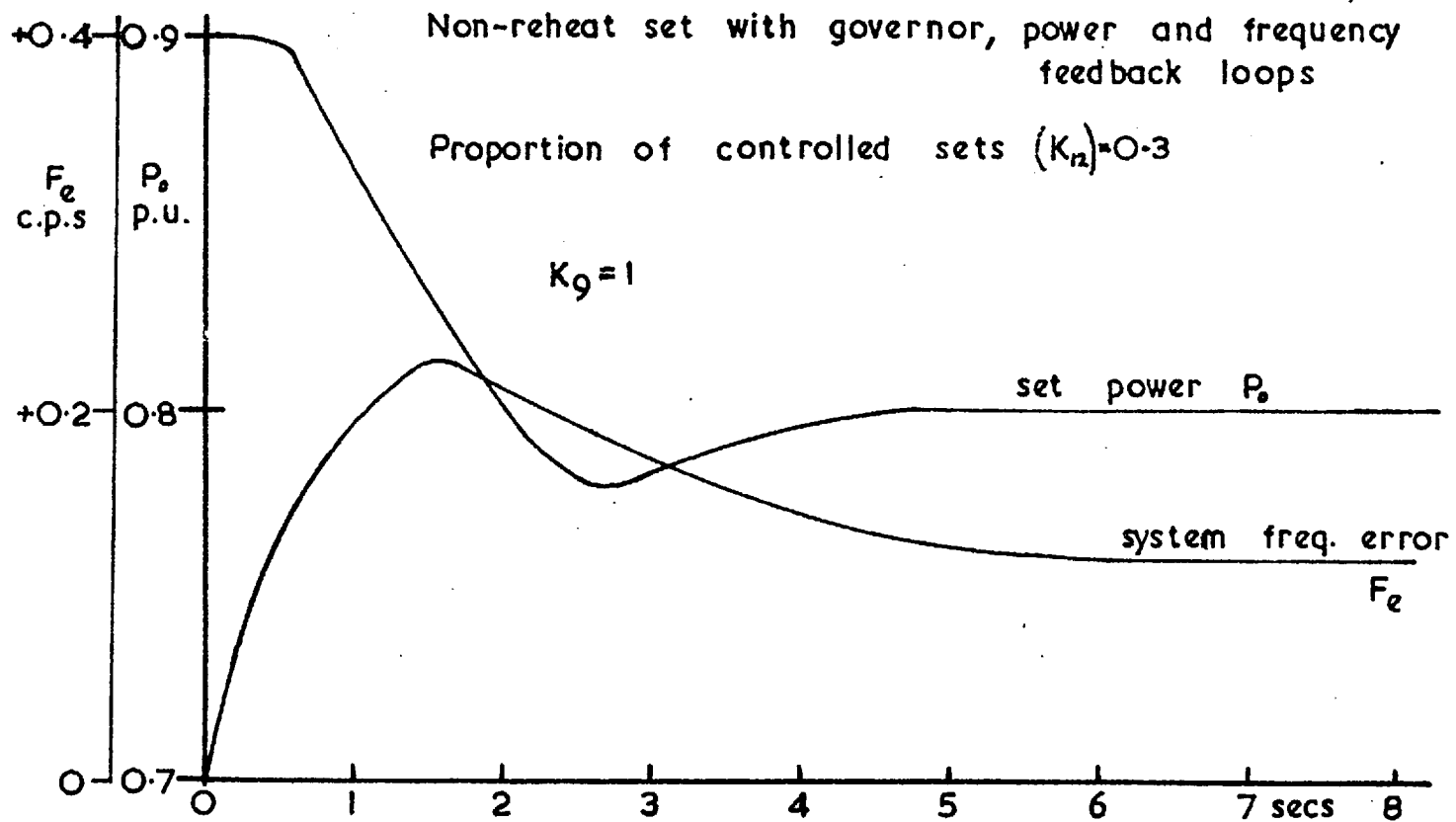


FIG. 18. SYSTEM RESPONSE TO STEP LOAD FALL

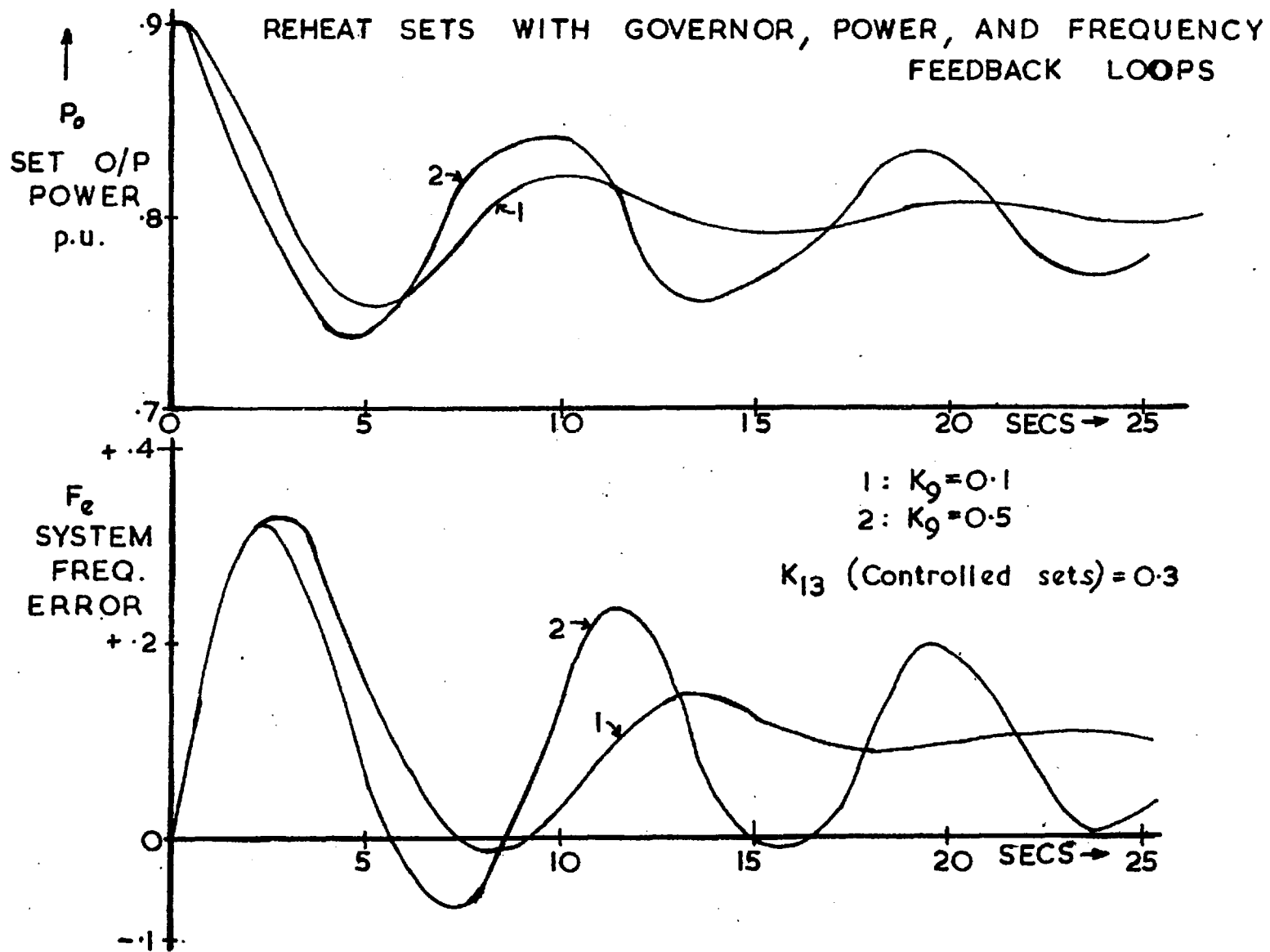


FIG. 19. SYSTEM RESPONSE TO STEP LOAD FALL

loops on these sets are complete. A step-load fall was applied to the system in each case, resulting in a small increase in system frequency. The performance of regulating non-reheat sets is admirable. When reheat sets are regulating under conditions of full automatic control, however, the system becomes highly oscillatory and rapidly approaches instability as control gain K_G increases.

2.6.3 Stability Boundary.

In view of the basically unsatisfactory behaviour of reheat sets in the analogue studies, it was decided to study further the effects of having varying proportions of these sets under automatic control on the system. It is useful, for example, to assess whether significant improvements in response could be made by using fast acting meters and speeder motors, i.e. reducing the time constants of these elements substantially. A satisfactory means of control for reheat sets assumes great importance in future power system planning, because, although all these highly efficient sets now run as base load plant, and regulation is carried out on older non-reheat plant, the time will come when reheat sets are required to regulate for economic reasons at times of light system load. Furthermore, all new sets will be reheat, and will thus comprise a growing proportion of total system generating capacity.

Fig. 20 shows the stability boundary in terms of K_G , the control gain, for a range of proportions K_{13} of reheat regulating plant. Points on this boundary were obtained by adjusting K_G , for given K_{13} , until power output, - or system

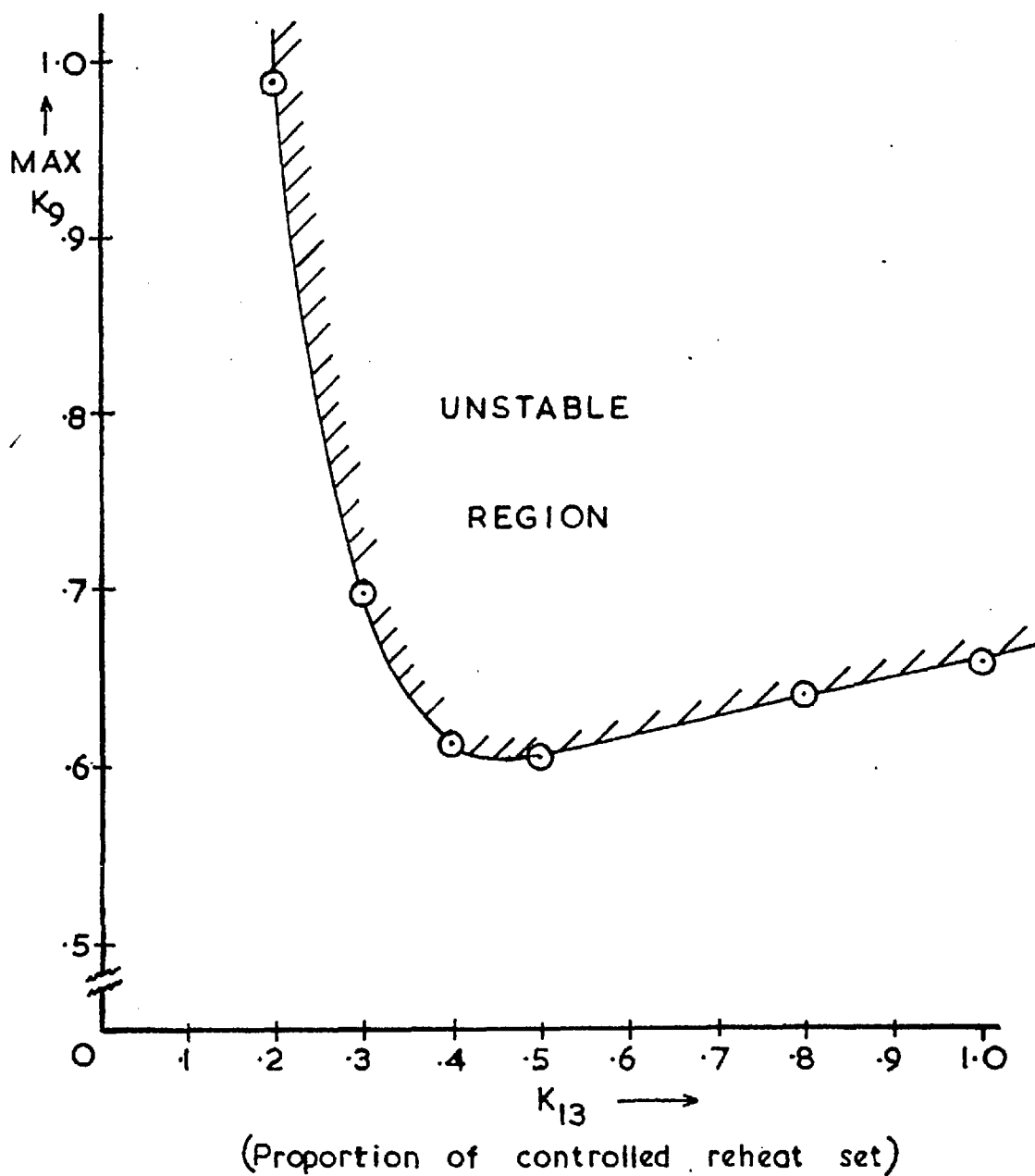


FIG. 20. STABILITY BOUNDARY FOR DIFFERENT PROPORTIONS OF CONTROLLED REHEAT SET

frequency, oscillations of constant amplitude were recorded in response to a small step change in system load. The practical criterion for the critical value was taken as the setting for which five consecutive wave peaks in P_o were constant in amplitude. It can be seen that stability is theoretically attainable for $K_{13} < 0.2$, but the boundary descends abruptly in the neighbourhood of $0.4 < K_{13} < 0.5$. Thereafter there is a slight rise.

Fig. 20 suggests that although stability of a kind could be achieved in the early stages of automation, with only a few regulating reheat sets on the system, there will be a rapid decline in the margin of stability as more of these sets come into service. Even if the value of K_g is kept low, which undesirably makes control response sluggish, it is still apparent from Fig. 19 that the oscillatory response is unsatisfactory, having a poor rate of exponential decay.

Fig. 21 shows the shift in stability limit achieved when individual control loop time constants are reduced. It is seen that although there is advantage in keeping these time constants down from seconds to $\frac{1}{10}$ ths of seconds, very little further improvement is possible in reducing them from $\frac{1}{10}$ ths to $\frac{1}{100}$ ths of seconds. Thus the solution to instability tendencies does not lie in greatly improved instrumentation.

2.6.4 Pulsed Operation of Speeder Motors.

It was observed that pulsed control of individual sets produced similar results to those shown in Figs. 15 and 16. In system studies it is more appropriate to use velodyne simulation only, because a large number of controlled sets working together.

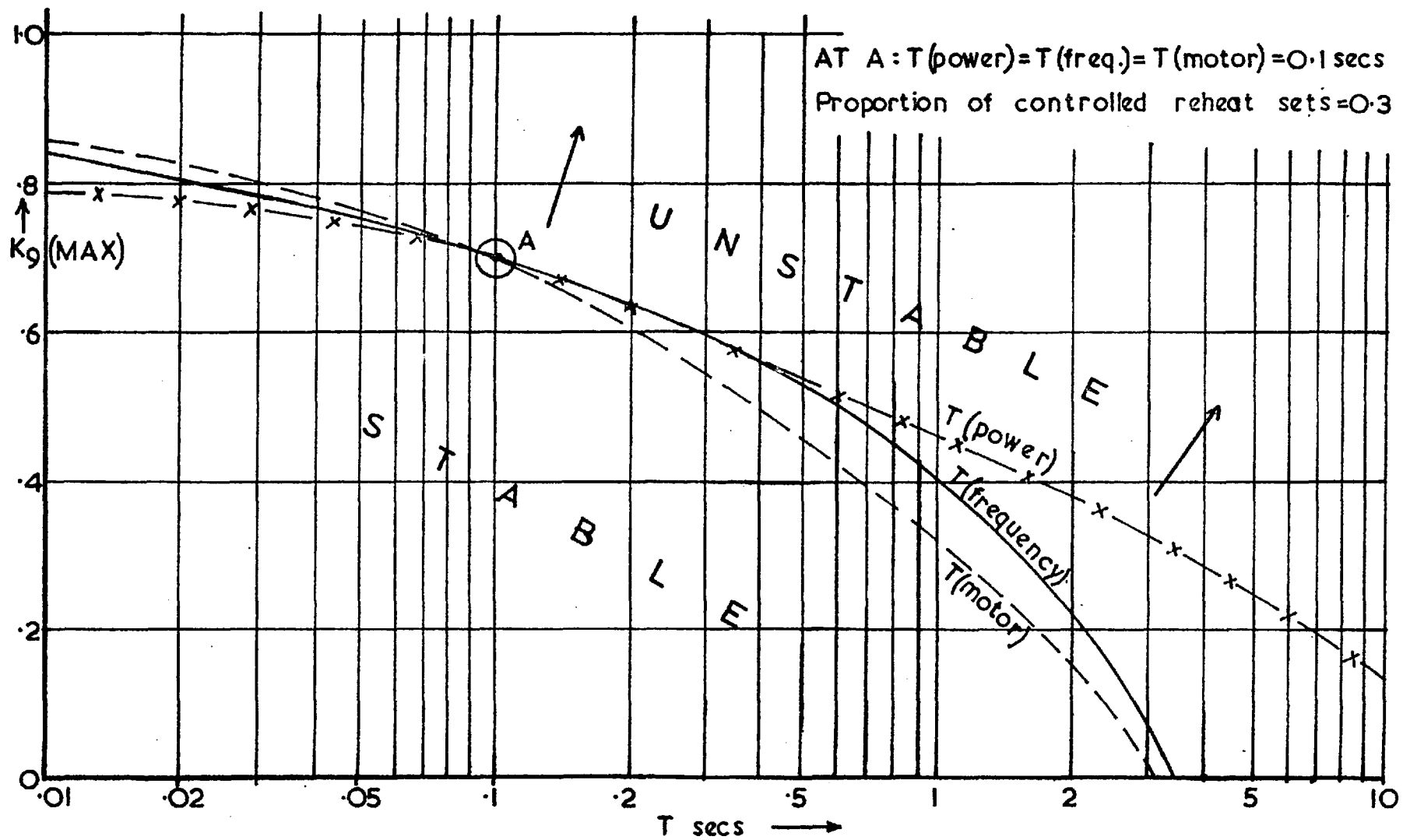


FIG. 21. STABILITY BOUNDARIES AS TIME CONSTANTS VARY

under pulsed operation produce a steady, continuous response in combination.

CHAPTER 3

CONJOINT USE OF NETWORK

ANALYSER AND ANALOGUE

COMPUTER

1. THE NEED FOR A HYBRID SIMULATOR

In this part of the chapter, the reasons for devising a Power System Model are outlined (1.1). Other work which has already been done in this field is surveyed (1.2), and the factors which determine the nature of the scheme adopted here are summarised (1.3).

1.1 The Main Objectives.

The simple analogue computer studies described in the previous chapter showed that the chief source of control instability in power systems is the time delay inherent in a reheat steam turbine, which is of so high a magnitude that it over-rides the combined effects of all other delays. Since all large turbo-alternators are of the reheat type, because this feature makes for higher turbine efficiency, while all future sets to be installed and commissioned will include the reheat cycle for the same reason, it will be necessary to study methods of control of these, both individually and in groups, in greater detail.

The analogue circuitry to represent one machine, according to the simple mathematical model of Fig. 6, required some 18 operational amplifiers plus a number of simple R-C networks for certain of the time constants. To study the problems of automatic control of groups of machines with widely different characteristics (e.g. reheat, non-reheat or hydro sets in thermal, nuclear and hydro stations) it would be necessary to multiply the unit quantity of analogue equipment by the number of separate simulations it is desired to combine in the group.

Furthermore, the transfer functions so far evaluated take account only of bulk power flow: from steam to turbine, turbine to alternator, and from alternator to the power system as a whole. There is no representation of transmission lines or of electrical quantities such as voltages and impedances. Hence there is no provision for study of the special problems created by various electrical interconnection arrangements between machines and by the possible remoteness of load centres from generation sources. Thus the important requirements of voltage control and VAR supply cannot be studied integrally with frequency control and load despatching. (Note that, in chapter 2, generation at unity p.f. and at constant machine terminal voltage of 1 p.u. were assumed, the latter assumption implying the presence of an automatic voltage regulator fast enough to keep machine terminal volts sensibly constant during rotor swings - see section 1.6 in Chapter 2.)

A more sophisticated analogue would incorporate general machine equations (see section 5.1, Chapter 1) for simulation of alternator electrical behaviour and include AVR, transformer and transmission line representation. On the mechanical side, a fully detailed evaluation of boiler, governor and turbine dynamics would be necessary, including simulation of constraints, dead bands and non-linearities. Much of the essential data is not available at present but may be forthcoming from more fully instrumented tests than have been carried out in the past. Results from such tests may verify, for example, a recent proposal by C.E.G.B. workers that the performance of the reheat cycle could more accurately be

represented by a pure time (transport) delay followed by one or more simple time delays, or alternatively, and perhaps better, by a succession of some five or six simple time constants.

When general machine theory is employed, a rotating frame of reference is adopted to reduce the inherent analytical complexity. A rigorous study of the dynamics of a synchronous machine must commence with a choice of an appropriate reference frame. If the differential equations are to be solved on the analogue computer correct choice of reference frame can clear the equations of all terms varying periodically with time and direct d.c. solutions are obtained. This practice was adopted by Aldred, Miles and Shackshaft, for example.^{19,20,21,28}

However, the necessity to envisage power systems within a reference frame distorts the equations into a form that is sometimes difficult to relate to the physics of the system. It should also be remembered that there are several limiting assumptions involved (see section 5.2, Chapter 1). Analogues become very complex when several machines are considered, and this complexity will be accentuated when steam turbines, governors, transmission networks and loads are satisfactorily represented also. Comprehensive power system studies would thus be difficult using entirely d.c. analogue methods. In a very large analogue there are significant accumulated errors from inaccurate coefficient and initial condition settings and from integrator drifts, particularly when long dynamic runs or control sequences are under study.

In order to carry out steady-state stability studies relevant to automatic control investigations concerning load/frequency control, load despatching, system optimisation, voltage/VAR control etc., it is necessary to devise a model which is liberated from artificial references, such as the infinite busbar or source with reference voltage vector of constant amplitude and speed. The model should be fully self-contained and dynamically free to fluctuate in speed in accordance with the true power/frequency characteristics of a power system. It is clear that some suitable means of combining the transfer functions of a mathematical model of generating plant and control equipment with an electrical representation of a power system will facilitate comprehensive control studies.

Thus the need for a hybrid simulator emerges, and the main objectives to be met may be summarised as follows:

- i. To study the general system with different categories of plant and overall automatic control: implying the setting up of full models of at least three machines.
- ii. To liberate the model from artificial references, i.e. to allow it to run free of a.c. sources and busbars in correspondence to the behaviour of real systems. (This objective eliminates the adoption of analogue or digital computers or simple micro-machine methods alone.)
- iii. To incorporate an adequate representation of every part of the system relevant to the overall control problem in the sequence: boiler/governor/valves/turbine/machine electrodynamics/voltage regulator/transmission network/load characteristics.

A flexible simulation of the significant parameters, constraints and delays of each item in this sequence is desired.

The above objectives can be met by a hybrid simulator in which a network analyser is used conjointly with an analogue computer. The fundamental limitations of the analysers and analogues used alone can then be overcome. The transmission network and loads in the power system can be represented directly on the analyser while the dynamics of turbines and machines can be simulated on the analogue equipment. Suitable conversion units are needed to link the two sections of the simulator together, resulting in a complete model of a multi-machine power system.

In the next section, a survey is made of some of the automatic analysers and simulators which have already been designed. Some of the features described in them are relevant to the requirements here, and so form the background from which a suitable scheme can be developed and adopted.

1.2 Survey of Automatic Analysers and Simulators.

The uses and capabilities of network analysers have been briefly mentioned in section 4.1 Chapter 1, where it is pointed out that since the system representation is steady-state, it becomes necessary to use step-by-step processes for stability investigations. This procedure soon becomes unwieldy for the purpose of multi-machine control studies, and section 4 in Chapter 1 has outlined the main alternative techniques that are available - i.e. the possible uses of micro-systems, digital computers, analogue computers or hybrid simulators.

The use of some suitable kind of hybrid simulator emerges as a worthwhile possibility, as discussed above, and those developed in the past were mainly for the solution of simple transient stability problems. Some of the significant practical aspects are high-lighted in the survey which now follows.

Early 'automatic analysers' were developed to save time and labour by mechanising the step-by-step method of solving the differential equations in transient stability studies. Mortlock,⁵⁴ for example, describes a semi-automatic computer which he used in conjunction with a network analyser for this purpose. In this computer, information was stored as settings of potentiometers fed from a common source. For power and angle accumulation, two summators were used. To transfer information from these summators a null balancing method was used, then generator parameters were accordingly adjusted by hand. Jones⁵⁵ used the same technique to develop a computer which only involved one balancing instead of two in Mortlock's computer. Watkins⁵⁶ describes an automatic computer which automatically programmed the step-by-step method. Power was measured by a wattmeter which produced a signal proportional to power. Increments of angle were calculated by a computing device and a summator gave the angle to be set on the network analyser.

Boast and Rector⁵⁷ designed a special purpose analogue computer for transient stability studies. The equation of motion was represented by an L-C-R circuit while photo-formers and amplifiers were used to obtain the power flow.

Kaneff⁵⁸ built a high frequency simulator which used a capacitor to simulate the relation between the stored energy of the machine and its frequency. The synchronous machines were represented by frequency modulated oscillators, the oscillator frequency being controlled by a signal proportional to the accelerating power. Disturbances on the system were repeated by a synchronous switch to get a stationary swing curve on a cathode ray tube. Shen and Packer⁵⁹ developed this simulator further, by using electronic double integrators. The integrator output, a voltage proportional to displacement, operated a cascaded phase modulator to set the machine rotor angle.

A paper by Bekey and Schott⁶⁰ describes a method for direct determination of swing curves by the interconnection of a network analyser and a differential analyser. Electrical power flow from the generator was metered by a wattmeter and converted by an operator to a shaft rotation. Synchros were used to transmit this rotation to the differential analyser, the output of which was fed back to the generator phase shifters.

Among the above devices, the step-by-step types work effectively, but naturally do not permit any improvement in the approximations used in the normal step-by-step method. The L-C-R analogue may be satisfactory for simple transient stability studies but in multi-machine systems a large number of components is required to represent the system analogue. Thus an n -machine system needs $n.(n - 1)$ photo formers and $n.(n - 1)$ amplifiers. In such a complicated system, the correct representation of damping is difficult. Although the analogue operates

independently of a network analyser, the initial conditions, driving point and transfer impedances must be obtained from a network analyser or by computation.

High frequency simulators can only operate with a high frequency network analyser. The accuracy of the electronic wattmeters used (by Kaneff,⁵⁸ and Shen and Packer⁵⁹), was not great. For wide frequency variations such as those arising in asynchronous operation, the linearity of the frequency modulated oscillators would not be satisfactory and one of the main difficulties in design is the elimination of drift from the several oscillators required.

From basic considerations a device is required which can simulate the electro-mechanical equation of motion of a machine in the simplest, most economic way, preferably being continuously actuated, so that more accurate and rapid solutions are obtained than are possible by any step-by-step methods. One of the earliest devices of this kind was developed by Faragalla,⁶¹ who used a motor-generator to drive the selsyn which supplied his analyser network.

The fundamental assumption in these continuous simulators is that, for a single machine connected to an infinite busbar at constant voltages:

$$M \cdot \frac{d^2\delta}{dt^2} + P_d \cdot \frac{d\delta}{dt} + \frac{E \cdot E_1}{X} \sin \delta = P_s$$

where $X = X_e + X'$, M is machine inertia, P_d is damping coefficient, so that at any instant, accelerating power:

$$\begin{aligned}
 P_a &= (P_s - \frac{E.E_1}{X} \sin \delta) \\
 &= P_s - P_o,
 \end{aligned}$$

and this signal is applied to the selsyn which supplies the analyser. Faragalla varied his servo-amplifier gain to represent different inertia constants and damping was simulated by tacho-generator feedback networks.

One of the best accounts of the dynamic operation of an A.C. network analyser was published by Kaneff in 1955²². Kaneff's earlier high frequency simulator (working at 10 Kc/s)⁵⁸ was complicated and required a great deal of special purpose electronic equipment. The advantages of repetitive operation did not justify the complications involved, and a better scheme is to modify the existing selsyn units which supply a conventional network analyser. Accordingly, Kaneff describes a scheme for representing the above electro-mechanical equation of motion of a synchronous machine. A velodyne is used to drive the phase-shifting selsyn and a capacitor serves as an energy store. A special 3-element wattmeter, incorporating a photo-electric error sensing device, was designed to detect power disturbances $P_s - P_o$.

Kaneff claimed that his system could be used on any analyser working in the range of 50 c.p.s. to 10Kc/s. It is useful to have an arbitrary electro-mechanical time scale, and the advantages of setting one minute on the analyser equivalent to one second real time (for fault and transient stability studies) are:

- i. Direct pen recordings are possible (e.g. of swing curves)
- ii. Ordinary relays or mechanical switching for fault studies etc.

can be used.

iii. Equipment design is simplified.

iv. Waiting time for tracing of swing curves is not too long.

The overall delay from initiation of a disturbance on the system to the start of the correct selsyn transformer shaft motion was $\approx$ 15-20 millisecs, and Kaneff claimed that solutions and repeatability were to an accuracy better than 1%.

The chief disadvantage of Kaneff's scheme is probably the need to construct a special wattmeter of high sensitivity, and this was central to his principle of operation.

A paper by Adamson, Barnes and Nellist²³ later compared an automatic step-by-step computer (network analyser) with a direct analogue system for producing power system transient swing curves. Almost all features of previous work along these two lines of approach are summarised. The direct analogue system used is of special interest in that a simple electronic technique is described for obtaining a measure of electrical power output P_o , for constant generator voltage.

A recent paper by Dineley (January, 1964)²⁴ describes the combination of an analogue computer and network analyser for studies of power-system transient stability. The analogue computer solves the general machine equations for the generator and controls electronic phase and amplitude modulators through which a.c. power flows from source to network analyser. The analyser is directly representational, working at a frequency of 1.592 kc/s. The usual assumption of a reference infinite 'busbar' is made.

Dineley's computer probably represents the ultimate in automatic transient-stability analysers. Use of the general machine equations and transformation involves the difficulties and limitations discussed in the previous section of this chapter so that this computer per se would be unsatisfactory for automatic governing and regulating studies of a power system as a whole. Employment of the direct analyser representation, necessitating a supply at 1.592 kc/s is also unfortunate, as this requires an oscillator of high stability with associated power amplifiers (combined with the phase and amplitude modulators). Thus for multi-machine control studies, the technique would require a large analogue computer installation together with many electronic a.c. units.

At the stage when the author was developing the equipment described in the following sections of this chapter, he visited the Central Electricity Research Laboratories (C.E.R.L.) of the C.E.G.B. at Leatherhead, where work was also progressing on the construction of a Power System Model. No details of this model have yet been published, but some general remarks are of relevant interest to the topic of this Thesis.

The C.E.R.L. model has the form of a direct, single phase, A.C. network analyser (at 50 c.p.s.), and includes real time dynamic simulation of generators and loads. Generators are represented as an a.c. voltage of variable amplitude and frequency behind a reactance. Servo loops drive motor/resolver units so as to simulate A.V.R. action and the mechanical energy equation. Loads are simulated as real and reactive power sinks.

The model simulates directly an entire Grid Control Area of the C.E.G.B., and as such there are also facilities for controlling it from a digital computer. The purpose is to develop and test practicable load scheduling programmes. Unlike ordinary network analysers, the frequency of this model can change with excess or deficiency of generation, as in the real system.

The model was designed to simulate overall system dynamics in an economic way, and the representation of each machine is simple, having no facility for detailed simulation of any governor or turbine characteristics, for example, or of non-linearities. The object is to gain an understanding of long-term load flow patterns in the system, and of the general provision that should be made for frequency control as load demand varies. Thus the servo loops of the machines are damped to preserve stability of response, and in fact no disturbances faster than 1 c.p.s. can be followed spontaneously.

The C.E.G.B. workers have said that the decision to design and construct the model was based on such facts as:

- i. The alternative use of a digital computer for the load flow and scheduling studies would have been too slow. Thus it was found that the I.B.M. 7090 computer could only reach solutions at three minute intervals -- by simultaneous solution of sets of equations.
- ii. The alternative use of an analogue computer would be too expensive. An analogue using Park's equations etc. would be elaborate and require 1100 operational amplifiers -- resulting in a cost of the order of £250,000.

In the author's view the model possesses the additional, substantial, advantage that the observer is presented with a real-time, direct, physical simulation of the actual behaviour of a power system.

1.3 The Adopted Scheme.

The scheme adopted to enable a network analyser to be used conjointly with an analogue computer was determined by the following factors:

- i. The objectives listed in section 1.1 above.
- ii. A consideration of the practical techniques reviewed in the survey of section 1.2 above.
- iii. The decision to keep the need for special-purpose units to a minimum.
- iv. The performance of the model should have an accuracy of the order 1-2%.
- v. Interconnection facilities should be flexible, so that different power system configurations can be easily modelled.
- vi. The task of establishing initial conditions prior to a study should be as simple as possible.
- vii. A direct visual display of the dynamic behaviour of the model is desirable.
- viii. Facilities must exist for direct recording of such quantities as power flows, voltage levels, machine rotor angles, system frequency, etc.

The network analyser used in the laboratory model is of the conjugate impedance type, operating at 50 c.p.s., manufactured by Nash and Thompson. A full description of this analyser, including

specifications, has been published in an I.E.E. paper by Casson and Hales.⁶²

The analogue computer consists of the equipment described in Chapter 2, section 2.1, with the addition of a second Solarton Minispace (SCD 10) containing ten operational D.C. amplifiers and six electronic multiplier units.

Coupling between the network analyser and analogue computer is achieved by means of specially developed velodyne/magslip units. The velodynes are actuated by d.c. servo amplifiers of conventional design. The way in which the simulation of elements of a power system is distributed between analogue computer, coupling units, and network analyser is shown in the block diagram of Fig. 22. A general view of the equipment is shown in Fig. 23.

2. DESCRIPTION OF POWER SYSTEM MODEL

The adopted Power System Model is first described in general terms (2.1), and then the special principles of operation of the coupling units are discussed (2.2 and 2.3). The coupling equipment can be mounted in a 19" rack (2.4). Details of the circuits follow in the next chapter.

2.1 General.

The block diagram of Fig. 22 shows how the conjugate network analyser representing lines and loads can be operated conjointly with an analogue computer representing the generating plant and its associated control equipment. The appropriateness of the configurations of the two representations for their respective purposes gives a flexibility which enables a system to be modelled with economy and speed, and has been found to possess a realism that is both educative and suggestive. In the pages which follow, 'Power System Model' refers to the complete range of equipment pictured in Fig. 23.

Since the power system laboratories at Imperial College already possessed a conjugate network analyser, intended for steady state power flow studies, and a range of Solarton D.C. analogue computer equipment, the author decided to incorporate this equipment in the Power System Model for reasons of economy and convenience, and work commenced with the development of prototype coupling units of a suitable nature.

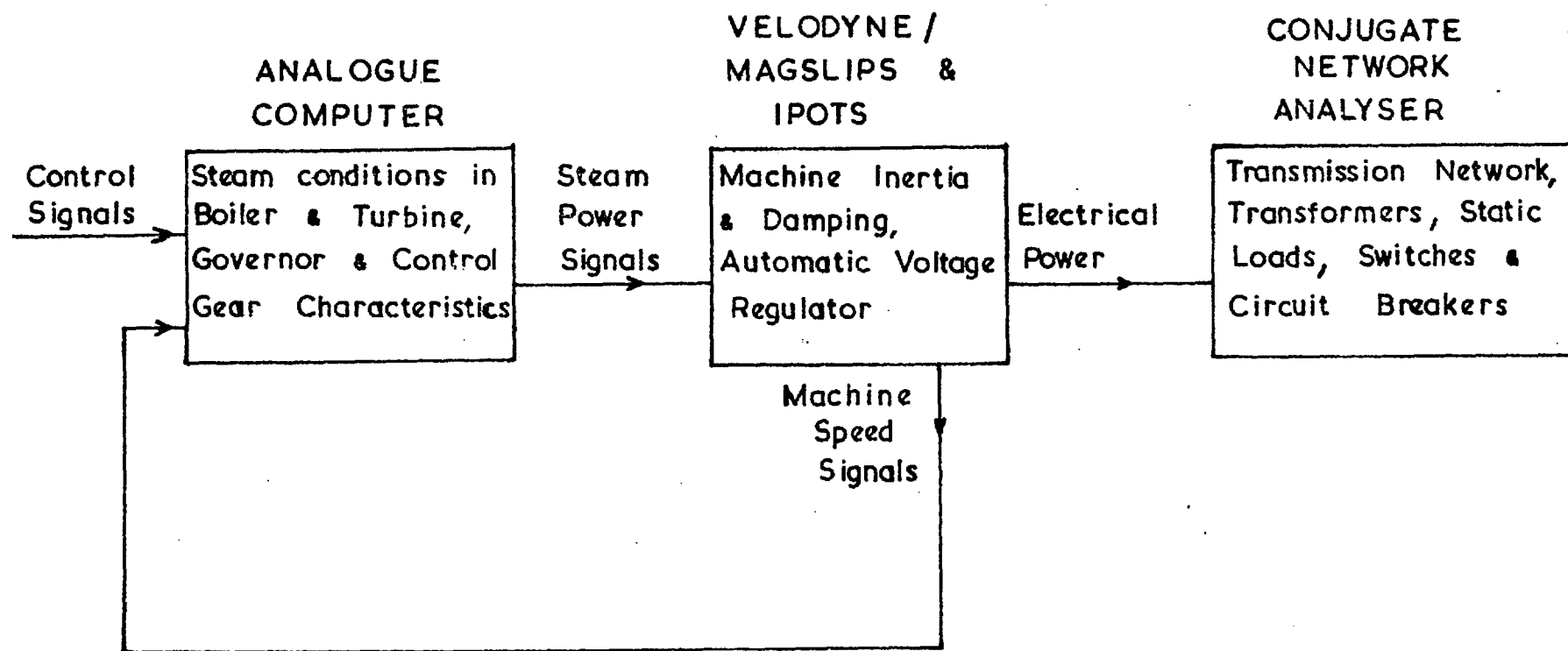


FIG. 22. POWER SYSTEM MODEL

ANALOGUE COMPUTER

MACHINE
UNITS

CONJUGATE NETWORK
ANALYSER

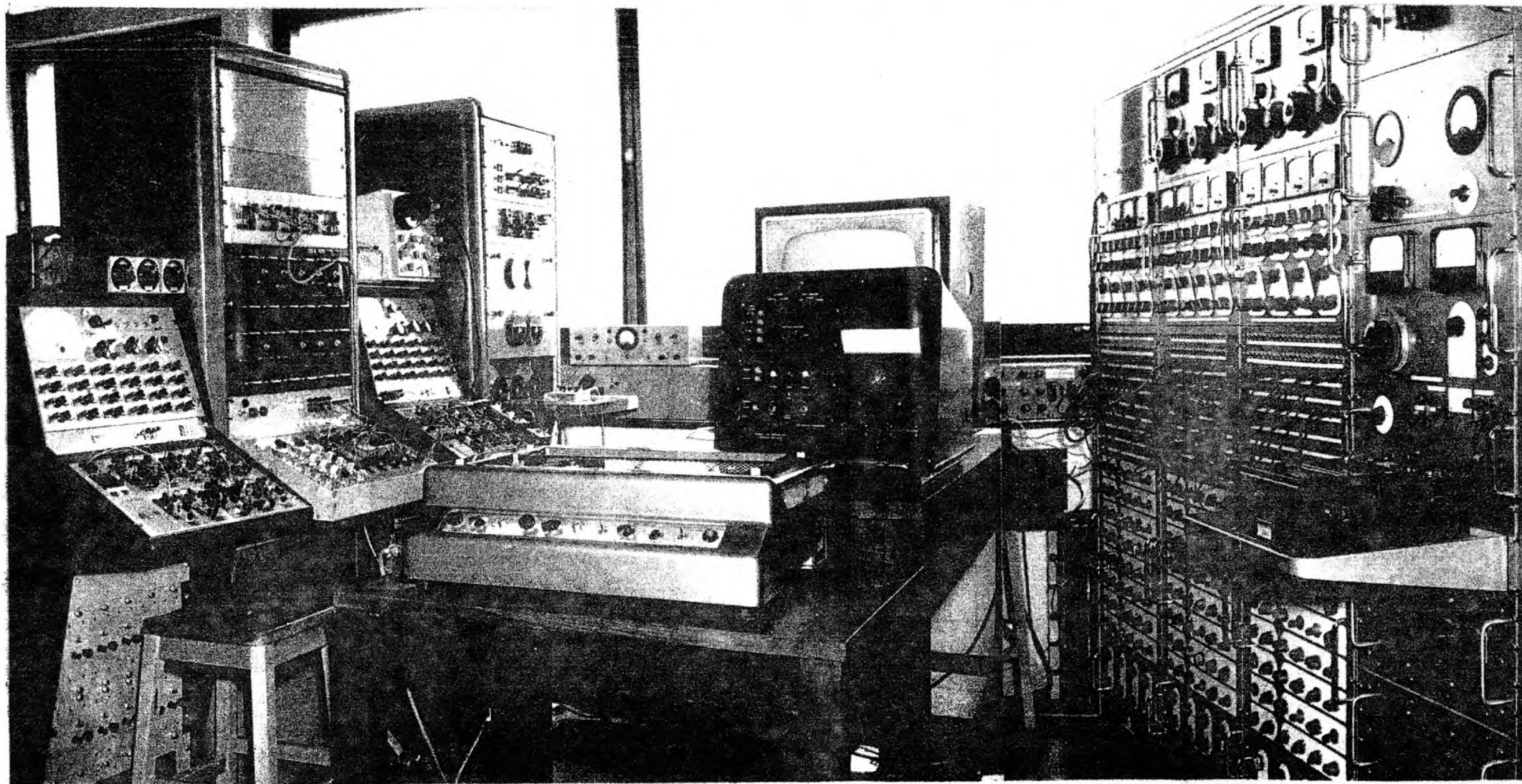


FIG. 23. POWER SYSTEM MODEL — GENERAL VIEW

It was broadly decided that boiler and turbine characteristics, governors and control equipment would be simulated on the analogue computer which would provide actuating signals for velodynes coupled to magslips, from which the A.C. supply to the analyser is derived. Special feedback loops round the velodynes would be employed to synthesise the inertia and damping characteristics of the turbo-alternators, and the entire electrical side of a power system would be represented in conjugate form on the analyser. When equipped with comprehensive metering and recording facilities it was anticipated that the Model would be adequately versatile to enable a variety of control techniques to be studied.

The prototype velodyne/magslip units are mounted on steel baseplates which can be conveniently fitted into a standard 19" Imhof rack. A pair of these units is shown in Fig. 24a. The gearing through which the velodynes drive the magslips can be clearly seen. The associated voltage regulators are simple position control servomechanisms, utilising inductive potentiometers. An assembly of three automatic voltage regulator units (A.V.R.'s) is shown in Fig. 24b, these being also mounted on a baseplate. The principles of operation and the schematic circuits of these coupling units are described in the following sections of this chapter. Details of the circuits, including special equipment and interconnections, are described in chapter 4.

Four basic machine units and three voltage regulators were finally constructed, together with the necessary auxiliary devices, associated servo-amplifiers, power supplies and suitable interconnection arrangements. Thirty d.c. operational amplifiers

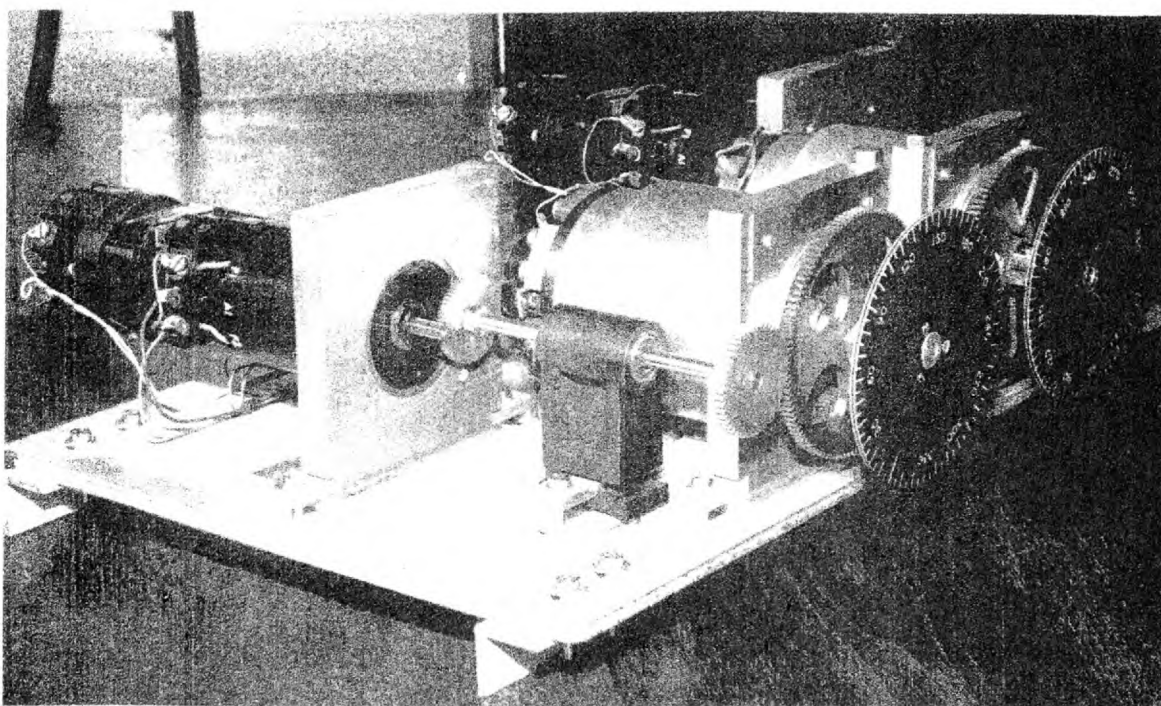


FIG. 24a. A PAIR OF VELODYNE/MAGSLIP UNITS

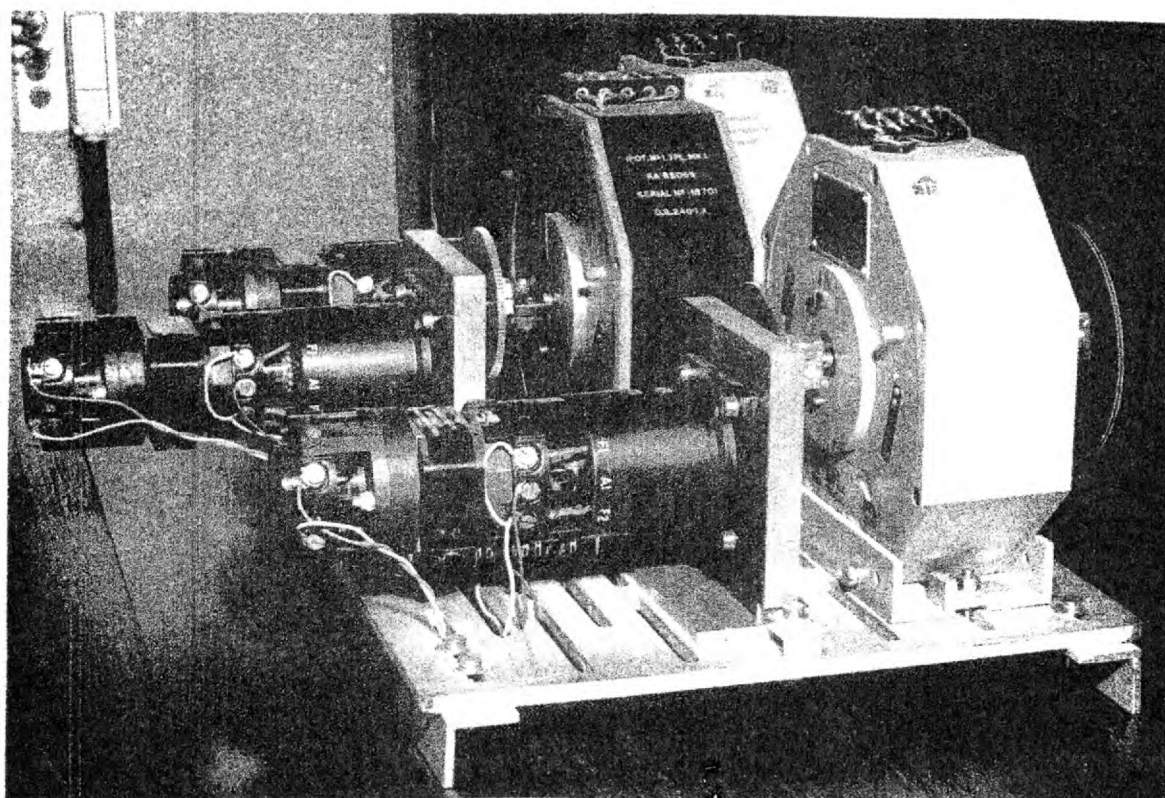


FIG. 24 b. ASSEMBLY OF THREE A.V.R.s.

are available in the analogue computer, together with six mark-space electronic multiplier units, one diode function generator, and a specially assembled network of passive R-C elements. There is adequate capacity on the network analyser for setting up machine, transmission line and load impedances and system transformers, relating to the study of 4-machine systems. The main recording instruments used are a 4-beam long persistence Airmec CRT, a Bryans X-Y plotter, and a multi-channel UV recorder. Ordinary laboratory oscilloscopes and meters are used for monitoring purposes.

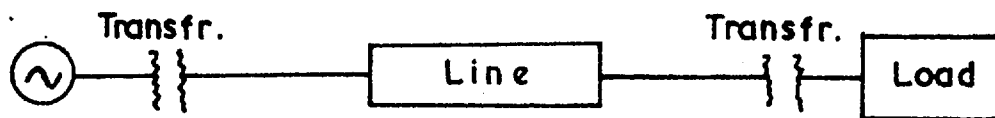
The overall accuracy attainable in the Solartron Minispace equipment is of the order of $\pm 1\%$. In the conjugate network analyser, the accuracy of the measuring equipment is stated to be better than $\pm 1\%$, and $\pm 2\%$ overall.⁶² To achieve the required degree of accuracy of 1-2% for the Model as a whole, a figure of $\pm 1\%$ was aimed at in the design of the coupling units and their associated auxiliary circuits.

It is not intended here to present a comprehensive account of the various types of network analyser which might well be alternatively used in the Power System Model. This matter was mentioned in section 4.1 of Chapter 1. There are, however, some special advantages in using an analyser of the conjugate impedance type, and it is worth recalling these here. There is also a consequence of special note concerning the representation of machine electrodynamics.

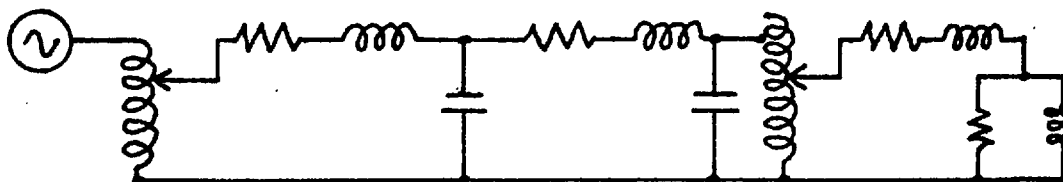
The advantages of using a conjugate network analyser in the model are:

- i. It is convenient to draw supplies (for magslip stators) direct from the 3-phase 50 c.p.s. mains. Hence a separate oscillator and ancilliary amplifier are not required.
- ii. The transposition of inductive and capacitative elements enables lines to be represented chiefly by capacitors, which, for suitable choice of base quantities will be less bulky and more economic than the equivalent inductors. The predominance of capacitors in a conjugate impedance representation of a system is shown clearly in Fig. 25c.
- iii. Minimum cost is secured by employing uncalibrated network impedance elements. Since these consist, for the most part, of resistors and capacitors, the use of readily available commercial wide-tolerance components is permissible. (Capacitors and resistors are arranged in decades with potentiometers for fine-setting of resistive impedances. Calibration of the impedances is carried out with the aid of the metering equipment in the analyser.)

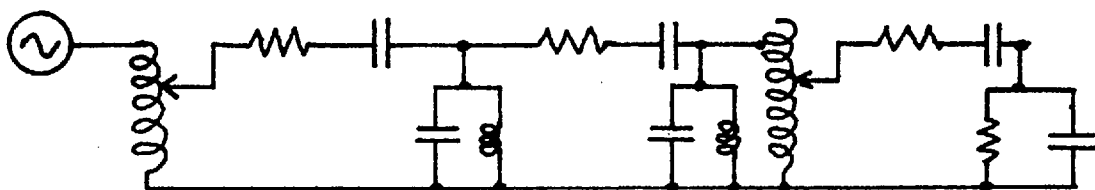
The conjugate impedance principle and 50 c.p.s. operation having been adopted, the remaining base operating quantities are determined by the operating voltage of the magslip transmitters used in the generator and impedance calibration units and the range of commercially available capacitors. The magslip transmitters in the generator units operate at 50 volts r.m.s., and this is adopted as a convenient base voltage for the analyser. To secure the maximum financial economy it is desirable to use the minimum sizes of capacitor, and to this end a high-impedance base is desirable: however, too high an impedance would result in the adoption of an undesirably low current base, and from considerations of metering



25 a. ACTUAL SYSTEM



25 b. CONVENTIONAL REPRESENTATION



25 c. CONJUGATE

NOTE PREDOMINANCE OF CAPACITORS IN
CONJUGATE

FIG. 25.

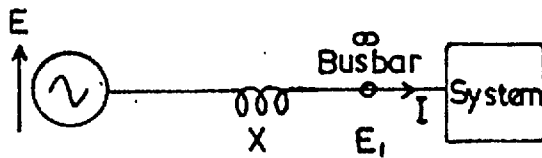
equipment and auto-transformer design it is not prudent to use a base current of less than 5mA. Consequent upon the decision to use this base current the resulting base values are:

Voltage : 50v
 Current : 5mA
 Impedance : $10K\Omega$ ($C = 0.3183\mu F$)
 Power : 250 mVA
 Admittance : 100 micromhos
 Frequency : 50 c.p.s.

It is of interest to note that a comparative assessment of the costs of an a.c. network analyser of the type outlined by Casson and Hales⁶² relative to

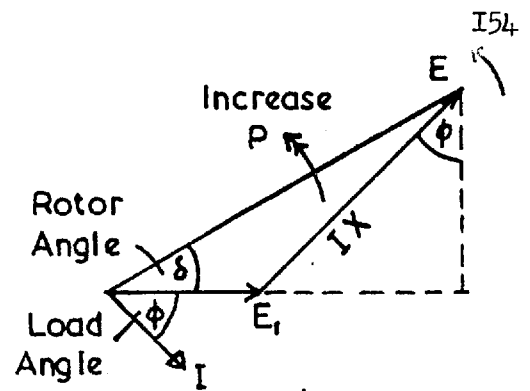
- i. a conventional d.c. network analyser
 - ii. a conventional direct impedance 1 Kc/s network analyser,
- on the basis of similar conditions of manufacture, indicates that the cost of (i) is approximately half that of the 50 c.p.s. equipment while (ii) is approximately three times as costly. It further follows that the manifold advantages attendant upon having available an a.c. rather than a d.c. equipment can be obtained for a modest increase in capital outlay.

The particular consequence of a conjugate representation upon machine electrodynamic simulation is made clear in Fig. 26. It can be seen that in the conjugate system, the load/speed relationship is reversed. Thus load increases must be met dynamically by retarding the magslip rotors, not by advancing them, which is analogous in real power system operation to 'speeding up' a turbo-alternator by admitting more steam to increase the rotor



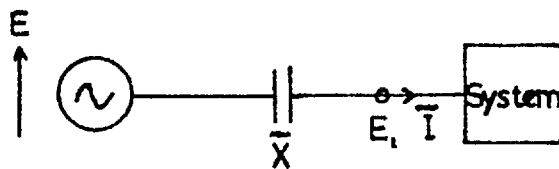
POWER TRANSFER

$$P = E_1 I \cos \phi = \frac{E E_1 \sin \delta}{X}$$



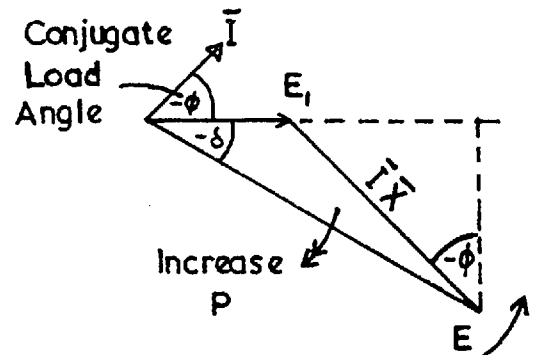
To increase P (by increasing δ) Rotor Vector E must be ACCELERATED relative to ∞ Busbar Vector E_1

NORMAL ELECTRODYNAMICS



POWER TRANSFER

$$P = E_1 \bar{I} \cos(-\phi) = \frac{E E_1 \sin(-\delta)}{X}$$



To increase P (by increasing δ) Rotor Vector E must be RETARDED relative to ∞ Busbar Vector E_1

CONJUGATE ELECTRODYNAMICS

FIG. 26. CONSEQUENCE OF CONJUGATE REPRESENTATION ON MACHINE ELECTRODYNAMICS

angle δ . The machine frequency F_M , in the Model, at any instant, will be:

$$F_M = 50 \left(\frac{\text{mains}}{\text{nominal}} \right) + \frac{\dot{\delta}}{2\pi} \text{ c.p.s.}$$

2.2 Velodyne/Magslip Units.

In a velodyne/magslip unit, inertia and damping are controlled by capacitative and resistive feedback from the tacho generator to the servo-amplifier. An electronic wattmeter provides a D.C. signal proportional to electrical power output from magslip rotor to network analyser. The difference between the electrical power signal and the steam power signal from the analogue computer (both D.C. voltages) is applied to the servo amplifier which causes acceleration of the velodyne/magslip unit. The sense of the acceleration is arranged to correspond to the conjugate electrodynamic representation discussed above.

2.2.1 Velodynes.

The velodyne is fundamentally an electromechanical system in which speed of rotation of a shaft is accurately proportional to a control voltage. A complete unit consists of a motor and generator mounted in the same frame, the motor and generator armatures being wound on the same shaft, the generator field occupying one end of the frame and the motor field the other. The armature of the motor is fed with a substantially constant current, usually from a fixed voltage higher than the maximum back e.m.f. through a series resistance. The motor field, which is wound in two sections, is connected directly into the anode circuits of two valves, the output valves of the associated servo-amplifier. If the amplifier input is zero then the field

current through the motor may be brought effectively to zero by suitable adjustment of the amplifier. If a voltage input is then applied to the amplifier, unbalanced field currents will flow and the motor will accelerate. The generator output voltage is so connected that it opposes the actuating voltage and ultimately a state of equilibrium is attained where the motor rotates at constant speed. Smooth rotation at as low a speed of 4 r.p.m. is attainable. If a load is connected to the motor shaft, the speed tends to fall hence reducing the generator output and increasing the effective input to the amplifier. Thus the load on the motor may vary over a wide range without materially affecting the motor speed. Information on Velodyne motor generators has been given by Williams and Uttley.⁶³ Discussion of the servo-control circuitry appears in Porter's Monograph,⁶⁴ p. 23.

The velodyne motor generator used in the prototype velodyne/magslip units was the FAD/6 64/BD (Evershed and Vignoles), which has the following characteristics:

<u>Motor</u>	armature current	: 500 mA
	field supply	: 40/40 mA
	full load torque	: 0/80 mA.
	$\frac{1}{4}$ " diameter plain shaft	
<u>Generator</u>	permanent magnet field	
	output	: 20V/1000 R.P.M. (into 10K Ω resistor)
	working range	: 0 - 6000 R.P.M.

The MG units can be seen in Fig. 24a.

After building the prototypes, two more model machine units were assembled, and these incorporated motor generators of the type FAG/1 K4 (Evershed and Vignoles). These differ from the above FAD types only in requiring a motor armature current of 350 mA and in having a pinion shaft of 10 teeth, 48 D.P. They were used for the A.V.R.'s also, because a batch of one dozen were obtainable cheaply from Servo and Electronic Sales Ltd.

2.2.2 Magslips.

The nomenclature concerning magslips, selsyns and synchros is involved. Unfortunately, the term 'Synchro', which was originally an American term, is now generally understood to apply only to rotary inductors of recent design to NATO specification. The term 'Synchro' strictly refers to the whole family of electromechanical instruments of the rotary inductor family used to produce an electrical signal dependent on relative shaft position. The three main groups of Synchros are MAGSLIPS, originally developed by the Admiralty Research Laboratory, SELSYNS and SYNCHROS used in its restricted sense.

A synchro is a machine resembling an electric motor in so far as it possesses rotor and stator windings, the rotor being supported in bearings mounted at each end. The winding details differ widely according to the function which the synchro is to be called upon to perform. The operation of a synchro depends on the varying degree of coupling between the windings when the rotor is rotated. Most synchros have their rotors fitted with slip rings for connection to the external circuit. Synchros are generally fitted with close tolerance bearings which assist in keeping vibration,

dependent on the supply frequency, to a minimum. Where free rotation is desirable, however, it is usual to fit standard free races or magneto type races together with a specially designed brush and slip ring assembly or flexible ligaments to keep to a minimum frictional forces. Skewed slots are usually incorporated either in the rotor or stator assemblies in order to prevent locking of the machine to the supply frequency.

The simplest function of Synchros is their use as a synchronous link or for remote indication. The behaviour of this kind of system is described by Porter, p. 6.⁶⁴

Synchros may also be used as a high precision variable phase source, and this is the application required here. Two suitable types of magslip are the 3" X-CO Transmitter AP10747 and the 3" Transmitter AP6547, obtainable from Servo and Electronic Sales Ltd., at £4.0.0 and £2.5.0 respectively. The winding connections are shown in Fig. 27. The method of use is to supply the stator with 3-phase 50V 50 c.p.s. Output is taken from X and 3R connections on AP10747 or from X and Y on AP6547. The sinusoidal waveform obtained from the rotor is good, being 50V a.c. and varying in phase relative to a supply phase through 360° as the rotor is turned through one revolution. If the magslip rotor is driven at a speed $\dot{\delta}$, then the resultant output frequency F_M is:

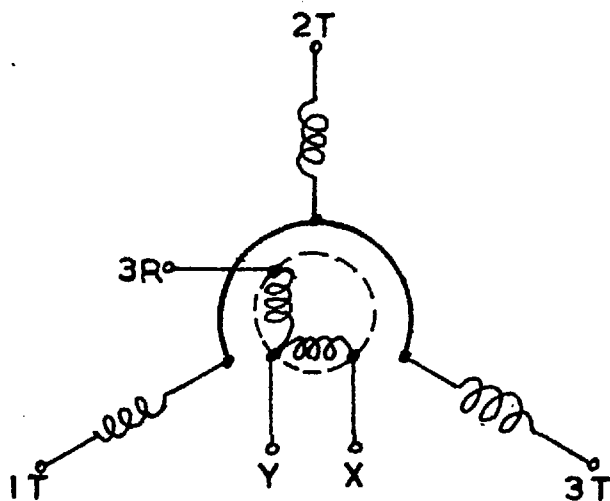
$$F_M = 50 \left(\frac{\text{mains}}{\text{nominal}} \right) + \frac{\dot{\delta}}{2\pi} \text{ c.p.s.}$$

Electrical data of the magslips used is:

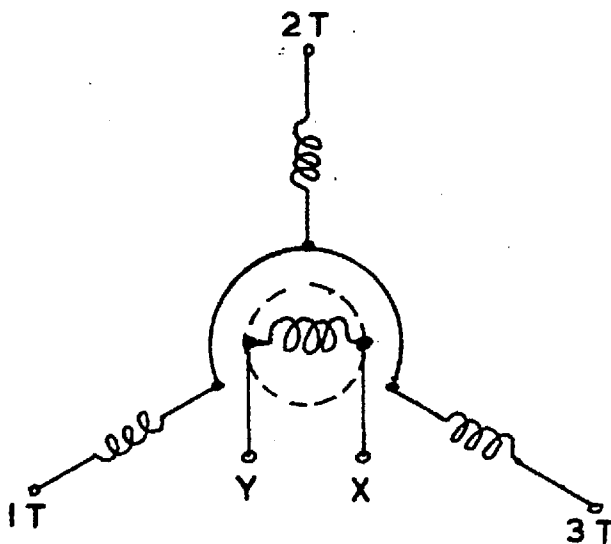
Stator 3-phase star connected sinusoidally distributed.

Impedance between terminals at 50V 50 c.p.s. = $30 + j 140$

ohms.



3" X-CO TRANSMITTER
E-54-A/1 (AP 10747)



3" TRANSMITTER
(AP 6547)

FIG. 27. MUIRHEAD MAGSLIPS

Rotor Impedance at 50V 50 c.p.s. = $20 + j 100$ ohms.

It is seen that the winding impedances are well below the $10K\Omega$ base for the network analyser, and are consequently negligible (being of the order of 1%).

2.2.3 Simulation of Machine Inertia and Damping.

Machine inertia and damping may be simulated by the use of suitable feedback networks. The technique has been described by Morris.⁶⁵ The principle of operation here is best discussed with reference to Fig. 28.

An electronic wattmeter delivers a d.c. voltage, V_{P_o} , proportional to the electrical power output, P_o , from the mag-slip rotor to the network analyser. The difference between the electrical power signal V_{P_o} and the steam power signal V_{P_s} (from the analogue computer), V_1 , is applied through R_1 to the input of the servo-amplifier. Thus

$$V_1 = V_{P_s} - V_{P_o} = \text{accelerating power, } P_a.$$

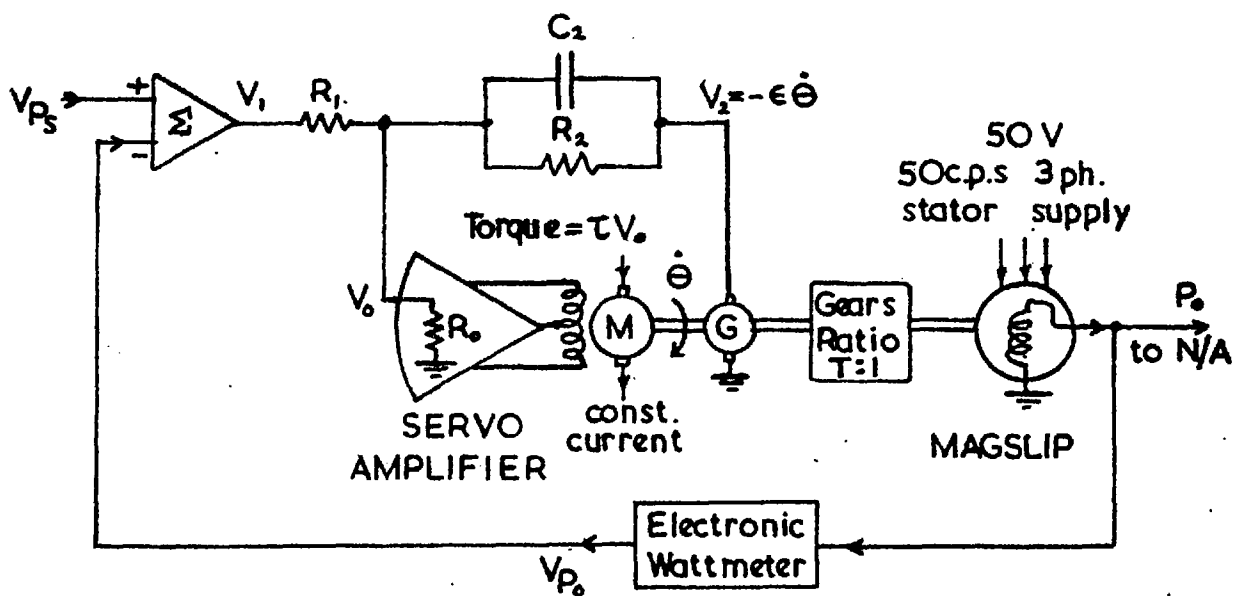
If small system speed changes are ignored, then power unbalance P_a may be identically equated to torque unbalance and hence V_1 represents torque.

In Fig. 28, let $G_o = \frac{1}{R_o}$, $G_1 = \frac{1}{R_1}$, $G_2 = \frac{1}{R_2}$, and

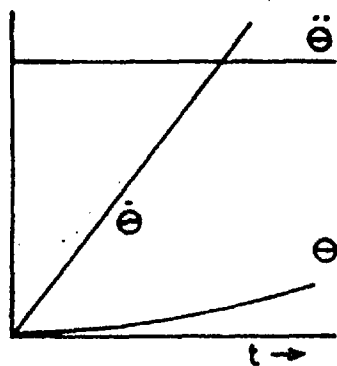
$$G_s = G_o + G_1 + G_2.$$

Now, in the ideal case, the gain of the servo-amplifier is very high so that $V_o \approx 0$. Hence current summation at the servo-amplifier input yields the relation:

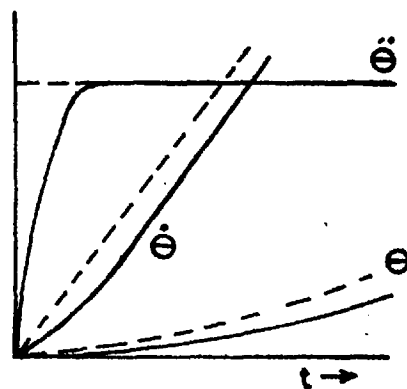
$$G_1 V_1 + (G_2 + pC_2) V_2 = 0$$



INERTIA OF VELODYNE, GEARS & MAGSLIP = M
 DAMPING ----- = D
 CONST.



IDEAL



SIMULATION

FIG. 28. SIMULATION OF MACHINE INERTIA AND DAMPING

or
$$V_1 = -V_2 \left\{ \frac{G_2}{G_1} + p \cdot \frac{C_2}{G_1} \right\}$$

and since
$$V_2 = -\epsilon p \theta,$$

we get V_1 , representing torque
$$= \left\{ \frac{\epsilon G_2}{G_1} \right\} \cdot p \theta + \left\{ \frac{\epsilon C_2}{G_1} \right\} \cdot p^2 \theta$$

Hence, in principle, $\left\{ \frac{\epsilon \cdot C_2}{G_1} \right\}$ is analogous to inertia and $\left\{ \frac{\epsilon \cdot G_2}{G_1} \right\}$

to viscous friction. Thus, for constant R_1 , the desired values of inertia and damping can be simulated by appropriate choice of the C_2 and R_2 feedback elements.

In the practical case, the gain is finite, so let torque $= \tau V_o$, and let M and D be the inertia and damping constants seen by the velodyne motor. Then the current summation at the servo-amplifier input is now:

$$G_1 (V_1 - V_o) + (G_2 + pC_2) (V_2 - V_o) - G_o V_o = 0$$

$$\therefore G_1 V_1 + (G_2 + pC_2) V_2 - (G_s + pC_2) V_o = 0$$

$$\therefore V_1 = - \left\{ \frac{G_2}{G_1} + \frac{pC_2}{G_1} \right\} V_2 + \left\{ \frac{G_s}{G_1} + \frac{pC_2}{G_1} \right\} V_o$$

now, as before,
$$V_2 = -\epsilon p \theta,$$

while in the practical case, $\tau V_o = (pD + p^2 M) \theta,$

$$\text{or } V_o = \left(p \frac{D}{\tau} + p^2 \frac{M}{\tau} \right) \theta.$$

therefore substitution for V_2 and V_o in the above equation for V_1 , and re-arrangement, gives:

$$V_1 \text{ (input torque)} = \left\{ \frac{\epsilon \cdot G_2}{G_1} + \frac{DG_s}{\tau G_1} \right\} \cdot p \theta + \left\{ \frac{\epsilon \cdot C_2}{G_1} + \frac{MG_s + DC_2}{\tau G_1} \right\} \cdot p^2 \theta$$

viscous
friction

inertia

$$+ \left\{ \frac{MC_2}{\tau G_1} \right\} \cdot p^3 \theta.$$

'superinertia'

If $\epsilon \tau C_2$ is made sufficiently large, the synthetic inertia swamps the natural inertia, and the natural friction then gives rise to very little damping. The damping is made consistent by making G_2 large enough for the synthetic friction to swamp the natural friction. The damping is then controlled by G_2/G_1 , and can be made as small as required.

At very high frequencies the response departs from the ideal because of the 'superinertia' term. The response to a step-function of voltage, representing torque, consequently takes the form shown in Fig. 28.

However, by using a servo-amplifier of high gain, τ , keeping the inertia of the system, M , low by using light gears, and by keeping friction, D , to a minimum by careful alignment and lubrication, a close approximation to ideal simulation may be achieved.

In the prototype assembly, generator output 20V/1000

R.P.M.,

$$\text{hence } \epsilon = \frac{20}{1000/60 \times 2\pi} = 0.191 \text{ volts/radian per sec.}$$

Gear ratio between velodyne and magslip is 5:1, hence

$$\theta = 5\delta$$

$$p\theta = 5.p\delta$$

$$p^2\theta = 5.p^2\delta,$$

where δ is the magslip rotor angle.

Thus the relation between input torque, V_1 , and magslip rotor angle δ may be written in the approximate form:

$$V_1 = \left(0.191 \times 5 \frac{G_2}{G_1}\right).p\delta + \left(0.191 \times 5 \frac{G_2}{G_1}\right).p^2\delta$$

$$\dot{\delta} \approx \frac{R_1}{R_2} \cdot p\delta + R_1 C_2 \cdot p^2 \delta.$$

If R_1 is chosen as $100K\Omega$, or $1M\Omega$, then machine inertias can be simulated by setting C_2 in the range $0.01 \rightarrow 1.0\mu F$, and damping by setting R_2 in the range $0.1 \rightarrow 10M\Omega$.

In practice it is convenient to supply fixed feedback elements C_2 and R_2 through (relatively) low impedance potentiometers fed from the generator voltage V_2 . Ten-turn, $30K\Omega$, helical potentiometers are suitable, and if c_2 and k_2 are the settings of the potentiometers feeding C_2 and R_2 respectively, then the velodyne/magslip equation takes the form:

$$V_1 \approx k_2 \cdot \frac{R_1}{R_2} \cdot p\delta + c_2 \cdot R_1 C_2 \cdot p^2 \delta.$$

Damping and inertia can now be adjusted to a high degree of accuracy. Calibration procedures are described in section 2.2 Chapter 5.

Circuits for an electronic wattmeter to deliver V_{P_o} are described in section 1.4 of Chapter 4.

2.3 Automatic Voltage Regulators (A.V.R.'s)

The simulation of automatic voltage regulator action in the Power System Model is achieved by using an inductive potentiometer (I pot) fitted with a simple servo-mechanism. In modern A.V.R.'s there is a reference voltage setting to which the rectified output of the alternator is compared. Any difference between the two signals is passed through amplifying devices and ultimately controls the excitation level of the alternator. It is not the intention here to discuss details of the many types of automatic voltage regulators and excitation systems generally in use, since literature

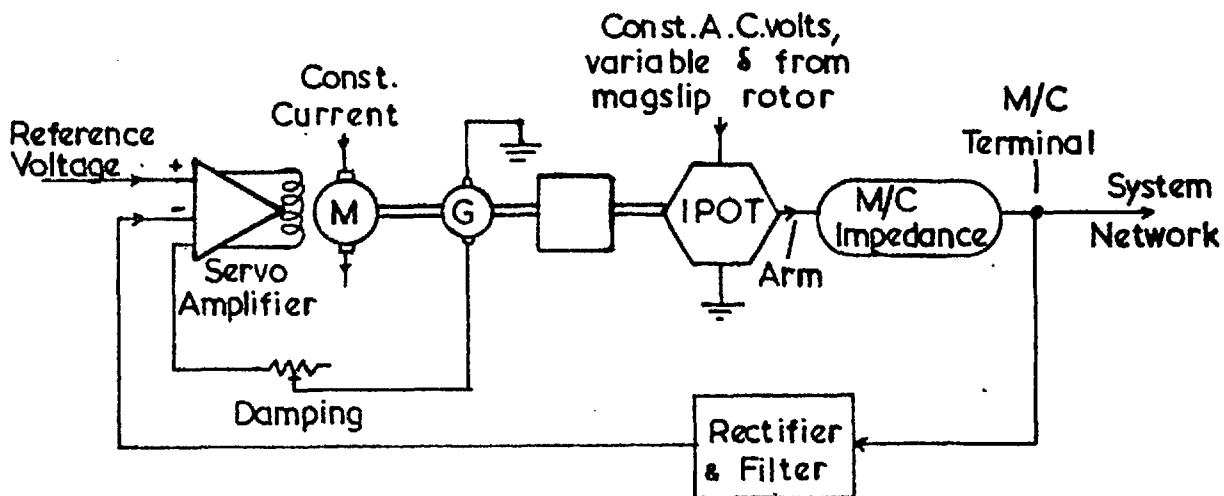
can be readily obtained from manufacturers - a representative selection is listed in references 66 to 71.

A block diagram of a voltage regulator and a set of equations has been given by Shackshaft.^{28,53.} Some typical parameters are also listed by Dineley.²⁴

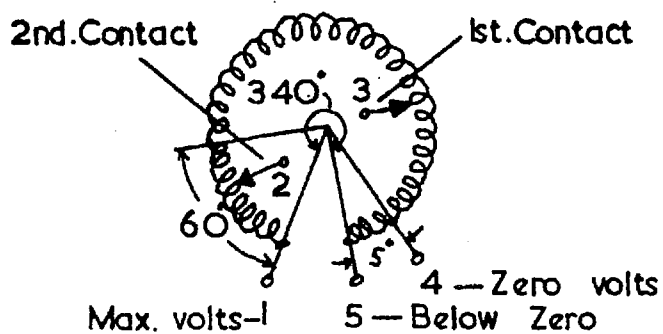
Here, the overall performance is of chief interest, and the Model A.V.R. is designed to simulate the changes of excitation necessary to maintain constant machine terminal voltage during changes of load. The characteristics may be set up in terms of the change in machine e.m.f. E (behind transient reactance) following a small step change in the A.V.R. reference level, and this data is often known from full load rejection, or open circuit, tests on generators. The time-constant is usually dominated by that of the field circuit of the alternator, and can be from two to sixteen seconds, or more in certain cases, but modern fast regulation systems usually have a speed of response of the order one to two seconds.

The principle of operation of the Model A.V.R. can be seen in Fig. 29.

The I pot is a precision wound auto transformer carrying a toroidal winding on a Mumetal core. One of the main applications is in electro-mechanical computers and many mathematical operations may be carried out electrically by its use. The instrument may broadly be described as a precision manufactured 'Variac' type of transformer with refinements, the output derived from the moving contact, in the case of the Linear I pot used here, being accurately proportional to the angle of rotation.



AVR SERVO-MECHANISM



IPOT CONNECTIONS

FIG. 29. AUTOMATIC VOLTAGE REGULATOR

The I pot used was originally developed by the Admiralty, designation No. 1 Mk. 1, and is illustrated in Fig. 24b. The winding is of enamelled copper wire accurately spaced on a former in which slots have been cut every $\frac{1}{4}$ degree for location of the winding. The moving contact consists of a carbon roller mounted on a castor which bears on a suitable track on the winding, from which the insulation has been removed. A 340° rotation is possible by this contact arm. There is a second contact rotatable through 60° , bearing on its own track on the inside face of the core. The main contact arm is rotated by the main spindle while the auxiliary contact can be adjusted by a preset control mounted off centre.

I pot connections are brought out to a numbered terminal block and are shown in Fig. 29. The D.C. resistance of the winding is approximately 60 ohms, and it may be used at frequencies between 15 and 2000 c.p.s. The impedance at 50 c.p.s. is approximately 20,000 ohms. Saturation of the core commences at approximately 55 volts, 50 c.p.s., and this is the chief factor limiting the range: the normal operating conditions are with a supply of 50V, and at 50 c.p.s. the magnetizing current is two to three mA. When loaded with 10,000 ohms or more, the accuracy is within 0.1% of the maximum voltage, but will fall to 2% or 3% when the output current is of the order of 0.5A. Clearly the unit is admirable for the required working range of supply to the network analyser. The I pots used were obtained for £5 each from Servo and Electronic Sales Ltd.

The output from a magslip rotor is fed into the I pot and the effective machine excitation e.m.f. is drawn from the main contact arm (connection 3). The machine impedance is set up on the network analyser, and at the equivalent machine terminal a rectifier/filter unit delivers a d.c. voltage proportional to machine terminal (a.c.) volts. This d.c. voltage is compared with a reference level at a summing junction at the input to the servo-amplifier. Any difference between the voltages results in a restoring torque in the servo-motor. The servo-motor used is the Evershed and Vignoles FAG/1 K4 described in the previous section (2.2.1) and the shaft of this unit is geared directly to the main spindle of the I pot. It is seen that the assembly corresponds to an elementary position control servo, and performs accordingly. Damping can be adjusted by varying the amount of feedback from the generator G in Fig. 29. Speed of response can be controlled by varying the loop gain and by adjusting the time constant of the rectifier/filter unit. Thus the overall characteristics of any A.V.R. can be readily simulated and calibration techniques are described in Chapter 5.

The rectifier/filter unit is described in section 1.5 of Chapter 4.

2.4 Rack Mounting.

The magslip rotors and the I pot spindles of the A.V.R.'s were fitted with graduated indicator dials so that their dynamic behaviour could be observed directly. Provision of the dials also facilitates the setting up of initial conditions in the Model.

The positions of the two pairs of velodyne/magslip units and the assembly of 3 A.V.R.'s, when located on shelves in a 19" rack, are shown in Fig. 30. The magslip shafts and the I pot spindles protrude through holes cut in cover-plates. The indicator dials, fitted on the outside, are clearly seen in Fig. 30. Scale pointers on the cover-plates enable angular readings to be taken directly.

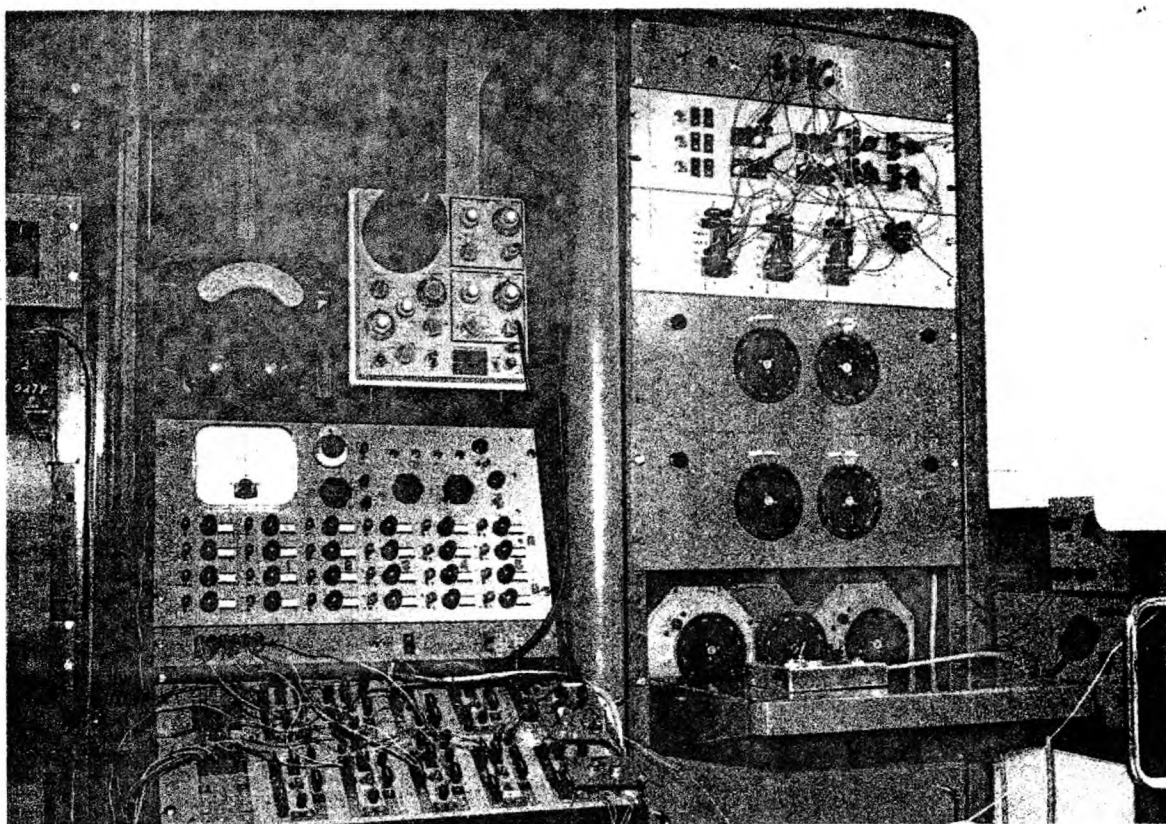


FIG. 30. VELODYNE/MAGSLIPS AND A.V.R.s.,
SHOWING INDICATOR DIALS.

CHAPTER 4

DETAILS OF THE CIRCUITS

1. SPECIAL EQUIPMENT

In this chapter, section 1 gives design details and circuit diagrams of the special equipment used in the Model. The apparatus described comprises servo amplifiers (1.1), power supplies (1.2), time-constant elements (1.3), electronic wattmeters (1.4), A.V.R. Rectifier/Filter (1.5), and methods of rotor-angle measurement (1.6).

1.1 Servo Amplifiers.

For the prototype velodyne/magslip units, two Servomex Servo-Amplifiers, type SA61, were purchased.

The SA61 is a low-drift d.c. amplifier suitable for driving standard split field motors with 40mA in each half of the field winding at balance. Full torque (80mA in one half of the field winding) is obtained for about 65mV d.c. input applied between one grid and earth. For small inputs the gain is about 2000mA per volt (i.e. if field currents at balance are 40/40mA in each half, then a gain of 2000mA per volt means that 1mV d.c. applied between one input terminal and earth changes the field currents to 39/41mA, an effective current of 2mA). The gain is subject to variations of about 2:1 due to changes in valve characteristics.

The circuit diagram of the SA61 is shown in Fig. 31. Four valves are used in two balanced stages. Each stage is a cathode-coupled 'long tailed pair'. Two controls are provided marked 'BALANCE' and 'SET+95V'. The 'BALANCE' control RV2 is intended to take up differences between the two input valves and has sufficient range to ensure that when the two input terminals are both joined to EARTH it is possible to set the 'BALANCE' control

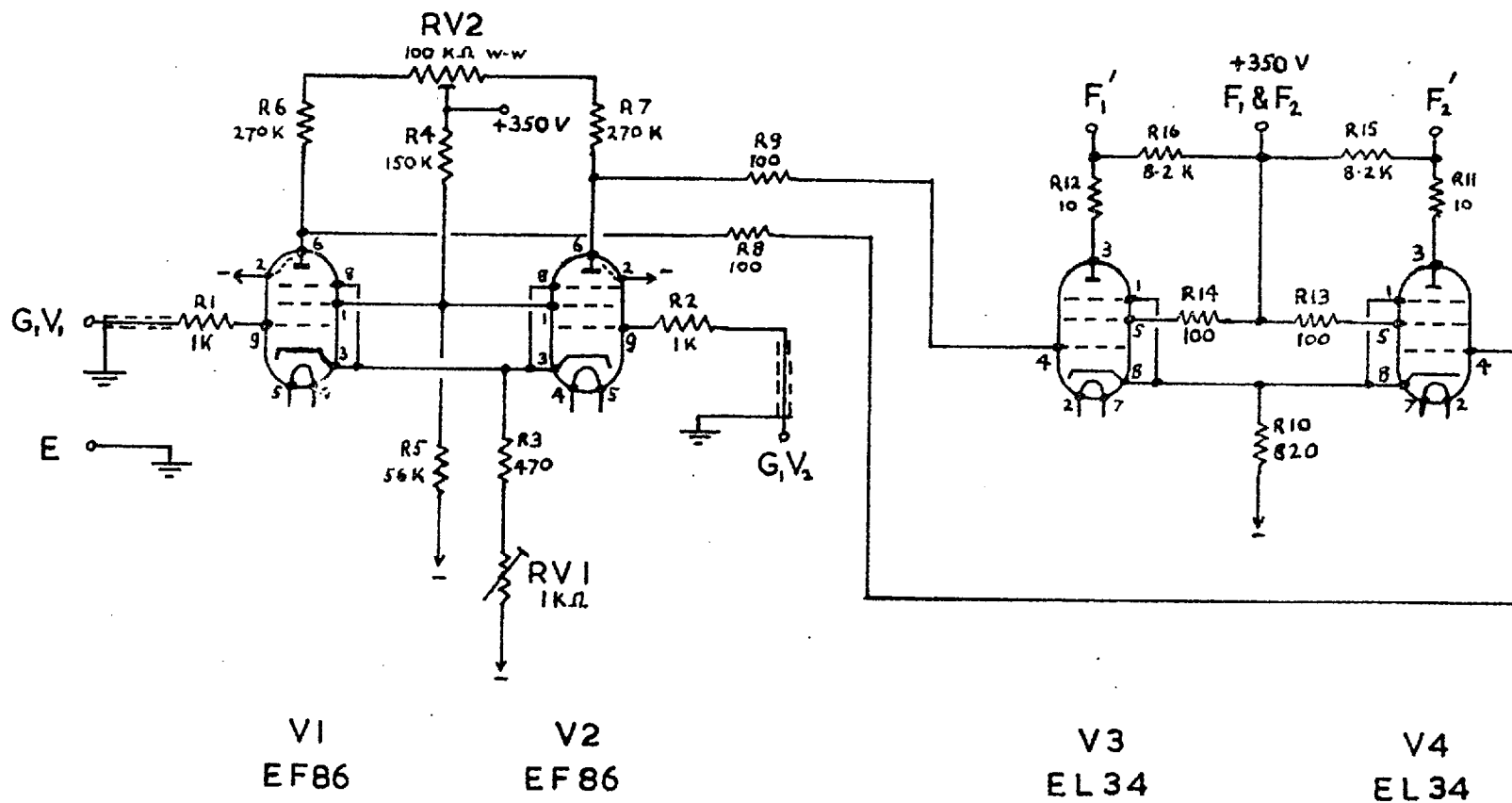


FIG. 31. SA 61 SERVOAMPLIFIER

to give zero net output (40/40mA). The 'SET+95V' control is RV1 which sets the d.c. level of the output cathodes. Full specifications may be found in the relevant data sheet issued by the manufacturers.

For use in the prototype velodyne/magslip systems, one input control grid is earthed and the control signal is applied between the other grid and earth. It was found convenient to disconnect the balance controls RV2 on the amplifiers themselves and to use instead similar controls mounted on the front cover plate of the velodyne/magslip units, and wired up appropriately. Each balance control has a knob and is positioned at the side of the corresponding magslip - see Fig. 30.

The Servomex amplifiers were found to produce excellent results when used with the velodyne/magslip units described in section 2.2 of Chapter 3.

Subsequent to the use of the Servomex SA61 servoamplifiers, (which cost £20 each), a batch of ex-Service servoamplifiers were obtained (at £5.10.0 each) from Servo and Electronic Sales Ltd. These latter amplifiers (type MF154) were unsuitable for use in their original form since they contained a.c. input stages designed for working on 1100 c.p.s. signals. However, for economic reasons, it was decided that it was worth modifying these amplifiers for d.c. working, the aim being to attain a gain and performance similar to the Servomex SA61.

The circuit of the MF154 in its original form is shown in Fig. 32.

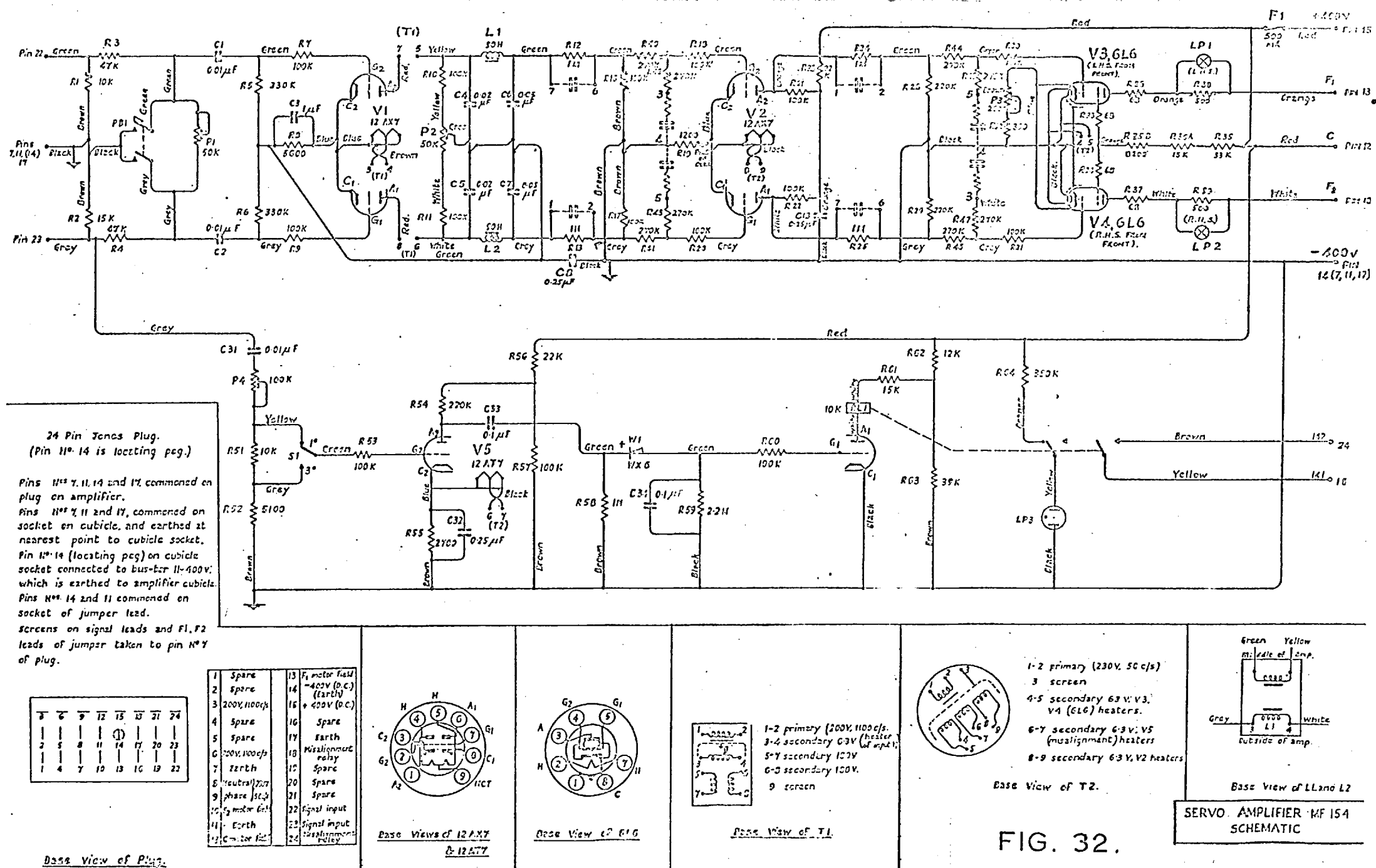
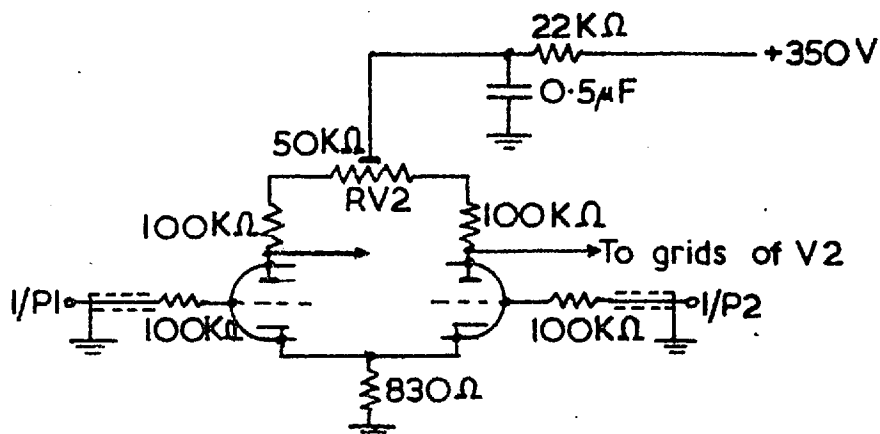


FIG. 32.

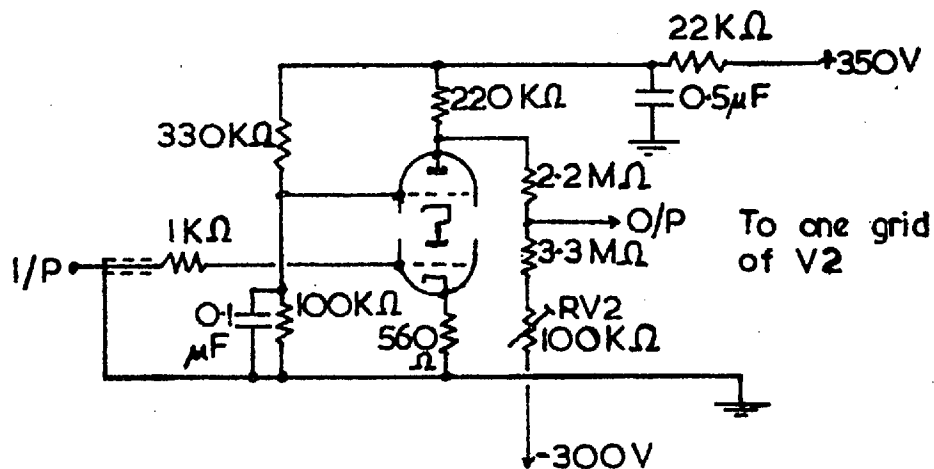
The chief difficulty in achieving a successful modification of a simple form arises from the 6L6 output valves having only half the mutual conductance ($5\text{--}6\text{mA/V}$) of the EL34 types in the Servomex amplifier (11mA/V). Thus a high gain is essential in the preceding stages, V1 and V2 in Fig. 32. It was found that this could not be obtained in a satisfactory manner using the 12AX7 double triodes available in the original amplifiers. The common-cathode circuit of Fig. 33a, for example, arranged for d.c. working, proved to be ineffective in producing the overall gain of 2000mA/V required of the servo-amplifier.

Other possible configurations for the 12AX7 were investigated - the cascode circuit (Fig. 33b) and the simple cascade (Fig. 33c). These both yielded adequate voltage gain (being of the order of $\times 100$ from I/P to O/P for the stage), but had to be rejected because of instability. The drift rate was such that the balance control of the amplifier, RV2, had to be re-adjusted every few minutes. In this respect, it may be noted that the cascode circuit of Fig. 33b behaved rather better than the simple cascade of Fig. 33c. Drift appears to be an inherent disadvantage of the 12AX7 valve, used in direct-coupled circuits, but the valve would undoubtedly be satisfactory for a.c. working. Another, lesser, disadvantage is that only one input grid is available in the amplifier when configurations other than the common-cathode are used.

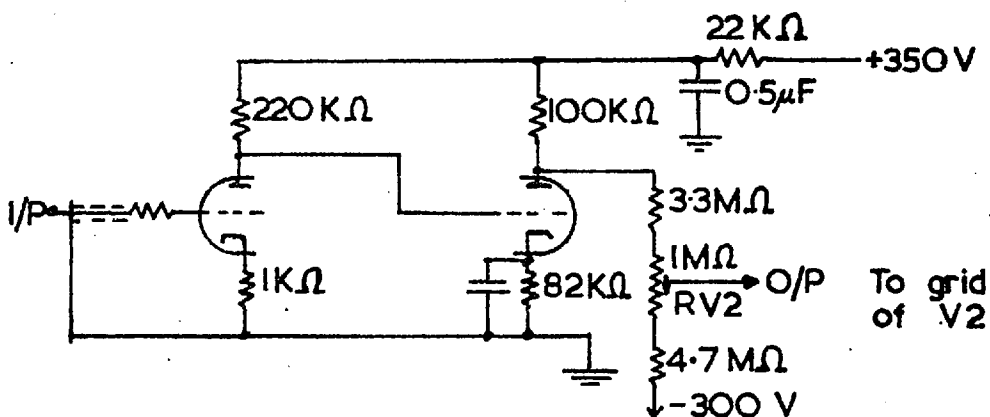
Ultimately, the 12AX7 was discarded for V1 and the stage was composed instead of two ~~ET86~~ pentodes, as in the Servomex amplifier. All components associated with the valves V1 and V5 in Fig. 32 were stripped from the chassis, and bases were fitted to accommodate



a. COMMON - CATHODE



b. CASCODE



c. SIMPLE CASCADE

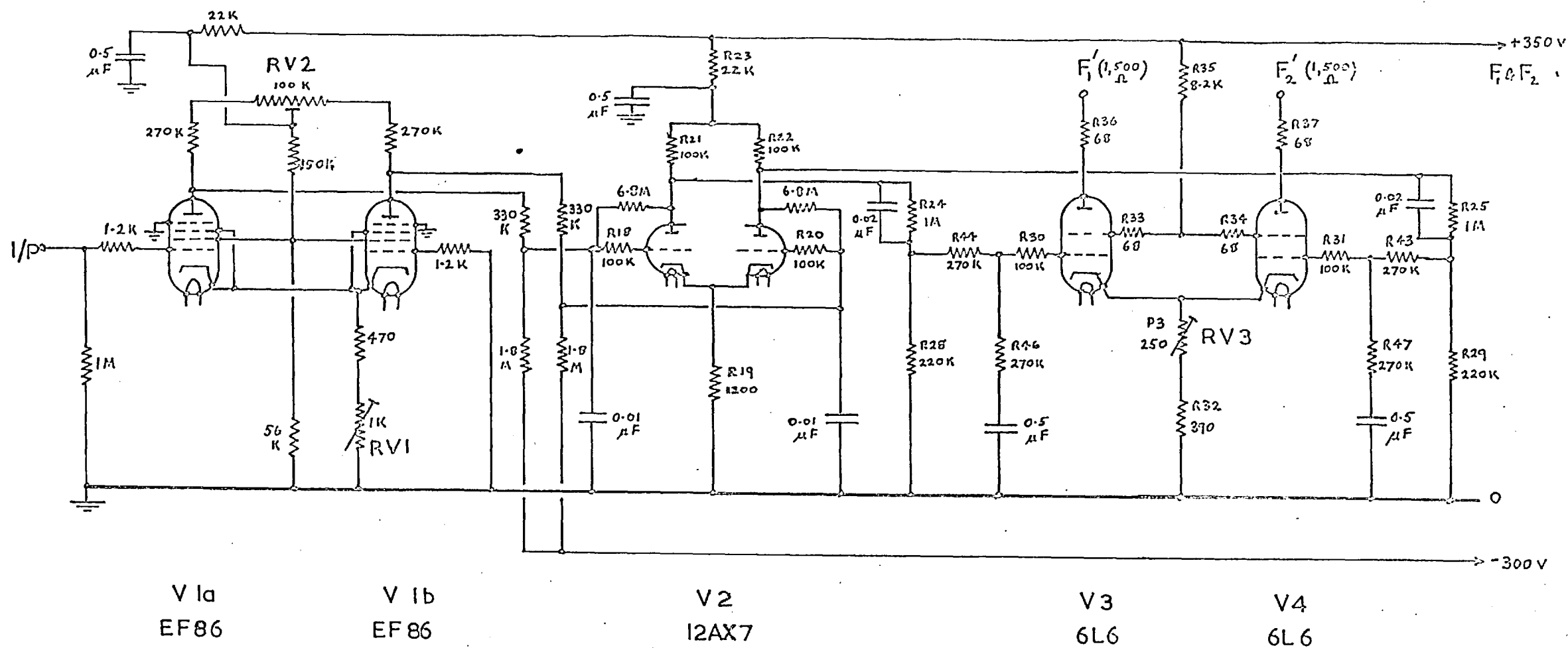
FIG. 33. INPUT STAGES, USING 12AX7

the EF86 valves. The final circuit with the adopted modifications is shown in Fig. 34. Valves V2, V3 and V4 remain as in the original with the modifications:

- i. Feedback resistors of $6.8\text{M}\Omega$ from anodes to grids on V2, to stabilise the gain of this stage.
- ii. Capacitors of $0.01\mu\text{F}$ from grid inputs to earth on V2, to eliminate spurious R.F. oscillations sometimes induced by transients.
- iii. Common screen resistor R35 supplying V3 and V4 reduced to $8.2\text{K}\Omega$ to increase the screen potentials. This enables the balanced working condition of $40/40\text{mA}$ output to be obtained for an H.T. supply of $+350\text{V}$ (the supplies are $\pm 400\text{V}$ in the original circuit of Fig. 32, an overall H.T. for the output stage of 800V).

The amplifiers are mounted in the 19" rack behind supporting face plates bolted to the front. Two are mounted side-by-side for use with velodyne/magslip units 3 and 4. A row of three are mounted below these for use with the assembly of three A.V.R.'s. Multiple sockets are fitted to the combined amplifier chassis for the provision of power supplies and for input and output connections. The balance controls, RV2, are fitted to the front plates, as in the case of the prototypes, and the balanced output **current level** of $40/40\text{mA}$ is achieved by adjustment of RV3, also accessible from the front. The pre-set control RV1 is fitted internally, at the rear of each amplifier chassis, and is adjusted until the best overall gain is obtained for each amplifier (it controls the operating points for V2).

The performance of the modified servo-amplifier of Fig. 34 is in every respect identical to that of the Servomex SA61, and even including the cost of the EF86 valves and additional



D.C. SERVO AMPLIFIER
350V WORKING

I/P mV	1	2	5	10	20	25	40
O/P mA/mA	39/41	38/42	35/45	30/50	24/56	20/60	8/72
Gain mA/V	2000	2000	2000	2000	1600	1600	1600

FIG. 34. ADOPTED MODIFICATIONS

components, results in a substantially cheaper unit. If the modifications were to be carried out by a technician instead of by the author, however, the cost would probably be comparable.

1.2 Power Supplies.

Power supplies for the servo-amplifiers are obtained from stabilised power packs of conventional design. Each of the two Servomex SA61 servo-amplifiers is supplied from an associated Servomex DC.68 power unit, as intended by the manufacturers, from whom full specifications are obtainable.

Supplies for the five modified servo-amplifiers are drawn from a regulated power-pack which was constructed at Imperial College, and used by the author. This power-pack is a 250 watt unit, being capable of supplying 500mA at 500V. It has 4 x 5 U4G rectifier valves in parallel, and stabilisation of the H.T. supply is achieved by a unit of conventional design in which 8 x 807 I.F. Pentodes are connected in parallel to handle the load current. The mains transformer, rectifier and filter unit is mounted in the bottom of the Minispace Extension rack, and the H.T. voltage regulator unit is mounted in the bottom of the 19" rack containing the servo-mechanisms (shown in Fig. 30). For operation with the servo-amplifiers, the H.T. voltage is set at +350 when on load by means of the control on the regulator unit accessible from the rear of the rack.

All other d.c. and reference supplies are derived from sources associated with the Solartron analogue computer equipment, common references of $\pm 100V$ and $\pm 300V$ being used throughout the Power System Model.

The Conjugate Network Analyser is provided with its own stabilised 50V 3-phase a.c. equipment, fed from the Laboratory 400V 3-phase supply. This Network Analyser supply is employed for the magslips used in the Model.

The velodyne motor armatures draw their d.c. supply from the laboratory $\pm 100\text{V}$ d.c. busbars. Series rheostats are used to establish the specified armature current for each motor (see section 2.2.1, Chapter 3).

1.3 Time-constant Elements.

A unit containing 1% resistors and capacitors was constructed, using 'electro-kit', to facilitate the setting up of passive RC networks in the analogue circuitry. The way in which the components are connected to sockets on the front panel is shown in Fig. 35. The resistors have values of $100\text{K}\Omega$, $250\text{K}\Omega$ and $1\text{M}\Omega$ and are 1%, hi-stabs. The capacitors are of $0.1\mu\text{F}$ and $1\mu\text{F}$ and are 1% polystyrene types. The sockets are arranged so that a variety of time constants can be readily selected with the aid of shorting links (from 0.01 secs with $100\text{K}\Omega$ and $0.1\mu\text{F}$ to 2 secs with $1\text{M}\Omega$ and $2 \times 1\mu\text{F}$).

There are five groups of sockets as shown in Fig. 35, and the complete unit is mounted in the Minispace extension rack, above the operational amplifiers - as can be seen in Fig. 23.

1.4 Electronic Wattmeter.

The electronic wattmeter (see section 2.2.3 of Chapter 3 and Fig. 28) is required to deliver a d.c. voltage proportional to average electrical output power, P_o , from a Model machine unit. Linearity should be within 1% over the appropriate operating ranges

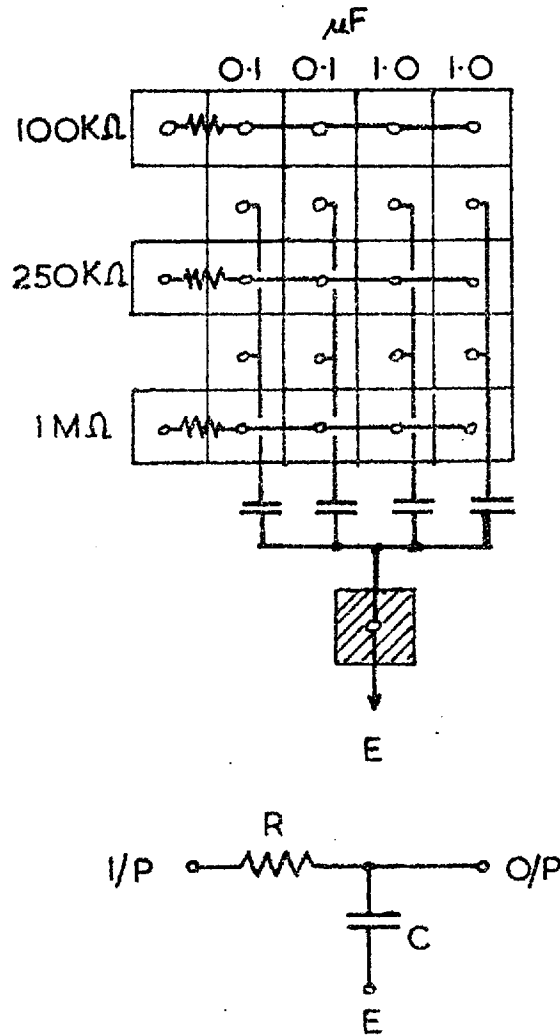


FIG. 35. TIME CONSTANT ELEMENTS

of voltage and current. Time delay in producing the signal must be kept to a minimum so that no appreciable errors will occur in the solution of the machine electro-dynamic equation. Drift must be non-existent, and long term stability must be such that frequent adjustment is unnecessary.

A range of power sensing devices is listed in Table 1, Chapter 1. Wattmeters, in general, could be classified into three types:

- i. Thermal (heating effect of power)
- ii. Torque producing (dynamometers, integrating motors)
- iii. Electronic and analogue multiplying circuits.

A critical review of these types has been given by Faragalla.⁶¹ A specially developed dynamometer scheme for a dynamic network analyser was described by Kaneff.²¹ However, when analogue computing equipment is being employed, the most accurate and expedient technique which suggests itself is the use of electronic multipliers and this method was used in the Model here in the first instance, (described in 1.4.1). Later, a transistorised unit was developed (section 1.4.2).

1.4.1 Use of Electronic Multipliers.

The electronic multiplier principle is to form the instantaneous product of volts and current to yield a voltage proportional to watts.

If V_E is the voltage corresponding to machine terminal volts, where $V_E = \hat{V}_E \sin \omega t$, and if V_I is a voltage proportional to the corresponding current in the circuit, where $V_I = \hat{V}_I \sin (\omega t + \phi)$, then

$$\hat{V}_E \sin \omega t \cdot \hat{V}_I \sin (\omega t + \phi) = \frac{1}{2} \hat{V}_E \cdot \hat{V}_I [\cos \phi + \cos (2\omega t + \phi)]$$

where ω = frequency, ϕ = power factor angle, and $\cos (2\omega t + \phi)$ averages zero over any integral number of cycles. Thus the average of $\hat{V}_E \sin \omega t \cdot \hat{V}_I \sin (\omega t + \phi) = \frac{1}{2} \hat{V}_E \cdot \hat{V}_I \cos \phi$, which is a d.c. component of multiplier output analogous to the average real power in watts.

The derivation of voltages V_E and V_I for the electronic multiplier inputs is shown in Fig. 36, which also shows the normal connections used in the Model for a magslip and I pot when these are arranged to simulate a machine equipped with an A.V.R.

The machine terminal is connected through an impedance of 6.8M Ω to the summing junction of an operational amplifier in the analogue computer. The gain of the amplifier is set at a suitable level (to yield an output in the range 0-70V r.m.s. maximum) by means of a feedback potentiometer. The amplifier output, V_E , is also used to supply the A.V.R. rectifier/filter, a machine terminal a.c. voltmeter, and recorder circuits. The use of a buffer amplifier in this way, with high input impedance, renders negligible the errors which otherwise arise through undue loading of the machine terminal point in the network analyser with auxiliary circuit connections.

Referring again to Fig. 36, a voltage proportional to machine current appears across a 110 Ω , hi-stab resistor, R_I , connected in series with the end of the I pot winding and the common ground for the network analyser. The value of 110 Ω is low enough (approximately 1% of analyser base impedance 10K Ω) to introduce negligible error in the analyser impedance configuration,

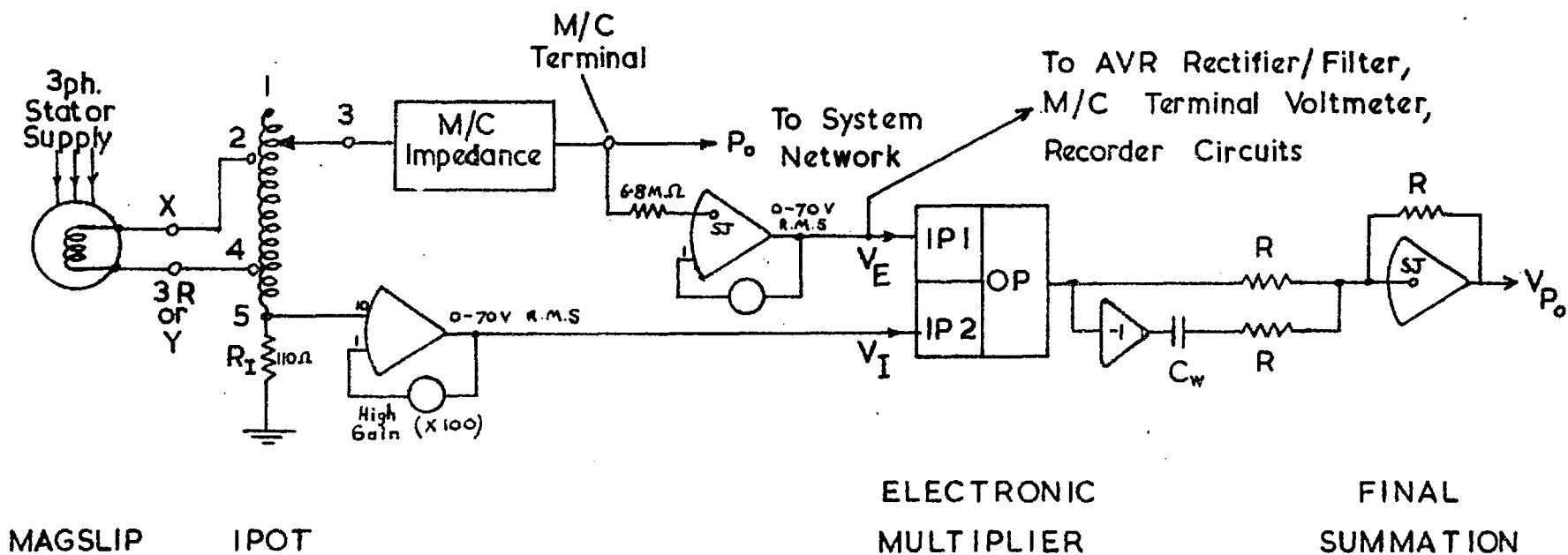


FIG. 36. POWER MEASUREMENT BY ELECTRONIC MULTIPLIER

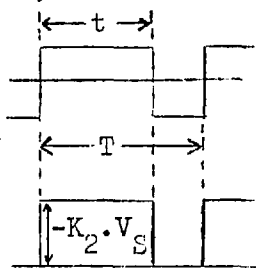
but could in any case be incorporated as part of a resistive component of machine impedance. If 5mA is being adopted as base current (see section 2.1 Chapter 3), then the corresponding a.c. voltage across R_I is only 0.5V r.m.s. and it is necessary to amplify this (X100 approximately) to yield a suitable voltage, V_I , for the electronic multiplier. An operational amplifier is also used for this purpose.

The electronic multipliers used are Solartron units fitted into the SCD10 Minispace. They consist of TX1322 Mark-Space Modulators (M) and TX1323 Height Modulators (S) mounted in a TX1321 rack (for six units). An M unit produces a constant height pulse train modulated linearly by the applied signal about the symmetrical mark-space value 1:1. The carrier frequency is $\approx$ 9Kc. An S unit modulates the mark-space train from M according to its input signal, and contains an output stage.

TR 1322:
(M)

$$(t - \frac{T}{2}) = K_1 \cdot V_M$$

TR 1323:
(S)



After filtering to remove carrier components, average signal

$$V_A = -K_2 V_S \frac{t}{T},$$

and substituting for $\frac{t}{T}$: $V_A = -K_2 V_S \left(\frac{K_1 V_M}{T} + \frac{1}{2} \right)$.

$V_B = \frac{1}{2} K_2 V_S$ is added in the S unit

and the result scaled by $-K_3$, $\therefore V_O = +K_1 K_2 K_3 V_M V_S / T$,

and as $\frac{K_1 K_2 K_3}{T} = \frac{1}{100}$, so $V_O = + \frac{V_M V_S}{100}$.

The units are arranged in the rack so that each S unit has an M unit to supply it. Three pairs of independent products can be formed by arranging the units in the order MSMSMS, the three outputs being taken from each S unit. Specifications are:

$$-100V \leq V_O, V_M, V_S \leq +100V$$

Static Accuracy: max. errors from true product $\pm 0.2V$.

Dynamic Accuracy: phase shift 1° at 10 c.p.s., 10° at 100 c.p.s.
amplitude $\pm 2\%$ at 100 c.p.s.

Further details can be found in the appropriate Solartron data sheet.

The electronic multiplier output, V_{EM} , contains the term $\frac{1}{2} \hat{V}_E \cdot \hat{V}_I \cos(2\omega t + \phi)$, as discussed above. This term is seen to have twice the a.c. frequency of the magslip rotor output and is thus of the order of 100 c.p.s., with an amplitude of $\frac{1}{2} \hat{V}_E \cdot \hat{V}_I$ which equals the level of the d.c. component when this measures average real power at unity p.f. A glance at Fig. 28 makes it clear that if V_{EM} were applied direct to the servo-amplifier input network, the 100 c.p.s. signal would be amplified and appear as a large a.c. voltage across the field windings of the servo-motor. Although the d.c. performance of the servo-motor may not be adversely affected, as the a.c. components in the two halves of the field cancel, the presence of any appreciable a.c. voltage results in a.c. components of current which substantially add to power dissipation in the field windings with the consequent danger of overheating. It is also likely that saturation and overloading will occur in the servo-amplifier.

To reduce the a.c. component of V_{EM} to an acceptable level, the arrangement shown in Fig. 36 may be used, where the final output is V_{P_O} . Considering the summing junction, SJ, at the output amplifier,

$$\frac{-V_{P_O}}{R} = V_{EM} \left(\frac{1}{R} - \frac{1}{R + \frac{1}{pC_W}} \right),$$

or
$$V_{P_O} = -V_{EM} \left(\frac{1}{1 + p\tau_W} \right), \text{ where } \tau_W = C_W R.$$

V_{P_O} is seen to suffer from a time delay, in response to a step change of power level, P_O , where the time constant for the electronic wattmeter is τ_W . If, in practice, $C_W = 0.1 \mu F$, $R = 1 M\Omega$, then the time constant $\tau_W = 0.1$ secs. With these values for C_W and R , the steady 100 c.p.s. component of V_{EM} is reduced in amplitude by approximately $\frac{1}{2\pi \cdot 100 \cdot 0.1} \approx \frac{1}{60}$. This was found to be an acceptable reduction for the velodyne control system.

The practicability of the electronic wattmeter when electronic multipliers are used, and calibration and attainable accuracy, are discussed in the next chapter in the section on Power Measurements.

1.4.2 A Transistorised Unit.

There are two circumstances arising in practice where a voltage of constant amplitude exists in a Model machine unit:

- i. In a machine with fast AVR representation, where the AVR reference level remains unchanged throughout a series of studies, and the machine terminal voltage is maintained sensibly constant by AVR action throughout.

ii. In a machine without AVR representation. In this case either the I pot remains at a constant static setting, representing a constant level of excitation between terminals 3 and 5, or the I pot is omitted, and the machine e.m.f. comes direct from the magclip rotor, at constant voltage, between terminals X and 3R (or Y).

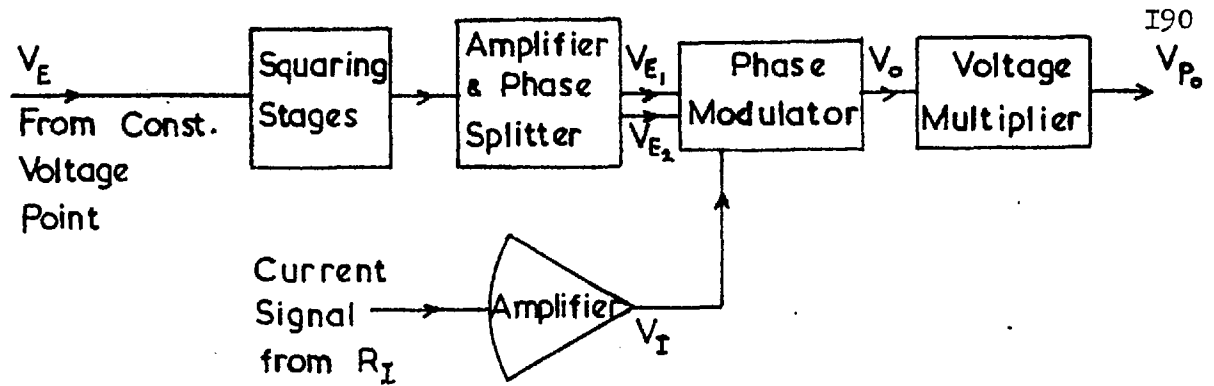
It has been observed by Adamson, Barnes and Nellist²³ that when such a point of constant voltage exists throughout a study, then a phase-sensitive rectifier circuit may be employed (i.e. if average power = $\frac{1}{2} \hat{V}_E \hat{V}_I \cos \phi$, and V_E is constant, then average power is proportional to $\hat{V}_I \cos \phi$). The principle of operation of a practicable scheme is illustrated in Fig. 37.

Fig. 37a is a block diagram of the sequence of operations. The phase modulator and its voltage waveforms are shown in Fig. 37b. The passage of current due to V_I is governed by the sign of the voltage across the diodes (i.e. by the polarities of square waves V_{E1} and V_{E2}). When V_{E1} is positive and V_{E2} negative current due to V_I flows and develops a voltage V_O in the load R_O . The mean d.c. value of V_O is a function of the magnitude of V_I and the phase difference between V_E and V_I .

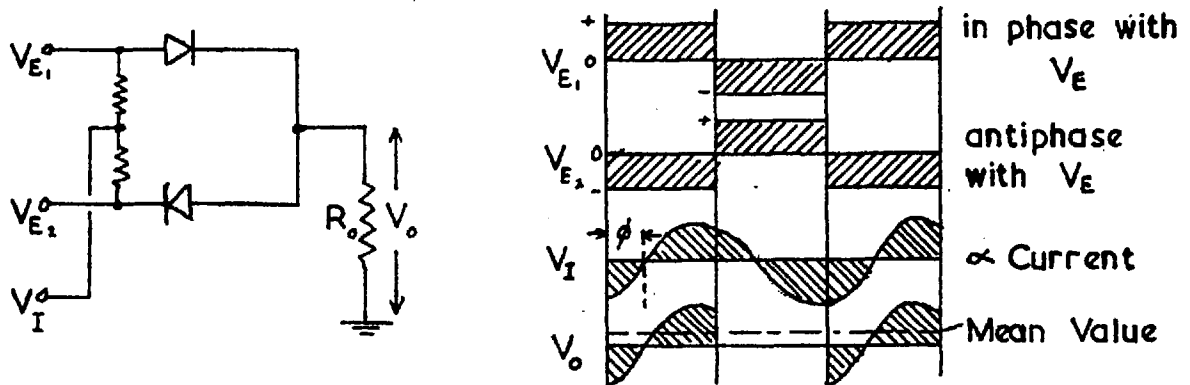
Suppose $V_I = \hat{V}_I \sin \theta$, p.f. angle = ϕ ,
then mean d.c. output of wattmeter

$$\begin{aligned} &= \frac{k}{2\pi} \int_{\phi}^{\pi+\phi} \hat{V}_I \sin \theta \cdot d\theta \\ &= \frac{k\hat{V}_I}{\pi} \cos \phi \end{aligned}$$

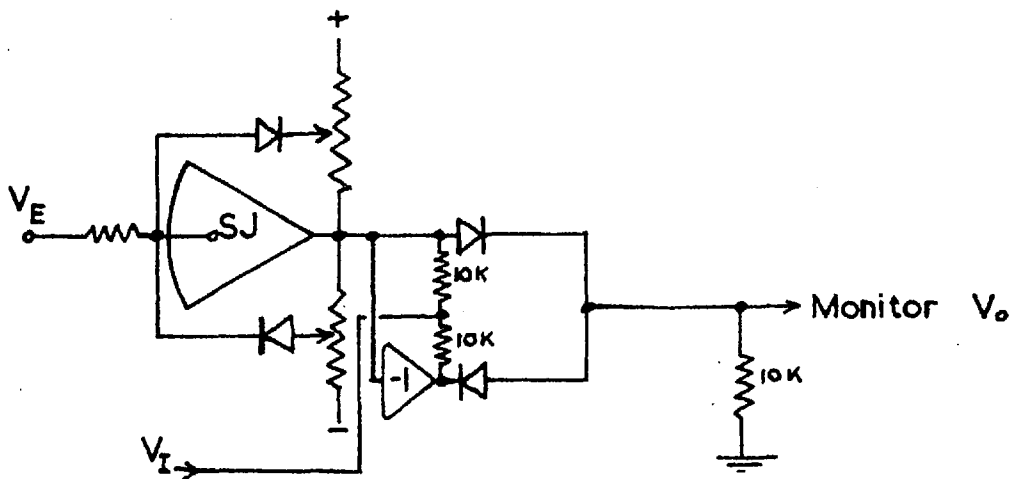
hence the wattmeter output voltage is proportional to current and p.f., but independent of voltage V_E . The mean level of the output V_O can be followed by an RC filter.



37 a. BLOCK DIAGRAM



37 b. CIRCUIT VOLTAGE WAVEFORMS



37 c. ANALOGUE VERIFICATION

FIG. 37. PRINCIPLE OF CONSTANT VOLTAGE WATTMETER

The principle of operation was verified successfully by means of the analogue circuit of Fig. 37c. An operational amplifier, fitted with limiting diodes, produces the square wave V_{E_1} , and a sign reversing amplifier gives V_{E_2} . The output waveform V_o was observed on an oscilloscope, and tests over a range of current amplitudes and power factors showed that the mean level of V_o , measured on a centre-zero d.c. voltmeter, was proportional to $\hat{V}_I \cos \phi$.

It can be seen that the circuit of Fig. 37b corresponds to that of a series bridge modulator using two diodes. An alternative arrangement is the shunt bridge modulator of Fig. 38a, which can be shown to yield a mean output voltage in the load resistor R_o of $\frac{k}{\pi} \hat{V}_I \cos \phi$ by similar consideration. A full account of the theory of these modulators has been given by Tucker.⁷²

A shunt bridge modulator forms the basis of a transistorised unit which was developed according to the above principles for the Power System Model. The reasons for so-doing are threefold:

- i. The electronic multipliers described in the previous section are expensive, and only three pairs are available in the Minispace.
- ii. In a case where V_E is constant, one electronic multiplier input is essentially redundant, and it is desirable to free the multiplier altogether for other potential uses in the analogue.
- iii. The alternative use of the analogue phase modulator circuit of Fig. 37c is extravagant in its use of operational amplifiers, and it is therefore of interest to explore the



FIG. 38. TRANSISTORISED UNIT

possibility of using a simple inexpensive transistorised unit in its own right, if comparable accuracy can be achieved.

Theory of Operation.

The circuit developed is shown in Fig. 38c. The design of the circuit is best discussed in relation to the general theory of shunt bridge modulators. Let $V_E = \hat{V}_E \cos \omega t$ and $V_I = \hat{V}_I \cos (\omega t + \phi)$.

Fig. 38a shows the schematic circuit of the shunt bridge modulator (using two diodes). When V_{E1} is positive and V_{E2} negative the diodes are forward biased and have resistance $r = r_f$. With V_{E1} -ve. and V_{E2} +ve. the diodes are reverse biased and have $r = r_b$. Thus the insertion loss due to the bridge between signal and load switches between two extreme values on alternate half cycles of switching voltage $V_E \cos \omega t$.

For V_{E1} positive: $r = r_f$ and in the equivalent circuit, Fig. 38b:

$$R_E = \frac{r_f + R_B}{2}.$$

$$\text{Hence load current } I_1 = \frac{V_I}{R_o + \frac{R_o R_E}{R_o + R_E}} \cdot \frac{R_E}{R_o + R_E} = \frac{V_I \cdot R_E}{R_o (R_o + 2R_E)}.$$

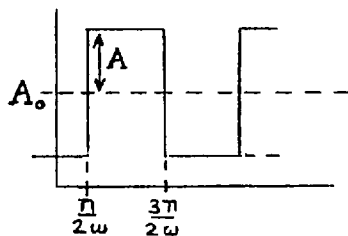
In the absence of the bridge (R_E omitted)

$$\text{load current } I_2 = \frac{V_I}{2R_o}.$$

$$\begin{aligned} \text{Hence insertion loss } L_f &= \frac{I_2}{I_1} = \frac{R_o + 2R_E}{2R_E} \\ &= \frac{R_o + r_f + R_B}{r_f + R_B} \end{aligned} \quad \dots (1)$$

For V_{E1} negative: $r = r_b$ and so now

$$L_b = \frac{R_o + r_b + R_B}{r_b + R_B} \quad \dots\dots (2)$$



Thus the modulating function $\phi(t)$ is a square wave of amplitude A about a mean value A_o , where:

$$A = \frac{1}{2} \left(\frac{1}{L_b} - \frac{1}{L_f} \right) = \frac{1}{2} \left(\frac{r_b + R_B}{R_o + r_b + R_B} - \frac{r_f + R_B}{R_o + r_f + R_B} \right) \quad \dots\dots (3)$$

$$A_o = \frac{1}{2} \left(\frac{1}{L_b} + \frac{1}{L_f} \right) = \frac{1}{2} \left(\frac{r_b + R_B}{R_o + r_b + R_B} + \frac{r_f + R_B}{R_o + r_f + R_B} \right) \quad \dots\dots (4)$$

The output waveform obtained in load R_o may be written: $O/P = \phi(t) \cdot v_I$ (5)

where v_I is the signal voltage developed in the load R_o in the absence of the bridge. Thus for matched source and load impedances R_o , $v_I = \frac{1}{2} V_I$. When the square wave modulating function $\phi(t)$ is expanded as a Fourier series, equation (5) becomes:

$$O/P = \left[A_o + \frac{4A}{\pi} \sum_{n=1}^{\infty} (-1)^{n-1} \frac{\cos(2n-1)\omega t}{2n-1} \right] \cdot \frac{1}{2} \hat{V}_I \cos(\omega t + \phi),$$

$$\text{or } V_o = \frac{1}{2} A_o \hat{V}_I \cos(\omega t + \phi) + \frac{A}{\pi} \hat{V}_I \sum_{n=1}^{\infty} (-1)^{n-1} \frac{\cos[2(n-1)\omega t - \phi]}{2n-1}$$

$$+ \frac{A}{\pi} \cdot \hat{V}_I \sum_{n=1}^{\infty} (-1)^{n-1} \frac{\cos(2n\omega t + \phi)}{2n-1} \quad \dots\dots (6)$$

where A and A_o are as defined in equations (3) and (4).

Thus the output waveform contains a term $\frac{A}{\pi} \hat{V}_I \cos \phi$ (when $n = 1$) and other components of frequencies ω ; 2ω ; 4ω ; $2n\omega$. The d.c. term $\frac{A}{\pi} \hat{V}_I \cos \phi$, proportional to average power, is the one of interest here, and it is possible to filter out the

a.c. components of V_o by a similar technique to that discussed in the previous section (3.4.1).

An ideal shunt modulator has four diodes in the bridge (two of them replacing the resistors R_B in Fig. 38) and they are assumed to behave as perfect switches, with $r_f = 0$, $r_b = \infty$. In this case the modulating function is a square wave of amplitude $\frac{1}{2}$ about a mean height of $\frac{1}{2}$ (i.e. $A = A_o = \frac{1}{2}$), since $I_f \rightarrow 0$ and $L_b = 1$.

The efficiency, η , of a practical shunt modulator can be expressed as the ratio of A achieved in practice to the ideal value, i.e. $\eta = A/\frac{1}{2} = 2A$, or using equation (3) above we get, for the practical shunt modulator of Fig. 38a:

$$\eta = \frac{r_b + R_B}{R_o + r_b + R_B} - \frac{r_f + R_B}{R_o + r_f + R_B} \quad \dots\dots (7)$$

For given values r_b , r_f (i.e. a matched pair of diodes), the value of R_o which gives maximum efficiency is found by solving $\frac{d\eta}{dR_o} = 0$, whence $R_o \text{ optimum} = \sqrt{(r_f + R_B)(r_b + R_B)}$ (8)

Suitable diodes (with high back resistance r_b) are Mullard OA81 s. These have, typically, r_f in the range $100 \rightarrow 200$ ohms, $r_b \approx 2.5M\Omega$. The switching voltage for the shunt bridge is derived from the collectors of transistors TR1 and TR2, in Fig. 38c, which have coupled emitters. V_E is applied to the base of TR1 through a high series resistance ($2.2M\Omega$) and the resultant a.c. in the common R_E creates a varying base emitter potential for TR2, hence providing a drive for this latter transistor whose output is consequently 180° out of phase with that of TR1. The base of TR2 is grounded.

For perfectly balanced voltages V_{E_1} , V_{E_2} , transistors TR1 and TR2 should be matched but this is not essential for the intended application here. Using component values shown in Fig. 38c operating points are established at approx. $I_c = 3\text{mA}$, $V_{c_E} = -6\text{V}$ for supplies of -20V , $+2\text{V}$. V_{E_1} and V_{E_2} have amplitudes of 5V (when $V_E = 50\text{V a.c.}$) and collectors TR1 and TR2 are coupled to the shunt bridge by capacitors C_1 and C_2 .

Practical Performance.

The above theory of the shunt bridge modulator assumes that the diodes switch instantly between constant values of forward resistance r_f and reverse resistance r_b for each half cycle of switching voltage. In practice the ideal performance of the shunt modulator is affected by the following factors:

- i. Non-linearity of diode characteristics when biased either forward or backwards (i.e. the slope, or a.c. resistance is not constant and therefore varies over the cycle of superimposed signal voltage - see typical characteristic curves on Mullard Data Sheets).
- ii. The interference with the switching of the diodes from forward to backward condition and vice-versa caused by the superimposition of the signal voltage.
- iii. Bridge unbalance.

These factors give rise to non-linear distortion, so that harmonics and carrier leak (proportion of switching voltage) appear in the output circuit. Of the above factors (i.) is discussed in papers by Tucker, Jeynes and Belevitch^{75,76,78,80}

and in chapter 4 of ref. ⁷². Factor (2) is discussed in papers by Belevitch^{73, 76, 77}, by Tucker and Jeynes⁷⁵, and by Tucker^{72, 74, 79}.

There are two main aspects of this factor:

- a. Overload at relatively high signal levels.
- b. Harmonic products at relatively low signal levels. Overload occurs when the signal voltage across a diode exceeds the passing carrier current. These overload effects are analysed in detail in refs. ^{75, 76, 77} which also discuss the influence of carrier source resistance. Aspect (b) is treated in detail in Tucker's paper ⁷⁹.

Factor (3) is chiefly responsible for carrier leak. This is discussed by Tucker, ref ⁷² chapter 5. Belevitch ⁷⁷ also points out that as the carrier peak voltage is different across the diodes for each half cycle (because $r_f \ll r_b$) there is a d.c. component in the waveform. This provides a means of monitoring carrier leak with a d.c. meter as described by Tucker⁷⁸.

Circuit Optimisation.

From a consideration of the ideal theory and the practical problems outlined above, it is possible to deduce certain criteria which enable the optimum circuit of the shunt modulator to be designed.

It has been stated above that the ideal shunt modulator has $A = A_0 = \frac{1}{2}$. From equations (3) and (4) we have:

$$A = \frac{1}{2} \left(\frac{1}{L_b} - \frac{1}{L_f} \right),$$

$$A_0 = \frac{1}{2} \left(\frac{1}{L_b} + \frac{1}{L_f} \right).$$

Hence the ideal is approached when $\frac{1}{L_b} \rightarrow 1$ and $\frac{1}{L_f} \rightarrow 0$,

$$\text{or when } L_b \rightarrow 1, L_f \rightarrow \infty \quad \dots (9)$$

$$\text{now } L_b = \frac{R_o + r_b + R_B}{r_b + R_B}, \quad L_f = \frac{R_o + r_f + R_B}{r_f + R_B} \quad \text{from (1) and (2),}$$

from which it is seen that conditions (9) are achieved when

$$r_b \gg R_o \gg r_f + R_B \quad \dots (10)$$

From (10) it follows that R_B must be small, or preferably of similar order to r_f . There is another reason why R_B should be small. In the circuit of Fig. 38c the bridge resistors R_B constitute the main a.c. load on transistors TR 1 and TR 2. Tucker has noted ⁷⁴ that the values of R_B should not be too high if the diodes are to be switched efficiently, since a bias voltage would then develop across the coupling capacitors C_1 and C_2 and tend to keep the diodes delayed in the backward condition. If $R_B \gg 2r_f$, this bias will cause less than 0.1 db reduction in efficiency (Tucker). However, it is not possible to make R_B exceedingly small, as the resultant steepening of the a.c. load lines for TR 1 and TR 2 would then result in the reduction of maximum output switching voltage obtainable across the diodes. Practically, it was found that a compromise value of $R_B = 1 \text{ K}\Omega$ was suitable.

Having selected R_B , the optimum value for R_O can be calculated from eqn. (8), using typical values of r_f and r_b for the OA 81.

$$\text{Thus } R_O \text{ (optimum)} = \sqrt{(150 + 1 \text{ K}\Omega) (2.5 \text{ M}\Omega + 1 \text{ K}\Omega)}$$

$$\approx 54 \text{ K}\Omega$$

In practice, good results were obtained with a signal resistance (in series with V_I) of $100 \text{ K}\Omega$, and a load impedance of $100 \text{ K}\Omega$ ($\times 10$ input to amplifier delivering V_{F_O}) in parallel with the loading effect of stage TR 3 (also of the order of $100 \text{ K}\Omega$), making a total load impedance of the order of $50 \text{ K}\Omega$.

The purpose of TR 3, which is a.c. coupled to the bridge modulator output circuit, is to produce an output, $^o/P2$, with a.c. components 180° out of phase with those from the modulator. $^o/P2$ is then added at the output amplifier to minimise ripple in V_{P_O} in a manner similar to that described at the end of section 1.4.1, on the use of electronic multipliers. A time constant, τ_ω , for the wattmeter again arises.

The normal method of minimising carrier leak is to include a potentiometer in the bridge circuit for balancing purposes (see Tucker ⁷², chapter 5). This is shown in Fig. 38c at RV1 included in the diode side of the bridge. In order that RV1 can be as small as possible it is desirable to use closely matched diodes. By including the potentiometer RV1 in series with the diodes, it contributes to the effective values of r_f and r_b . It is negligible in relation to r_b , but its effect on r_f is to assist in swamping to some extent

the non-linearity of the forward a.c. resistance characteristics of the individual diodes, and this feature is of value in reducing the harmonics and carrier leak due to this cause. A value for R_{V1} of $100\ \Omega$ is found suitable. Carrier leak is minimised in practice by adjustment of R_{V1} until the d.c. component of V_p is zero for zero signal voltage V_I according to Tucker's principle⁷⁸.

The transistorised unit described above has a performance comparable with that using electronic multipliers. It has the advantage that the number of associated operational amplifiers required is reduced from 4 (in Fig. 36) to 1 (Fig. 38c). This saving occurs because:

1. Input impedance to V_E is high ($> 2\ M\Omega$), and a buffer amplifier is not essential.
2. V_I may be taken direct from R_I , because a higher amplitude is not required.
3. Sign reversal of the ripple components is carried out by a simple additional transistor stage.

The circuit is simple and inexpensive to construct. Hence, whenever circumstances of constant voltage V_E exist, as discussed at the beginning of this section, it is preferable to use a transistorised unit. Two such units were built for the Model. Further particulars of performance and accuracy appear in the next chapter (section 1.1.2).

1.5 AVR Rectifier/Filter.

The circuit developed for the rectifier/filter is shown in Fig.

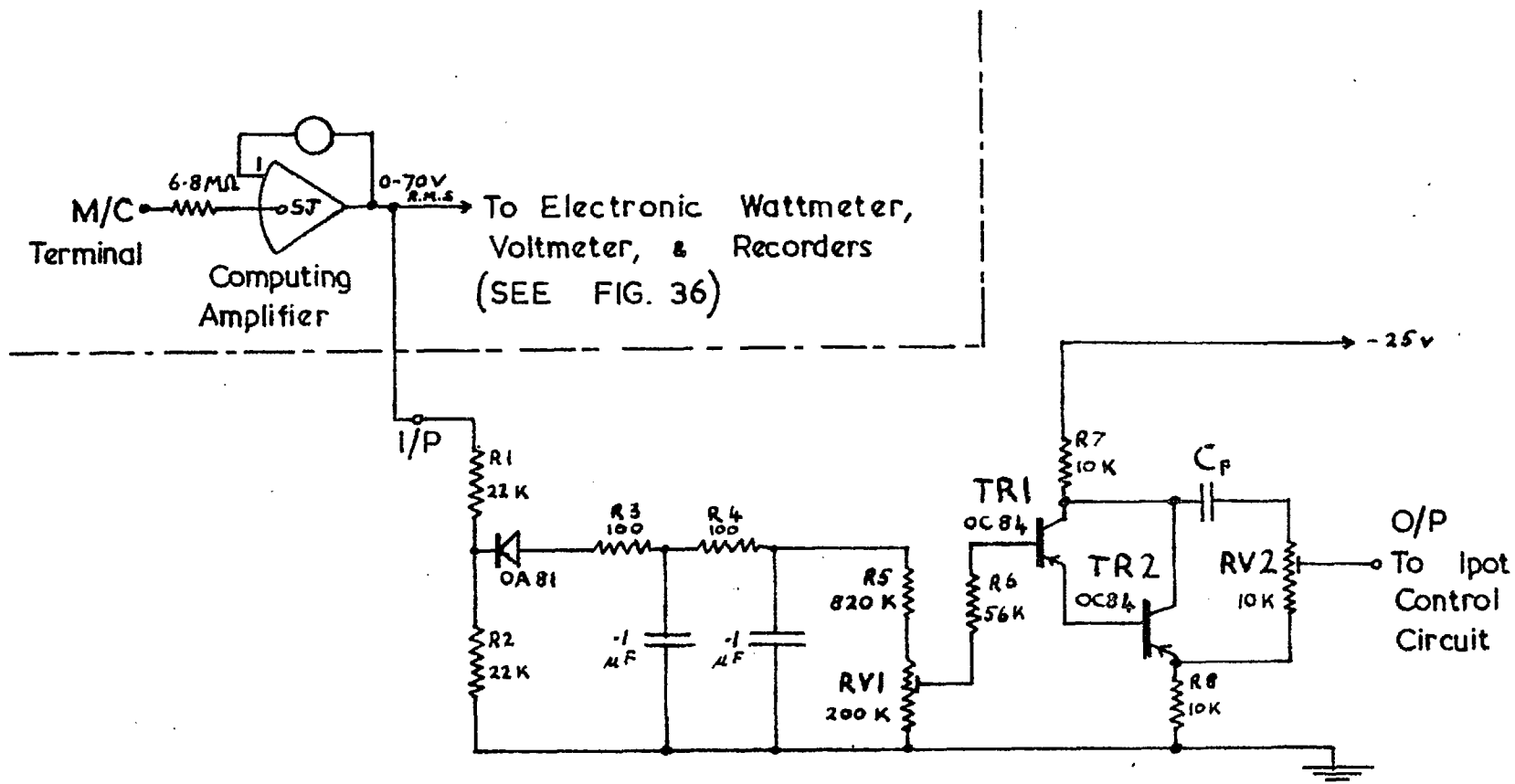


FIG. 39. A.V.R. RECTIFIER/FILTER

The rectifier stage is a conventional half-wave circuit utilising an OA 81 diode. The output of the stage is taken from potentiometer RV1, which serves as a gain control for the unit.

The filter and output circuit employs two transistors TR 1 and TR 2, arranged to have a low output impedance ($<10\text{ K}\Omega$) and a high input impedance - so that loading on the diode rectifier is minimal, thus achieving good linearity over the required working range (0 - 70 V r.m.s. input). The input impedance at the base of TR 1 is approximately $B^2 \cdot R_g$, where B is the current gain $\frac{\text{collector current}}{\text{base current}}$ for the matched transistors TR 1 and TR 2. When B is of the order of 40 and $R_g=10\text{ K}\Omega$, then impedance = $40^2 \times 10\text{ K}\Omega = 16\text{ M}\Omega$.

The d.c. voltage from the rectifier stage possesses a ripple with 50 c.p.s. fundamental component and can be drawn from the emitter of TR 2. The ripple is also present at the collector of TR 1 where it is 180° out of phase with that at the emitter of TR 2. Hence, if a capacitive coupling is made from the collector of TR 1 through C_F (in Fig. 39) to one end of a potentiometer RV2, the other end being connected to the TR 2 emitter, a point can be found on the potentiometer where the resultant ripple is at a minimum, since the two ripple signals cancel each other. Good output smoothing is thus obtainable.

The presence of C_F results in a time delay in the overall response of the rectifier/filter unit. The larger C_F , the better the a.c. coupling - hence the better the smoothing of the d.c. output, but the longer the time constant. However, this feature is utilised to advantage in controlling the speed of response of the AVR servomechanism - as described in chapter 3, section 2.3.

The use of the AVR rectifier/filter, together with its characteristics and accuracy, is discussed in the next chapter (section 1.3).

Three rectifier/filter units were constructed, and input and output connections are brought out to sockets on an auxiliary patch-panel (Panel A in Fig. 44).

1.6 Rotor Angle Measurement.

An important requirement of the Power System Model is a satisfactory facility for displaying and recording the dynamic behaviour of the rotors of the machines. This is central to the study of stability, from whatever point of view. It has already been explained, in section 2.4 of chapter 3, that graduated indicator dials are fitted to the magslip rotors (see Fig. 30) to provide a direct visual display of the relative angular positions of the machine rotors. This provision assists in the preliminary setting up of initial power flow conditions in the Model. However, some additional means is required for enabling recordings of angle to be made, especially the relative angles between machines, when system dynamics and load/frequency changes are under study. Two methods are described here.

1.6.1 1st Method.

A simple, direct, method of obtaining a voltage V_δ proportional to angle δ is to integrate the output of d.c. tachogenerator voltage of the velodyne which drives the magslip. Reference to Fig. 28 shows that if the gear ratio between velodyne and magslip rotor is $T : 1$, then we have

$$\text{tachogenerator voltage } V_{TG} = - e \dot{\theta} = - \frac{\epsilon}{T} \dot{\delta} = - \frac{\epsilon}{T} \cdot \frac{d\delta}{dt}.$$

If this voltage is applied to an integrator (x 10 input) through a coefficient potentiometer, setting k , (see Fig. 40a), then integrator output voltage = $V_{I.C} - \int_0^t - 10 k \frac{\epsilon}{T} \cdot \frac{d\delta}{dt} \cdot dt$

$$= V_{I.C} + 10 k \frac{\epsilon}{T} \cdot \Delta\delta,$$

where $\Delta\delta$ = change in angle δ in time t .

If $\delta = \delta_0$ at time $t = 0$, and we put $V_{I.C.} = \frac{10 k \epsilon}{T} \cdot \delta_0$, then output voltage at time $t = V_\delta = 10 k \frac{\epsilon}{T} (\delta_0 + \Delta\delta) = 10 k \frac{\epsilon}{T} \cdot \delta$,
i.e. V_δ is analogous to rotor angle, δ , and may be recorded accordingly.

To obtain a measure of relative rotor angle, two tacho-generator signals are fed to the integrator with opposing polarities, as shown in Fig. 40b. In this case, integrator output voltage

$$\begin{aligned} &= V_{I.C} - \int_0^t - 10 k_1 \frac{\epsilon_1}{T} \cdot \frac{d\delta_1}{dt} - \int_0^t + 10 k_2 \frac{\epsilon_2}{T} \cdot \frac{d\delta_2}{dt} \cdot dt, \\ &= V_{I.C} + 10 k_1 \frac{\epsilon_1}{T} \cdot \Delta\delta_1 - 10 k_2 \frac{\epsilon_2}{T} \cdot \Delta\delta_2, \end{aligned}$$

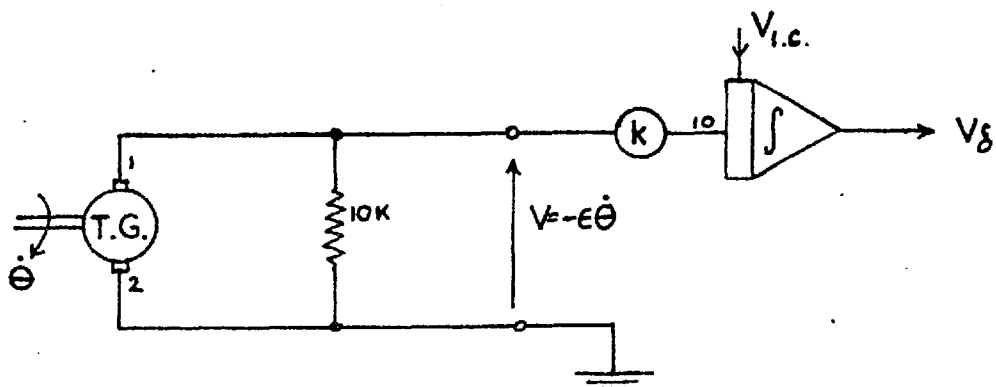
where $\Delta\delta_1$ = change in angle δ_1 in time t ,

$\Delta\delta_2$ = change in angle δ_2 in time t .

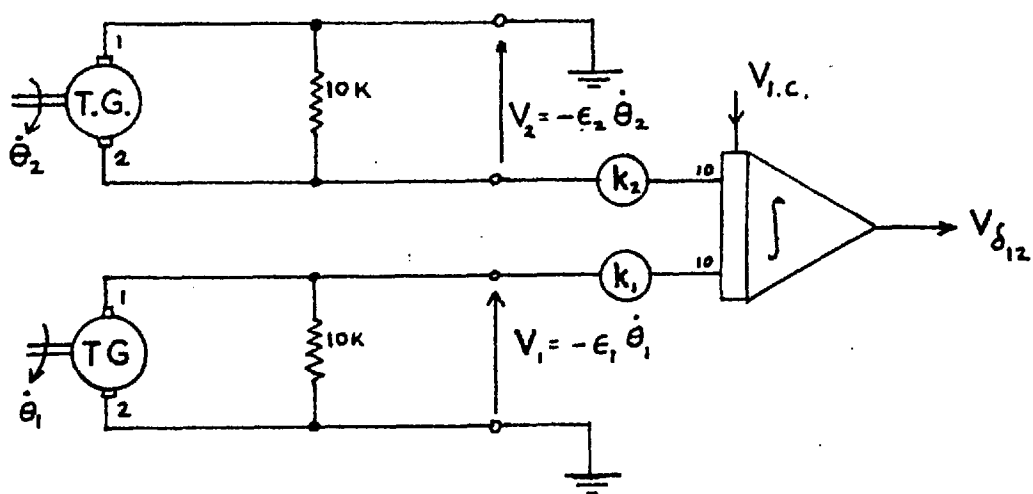
If now $10 k_1 \frac{\epsilon_1}{T} = 10 k_2 \frac{\epsilon_2}{T} = 10 k \frac{\epsilon}{T}$, and $V_{I.C} = 10 k \frac{\epsilon}{T} \cdot \delta_{12_0}$, then integrator output voltage at time $t =$

$$\begin{aligned} V_\delta &= 10 k \frac{\epsilon}{T} \cdot (\delta_{12_0} + \Delta\delta_1 - \Delta\delta_2) \\ &= 10 k \frac{\epsilon}{T} \cdot (\delta_{12_0} + \Delta\delta_{12}) = 10 k \frac{\epsilon}{T} \delta_{12}, \end{aligned}$$

so that V_δ is analogous to relative rotor angle δ_{12} .



40 a. SINGLE MACHINE



40 b. TWO MACHINES - RELATIVE ANGLE

FIG. 40. ROTOR ANGLE MEASUREMENT -
1st METHOD

The method works well when magslip rotors swing about initial angles set up with the rotors stationary and return again to rest after a short interval.

However, when Model System load changes result in equilibrium at steady magslip rotor speeds other than zero, certain difficulties arise. In the first place the recording of a single machine angle δ can only proceed for a limited time, since the integrator will eventually overload. Secondly, when relative angles δ_{12} are being followed by the integrator, it is found that drift occurs in $V_{\delta_{12}}$ due to non-linearities in tachogenerator output voltages (ie. $k_1 \epsilon_1$ can be set equal to $k_2 \epsilon_2$ at a given speed, but irregularities in ϵ_1 and ϵ_2 at other speeds produce an error voltage signal which is integrated).

A disadvantage is that rotor angles relative to busbars or terminal points cannot be recorded by this method. It is troublesome to be required to set up correct initial conditions for the integrators at the start of each study. The demand for operational amplifiers (as integrators) can also be regarded as unfortunate.

1.6.2 2nd Method.

As a result of the serious difficulties mentioned above in successfully obtaining accurate rotor angle recordings by the 1st method, it was decided to use a technique based on electrical signals derived from the magslip rotor windings and other appropriate points in the electrical network. A device was developed using transistors, the principle of which is shown in Fig. 41. V_1 and V_2 are voltages

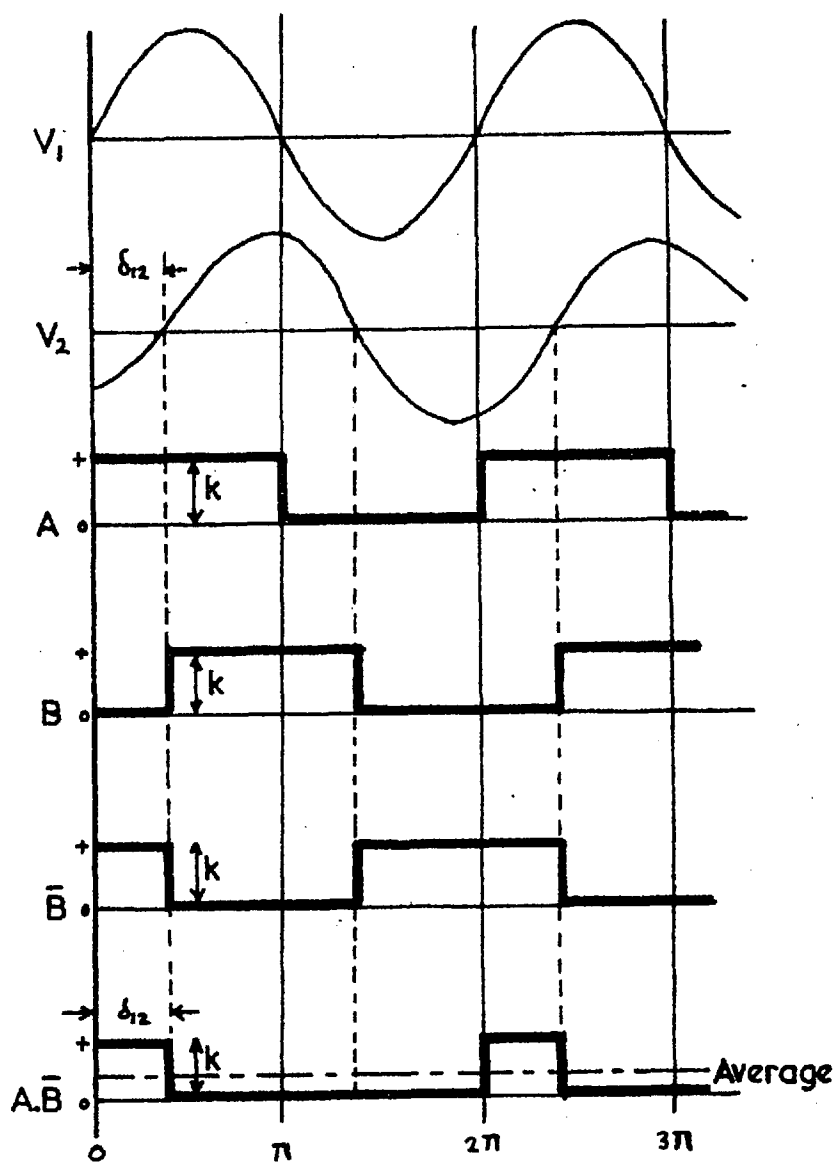


FIG. 41. ROTOR ANGLE MEASUREMENT
— 2nd METHOD

(e.g. derived from magflip rotors) which differ in angle by δ_{12} . The sinusoidal waveforms are squared to a constant amplitude K , and the results shown at A and B. The quantity $\bar{B}$ is formed. Then the operation $A.\bar{B}$ yields a train of pulses of constant height K and width δ_{12} . The average level of the pulse train (taken over a cycle $0 \rightarrow 2\pi$) $= K \cdot \frac{\delta_{12}}{2\pi}$, and is seen to be proportional to δ_{12} .

The above operations are carried out in the device whose circuit is shown in Fig. 42. The principles of operation are simple. The input voltages V_1 and V_2 are applied to stages composed of emitter coupled pairs of transistors TR1, TR2 and TR5, TR6. High input impedances ($>2.7 \text{ M}\Omega$) to the bases of TR1 and TR5 enable the device to be operated by voltages from any part of the Model network without significant loading errors.

Generation of the square waves A and $\bar{B}$ is achieved by over-driving emitter transistor pairs TR3, TR4 and TR7, TR8 so that TR4 and TR8 are switched hard on and off by alternate half cycles of V_1 and V_2 respectively. The use of transistor circuits in this way is described by Cattermole⁸¹. The drive for TR3 is taken from the collector of TR1 to form A at the collector of TR4, and the drive for TR7 is from TR6 to form $\bar{B}$ at the collector of TR8. Good square waves are obtained at the TR4 and TR8 collectors, which switch between ground potential and -20 V approximately, so that K , in Fig. 41, $= -20 \text{ V}$.

The operation $A.\bar{B}$ is carried out using the diode AND gate D1 and D2, and the output is taken from a $10 \text{ K}\Omega$ load. Pulse width,



proportional to δ_{12} , may be displayed directly on a CRO, or the mean level of a train measured on a d.c. voltmeter, or fed through a simple RC smoothing circuit to a recorder.

The device produces good results and does not suffer from any of the difficulties of the 1st Method of section 1.6.1. The range is limited to angles such that $0 \leq \delta_{12} < \pi$ during which the average output $A.\bar{B}$ varies linearly from 0 to $\frac{1}{2} K$. Over the range $\pi \leq \delta_{12} < 2\pi$, the average output drops from $\frac{1}{2} K$ to 0 (inspection of Fig. 41 helps to make this clear). Thus for a given average output level there is ambiguity in the value of δ_{12} . However, this can be resolved by reference to initial mag-slip rotor dial readings. The operating range is adequate in practice, since stability between machines can only exist in the range $0 \leq \delta_{12} < \frac{\pi}{2}$, or exceptionally in the range $\frac{\pi}{2} \leq \delta_{12} < \pi$. Care must be taken in the interpretation of angular recordings of pole-slip or asynchronous operation, however.

2. INTERCONNECTIONS.

This section describes the arrangements for interconnection in the Model. There is a main patch panel (2.1), a dynamic control box (2.2), subsidiary patch panels (2.3), and certain internal interconnections (2.4).

2.1 Main Patch Panel.

The main patch panel for the equipment which couples the

analogue computer to the network analyser is mounted in the 19" rack above the velodyne/magslip units and can be seen in Fig. 30. There are three groups of 17 multi-coloured 3 mm. sockets for three velodyne/magslip units associated with the three AVRs. The fourth velodyne/magslip unit has its own group of 8 sockets (being without an AVR).

The layout of the connections to one group of sockets is shown in Fig. 43a. The list of connections is as follows:

1. G_1 and G_2 (white) are the input control grids of the servo-amplifiers driving the velodynes.
2. Black sockets are common ground.
3. TG_1 and TG_2 (red and blue) are tacho-generator outputs, each pair having an internally connected 10 K Ω load resistor.
4. X and 3R (yellow and green) are magslip rotor winding outputs.
5. 2 and 4 (yellow and violet) are I pot connections (see Fig.29).
6. G (white) is the input control grid for the servoamplifier in the AVR servomechanism circuit.
7. 5 (yellow) is an I pot connection, internally connected to common ground through a 110 Ω resistor R_I .
8. 3 (green) is the output from the main contact arm of an I pot, and a cable also connects this socket to a flying lead and plug at the conjugate network analyser plugboard.
9. $\frac{M}{T}/C$ (blue) is connected by cable to a flying lead and plug at the conjugate network analyser where the plug is inserted at the point representing the electrical machine terminal.

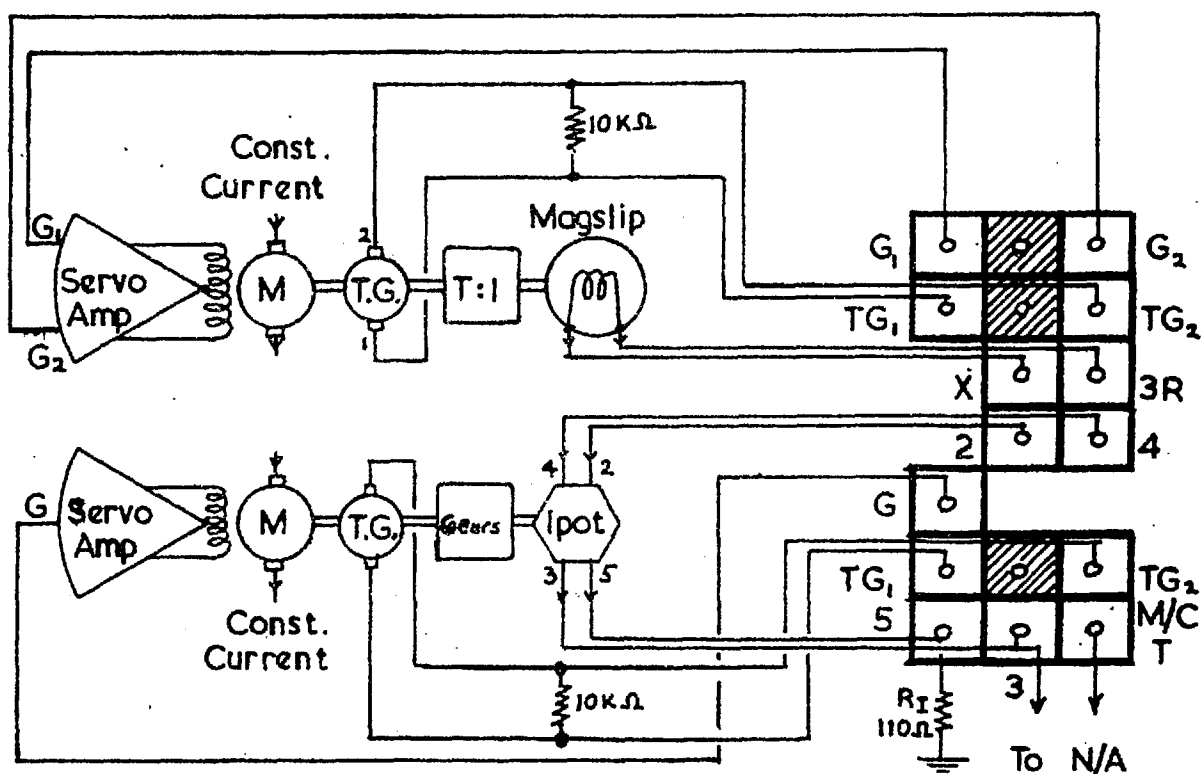


FIG. 43 a. MACHINE UNIT CONNECTIONS

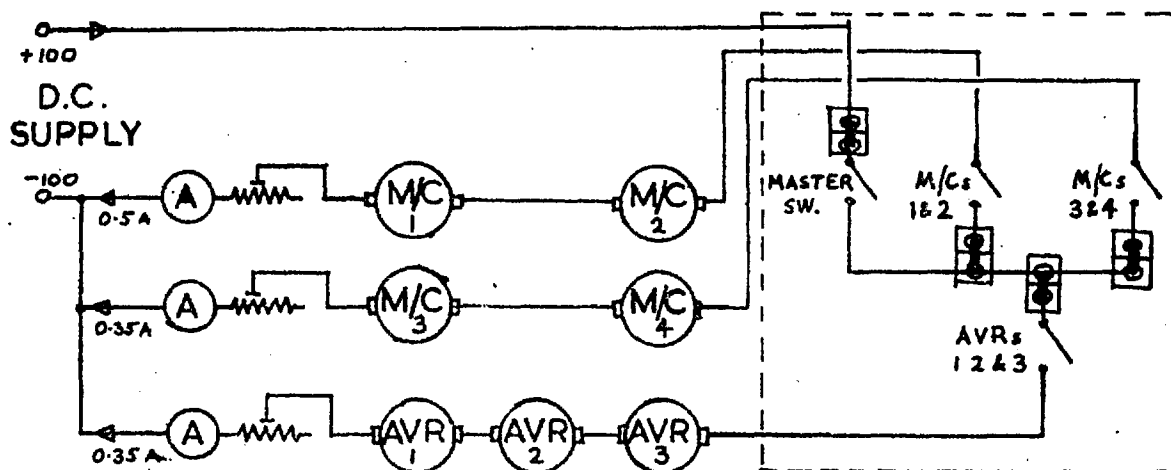


FIG. 43 b. DYNAMIC CONTROL BOX

Sockets X and 2, and 3R and 4 can be joined by shorting links to establish the magslip rotor/I pot connections shown in Fig. 36 for a complete machine unit.

Shorting links can also be used to ground G_1 or G_2 and TG_1 or TG_2 terminals at the adjacent black sockets.

Magslip rotor, I pot and tachogenerator connections are made internally using 12-core cables and McMurdo plugs and sockets. Servoamplifier grid connections to their patch panel sockets are made by screened leads, with screening earthed at the amplifier ends.

2.2 Dynamic Control Box.

The armatures of the velodyne motors are fed with constant current in accordance with the velodyne principle discussed in section 2.2.1 of chapter 3. The laboratory ± 100 V d.c. supplies are suitable, and series rheostats are used to establish the rated current for the appropriate motor. The supplies to the motor armatures are wired through a "dynamic control box" according to the layout shown in Fig. 43b.

The dynamic control box is fitted with 4 switches:

1. A "MASTER" switch, through which all armature currents must flow.
2. M/C 1 and 2 switch, which controls current to velodyne/magslip units 1 and 2, whose motor armatures are in series.
3. M/C 3 and 4 switch, which controls current to units 3 and 4, whose motor armatures are in series.

4. AVR 123 switch, which controls current to the AVR assembly, whose three motor armatures are in series.

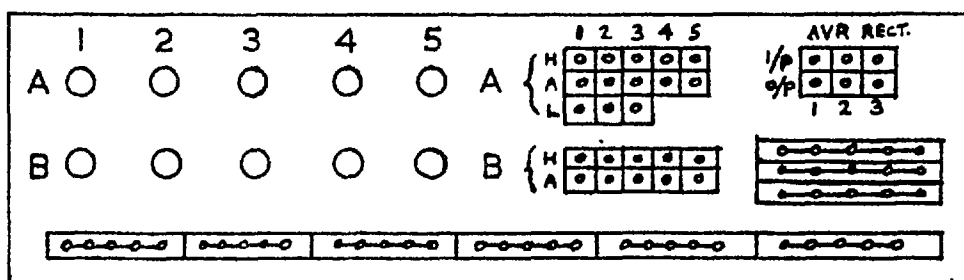
Each switch circuit includes a pair of 3 mm. sockets, normally fitted with shorting links.

Use of the MASTER switch enables the dynamic performance of the Model to be "frozen" at any instant by interrupting the d.c. supplies to the armatures of the servo-motors. Observations of Model system conditions can then be made, after which normal action can be resumed. If the master shorting link is replaced by a relay, the Model can be remotely stopped and started at predetermined instants by signals from the analogue computer.

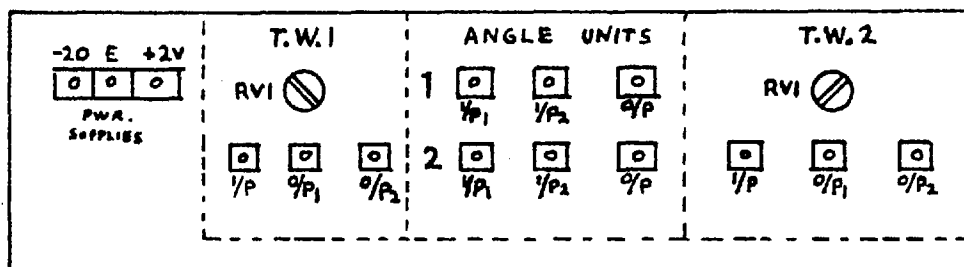
Use of the control box facilitates the setting up of initial conditions in the Model. The control circuits of each pair of machine units, and of the AVRs as a group, can each be set up and tested separately. System behaviour with and without AVR action can be readily examined.

2.3 Subsidiary Patch Panels.

Subsidiary patch panels are shown in Fig. 44. Panel A is mounted above the main patch-panel in the 19" rack, and its chief purpose is to facilitate the patching up of the velodyne/magslip and I pot control circuits. There are 9 groups of 5 sockets linked as busbars, which can be conveniently used as summing junction points for connections to servo-amplifier input grids. Also mounted on the panel are 10 potentiometers. Row A are 10 turn helical 30 k Ω



PANEL A



PANEL B

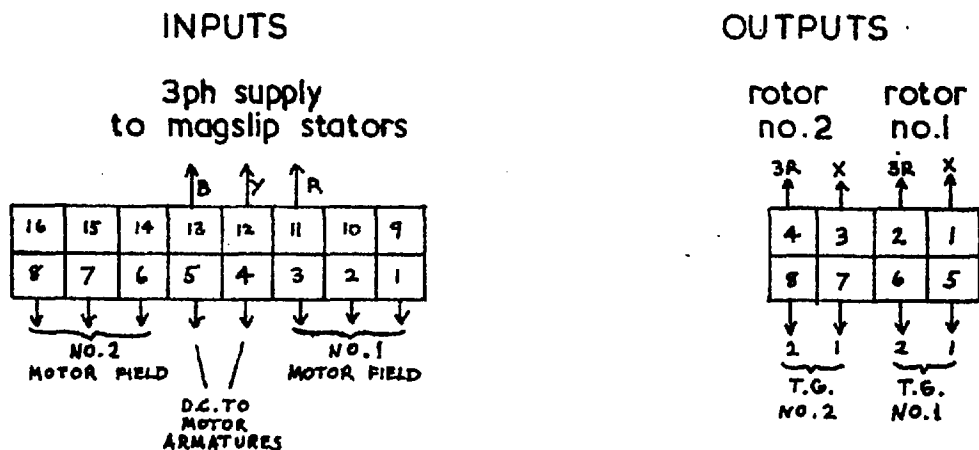
FIG. 44. SUBSIDIARY PATCH PANELS

potentiometers. Row B are 50 K Ω wire-wound pots.. Connections to the potentiometers are brought out to batches of sockets marked A and B. Ends of potentiometers go to "H" and "L" sockets, the moving contact arm to "A". Potentiometers with "L" sockets have this point connected internally to common ground. Also mounted behind panel A are the three AVR Rectifier/Filter units, whose input and output connections are brought out to the sockets shown in Fig. 44a.

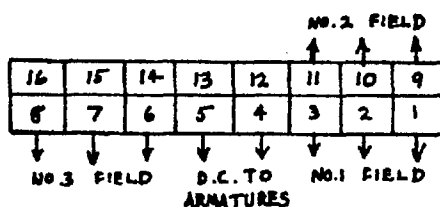
Panel B is mounted in the Minispace Extension Rack and is attached to a unit containing two transistorised wattmeter circuits (see Fig. 38c) and two angle measurement devices (see Fig. 42). Input and output sockets are provided, as shown in Fig. 44b. Also provided on Panel B are sockets for power supply to the transistor circuits, which share common supplies of - 20 V and +2V from their own transistor power-pack. The potentiometers for minimising carrier leak in the transistor wattmeters (RV1 in Fig. 38c) are also fitted to Panel B.

2.4 Internal Interconnections.

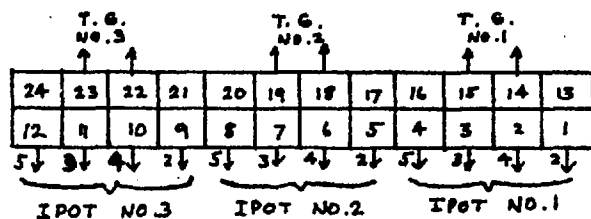
The velodyne/magslip and AVR assembly baseplates are fitted with McMurdo multiple sockets to which the electrical connections are made. Cables attached to corresponding plugs are connected to associated servo-amplifiers, power supplies and main patch-panel sockets, and the wiring to the plugs and sockets is shown in Fig. 45.



VELODYNE/MAGSLIP UNITS

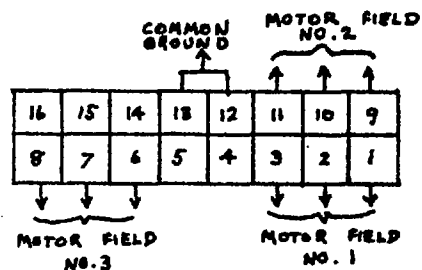
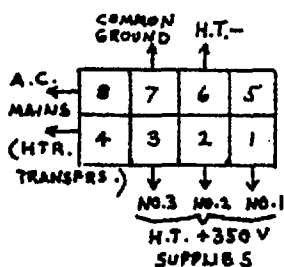


MOTOR INPUTS



T.G. & IPOT CONNECTIONS

AV.R. ASSEMBLY



SERVO AMPLIFIERS (MODIFIED GROUPS)

FIG. 45. INTERNAL INTERCONNECTIONS

The groups of modified servo-amplifiers also have multiple sockets for connections, and these also are shown in Fig. 45.

Other power supply connections are wired up inside the 19" rack and switches for a.c. mains and laboratory d.c. supplies are fitted in the front, at the top. Interconnections with the Solartron Analogue Computer equipment are made through external cables with multiple plugs.

CHAPTER 5

CAPABILITIES OF THE MODEL

1. ACCURACY.

In this section, the practical accuracy of the Power System Model is discussed in terms of experimental tests on the equipment. Thus the accuracy of power readings is assessed (1.1), using either electronic multipliers (1.1.1) or the transistorised units (1.1.2). The transistor devices for measuring angle are discussed (1.2) and the linearity of the AVR rectifier/filter devices has been determined (1.3). Finally, some comments are made on overall accuracy of the Model (1.4).

1.1 Power Measurements.

As explained in the previous chapter, two principal methods are used for measurement of electrical power flow. In both cases operational amplifiers are used, the electronic multiplier method requiring 4 amplifiers (see Fig. 36) and the method using the transistorised unit requiring 1 amplifier (see Fig. 38c). The operational amplifiers (Solartron types) have the specifications listed in section 2.1 of Chapter 2. Use in power measuring circuits involves the handling of 50 c.p.s. signals, and a frequency response test was conducted on typical operational amplifiers, at unity gain, to check their suitability. A characteristic range of results, for an input signal of 10 V.r.m.s. is:

FREQ (c.p.s.)	50	500	1Kc	4Kc	5Kc	6Kc	7Kc	10Kc
°/P Phase Lag (°)	< 1	1	2	5	6	8	10	17

It is seen that these amplifiers may be used with confidence, since phase shift is negligible in the vicinity of 50 c.p.s.

Accuracy of power measurement using electronic multipliers and the transistorised unit was determined by test experiments and is as follows:

1.1.1 Electronic Multipliers.

The electronic multipliers were first aligned following the procedure given in the manufacturer's instruction manual. Frequency response tests were also carried out. Typical results are as follows:

Alignment ± 100 V inputs to M and S units

<u>M</u>	<u>S</u>	<u>$\circ/P$ error (from S)</u>
+100	+100	+ .35 V
-100	-100	- .35 V
+100	-100	- .25 V
-100	+100	- .15 V

hence errors are within $\pm 0.5\%$ for all quadrants at max. voltage levels.

Frequency Response.

1. M input + 100 V	FREQ (c.p.s.)	20	40	60	80	100	200	300	400	500	800	900	1Kc
S. input 10 V r.m.s.	$\circ/P$ Phase lag($^\circ$)	2	4	6	8	10	20	31	41	50	80	89	98

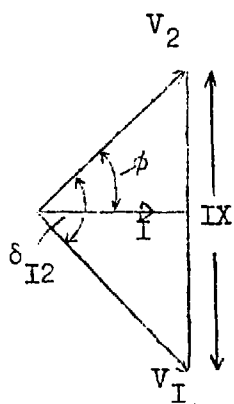
2. M input 10 V r.m.s.	FREQ (c.p.s.)	20	40	60	80	100	200	300	400	800	1Kc
S input + 100 V	$\circ/P$ Phase lag($^\circ$)	2	5	7	10	12	24	36	48	90	111

Summary Static accuracy is better than $\pm 1/2 \%$
 M unit has 6° phase shift at 50 c.p.s.
 S unit has 5° phase shift at 50 c.p.s.

Power Measurements at 50 c.p.s.

To test the electronic multiplier method the test circuit of Fig. 46a was used. Two machine units were interconnected so that an exchange of electrical power occurred. In the test circuit shown,

power flow $P = \frac{V_1 V_2 \sin \delta_{12}}{x_1 + x_2 + x_3}$.



If the excitation voltages V_1 and V_2 are maintained constant at 1 p.u., and $x = x_1 + x_2 + x_3 = 1$ p.u. reactance, then power flow $P = \sin \delta_{12}$ p.u.. From the diagram it is clear that power factor angle $\phi = \frac{\delta_{12}}{2}$, and current $I = \frac{2V}{X} \sin \frac{\delta_{12}}{2}$, so when $V = V_1 = V_2 = 1$ p.u., and $X = 1$ p.u., $I = 2 \sin \frac{\delta_{12}}{2}$.

In the test, values of power readings were taken for a full range of relative rotor angles δ_{12} from 0° to 360° . Over this range it is seen that, ideally, P varies sinusoidally between ± 1 p.u. and I increases from zero at $\delta_{12} = 0$ to 2 p.u. at $\delta_{12} = 180^\circ$ and then falls to zero again at $\delta_{12} = 360^\circ$. Power factors cover a full range of values from $\phi = 0$ to $\phi = 90^\circ$. The test thus covers typical working ranges of power levels, currents, power factors and M/C terminal volts.

FIG. 46 TEST CIRCUITS -I

Connections to electronic multiplier units were made according to the method described in section 1.4.1 of chapter 4 and first shown in Fig. 36. The smoothing circuit following the electronic multiplier output was omitted, and the d.c. component of voltage measured directly on a d.c. (moving coil) voltmeter. The gain of amplifier A was adjusted by means of potentiometer A so that the level of $1/P_1$ was 70 V r.m.s. for 50 V r.m.s. (= 1 p.u. volts) at M/C T1. The gain of amplifier B was adjusted by potentiometer B so that the level of $1/P_2$ was 70 V r.m.s. for 10 mA r.m.s. (= 2 p.u. current) in R_I . Hence, ideally, $\frac{70 \times 70}{100} = 49$ V d.c. = 2 p.u. power for the multiplier output (at unity power factor). In the test, therefore, the d.c. voltage component of multiplier output should lie in the range ± 24.5 V (corresponding to ± 1 p.u. power). A typical range is tabulated below:

1.	relative rotor angle δ_{12}°	10	20	30	40	50	70	90
2.	multiplier $^\circ/P$, D.C. volts	4.3	8.6	12.4	16	18.9	23	24.2
3.	" normalised $\frac{(2)}{24.5} \text{ p.u.}$	.175	.345	.506	.653	.771	.94	.99
4.	$\sin \delta_{12}$, power, p.u.	.174	.342	.5	.643	.766	.938	.766
5.	% error $\frac{(3) - (4)}{(4)} \times 100$ %	+0.6	+0.9	+1.2	+1.5	+0.7	+0.2	-1.0

1.	110	130	140	150	160	170	180	190	200	210
2.	22.6	18.1	15.1	11.7	7.5	3.7	1.1	5.5	9.6	12.6
3.	.923	.739	.617	.478	.306	.151	.045	.204	.372	.515
4.	.938	.766	.643	.5	.342	.174	0	-.174	.342	.5
5.	-1.6	-3.5	-4.0	-4.4	-10.5	-13.2	-	+17.2	+8.8	+3.0

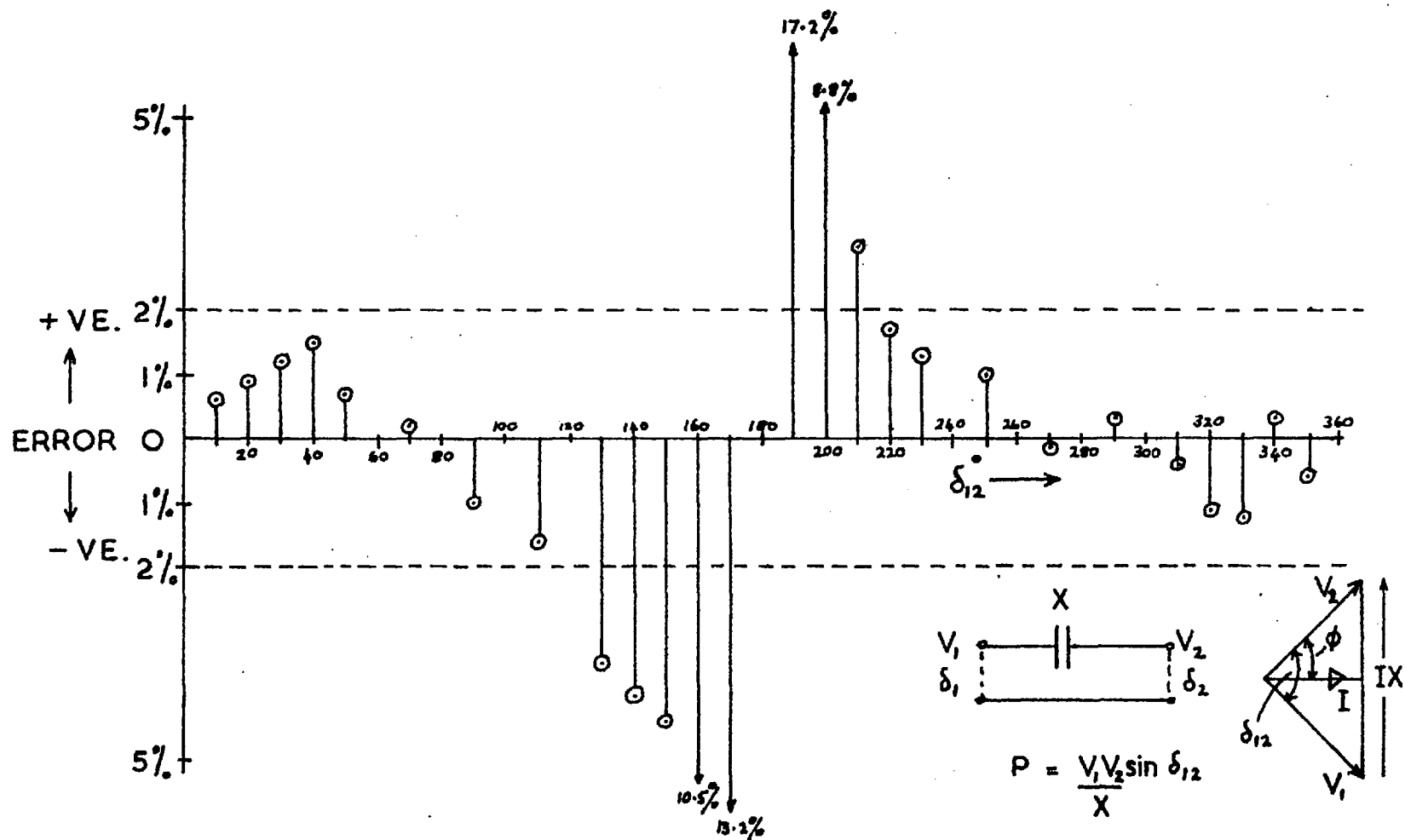
1.	220	230	250	270	290	310	320	330	340	350
2.	16	19	23.2	24.4	22.9	18.7	15.6	12.1	8.4	4.25
3.	.654	.776	.947	.998	.935	.763	.636	.494	.343	.173
4.	.643	.766	.938	1.0	.938	.766	.643	.5	.342	.174
5.	+1.7	+1.3	+1.0	-0.1	+0.3	-0.4	-1.1	-1.2	+0.3	-0.6

The errors over the full range of δ_{12} are plotted in Fig. 47. It is seen that accuracy is within $\pm 2\%$ for $0^\circ < \delta_{12} < 120^\circ$, and for $220^\circ < \delta_{12} < 360^\circ$: i.e. the method is acceptable for values of relative rotor angle in the range $-120^\circ \leq \delta_{12} \leq +120^\circ$, which is the range to be encountered in practicable power system studies. The test results show that power measurements by the electronic wattmeter in the vicinity of $\delta_{12} = 180^\circ$ are poor (current level is near the maximum, of 2 p.u., and power factors are near zero.)

The test described above also serves to establish that the magclip and I pot configuration acts as a suitably accurate source of variable angle excitation voltage of amplitude set by the position of the main contact arm of the I pot. The insertion of the 110 ohm resistor R_I to monitor current, and the method of measuring M/C terminal volts through the 6.8 M Ω resistor, are evidently acceptable techniques.

1.1.2 Transistor Wattmeter.

The test circuit of Fig. 46 b was used. The connection arrangements for the machine units are the same as for the test above.



see test circuit of FIG. 46a.

FIG. 47. POWER MEASUREMENT BY MULTIPLIER

The voltage signal for the transistorised unit was taken direct from the I pot output, at terminal 3. The current signal was fed direct from R_I to the $^{\circ}/P$ 1 connection on the transistorised unit through a 100 K Ω resistor - in accordance with the circuit of Fig. 38 c.

Setting up procedure for Transistor Wattmeter,

1. At zero power reading (current signal disconnected at terminal 5 and grounded), RV1 on the transistorised unit (see Fig. 38c) is adjusted until zero d.c. output is obtained from A. This adjustment minimises the carrier leak from the bridge modulator.
2. At maximum output power (1 p.u. when $V_1 = V_2 = 1$ p.u. and $\delta_{12} = 90^{\circ}$), potentiometer A is adjusted to obtain 10 V d.c. output from amplifier A. This sets the gain of amplifier A.
3. At maximum current ($\delta_{12} = 180^{\circ}$), RV2 is adjusted for minimum ripple from A (waveform viewed on oscilloscope).

With these conditions, readings were taken for a range of angles δ_{12} while maintaining voltages V_1 and V_2 constant at 50 V r.m.s. (= 1 p.u.) - as in the test of the electronic multiplier system. A typical table of results follows:

1.	Relative rotor angle δ_{12}	10	20	30	40	50	70	90	110	130
2.	$^{\circ}/P$, D.C. volts	1.7	3.3	4.9	6.4	7.6	9.5	10	9.3	7.3
3.	" normalised $\frac{(2)}{10}$ p.u.	.17	.33	.49	.64	.76	.95	1.0	.93	.73
4.	$\sin \delta_{12}$	.17	.33	.5	.64	.77	.94	1	.94	.77
5.	$^{\circ}/_o$ error $\frac{(3)-(4)}{(4)} \times 100$	0	-3	-2	0	-1.3	+1.1	0	-1.1	-5.2

1.	140	150	160	170	180	190	200	210	220	230	250
2.	6.1	4.7	3.1	1.5	0.2	1.2	2.9	4.4	5.7	7	9.15
3.	.61	.47	.31	.15	.02	.12	.29	.44	.57	.7	.92
4.	.64	.5	.34	.17	0	.17	.34	.5	.64	.77	.94
5.	-4.7	-6	-8.8	-11.8	-	-29.4	-14.7	-12	-11	-0.9	-2.1

1.	270	290	310	320	330	340	350
2.	10.2	9.75	7.8	6.65	5	3.35	1.7
3.	1	.98	.78	.67	.5	.34	.17
4.	1	.94	.77	.64	.5	.34	.17
5.	0	+4.2	+1.3	+4.7	0	0	0

The errors are plotted in Fig.48. In general, accuracy is within $\pm 2\%$ for $0^\circ < \delta_{12} < 120^\circ$ and $240^\circ < \delta_{12} < 360^\circ$, although there are a few errors (not $> 5\%$) at certain points. Hence the transistor wattmeter is acceptable for practicable rotor angles where $-120^\circ \leq \delta_{12} \leq +120^\circ$.

Accuracy outside this range in the vicinity of $\delta_{12} = 180^\circ$ is poor. A possible explanation is that the high current signals over this region cause overload in the bridge modulator - as mentioned in the discussion of practical performance in section 1.4.2 of chapter 4.

1.2 Angle Recordings.

The transistor devices for measuring relative angle δ_{12} were tested using the circuit of Fig. 49a. As described in section 1.6.2 of chapter 4, the output of the device is a pulse train, the width of

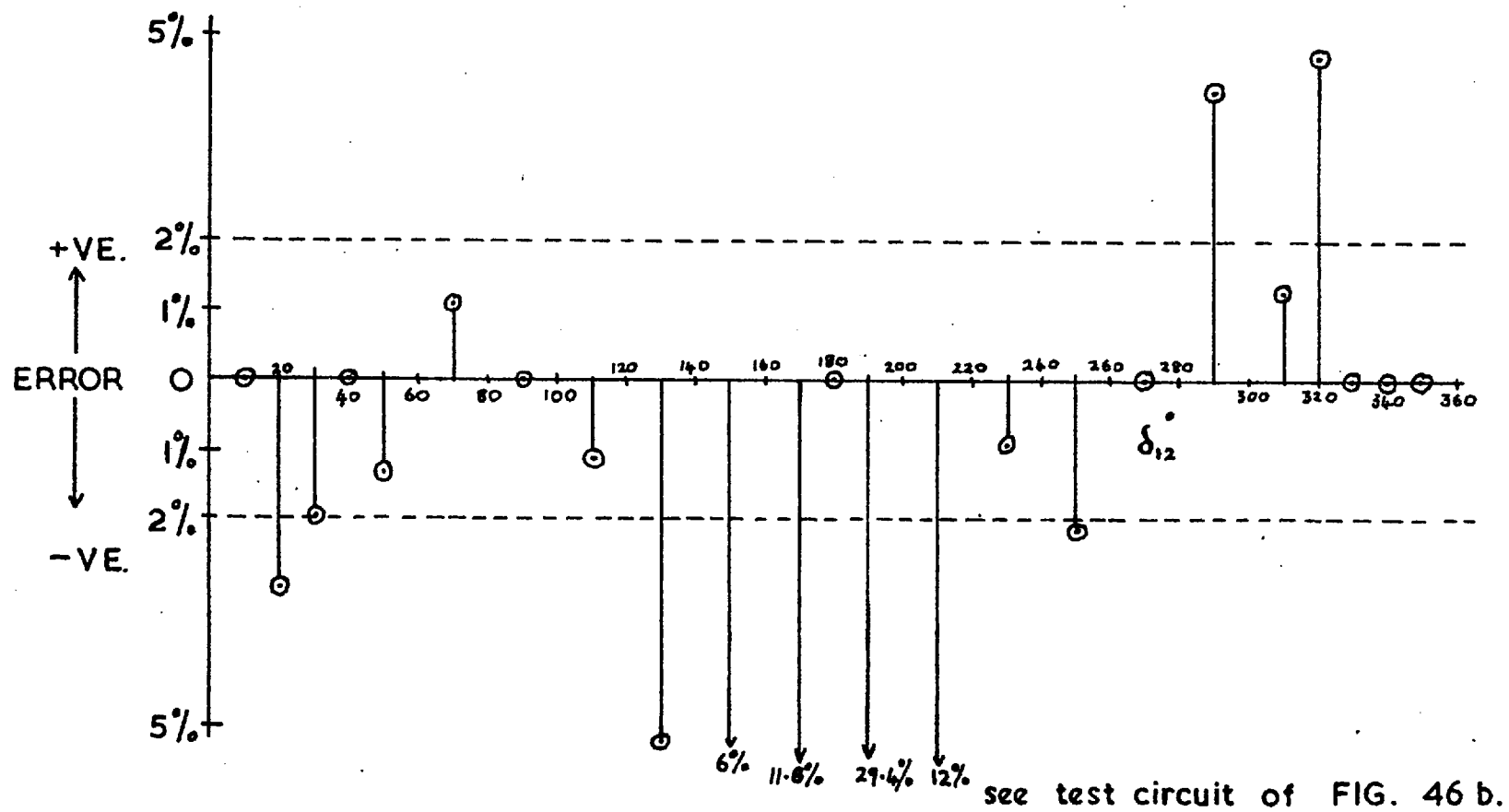
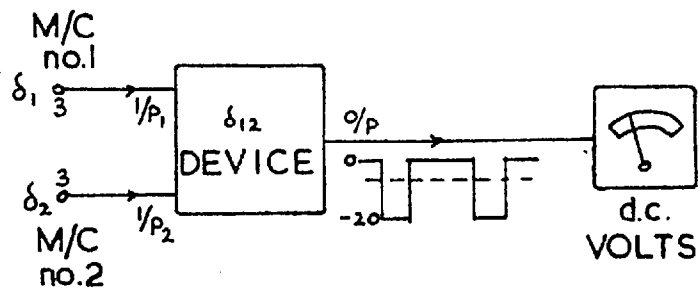
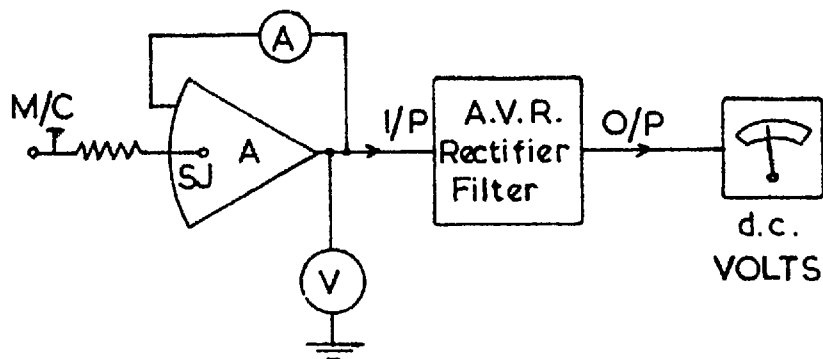


FIG. 48. POWER MEASUREMENT BY TRANSISTOR WATTMETER



49 a. ANGLE RECORDER
(results shown in FIG. 50)



49 b. A.V.R. RECTIFIER / FILTER
(results shown in FIG. 51)

FIG. 49. TEST CIRCUITS - II

the pulses being proportional to angle δ_{12} , and the height constant at - 20 V approximately. The mean level of the output pulse train was read on a d.c. voltmeter as δ_{12} was varied through the range 0 - 360°. A typical table of results is below:

Maximum d.c. output volts = - 9.45 (equivalent to $\delta_{12}=180^\circ$)

1.	Relative angle δ_{12}°	0	20	40	60	80	100	120	140
2.	D.C. °/P volts (-ve)	0	1	2.1	3.2	4.3	5.38	6.4	7.46
3.	Ideal °/P $\frac{\delta_{12}}{180} \times 9.45$	0	1.05	2.1	3.15	4.2	5.25	6.3	7.35
4.	% error $\frac{(2) - (3)}{(3)} \times 100$	0	-4.8	0	+1.6	+2.4	+2.5	+1.6	+1.5

1.	160	180
2.	8.52	9.45
3.	8.4	9.45
4.	+1.2	0

1.	Relative angle δ_{12}°	200	220	240	260	280	300	320
2.	D.C. °/P volts (-ve)	8.5	7.45	6.4	5.32	4.3	3.18	2.1
3.	Ideal °/P $\frac{360 - \delta_{12}}{180} \times 9.45$	8.4	7.35	6.3	5.25	4.2	3.15	2.1
4.	% error $\frac{(2) - (3)}{(3)} \times 100$	+1.2	+1.4	+1.6	+1.3	+2.4	+0.95	0

1.	340	360
2.	1	0
3.	1.05	0
4.	-4.8	0

The results are plotted in Fig. 50, which may be regarded as a calibration chart for the angle recorders.

The average error over the full range $0 \leq \delta_{12} \leq 360^\circ$ is 1.5%.

The device may thus be used to record angles with confidence.

1.3 AVR Rectifier/filter.

The test circuit used for the AVR Rectifier/filters is shown in Fig. 49b. The devices were tested over the range 0-70V r.m.s. from amplifier A. Potentiometer RV2 (see Fig. 39) was set for minimum ripple in the output signal (viewed on CRO). RV1 (the gain control) was adjusted to obtain 6 Vd.c. from the output when input signal level was 70Vr.m.s..

The table of the results for the three units is below:

1.	1/P (r.m.s. volts) a.c.	0	10	20	30	40	50	60	70
2.	°/P No. 1 (D.C.-VE.)	1.2	1.88	2.58	3.26	3.94	4.65	5.34	6
3.	°/P No. 2 "	.72	1.54	2.33	3.1	3.86	4.63	5.32	6
4.	°/P No. 3 "	1.19	1.56	2.31	3.07	3.8	4.57	5.28	6

The results are plotted in Fig. 51.

Each AVR rectifier/filter is seen to have good linearity over most of the range. The average characteristic slope is $\frac{0.7V \text{ d.c. output}}{10V \text{ a.c. r.m.s. input}}$ approximately. The d.c. level at zero input signal is created by the operating potential of the emitter of the output transistor (see circuit diagram, Fig. 39). This must be taken into account when feeding reference

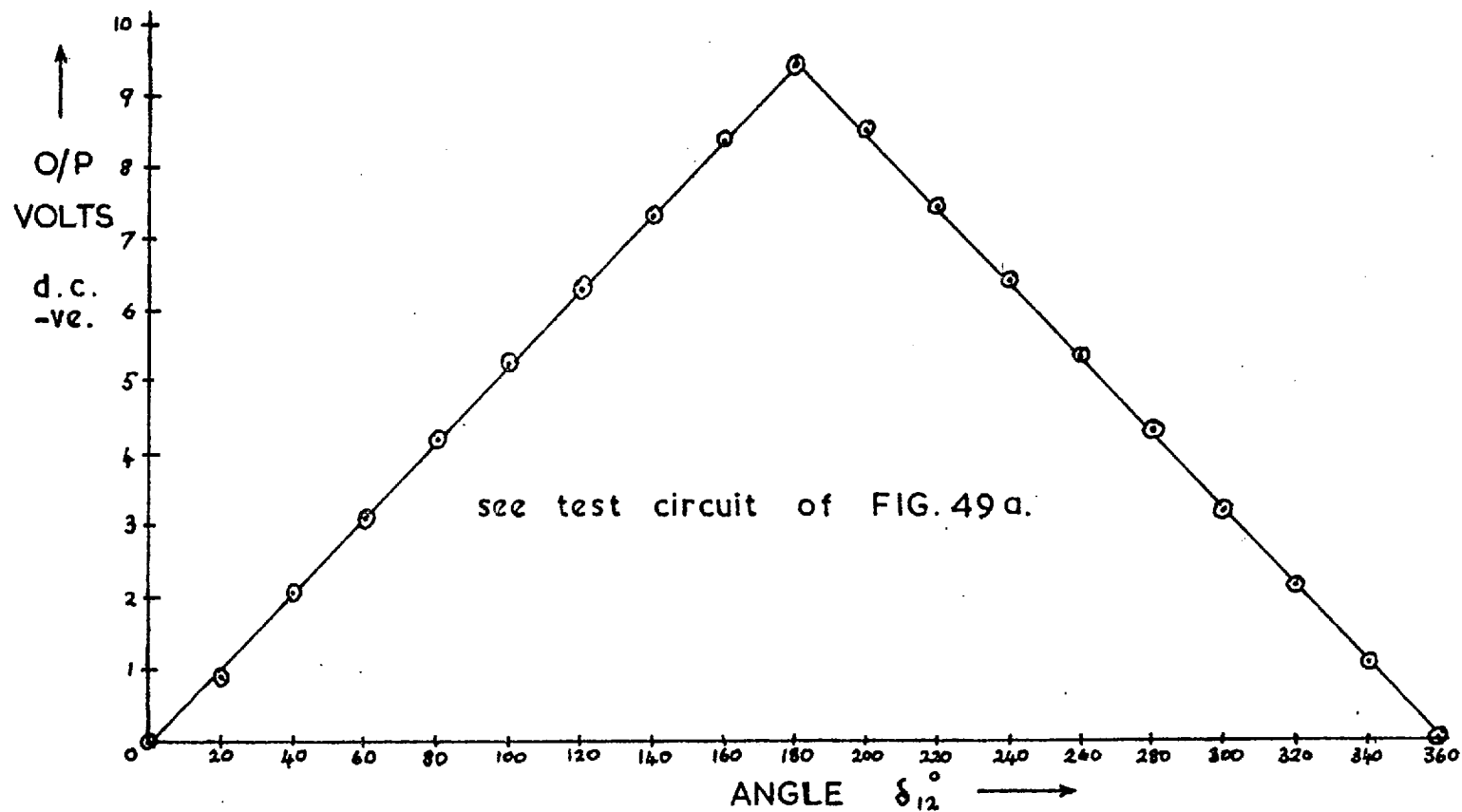
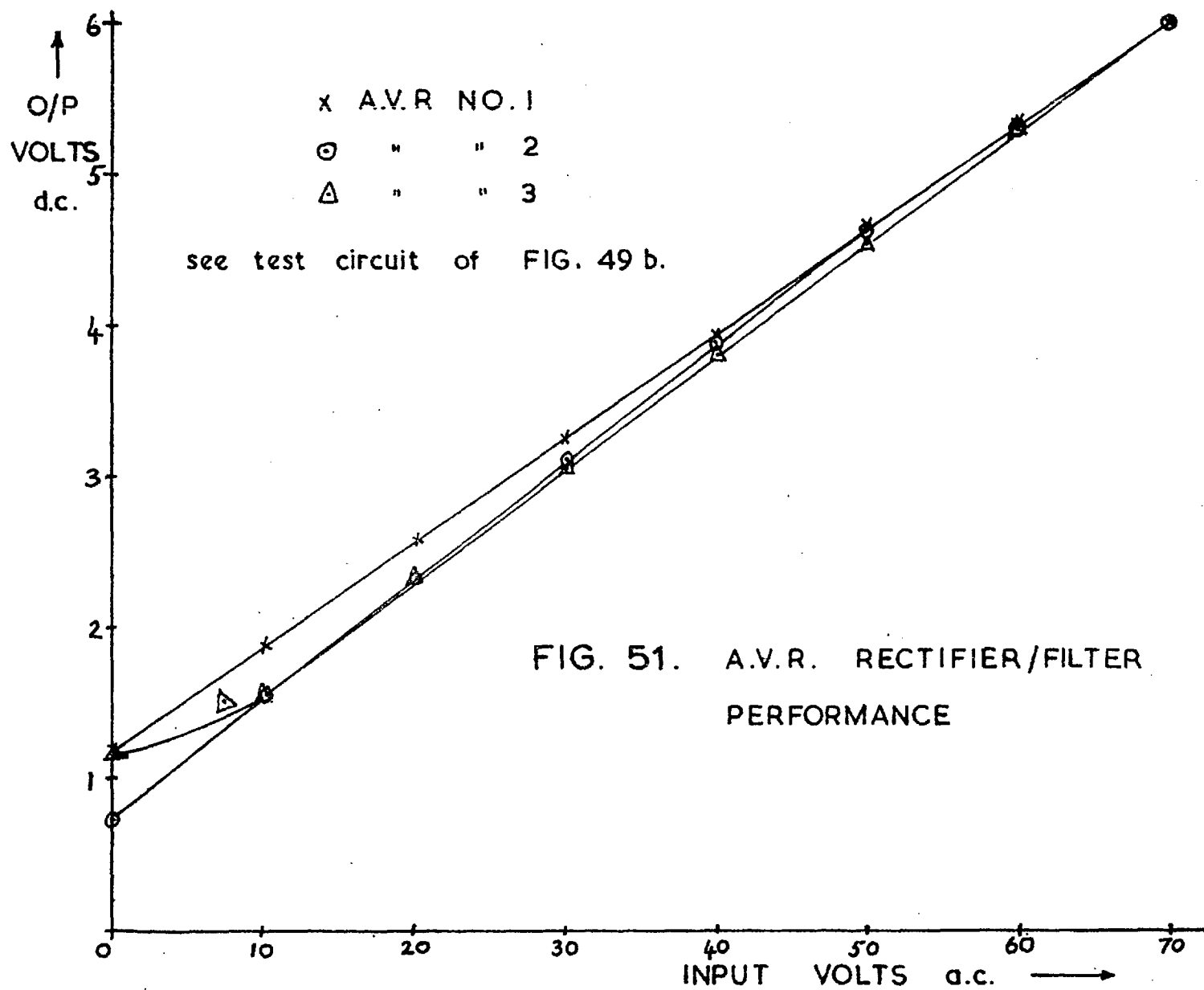


FIG. 50. ANGLE MEASURING DEVICE — CALIBRATION CHART



signals into AVR control circuits, but is otherwise irrelevant to their principle of operation (see Fig. 29 and section 2.3, chapter 3).

1.4 Overall Accuracy.

The accuracy of the Solartron analogue computing equipment used in the Model is $\pm 1\%$ overall, as previously stated in section 2.1, chapter 2. The impedance units in the conjugate network analyser can be calibrated to an accuracy better than $\pm 2\%$. The above sections of this chapter have shown that the auxiliary circuits associated with the machine coupling units, namely electronic wattmeters, angle recorders and AVR rectifier/filters, have practicable working ranges with nominal accuracies within $\pm 2\%$. Thus objective 4, section 1.3, chapter 3 (that the performance of the Model should have an accuracy of the order 1 - 2%) has been achieved, with regard to the static characteristics of all component parts of the complete Model.

The dynamic performance of the Model is affected by its inherent time constants. It was pointed out in section 1.4.1, chapter 3, that smoothing is necessary in the electronic wattmeter (and also in the AVR rectifier/filter) to keep to a minimum servo-motor heating and servo-amplifier overloading. In the case of the electronic multiplier circuit it has been shown that the 100 c.p.s. component of multiplier output can be reduced by $\frac{1}{60}$ if an associated time delay in the filter of 0.1 secs. is tolerated. However, it has been found that the servo-systems will operate successfully with higher levels of a.c. components, such as a reduction of only $\frac{1}{12}$, where the time delay is only 0.02 secs.

A cooling fan is fitted in the top of the 19" rack to improve the situation, and dynamic runs of 30 mins to 1 hour can be undertaken without excessive heating. Time delays of the order of 0.02 seconds are not unreasonable when system studies involve machines of natural frequencies greater than 1 c.p.s. (see Table 2) and when AVR time constants are not less than 1 second. In fact reheat turbine delays and many actual AVR time constants are much longer than 1 second.

From the above discussion it is not unreasonable to suppose that the overall accuracy of the Power System Model is within $\pm 5\%$. Performance and repeatability have been found in practice to be of this order, and certainly well within $\pm 10\%$. An accuracy of this order is adequate for evaluation of automatic governing and regulating studies. It enables practical comparisons to be made and the effects of changes in order of magnitude of different parameters to be confidently assessed.

In the final analysis, the accuracy of results is further influenced by the capabilities of the associated recording equipment. Power, voltage, angle signals etc. may be directly observed on oscilloscopes, but when a pen recorder or an X-Y plotter is used, it is usually necessary to include smoothing circuits, which create delay. Account has also to be taken of the frequency response, maximum rate of travel etc. of pens and galvanometers in the recorders.

2. OPERATION.

This section describes how the Power System Model may be set up, calibrated and operated. Suitable per-unit working values are recommended (2.1) and then calibration procedures for setting up the parameters of a power system are given (2.2). Notes on operating techniques are followed by a description of a schematic arrangement for a three machine system.

2.1 Per Unit Values .

2.1.1 Network Analyser .

Notes on the conjugate network analyser and its appropriate base values were first given in section 2.1, chapter 3, to which reference should be made.

The normal per unit values for the Conjugate Network Analyser are:

50 V r.m.s. $\longrightarrow$ 1 p.u. volts

5 m A $\longrightarrow$ 1 p.u. current

10 K Ω $\longrightarrow$ 1 p.u. impedance

and the consequent p.u. power is 250 m W.

These base quantities were found to be suitable for certain types of studies in the Model, but it is sometimes necessary to accommodate wider ranges of volts (AVR control, forced excitation up to 2 p.u. etc.) and wider power ranges (different sizes of generator). In these circumstances it is convenient to adopt:

25V r.m.s. $\longrightarrow$ 1 p.u. volts

2.5 m A $\longrightarrow$ 1 p.u. current

thus keeping the same impedance base of 10 K Ω as before, but the p.u. power level is now 62.5 m W. Wider ranges are consequently available for power, voltage, current, and control circuits.

2.1.2 Analogue Computer.

The best working level for the turbine simulation circuits and servo-control signals has been found to be 20 V d.c. $\longrightarrow$ 1 p.u. power. All reference and control voltages are derived from common sources of $\pm$ 100 V on the Minispace. All metering of d.c. voltages is done on the Minispace voltmeter, making use of the reference potentiometer and null balancing technique described in the Instruction Manual when accurate measurements are required (correct to three significant figures).

2.2 Calibration Procedures.

A practicable technique for impedance calibration is given (2.2.1). A discussion of procedures for setting up machine H constant and damping follows (2.2.2 and 2.2.3). Comments on AVR simulation (2.2.4) are followed by the procedure for time scaling (2.2.5).

2.2.1 Impedances.

Calibration of line and load impedance units on the network

analyser is carried out with the aid of an electronic multiplier circuit for power measurements. The multiplier circuit is first set up as described in section 1.1.1 above such that:

50 V r.m.s. ($\equiv$ 1 p.u. volts) produces 70 V r.m.s. from amplifier A (see Fig. 46a).

10m A ($\equiv$ 2 p.u. current) through R_I produces 70 V r.m.s. from amplifier B.

Hence 2 p.u. power $\longrightarrow$ -49 V d.c. from electronic multiplier.

1 p.u. " $\longrightarrow$ -24.5 V d.c. from electronic multiplier.

A line unit is calibrated in two stages, the reactive component X first, then the resistive component R. The impedance to be set up is connected between terminal 3 of a machine unit (see Fig. 46a) and common ground. The voltage signal for the electronic multiplier is also taken from terminal 3, and the voltage of this point is set at 1 p.u. (50 V r.m.s.) by means of the I pot, the voltage being monitored by an a.c. voltmeter at the output of amplifier A. X is then adjusted until current $I = \frac{1}{X}$ p.u., as indicated by monitoring the output of amplifier B (R is zero while this is done).

The resistive component R is next calibrated with X short-circuited. V is adjusted until 1 p.u. current flows. R is adjusted keeping I constant, until $I^2 R = P$ p.u. as measured at the multiplier output. Then, with I const. ($=$ 1 p.u.), $R = P$ p.u.

A load unit can be calibrated in a similar way.

2.2.2 Machine H Constant.

In this section it is useful to begin by reviewing the meanings of inertia constant and H constant when applied to electrical machines. After every disturbance in a power system the machines must adjust the relative angles of their rotors to meet the conditions of power transfer imposed. The process involves the electrodynamics of the machines.

For a rotating body, torque $T = I\alpha = I \cdot \frac{d\omega}{dt}$

where $I =$ the Moment of Inertia $(= \int r^2 dm)$ in Kg - meter²

$\alpha =$ angular acceleration $(= \frac{d\omega}{dt})$ in radian/sec².

The unit of torque T in the above equation is (newton - meter or joule)/radian. The kinetic energy of a rotating body is

$$\text{K.E.} = \frac{1}{2} I \omega^2 \text{ joules (or watt-seconds),}$$

and from this it follows that Moment of Inertia may also be expressed in the units of $\frac{\text{joules}}{\omega^2} = \frac{\text{joules}}{(\frac{d\omega}{dt})^2} = \text{joule-seconds}^2/\text{radians}^2$.

Since angular momentum $M = I \omega$, the unit of M becomes joule-seconds²/radians² x radians/second, or joule-second per radian.

When dealing with electrical machines the stored energy is more conveniently expressed in megajoules, and angles are more often measured in degrees. ~~Accordingly, angular momentum M is often measured in~~

~~megajoule-seconds per electrical degree. When M is computed from Iω,~~

~~with ω determined by the synchronous speed of the machine, M is called~~

the inertia constant. i.e.

inertia constant 'M' = $I \cdot \omega_s$ = angular momentum at synchronous speed.

In practice, confusion sometimes arises when another term, denoted by the letter H, is also called the inertia constant. The H constant is defined as stored energy of a machine at synchronous speed.
machine electrical rating

Thus the units of H are megajoules (or megawatt-seconds)
machine megavolt-amperes

$$= \frac{M \text{ W sec}}{\text{MVA}} \text{ (or } \frac{K \text{ W sec}}{\text{KVA}}, \text{ when numerator and denominator are multiplied by } 10^{-3})$$

The relation between M and H may be derived by letting G = rating of machine in MVA, then

$$\text{stored energy} = GH \text{ megajoules}$$

$$= \frac{1}{2} I \omega^2 = \frac{1}{2} M \omega$$

$$\therefore M = \frac{2GH}{\omega} = \frac{GH}{180f} \text{ megajoule-secs/electrical degree,}$$

since $\omega = 360f$ electrical degrees per second, where f is frequency in c.p.s. (considering a 2 pole machine).

The inertia constant M depends on the size of a machine as well as on its type, whereas the H constant does not vary widely with size. In fact H has a relatively narrow range of values for each class of machine regardless of the KVA and speed rating of the machine. Thus Stevenson¹² (p. 338 - 339) lists the following:

<u>Type of machine</u>	<u>H constant, M W sec/MVA</u>
Steam turbo-alternators	2 - 10
Waterwheel generators	1 - 4.5
Synchronous capacitors	1 - 1.25
Synchronous motors	2

Typical turbo-alternators on the C.E.G.B. system at present have H constants in the range 2-6 (see table 2 in chapter 2).

When several machines at one location are considered as one machine, the single equivalent machine has a rating equal to the sum of the ratings of the several machines considered to act together. The inertia constant M of the equivalent machine is the sum of the inertia constants M of the individual machines.

For any machine, or equivalent machine, accelerating power at any instant $P_a (= P_s - P_o) =$ accelerating torque x angular velocity,

$$\begin{aligned} \text{i.e. } P_a &= T_a \omega \\ &= I \alpha \omega = M \alpha \end{aligned}$$

Thus the accelerating power P_a is in megawatts if M is in megajoule-seconds per electrical degree and the angular acceleration α is in electrical degrees per second².

Now substituting for M,

$$\begin{aligned} P_a (\text{MW}) &= \frac{GH}{180f} \times \alpha = \frac{GH}{180f} \times \frac{\omega_2 - \omega_1}{t_{I2}} \quad \text{where the angular speed increases from } \omega_1 \text{ to } \omega_2 \text{ in time } t_{I2} \text{ secs.} \\ \text{If } P_a \text{ and } G \text{ are expressed in p.u. quantities,} \\ \text{then } P_a (\text{p.u.}) &= \frac{H}{180f} \times \frac{\omega_2 - \omega_1}{t_{I2}}, \text{ and this equation forms the basis of H constant calibration in the Model. If we take } \omega_2 - \omega_1 = 1 \text{ c.p.s. in the neighbourhood of } f = 50 \text{ p.s., with constant accelerating power } P_a \text{ during time } t_{I2} \text{ secs., then substitution in the above equation gives: } \\ P_a &= \frac{H}{180 \times 50} \times \frac{360 \times 1}{t_{I2}} \text{ whence } H = P_a \times 25 \times t_{I2} = 2.5 t_{I2} \text{ (when } P_a = 0.1 \text{ p.u.).} \end{aligned}$$

If the assumption is made that, when the machine runs at or very near steady synchronous speed, power is equivalent to torque, or "torque-balance" exists, then : p.u. power = p.u. torque x p.u. speed,

or p.u. power is analogous to p.u. torque,

so that the above relation for H may be interpreted in terms of time t_{12} seconds for an increase of 60 r.p.m. in magslip rotor speed when 0.1 p.u. torque is applied to the velodyne/magslip unit.

It was shown in section 2.2.3, chapter 3, that, for the control circuit of Fig. 28:

$$V_1 = k_2 \cdot \frac{R_1}{R_2} \cdot p\delta + c_2 \cdot R_1 C_2 \cdot p^2\delta$$

where V_1 is the d.c. input voltage representing p.u. torque (or p.u. power). The coefficient $c_2 R_1 C_2$ is analogous to inertia, and consequently proportional to H constant. If H is evaluated for given components R_1 and C_2 with $c_2 = 1$, then this determines the calibration of the unit and values of H may subsequently be set at will in this range by adjustment of the potentiometer setting c_2 . The test circuit used for calibration purposes is shown in Fig. 52a.

All servo control signals are normally summed at the grid terminal of the servo amplifier. Input impedances and capacitors are components which are connected to the patch panels externally by means of individual leads and plugs. Reference to the schematic diagram of Fig. 28 (chapter 3) will assist in the interpretation of the connections shown in Fig. 52a. For the calibration tests, the normal electrical power feedback signal is disconnected and the input impedances grounded at SW2. The damping signal from the tachogenerator (normally applied through R_2) is also disconnected and the end of R_2 grounded through SW 3. The reason for grounding the input ends of these summing resistors is to keep the loading at grid terminal G consistent with that existing in normal operation.

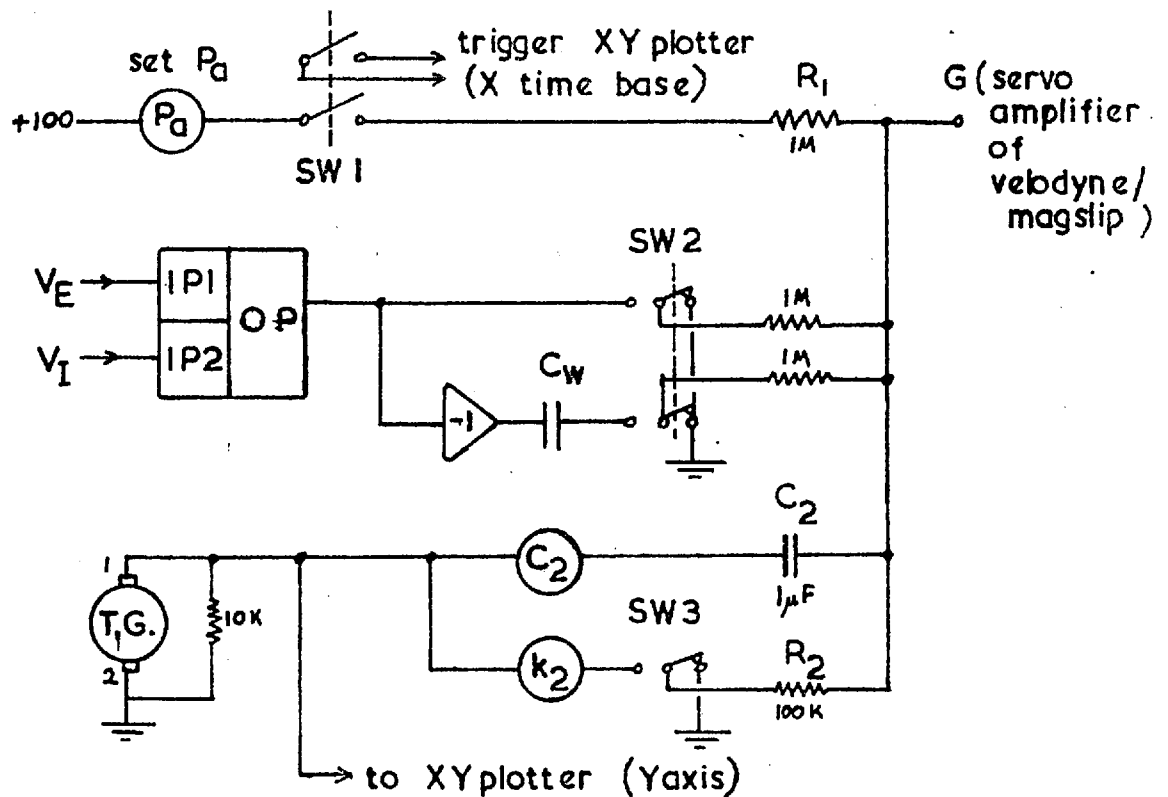


FIG. 52a. H CONSTANT CALIBRATION
(see section 2.2.2)

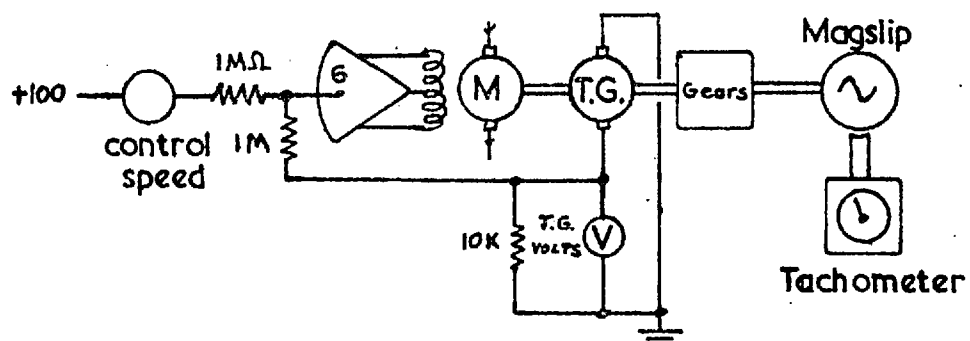


FIG. 52 b. MEASUREMENT OF T.G.
CHARACTERISTIC (results shown
in fig. 53)

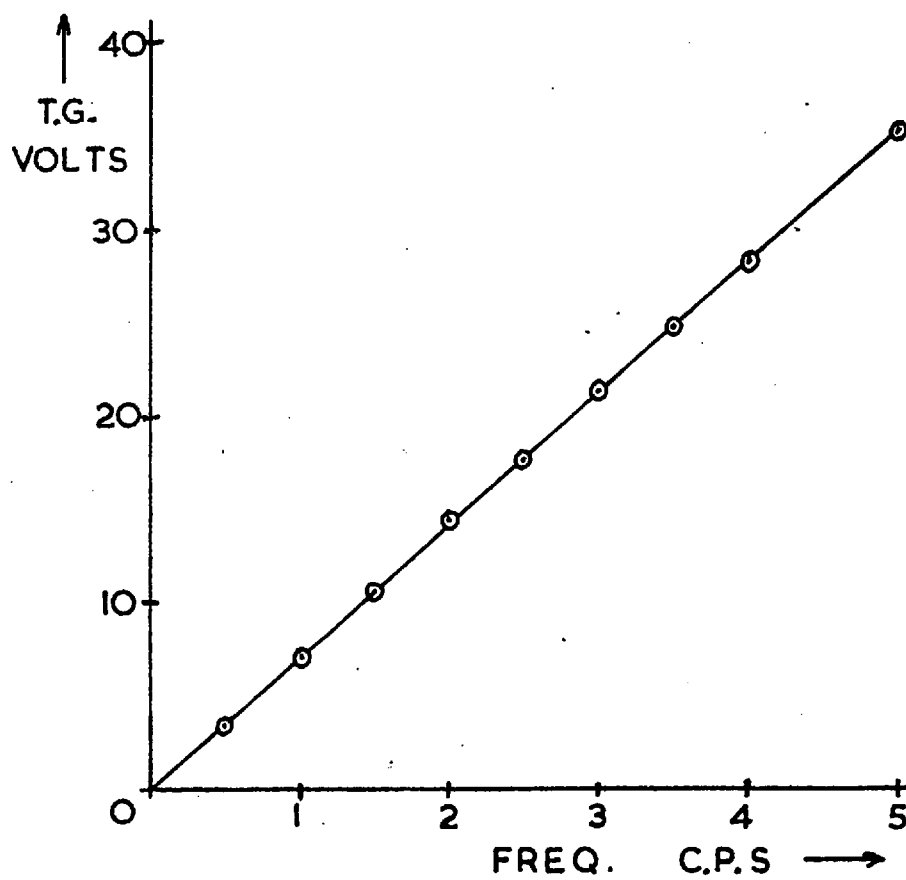
The capacitive feedback element C_2 is a $1\mu\text{F}$ high stability 1% polystyrene capacitor, and c_2 is set at unity. TG output voltage, taken as a measure of speed, is fed to the Y axis of an XY plotter. The accelerating signal, P_a , is set equivalent to 0.1 p.u. (2v input) and is applied through SW1, which also triggers the X time base of the XY plotter.

Interpretation of the tachogenerator voltage necessitates calibration in terms of magslip rotor speed. This may be done using the simple speed control circuit of Fig. 52b. Magslip rotor speed was measured in r.p.m. using a Smiths tachometer, for a range of rotor speeds of ± 300 r.p.m. (corresponding to an electrical frequency range of ± 5 c.p.s.). The results for velodyne/magslip unit no. 1 were as follows:

1.	Speed (r.p.m.)	6	12	30	60	90	120	150	180	210
2.	Frequency (c.p.s.)	.1	.2	.5	1	1.5	2	2.5	3	3.5
3.	TG $^{\circ}$ /P volts	.6	1.5	3.6	7.1	10.7	14.3	17.8	21.4	24.3

1.	240	300
2.	4	5
3.	27.8	35.2

The tachogenerator characteristic, for velodyne/magslip unit No.1, is plotted in Fig. 53, in terms of magslip rotor speed, (as equivalent electrical c.p.s) and tachogenerator output voltage. The slope is



VELODYNE/MAGSLIP UNIT NO. 1

see test circuit of FIG. 52 b.

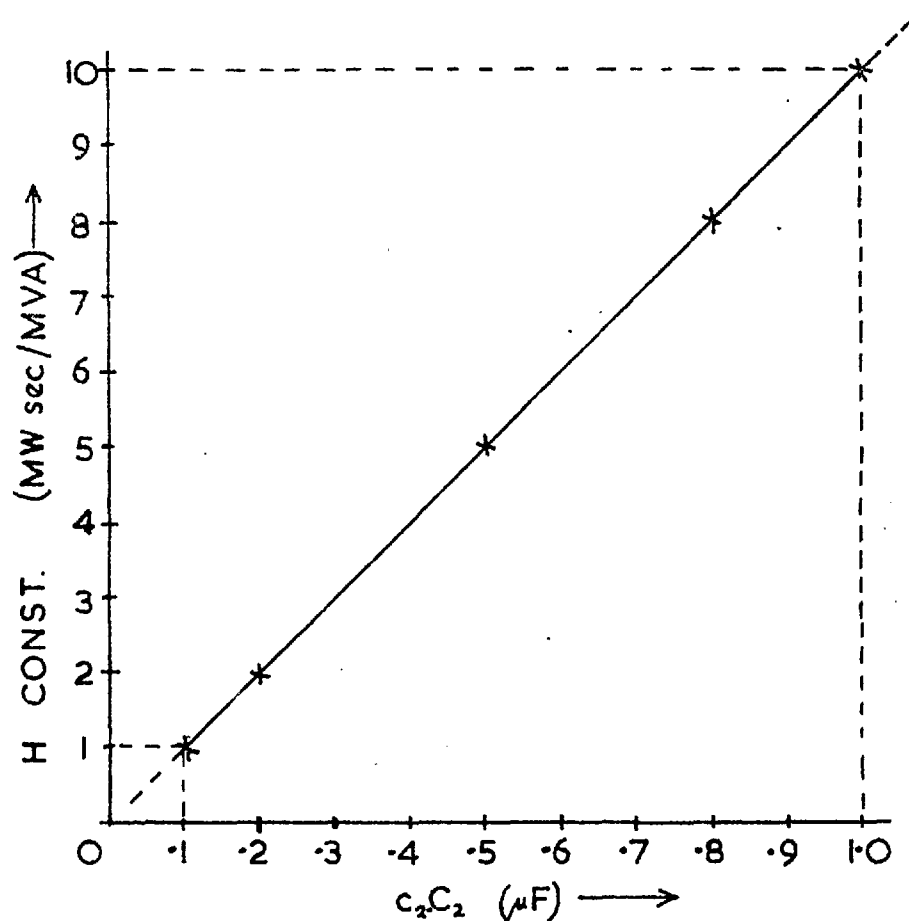
FIG. 53. TACHOGENERATOR
CHARACTERISTIC

approximately 7 volts/c.p.s.. Characteristics of the other velodyne/magslip units are obtainable in a similar way.

The value of t_{12} for the H constant calibration test can now be determined. A repeatably consistent result is obtained when t_{12} is measured over the speed range 60 - 120 r.p.m. (51 - 52 c.p.s.), for which the tachogenerator voltage increases from 7 to 14, approximately. This procedure eliminates the irregularity in tachogenerator output voltage at very low speed and the initial small delay in velodyne response to the step accelerating signal of 0.1 p.u..

From a series of tests, to ensure repeatability and accuracy, $t_{12} = 4$ seconds when $c_2.C_2 = 1 \mu F$. Hence $H \approx 2.5 t_{12} = 10$ when the value of capacitive feedback in Fig. 52a is equivalent to $1 \mu F$. Further tests were carried out with $c_2 = 0.1$ to establish that the corresponding $t_{12} = 0.4$ seconds, whence $H = 1$, thus ensuring the linearity of the inertia simulation principle. Other values in the range $0.1 < c_2 < 1$ were also checked. In accordance with these results, the calibration chart for machine H constant is drawn in Fig. 54. Other charts can be drawn for the remaining velodyne/magslip units and for alternative control and summing networks (such as that of Fig. 52a).

To test the linearity of the servo-amplifier and velodyne/magslip system, accelerations were measured for a range of values of P_a from 0.05 p.u. to 1 p.u. (1 V d.c. to 20 V d.c. input volts). Since $H = P_a \times 25 \times t_{12}$, then with H at a constant value (e.g. 10), t_{12} is inversely proportional to P_a . A typical range of results is:



VELODYNE / MAGSLIP UNIT NO.1

1p.u. accelerating power (P_a) $\equiv$ 20 Vd.c.

servo amplifier input network as

in FIG. 52a.

FIG. 54. CALIBRATION CHART FOR
MACHINE H CONST.

1.	P_a (volts)	1	2	4	8	20	} for $c_2 C_2 = 1$ (i.e. $H=10$)
2.	t_{12} (secs.)	8	4	2	1	0.4	
3.	$H (= \frac{a}{20} \times 25 \times t_{12})$	10	10	10	10	10	

An excellent degree of linearity is confirmed.

In the above work it should be noted that the definitions of M and H , and the relations between them, are specified in terms of angular momentum and stored energy of a machine at synchronous speed. In reality the angular momentum M of a machine is not constant since the angular velocity changes, but M is traditionally treated as a constant since the speed of the electrical machines in a system does not differ much from the synchronous speed unless instability occurs. The equation relating accelerating power, H constant and angular acceleration may consequently be regarded as valid for small excursions from synchronous speed.

A rigorous analysis, in an absolute sense, would proceed in terms of accelerating torque, T_a , moment of inertia, I , and rotor acceleration, $\frac{d^2\delta}{dt^2}$, according to the relation:

$$T_a = I \frac{d^2\delta}{dt^2},$$

and here, I is truly constant for any machine. This would be the basis of an accurate machine simulation in the Model, as opposed to the traditional method.

2.2.3 Machine Damping.

Crary⁽¹⁾ (Vol. II, 2nd Edition, p. 151 et seq.) lists three sources of damping in a multi-machine power system:

1. Prime mover,
2. Generator,
3. System.

Prime mover damping arises from the increase of shaft torque with decrease in speed. The damping torque coefficient may be defined as $P_d(\text{p.u.}) = - \frac{\text{per unit change in torque}}{\text{per unit change in speed}}$.

Generator damping during rotor oscillations is due to currents induced in the rotor due to rate of change or slip of rotor with respect to the armature m.m.f. wave. The damping torque is analogous to the torque induced in an induction motor due to its slip. If the slip is sufficiently small, the damping torque or power may be considered directly proportional to slip (linear damping, with symmetrical rotors). In many practical cases, however, the "induction" torque of a synchronous machine is a complex function of the transient performance of the machine during a disturbance or oscillation, being a function of rotor angle and rate of change of angle as well as of other factors.

System damping arises from load characteristics and is due to damping torque developed in induction motors as well as in synchronous motors.

A rigorous and comprehensive analysis of damping is difficult

and is the subject of much research at the present time - one of the objectives of the Braehead tests described in section 1.9, chapter 2, is to throw light on alternator damping effects. The author has no intention of presenting a general review of the problem here. It is sufficient to summarise the conventional analytical approach. Thus Dahl⁽⁸²⁾ (p.678 et seq.) sets out the elementary equation for a single machine connected to an infinite busbar, with constant voltages, in the form:

$$M \frac{d^2\delta}{dt^2} + P_d \frac{d\delta}{dt} + P_o(\delta) = P_s ,$$

which is the basis of the transient stability studies of many subsequent workers.^{(22), (23), (54), (58), (61) etc.}

Dahl discusses damping as a function of relative slip $S (= \frac{d\delta}{dt})$. For a 2 machine system, the damping power term for machine 1 would therefore be written:

$$P_{d_1} \frac{d(\delta_1 - \delta_2)}{dt} ,$$

while the corresponding term for machine 2 would be:

$$P_{d_2} \frac{d(\delta_2 - \delta_1)}{dt} .$$

When machine oscillations occur in a multi-machine system Dahl (p.681) imagines each machine as having a distinct slip with respect to each of

the other machines. By applying the principle of superposition to the calculation of damping, the equation for the n^{th} machine becomes:

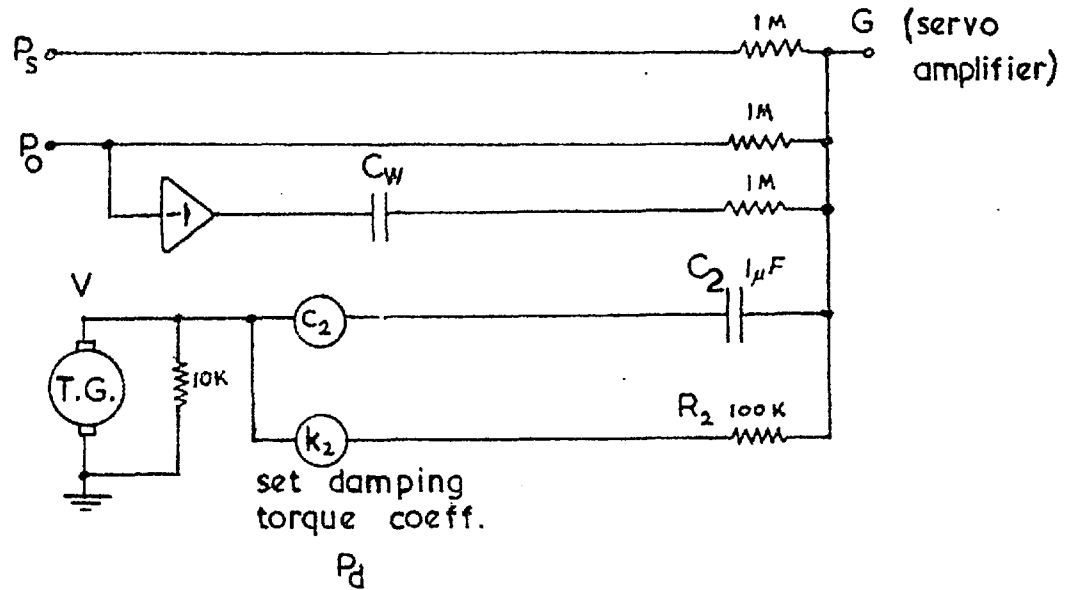
$$M_n \frac{d^2 \delta_n}{dt^2} + P_{d_{n_1}} \frac{d(\delta_n - \delta_1)}{dt} + P_{d_{n_2}} \frac{d(\delta_n - \delta_2)}{dt} + \dots + P_o \left[(\delta_n - \delta_1)(\delta_n - \delta_2) \dots \right] = P_s .$$

δ_n is taken with respect to a common reference axis for all the machines.

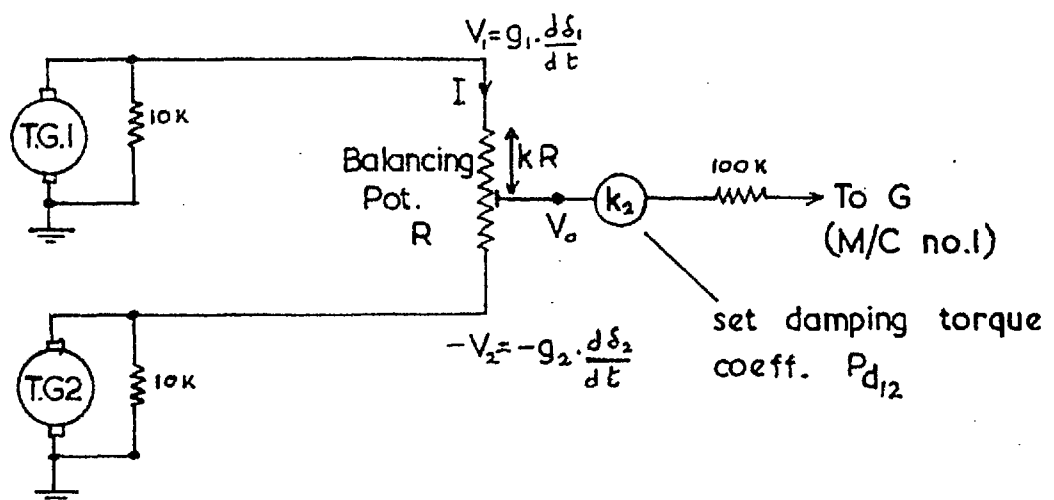
In the Model, damping can be simulated for a single machine according to the principle of section 2.2.3, chapter 3, by adjusting potentiometer k_2 in Fig. 55a. However, it is obvious that when multi-machine studies are undertaken in which the system frequency changes, steady state errors $P_d \cdot \frac{d\delta}{dt}$ will arise in power conditions in the Model when magslip rotors run at various speeds $\frac{d\delta}{dt}$. Such errors can be eliminated in a multi-machine study and the more generalised damping terms $P_{d_{n_k}} \frac{d(\delta_n - \delta_k)}{dt}$ set up by means of the arrangement shown in Fig. 55b.

The voltage V_1 and V_2 derived from the tachogenerators of two velodyne/magslip machine units 1 and 2 are connected through a potentiometer of resistance R . When V_1 and V_2 are arranged with opposite polarities, the current I through the potentiometer is determined by the equation

$$IR = V_1 + V_2,$$



55 a. CONTROL CIRCUIT FOR SINGLE MACHINE



55 b. DERIVATION OF DAMPING TORQUE FROM TWO MACHINES

FIG. 55. MACHINE DAMPING

$$\text{where } V_1 = g_1 \cdot \frac{d\delta_1}{dt} ,$$

$$V_2 = g_2 \cdot \frac{d\delta_2}{dt} ,$$

and g_1 and g_2 are the respective tachogenerator constants.

If the arm of the potentiometer is set such that the resistance is kR between output voltage V_o and the end V_1 , then

$$\begin{aligned} V_o &= V_1 - k IR \\ &= V_1 - k (V_1 + V_2) \\ &= V_1 (1 - k) - k V_2 \\ &= (1 - k) g_1 \frac{d\delta_1}{dt} - k g_2 \frac{d\delta_2}{dt} \\ &= K \cdot \frac{d(\delta_1 - \delta_2)}{dt} , \end{aligned}$$

where $K = (1 - k) g_1 = k g_2$,

$$\text{i.e. } k = \frac{g_1}{g_1 + g_2} .$$

Hence if k is set equal to $\frac{g_1}{g_1 + g_2}$, $V_o = 0$ when $\frac{d\delta_1}{dt} = \frac{d\delta_2}{dt}$:

i.e. no output voltage is obtainable whenever the magslip rotors have equal speeds, but a voltage $V_o = K \frac{d(\delta_1 - \delta_2)}{dt}$ is produced whenever relative rotor oscillations result in a quantity $\frac{d(\delta_1 - \delta_2)}{dt}$. If V_o is

applied through k_2 and the 100 K Ω resistor to the servo amplifier grid,

then a damping torque signal of the form

$$k_2 \cdot K \cdot \frac{d(\delta_1 - \delta_2)}{dt}$$

is applied to machine no. 1. A similar signal can be applied, in the appropriate sense, to machine no. 2.

Calibration in terms of $P_d(\text{p.u.}) = k_2 \cdot K$ may be carried out by setting $P_s = -P_d$ (in Fig. 55a), disconnecting the P_o feedback

signal and grounding this input, and adjusting k_2 until the magslip rotor is driven at p.u. speed by the control system (or more practicably, set $P_s = -0.1 P_d$ p.u. and adjust k_2 until rotor speed = 0.1 p.u. $\equiv 5$ c.p.s. $\equiv 300$ r.p.m.). The value of k on the 'balancing' potentiometer should be first set by driving machine no. 2 as a constant speed unit (by a control circuit such as Fig. 52b) and then by setting k until machine no. 1 runs in synchronism, thus satisfying the conditions that $(1 - k) g_1 = k g_2$ when $\frac{d\delta_1}{dt} = \frac{d\delta_2}{dt}$ so that $V_o = 0$.

Damping calibration when this is known in terms of damping ratio z for small oscillations (see section 1.2, chapter 2 and Table 2) may be set up in the Model by causing machine unit no. 1 to oscillate (with $k_2 = 0$) and the remaining machine units stationary. k_2 is then adjusted until the required decremental damping ratio is obtained in successive rotor oscillations, as recorded with the aid of an angle recorder unit.

2.2.4 AVR Simulation.

The AVR (Automatic Voltage Regulator) control system is designed as a position control servo, and the response can be adjusted accordingly, as described in section 2.3, chapter 3. Loop gain, and time delay are adjustable in the AVR Rectifier/filter Unit, described in section 1.5, chapter 4, and also by means of the control circuit connections at the servo-amplifier input grid.

A typical control circuit for an AVR unit is shown in Fig. 56 With maximum gain in the rectifier/filter and no damping, the system

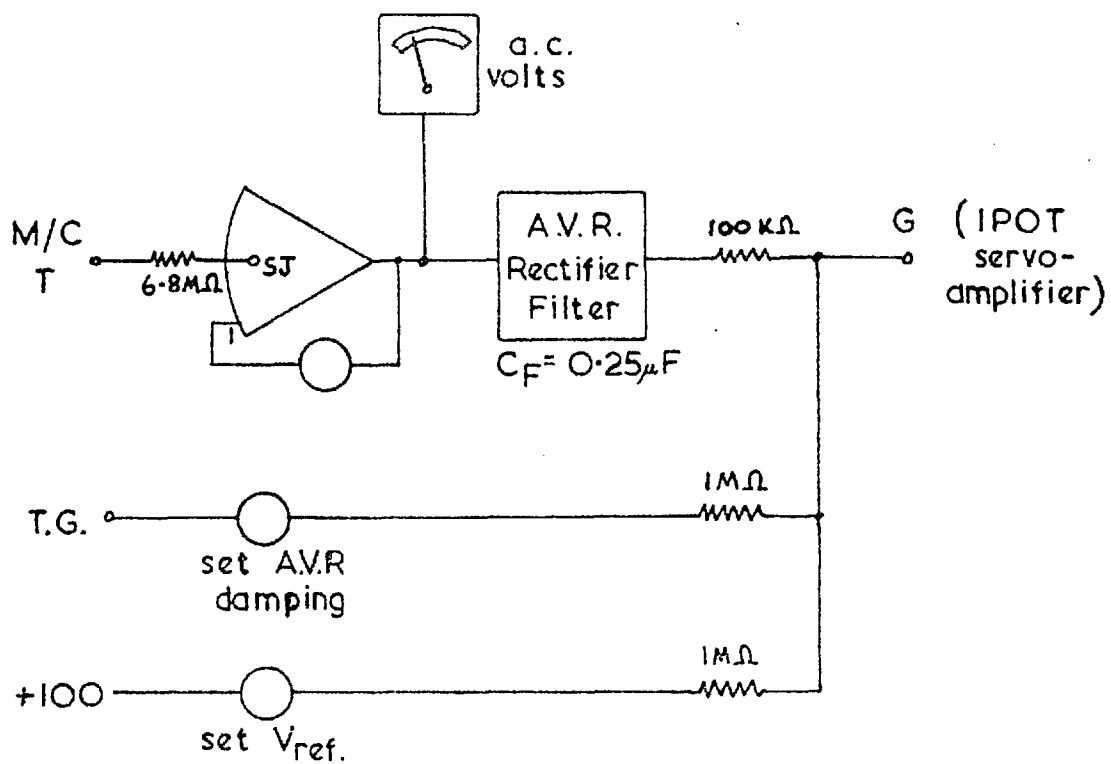


FIG. 56. A.V.R. CONTROL CIRCUIT
 (see section 2.2.4.)

reaches the maximum of step changes applied by V_{ref} in approx. 0.2 secs. Slower and/or more oscillatory responses may be readily simulated. The units are thus capable of simulating very fast AVR action indeed, and there is no difficulty in representing practicable voltage regulators when the basic characteristics of their performance are known.

2.2.5 Time Scaling.

It is sometimes convenient to operate the Model at a slower dynamic rate than real time. This enables more accurate XY plotting and pen recording to be achieved when responses faster than 1 c.p.s. (in real time) are expected in a System study. The dynamic errors arising from time delays in the Model, as a result of the necessary smoothing circuits in the servo-mechanisms, which have already been discussed, may be diminished in magnitude by operating at slower time scales. Another advantage of slower rates of operation is that relay-operated control sequences can be more accurately effected and the "freezing" of the Model with the aid of the dynamic control box (see section 2.2, chapter 4) may be more precisely pre-determined.

Suppose that t' (Model time) = st , where s is a scaling factor and t is the real time. Then the Model electrodynamic machine equation can be written:

$$M' \frac{d^2\delta}{d(st)^2} + P'_d \cdot \frac{d\delta}{d(st)} + P_o = P_s,$$

$$\text{i.e.} \quad \frac{M'}{s^2} \cdot \frac{d^2\delta}{dt^2} + \frac{P'_d}{s} \cdot \frac{d\delta}{dt} + P_o = P_s.$$

Thus if the Model inertia constant $M' = s^2 M$,

and the model damping coefficient $P'_d = s P_d$, division of Model time scales by s converts the time varying curves derived from a Model study to those corresponding to real system behaviour.

Time constants, set up in the analogue computer equipment and with the groups of time-constant elements (section 1.3, chapter 4), must be correspondingly multiplied by the scale factor s .

2.3 Operating Technique.

Before using the Power System Model for automatic governing and regulating studies, it is necessary to calibrate the equipment and to establish appropriate initial conditions. There are three aspects of these requirements:

1. The transfer functions representing the steam conditions, governor system and control equipment (such as those evaluated in section 1, chapter 2) must be set up on the analogue computer. Typical functions were shown in Fig. 5 and a corresponding analogue in Fig. 12b.
2. The velodyne/magslip and AVR coupling units must be set up with the required machine inertia constants, damping and AVR characteristics.
3. The electrical impedance network of the power system configuration must be correspondingly connected up and calibrated on the network analyser.

There is little difficulty in practice in setting up the analogue computer equipment, since the transfer functions are for the most part

simple time constants involving gain terms and summing junctions. A level of 20 V d.c. in the analogue is recommended as equivalent to 1 p.u. steam power, as already mentioned, and it is merely necessary to establish the desired initial conditions in the integrators, when these are used in time constant circuits and elsewhere(e.g. velodyne speeder motor representation), as shown in Fig. 12b. The electronic multiplier output must also be scaled such that 20 V d.c. is equivalent to 1 p.u. in V_{P_o} .

The calibration of the Model machine and AVR units can proceed as outlined in sections 2.2.2 to 2.2.4 of this chapter.

Impedances on the conjugate network analyser should be calibrated as described in section 2.2.1 of this chapter. It has been found that use of an electronic multiplier circuit for power measurement results in greater consistency than use of the metering equipment on the network analyser. This is because there is inconsistency in current, voltage, and power measurements when different ranges are selected on the analyser meter.

Normally, the setting up on the conjugate network analyser of the equivalent sequence network of the power system is followed by the tedious manual process of adjusting the analyser generator units (magslips and I pots) until the initial values of power and voltage, obtained from system information, are attained. However, the Model itself may be employed for this purpose as a preliminary to a series of automatic governing and regulating studies, by means of the following procedure:

1. The armature d.c. supplies to the velodyne motors are switched off (by means of the master switch on the dynamic control box.)
2. Equivalent inertias of the velodyne/magslip units are set to minimum values (e.g. by open-circuiting the feedback capacitor C_2 connections).
3. Machine and AVR damping controls are set to maximum values (e.g. by-pass the damping coefficient potentiometers).
4. Values of P_s controls and AVR reference voltage levels are adjusted to the required values.
5. After setting up the network analyser and machine unit inter-connections the d.c. supplies to the velodyne motors are switched on at the master switch. Owing to the low inertias and high damping the magslips and the I pots are immediately positioned to establish the correct phase-angles and system conditions, provided an additional static, magslip unit is available for supplying the system losses.
6. The power being derived from the static magslip is either taken up by adjustment of a P_s control on one of the controlled machine units, so that this static magslip may be disconnected from the network, or a power control loop on the static magslip unit can be balanced after which it is itself switched over to dynamic control. In consequence, all magslip rotors are held stationary, but are at various initial angular displacements with respect to each other.
7. Inertia and damping settings are now restored to the correct levels (with master switch open), and the programme of switching, faulting and desired control sequences is set up on the analogue

computer and recording equipment.

8. The master switch is closed simultaneously with the switching of the analogue computer to the 'Operate' mode and the triggering of XY plotter, recorders, oscilloscopes etc.. The Model now follows the imposed pattern of changing power conditions by solving the electrodynamic equations for all the machine units, resulting in free rotor speed changes corresponding to the normal behaviour of governors and power/frequency control schemes in real power systems.
9. The subsequent changes in system frequency are best recorded by directly monitoring the tachogenerator voltage of one of the velodyne/magslip units (e.g. one which is running as a load), or by recording the average summation of all such tachogenerator voltages to get a measure of mean system frequency error. The relative rotor oscillations between machines are recorded with the assistance of the transistor devices designed for this purpose.

2.4 Representative Three Machine System.

This section describes a minor study of a three machine system which has been set up on the Model. Although detailed quantitative work remains to be done, a good qualitative representation has already been obtained.

The schematic connections in the Model for a three machine system are shown in Fig. 57. There are two full turbo-alternator simulations on machine-units nos. 1 and 2. Machine unit no. 3 runs as a load, and is arranged to simulate dynamic load/frequency characteristics

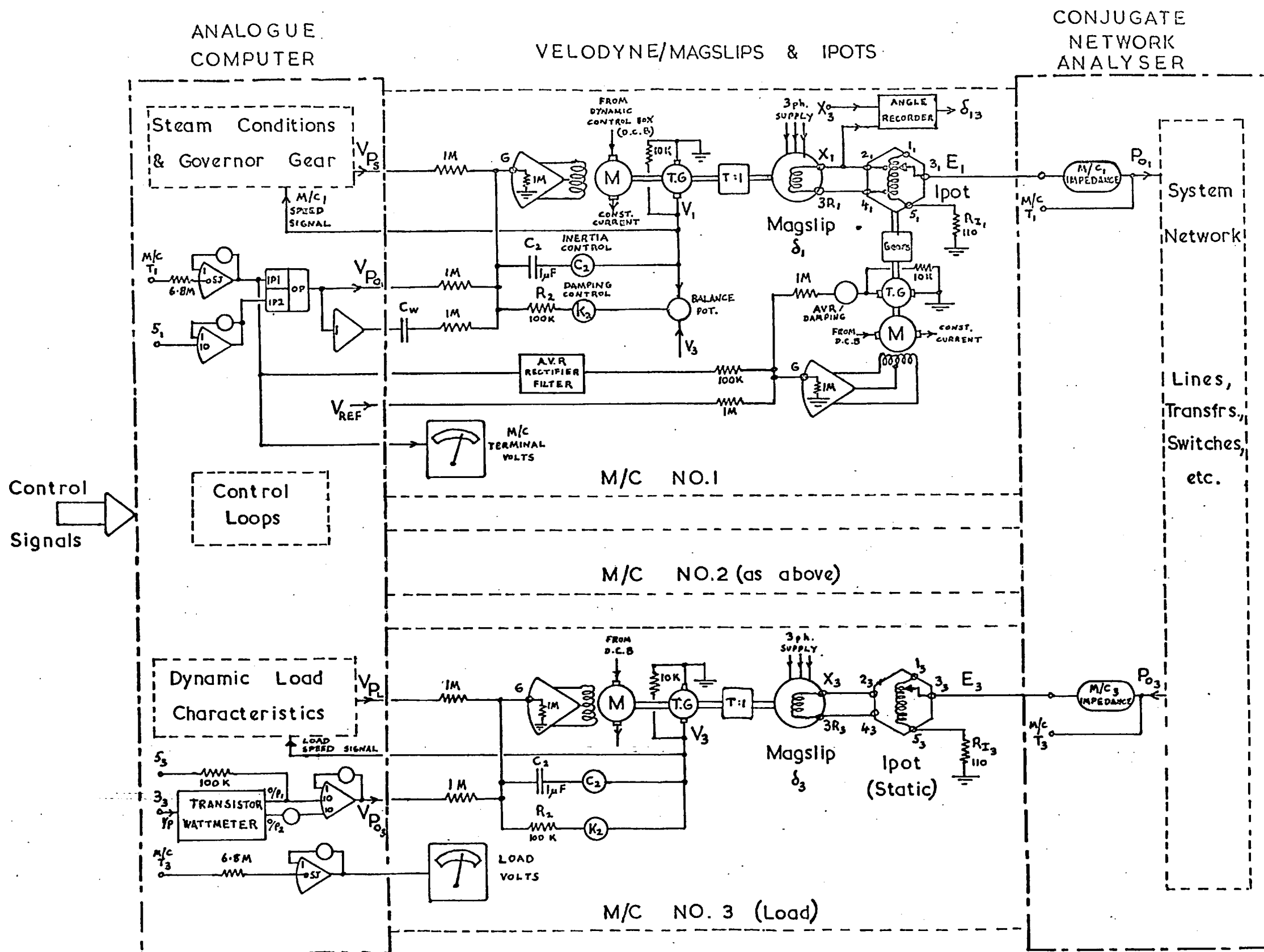
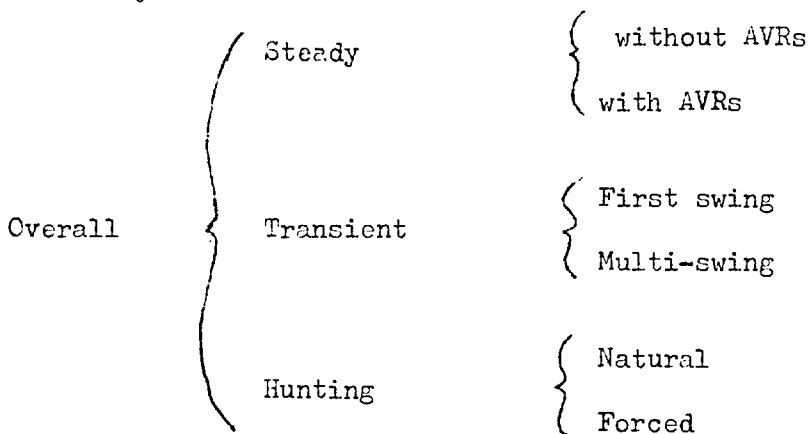


FIG. 57. A REPRESENTATIVE THREE MACHINE SYSTEM

in the system. Load machine no. 3 may conveniently incorporate a transistor wattmeter unit, since there is no AVR action involved.

Some preliminary studies have confirmed the findings of chapter 2 - namely that the long delays in reheat turbines promote oscillatory conditions when system disturbances occur. Adequate damping of the control circuits and appropriate matching of AVR performance can lead to smooth load/frequency and regulation characteristics for the system as a whole. In particular, the effects of fast AVR action in improving stability can be observed and noted.

In the discussion and comparison of system operation and control studies, the concept of 'overall stability' is important. The presence of automatic control devices in power systems means that stability is desired before, during, and following either slow or sudden changes. Crary ⁽¹⁾ (Vol. II, p.242) has classified the main categories of stability thus:



and it is useful to contemplate overall stability in this way.

It is anticipated that detailed investigations and studies, based on the representative three-machine system, will be presented in a future Power Systems Report.

3. OTHER POTENTIALITIES OF THE MODEL.

The Power System Model has several useful applications which are described here. It can serve as a teaching and training aid (3.1) and is helpful in obtaining speedy solutions to conventional analyser studies (3.2). A potentiality which may prove of particular value is the use of the Model as an on-line dynamic security assessor (3.3), which is discussed here in relation to existing aids to power system operation. Ways of carrying out transient stability studies are suggested (3.4). Extension of the Model and some practicable improvements are mentioned (3.5).

3.1 Teaching and Training Aid.

With the aid of the Power System Model the fundamentals of the theory of power system analysis can be readily illustrated. Simple examples are the elementary equations for power transfer, the "equal-area" criterion of stability and the action of automatic voltage regulators in improving machine transient stability. A display may be readily made of a representative system under free governor action

and manual control.

It is suggested that, wherever a teaching or research laboratory already possesses some analogue computing equipment and a network analyser, there would be value in assembling three velodyne/magslip and AVR machine units to make available a complete demonstration Power System Model. The machine units and auxiliary circuits (transistor wattmeters, angle recorders and AVR rectifier/filters), together with power supplies and servo-amplifiers, could all be fitted into a 19" rack unit, provided with a single comprehensive patch-panel, and suitably interconnected with the analogue computer and network analyser.

The Model could also find direct application as a simulator for training purposes. Power station and power system control engineers could be given a physical insight into the "feel" of a power system and instructed in the principles of operation. In this respect the Model would serve a purpose comparable to the flight simulators commonly used to train aircraft pilots. This potential as a training aid may become important in the future when power systems become fully automated and are not normally controlled by manual methods. In the event of breakdown or emergency conditions, the supervisory engineers would be required to assume manual control, and experience on the simulator would then prove valuable. Control engineers cannot, in any case, experiment with and explore unusual operating conditions on a real power system for fear of loss of stability. No such restriction would apply to use of the Model for this purpose.

3.2 Conventional Analyser Studies.

Steady state power flow problems can be readily solved by using the Model without the need for step-by-step iterative methods which are often lengthy and tedious. The procedure is similar to that described earlier in the section on operating techniques, (section 2.3), for setting up initial conditions in the analyser. Simple transient stability studies can quickly be set up and solved also. Since the action of governors and AVRs can be inherently included, the effects of these devices need not be ignored, as is often the practice in traditional stability studies.

3.3 On-Line Dynamic Security Assessor.

The potentiality exists of keeping the Model in step with the corresponding real system by means of suitable data links. In these circumstances the Model would be an on-line representation of the state of the system and could then be isolated for assessment. A programme of disturbances can be applied to a continually up-dated Model, and thus a continuous assessment can be made of the stability and security of the real system.

Before proposing a practicable scheme for an "On-line dynamic security assessor" it is worthwhile here to review briefly the analogue and digital devices which have so far been developed by the C.E.G.B. as an aid to system operation.

At National Control there are two Analogue calculators and one combined Analogue/Digital computer. All are used exclusively by the System Operation Branch to resolve problems associated with Line Outage programming, load despatching, and assessment of system security under actual operating conditions. These devices are briefly described here from material in National Control Information Sheets.

1. The Line Outage Calculator.

Grid Control Engineers have frequent need to determine the load flows which occur as the result of changes to the system. Such alterations may arise from fault conditions, maintenance work on transmission lines or from sectionalisation of the system for operational purposes. Network analysers are commonly employed to determine these effects, but full representation of load and generation has to be made before line outage conditions can be studied. With the present Grid System this would require a considerable number of transfer points, an extremely large calculator and an hour or two to set up and take readings. The Line Outage Calculator has been constructed to give in a few moments the information expressed as "percentage of original power flow picked up" rather than the new flows on the lines in MW.

The calculator operates on the basis of the Superposition Theorem so that if a line carrying PMW from A to B is taken out of circuit, then the effect of such switching on the system is simulated by injection of PMW into the system from B to A, with the system configuration remaining unchanged. The division of the injection into the branches of the system is determined by the impedances of the various branches.

Provision is made for measuring the flow in each branch of the network and an arbitrary value proportional to 100 MW is injected from B to A. The branch reading is then the direct percentage increase of the original power flow from A to B, which the branch line carries.

There is no need to make separate provision for generation and load as these are already provided for by reason of P and the existing load flows being the result of such generation and load. This assumes that generation and load remain unchanged following the loss of the line.

The calculator also serves to determine the effect of closing the circuit when indications are available from either a phase angle voltmeter or from a synchroscope. The current which flows through a switch subsequent to its closure is proportional to the voltage across the switch divided by the impedance of the network across the open-circuited switch terminals (Thevenin's Theorem).

The calculator is provided with a synchronising factor meter to give an indication proportional to the impedance between the switch terminals and this reading is divided into the phase angle voltmeter reading (kV) to give the power flow in MW.

In the calculator there is a single line diagram representing the physical arrangement of the system with provision for busbar selection by tumbler switches. The impedance of each line is represented by a resistor.

2. The Incremental Loss Calculator.

The loss calculator recently reached the limit of its practical

extension, and after an appraisal of the economic and technical merits of a second version or a change to digital computation of Transmission Loss factors, the Board have decided to use digital methods in future.

However, the Loss Calculator has had some three years of useful life as an aid to System Operation and is worthy of inclusion as an item of technical and historical interest.

A loss of power occurs when power is transmitted over any electrical power system. The power loss is a function of the square of current transmitted and the resistance of the transmission system. This fact is not of itself an argument against the transmission of power on electrical systems until such time as the cost of the transmission losses exceeds the difference in cost of generation at the receiving end, less the cost of generation at the sending end. Therefore when considering the transmission of power from A to B, it is only economical to do so up to the point where the cost of generating such power at A plus the cost of the losses involved in the transmission of such power equals the cost of generating the power at B.

The purpose of the Calculator is to evaluate the incremental losses on the main transmission system as an aid to the economic load despatching procedure. The device consists of an analogue of the 275 kV system. Information on the system arrangement, the power flows and incremental generating costs is set up by the operator. The instrument calculates the effect of line losses and indicates the cost of supplying an increment of power to a given point in the system. The impedances of the transmission lines and transformers which form the system are represented by

a network of resistors in the Calculator connected together to simulate the bussing of the actual system.

The design and principles of operation of the device have been described by Wardrop (83).

3. The Security Assessor.

The Security Assessor is the newest of the aids to system operation and has as yet not reached its ultimate stage of development. Its functions do not cover new aspects of system operation work since the assessment of security has always been a major consideration of System Operating Engineers. Essentially, the Assessor reduces the time required for a complete assessment of system security from the order of 8 - 10 man hours to the order of 15 - 20 minutes.

By achieving a very significant reduction in time, security assessment is removed from the field of speculation and placed more firmly in the realm of practical operational reality. The 15 - 20 minutes mentioned above is not the time the assessor takes to compute and display all its investigations, but includes the margin of time that is necessary for the Control Engineer to observe the display and formulate or confirm any course of action he may consider necessary as a result of the indication he obtains from the assessor.

The Security Assessor has resulted from experimental development of the Line Outage Calculator and its mode of operation is based on the principle of the Superposition Theorem. It is an "on-line" computer

which calculates and displays the effects on the system caused by taking out of service either a single or double circuit run of 275 kV transmission lines. The result is obtained by combining digital and analogue techniques.

In order to determine the result of any change in system configuration (e.g. taking lines out of service) it is necessary to obtain the following data:

- (i) The number and location of all the lines forming the network.
- (ii) The impedance of all such lines.
- (iii) The arrangement by which the lines are connected together (bussed) to form the system.
- (iv) The load flow in all the lines (MW).
- (v) The limit to which a line may be loaded with safety (MW).

The data for items (i), (ii), and (iii) has been collected together and from it a model (Analogue) of the system has been built with provision to permit those variations in system bussing which occur daily in the course of operations. This is done automatically for the 275 kV system, by the use of auxiliary contacts on the 275 kV Switching diagram in National Control. The 132 kV system changes are made by the insertion of keys in an auxiliary console, which also houses the line limit selectors.

The load flows are obtained from the same Telemetering System which provides the line flow information on the Loading Diagram.

Having obtained the basic system data it is then necessary to determine how the flow on any particular line, or double circuit run of lines, will divide between the remaining lines when such a circuit is taken out of service. This is done by a sequence of switching operations

on the network model (Analogue).

The line to be taken out of service is open circuited on the model, by means of a relay. Current from a constant current generator is then injected into the system model, between the nodes of the open circuited line by means of a relay known as the Current Injection Relay. The injected current has reversed polarity to the flow which was originally in the line. This injected current divides in the branches of the network as an inverse function of the impedance of the branches joining the two nodes. The current in the branch is converted to a voltage measurement by the use of a linear sampling resistor (100 ohms which forms part of the total line impedance) and therefore produces a voltage proportional to the current flow.

All lines in the system are "scanned" to determine the division of line flow following the open circuiting of a line. The relays which perform this function are known as fast scan relays.

Having determined what proportion of the original flow will divide into each branch of the system, the information is used as a scaling operation on the original flow in the "Line Outed" to obtain the MW increase or decrease which will appear on each line.

From a knowledge of the flow in each line, $\pm$ the increase/decrease resulting from the outage considered, the final flow in the line is calculated. This is then compared with the safe limit for the line. This limit is dependent on the MW rating of the line itself, its associated equipment, and line protection settings. If the resultant loading of the line does not exceed 75% of the limit setting a "green" signal is

made and stored; if the resultant load exceeds 75% but not 100% of the limit an "amber" signal is made and stored, and if the resultant load does exceed 100% of the limit setting a "red" signal is made and stored.

The Analogue model is now returned to "Normal", that is the line which was originally open circuited at the start of the slow scan sequence is now reclosed.

In all that has been described so far one Slow Scan Cycle has been completed. The Assessor does all this in less than 1 second.

The Assessor is programmed to repeat this series of operations for each of the 71 specified slow scan sequences. It completes the whole process of recognition, conversion, calculation, storage and display for the 71 cases in just a little over 1 minute.

A display unit converts the signals into an illuminated semi-geographical representation of the 275 kV System Diagram. The colour of the illumination is determined by the result of the comparison made between resultant line loading and the line limit. An auxiliary to the illuminated display is the digital printer which extends the presentation of information from the Assessor. The printer shows the link between the cause and effect of taking a circuit out of service.

The Security Assessor described above is one part of an extensive programme of studies to consider the feasibility of a fully automated Control System which the C.E.G.B. is now undertaking.

In the descriptions above it is to be noted that the principle

of superposition is the basis on which both the Security Assessor and Line Outage Calculator operate. The assumption that one may calculate the effects of a change of power flow in one part of the system by determining the component changes which occur as the result of such change, and then superimposing these component changes on the known original flows in other parts of the system, is valid providing the response of the system is linear, and bilateral. That is to say that equal amounts of change in "cause" produce the same changes in "effect" over the whole range of operation, and that the response to such changes is equal in either direction of application. These conditions are usually met under normal stable operating conditions for small variations, but if the system is operating at the limit of its stable operating condition then the assumption is no longer valid. Nor may the assumption be valid when the system is subject to the actions of automatic governing and regulating equipment.

It is to enable a prediction of unstable conditions of operation to be continuously made that it is proposed here that the Model described by the author has the potential of being used as an "on-line dynamic Security Assessor". Such a device would be a natural and more complete development of the Analogue aids made available so far for the benefit of System Operating Personnel.

Information on load flows, network voltages and line impedances and interconnections is already telemetered to National Control for the main display boards and the Security Assessor. This data could be used to establish analogous conditions in the Power System Model so that it

possessed all the principal features of the state of the real system at any time, thus enabling stability to be determined. After isolating the Model from the constraining data links, a programme of disturbances and faults would be applied to determine whether loss of stability or synchronism would be likely to occur in the real system. A relay scanning technique like that described for the Security Assessor above would be suitable, and a display could be arranged to show where instability or loss of synchronism would occur in the real system as a result of what cause.

Each node of the main 275 kV network would be represented in the dynamic Security Assessor by a velodyne/magslip - I pot unit, constrained to follow the load flow and voltage existing at that point in the real system. If the complex impedances of the lines, transformers etc. are set up on the network analyser, then the Model will automatically adopt the correct disposition of phase angles in the system by appropriate positioning of the magslip rotors.

Additional information necessary for the dynamic Security Assessor would be:

1. Load-frequency characteristics of Areas as a whole, linked to the various nodes of the 275 kV network.
2. The number of generators connected at any time, with their equivalent H constant and damping characteristics, as a group.
3. The governing and regulating characteristics of each Area.
4. Details of boiler and machine constraints and rate limits.

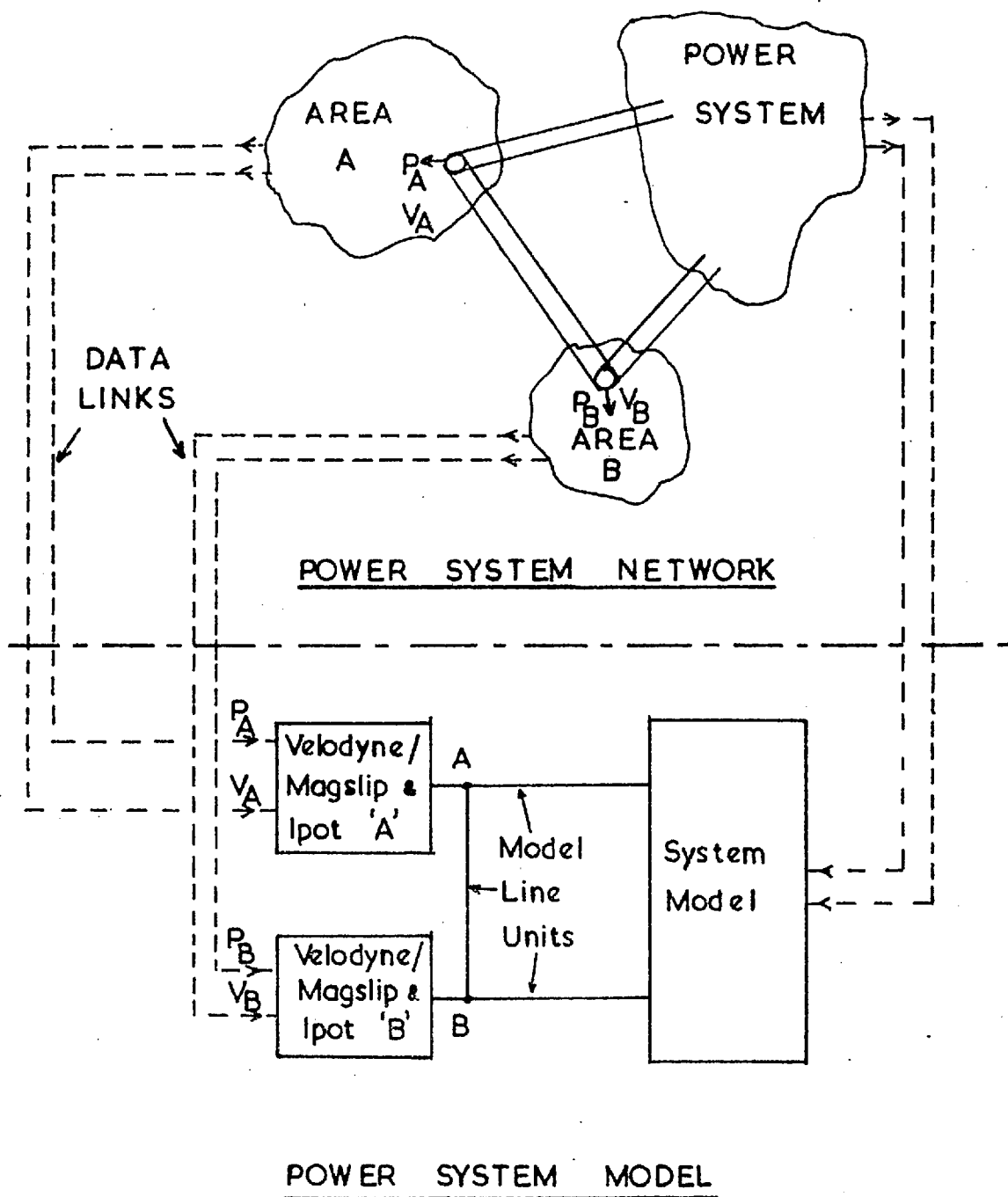


FIG. 58. SCHEMATIC DIAGRAM SHOWING OPERATION OF THE MODEL AS AN ON-LINE DYNAMIC SECURITY ASSESSOR

Much of the above information is known at the present time for hour-to-hour operation by the National Control Engineers. The remaining details could be computed digitally by combining this information with the results of System Tests (which enable an analysis to be made of equivalent load/frequency characteristics, H constants and damping). The continually up-dated digitally calculated information would be used to set up the corresponding parameters (by digital-analogue converters) in the Model machine units.

Using telemetered data on power flows and voltages, a practicable scheme for operating the Model on-line is shown in Fig. 58. The power levels of the equivalent machines are applied as control signals to the velodyne/magslip servo-amplifiers, while voltage information goes to the I-pot servomechanisms. The Model is operated according to the mode described in section 2.3 for setting up initial conditions. When subsequently isolated for stability assessment, the normal control loops are completed and the Model assumes independent behaviour.

3.4 Transient Stability Studies.

Apart from the simple swing curve plots of conventional transient stability studies, with the usual simplifying assumptions, it is practicable to incorporate a more detailed representation in the Model of transient reactances, saturation, amortisseur damping and saliency. Saturation and transient reactance could be simulated by modifying machine impedances and/or AVR action with time, for example. A diode function generator is available in the Solartron Minispace for representing non-linear functions, and can be included in a velodyne/magslip

or I-pot Control circuit to assist in the simulation of machine transient characteristics.

It is thus possible to use the Power System Model to carry out transient stability studies of individual machines within a system. The studies can be extended to the investigation of asynchronous operation and re-synchronising techniques.

3.5 Extension and Improvements.

The number of velodyne/magslip and I-pot units could readily be increased in the Power System Model to enable elaborate multi-machine studies to be undertaken. Alternatively, remote machines could be represented by stationary magslip generator units in the Analyser, and the dynamic behaviour of a particular group of machines within a large " ∞ " system studied, with the existing Model facilities.

In the author's opinion, the Model, with its direct dynamic behaviour and recording equipment, can produce the results of experimental and theoretical studies in multi-machine power systems in a substantially simpler way than is possible with the best digital or analogue computer techniques.

Practicable improvements would include the re-design of all auxiliary transistor circuits to operate at common supply voltages, and their assembly in a combined unit.

Certain advantages could be gained by using a higher operating frequency for the magslips and network analyser. Possible values would

be 400 c.p.s. or 1000 c.p.s.. The magslips and I-pots would be smaller and more compact (2" magslips for 400 c.p.s., for example), and the associated velodynes and servo-amplifiers could be correspondingly lower in rating. The undesirable delays in smoo^hting circuits would be much reduced - at 1000 c.p.s. working, for example, satisfactory smoothing for the servo-circuits could be achieved by filters with time constants of only a few milliseconds.

Another advantage of a higher operating frequency is that the analyser network representation could more economically be direct because inductance units with acceptable Q values would be of a lower cost.

The chief disadvantage of using a higher frequency of operation is that a special oscillator and power amplifier are necessary. The cost of this must be offset against savings in the machine units. In the Model described here, power is drawn from the laboratory 3 ph. 50 c.p.s. supply.

4. CONCLUSION.

4.1 Summary of Discussions and Findings.

The advancement of an industrialised country is necessarily accompanied by a rapid expansion of its electric power system. Typically, the electricity demand in the U.K. doubles in less than 10 years. Consequently, many new power stations must be commissioned while the transmission network

or grid system, which interconnects them, requires reinforcement and enlargement in order that power demands are everywhere met adequately and securely.

As a power system becomes more complex in nature, the problem of successful control requires more detailed attention than hitherto. When a fault, or short-circuit, occurs, causing a line or generator to trip out of circuit, the resultant redistribution of power in the system may cause other lines and generators to overload and trip out also, precipitating "cascade" effects, which often black out entire regions of the country. A human operator, in these circumstances, cannot always act sufficiently accurately. The general public does not always fully appreciate how heroic are the attempts of system control engineers at times to avert disaster by stretching to its limits the capacity of their telephone network - the traditional means of communication and control. Again, it may seem hard to credit that steam turbines, in even the most modern power stations, are still controlled by governors which have the same flyball principle of operation as that invented by James Watt for his first reciprocating steam engine.

An automatically governed and regulated power system of the future will have a central computer which, after performing the necessary optimising calculations from telemetered data, would issue coded instructions through satellite computers to electronic controlling devices in the power stations. Hence maximum security, protection and economy could be effected at all times.

Meanwhile, it is necessary to conduct theoretical and practical studies of control techniques. The Power System Model described here consists of the conjoint use of a network analyser and an^alogue computer which are coupled together by specially developed machine units. Characteristics of typical turbo-alternator plant, governors, AVR's and control equipment can be modelled together with a representation of the transmission system and loads. The effects of constraints and non-linearities can also be incorporated. By adjustment of the appropriate parameters and transfer functions, any existing or proposed power system anywhere in the world is amenable to study, including, for example, systems with high proportions of hydro or nuclear plant. A variety of control techniques can be studied and assessed. It is to be anticipated that a generalised philosophy of automatic control will be developed.

It has been found that the Model can be used for traditional load flow and stability studies, and also has potentialities as a teaching and training aid, and as an aid to system operation when partial automation already exists and a transition from manual operation is taking place.

Many of the simplifications and generalisations in traditional theories and stability studies are open to question in the context of modern plant design and operation. The difficulties of representation and problem solution can be reduced with the aid of the Model.

One of the author's chief findings is the extent of uncertainty and often downright ignorance of the transient characteristics

of boilers, turbines and control equipment now in use on the system. A strong case exists for it being made an economic obligation for manufacturers to meet transient specifications in contracts. Complementary to this obligation should be the coordinated planning of carefully instrumented tests to extract information about plant performance both by manufacturers and power system operators.

4.2 Suggestions for Further Work.

Apart from the improvements and other applications mentioned above, it is desirable that further work should include comparison of Power System Model studies with the results from tests on real machines and systems, or on micro-machine systems, and with digital computer studies. This would enable confidence to be gained in the use of the Model for automatic governing and regulating studies.

Thus further work would initially be concerned with a careful assessment of the validity of the Model for representing the performance of real machine systems. A comparison could be made with the ^{state} steady characteristics of an alternator or micro machine in the laboratory. The impedances, H constant, damping and other principal parameters of the machine, measured by laboratory tests would be simulated on the Model, and the factors making for success in obtaining identical swing curves, when both machine and model are subjected to small disturbances, would be analysed.

Having established a Power System Model, as described here, the whole field of power system operation and control is open for

experimental study. Other regions of enquiry are the economics of reactive power scheduling, techniques of compensation using synchronous reactors, and the arbitrary control and shaping of overall system load/frequency characteristics by compound control of governors and AVRs.

Systems often have high proportions of induction motor load, and work could be directed to a means of simulating induction motor characteristics with a Model machine unit. Problems of the stability of such systems could then be examined.

A considerable amount of power system and machine research is now being carried out using digital computing methods. System stability and control studies carried out on the Model could be compared with similar studies using digital computer programmes. An analysis should then be made of the relative merits of the two techniques and of the economics involved. Time on digital computers costs money. It would be pertinent to make an economic comparison with the capital cost of building a Power System Model capable of achieving an adequate degree of accuracy for engineering studies. Once constructed, the Model is permanently available for experimental studies, at no further cost.

POSTSCRIPT

'Science is always wrong; it never solves a problem without creating ten more.'

George Bernard Shaw.

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