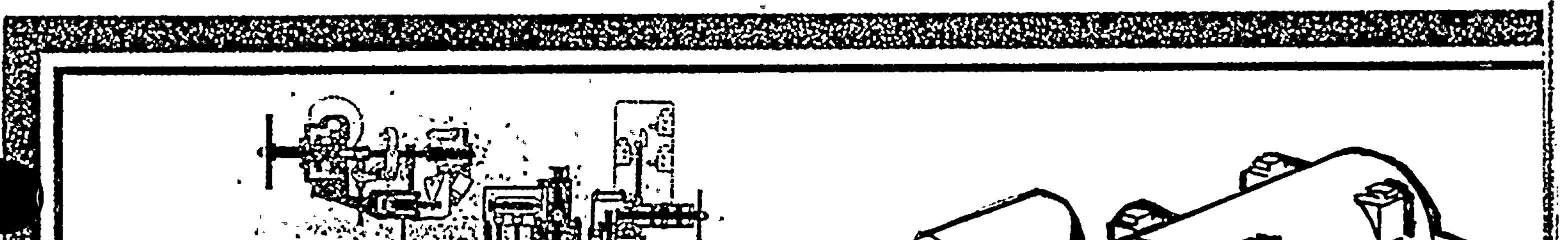
INTRODUCTION
to the
BASIC ELEMENTS
of
CONTROL SYSTEMS

FOR LARGE STEAM TURBINE-GENERATORS

by

M. A. Eggenberger

LARGE STEAM TURBINE-GENERATOR DEPARTMENT



GENERAL ELECTRIC

INTRODUCTION TO THE BASIC ELEMENTS OF CONTROL SYSTEMS FOR LARGE STEAM TURBINE-GENERATORS

Mechanical-hydraulic systems . . . . Electrohydraulic systems

by

M. A. Eggenberger

CONTENTS

CONTENTS (Cont'd)

INTRODUCTION

A great deal of ingenuity has gone into the early design of mechanical-hydraulic control systems, which do most of their "thinking" by means of mechanical components. Common sense and engineering intuitions were the most important ingredients in the design of these pioneer control systems.

In recent years we have gained much more exact information on the process with which the devices accomplish their functions. We have learned to express their performance mathematically and to identify their inherent limitations in more precise terms. We have also found that the expressions used to describe mechanical systems have a complete set of analogs in electrical systems. Within certain reasonable limitations either one of the systems can do the same thing as the other one, if we are immune to complexity.

However, immune to complexity we are not. As the control tasks become more complex we will steer in the direction of the less complex system that accomplishes the specified functions.

The picture of the complexity of the control task to be fulfilled is shown in a general way in Fig. 1.

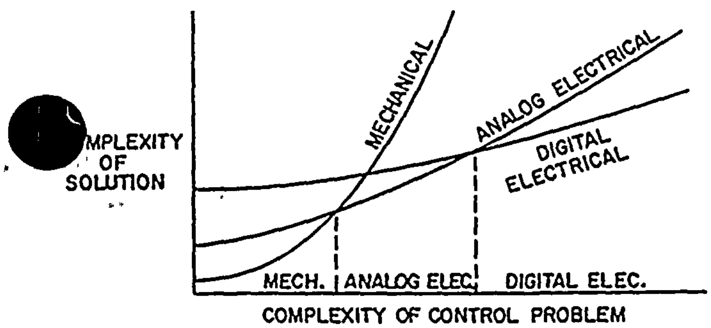


Fig. 1. General philosophy of control systems

In Fig. 1:

The abscissa is the *complexity of the problem* that has some relation to the number and the nature of the controlled variables and the needed performance (steady-state accuracy and transient deviation).

The ordinate is the *complexity of the solution* that has some relation to the cost, the effort of adjustment, and the effort of maintenance of the entire control system.

The *mechanical system* starts out with the least complex solution for a very simple task (a floating lever is a very simple summer), but as the problem gets more intricate, the complexity of the solution increases rapidly.

The *analog electrical system* is more complex to start with (we need an operational amplifier to add with minimum error), but its complexity increases more slowly; (if we want to add one more variable, we just need one more resistor).

The *digital electrical system* is still more complex for simple tasks, (we need computer elements); but adding very complex functions is relatively easy, (we merely need to program them).

Fluidics, a fourth principle developed recently, appears to have high capabilities with a relatively moderate complexity of the solution, but practical experience is limited at this time.

Assuming that the curves in Fig. 1 represent the general picture sufficiently well, we could draw the conclusions that the simple control system would most likely be mechanical, the system for intermediate complexity would be predominantly analog electrical, and the highly complex system would prefer a digital electrical solution.

Our present reheat turbine control systems would probably fall in the category of intermediate complexity.

MAJOR FUNCTIONS OF THE BASIC ELEMENTS OF CONTROL SYSTEMS

The basic elements of a control system can all be called computing elements and their functions can always be expressed in equations.

They can be classified according to their functions as follows:

- Transducers
- Summers
- Differentiators
- Integrators
- Amplifiers (multiplies a variable with a given constant)
- Overriding devices (gating)
- Function generators

Any one device may perform several of these functions simultaneously.

The functions of these devices are explained on the following pages, with typical examples for mechanical and analog electrical systems.

1. THE TRANSDUCER

A transducer measures a certain quantity and produces an output that has a given relation to that quantity, probably including some limits.

A *mechanical transducer for rotational speed* is the flyball governor shown in Fig. 2.

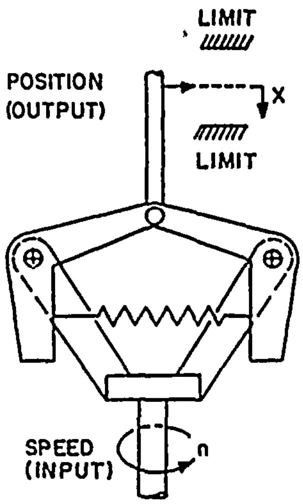


Fig. 2. Mechanical speed governor

The approximate transfer function of this speed transducer is:

$$\Delta X = K_1 \; \Delta n \qquad (1)$$

Actually, this particular speed governor is a function generator with a characteristic as shown in Fig. 3.

Interpreting equation (1) on Fig. 3 points out the process of linearization, whereby the slope of the

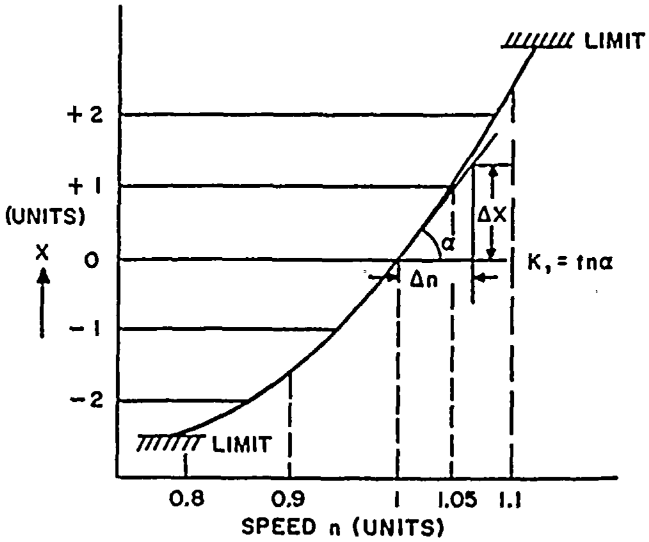


Fig. 3. Characteristic of mechanical speed governor

characteristic at rated speed α is used to compute K_1 as:

$$K_1 = \left(\frac{\Delta X}{\Delta n}\right)_{\text{at rated speed}} = \text{tn}\,\alpha \qquad (2)$$

An *electrical transducer for rotational speed* is a simple permanent magnet (a-c) generator operating a high impedance load (Fig. 4).

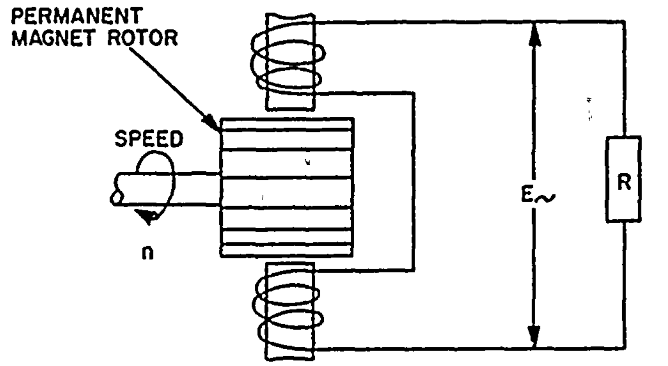


Fig. 4. Permanent magnet generator speed transducer

The characteristic of the permanent magnet generator is for practical purposes linear, Fig. 4a. The transfer function of this speed transducer is

$$E(\sim) = K_2 n \qquad (3)$$

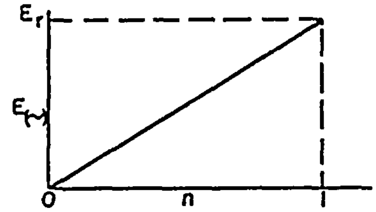


Fig. 4a. Characteristic of permanent magnet generator speed transducer

Another type of *electrical speed transducer* uses a tooth wheel and a magnetic pickup that sends pulses to a frequency-to-voltage converter which transforms the pulses into a d-c voltage proportional to the frequency of the pulses, Fig. 5.

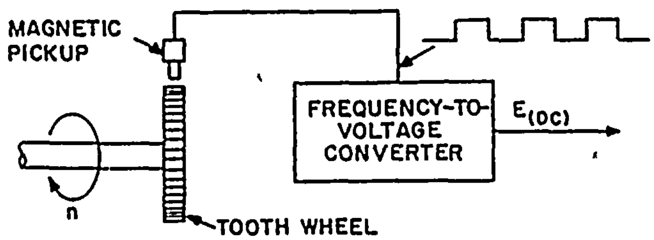


Fig. 5. Magnetic pickup speed transducer

This speed transducer is very linear down to approximately five percent of rated speed. Its transfer function is, therefore, similar to equation (3).

$$E_{(DC)} = K_3 n \tag{3a}$$

A *mechanical pressure transducer* is a spring-loaded bellows, Fig. 6.

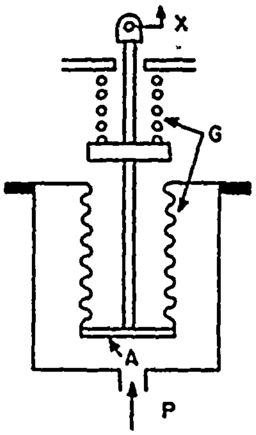


Fig. 6. Mechanical pressure transducer (low pressure)

The transfer function of this pressure transducer is

$$\Delta X = \Delta P \frac{A}{G} \tag{4}$$

where:

P = input pressure
A = effective bellows area
G = system spring gradient

An *electrical pressure transducer* can be in the form of a Bourdon tube, operating a linear variable differential transformer (LVDT), (Fig. 7). This transducer actually transforms pressure into mechanical motion (X) with small forces and this motion is changed to an electrical signal by the LVDT and the demodulator.

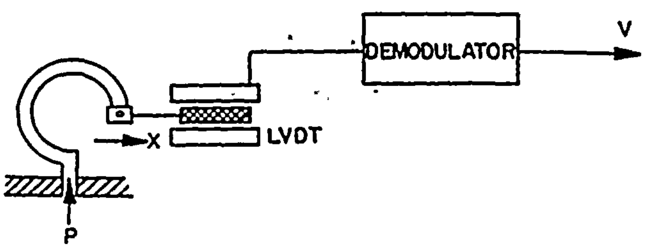


Fig. 7. Electrical pressure transducer (high pressure)

The transfer function of this pressure transducer is

$$\Delta V = K_4 \Delta P \tag{5}$$

where:

P = input pressure
V = output voltage
$K_4 = \frac{\Delta V}{\Delta P}$ = transducer gain

Transducers of this kind are usually very linear down to almost zero pressure.

Mechanical vibration can produce undesirable noise in the transducer output. The mounting of the transducer must be done with this noise problem in mind.

The LVDT is actually a position-measuring device that can be used in such applications as the measurement of valve positions.

2. THE SUMMER

A summer is a device that performs the summation of two or more quantities. If any of these quantities is added with a negative sign, the operation amounts to a subtraction (computing of a difference). The added quantities can be either variables or constant values.

In most cases the summer also multiplies each variable with some constant value before adding it.

The simplest *mechanical summer* is a "floating lever", Fig. 8.

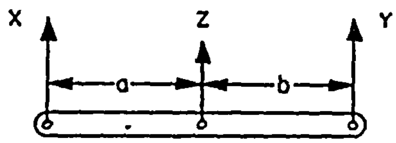


Fig. 8. Mechanical summer (floating lever)

The following equation applies to Fig. 8.

$$Z = X\left(\frac{b}{a+b}\right) + Y\left(\frac{a}{a+b}\right) \tag{6}$$

In the particular case where a = b, the sum becomes

$$Z = \frac{X + Y}{2} \tag{6a}$$

The result of this summation will be reasonably accurate only if the tilt of the lever is not excessive (30° should not be exceeded).

The addition of three quantities can be performed mechanically by using a triangular plate, Fig. 9.

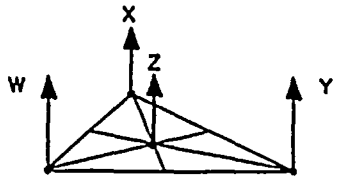


Fig. 9. Mechanical summer for three variables (wobble plate)

If the plate is an equilateral triangle, the sum Z is

$$Z = \frac{W + X + Y}{3} \quad (7)$$

Note that the joints with which the rods w, x, y and z are connected to the plate must be ball joints with two degrees of freedom.

A larger number of quantities can be added mechanically by breaking the addition into several partial additions

$$V + W + X + Y = (V + W) + (X + Y) \quad (8)$$

and performing the addition in several steps using floating levers to add each group of two quantities.

The mechanical summation of more than three variables is usually difficult because of conflicting solutions to the problems of friction and backlash.

Electrically the summation of d-c voltages is performed by means of a high gain d-c amplifier (A) called "Operational Amplifier", represented by a piece-of-pie-shaped wedge, Fig. 10.

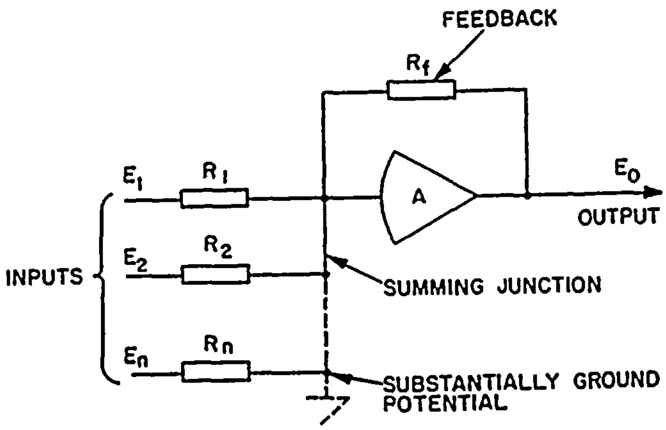


Fig. 10. Electrical summer (with resistors)

Here the equation for the output voltage is

$$E_0 = -\left(E_1 \frac{R_f}{R_1} + E_2 \frac{R_f}{R_2} \cdots + E_n \frac{R_f}{R_n}\right) \quad (9)$$

The following points should be noted and well remembered for the understanding of the subsequent material.

1. The output of the operational amplifier is always of reversed polarity. (It can be said that a multiplication with -1 is inherent in this summer.)

2. The gain with which each input signal is added is proportional to the feedback resistance (R_f) and inversely proportional to the respective input resistance (R_1, R_2, ... R_n).

3. The possible number of inputs is almost unlimited.

4. The summing junction can be considered to be substantially at ground potential because of the extremely high gain of the amplifier.

5. The simple resistors R_f, R_1 ... R_n can be replaced by any other kind of impedances (Z) in order to produce almost any desired transfer function of the circuit, Fig. 11.

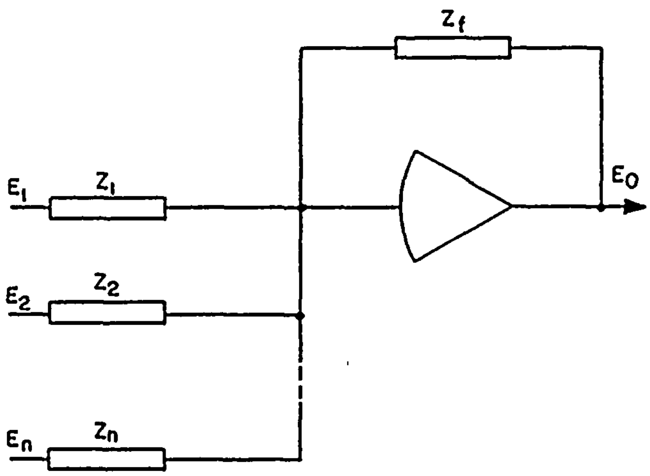


Fig. 11. Electrical summer (with impedances)

Here the output voltage is:

$$E_0 = -\left(E_1 \frac{Z_f}{Z_1} + E_2 \frac{Z_f}{Z_2} + \cdots E_n \frac{Z_f}{Z_n}\right) \quad (10)$$

See Appendix for impedance concept.

An *impedance* is in general an element in which the magnitude and the phase relation of the current with respect to an impressed voltage are functions of the time variations of the impressed voltage.

In most cases a combination of resistors (R : —▭—) and capacitors (C : —|(——) is used to produce impedances of different character. However, it is possible to use inductances (L: —ᗰᗰ—) as well.

In order to express impedances mathematically, it is necessary to use the complex representation by means of the Laplace operator "s". For a sinusoidal input voltage the Laplace operator can be interpreted as

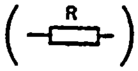
$$s = j\omega \tag{11}$$

where

$$j = \sqrt{-1}$$

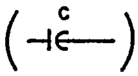
and ω = angular frequency (of impressed voltage) in rad/sec

The impedance can now be evaluated as follows:

1. Resistor 

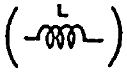
$$Z = R \tag{12}$$

The impedance of a resistor is not frequency dependent.

2. Capacitor 

$$Z = \frac{1}{C\,s} = \frac{1}{C\,j\,\omega} \tag{13}$$

The impedance of a capacitor is ∞ at $\omega = 0$ and zero at $\omega \to \infty$.

3. Inductance 

(ideal coil)

$$Z = sL = j\omega L \tag{14}$$

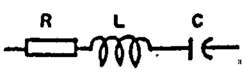
The impedance of the ideal coil is zero at zero frequency and infinity at infinitely high frequency.

Actually a coil will always have a finite resistance, so that the impedance of the real coil would have to be represented by

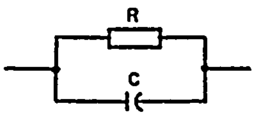
$$Z = R + j\omega L \tag{14a}$$

and would have the value of R for $\omega = 0$.

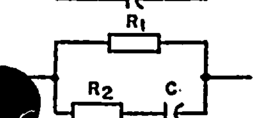
A selection of typical transfer impedances is:



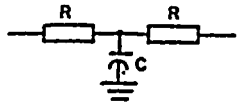
$$Z = R + sL + \frac{1}{C\,s} \tag{15}$$



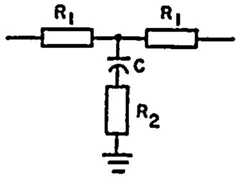
$$Z = \frac{R}{1 + RCs} \tag{16}$$



$$Z = R_1 \frac{1 + R_2\,C\,s}{1 + (R_1 + R_2\,C)\,s} \tag{17}$$



$$Z = 2R\,(1 + \frac{RCs}{2}) \tag{18}$$



$$Z = 2R_1 \cdot \frac{1 + (R_2 + \frac{R_1}{2})\,C\,s}{1 + R_2\,C\,s} \tag{19}$$

3. THE DIFFERENTIATOR

The rate of change of a certain variable can be measured by differentiating its value with respect to time:

The rate of position (X) change is a velocity:

$$\frac{dX}{dt} = v \tag{20}$$

The rate of a rotational speed (n) change is an angular acceleration

$$\frac{dn}{dt} = \alpha \tag{21}$$

A differentiation of a variable can also be expressed by the Laplace operator "s" (see Appendix), for instance, the velocity of equation (20)

$$\mathcal{L}\left(\frac{dX}{dt}\right) = sX_{(s)} \tag{22}$$

or the rotational acceleration of equation (21)

$$\mathcal{L}\left(\frac{dn}{dt}\right) = sn_{(s)} \tag{23}$$

A dashpot, a *mechanical* device that acts very much like a *differentiator* (at low input frequencies) is shown in Fig. 12.

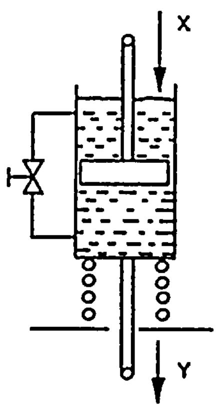


Fig. 12. Mechanical position differentiator (for low frequency)

The transfer function of this device is

$$\frac{Y(s)}{X(s)} = \frac{Ts}{1 + Ts} \tag{25}$$

It can be seen that, as long as

$$Ts \ll 1 \tag{25a}$$

($s = j\omega$ — very small)

the value of $\frac{Y}{X}$ is close to

$$\left(\frac{Y}{X}\right)_{(Ts \ll 1)} \doteq Ts \tag{25b}$$

or

$$Y_{(s)} = T\,X\,s \tag{25c}$$

or

$$Y_{(t)} = T\frac{dX}{dt} \tag{25d}$$

T is the time constant (sec) associated with the dashpot configuration.

An *electrical differentiator* can be built with an operational amplifier using a capacitor as the input impedance, Fig. 13.

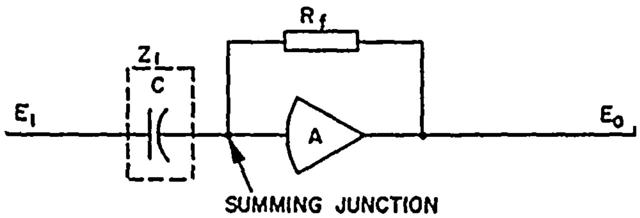


Fig. 13. Electrical differentiator

The impedance of the capacitor C is (see equation (13))

$$Z_1 = \frac{1}{C\,s} \tag{26}$$

and the transfer function of the circuit is, assuming a perfect amplifier

$$-\frac{E_o}{E_1} = R_f\,C\,s \tag{27}$$

or

$$E_{o(s)} = -R_f\,C\,s\,E_1 \tag{27a}$$

or

$$E_{o(t)} = -R_f\,C\frac{dE_1}{dt} \tag{27b}$$

This is a pure differentiator at all frequencies ($j\omega$) of E_1 but if the differential becomes too big, the operational amplifier will saturate and give a wrong output. This will happen when the input signal E_1 is noisy. Differentiators must be handled with a good analytical knowledge. In general, it is *not* advisable to have an input capacitor connected directly to the summing junction of an operational amplifier.

4. THE INTEGRATOR

An integrator is a device that integrates the value of a variable with respect to time. A good example of a mechanical integrator is the combination of a pilot valve and a piston, Fig. 14.

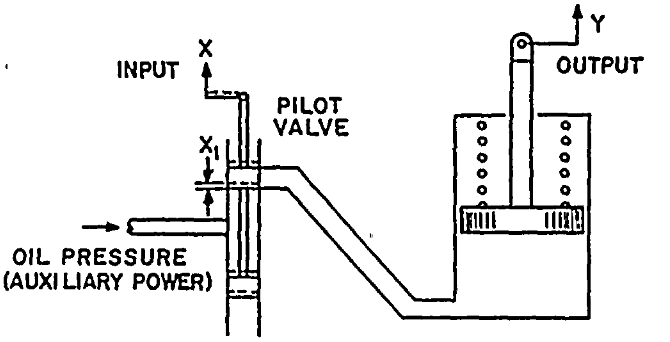


Fig. 14. Mechanical integrator

From this illustration it can be seen that if the pilot valve is lifted by the amount X_1 above the neutral position, the piston will start moving immediately and keep on traveling at a given speed until the pilot valve is returned to the neutral position, or until the piston reaches a stop (which is also called saturation).

The particular meaning of the term "integration" can be seen in Fig. 15.

Expressed mathematically, the integration performed in Fig. 15 is

$$Y_{(t)} = K\int_0^t X_{(t)}\,dt \tag{28}$$

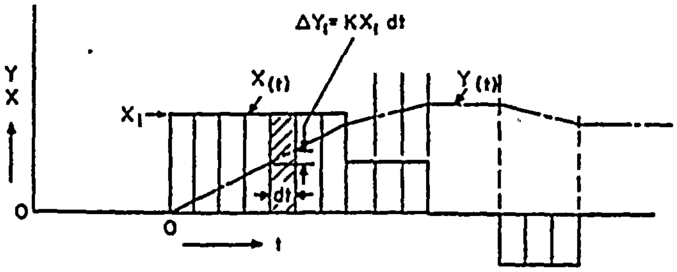


Fig. 15. Integration

Using the Laplace operator s, this can be written as

$$Y_{(s)} = \frac{K\,X_{(s)}}{s} \qquad (29)$$

The operator s in the denominator signifies an integration.(See Appendix).

K is called the gain of this integrator. It is a constant containing the fixed physical parameters such as oil pressure, port width, piston area and flow coefficients.

By rearranging equation (29) we can immediately see that the rate of change (the linear speed) of Y is proportional to X:

$$s\,Y_{(s)} = K\,X_{(s)} \qquad (30)$$

This simple example points out how the simplification of the control language using the Laplace operator s works.

We can also see that the piston (Y) will keep on moving until X becomes zero, which is one of the basic qualities of an integrator (as long as it is not saturated).

Other examples of integrators are the turbine shaft of which the rotational energy is the time integral of the sum of all torques applied to it, or the pressure in a steam vessel that is the time integral of the algebraic sum of steam flows into the vessel (flow out of the vessel has a negative sign).

The *electrical integrator* can again be built with an operational amplifier, Fig. 16.

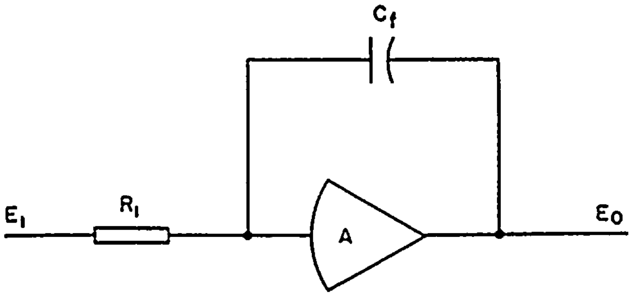


Fig. 16. Electrical integrator

The impedance Z_f of the feedback capacitor is again

$$Z_f = \frac{1}{C_f s} \qquad (31)$$

and the transfer function of the amplifier circuit is

$$E_{o(s)} = -\frac{E_1}{R_1 C_f s} \qquad (32)$$

or

$$E_{o(t)} = -\frac{1}{R_1 C_f}\int_0^t E_1\,dt \qquad (32a)$$

Similar to the mechanical integrator, $\frac{1}{R_1 C_f}$ is called the gain of this integrator and its dimension is $\frac{1}{sec}$. It is the rate at which E_o changes with one volt at the input (E_1) (until saturation occurs).

5. THE AMPLIFIER

Amplifiers cover a wide range of devices basically intended to increase the level of a signal to a higher level in magnitude or in force, or in voltage or current --- in short, to transform a signal in a predetermined way to a higher level.

Mechanical stroke amplifier. A simple example is a lever, Fig. 17.

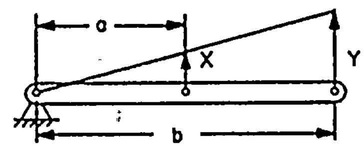


Fig. 17. Mechanical stroke amplifier

Its transfer function is

$$Y = K\,X = \frac{b}{a}\,X \qquad (33)$$

This amplifier has no time lag; its gain K is the lever ratio. It amplifies only the stroke, while the energy level of the output is substantially the same as the input.

Mechanical-hydraulic amplifier. The most common one is the servomotor. It uses hydraulic fluid under pressure for auxiliary power, Fig. 18.

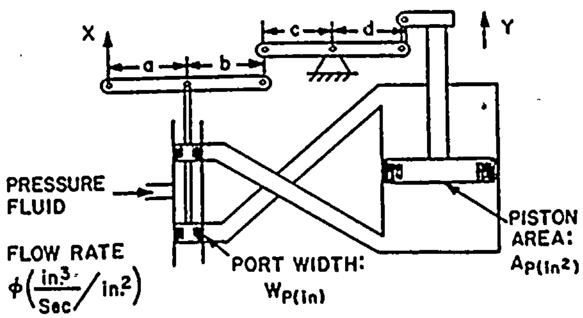


Fig. 18. Mechanical-hydraulic power amplifier (servomotor)

The amplifier shown in Fig. 18 usually amplifies stroke and the energy level ... the latter appreciably (about 1000:1) ... and can be used to drive substantial loads. The output (Y) follows a change in input (X) position with a time lag.

The transfer function of this servomotor is

$$\frac{Y_{(s)}}{X_{(s)}} = \frac{K}{1 + Ts} \qquad (34)$$

where K is the lever ratio:

$$K = \frac{bd}{ac} \qquad (34a)$$

also called the steady-state gain, and T is the time constant of the servomotor (in seconds)

$$T = \frac{A_P\,[\text{in.}^2]}{\frac{ac}{(a+b)d} W_P\ \phi}\ (\text{sec}) \qquad (34b)$$

A step change of the input X is followed by a movement of Y as shown in Fig. 19. This response is described completely by the transfer function (34).

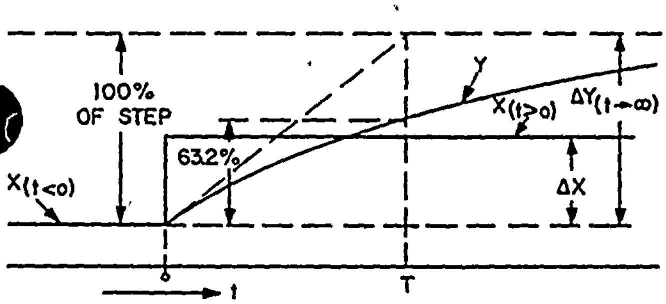


Fig. 19. Response of servomotor

A servomotor can also be built "single acting", which means simply that the oil forces on one side of the piston are replaced by a strong spring, Fig. 20.

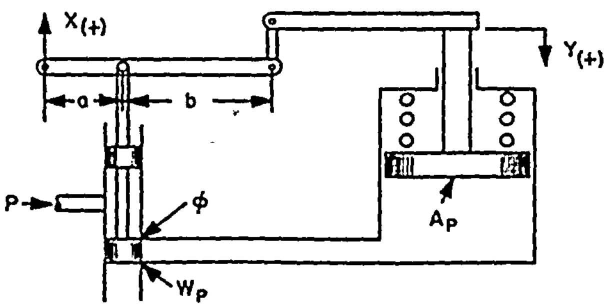


Fig. 20. Single-acting servomotor

In this particular case the reversing lever in the feedback has been omitted so that Y has the opposite direction of motion of X. The transfer function of this servomotor is the same as equation (34) with

$$K = -\frac{b}{a} \qquad (34c)$$

and

$$T = \frac{A_P}{\frac{a}{a+b} W_P\ \phi}\ (\text{sec}) \qquad (34d)$$

From this example it can be seen that sign reversals in the chain of control components can very easily be applied, and it is basically not important what a specific sign in the chain is. The important thing is that the end effect of all sign changes makes the final element operate in the proper direction.

Occasionally the sign of intermediate steps can be chosen so that failure of a given link in the chain makes the system fail in the right direction.

If, for example, the connection at X in Fig. 18 breaks, the pilot valve will fall down and decrease Y which will close the valves, therefore constituting a failsafe system.

If the connection at X in Fig. 20 breaks, and the pilot valve falls down, Y will increase; if this would open the valves it would not be a failsafe system.

Therefore it can be said that the sign of intermediate control quantities can be significant in the failure analysis of the system.

Electrical amplifier. Electrical signals can be amplified in a number of ways.

A *voltage amplifier* where a sign reversal can be tolerated is the simple use of the operational amplifier, Fig. 21, where

$$E_0 = -E_1 \frac{R_f}{R_1} \qquad (35)$$

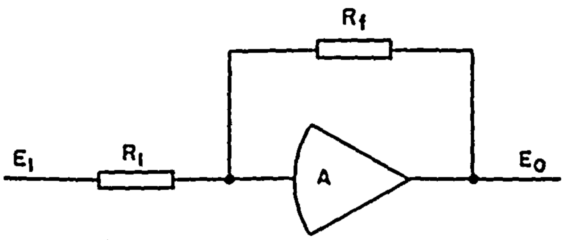


Fig. 21. D-c voltage amplifier

The increase in energy level of this amplifier is insignificant.

Usually the amplifying function can be incorporated in a device that performs other functions as well.

Occasionally, when a sign reversal is needed, this voltage amplifier is used as a reversing amplifier.

A *current amplifier* can be built with a transistor, Fig. 22.

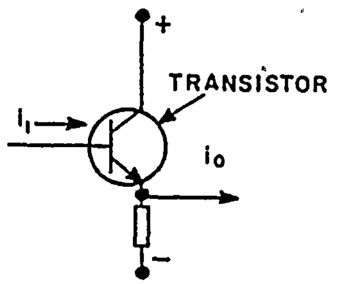


Fig. 22. Current amplifier

This amplifier can produce a higher current that might be needed to drive the next stage. It will change the voltage only slightly and it will not change the sign.

Electrohydraulic amplifier. An amplifier combining electrical and hydraulic components is used in electrical systems to drive substantial loads such as steam valves, Fig. 23.

While the transfer function of this amplifier is too complicated to be discussed here, it can be seen that the freedom of choice of Z_1 and Z_2 makes it possible to design the loop so that it operates under optimum conditions (as shown in Fig. 24 for a step input change).

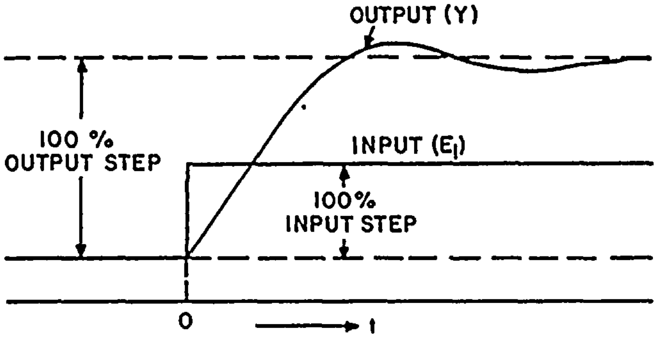


Fig. 24. Response of electrohydraulic amplifier

The new position is reached somewhat faster than on the mechanical system and the positioning accuracy is generally better.

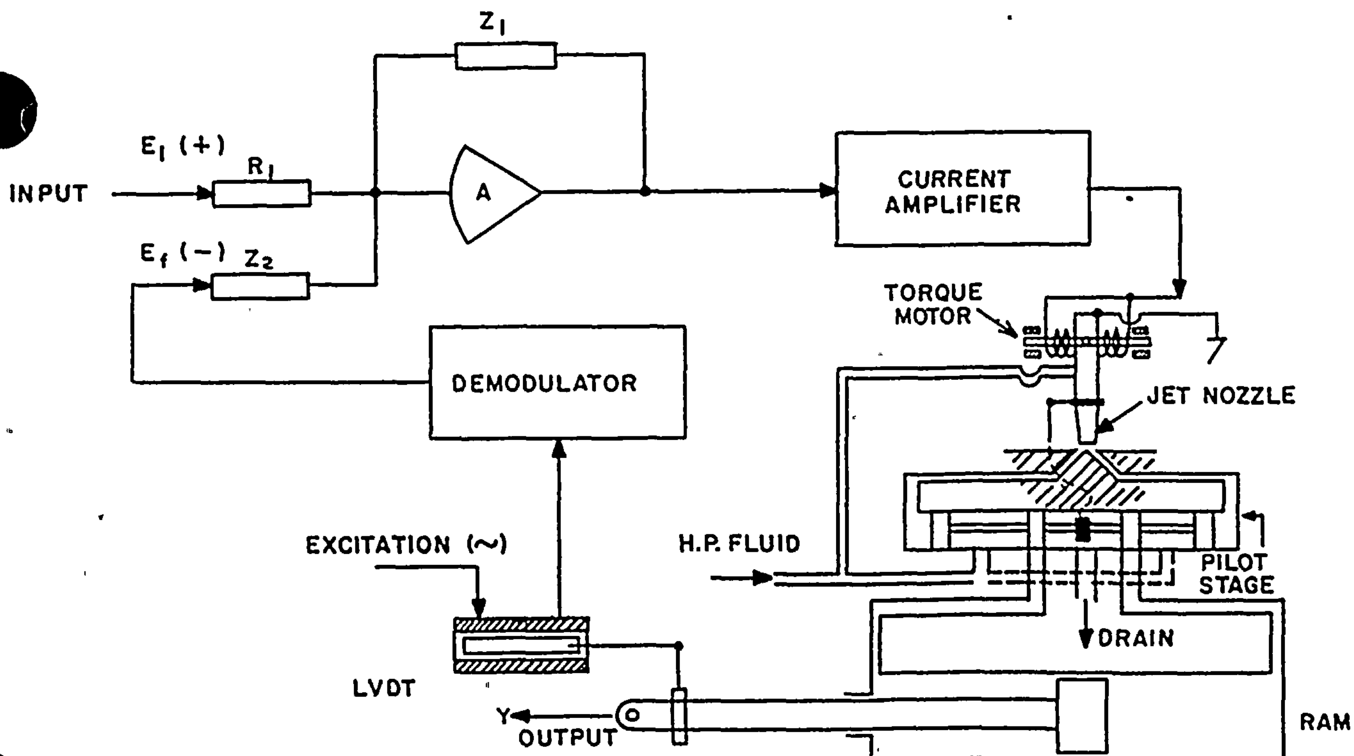


Fig. 23. Electrohydraulic amplifier

6. OVERRIDING DEVICES (GATES)

An "overriding device" is a component of a mechanical or electrical system which makes a choice between two signals, causing only one of them to perform the controlling function.

In a mechanical system a typical example is the load limit which can call for the valves to be closed further than the position set by the speed governor. The principle is shown in Fig. 25a for a single-acting relay (not exactly the speed governor load limit) and in Fig. 25b for a double-acting relay.

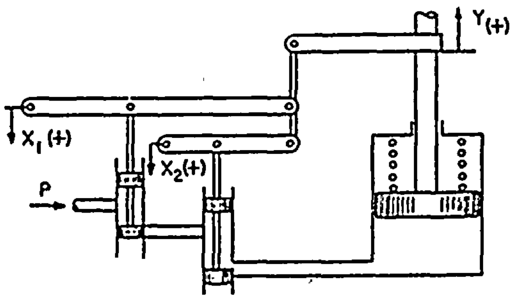


Fig. 25a. Mechanical overriding device (single-acting relay, X_1 controlling)

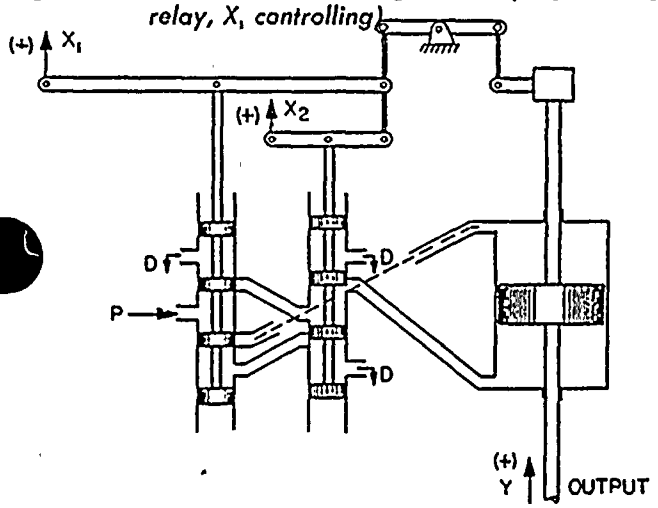


Fig. 25b. Mechanical overriding device (double-acting relay, X_1 controlling)

One or both inputs can be either controlling signals or manually or automatically adjusted limit signals. Since there is no switching action when one signal takes over from the other, the transfer is entirely smooth.

For the purpose of protection (trip devices) a series arrangement of mechanically, hydraulically, or electrically operated three-way valves can be used to obtain the desired trip action.

In electrical systems this function is called "gating" and the circuits that perform it are called either "low value gate" or "high value gate", depending on the application. A low value gate circuit is shown in Fig. 26.

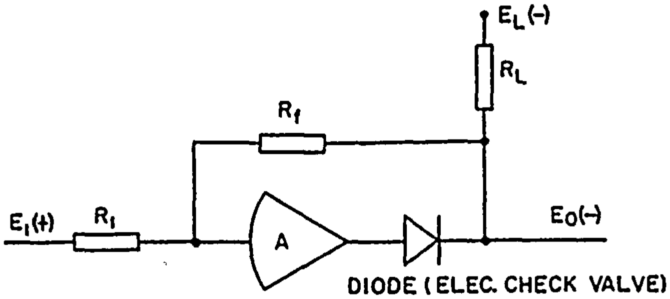


Fig. 26. Electrical low value gate

The voltage E_L (-) can, for example, be produced by a voltage divider (which is the case for the load limit) or by another control circuit, such as the initial pressure limit circuit.

> NOTE: Because of the fact that these gating functions are all done in the electrical circuits, there will be no load-limit handwheel or IPR at the turbine front standard; these devices are all incorporated in the control panel and the control cabinet.

The output voltage E_0 will be the less negative of either E_L (-) or $-E_1$ (disregarding the diode voltage drop).

It is, of course, possible to give E_L (-) any number of characteristics such as those used for runbacks or step-backs.

7. THE FUNCTION GENERATOR

Function generators are used to compensate for the nonlinear flow characteristic of steam valves.

In the *mechanical system* we use cams in the forward loop for the control valves, Fig. 27.

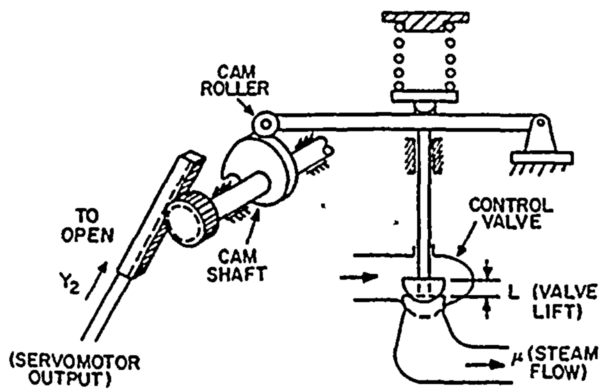


Fig. 27. Mechanical function generator (cam-operated control valve)

In block diagram form this combination of function generators is represented in Fig. 28.

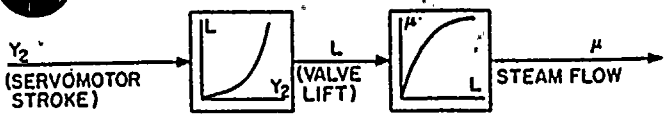


Fig. 28. Block diagram for cam shaft and valve function generators

The effect of the series arrangement of these two function generators is an approximately linear relation between μ and Y_2.

A function generator with a characteristic similar to the valve characteristic can be used in the feedback of the pre-amplifier. This is widely used on the intercept valve relay that produces the input stroke Y_1' to the intercept valve servomotor and compensates for the nonlinear flow characteristic of the intercept valve. This feedback function generator (cam) is shown in Fig. 29.

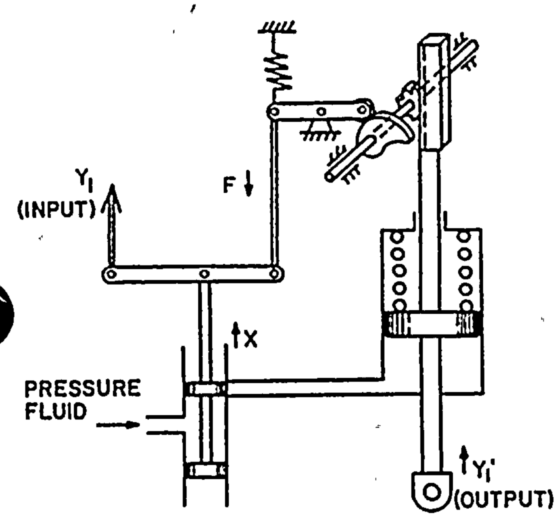


Fig. 29. Mechanical function generator in feedback (intercept valve relay)

In block diagram form this intercept valve control is represented in Fig. 30.

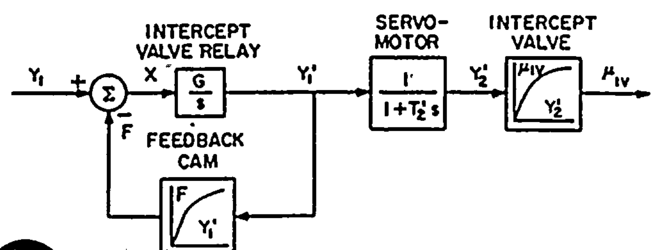


Fig. 30. Block diagram of mechanical intercept valve flow control with feedback function generator

In Fig. 30:

Y_1 = Intercept valve relay input

X = Pilot valve position (off neutral)

Y_1' = Intercept valve relay output

Y_2' = Intercept valve lift

μ_{IV} = Intercept valve flow

In order to obtain an approximately linear relation between the intercept valve flow (μ_{IV}) and the input (Y_1) the feedback function generator should have very much the same characteristic as the valve flow-lift relation.

In the *electrical system* we use "electrical cams" in the feedback circuit of the valve positioning loop, Fig. 31.

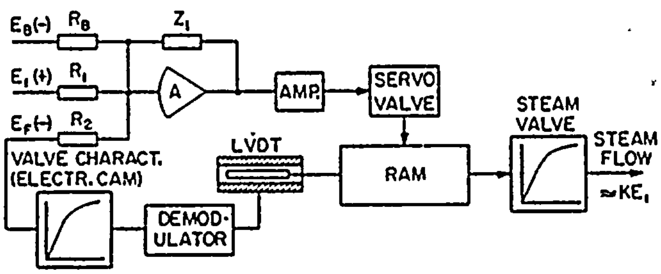


Fig. 31. Electrohydraulic valve flow control with feed back function generator

This nonlinear feedback can be implemented as shown in Fig. 32.

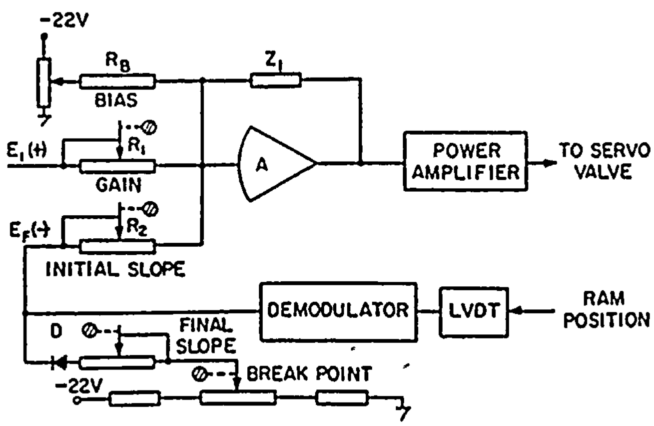


Fig. 32. Example of an electrical function generator in feedback circuit

The feedback circuit, Fig. 32, will approximate valve characteristic by two straight lines, where-the transition from one slope to the other is gently rounded by the characteristic of the diode D, Fig. 33.

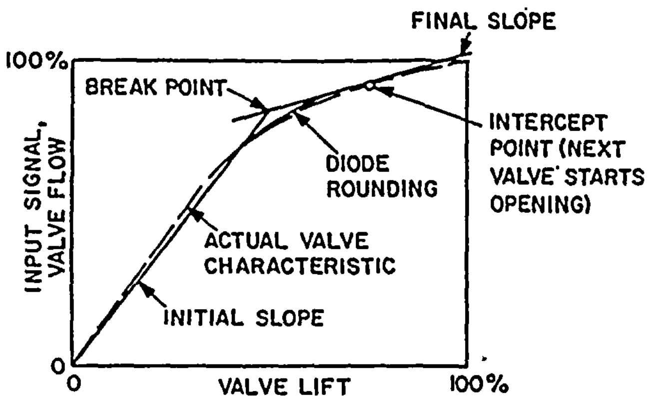


Fig. 33. Approximation of valve characteristic by electrical function generator (two slopes)

THE REHEAT TURBINE SYSTEM

The reheat turbine system we are concerned with is shown schematically in Fig. 34.

SYSTEM OPERATION

The steam is admitted through main stop valves and subsequently through a set of control valves. Each of these control valves admits steam through a different set of nozzle sections. Since these sections have been distributed around the periphery of the first stage, they divide the steam admission into partial arcs. If only a portion of the control valves are open, steam is being admitted along a partial arc of the first stage rather than through all 360 degrees of the circumference. This mode of operation is called "partial-arc admission."

During the startup process the thermal stresses can be reduced by symmetrically admitting steam to all nozzle sections of the first stage. Turbine control, up to a predetermined fraction of rated load, is achieved by fully opening the control valves and controlling the steam flow by the stop valves. This mode of operation is called "full-arc admission."

During full-arc admission operation the speed of the unit can be controlled by some speed-controlling means, either from auxiliary speed control equipment (mechanical control system) or by the main speed control (electrohydraulic system) acting on the stop valves.

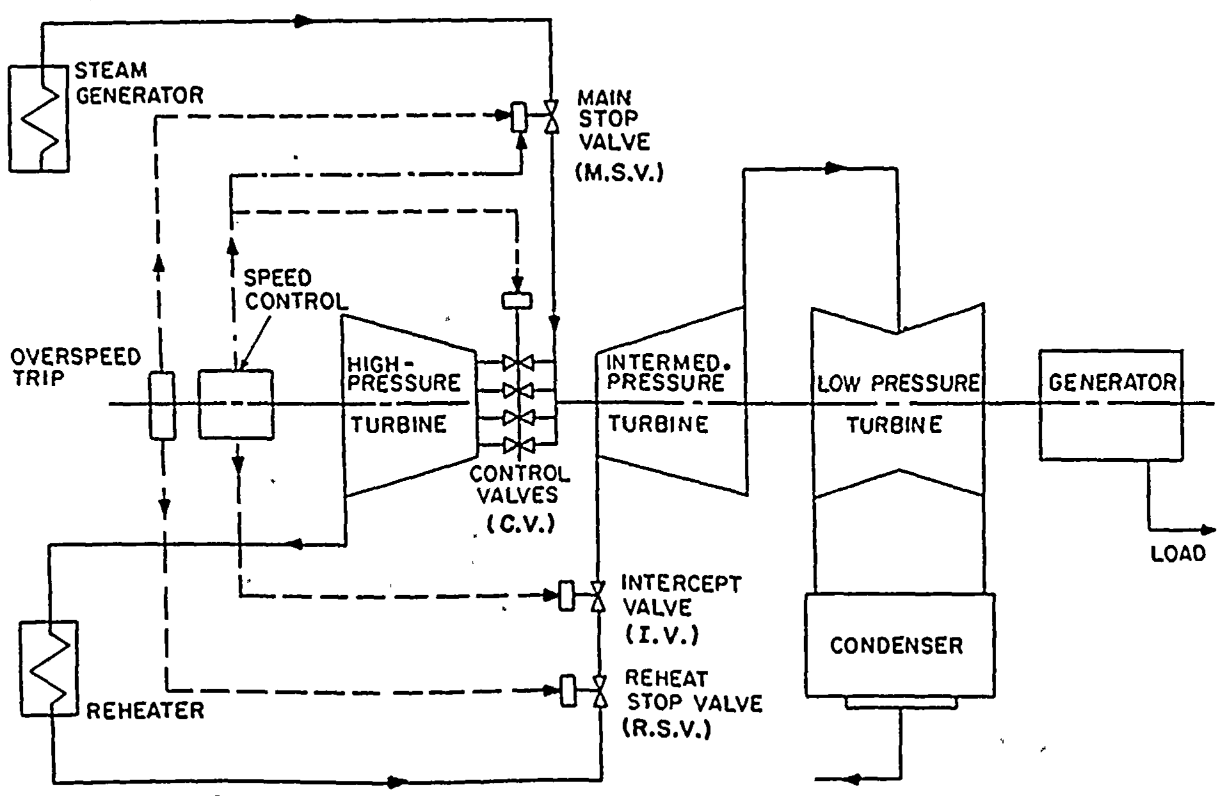


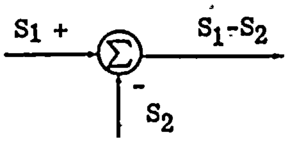
Fig. 34. Reheat turbine flow diagram

Two independent lines of defense against exces-ve speed are provided. The first consists of the rmal speed control system operating the control valves and the intercept valves. The second comprises the overspeed trip system which closes the main and reheat stop valves on overspeeds in excess of the preset trip speed and shuts the turbine down.

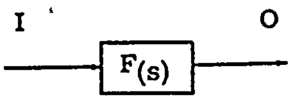
It is the task of the control system to use the previously described elements in order to control the four valve sets properly under any operating conditions and within the safety limits of the turbine-generator.

SYSTEM REPRESENTATION

A system is usually represented in block diagram form where:



is a summing point where the signal S_1 and the signal $-S_2$ are algebraically added.



is a control function (transfer function $F_{(s)}$) that transforms the input signal I into the output signal and can either be described in words or as a mathematical term (in most cases as a function of "s", the Laplace operator).

MECHANICAL CONTROL SYSTEM

This system consists of an operating control system, supplemented by auxiliary controls and protections.

Operating speed/load control system

For simplicity the operating speed/load control system shall be discussed separately ... first, without the auxiliary controls and protections. This simplified system is shown in Fig. 35.

The speed reference (position of the speed/load changer $\rho\sigma$) is compared to the speed (position of speed governor ξ) and the difference (ϵ) operates the speed relay, which is a small servomotor. The speed relay signal (η_1) is further amplified in the main servomotor (η_2) (see Fig. 18, equation 34) and produces a valve position through nonlinear cams (function generators).

The valves (also nonlinear) will produce a steam flow (μ_V) that produces the turbine flow (μ_T) with a time lag of T_3 caused by the bowl volume and drives the turbine with the fraction f (approximately 0.3) of its power in the high-pressure turbine and 1-f (approximately 0.7) in the intermediate and low-pressure turbine after the reheater time delay (T_R) is taken into account.

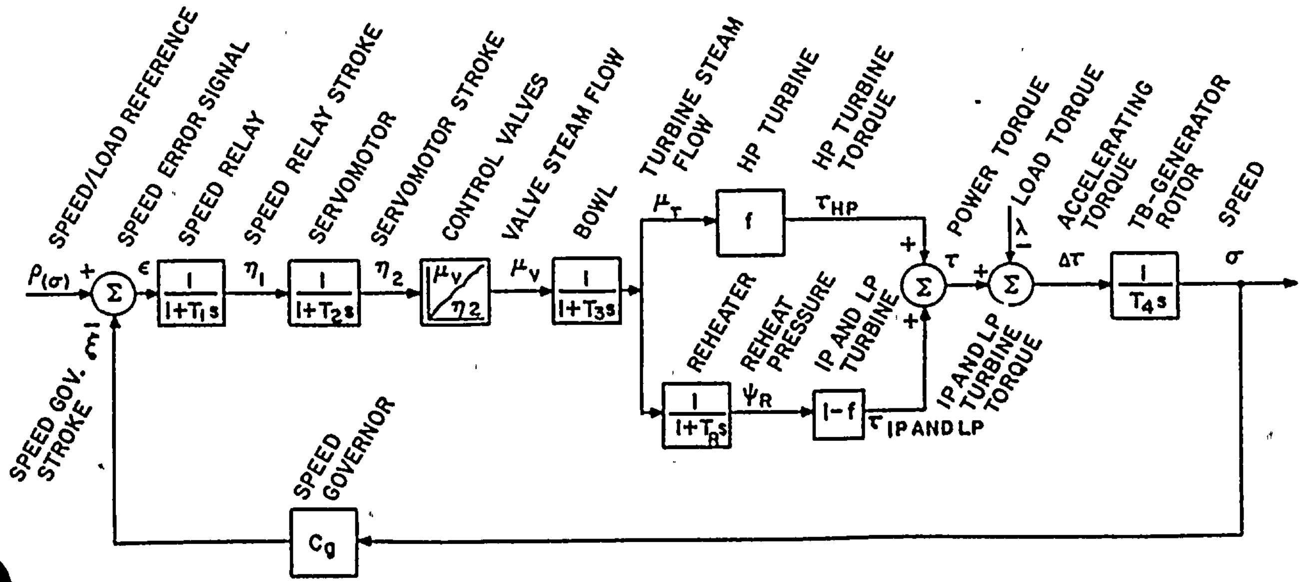


Fig. 35. Block diagram of mechanical reheat turbine speed control

The sum (τ) of the two partial turbine torques (τ_{HP} & $\tau_{IP \text{ and } LP}$) is compared to the load torque and the difference is the accelerating torque ($\Delta\tau$) that drives the rotor (an integrator with a gain of $\frac{1}{T_4}$ where T_4 is the time it would take the turbine to accelerate from standstill to rated speed with rated torque). The output of this integrator is the shaft speed which drives the speed governor, normally with a gain (Cg) of 20 (5 percent regulation).

Auxiliary control functions and protection

Most auxiliary functions and protections work through low value gates, Fig. 36. A "low value gate" is a device that has two or more inputs and its output is equal to the lowest one of the inputs.

Auxiliary speed control functions:

- The intercept valve control that holds the intercept valves open during normal operation (by a + bias) and will close them quickly on overspeed in order to prevent the reheater energy from increasing the speed excessively.

- The long-range speed control (LRSC, optional equipment) that can operate the stop valve bypass valve for controlled full-arc admission starting (C.V. open, stop valve bypass controlling through CV-SV low value gate).

- The load limit and the stop valve bypass handwheel for manual control in partial-arc or full-arc admission respectively.

Auxiliary pressure control function:

- The initial pressure limiter will close the control valves if the boiler pressure (ψ_B) decreases below 90 percent and will control the control valves with a 10 percent pressure regulation approximately. It can also be made to respond to the rate of pressure decrease.

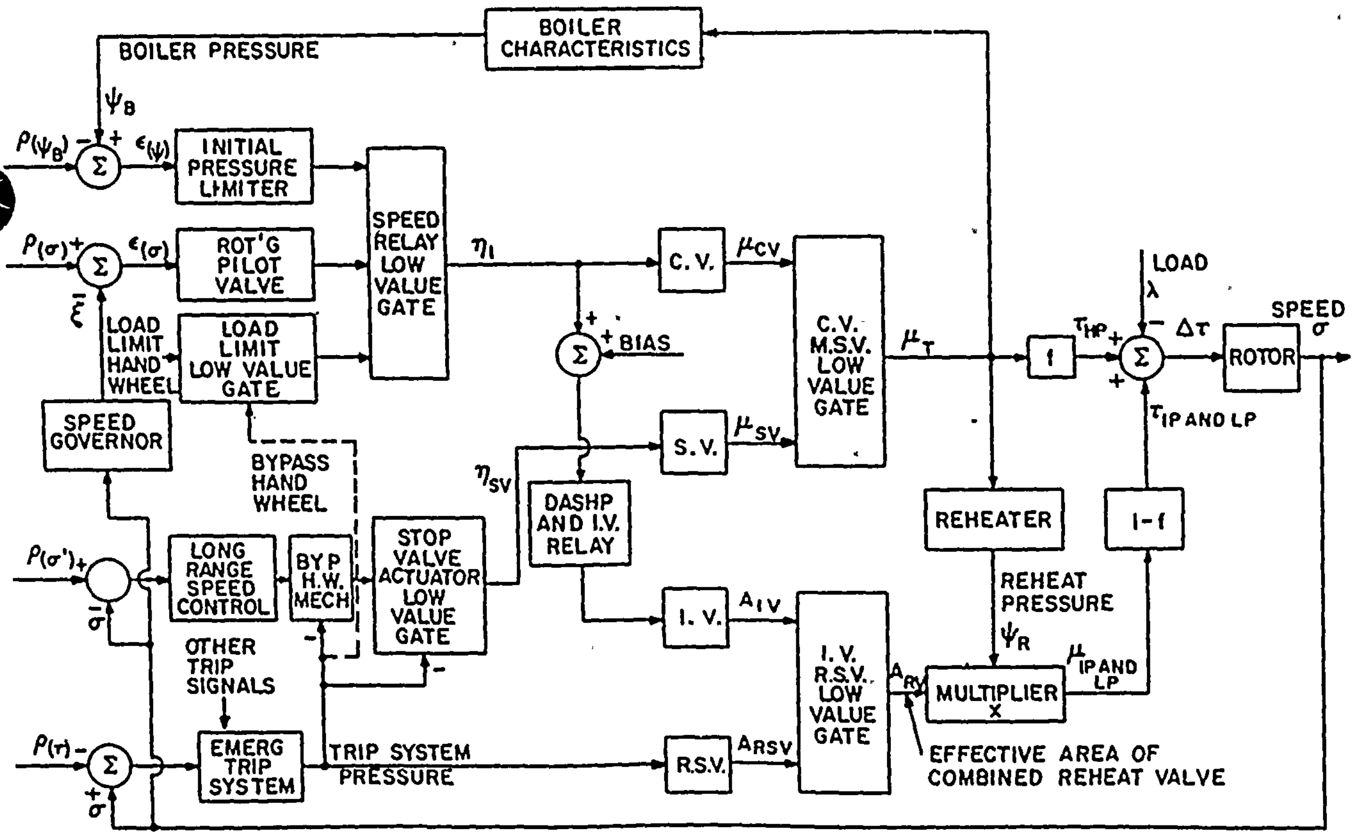


Fig. 36. Block diagram of mechanical reheat turbine control with auxiliary functions and protections

Overspeed protections:

- The speed (σ) is compared to an overspeed trip reference speed (ρ_T). If it exceeds ρ_T the emergency trip system trips the stop valves and the reheat stop valves close directly. Tripping of the bypass handwheel mechanism will prevent re-opening of the stop valves until the operator has reset the bypass handwheel mechanism to zero.

- On units originally shipped without stop valve bypass the load limit is tripped by the emergency trip system (dotted line).

Other protections:

- Other trip signals that can shut the unit down through the emergency trip system include:

  - low vacuum
  - thrust-bearing failure
  - generator protections
  - high exhaust temperature
  - excessive vibration
  - excessive differential expansion
  - others.

Trip Anticipator (T.A.)

- Used on units with high overspeed on loss of load. The T.A. closes the M.S.V. and the R.S.V. at a low enough speed to limit the overspeed to 20 percent in case of a failure of the C.V. or the I.V. to close. But if the unit did not trip on overspeed, it will re-open the M.S.V. and the R.S.V. again in time so that the I.V. can blow down the reheater and go back to no load rated speed on speed control.

Power supply

The power supply for the hydraulic amplifiers of the mechanical control system is a 200 to 250 psi oil system supplied with oil from a shaft pump (auxiliary motor-driven pump for startup).

The characteristic of the shaft pump is such that it can furnish large transient flow requirements with an acceptably small drop in pressure so that (in most cases) no accumulators are needed.

The emergency trip system is also supplied with pressure oil from the same system.

Power for electrical trip functions (remote trip, thrust-bearing wear trip and generator protections) is furnished by a 125 or 250 VDC station battery.

ELECTROHYDRAULIC CONTROL SYSTEM MARK I

The electrohydraulic control system has been organized into three major subsystems. One purpose of these subsystems is to minimize interactions. As shown in Fig. 37, the speed control unit compares actual turbine speed with the speed reference, or actual acceleration with the acceleration reference, and provides one speed error signal for the load control unit. The load control unit combines the speed error signal with the load reference signal and biases to determine desired steam flow signals for the main stop valves, control valves, and intercept valves. Finally, the valve flow control units accurately position the appropriate valves to obtain the desired steam flows through the turbine.

Speed control unit

The speed control unit, Fig. 38, produces the speed error signal that is determined by comparing the desired speed with the actual speed of the turbine at steady-state conditions, or the desired acceleration with the actual acceleration during start-up.

When the desired speed signal is increased in a step, the acceleration control will take over and accelerate the unit at the set rate up to the value of the new speed reference, where the speed control will take over again automatically.

Upon decrease of the speed reference, the unit will coast down with the valves closed. They will re-open only when the new set speed has been reached; there is no limit in deceleration.

During normal operation at rated speed, the speed error signal is zero, regardless of load.

Because of the extreme importance in safeguarding against overspeed, the speed control unit has two redundant channels. If both speed signals fail, the unit will shut down.

Load control unit

The prime purpose of the load control unit is to develop signals to which steam flow for the main stop valves, control valves, and intercept valves may be proportioned. These outputs are based on a proper combination of the speed error and load reference signal modified by power/load unbalance, full-arc and partial-arc transfer bias signals, the load limit and the initial pressure limiter.

The regulation is introduced to modify only the speed error signal; the input representing desired

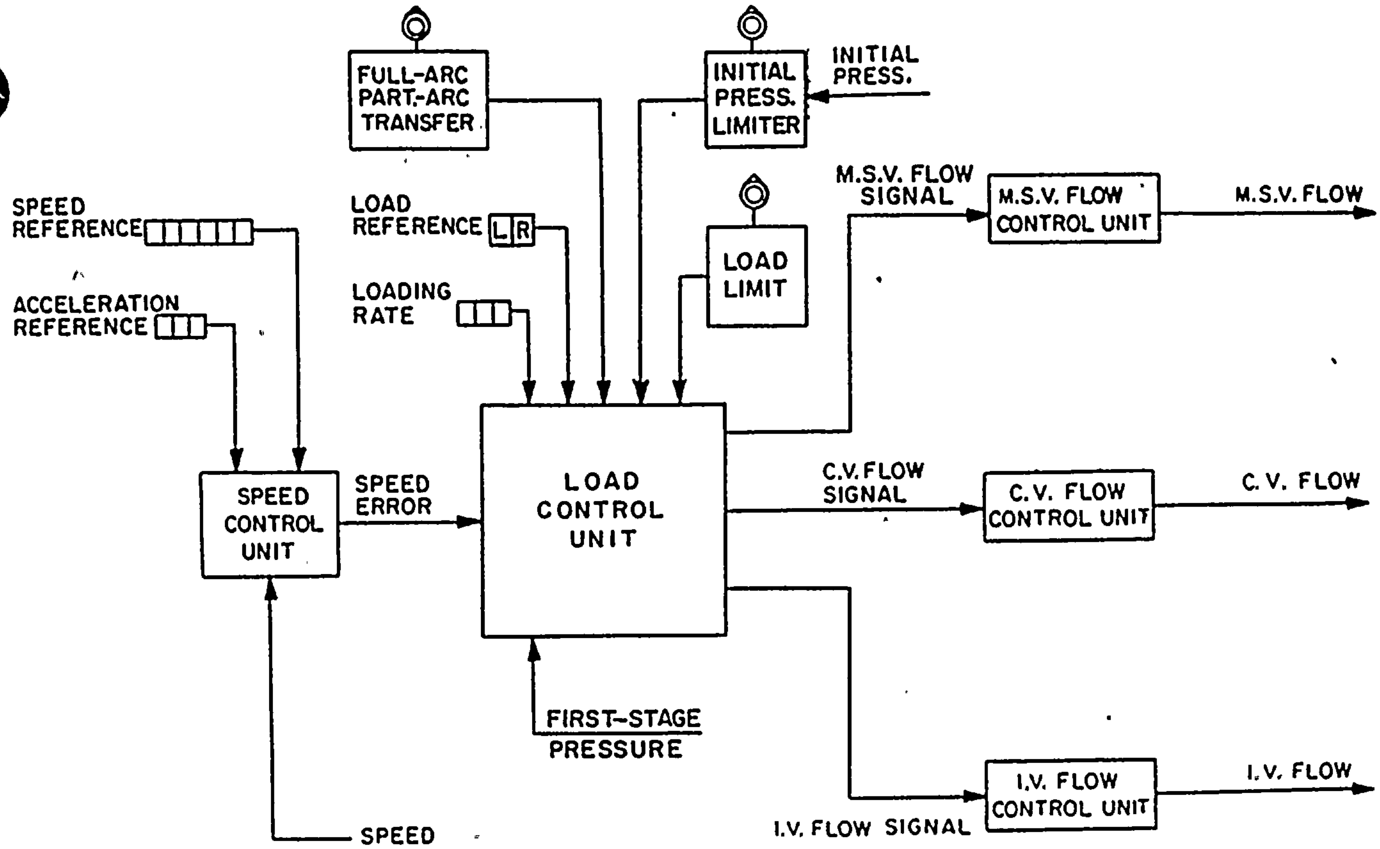


Fig. 37. Block diagram of electrical reheat turbine control system

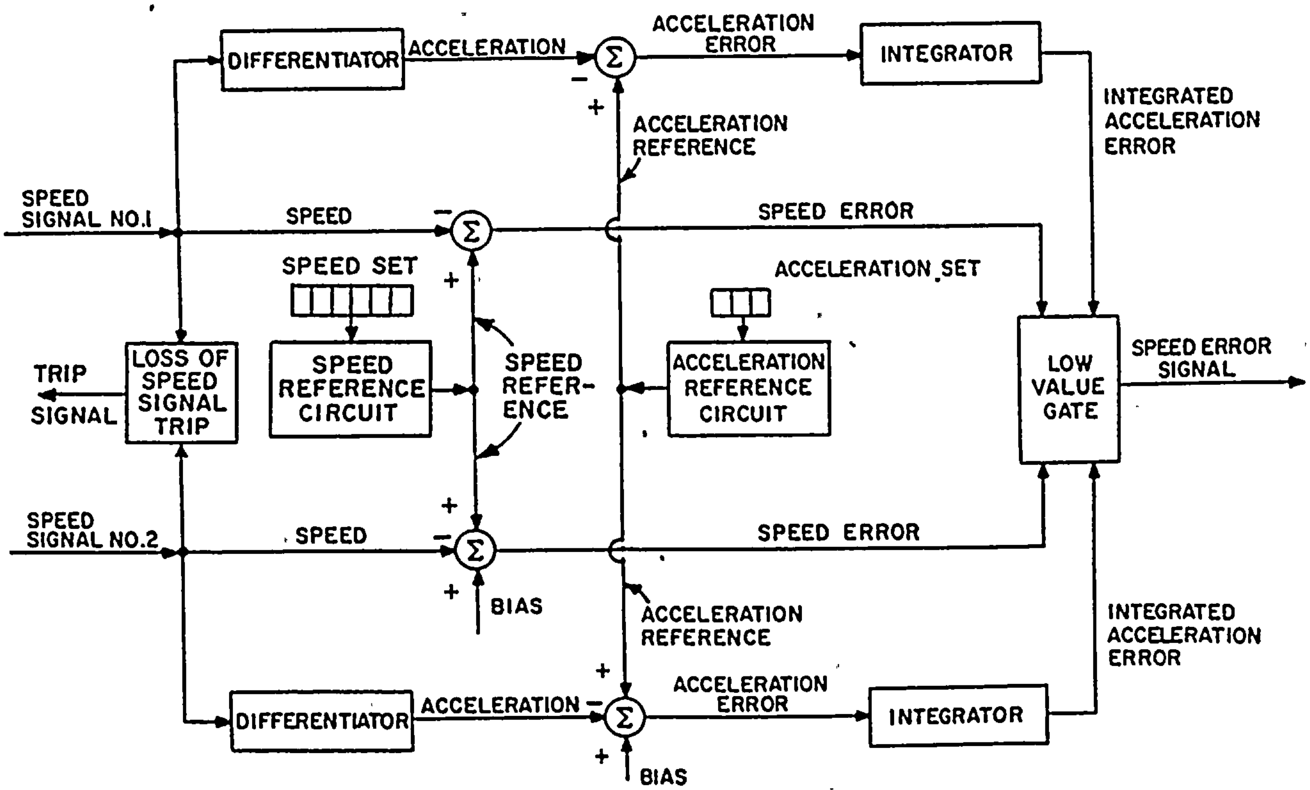


Fig. 38. Electrical speed control unit

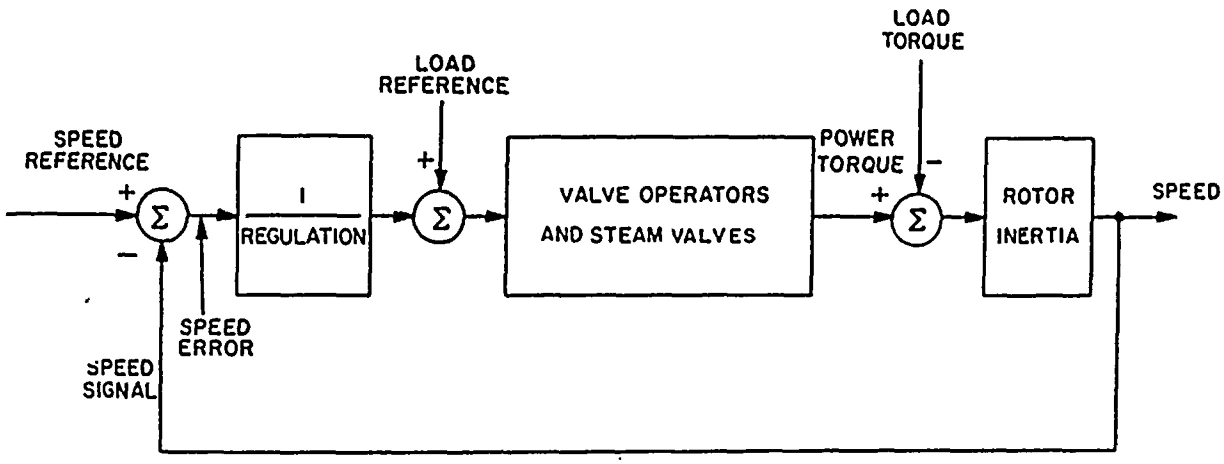


Fig. 39. Electrohydraulic control system: speed control loop

load is added after this point. Figure 39 is a basic block diagram of the speed/load control loop of this system.

It can be seen that the load reference signal needed to produce a certain load at constant speed is independent of the speed regulation. This means that for a given load reference change, the load change will be of the same magnitude regardless of the speed regulation that can be set from 2.5 to 7 percent (required by IEEE 122 standard).

Therefore, it is now possible to calibrate the load reference dial in percent of full load at rated speed and maintain this calibration regardless of what the regulation is going to be.

Figure 40 is the basic arrangement of the entire load control unit.

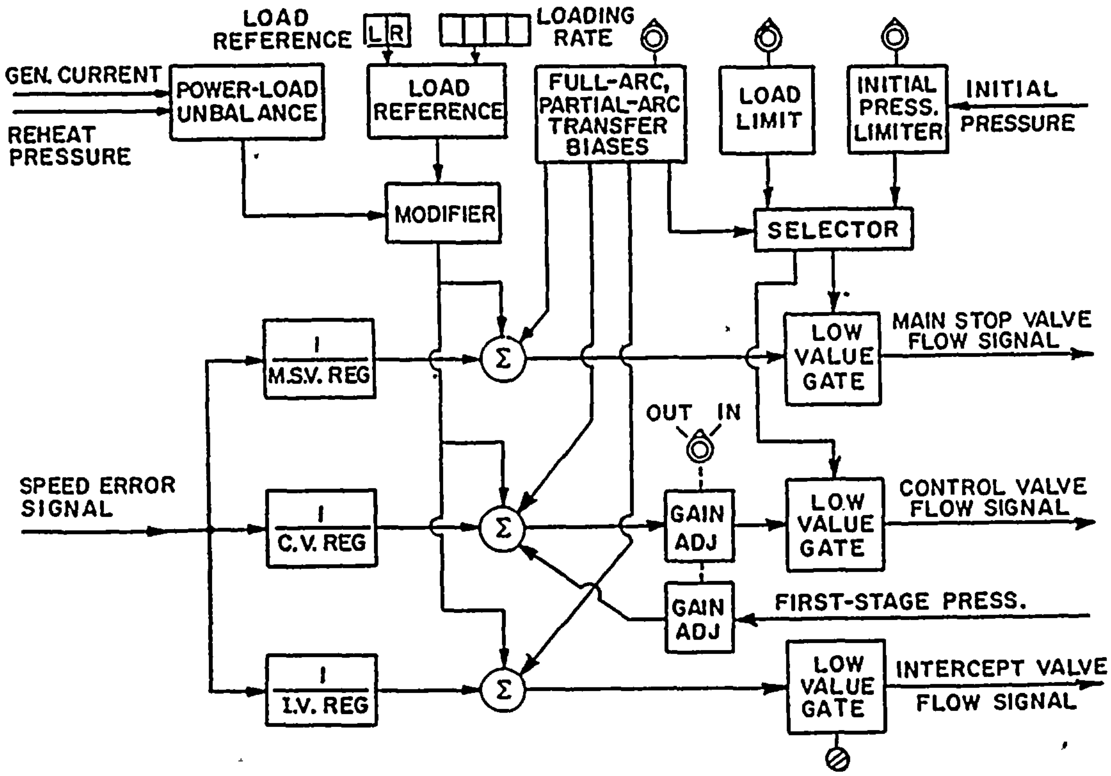


Fig. 40. Electrical load control unit

The following are the operating features of the control unit.

When the speed increases over rated speed, the negative speed error will decrease the flow signal of the controlling valves at a rate defined by the particular valve regulation. For example, in partial-arc operation, if the control valve regulation were five percent, a five percent speed error would cancel a 100 percent load reference signal. This would result in reducing the control valve position from the fully open to no-load position.

Load reference

The calibrated load reference can be set locally or remotely by jogging a push button switch, or automatically by a dispatching or computer system. The rate-of-load increase is adjustable in discrete steps, thereby providing the feature of programmed automatic loading. Typical rates are 0.5, 1, 3 and 10 percent per minute. A decrease in load reference settings is followed substantially without delay.

Since the load reference is in effect a speed vernier adjustment, it is used for synchronizing the turbine.

Full-arc / partial-arc admission

Biases are used to hold any noncontrolling valves the wide-open position. When the unit is started control valve bias calls for wide open control ves and the main stop valves are controlling (M.S.V. bias = 0).

When transferring from full-arc to partial-arc operation, it is first necessary to remove the control valve opening bias and then to apply an opening bias to the main stop valve. By properly programming the shifting of the transfer biases, both load variations and thermal stresses will be kept within acceptable limits. Although transfer is performed automatically at preselected valve openings, it is possible for the operator to modify or override the automatic transfer action. The bias to the intercept valve is proportioned so that on slow acceleration the intercept valve will, in any mode of operation, start closing just after the controlling valve set has come to the closed position.

Power / load unbalance

When the generator loses the electrical load, it ecessary to quickly close the control valves and rcept valves to stop the steam flow to the turne, thereby limiting the speed increase. The power load unbalance relay initiates this action simultaneously with the start of the speed increase.

The power-load unbalance relay compares reheat pressure (a measure of steady-state power) with generator current (representing generator load). It also determines if the current decrease is occurring rapidly (in less than 0.05 sec.). If the unbalance is over 40 percent and the current has decreased rapidly the following actions are initiated:

1. The fast closing of the control valves is initiated directly.

2. The load reference signal is switched to zero by the "MODIFIER" such that the slightest speed increase will start closing the intercept valves.

3. The load reference motor is run back toward zero at full speed.

4. The automatic transfer to F.A. admission is temporarily inhibited until the reheater pressure has come down to approximately 10 percent of rated such that the transfer operation will not interfere with the blowing down of the reheater by the intercept valves.

Generator load current (instead of power = voltage x current) is used to avoid unnecessary closing of the valves by a clearable short circuit on the transmission system. Inhibiting the action in a case where the current is decreasing more slowly than the set rate avoids actuating of the power-load unbalance relay during the sometimes substantial power swings that follow clearing of a short circuit in the transmission system.

The power-load unbalance logic is shown in Fig. 40a.

First-stage pressure feedback

The lift/flow characteristic of any steam valve is highly nonlinear. A first order linearization is made in the valve positioning loops, as will be seen later. In order to refine the linearization in normal operation on the control valves, the first-stage pressure feedback can be used. When this is done the gain of the control valve flow signal must be changed in order to retain the same overall gain of the control valve loop. This is shown in Fig. 40b.

The first-stage pressure feedback can be put in operation only when the unit is in P.A. admission operation and when the initial pressure is at least 0.95 (95 percent). During the process of putting it into operation the pressure feedback signal gain will be increased from zero to 0.67 gradually, while the gain of the control valve signal is increased from 1

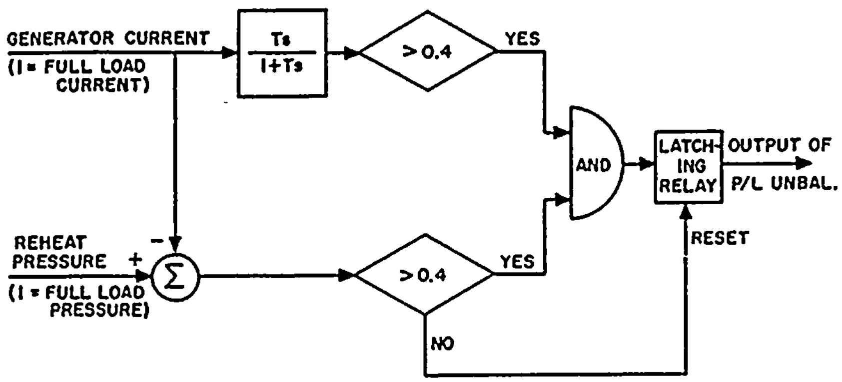


Fig. 40a. Power/load unbalance logic (T = 0.02 to 0.05 sec)

to 3. Some load changes will occur during this transfer, but if all circuits are properly adjusted they should be minor.

On loss of the pressure feedback signal (signal below 0.2) the loop will switch to the feedback "out" conditions. A loss of load will also remove this feedback.

Load limit

The load limit can be used to manually override the signal to the controlling valve set to a lower valve position than what the speed/load control dictates. The "SELECTOR" will automatically direct the load limit signal to the main stop valve flow signal in F.A. operation and to the control valve flow signal in P.A. operation. When the load limit is in control, the speed control is not modulating the controlling valve position; therefore, the unit is not participating in the frequency control of the power system. Because of this fact, the load limit should not be used to control unless a malfunction in the boiler or turbine control makes it necessary to temporarily peg the valve position until the malfunction can be corrected.

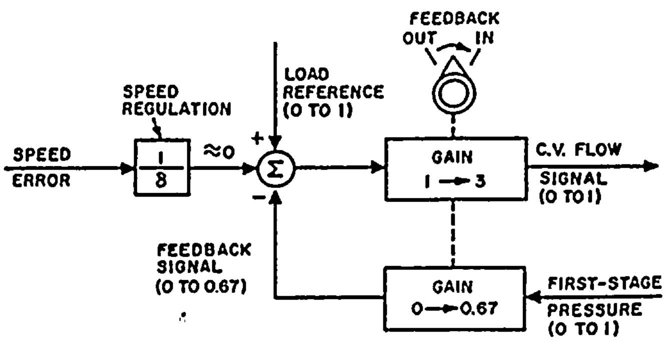


Fig. 40b. First-stage pressure feedback

Initial pressure limiter (IPL)

The initial pressure limiter will take control away from the speed/load control (or the load limit if it was controlling) when the initial steam pressure falls to 0.9 (90 percent, normal setting) in normal operation at full load. If the pressure keeps on falling it will reduce the valve position down to no load by the time the initial pressure has fallen to 0.8 (80 percent).

For startup when the boiler pressure is low the pressure reference of the IPL can be set down to any desired value or the IPL can be switched off altogether. For extended light load operation the setting can be raised above 90 percent in order to reduce the delay before the IPL starts closing the valves.

The "SELECTOR" will direct the output of the IPL to the proper valve signal depending on the operating mode (F.A. or P.A.) of the turbine.

Intercept valve limit

The intercept valve limit is intended to be used only for lowering the I.V. position in order to set reheat safety valves. Its adjustment is done on a screwdriver pot in the cabinet. During normal operation the pot must be set out of the way (not limiting) so that the valves are stem sealing.

Valve flow control units

The purpose of the valve flow control units is to produce the steam flows that are commanded by the load control unit. Because of the appreciably nonlinear steam flow characteristic of the steam valves, compensation circuits must be introduced to obtain quasi-linear steam flow response with respect to steam flow signal.

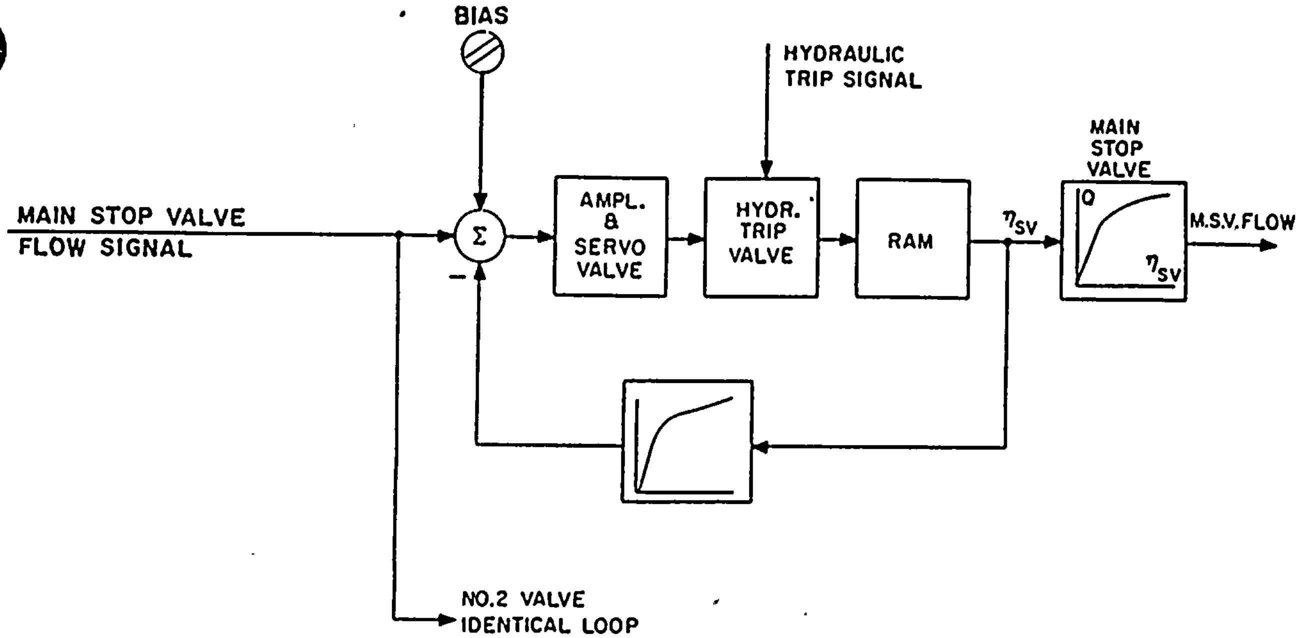


Fig. 41. Main stop valve flow control unit

The *main stop valve flow control* unit is shown in Fig. 41. During full-arc admission operation it receives the flow signal that can be limited by the load limit or the initial pressure limit. During partial-arc admission it receives a valves-full-open signal that is independent of speed and the limit functions.

The flow signal operates a servo amplifier whose output positions a servo valve, which in turn operates the ram across a trip valve (low value gate). The feedback is modified by a function generator having a characteristic similar to the valve (similar to Fig. 31).

The hydraulic trip valve can close the main stop valve on loss of emergency trip system pressure, regardless of the flow signal.

All main stop valve loops are identical.

The *intercept valve flow control* unit (Fig. 42) is similar to the main stop valve flow control unit.

In order to close the intercept valves rapidly on loss of load, a trigger amplifier is used that will actuate a dump valve on a large closing error signal.

All intercept valve loops are identical.

The *control valve flow control* unit (Fig. 43) consists of as many similar positioning loops as there are control valves. The input to each servo amplifier for the control valves has a bias for sequencing the valve operation. A nonlinear feedback and a trigger and dump valve are also used. The trigger is operated by the power-load unbalance relay.

In order to further linearize the load response of the unit, a stage pressure feedback can be used on the control valve flow signal.

This feature should be used as operating control only in cases where it is compatible with the boiler control system.

Operating control system

The operating electrohydraulic control system with the basic transfer functions is shown in Fig. 44 (in partial-arc admission, all auxiliary functions have been omitted).

The following nomenclature is used:

$\rho_{(\sigma)}$ = speed reference (0 to 1 + [per unit] discrete values and "overspeed")

σ = speed ($\sigma = \frac{n}{n_r}$: 0 to 1 + [per unit])

n = speed [rpm], n_r = rated speed [rpm]

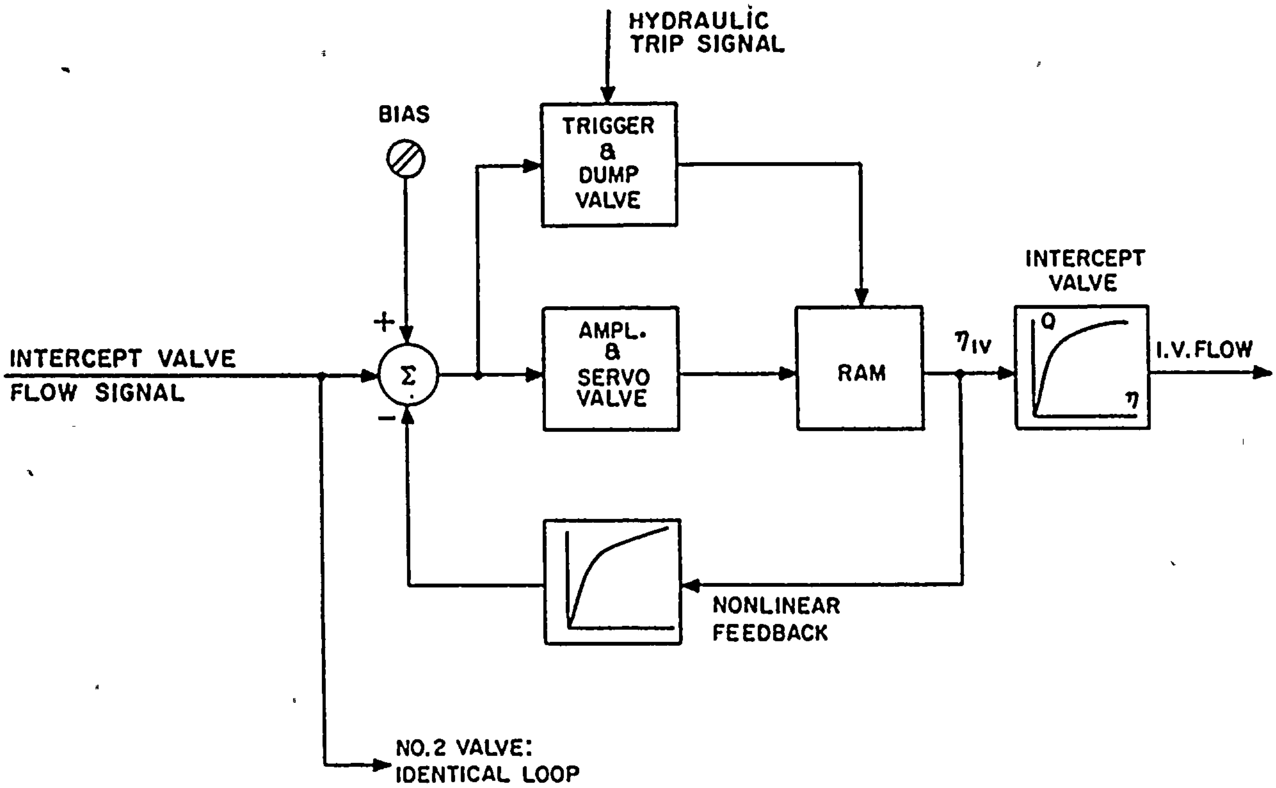


Fig. 42. Intercept valve flow control unit

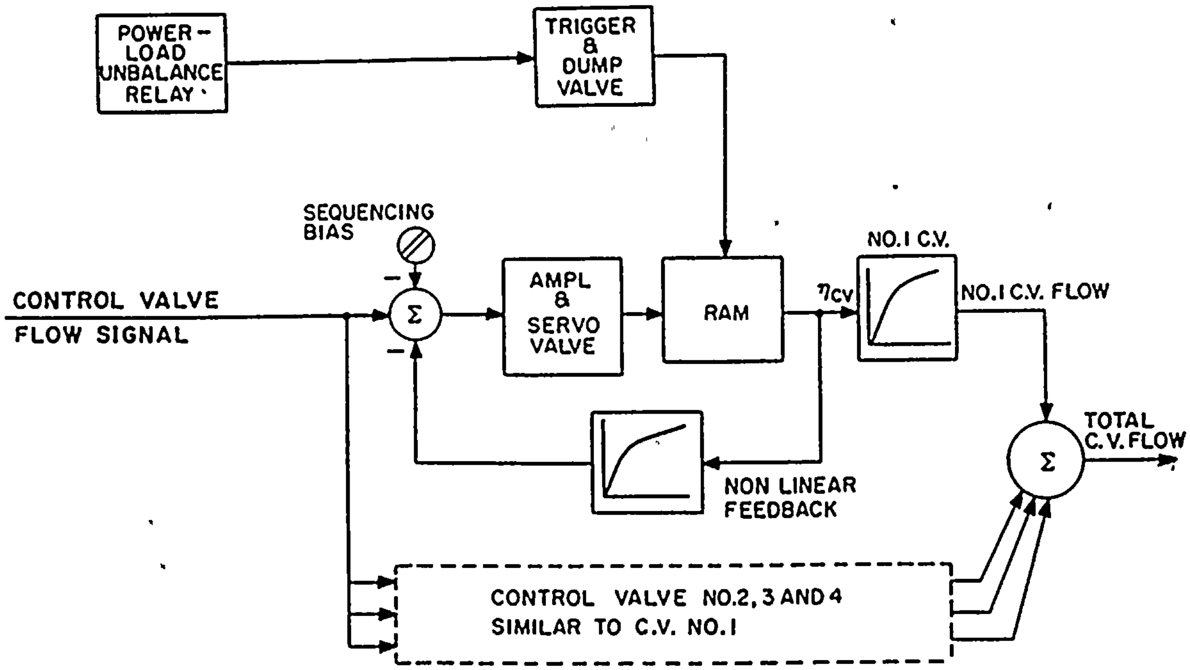


Fig. 43. Control valve flow control unit

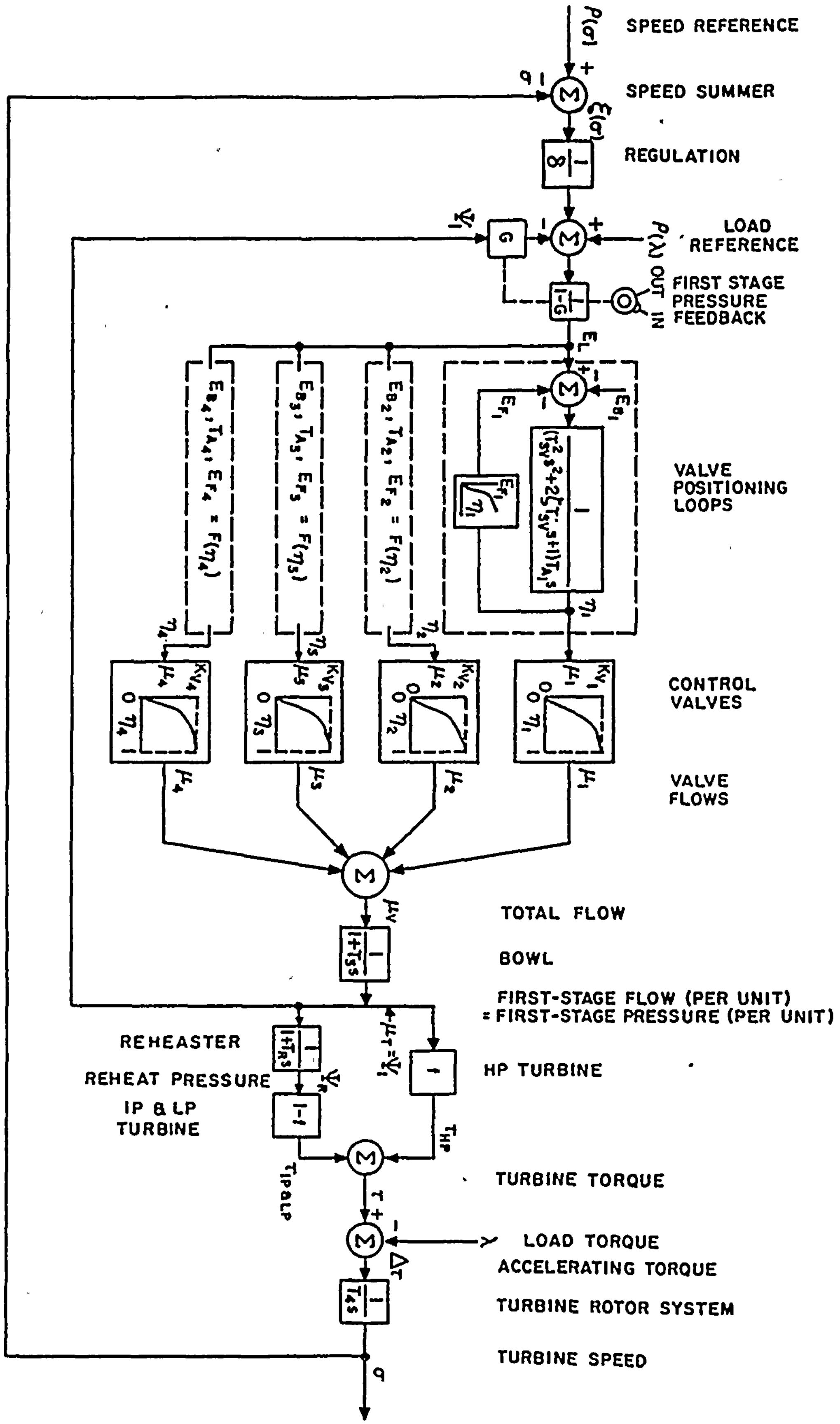


Fig. 44. Operating EHC system basic transfer functions

ϵ_σ = speed error

δ = speed regulation (δ = 0.025 to 0.07 [per unit], 2.5 to 7 percent; normally δ = 5%)

ρ_λ = load reference (-1→0→+1.4 [per unit], $\rho_{(\lambda)}$ = 1 for full load at rated speed)

G = gain of first-stage pressure feedback (G = 0 no feedback, G = 0.67 full feedback)

E_L = total flow signal [per unit]

E_{B_i} = bias signal of valve i; typical values are:

#1 valve: $E_{B1} \approx 0$

#2 valve: $E_{B2} \approx -0.4$ [per unit]

#3 valve: $E_{B3} \approx -0.65$ [per unit]

#4 valve: $E_{B4} \approx -0.85$ [per unit]

T_{sv} = servo valve time constant (T_{sv} = 0.016 sec)

T_{A_i} = integration time constant of actuator i (for small changes)

T_{A_i} = 0.1 to 0.2 sec (for all four actuators approximately equal). For large changes in the opening direction the valve can go through full stroke in approximately 10 seconds. (Input current to the servovalve is limited to achieve this).

η_i = valve lift per unit of each individual control valve (full lift = 1)

K_{v_i} = per unit maximum flow of each individual control valve; typical values are:

K_{v1} = 0.4 per unit of max. turbine flow

K_{v2} = 0.25 per unit of max. turbine flow

K_{v3} = 0.2 per unit of max. turbine flow

K_{v4} = 0.15 per unit of max. turbine flow

ΣK_{v_i} = 1 per unit

μ_i = valve flow [per unit of max. turbine flow] of individual control valve

μ_v = total valve flow [per unit]

T_3 = bowl time constant (T_3 = 0.1 to 0.5 sec)

μ_T = turbine steam flow [per unit]

Ψ_1 = first-stage pressure [per unit]: for steady-state conditions

$$\mu_T = \Psi_1$$

f = fraction of total power developed by the high pressure turbine

f = 0.25 to 0.32 [per unit]

T_R = reheater time constant [sec]

$$T_R = \frac{W_R}{Q_R}$$

W_R = total steam weight [lb] at max. load in reheater system (including pipes to and from turbine)

Q_R = Maximum reheater steam flow [lb/sec]

τ = driving torque [per unit]

λ = load torque [per unit]

$\Delta\tau$ = accelerating torque [per unit]

T_4 = turbine time constant

$$T_4 = 5.98 \times \frac{WR^2}{P_{max}} \left(\frac{n_r}{3600}\right)^2 \text{ [sec]}$$

WR^2 = Weight moment of inertia [lb ft^2]

P_{max} = Max. power [KW]

n_r = rated speed [rpm]

The steady-state characteristic of the speed/load control system set at five percent regulation and a speed reference of 1 (rated speed) is shown in Fig. 45.

Power supplies (Mark I)

Electrical power to the electrical control and protection system is supplied by redundant power supplies at +30 VDC and -22 VDC for the control functions. A +24 VDC system is used for relay circuits. These power supplies are fed by the 115V 60-cycle a-c line or by a permanent magnet generator on the turbine shaft. Either one of these power sources can sustain operation of the electrical control system.

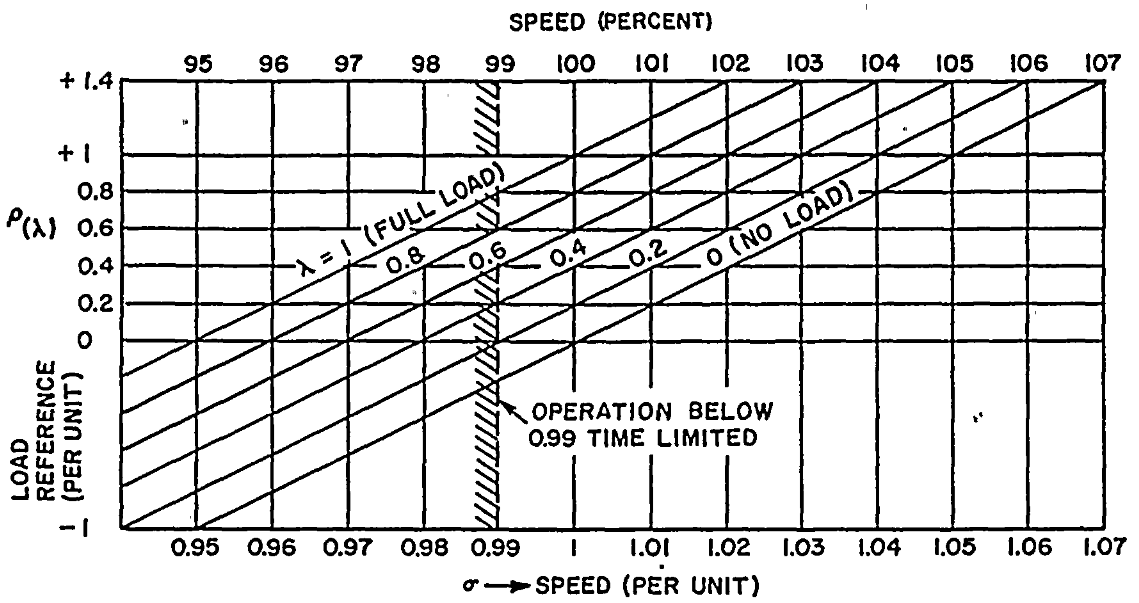


Fig. 45. Speed/load control characteristic of EHC system

Hydraulic power is supplied by a redundant high-pressure fluid pumping system at 1600 psi with fire-resistant fluid.

Two full-size variable displacement pumps with a-c motor drive are provided. One pump is normally in operation pumping only the actually used oil flow. The other pump is on standby, with automatic starting provisions if the operating pump should not supply sufficient pressure.

For large transient flow requirements accumulators are used.

Filtering and fluid treatment equipment as well as heating and cooling provisions for the fire-resistant fluid are incorporated in the hydraulic power unit.

Protection system (Mark I)

Trip System Mechanism

The trip system mechanism in the front standard, Fig. 46, consists of:

- the conventional overspeed trip device (eccentric ring)
- the solenoid-operated oil trip valve
- the manual trip with mechanical trip solenoid
- the mechanical trip valve
- the solenoid-operated lockout valve
- the dual solenoid-operated master trip solenoid valve
- the reset solenoid valve actuating the bearing oil-operated reset mechanism

The trip system mechanism controls the emergency trip fluid system pressure which is needed to operate the main and reheat stop valves directly, and supplies power fluid for operating the control and intercept valves.

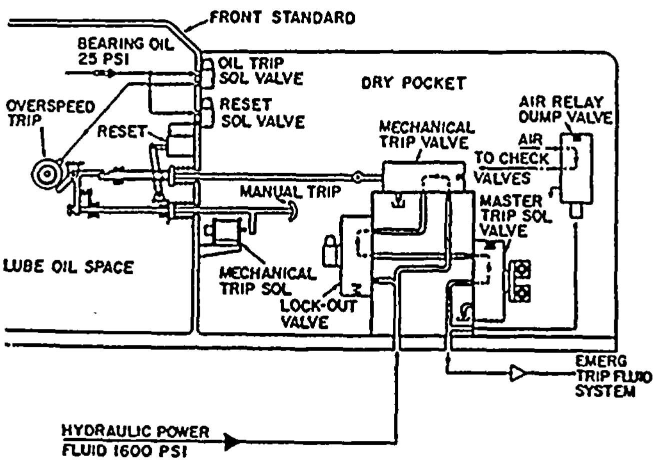


Fig. 46. Trip system mechanism

The overspeed trip device can be tested during normal operation at rated speed by locking out the trip action of the mechanical trip valve temporarily by means of the lockout valve. During this test the electrical back-up overspeed trip will assume the function of the second line of defense against overspeed. An electrical trip test logic system is provided to minimize the possibility of misoperation during this test.

Electrical Trip System

All external trip signals are obtained by closing contacts at the station battery voltage level (125 VDC or 250 VDC) and operating sealed relays in the electrical trip system (24 VDC).

Trip signals from within the electrical control system are obtained by closing contacts in the 24 VDC trip system directly or through sealed relays.

Any of these trip signals will energize the master trip relay (24 VDC), which will initiate the following redundant trip actions:

- *de-energizing* of the two pilot solenoids of the master trip solenoid valve (24 VDC)

- *energizing* of the mechanical trip solenoid (125 VDC or 250 VDC from station battery).

Either one of these actions will trip the system.

Since loss of the 24 VDC power would render the electrical trip system ineffective, the master trip solenoid valve is held in the reset position by having at least one pilot solenoid energized with the same 24 VDC power. Loss of this power will, therefore, trip the unit (see "Electrical Power Supplies").

The redundant pilot solenoid arrangement reduces chances of false trip-outs and makes testing of the pilot-solenoid valves possible.

Important features of this protection system are:

- solenoid coils can be replaced while maintaining safe operation

- solenoid-operated fluid valves can be tested (exercised) regularly

- trip actions are redundant in their final action.

A FIRST HIT monitoring system is incorporated in order to help analyze trip incidents and diagnose malfunctions.

Trip anticipator (T.A.)

On units with high overspeed on loss of load the overspeed trip must be set high, in order not to trip on loss of rated load. On some units this would result in an overspeed above 20 percent in case the first line of defense against overspeed should fail to work properly. If this is the case, an electrical speed signal is used to trigger a trip anticipator signal, that will operate the fast acting valves on the main and reheat stop valves at a speed sufficiently low to limit the emergency overspeed to 20 percent if an anticipated trip should take place. If, however, the first line of defense against overspeed has worked properly and the anticipated trip did not occur, the T.A. signal will reset in time to let the MSV and RSV re-open again and permit the intercept valves to blow down the reheater, and later the control valves to re-open and control rated speed-no load in order to be ready for synchronizing at the earliest possible opportunity. The trip anticipator signal is obtained from a third speed pick-up that produces the back-up overspeed trip signal on units that are not using a trip anticipator.

CONCLUSION

The electrohydraulic approach to turbine control has two important advantages: (1) it allows us to incorporate a number of features that cannot reasonably be obtained on mechanical systems; (2) it improves the performance of features that are present in some form in the mechanical system. The development of an electrohydraulic control system is a logical step in the continuing advance of turbine-generator technology.

APPENDIX I

THE IMPEDANCE CONCEPT

With the impedance concept it is possible to express the transfer function of a frequency-sensitive element by the use of a differential operator notation.

The transfer function of an element describes the ratio of the output (O) of this element to its input (I), whereby the magnitude and the phase relation of the output are determined by the time variations of the input.

In a study of differential equations Heavyside formulated a method by which an equation such as

$$Y = K \frac{dX}{dt} \qquad \text{(A-1)}$$

can be represented as

$$Y = K\,p\,X \qquad \text{(A-2)}$$

or

$$\frac{Y}{X} = K\,p \qquad \text{(A-3)}$$

where p is an operator replacing $\frac{d(\;)}{dt}$.

Laplace later introduced a new operator (s) defined by the equation

$$F_{(s)} = \int_0^\infty f_{(t)}\, e^{-st}\, dt \qquad \text{(A-4)}$$

where F and f represent functions of the variables in parentheses (s = Laplace operator, t = time) and e is the base of the natural logarithm.

It can be shown that equation (A-2) is valid for zero initial conditions when written as

$$Y = K\,s\,X_{(s)} \qquad \text{(A-5)}$$

or

$$\frac{Y}{X_{(s)}} = K\,s \qquad \text{(A-6)}$$

It can be said that s as a factor (in the numerator) signifies a differentiation.

Equation (A-1) can be rewritten as

$$\int_0^t Y_{(t)}\, dt = K\, X_{(t)} \qquad \text{(A-7)}$$

or from (A-5)

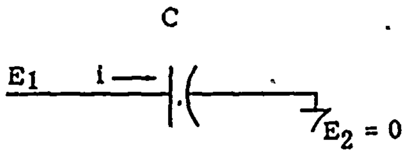
$$\frac{Y}{s} = K\,X \qquad \text{(A-8)}$$

The operator s in the denominator signifies an integration.

As seen from equations (A-5, A-6 and A-8) the factor s can be manipulated according to the simple laws of algebra.

From this starting point it is now possible to show that frequency-sensitive elements can be represented by their transfer functions with the Laplace operator "s".

This is exemplified by the capacitor



The voltage on the capacitor is the time integral of the current divided by the capacitance

$$E_{1(t)} = \frac{1}{C} \int_0^t i\, dt \qquad \text{(A-9)}$$

or with the Laplace operator

$$E_{1(s)} = \frac{1}{C}\,\frac{i_{(s)}}{s} \qquad \text{(A-10)}$$

The transfer impedance is now

$$Z = \frac{E_{1(s)}}{i_{(s)}} = \frac{1}{C\,s} \qquad \text{(A-11)}$$

which is the same as stated in equation (26).

APPENDIX II

SPECIAL FEATURES OF THE EHC MARK II SYSTEM

The EHC Mark II System is a second generation analog control system built for greater reliability and serviceability.

A block diagram of the operating control system for a reheat turbine - EHC Mark II is shown in Fig. 47.

The basic concept of the Mark I system has been retained in Mark II; however, extensive technology advances have been incorporated which, in some cases, resulted in an adaptation of the system. In particular, two new groups of equipment were added:

- the standby control
- the plant communication system

An electrical equipment numbering system was created for computer use that identifies every piece of electrical control equipment with a coded number giving location, general function, type of circuit, an assembly identification and a component number.

Operational amplifiers

All operational amplifiers used in the MK II System are integrated circuit operational amplifiers that made the following improvements possible:

(1) a rated signal level of 10 volts DC is used

(2) the 1kHz oscillator for stabilization was eliminated and the central 3kHz oscillator was replaced by individual 3kHz oscillators for each position indicating circuit.

(3) the I. C. op. amps occupy only the space of a transistor (compared to a whole circuit board for the Mark I op. amp) and use only eight connections (compared to about 150 in the discrete component op. amp of Mark I)

With the use of these integrated circuit operational amplifiers a functional packaging technique became possible that further reduced the number of connections and made servicing simpler.

Relays and logic systems

Bifilar relay coils that reduce the duty on the coil operating contact used in sealed multi-contact relays, together with functional repackaging on printed circuit-boards, made it possible to handle substantially more complex logic systems with only modest increase in wiring.

A two-out-of-three logic principle that increases the reliability of a function compared to a single

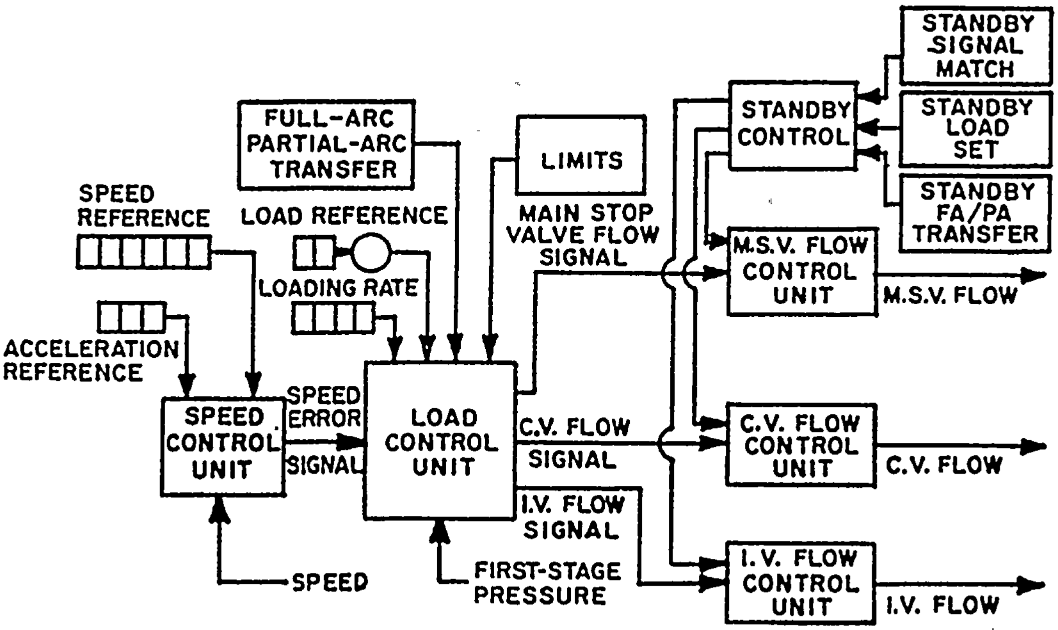


Fig. 47. Operating control system for reheat turbine — EHC Mark II

contact by several orders of magnitude has been introduced for the most important switching functions.

Such techniques were extensively used in the TRIP and MONITORING SYSTEM that will be discussed later.

Power supplies

A 115V, 60 Hz, 7.5 KVA permanent magnet generator (PMG) driven by the turbine is used. Its output is sufficient to supply all operating and emergency circuits of the control system with power in a black-out condition, as long as the turbine is above 90 percent speed.

A 125 VDC system, supplied redundantly by the PMG or the 115 VAC line is used for the protection and test logic external to the cabinet.

A redundantly supplied 24 VDC is used for the analog logic interface in the control cabinet and for the redundant overspeed protection.

Also redundantly supplied are the analog voltages +22 VDC and -22 VDC.

Logic powered by the 125 VDC of the customer's battery can still be used to interface with the EHC logic, if desired.

Standby mode of operation

A STANDBY CONTROL has been added that will permit operation of the unit by manually controlled valve position while the speed control unit and most of the load control unit are disconnected for maintenance and tests.

In this mode of operation the backup overspeed trip, usually set one percent above the mechanical trip speed, will be reset to 105 percent of rated speed, such that the backup overspeed trip assumes the role of the first line of defense against overspeed and the mechanical overspeed trip remains the second line of defense. The power/load unbalance relay and the trip anticipator remain in operation during standby operation.

The transfer to standby operation is manual: a thorough failure analysis on Mark I has shown that the cases in which automatic switch-over would have prevented a shutdown were practically nonexistent and that the additional complexity of an automatic switch-over system and its increased probability of false operation could not be justified.

For smooth transfer the valve position signals are manually matched and the switch-over can only be performed after proper signal matching has been confirmed by logic. An emergency switch-over with unmatched valve signals is possible by pressing an override button, but this should be necessary only in cases of very rare emergencies.

It should be noted that for standby operation the portions of the system listed below still have to operate:

- Power supplies, electrical and hydraulic
- The valve flow controls
- The power/load unbalance
- The trip and monitoring system including back-up overspeed trip and other trip functions

It is possible to start the unit in standby operation, bring it to speed and synchronize it with an acceleration indicator (similar to stop valve bypass startup on mechanical-hydraulic control system), load it part way in full-arc admission, transfer to partial-arc admission and load it further in partial-arc admission, and also a reversal of this sequence. The loading and unloading rates in standby operation are not restricted by the system; the operator has full responsibility.

Protection system

The protection system was built using the following new philosophy:

Three degrees of importance for protections were defined and a concept of redundancy and/or testing was established corresponding to each of the degrees of importance:

- *VITAL PROTECTIONS*, the failure of which could result in a major catastrophe endangering people and equipment

  Shall use CONCEPTUAL REDUNDANCY: sensors, transmission medium, path and output devices of different design and nature

  AND shall be COMPLETELY TESTABLE during normal operation.

- *IMPORTANT PROTECTIONS*, the failure of which would result in increased maintenance but would not endanger people

Shall use EQUIPMENT REDUNDANCY: two-out-of-three or two-out-of-two logic using identical hardware for the three (or two) branches

OR shall be FULLY TESTABLE during normal operation.

- *OPERATIONAL PROTECTIONS* or *LIMIT FUNCTIONS*, the failure of which could cause minor damage or misoperation

Shall use an ALARM when the condition becomes marginal

AND a TRIP of a single function line, when the condition becomes intolerable.

Statistics and failure probability calculations have played an important role in deciding what the degree of importance of a given protection should be and what redundancy and testing features should be used to implement the protection.

The Mark II protection system is shown in block diagram form in Fig. 48. It consists of

- the 125 VDC (EHC) trip and reset logic that handles all trip functions external to the cabinet
- the 24 VDC trip and reset logic functions internal to the cabinet and the 24 VDC electrical trip solenoid valves in the front standard
- the cross trip functions
- the manual trip and reset push buttons
- the overspeed trip reset and test monitoring logic
- the MECHANICAL-HYDRAULIC TRIP SYSTEM at the front standard

The mechanical trip pilot valve, the mechanical shut-off valve and the mechanical trip valve as well as the electrical trip pilot valves and the electrical trip valve have been designed such that there is no close fitting sliding seal under pressure drop during normal operation. Both the mechanical and electrical trip line are fully testable during operation by way of automatic test sequences.

As in the Mark I system, loss of 24 VDC power will trip the unit through the electrical trip valve.

A FIRST HIT monitoring system is provided to help analyze trip incidents and diagnose malfunctions in each one of three groups of equipment; it then determines which of the three groups was first to trip.

Cabinet

The cabinet has been designed for:

- ample room for servicing
- strict circuit separation for elimination of noise
- accommodating four different terminal board designs
- accommodating a standard option package that will be sufficient for most users

The four-bay cabinet is divided into:

- the power supply bay
- the analog bay
- the relay bay
- the terminal strip bay (wide bay)

MARK II CONCLUSION

The Mark II EHC system is the result of an intensive effort to build the most reliable electro-hydraulic control system without departing from the well-proven basic functional principles of its predecessor, the Mark I.

ACKNOWLEDGEMENT

The author wishes to express his appreciation to Patrick C. Callen, George W. Kessler and Paul E. Malone for their assistance in updating this paper.

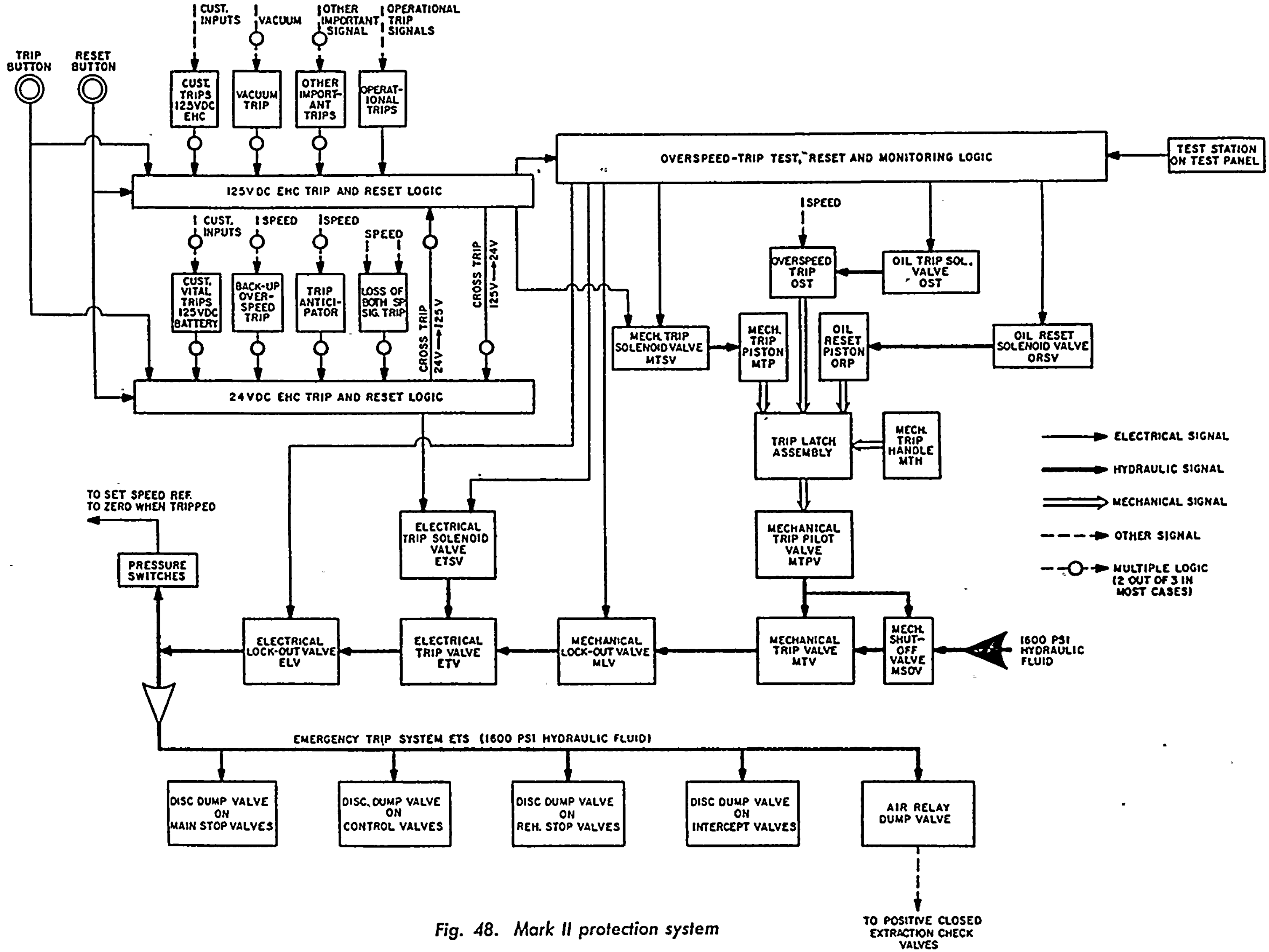


Fig. 48. Mark II protection system

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VALVE TEST LOGIC

(BWR)

GENERAL

See *Schematic Wiring Diagram – Valve Test Logic* following this publication.

The purpose of valve tests is to permit regular checking of the operation of all turbine steam valves during normal ON-LINE OPERATION.

The *Schematic Wiring Diagram – Valve Test Logic* also contains the controlling logic of all non servo-controlled (non positioning) valves.

VALVE TEST FOR CONTROL VALVES

The control valves are tested separately. When the test button of the CV-1 valve is depressed, CV-1 will close at a moderate velocity until, at approximately 1/2-inch of stroke of the servomotor, the fast-acting valve is operated to close the valve rapidly for the remaining stroke. Both the normal operating devices and the fast-acting devices are thereby tested.

When the control valve has closed, and the operator releases the test button, the control valve will open.

All other associated CV's are tested in a like manner.

> NOTE: The operator should test only <u>one</u> control valve at one time. When one test button is released to allow the tested valve to reopen, the opening movement should be observed and the next valve of the set should only be tested after the first one has again assumed normal operating position.

The CV's should be tested weekly.

MULTIPLE ADMISSION UNITS: The following CV testing procedure is recommended for multiple admission units.

Decrease load so that CV-4 is more than 90% closed. Test CV-4 to check the fast-acting valve operation. This procedure will minimize load swing due to CV-4 fast closing.

Continue to decrease load so that CV-3 (3 or 4 admission) or CV-1, 2, 3 (2 admission) have just partially closed. Test CV-1, CV-2, and CV-3 in sequence. This procedure will minimize load swing during CV-1, 2, and 3 test.

The unit may see some bypass valve action to compensate for the pressure increase.

<u>SINGLE ADMISSION UNITS:</u> The following CV testing procedure is recommended for single admission units.

Decrease load to approximately 70% to allow for increased flow pickup in those CV's not being tested. This will minimize load swing. Test each valve in sequence.

VALVE TEST FOR STOP VALVES

INDIVIDUAL TESTING

The stop valves are tested separately. When the test button on the SV-1 valve is depressed, SV-1 will close at a moderate velocity until, at approximately 1-inch of stroke of the servomotor, the fast-acting valve is operated to close the valve rapidly for the remaining stroke. Both the normal operating devices and the fast-acting devices are thereby tested.

When the stop valve has closed, and the operator releases the test button, the stop valve will open.

All other associated SV's are tested in a like manner.

> NOTE: The operator should test only <u>one</u> stop valve at one time. When one test button is released to allow the tested valve to reopen, the opening movement should be observed and the next valve of the set should only be tested after the first one has again assumed normal operating position.

Individual testing should be done daily.

MULTI-TESTING

Any combination of 2 stop valves can be tested simultaneously by pushing the associated test buttons simultaneously. The valves will slowly move to the

0% closed position and stop. When the buttons are released, the valves will re-open.

For multi-testing procedures refer to APED specifications.

VALVE TEST FOR INTERCEPT AND INTERMEDIATE STOP VALVE

The intercept valve and its associated intermediate stop valve are tested together. When the test button of the IV-1/ISV-1 valve combination is depressed, IV-1 will close at a moderate velocity, until, at approximately 1-inch of stroke of the servo-motor, the fast-acting valve is operated to close the valve rapidly for the remaining stroke. Both the normal operating devices and the fast-acting devices are thereby tested.

When the intercept valve has closed, the associated intermediate stop valve starts closing. Again, as mentioned above, both the normal operating devices and the fast-acting devices are thereby tested. When both valves are closed and the operator releases the test button, the intermediate stop valve will open first and afterwards the intercept valve will open.

> NOTE: The operator should test only one intercept/intermediate stop valve combination at one time. When one test button is released to allow the tested valve(s) to reopen, the opening movement should be observed and the next valve of the set should only be tested after the first one has again assumed normal operation.
>
> Combined valves should be tested daily.

The combined valves test circuits also contain the necessary logic to control the slave intercept valves. The slave intercept valve is controlled by means of limit switches, which are mounted on the master intercept valve, and associated relay logic.

VALVE TEST FOR BYPASS VALVES

See *Schematic Wiring Diagram – Bypass Valve Test Logic* included in this Tab. For bypass valve testing procedures refer to APED specifications.

a. Units with selector switch and fast acting operation

   These units are tested individually. The operator chooses the bypass valve to be tested by turning a selector switch. When the operator depresses the valve test button, the selected bypass valve starts opening at a moderate velocity. When the bypass valve is 90% open a fast-acting solenoid valve is operated to open the valve rapidly during the remaining stroke. When the valve is fully open, the operator releases the test button and the valve will close.

   A light will indicate when the next valve can be selected.

   The selector switch is used on units having more than four (4) bypass valves.

   The bypass valve test amplifier is a ramp generator, which opens and closes the bypass valve at a moderate velocity during test.

b. Units with Selector Switch.

   Same as (a) but without fast opening operation.

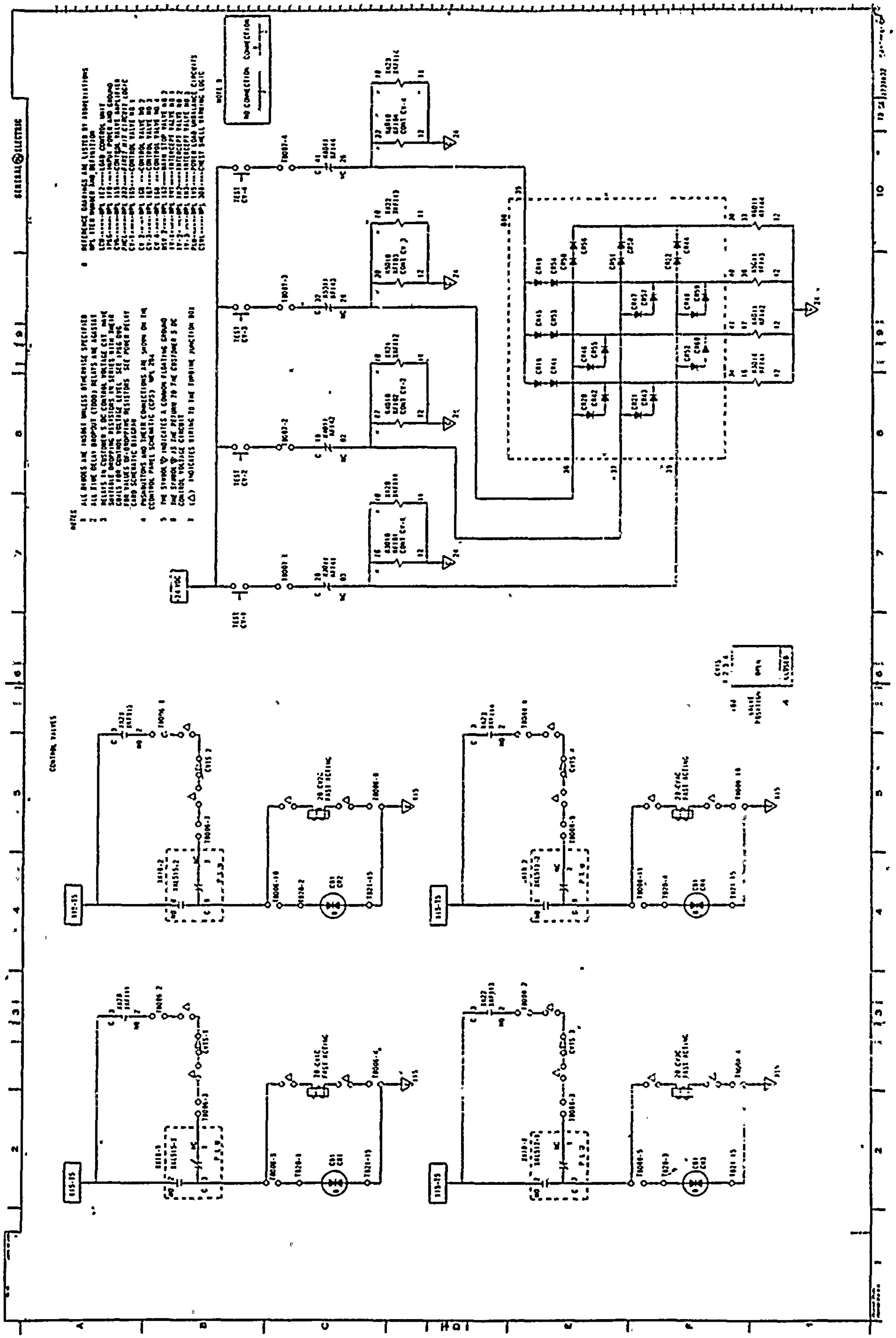
c. Units with Push Buttons and Fast Opening Operation

   These valves are tested individually by depressing the appropriate push button. When the operator depresses the valve test button, the selected bypass valve starts opening at a moderate velocity. When the bypass valve is 90% open, a fast-acting solenoid valve is operated to open the valve rapidly during the remaining stroke. When the valve is fully open, the operator releases the test button and the valve will close.

   A light will indicate when the next valve can be selected.

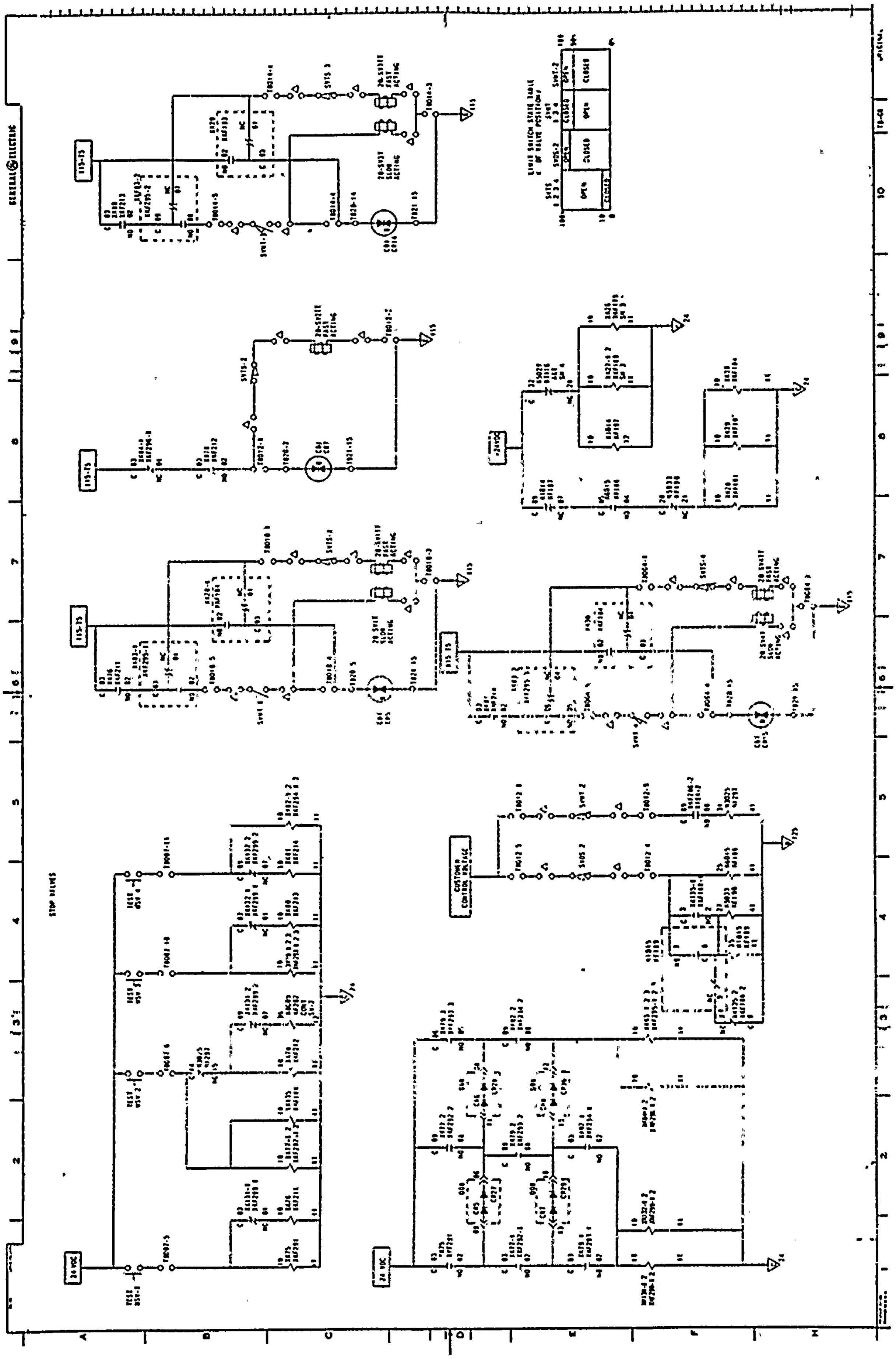
   Push buttons are used on units having up to four (4) bypass valves.

   The bypass valve test amplifier is a ramp generator, which opens and closes the bypass valve at a moderate velocity during test.



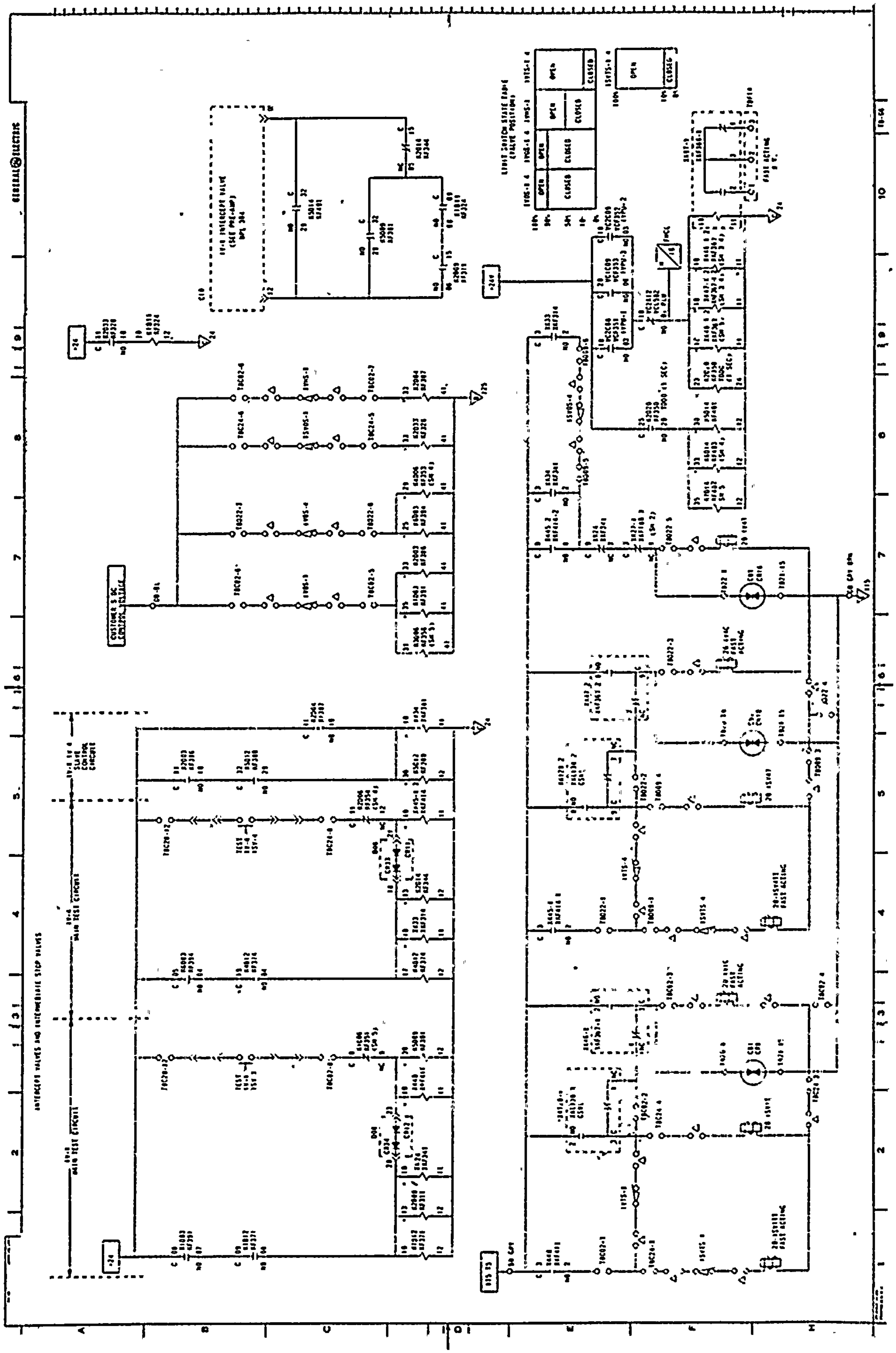
Schematic - Valve Test Logic
Dwg. 133D5133 (Rev. 0) Sh. 1

Fig. 43-14



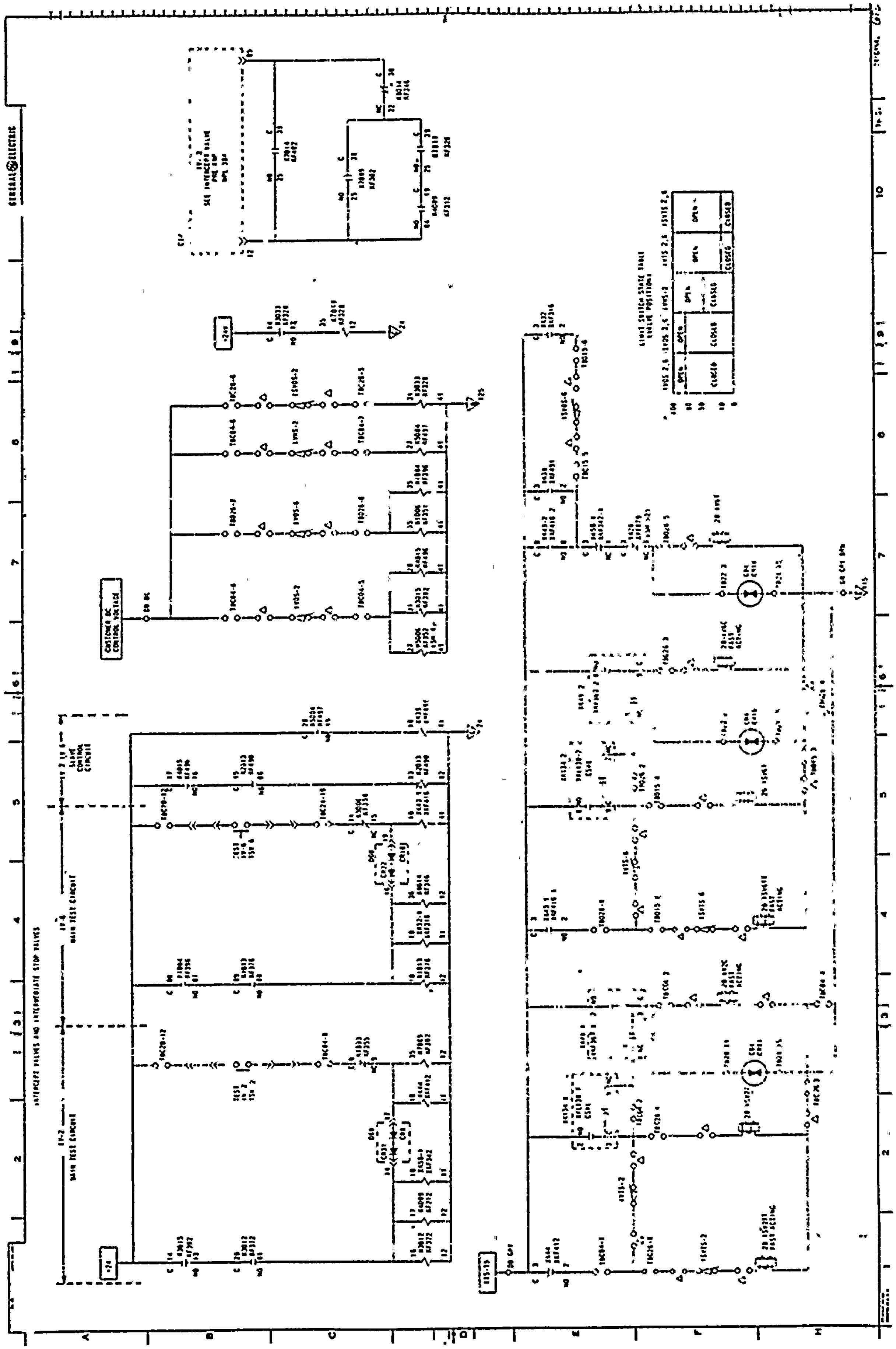
Schematic - Valve Test Logic
Dwg. 133D5133 (Rev. 0) Sh. 2

Fig. 43-14A



Schematic - Valve Test Logic
Dwg. 133D5133 (Rev. 0) Sh. 3

Fig. 43-14B



Schematic - Valve Test Logic
Dwg. 133D5133 (Rev. 0) Sh. 4

Fig. 43-14C