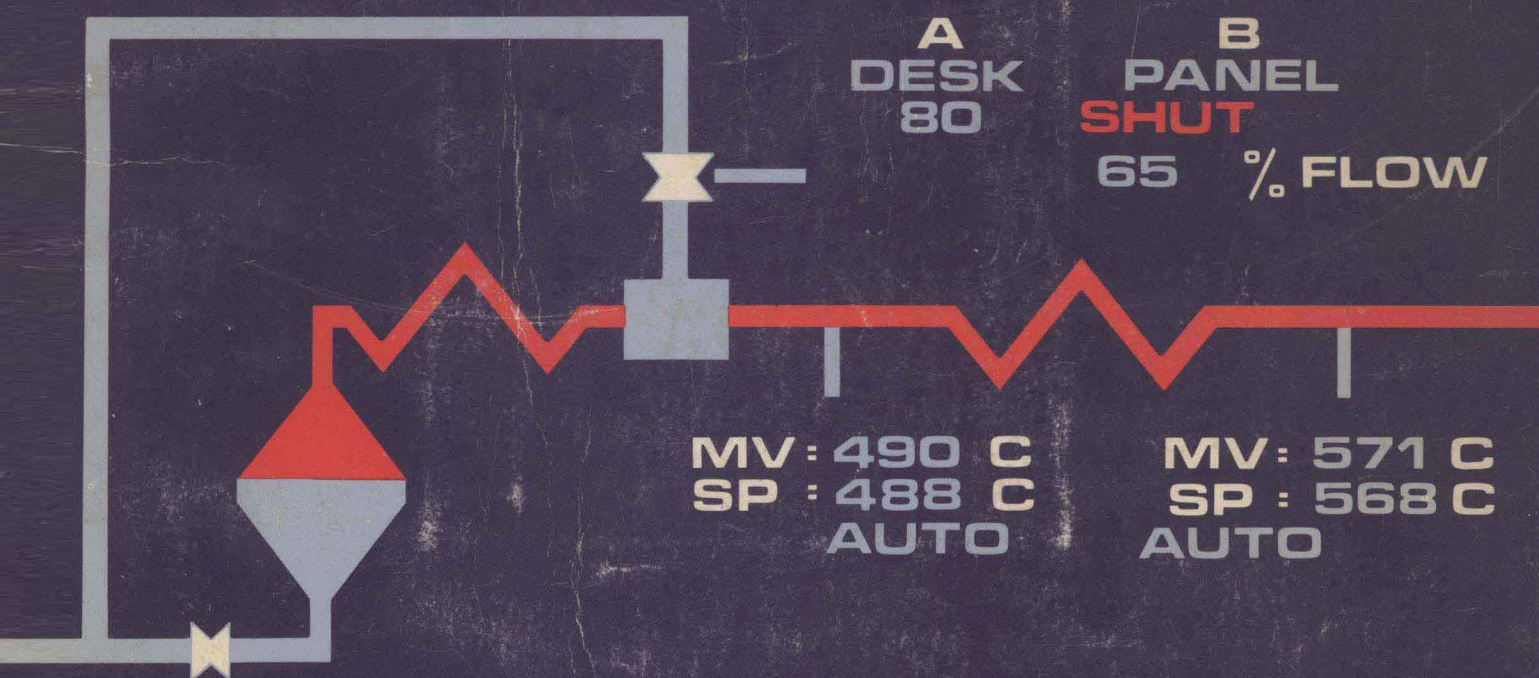


DIRECT DIGITAL CONTROL FOR POWER PLANT

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DIRECT DIGITAL CONTROL FOR POWER PLANT

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Micro-processor applications in turbine-generator instrumentation and control

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SYNOPSIS

The application of digital techniques to controllers of modern steam turbine-generators to improve the capabilities and integrity of the control functions has expanded in recent years with the introduction of low cost microprocessors.

Some areas of turbine-generator instrumentation and control, however, still rely heavily on well-known relay logic and pneumatic systems and it is possible that in due course these may be superseded by digital systems also.

Work has concentrated on a number of selected areas of instrumentation and control in which the application of microprocessor techniques appears to be particularly appropriate. The principle has been adopted of employing a standardised range of hardware modules, thus reducing the spares requirement at the same time as encompassing a wide range of separate applications.

The systems described cover an Overspeed Trip System, an Acceleration-Sensitive Detector, a Speed Monitor System, a Turbine Rotor Thermal Stress Evaluator, Turbine Supervisory Equipment an Auto Run-up and Loading System and various forms of Electro-hydraulic Governor System intended for both Original Equipment and Retrospective Conversions.

1 INTRODUCTION

Modern steam turbine-generators depend for their operation on a number of sophisticated instrumentation and control schemes. The variation in level of technology is, however, somewhat wide with some control loops, such as the turbine Governor, now incorporating modern electronic and electro-hydraulic techniques whereas others, such as the Generator Cooling system, may still be reliant on relay logic and pneumatic control. Some other functions, which strictly also pertain to the turbine plant such as Automatic Run-up, have gained in sophistication but have frequently been implemented on a higher level system such as the Station Computer.

It is wholly possible that some of these functions may well in the future benefit from recent developments in the process-control field, whereby

distributed microprocessor-based control schemes can operate with the integrity and autonomy of a number of individual controllers but, by means of remote supervision networks, can also exhibit all the power and flexibility of a centralised computer installation. There remains, however, a significant number of instrumentation and control functions which are very specific to turbine-generators and which it is not possible to satisfy with a standard range of industrial hardware. It is these areas with which we are chiefly concerned in this Paper.

The application of digital techniques to specific turbine-generator control functions is not new and systems for governing were first introduced more than a decade ago (1). The widespread availability of microprocessors in the second half of the 1970's led, however, to the development of systems incorporating them for both governing applications (2) and, on a developmental basis only for voltage regulation (3). Whereas it must be conceded that at the present time there are but few microprocessor-based governor systems actually installed in the U.K., there is every indication that they will shortly become commonplace in plant built by at least some overseas companies (4).

The past decade has seen considerable advances in control techniques (e.g. optimality) which take advantage of the increases in computing power now available. A distinction should, however, be drawn between research studies of forms of turbine-generator control system in which microprocessors are almost incidentally employed, and fully-engineered designs or design studies in which the problems of achieving a good operational reliability using microprocessors are properly addressed. This requires an appropriate redundancy structure (5) and may also involve various forms of software structure to provide fault tolerance (6). In a more general context the methodology of fault-tolerant computing has received considerable attention in the past decade (7) although it should be pointed out that many of the basic concepts may well not be new. Particular techniques have met prior application in an analogue control context (8), and more recent developments (9) provide clear pointers in the application to digital control.

It will be clear that turbine-generators can in the future be expected to incorporate a rapidly-increasing number of microprocessor-based instrumentation and control schemes. The principal feature of such schemes will be a reduction of cost combined with a considerable increase in reliability, accuracy and flexibility of control. The life of the main plant, however, is usually quoted as 30 to 40 years, and it is to be expected that there will be a considerable amount of existing plant in operation for some years to come which will not have the benefit of these developments. In such cases, it may well prove advantageous, at an appropriate stage, to consider some form of updating or retrospective improvement.

2 CONSIDERATIONS IN PLANT IMPROVEMENTS

In effecting plant improvements, it is necessary at the outset to define the scope of the operation. A particular section or area of plant must be considered for which the overall balance of technical improvement must justify the cost of the change, always bearing in mind that some way of quantifying wider or more nebulous issues may have to be made.

The relative apportionment of the various factors will vary widely according to the policy and practices of the operating authority, but in general terms it will be based on the following:

- a) An anticipated reduction in unscheduled outages.
- b) The implementation of more efficient or economic modes of control.
- c) A reduction in routine or unscheduled maintenance procedure.
- d) An improvement in safety.
- e) Any general move towards a greater overall degree of automatic operation, so reducing staff requirements.
- f) Any local shortage of suitable skilled staff for either maintenance or operation.

At a technical level, any improvement may fall into one of two broad categories:

- i) The replacement of a function now regarded as unsatisfactory.
- ii) The provision of a function not previously existing.

An example of an unsatisfactory function would be a centrifugal governor showing persistent stability problems after a long period of service; such a situation could well reflect in operational problems or higher maintenance costs.

More commonly, an operational performance may well have been regarded as satisfactory at the time of initial commissioning, but is no longer so in the sense that it would not be acceptable for new plant. There are a number of examples to be found in this category, of which we may cite the hysteresis and deadband of mechanical governor systems, and the incremental droop over the full load range. Since the advent of electro hydraulic governor systems, it has become clear with what relative ease a good performance may be obtained in these respects and attitudes have changed accordingly. In some instances, it has proved difficult to maintain a good long-term performance with the traditional technology; the Hydraulic Acceleration Detector (HAD) is one area in which this may apply. (See Section 4.2).

When we come to consider the provision of new functions, it is perhaps even more relevant to bear in mind the implications of the change to a software-based technology, with the future flexibility that implies. It may be possible to provide, at quite moderate cost, for longer-term developments at the same time as the more immediate requirements. For example, interface provisions with other controllers, or with higher-level computer-based systems become a particularly easy matter. More immediately, some additional functions may now be provided at almost zero extra cost, such as the ability to select a range of run-up or loading rates in an electro hydraulic governor.

The need to improve overall efficiency of the plant may well provide the initial impetus for some forms of improvement; a control mode now considered desirable in certain contexts is that of "turbine-following-boiler", whilst in Industrial pass-out machines the minimisation of steam flow to the condenser may be important.

A further issue is that of Power System stability, and in a particular instance, the provision of a discontinuous mode of control has proved of considerable advantage as a modification to an existing electro hydraulic governor system (10). In yet another context, the assessment of turbine rotor thermal stress has attracted increasing interest, being of particular relevance in circumstances where it is hoped to extend the operational life of older plant or change from a base-load to a two-shifting role.

3 DESIGN FEATURES OF THE ELECTRONIC SYSTEM

The Electronic System which is used in all the Conversions described has been designed for high integrity, dedicated control applications in a power station or similar environment. It incorporates the powerful Texas TMS9900 family of integrated circuits, but also includes a number of unique hardware peripherals designed specifically for use in a turbine-generator control application. Of particular note are the fast and highly accurate speed measurement system using a toothed wheel and probes (11) and the steam valve control amplifier (12).

The combined Processor and Memory module is built as a single, rugged unit which is able to function alone in its own right, but which has all the built-in features to permit its use in a Triplex Modular Redundant (TMR) control system. Parallel bus links are used for communication with peripherals, whilst secure serial links provide inter-channel communication for channel harmonisation and fault detection purposes. Two-from-three Majority Voting is used at key points in the TMR system, and a typical diagram of a system of this kind is shown in Fig. 1.

The use of Microprocessor-based technology enables a wide range of control applications to be met with a minimum of different hardware module designs; it can also permit changes in control logic to be made subsequent to commissioning. At the same time, the system is based on the use of Read-Only-Memory (ROM), and is therefore not intended to be re-programmed by the Operator in normal service. Indeed, every effort has been made so that the presentation to the Operator is both simple and conventional.

The low spares holding which results from a modular approach, together with some fairly sophisticated automatic fault-detection systems which are embedded in the equipment, produce an excellent degree of serviceability, based upon a simple module replacement.

4 RANGE OF IMPROVEMENTS

The development of the microprocessor system described above was originally directed toward the introduction of electro hydraulic governors for installation on new plant in the 1980's. The degree of inherent flexibility of the system, coupled with the favourable cost trends, has enabled a number of other applications to be now considered for both existing plant as well as new plant.

The particular features of reliability and fault tolerance which make this equipment well suited to turbine-generator applications have been considered in greater depth elsewhere (2, 5), together with a fuller list of the range of applications which might ultimately benefit from the introduction of microprocessor technology (5). Certain of these applications have received active consideration and equipments have either already been supplied or will be supplied in the foreseeable future; they are described below.

4.1 Overspeed Trip System

This equipment is specifically aimed at Boiler Feed Pump or other small turbines where the fitting of conventional centrifugal bolts is difficult; it could, however, serve as a back-up device in a larger turbine where speed of response or accuracy of setting is not adequate, or it could be supplied as a stand-alone device.

The Overspeed Trip has a TMR configuration as standard, and is shown in simplified Block Diagram form in Fig. 2 in which a single toothed wheel fitted with three probes supplies signals to three independent hardware Speed-Measurement Modules. Each is fitted with a hardware-programmed speed level detector which is also interlocked with the probe input for failure-to-safety. The outputs may be majority-voted internally or supplied separately to external logic.

A single Processor Module is fitted for the purpose of running operator-initiated automatic test procedures, but it plays no functional part in the operation of the Trip device. It does, however, considerably enhance the presentation of information; a continuous readout of median speed value is provided, the progress of a test is displayed before the result is given, and a range of error messages provided in plain English to assist in servicing by module replacement.

4.2 Acceleration-Sensitive Detector

This equipment is intended as an electronic replacement for a Hydraulic Acceleration Device (HAD). Such devices are entirely hydraulic/mechanical in form and operate by sensing a rapid change in Pilot Oil pressure, within conventional governing systems, for the purpose of minimising speed rises upon a full-load rejection. As such, they produce problems in the maintenance of long term accuracy which are alleviated by the adoption of a digitally-based electronic system. In standard form, a single-channel system is considered adequate, but a TMR system could be supplied if thought necessary.

Signals from a shaft-mounted toothed wheel and probe system are fed to a hardware speed-measurement module and thence to the processor where successive speed values are calculated and used to determine acceleration. An output signal is provided if a specified acceleration threshold is exceeded for a given length of time. The system may be self-tested automatically.

4.3 Speed Monitor System

In hardware terms, this equipment differs in only minor respects from that of (4.2) above, but is a good illustration of the flexibility of application of a software-based system. The speed measurement technique common to many of the applications described here has an accuracy of 0.1% and an update rate of approximately .01 secs. It is a self-adaptive system which selects the number of teeth over which to take each successive measurement in order to maintain the update rate at an approximately constant value through a speed range from 20 to 4 000 r.p.m.

An Application has arisen, however, where an accuracy of better than .001% has been required, with the trade off of a slower measurement rate. A measurement algorithm has thus been developed which allows a number of successive speed measurements to be accumulated to give an enhanced resolution to the degree required. In the system developed, forty successive measurements are employed; the inherent crystal reference accuracy does not warrant any extension beyond this point.

The system is intended to supply a higher-level Computer system with an accurate measure of shaft speed; the data is transmitted by means of a suitably-formatted serial link, as shown in Fig. 3.

4.4 Turbine Rotor Thermal Stress Evaluator

Current practice for determining turbine-generator run-up and loading rates is based upon an initial metal temperature measurement, the whole of the subsequent sequence being pre-determined to lie within acceptable thermal stress limits. In more recent years, techniques have been established to calculate thermal stress on a real-time basis, using the Station Computer or a dedicated mini-computer. It is now possible, however, to perform the same function using a microprocessor system.

The equipment evaluates thermal stresses at the most critical locations in the HP and IP turbine rotors; in each cylinder four thermocouples are fitted to read turbine inner cylinder temperature, at the inlet belt as close as possible to the inner surface. A local proprietary data-acquisition system simultaneously provides cold-junction compensation and marshalls the inputs for transmission along a single serial highway. This is accepted through one of the serial ports of the standard microprocessor/memory module, and the calculated stresses, expressed as a percentage of that allowable, are then available for display in analogue or digital form.

The use of four thermocouples per cylinder provides a means to average the scatter often encountered in this kind of measurement, and enables majority-voting algorithms to be employed to reject up to two thermocouples which differ by more than a certain amount from the average.

4.5 Turbine Supervisory Equipment

The replacement of existing analogue electronic modules with microprocessor-based systems to monitor the mechanical behaviour of the machine shaft is a natural development easily implemented in a most comprehensive form. Such a system is currently under development and would monitor shaft vibrations, eccentricity, differential expansion etc., to enable alarm and hold conditions to be monitored and used in conjunction with the Automatic Run-up and Loading System.

In order to maximise interchangeability and reduce costs, the processor module associated with each channel of measurement would communicate with a main processor via a two wire serial ring to enable a start-up routine to initiate loading of gains, alarm levels etc., from the main processor into the assigned channel processor. Communication of processed data from the channel to the main processor for display on a VDU would use the same serial link with the required protocol arrangements.

In this way each channel processor would be identical, identification of individual channel functions being resident in the main processor to facilitate replacement of a faulty channel.

4.6 Auto Run-Up and Loading System

This system is now available for installation as Original Equipment, or in retrospective conversions, on turbines of all sizes equipped with either conventional mechanical governing or electro-hydraulic governing. It replaces a hard-wired equipment which is now obsolete. Whilst the general form of the Run-up and Loading procedure is common to all systems, the scope of the facilities available, the number of input parameters, and the nature of the output control signals, will naturally vary between different embodiments.

As a stand-alone ARU System for a large turbine, the electronic equipment occupies approximately 3' 6" vertical height in a single-bay cubicle. Over half of this space is dedicated to Operator Display and Simulator Panels, and it thus compares very favourably with the 5-bay cubicle of the obsolete equipment. In the case where an electro-hydraulic governor is being supplied at the same time as the auto run-up equipment, it is possible to combine many of the functions in a single integrated set of hardware, thereby economising on initial cost and spares requirements.

It is arranged that defects, or loss of interface signals, will automatically return control to a manual mode, and hence all auto run-up and loading systems are offered as single-channel hardware systems except for thermocouples, where a TMR configuration is used. The general form of an automatic run-up and loading system is shown in the flowchart of Fig.4. The various steps are described in more detail in the following paragraphs.

4.6.1 Pre-start Checks

Before start-up, the system performs checks to confirm that certain plant conditions are satisfied. Although arrangements to bypass any check can be provided to increase availability in the event of plant transducer failure, the following list of "Status 1" parameters is mandatory for a typical large turbine:

- Bearing oil pressure satisfactory
- Machine on barring gear
- Emergency trip plungers reset
- ESV's full open
- Wide range governor reset
- Narrow range governor reset
- Drains before ESV open
- Steam chest drains open
- Interconnecting pipe drains open
- Steam pressure satisfactory
- Extractor pumps satisfactory

The following list of "Status 2" checks is normally permitted to be bypassed by the Operator:

- Unloading gear gagged
- Condenser cooling water flowing
- Exciter field CB open
- AVR control at minimum

The pumps, motors, etc., which these checks are intended to monitor are normally started manually, and where standby units are provided, the automatic changeover gear is self-contained. Where a high degree of unattended operation is required, however, it can be arranged that the ARU system also starts these auxiliaries automatically before carrying out the pre-start check routine.

4.6.2 Rate Selection

An optimum rate for both run-up and loading is initially determined as a function of inlet metal temperatures. A minimum of three rates corresponding to cold, warm or hot start is normally provided but additional intermediate values can be supplied. In fully-automatic systems the optimum rate is subsequently used in the program, but more typical systems allow Operator selection of any available rate and not merely the optimum value.

The control of the governor set-point to obtain the desired rate is appropriate to the type of governor. Thus for a conventional mechanical governor, the governor and ESV bush motors are controlled in a "Raise/Lower" mode using solid-state power relays. For microprocessor-based governor systems, the whole process is carried out in software. The net result, in terms of the control of turbine speed or load, is in all cases the same.

4.6.3 Compatibility Checks and Supervisory Holds

The initiation, and the continuation, of the run-to-speed of the turbine is conditional upon certain parameters being monitored and found correct.

Before the run-to-speed can begin at all, steam temperature and vacuum conditions must be appropriate to the selected rate. During the run-up, as described in section 4.5, the supervisory equipment monitors various parameters including vibration and differential expansion, and initiates a hold or runback by the ARU equipment if the levels are excessive. The system is programmed to avoid holds being applied during critical speed bands.

4.6.4 Automatic Synchronisation and Loading

When the rated speed of the machine has been reached, control is passed to a separate auto-synchroniser unit, the operation of which is completed by a signal to indicate that the circuit breaker has closed. Control is then returned to the ARU system.

Automatic loading to a "target" value set by the Operator may now follow, using the optimum rate previously found, or some other value selected manually. The supervisory equipment provides a hold in the event of incorrect conditions in the same manner as during the run-to-speed phase.

It should, perhaps, be noted that the range of interfaces already required for run-to-speed and synchronisation encompass virtually all those required for automatic loading.

4.6.5 Automatic Shut-down

The equipment further provides the facility of de-loading the set automatically at optimum rates prior to opening the circuit breaker.

4.7 Electro-Hydraulic Governing

A full range of electro-hydraulic governing systems, covering all sizes and types of machine, including Industrial Pass-Out and Back-Pressure sets, has been developed. Whereas a TMR microprocessor-based system is used as the electronic nucleus of all these systems, the electro-hydraulic interface arrangements do, of necessity, vary considerably according to the size and type of the particular turbine.

In this context, there are four types of electro-hydraulic governor systems which may be classified as follows:

Type I

High-pressure Fire-resistant Fluid (FRF) System.

Type II

Medium-Pressure Mineral Oil System.

Type III

Low-Pressure Mineral Oil Conversion with Mechanical Transmission.

Type IV

Low-Pressure Mineral Oil Conversion with Hydraulic (Pilot Oil) Transmission.

4.7.1 Application of Governor Types

As a general policy, all new turbines greater than about 100MW capacity are supplied with a Type I EHG system as Original Equipment. The fluid used is phosphate-ester based and is supplied at 68 bar (1 000 psi) from a completely separate pumpset. A Type I system is technically excellent but is costly the more so if supplied as a retrospective conversion.

For new machines up to 100MW, or for Conversions of larger machines where the performance requirements are particularly onerous, Type II system offers the most cost-effective solution. The fluid used is a mineral oil (generally of the same formulation as the lubricating oil) supplied at a pressure between 34 and 68 bar from a completely separate pumpset. This, however, is a less costly item than a pumpset intended for use with an FRF system. The fire risk in a Type II system is minimised by careful attention to segregation and enclosure of the pipe runs.

The valve control mechanisms for either a Type I or a Type II system are essentially similar. Each steam valve is separately controlled by means of an independent electro-hydraulic servo; a proprietary servo valve is used to control a pilot valve in a multi-stage configuration. A conversion to this standard necessitates complete replacement of all the valve control mechanisms and steam chests, and may well involve the tripping system.

The application of the Type III or Type IV system however, is confined entirely to conversions of existing machines. Suitable machines for conversion are those in which a conventional centrifugal governor controls the steam valves by means of mechanical-hydraulic mechanisms using lubricating oil at a pressure of approximately 7 bar. Two basic types of system have commonly been used to couple the centrifugal governor motor to the steam valves, namely a mechanical linkage arrangement or a Pilot Oil system; the former requires the fitting of a Type III conversion and the latter a Type IV conversion.

These conversions essentially aim to retain the original steam valve mechanisms and transmission system and to replace the centrifugal governor; a special type of "electro-hydraulic convertor" provides an interface between the newly installed electronic system and the mechanical linkage or pilot oil system.

The following advantages may be obtained from such a conversion:

- a) The centrifugal governor element is replaced by an electronic system which is highly accurate, stable, free from deadband and does not wear out.
- b) Considerable flexibility is conferred upon the machine control, providing a ready interface with boiler control schemes, load despatching system etc.
- c) Regulation, (i.e. droop) of the turbine may be made variable on-line between specified limits and, perhaps more importantly, the incremental regulation may be linearised over virtually the complete load range of the machine.
- d) Other control functions, such as boiler pressure or condenser vacuum unloading, can be incorporated with only the addition of the necessary transmitters and electronic interface modules; back-pressure control can be included in the case of industrial machines in exactly the same way.

- e) Depending upon the steam valve configuration, the system is readily extended to incorporate fully automatic control of the turbine from barring speed to full load.

It should, however, be noted that notwithstanding the range of advantages outlined above, a Type III or Type IV Conversion cannot be expected to significantly improve the dynamic response of the overall control system, nor can it be expected to eliminate the dead-band associated with the steam valve control mechanisms.

4.7.2 The Electro-Hydraulic Convertor

The Electro-Hydraulic Convertor has been developed in conjunction with the CEBG specifically for conversion applications and has undergone extensive testing on Machine No.1 at Kingsnorth Power Station. Its particular feature is that it will operate on mineral oil at approximately 7 bar from the existing lubricating oil supply with a moderate degree of additional filtering. In a Type III Conversion it is used to control the position of a Primary Relay which physically replaces that previously controlled by the centrifugal governor and control handwheel system. In a Type IV Conversion it is used to regulate the Pilot Oil Pressure.

In order to provide a high degree of reliability and serviceability, the convertor itself consists of two separate electro-hydraulic servo valves which are mounted on a single transfer block. This incorporates a manually-operated changeover valve which permits either servo valve to be removed for servicing whilst the other unit continues in operation; in normal operation, both servo valves are run in parallel. An electro-mechanical interlock connected to the electronic system prevents inadvertent removal or disablement of the wrong valve.

A separate control loop is provided for each servo valve, each comprising a servo valve amplifier and feedback transducer. The connection to the TMR microprocessor-based electronic system is made by means of two majority-voter units. This is illustrated in basic principle, in Fig.5. The arrangement allows "no break" servicing to be carried out on every significant module or sub-unit of the system, and virtually eliminates the possibility of an outage due to a single random equipment failure.

The servo valve itself is a two-stage design in which an inner pilot spool controls the movement of a larger, concentric main spool. The input motion is provided by a moving-coil thruster acting against a diaphragm spring; high thrust levels are available to overcome the effects of fluid contamination. Work is in progress to evaluate equivalent proprietary servo valves in pursuit of further cost reduction.

5 CONCLUSIONS

After a brief outline of the historical background of digital control techniques as applied to steam turbine generators, this paper has discussed the considerations leading to the design features of the system herein described. Within a standardised hardware framework, a number of applications have been outlined, many of which may be well suited for retrospective incorporation in existing machines as well as installation on new plant.

The applications discussed range in scope from a fairly simple acceleration - monitoring system to a high-integrity TMR electro-hydraulic governing system. Equipment has been installed on certain new machines and is on order for a number of others yet to be delivered. Negotiations have been also conducted in respect of a range of plant improvement applications to existing machines - largely overseas - and equipment will be supplied in due course.

The authors anticipate that over the next few years, the application of microprocessor-based equipment to the control and instrumentation of turbine generator plant will become both a technical norm and a commercial necessity.

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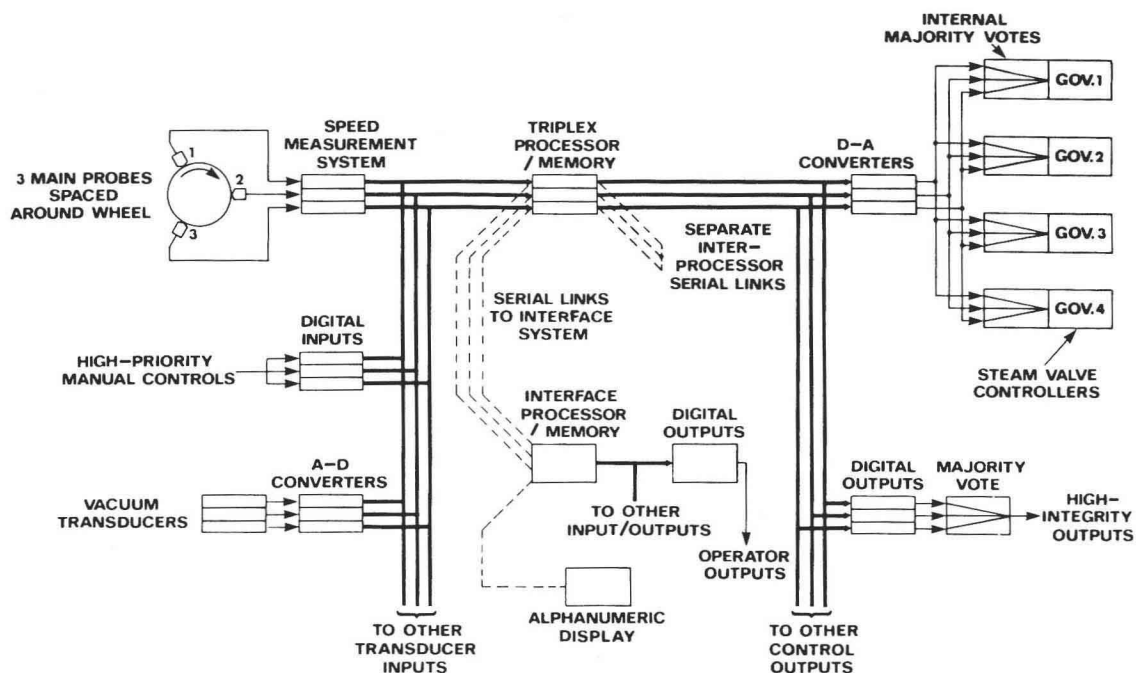


Fig 1 General control system redundancy scheme

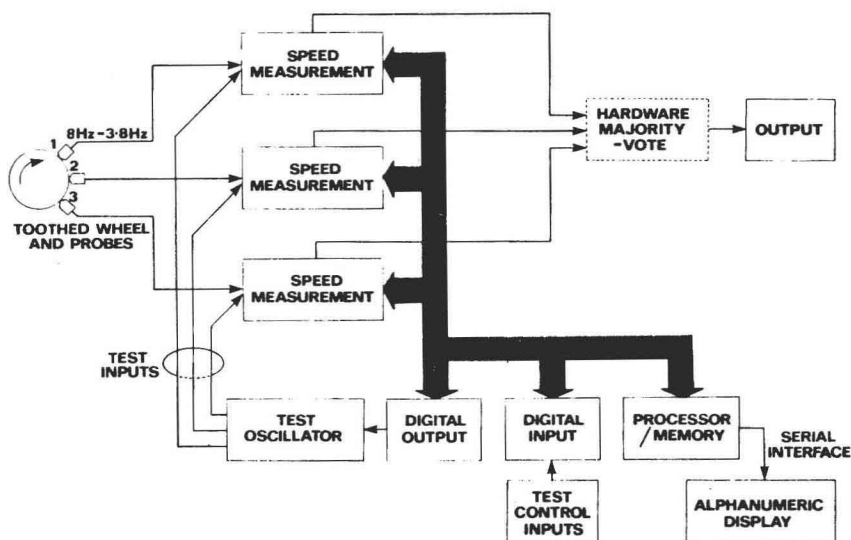


Fig 2 Triuplicated overspeed detector

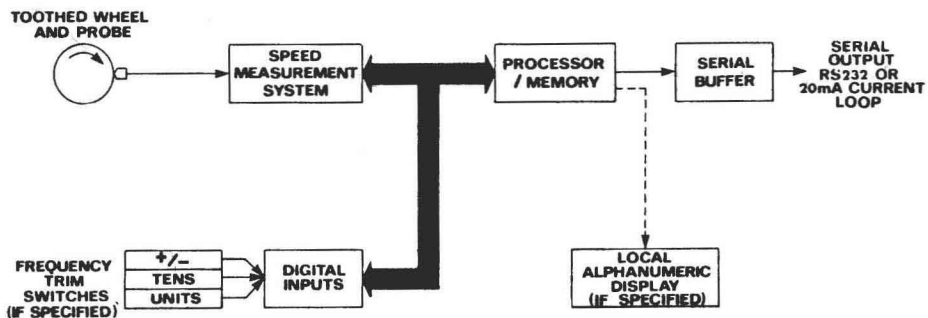


Fig 3 High resolution speed measurement

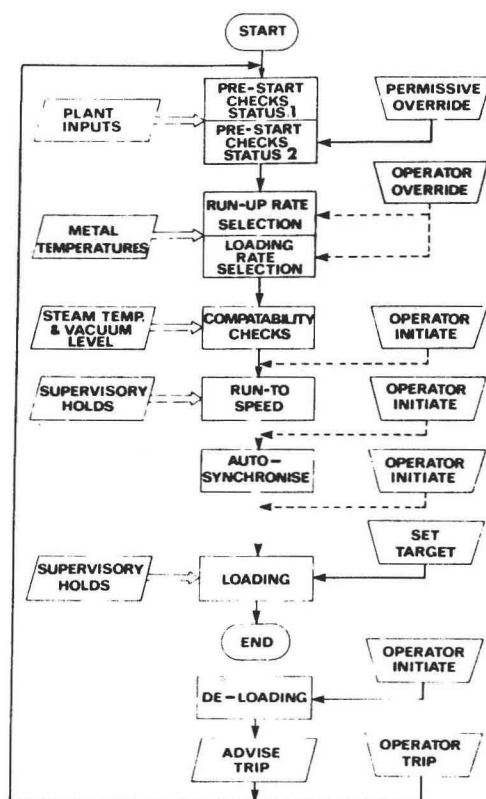


Fig 4 Basic ARU flow diagram

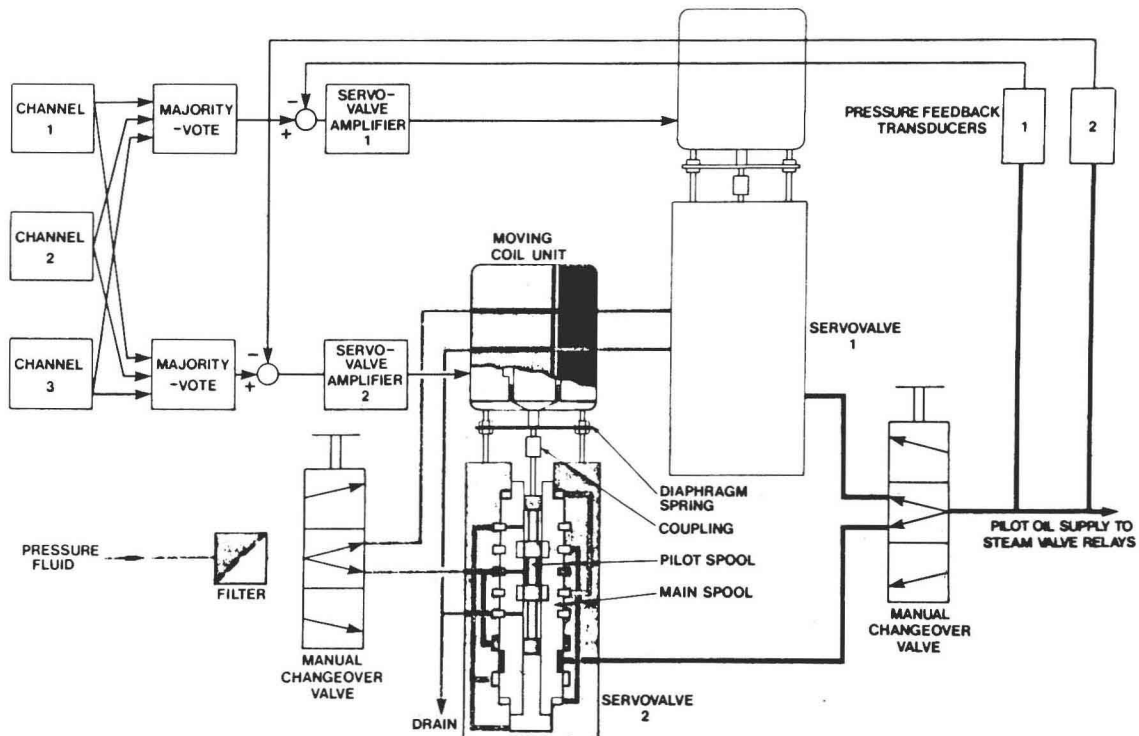


Fig 5 Diagram of type IV electrohydraulic conversion governor

